Summary of Calorimetry

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A Brief Overview

- More than 40 abstracts received, showing enthusiasm of the community.
- 23 presentations given in 5 CAL sessions (C1 to C5: 5, 5, 5, 3 and 3) and 2 EC sessions, covering simulation (3), high granularity (HG, 5), dual readout (DR, 7), organic (7) and inorganic (7) scintillators for Mu2e (2), EIC (1), Higgs factory (9) and HL-LHC/FCC-hh (11).
- All presentations respond to the PRD for calorimetry from the 2019 DOE BRN Study:

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<th>Priority Research Direction</th>
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<td><strong>PRD 1</strong>: Enhance calorimetry energy resolution for precision electroweak mass and missing-energy measurements</td>
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<td><strong>PRD 2</strong>: Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments</td>
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<td><strong>PRD 3</strong>: Develop ultrafast media to improve background rejection in calorimeters and improve particle identification</td>
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Calorimetry Session 1

C1-1: Digital Hadron Calorimeter

- The first Digital Hadron Calorimeter was built and tested successfully. By construction, the DHCAL was the first large-scale calorimeter prototype with embedded front-end electronics, digital readout, pad readout of RPCs and extremely fine segmentation.

- Fine segmentation allows the study of electromagnetic and hadronic interactions with unprecedented level of spatial detail, and the utilization of various techniques not implemented in the community so far (software compensation, leakage correction, ...).

- Standard Geant4 simulation package fails to reproduce data well. Some optional packages allow big improvement in the agreement. The disagreements are at the very fine level of detail which is not available in conventional calorimeters.

The concept of Digital Hadron Calorimetry is validated.

C1-2: CMS HCAL

- D increases linearly vs logR for dose rates up to 70 Gy/hr.
- Above 70 Gy/hr:
  - for PVT, it is constant or continues to rise depending on doping concentration.
  - for PS, it is constant or decreases

- Results from varying thickness rods suggest that damage to the initial light output is dominant for thicknesses up to 1 cm.

- Thicker samples will be more sensitive to color center absorption.

- For the blue scintillator (EJ-200), the transmission measurements indicate damage to the fluors.

C1-3: HG Strip ECAL

- Sc-ECAL technological prototype
  - Full 32 layers and mechanical structure constructed
  - High efficiency and 2 mm position resolution achieved
  - Cell-to-cell MP calibration implemented
  - LED calibration such as inter-calibration is ongoing

- Test beam experiments
  - Test beam using electron beam at DESY in 2021
  - Combined test beam experiments together with other CALICE calorimeter prototype
    - such as AHCAL

- Remaining
  - Detector assembly system for large-scale production
  - Test of power pulsing operation of integrated electronics for ILSc-ECAL
  - Optimization of cooling system of integrated electronics for CEPC Sc-ECAL
  - Continuous operation required for CEPC

C1-4: CMS HGCAL

CALICE-inspired HGCAL effort will provide valuable experience to the field of constructing a PF-inspired calorimeter.

HGCAL project is moving towards production through an extensive series of prototypes and test setups.

Extensive work on managing trade-offs and challenges, including:
- Mechanical design
- Active sensor elements (including an important QC program)
- Readout electronics and ASICs

Lots of work ahead to complete the construction.

The HGCAL experience should increase our confidence that other calorimeters of this basic type can be successfully constructed at future experiments.

C1-5: HG SiPM on Tile for Higgs factory

- SiPM-on-Tile calorimeter offers high granularity and good energy resolution at reasonable cost
- Performance demonstrated with CALICE AHCAL physics prototype
- Engineering design demonstrated with CALICE AHCAL technological prototype
- SiPM-on-Tile technology can be adapted to different conditions
  - CMS HGCAL
  - DUNE Near Detector
  - Open for new ideas, e.g. timing information in compensation methods
  - Active community, new collaborators welcome!
Calorimetry Session 2

C2-1: Hadron Simulation

- Many ways to configure and customize Geant4 physics to meet your requirements.
- Validation is a continuous effort.
- Geant4 under active development, it’s continuously being improved.
- Geant4 is very well documented, open source, provides many excellent examples and tutorials and has very active user community.
- Very good tool to learn and teach physics 😊.
- Geant4 needs user feedback to identify shortcomings and bugs.
- We need a program to systematically study the dynamics of hadronic showers. Geant4 is a very powerful predictive tool that allows to:
  - Identify the most important contributions, variables and particle types,
  - Develop and test new concepts and ideas and make predictions with high confidence,
  - Identify observables that can be tested in small experimental test setups.
- Simulation is important. The US community needs to stay actively involved (funded).

