CPAD Instrumentation Frontier Workshop 2021

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Book of Abstracts

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Development of the Mu2e electromagnetic calorimeter mechanical structures

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The "muon-to-electron conversion" (Mu2e) experiment at Fermilab will search for the Charged Lepton Flavour Violating neutrino-less coherent conversion μ-N(A,Z) → e-N(A,Z) of a negative muon into an electron in the field of an aluminum nucleus. The observation of this process would be the unambiguous evidence of physics beyond the Standard Model. Mu2e detectors comprise a straw-tracker, an electromagnetic calorimeter and an external veto for cosmic rays. The calorimeter provides excellent electron identification, complementary information to aid pattern recognition and

track reconstruction, and a fast online trigger. The detector has been designed as a state-of-the-art crystal calorimeter and employs 1340 pure Cesium Iodide (CsI) crystals readout by UV-extended silicon photosensors and fast front-end and digitization electronics. A design consisting of two annular disks positioned at the relative distance of 70 cm downstream the aluminum target along the muon beamline satisfies Mu2e physics requirements.
The hostile Mu2e operational conditions, in terms of radiation levels, 1 tesla magnetic field and 10^-4 Torr vacuum have posed tight constraints on the design of the detector mechanical structures and materials choice. The support structure of the two 670 crystals matrices employs two aluminum hollow rings and parts made of open-cell vacuum-compatible carbon fiber. The photosensors and front-end electronics associated to each crystal are assembled in a unique mechanical unit inserted in a machined copper holder. The 670 units are supported by a machined plate made of vacuum-compatible plastic material. The plate also integrates the cooling system made of a network of copper lines flowing a low temperature radiation-hard fluid and placed in thermal contact with the copper holders to constitute a low resistance thermal bridge. The digitization electronics is hosted in aluminum crates positioned on the external surfaces of the two disks. The crates also integrate the digitization electronics cooling system as lines running in parallel to the front-end system.
In this talk we will review the constraints on the calorimeter mechanical structures, the mechanical and thermal simulations that have determined the design technological choices, and the status of components production, tests and assembly.

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Metastable Liquids: Breakthrough Technologies for Dark Matter and Neutrinos

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We will present a discussion of our revolutionary new detector technology, the "Snowball Chamber," which is based on the phase transition (of liquid to solid) for metastable fluids, and has been shown to be neutron-sensitive. A water-based supercooled detector has the potential to move past the Neutrino "Fog," and extend the reach of direct detection dark matter experiments to GeV-scale WIMP candidates for both proton spin-dependent and spin-independent interactions. We also will consider supercooled noble elements to observe scintillation for energy reconstruction. Some of the foreseeable, potential pitfalls will be presented, alongside a brief vision of an R&D program toward the maturation of this technology. A host of related measurements within neutrino physics, utilizing the CEvNS interaction on different nuclei, and/or the potential of these detectors to track electron and gamma-ray interactions, is likewise possible. Low-cost and modular designs would enable searches for sterile neutrinos with a total neutral current disappearance experiment at multiple baselines. A large-scale world-wide deployment would also play an important role for supernova neutrino burst detection. A detector using deuterated water could be a viable technology for normalizing low-energy neutrino fluxes from stopped-pion beams. Lastly, liquid Xe and Ar versions will be discussed with their benefits.

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Development of the Mu2e electromagnetic calorimeter front-end and readout electronics

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The "muon-to-electron conversion" (Mu2e) experiment at Fermilab will search for the Charged Lepton Flavour Violating neutrino-less coherent conversion ⊠-N(A,Z) ⊠ e-N(A,Z) of a negative muon into an electron in the field of an aluminum nucleus. The observation of this process would be the unambiguous evidence of physics beyond the Standard Model. Mu2e detectors comprise a straw-tracker, an electromagnetic calorimeter and an external veto for cosmic rays. The calorimeter provides excellent electron identification, complementary information to aid pattern recognition and track reconstruction, and a fast online trigger. The detector has been designed as a state-of-the-art crystal calorimeter and employs 1348 pure Cesium Iodide (CsI) crystals readout by UV-extended silicon photomultipliers (SiPM) and fast front-end and digitization electronics. A design consisting of two annular disks positioned at the relative distance of 70 cm downstream the aluminum target along the muon beamline satisfies Mu2e physics requirements.
The front-end electronics consists of two discrete chips (Amp-HV) for each CsI crystal directly connected to the back of the SiPM pins. These provide the amplification and shaping stage, a local linear regulation of the SiPM bias voltage, monitoring of current and temperature of the sensors and a test pulse. The SiPM and front-end control electronics is implemented in a battery of mezzanine boards each equipped with an ARM processor that controls a group of 20 Amp-HV chips, distributes the low voltage and the high-voltage reference values, sets and reads back the locally regulated voltages. The mezzanine boards are hosted in crates located on the external lateral surface of the calorimeter disks. The crates also host the waveform digitizer board that perform digitization of the amplified and shaped SiPM signals and transmit the digitized data to the Mu2e DAQ. The core of the DIRAC board is a large FPGA SoC (MicroSemi® SmartFusion2 M2S150T), that handles 10 ultralow-power double channels 12 bits and maximum sample rate of 250 MSPS analog-to-digital converters ADCs (Texas Instruments® ADS4229) protocol and timing, sparsifies and compresses the digitized data and forms a packet that is sent optically, thru a dual fiber optical transceiver (Cotswork® RJ-5G-SX-DPLX) to the event builder using a custom protocol.
In this talk we will review the constraints on the calorimeter front-end and readout electronics, the design technological choices, and the status of components production, tests and commissioning.

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Mu2e TDAQ and slow control systems

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The muon campus program at Fermilab includes the Mu2e experiment that will search for a charged-lepton flavor violating processes where a negative muon converts into an electron in the field of an aluminum nucleus, improving by four orders of magnitude the search sensitivity reached so far.
Mu2e's Trigger and Data Acquisition System (TDAQ) uses {\it otsdaq} as its solution. Developed at Fermilab, {\it otsdaq} uses the {\it artdaq} DAQ framework and {\it art} analysis framework, under-the-hood, for event transfer, filtering, and processing.
{\it otsdaq} is an online DAQ software suite with a focus on flexibility and scalability, while providing a multi-user, web-based, interface accessible through a web browser.
The detector Read Out Controller (ROC), from the tracker and calorimeter, stream out zero-suppressed data continuously to the Data Transfer Controller (DTC). Data is then read by a software filter algorithm that selects events considering data flux that comes from a Cosmic Ray Veto System (CRV).

A Detector Control System (DCS) for monitoring, controlling, alarming, and archiving has been developed using the Experimental Physics and Industrial Control System (EPICS) open source Platform. The DCS System has also been integrated into {\it otsdaq}.
A prototype of the TDAQ and the DCS systems has been built at Fermilab's Feynman Computing Center. We report the developments and achievements of the integration of Mu2e's DCS system into the online {\it otsdaq} software.

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Neutrinos

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Explore the Unknown

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Closing Remarks and Road Ahead

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Summary of Quantum Sensors

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Summary of Noble Elements

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Summary of Photodetectors

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Summary of Gaseous Detectors

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Noble Elements / 28

Wavelength-Shifting Performance of Polyethylene Naphthalate Films in a Liquid Argon Environment

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Liquid argon is commonly used as a detector medium for neutrino physics and dark matter experiments in part due to its copious scintillation light production in response to its excitation and ionization by charged particle interactions. As argon scintillation appears in the vacuum ultraviolet (VUV) regime and is difficult to detect, wavelength-shifting materials are typically used to convert VUV light to visible wavelengths more easily detectable by conventional means. Here we present the results of recent investigations into the wavelength-shifting and optical properties of polyethylene naphthalate (PEN), a proposed alternative to tetraphenyl butadiene (TPB), the most widely-used wavelength-shifter in argon-based experiments.

Noble Elements / 29

Designing and building a pair of scintillating bubble chambers for WIMPs and reactor CEvNS

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The Scintillating Bubble Chamber (SBC) is a rapidly developing novel technique for 0.7 - 7 GeV nuclear recoil detection. Demonstrations in liquid xenon at the few-gram scale have confirmed that this technique combines the event-by-event energy resolution of a liquid-noble scintillation detector with the world-leading electron-recoil discrimination capability of the bubble chamber, and in fact maintains that discrimination capability at much lower thresholds than traditional Freon-based bubble chambers. The promise of unambiguous identification of sub-keV nuclear recoils in a scalable detector makes this an ideal technology for both GeV-mass WIMP searches and CEvNS detection at reactor sites. We will present progress from the SBC Collaboration towards the construction of a pair of 10-kg argon bubble chambers at Fermilab and SNOLAB to test the low-threshold performance of this technique in a physics-scale device and search for dark matter, respectively.

Noble Elements / 30

Using Photo-converting Dopants to Improve Large LArTPC Performance

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A challenge in large LArTPCs is efficient photon collection for low energy, MeV-scale, deposits. Past studies have demonstrated that augmenting traditional ionization-based calorimetry with information from the scintillation signals can greatly improve the precision of measurements of energy deposited. We propose the use of photo-converting dopants to efficiently convert the scintillation signals of the liquid argon directly into ionization signals. This could enable the collection of more

than 40% of all the scintillation signal, a considerable improvement over conventional light collection solutions. We will discuss the implications this can have on LArTPC physics programs, what hints of performance improvements we can gather from past studies, and what R&D we envision are needed to establish using these dopants in large LArTPCs.

Gaseous Detectors / 31

Options for gain elements and gas mixtures in a high rate EIC Time Projection Chamber

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In order to investigate options for a future high rate TPC we have tested various gas gain structures and gas mixtures. Our goal was to focus on crucial TPC parameters: ion back flow, energy resolution (dE/dx), electron and ion drift speed, electron diffusion (in E- and B-fields), and stability. We concentrated on two options for the gain structure: 4 GEMs and MMG+2GEMs. For the hybrid option we achieve simultaneously an ion back flow below 0.3% and an energy resolution better than 12% for 55Fe X-rays at a gain of ≈2000 in a variety of gas mixtures. A few gas mixtures that we studied haven't typically been used in a TPC, but appear promising, and further testing is recommended. Additionally, we investigated a potential instability (especially for MMGs) that occurs primarily from a high voltage (HV) power supply (PS) voltage drop in reaction to a discharge. It was demonstrated that a resistive protection layer on a pad / strip readout structure reduces the HV PS voltage drop after a spark to practically negligible levels. The hybrid micro-pattern gas amplification stage allows for a TPC design that can operate in a continuous mode, serves as a viable option to limit space charge distortions in high-rate TPCs, and guarantees that dE/dx, ionization cluster space reconstruction resolution, drift parameters and detector stability will not be compromised.

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2021 DPF Instrumentation Award

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2020 GIRA Award - Runner up

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2020 GIRA Award

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Picosecond Timing Layers for Future Calorimeters: Updates from the Askaryan Calorimeter Experiment (ACE)

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We report on new results and simulations from the Askaryan Calorimeter Experiment (ACE) which uses the coherent microwave Cherenkov emission from high energy particle showers in dielectric-loaded waveguides as calorimetric timing layers with ~1 ps resolution. Above ACE's energy threshold, a single 5 cm thick (1.4 X_0) layer of ACE waveguides would provide ~1 ps timing resolution, 3D spatial constraints on the scale of ~300 μm - 5 mm, and an additional energy measurement, making ACE a true 5D detector. When embedded inside another calorimeter technology, ACE timing layers could provide a powerful additional measurement for particle-flow reconstruction algorithms as well as unique vertexing capabilities to significantly reduce pileup. Due to thermal noise limits, ACE elements have a relatively high energy threshold so they are currently limited to future high CoM colliders like the proposed 100 TeV FCC-hh. We report on new simulation results from deploying ACE timing layers in the barrel and forward calorimeters at a future 100 TeV CoM collider and discuss ongoing research to further develop and improve the ACE detector concept.

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TPC Development by the LCTPC Collaboration for the ILD Detector at ILC

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A large, worldwide community of physicists is working to realise an exceptional physics program of energy-frontier, electron-positron collisions with the International Linear Collider (ILC). The International Large Detector (ILD) is one of the proposed detector concepts at the ILC. The ILD tracking system consists of a Si vertex detector, forward tracking disks and a large volume Time Projection Chamber (TPC) embedded in a 3.5 T solenoidal field. An extensive research and development program for a TPC has been carried out within the framework of the LCTPC collaboration. A Large Prototype TPC in a 1 T magnetic field, which allows to accommodate up to seven identical Micropattern Gas Detector (MPGD) readout modules of the near-final proposed design for ILD, has been built as a demonstrator at the 5 GeV electron test-beam at DESY. Three MPGD concepts are being developed for the TPC: Gas Electron Multiplier, Micromegas and GridPix. Successful test beam campaigns with different technologies have been carried out between 2014 and 2019. Fundamental parameters such as transverse and longitudinal spatial resolution and drift velocity have been measured. In parallel, a new gating device based on large-aperture GEMs have been produced and studied in the laboratory. In this talk, we will review the track reconstruction performance results and summarize the next steps towards the TPC construction for the ILD detector.

Photodetectors / 38

Time resolution and efficiency of SPADs and SiPMs for photons and charged particles

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Single-photon avalanche diodes (SPADs) and silicon photomultipliers (SiPMs) are important tools for the detection and counting of single photons with excellent timing capabilities. I will give an overview of the physical mechanisms that determine the time resolution and the efficiency of these detectors. I will show calculations indicating that single-photon time resolutions of better than 10 ps should be achievable at high electric fields. The same arguments suggest that SPADs and SiPMs can also be used as detectors for charged particles with high efficiency and comparable time resolution.

Based on https://arxiv.org/abs/2102.00091 and https://arxiv.org/abs/2012.11285

Detector R&D Townhall / 39

Thoughts from the DOE

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overview of KA25 program
funding opportunities
special initiatives
after the BRN
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Noble Elements / 40

Modeling xenon and argon physics with the Noble Element Simulation Technique (NEST)

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As noble elements like liquid xenon and argon have become an indispensable mode of particle detection, it has become increasingly crucial to understand and model their intrinsic physics. The Noble Element Simulation Technique (NEST) allows us to do this by offering a comprehensive, mature framework to simulate the atomic and nuclear physics of energy deposition and the resulting detector response in xenon and argon detectors. On behalf of the NEST collaboration, I will present the most important features of the NEST model, including light and charge yields of various interactions, the physics of recombination fluctuations, and energy resolution. I will also present our recent updates to implement the models in Python, further develop the argon models, and build an updated model for electronic recoils in xenon. Finally, I will discuss how NEST fits into the grand challenges, science drivers, technical requirements, and priority research directions identified in the 2020 BRN for HEP Detector Research and Development. NEST is most directly applicable to PRD 6, "Improve the understanding of detector microphysics and characterization," but our models and code are also useful for understanding signals and backgrounds, signal reconstruction, the challenges associated with scaling-up detectors, and other challenges.

Award and Blue Sky Plenary / 41

Large Area SiPMs for Ton-scale $0\nu\beta\beta$

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nEXO is a 5 tonne monolithic liquid xenon (LXe) time projection chamber (TPC) planned to search for the neutrinoless double beta decay of Xe-136 with an estimated half-life sensitivity of ~10^28 years at 90% C.L.. Scintillation light from events in the detector will be collected with 4.5 m^2 of Silicon Photomultipliers (SiPMs), which over the last decade have matured substantially and have become a preferred alternative to traditional light detection solutions. Their key features are low radioactive background, single-photon resolution, low bias voltage and geometrically efficient scaling to large areas. In this talk I will discuss techniques that were developed by nEXO to fully characterize the performance of the devices and integrate them into large area arrays that meet stringent requirements in therms of radio-purity and LXe purity. In addition, I will show how more dedicated simulation tools, such as GPU-accelerated ray tracing software, can be powerful in evaluating and optimizing the detector design based on R&D input.

Solid State Vertexing and Tracking / 42

New Approaches to Fine Granularity Timing Detectors

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A collaboration involving a US National Laboratory (Brookhaven National Laboratory), a private-sector technology company (Cactus Materials, Inc.) and a University institute (the Santa Cruz Institute for Particle Physics at the University of California, Santa Cruz) has been working on new approaches to the development of highly-granular timing layers for minimum-ionizing particle and X-Ray detection. Progress has been made in the design and prototyping of the Deep Junction LGAD, a novel approach to the implementation of impact-ionization gain in silicon diode detectors that allows for the reduction of the granularity scale to below 100 microns, while maintaining DC coupling to the readout electrodes. Work is also progressing on high-density interconnect ("3D Integration") technology geared towards the enabling of commensurate high-density readout of granular systems. Progress in both of these areas will be presented.

Calorimetry / 43

Dose rate effects in radiation damage of plastic scintillator

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Sampling calorimeters for high energy physics experiments often use plastic scintillator as the active medium due to its low cost and ease of use. However, response to radiation damage is a critical factor in detector design. This talk will present the effects of ionizing radiation on the signal produced by plastic scintillator rods for various substrate materials, dopant concentrations, fluors, anti-oxidant concentrations, scintillator thicknesses, and dose rates. The light output is measured, before and after irradiation, using an alpha source and a photomultiplier tube, and the light transmission by a spectrophotometer. The change in light output is quantified using the exponential dose constant D. The D values are similar for primary and secondary doping concentrations of 1 and 2 times, and anti-oxidant concentrations of 0, 1, and 2 times the default manufacturer's value. The D value depends approximately linearly on the dose rate's logarithm for dose rates between 2.2 Gy/hr and 70 Gy/hr for all materials. Above 70 Gy/hr, for polyvinyltoluene-based scintillators, the dose constant is constant or continues to rise, while for polystyrene-based scintillators, it remains constant or decreases, depending on doping concentration. The results from rods of varying thickness and different fluor concentrations suggest that damage to the initial light output is a larger effect than color center formation. For the blue scintillator (EJ-200), the transmission measurements indicate damage to the fluors.

Cross Cutting Plenary / 44

Fast imaging of single photons for astronomical applications

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Fast imaging of optical photons may play important role not only in particle physics experiments but also in astronomical observations. It has been recently suggested that optical interferometers would not require a phase-stable optical link between the stations if instead sources of quantum-mechanically entangled pairs could be provided to them, enabling extra-long baselines and, therefore, much improved astrometrical precision. To efficiently interfere the photons must be close enough in time and frequency or, formulating it differently, to be indistinguishable within the Heisenberg uncertainty principle. This sets stringent requirements on temporal measurements needed to determinate the two-photon correlators. Here we discuss requirements on the instrument for those observations, in particular, on its temporal and spectral resolution. We will also discuss possible technologies for the instrument implementation and first proof-of-principle experiments.

Calorimetry / 45

Calorimeter performance studies using Monte Carlo simulations for future collider detectors

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Performance requirements for future calorimeter designs in the context of reconstruction of tens-of-TeV jets at 100 TeV colliders are discussed. Lateral cell segmentation was studied by reconstructing

substructure variables for hadronic jets above 10~TeV in transverse momentum using the Geant4 simulations with a different granularity of calorimeter cells. The physics potential of timing layers in calorimeters with a few tens of pico-second resolution is also explored. These studies show how calorimeters with precise timing information can be used for particle identification. We also illustrate the potential of precise timing information for detecting new event signatures originating from physics beyond the standard model.

TDAQ / 46

Does anybody really know the time it is?

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Every timing detector needs to know the time, and every timing detector needs to refer to the same reference clock. As we push the limits of the timing precision of new detectors, we need to distribute to these detectors a reference clock that has a precision that is much better than the detector's. In this presentation we will describe how we have demonstrated the feasibility of delivering multiple reference clocks, with an inter-clock precision of less than 0.5 picoseconds, how to measure small changes between the clocks due to environmental and other effects, and how to correct them in real time.

Gaseous Detectors / 47

A High-Pressure Gaseous-Argon TPC as a Component of DUNE Near Detector

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The main goals of the Deep Underground Neutrino Experiment (DUNE) are to measure CP violation in the lepton sector, to make precise measurements of neutrino oscillation parameters, to observe supernova burst neutrinos, and to detect rare processes such as proton decay. To fulfill these goals, DUNE will use a highly capable suite of near detectors with several components, one of which is the high-pressure gaseous-argon TPC (HPgTPC) surrounded by a calorimeter and a magnet. As a fine-grained tracker with a low detection threshold, HPgTPC is capable of measuring one of the most crucial sources of systematic uncertainties in neutrino oscillation measurements: nuclear effects in argon at the neutrino interaction vertex. In this talk, an overview of the HPgTPC design and the on-going R&D efforts will be presented.

Noble Elements / 48

A Digital Tension Measurement Device for Multi-Wire Particle Detectors

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We present s a novel and efficient device to measure wire tensions in particle physics detectors. Traditionally, a common method was to physically pluck each wire and detect its natural frequency with a laser.
In this new method, an alternating electric field across the neighboring wires vibrates the test wire in the middle. Due to the corresponding change in capacitance, a bipolar resonance in current amplitude can be detected when the wire's oscillation reaches its natural frequency.
This device can test multiple wires in parallel, and combined with the automation of the oscillation, it enables to considerably shorten the time taken by the quality check of the detectors.

