



HFCC Calorimetry: past, current, and planned efforts

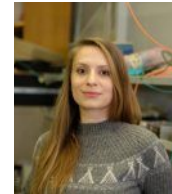
Bob Hirosky
Michael Begel

20-Dec-2024

L3 coordination (Calorimetry)

Calorimeter (us-hfcc-calorimetry@cern.ch)

- Dual Readout: Grace Cummings
- Nobel Liquid: Erich Varnes
- Si-W: Jim Brau
- Tile-Scint: Vishnu Zutshi



US HEP has demonstrated expertise and leadership across multiple calorimeter technologies, e.g.

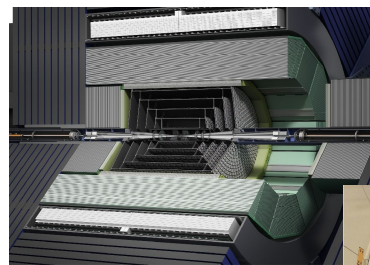
- **DR Calorimetry**
 - Calvision, DREAM/RD52
- **Noble Liquid**
 - ATLAS ECAL, D0
- **Silicon-Tungsten**
 - CMS HGCAL, CALICE
- **Tile-Scint**
 - ATLAS Tile CAL, CMS HCAL/HGCAL

Large amount of proposed/planned activities

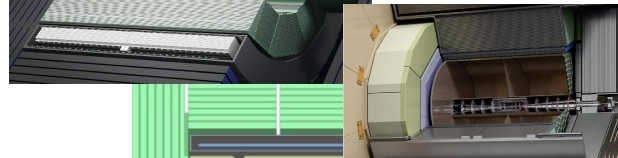
- Surveys across all L3 areas
- Some supported by SBIR/LRDR
- Some have proposals under review
- **Focus on new asks at the end => prioritized by impact on international leadership in short term**

Proto detector concepts

ECAL: Si/W - HCAL: Sci Tile

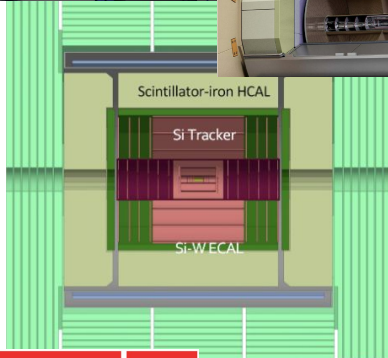


SiD (MAPs)

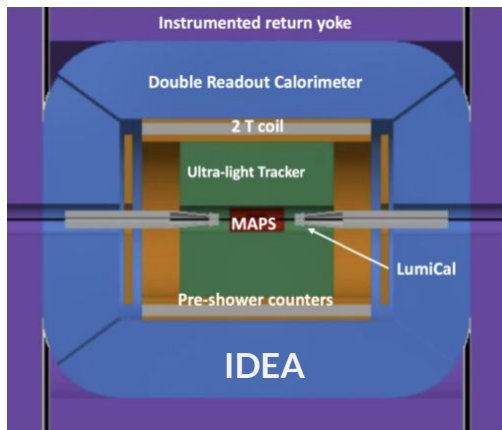


ILD

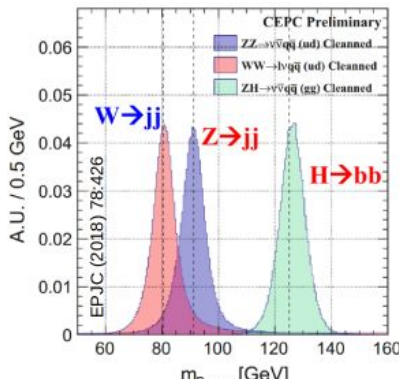
CLD



CLICDet



ECAL: dual-readout crystal
HCAL: Copper with S/C fiber



ECAL: LAr/LKr with Pb/W absorber
HCAL: CALICE- or TileCal-like



Why we need precision calorimetry

CalVision - DR for e+e- colliders

Single crystal + matrix studies

PbF₂

UMich, Y. Guo - image

Single Crystal MC
M. Paranjape

G. Cummings

Full detector sim

Particle Flow Algos

SCEPCal

2020 JINST 15 P11005

Heavy Glasses for Homogenous HCAL

Aluminoborosilicate Glass

AS-1 AS-2 AS-3 AS-4 AS-5

R. Zhu EPAD 2023

DR Fiber HCAL

TTU S. Kunori

Mechanics

Andy Jung

Andy Jung

W. Chung

Brandeis

Fermilab Caltech Argonne NATIONAL LABORATORY UNIVERSITY OF MARYLAND M T

Stony Brook University R DEGLI STUDI UNIVERSITÀ DI BOLOGNA MIT OAK RIDGE National Laboratory P UNIVERSITY OF VIRGINIA BU

SiW Calorimetry for the Higgs Factory

- SLAC/Oregon
Caterina Vernieri, Lorenzo Rota, Martin Breidenbach, Jim Brau, David Strom
- CMS HGCal group
Lindsey Gray, Murtaza Safdari, Zoltan Gecse
- Graham Wilson (Luminosity monitor and forward calorimetry)
- Larger community including CMS HGCal groups...

