Dual Readout in Homogenous Calorimetry

Grace E. Cummings, somewhat on behalf of CalVision/MaxiCC

USFCC Meeting, 15 August 2024

Challenges of Hadron Calorimetry

- quarks hadronize
  - Jets have
    - "electromagnetic" (EM) fraction
      - really a charged, relativistic fraction (mostly π^0)
    - "hadronic" (had) fraction
      - slower stuff
      - lots of protons and neutrons
- EM to hadronic ratio fluctuates event-to-event
- Detector response to EM energy deposition differs from hadronic energy deposition

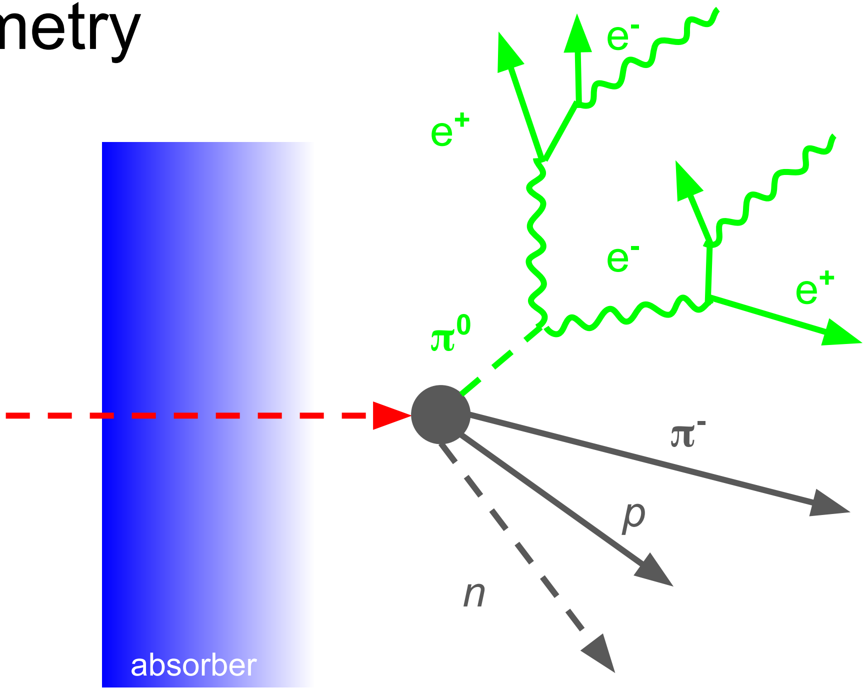
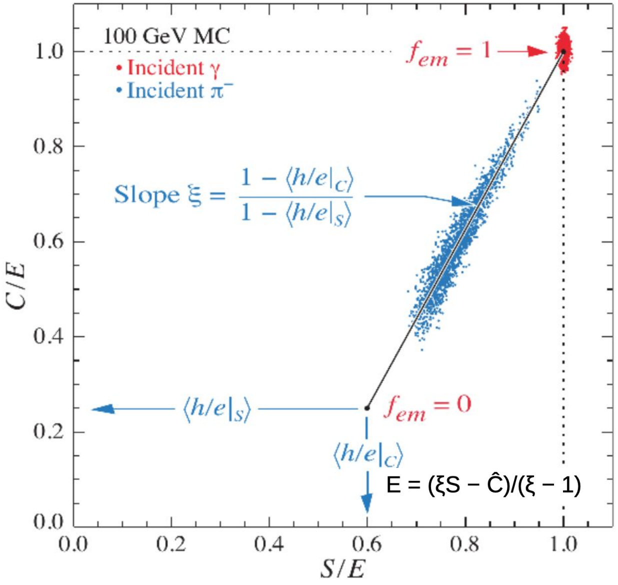


Figure adapted from Sehwook Lee 2019 *J. Phys.: Conf. Ser.* **1162** 012043

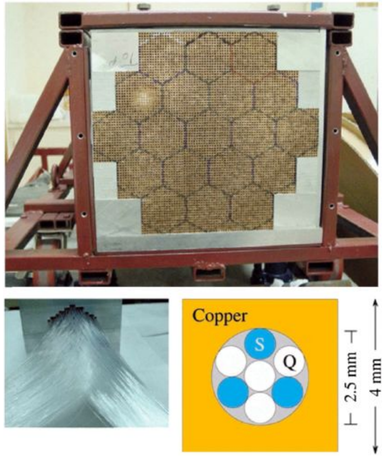
What is Dual Readout (DR)?

- EM/had ratio can be inferred from ratio of Cerenkov to scintillation light
  - *Event-by-event correction* to account for EM/had deposition fluctuations

2 methods



S. Lee, M. Livan, and R. Wigmans, Rev. Mod. Phys. 90, 025002



Dedicated Cerenkov radiators and scintillators
(like DREAM/RD52/IDEA)

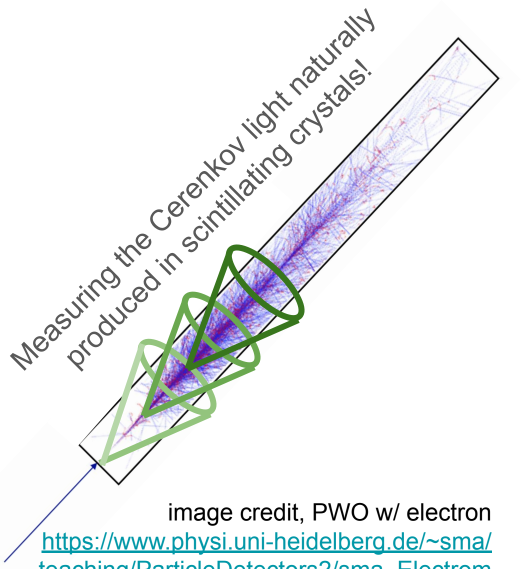


image credit, PWO w/ electron
https://www.physi.uni-heidelberg.de/~sma/teaching/ParticleDetectors2/sma_ElectromagneticCalorimeters.pdf

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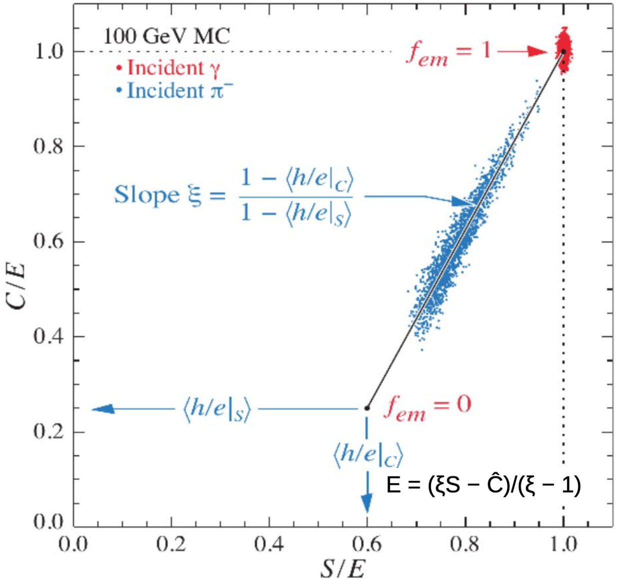

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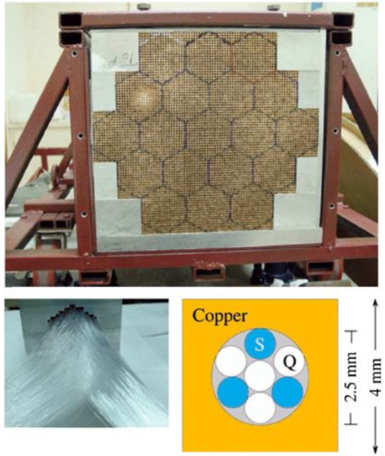

