Detector Needs for Neutrino And Rare Processes Frontiers

Wes Ketchum

Fermi National Accelerator Laboratory

20 July 2022

Intro/caveat slide

As always, the talk scope is large, the time is limited, and I am only one person*

*granted, one who had massive help preparing material

I have no doubt missed something important to you, which is not a statement of its importance to us all!

Intro/caveat slide

As always, the talk scope is large, the time is limited, and I am only one person*

*granted, one who had massive help preparing material

I have no doubt missed something important to you, which is not a statement of its importance to us all!

Please enjoy this by imagining a 'my-favorite-things-Wes-missed BINGO'

Neutrinos

Future experiments will use neutrinos to probe physics beyond the Standard Model

- Determine the nature and origin of neutrino masses
- Exploit connections of neutrino interactions and oscillations to new particles and new broken symmetries

These experiments require detectors (and facilities) that go beyond detecting neutrinos to using them as a driver for discovery

Many connections to technology for other physics, particularly dark matter detection, proton decay, nnbar oscillations, …

Noble elements detectors

Liquid and gas noble elements detectors well-demonstrated for $0\nu\beta\beta$, dark matter, and neutrino interactions/oscillations

For future, key concerns are scalability, sensitivity to low energies, improved energy resolution and calibrations, and reduced background rates

Focus on enhancing existing modalities and exploring new ones

Noble element detector improvements

QPix Dual Charge+Light Readout

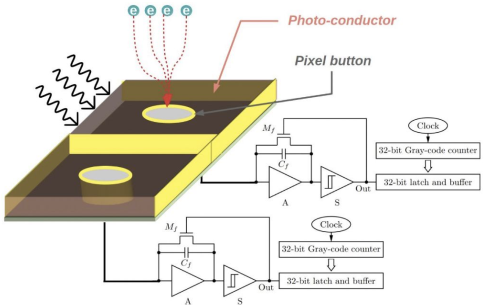
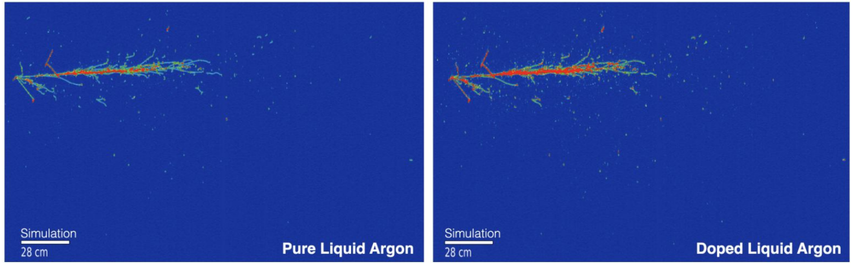


Photo-ionizing dopants in LArTPCs



Improve event reconstruction and lower detection thresholds through pixelated charge and light readout

Improve sensitivity and energy resolution in to VUV scintillation photons through dopants or WLS surfaces, improved sensors

…or with photo-ionizing dopants that convert light to charge

Further development of optical TPCs and high-pressure gas TPCs

New modalities in noble detectors

Ion detection and micron-scale track reconstruction for low energy interactions and directional dark matter detection

- Ion drift overcomes diffusion problems for drifting large distances
- Ion transport also key for barium tagging (for $0\nu\beta\beta$ background discrimination)

Metastable fluids, e.g. scintillating bubble chambers (super-heated noble liquids)

- Main instrumentation challenge is backgrounds from surface nucleation (beyond ton-scale)

New modalities in existing noble-element detectors: e.g. KAMLAND-Zen, and dissolving H or LXe targets in LZ for light dark matter sensitivity and enhanced background tagging

Challenges for BIG future noble detectors

- Scaled-up target procurement and purification
  - E.g. extraction of underground Ar
- Large-area charge- and photo-sensor development
  - Low noise, low power, operate cryogenically
- High voltage/maintaining large electric fields
  - Maintain multi-meter drifts and drive larger detection volumes
- Understanding of and reduction techniques for low-energy backgrounds
- Effective triggering and data acquisition for larger detector size and low threshold (e.g. Fast ML)
- Automated operation and in-situ calibration to improve detector uptime and data uniformity

