Crystal (or homogenous) calorimetry for the FCC - Status and Plans of CalVision/MaxiCC

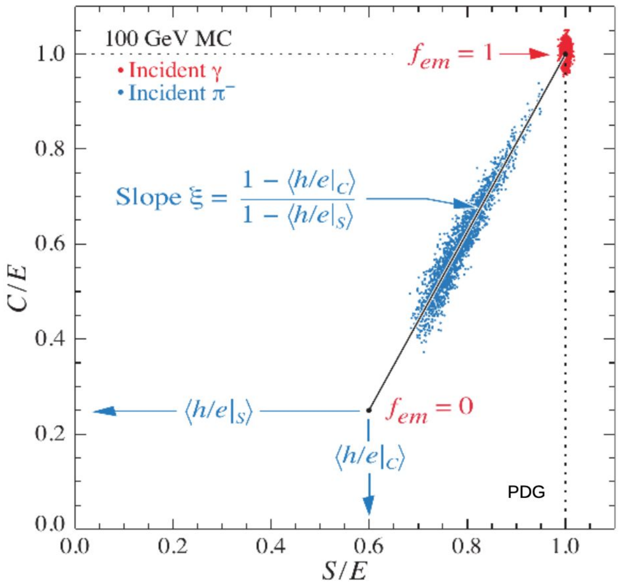
Thomas Anderson, Andrea Benaglia, Karl Bue, Marcello Campajola, Wonyong Chung, ***Grace Cummings***, Tim Edberg, Sarah Eno, Marco Francesconi, Giovanni Gaudino, Liang Guan, Yuxiang Guo, Bob Hirosky, Hayden Hollenbeck, Alberto Orso Mario Iorio, Daniel Levin, Alexander Ledovskoy, Hui-chi Lin, Marco Lucchini, Stefano Moneta, Sara Nabili, Mekhala Paranjpe, Jianming Qian, Jon Wilson, Jessaly Zhu, Junjie Zhu…

And many others I have missed!

8th FCC Physics Workshop, 15 January 2025

Dual Readout in crystals: CalVision/MaxiCC

- Homogeneous crystal calorimeters promise excellent electron/γ energy resolution
  - but have poor energy resolution for hadrons
- Dual readout (DR) technique
  - quantify the electromagnetic fraction of hadronic showers via Cherenkov light
  - Event-by-event response correction possible
  - **recover hadron energy resolution in a crystal layer**



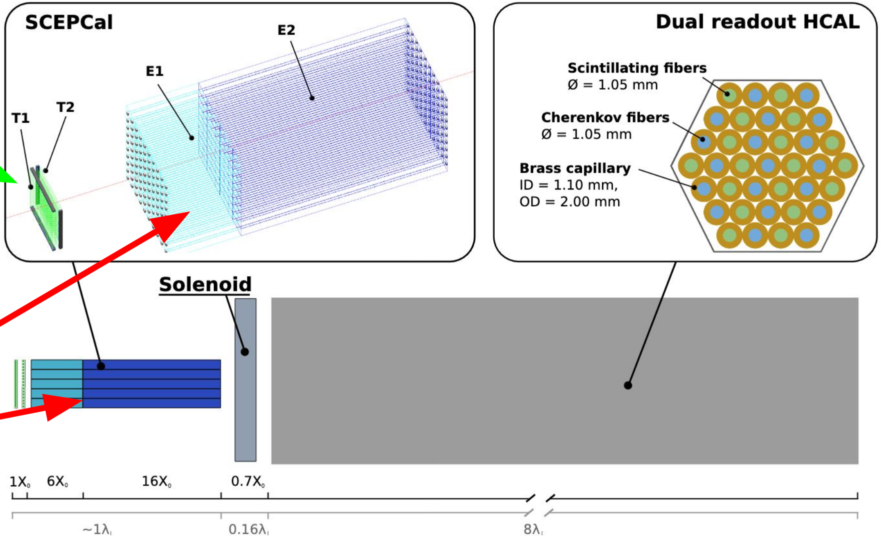
S. Lee, M. Livan, and R. Wigmans, Rev. Mod. Phys. 90, 025002

