

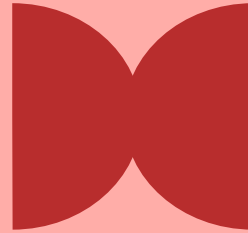
# Test Beam Studies of a Segmented Crystal Dual-Readout Calorimeter Module

Bob Hirosky  
University of Virginia

2026 CPAD Workshop



MaxiCC



# Hybrid DR Calorimetry

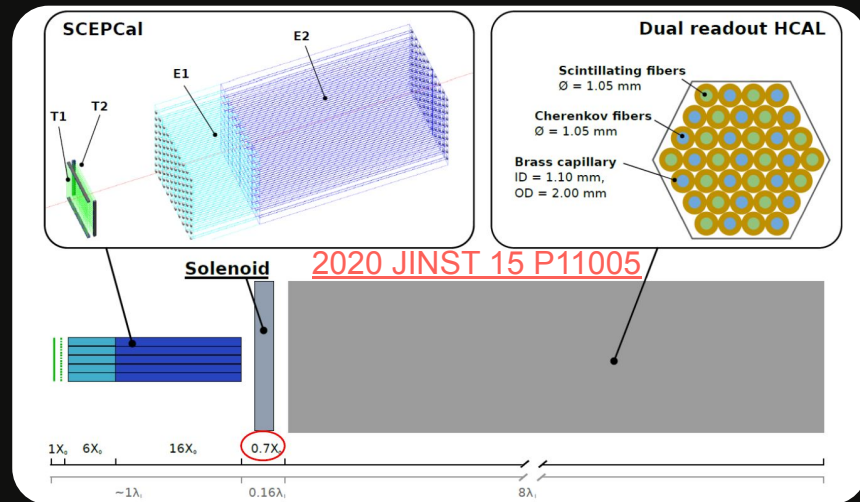
The DR concept was introduced in Yongbin's talk.

A hybrid concept comprises a homogeneous DR crystal EM + DR fiber HCAL

"Best of both worlds" strategy for high resolution calorimetry design.

- A Segmented DR Crystal ECAL
- DRO Fiber HCAL

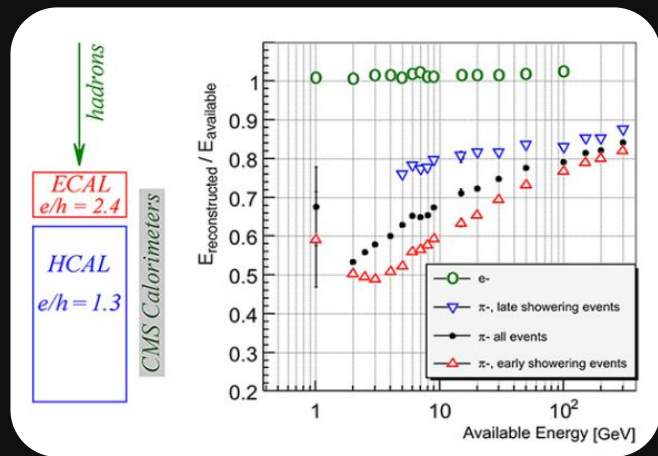
CalVision crystal ECAL R&D is also in coordination w/ MaxiCC WG of DRDCALO Collaboration



- Maintain state of the art EM energy resolution
- Brem. recovery
- $\gamma/\pi^0$  id plus jet matching for PF
- DR correction in ECAL to preserve jet energy resolution

# Hybrid DR Calorimetry

DR ECAL solves the problem of different e/h ratios degrading hadron response



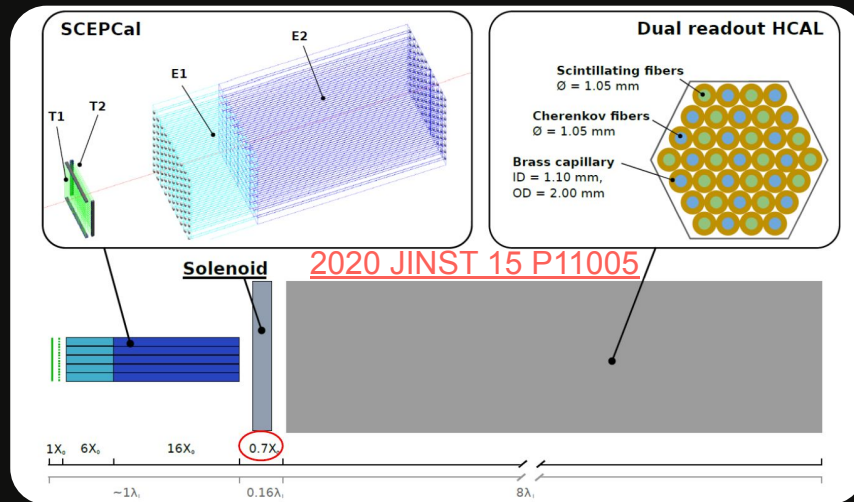
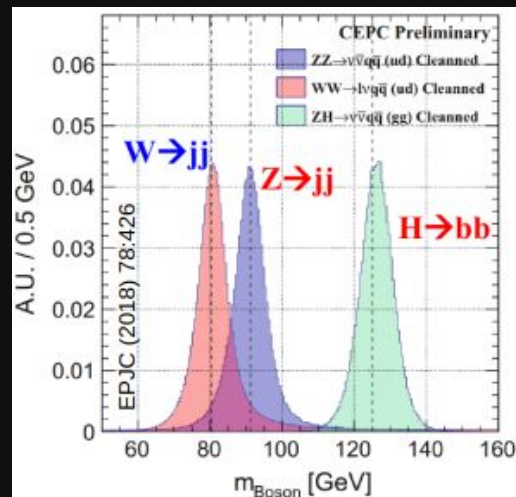
[10.1016/j.nima.2011.10.035](https://doi.org/10.1016/j.nima.2011.10.035)

$$E_{\text{HCAL}} = \frac{S_{\text{HCAL}} - \chi_{\text{HCAL}} C_{\text{HCAL}}}{1 - \chi_{\text{HCAL}}}$$

$$E_{\text{ECAL}} = \frac{S_{\text{ECAL}} - \chi_{\text{ECAL}} C_{\text{ECAL}}}{1 - \chi_{\text{ECAL}}}$$

$$E_{\text{total}} = E_{\text{HCAL}} + E_{\text{ECAL}}$$

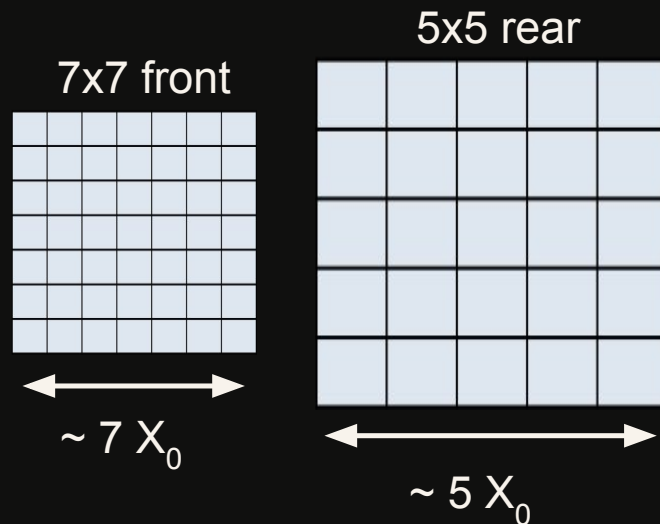
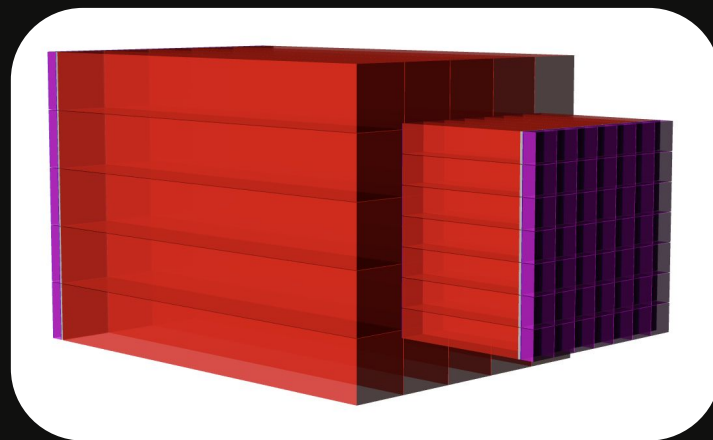
Satisfying Higgs  
factory needs



# CalVision: Crystal ECAL

## Construction of 2-layer EM Matrix (UVa)

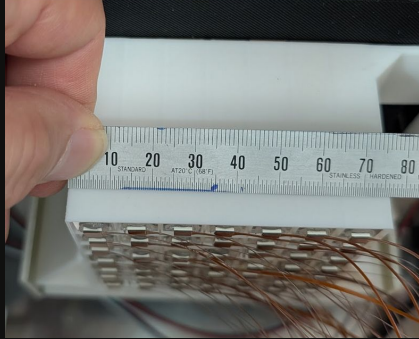
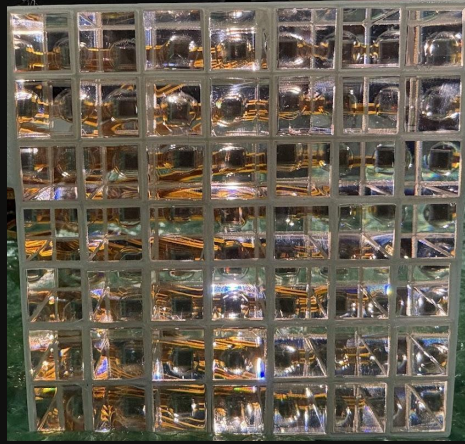
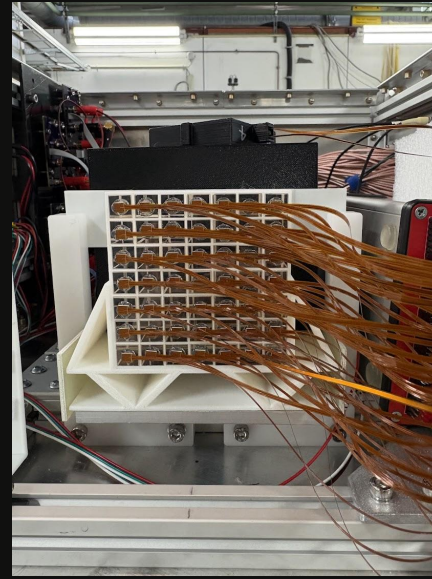
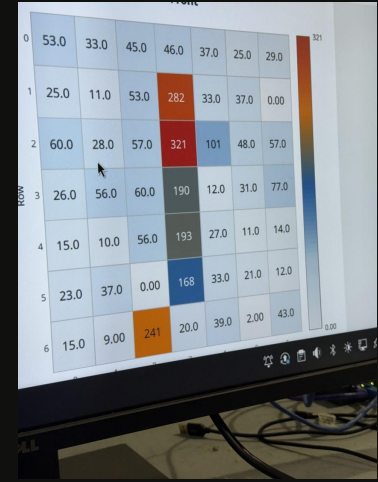
- Front  $\text{PbWO}_4$  (single readout)
  - 1cm x 1cm x 5cm
  - 49 channels => CAEN FERS
  - 3mm x 3mm 10u cell SiPMs (HPK)
- Rear BGO
  - 2.2cm x 2.2cm x 16cm + U330 filter
  - 100 channels (4x25 crystals)
  - 6mm x 6mm 40u cell SiPMs (Broadcom)
  - Samples w/ DRS at 5GS/s
- Total depth  $\sim 20 X_0$



We were able to complete sourcing materials this July for a DESY TB run the last week of August.

Crystal testing Caltech/UMD/CUA

# Crystal ECAL Front

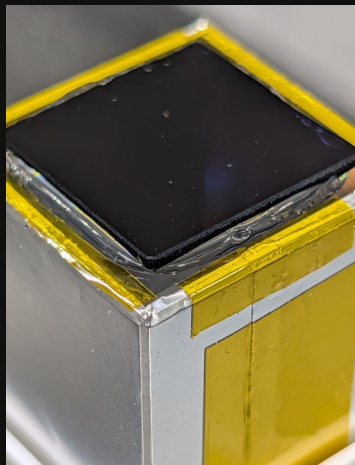


Cosmic ray  
track

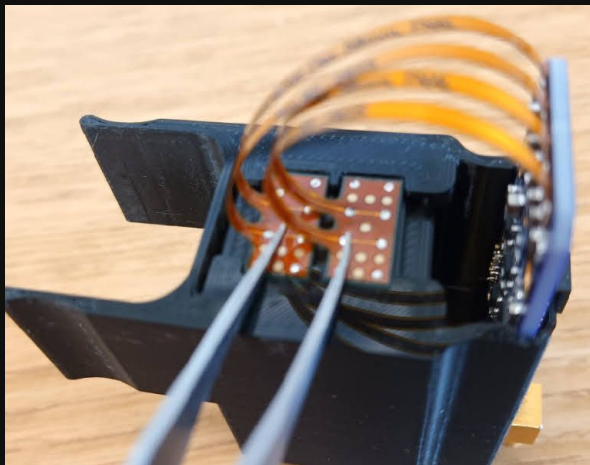
## Front $\text{PbWO}_4$

- Peak detection only (FERS/CITIROC), no S/C separation
- Why PWO?
  - High density allows more compact ECAL
  - More available right now due to trade issues...

