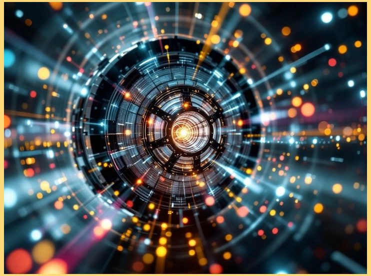
Report on Dual-Readout Calorimetry Studies



Bob Hirosky
University of Virginia

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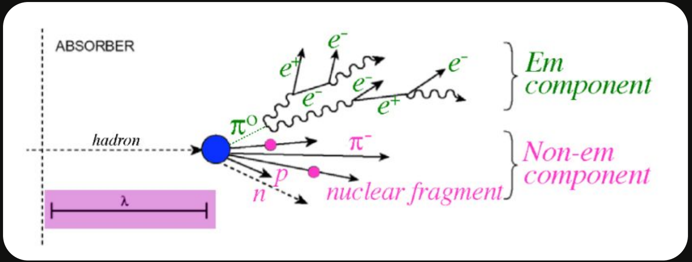
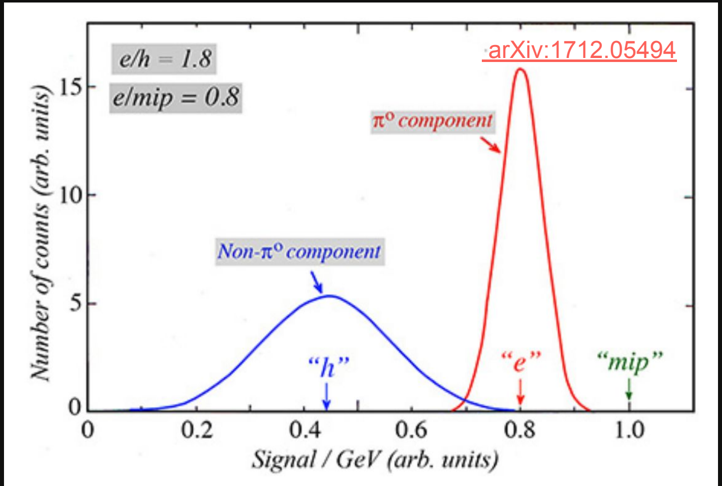
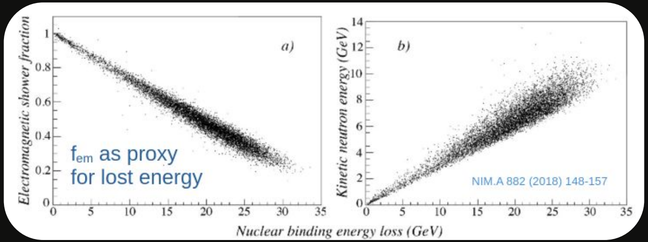
Argonne NATIONAL LABORATORY

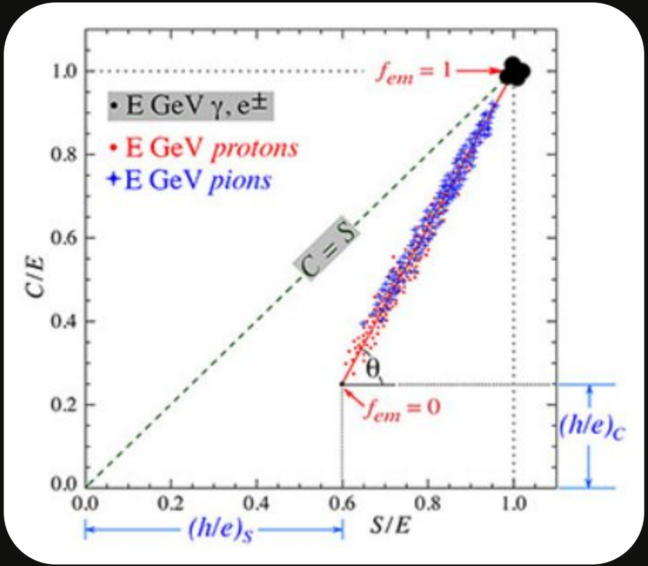
Dual-readout (DR) Calorimetry

In a nutshell DR calorimetry combines an energy signature (eg scintillation light) with a proxy for the EM component of a hadron shower (typically cherenkov light) to define an event-by-event correction accounting for non unity e/h ratio $\otimes$ fluctuations in hadronic showers







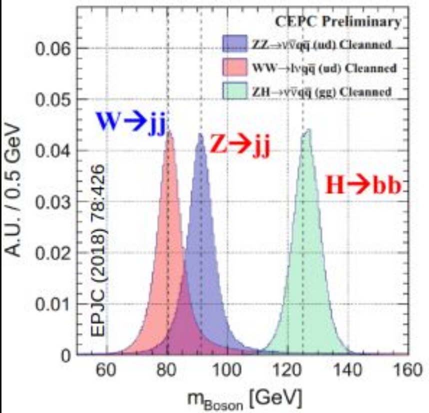


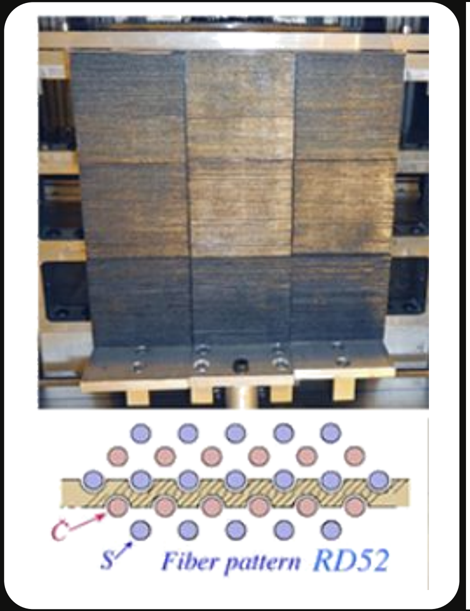
Dual-readout correction

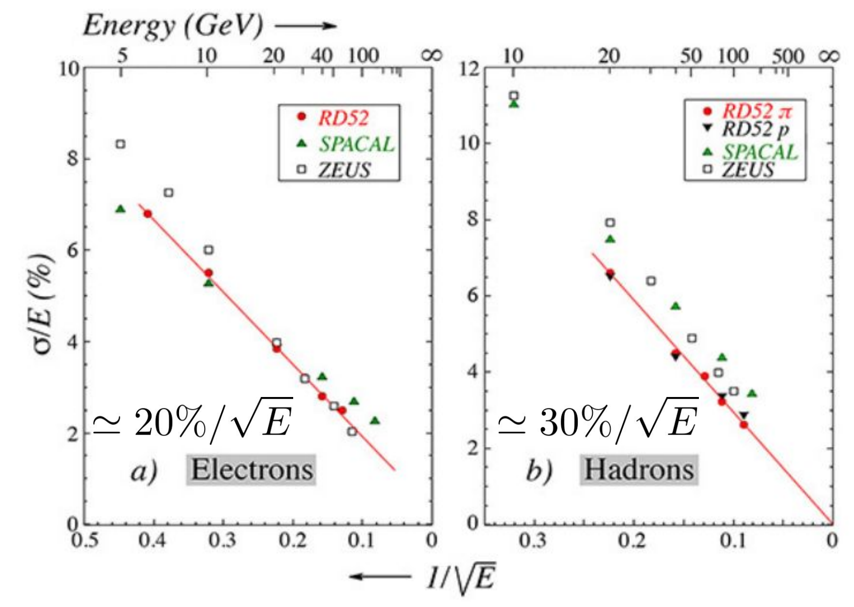
First referenced at the 11th SLAC Summer Institute in 1983!

Dual-readout (DR) Calorimetry

The DR correction leads to significant improvements in hadron resolution as previously shown by the RD52 collaboration







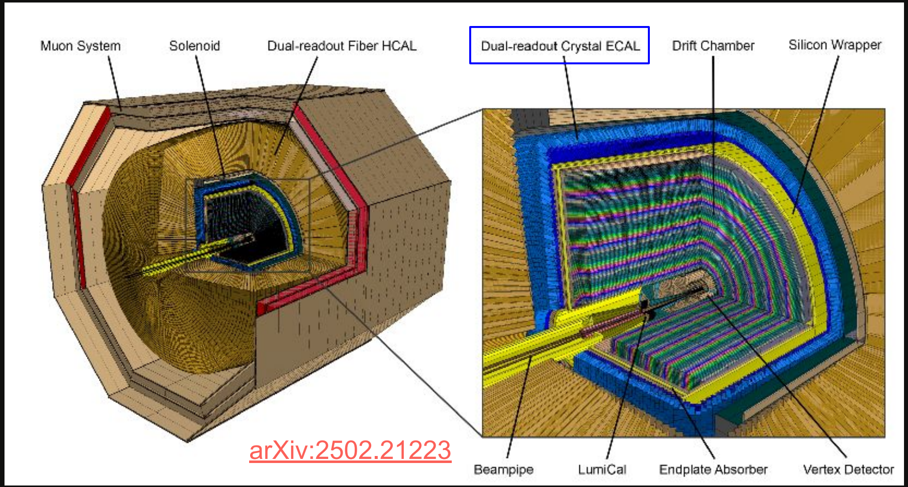
Rev.Mod.Phys. 90 (2018) 2, 025002

Impressive results! Already on par with needs for jet resolution at a Higgs factory. Good EM performance but significantly below that of crystal EM calorimeters which can achieve ~3%/√E.

