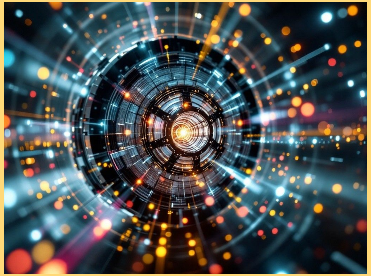
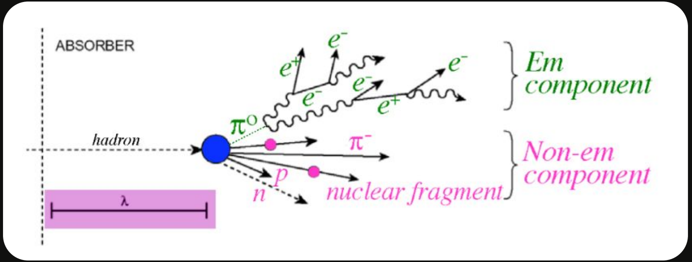
Results of Dual Readout single crystal test beams and matrix test plans for CalVision

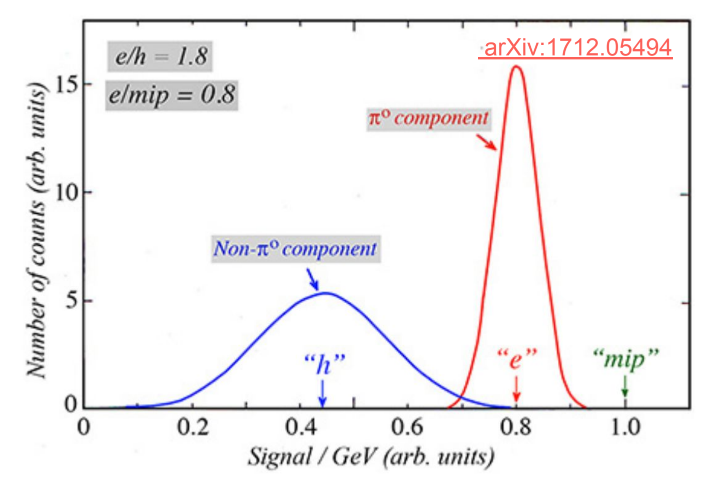
Bob Hirosky
University of Virginia

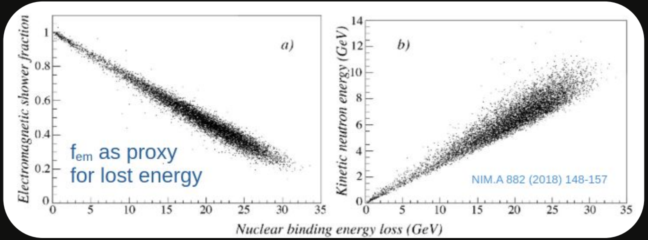


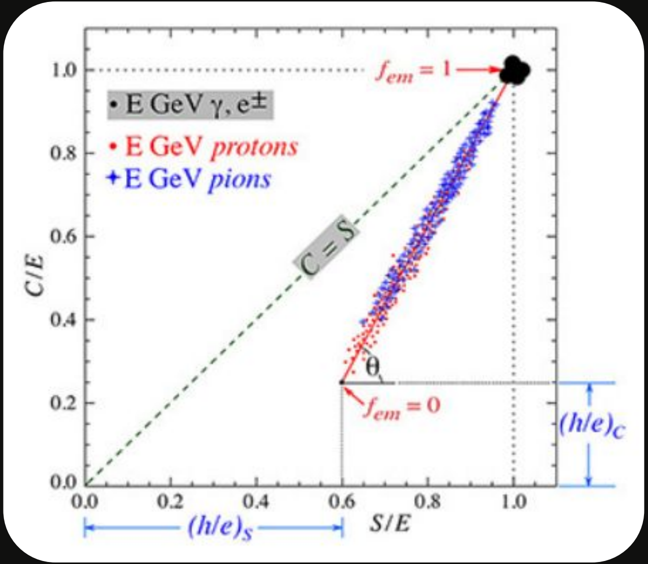
Dual-readout (DR) Calorimetry

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 ⊗ fluctuations in hadronic showers