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Scintillator-SiPM Hadron Calorimetry

Large community working in this area, esp for CMS HGcal

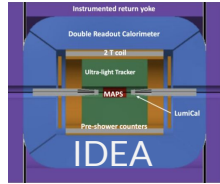
- NIU, FSU, UMD, Notre Dame, Minnesota, ...

Noble Liquid Calorimetry

US groups expressing interest:

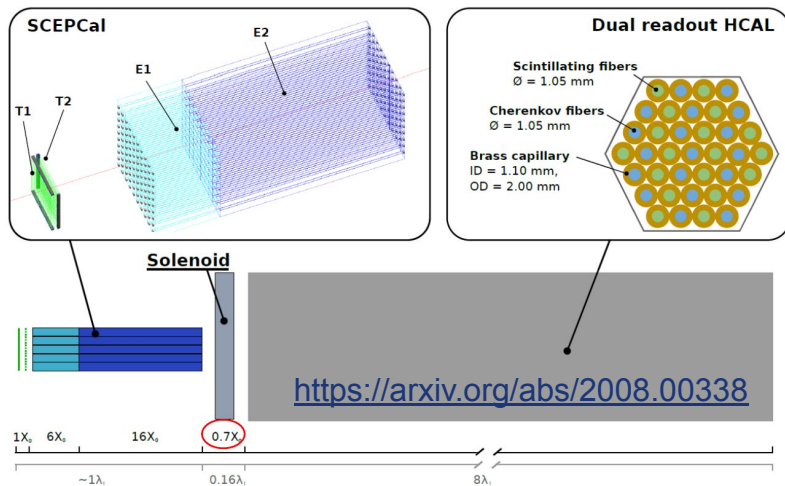
- Arizona, Brookhaven, Irvine, Columbia, SMU, StonyBrook, Austin

Dual Readout (DR)

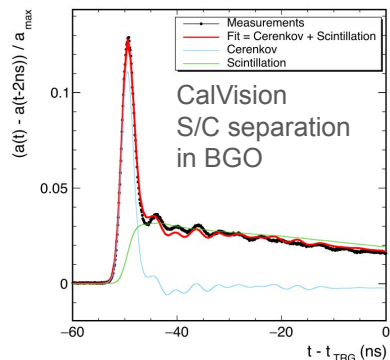
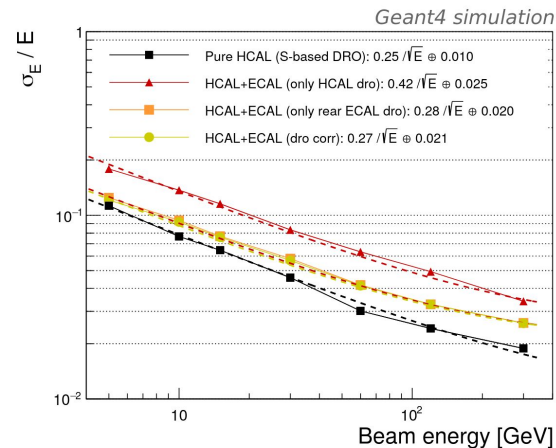


- Significant US contributions to construction, operation, calibration of CMS precision crystal ECAL
- **DREAM/RD52**: In the last decade, demonstration of DR technique in spaghetti-style (fiber) calorimeter + initial study of S/C separation in DR homogeneous crystal ECAL (DOE supported)
- **CalVision**:
 - First (and so far only) to demonstrate collection of sufficient Cherenkov signal for DR application in crystals
 - Advanced DD4HEP GEANT model
 - Innovative studies in longitudinal segmentation via timing in fiber HCAL
 - Extensive R&D program proposed to study practical detector design and bluesky materials
 - Funding via DOE HEP R&D program (7/22--3/25), \$900k this year. Renewal submitted.
 - Primary goals: first demonstrations of (1) state-of-the-art EM resolution in xtal+SiPM, 2 layer ECAL and (2) DR application in xtal(EM)+fiber(HAD) hybrid calorimeter
- Building strong US collaboration in DR: High levels of participation.
 - US groups are already making leading contributions to detector R&D in this area
 - **Complementary approaches, both targeted and blue sky, compared to international R&D** (eg first results on S/C separation in heavy glass scintillators)

Hybrid dual-readout concept (new baseline for IDEA detector planning)