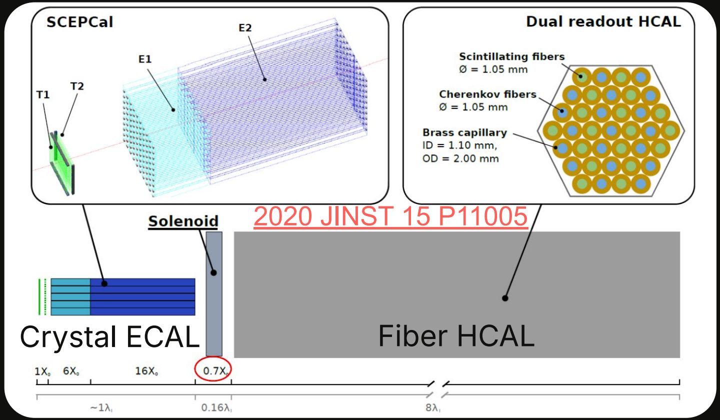
Hybrid DR Calorimetry

The IDEA detector concept for FCC-ee adopts a unique hybrid DR model:

Homogeneous DR crystal EM + DR fiber HCAL



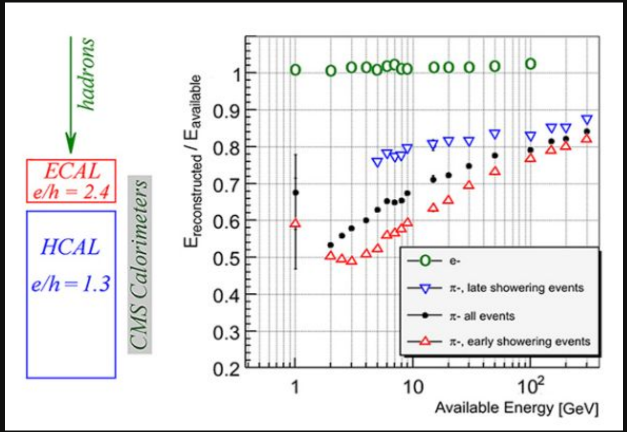
arXiv:2502.21223



2020 JINST 15 P11005

Apply the DRO correction on the energy deposits in the crystal and fiber segments independently

=> corrects for dispersions in response due to early/late showers in different materials (e/h ratios)



See reference for further discussion of EM segmentation and physics motivation

Hybrid DR Calorimetry

Research Areas

- Separation of S/Č components in homogeneous crystals
- Studies of materials (crystals/fibers), novel new heavy scintillators
- Light Photon statistics in NČ. ~50 PE/GeV needed for corr. Factor
- Light sensors and readout electronics
- Assembly studies
- Calorimeter performance measures
- Algorithms for signal analysis
- …

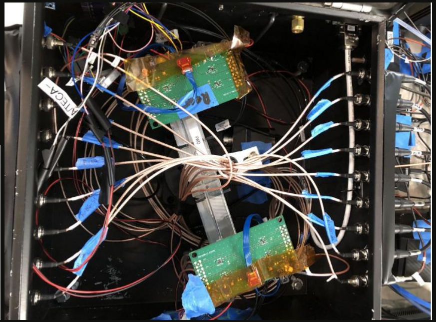
Prior highlights: ECAL

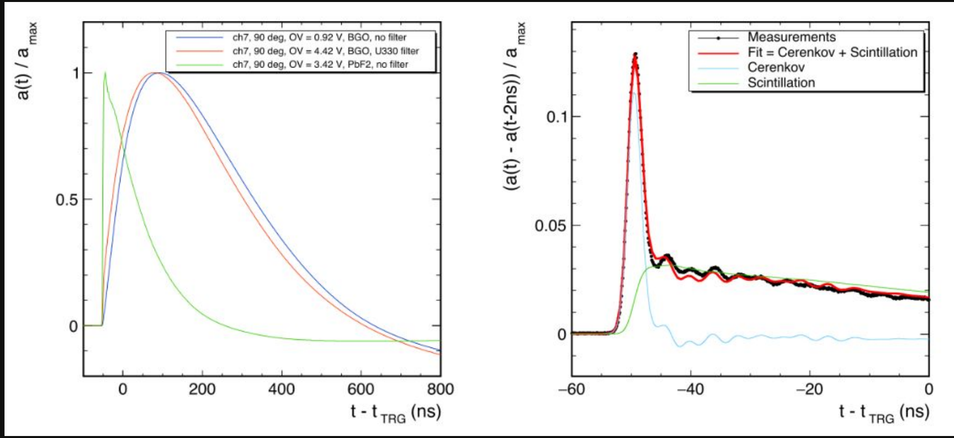
Test beam at DESY (April 2024) ~ 2-5 GeV e-

- Coordinated by CalVision US groups with participation from Milano-Bicocca
- Test of PbF_2 as a pure Cherenkov radiator for reference, PWO, BGO and heavy glasses
- Test of different filters using silicon cookies as optical interface and Broadcom SiPMs
- Focus on large crystals with multiple SiPM readout

BGO studies w/ SPE calibration show ~160 PE/GEV in Č signal component w/ 4 SiPM readout. Further optimization possible w/ improved optical coupling

=> first demonstration of sufficient Č signal for hybrid DR.





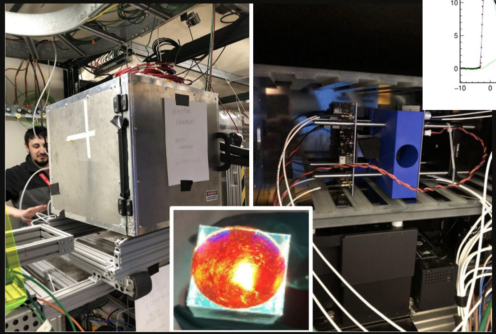
Pure Cherenkov signal from PbF2 and BGO w/, w/o optical filter
(left) original waveforms and component fits
(righ) component fits after digital SDL filter

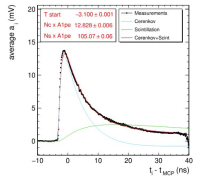
See details in 2024 CPAD, talk by G. Cummings

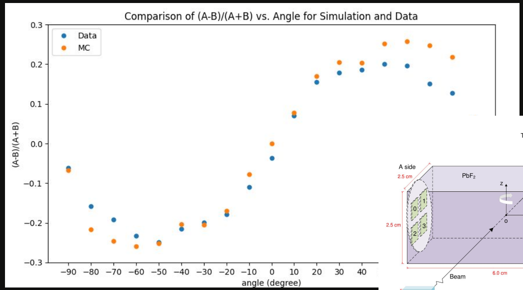
Prior highlights: ECAL

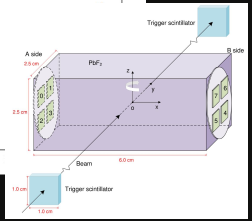
Summary of earlier test beams

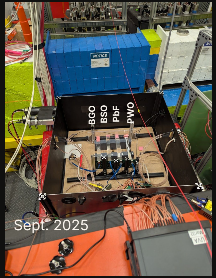
- April 2023: Cherenkov and scintillation separation in BGO w/ full waveform analysis + timing in PbWO4 w/ FNAL 120 GeV protons: arXiv:2408.11973
- June 2023: Cherenkov acceptance characterization and modeling in PbF2 using FNAL 120 GeV protons: arXiv:2407.08033
- April 2024: DESY (previous slide)
  Also included studies of new heavy glasses (ABS, DSB-3 samples).
- Sep. 2025: Additional studies w/ e+ beam at JLAB Hall D. Study signals in different crystals with faster amplifier shaping. See CPAD2025 talk