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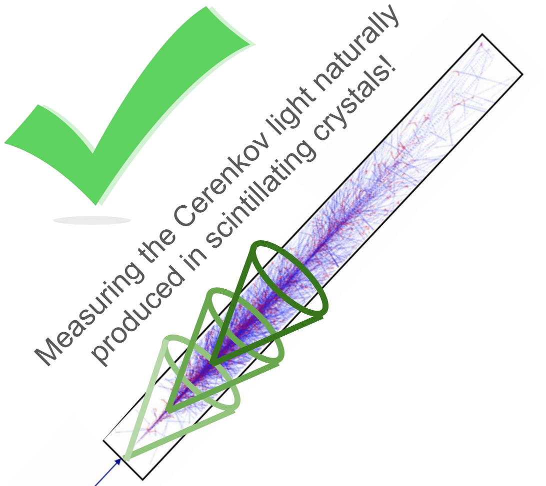

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Why DR in Crystal Electromagnetic Calorimeters?

- Why crystals?
  - Homogenous calorimeters
  - Scintillating? → more light, better energy
  - Good for electromagnetic sections
    - dense
    - large EM/had ratios
- Why use DR technique in crystals?
  - **Combine few % EM energy resolution with good hadron energy resolution!**
  - precision of a crystal ECAL
  - less hadron energy degradation!

Electromagnetic Calorimeter Examples

Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/E^{1/4}$	1983
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	$16\text{–}18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998
CsI(Tl) (BES III)	$15X_0$	2.5% for $E_\gamma = 1$ GeV	2010
$PbWO_4$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
$PbWO_4$ (PWO) (ALICE)	$19X_0$	$3.6\%/\sqrt{E} \oplus 1.2\%$	2008
Scintillator/Pb (CDF)	$18X_0$	$13.5\%/\sqrt{E}$	1988
Scintillator fiber/Pb spaghetti (KLOE)	$15X_0$	$5.7\%/\sqrt{E} \oplus 0.6\%$	1995
Liquid Ar/Pb (NA31)	$27X_0$	$7.5\%/\sqrt{E} \oplus 0.5\% \oplus 0.1/E$	1988
Liquid Ar/Pb (SLD)	$21X_0$	$8\%/\sqrt{E}$	1993
Liquid Ar/Pb (H1)	$20\text{–}30X_0$	$12\%/\sqrt{E} \oplus 1\%$	1998
Liquid Ar/depl. U (DØ)	$20.5X_0$	$16\%/\sqrt{E} \oplus 0.3\% \oplus 0.3/E$	1993
Liquid Ar/Pb accordion (ATLAS)	$25X_0$	$10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996

SAMPLING!

https://pdg.lbl.gov/2022/web/viewer.html?file=../reviews/rpp2022-rev-particle-detectors-accel.pdf

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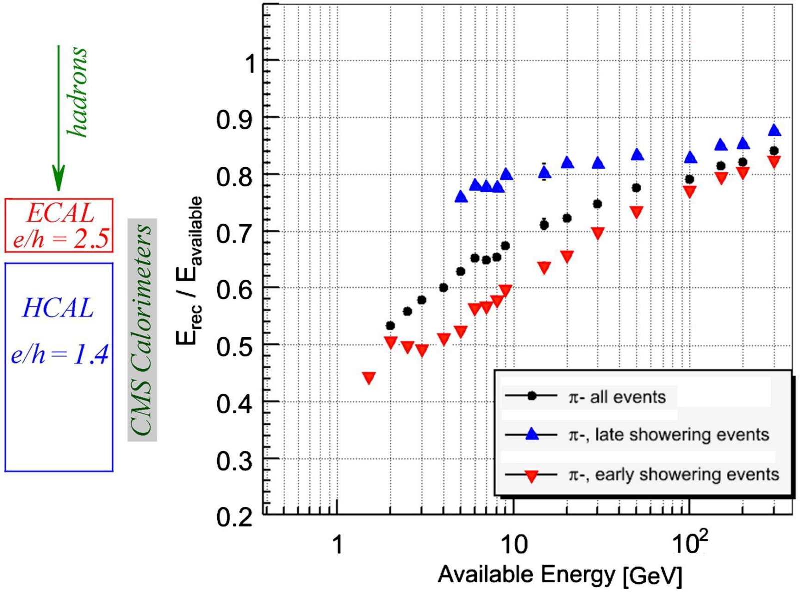
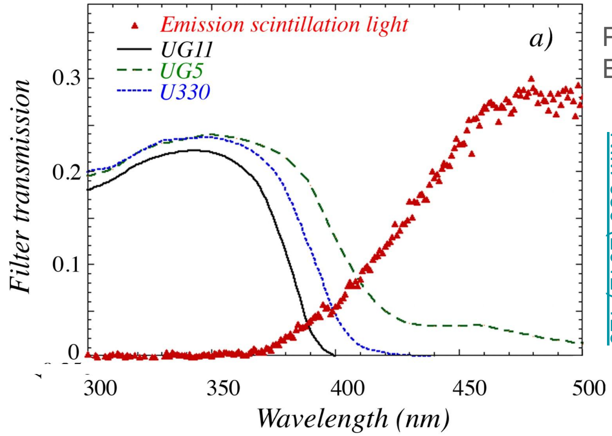
Great ECALs can degrade good HCALs



N. Akchurin, R. Wigmans, (2012) Nucl. Instr. and Meth. **A666** (80)

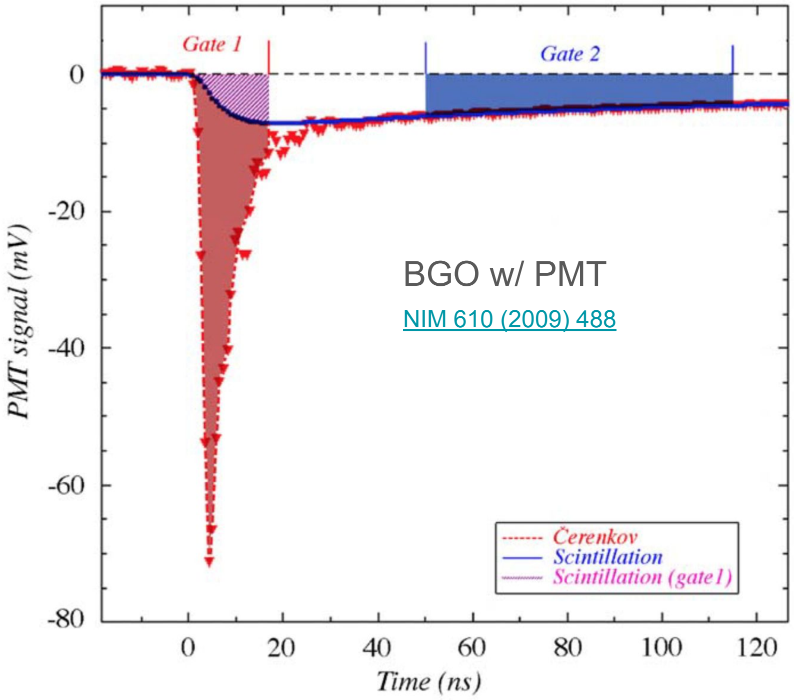
Previous homogenous DR attempts

- Successfully separated Cherenov and Scintillation light!
  - wavelength
  - timing