# Crystal ECAL Rear



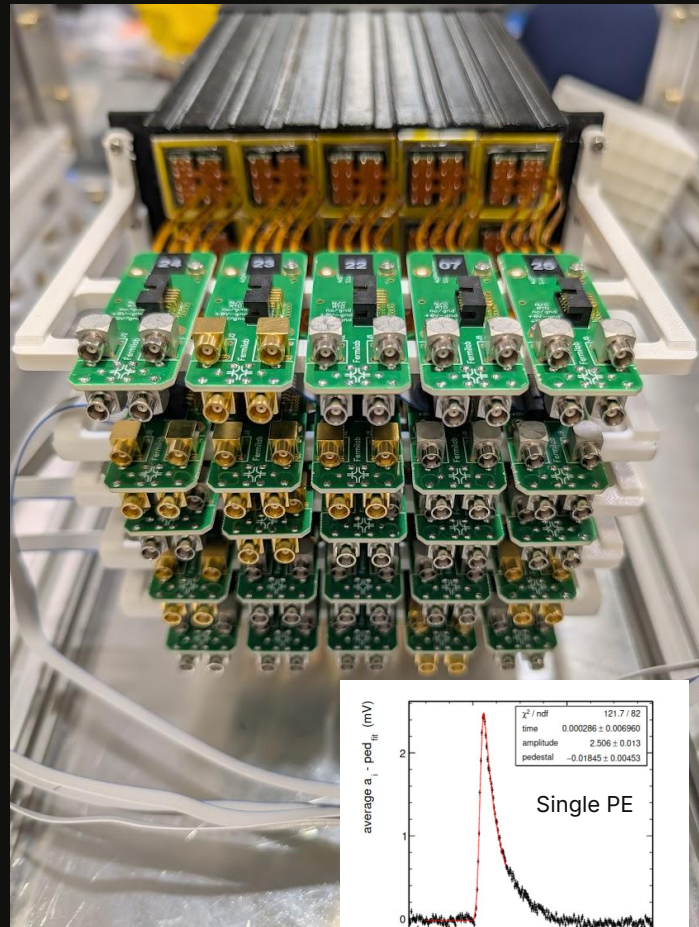
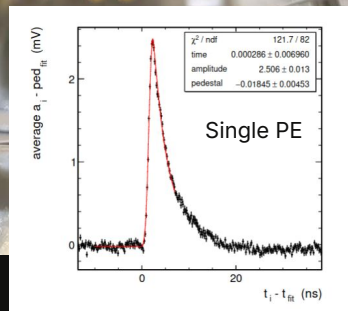
Rear crystal  
with U330 notch  
filter



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

Multiple design choices to improve systematics  
from previous test beams

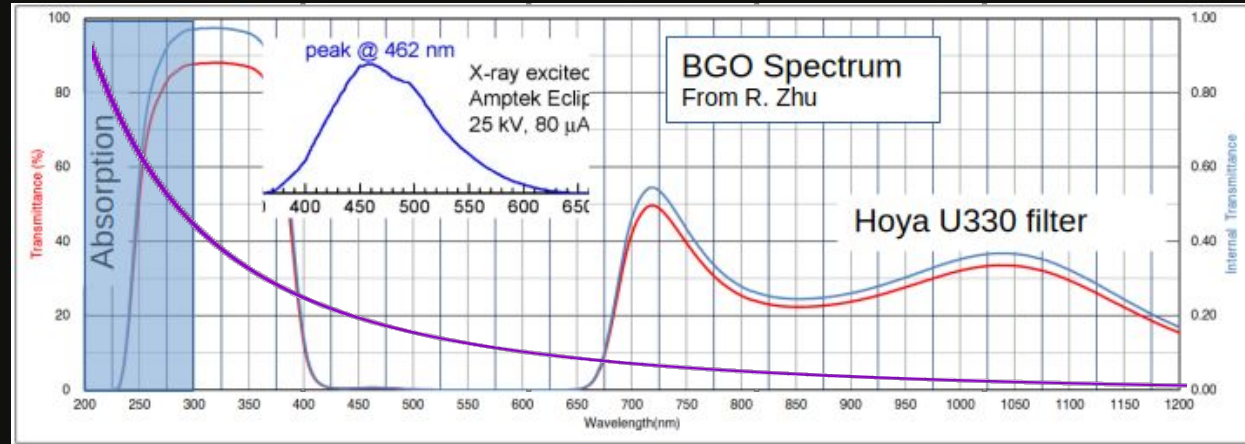
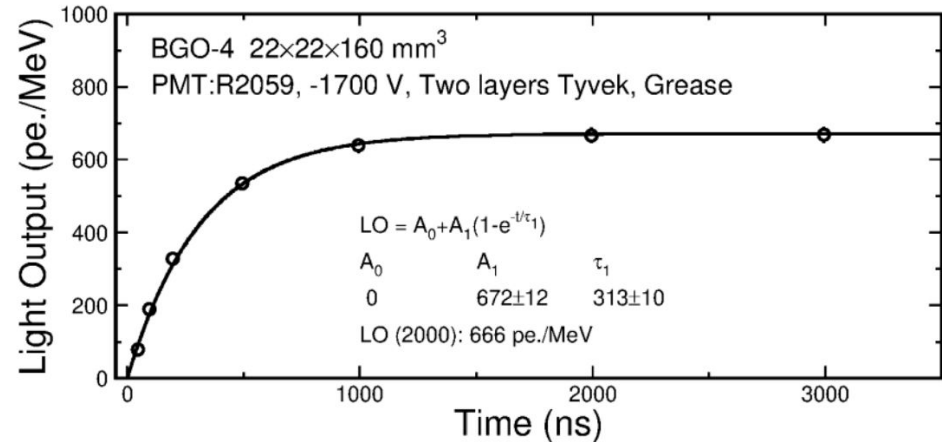
## Rear matrix with FNAL amplifiers



# 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. Allows maximizing of light sensor area and Č/S via pulse analysis.
- Commercial market for PET

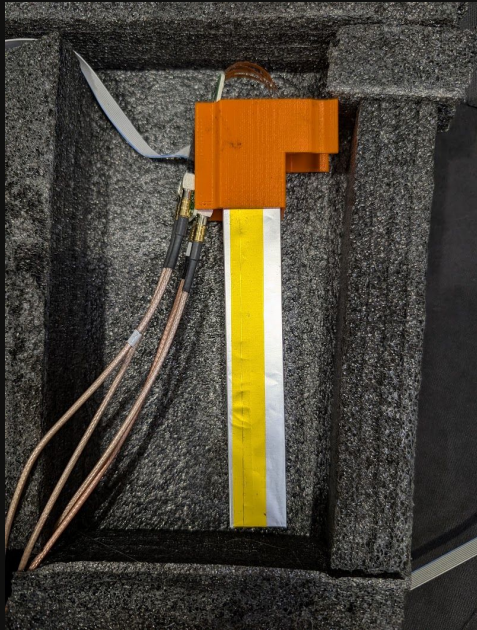
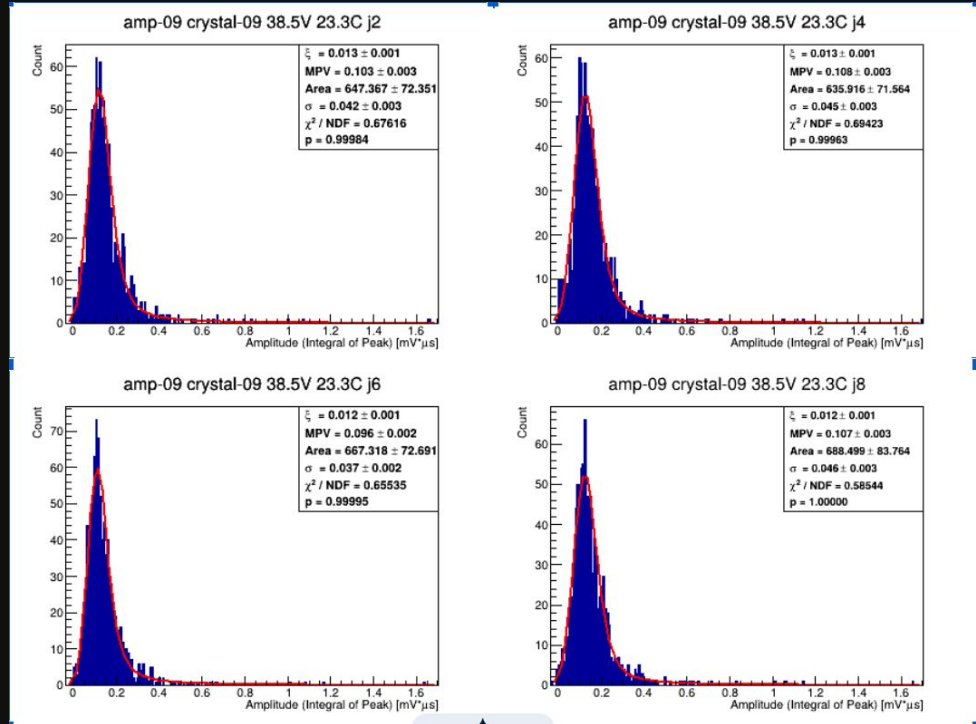
Alternatives: PWO, BSO, ...  
require different optimizations



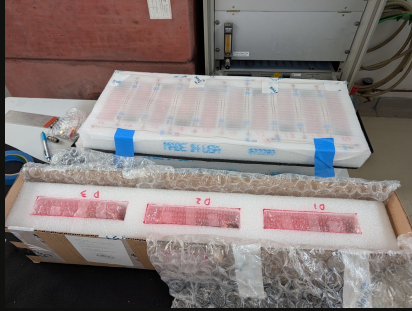
# Module testing with cosmics

Used to check uniformity of assembly

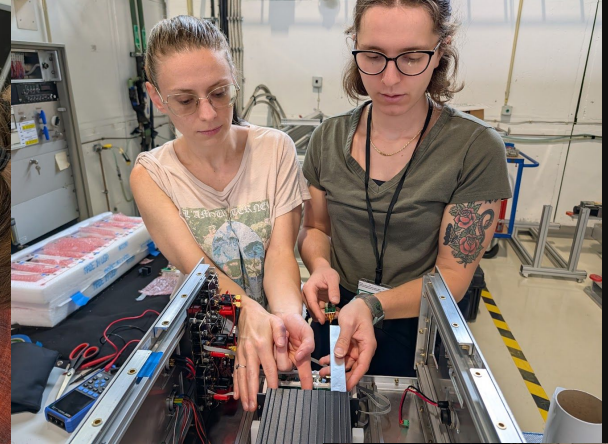
- 4 channel coincidence on scope
- Essentially 0 noise triggers



# DESY Test Beam 24-Aug--1 Sep 2026



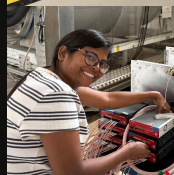
Crystal modules survive shipping.



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

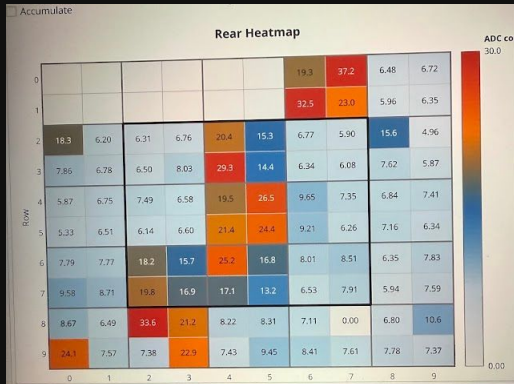


# DESY Test Beam 24-Aug--1 Sep 2026

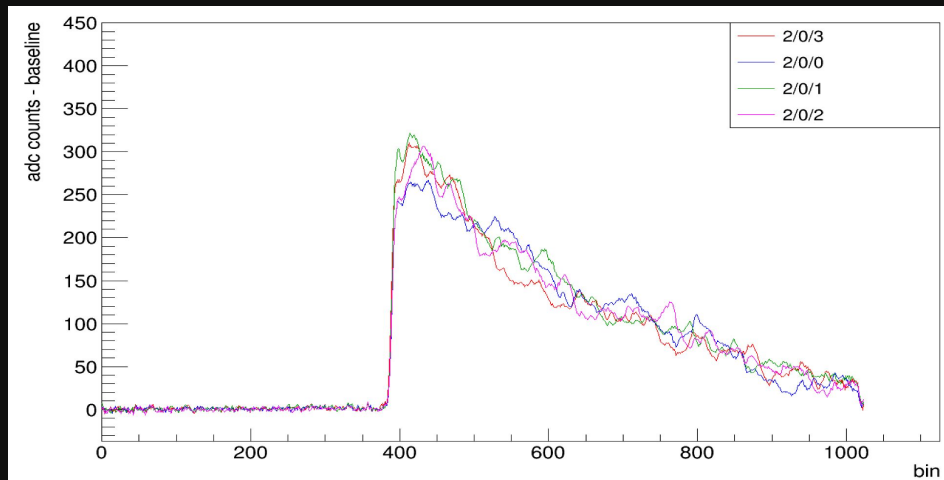


Testbeam participants from Baylor, CUA, FNAL, Michigan, UVa

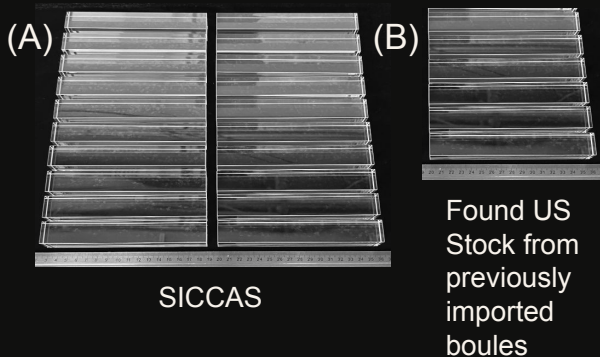
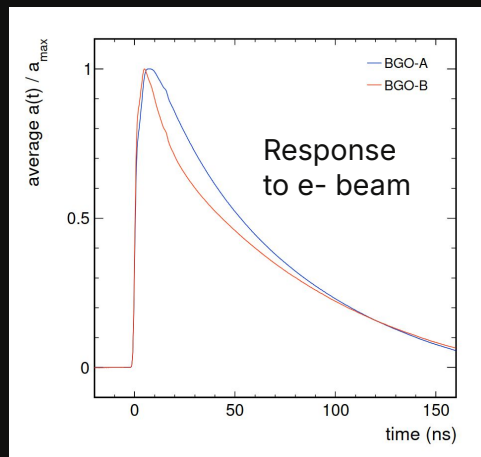
Completing assembly  
on the test beam  
table and 1st  
cosmics in partly  
assembled rear  
matrix



# A first look at data



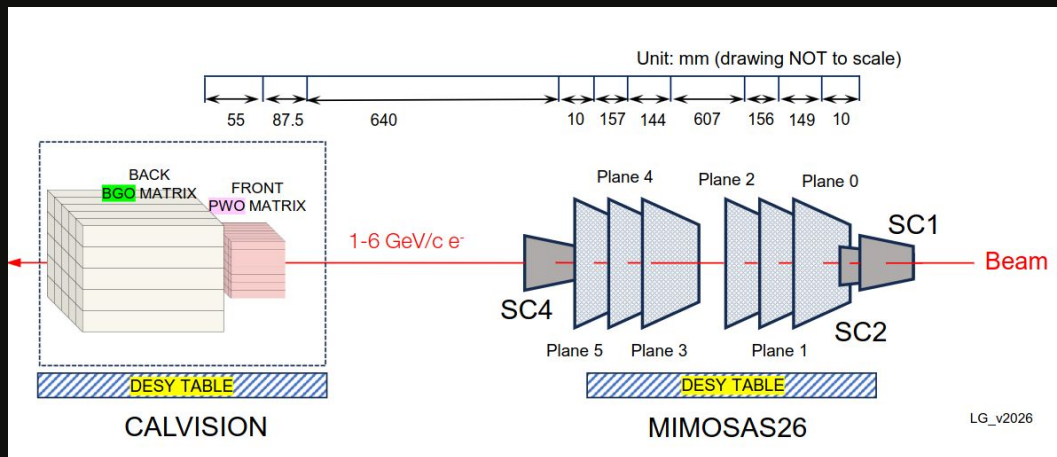
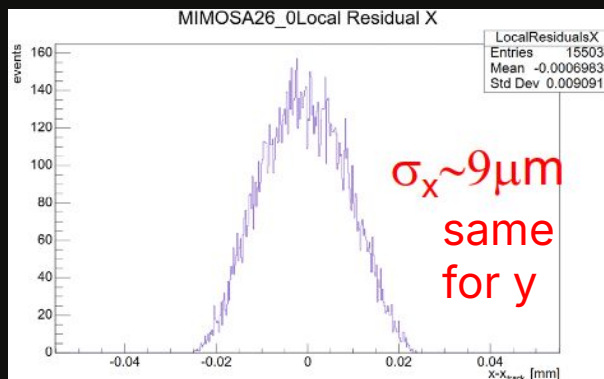
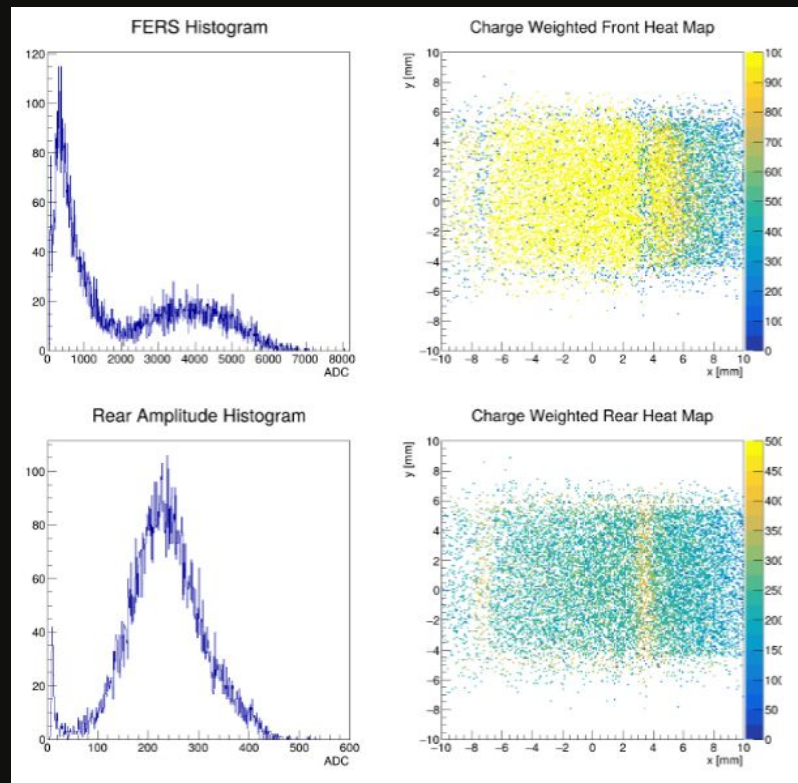
Waveforms for 4 channels in a typical BGO crystal show good uniformity