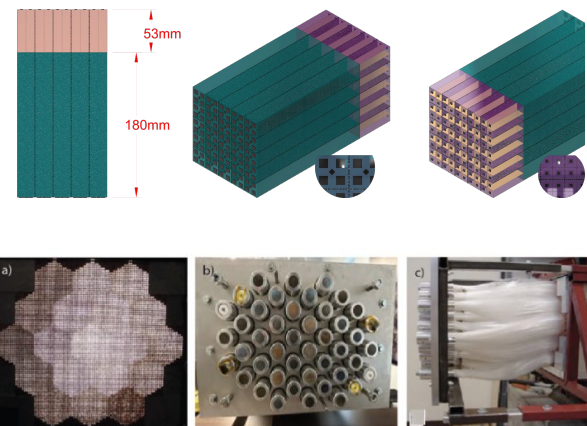


Crystal EM $\sim 3\%/\sqrt{E}$ + straw HAD calorimeter, Both DR, use S/C light signals for shower-by-shower hadron corrections $< 30\%/\sqrt{E}$



⇐ Phase 1 proof of principle for collecting significance C signal

Phase 2 prove EM performance w/ SiPM+Xtal ⇒ performance in test beams

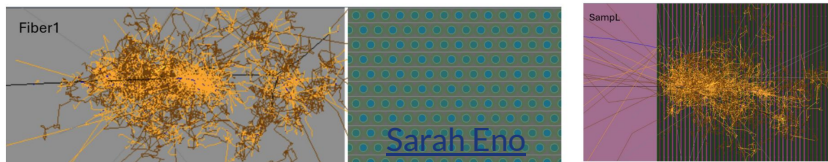
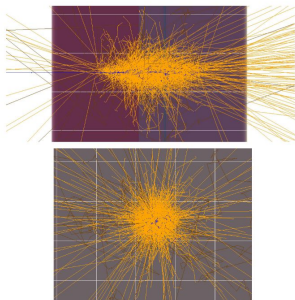


Progress in optical & DR simulation (presented yesterday)

Array with HCAL

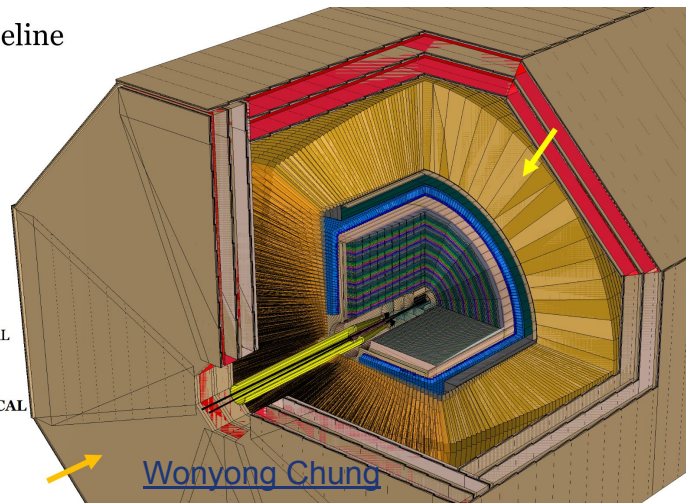
We have updated this to a flexible code allowing different configurations of HCAL + HCAL.

- ECAL currently has 2 crystal segments
- HCAL allows two options: a CMS-HCAL-like sampling calorimeter with scintillating and non-scintillating tile layers for active media and a IDEA-like fiber HCAL with scintillating and non-scintillating fibers in individual absorbers (either tube or square with circular hole).
- General user code at: gitlab
- Beta test version at: <https://github.com/saraheno/DualTestBeam>

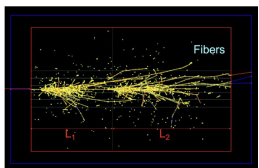


New IDEA baseline

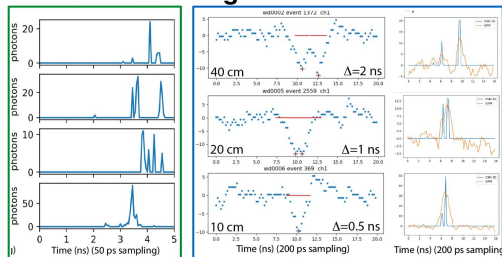
- Beampipe
- LumiCal
- Vertex Detector
- Drift Chamber
- Silicon Wrapper
- Endplate Absorber
- Dual-readout Crystal ECAL
- Solenoid
- Dual-readout Fiber HCAL**
- Muon System**



Longitudinal Segmentation with Timing



Signal time = $L_1/c + L_2/(c/n)$,
 $(c/n) \sim 1 \text{ cm}/50 \text{ ps}$

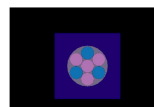
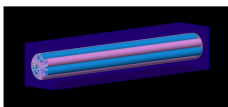


- Hadronic showers can vary dramatically from event to event as shown in green
- With the use of a CNN we have demonstrated you can reconstruct signals resolving position dependence of hits using the timing information
- Providing longitudinal segmentation to $\sim 10 \text{ cm}$ resolution