Summary

C2-4: RADiCAL for HL-LHC/FCC-hh

- RADICAL R&D to develop highly efficient, ultra-compact and rad hard EM calorimetry elements.
  Development and testing of modular elements that can provide:
  1. Energy measurement.
  2. Shower Max timing measurement.
  3. Shower Depth measurements for shower profile measurement.
  4. Incorporation of dual readout for both scintillation and Cerenkov measurement – including for timing

- Potential applications in other areas:
  - Hadronic calorimetry
  - Forward calorimetry
  - Scintillation/WLS detection over compact and larger areas
  - Timing detectors

Work Supported by in part by:
Department of Energy: DE-SCO017810.003
National Science Foundation: NSF-PHY-1914059
University of Notre Dame: Resilience and Recovery Grant Program

C2-2: Inorganic Scintillators

The HL-LHC and FCC-hh requires fast and rad hard calorimetry. The RADICAL concept uses radiation hard LuAG:Ce ceramics as WLS for LS(C)O:Ce crystals for an ultra-compact, fast and longitudinally segmented shashlik calorimeter.
Undoped BaF2 crystals provide ultrafast light with sub-ns decay time and a good radiation hardness up to 100 Mrad. Yttrium doping suppresses its slow light and promises an ultrafast calorimeter. R&D is needed for optimizing yttrium doping and radiation hardness in large size BaF2-Y crystals for Mu2e-II. Solar-blind VUV photo-detectors are also needed for controlling the radiation induced readout noise.
The longitudinal segmented Calvision crystal ECal with dual readout combined with an IDEA HCAL promises excellent EM and Hadronic resolutions for the Higgs factory. Homogeneous HCAL (HHCAL) promises the best jet mass resolution by total absorption with a challenge in cost. R&D is needed for cost-effective mass produced inorganic scintillators.
Novel inorganic scintillators will play important role in all these calorimeter concepts

C2-3: Calvision for Higgs Factory

With the advancement in SiPM technologies, a dual readout crystal ECAL becomes an attractive option for future Higgs factories.

When combined with the DRO fiber HCAL, the EM energy resolution can be significantly improved while the hadronic energy resolution is not expected to be adversely affected.

Significant R&D effort is needed to demonstrate DRO capability of a crystal ECAL through simulation, cosmic and beam tests.

Integration with the IDEA detector concept in simulation to optimize the design of the crystal ECAL.

The CALVISION team plans to carry out some of these R&D (if funded).

Summary

C2-5: HHCAL for Higgs Factory

- To maximally exploit future facilities and advance our understanding of fundamental forces, major improvements in hadron calorimetry are required.

- Progress with development of dense scintillating materials and compact photodetectors enables construction of hadron calorimeters with energy resolution reaching 10%/\sqrt{E}

- Significant progress in further understanding of the underlying physics of hadronic showers is being made.

- The potential return on a modest R&D investment could be very large.
Calorimetry Session 3

Summary

- Scintillator continues to be very important tool for detector design
  - More light yield
  - Faster materials
  - New methods such as co-molded cladding and through holes
  - New methods for reducing cost/improving material

C3-2: CMS HCAL

- CMS utilizes a variety of data to calibrate the energy measurements obtained from its hadron calorimeter
- Mean noise level of all channels are monitored for each fill of LHC and scale factors are checked for each run period
- HB, HE, HF makes use of azimuthal symmetry of energy flow in minimum bias events for inter-calibration of the channels, while HO uses muons for inter-calibration
- Absolute energy scales in HB, HE are determined using isolated charged hadrons. Energy scale in HF is determined from events of the topology $Z \rightarrow e^+e^-$. Absolute scale in HO utilizes $p_T$ balance in di-jet events
- Using $35.9 fb^{-1}$ collision data at 13 TeV, calibration constants are determined with systematic uncertainty of 3% for inter-calibration and 2% for absolute calibration

C3-3: Organic Scintillator

- Zero Degree Calorimeters developed for Run 4 HL-LHC
  - Better energy resolution and $\gamma/n$ separation
  - Reaction Plane Detector for neutron orientation measurement
- Radiation hard and compact ZDC design
  - Radiation tolerance for increased luminosity in Run 4
  - Compatible with TAXN modification
- Beam tests
  - 2018, 2019, 2021
- Well defined schedule