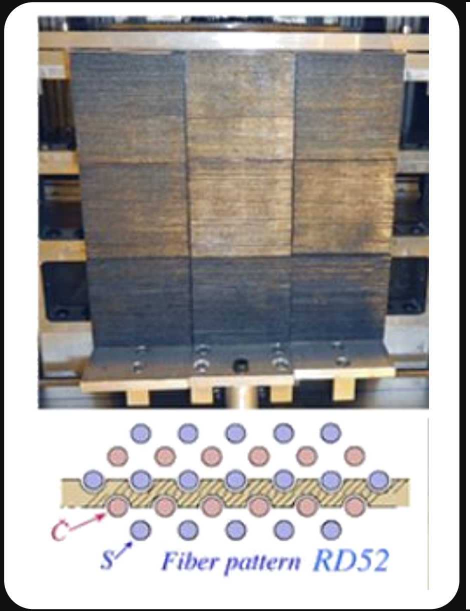


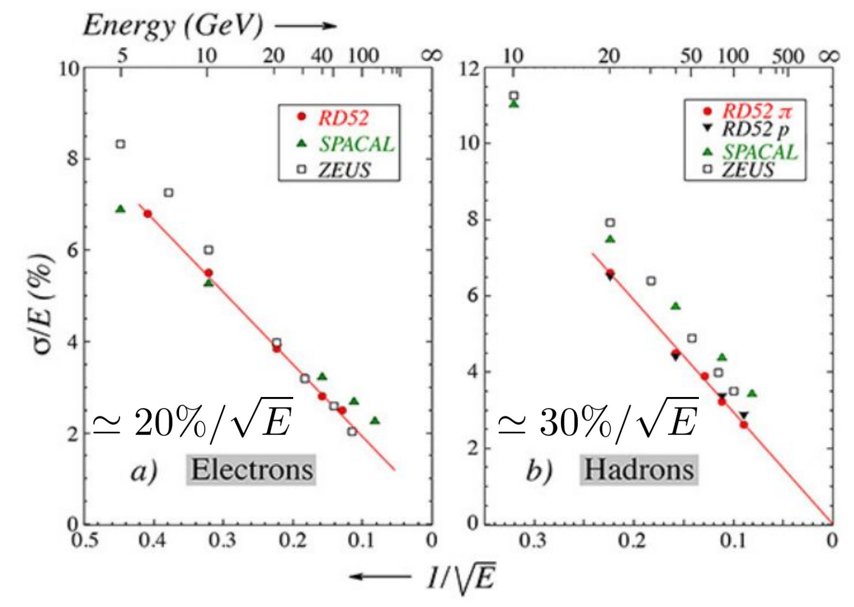


Dual-readout correction

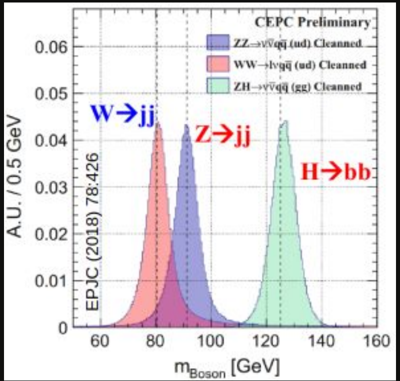
Dual-readout (DR) Calorimetry

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





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

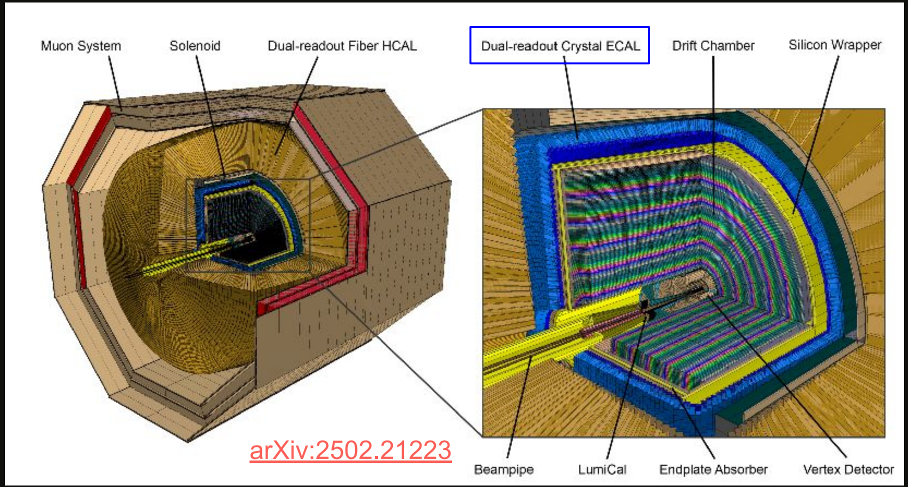


Impressive results! Already on par with needs for jet resolution at a Higgs factory. Good EM performance but significantly below that of crystal EM calorimeters which can achieve ~3%/√E.