PWO Scint Emission

NIM 686 (2012) 125

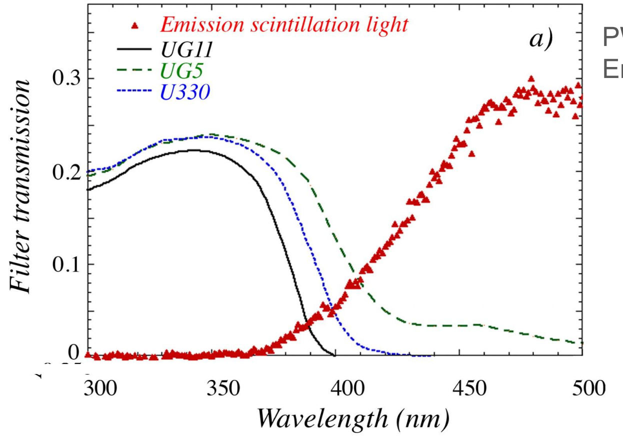


BGO w/ PMT

NIM 610 (2009) 488

Previous homogenous DR attempts

- BGO and PWO matrices
  - instrumented w/ PMTs
  - targeted UV spectrum
- Not enough light for good resolution
  - scint spectrum killed w/ filters
  - not accepting enough cherenkov



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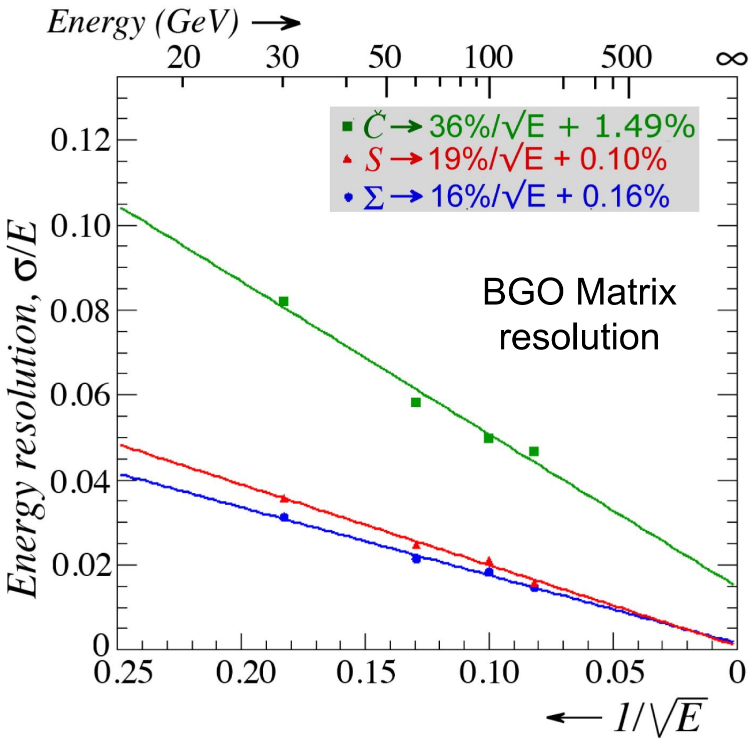

BGO Matrix resolution

N. Akchurin et al, (2012) Nucl. Instr. and Meth. **A 686** (125)

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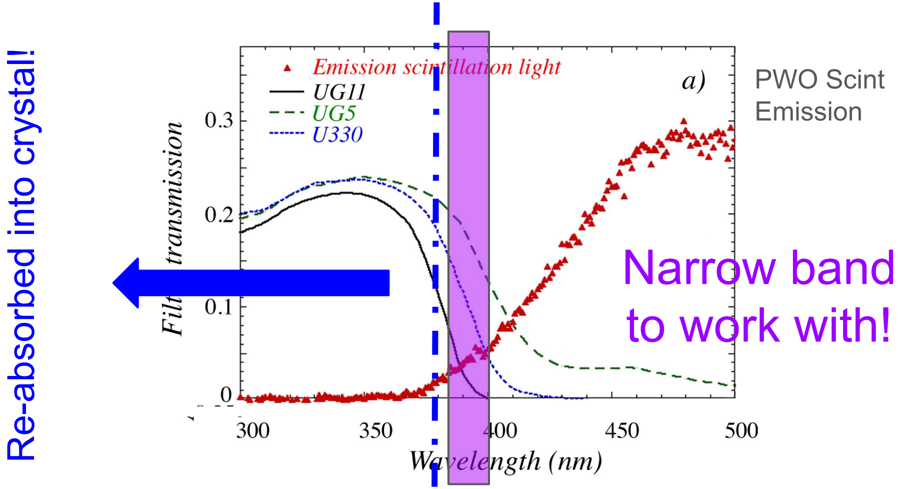
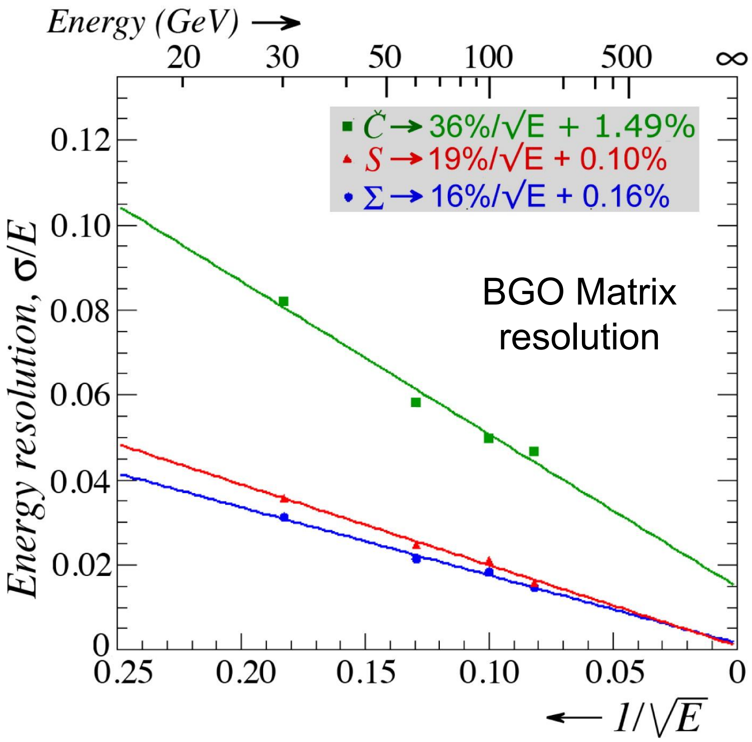
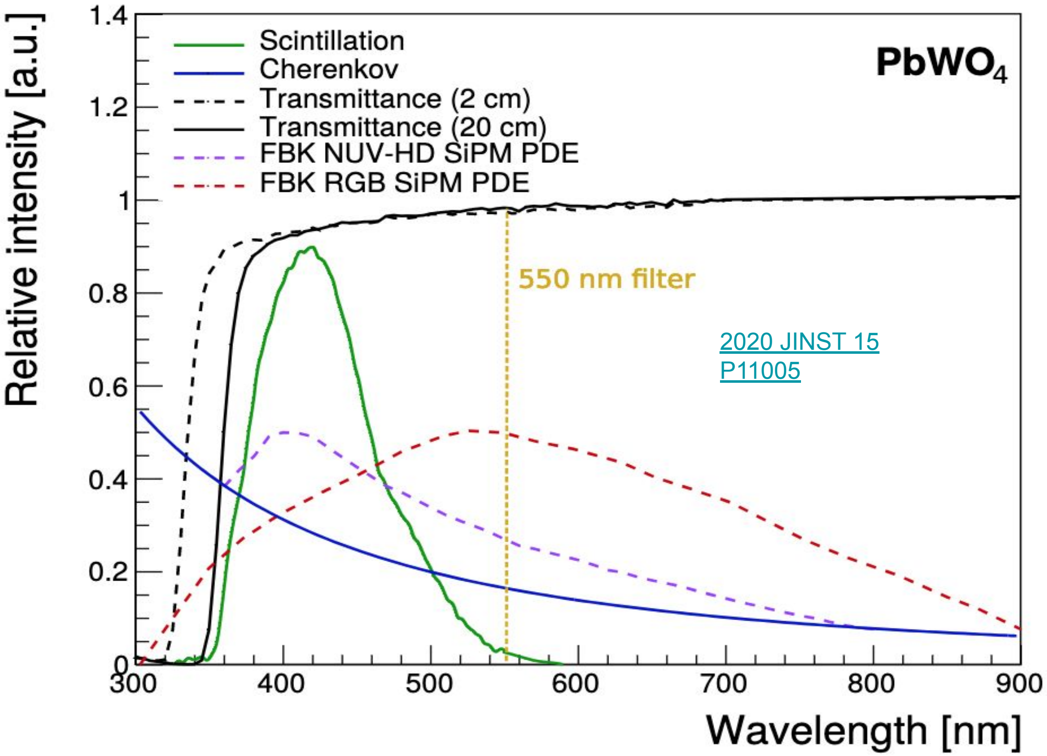