SCEPCal Overview: the target concept

Segmented **C**rystal **E**lectromagnetic **P**recision **Cal**orimeter

Timing layers

Crystal DR Layer

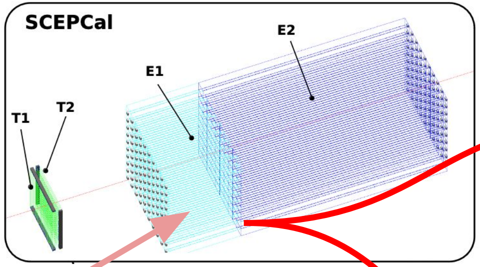


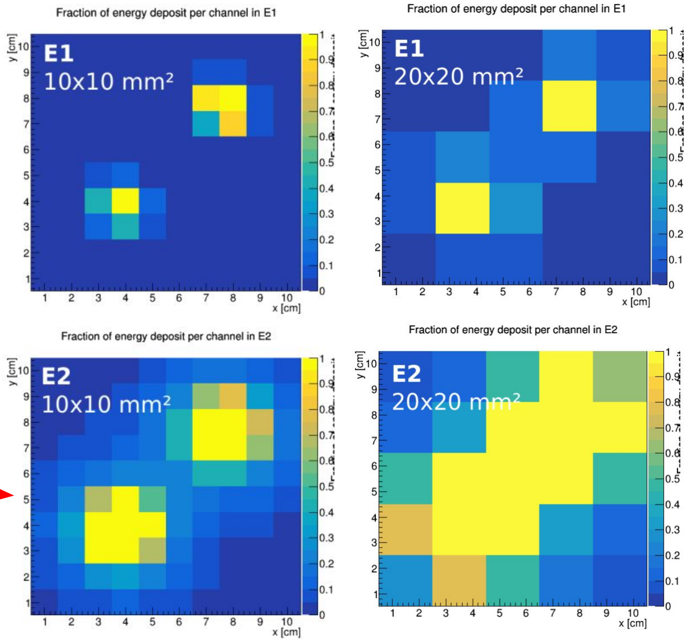
IDEA detector concept

2020 JINST 15 P11005

SCEPCal Overview: the target concept

Segmented **C**rystal **E**lectromagnetic **P**recision **C**alorimeter





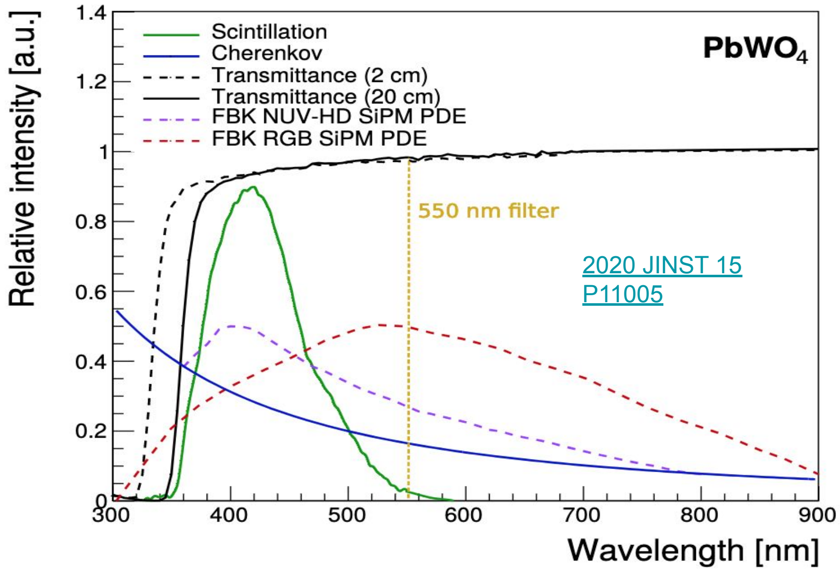
Crystal DR Layer

segmentation allows for better photon separation → π_0 PID!