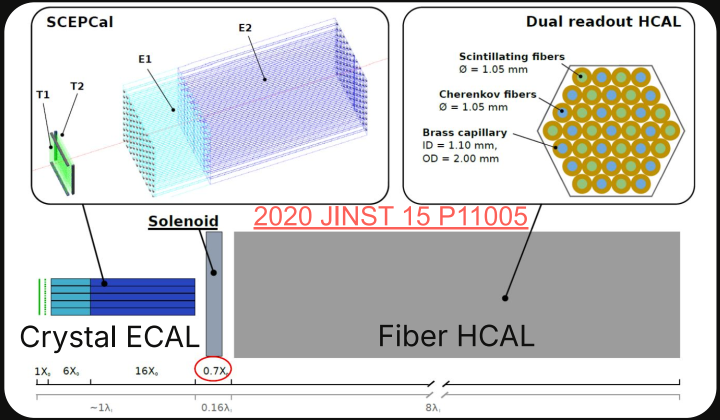
Hybrid DR Calorimetry

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

Homogeneous DR crystal EM + DR fiber HCAL



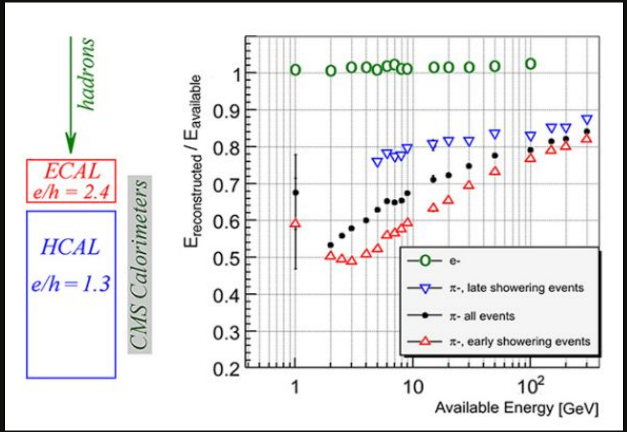
arXiv:2502.21223



2020 JINST 15 P11005

Apply the DRO correction on the energy deposits in the crystal and fiber segments <u>independently</u>

=> 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

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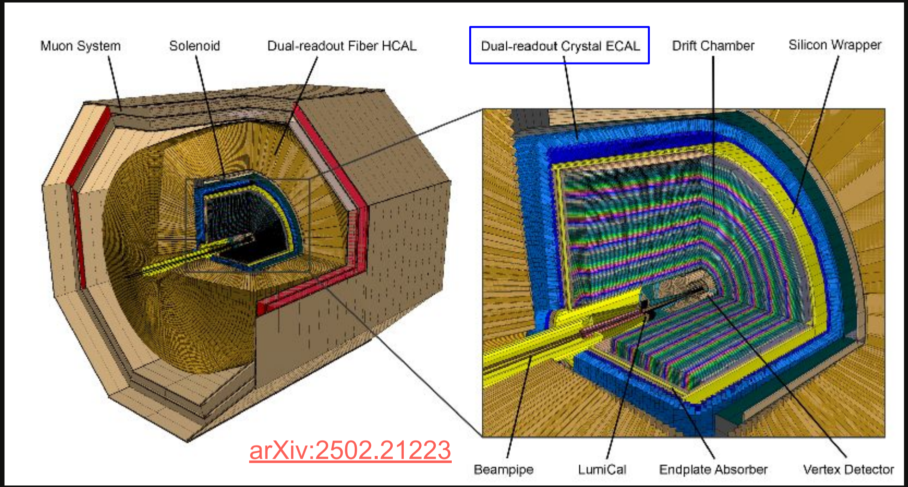
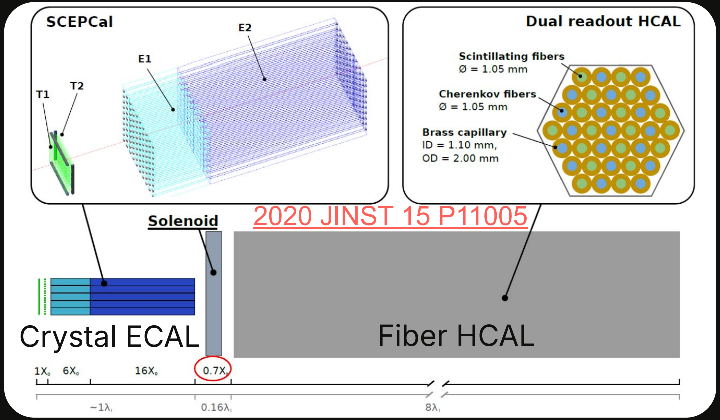




Challenges

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

See reference for further discussion of EM segmentation and physics motivation

*See also WbLS talks from yesterday's session for general comments on S/Č light properties.

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.

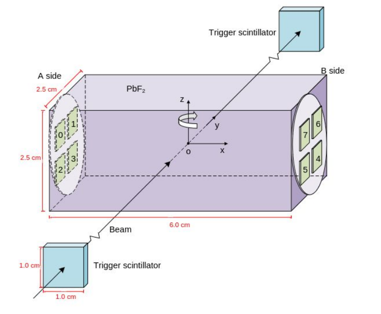
Major goals for the overall research program include:

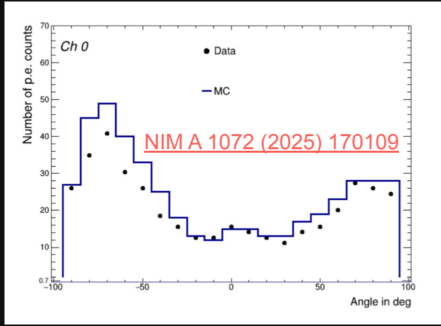
- Validation of modeling for our optical detector elements (good results)
- Demonstration of S/Č component analysis and collection of sufficient photon statistics in crystal calorimeter elements (good results)
- Demonstration of the EM performance of a segmented crystal ECAL with SiPM readout (in progress)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