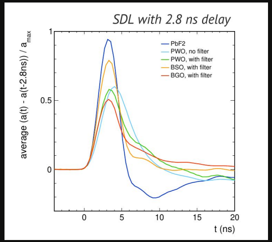










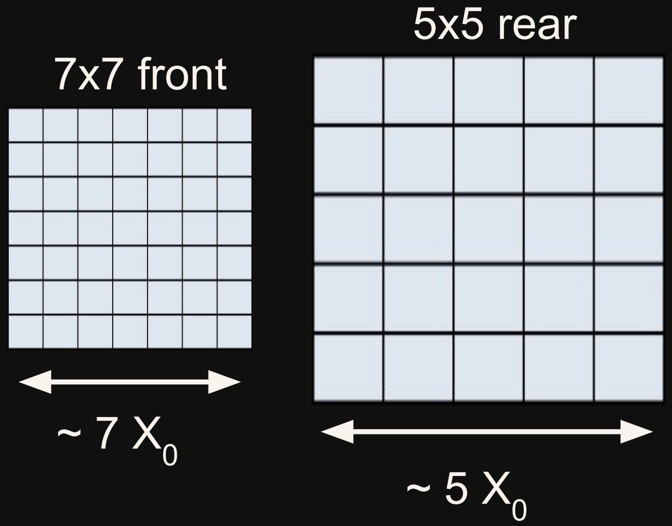


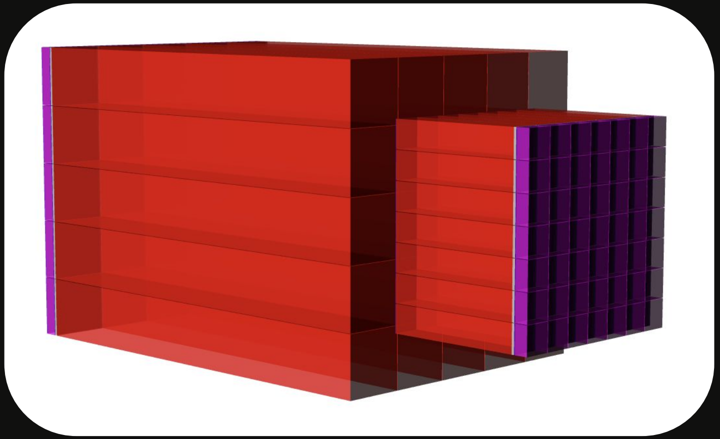
Virginia, Michigan, Maryland, FNAL

New Work: Crystal ECAL

Construction of 2-layer EM Matrix (UVa)

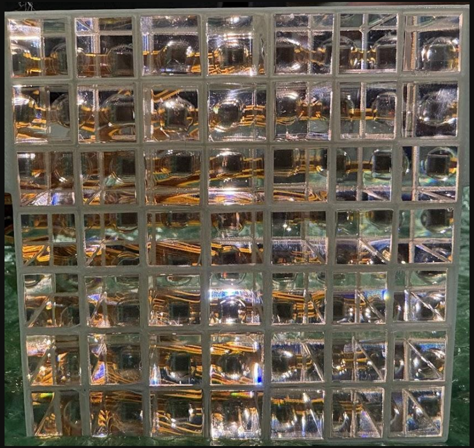
- Front $PbWO_4$
  - 1cm x 1cm x 5cm
  - 49 channels => CAEN FERS
  - 3mm x 3mm 10u cell SiPMs (HPK)
- Rear BGO
  - 2.2cm x 2.2cm x 16cm + U330 filter
  - 100 channels (4x25 crystals)
  - 6mm x 6mm 40u cell SiPMs (Broadcom)
  - Samples w/ DRS at 5GS/s
- Total depth ~ 20 X_0

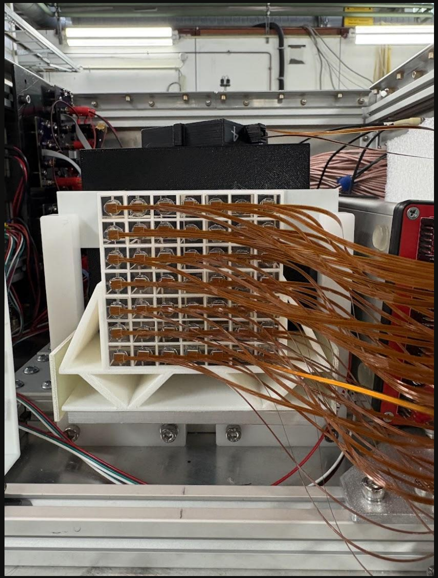


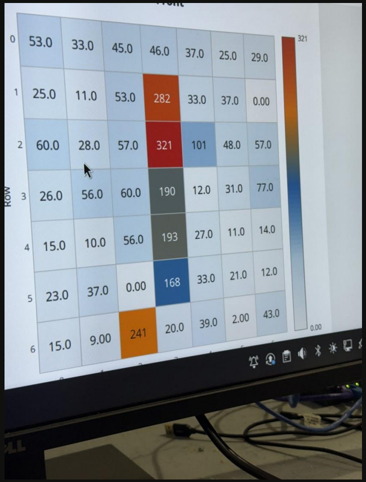


We were able to complete sourcing materials this July to make the final week of DESY TB running!
Crystal testing Caltech/UMD/CUA

Crystal ECAL Front







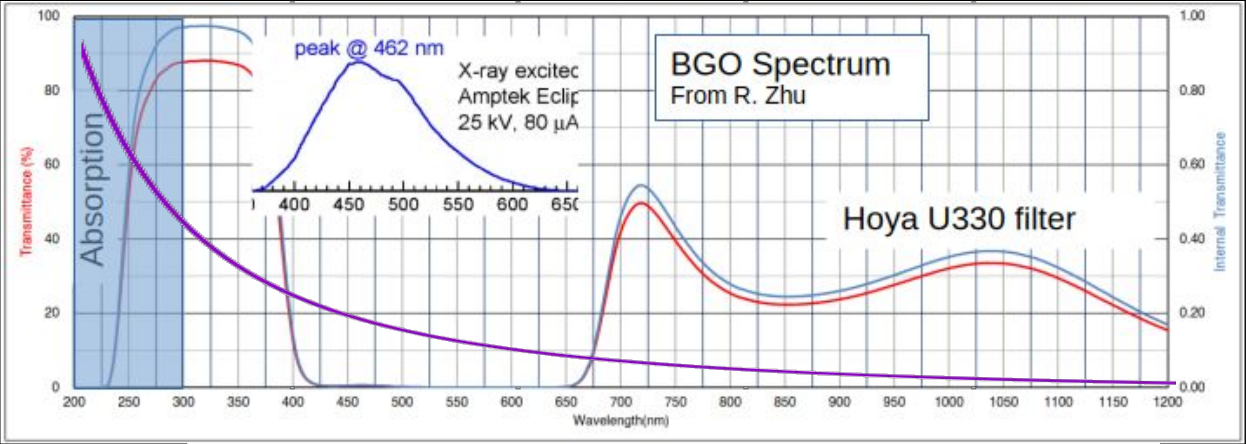
Cosmic ray track

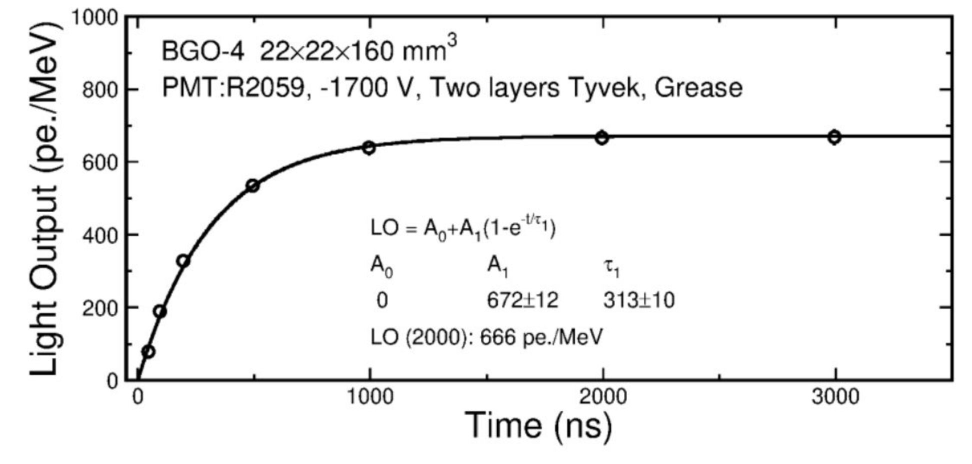
Front $PbWO_4$

- Peak detection only, no S/C separation
- Why PWO?
  - High density allows more compact ECAL
  - More available right now due to trade restrictions (AML)
  - IMO PWO+BGO is potentially a superior design

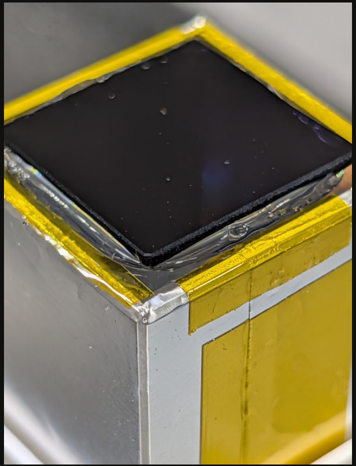
Why BGO for Č/S separation?