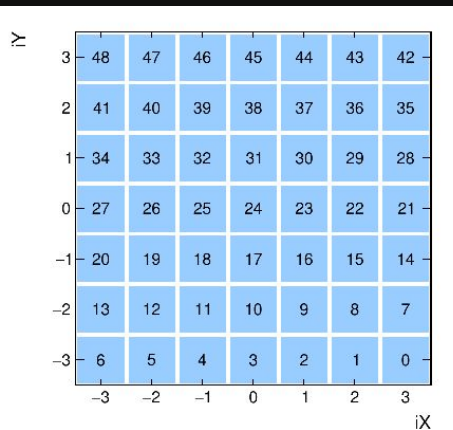
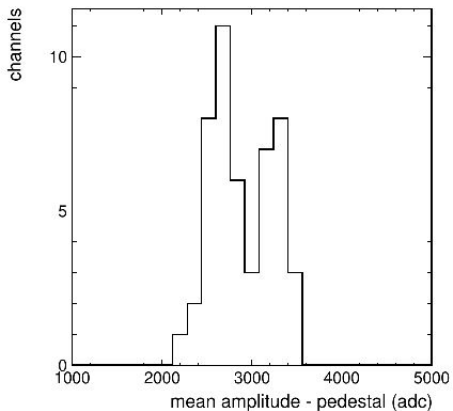
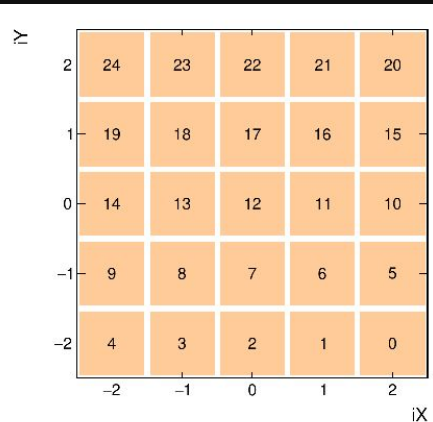
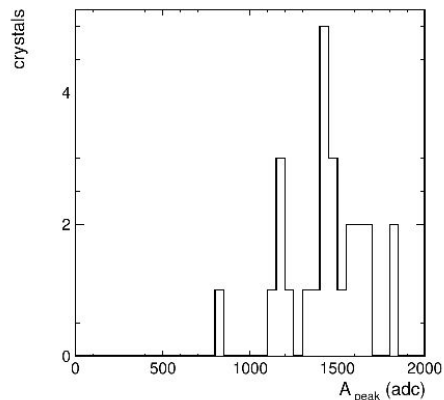
Average waveforms for two sources of BGO crystals. Sample (B) appears to have a stronger fast scintillation component.

Differences among vendors are common, also seen in PWO/BSO samples by MaxiCC

# Precision track reconstruction

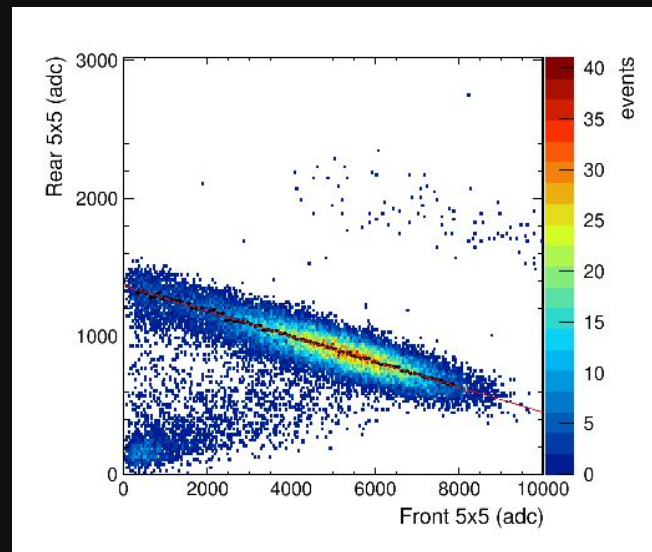


# Calibration of front/rear channels

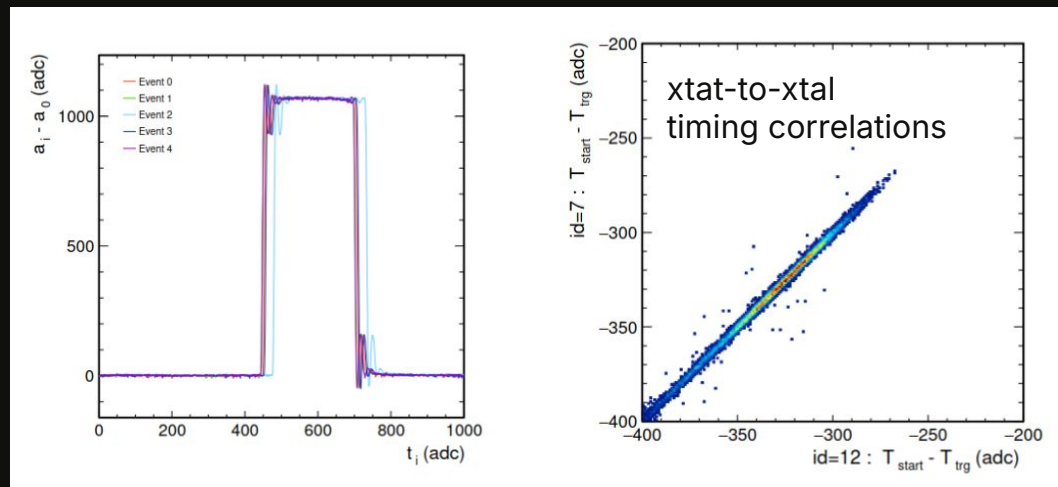


⇐ First pass at relative calibration of front/rear channels

Energy correlations post correction (no event cleaning/tracking applied) ↓

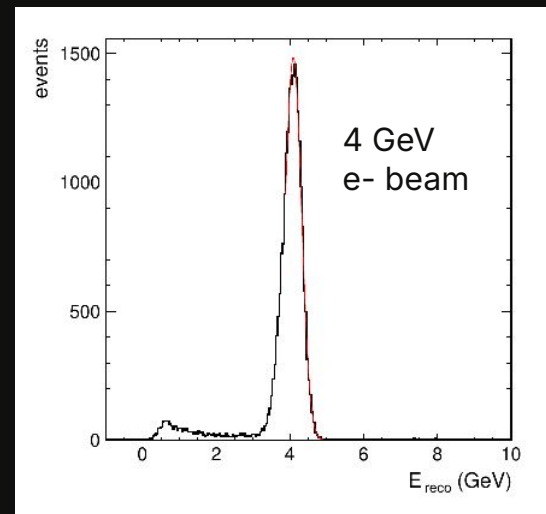


# Preliminary measurements



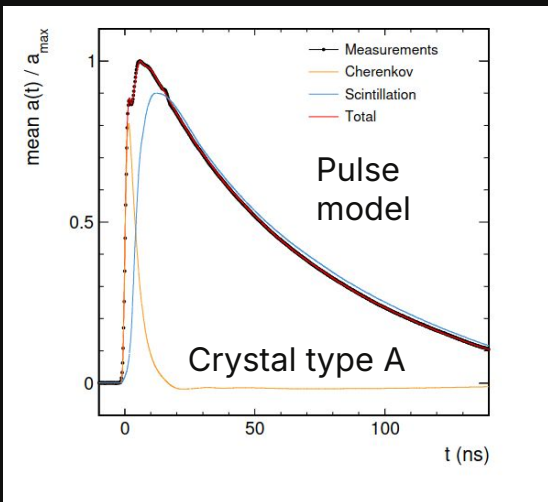
Channel-to-channel timing corrections

**The calorimeter is working well  
out of the box!**

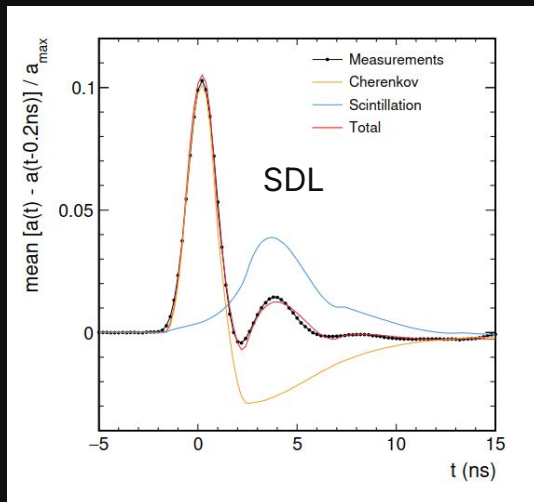


Early response distribution  
(no event selection/cleaning)

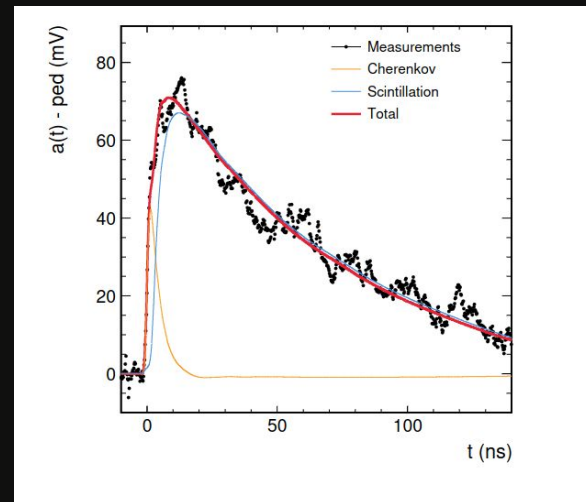
# Preliminary measurements



Mean waveform  
for rear crystal with  
 $S/\hat{C}$  component  
models



Derivative enhances  $S/\hat{C}$   
component differences.  
Interesting possibilities to  
analog processing.



Central crystal in a shower.  
Normalizing to 1PE  
response yields  
 $> 100 \hat{C}$  photons/GeV  
(continuing to meet specs  
for hybrid DR correction)

# Other developments informing an optimal DR reference design

To optimize performance, power and data rates

- Detailed simulation, incl. optical photons→electronics response
- Amplifier optimization, ideally multigain
- Analog processing studies

[Hendricks]  
[Hollenbeck]

## Physics detector design efforts

- 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

[Madrid]  
[Markovic]  
[Yoshihara]  
[Liu]

# US R&D explores unique aspects of DR calorimetry for FCC applications

- **US science has lead major advances in DR Calorimetry from the beginning:**
  - 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.**
  - **Need to be ready for joint EM/HAD studies when proton beams return!**

**FCC-Conceptual studies now, LOIs/Collaborations expected in just a few years!**



# 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.

# 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](#))

# 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.  $\sim 50$  PE/GeV needed for corr. Factor
- Photon collection efficiency
- Light sensors and readout electronics
- Assembly studies
- (Optical) detector simulation
- Calorimeter performance measures
- Efficient data transmission and signal analysis
- ...

**CalVision R&D is also in coordination w/ MaxiCC WG of DRDCALO Collaboration**

# Status/plans timeline

EOI for FCC  
detector concepts  
& CERN Council  
approval

CERN June TB SPS

CERN Sept TB

CERN May

DESY August TB

2025

2026

Now

2027

2028

Single sensor beam test with various flavors  
of crystal, filters and SiPMs

Study of BSO and PWO crystal from different vendors

Full containment EM calorimetric module prototype  
(9x9 matrix) with PWO crystals built and tested

Design and construction of central  
tower (3x3) EM calorimetric module  
prototype with BSO crystals

First combined test  
beam with fibre  
calorimeter prototype

Analysis of 2026 test beam data

Study of ultra small cells size HDR SiPMs (6/10  $\mu\text{m}$ )

Optimization of BSO and PWO crystal quality

Upgrade/optimization of existing PWO prototype  
and completion of BSO 3x3 prototype + testing

Explore the potential of EM shower acceleration  
through oriented crystal axis (OREO)

# Summary and outlook

## Exciting progress during 2026 towards the demonstration of the IDEA EM crystal calo concept:

- Full PWO prototype successfully completed and beam-tested, including a first combined run with HIDRA.
- Hybrid **BSO** and **BGO** prototypes were also assembled and beam-tested, exploring **complementary dual-readout approaches**.
- We identified the key technological challenges and defined the next R&D priorities.

Priorities for 2027 (and beyond):

- Complete **analysis** of the **2026 TB data**.
- Address the **remaining technology challenges**: sensors, FEE, and optical/mechanical integration.
- Test **upgraded prototypes**
  - TB @**DESY** planned for 2nd half of 2027
  - TB @**SLAC** (4–8 GeV electrons) aimed at energy resolution and timing studies (in 2027, subject to availability)
- Progress on **full simulation** in key4hep → see [Julia's talk](#) this afternoon.