Chris Madrid

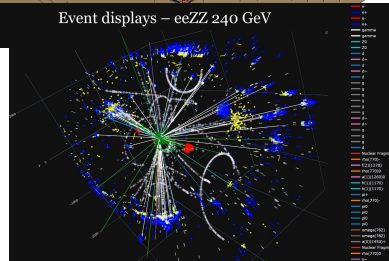
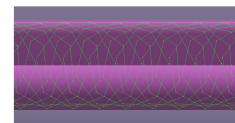
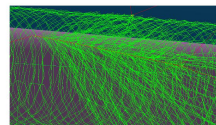
Simulation

- Current simulations are based on Geant4

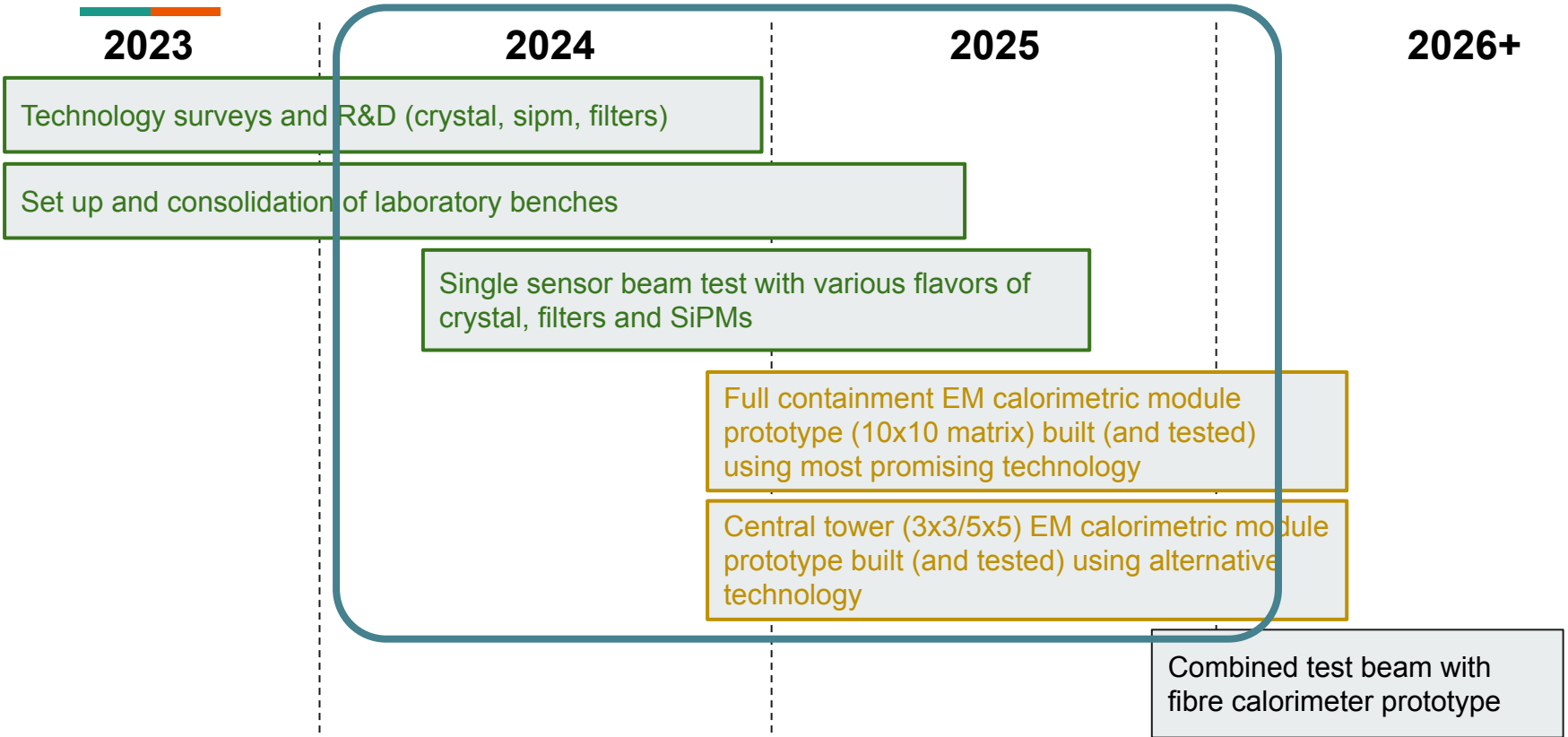


- Working on studying the (hadronic) shower developments and optical photon propagations in the fibers
- **Focusing on the timing properties**

- Exploring different fiber parameters (size, multi-cladding, helical, etc in order to improve photon capturing efficiency)
- Plan to move to DD4HEP and Key4HEP once more mature