Photon detection beyond just noble elements

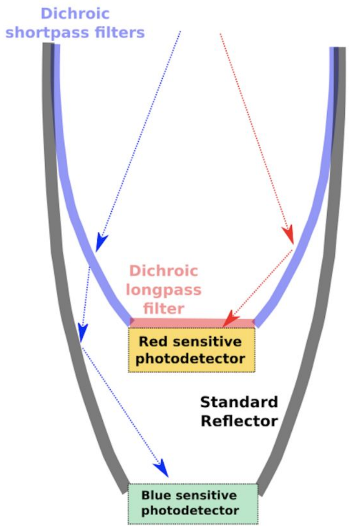
Can extend the capabilities of Cerenkov detectors with technologies that allow separation and detection of scintillation light (so-called *hybrid* detectors)

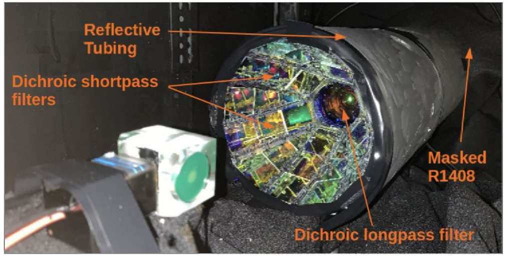
- Separate temporally through fast/precise-timing detectors or slow-fluors/WbLS
- Separate spectrally through filters (including dichroic) or narrow-band fluors

All should be coupled with improved performance of existing technologies (quantum efficiency and timing), especially for VUV

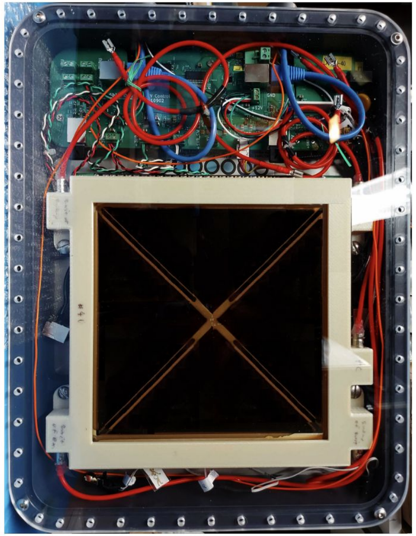
Photon detector technologies

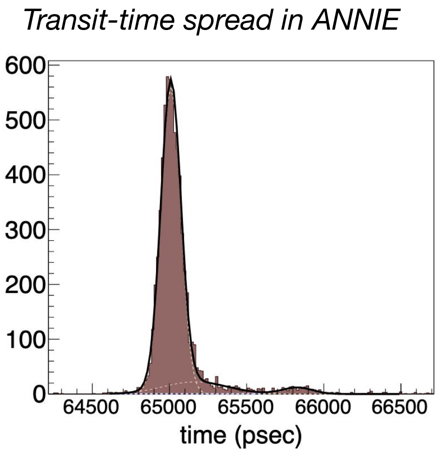
Dichroic filter design





Fast timing with LAPPDs





Pushing to the lowest energies

Breakthroughs in measuring nuclear recoils enable new neutrino probes through CEνNS detection and extend dark matter capabilities

- Variety of technologies, from phonon detectors, CCDs, and HPGe to scintillators, MPGDs, noble liquids, and bubble chambers

Next challenges largely common across detector technologies:

- Improved sensitivity, optimization, and multiplexing of readout sensors
- Reduce backgrounds and understand low-energy response (via in-situ calibration)