- Some NUV transmission above scintillation spectrum
- Decay time facilitates separation of Č(prompt) light by signal shape analysis
- High LO simplifies filtering for Č/S and allows maximizing of light sensor area
- Commercial market for PET
- Alternatives: PWO, BSO, … require different optimizations

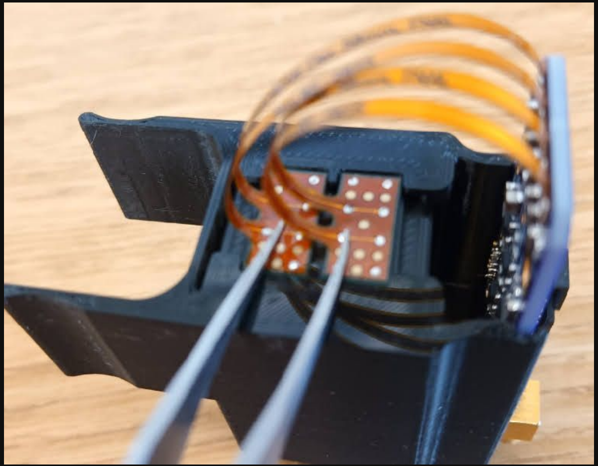




Crystal ECAL Rear



Rear crystal with U330 notch filter

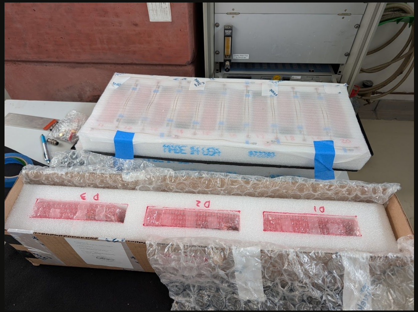


4x 6mm x 6mm Broadcom SiPMs provide large area for collecting Č light

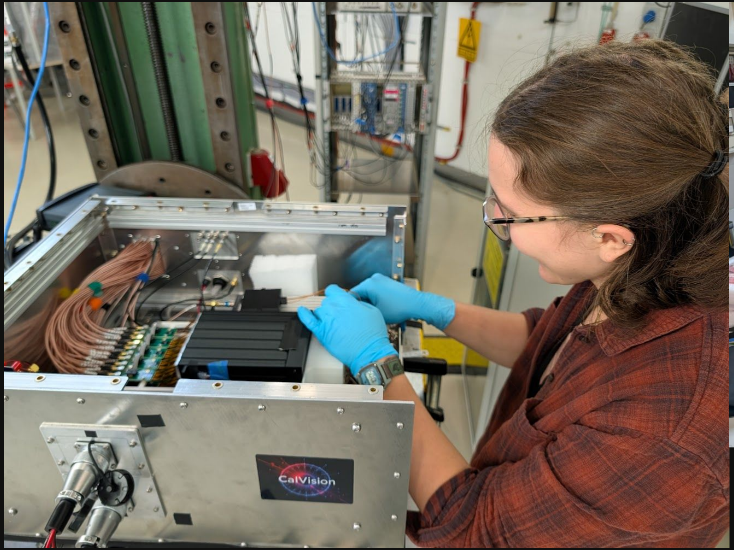
Multiple design choices to improve systematics in previous test beams

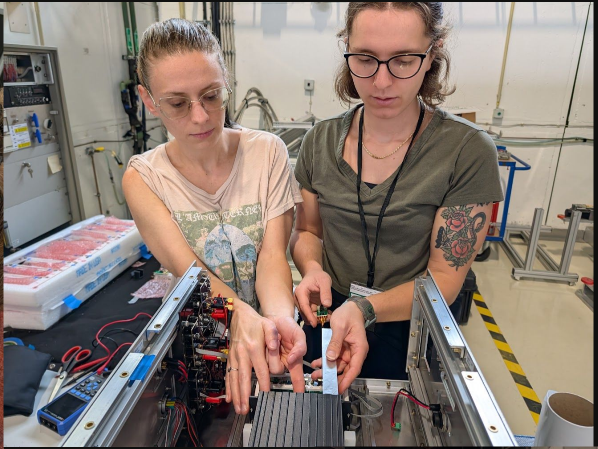
Rear matrix with new FNAL amplifiers

DESY Test Beam 24–Aug--1 Sep 2026



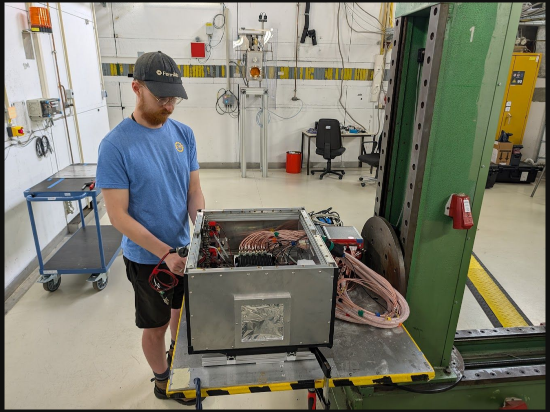
Crystal modules survive shipping.

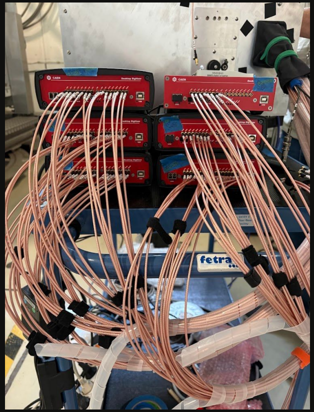




Sophia and Grace assemble parts of the matrix, Bob inspects the front matrix

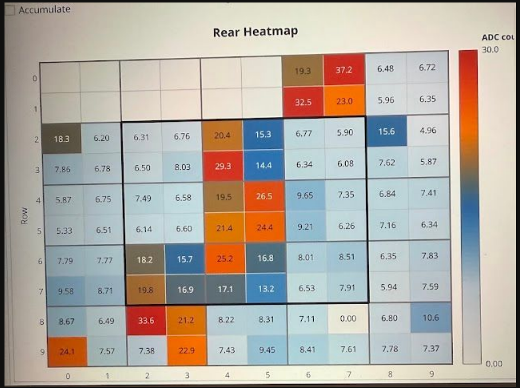
DESY Test Beam 24-Aug--1 Sep 2026





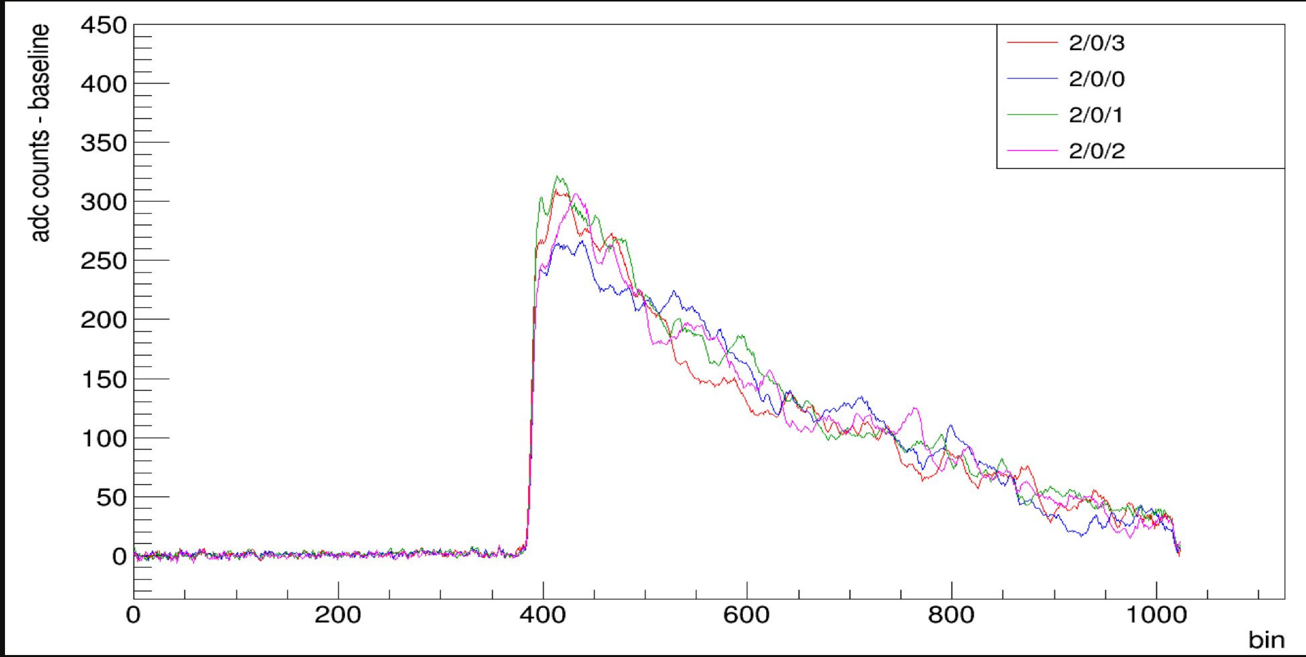
Testbeam participants from Baylor, CUA, FNAL, Michigan, UVa