CalVision test beam studies

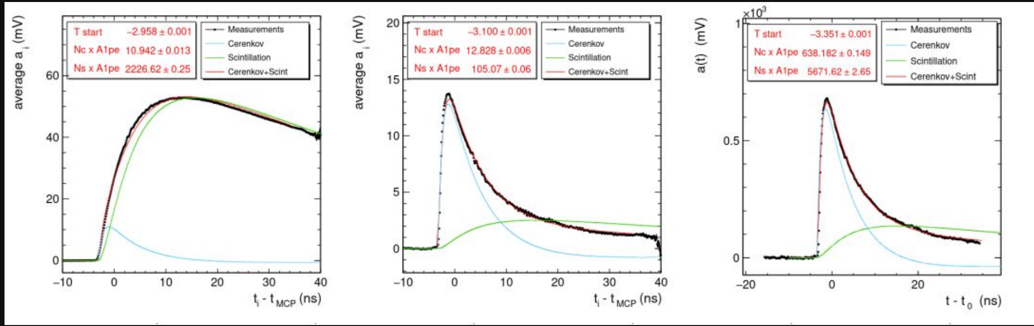
FNAL test beams (2023)

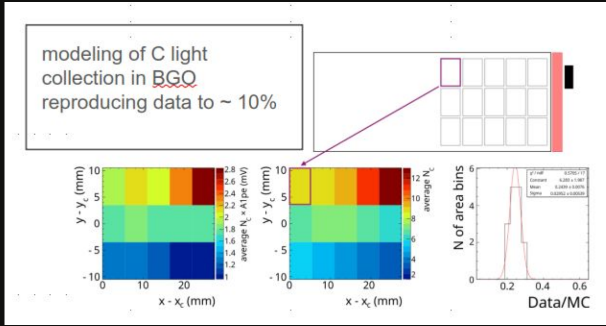
Study modeling of light collection in of PbF_2 (pure Cherenkov radiator) 120 GeV protons





SiPM signals

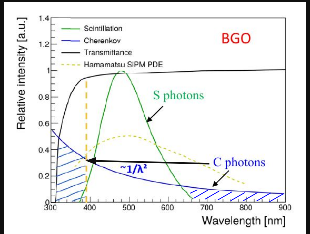




mean MiP signal after optical filter => single shower event , modeling light propagation

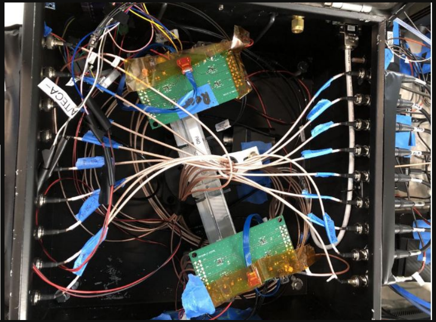
Initial tests of S/Ĉ light collection and modeling in BGO [https://doi.org/10.1051/epjconf/202532000021]

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



Virginia, Michigan, Maryland, FNAL

CalVision test beam studies

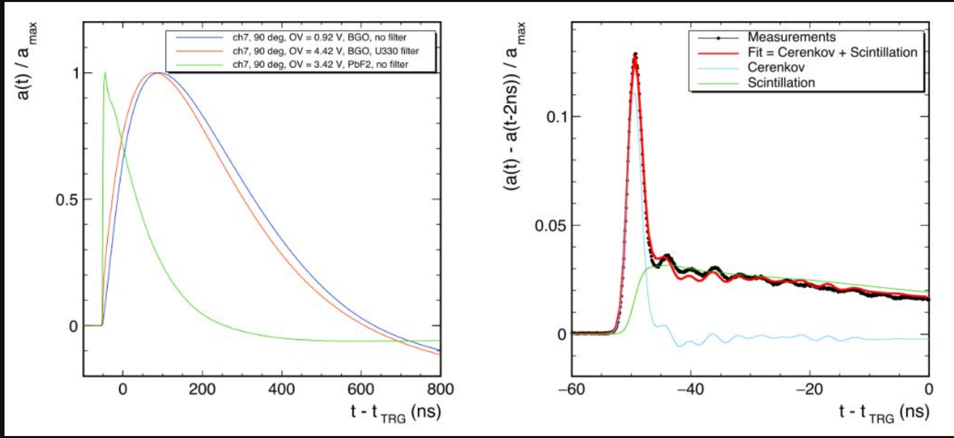


Test beam at DESY (April 2024) ~ 2-5 GeV e-

- 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.

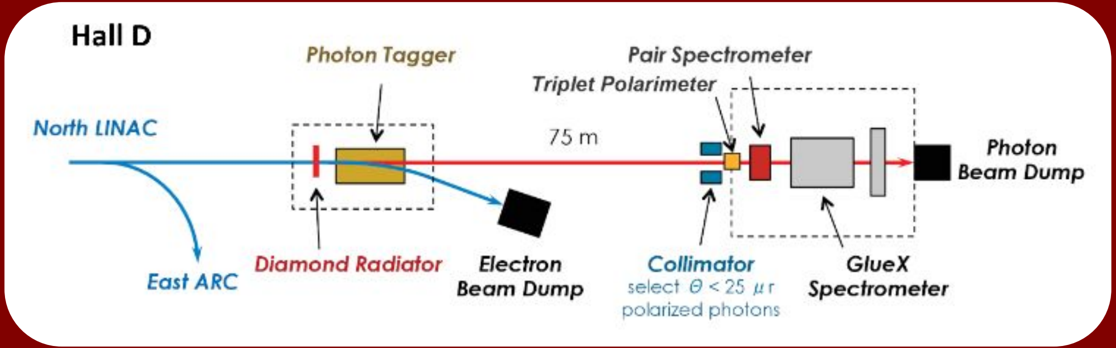


Pure Cherenkov signal from PbF2 and BGO w/, w/o optical filter
(left) original waveforms and component fits
(righ) component fits after digital SDL filter