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A Dual-Readout Calorimeter with a Crystal ECAL for Future e+e- Higgs Factories

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In the past, homogeneous electromagnetic calorimeters have allowed precision measurements of electrons and photons, while high granularity, dual-readout, and compensating calorimeters have been considered promising paths for improving hadronic measurements. In this talk, the possibility of using a homogeneous high-granularity crystal electromagnetic calorimeter using SiPMs photodetectors with a wavelength sensitivity with a spaghetti hadronic calorimeter with clear and scintillating fibers is explored using simulation. By employing wavelength and timing measurement in both calorimeters, the excellent electromagnetic resolution typical of crystal calorimeters is preserved, and the excellent hadronic resolutions are enabled for particle momentum ranges important to physics at future Higgs factories. We also discuss past experimental tests of components of this system, and plans for future integrated tests.

Solid State Vertexing and Tracking / 50

Development of AC-LGADs for large-scale high-precision time and position measurements

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We present here measurements on AC-LGADs that can be made with greater segmentation than the DC-coupled devices planned for the HL-LHC. The new devices maintain a 100 % fill factor for charge collection. This is achieved by employing un-segmented (p-type) gain layer and (n-type) N-layer separated from metal readout pads by a thin dielectric layer. The design allows great flexibility in the choice of the geometry of the metal readout pads, which can be sparsely located. High spatial precision can be achieved by using the information from multiple pads, exploiting the intrinsic signal sharing provided by the common N-layer. The sharing is determined by the pitch and size of the pads. Excellent time resolution, similar to the DC coupled LGADs at comparable gain, results from the gain layer. Using data collected with IR-laser scans we explore the dependence of the detector performance on some of the major sensor parameters: sheet resistance and termination resistance of the N-layer, thickness of the isolation dielectric, and pitch and size of the readout pads.

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Development of Novel Inorganic Scintillators for Future High Energy Physics Experiments

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Development of Novel Inorganic Scintillators for Future High Energy Physics Experiments

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Total absorption electromagnetic calorimeters (ECAL) made of inorganic crystals provide the best energy resolution and detection efficiency for photon and electron measurements, so are the choice for those HEP experiments where high resolution is required. Recent HEP applications are the CMS PWO ECAL [1], the g-2 PbF2 ECAL [2], the Mu2e CsI ECAL [3] and the CMS LYSO-based barrel timing layer (BTL) detector [4]. Novel crystal detectors are continuously being discovered in academia and in industry. We report recent progress on novel inorganic scintillators of three categories for future HEP experiments at the energy and intensity frontiers. They are (1) bright, fast, radiation hard inorganic scintillators, such as LYSO:Ce crystals and LuAG:Ce ceramics, for an ultra-compact and radiation hard ECAL at the HL-LHC and FCC-hh, (2) ultrafast crystals, such as BaF2:Y, for an ultrafast calorimeter and a precision time of flight (TOF) detector, and (3) cost-effective inorganic scintillators for a homogeneous hadron calorimeter at a future lepton Higgs factory collider, such as the ILC or FCC-ee.

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Calorimetry for the Electron Ion Collider

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The Electron Ion Collider (EIC) is a new facility that has been proposed in the US to study the structure of nuclear matter in the gluon dominated regime of QCD using Deep Inelastic Scattering (DIS) with precision electromagnetic probes. The project received DOE CD-0 approval in January 2020 and will be sited at Brookhaven National Laboratory. It will utilize the existing RHIC collider to provide beams of polarized electrons in the energy range from 2.5-18 GeV to collide with heavy ions in the energy range from 10-100 GeV/A and protons up to 275 GeV/c. It will require major new detector systems to measure the scattered electron with high precision and full calorimeter, tracking and particle id systems to reconstruct the overall event. The physics and detector requirements were recently summarized in a Yellow Report prepared by the EIC Users Group which includes a conceptual design for a baseline Reference Detector along with many other details. This talk will focus on the calorimeter systems for an EIC detector and describe some of the detector technologies that are being considered, along with results from a generic Detector R&D program that has explored some of these technologies over the past 10 years.

Readout and ASIC / **53**

The VMM ASIC - From R&D to production

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The VMM3a is a System on Chip (SoC) custom Application Specific Integrated Circuit (ASIC). It is the production version which will be used as the front ASIC for both Micromegas and sTGC detectors of the ATLAS Muon New Small Wheels upgrade. Due to its highly configurable parameters it can be used in a variety of tracking detectors and it is already proposed for another experiments. It is fabricated in the 130nm Global Foundries 8RF-DM process. The ASIC integrates 64 channels, each providing charge amplification, discrimination, neighbour logic, amplitude and timing measurements, analog-to-digital conversions, and either direct output for trigger or multiplexed readout within a data-driven readout system. The front-end amplifier can operate with a wide range of input capacitances, has adjustable polarity, gain and peaking time. The ASIC has been tested on resistive Micromegas and sTGC prototypes in test beam campaigns at CERN. The roadmap from R&D to production and the performance of the VMM3a at the production stage will be presented. Moreover the yield of the 70'000 production ASICs will be presented.

Noble Elements / 54

QPIX, a novel pixel technology for very large noble element detectors

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A large pixelated liquid argon detector could offer great advantages in studying neutrinos. The 3D imaging capabilities of such a detector could enhance and expand the physics reach of future large-scale detectors such as DUNE. We will present the current status of the Q-Pix development. This novel concept uses continuously integrating low-power charge-sensitive chips that sends signals once the accumulated charge has reached a certain threshold. The time differences between these signals provide a powerful tool to study events from a wide range of energies. After reviewing the Q-Pix concept, we will discuss the recent developments in producing and testing the Q-Pix chips.

Photodetectors / 55

A SiPM for the readout of the fast component of barium fluoride

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Barium fluoride (BaF_2) has a scintillation light component with a decay time shorter than 600 ps, the fastest of any inorganic scintillator, and is also quite radiation hard. This makes BaF_2 an excellent candidate for an electromagnetic calorimeter for the next generation of rare decay experiments, as it could provide superb time resolution, high rate capability and excellent radiation hardness. In addition to future high energy physics and nuclear physics experiments a BaF_2 calorimeter would find use in GHz hard x-ray imaging for future X-ray Free Electron Laser (XFEL) facilities and PET scanning.

The use of BaF_2 in such applications has, however, been stymied by several difficulties: 1) the fast scintillation component peak is at 220 nm, a difficult VUV wavelength for photon detection, and 2) there is a much larger 650 ns scintillation component nearby at 300 nm, which would cause pileup and noise in an ultrafast environment.

The past several years have seen significant progress in confronting these issues by attacking the problems in two ways: doping BaF_2 with yttrium to significantly reduce the slow component (the subject of a separate submission by R.-Y. Zhu), and developing a photosensor that has excellent sensitivity at 220 nm while having greatly reduced response at 300 nm, the subject of this paper.

Working with FBK and JPL, we have produced a first version a SiPM well-matched to BaF_2 readout. The sensor consists of 3 x 2 array of 6mm x 6mm SiPMs that incorporate a three-layer interference filter. We have measured a PDE of ~30% at the fast component, with efficiency at the slow component reduced by a factor of about 5. These devices have been employed to read out BaF_2 crystals with good signal-to-noise performance.

We next plan to improve these SiPMs in two important ways. The filter performance can be substantially improved using a five-layer interference filter, and these techniques can be employed to fabricate a back-illuminated device incorporating a delta-doped structure that will substantially improve UV radiation hardness, PDE and timing characteristics.

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Advanced Optical Instrumentation for Ultra-compact, Radiation Hard, Fast-timing EM Calorimetry

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To address the challenges of providing high performance calorimetry and other types of instrumentation in future experiments under high luminosity and difficult radiation and pileup conditions, R&D is being conducted on promising optical-based technologies that can inform the design of future detectors, with emphasis on ultra-compactness, excellent energy resolution and spatial resolution, and especially fast timing capability.

The strategy builds upon the following concepts: use of dense materials to minimize the cross sections and lengths (depths) of detector elements; maintaining Molière Radii of the structures as small as possible; use of radiation-hard materials; use of optical techniques that can provide high efficiency and fast response while keeping optical paths as short as possible; and use of radiation resistant, high efficiency photosensors.

High material density is achieved by using thin layers of tungsten absorber interleaved with active layers of dense, highly efficient crystal or ceramic scintillator. Several scintillator approaches are currently being explored, including rare-earth 3+ activated materials Ce3+ and Pr3+ for brightness and Ca co-doping for improved (faster) fluorescence decay time.

Light collection and transfer from the scintillation layers to photosensors is enabled by the development and refinement of new waveshifters (WLS) and the incorporation of these materials into radiation hard quartz waveguide elements. WLS dye developments include fast organic dyes of the DSB1 type, ESIPT (excited state intermolecular proton transfer) dyes having very large Stokes' Shifts and hence very low optical self-absorption, and inorganic fluorescent materials such as LuAG:Ce, which is noted for its radiation resistance.

Optical waveguide approaches include thick-wall quartz capillaries containing WLS cores to: (1) provide high resolution EM energy measurement; (2) with WLS materials strategically placed at the location of the EM shower maximum to provide high resolution timing of EM showers, and (3) with WLS shifter elements placed at various depth locations to provide depth segmentation measurement of the EM shower development.

Light directly from the scintillators or indirectly via wave shifters is detected by pixelated, Geiger-mode photosensors that have high quantum efficiency over a wide spectral range and designed to avoid saturation. These include the development of very small pixel (5-7 micron) silicon photomultiplier devices (SiPM) operated at low gain and cooled (typically -35℃ or below), and longer-term R&D on photosensors based upon large band-gap materials including GaInP. Both efforts are directed toward improved device performance in high radiation fields.

The main emphases of this research program are: (1) the bench, beam and radiation testing of individual scintillator, wave shifter and photo sensing elements; and (2) by combining these into ultra-compact modular structures, to characterize and assess their performance for measurement of energy, fast timing, and depth segmentation. Recent results and program plans will be presented.

Calorimetry / 57

Advanced R&D of the dual-readout calorimeter for future collider projects

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We present various R&Ds of the dual-readout calorimeter for future collider projects. This presentation is based on six letters of interest submitted to Snowmass 2021 and they proposed various interesting studies related to the dual-readout calorimeter. In the letters, following topics are for future e+e- collider experiments (FCC-ee and CEPC): 1) fast optical photon transport at GEANT4, 2) tau reconstruction and identification using ML, 3) sensitivity study of Higgs decaying to Zgamma, 4) feasibility study of combining a MTD, and 5) heavy flavour tagging using ML with a silicon vertex detector. In addition, we are also interested in applying the dual-readout calorimeter detector for future Electron-Ion collider (EIC) experiment. In this presentation, we will discuss our idea, plan and status of the proposed topics.

Photodetectors / 58

Thickness Uniformity of Amorphous Selenium Films Utilizing the University of California, Santa Cruz Fabrication Facility

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Amorphous selenium (a-Se) is a glass-former capable of deposition at high rates by thermal evaporation over a large area. It has a bandgap of 2.2 eV and can achieve a photodetection efficiency of approximately 90% at a wavelength of 400 nm. The optical photogeneration efficiency in a-Se depends on the photon energy, the applied electric field and temperature. The Onsager approach has been used to explain the dependency of photogeneration efficiency in a-Se to the applied electric field, incident wavelength and temperature. Juska, et al., first observed avalanche multiplication in a-Se in 1980 while they were studying the photogeneration efficiency and mobility of electrons and holes in a-Se at high electric fields. Low dark current, impact ionization, large area capability, and low fabrication cost makes a-Se attractive for direct detection in X-ray imaging and indirect detection to detect short wavelengths (<450nm). When fabricating a-Se over a large area, thickness uniformity is important to achieve similar performance across the area.

In this paper we will describe the simulation and experimental results of fabricating uniform a-Se films over a 4 inch by 4 inch area. Thermal evaporation in the molecular flow regime was simulated in COMSOL with the chamber geometry and two different furnaces (boat and crucible). An optimized source-substrate throw distance and source geometry were determined for uniform selenium evaporation. It was shown that uniformity of 95-97% over a 4 inch diameter and 98-99% over a 2

inch diameter at throw distances of 13-17 inch using both crucible and boat geometries are possible. A recipe for fabrication of an a-Se film from stabilized a-Se alloy (containing 0.3% Arsenic: As and 10 ppm Chlorine: Cl), with thickness of 15 µm was developed on a glass substrate with maximum throw distance (17 inch). We will report on the uniformity measurement of 25 samples fabricated using the developed recipe and will discuss an optimized device structure based on a-Se for high photon detection efficiency to UV light.

Photodetectors / 59

Transparent Thermoplastic Acrylic Scintillator

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Active shielding is essential in modern experimental particle physics, it provides a robust means to cross-check the potential signal of the main detector. The liquid scintillator (LS) is widely used in neutrino and dark matter physics. Their high light yield, long term stability and potential for mass production makes them an ideal material for large scale detectors. However, the production of high purity scintillators is not trivial and the liquid scintillator has to be contained in UV-transparent containers that leads to design constraints. We propose a new type of veto scintillator by doping LS into acrylic. Acrylic is a commonly used material in experimental particle physics with well-known properties. Such acrylic scintillators have the potential to be mechanically strong, inexpensive and stable. In addition, by doping different rare earths one can build multilayer detectors that enable particle discrimination.

Gaseous Detectors / 60

The CYGNO TPC: Optical Readout for Directional Study of Rare Events

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CYGNO is a project realising a cubic meter demonstrator to study the scalability of the optical readout concept for a large-volume, GEM-equipped TPC,
to be employed as directional detectors for rare events detection.
The combined use of high-granularity sCMOS and fast sensors for reading out the light produced in GEM channels during the multiplication processes was shown to allow
reconstructing 3D direction of the tracks, offering accurate energy measurements and sensitivity to the source directionality. This type of detector has demonstrated a high particle identification capability, very useful to distinguish nuclear from electron recoils.
Performance of the large prototype (50 litres sensitive volume, 50 cm drift gap, 1000 cm^2 readout plane) will be shown and discussed.

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Scintillator Developments at Fermilab for New Generation Experiments

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Large new experiments are focusing on plastic scintillator for their detector design.

MATHUSLA, a proposed long-lived particle detector to be build near CMS at the LHC, plans to use scintillator as its active detector component. It foresees use of 1000+ tons of scintillator extrusions with WLS fiber readout into SIPMs. The spatial coordinate along the extrusion is formed by measuring the difference in arrival time of the light pulses from each end of the fiber. Optimizations include increasing the light yield of the extrusion and developing techniques to shorten the electrical pulse from the SIPM, including making faster WLS dopants and improving electrical pulse shaping.

The 3DST component of the DUNE near detector is a 3-D tracking detector based on ~1.5cm cubes of scintillator threaded with WLS fiber in the XYZ axes. Each "voxel" should be optically isolated from each other. The creation of the required 3M voxels requires advances in technology. We are developing procedures to injection mold the voxel with integrated fiber holes and co-molded opaque optical cladding. Another pressing issue is to improve the overall light yield of injection-molded scintillator. The existing state-of-the-art in scintillator injection-molding produces parts with low light yield (only 50% to 60% of that of commercial cast scintillator). We are working to optimize the formulations and the injection-molding process to increase the scintillation light yield.

Photodetectors / **62**

Development of (V)UV-Sensitive GaN Geiger-Mode Photodiodes

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We present results from our ongoing development of Geiger-mode GaN-photodiodes. Motivated by the silicon photomultiplier's great success, our objective is to transfer the silicon-photomultiplier concept - a matrix of individually quenched single-photon avalanche diodes - to GaN and AlGaN. These are wide band-gap III-N semiconductors with much better intrinsic (V)UV sensitivity than silicon, making them interesting photon-detector materials, for example, to detect scintillation light from liquid Xe and Ar detectors.

The purity of III-N semiconductor substrates is now sufficiently high to envision single-photon sensitive photodiodes operating in Geiger mode. And indeed, we successfully fabricated GaN photodiodes and could demonstrate their Geiger-mode characteristics and single-photon sensitivity.

This presentation will discuss the electrical and optical characteristics of our GaN structures and their implications for developing a GaN solid-state photomultiplier.

Solid State Vertexing and Tracking / **63**

Response of LGAD prototypes to gamma irradiation

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Measurements of electrical characteristics of LGADs and 3D sensors before and after exposure to radiation levels foreseen in LHC upgrade conditions are presented.

Calorimetry / 64

Digital Hadron Calorimetry

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Digital Hadron Calorimetry

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On behalf of CALICE collaboration

Particle Flow Algorithms (PFAs) attempt to measure each particle in a hadronic jet individually, using the component or detector subsystem providing the best energy/momentum resolution. The application of PFAs has been shown to achieve energy resolutions of 3 – 4% for hadronic jets produced in a future lepton collider. In this context the CALICE collaboration developed the Digital Hadron Calorimeter (DHCAL) which emphasizes granularity over single particle energy resolution. The large DHCAL prototype was built in 2008-2010, following the successful completion of the test beam program of a small size prototype.

The DHCAL uses Resistive Plate Chambers (RPCs) as active media and is read out with 1 x 1 cm2 pads and digital (1 - bit) resolution. A single layer of the DHCAL measures roughly 1 x 1 m2 and consists of 96 x 96 pads. In order to obtain a unique dataset of electromagnetic and hadronic interactions with unprecedented spatial resolution, the DHCAL went through a broad test beam program. The DHCAL was tested with steel and tungsten absorber structures, as well as with no absorber structure, at the Fermilab and CERN test beam facilities over several years. In addition to conventional calorimetric measurements, the DHCAL offers detailed measurements of event shapes, rigorous tests of simulation models and various tools for improved performance due to its very high spatial granularity.

Here we report on the results from the analysis of pion and positron events, including the intricate calibration procedure. Results of comparisons with the Monte Carlo simulations are also discussed. The analysis demonstrates the unique utilization of detailed event topologies and the development of software compensation tools.

Readout and ASIC / 65

The QPIx pixelated readout concept for future Liquid Argon Time Projection Chambers: status and prospects

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Future long baseline neutrino experiments such as the Deep Underground Neutrino Experiment (DUNE) pose challenges for development of readout techniques for multi-kiloton LAr Time Projection Chambers (TPC). In contrast to wire/strip anode readout, a pixelated readout eliminates disadvantages such as disambiguation in 2D track reconstruction. The Q-Pix Consortium, established in 2019, is developing a pixelated readout technique for LAr TPCs based on charge-integrate/reset (CIR) circuits. The CIR blocks generate a sequence of reset pulses with time intervals corresponding to fixed charge integrals, allowing signal reconstruction without continuous digitization. The Q-Pix ASIC, intended for reading out pixel arrays, comprises CIR blocks along with digital components responsible for communication and reconfigurable data routing. This talk will give an overview of the Q-Pix project, its status, and prospects, with emphasis on the development and prototyping of the Q-Pix readout ASICs.

Noble Elements / 66

Low-energy Monoenergetic Neutron Production with a DD-Neutron Source for sub-keV Nuclear Recoil Calibrations in the LUX and LZ Experiments

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Nuclear recoil (NR) calibrations are vital for understanding detector responses to dark matter candidates and neutrino-nucleus signals in direct detection experiments. Low-mass (<5 GeV) dark matter candidates and ^{8}B neutrinos drive the need for high-statistics/low-systematic calibrations at sub-keV NR energies.
We report the results of NR calibrations in the LUX dark matter detector using 2.45 MeV (94 keV FWHM) neutrons from an Adelphi Technologies, Inc. DD neutron generator and describe the R&D done to increase the instantaneous intensity to 10^{10} n/s and reduce pulse width to 12 μs FWHM. Complete kinematic reconstruction has allowed the charge and light yields to be determined down to 0.27 keVnr and 0.45 keVnr, respectively.
We also describe techniques to reduce the incident neutron energy via controlled backscattering off deuterium- and hydrogen-based targets, achieving neutron energies of 350 keV (85 keV FWHM) and 10-100 keV, respectively, needed to probe even lower mass dark matter candidates.

Calorimetry / 67

Towards ultra-high granularity calorimetry

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We are developing a new type of electromagnetic calorimeter based on a SiW sampling design using silicon pixel sensors with digital readout. A binary readout is possible due to the pixel size of $\approx 30 \times 30\,\mu\text{m}^2$. At the same time, this unprecedented granularity allows us to measure electromagnetic shower properties with extreme detail. This kind of detector will have superior two-shower separation capabilities, and it should have unique properties beneficial for particle flow algorithms. The R&D is performed in the context of the Forward Calorimeter upgrade proposal within the ALICE experiment; it is equally applicable to other future collider projects such as EIC, ILC, CLIC or FCC.

Based on experience with the first full prototype of such a calorimeter, which demonstrated a proof of principle 1, we have constructed an advanced second prototype, EPICAL-2, which makes use of the Alpide MAPS sensor developed for the ALICE ITS upgrade. The prototype consists of alternating W absorber and Si sensor layers, with a total thickness of ~20 radiation lengths, an area of $30\mathrm{mm} \times 30\mathrm{mm}$, and ~25 million pixels. This prototype has been successfully tested with cosmic muons and with electron beams at the DESY test beam facility.
We will report on first results regarding alignment and calibration with muons and on the calorimetric response to electrons. The prototype shows good energy resolution and linearity, comparable with those of a SiW calorimeter with analog readout. MC simulations within the Allpix2 framework [2] have been performed and show agreement with the experimental results. We will also show first results of shower-shape studies with unprecedented spatial precision.
In addition, we will discuss the further R&D path for other applications in particle and nuclear physics.