→ reach a **solid reference detector design** by the CERN FCC-ee decision in 2028/29

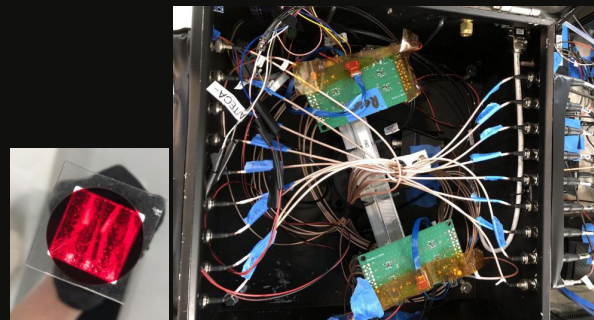
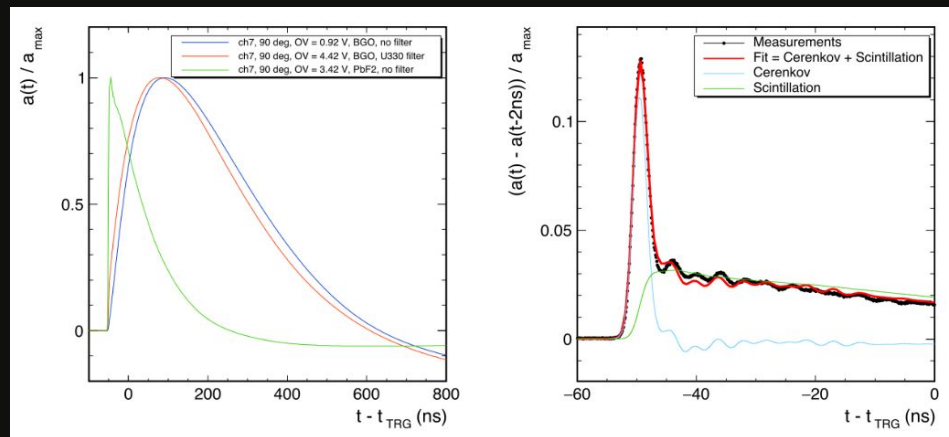
# Prior highlights: ECAL

Test beam at DESY (April 2024)  $\sim 2\text{-}5\text{ GeV e-}$

- Coordinated by CalVision US groups with participation from Milano-Bicocca
- Test of  $\text{PbF}_2$  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  $\sim 160$  PE/GEV in  $\check{C}$  signal component w/ 4 SiPM readout. Further optimization possible w/ improved optical coupling

**=> first demonstration of sufficient  $\check{C}$  signal for hybrid DR.**

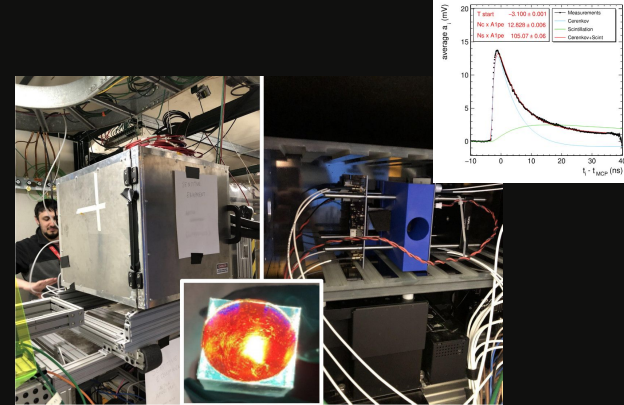
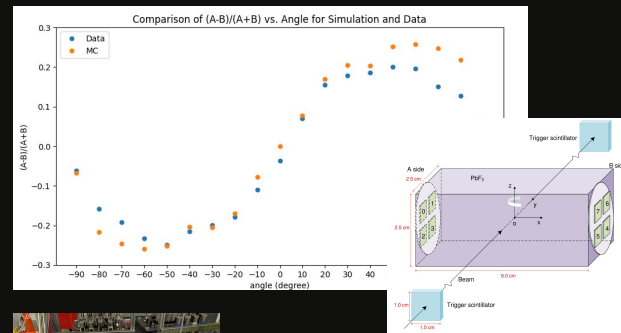
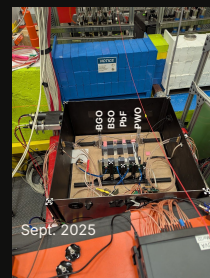
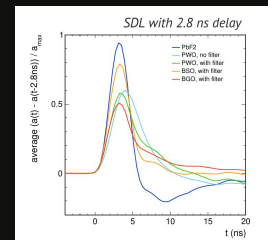


Pure Cherenkov signal from  $\text{PbF}_2$  and BGO w/, w/o optical filter  
(left) original waveforms and component fits  
(right) component fits after digital SDL filter

# Prior highlights: ECAL

## Summary of earlier test beams

- April 2023: Cherenkov and scintillation separation in BGO w/ full waveform analysis + timing in PbWO<sub>4</sub> w/ FNAL 120 GeV protons: [arXiv:2408.11973](#)
- June 2023: Cherenkov acceptance characterization and modeling in PbF<sub>2</sub> 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<sup>+</sup> beam at JLAB Hall D. Study signals in different crystals with faster amplifier shaping. See [CPAD2025 talk](#)



# IDEA

IDEA is pursuing a new organization. See Paolo's presentation on the Sept 22, IDEA study Group Meeting.

## The Strategy changes the task

*The conclusion of the European Strategy Update marks a major paradigm shift*

FEASIBILITY STUDY

Study what  
FCC-ee could achieve



REFERENCE DESIGN PHASE

Prepare a project that can be  
approved, implemented and  
exploited

CERN transitions from evaluating the FCC-ee proposal to preparing its formal delivery

The basic plan is to form a traditional collaboration structure w/ caveat that collaborations won't exist until ~2030.

Prepare for downselect phase of FCC detector strategy!

2026-2028

After approval

Collaboration forming

~2030

Mid-2040s

Concept studies  
and R&D



Documented  
detector Eols



Open community  
process



Four  
collaborations  
and Iols



Experiments  
in operation

- CPAD is next week w/ a strong showing on DR adjacent topics:
  - A Simulation Approach to Dual-Readout Calorimetry (Walker)
  - GPU-Accelerated Optical Simulation for Dual Readout Calorimetry with Celeritas (Hayden)
  - Test Beam Studies of a Segmented Crystal DR Calorimeter Module (Bob)
  - FLASH: Photon-Level Time-Resolved Calorimetry with Digital SiPMs (TTU/SLAC)
  - Performance of High-Granularity Dual-Readout Calorimeter with High Energy Particle Beams (Yongbin)
  - 28 nm Readout ASICs for 3D-Integrated LGAD Sensors with 10 ps-Level Timing Performance (SLAC)
  - On-detector ML for Real-Time Waveform Processing: Applications to Dual-Readout Calorimetry and Drift Chambers (Qibin)
  - others?
- Test beam analysis and simulation projects are underway. Some updates today.

Additional slides

# General plans 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...

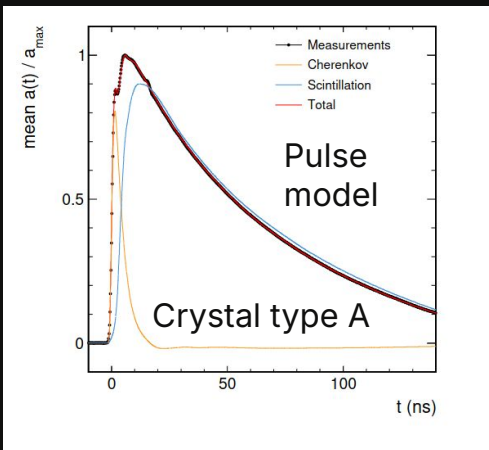


We have sourced a new PWO rear matrix with complementary geometry to the MaxiCC matrix. Will allow additional studies for optimizing Č collection and detector segmentation with alternate material.

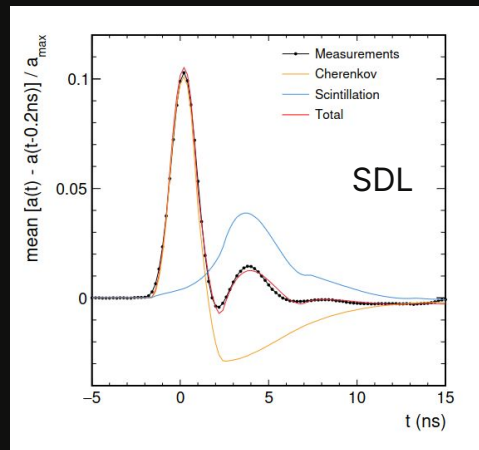
Timing + precision resolution test beam, ideally at LESA, proposed w/in USFCC.

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

# Preliminary measurements



Mean waveform for rear crystal with S/ $\check{C}$  component models

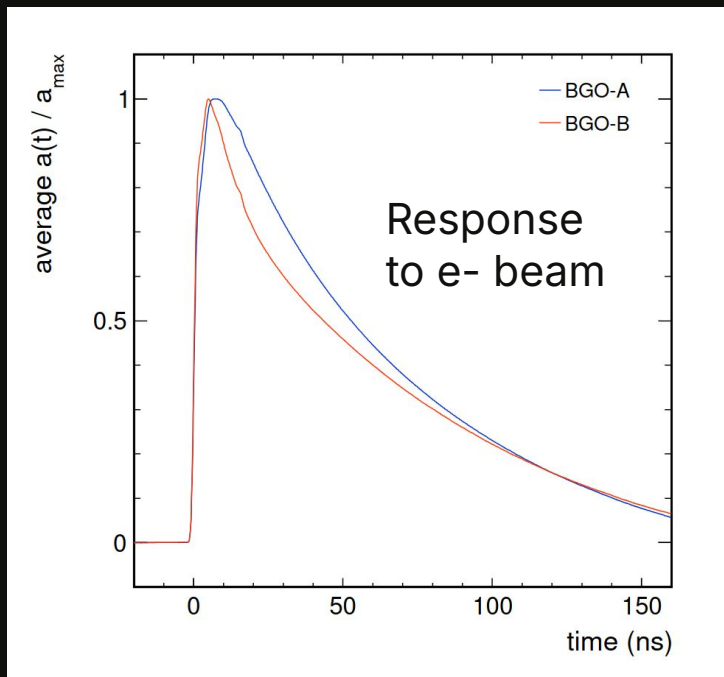


Derivative enhances S/ $\check{C}$  component differences. Interesting possibilities to analog processing.

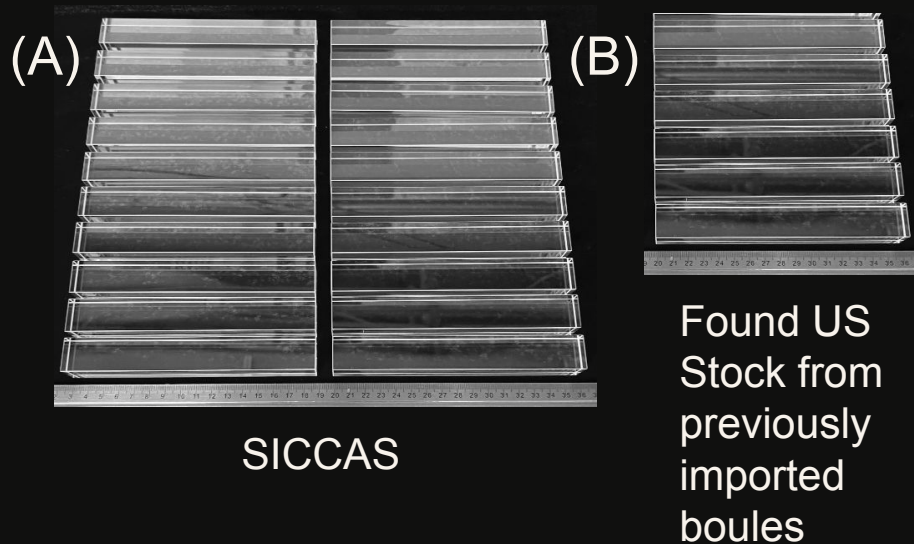
## Estimation of S and $\check{C}$ yield

- Model S,  $\check{C}$  shapes using measured data, SPE response function, small corrections for photon propagation times
- Normalize to 1pe amplitude at +25C and 36 V bias giving  $\sim 0.35$  mV/PE

# A first look at data



Average waveforms for two sources of BGO crystals. Sample (B) appears to have a stronger fast scintillation component



# Estimation of S and Č yield

- Model S, Č shapes using measured data, SPE response function, small corrections for photon propagation times
- Normalize to 1pe amplitude at +25C and 36 V bias giving  $\sim 0.35$  mV/PE

Most probable  $A_{\max} = 900$  adc or 225 mV

1pe amplitude at +25C and 36 V is

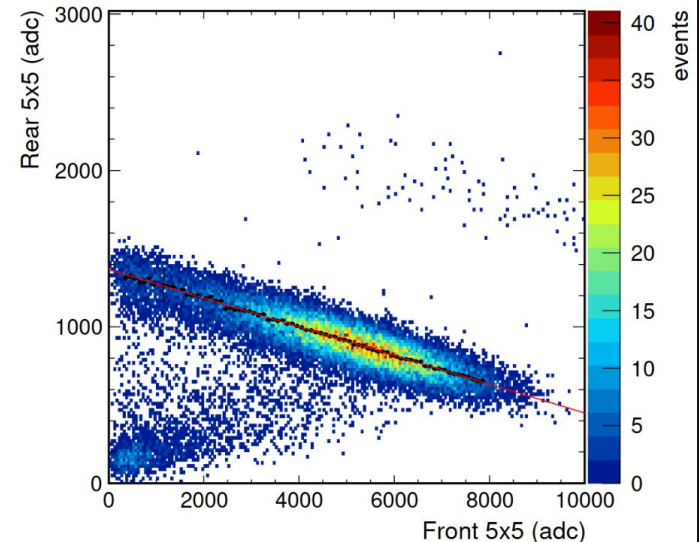
$$A_{1pe} = 0.2073 \cdot (36 - 34.31) = 0.35 \text{ mV}$$

$$A_{\max} / A_{1pe} = 225 / 0.35 = 643$$

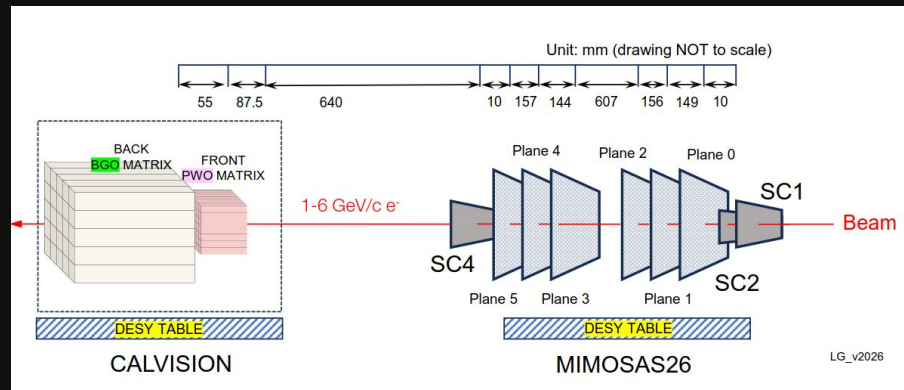
$$N_c = 0.58 \cdot 643 = 373 \text{ pe}$$

$$N_s = 44.0 \cdot 643 = 28300 \text{ pe}$$

$$N_s \text{ in } 20\text{ns} = 4.31 \cdot 643 = 2770 \text{ pe}$$



# Good progress on telescope RECO

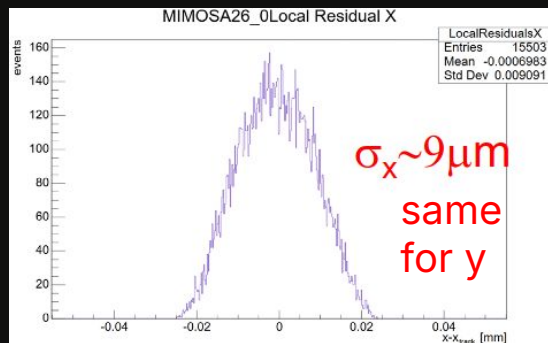
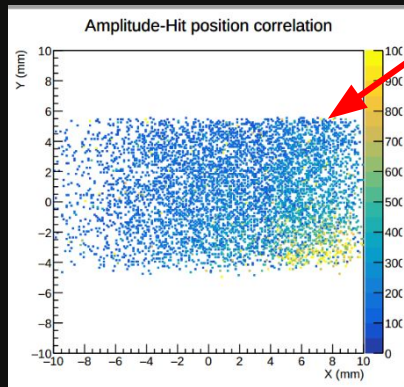
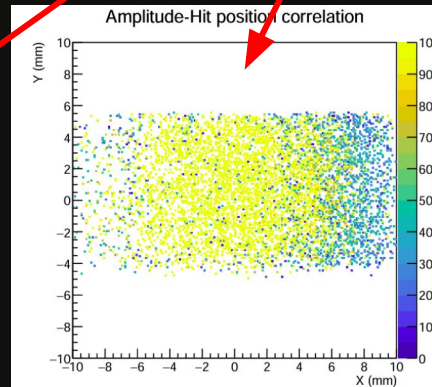
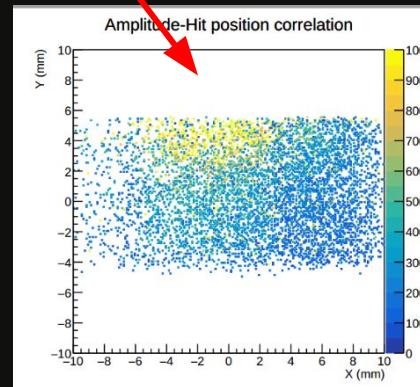