See details in 2024 CPAD, talk by G. Cummings

Virginia, Michigan, Maryland, FNAL

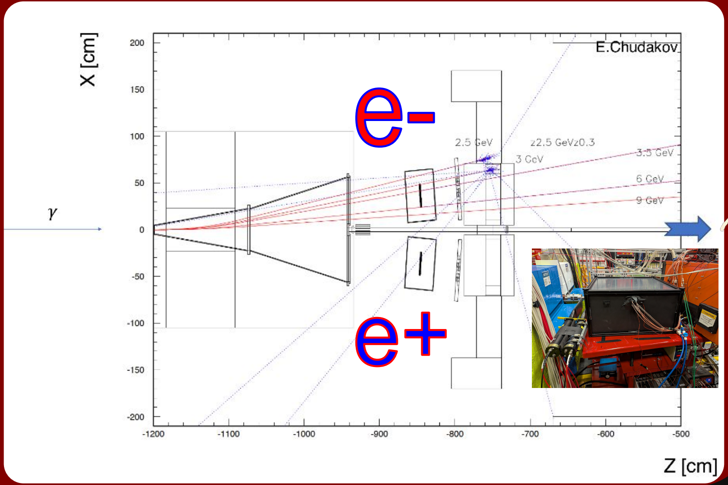
Recent test beam at JLab's Hall D

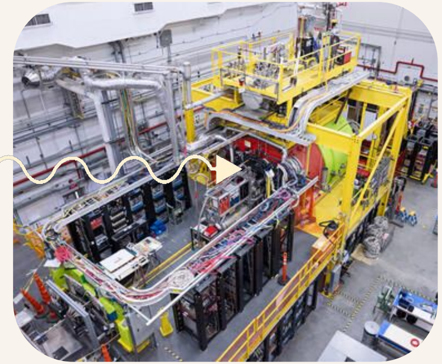


Parasitic test facility in parallel w/ GlueX exp.

Tertiary e+/e- beams ~3–10GeV/c following spectrometer

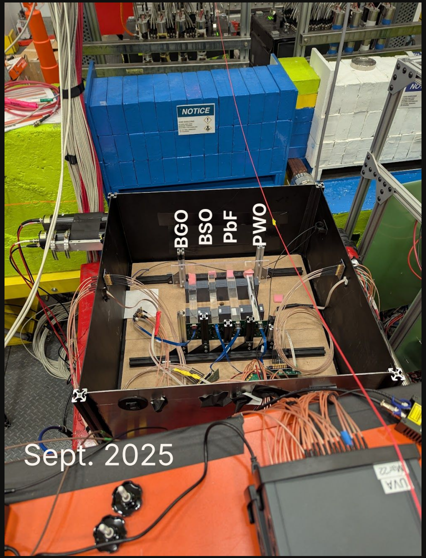
- Rates ~ O(kHZ)
- Electrons in 3.5-6 GeV/c range are measured to ~0.5-1% resolution.