1 JINST13 (2018) P01014.
[2] NIM A901 (2018) 164–172.

Cross Cutting Plenary / 69

Enabling Progress for Single Photon Detection Systems

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Single photon counting and timing devices, such as SiPMs and Photon-to-Digital Converters (PDC—a.k.a. digital SiPM) are playing a key role in breakthrough experiments. From dark matter search and neutrino physics in noble liquids, neutron imaging, medical imaging (positron emission tomography and computed tomography), to quantum sensing devices for quantum key distribution systems, these devices are at the forefront of research for detector systems. This contribution presents the strategic importance to pursue R&D for 3D-integrated PDCs over conventional analog SiPM technology. The presentation also outlines the importance to pursue enabling technologies to implement PDC-based Photon Detection Module for scalability, operations in various environmental conditions (cryogenic and space) and improved performances.

Solid State Vertexing and Tracking / 70

Characterization of AC-LGAD performances for 4D detectors

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The Low-Gain Avalanche Diode (LGAD) silicon detector has already shown excellent timing performances. Since fine pixelization of LGADs is difficult to achieve, the AC-coupled LGAD (AC-LGAD) approach was introduced to provide high spatial resolution. In this type of device, the signal is capacitively induced on fine-pitched electrodes placed over an insulator and is shared among multiple electrodes. LGAD and AC-LGAD prototypes have been designed and fabricated at the Brookhaven National Laboratory and segmented in either pixels, strips, or new topologies. Signal sharing between strips and pixels has been characterized with Transient Current Technique using IR and red lasers. Comparisons will be made with results from test beams at Fermilab, using 120 GeV protons. AC-LGAD devices have been read out by either a fast transimpedance amplifier readout board or a fast-time ASIC and signals generated by betas from ^{90}Sr decay have been characterized using the two systems.

Gaseous Detectors / 71

Detecting neutrinos and measuring nuclear quenching factors with spherical proportional counters

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NEWS-G (New Experiments With Spheres-Gas) is a rare event search experiment using Spherical Proportional Counters (SPCs). Primarily designed for the direct detection of dark matter, this technology also has appealing features for Coherent Elastic Neutrino-Nucleus Scattering (CEνNS) studies and, potentially, searches for neutrinoless double beta decay. A study to assess the feasibility of observing CEνNS at a nuclear reactor will be presented.
Both direct dark matter detection and CEνNS consist of nuclear recoils from elastic scatters. The nuclear quenching factor, defined as the ratio of the measured energy induced by a nuclear recoil and an electronic recoil of the same energy, is a property of the target material and must be determined. Nuclear quenching factor measurements in a neon based gas mixture were performed at TUNL (Triangle Universities Nuclear Laboratory) using a neutron beam and preliminary results will be presented.

Solid State Vertexing and Tracking / 72

Forward silicon tracking detector design and R&D for the future Electron-Ion Collider

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The proposed high-luminosity high-energy Electron-Ion Collider (EIC) will provide a clean environment to precisely study several fundamental questions in the high energy and nuclear physics fields. To realize the proposed physics measurements at the EIC, a high granularity, large coverage and high precision detector, which can cover pseudorapidity range from -3.5 to 3.5, provide percentage momentum/energy resolution and be able to separate nanosecond bunch crossings, is required. A low material budget silicon vertex/tracking detector with fine spatial and temporal resolutions is critical

to carry out a series of hadron/jet measurements at the EIC especially for the heavy flavor product reconstruction/tagging. We will present initial designs of a proposed forward silicon tracking detector (with pseudorapidity coverage from 1 to 3.5) integrated with different magnet options and detector sub-systems for the EIC. The evaluated performance of this detector meets the EIC detector requirements. The detector R&D work for the silicon technology candidates: Low Gain Avalanche Diode (LGAD) and radiation hard Monolithic Active Pixel Sensor (MALTA) will be shown as well.

Photodetectors / 73

Nuisance Processes in p-on-n SiPMs

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Silicon Photo-Multipliers (SiPMs) have emerged as a compelling photo-sensor solution over the course of the last decade. SiPMs consist of an array of tightly packed microcells with each microcell acting as an avalanche photodiode that can behave in the Geiger mode regime when the device is reverse biased above a threshold voltage (breakdown voltage). In contrast to the widely used Photomultiplier Tubes (PMTs), SiPMs are low voltage powered, optimal for operation at cryogenic temperatures, and have low radioactivity levels with high gain stability over the time in operational conditions. For these reasons, large-scale low-background cryogenic experiments, such as DarkSide and nEXO plan to use this type of photodetector for their dark matter and neutrinoless double beta decay search. Despite their excellent Photon Detection Efficiency (PDE) SiPMs suffer however from Dark and correlated avalanche noise (After Pulse and Cross-Talk) that can reduce their pulse counting characteristics. In order to optimize the performances of new generation of SiPMs and to understand the noise characteristics of the existing ones in this talk we will propose a new physics motivated model to explain the over voltage dependence of the SiPM nuisance processes i.e. Dark Noise, After Pulse and Cross-Talk. The starting point is the extraction of the electron and hole avalanche triggering probabilities. Then we show that we can describe the over-voltage dependence of these three processes using a minimum set of parameters. In particular we will explain how it is possible to use the over voltage dependence to discriminate the type of carrier that initialise the avalanche and therefore extract the relative contribution of electrons vs holes in p-on-n SiPMs. In the talk we will show preliminary results for the characterization of the Hamamatsu VUV4 MPPC one Fondazione-Bruno-Kessler (FBK) SiPM.

Solid State Vertexing and Tracking / 74

Overview of radiation resistant LGAD designs

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Low Gain Avalanche Detectors (LGADs) are thin silicon detectors (ranging from 20 to 50 um in thickness) with moderate internal signal amplification (up to a gain of ~50) 1. LGADs are capable

of providing measurements of minimum-ionizing particles with time resolution as good as 17 picoseconds [2]. In addition, the fast rise time (~500ps) and short full charge collection time (~1ns) of LGADs are suitable for high repetition rate measurements in photon science and other fields.
The first implementation of this technology will be with the High-Granularity Timing Detector (HGTD) in ATLAS and the Endcap Timing Layer (ETL) in CMS for the high luminosity upgrade at the Large Hadron Collider (HL-LHC). The addition of precise timing information from LGADs will help mitigate the increase of pile-up and improve the detector performance and physics sensitivity.
Past publications [3-4] have proven the vast improvement in term of radiation hardness of deep gain layer and carbon implantation in LGAD designs. In this contribution a study will be shown on the tuning of the doping concentration in the deep gain layer of HPK sensors to optimize the performance before and after radiation damage. Furthermore the effect of the combination of a deep gain layer and carbon implantation in FBK sensors will be shown alongside an optimization of the carbon concentration level.
Results on electrical properties and charge collection will be shown on pre and post irradiation. Sensors were irradiated at JSI (Ljubljana, Slovenia) with neutrons and at CYRIC (KEK, Japan) with protons, then tested using the beta-scope setup and probe stations at UCSC.

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Gaseous Detectors / 75

Vector tracking in low-energy nuclear recoils

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Gaseous Time Projection Chambers (TPCs) can be used in Directional Dark Matter (DDM) searches to unambiguously identify a galactic origin for Dark Matter candidates. Directional sensitivity at low recoil energies is limited by diffusion, dispersion during amplification, and digitization effects such as charge pileup. We discuss a new algorithm that models and partially removes these effects for a model TPC based on current technology. Furthermore, we show that it is possible to largely recover the primary 3D ionization charge distribution, leading to a reduction in reconstruction errors. These results have implications for the next generation of DDM detectors, which we will briefly discuss.

Calorimetry / 76

Development of Highly Granular Scintillator Strip Electromagnetic Calorimeter

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Highly granular electromagnetic calorimeter based on scintillator strip with SiPM readout (Sc-ECAL) is under development in the framework of the CALICE collaboration for future electron-positron colliders such as ILC and CEPC. The detection layers with scintillator strips (45 mm × 5 mm × 2 mm each) coupled to SiPMs are stacked alternately in an orthogonal orientation. This technique achieves an effective transverse segmentation of 5 mm × 5 mm, and allows to significantly reduce the number of readout channels. After the validation of the concept with the physics prototype, the fully integrated technological prototype with 32 layers has been constructed to demonstrate the performance of Sc-ECAL with more realistic technical implementation. The assembly of the prototype has been completed and the commissioning is in progress. The technological prototype is supposed to be tested in beam at the DESY test beam facility this year. The status and prospects of the R&D of Sc-ECAL will be reported.

Early Career Plenary / 77

Custom Electronics and the Front-End Board of the ATLAS LAr Calorimeter Readout for the HL-LHC

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The High Luminosity era of the Large Hadron Collider (LHC) starting in 2027 promises exciting discovery potential, giving unprecedented precision on key new physics models and characterization of the Higgs boson. In order to maintain current performance in this challenging environment, the ATLAS Liquid Argon electromagnetic calorimeter will get an entirely new readout that is fast enough to read out the entire detector with full precision at the LHC frequency of 40 MHz while withstanding high operational radiation doses. On the detector, the new Front-End Board 2 (FEB2) integrates several custom ASICs into a 128 channel board to sample the LAr calorimeter cells, amplify, shape, and digitize the signal pulse, and optically transmit serialized digital data off-detector for further processing. The development of the FEB2 and related custom electronics will be described. New results from the current 32 channel "Slice Testboard" pre-prototype of the FEB2 will be presented. The future steps and outlook of the project will be outlined, with an eye towards installation in the ATLAS cavern beginning in 2025.

Early Career Plenary / 78

Real-time detection of alpha-particles and gammas using a fast optical camera

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Real-time detection of alpha-particles is an essential requirement for a variety of applications, such as in nuclear medicine, nonproliferation, and other security applications. We present a new imaging technique for alpha-particles using a fast optical camera focused on a thin scintillator. Detection of alpha-particles is based on their interaction in a thin layer of LYSO fast scintillator, which produces a localized flash of light. The light is collected with a lens to a Tpx3Cam, an intensified optical camera with single photon sensitivity. Bump-bonded onto the Timepix3 readout chip in the optical camera is an optical sensor with 256×256 pixels, each with dimensions of 55×55 μm^2, providing excellent spatial resolution and a temporal resolution in the order of a few nanoseconds. The interaction of photons with the camera is reconstructed by means of a custom algorithm, capable of discriminating single photons using time and spatial information, as well as by means of a centroiding algorithm, which combines position information, Time of Arrival, and Time over Threshold for each particle hit. Measurements of the detection efficiency, time resolution, and discriminating power of this technique will be presented.

Photodetectors / 79

MPGD-based detectors of Cherenkov photons in COMPASS and for future applications

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The RICH-1 detector of the COMPASS Experiment at CERN has been upgraded in 2016 with four MPGD-based photon detectors covering a total active area of 1.5 m^2. They consist in a hybrid combination of two THGEM layers and a Micromegas and convert VUV photons in a CsI layer on one THGEM. The anode is segmented in square pads of 8 mm pitch and the signal is read out via capacitive coupling by an APV-25 based FEE system. The new photon detectors operated stably with an effective gain of 14000, with a stability better than 5%, and an ion back-flow rate smaller than 3%. They provided about 11 photons per ring at saturation, with a single photon angular resolution of 1.8 mrad. The characteristics and the performance of the COMPASS MPGD-based photon detectors will be described in detail.
An R&D effort to improve this technology to cope with the challenging requirements of the high-momentum hadron PID at the EIC is ongoing. To validate a modular design with high anode granularity (pads of 3x3 mm^2), a prototype has been built and tested in laboratory and in a test beam. The prototype, the results of the tests and the perspectives of this study are illustrated.
A dedicated R&D exploratory study of a new VUV photoconverter, more robust than CsI, has provided promising first results: hydrogenated diamond nanograins have been sprayed on THGEM samples and showed to be compatible with the operation of the THGEM as an electron multiplier.
This R&D programme and the preliminary results are presented and discussed.

Gaseous Detectors / 80

A Low Energy Recoil Tracker hyperbolic drift chamber

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A Low Energy Recoil Tracker (ALERT) experiment will occur in Hall B at Jefferson Laboratory, Virginia, USA. It will study the partonic structure of bound nucleons in He-4. The ALERT detector must track and identify low energy nucleons and light nuclei of momenta ranging from 70 MeV/c to 250 MeV/c at a rate up to 60 MHz. It will be used in tandem with the already installed CLAS12 spectrometer in Hall B to detect the scattered electrons.

ALERT is composed of a tracker and a time of flight detector (TOF). The tracker is designed to minimize the amount of material before the particles reach the TOF. This talk will present the ALERT Hyperbolic Drift Chamber developed for the tracker suitable for the high counting rate, high acceptance, and resolution needs of the experiment. After showing the wire support evolution, the mechanical challenges and mounting procedure of the wires that are 2 mm apart will be detailed.
I will then present the performance of a prototype obtained during beam tests performed at a local facility (ALTO) in Orsay, France.

Calorimetry / **81**

SiPM-on-Tile Calorimetry for future Higgs factories and beyond

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The CALICE collaboration develops highly granular calorimeters for future particle physics experiments. The Analogue Hadron Calorimeter (AHCAL), a sampling calorimeter using small plastic scintillator tiles directly read out by silicon photomultipliers (SiPMs) as active material, is a scalable concept for the hadronic calorimeter, providing good energy, spatial and time resolution at moderate cost.

The CALICE collaboration has built a large AHCAL prototype consisting of 38 active layers in a steel absorber structure of ~4 interaction lengths. The readout electronics for the ~22000 readout channels are fully integrated in the active layers. The prototype has been tested in muon, electron and pion beams at DESY and CERN in 2018, and the analysis of the collected data is ongoing. To fully exploit the potential, beam tests with improved hit time resolution (~1 ns), with an alternative absorber structure made from tungsten, and a combined running with an ECAL prototype are foreseen.

Further possible studies include alternative scintillator materials, scintillator geometries (mega-tiles instead of individual tiles wrapped in reflector foil) and SiPM types. Together with the silicon-tungsten ECAL developed within CALICE, we plan to work on a homogeneous readout system, taking into account the requirements of both technologies. This should also be able to accommodate timing layers with tens of ps hit time resolution. The testbeam programme and the further studies are open to new collaborators and to additional proposals.

The SiPM-on-tile technology has already found an application in the upgrade of the calorimeter endcap of the CMS detector for HL-LHC. The experience gained there in terms of robustness for operation in harsh conditions and construction and commissioning of a large detector is expected to provide important input for further developments.

Gaseous Detectors / **82**

Performance and stability of a High Granularity Resistive Micromegas at high particle rates.

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Nowadays Micromegas (MM) are being used as tracking detectors in HEP experiment upgrades as in ATLAS experiment at LHC. Nevertheless, next experiments at very high energy and intensity accelerators will demand stable and efficient operations up to particle fluxes of few orders of magnitude higher. To fulfill such requirements, we are developing the MM technology to increase its rate capability up to 10 MHz/cm2.
In resistive MM, the anodic readout elements are overlayed by a resistive protection layer to reduce the spark probability. We tested several MM prototypes with a high-granularity readout plane, with 1x3 mm2 size pads, and different resistive protection schemas exploiting a pad-patterned layer or two uniform DLC layers.
To cope with the high number of readout channels and allow for the size scalability of the detector avoiding dead areas, we are studying the integration of the readout electronics in the back of the detector.
Characterization and performance studies of many detectors have been carried out by means of radioactive sources, X-Rays, and test beam. A comparison of the performance obtained with the different resistive layout is presented, in particular focusing on the response under high irradiation and high-rate exposure

Photodetectors / **84**

Micro- and Nano- Machined Vacuum Photodetectors

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We survey developed techniques in MEMS/NEMS and silicon foundaries used to form vacuum micromachined photodetectors, with gain from dynodes or nanomachined microchannel plates, and to form high quantum efficiency photocathodes because of geometric field or topological areal enhancements. Examples and properties of recent and proposed devices will be shown. Prospects for novel materials such as GaAs MCP and diamond SE dynodes are discussed. Some allied applications of micromachining in all solid state detectors such as APD or integration with readout electronics will be presented. Benefits for high energy physics include fully channelized no-cross-talk pixels, high gain-bandwidths, thickness to the beam of a few mm, tileablility/low dead area, low areal mass, and high magnetic field operation. Because the technologies are amenable to standard wafer fab practice, lower costs may result. Potential applications in selected HEP experiments will be surveyed, varying between very large photodetectors for astroparticle physics, and fiber array detectors.

Readout and ASIC / 85

Characterization of ITkPix-V1 pixel readout chip

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The ITkPix-V1 readout front-end (FE) chip, based on 65 nm CMOS technology, is designed by the RD53 collaboration as the pre-production chip for the upgraded ATLAS Inner Tracker Pixel detector operating with extreme rates and radiation at the High-Luminosity LHC. The ITkPix-V1 chip uses a novel differential analog FE design featuring low noise and small time-walk. ITkPix-V1 was submitted in March 2020. In this talk, we will summarize the most novel features and recent results from studies characterizing the ITkPix-V1 chip.

Photodetectors / 87

Photomultiplier and Dynode Techniques for rad-hard in-situ Calorimeter Sensors

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This note concentrates on calorimetry which will survive, with energy-flow, rate, and timing, in the forward region of future colliders, high intensity experiments, and orbiting systems. It uses PMT as direct calorimeter sensors to detect shower particles via Cerenkov light in the PMT window, and/or by direct secondary emission from shower particles traversing the dynodes. The secondary emission proportional to dE/dx provides compensating information.

Calorimetry / 90

Dual-Readout Compensated Calorimetry with Tile Sensors

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We discuss techniques and materials to develop optimize the energy resolution in the long-term performance of calorimeters as required by the challenging environment of future colliders and high intensity experiments. We extend the Dual Readout/Cerenkov compensation by using 2 tile types, one sensitive to to e-m showers, such as quartz, aerogel, Teflon AF or other low index Cerenkov tiles, and scintillator tiles, sensitive to low energy particles such as neutrons, nuclear fragments. The many advantages over fiber calorimeters for dual readout are discussed.

Low background / Low threshold detectors / 91

Novel Low Workfunction Semiconductors for Dark Matter, Neutrino Phenomena and x-ray Astronomy

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In frontier physics, precision calorimetry from photons and charged and neutral massive particles have been crucial to major discoveries. Better resolution and low detection thresholds are of great interest for dark matter searches, solar and reactor neutrino detection and oscillations, neutrino mass measurements, x-ray astronomy, and double-beta decay. A Challenge for semiconductor detectors: �E~10-100 eV. We discuss semiconductor photocathode materials Cs3Sb(S-11) and Ag-O-Cs(S-1)fabricated as possible bulk detectors both by thermal melts and ALD. The pair energy is a low as 0.7 eV for S-1, and the thermal noise for the S-11 is lower than Si despite a lower pair 2 eV compared to 3.6 eV because the bandgap is 1.6 eV, compared with 1.1 eV for Si. Mobilities for both are an order of magnitude larger than Si. ALD has the ability to make perfect crystals of these weakly bound semiconductors.

Photodetectors / 92

Theia Physics Potential

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New developments in liquid scintillator and photon detection technologies make it possible to discriminate between Cherenkov and scintillation signals in large scale detectors. The Theia design leverages these advances to combine the particle direction and identification properties of Cherenkov light with the higher light yield and energy resolution of scintillator to create a broad physics program which spans from hundreds of keV to many GeV. The scientific program would include low and high-energy solar neutrinos, neutrino mass ordering, measurement of neutrino CP-violating phase, observation of diffuse supernova neutrinos and neutrinos from a supernova burst, the search for various modes of nucleon decay, and a search for neutrinoless double beta decay. This talk will present the latest advances in detector research and development, and provide an overview of the physics it enables.

Noble Elements / 93

Improving the Proportional Scintillation Signal of Liquid Argon by Xenon Doping

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Argon has advantages over xenon in cost, kinetic matching, and ease-of-purification when used as a target for the detection of nuclear recoils from coherent neutrino-nucleus scattering (CENNS) and light WIMP dark matter. However, the detection of low-energy ionization signals in argon by the proportional scintillation signal (S2) mechanism is frustrated by the long lifetime and short wavelength of the argon proportional scintillation light. Doping the argon gas with small (tens of ppm) quantities of xenon shortens the emission lifetime and shifts the wavelength to 149 nm, which can be efficiently sensed by SiPMs. We describe a system to measure the range of mixtures that can be stably maintained and the improvements to proportional scintillation light and nuclear recoil ionization yield they provide.

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Early Career Plenary / 94

STOPGAP - a Time-of-Flight Extension for the TOP Belle II Barrel PID System

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The Belle II barrel region is instrumented with the Time of Propagation (TOP) particle identification system based on sixteen quartz radiator bars arranged around the interaction point. Due to the mechanical design of the TOP system these quartz bars do not overlap, but leave a gap of around 2cm between them. This leads to around 6% of all tracks in the nominal TOP acceptance region to escape without traversing any of the quartz bars and thus not giving any usable particle identification information from the TOP system and an additional 3% of tracks being degraded due to edge effects.
We propose a possible solution to remedy these gaps in the TOP acceptance in the form of a Supplemental TOP GAP instrumentation (STOPGAP) that covers the dead area between adjacent quartz bars with fast silicon detectors to directly measure the time-of-flight of traversing particles for particle identification purposes. Modern, fast timing silicon sensors and readouts can offer sufficient time resolution for the task at hand, so that STOPGAP modules could be built compact enough to fit into the limited space available in the area of interest between the Belle II central drift chamber (CDC) and the TOP system.

This talk will present a simulation study demonstrating the feasibility of a silicon time-of-flight system, based on its reconstruction performance in simulated Y(4S) -> BBbar events. It will discuss the performance requirements for possible sensor technologies and demonstrate that such a project could be realised with novel, fast monolithic CMOS sensors that are expected to reach MIP timing resolutions of down to 50ps.