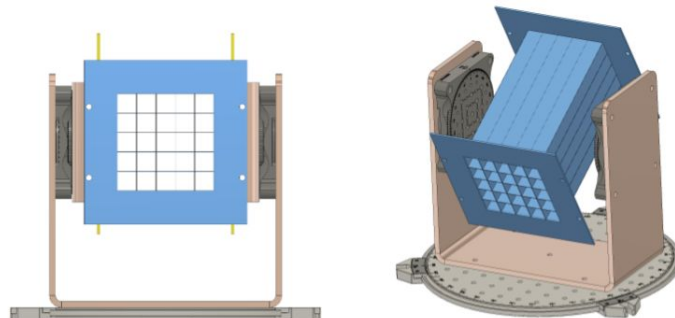
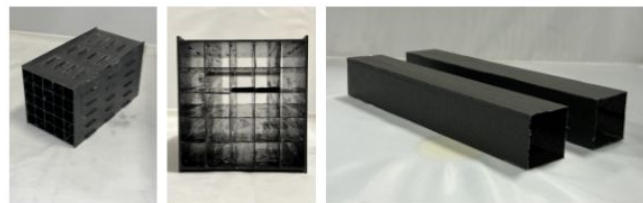
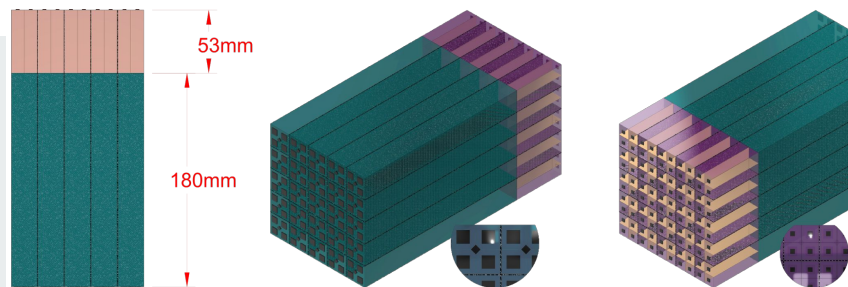


Mid-term plans for DR: MaxiCC/Calvision



Complementary matrix plan (Calvision version)

- **BGO matrix: $22X_0$ deep, $5X_0 \times 5X_0$ lateral with $1X_0$ and $\frac{1}{4}X_0$ lateral granularity**
 - Crystal purchase in progress - expected to arrive and complete testing in spring
- **Crystals ordered**
- **Carbon fiber alveolar, mechanical support, and cooling options, R&D in progress**
- **Studies to improve electronics (e.g. linearity, pulse shape optimization, interconnects) over next 6-8 months**
 - Similar readout w/ FERs 5200 for front section, most likely DRS or NALU HDSoc for rear section
- **Form factors and mechanics of electronics for EM containment scale will be challenging**



Dual Readout: 2025 R&D proposed/planned

- CalVision renewal submitted
 - Construct EM module $22 X_0 \times 5(-7) R_M$ and readout for EM resolution and hybrid DR studies
 - Re-instrument DREAM module, study longitudinal segmentation with timing
 - Continue unique contributions to Generic R&D with DR in new (low cost) scintillators.
 - Research goals, particularly maintaining leading ECAL R&D + integrating ECAL with international HCAL efforts, depends on 2025 support. This will be prioritized in any funding scenario. **Missing the 2025 deliverable will likely set us back several years wrt international efforts b/c we will miss needed individual and joint test beam opportunities before beams end.**
- Accelerate development of analog front end for DR crystal matrix (UVa, FNAL): Starting early on engineering design to reduce risk instrumenting matrix => very complex $O(200)$ channel readout
- **FY25 new ask: ~\$50k for 1 month FNAL EE + early prototyping efforts**
- Portable tracking and timing for calorimeter test beams w/ low mass sensors (UVa/other, FNAL):
- **FY25 new ask: \$30k in M&S for LAPPD (or potentially LGAD)-based timing/trigger, minimize e- showering**
- Band-pass optical interference filters for separation of C/S light (FNAL, univ partner) Develop custom ultra thin-film filters for Cherenkov and scintillation wavelength separation and reduce light loss. Capitalizes on Fermilab's Thin Film facility.
- **FY25 Needs: ½ graduate student, ideally ½ a postdoc.**

Dual Readout: 2025 R&D proposed/planned



- Full ECAL+HCAL Combined Detector Simulation and AI/ML Reconstruction (Princeton, MIT): Complete integration of crystal ECAL with IDEA fiber HCAL, tracker, etc., for full detector concept sim. Advance reconstruction studies with combined full sim.
Developing AI/ML algorithms utilizing the timing structure of DR signals from fiber calorimeters (TTU, FNAL)
- FY25 new ask: ~\$40k for 1.0 student FTE. Partially covered in CalVision proposal
- Geant4 and TCAD simulation of precision timing photon detectors measuring DR fibers (TTU, FNAL) design and simulate the performance of future SiPMs for precision timing
- FY25 new ask: ~\$40k for 0.5 postdoc FTE, partly covered by CalVision proposal
- East coast center for crystal characterization (CUA) expand the crystal and glass characterization facilities at CUA.
- FY25 new ask: 5k for material, 3-5k travel, ½ of graduate student salary (12.5K)
- On-detector intelligence for waveform processing and longitudinal shower development for DR crystal ECAL (Baylor)
- Broad Spectrum Photodetectors based on Heterogeneous Integration for VIS and NIR (UVA)
- FY25 Needs covered by SBIR