Completing assembly on the test beam table and 1st cosmics in rear matrix



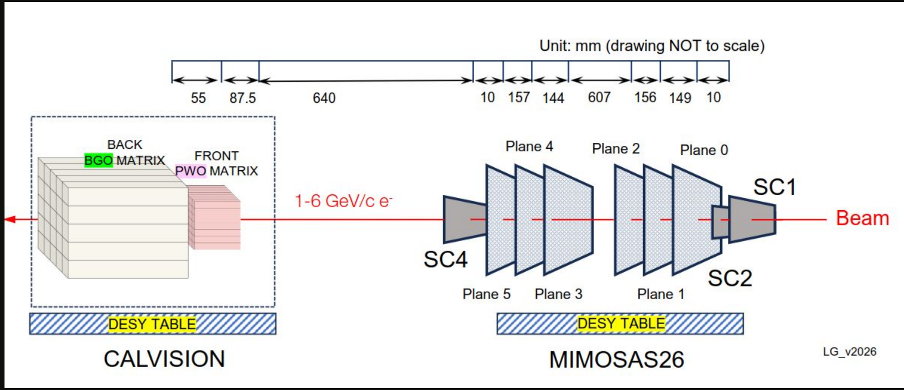
A very preliminary look at data

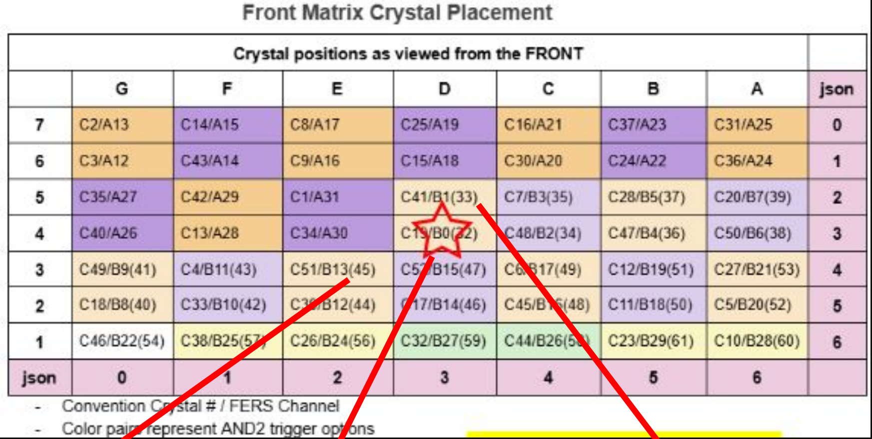
Disclaimer: the data are just over a week old. We'll aim for a more comprehensive update at the CPAD Workshop.



Waveforms for 4 channels in the central BGO crystal showing good uniformity

Good progress on telescope RECO

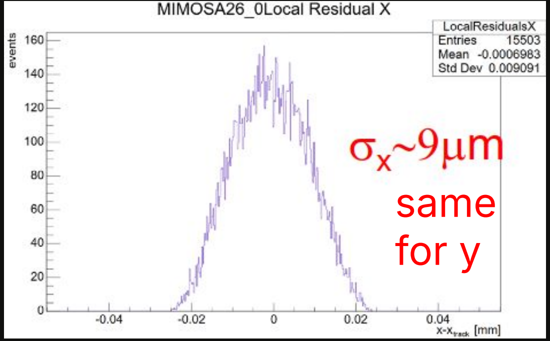




Front Matrix Crystal Placement

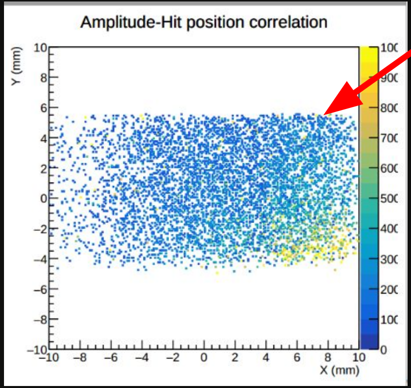
Crystal positions as viewed from the FRONT								
	G	F	E	D	C	B	A	json
7	C2/A13	C14/A15	C8/A17	C25/A19	C16/A21	C37/A23	C31/A25	0
6	C3/A12	C43/A14	C9/A16	C15/A18	C30/A20	C24/A22	C36/A24	1
5	C35/A27	C42/A29	C1/A31	C41/B1(33)	C7/B3(35)	C28/B5(37)	C20/B7(39)	2
4	C40/A26	C13/A28	C34/A30	C19/B0(32)	C48/B2(34)	C47/B4(36)	C50/B6(38)	3
3	C49/B9(41)	C4/B11(43)	C51/B13(45)	C5?B15(47)	C6?B17(49)	C12/B19(51)	C27/B21(53)	4
2	C18/B8(40)	C33/B10(42)	C3?B12(44)	?17/B14(46)	C45/B?6(48)	C11/B18(50)	C5/B20(52)	5
1	C46/B22(54)	C38/B25(57	C26/B24(56)	C32/B27(59)	C44/B26(5?	C23/B29(61)	C10/B28(60)	6
json	0	1	2	3	4	5	6	

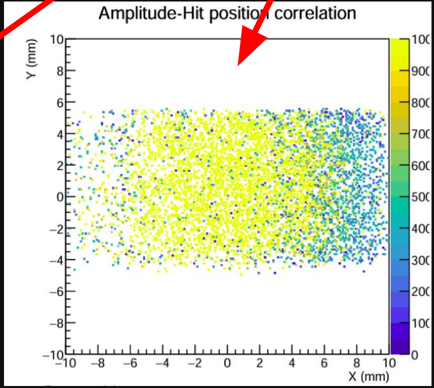
- Convention Crystal # / FERS Channel
- Color pairs represent AND2 trigger options