[2020 JINST 15 P11005]

How to separate Cherenkov and Scintillation light

Wavelength Filters



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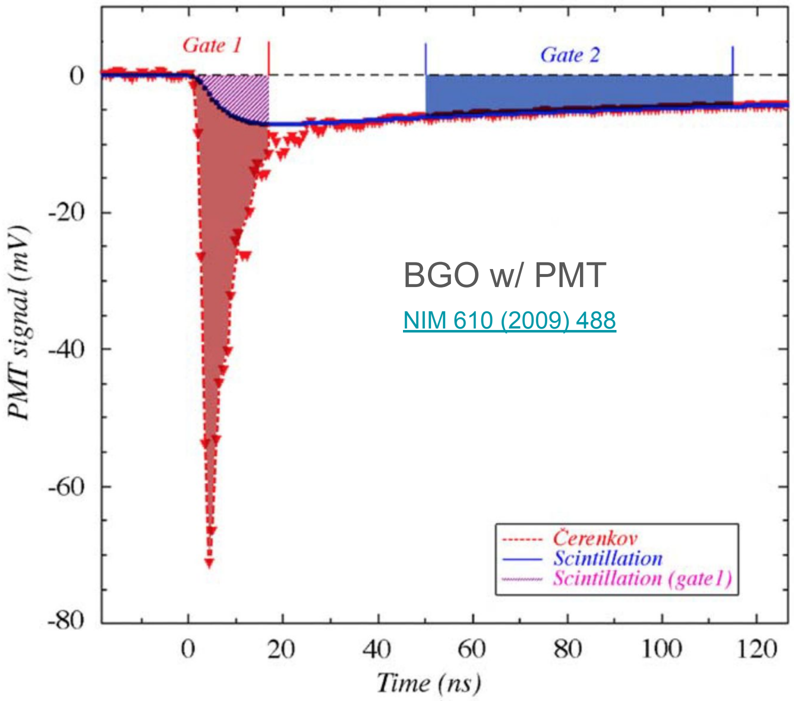
Time structure (waveform analysis)



BGO w/ PMT

NIM 610 (2009) 488

How to separate Cherenkov and Scintillation light

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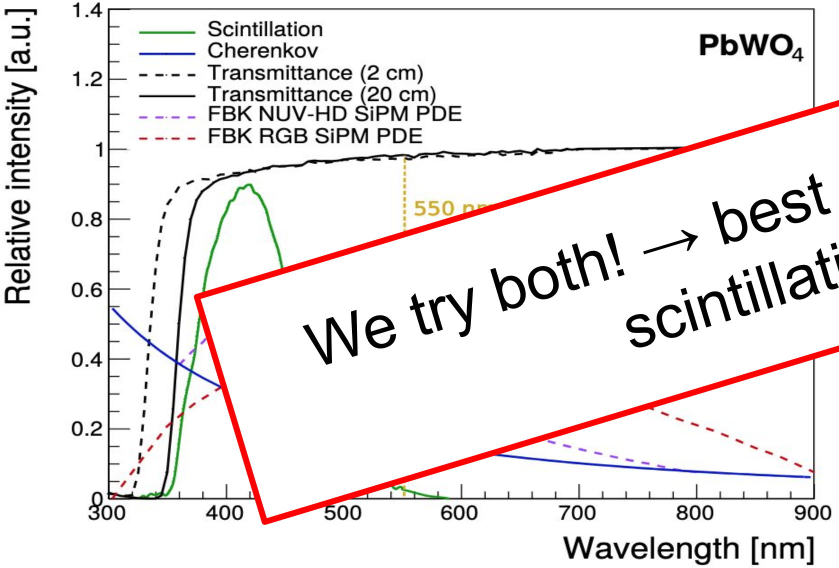