N. Akchurin et al, (2012) Nucl. Instr. and Meth. **A 686** (125)

SiPMs bring new opportunities

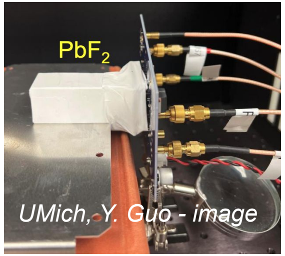
- target the **infrared**
  - avoid self-absorption
  - In peak of SiPM acceptance
- Goal: ~ 100 Cherenkov photons / GeV

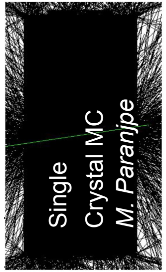


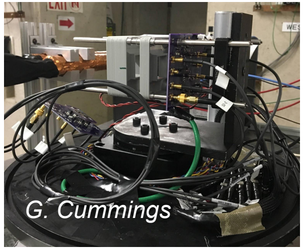
2020 JINST 15 P11005

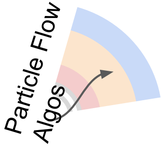
CalVision - homogenous DR for e+e- colliders

Single crystal + matrix studies



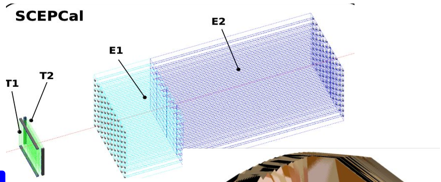


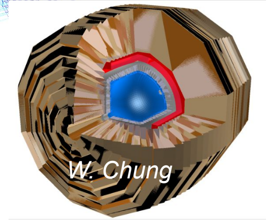




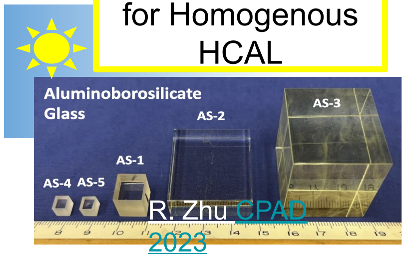
Full detector sim

2020 JINST 15 P11005



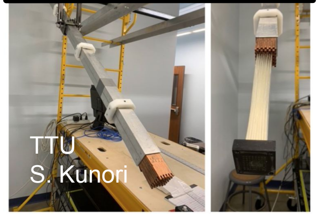


Heavy Glasses for Homogenous HCAL

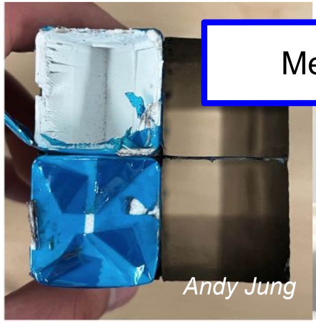


R. Zhu CPAD 2023

DR Fiber HCAL



Mechanics



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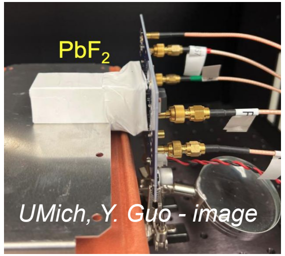
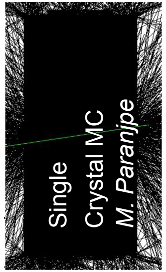
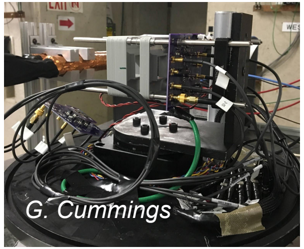
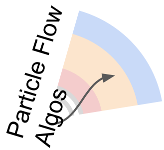


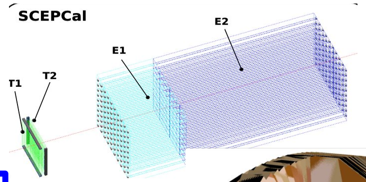


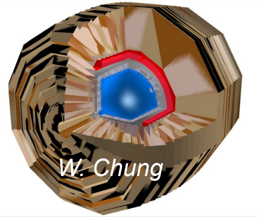




Full detector sim

[2020 JINST 15 P11005]





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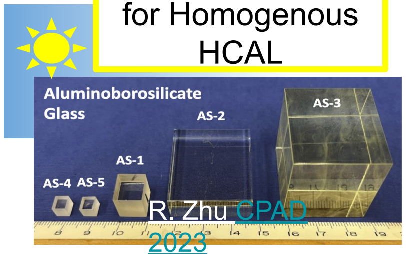

R. Zhu [CPAD 2023]

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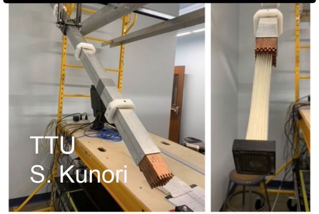

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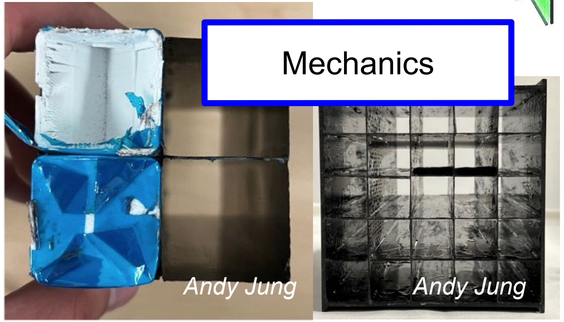

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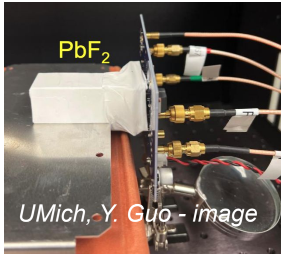
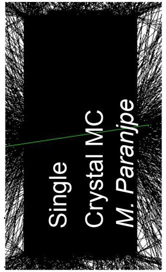
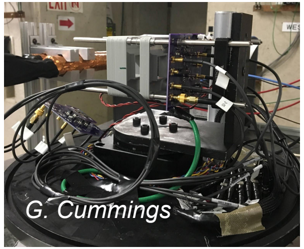
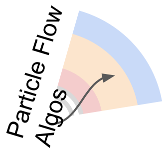