Gaseous Detectors / 95

A novel TPC concept for a fast tracker for MAGIX

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MAGIX is a new precision experiment, currently being developed at the Johannes Gutenberg University in Mainz, that will explore fundamental nuclear and particle physics at energies up to 100 MeV at the MESA high intensity electron beam.
To achieve its goals, MAGIX requires two short-drift, low material budget TPCs. Those detectors will feature a novel open field-cage concept to reduce the material budget and will be among the first major users of the new SRS+VMM3 readout system which will allow them to achieve readout rates above 100 kHz.
In this work, we will illustrate the most innovative aspects of this project and present the results of the first measurement campaigns.

Photodetectors / **96**

3D printing of photocurable scintillating and low-background materials

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Plastic scintillators are one of the most widely used active materials in nuclear and particle physics experiments. Their reliability, simplicity to operate, and low-cost make them the material of choice for many applications. The introduction of modern additive manufacturing techniques opens the possibility of expanding their use to increased complexity or production scales through 3D printing. While multiple techniques for 3D printing of plastics exist, light-based techniques such as stereolithography (SLA) and digital light processing (DLP) are particularly attractive due to the optical clarity of SLA or DLP printed components. SLA and DLP also provide a near-contactless manufacturing technique, which is desirable for low-background experiments. In this talk, we will present on the development of photocurable scintillating resins for 3D printing of plastic scintillators using SLA and DLP methods. Resin methodology, characterization of photocured scintillators, and use their use in different 3D printing techniques will be discussed.

Gaseous Detectors / **97**

Toward studying photonuclear reactions with active-target TPC

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Stellar evolution modeling requires knowledge of the mechanism and cross-section of nuclear reactions. Given the conditions in the stellar interior, the stellar reactions occur predominantly within

relatively narrow energy ranges well below the Coulomb barrier.
For many (α,γ), (p,γ) reactions important for stellar nucleosynthesis the measurement of their cross-sections at the relevant energies is impossible with present experimental conditions. Among these reactions is the ^{12}C(α,γ)^{16}O reaction, which determines the carbon to oxygen ratio at the end of stellar helium burning — a paramount importance problem in nuclear astrophysics.
Thanks to the availability of intense, monochromatic γ-ray beams, to obtain accurate cross-sections at relevant energies, the time-reversal photodisintegration reactions can be investigated instead. Given the time-invariance of the strong and electromagnetic interactions, the cross-sections of (α,γ), (p,γ) reactions can be calculated according to the detailed balance principle from the cross-section of the corresponding time-reversal photodisintegration. The photodisintegration approach has the advantage of larger cross-section, lower background, and different systematic uncertainties.
A detector capable of measuring the low energy products of such photonuclear reactions — an active-target Time Projection Chamber with electronic readout (ELITPC) — is being developed at the University of Warsaw. Full kinematic reconstruction of the charged reaction products will be possible. The flagship experiment of the detector is the measurement of the cross-section of ^{16}O(γ,α)^{12}C photodisintegration reaction down to the energy of 1 MeV using γ-ray beams of HIγS, USA and ELI-NP, Romania.
In my talk, I will present the design of the ELITPC detector and describe its experimental program. Within the ELITPC collaboration, my main contribution is the development of event reconstruction software using classic computer vision algorithms and dedicated detector control system.

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Cross Cutting Plenary / **98**

Integration of Squid/Memristor Neurons with Precision Space and Time Particle Physics Detectors for 4D Image Reconstruction using Neuromorphic Computing

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Neuromorphic computing (NC), which uses a network of artificial synapses and neurons to construct individual neural units, can enable the information processed and storage in the same units. If networks are formed with these neural units and new algorithmic models using the neuron's spike capabilities are used, NC is expected to provide critical computing hardware for emerging artificial intelligence and machine learning applications, and may converge with quantum computing for quantum neuromorphic computing. Meanwhile, recent advances in sensors used for particle physics applications have allowed the possibility of detecting signals with both fine spatial resolution (~μm) and time resolution (~10ps). New paradigms for using this 4-dimensional information are also needed in order to achieve on-detector, real-time, continuous data processing which enables the scalability to large channel counts. An application is discussed whereby a neuromorphic readout system could be used as the backend for an AC coupled, Low-Gain Avalanche Detector front end to provide good spatial and temporal resolution.

Calorimetry / **100**

Longitudinal Segmentation of Multi-readout Fiber Calorimeters by Timing

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We report on benchtop measurements and analysis techniques that enable us to effectively segment a fiber hadronic calorimeter longitudinally by fast digitization of pulse shapes. By combining subnanosecond digitization and silicon photomultipliers in a fiber calorimeter, we propose an enhancement to the traditional dual readout design that would provide benefits of both high-granularity and multi-readout. We demonstrate that better than 100 ps timing resolution, or roughly 2 cm longitudinal segmentation, is possible when highly sampled waveforms are processed using recurrent neural networks. In addition, we also show the merits to fiber calorimeters of machine learning techniques, namely Convolutional Neural Networks, Graph Neural Networks, and Recurrent Neural Networks. For instance, in the simple high granularity setup, we see that the CNN improves reconstructed energy resolution from ~40 to ~33 %/sqrt(E). These results indicate that the spatial distribution of energy deposition within the sensitive elements is both identifiable (able to be learned) and representative of underlying physical processes.

Noble Elements / 102

Purity monitoring for ProtoDUNE-SP

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The Deep Underground Neutrino Experiment (DUNE) is a next-generation long-baseline neutrino oscillation experiment based on liquid argon TPC (LArTPC) technology. DUNE's single-phase prototype ProtoDUNE-SP at CERN finished its 2-year Phase-1 running in July 2020, which successfully collected test beam data and cosmic ray data. The DUNE collaboration is preparing ProtoDUNE-SP Phase-2 run which is expected to start in late 2022. A key component of calibration for LArTPCs is the lifetime of drift electrons, which corrects the charge attenuation caused by drift electrons being captured by impurities. A purity monitor is a miniature TPC that measures the lifetime of electrons generated from the photocathode via the photoelectric effect. The purity monitoring system in ProtoDUNE-SP Phase-1 continuously monitored liquid argon purity throughout the entire lifetime of ProtoDUNE-SP Phase-1, which was critical to the experiment's successful commissioning, operation, and data taking. I will discuss the design, implementation and results of purity monitors in ProtoDUNE-SP Phase-1, as well as the development of purity monitors for ProtoDUNE-SP Phase-2.

Low background / Low threshold detectors / 103

Ba-tagging with fluorescence bicolor molecules for background-free $0\nu\beta\beta decay experiment.

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The next generation of neutrinoless double beta decay searches aims to reach sensitivities in the half-life of the process up to 10^{28} years. This will require tonne scale detectors with essentially no background in their region of interest. One of the most promising solutions, which may be implemented by gas or liquid xenon TPCs, is the possibility of tagging the daughter ion produced in the decay. The NEXT collaboration is currently involved in an intense R&D program based on fluorescent molecular indicators able to capture the Ba^{++} cation, changing their spectral response when chelated. In this talk, I will present one of the NEXT R&D lines, called BOLD, which proposes the use of fluorescent bicolor indicators (FBI). I will show the latest results based on the spectral shift of the emission fluorescence of this molecule after Ba^{++} capture in dry media. The emission light must be scrutinized to differentiate the signal of one chelated molecule among a background of non-chelated ones. I will show our current approach to the problem for Single-Molecule Fluorescence Imaging (SMFI) and the strategy to achieve the goal, i.e. integration of detection technique into a pressurized xenon gas detector.

Readout and ASIC / 104

A reconfigurable neural network ASIC for detector front-end data compression at the HL-LHC

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Despite advances in the programmable logic capabilities of modern trigger systems, a significant bottleneck remains in the amount of data to be transported from the detector to off-detector logic where trigger decisions are made. We demonstrate that a neural network autoencoder model can be implemented in a radiation tolerant ASIC to perform lossy data compression alleviating the data transmission problem while preserving critical information of the detector energy profile. For our application, we consider the high-granularity calorimeter from the CMS experiment at the CERN Large Hadron Collider. The advantage of the machine learning approach is in the flexibility and configurability of the algorithm. By changing the neural network weights, a unique data compression algorithm can be deployed for sensors in different detector regions or for changing detector or collider conditions. To meet area, performance, and power constraints, we perform a quantization-aware training to create an optimized neural network hardware implementation. The design is achieved through the use of high-level synthesis tools and the hls4ml framework, and has been implemented in an LP CMOS 65 nm process. It occupies a total area of 3.6 mm^2, consumes 95 mW of power, and is optimized to withstand approximately 200 Mrad ionizing radiation. The simulated energy consumption per inference is 2.4 nJ. This is the first radiation tolerant on-detector ASIC implementation of a neural network that has been designed for particle physics applications.

Photodetectors / 105

A Cooper pair transistor single photon detector with quantum enhanced sensitivity

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We propose the design of an ultra-sensitive THz photon detector based on a superconducting Cooper Pair Transistor (CPT). A photon absorber is connected to the gate electrode, which is coupled to a quarter wavelength coplanar-waveguide (CPW) resonator. Photon-generated quasiparticles in the absorber modify the charge on the gate, which modulates the resonator inductance that results in a shift of the resonant frequency of the CPW resonator. The exceptional charge sensitivity of the CPT provides an ideal architecture to realize a THz detector architecture capable of detecting single THz photons. Furthermore, the inherent non-linearity of the CPT allows parametric amplification by pumping on the CPT Josephson inductance to further enhance the detector sensitivity. I will present an overview of the device design, preliminary simulations, and provide initial estimates of the detector sensitivity. Phosphor

Photodetectors / 106

Superconducting mm-wave detector development at Argonne National Laboratory

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Over the past decade, advances in arrays of superconducting detectors have revolutionized the field of mm-wave cosmology. Large-format arrays of thousands of transition-edge sensors (TESs) have provided an exquisite view of the mm-wave sky. The next decade promises to continue this trend, with a number of upcoming experiments such as the Simon's Observatory, CCAT-prime, SP-TMA, and CMB-S4. Kinetic inductance detectors (KIDs) offer an alternative path to densely packed focal plane arrays. With a significant reduction in manufacturing and readout complexity, KID arrays are set to play a key role in applications in both imaging and spectroscopy. I will present an overview of the ANL detector programme, focusing primarily on the on-going development of TES and KID arrays. In particular, I will describe aspects of the design, fabrication, and preliminary characterization of the dichroic OMT-coupled TES arrays for CMB-S4, the advances toward large-format KID arrays, and present two new KID-based instruments, SPT-SLIM and SPT-4, that are under development for the South Pole Telescope.

Solid State Vertexing and Tracking / 107

Experimental determination of proton hardness factors at several irradiation facilities

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The radiation hardness of detectors is of key importance for experiments at future facilities. This requirement drives a global R&D campaign on radiation hard sensors and the development of new irradiation facilities worldwide. The effect of radiation damage is conventionally communicated in terms of the equivalent 1 MeV neutron fluence, converted using a "hardness factor" which depends on the particle species and energy used for irradiation. A campaign of measurements for the determination of the hardness factors at several irradiation facilities (University of Birmingham, CERN, Katlsruhe Institute of Technology and Bonn University), using a common methodology has been undertaken and the results will be presented. Future steps towards the standardisation of the hardness factor determination will be discussed, along with the main sources of uncertainty. The advantages and disadvantages of different approaches will be outlined.

Gaseous Detectors / 108

NEWS-G: Search for Light Dark Matter with Spherical Proportional Counters

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The NEWS-G collaboration is searching for light dark matter candidates using a novel detector concept, the spherical proportional counter.
Access to the mass range from 0.05 to 10 GeV is enabled by the combination of low energy threshold, light gaseous targets (H, He, Ne),
and highly radio-pure detector construction. Initial NEWS-G results obtained with SEDINE, a 60 cm in diameter spherical proportional counter operating at LSM (France), excluded for the first time WIMP-like dark matter candidates down to masses of 0.5 GeV. The construction and on-going commissioning of a new, 140 cm in diameter, spherical proportional counter constructed at LSM using 4N copper with 500 um electroplated inner layer will be presented. The detector is scheduled to collect data in SNOLAB (Canada) later this year. The design and construction of ECUME, a 140 cm in diameter spherical proportional counter fully electroformed underground will be discussed. The potential to achieve sensitivity reaching the neutrino floor in light Dark Matter searches, with a next generation detector are also summarised.

Photodetectors / 109

Cosmology with On-Chip Superconducting Millimeter-Wave Spectrometers

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Line intensity mapping (LIM) is an emerging observational technique to measure the large-scale structure of the Universe in three dimensions, traced by a redshifted emission line, without resolving individual objects. Future experiments promise to extend the observable volume beyond the redshift reach of traditional galaxy surveys, improving precision on the LCDM cosmological model and extensions to it. I will outline the science potential of mm-wave LIM experiments, highlighting the need for on-chip spectrometers to dramatically improve sensitivity over current instruments.

I will introduce SPT-SLIM, a pathfinder for the South Pole Telescope that will demonstrate LIM using on-chip spectrometers. Finally I will discuss how this technology could power future LIM instruments with orders of magnitude more detectors and the sensitivity to constrain the expansion history at high redshift, primordial non-Gaussianity, and more.

Gaseous Detectors / **110**

Recent advancements on the spherical proportional counter instrumentation for NEWS-G

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NEWS-G (New Experiments With Spheres-Gas) is an innovative experiment aiming to shine a light on the dark matter conundrum with a novel gaseous detector, the spherical proportional counter. It uses light gases, such as hydrogen, helium, and neon, as targets, to expand dark matter searches to the 0.05 - 10 GeV/c^2 mass region. NEWS-G produced its first results with a detector -60 cm in diameter- installed at LSM (France), excluding cross-sections above $4.4\ 10^{37}$ cm^2 for 0.5 GeV/c^2 WIMP using neon gas. Currently, a larger detector -140 cm in diameter- is being installed at SNOLAB (Canada) and the commissioning is expected to commence in March 2021, before operation later this year. In this talk, I present developments incorporated in this new detector: a) sensor technologies using resistive materials and multi-anode read-out that allow high gain - high-pressure operation, b) gas purification techniques to remove contaminants (H_2O, O_2) and radon impurities, c) reduction of ^{210}Pb induced background through copper electroforming methods, d) utilisation of UV-lasers for detector calibration, detector response monitoring and estimation of gas-related fundamental properties, e) field correction electrodes to achieve a homogenous response from the whole detector volume. This next experimental phase of NEWS-G will allow searches for low mass dark matter with unprecedented sensitivity. Finally, ideas on future R&D for spherical proportional counter sensor instrumentation, aiming at high-pressure operation in larger volumes are outlined.

Noble Elements / **111**

Augmented Signal Processing in Liquid Argon Time Projection Chambers with a Deep Neural Network

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As an advanced neutrino detector technology the Liquid Argon Time Projection Chamber (LArTPC) is widely used in recent and upcoming accelerator neutrino experiments. It features a low energy threshold and high spatial resolution that allow for comprehensive reconstruction of event topologies. Both hardware and reconstruction technologies are evolving to improve the LArTPC performance. In current-generation LArTPCs with wire readout, the recorded data consist of digitized waveforms on wires produced by induced signal on wires of drifting ionization electrons, which can also be viewed as two-dimensional (2D) (time versus wire) projection images of charged-particle trajectories. For such an imaging detector, one critical step is the signal processing that reconstructs the original charge projections from the recorded 2D images. For the first time, we introduce a deep neural network in LArTPC signal processing (DNN-SP) to improve the signal region of interest detection. By combining domain knowledge (e.g., matching information from multiple wire planes) and deep learning, this method shows significant improvements over traditional methods. In this presentation, we will report the details of the DNN-SP method, software tools, and performance evaluations.

Solid State Vertexing and Tracking / 112

Time measurements using ultra fast silicon detectors with a 120 GeV Proton Beam for the TOPSiDE Detector Concept at The Electron-Ion Collider

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The Timing Optimized PID Silicon Detector for the EIC (TOPSiDE) is Argonne's proposed central detector concept for the Electron-Ion Collider, with its physics goals of perturbative and non-perturbative Quantum ChromoDynamics (QCD) studies of the structure of nucleons and nuclei. It requires high precision tracking, good vertex resolution, and excellent particle identification with a timing resolution of around 10 ps or better. TOPSiDE uses Ultra-Fast Silicon Detectors (UFSD) based on the Low-Gain Avalanche Detector (LGAD) technology. The LGADs are proven to provide timing resolutions of a few 10s of picoseconds. The speaker will present the results of 35 μm and 50 μm thick LGAD tests at Fermilab Test Beam Facility with 120 GeV proton beam. The best timing resolution of UFSDs in a test beam to date is achieved using three combined planes of 35 μm thick LGADs at -30 °C with a precision of 14.3 $\pm$ 1.5 ps. The latest test results for AC-LGADs with 120 GeV proton beam might also be presented.

Noble Elements / 113

HeRALD - light dark matter search with superfluid Helium-4

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HeRALD - Helium Roton Apparatus for Light Dark Matter uses bolometers with TES readout to detect signals in superfluid Helium-4 from light dark matter. The low energy threshold enabled by cryogenic bolometers, with signal amplified by quantum evaporation of helium atoms from phonons/rotons in superfluid Helium-4 and the low atomic mass of Helium-4 with better kinematic matching for light dark matter, make HeRALD promising to search for light dark matter. I will present preliminary results of light yield measurements of superfluid Helium-4 from electronic recoils from 36 keVee to 185 keVee and nuclear recoils from 53 keVnr to 1 MeVnr. I will also present some recent development on helium testing cells in Helium-3/Helium-4 dilution refrigerators, constructed to demonstrate several key technologies, including helium film burners, Cs film stoppers, and knife-edge film thinners.

TDAQ / 114

The Challenges of Machine Learning at the Edge

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As detector technologies improve, the increase in resolution, number of channels and overall size create immense bandwidth challenges for the data acquisition system, long post acquisition processing times and growing data storage costs. Much of the raw data does not contain useful information and can be significantly reduced with veto and compression systems. The improvements in artificial intelligence (AI), particularly the many flavours of machine learning (ML), adds a powerful tool to data acquisition strategies. Leveraging ML's flexibility and versatility, we propose to embed intelligent algorithms at the edge, that is, early in the detector chain, including within the photon and particle detector readouts themselves, to veto, analyze and compress the data in real-time. Placing ML algorithms at the edge of the system includes some of the same challenges as non-AI trigger systems, such as managing power, data flow and calibrations. However, it also adds some new elements to consider such as model training, continuous model updating and stringent data provenance tracking for the data used to train these models. This presentation will discuss the strategic importance of developing tools to aid in the design of embedded ML and building strong validation strategies for ML models used in scientific instruments.

Low background / Low threshold detectors / 115

A Quasi-Monoenergetic Neutron Beam for Calibrating Dark Matter Detectors

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At the 8 MeV proton accelerator of the Queen's University Reactor Materials Testing Laboratory, we are establishing a quasi-monoenergetic beam of neutrons. These neutrons will be used to induce nuclear recoils of known energy in the dark matter detectors of the NEWS-G experiment. This is needed to to measure the quenching factors of the various gases used, in particular in proton-rich gases such as methane and at lower recoil energies where no data exist. The quenching factor is ratio of detector response from a nuclear recoil compared to an electronic recoil of the same energy (see Marie Vidal's contribution for more details). Beyond NEWS-G, access to the neutron beam will be opened up to other dark matter experiments or other users.

The requirement is a controllable beam of neutrons with ~30 keV kinetic energy with ~10% width. Working in this "intermediate" range of neutron energies is quite challenging, as most detectors are optimized for thermal or high-energy neutrons.

I will describe our progress since 2019 in producing neutrons from bombarding lithium fluoride with protons, attempts to characterize the beam, shielding, and detectors.

Award and Blue Sky Plenary / 117

Calibration and Operation Plans for SBC's first 10 kg Argon Bubble Chamber

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The bubble chamber is a vetted technology for low background low energy nuclear recoil detection, which has for the past decade been employed primarily in the search for spin-dependent dark matter, for WIMP masses above ~10 GeV. New technology is being developed by the Scintillating Bubble Chamber (SBC) collaboration to bring liquid noble bubble chambers to the search for low-mass dark matter (~1 GeV) and Beyond-the-Standard-Model neutrino physics with CEνNS at reactors. A small chamber filled with xenon has already demonstrated electron-recoil blindness and scintillation-channel veto power with a noble liquid, aspects of the technology crucial to background reduction. We are now building a 10 kg chamber with argon target fluid, which will be used to perform calibrations at Fermilab to confirm the efficacy of this technology at a larger scale. I will describe the suite of proposed measurements which will be used to calibrate nuclear recoils down to 100 eV, including scattering of low-energy neutrons from photoneutron sources, Thomson scattering of gammas, and gamma emission recoils following thermal neutron capture. We will also test the superheated argon's electron recoil response with gamma sources over a range of gamma energies and detector conditions, and demonstrate the power of argon's scintillation properties to veto alpha decays, cosmic backgrounds, and high energy neutron backgrounds.