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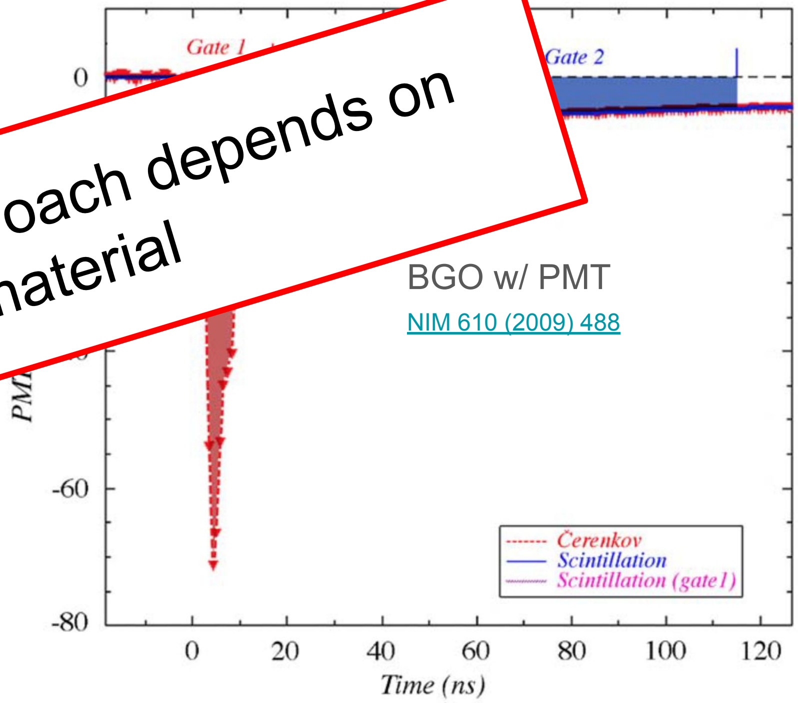


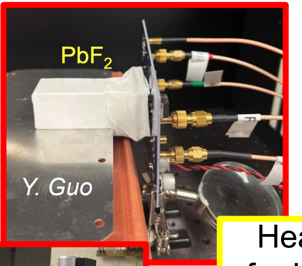
We try both! → best approach depends on scintillating material

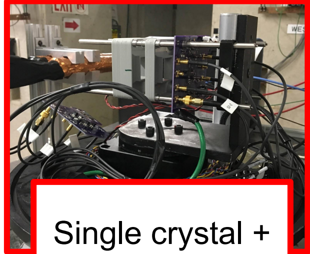
CalVision/MaxiCC - DR for e+e- colliders

Consortia of universities and labs

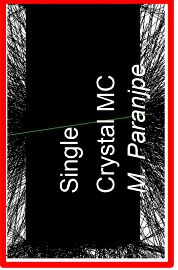
CalVision/MaxiCC - DR for e+e- colliders

Variety of research areas!