### Front Matrix Crystal Placement

Crystal positions as viewed from the FRONT

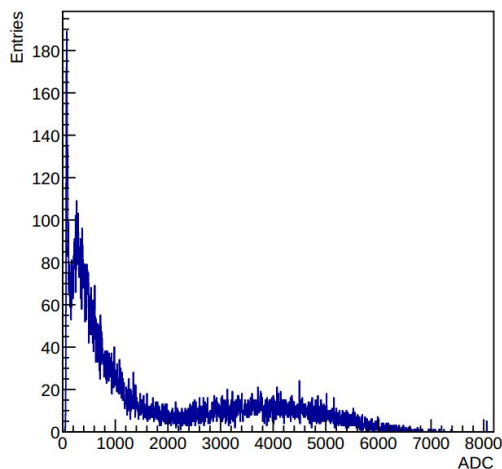
|      | G           | F           | E           | D           | C           | B           | A           | json |
|------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|------|
| 7    | C2/A13      | C14/A15     | C8/A17      | C25/A19     | C16/A21     | 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(42)  | C48/B2(34)  | C47/B4(36)  | C50/B6(38)  | 3    |
| 3    | C49/B9(41)  | C4/B11(43)  | C51/B13(45) | C57/B15(47) | C68/B17(49) | C12/B19(51) | C27/B21(53) | 4    |
| 2    | C18/B8(40)  | C33/B10(42) | C36/B12(44) | C17/B14(46) | C45/B16(48) | C11/B18(50) | C5/B20(52)  | 5    |
| 1    | C46/B22(54) | C38/B25(57) | C26/B24(56) | C32/B27(59) | C44/B26(58) | 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

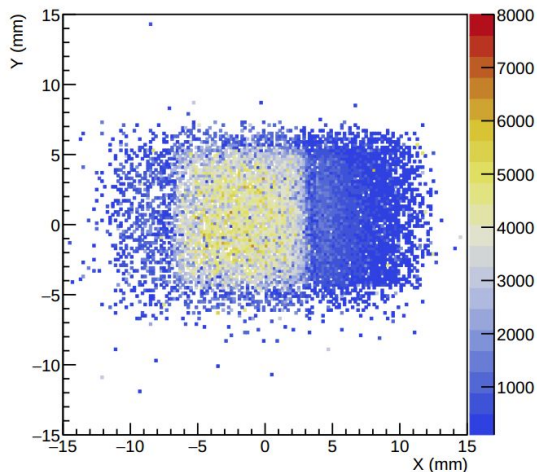


# Good progress on telescope RECO

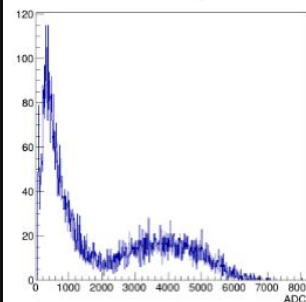
Front HG Histogram



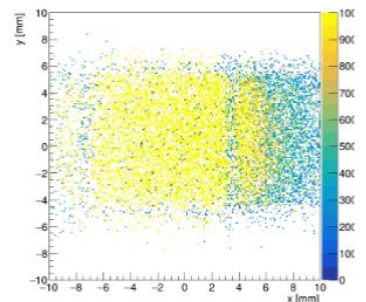
Amplitude-Hit position correlation



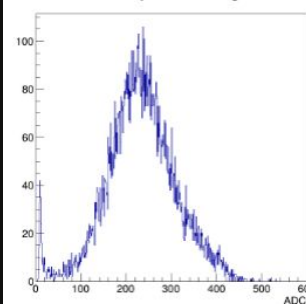
FERS Histogram



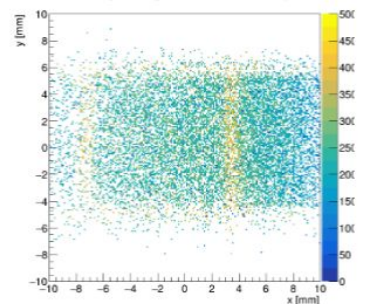
Charge Weighted Front Heat Map



Rear Amplitude Histogram

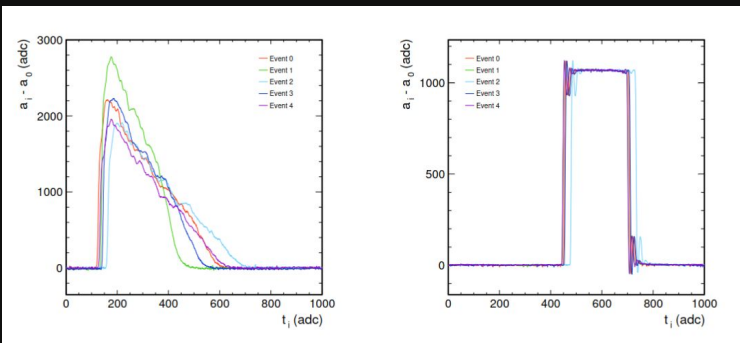


Charge Weighted Rear Heat Map

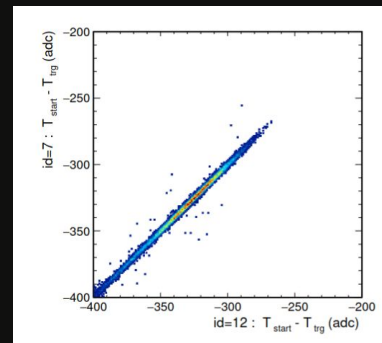
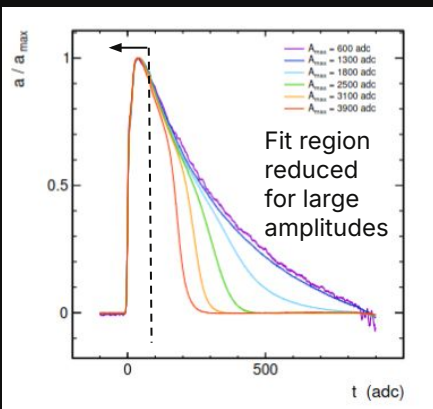
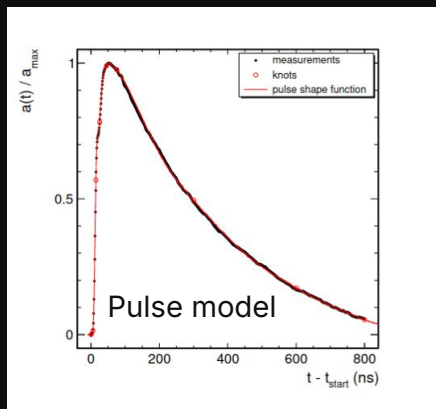
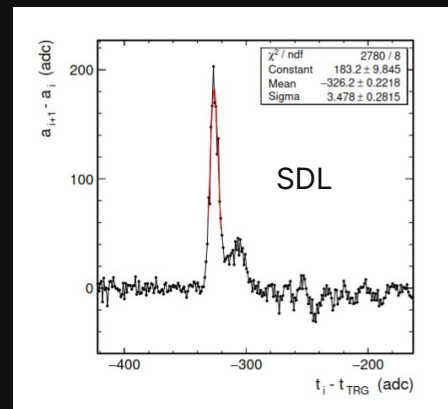
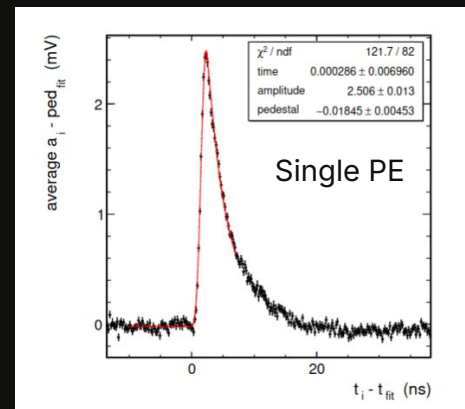


# Timing and pulse shapes

A. Ledovsky (UVA)



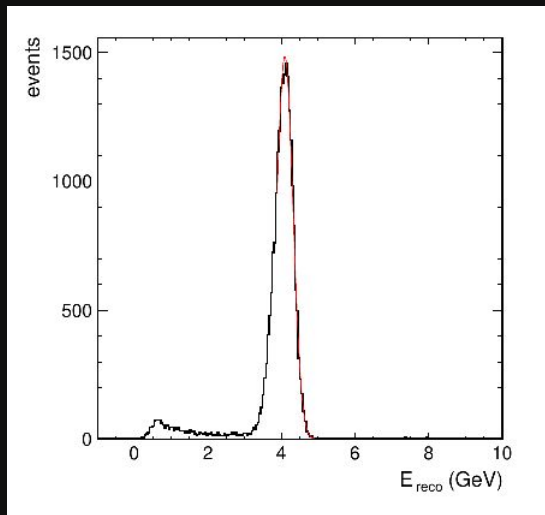
After timing corrections, all SiPM WFs will have the same phase. Multiple WFs can be combined to enhance the signal.



Observe significant tail distortion for larger amplitudes, but rising edge and the peak of the pulse is not distorted  
Mitigate pulse distortion for larger amplitude: introduce amplitude dependent fit interval (exclude distorted pulse tail)  
Also have data w/ lower Vbias to lower gain/remove distortion

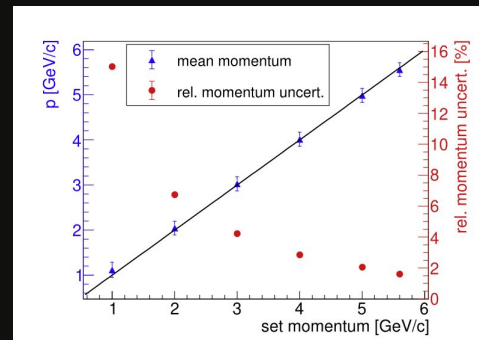
# Calibration of front/rear channels

Early response distribution  
(no event selection/cleaning)



**The calorimeter is working well out of the box!**  
Work is in progress. 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.



A. Ledovskoy (UVa)

NIM A 922 (2019) 265–286

# CalVision test beam studies

Our test beam programs seek to definitely demonstrate performance a hybrid DR calorimeter. The CalVision crystal EM (fiber HCAL) efforts are pursuing **complementary** approaches while collaborating w/ the EU MaxiCC ECAL (EU/Korean fiber HCAL) projects.

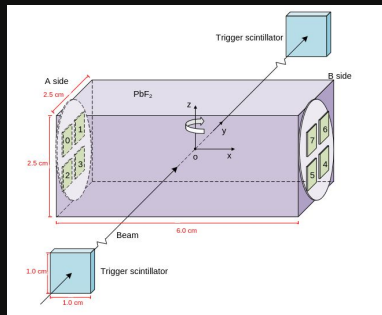
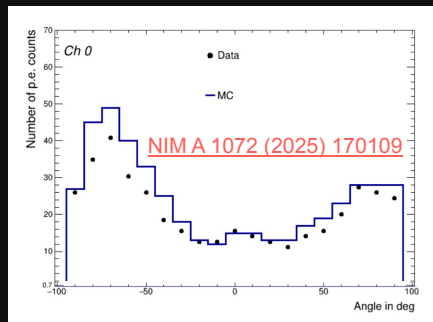
Major goals for the overall research program include:

- Validation of modeling for our optical detector elements (good results)
- Demonstration of S/Č component analysis and collection of sufficient photon statistics in crystal calorimeter elements (good results)
- Demonstration of the EM performance of a segmented crystal ECAL with SiPM readout (in progress)
- Demonstration of the hadron resolution of a full hybrid DR prototype (in progress)

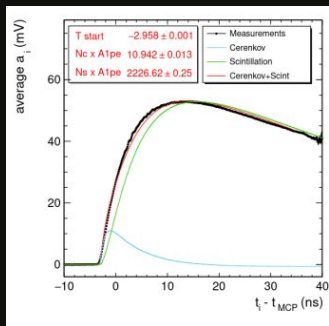
# CalVision test beam studies

FNAL test beams (2023)

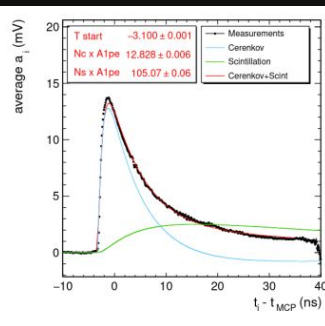
Study modeling of light collection in of  $\text{PbF}_2$  (pure Cherenkov radiator) 120 GeV protons



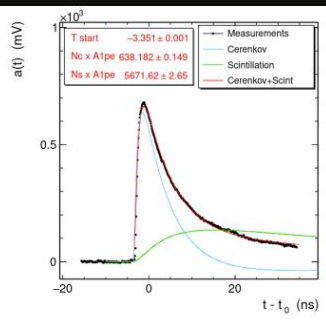
SiPM signals



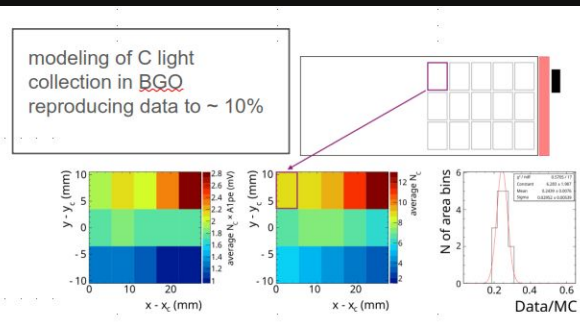
mean MiP signal



after optical filter

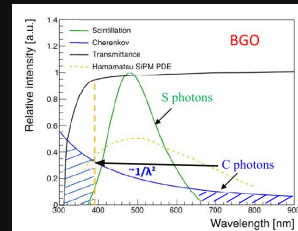


=> single shower event , modeling light propagation



**Initial tests of S/C light collection and modeling in BGO** <https://doi.org/10.1051/epjconf/202532000021>

- Use wavelength filters to enhance S/C separation w/in a readout channel
- Perform component fit analysis



Virginia, Michigan, Maryland, FNAL

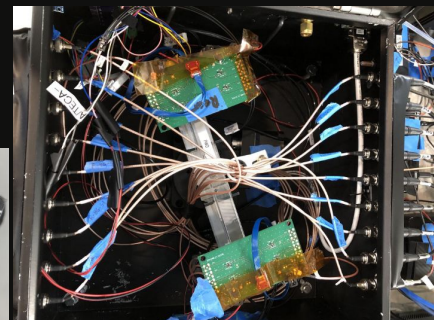
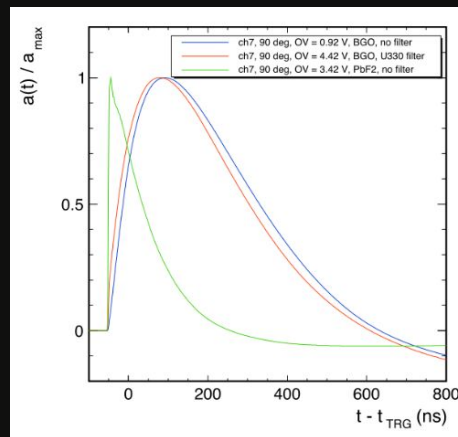
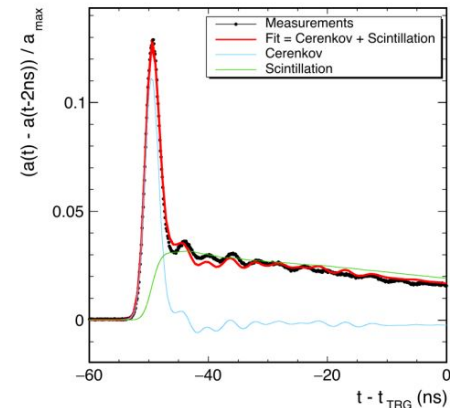
# CalVision test beam studies