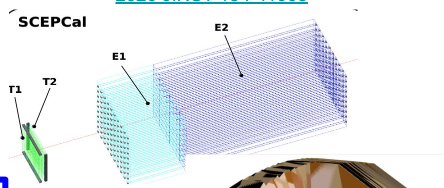






Full detector sim

2020 JINST 15 P11005



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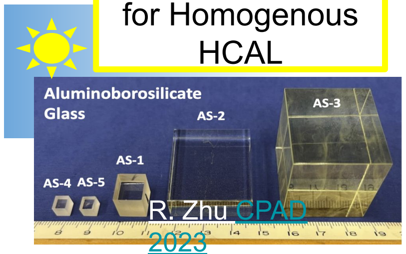

R. Zhu CPAD 2023

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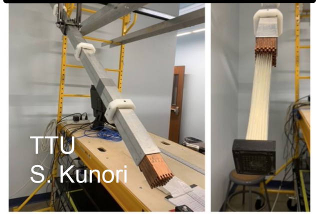

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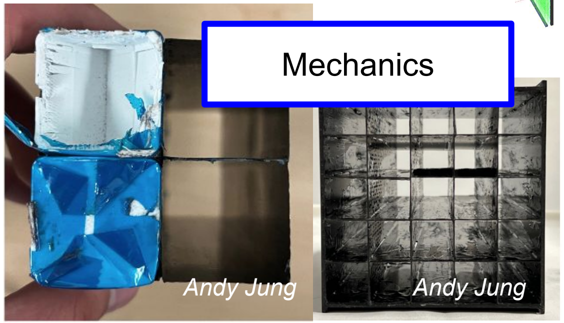
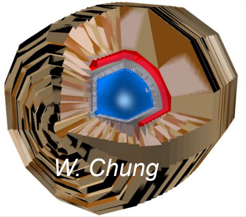




Brandeis

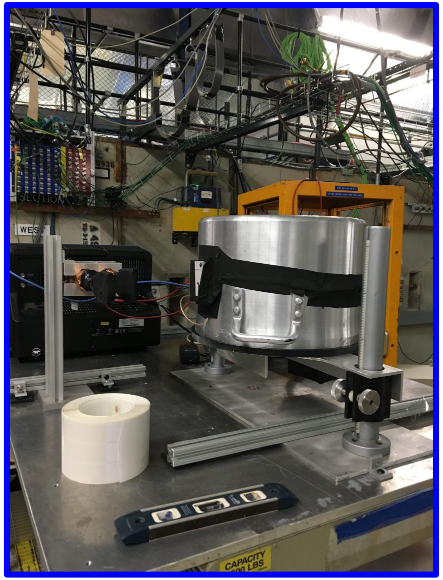
Fermilab Caltech Argonne NATIONAL LABORATORY UNIVERSITY OF MARYLAND

Stony Brook University UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA OAK RIDGE National Laboratory UNIVERSITY of VIRGINIA

First two test beams

Test beam at Fermilab, April 24th - 26th

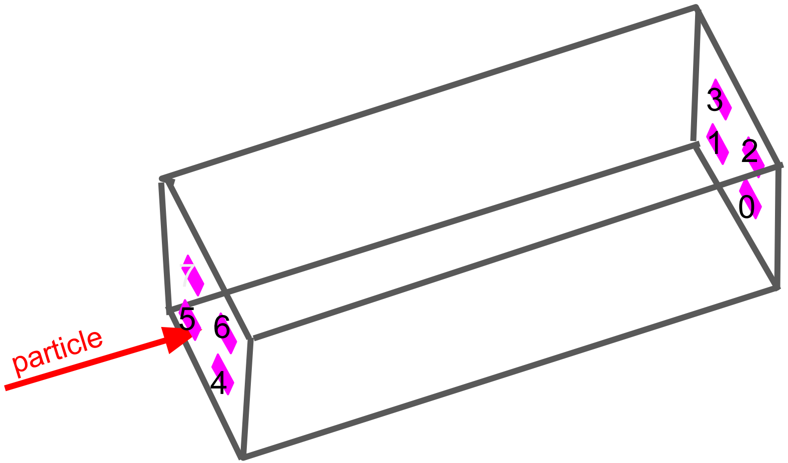
Test beam at Fermilab, May 31st - June 7th



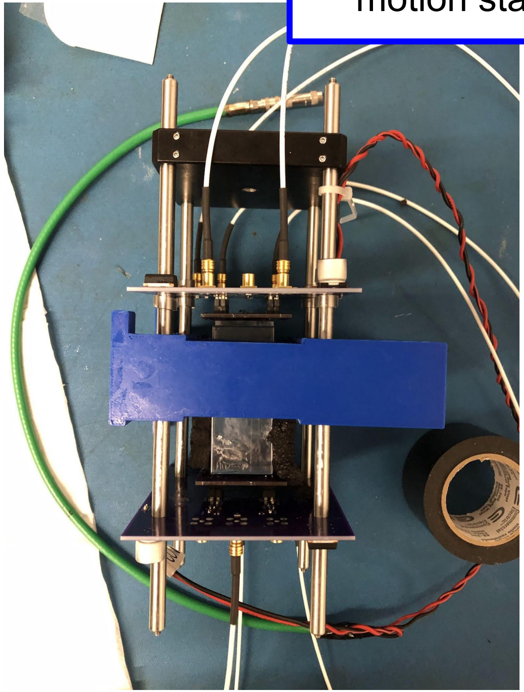
2 test beams with 120 GeV protons @ Fermilab in 2023

Single Crystal Test Module - First Generation

- 4 Hamamatsu S14160-6050HS 6x6 mm SiPMs per end
  - single amplifier stage
  - ~0.6 mV per photon electron
- 2.5 x 2.5 x 6.0 cm crystals
  - **will not contain a shower**