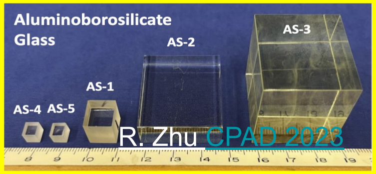




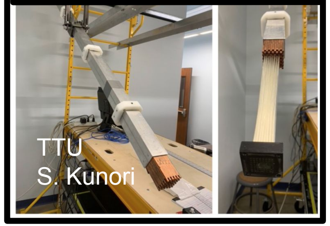
Single crystal + matrix studies



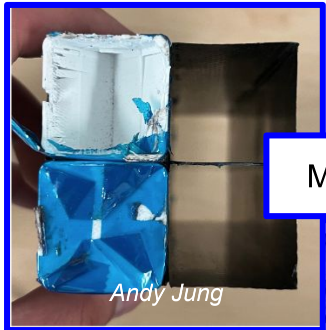
Heavy Glasses for Homogenous HCAL



DR Fiber HCAL

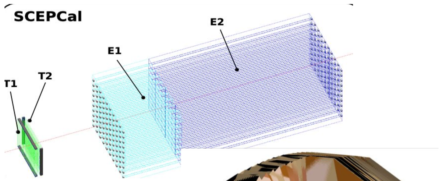


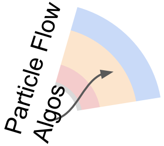
Mechanics

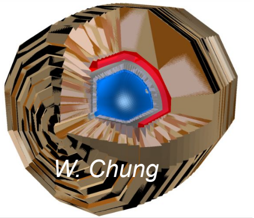


Detector sim

2020 JINST 15 P11005

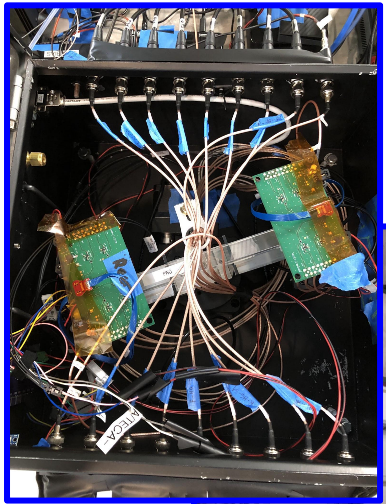




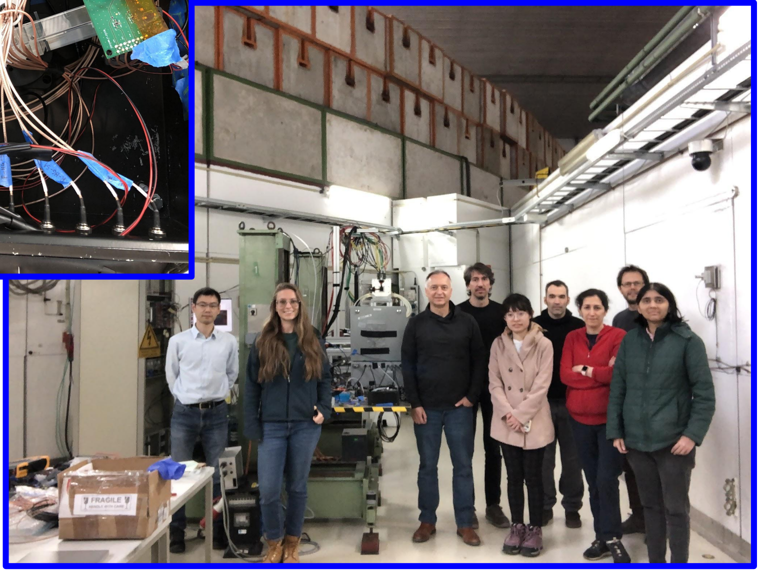


Test Beams

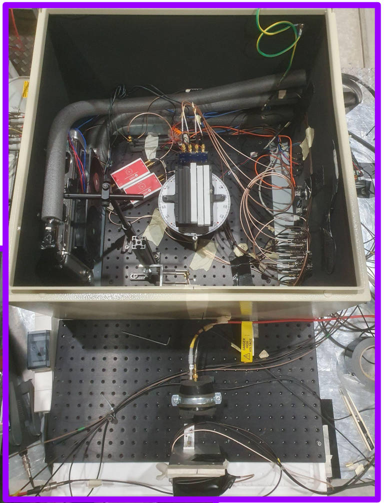
Most Recent Results: Two 2024 test beams



DESY April 2024



CERN August 2024



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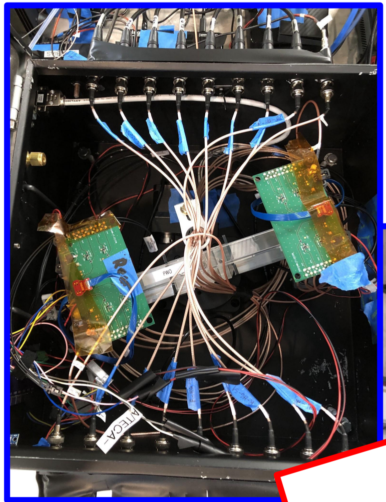