Calorimetry / 118

Homogeneous Hadron Calorimetry for a Future Higgs Factory

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At a future Higgs factory, detectors providing ultimate resolution will be required. A limitation to date has been the measurement of hadronic energy, this in contrast to the measurement of electromagnetic energy. Total absorption electromagnetic calorimeters made of inorganic crystals provide the best energy resolution and detection efficiency for the measurement of photons and electrons and are the media of choice when high resolution is required. To obtain the best hadronic energy resolution the concept of a homogeneous calorimeter will be introduced, featuring total absorption for electrons, photons and jets. Its totally active medium collects the full signal, produced over a very large volume while preserving spatial information, and allows event-by-event correction for

binding energy losses. Inorganic scintillator-based calorimeters are a practical solution with several possible techniques available for compensation of the binding energy losses by either dual readout and/or dual gate. The concept of total absorption calorimetry will be described with its projected performance

Quantum Sensors / 119

The Global Network of Optical Magnetometers for Exotic physics searches (GNOME)

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Over 80% of the mass in the universe is made up of an invisible substance known as dark matter. But exactly is dark matter? This is a complete mystery. There are a number of hypotheses being tested by experiments throughout the world, among them the idea that dark matter is an ultralight bosonic field that interacts with atomic spins. The Global Network of Optical Magnetometers to search for Exotic physics (GNOME) is a worldwide array of atomic magnetometers that searches for transient interactions of atomic spins with invisible bosonic "walls" or "stars" or even bursts emanating from a cataclysmic astrophysical events like binary black hole mergers. We will discuss recent analysis of over a year of GNOME data to test a variety of beyond-the-Standard-Model theories, as well as future plans to improve GNOME's sensitivity to various dark matter scenarios.

Solid State Vertexing and Tracking / 120

CMOS Monolithic Sensor for Calorimetry and Outer Tracking at Future Colliders

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The DECAL sensor, a depleted monolithic active pixel sensor (DMAPS), was developed for digital calorimetry, where the number of pixels above threshold are counted to estimate the shower energy. The pixel size must be sufficiently small to avoid hit saturation (where in the core of dense showers

multiple particles hit the same pixel). The DECAL and DECAL FD sensors have been fabricated in the TowerJazz 180 nm standard and "modified" imaging process (see below), respectively. They each feature a single cell with 64 x 64 matrix of 55 um pitch pixels read out every 25ns. Within in each pixel are 4 collection electrodes, trimming logic, shaper, comparator, and discriminator with digital output. The pixel configuration logic provides a five-bit calibration DAC and a mask flag.

The DECAL can be reconfigured as a strip sensor (reading out the column address of hits) for pre-shower and tracking applications. A detector with 55 um pitch crossed strips at the start of the calorimeter should enhance bremsstrahlung recovery for electrons and aid discrimination of high energy pi_0s from gammas. Results on the latter for such a detector are presented from simulation. Combining columns from neighbouring cells and assuming a final wafer-scale design with stitching, would provide a single CMOS sensor which could be configured in different layers to serve as either outer tracker, pre-shower or pad calorimeter.

This talk will present characterization results on the DECAL and DECAL FD prototypes, where the latter (modified process) has been fabricated with an additional continuous low doped n-type layer, using a low dose high energy implant. This moves the diode boundary to the interface of this layer with the p-type epitaxial layer, allowing full depletion of the device with charge collection by drift rather than diffusion. This greatly speeds up charge collection, even from corners of the pixel far from the electrodes, which also significantly improves the radiation hardness, even to the levels required for barrel ECAL regions of FCC-hh. Along with the DECAL results, initial results on DECAL FD, such as threshold scans and analogue pixel measurements will be presented

Photodetectors / 121

Integration of mini TECs on the CMS MTD barrel timing layer 16 ch SiPM array to reduce the DCR after very high irradiation

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The need to operate SiPM after very high radiation levels in current and future HEP detectors is growing. The proposed CMS MTD Barrel timing layer (BTL) will see a total neutron flux of 2E14 n/cm2 (1 MeV eq.) at the end of operation (EOO). This new sub-detector is located just outside of the CMS Tracker and is already planned to be operating at a cryogenic temperature of -35℃. In the last two years R&D was conducted to investigate the potential integration of mini thermal electric coolers (TECs) directly on the BTL 16 channel SiPM package. It is shown that the SiPM operating temperature can be further decreased from -35 to -45℃ and the SiPM current reduced by a factor of 1.9 with little additional overall power consumption if the TEC coefficient of performance (COP) is optimized. We also show that by reversing the current in the TECs, the local increase in the SiPM temperature can be exploited to enhance the annealing of the SiPM's Dark Count Rate (DCR) during yearly LHC shutdowns.
We review the current knowledge on the evolution of the SiPMs under irradiation up to the full EOO integrated fluence and what level of dark current mitigation could be achieved by integrating the TECs into the BTL design.

Quantum Sensors / 122

BREAD: Broadband Reflector Experiment for Axion Detection

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I will discuss the design of broadband dish antenna axion search experiments targeting the mass range 10 microeV to 10 millieV and the sensor requirements for discovery of QCD axions.

Quantum Sensors / 123

Probing Fundamental Physics with Long-baseline Atom Interferometry

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Atom interferometers exploit spatially delocalized quantum states to make a wide variety of highly precise measurements. Recent technological advances have opened a path for atom interferometers to contribute to multiple areas at the forefront of modern physics, including searches for wave-like dark matter, gravitational wave detection, and fundamental quantum science. In this talk, I will describe MAGIS-100, a 100-meter-tall atom interferometer being built at Fermilab to pursue these directions. MAGIS-100 will serve as a prototype gravitational wave detector in a new frequency range, between the peak sensitivities of the LIGO and LISA, that is promising for pursuing cosmological signals from the early universe and for studying a broad range of astrophysical sources. In addition, MAGIS-100 will search for wave-like dark matter, probe quantum mechanics in a new regime in which massive particles are delocalized over macroscopic scales in distance and time, and act as a testbed for advanced quantum sensing techniques. Finally, I will discuss the potential and motivation for follow-on atomic detectors with even longer baselines.

Early Career Plenary / 124

LArPix-v2: a commercially scalable large-format 3D charge-readout scheme for LArTPCs

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3D ionization information facilitates unambiguous mm-scale fine-tracking in high occupancy liquid argon time-projection chamber (LArTPC) environments. LArPix-v2 incorporates low-power, low-noise 64-channel custom ASICs that can operate at cryogenic temperatures with a mixed-signal large-format printed circuit board for an unambiguous 3D charge-readout anode. With robust I/O and control architecture, a 10-by-10 array of ASICs instrument a 4,900-pixel PCB-based anode. The system is compatible with standard large-scale commercial electronics production techniques, enabling low-cost quick-turn production. Here I present a system design overview alongside performance evaluation from cosmic ray muons imaged in the SingleCube prototype (a 40-kg LArTPC

with 30-cm drift). This system will be deployed in the upcoming ProtoDUNE-ND LArTPC physics operation.

Photodetectors / 125

Development Towards a Camera Readout and Barium Tagging Optical TPC,or CRAB-OTPC, for the NEXT Collaboration

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Neutrinoless double beta decay ($0\nu\beta\beta$) is an extremely rare nuclear decay that occurs when two neutrons in a nucleus simultaneously beta decay without producing any antineutrinos. If observed, $0\nu\beta\beta$ would be the rarest decay process observed, and long target half lives of 10^{28} years necessitate development of new background suppression and signal identification methodologies. The NEXT experiment uses gaseous ^{136}Xe and is pursuing an aggressive R&D campaign to implement Barium Tagging, detection of single daughter ions via super resolution fluorescence microscopy. This technique, if implemented with stringent energy cuts and topological identification, could effectively reduce experimental backgrounds to zero at the multi-ton scale. This talk will summarize R&D toward barium tagging in NEXT, with a particular focus 1) a novel class of switch-on fluorescence sensors that have enabled dry single barium dication detection for the first time; 2) progress toward implementation of topological event reconstruction using high speed optical cameras that would allow incorporation of a barium sensing plane in a xenon gas TPC, via the CRAB (camera readout and barium tagging) concept.

Quantum Sensors / 126

Searching for dark matter with a superconducting qubit

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Detection mechanisms for low mass bosonic dark matter candidates, such the axion or hidden photon, leverage potential interactions with electromagnetic fields, whereby the dark matter (of unknown mass) on rare occasion converts into a single photon. Current dark matter searches operating at microwave frequencies use a resonant cavity to coherently accumulate the field sourced by the dark matter and a near standard quantum limited (SQL) linear amplifier to read out the cavity signal. To further increase sensitivity to the dark matter signal, sub-SQL detection techniques are required. Here we report the development of a novel microwave photon counting technique and a new exclusion limit on hidden photon dark matter. We operate a superconducting qubit to make repeated quantum non-demolition measurements of cavity photons and apply a hidden Markov model analysis to reduce the noise to 15.7 dB below the quantum limit, with overall detector performance limited by a residual background of real photons. With the present device, we perform a hidden photon search and constrain the kinetic mixing angle to $\epsilon \leq 1.68 \times 10^{-15}$ in a band around 6.011 GHz (24.86 μeV) with an integration time of 8.33 s. This demonstrated noise reduction technique enables future dark matter searches to be sped up by a factor of 1300. By coupling a qubit to an arbitrary quantum sensor, more general sub-SQL metrology is possible with the techniques presented in this work.

Calorimetry / 127

Calibration of the CMS hadron calorimeters using proton-proton collision data at $\sqrt{s}$ = 13 TeV

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Methods are presented for calibrating the hadron calorimeter system of the CMS detector at the LHC. The hadron calorimeters of the CMS experiment are sampling calorimeters of brass and scintillator, and are in the form of one central detector and two endcaps. These calorimeters cover pseudorapidities $|\eta| < 3$ and are positioned inside the solenoidal magnet. An outer calorimeter, outside the magnet coil, covers $|\eta| < 1.26$, and a steel and quartz-fiber Cherenkov forward calorimeter extends the coverage to $|\eta| < 5.19$. The initial calibration of the calorimeters was based on results from test beams, augmented with the use of radioactive sources and lasers. The calibration was improved substantially using proton-proton collision data collected at $\sqrt{s}$ = 7, 8, and 13 TeV, as well as cosmic ray muon data collected during the periods when the LHC beams were not present. The present calibration is performed using the 13 TeV data collected during 2016 corresponding to an integrated luminosity of 35.9 fb^{-1}. The intercalibration of channels exploits the approximate uniformity of energy collection over the azimuthal angle. The absolute energy scale of the central and endcap calorimeters is set using isolated charged hadrons. The energy scale for the electromagnetic portion of the forward calorimeters is set using $Z \to e^+e^-$ data. The energy scale of the outer calorimeters has been determined with test beam data and is confirmed through data with high transverse momentum jets. In this paper, we present the details of the calibration methods and accuracy.

Gaseous Detectors / 128

Electroluminescence studies for CYGNO - Directional Dark Matter search with an optical TPC

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CYGNO (a CYGNus TPC with Optical readout) is a gaseous TPC Dark Matter directional experiment, to be hosted at Laboratori Nazionali del Gran Sasso, Italy. It fits into the context of the wider CYGNUS international proto-collaboration, for the development of a Galactic Nuclear Recoil Observatory at the ton-scale with directional sensitivity, having as the main goal the probing of the DM hypothesis below the Neutrino Floor and perform Solar Neutrino Physics.
In the CYGNO-TPC, the output signal results from the electroluminescence produced in the avalanches which develop in the strong electric fields inside the holes of the micropattern-type structures used for charge multiplication, and is collected by suitable photosensors. For the purpose of the experiment, the best gas and gas mixtures are being optimized, aiming at best performance in terms of the most relevant parameters, including identification of nuclear recoils and their direction.
We will present results for electroluminescence yield, charge gain and energy resolution for several gas mixtures of interest to the CYGNO project, namely He-CF4 mixtures and He-CF4-isobutane mixtures. The measurements were performed in a gaseous detector, equipped with a GEM for charge multiplication of the ionization signal and a Large Area Avalanche Photodiode to readout the electroluminescence produced in the electron avalanches.

Quantum Sensors / 129

Searching for axion-like dark matter with ensembles of nuclear spins

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Nuclear magnetic resonance is one of the promising approaches in searching for axion-like dark matter. We report the first science results of the CASPEr-electric search for the EDM and the gradient couplings of axion-like dark matter to nuclear spins in the mass range of 162 neV to 166 neV. The experiment employs an ensemble of ^{207}Pb nuclear spins inside a polarized ferroelectric solid PMN-PT crystal. We also demonstrate how the relaxation properties of this spin ensemble can be controlled using transient light-induced paramagnetic centers. Such spin ensemble engineering is necessary to achieve the sensitivity at the level of the QCD axion EDM coupling in the kHz to MHz frequency band.

Photodetectors / 130

Increasing photodetector light collection with metalenses

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We present a design concept and preliminary results for a method to increase the light collected by a sparse array of SiPMs, by placing a metalens in front of each photodetector. A metalens is a flat lens that uses nanostructures on the surface to focus incident light. Metalenses offer similar focusing power to traditional lenses, but with reduced bulk and cost, and can be mass-produced in industry nanofabrication facilities. Their use could allow the next generation of large-scale noble element detectors to obtain an increase in their light collection and further their science reach while simultaneously reducing the required number of readout channels needed to meet their design goals.

Quantum Sensors / 131

Data-driven dark matter-electron scattering rates from the dielectric function

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We present a fully data-driven approach for determining the spin-independent dark matter-electron scattering rate in any detector material. The scattering matrix element is completely determined by the complex dielectric function, which automatically contains all many-body effects and is directly measurable with X-ray scattering and electron energy-loss spectroscopy. We comment on the implications of this formalism for current and planned experiments, emphasizing how general properties of the dielectric function may help to identify optimal detector materials such as heavy-fermion compounds.

Photodetectors / 132

Spectral Photon Sorting with the Dichroicon in Large Neutrino Detectors

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Identifying Cherenkov photons produced when charged particles interact with scintillators provides additional information about the interaction, including directionality and particle identification, while maintaining the excellent energy and position resolution typical of scintillator detectors. The difference in arrival times of photons with different wavelengths also provides information about the distance to an event in dispersive media. Dichroicons provide access to this information by spectrally sorting photons using a Winston cone made from dichroic filters, which reflects long wavelength photons inconsistent with typical scintillation spectra to one PMT, and passes short wavelength photons to another PMT. A simulation model of dichroicon prototypes has been implemented in the GPU-enabled photon Monte Carlo package Chroma. This model is being used to evaluate the background rejection, particle identification, and direction reconstruction performance of a large liquid scintillator detector, such as Theia, instrumented with dichroicons as the primary photon detectors.

Noble Elements / 133

Light production in liquid and gaseous argon

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Most experiments using noble elements, past, current or planned, have exploited the abundant light yield in the vacuum ultraviolet (VUV) region ranging from 78-80 nm (Ne and He) to 128 nm (Ar), 150 nm (Kr) and 175 nm (Xe). It has however been known that noble elements, when excited by ionizing radiation, do also emit light at longer wavelengths, up to the near-infrared (NIR) although many questions remain on the exact nature of this scintillation both in terms of its atomic/molecular origin as well as its full characterization as regards the light yield, spectral and time structure. In this contribution we report preliminary results from a dedicated experiment in argon, sensitive to both the VUV as well as the non-VUV light. Data was taken both in gas and liquid argon with different concentration levels of nitrogen and we report on the effects of nitrogen on both the VUV and non-VUV light.

Low background / Low threshold detectors / 134

Phonon-mediated High-voltage Detector with Background Rejection for Low-mass Dark Matter and Reactor Coherent Neutrino Scattering Experiments

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SuperCDMS Z-sensitive Ionization and Phonon(ZIP, iZIP) detectors have shown great success in discriminating electron recoils and nuclear recoils, while the High Voltage (HV) detectors have reached very low (~100 eVnr) energy thresholds by sacrificing that discrimination. This talk focuses on a novel phonon-mediated two-stage silicon detector that will retain both an excellent threshold performance of the HV detector and maintain the iZIP-style background discrimination. The basic idea is to separate the measurement of primary phonons and charge estimate using Luke phonons in two different regions of a monolithic crystal. We have successfully demonstrated the discrimination ability of the first Si-based prototype detector for electron and nuclear recoil events. This new detector technology has the potential to significantly enhance the sensitivity to dark matter and coherent neutrino scattering experiments beyond the capabilities of current technologies which have limited discrimination at low energies.

Low background / Low threshold detectors / 135

Active Inner Veto for Improved Dark Matter Search and Neutrino Detection Sensitivity

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Many projects are underway aiming to experimentally detect the elusive dark matter candidate particle, the WIMP. Furthermore, some of these technologies are leveraging their strengths to explore other rare event phenomena, such as Coherent Elastic Neutrino-Nucleus Scattering (CEvNS). Both avenues require aggressively combating sources of background events that are detrimental to the overall sensitivity of the experiment. For the SuperCDMS Experiment, two of the dominating sources of background are Compton scattered gammas and events due to radon contamination on the detectors and surrounding materials. This talk describes the design, fabrication, and performance of a novel active veto detector instrumented with phonon sensors that immediately surrounds the primary detector to substantially reduce these backgrounds.

Calorimetry / 136

Status of hadronic calorimetry in GEANT4

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The performance of hadronic calorimeters will be a key parameter at the next generation of High Energy Physics accelerators. Energy resolution requirements might largely exceed the performance of today's detectors and therefore, require the development of new hadronic calorimeter concepts that combine fine granularity, excellent time resolution and possibly dual readout capabilities. The goal of this new calorimetric techniques is to compensate for effects that limit the performance of current hadronic calorimetry like nonlinear response to hadrons, energy deposition fluctuations etc. and will require
a high level of confidence in the performance of the simulation and its ability to make predictions.
The GEANT4 collaboration continuously evaluates the physics performance of the simulation utilizing mainly two approaches:
first detailed comparisons between GEANT4 predictions and thin target

experimental results are performed, directly comparing physics observables of single particle interactions. This is somewhat limited by the quality and availability of experimental data.
The other approach is the simulation and comparison with test beam results. These comparisons evaluate the overall performance of a detector system including the physics simulation, simulation of signal generation and other readout effects. In this presentation we report on recent developments of various Geant4 physics models and go over the validation results relevant to hadronic calorimetry and see how well experimental data is described and where there is need for improvements.

Noble Elements / 137

High pressure gas TPC technology for neutrinoless double beta decay searches: The NEXT program

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The NEXT experiment is a neutrino physics program searching for neutrinoless double beta decay using a high pressure gaseous xenon time projection chamber (HPGXeTPC). The HPGXeTPC technology offers several advantages, including excellent energy resolution, topological event discrimination, and low background. NEXT excels on each of these fronts, achieving 1% FWHM energy resolution at 2.6 MeV and a background rejection factor of 27 at 57% signal efficiency for 1.6 MeV electron-positron pairs. The resolution and event discrimination, along with our very radiopure detector, work together to allow us to achieve a background index of $4 \cdot 10^{-4}$ counts/(keV·kg·yr). We will discuss these strengths of the technology for the detection of rare events, as well as the performance of the current iteration NEXT-White detector and plans for future detectors. As discussed in this talk, the intrinsically excellent energy resolution and topological event discrimination of the technology requires continuous Kr^{83m} calibration throughout the active volume of the detector in order to be realized in practice.

Solid State Vertexing and Tracking / 138

Simulation and Measurement of the Shockley–Ramo Current from a Pixelated Silicon Detector

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TCAD and SPICE are used to simulate the response from a detector with a large detector-thickness-to-pixel-pitch ratio. The model indicates that the initial rising edge of the Shockley–Ramo current signal on the readout electrode has a very sharp rise time (~16ps), with an amplitude that is directly proportional to the weighting field. A silicon detector with this time resolution would have direct applications to high-energy particle physics. The modeled signal response will be validated on a sensor from a previous 8" wafer development with a pixel pitch of 30 x 100 μm and a thickness of 200 μm. The simulated induced current signal is of relatively small amplitude so a low-capacitance low-noise readout chain will be required. The simulated detector response and weighting field and proposed readout chain will be presented.

Readout and ASIC / 139

Multi-use advanced digital readouts using 3D stacking

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Recent advances in semiconductor 3D integration technology could enable modularity in sensors: An advanced digital chip may be combined with a separately fabricated analog detector front end and a separate detector. This technology will enable common use of highly capable but expensive digital components across sensing mode (imaging, photon counting, photon timing, etc) and wave band (gamma through LWIR). We report on recent efforts to produce an advanced digital imaging platform in an advanced (14nm) CMOS process as part of the DARPA ReImagine program. We give an overview of status and capabilities of the two digital chips produced to date, organized on Field Programmable Gate Array (FPGA) and System on a Chip (SoC) architectures respectively. We hope to spark a community discussion about potential uses of advanced digital circuitry and digital 3D integration for HEP sensing modalities such as self-triggering, photon counting and timing, and computational imaging.

Quantum Sensors / 141

Low-T_c TES as Sensors for Fundamental Physics

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Low-T_c TES based radiation detectors are excellent choices for experiments in fundamental physics such as direct detection of low-mass dark matter, neutrino-less double beta decay search, and coherent neutrino nucleus scattering, owing to their advantages of low threshold, high energy resolution, and fast response time. We have been developing low-T_c materials and devices with the goal of realizing low-T_c TES detectors for various applications in fundamental physics research. In this presentation, we will discuss work carried out in collaboration with UC-Berkeley, to develop large-area low T_c detectors as potential low-threshold light detectors for a neutrino-less double beta decay experiment. We have successfully developed a number of recipes for low-T_c superconductor films including Ir/Pt bilayer and Au/Ir/Au trilayer with tunable and reproducible T_c's down to 20 mK and

sharp superconducting transitions. Here we discuss our studies of thermal transport of our materials and present measurements of thermal conductance from both electron-phonon decoupling within our metals and materials interfaces.