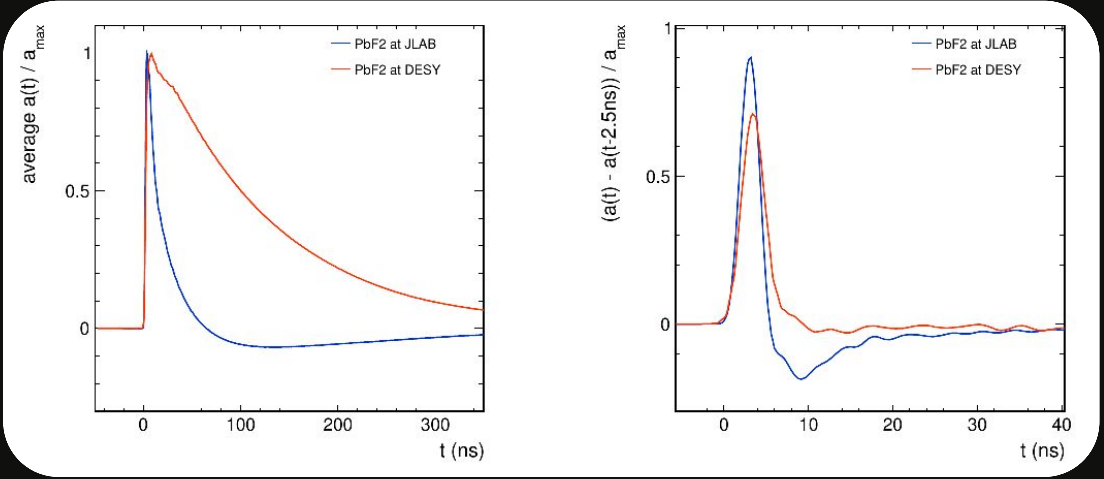
GlueX

Recent test beam at JLab's Hall D



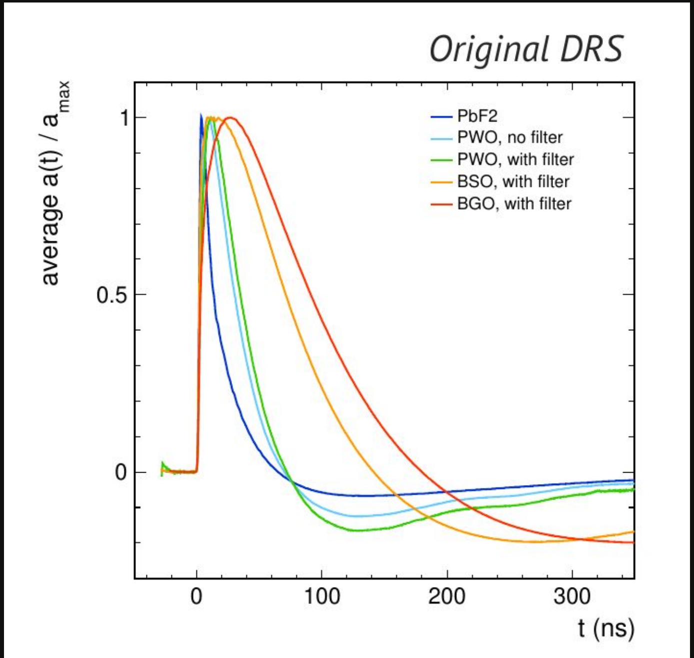
Main Goals

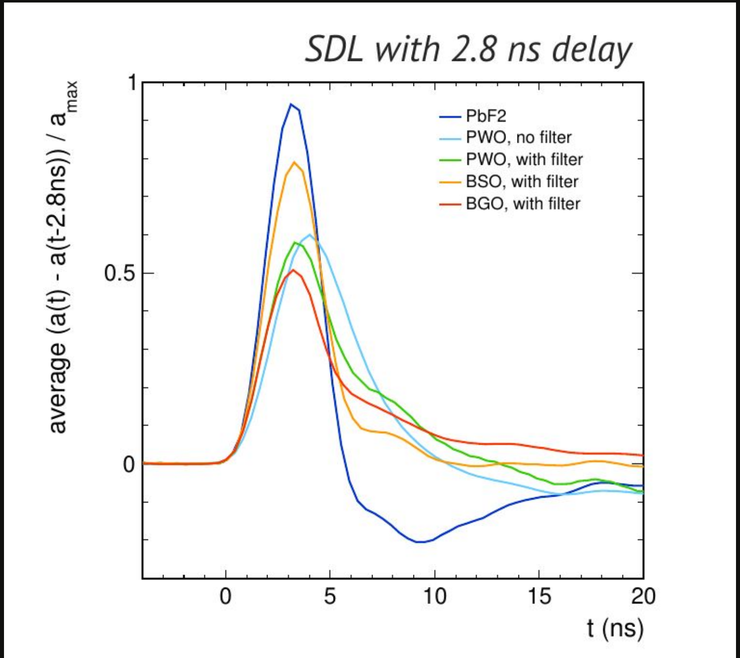
- Update DESY measurements using faster amplifiers
- High sample rates, low latency trigger (no tracking used)
  - Roughly ~7-10 GeV e+ based on crystal locations
  - Trigger on scint counters + any crystal signal above ZSP threshold
  - Low/high gain readout paths
- Repeat S/Č signal studies w/ more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