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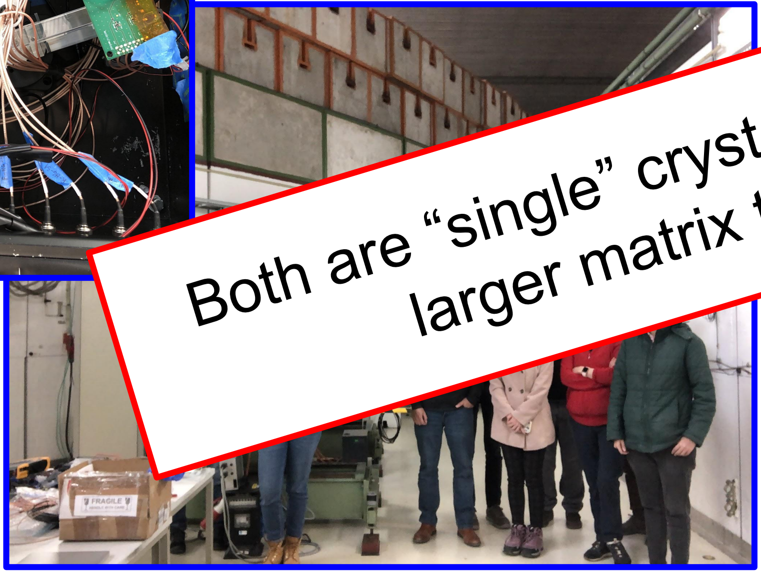
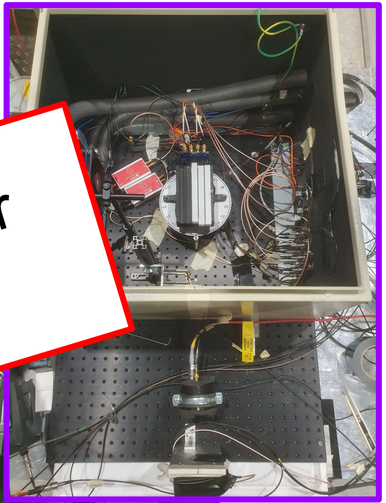


CERN August 2024

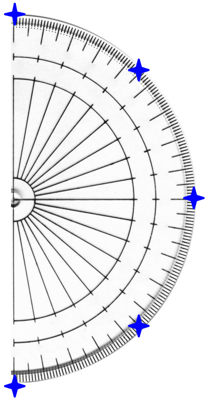


Both are "single" crystal tests to prepare for larger matrix tests this year!

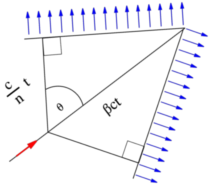
Test Beam overview

Similarities between both

- Crystal material and some filters!
- ***Angle scans***



Cherenkov inherently directional!



Ratio of Cherenkov to Scint will vary with angle -- if truly accepting Cherenkov!

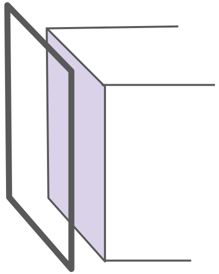
Differences

- Beam characteristics
  - DESY v. CERN
- Crystal setup
  - size, shape, type
  - readout particulars
- ***Filter-only v. waveform separation prioritization***

DESY CalVision: Dual-end 4 SiPM Readout

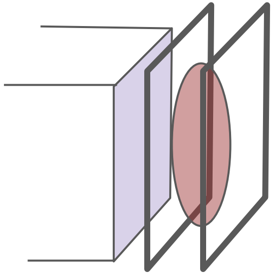
- 2 GeV Electron Beam
- **4** Broadcom 6x6 mm SiPMs **per end**
- Prioritized configurability
  - tested many crystal/filter combinations
  - used same SiPMs for each