Noble Elements / 143

Building low background kton-scale liquid argon time projection chambers for physics discovery

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With radiopurity controls and small design modifications a kton-scale liquid argon time projection chamber similar to DUNE could be used for enhanced low energy physics searches. This includes improved sensitivity to supernova and solar neutrinos, and even weakly interacting massive particle dark matter. This talk will focus on tools being developed to support a large-scale radiopurity assay campaign necessary to construct such a detector. These are adapted from software originally developed for low background dark matter detectors, including “radiopurity.org” and “Background Explorer”.

Readout and ASIC / 144

First Observations with the BMX 21cm Intensity Mapping Pathfinder

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The Baryon Mapping Experiment (BMX) at Brookhaven Laboratory is a 4-dish radio interferometer operating in the frequency band from 1100 to 1650MHz. It is designed as a technical pathfinder for a future cosmic survey using the intensity mapping technique to measure large-scale 3D cosmic structure traced by the redshifted emission of neutral hydrogen (rest frame wavelength 21cm). The array consists of four, 4-m diameter off-axis parabolic dishes and low-noise dual-polarization receivers. The digital back-end electronics includes digitization and real-time frequency channelization and correlation using fast GPU processors. In continuous operation, the telescope generates 28GB/day of time-ordered visibility data, resulting in a ~10TB dataset over ~380 days of observation.
A major objective of BMX is to investigate calibration techniques, which will be critical for a large future program. To date, we have used observations of astrophysical (Cyg A active galaxy) and artificial (UAV and GNSS satellite) sources as calibrators and have preliminary results for beam parameters as functions of frequency and polarization. We have also mapped the spatial and fine-scale frequency structure of the region of the Milky Way galaxy within the BMX footprint and found good agreement with the all-sky survey made with the Effelsberg 100m radio telescope (HI4PI collaboration, arXiv:1610.06175).
An upgrade of the digital back end electronics is underway which will replace the PCI digitizer cards and portions of the correlator F- and X-engines with recently-introduced RF System-on-Chip (RFSoC) hardware, capable of digitizing all 8 channels at 4-6 Gsamples/sec and streaming data out at 50GB/s.

TDAQ / 145

Trigger and Data Acquisition for the Mu2e-II experiment

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The Mu2e experiment at Fermilab will search for the charged-lepton flavor violating (CLFV) neutrinoless conversion of a negative muon into an electron in the field of a nucleus. Mu2e-II, a proposed upgrade of Mu2e, aims to improve the expected sensitivity by at least an order of magnitude. This upgrade will require a similar increase in the data rate and the radiation tolerance of the front end electronics. In this talk we will discuss the requirements for the Mu2e-II TDAQ and several conceptual ideas for upgrading the Mu2e system based on software triggers, GPU co-processors, or FPGA pre-processing.

Low background / Low threshold detectors / 146

Measuring cosmogenic activation rates in active detector material

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Long-lived radioactive isotopes produced by cosmogenic activation are a major source of background for rare event searches such as dark matter and neutrinoless double beta decay. Understanding the production rates of these cosmogenic isotopes is extremely important for determining the total allowable surface residence time of detector materials during fabrication, storage, and transportation. However, experimentally measuring the production rate is difficult due to low specific activities and because several of the decays of interest produce low energy electrons and x-rays that are not easily detectable. I will discuss a measurement technique that uses a high intensity neutron beam (with a spectrum similar to cosmic ray neutrons) in conjunction with low-background self-counting methods to determine production rates in active detector materials. Based on this technique I will briefly summarize previous results from the measurement of cosmogenic 39Ar and 37Ar production rates in argon, before presenting the first measurement of cosmogenic tritium production in silicon, as well as applications to other detector materials.

Gaseous Detectors / 147

Gaseous Time Projection Chamber for Ultra-low Radioactive Material Screening

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Ultra-low radioactive material screening is becoming a key requirement for a successful rare event search experiment such as dark matter and neutrinoless double beta decay searches. We proposed a low-background, large-area, and high-granularity gaseous time projection chamber (TPC) with Micromegas readout plane for surface alpha/beta contamination measurements. With the unique tracking capability, the gaseous TPC is able to distinguish the origin of events and identification of particle types. In this presentation, we will describe the conceptual design of the TPC, the screening sensitivity, and the preliminary test of a prototype.

Gaseous Detectors / 148

Status and prospects of TPC module and prototype R&D for CEPC

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To meet the high precision physical goals in the future e^+e^- circular collider (CEPC), the high resolution tracker detector for the particle track reconstruction (100μm) and particle identification are demanded. Time Projection Chamber (TPC) is one of the main concept option of the central tracker detector. On behalf of the track detector subgroup in CEPC, the status and update R&D results of TPC module and prototype for the specific requirements will be presented in this talk. TPC module will could suppress the ions in chamber continuously running in the different gains (2000-5000) and T2K mixture gases, and TPC prototype with MPGD detector module integrated the narrow laser calibration tracks system. the update results of the spatial resolution, dE/dx will be presented too, and the update results of the requirements, simulation and consideration will be given according to the pad and pixel TPC detector concepts will operate at the high luminosity Z pole at CEPC.

Gaseous Detectors / 149

The CGEM-IT of the BESIII experiment: preliminary results of the cosmic data taking

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Since 2008, the BESIII (Beijing Spectrometer III) experiment is running at the leptonic collider BEPCII (Beijing Electron Positron Collider II), hosted at the Institute of High Energy Physics of Beijing, PRC. A 10-year extension of the BESIII operations has been approved recently, and both the detector and the collider are now upgrading to cope with the extended physics program. One of the main upgrades is the replacement of the present inner tracker with a new detector based on Cylindrical GEM (Gas Electron Multipliers). The CGEM-IT (Cylindrical GEM Inner Tracker) detector is composed of three layers of cylindrical triple-GEMs and it will be read-out by the ASIC TIGER, which will allow to have simultaneous time and charge information for the hits. At present time, in Beijing, two of the final layers are collecting cosmic data to finalize the commissioning while waiting for the final later to be shipped from Italy. In this presentation, an overview of the CGEM-IT project will be presented, with a focus on the preliminary results from cosmic data taking.

Early Career Plenary / 150

The URANIA-V project: thermal neutron detection for radioactive waste and borders monitoring

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The applications of neutron detection are growing also outside the particle physics community: radioactive waste management (RWM), radioactive portal monitoring (RPM), and imaging are some of the most active fields. Due to the shortage of He^3, it is necessary to find reliable and effective alternatives. One of the most promising techniques is to use a Boron-coated gas detector: the neutrons convert into alpha particles (or Lithium ions) that can be later detected. The project μRANIA-V (μRwell Advanced Neutron Identification Apparatus) aims to detect thermal neutrons by means of the innovative μRwell gas detector. In particular, μRANIA-V is based on three pillars: increasing the neutron detection efficiency by introducing mesh and a grooved cathode; advance the technological transfer to industry, to reduce the production costs; prepare and test electronics to count the neutrons from the signals produced in the amplification stage. The optimization of the neutron detection technique, the first part of the study, has been developed within the EU-ATTRACT call. In this presentation, an overview of the project will be presented.

Early Career Plenary / 151

Monte Carlo simulation of CYGNO, an optical readout TPC for directional Dark Matter search

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The CYGNO experiment aims at making use of the directionality of nuclear recoils produced in the sensitive volume of a gaseous TPC with optical readout to uniquely identify Dark Matter signals, whose direction would point to the Cygnus constellation.
As one of the steps towards the CYGNUS-TPC network of underground observatories for directional DM search at the ton scale, CYGNO collaboration is working at a 1 m^3 demonstrator operated with a He:CF_4 gas mixture at atmospheric pressure at Laboratori Nazionali del Gran Sasso. Light produced in a triple-GEM stack is read by a set of sCMOS cameras, providing the 2D projection of the track on the GEM plane, and photomultiplier tubes, to use the signal time structure to determine the component along drift direction. This readout approach will allow to exploit the topological signatures of the events providing a very good background rejection capability.
A complete Monte Carlo simulation based on results obtained from different software packages as Garfield, SRIM, GEANT4 has being developed as a crucial tool for the comprehension and optimization of detector performance. Latest results will be shown along with a detailed comparison with experimental data obtained with CYGNO prototypes.

Solid State Vertexing and Tracking / 152

Quantum dot based scintillators for charged particle detection

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Advances in semiconductor research and development have enabled engineering of scintillation materials based on quantum dot (QD) photoluminescence. This has yielded low-mass and radiation tolerant scintillators with excellent timing and light-yield performance awaiting application in high energy physics experiments. We introduce a detector system of such a scintillator that consists of bulk GaAs with embedded sheets of self-assembled InAs QDs combined with physically integrated photodiodes for light collection. Early research and development of ~20 micron thin prototype sensors detecting 5.5. MeV α-particles have shown fast decay constants of 300 ps with ~70 ps time resolution and a light collection of 3.0×10^4 electrons / MeV using simple electronics readout. We describe results of recent measurements, discuss ongoing improvements in the detector and readout design, and present plans for performance testing to assess applications to high energy charged particle detection.

Readout and ASIC / 153

Towards scalable fast-neutron and reactor-antineutrino detectors based on 6Li-doped PSD plastic scintillators and SiPM arrays

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At the previous CPAD workshop (Madison, 2019), we presented observation of Pulse-Shape Discrimination (PSD) in segmented plastic scintillator developed at LLNL instrumented with modern photosensors — silicon-photomultiplier arrays.
This talk discusses the progress of various experimental efforts we have pursued for several potential applications of such detectors, ranging from nuclear non-proliferation to fundamental science of elementary particles. The current bottleneck in constructing finely-segmented low-power detectors instrumented with SiPM arrays is the readout electronics, as there are not many off-the-shelf scalable options. One promising solution is low-cost electronics for large-channel count readout as used in the Positron-Emission-Tomography (PET) scanners. The challenge arises in achieving the PSD in such system, as the electronics are not designed to store full waveforms — only charge and timestamp for a given integration window are recorded. The PSD in such systems is likely to be inferior to the full-waveform readouts. This talk is to discuss these challenges and to draw attention of the community to several key technological bottlenecks.

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Readout and ASIC / 154

A scalable low-noise skipper-CCD readout ASIC in 65 nm LP CMOS

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The MIDNA application specific integrated circuit (ASIC) is a prototype cryogenic skipper-CCD readout chip fabricated in a 65 nm LP CMOS process and intended for the OSCURA dark matter detection project. The MIDNA ASIC integrates four front-end channels designed to interface with the 4000 skipper-CCDs for a 28 gigapixel camera for dark matter detection. Each channel is only 0.156 mm² and achieves an equivalent noise charge of 1 e⁻_{rms} at 20 µs integration time in simulation. With the non-destructive readout capability of skipper CCDs, MIDNA and the skipper CCDs will be capable of sub-e⁻_{rms} noise by averaging samples of each pixel and at the scale required by OSCURA. Each readout channel contains a pre-amplifier, a DC restorer, and a triple-phase integrator. The channel has four gain settings to maximize dynamic range for a variety of CCD charge gains. The minimum integration time is 1 µs. The power consumption is 4.2 mW per channel. The linear dynamic range is 3000 e⁻ in nominal gain. The temperature range is 84-120 Kelvin as required by the skipper CCD, and the input referred noise is less than 6 nV/√Hz at 10 kHz.

Quantum Sensors / 155

ARIADNE: a laboratory search for the QCD axion with hyperpolarized 3He spins

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The Axion Resonant InterAction DetectioN Experiment (ARIADNE) will search for spin-dependent forces mediated by the QCD axion between an unpolarized Tungsten source mass and a sample of polarized helium-3 as the sensor by using a nuclear magnetic resonance based technique. The experiment relies on low magnetic gradients for the helium to remain polarized during transport to the sample cell, limiting ordinary magnetic noise with superconducting magnetic shielding as well as a stable rotary system to modulate the axion-signal from the source mass. Background and current progress on the experiment will be discussed.

Solid State Vertexing and Tracking / 156

Design, Simulation, Manufacturing, and Validation of Prototype for the CMS Phase II Tracker upgrades

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Several support structures for CMS Phase II Tracker upgrades, namely the IT support tube and the IT service cylinder, have been through their first iterations of prototyping at Purdue University's Composites Manufacturing and Simulation Center (CMSC) and Purdue Silicon Detector Lab (PSDL). The mass, stiffness, and dimensional tolerance were the primary design objectives. In order to meet the extreme mechanical performance and dimensional stability requirements, a stiff yet lightweight carbon fiber composite structure has been designed via performance and manufacturing simulations, manufactured as a prototype, and validated. Several layups and configurations of structural stiffeners were investigated to minimize the deflection of the service cylinder within the permissible design envelope. Design iterations and simulation results demonstrate the diminishing returns of increased mass vs structural rigidity under the defined load cases that include the weight of the detectors and services. The importance of performing tool shape compensation to account for anisotropic material coefficients of thermal expansion and their effect on part geometry during and after manufacturing is explored and implemented. Validation exercises with digital image correlation (DIC) fiducial marker tracking emphasize the importance of designing simple, yet meaningful, test load cases that allow validation of FEA methodology. Good agreement was found between the simulation and the experiment. With FEA methodology and boundary conditions validated for simplified load cases, more accurate load case simulations may be trusted for continuing design work until an assembled prototype allows for "full-scale" validation. Lessons learned during design, simulation, manufacturing, and validation are presented with a set of next steps to improve upon each for the creation of a successful service cylinder and IT support tube that meets final application requirements.

Quantum Sensors / 157

Design of low T_c TES chips as sensors for low background calorimeter arrays

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TES based radiation detectors with highly multiplexed SQUID readout have been widely adapted in microcalorimeter based experiments and are the technology of choice of many next generation experiments (CMB-S4, Athena X-ray satellite and others) owing to their excellent energy resolution, threshold and their fast response. These properties also make them a very desirable choice for applications like the search for neutrino-less double beta decay with 300 g-scale Li_2MoO_4 calorimeters in CUPID or a search for CEνNS with 40 g-scale absorbers in Ricochet. In this talk we will discuss a first design of a self-contained low T_c TES readout chip that can be readily connected to various absorbers via a deposited Au film as phonon collector on the target. We will discuss several design studies including their impact on the science case and present first performance estimates from the thermal modeling of these devices.

TDAQ / 158

Detector design for a Muon Collider experiment

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The US particle physics community engaged in the Snowmass process is studying collider projects for the post-LHC era. Among those, muon colliders are particularly interesting due to their ability to reach multi-TeV energies in the environment typical for lepton colliders where backgrounds due to other physics processes are significantly lower than at a hadron collider experiment. However, as muons are unstable particles such a machine will be accompanied with technological challenges for a collider experiment: an unprecedented amount of secondary and tertiary decay products will enter the detector volume. This contribution will present a detector design based on the strategies that have been studied to mitigate the beam-induced background by exploiting new detectors technologies and at the same time aims to meet the performance requirements needed for a vast physics program. Particular attention will be given to the tracker as it is most affected by the beam-induced background (BIB). Most reconstructed hits in the tracker are expected to come from the BIB. We will discuss how the BIB can impact the occupancy of a tracker at a muon collider experiment and demonstrate how precision timing information and spatial granularity of such a tracker can be used to keep the occupancy at an acceptably low level that will allow proper reconstruction of the tracks.

Calorimetry / **159**

Radiation Hard Zero Degree Calorimeters for ATLAS and CMS in the HL-LHC era

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Heavy Ion program of the LHC offers great physics opportunities for CMS and ATLAS.
The Zero Degree Calorimeters (ZDC) are increasingly important for characterizing A+A, p+A, γ+A and γ+γ collisions at the LHC and EIC.
We present the recent developments in radiation hard fast ZDCs by the ATLAS and CMS heavy ion groups to fully exploit the potential for the QCD physics during the high luminosity era, when the increasing luminosity places a significant strain on the current ZDCs.
We also present the developments of ZDC for the Electron Ion Collider for tagging the spectator neutrons and the identification of forward photons.

Gaseous Detectors / **160**

Lessons from Mu2e Tracker Construction and Mu2e-II Tracker Opportunities

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The Mu2e experiment at Fermilab will search for the neutrinoless conversion of a muon into an electron in the field of an Al nucleus, with a sensitivity improvement of four orders of magnitude over

previous measurements. Observation of this process would be unambiguous evidence for physics beyond the Standard Model. The signature of muon to electron conversion is a monoenergetic electron with energy nearly equal to the muon mass. Precise tracking with minimal energy loss or multiple scattering is paramount to this measurement. The Mu2e tracker will consist of 20,000 thin-walled straw tubes operating in a vacuum of 10^{-4} torr. The construction process of the tracker has imparted many lessons and techniques which have improved functionality and building efficiency of the detector. These lessons will help to improve the design for future detectors, such as the tracker required for Mu2e-II, a proposed upgrade to the Mu2e experiment. In this talk, we will discuss the Mu2e tracker, lessons learned during the ongoing construction process, as well as Mu2e-II tracker options and opportunities for improvement.

Noble Elements / 161

Modeling Impurity Concentrations in Liquid Argon Detectors

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Impurities in noble liquid detectors used for neutrino and dark matter experiments can significantly impact the quality of data. We present an experimentally verified model for describing the dynamics of impurity distributions in liquid argon (LAr) detectors. The model considers sources, sinks, and transport of impurities within and between the gas and liquid argon phases. Measurements of the oxygen concentration in a 20-L LAr multi-purpose test stand are compared to calculations made with this model to show that an accurate description of the concentration under various operational conditions can be obtained. A result of this analysis is a determination of Henry's coefficient for oxygen in LAr. These calculations also show that some processes have small effects on the impurity dynamics and excluding them yields a solution as a sum of two exponential terms. This solution provides a simple way to extract Henry's coefficient with negligible approximation error. The simplified model is applied to the data and the extracted Henry's coefficient for oxygen in LAr is consistent with published results. Based on the analysis of the data with the model, we further suggest that, for a large liquid argon detector, barriers to flow ("baffles") installed in the gas phase with large coverage can help reduce the ultimate impurity concentration in the LAr. A 260L LAr system is presently being commissioned for further studies of the model and also for future performance and optimization studies of LArTPCs.

TDAQ / 162

Streaming data acquisition system for CLAS12 Forward Tagger

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CLAS12 detector is installed at Jefferson Lab's experimental Hall-B and the purpose of its huge science program is to provide substantial progress in understanding the Quantum Chromo Dynamics (QCD). Such a detector requires a sophisticated trigger and current experiments use an on-line FPGA-based system that relies upon custom firmware and electronics both of which are difficult reconfigure from one experiment to the next. To overcome these challenges an effort is underway to develop streaming readout (SRO) data acquisition system. The latter would allow a more flexible, easier to debug, software trigger to be developed. A SRO prototype system has been developed based on four main components: front-end electronics based on JLAB-FADC250 and VTP modules , TriDAS and

CODA data acquisition systems and the JANA2 analysis/reconstruction framework.
In this contribution I will present the results of successful on-beam test performed in the the winter and summer of 2020 to read in streaming mode, with the cited triggerless chain, the CLAS12 Forward Tagger.

Low background / Low threshold detectors / 163

Dark side of afterglow: nuclear recoils and relaxation avalanches.

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Metastable excitations in materials can store energy longer than equilibration time for the rest of the system. This disequilibrating can arise from a many sources - ionizing radiation, electric breakdown, mechanical stress, changes in temperature, and changes in electric or magnetic fields. Relaxation of stored energy leads to afterglow in gases or temperature stimulated luminescence, exaelectron emission and conductivity in solids (TSL,TSEE and TSC effects). Similar effects are present in liquids, on surfaces of dielectrics and semiconductors, in films on metal surfaces, etc. Such metastable excitations can undergo a range of transformations –they can interact and diffuse in materials, form clusters, accumulate around defects and on surfaces and interfaces. Accumulation of these interacting excitations leads to possibility of avalanche relaxation events. A well-known example is self-organized criticality dynamics; it results in a noise power spectral density that is close to 1/f, and spectrum of avalanches energies decreasing polynomially with energy. Such avalanche relaxation events can mimic low-energy interactions with particles: several photons can be produced in scintillators, or several electrons in ionization detectors. Yet un- explained low energy background (few photons or electrons events) in scintillators, dual-phase noble liquid detectors and some solid-state detectors hint that avalanche relaxation of accumulated energy may be a culprit.
While quantitative ab -initio description of these effect is difficult, we discuss qualitative experiments that can help to identify these effects, what material mechanisms can be involved in scintillators and noble liquids, and how parasitic effects can be suppressed or mitigated.
This work was performed under the auspices of the US Department of Energy by the Lawrence Livermore National Laboratory under contract DE-AC52-07NA227344. Lawrence Livermore National Security , LLC

Quantum Sensors / 164

Anisotropy of quantized electronic excitations in semiconductors for directional dark matter searches

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We study the quantum effects that are associated with the nuclear recoil electronic excitations in semiconductor crystals. Our studies exhibit a rate modulation in very low threshold semiconductor detectors, for dark matter (DM) mass < 1 GeV/c^2, that is correlated with the target nucleus recoil direction. This anisotropic quantum excitation threshold can be used to perform directional DM search for the range of DM mass that is out of reach for conventional gaseous detectors. We will also present the effect of defect creation in solid state phonon-mediated detectors with $\sim$ eV threshold on the expected DM or coherent elastic neutrino-nucleus scattering spectrum.