Test beam at DESY (April 2024)  $\sim 2\text{-}5\text{ GeV e-}$

- Coordinated by CalVision US groups with participation from Milano-Bicocca
- Test of  $\text{PbF}_2$  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

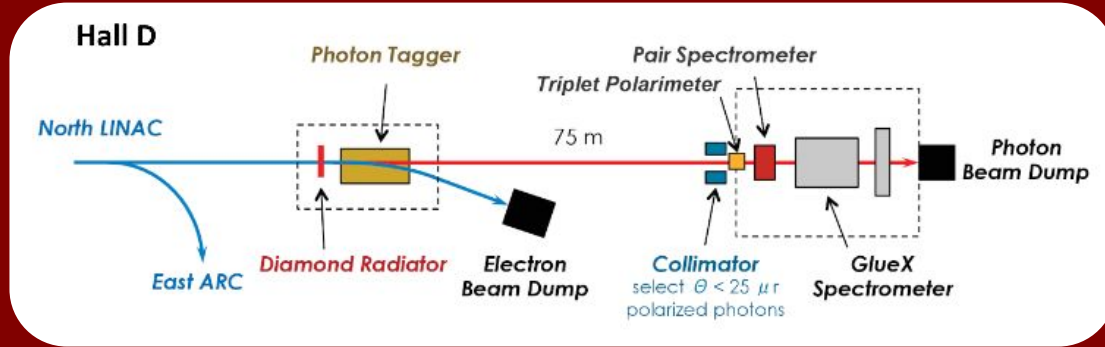
BGO studies w/ SPE calibration show  $\sim 160$  PE/GEV in  $\check{C}$  signal component w/ 4 SiPM readout. Further optimization possible w/ improved optical coupling

**=> first demonstration of sufficient  $\check{C}$  signal for hybrid DR.**



Pure Cherenkov signal from  $\text{PbF}_2$  and BGO w/, w/o optical filter  
(left) original waveforms and component fits  
(right) component fits after digital SDL filter

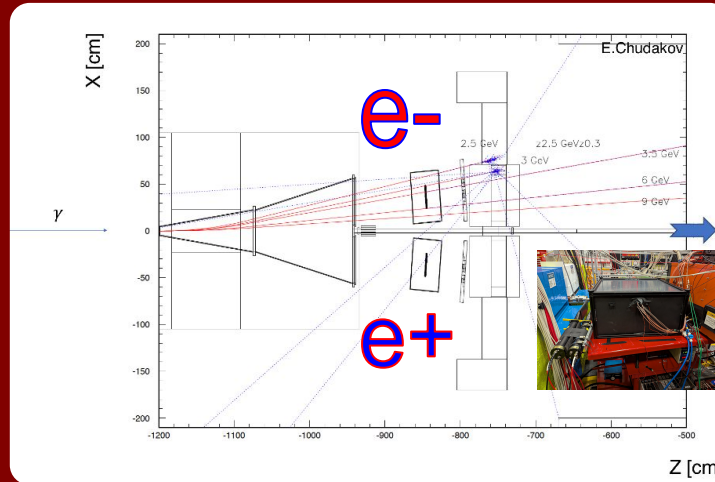
# Recent test beam at JLab's Hall D



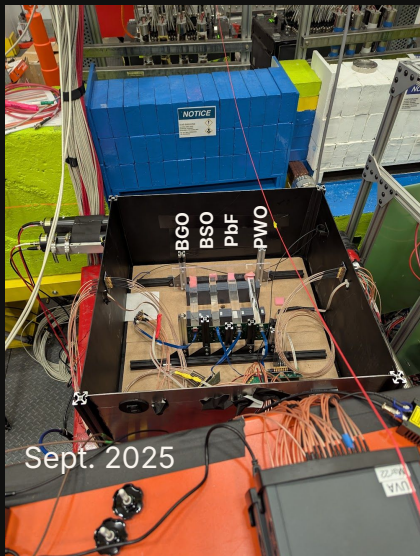
Parasitic test facility in parallel w/ GlueX exp.

Tertiary  $e^+/e^-$  beams  
 $\sim 3\text{--}10\text{ GeV}/c$  following spectrometer

- Rates  $\sim \text{O}(\text{kHz})$
- Electrons in  $3.5\text{--}6\text{ GeV}/c$  range are measured to  $\sim 0.5\text{--}1\%$  resolution.

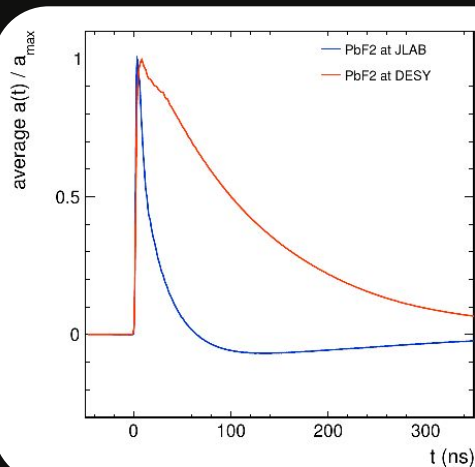
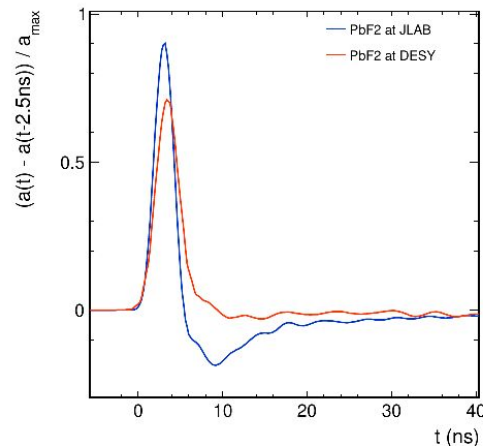


# Recent test beam at JLab's Hall D



## Main Goals

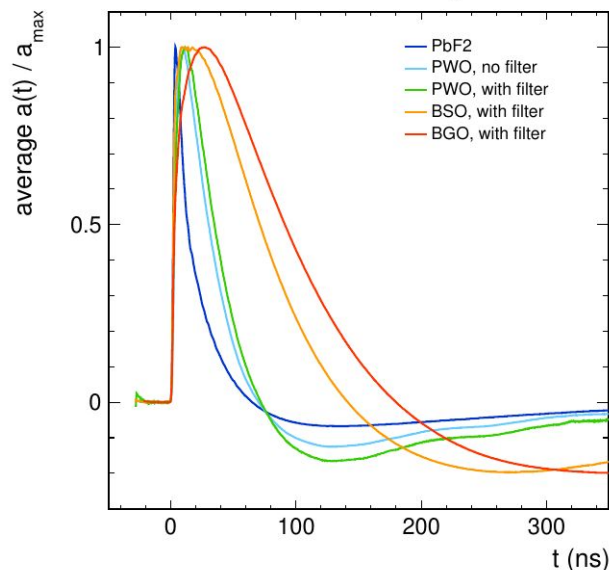
- Update DESY measurements using faster amplifiers
- High sample rates, low latency trigger (no tracking used)
  - Roughly  $\sim 7\text{-}10$  GeV  $e^+$  based on crystal locations
  - Trigger on scint counters + any crystal signal above ZSP threshold
  - Low/high gain readout paths
- Repeat S/C signal studies w/ more sensitivity to initial edge
- Apply method on PWO where S/C signals are more similar



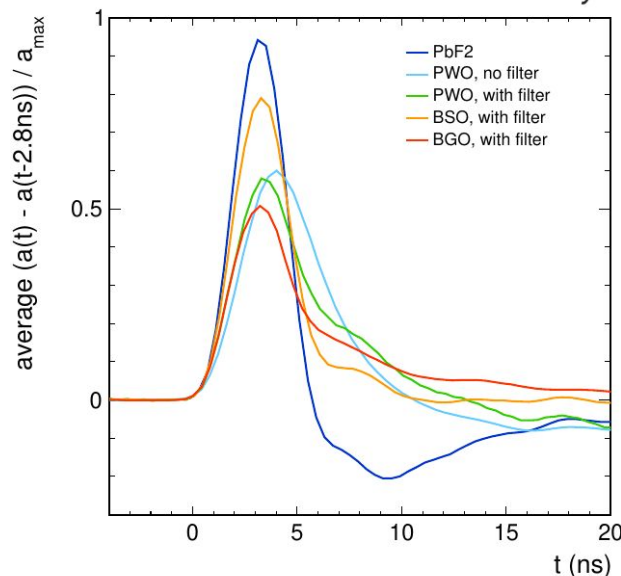
# Recent test beam at JLab's Hall D

Average Pulse Shapes at Low Gain (Measured at 2.5 GS/s)

*Original DRS*



*SDL with 2.8 ns delay*

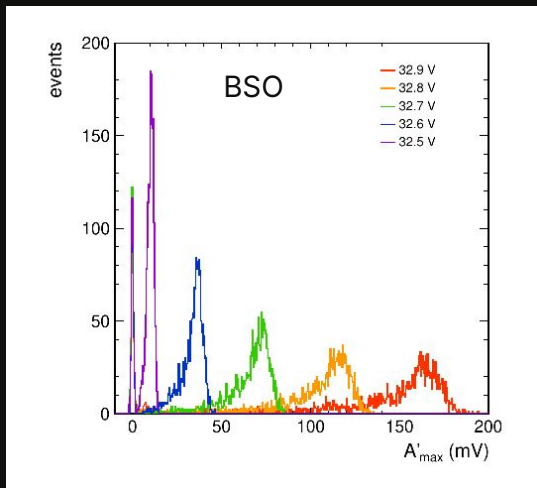
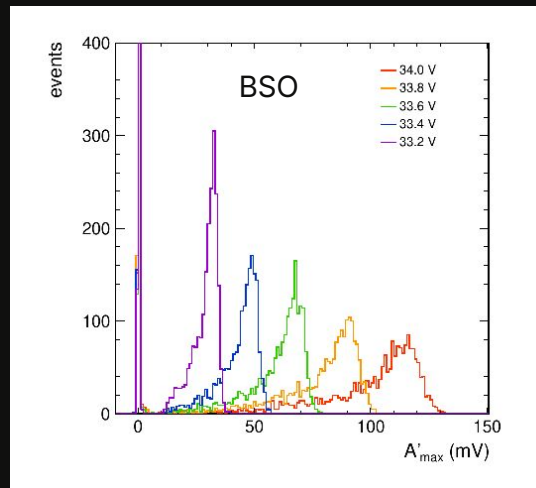
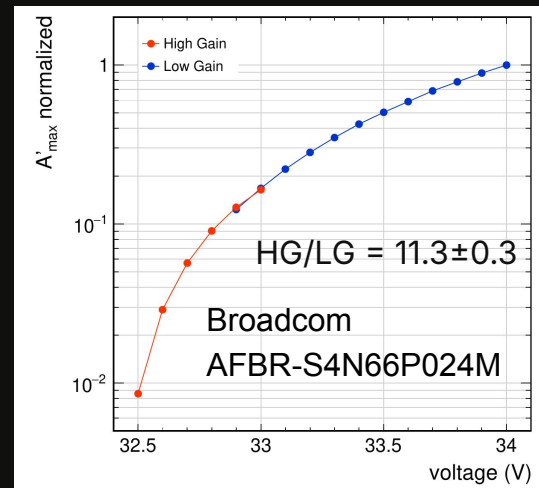


→ visible contribution from scintillation in all cases

Left: Pure Cerenkov (PbF2) pulse shape is very different from pulse shapes in other crystals

Right: Single Delay Line pulses show visible Cerenkov/scint contributions in [0,5] ns interval for all crystals

# Recent test beam at JLab's Hall D



Bias scans over large range starting from  $V_{br}$   
BSO with Hoya U330 filter; normalized to  $OV=1.5V$

Fit result for MPV shown

This is a product of  $Gain \times PDE$  for Broadcom SiPMs.  
Broadcom does not provide data in this range of OverV  
100x range observed.

Work in progress on new data:

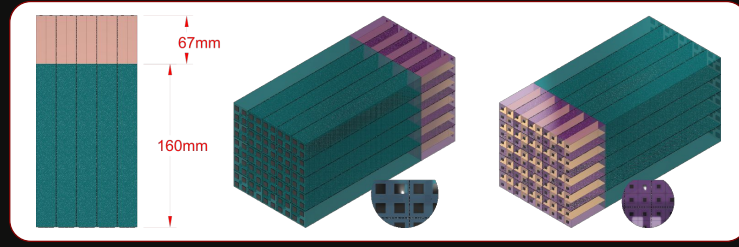
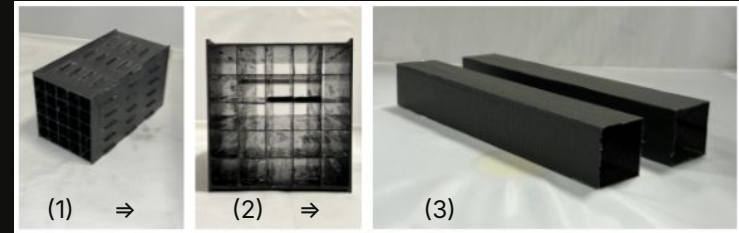
- 1-pe calibration: amplitude vs bias
- Estimation of pure scintillation pulse shapes
- Estimation of NC and NS from individual pulses using first two items
- Compare results wrt shaping times

# CalVision segmented crystal array

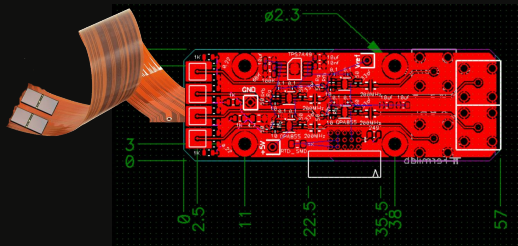
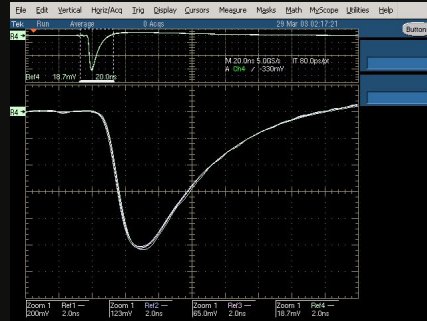
$5X_0 \times 5X_0$  matrix

## Construction of BGO matrix at EM shower containment scale

- Rear matrix
  - $5 \times 5$  geometry (22mm $\times$ 22mm)
  - 4 Broadcom AFBR-S4N66 SiPMs/crystal - 36mm $^2$ , 40u
  - Optical filters to enhance  $S/\hat{C}$  identification
  - Fast shaping amplifiers
  - Readout using 1-5 GS/s digitizers (DRS4)
- Front matrix geometry
  - Higher granularity  $10 \times 10$  matrix
  - Hamamatsu MPPC S14160 - 9mm $^2$ , 10u
  - Readout using FERS CITIROC



Carbon fiber alveolar prototypes. Already at 100u thickness, comparable to CMS



# CalVision segmented crystal array

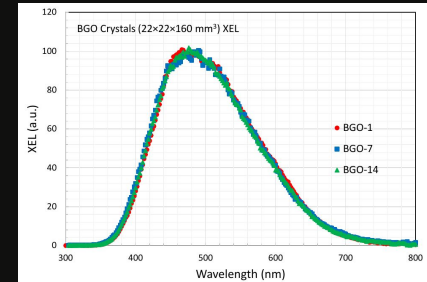
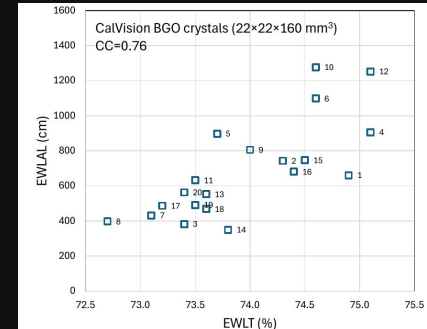
## Status

- Most large crystals in hand & tested - quality good
- Export issues delaying several large crystals and front matrix, hope for resolution soon.
- Amplifiers and flex cables are designed, final testing soon, then start of production for matrix & digitizer connection
- Start design of passive interface for 100 front SiPMs to FERS CITIROC

## To do

- Final mech. design: alveolar, support structure, and dark box
- Scale readout from original 16 channels to 200 channels and implement EUDAQ for compatibility at beam tests with international collaborators

Aim for completion of EM matrix for first performance studies by late Spring 2026



Emission weighted light attenuation length vs longitudinal transmittance

# Many related R&D activities related to DR calorimetry

Test beams, challenging development, blue sky R&D

- Novel scintillators, particularly development of new heavy glasses
  - Can a homogeneous HCLA (HHCAL) be feasible?
- Study of optical materials and modeling, including novel optical matching techniques and fiber technology
- Detector and physics simulations (including DR+PF algorithms)
- Advanced parameterizations and GPU approaches for optical ray tracing
- Electronics for on-detector signal processing
- AI/ML for signal analysis
- Optimization of module design for full scale detectors
- ....