Recent test beam at JLab's Hall D

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

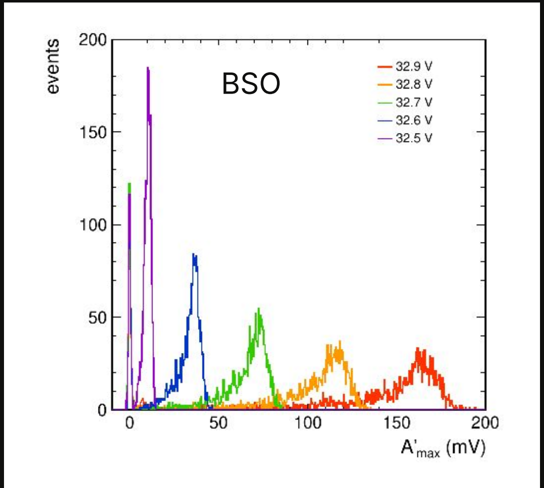


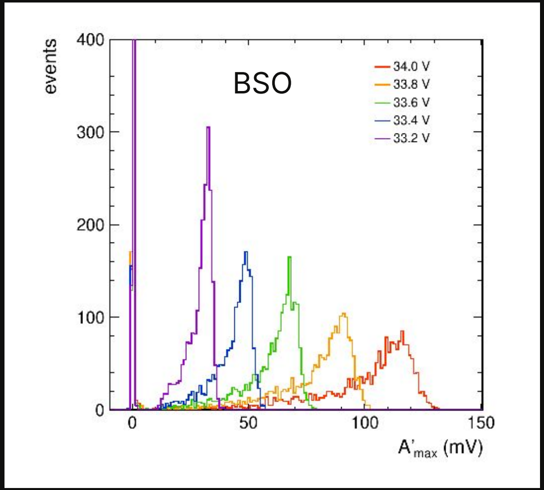


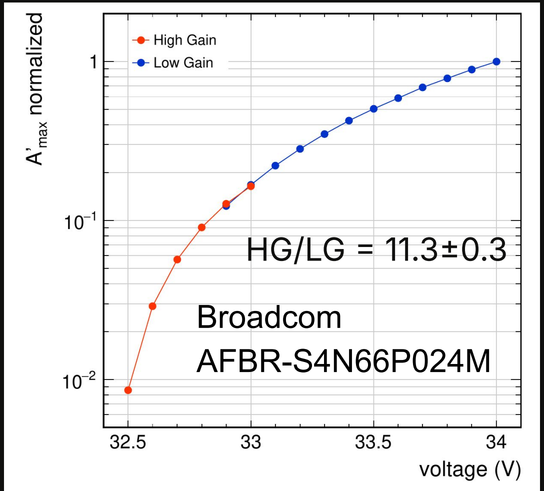
→ visible contribution from scintillation in all cases

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 Vbr
BSO with Hoya U330 filter; normalized to OV=1.5V

Fit result for MPV shown

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

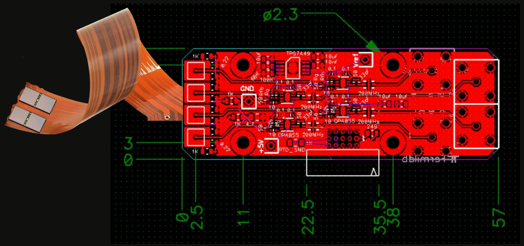
Work in progress on new data:

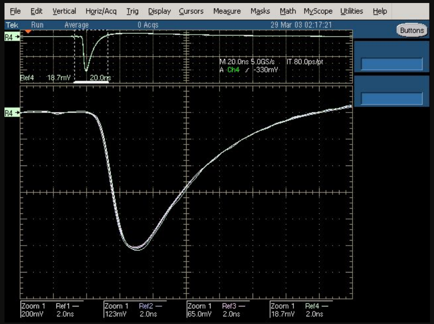
- 1-pe calibration: amplitude vs bias
- Estimation of pure scintillation pulse shapes
- Estimation of NC and NS from individual pulses using first two items
- Compare results wrt shaping times

CalVision segmented crystal array

Construction of BGO matrix at EM shower containment scale

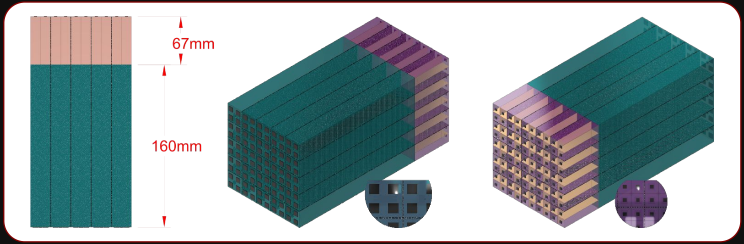
- Rear matrix
  - 5×5 geometry (22mmx22mm)
  - 4 Broadcom AFBR-S4N66 SiPMs/crystal - 36mm^2, 40u
  - Optical filters to enhance S/Ĉ identification
  - Fast shaping amplifiers
  - Readout using 1-5 GS/s digitizers (DRS4)
- Front matrix geometry
  - Higher granularity 10×10 matrix
  - Hamamatsu MPPC S14160 - 9mm^2, 10u
  - Readout using FERS CITIROC

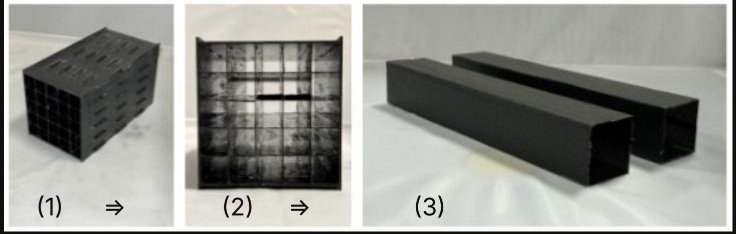




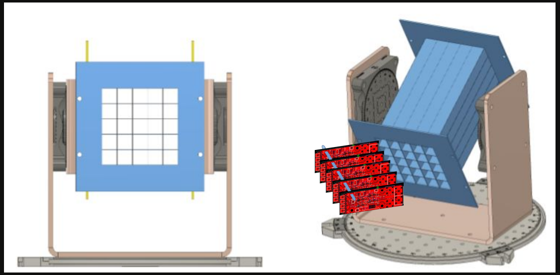
Virginia, FNAL, Maryland, Michigan,Purdue