Low background / Low threshold detectors / 165

Contact-free readout concept and recent progress toward single-electron resolution large-mass semiconductor detectors

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Semiconductor detectors, particularity those using CCD or Neganov-Trofimov-Luke (NTL) assisted phonon-mediated techniques are the technologies of choice for the experiments seeking rare and very low energy interactions such as low mass dark matter or coherent elastic neutrino nucleus scattering (CEνNS). The ultimate sensitivity reach of the current detector design is hindered by a stochastic carrier leakage that seems to be primarily due to the particular detector contact architecture at use. We will present a new semiconductor bias and readout design wherein the bias electrodes do not have a physical contact with the substrate. We will present recent progress toward single-carrier excitation in large mass Si or Ge of $\sim$100 g using this novel design. We will also present the application of this novel technique for fast and non-pervasive prescreening of semiconductor crystals for defect and impurity concentration evaluation.

Photodetectors / 166

Large Area Picosecond Photo-Detectors (LAPPDs) for ANNIE and Future Neutrino Experiments.

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The demand for fast-timing photodetectors is ever-increasing to enhance the capability for better event reconstruction in neutrino and high-energy physics experiments. Large Area Picosecond Photo-Detectors (LAPPDs), which are 20 cm x 20 cm flat panel, micro-channel plate (MCP) based photodetectors bring considerable new capabilities for neutrino event reconstruction in Cherenkov and scintillator detectors. Their single photoelectron (sPE) time resolution is about 50 picosecond and gain characteristics are exceeding 10^7. The Accelerator Neutrino-Neutron Interaction Experiment, ANNIE, a 26-ton of water Cherenkov detector on the Booster Neutrino Beam (BNB) at Fermilab will be the first neutrino experiment leveraging this technology to make detailed neutrino measurements. ANNIE is about to deploy the first LAPPD in the water volume, and more to be deployed very soon. In this talk, we will discuss efforts towards application readiness of LAPPDs in ANNIE and their relevance to future neutrino experiments.

Early Career Plenary / 168

Speeding up the search for axions with quantum squeezing

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The Haloscope at Yale Sensitive to Axion Cold dark matter (HAYSTAC) has now finished its first data collection run using quantum squeezed states to enhance the search for axions. The squeezed state receiver consists of two Josephson parametric amplifiers. The first squeezes vacuum noise, while the second amplifies a hypothetical axion signal against a background of squeezed noise. This protocol allows HAYSTAC to acquire data with noise levels below the standard quantum limit, increasing the rate at which we can scan axion parameter space by a factor of 2. In this talk, I will give an overview of the operations of the HAYSTAC experiment, and discuss our recent exclusion of axions in the 4.11 - 4.18 GHz range.

Calorimetry / 169

Experience in design and prototyping of CMS HGCAL

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The CMS High Granularity Calorimeter (HGCAL) has been heavily influenced by designs for detectors at future colliders, and the experience gained in constructing it will be crucial to those future projects. Designed to function in the end cap region of CMS at the HL-LHC, the calorimeter must cope with extremely high particle flux while delivering good physics performance.

The HGCAL is currently transitioning from the design phase into the construction of advanced prototype components. Soon construction of the final detector elements will commence.

In this talk, we review the important features of the design, describe some problems and solutions encountered along the way, and describe the plan to bring the construction of the calorimeter to a successful conclusion.

Gaseous Detectors / 170

CYGNUS: Imaging of low-energy nuclear recoils in gas TPCs

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With some leading direct dark matter detection experiments now observing background events and WIMP-nucleon scattering limits approaching the neutrino floor, there is renewed interest in constructing an observatory capable of detecting and distinguishing WIMP and coherent elastic neutrino-nucleus scattering (CEvNS) via directionality. CYGNUS aims to deploy gas-target time projection chambers (TPCs) capable of event-by-event nuclear recoil imaging. Smaller, near-term detectors with this capability would enable new precision measurements, including of the Migdal effect, searches for beyond the Standard Model (BSM) physics, and measurements of solar neutrinos. A large detector could establish the galactic origin of a dark matter signal, and subsequently be used to map the local WIMP velocity distribution and explore the particle phenomenology of dark matter. Therefore, there exists an opportunity to develop a long-term, diverse, and cost-effective experimental program around directional detection of nuclear recoils in gas TPCs at different scales. I will discuss the different technological approaches being pursued in CYGNUS, with a focus on activities in the US.

Readout and ASIC / 171

Recent Progress on Digital Frequency Domain Multiplexed Readout of Transition Edge Sensors

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Digital Frequency Domain Multiplexing (DfMux) is a method of biasing and reading out many Transition Edge Sensors (TES) with an $\mathcal{O}(1)$ MHz alternating-voltage bias using superconducting resonators and a Superconducting Quantum Interference Device (SQUID) array amplifier. DfMux has been deployed in several Cosmic Microwave Background (CMB) experiments with a multiplexing factor as high as 68 (including most recently POLARBEAR-2 and SPT-3G), is the baseline readout technology for the future satellite CMB mission LiteBIRD, and is an alternative readout technology for the future ground-based CMB experiment CMB-S4. Recent work has focused on modifications to the cryogenic circuit in order to further improve system performance and scalability for future experiments. Results from recent laboratory measurements will be presented demonstrating improved readout noise and parasitic impedance due to a modification to the cryogenic architecture and the use of a low dynamic impedance SQUID array.

Quantum Sensors / 172

TES Based Light Detectors for CUPID using an IrPt bi-layer transition edge sensor

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CUPID is a proposed upgrade to the ton-scale neutrinoless double beta decay experiment, CUORE which is current operating at the Laboratori Nazionali del Gran Sasso (LNGS). The primary background in CUORE are degraded α's, and CUPID aims to improve the background by over a factor of 100 by utilizing a two channel energy collection approach, light and heat. This will allow for event by event discrimination of α and γ/β interactions. In order to meet the timing and energy resolution requirements of CUPID, large area light detectors using low-Tc transition edge sensors (TES) on Si wafers are a promising technology to use. Here we will present the current state of the ongoing collaboration with ANL to develop light detectors using an IrPt bilayer TES with Au pads to enhance thermal conductivity to the Si wafer, reporting on the preliminary measures of timing and energy resolution. Additionally we will discuss ongoing plans to explore multiplexed readout and other improvements.

Readout and ASIC / 173

Testing Virtual ASICs with Real Data: an Example from CMS timing upgrade

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During the development of new detectors for future experiments or the Upgraded Collider detectors, the ASIC and sensor development often follow parallel paths. This implies that, for the last stages of ASIC development there often exists a significant body of data obtained with high quality waveform sampling that capture the subtleties of real response of the sensors to various particle beams.

Whereas the final validation of the ASIC, before production can begin, requires real "battle testing" of the sensor and ASIC in a test beam setup, the production cycle could be accelerated by an intermediate step where the ASIC simulation models developed as part of the design process are used to analyze quality waveforms captured in pre-existing test beam samples. These waveforms are then treated as input signals to which transfer functions are applied to exhibit the response at various nodes in the ASIC.

In contrast to an input signal model for the simulation, a library of test beam waveforms is more likely to expose subtleties arising from, for example, Landau fluctuations, high rate effects leading to signal pileup, etc.

Although the full blown simulation tools (eg CADENCE in the present example) could be used to analyze a large sample of digitized test beam waveforms, the cost of licenses and the relatively large CPU usage have discouraged this in the past. As an alternative to using lighter weight variants of the commercial packages we illustrate an approach wherein, starting from limited information about the key components in the ASIC, we developed a strategy to probe the transfer functions of a chip (in this case, the TOFHIR2 chip development for the CMS barrel timing layer).
We show that an adequate description can be obtained using a network of Resistors and Capacitors to replicate the transfer functions, resulting in a very efficient code for analyzing real test beam input data to the ASIC.

The events of 2020 shut down operation of laboratories providing crucial test beam facilities and exposed the vulnerabilities of the electronics development cycle in terms of training young engineers and overall impact on large experiments with interconnected subsystem schedules. Going forward, the current approach may also be beneficial in reducing vulnerabilities.

Solid State Vertexing and Tracking / 174

4D trackers for future collider experiments

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The next generation of high energy physics colliders call for major advances in tracking detector technology. For example, the proposed FCC-hh calls for a tracker with 5 um spatial resolution per hit and 5 ps time resolution per track, in order to disentangle the expected 1000 proton-proton collisions per bunch crossing. We will present results of the collaborative work by FNAL, BNL, and KEK in developing detector technologies to achieve these goals. Low-Gain Avalanche Detectors (LGADs), developed for High Luminosity LHC experiments have demonstrated precise time resolution (30 ps), but only coarse position resolution (1 mm). Recent advances in design, including AC-LGADs and Trench-Isolated LGADs, can extend the LGAD concept to smaller pitch sizes, and spatial resolution on the order of 10 um. Another avenue for advancement in LGAD design is the possibility to develop sensors based on Depleted Monolithic Active Pixel Sensors (DMAPS) technology using a CMOS process. Monolithic sensors are expected to significantly reduce costs while maintaining radiation hardness and time resolution performance. We will present recent advances in these technologies, results from laboratory and test beam measurements, and an outlook on the future directions of the technology.

Readout and ASIC / 175

Design and Integration of the Readout Electronics for ATLAS Liquid Argon Calorimeter for HL-LHC

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The luminosity of the High Luminosity Large Hadron Collider (HL-LHC) will be increased to $7.5\times10^{34}\text{cm}^{-2}\text{s}^{-1}$ in Run 4 that will start in 2027. The expected integrated luminosity will be 3000-4000 fb^{-1} at the end of the HL-LHC operation. The liquid argon calorimeter consists of electromagnetic barrel, electromagnetic end-cap, hadronic endcap and forward calorimeter. The electronics readout for the current liquid argon calorimeter will be upgraded to meet the requirements of the upgraded trigger rate of 1 MHz. The upgrade includes new front-end boards (FEB2) to sample and digitize total 182,468 calorimeter cell signals by using custom ADC with 40MHz sampling rate and 14-bit resolution, new liquid argon signal processors (LASP) to process the data in high performance Filed Programmable Gate Array (FPGA), new liquid argon timing trigger control distribution and front-end monitoring/configuration (LATOURNETT) to distribute the trigger, timing and control (TTC) signals, and new calibration board to emulate the response of the calorimeter cells.

A radiation hardness pre-amplifier and shaper ALFE is being developed in CMOS 130nm technology to meet the requirement of the LAr signal processing. The ALFE amplifies the calorimeter signals with a dynamic range up to 16 bits, transforms the signal to a multi-gain differential output, and

uses CR-(RC)^2 circuit to shape the signal to match the signal processing requirements. To evaluate the performance of the LAr upgrade for HL-LHC, a system integration platform is being developed. The system consists of calorimeter signal injection to emulate the detector signal, FELIX based data acquisition system to receive front-end electronics data, and back-end electronics to process data in FPGA. The system integration will evaluate the function and performance of the FEB2, LASP, LATOURNETT and also the full chain of the data processing, from calorimeter signal injection to the trigger and data acquisition (TDAQ) system of ATLAS.

The status of the upgrade will be introduced. Some test results of the ALFE prototype and studies on the system integration will be presented.

Quantum Sensors / **176**

Searching for dark matter using mechanical systems

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When properly engineered, simple quantum systems such as harmonic oscillators or spins can be excellent detectors of feeble forces and fields. Following a general introduction, I will focus on using optomechanical systems as sensors of weak acceleration and strain fields. Dark matter particles coupling to standard model fields and particles would produce a coherent strain or acceleration signal in an elastic solid. We discuss the feasibility of searching for dark matter consisting of ultralight scalar or vector fields in the 10^-12 eV–10^-6 eV/c^2 mass range using various optomechanical systems. I will also show that understanding and addressing issues around quantum control are essential steps towards building quantum noise limited detectors.

Photodetectors / **177**

Mapping the CMB at High-Frequency with Kinetic Inductance Detectors on the South Pole Telescope

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Microwave kinetic inductance detectors provide a scalable platform for mapping the cosmic microwave background, especially at frequencies above 150 GHz, where arrays of transition-edge sensors cannot be made densely enough to efficiently sample telescope focal planes. Arcminute-resolution CMB observations at these higher frequencies can fill a unique niche in cosmology, yielding high-fidelity foreground-cleaned measurements of the kinetic Sunyaev-Zeldovich effect, improved constraints on the optical depth to reionization and thus the neutrino mass, and an initial detection of Rayleigh scattering of the CMB at recombination. SPT-4 is a new experiment that aims to make these cosmological measurements by leveraging high-density MKID focal planes and next-generation RF readout deployed on the South Pole Telescope. I will describe the science goals of SPT-4 and the key technology developments that enable its powerful yet compact design.

Gaseous Detectors / 178

Gas-filled Neutron Imager Operating in Ionization Mode

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We describe the development of a new position-sensitive detector for neutrons that uses He-3 as the neutron sensing element and operates in ionization mode, without any electron multiplication. The electrons created by the thermal neutron - He3 interaction are collected by discrete anode pads, each connected to an input channel of an ASIC mounted on the back of the anode pad plane. The custom 64 channel ASICs and their readout board can process events up to 25k/s. Using this concept, we have designed and constructed a large area detector for small angle neutron scattering with nearly 40,000 channels, yielding a total count rate of 10**8 cps over an area of 1m x 1m. Early results demonstrate excellent, stable performance for small-angle scattering. The detection technique also allows the observation of ionizing tracks from recoil nuclei created by fast neutrons.

Photodetectors / 179

Recent results from the pixel-based accelerated aging of Large Area Picosecond Photodetectors ($LAPPD^{\mathrm{TM}}$)

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We present results from the aging test of a recently fabricated 20 cm × 20 cm Large Area Picosecond Photodetector (LAPPD) by INCOM Inc. A differentiating feature of LAPPD is the use of ALD-GCA-micro channel plates (MCPs) fabricated by utilizing atomic layer deposition (ALD) technology to coat the resistive and emissive films to the surface of bare glass capillary arrays. LAPPD has the largest active area among the commercially available planar MCP-photomultiplier tube (MCP-PMT) photodetectors. Accelerated aging of the LAPPD MCP-PMT has been achieved by exposing a highly localized region of the photodetector to 450 nm photons at high rates. Our previous investigations have shown that the radiation effects of a pixel-based exposure are highly localized with minimal damage beyond the exposed area making it possible to characterize performance results while retaining the future usability of the MCP-PMT. In the present accelerated aging experiment, we extract current densities of about 1.4 μA/cm^2 from the LAPPD MCP-PMT which is made possible by the reasonably high gain of the LAPPD at high event rates. In this presentation, we will discuss the pre-test characteristics of the LAPPD MCP-PMT along with its performance after irradiation up to a few coulombs per cm^2.

Readout and ASIC / 180

R&Ds of ASICs and Optical Modules for Detector Data Communication

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In HEP experiments, detector data communication is one of the key R&D areas. This is especially important when the operating environments inside the detectors preclude the use of COTS in these link systems. ASICs and optical modules are being developed to meet the challenges of detector upgrades in the LHC. This effort has been led by the CERN common projects GBT/lpGBT and Versatile Link/VL+. The GBT ASICs and the VTRx optical module are key components for optical links at 5 Gbps per fiber. The lpGBT ASIC and the VTRx+ optical module reach 10 Gbps per fiber for detector data transmission (the so-called up-link). The bandwidth of the data communication (clock, configure and control) to the detector (the down-link) is reduced to 2.56 Gbps (compared with GBT) to save power. What are also studied in these common projects are link protocols, correction schemes for transmission errors, optical power budgets, passive components such as fibers and connectors to meet the special operating environments inside HEP detectors. Moving forward, CERN has held workshops on future R&D programs for data rates as high as 56 Gbps with 28 nm ASIC technology and PAM4. While these common projects and collaboration among many institutions are efficient and effective, ideas and R&D from individual university groups should also be encouraged and supported. We will report on two R&D efforts: GBS20, the ASIC that builds on many design blocks from lpGBT (hence 65 nm technology) plus a PAM4 encoder and driver, to reach 20 Gbps per fiber. Prototypes of GBS20 will be available for test in the near future; cpVLAD, the array VCSEL driver that has an embedded charge pump to automatically raise the driving voltage inside the chip to above 3 V with a 1.2 and 2.5 V external power supply system, for applications in extreme conditions where the VCSEL forward voltage may increase due to accumulated radiation damage. To the best of our knowledge both PAM4 and the charge pump for high-speed circuits are the first attempts in HEP ASICs. GBS20 is in prototype stage and will provide valuable experience to the community when it moves to the more expensive 28 nm technology for 56 Gbps data rate. cpVLAD is fully developed and complete as an R&D program. Looking a few steps further forward, we are exploring the idea of using a charge pump in an array amplifier ASIC for p-i-n diode in the down-link channel to address several issues including radiation induced degradation of signal to noise ratio. After this we would like to address the SEE issue related to a p-i-n diode to recover long consecutive bit errors at hardware level with a special TIA and module design. While we continue our participation in the highly efficient and effective CERN led common projects and R&D programs, it is our hope that centers of excellence in universities and national labs will not be starved out for near term gain in specific projects. Long term investments immune to the success or failure of specific and ad-hoc proposals will establish a healthy foundation for the whole HEP program.

Noble Elements / 181

Measuring trace krypton for the LUX-ZEPLIN dark matter search

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As liquid xenon dark matter detectors grow to the multi-tonne scale, the requirements on xenon purity become more stringent. For the LUX-ZEPLIN (LZ) experiment, Kr impurities must be suppressed to concentrations less than 300 parts-per-quadrillion (ppq) (g/g) (Kr/Xe) due to backgrounds caused by Krypton-85, a beta emitter with a 10.8 year half life. This talk reviews the cold trap mass spectrometry instrumentation developed by LZ to detect Kr impurities in Xe with a concentration sensitivity of 50 ppq. This methodology is routinely employed by LZ both at the SLAC National Lab, where the Xe inventory is processed to remove Kr, and at the experimental site at SURF in Lead, SD.

Noble Elements / 182

Scintillation and Optical Properties of the Low-Background Scintillator, PEN

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To improve detector sensitivities, neutrino physics and dark matter searches are pursuing novel low background and self-vetoing materials for components. One material of interest is poly(ethylene-2, 6-naphatalate) (PEN) for its inherent scintillating and wavelength shifting properties, as well as its commercial availability and structural stability. Commercially available PEN material is typically limited to films with thicknesses less than 0.01 mm. As such, the PEN working group (a part of the LEGEND collaboration) has developed a method to produce PEN components with excellent optical properties of thicknesses up to 5 mm, and with a specific activity of less than mBq/kg. These thicker components typically have different molecular orientations, which exhibit different optical and luminescent properties. Using these thicker components, characterization of PEN was conducted at the University of Notre Dame's Nuclear Science Laboratory. In this talk we will discuss the results of this measurement as well as particle discrimination and quenching factor.

Readout and ASIC / 183

Low noise, low jitter cryogenic amplifier for superconducting nanowire detectors.

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We present the development of a cryogenic Low-Noise Amplifier (LNA) for the readout of Superconducting Nanowire Single Photon Detectors (SNSPDs). The integrated circuit operates at 4 K and is based on fourth-generation heterojunction bipolar transistors from a state-of-the-art, commercially available SiGe BiCMOS platform, which allows large scale integration and economy of scale. Target specifications for the fully differential LNA include >20 dB gain, ~6 GHz BW, ~10 ps jitter, and <10 mW/channel. We discuss cryogenic modeling of the devices, design and test results of the prototypes (AC and DC coupled), the latest received in Feb 2021. The project is a collaboration between Fermilab, Georgia Tech, Caltech and JPL. The target application is low-noise, low-jitter single photon detection for high-speed quantum networks. The scalability of this technology, however, coupled with the availability of small feature size CMOS transistors on the same die, provides a path for the integration of a large number of low-noise, fast front end readout amplifiers, together with low-power digital backend logic for digital signal processing; thus enabling large, multi-Gbps SNSPD arrays for photon and particle detection, with direct application to QIST, HEP and NP programs.

Early Career Plenary / 184

Thin A-Se films for novel scintillation light detectors

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VUV scintillation light detection in noble liquids is a hot topic in detector R&D given its wide range of applicability: from next generation of acceleration neutrino detectors to dark matters, to neutrino less double beta decay. In this talk, we present advancements in light detection R&D via coatings of thin semiconductive VUV sensitive films. With the proper choice of photoconductive material such a device could have a broad frequency response and thus all the detection of the full spectrum of light produced in Noble Element TPCs. The starting semiconductor of choice is amorphous selenium (A-Se), which is already used in imaging for medical applications in warm and in the X-ray spectrum. Our first challenge is the use of ASe coatings on mm wide pixels in cold subject to VUV light. An additional benefit of this research is to be the stepping stone towards the development of multiple modality pixels, i.e. pixel capable of reading both VUV light and fC charge simultaneously, applicable in future LArTPCs.

Quantum Sensors / 185

The future of Hugely coherent sensors for HEP

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I will discuss some of the most successful precision probes of fundamental physics to date, which make use of coherent systems of $\mathcal{O}(10^{23})$ particles to study extremely feeble beyond-the-standard-model interactions, such as fifth-forces, low mass dark matter and new sources of CP-violation. I will cover the systems which are currently the most sensitive to new scalar (gravitational) and pseudoscalar (spin) interactions, both as 5th force and I will suggest how they may improve in the near future. Several of the limiting factors at this juncture are most suitable to community-level R&D efforts: low-vibration facilities, improved material noise/properties and lower-noise read-out systems. Improvements in these technical areas are essential to any experimental system pushing the precision limits of new couplings to fermions. The impact that stretches across research groups and the long time-scales and "institutional" knowledge required for progress point to the need for joint rather than isolated R&D, and university/national lab partnerships.