# Related talks on dual-readout calorimetry

- Simulation of the CalVision crystal DR calorimeter testbeam array [Jon Wilson]
- Cosmic Ray Muon Detection and Commissioning with a Highly Granular DR Fiber Calorimeter (HG-DREAM) [Yongbin Feng]
- Performance of High Granularity DR Fiber Calorimeter (HG-DREAM) with High Energy Particle Beams [Weijie Jin]
- Developing Digital Silicon Photomultiplier (dSiPM) Specifications for a High-Granularity Calorimeter with Simulations [Liangyu Wu]



## About CalVision

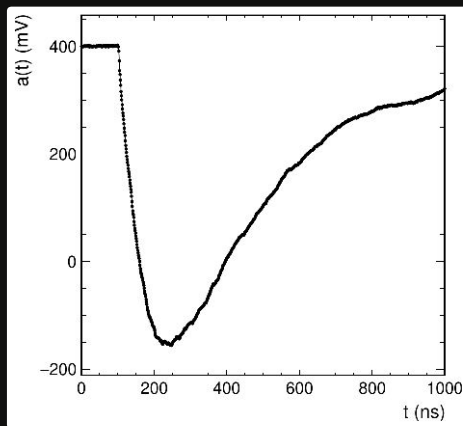
CalVision pursues dual-readout calorimetry efforts on multiple fronts and in collaboration with other projects, particularly IDEA/MaxiCC + international fiber calor groups

<https://detectors.fnal.gov/projects/calvision/>

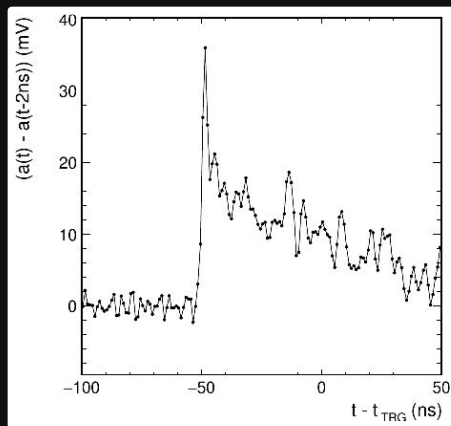
The work presented here received support through DOE  
DE-SC0022045,  
DE-SC0025956

# Determination of NS and NC

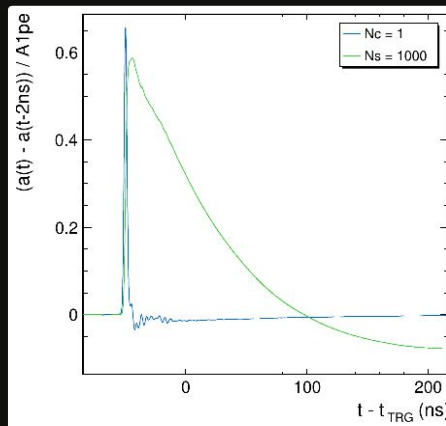
Example analysis of DSB heavy glass sample from DESY TB run



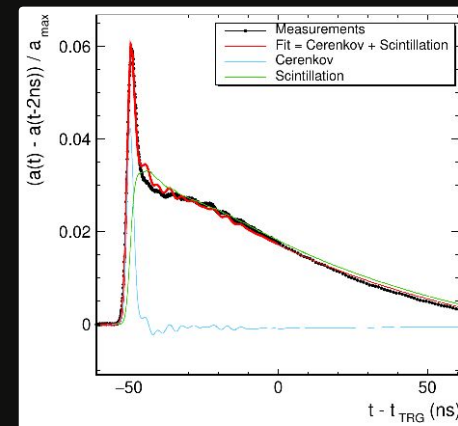
Measured signal



⇒ SDL filter

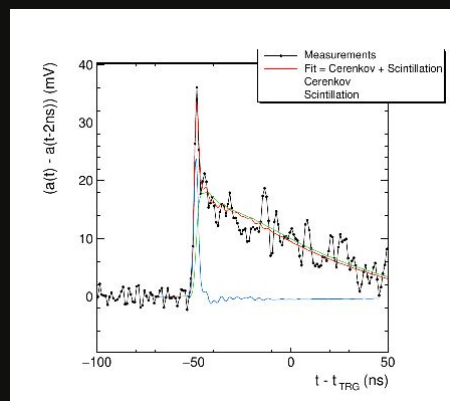


⇒ C/S components



⇒ validation on average waveform

Component fits to individual waveforms



C component from PbF sample  
S component from C ⊗ scint decay time  
Abs normalization from SPE measurements at gain setting

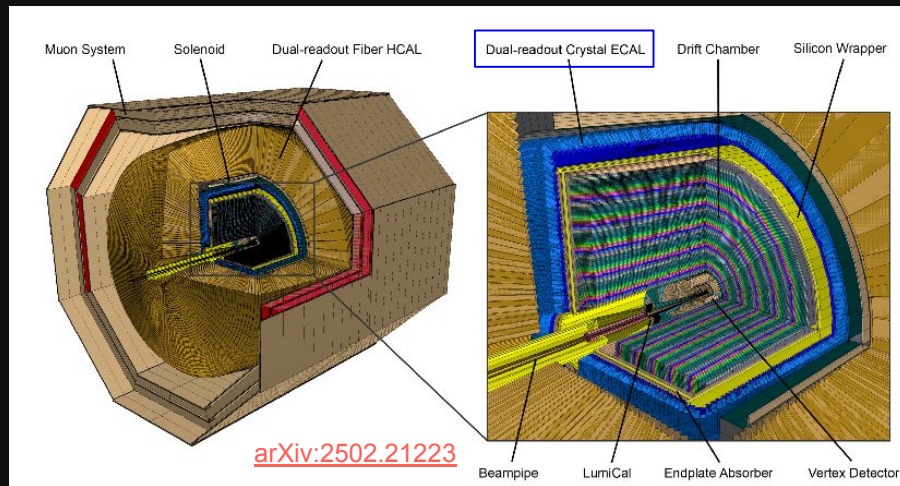
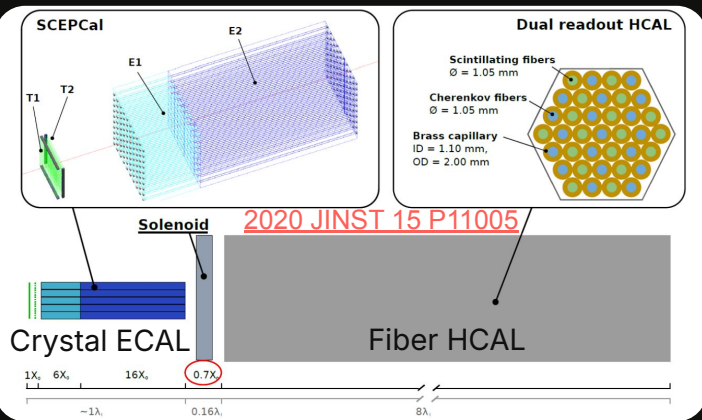
Here: NC=130  
NS=11070

Misc stuff, to be deleted

# Hybrid DR Calorimetry

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

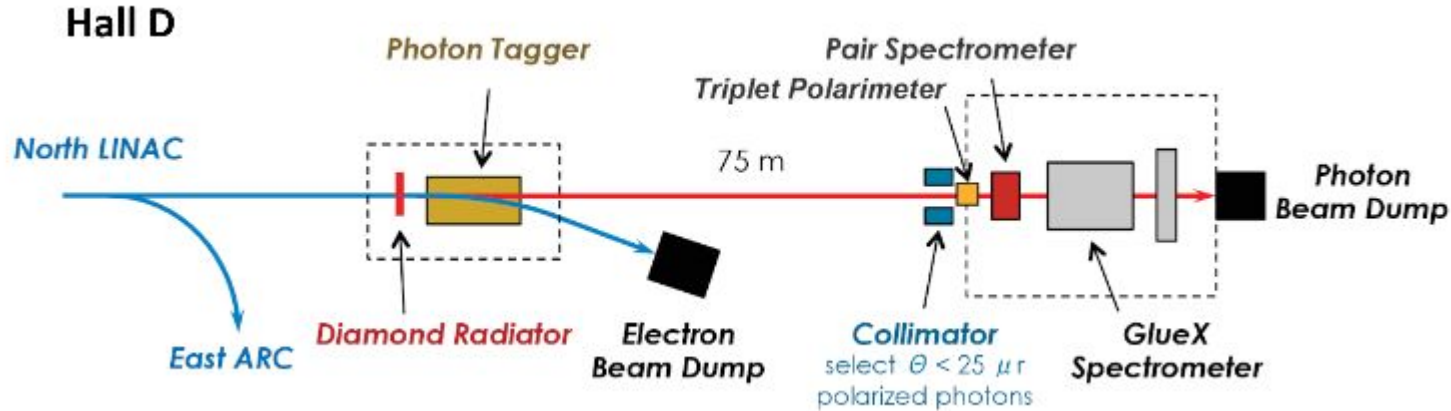
Homogeneous DR crystal EM + DR fiber HCAL



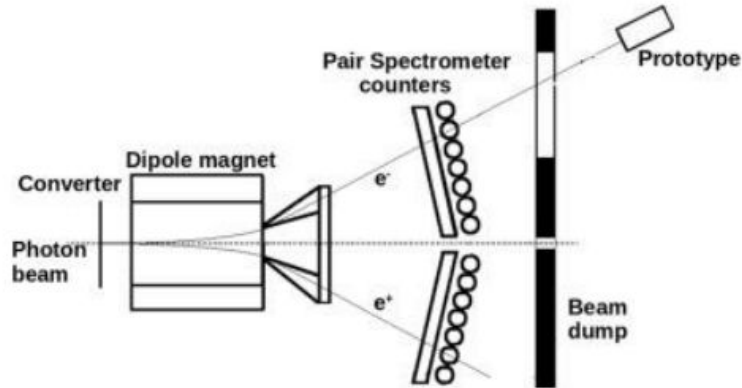
## General Challenges

- Separation of S/Č components in homogeneous crystals
- Photon statistics in NČ.  $\sim 50$  PE/GeV needed for corr. factor

# Overview of Hall D facility



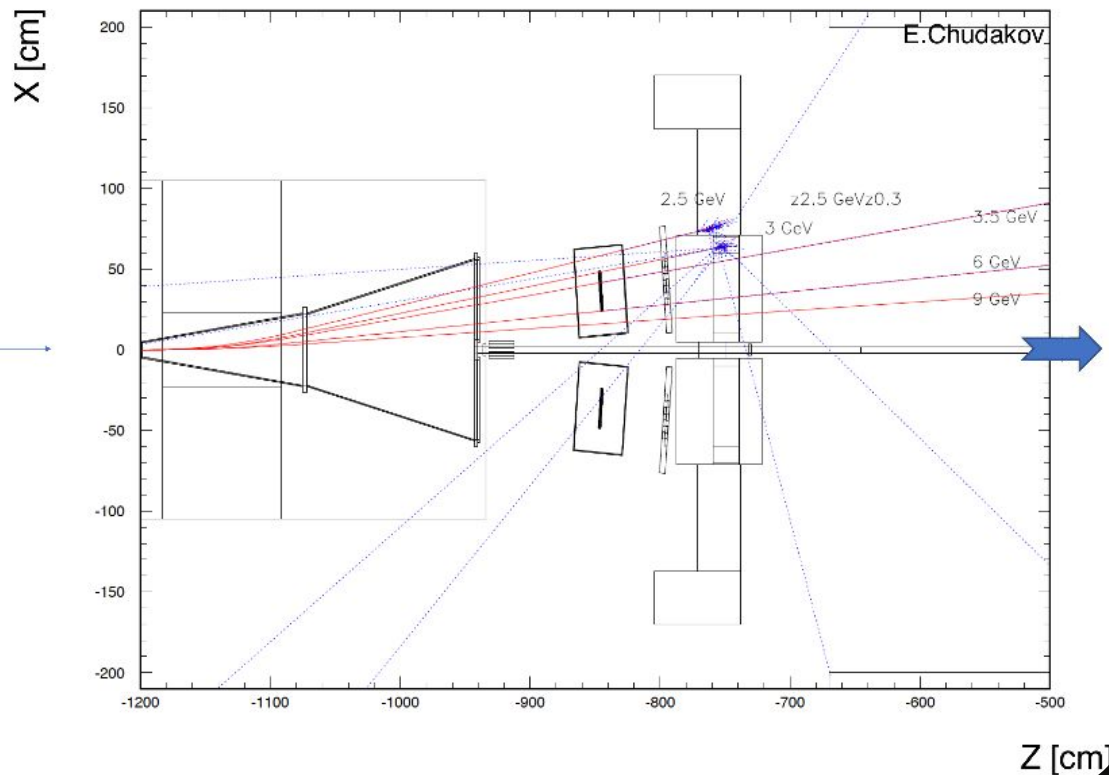
Production of  
'parasitic' tertiary  
 $e^+/e^-$  beams from  
 $\gamma$  beam used by  
GlueX experiment



**Left arm (tracking, timing, other detectors)**

**Right arm (calorimeters)**

# Overview of Hall D facility



Electrons in 3.5-6 GeV/c range are measured to  $\sim 0.5$ -1% resolution.

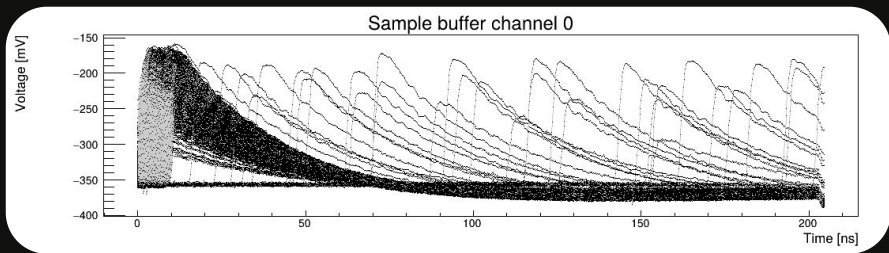
Flat beam: in-plane (y spread  $\sim 5$ mm) with  $\sim 10$ kHz rate

To GlueX

Low latency trigger, no tracking in this run.

Roughly  $\sim 7$ -10 GeV based on crystal loactions

CalVision's main goal of this run is to further study S/C light separation in crystal ECAL elements with faster electronics and sampling vs previous test beams.



Overlay of events in PbF crystal. (no tracking used). Late pulses correlate with 4ns bunch spacing of primary beam.