$5X_0$ x $5X_0$ matrix





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



Gantry concept

CalVision segmented crystal array

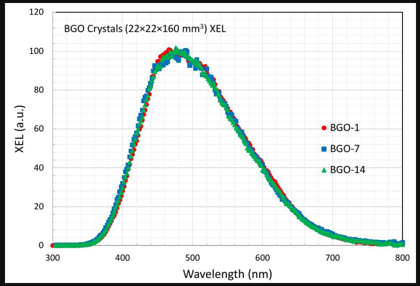
Status

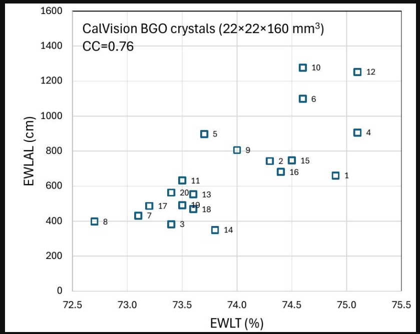
- Most large crystals in hand & tested - quality good
- Export issues delaying several large crystals and front matrix, hope for resolution soon.
- Amplifiers and flex cables are designed, final testing soon, then start of production for matrix & digitizer connection
- Start design of passive interface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

Caltech, CUA

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

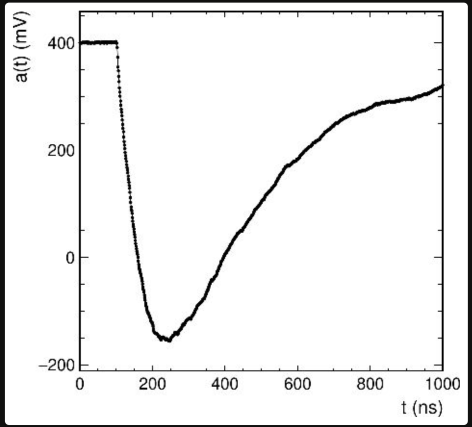
https://detectors.fnal.gov/projects/calvision/

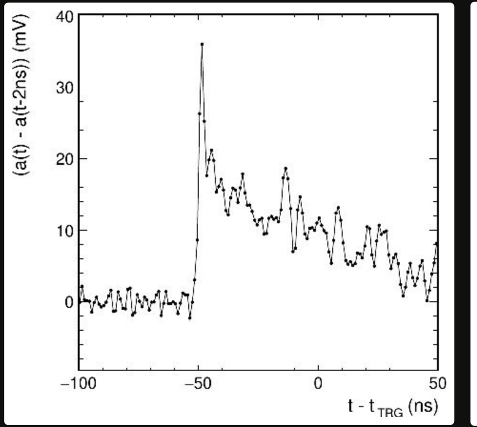
The work presented here received support through DOE DE-SC0022045, DE-SC0025956

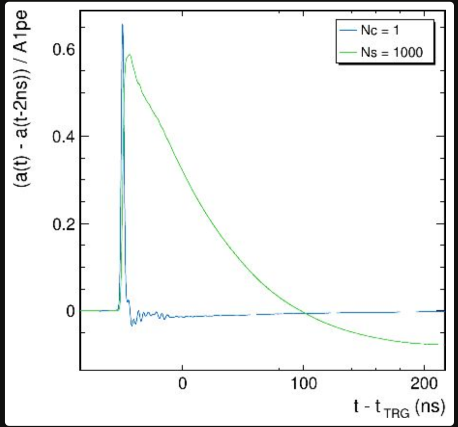
Additional slides

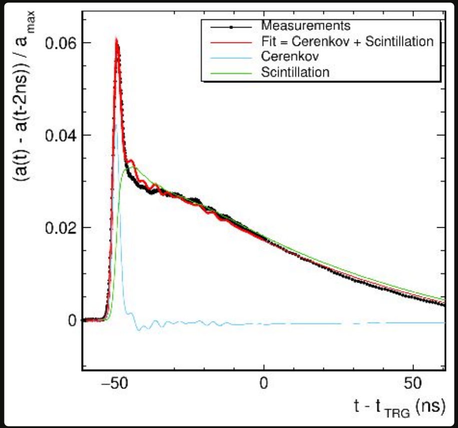
Determination of NS and NC

Example analysis of DSB heavy glass sample from DESY TB run



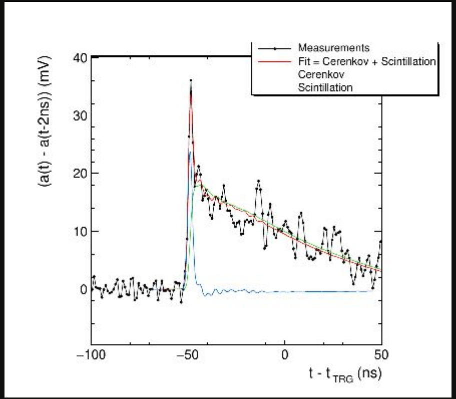






Measured signal ⇒ SDL filter ⇒ C/S components ⇒ validation on average waveform

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

A. Ledovskoy