"front" → Scint Channels



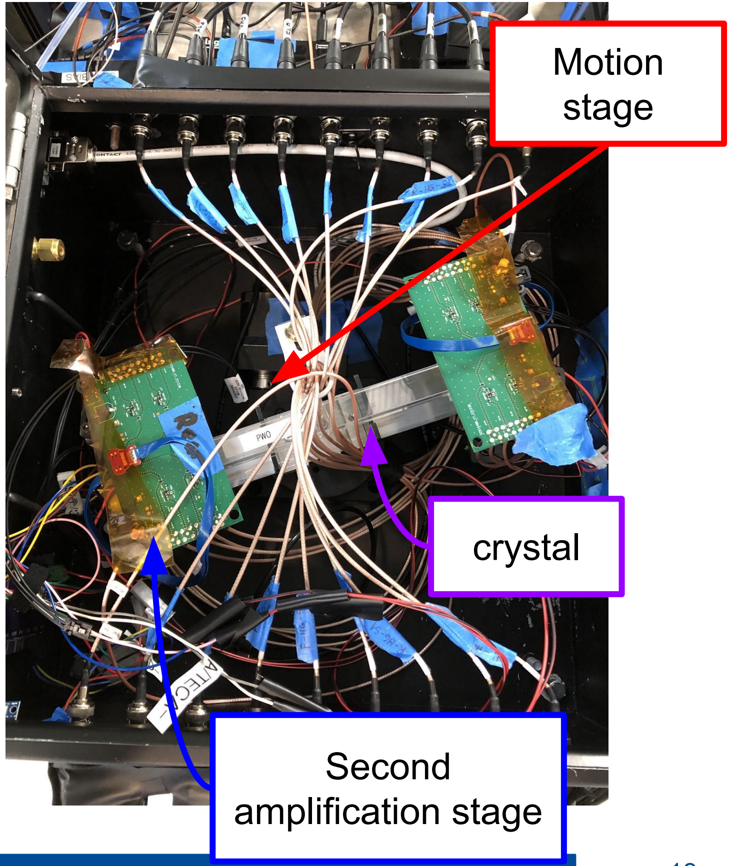
Crystal → cookie → SiPMs (not pictured)

"rear" → Cherenkov Channels



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

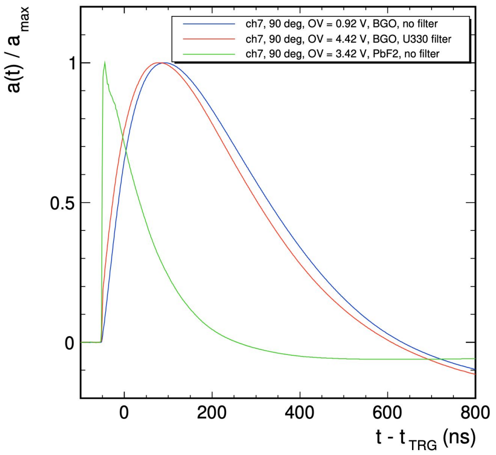
All SiPMs covered



3 Results to showcase today

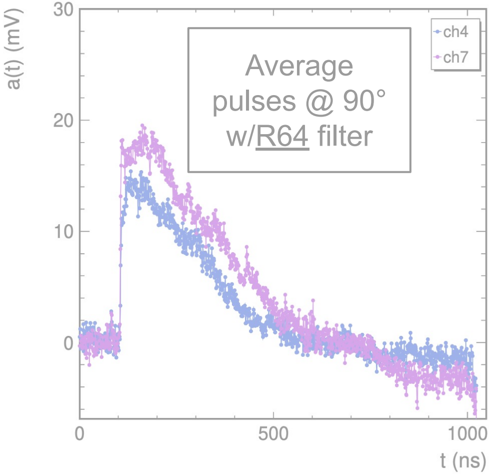
BGO

- 2.5 cm x 2.5 cm x 18 cm
  - ~16 X_0
- “rear” channels: Hoya U330 filter
- “front” unfiltered for scint-only



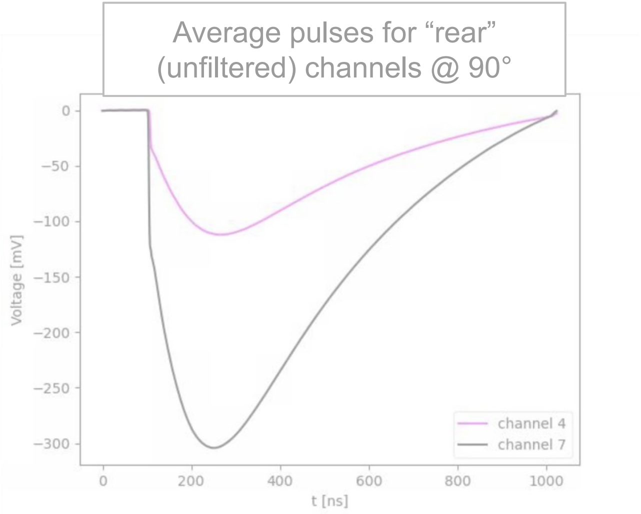
DSB Glass

- $BaO+SiO_2+Ce_2O_3+Gd_2O_3$
- 2 cm x 2 cm x 15 cm
  - ~6 X_0
- “rear” channels: Hoya R64 filter
- “front” unfiltered