C3-4: HG SiPM on Tile for Higgs factory
Calorimetry Session 4

C4-1: EIC Calorimetry

Conclusions

- EIC requires nearly $4\pi$ calorimeter coverage with regions requiring high resolution EMCAL and HCAL performance. However, there are severe space limitations, particularly along the beam direction.
- The most demanding requirements for the EMCAL are in the backward direction to measure the scattered electron.
- The most demanding requirements for the HCAL are in the forward direction where one would like to measure all hadrons and the tracking resolution deteriorates due to the axial magnetic field.
- There are a number of promising technologies to meet these requirements (e.g., new scintillating glasses, W/SciFi and W/Shashlik EMCAL technologies and tilted plate configurations for the HCAL).
- Given that the project is seeking CD2 approval in less than 2 years the schedule is very tight to come up with a detailed detector design.

Summary

C4-2: Multi-Readout Fiber Calorimetry

- We simulated a simple 3D imaging calorimeter with GEANT4.
  - Convolutional Neural Network (CNN) reconstructed energy well. It outperforms conventional calorimeters, e.g. EM-fraction corrected one.
- We started R&D of multi-readout fiber calorimeter with longitudinal segmentation with timing.
  - Bench tests of HW components (fibers, SiPM, FEE) are in progress.
    - SiPM has good potential for precision timing measurement.
  - Full Monte Carlo simulation program will be developed with realistic parameters from the bench tests.
  - The MC program will be used to develop HW design and ML algorithms.
- We are working with the IDEA collaboration on both HW and SW.
  - Longitudinal segmentation with timing will be evaluated with the IDEA prototypes.

C4-3: FCC-hh Simulation

Summary of jet substructure studies

- Boosted jets studied up to 30 TeV in transverse momentum using Geant4 simulation with realistic energy reconstruction
- Jet substructure benefits from HCAL granularity
- HCAL cell size $\Delta \eta \times \Delta \phi = 0.022 \times 0.022$ ($5 \times 5 \text{ cm}^2$) shows significant improvement for physics events compared to $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$ ($\sim$ CMS, ATLAS)
- Smaller than $0.022 \times 0.022$ cells show minor improvements for $>20 \text{ TeV}$ jets

Summary of timing layers studies

- Timing layers with tens of picosecond capabilities complements calorimeters with the standard $\sim 0.5 - 1 \text{ ns}$ readout
- Proof of principle for 2 timing layer design (before and after ECAL):
  - in combination with highly-granular ECAL/HCAL can lead to cost optimized calorimeter designs
- Timing layers can be used for:
  - Pile-up mitigation
  - Particle identification (baryons vs pions vs kaons etc.)
  - Reducing confusion terms in PFA $\rightarrow$ improvements for jets etc
  - b-tagging, lepton-isolation
  - BSM long-lived particles $\rightarrow$ See concrete example in backup
- Timing for boosted jets will further be studied during Snowmass21
Calorimetry Session 5

C5-1: Ultra-high Granularity Calorimetry

- Successful test of full digital pixel calorimeter (EPICAL-2)
  - ALPIDE sensor suitable for calorimeter use
  - Technology suitable for high-granularity layers of FoCal (e.g. separation power)
- Good performance from low-energy test
  - Good linearity
  - Energy resolution improved compared to EPICAL-1, close to CALICE SiW ECAL physics prototype
- Next steps
  - Detailed study of shower development
  - Further studies of high-energy behaviour (simulation and SPS test beam)
- Strong potential for other applications

C5-2: Mu2e Mechanics

- Mu2e EM calorimeter mechanical design finalized.
- It took many years of prototyping and engineering to reach this stage!
- Most of the large components already built and tested
- Some parts still being built, but not far in time
- Crystals, SIPMs production concluded, FEE, cables and DAQ boards under production
- Looking forward to start assembly in the summer!