Dual Readout: 2025 R&D proposed/planned



- Calibration & energy reconstruction in crystal DR calorimetry (SUNY Buffalo): demonstrate realistic calibration methodology, study optimal energy reconstruction algorithms for dual readout calorimetry, particularly CalVision
- FY25 new ask: 1/4 postdoc (20K) and travel (5K). Planning to join CalVision in 2025.
- Optimized Cerenkov and Scintillation Light Collection and 3D Shower Localization with Metasurfaces for Dual Readout Calorimetry (Caltech, ORNL, U. of Utah): Design and testing of nanostructured metasurfaces and engineered diffractive filters
- FY25 new ask: \$15k M&S for test setups in the crystal lab, 20% FTE staff engineering. Mostly in CalVision proposal.
- Novel readout geometry of DR crystal ECALs (FNAL)
- FY25 new ask: ~\$20k - \$50k in materials, ½ year of graduate student at partner univ. More generic R&D in nature.
- On-chip data processing for SiPM readout, fast-timing, and machine learning reconstruction (SLAC, univ partner): On-chip intelligent data processing of SiPM readout for the extraction of the S/C components in the front end.
- FY25 new ask: ½ of a graduate student to perform physics simulations and work together with the SLAC engineers defining detector requirements.
- Custom scintillator for dual readout (FNAL): Incorporate quantum dots to tailor scintillation spectrum/add neutron sensitivity
- FY25 Needs covered by SBIR
- Celeritas development for GPU acceleration of G4, including optical simulation (UVa, FNAL, ORNL)

Noble Liquid R&D



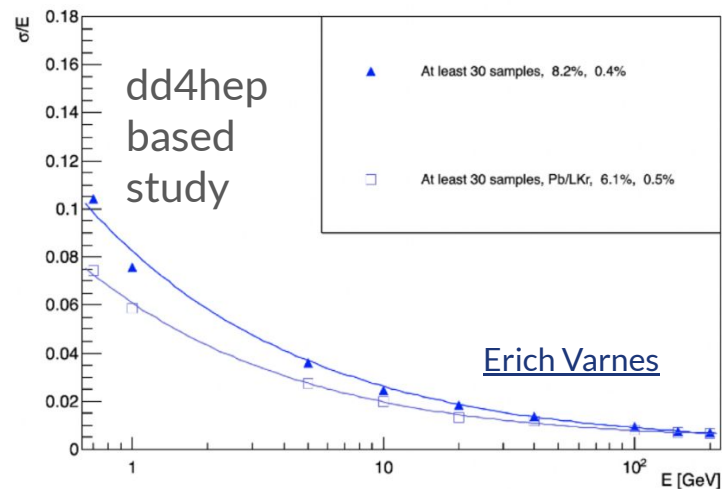
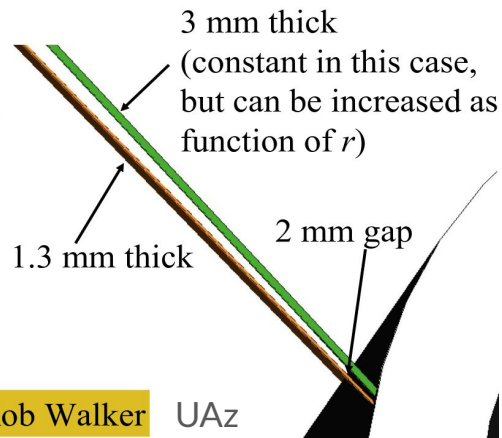
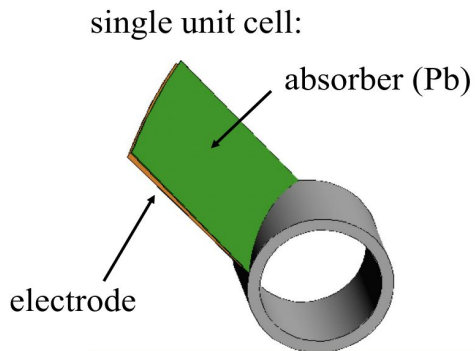
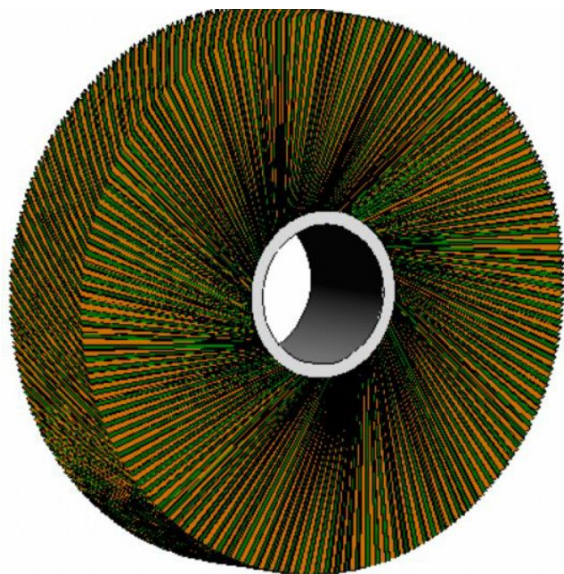
- LAr technology
 - excellent energy resolution and good timing properties with proven linearity, stability, and uniformity yielding small systematic uncertainties → crucial for precision measurements program
 - take advantage of recent developments for large LAr TPC including cold electronics (eg ASICs)
 - complementary to silicon- and gaseous-detector tracking systems [particle flow]
 - intrinsic radiation tolerance → important for FCC-hh
 - Interests expressed by: BNL,UAZ,USB,Austen,Columbia,Irvine