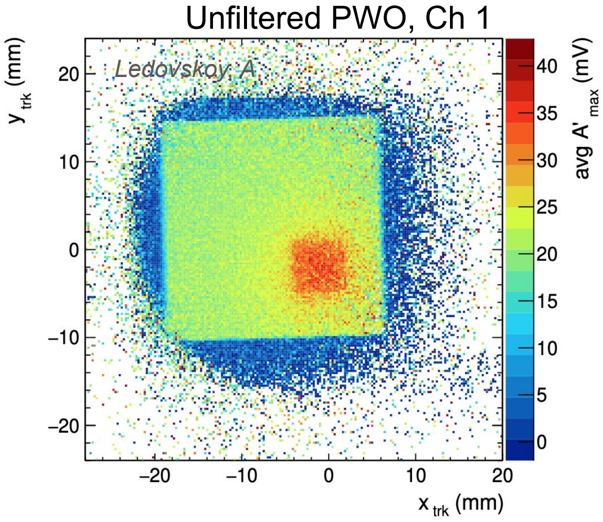


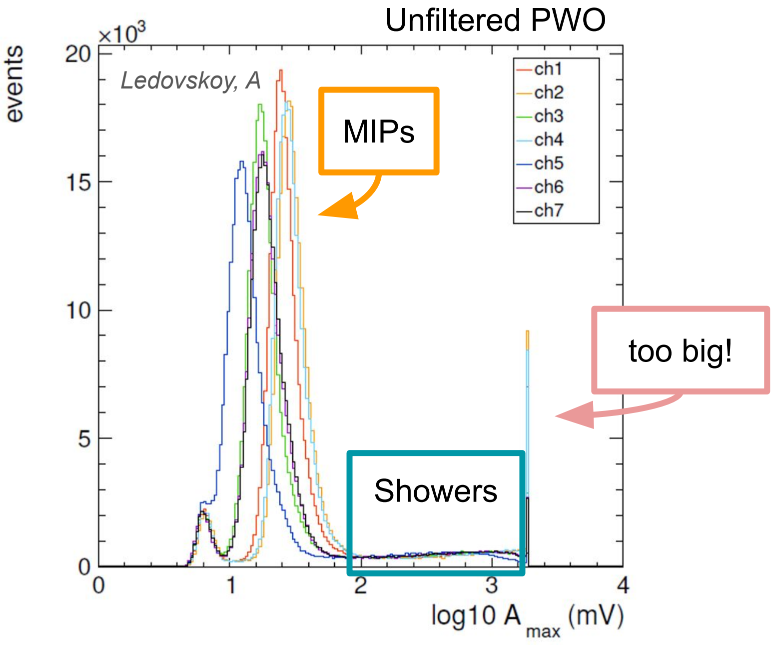
Can mount to a motion stage

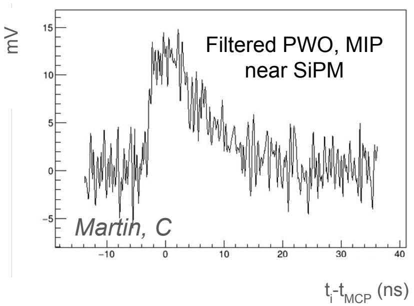


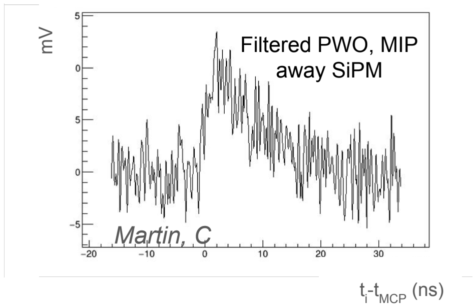
What did we see?

- Collection of MIP and showering events
  - remove events where pulse was truncated
- ~Good signal-to-noise
- Highly position dependent readout



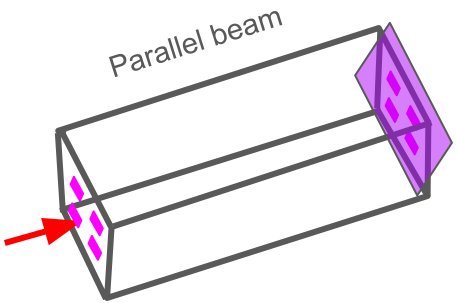






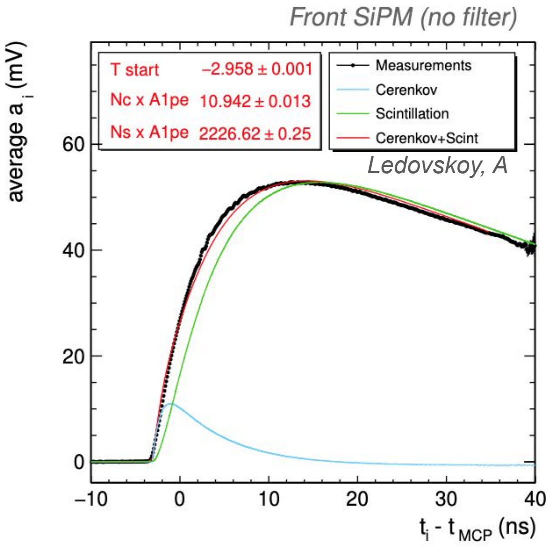
Preliminary Performance -BGO

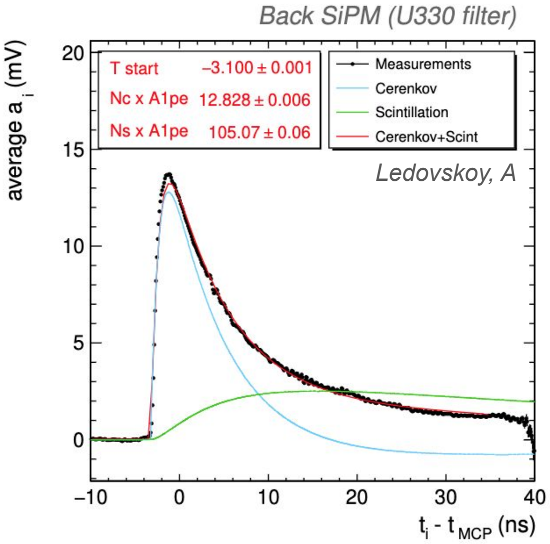
Hoya U330 notch filter between Crystal and SiPMs on back



- Pulse shape analysis to extract # of Cherenkov and Scint
  - take Scintillation shape from unfiltered channels
    - deconvolute with BGO scint function to get Cherenkov
  - Cherenkov shape fit with CR-RC Shaper + RC Differentiator model