The parasitic test facility seems to be mainly utilized in-house and by close collaborators on JLAB program and EIC. The facility is 'bare bones', but the beam parameters are quite interesting in light of many discussion here, eg see pulse width...

There is enthusiastic about exploring enhancements for testing. I'll try to summarize some of this meeting when I go back to to report on our crystal measurements.

TABLE III. Principal parameters for CEBAF in the 12 GeV era [59].

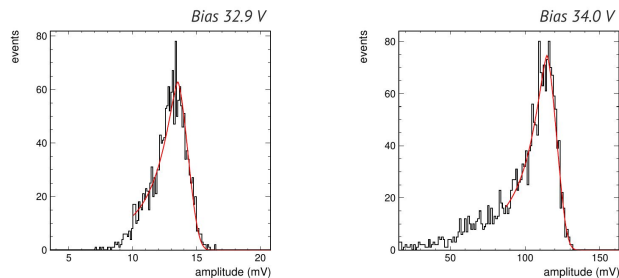
|                                 |                    |
|---------------------------------|--------------------|
| Energy (hall D)                 | 12 GeV             |
| Energy (halls A, B, and C)      | 11 GeV             |
| Average current (halls A and C) | 1–90 $\mu$ A       |
| Average current (hall B)        | 1–100 nA           |
| Average current (hall D)        | 0.1–5 $\mu$ A      |
| Bunch charge                    | <0.5 pC            |
| Repetition rate                 | 249.5 MHz/hall     |
| Beam polarization               | 90%                |
| Beam size (rms transverse)      | $\sim 150 \mu$ m   |
| Bunch length (rms)              | 300 fs, 90 $\mu$ m |
| Energy spread                   | $2 \times 10^{-4}$ |
| Beam power                      | <1 MW              |
| Beam loss                       | <1 $\mu$ A         |
| Number of passes                | 5.5                |
| Number of accelerating cavities | 418                |
| Fundamental mode frequency      | 1497 MHz           |
| Amplitude control               | $1 \times 10^{-4}$ |
| Phase control                   | 0.1° rms           |
| Cavity operating temperature    | 2.1 K              |
| Liquifier 2 K cooling power     | 10 kW              |
| Liquifier operating power       | 10 MW              |

## Main Goal of jlab TB

- Use higher BW amps
- Repeat DESY measurements
- Measure improvements in component extraction
- Attempt method on PWO where S/C signals are much more similar

### Distribution of pulse amplitudes

Examples of measured distribution at low gain in BSO with filter (black)  
 Red line: fit function = model for energy deposition, convoluted with gaussian noise  
 Model = same shape for all SiPMs at all bias voltages  
 Gaussian noise is fixed to measured value  
 Two fit parameters: MPV and magnitude  
 Distributions below 10 mV are distorted by Zero Suppression readout



- First steps in the analysis to probe possibilities at JLAB TB
- Next steps are:
  - 1-pe calibration: amplitude vs bias
  - Estimation of Pure Scintillation pulse shape
  - Estimation of NC and NS from individual pulses using first two items

Describe process of using g4 to get mV to GeV, etc....

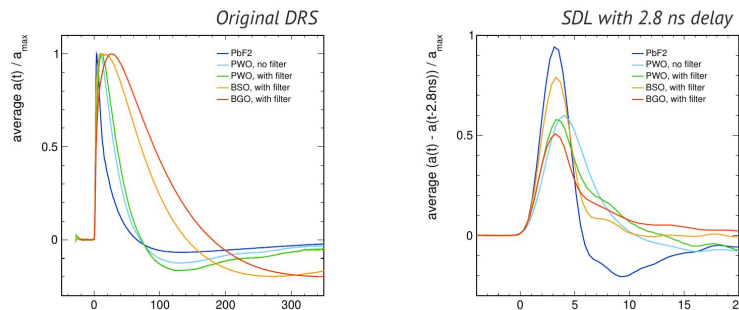
## Average Pulse Shapes at Low Gain

Measured at 2.5 GS/s

Left: Pure Cerenkov (PbF<sub>2</sub>) pulse shape is very different from pulse shapes in other crystals

→ visible contribution from Scintillation

Right: Single Delay Line pulses show visible Cerenkov contribution in [0,5] ns interval for all crystals



## Amplitude MPV vs Bias

Fit result for MPV

SiPM 1

BSO with filter

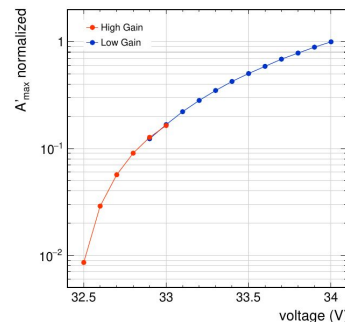
Low Gain + High Gain

Normalized to OV=1.5V

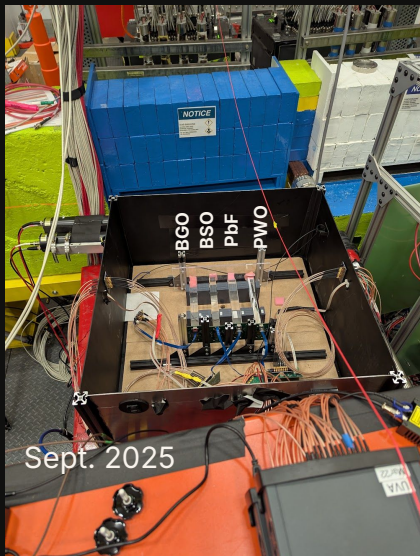
HG/LG =  $11.3 \pm 0.3$

This is a product of  $Gain \times PDE$  for Broadcom SiPMs.

Broadcom does not provide data in this range of OV

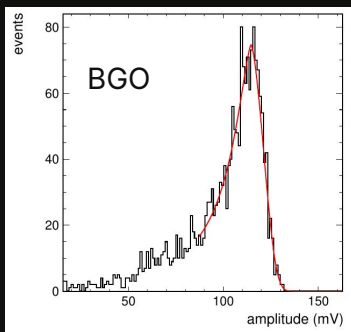


# Recent test beam at JLab's Hall D

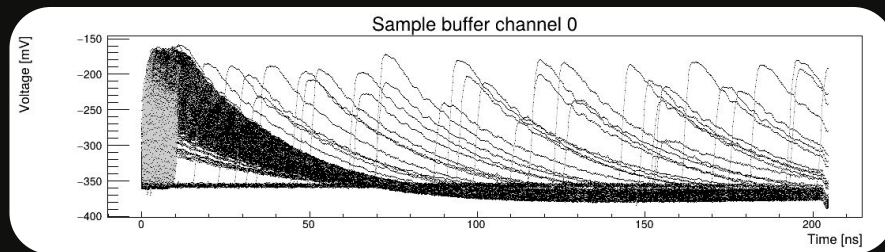


## Main Goals

- Update DESY measurements using higher BW amps
- High sample rates, low latency trigger (no tracking in this run)
  - Roughly ~7-10 GeV e+ based on crystal locations
  - Trigger on scint counters + any crystal signal above ZSP threshold
  - Low/high gain readout paths
- Repeat BGO S/ $\hat{C}$  component extraction w/ more sensitivity to initial edge
- Apply method on PWO where S/ $\hat{C}$  signals are much more similar



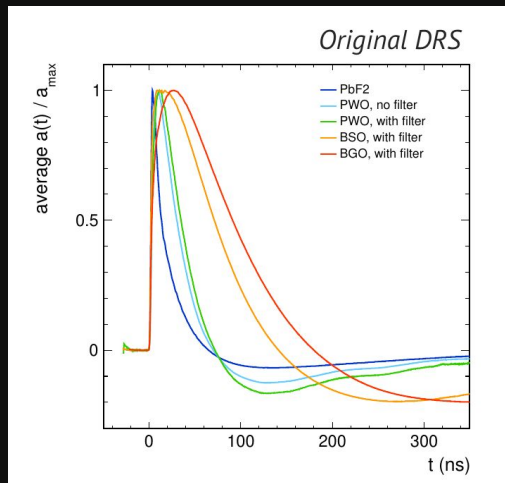
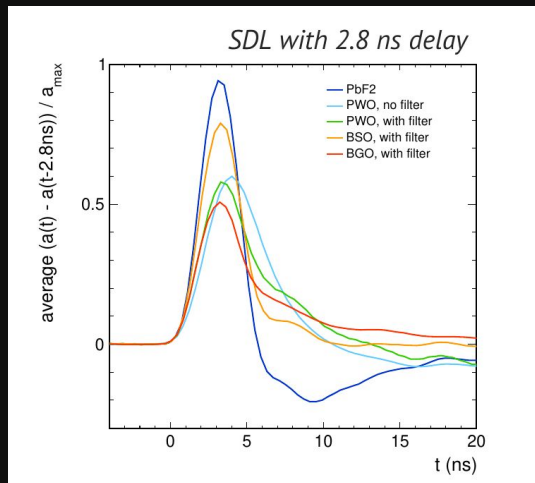
Example of single crystal pulse amplitude distribution



Overlay of events in PbF crystal. (no tracking used).  
Late pulses correlate with 4ns bunch spacing of primary beam.

To do: make a version corrected for trigger jitter / sample start time

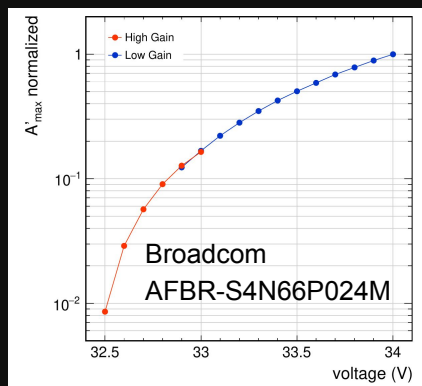
# Recent test beam at JLab's Hall D



Average Pulse Shapes at Low Gain  
Measured at 2.5 GS/s

Left: Pure Cerenkov (PbF2) pulse shape is very different from pulse shapes in other crystals  
→ visible contribution from Scintillation

Right: Single Delay Line pulses show visible Cerenkov contribution in [0,5] ns interval for all crystals



Fit result for MPV, scan to Vbr  
BSO with Hoya U330 filter

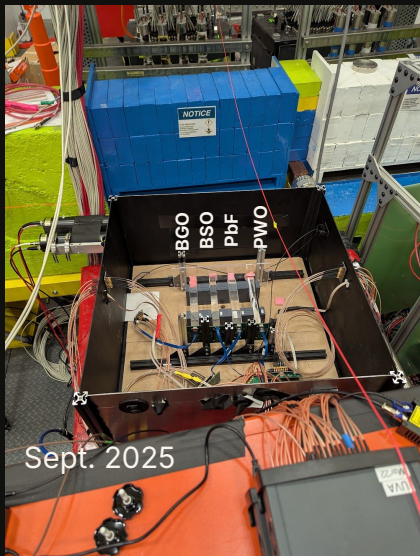
Normalized to OV=1.5V  
HG/LG =  $11.3 \pm 0.3$

This is a product of Gain $\times$ PDE for Broadcom SiPMs.  
Broadcom does not provide data in this range of OV

Work in progress on new data:

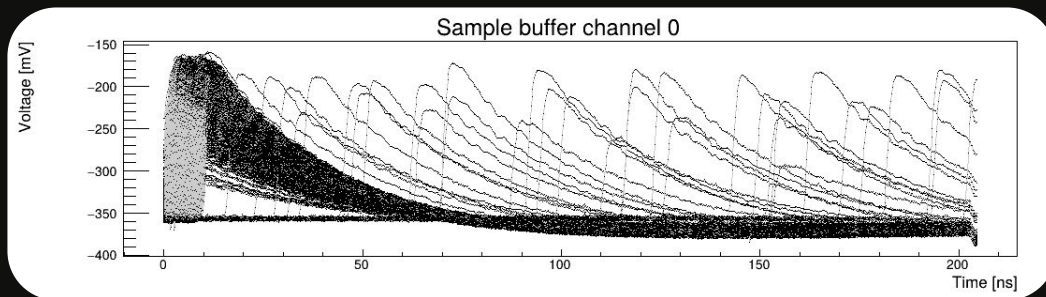
- 1-pe calibration: amplitude vs bias
- Estimation of pure scintillation pulse shape
- Estimation of NC and NS from individual pulses using first two items

# Recent test beam at JLab's Hall D



## Main Goals

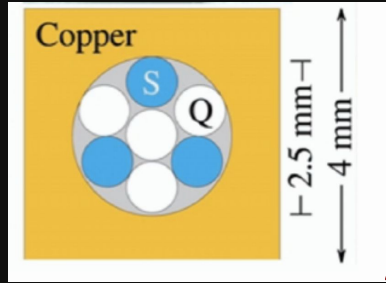
- Update DESY measurements using higher BW amps
- High sample rates, low latency trigger (no tracking in this run)
  - Roughly  $\sim 7\text{--}10$  GeV  $e^+$  based on crystal locations
  - Trigger on scint counters + any crystal signal above ZSP threshold
  - Low/high gain readout paths
- Repeat BGO S/ $\hat{C}$  signal extraction w/ more sensitivity to initial edge
- Apply method on PWO where S/ $\hat{C}$  signals are much more similar



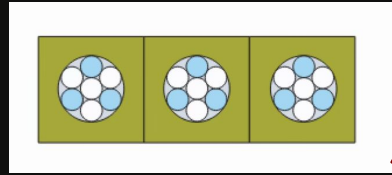
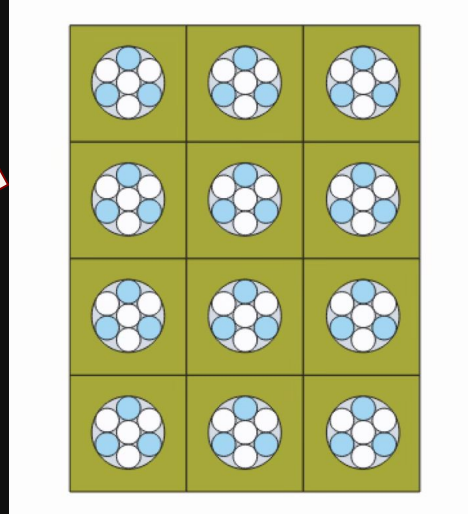
To do: make a version corrected for trigger jitter / sample start time

Overlay of events in PbF crystal. (no tracking used).  
Late pulses correlate with 4ns bunch spacing of primary beam.

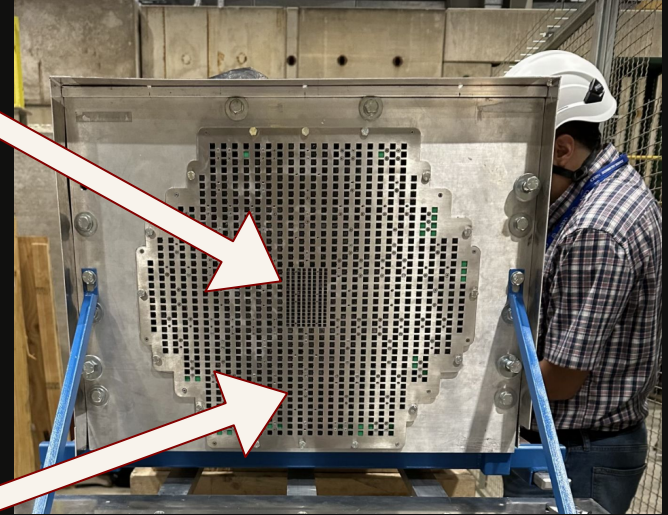
# Fiber HCAL Channels



Copper size 0.4cm x 0.4cm,  
filled in with 4 Cherenkov  
fibers and 3 scintillation  
fibers



Readout tower size is 1.2cm x  
0.4cm in the central region;  
1.2cm x  
1.6cm in the outer region.



Whole detector is 34cm x 32cm x  
200cm, with 448 towers (896  
channels)