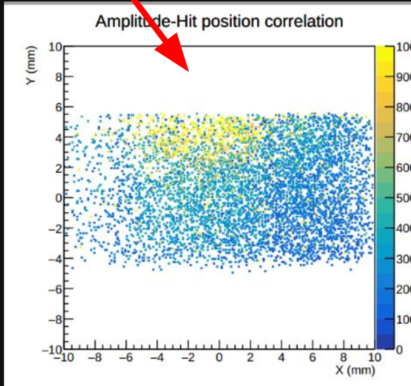


σ_x~9μm

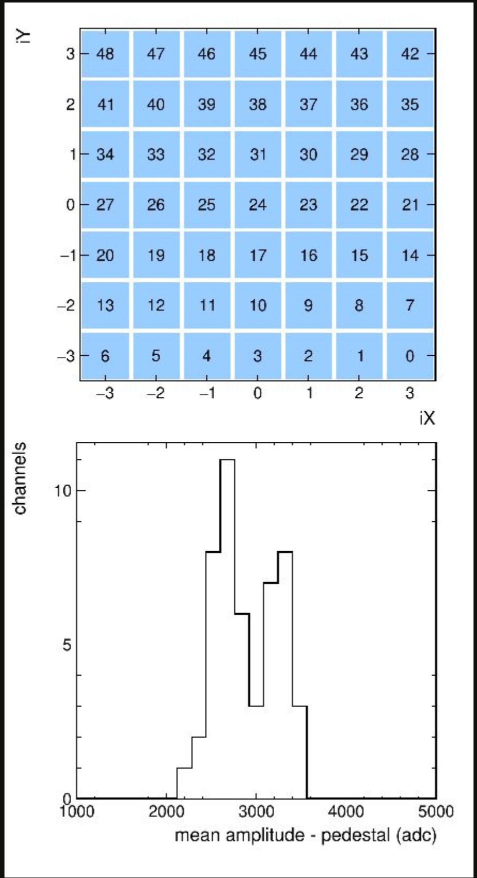
same for y

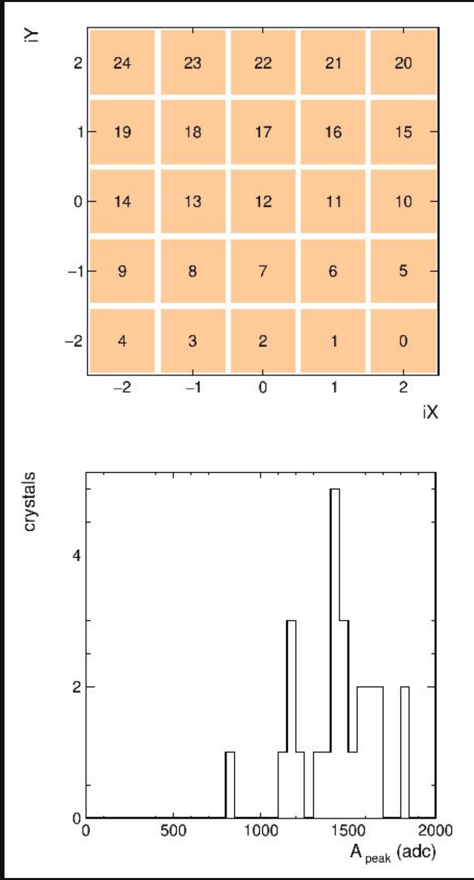






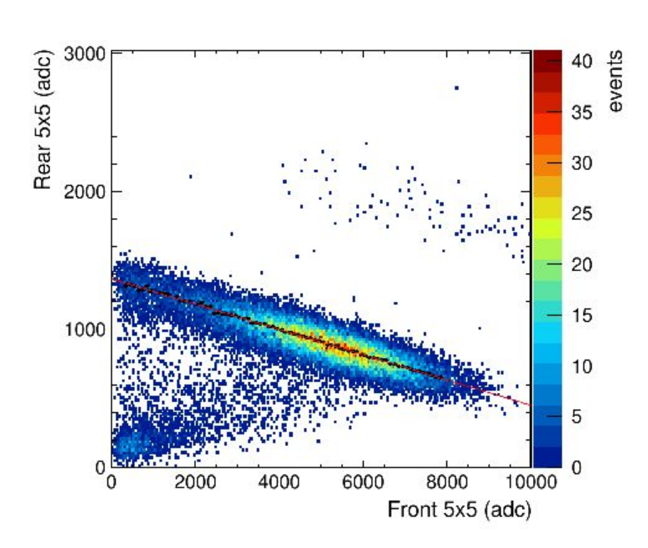
Calibration of front/rear channels





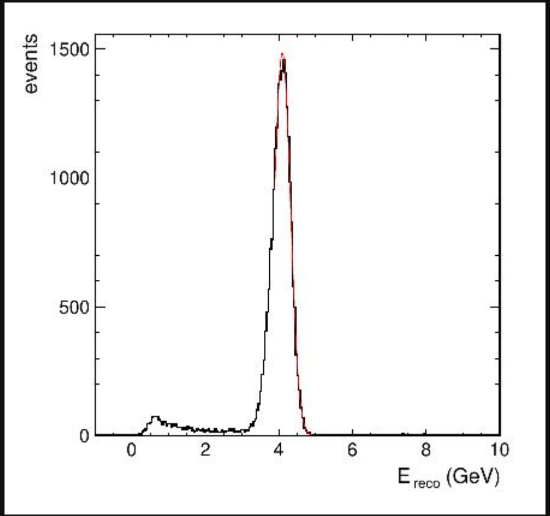
⇐ First pass at relative calibration of front/rear channels

Energy correlations post correction (no event cleaning applied) ⇓



Calibration of front/rear channels

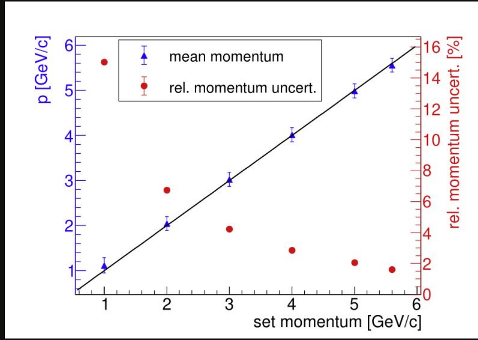
Early response distribution
(no event selection/cleaning)



A. Ledovskoy (UVa)

The calorimeter appears to be working well out of the box! Work is in progress. The data is barely a week old… Many items in the queue:

- Optimizing pedestal subtraction
- Waveform fits for rear pulse shapes
- Merging track information for event selection and cleaning
- Inclusion of beamline resolutions
- Include temperature and electronics effects on scale and linearity
- New waveform analysis to study Č/S separation and estimate Č photon stats.



NIM A 922 (2019) 265–286

General plans/goals for DR ECAL

Calvision also includes a contributions to the Celeritas project, especially for acceleration of optical processes on the GPU. Good progress this year, stay tuned...

We have sourced a new PWO rear matrix with complementary geometry to the MaxiCC matrix. Will allow additional studies for optimizing Č collection and detector segmentation with alternate material.

Timing + precision resolution test beam, ideally at LESA, proposed w/in USFCC.

Continue enlarging the community through shared analysis projects, simulation studies for IDEA, and general physics studies of DR calorimetry.

Other developments crucial to an optimal DR reference design

To optimize performance and control power and data rates

- amplifier optimization, ideally multigain
- analog processing studies

Other factors affecting detector precision

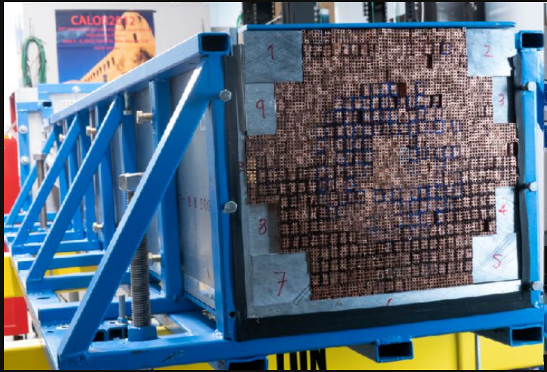
- precise thermal management in darkbox design
- optimization of assembly procedures

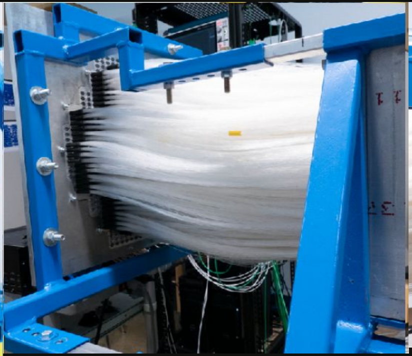
New instrumentation/Bluesky R&D for performance and cost reductions

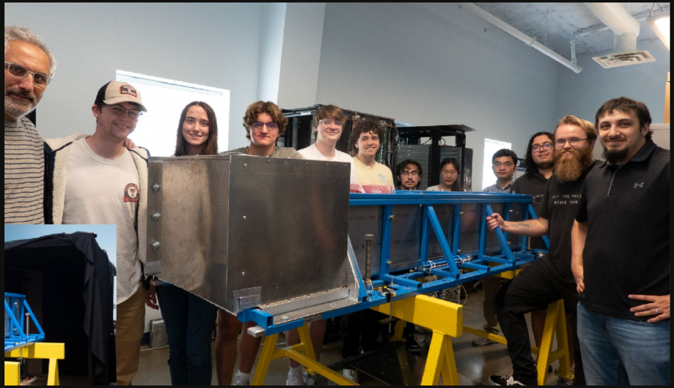
- R&D on heavy glasses, optimized filters, ...
- Sensor optimizations
- massively scalable digitization solutions and data transmission
- on detector intelligence

Fiber HCAL

Completed reinstrumentation of lage fiber calorimeter prototype to begin test beams in 2025





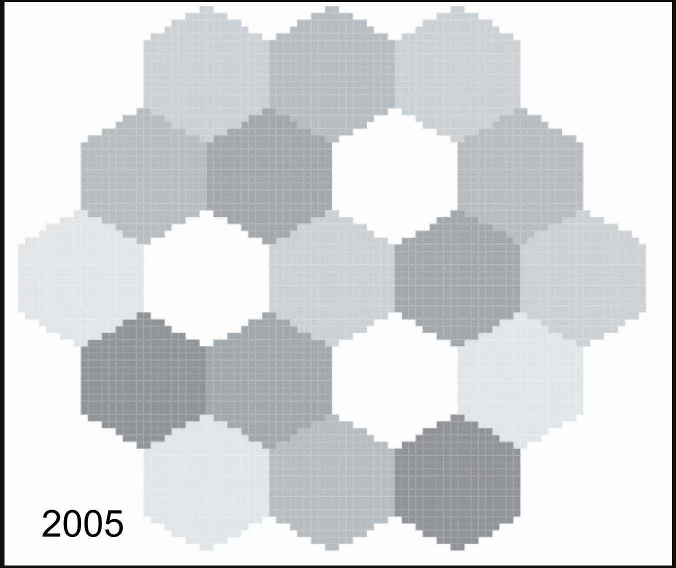


Improved configuration compared with ~2005, including

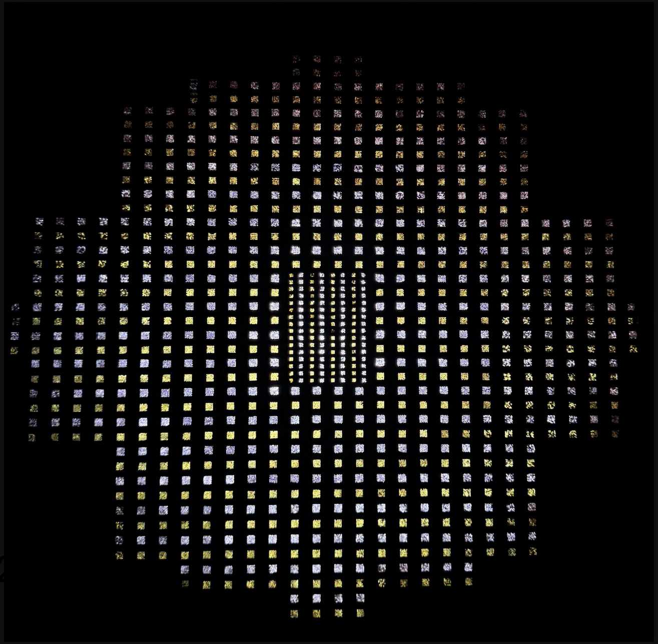
- Higher granularity
- PMTs -> SiPMs:
- Readout electronics