Central MIP signals



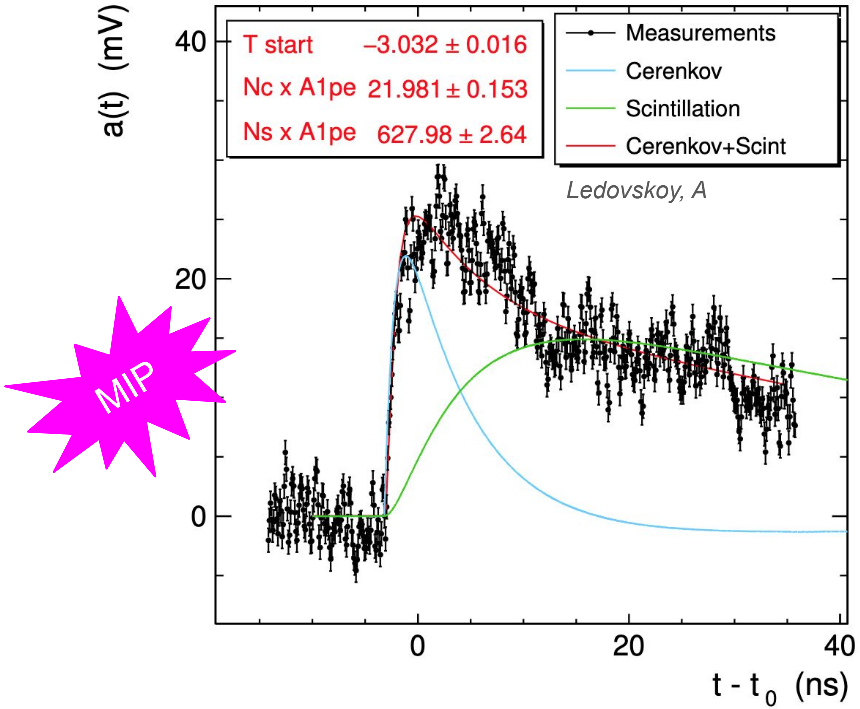


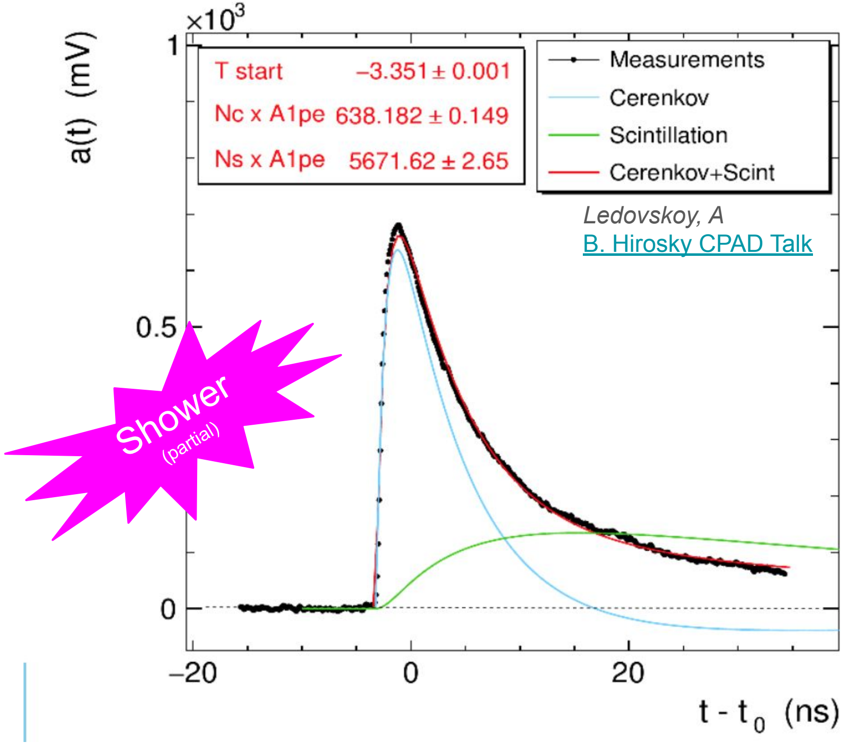
Assume single photon electron peak of ~0.6 mV

Discrimination driven by time profile

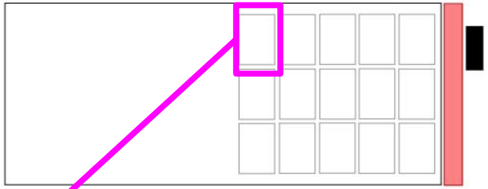
B. Hirosky CPAD Talk

Preliminary Performance - BGO single pulses

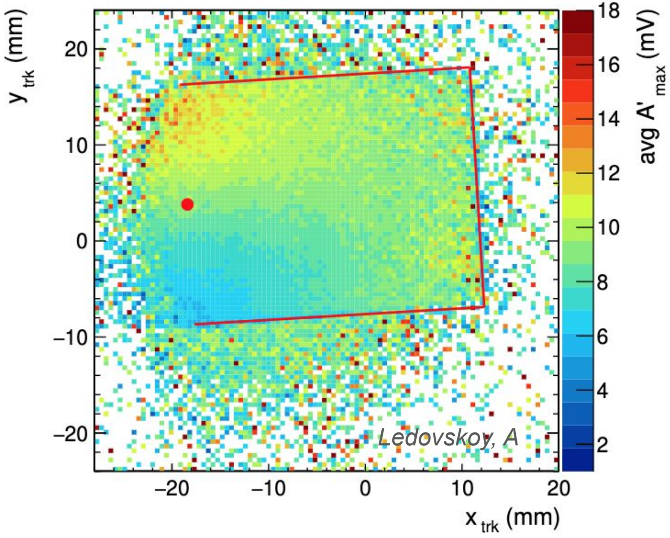




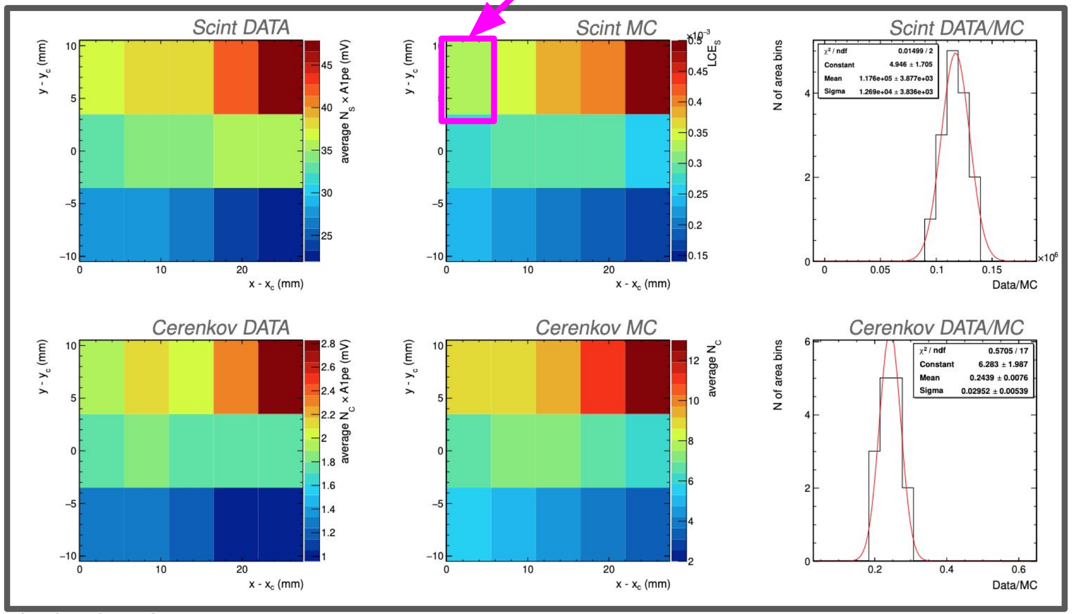
BGO Modeled well in MC ~ 10% level



- Perpendicular Data → simpler to understand
  - No Cherenkov from filter/grease



Red Dot center of crystal - can image with the data (unfiltered channel 5)