Example concept for ALLEGRO forward calorimeter

Turbine concept



- more similar to barrel design
- Improved symmetry
- but design optimizations needed

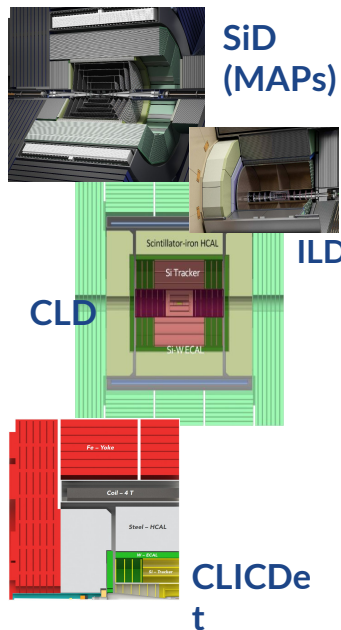


Noble Liquid: 2025 R&D proposed/planned



- BNL-funded LDRD on new LAr calorimeter and TPC technology
 - collaboration with CERN et al towards new LAr calorimeter module [ALLEGRO]
 - **additional support to US institutes would be useful to take advantage of this effort**
- Design of endcap EM calorimeter for ALLEGRO (and associated readout PCBs) (Arizona)
 - **FY25 new ask: ~\$50k engineering**
- Detector simulation for physics optimization and possible joint work on module development and testing (Stony Brook Univ)
 - FY25 new ask: ~\$11k for summer student
- Study requirements and feasibility of including AI/ML algorithms on the readout ASICS (UT Austin)
 - FY25 new ask: ~\$12k for summer student

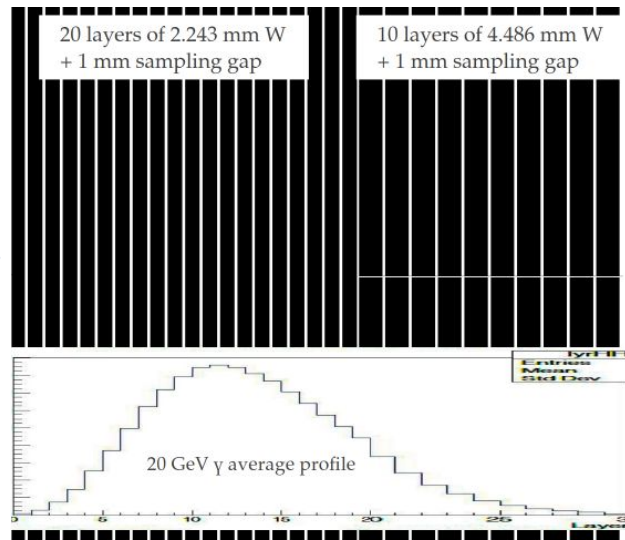
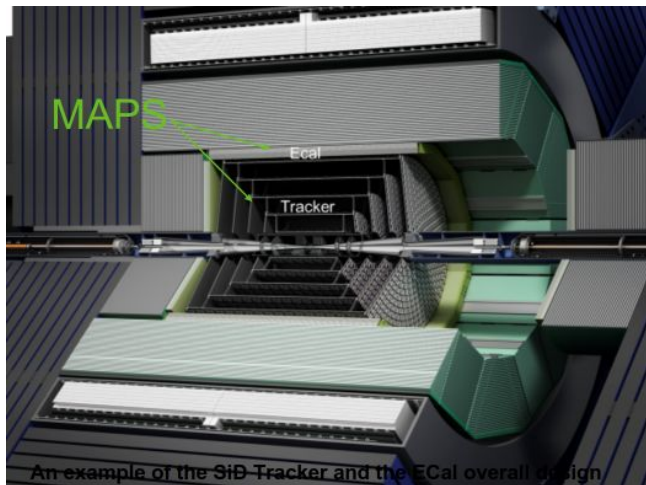
Si-W R&D