Readout and ASIC / 186

Towards Edge Computing: Co-Design for Machine Learning based ASICs for Scientific Applications

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In a multi-channel detector readout system, waveform sampling, digitization and transmitting bits to the data acquisition system constitutes a conventional processing chain. Quantities, such as time-of-arrival and signal magnitude, i.e deposited energy, are estimated by fitting analytical models over the acquired digital data, hence enabling the extraction of signal starting time, peak amplitude, and more. These tasks could be carried out through machine learning algorithms: their implementation in the front-end ASIC comes with enormous benefits, especially when the analytical response signals are not fully known or the registered waveforms suffer from the imperfection of practical implementations. This approach significantly reduces the bandwidth of data throughput, thereby reducing the overall cable count in experiments.

Initial studies are focused on various neural networks, their implementation and training with test waveforms typical for silicon sensors. The most accurate model is further optimized in terms of layers and neurons while still targeting prediction with acceptable accuracy. The translation of machine learning algorithms to transistor level circuit not only requires new design methodologies but also the introduction of novel devices such as memristors, needed to reduce the overall memory footprint and total power dissipation. In this workshop, we would like to present the status of this new research and development initiative with a final goal towards edge computing in scientific applications.

TDAQ / 187

Liquid Argon Time Projection Chamber Trigger Development with MicroBooNE and SBND

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The MicroBooNE and Short Baseline Near Detector (SBND) experiments are Liquid Argon Time Projection Chamber (LArTPC) neutrino detectors that have been collecting or will soon be collecting neutrino and cosmic data in the Fermilab Booster Neutrino Beam. They collectively aim to perform ν-Ar cross-section measurements, explore the low-energy excess in the νe spectrum reported by the MiniBooNE experiment, and search for sterile neutrino oscillations as part of three LArTPCs that make up the Short Baseline Neutrino (SBN) Program at Fermilab. Both detectors provide a unique opportunity for the implementation and testing of TPC-based triggers as R&D towards Deep Underground Neutrino Experiment (DUNE). One of the technical challenges that these studies aim to address is that of efficient self-triggering of a LArTPC utilizing TPC signal information. This capability will enable searches for rare processes in the DUNE, such as neutrino interactions from a potential galactic supernova burst, or baryon number violating nucleon decays. This talk will describe the MicroBooNE and SBND TPC readout systems and ongoing R&D efforts to develop and demonstrate TPC-based triggering.

Early Career Plenary / 188

Test beam study of SiPM-on-tile configurations for the CMS HGCAL

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The scintillator section of the CMS high granularity calorimeter (HGCAL) will be composed of the SiPM-on-tile technology, where the SiPM is located in a dimple machined into the scintillator tile surface. This design directly couples the light produced from a scintillator tile to an individual SiPM, which is crucial for calibrating the detector throughout its lifetime. We report the light collection and spatial uniformity for a large variety of configurations of scintillator tiles. The varied parameters include tile transverse size, tile thickness, tile wrapping material, scintillator composition, and SiPM model. These studies were performed using 120 GeV protons at the Fermilab Test Beam Facility. External tracking allowed the position of each proton penetrating a tile to be measured. The results were compared to a GEANT4 simulation of each configuration of scintillator, wrapping, and SiPM.

Solid State Vertexing and Tracking / 189

Silicon Carbide Detectors for Ionizing Radiation: history, state of the art and perspectives

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Silicon Carbide (SiC) is a wide bandgap semiconductor with outstanding physical properties for detectors of ionizing radiation. The wide band gap (up to 3.2 eV), high saturation velocities of the charge carriers (200 um/ns), high breakdown field (2 MV/cm), high thermal conductivity (4.9 W/cm²) and relatively large threshold displacement energy (21-35eV), allow low-noise, fast response and stable operation in environments and conditions forbidden to other semiconductors. Since 1998, considerable R&D efforts have been devoted worldwide to develop SiC radiation detectors and this presentation focuses on the results obtained with different crystals (semi-insulating or undoped-epitaxial) and detector types (pad, pixel, microstrip) operating in different contests: from the extremely low signals of soft X-ray spectroscopy to the huge radiation exposure in TW/PW laser-induced plasmas experiments. The perspectives for further development and application of SiC detectors and their advantages will be finally discussed.

Photodetectors / 190

Skipper-CCD for quantum microscopy: status and plans

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Skipper-CCD is able to measure the charge in each pixel, repeatedly, in a non-destructive way. As a result, the readout noise can be reduced as much as desired [Tiffenberg et al, 2017]. It allows the precise counting of the number of electrons in each pixel ranging from empty pixel to more than 1900 electrons [Rodrigues et al. 2021]. In addition, they account for very high quantum efficiency (above 90% in the visible range), extremely low dark current (less than 1 electron per pixel per day), and high resolution (pixel size of 15 microns by 15 microns). There are many promising applications of this sensor on Quantum Imaging. In particular, they can provide the same resolution and Noise Reduction Factor in Quantum Microscopy using a factor of hundreds of fewer photons per pixel than the current best achievement in this field [Samantaray et al, 2017]. The same advantage can be expressed as an order of magnitude better resolution at the same number of photons per pixel. This presents a valuable impact of the Quantum Microscopy applications in biology and chemistry when avoiding damaging the sample is required [Taylor et al, 2012]. During this talk, we will present the status and plans for the implementation of Skipper-CCD in this field.

Tiffenberg et al. Single-Electron and Single-Photon Sensitivity with a Silicon Skipper CCD. Phys. Rev. Lett.,119,13,131802,2017,10.1103/PhysRevLett.119.131802

Rodrigues et al. Absolute measurement of the Fano factor using a Skipper-CCD. arXiv:2004.11499v3

Samantaray, N., Ruo-Berchera, I., Meda, A. et al. Realization of the first sub-shot-noise wide-field microscope. Light Sci Appl 6, e17005 (2017). https://doi.org/10.1038/lsa.2017.5

Taylor, M., Janousek, J., Daria, V. et al. Biological measurement beyond the quantum limit. Nature Photon 7, 229–233 (2013). https://doi.org/10.1038/nphoton.2012.346

Enjoy / 192

Enjoy your weekend, see you Monday!

Enjoy / 193

Enjoy your weekend, see you Monday!

Solid State Vertexing and Tracking / 194

Potential of Thin Film Detectors

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Nanoscience technologies are developing new cutting edge materials and devices for a wide range of applications. HEP can take advantage of the many advancements by looking toward thin film fabrication techniques to implement a new type of particle detector. Thin Film Detectors have the potential to be fully integrated, large area, low power, low dead material, and low cost. I will discuss potential research paths using thin film technologies and the potential performance benefits for future particle physics experiments.

Cross Cutting Plenary / 196

Cryogenic Facility Needs for High Energy Physics

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Cross Cutting Plenary / 197

Test Beam Needs for HEP

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Cross Cutting Plenary / 198

Industrial Trends in Radiation Hard Foundries

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On-Sky Test Facilities

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Solid State Vertexing and Tracking / 200

Three-dimensional integration of sensors and electronics

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We discuss the current status and prospects for three-dimensional integration (3D) of sensors and electronics. 3D consists of a suite of technologies including through-silicon vias, wafer bonding and thinning, and fine pitch interconnection. These technologies have the potential to transform the capabilities of pixelated sensors in High Energy Physics providing finer pitch, more complex electronics, and heterogeneous integration. In the last 5 years 3D integration techniques have been widely adopted in the image sensor industry. However scientific applications are lagging. We will discuss experience with 3D sensors and electronics in HEP and technical and commercial roadblocks to adaptation. We will survey the availability of foundries that support the critical bonding and via technologies. Finally, we will discuss examples of possible applications of these technologies to future experiments.

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Coherent Neutrino Nucleus Scattering at Reactors with Solid State Detector

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In the last years, there has been a growing interest in the use of low energy threshold technologies in nuclear reactors as a test bench for neutrino properties, new neutrino interactions at low energy, and the observation of new particles like dark photons, axion-like particles, etc. (through photon-production mechanisms). Nuclear-reactor cores produce the largest neutrino and gamma fluxes accessible on the earth, with energies up to a few MeV's. Solid-state sensors have demonstrated to provide the low threshold energies (below 1keV of transferred energy) needed to access to these new physic models. In this talk, I will discuss the results obtained by the CONNIE experiment (Coherent Neutrino-Nucleus Interaction Experiment) using silicon CCD sensors (Charge Coupled Devices) with a threshold energy of approximately 100 eVee for the detection of low energy neutrino interactions at the Angra II nuclear reactor in Brazil. I will present a new sensor technology, called the Skipper CCD, which allows to set threshold energies around 1 eVee thanks to its single charge counting capability. Single electron-hole pair ionizations in the silicon can be detected by the nondestructive readout output stage (which overcomes the electronic noise limiting factor of regular CCDs. I will also comment on the scientific reach of new experiments based on Skipper CCDs at nuclear reactors.

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Direct method for the quantitative analysis of surface contamination on ultra-low background materials from exposure to dust

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Dust fallout on material surfaces can be a significant contribution to radioactive background in rare-event ultra-sensitive radiation detectors. Until now, estimates of such contribution have been largely performed based on fallout models and assumed dust composition. This work presents an effective method for the direct determination of contaminant fallout rate on material surfaces from exposure to dust. The method involves the exposure of low-background collection media to dust, followed by surface leaching and leachate analysis via inductively coupled plasma mass spectrometry (ICP-MS). The method was validated and applied in selected cleanroom and non-cleanroom locations at Pacific Northwest National Laboratory (PNNL) and the SNOLAB underground facility. Fallout rates of naturally occurring radionuclides K-40, Th-232, U-238 and stable Pb were investigated. A comparison between directly measured fallout rates and those estimated from current model-based predictors was also performed. Results show that the composition of dust in cleanrooms, and hence the material contamination from particulate fallout, strongly depend on the current ongoing activities and do not necessarily reflect the local composition of soil. Discrepancies of one order of magnitude or higher are observed between directly measured and model-based estimates. While originally developed to quantify contaminations of long-lived radionuclides and stable lead, the method can potentially investigate contamination from any stable element in the periodic table, providing localized elemental fingerprint to dust sources.

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Low Background 3-D Printed Parts: Investigations into Producing Radiopure Polymer Materials Using Additive Manufacturing

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Low background rare-event physics experiments and ultrasensitive radiation detectors require materials of the utmost radiopurity to meet their sensitivity goals. Polymers are important materials used extensively in these detectors in a variety of roles, including as insulators and structural supports. Oftentimes, specialized polymer parts are co-located with the active detection target, necessitating their radioactive background contribution to be as low as possible. Additive manufacturing, or 3D-printing, has been discussed as a possible means to fabricate complex parts of low mass for niche applications but requires vetting for radiopurity. This work investigated several different polymer feedstocks, including polyphenylene sulfide (PPS), polyvinylidene fluoride (PVDF), polyetherimide (PEI), and utilized a fused deposition modeling printer to fabricate parts. Both simple and complex parts were fabricated and assayed along with the starting filament feedstocks. Results indicate that both simple and complex parts can be produced with little-to-no radioactivity added, with the best polymer showing levels for Th-232 and U-238 at single digit parts-per-trillion levels (ca. 100 microBq/kg).

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A Novel Scintillator Detector for the Mu2e-II Experiment and a Muon Tomography Search for Hidden Chambers in the Great Pyramid

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The Mu2e experiment is designed to search for the charged-lepton-flavor-violating process, ⊠− to a ⊠−, with unprecedented sensitivity. The single 105-MeV electron that results from this process can be mimicked by electrons produced by cosmic-ray muons traversing the detector. An active veto detector surrounding the apparatus is used to detect incoming cosmic-ray muons. To reduce the backgrounds to the required level it must have an efficiency of about 99.99\% as well as excellent hermeticity. The detector consists of four layers of scintillator counters, each with two embedded wavelength-shifting fibers, whose light is detected by silicon photomultipliers. An upgrade of the experiment, Mu2e-II, that will provide an order of magnitude more sensitivity is under design. The cosmic-ray veto detector is being redesigned to handle the higher rates. This redesign is also being used for a proposed high-resolution search for hidden chambers in the Great Pyramid of Khufu. The design and expected performance of the detector will be described.

Early Career Plenary / 205

Designing and building a pair of scintillating bubble chambers for WIMPs and reactor CEvNS

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The Scintillating Bubble Chamber (SBC) is a rapidly developing novel technique for 0.7 - 7 GeV nuclear recoil detection. Demonstrations in liquid xenon at the few-gram scale have confirmed that this technique combines the event-by-event energy resolution of a liquid-noble scintillation detector with the world-leading electron-recoil discrimination capability of the bubble chamber, and in fact maintains that discrimination capability at much lower thresholds than traditional Freon-based bubble chambers. The promise of unambiguous identification of sub-keV nuclear recoils in a scalable detector makes this an ideal technology for both GeV-mass WIMP searches and CEvNS detection at reactor sites. We will present progress from the SBC Collaboration towards the construction of a pair of 10-kg argon bubble chambers at Fermilab and SNOLAB to test the low-threshold performance of this technique in a physics-scale device and search for dark matter, respectively.

Award and Blue Sky Plenary / 206

CPAD GIRA Award

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Closing Plenary / 207

Summary of Low Background/Low Threshold Detectors

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Readout and ASIC / 208

Roundtable

Discussion: electronics design resources, training, tools, circuit and systems techniques, access to technology, and important community forums.

TDAQ / 209

Designing a 30 MHz GPU trigger, the LHCb experience

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LHCb will deploy a new fully GPU-based first level tracking trigger in Run 3, processing at 30 MHz (5 TB/s). A close integration with the DAQ and event building allows for a particularly compact system, with the GPUs hosted in the same servers as the FPGA cards receiving the detector data, which reduces the network to a minimum. This architecture also inherently eliminates latency considerations, allowing GPUs to be used despite the very high required throughput. We review the software and hardware design of this system, reflect on the challenges of developing for heterogeneous architectures, and discuss the anticipated performance of the system.

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Real-time analysis in Run 3 with the LHCb experiment

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LHCb's second level trigger, deployed on a CPU server farm, not only selects events but performs an offline-quality alignment and calibration of the detector and uses this information to allow physics analysts to deploy essentially their full offline analysis level selections (including computing isolation, flavour tagging, etc) at the trigger level. This "real time analysis" concept has also allowed LHCb to fully unify its online and offline software codebases. We cover the design and performance of the system which will be deployed in Run 3, with particular attention to the software engineering aspects, particularly with respect to quality assurance and testing/limiting failure modes.

TDAQ / 211

FELIX: the Detector Interface for the ATLAS Experiment at CERN

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The Front-End Link eXchange (FELIX) system is an interface between the trigger and detector electronics and commodity switched networks for the ATLAS experiment at CERN and other experiments. The detector and trigger electronic systems of the ATLAS experiment are largely custom and fully synchronous with respect to the 40.08 MHz clock of the Large Hadron Collider (LHC). The FELIX system uses FPGAs on server-hosted PCIe boards to pass data between custom data links connected to the detector and trigger electronics and host system memory over a PCIe interface then route data to network clients via a dedicated software platform running on these machines. The FELIX approach takes advantage of modern FPGAs and commodity computing to reduce the system complexity and effort needed to support data acquisition systems in comparison to previous designs.

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Towards an Interpretable Data-driven Trigger System for High-Throughput Physics Facilities

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Data-intensive science is increasingly reliant on real-time processing capabilities and machine learning workflows, in order to filter and analyze the extreme volumes of data being collected. This is especially true at the intensity frontier of particle physics. Data filtering algorithms, or trigger algorithms, at the LHC drive the data curation process, funneling event records with certain features into categories that are predefined based on the labels extracted by the trigger algorithms.

The design, implementation, monitoring, and usage of these trigger algorithms is resource-intensive and can include significant blindspots. The menu of trigger algorithms is manually designed based on domain knowledge (involving ~100 data filters). In this presentation, we introduce a new data-driven approach for de- signing and optimizing high-throughput data filtering and trigger systems such as those in use at physics facilities like the LHC. Concretely, our goal is to replace the current hand-designed trigger system with a data-driven trigger system with a minimal run-time cost, while preserving the distribution of the output. We introduce key insights from interpretable predictive modeling and cost-sensitive learning in order to account for non-local inefficiencies in the current paradigm and construct a cost-effective data filtering and trigger model that does not compromise physics coverage. We next plan to use this model to expand to a self-driving and continuous learning triggering algorithm, that will allow us to discover new physics without extensive knowledge of the parameter space.

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The Expandable Modular ATCA hardware design for high-energy physics experiment applications

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The CMS experiment has adopted ATCA standard for the upcoming Phase-II upgrade. We have developed a novel approach to the design of ATCA boards for this upgrade. Instead of relying on a regular single-PCB framework, with possibly some additional mezzanine cards, the X2O design is using a large heat sink as a main mechanical carrier, with various modules attached to it as needed. The modules designed so far are: Power module that includes DC-DC power converters and a control device based on Xilinx ZYNQ System-on-Chip (SoC), FPGA module based on XCKU15P FPGA, and an optical module based on industry-standard QSFP+ optical engines with the bandwidth of up to 25.78 Gbps. Additionally, the collaborating groups are designing their own FPGA and optical modules based on different FPGAs and optical engines.
A typical approach in ATCA hardware design for CERN experiments is to use two separate control devices: an IPMC controller is responsible for negotiating with ATCA Shelf Manager via IPMB protocol, and another microcontroller is typically used for all other control functionality, such as register settings, status readout, etc. This usually leads to considerable cost increase and reduces the PCB real estate.
We have combined both functions in a single device. It is a very inexpensive and small off-the-shelf module based on Xilinx ZYNQ-7000 SoC, running Centos 8 Linux. In order to do that, we have reworked an open-source software to operate as a full-featured IPMC controller in Linux environment. The entire IPMC project has been published in an open-source repository as well. The IPMC software is designed to be modular and expandable by users.

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Real-time Artificial Intelligence for Accelerator Control: A Study at the Fermilab Booster

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We describe a method for precisely regulating the gradient magnet power supply (GMPS) at the Fermilab Booster accelerator complex using a neural network (NN). We demonstrate preliminary results by training a surrogate machine-learning model on real accelerator data, and using the surrogate model in turn to train the NN for its regulation task. We additionally show how the neural networks that will be deployed for control purposes may be compiled to execute on field-programmable gate arrays (FPGAs). This capability is important for operational stability in complicated environments such as an accelerator facility.

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Global Trigger for the ATLAS Phase-II upgrade

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The ATLAS detector at CERN's LHC will undergo a major upgrade prior to the startup of High-Luminosity LHC which affects all major subsystems including trigger and data acquisition. The new Level-0 hardware trigger will be comprised of legacy as well as new systems, among them the Global Trigger which processes full-granularity calorimeter information at 40 MHz and allows for the execution of complex algorithms and topological selection in firmware by concentrating full event data onto a single FPGA processing node. In order to do so the Global Trigger will make use of a Global Common Module that hosts the most sophisticated available FPGAs and optical modules. The first prototype of this module has been designed and constructed recently.

Detector R&D Townhall / **216**

Thoughts from the NSF

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Detector R&D Townhall / **217**

Roundtable discussion and Q&A

TDAQ / **218**

Liquid Argon Time Projection Chamber Trigger Development with MicroBooNE and SBND

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Coprocessors as aservice for accelerated inference of DL algorithms

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DL algorithms have been widely adopted in LHC analyses. Use of DL in triggering, however, has been limited because of stringent throughput limitations and limited hardware availability. This limitation is compounded as LHC physicists look for new particles below existing trigger thresholds. We begin to address these challenges by developing SONIC, a tool for running DL algorithms into CMS workflows. SONIC leverages highly optimized DL inferences on GPUs, and it allows application-specific integration of DL algorithms onto heterogeneous clusters with minimal changes to workflows. In this talk, we will present the first scaled tests of realistic DL algorithms integrated in a HEP High Level Trigger system using GPUs and FPGAs as a service, and discuss ongoing efforts in HEP and beyond.

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hls4ml: enabling real-time deep learning in HEP trigger and DAQ systems

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Hls4ml is a user-friendly software, based on High-Level Synthesis (HLS), designed to deploy deep neural networks on FPGAs within applications characterized by tight constraints in terms of latency and resources. In this talk we present the core features of the library and recent progresses in supporting quantization-aware training with arbitrary precision, DNN architectures with large convolutional layers as well as the exploration of custom graph neural networks. Examples of applications to the trigger and DAQ of HEP experiments, such as the particle detectors at the LHC, will also be described.

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Triggering on Long-Lived Particles decaying to Hadronic Showers in CMS Muon System

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Long-lived particles (LLPs) are predicted in many extensions beyond the standard model. They often have unique signatures in collider detectors. A particularly interesting model considers long-lived particles that decay hadronically in the CMS muon system. Such particles are capable of producing a shower of hits in the muon chambers. Because of design considerations and bandwidth limitations, the current CMS muon trigger is not equipped to detect hadronic showers. In this presentation we explore options to improve the trigger for Run-3 data taking. We show that a per-chamber hit counter is a powerful discriminator that increases the sensitivity to hadronically decaying LLPs by at least a factor ten. We discuss the baseline scenario and potential future improvements.

Solid State Vertexing and Tracking / 222

Panel Discussion on Fast Electronics for Timing Detectors

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Discussion Session

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Group Photo