Fast response for better timing capability, together with much higher granularity, to capture fine shower structures

Increased granularity in XY

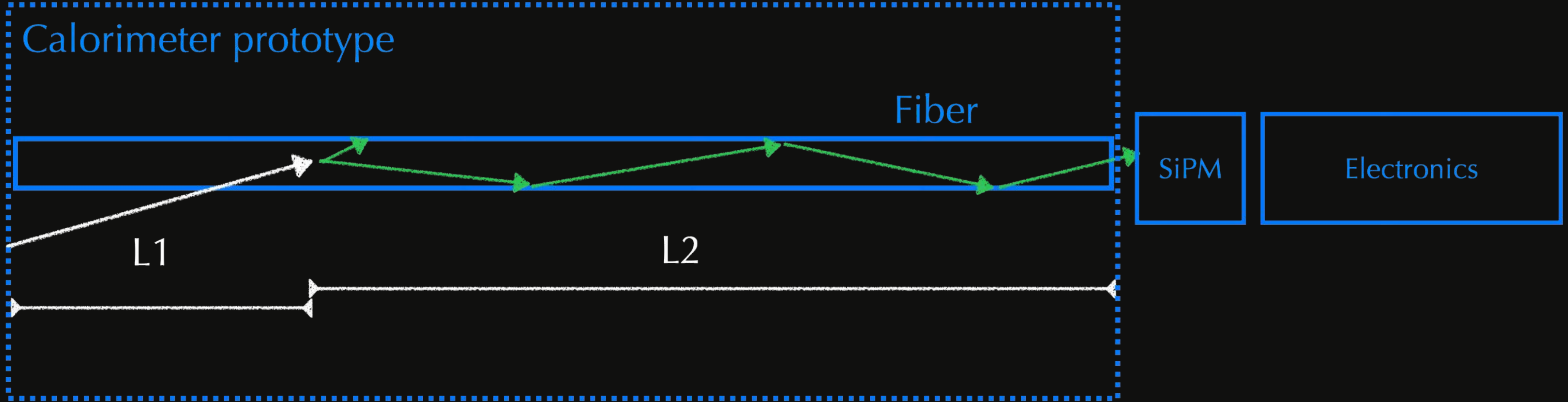


Original “DREAM” in ~2005, **19 towers**, with Cherenkov and scintillation signals read out separately by PMTs -> **38 channels in total**



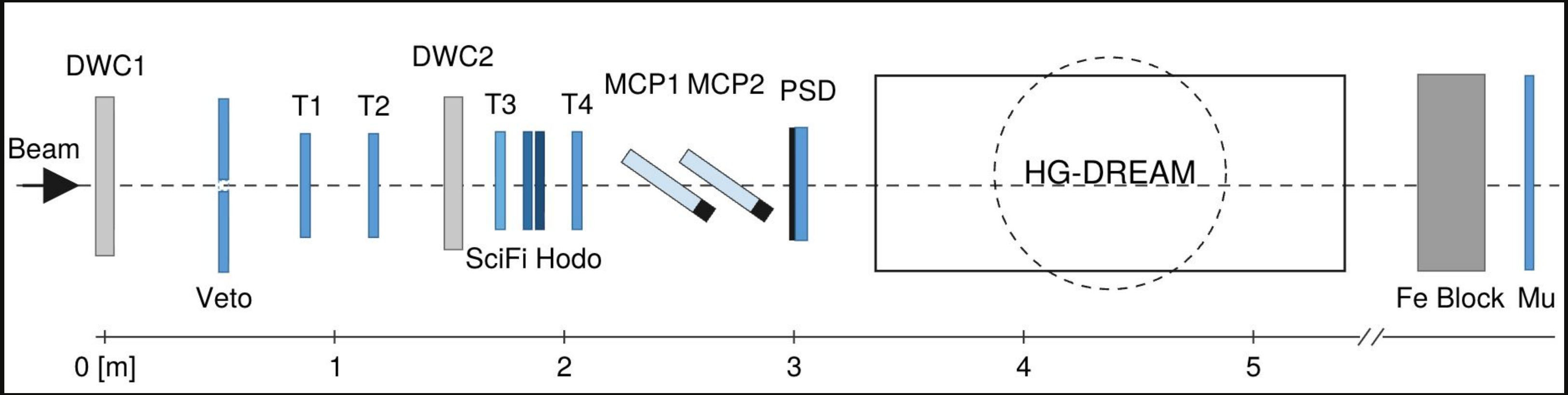
High-Granularity DREAM in ~2025, **448 towers**, read out by 3mm and 6mm SiPMs, -> **896 channels in total**

Timing information: Longitudinal Segmentation

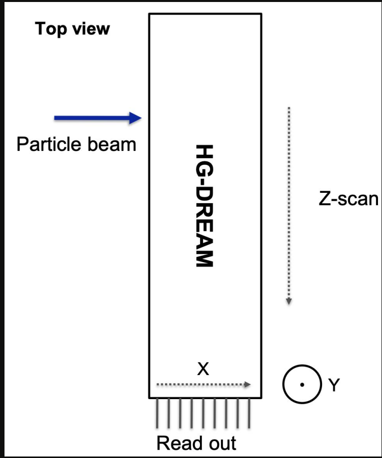


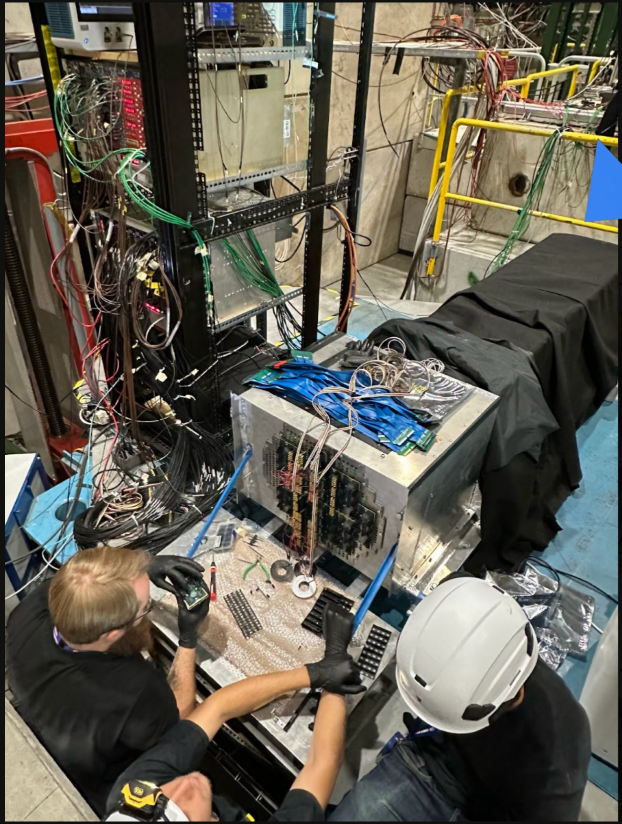
- Photon arriving time ~= L1 / c + L2 / c * n
- Can use photon timing to infer energy deposit position, i.e., longitudinal shower information
  - **Treat fibers as drift chambers**! Use O(n^2) channels to reconstruction O(n^3) information to improve particle-flow, while preserving excellent hadron energy resolution
- Timing information can also help clustering and reconstruction in (X, Y, E, t) space, attenuation corrections, particle identification, and pileup mitigation, etc