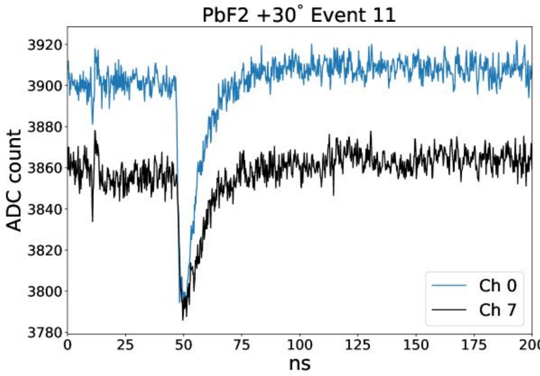


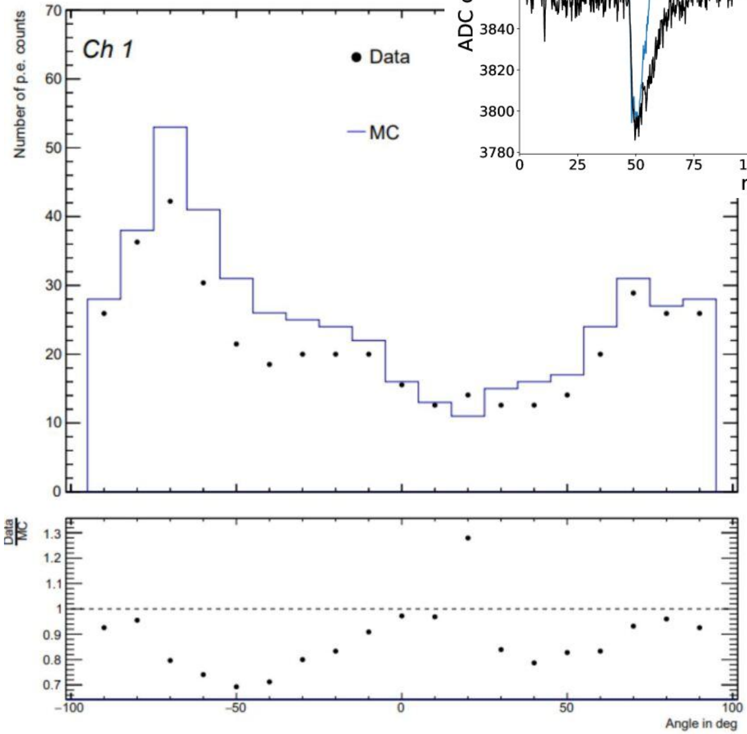
Ledovskoy, A

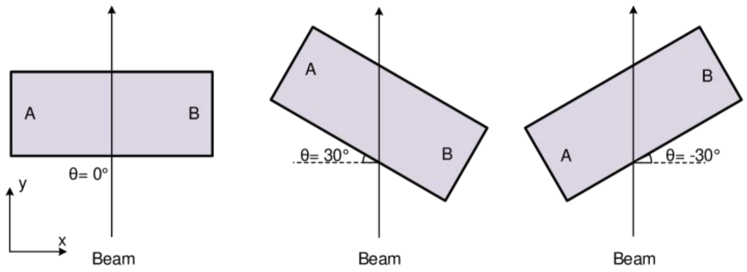
*LCE = N_detected/N_Generated

PbF2 results - June Test Beam

- Extensive characterization of Cherenkov acceptance
  - PbF2 → no scintillation
  - Close in refractive index
  - angle scans
- Understand Cherenkov modeling in single crystal







arXiv:2407.08033v1

Second Generation Setup

- 4 Broadcom 6x6 mm SiPMs per end
  - **2 amplifier stages**
    - high and low gain readout
  - ~0.7 mV per photon electron
- Easier calibration!

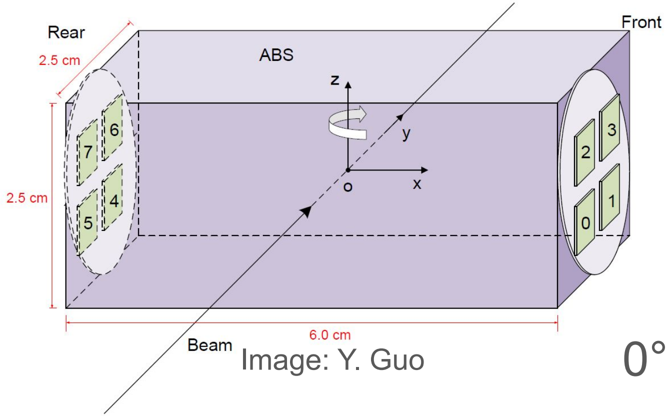
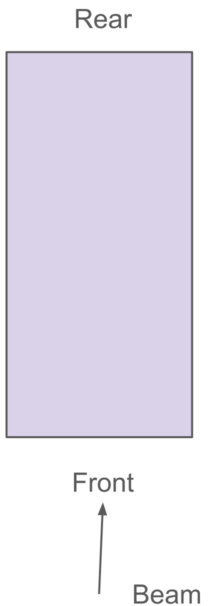
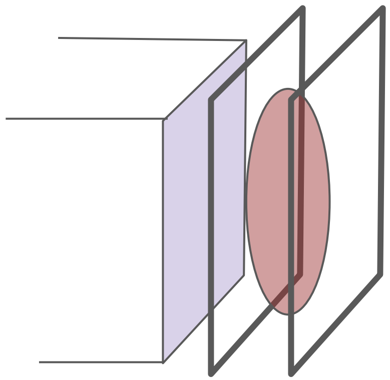


Image: Y. Guo

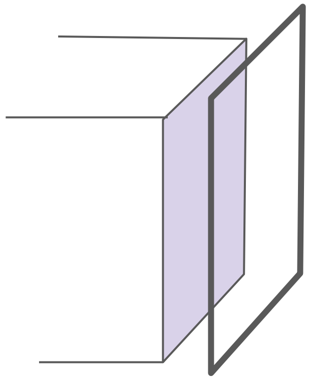
0°



90°



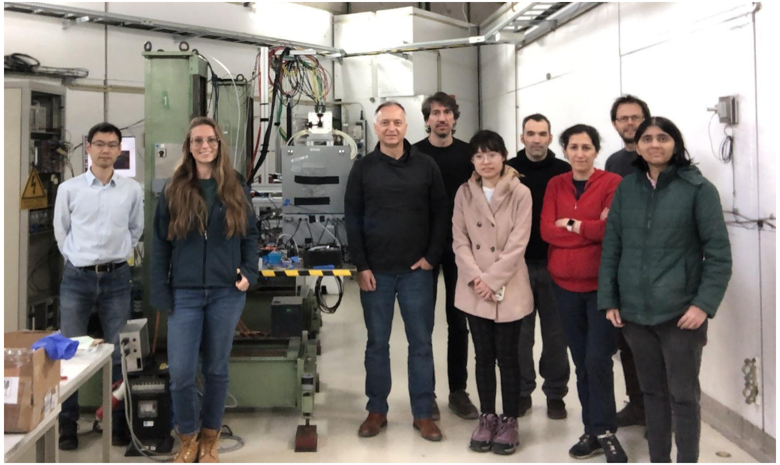
Crystal → cookie → filter → cookie → SiPMs (not pictured)

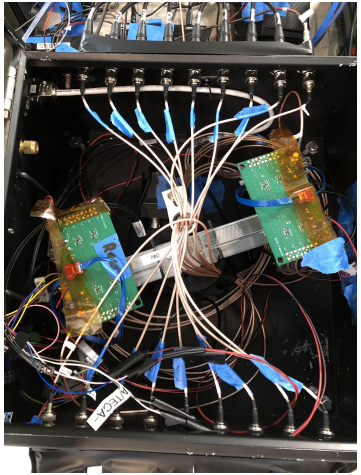


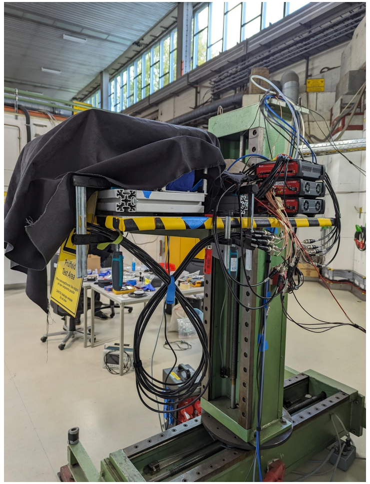
Crystal → cookie → SiPMs (not pictured)

April 2024 DESY Testbeam

- 2 GeV Electrons (mostly)
  - functionally continuous beam
- Large variety of materials tested
  - full-length crystals (and more of them)
  - first heavy glasses
  - variety of filters
- Angle Scans
- Analysis ongoing!







Summary

- DR is a promising method for improving hadron calorimetry
  - SiPMs enable its pursuit in homogenous calorimeters
- CalVision is exploring DR in homogeneous calorimeters for future colliders
  - DR in crystals
  - Scintillating glasses for homogenous HCALs
  - Detector simulation
  - Algorithms
  - Front end electronics and readout → not covered today
- Test beam results are promising!
  - Can separate Cherenkov and Scint through same methods as RD52/DREAM
  - More results are in progress
- Next year: full matrix tests!