Direct detection of neutrino mass

Calorimetric

HOLMES: Embed ^{136}Ho in sensor and detect phonons from captured β

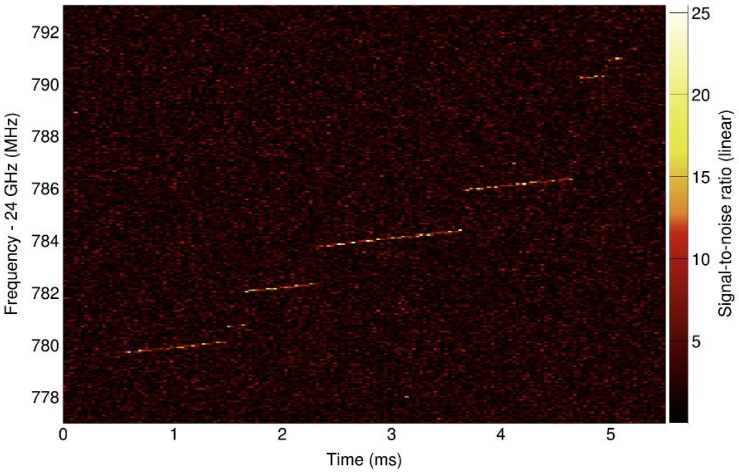
Requires scaling up of detectors using TES arrays through SQUID multiplexing

Cyclotron radiation emission spectroscopy (CRES)

Project 8: measure cyclotron radiation from atomic tritium β in ~ 1T magnetic field

Exploring scaling technologies, via high-frequency antenna arrays and cavity resonators

Demonstration of CRES Method from Project8

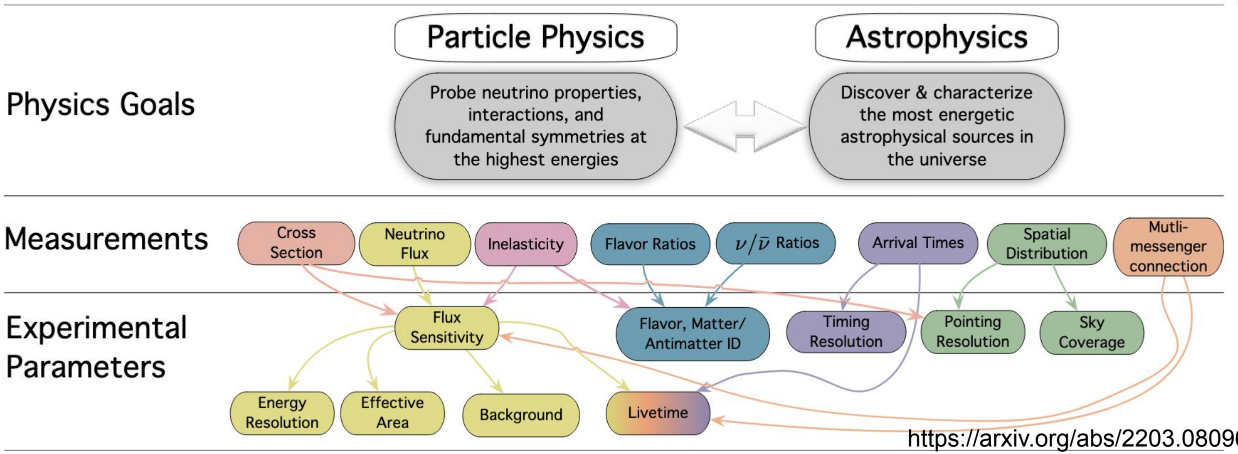


https://arxiv.org/abs/2203.07349

Pushing to the highest energies

Exploring high- (TeV-PeV) and ultra-high-energy neutrinos (PeV-EeV)

Techniques include optical Cerenkov detection, radio detection (in ice and air showers) and air-shower imaging via Cerenkov and fluorescent light



https://arxiv.org/abs/2203.08096

Commonly require good siting, large exposures, good energy, pointing, and timing resolution

Improvements in remote power and communication (and timing synchronization) for very large extended arrays

Optimizations in electronics, e.g. improving power consumption for Radio Frequency System on Chip

Detecting neutrinos at colliders

New opportunities possible with LHC forward physics facility

Variety of possible detectors exploiting many technologies

Technology	FASER2	FASERnu2	Adv-SND	FLArE	FORMOSA
Large aperture SC magnet	x				
High resolution tracking	x		x	x	
Large scale emulsion		x			
Silicon tracking			x		
High purity noble liquids				x	
Low noise cold electronics				x	
Scintillation				x	x
Optical materials				x	x
Cold SiPM				x	
Picosec synchronization			x	x	x
Intelligent Trigger	x		x	x	x

NF10 Report

Rare processes and precision experiments

SM particles as a gateway to understanding the origins of flavor and generations, and fundamental symmetries