- Strong efforts over the years including contributions to CALICE collaboration and CMS HGCAL design and construction
 - Supports highly granular readout for 3D shower imaging
 - Well suited to particle flow algorithms
 - Can have fast timing capabilities
 - Interests expressed by: Oregon, Kansas, SLAC

SiD MAPS + Tungsten concept

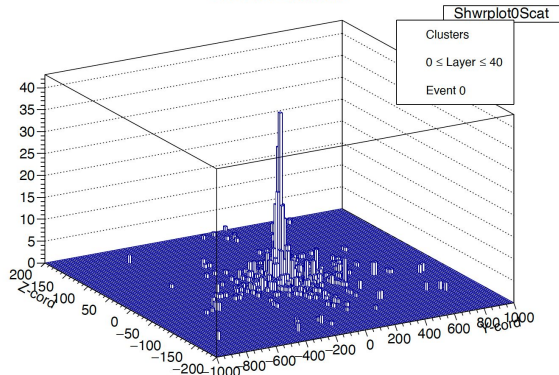
Digital ECal Based on Monolithic Active Pixel Sensors



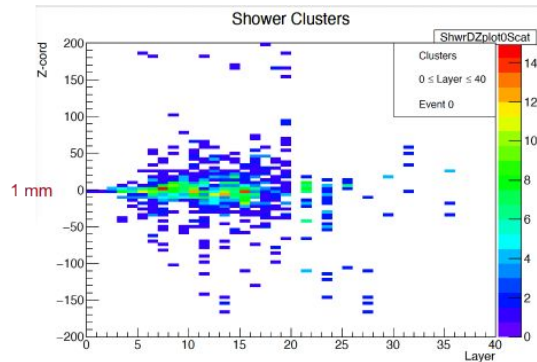
HCAL

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Shower Clusters



10 GeV EM shower



Si-W: 2025 R&D proposed/planned

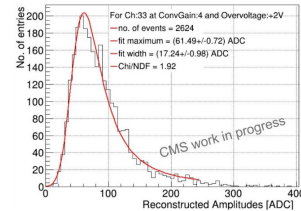
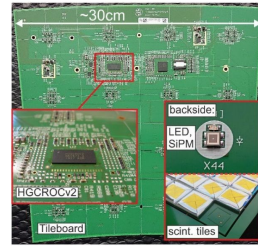
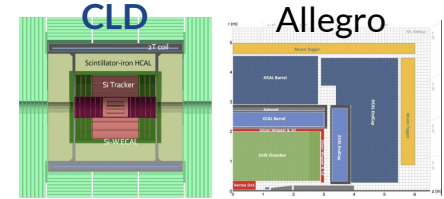


- **MAPS for Future Collider Calorimetry** (Oregon, SLAC)
 - SLAC National Accelerator Laboratory is leading a collaborative effort to develop MAPS for future colliders. The U. Oregon group is assuming responsibility for simulation of the performance of the MAPS applied to the electromagnetic calorimeter (ECal).
 - **FY25 needs: ~\$34k to Oregon for partial GS and travel support**
- **Si-W based e+e- collider precision luminosity measurements** (Kansas):
 - New approach to the design of the luminosity calorimetry as applied to future e+e- colliders. The study is exploring the limits of precision fine sampling electromagnetic calorimetry with a focus on both energy and position.
 - **FY25 needs: ~\$20k for partial GS support and some travel**

Tile-Scint R&D intro

Application to: CLD/Allegro detector concepts

- Long history of US expertise in tile-scint Calorimetry
 - Scintillator production facility and R&D at FNAL
 - CMS HCAL construction, readout, operations
 - CMS HGCAL hadronic section
 - Interests expressed by: NIU, UT Arlington, UMD, Iowa, FNAL
- Include R&D on simulation/scintillator development



This is a mature technology area in US HEP. Expect significant contribution to prototyping/design work in coming years.

Prioritized new funding requests for 2025 R&D

Prioritized by potential short term impact on US leadership

- DR: readout electronics engineering \$50k => reduce risk for very limited window of beam tests
- NL: ALLEGRO endcap design work \$50k => build on US expertise to lead conceptual development
- SiW: Student support/travel (MAPs) \$35k => build on US expertise to lead conceptual development

- DR: Testbeam low mass timing/trigger instrument \$30k
- Travel for L2/L3' and key institute experts to attend FCC & LC workshops & meetings \$50k
- SiW: Student support/travel (Lumi EM Calo) \$20k
- DR: Development of ultra thin optical filters \$20k

- Tile: Student+M&S for scint R&D \$25k
- NL: Summer student support for simulations (Ai/ML): \$12k
- NL: Summer student support for simulations (det. optimization): \$12k
- Tile: Travel \$20k

Some
redundancy
with travel
above