Test Beam Setup at CERN H8 beamline

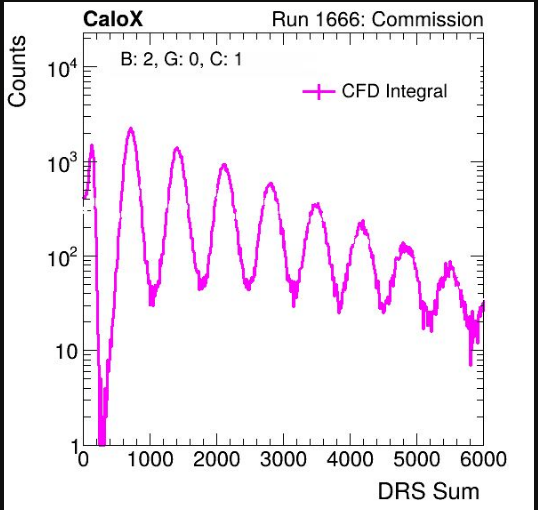


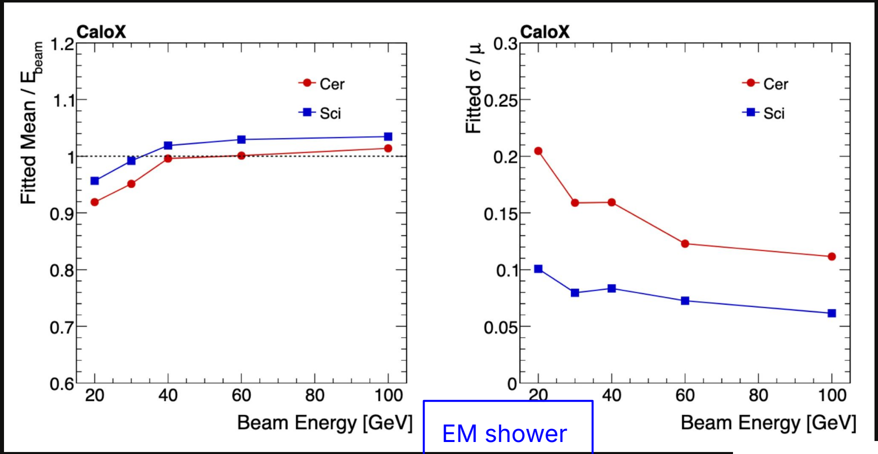
- Beam tests carried out at CERN H8 beamline in summer 2025+2026
  - e^+ runs at different energy and positions for calibrations
  - pion runs at different energies for hadron performance studies
  - Runs with detector rotated 90 degrees to study timing and photon propagation properties
- Channels read out by CAEN FERS A5202 for energy measurements, and by CAEN DRS V1742 for timing information (running at 5GHz sampling frequency, 12 bits)



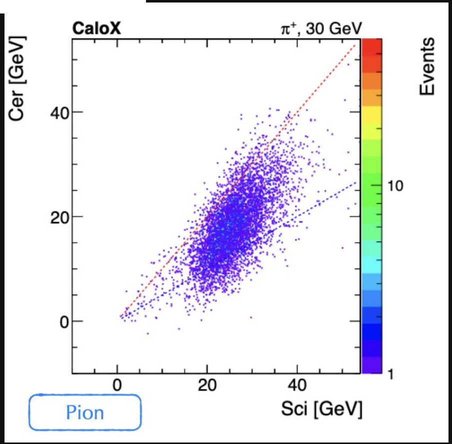


Energy performance



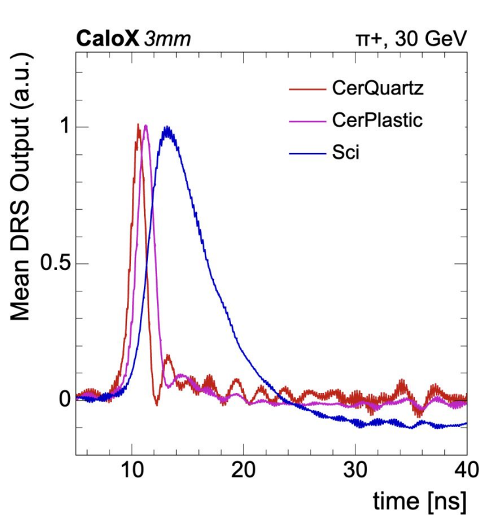


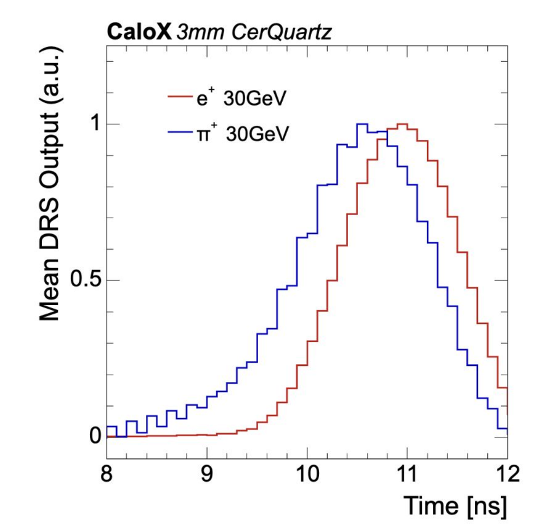
EM shower

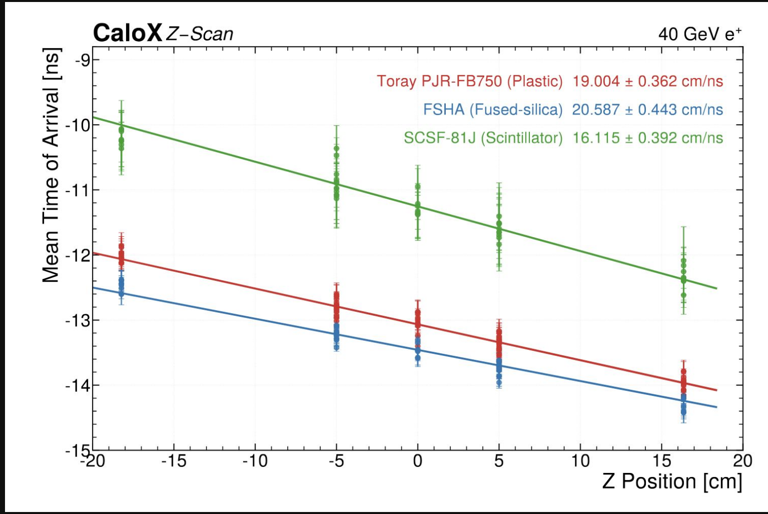


- Nice individual photoelectron peaks observed
- For EM shower, uniform response (up to 5% difference) and reasonable energy resolution after calibrations
- For pion/proton hadron showers, observed the correlation between Cherenkov and scintillation signals
  - detailed studies on pion energy measurements in progress

Timing performance







- Left plot: differences in timing profiles of different types of fibers:
  - Scintillation long tail due to scintillation decays
  - Quartz cherenkov vs plastic cherenkov difference due to different refractive indices
- Middle plot: differences in timing profiles for EM vs hadronic showers
  - Hadronic shower goes deeper, leaving longer tails on the left (photons arriving earlier)
- Right plot: measuring photon propagation speed for different fibers using z-scans
  - Linear relationship of photon arriving time change when varying the z position. Slope differences correspond to refractive index difference

Fiber HCAL Future plans

- Finalize the results from test beam studies and prepare journal submission
- More GEANT4 simulation and (AI/ML-based) reconstruction studies on further improving the energy resolutions and physics performance
- Incorporating realistic detector response models learned from test beam into full FCC-ee/IDEA simulations, to evaluate performance enhancements in jet, ptmiss, and representative physics processes.
- Meanwhile, the work has received the support from SLAC LDRD on designing digital SiPMs targeting precise timing stamps at single photon level precision to study 4D/5D calorimetry
    - Plan to test performance at SLAC test beam facility using a smaller prototype, which will benefit from the excellent timing properties of the facility

Summary

US DR R&D continues to explore unique aspects of this calorimetry for FCC applications

- US science has lead major advances in DR Calorimetry from the beginning, including
  - First demonstrations of DR corrections for hadronic calorimetry
  - First proof of principle studies for necessary Č/S separation and measurement in a crystal ECAL.
  - Leading role in the hybrid DR concept
- Unique studies of timing and advanced reconstruction for Fiber HCAL

Our R&D will have profound impacts on IDEA detector design choices. Especially with readiness for precision studies when proton beams return.

The work presented here received support through the US DOE and the University of Virginia

Bibliography

- New perspectives on segmented crystal calorimeters for future colliders
- The IDEA detector concept for FCC-ee
- Fiber HCAL CALOR talk on energy performance: https://indico.cern.ch/event/1572594/contributions/7072387/
- Fiber HCAL CALOR talk on timing performance: https://indico.cern.ch/event/1572594/contributions/7072388/
- Recent developments in dual readout calorimetry in homogenous inorganic scintillators with CalVision (CALOR 2026)
- Progresses of Inorganic Scintillators for Future HEP Calorimeters (CPAD2023)