Search for the dark sector through deviations from the SM

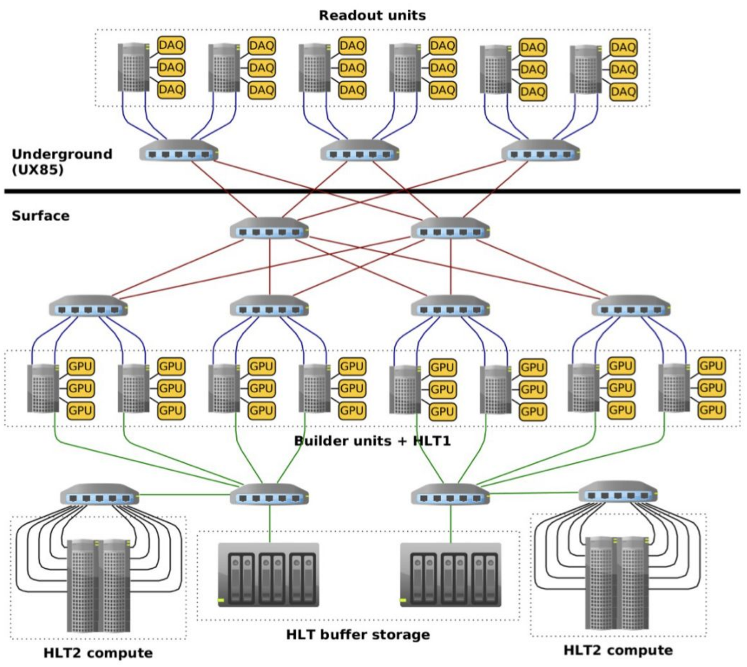
- At colliders, accelerator neutrino experiments, and other high-intensity beams

Detector needs sometimes overlap with those of other frontiers, but also many specific needs

Weak decays of heavy quarks

Heavy quarks (b and c) largely explored at *pp* and e^+e^- colliders

- Overlapping needs with EF on precision tracking in ever-complicated environments
- Leading way on many aspects of detector development
    - E.g. fully software L1 trigger / streaming DAQ in LHCb



https://cds.cern.ch/record/2809810/files/analysis_note_B2ppkpiTP.pdf

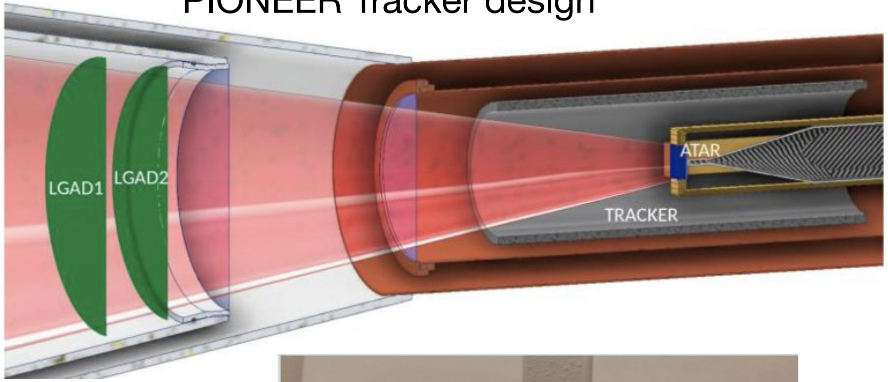
Weak decays of light quarks

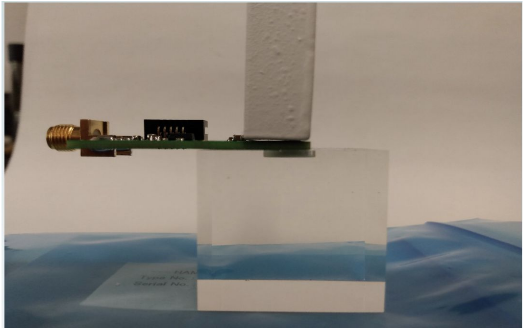
Searches in decays of kaons, hyperons, pions, and etas

Common needs: tracking and calorimetry with both excellent timing and position resolution

- Thin Si LGADs for tracking
- 5D calorimetry
- Fast triggering to suppress the large backgrounds