C5-3: DR Tile Calorimetry

FUTURE Dual Readout

- Adding sensor tiles relatively insensitive to MIPs, more sensitive to γβ→0
  - increases the contrast between e-m and hadronic energy (enhancing the low energy hadronic signal)
- Secondary Emission: Signal scales ~ dE/dx,
  - MIP SE signal ~100x less than that of the energy of the peak signal (peak signal for protons occurs at ~200keV - n+p→p+n knock-on protons).
- Homogeneous dense inorganic scintillators (LYSO, PbWO₄, CeF₃, LAr, LXe...)
  - h/e⁻ ~ 0.4 and h/eC ~ 0.25, or [h/e]_L/[h/e]_C ~ 1.6:
  - Homogeneous calorimeters cannot achieve dual readout compensation better than ~50%/E on hadrons, even with perfect separation between scintillator light & Cerenkov light in the homogeneous detector. [LAr/CH₄ ions instead of Scintillator]

σ_b/E ~15%-18%/E on jets: scintillator sensors with h/e⁻ ~ 0.6-0.8 and Cerenkov sensors with h/eC ≤ 0.2 are needed. To achieve h/eC < 0.2, lower n Cerenkov radiators are required (β_{thresh} >-1). Requires photons for e-m resolution < 70%/E(GeV) or N_{pe} > 2 pe/GeV.
RADiCAL: LYSO/LuAG Shashlik Cal

A 4x4 LYSO/DSB1 capillaries show consistent resolution with LYSO/Y11

Excitation of LuAG:Ce ceramics matches well LYSO:Ce emission:
RADiCAL
RADiation hard innovative CALorimetry
R. Ruchti, in the 2021 CPAD workshop

C2-4: RADiCAL for HL-LHC/FCC-hh

Φ1x40 mm SIC LuAG:Ce ceramic LHPG fibers
Calvision: Longitudinally Segmented Crystal ECAL

Aiming at excellent EM and jet resolutions for Higgs Factory

M. Lucchini et al., JINST 15 (2020) P11005
J. Qian, in the 2021 CPAD workshop
Technical Implementation

• Until recently the technical challenges were significant to even consider a homogenous calorimeter

• There have been tremendous technical advances that make this option viable with further R&D
  - Low form factor photo-detectors that can operate in a magnetic field (SiPM)
  - High density scintillating crystals/glasses ($\lambda \sim 20$ cm)
Longitudinal Segmentation of Multi-readout Fiber Calorimeters by Timing for 3D Imaging Cal

Fiber Calorimeter with Longitudinal Segmentation with Timing

Channel counts reduction
3D Calo: \( Nx \times Ny \times Nz \)
\( Nz \rightarrow 1 \)

Major Components:
- Absorber
- Fibers
- SiPMs
- Frontend Electronics
  - Amplifiers
  - Waveform digitizers
- DAQ

- R&D on bench started!

Signal Time = \( L1/c + L2/kc \),
c = velocity of particle
\( kc = \) velocity of light in fiber \( (k \approx 0.6) \)
\( \Delta L = 2 \text{ cm} = 44 \text{ ps} \)
# Mu2e Ultrafast Calorimeter

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<th>Specification</th>
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<td>Energy resolution</td>
<td>$\sigma &lt; 5%$ (FWHM/2.36) @ 100 MeV</td>
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<tr>
<td>Time resolution</td>
<td>$\sigma &lt; 500$ ps</td>
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<tr>
<td>Position resolution</td>
<td>$\sigma &lt; 10$ mm</td>
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**Radiation hardness**
- Crystals: 1 kGy/yr and a total of $10^{12}$ $n_{-1}$ MeV equivalent/cm$^2$ total
- Photosensors: $3 \times 10^{11}$ $n_{-1}$ MeV equivalent/cm$^2$ total

**Mu2e-I:** 1,348 CsI of 34 x 34 x 200 mm

**Mu2e-II:** arXiv:1802.02599

**Mu2e-II:** 1,940 BaF$_2$:Y of 30 x 30 x 218 mm

**PIP-II/Mu2e-II:** higher rates (~x3) and duty factor from higher ionizing radiation (10 kGy/yr) and neutron levels ($10^{13}$ $n_{-1}$ MeV equiv/cm$^2$ total), which are particularly important at the inner radius of disk 1.
C3-5 Askaryan Calorimetry

5D Picosecond Timing Layers for Future Calorimeters

Updates from the Askaryan Calorimeter Experiment (ACE)

Remy Prechelt for the ACE Collaboration

P. W. Gorham¹, J. Bynes¹, B. Fox¹, C. Hast², B. Hill³, K. Jobe², C. Miki¹, M. Olmedo¹, R. Prechelt¹, B. Rotter¹, D. P. Saltzberg³, S. A. Wissel¹, G. S. Varner¹, S. Zekioğlu³

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²SLAC National Accelerator Laboratory (SLAC)
³Univ. of California, Los Angeles (UCLA)
⁴Penn. State University (PSU)
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