PIONEER Tracker design





ARIADNO2 Calorimeter tile for REDTOP

Quantum sensors

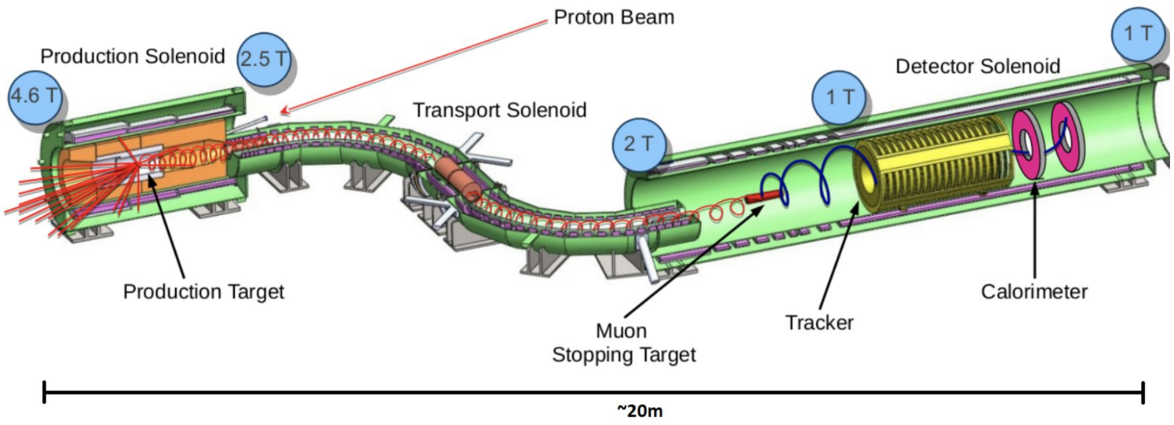
Quantum sensors are a key components of electric and magnetic dipole moment measurements and precision tests of gravity

- Atomic interferometers, optomechanical sensors, optical clocks, and spin-dependent sensors
- Key avenue for improvement includes improved techniques on back-evasion and squeezing to push beyond standard quantum limit (SQL)
- Theory support to address issues of materials and measurement methods

Detector R&D for Charged lepton violation in Mu2e-II

PIP-II upgrades would allow for higher intensity and higher duty factor muon source for Mu2e

Poses significant problems in handling higher rate and backgrounds occupancy



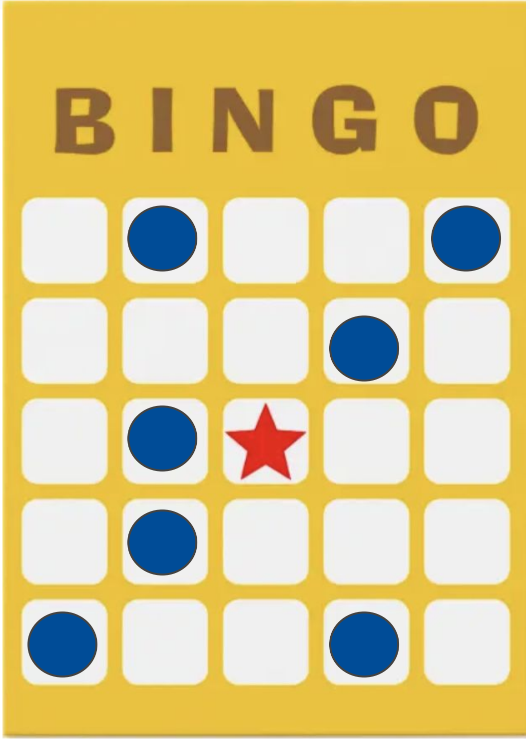
- Thinner straw tubes to reduce multiple scattering
- New calorimeter materials (e.g. doped BaF_2 crystals)
- TDAQ upgrades (e.g. through use of heterogeneous computing)

Summary

We are using intense particle sources to probe for the physics of neutrinos, flavor violation, and searching for dark matter

Future detector technologies to meet the physics needs include enhancing existing techniques and developing new materials and methods

A common message: new detection technologies require investment in facilities and people, spanning from design and prototyping through construction, integration, commissioning, and operations


BINGO