ABS Glass

- $B_2O_2+SiO_2+Al_2O_3+Ce_2O_3+Gd_2O_3$
- 2.5 cm x 2.5 cm x 6 cm
  - ~4 X_0
- unfiltered runs best!



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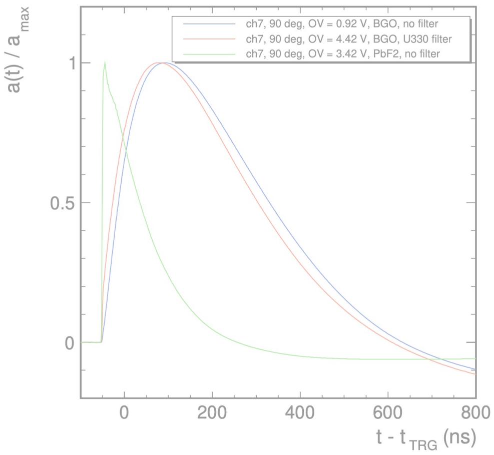

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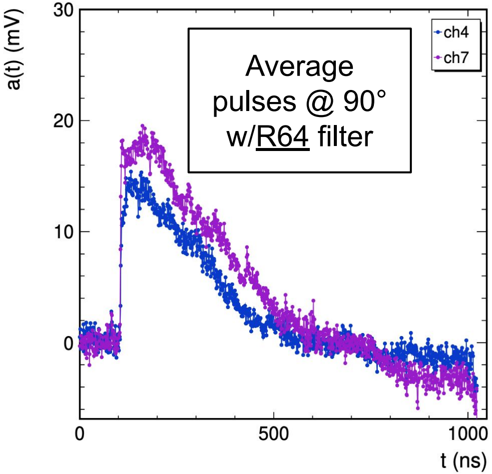

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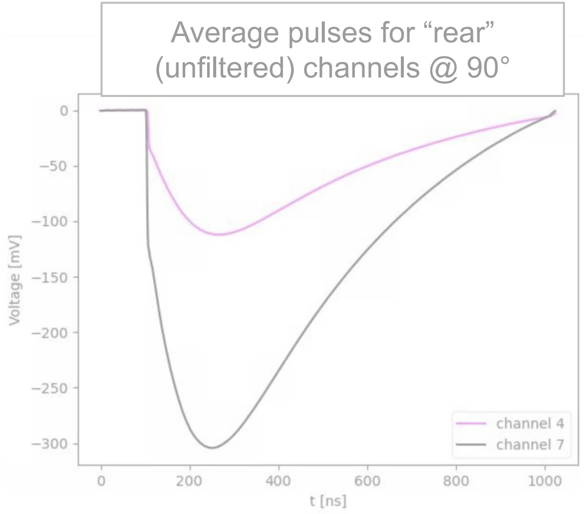

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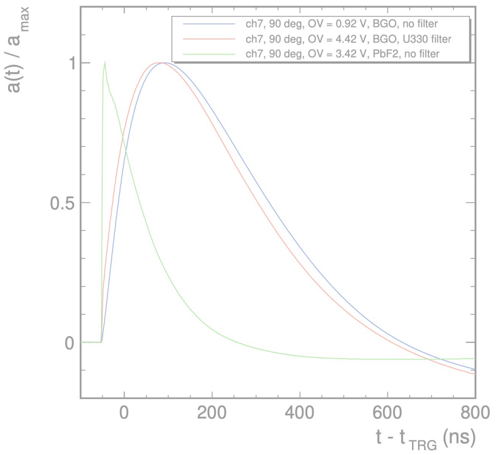

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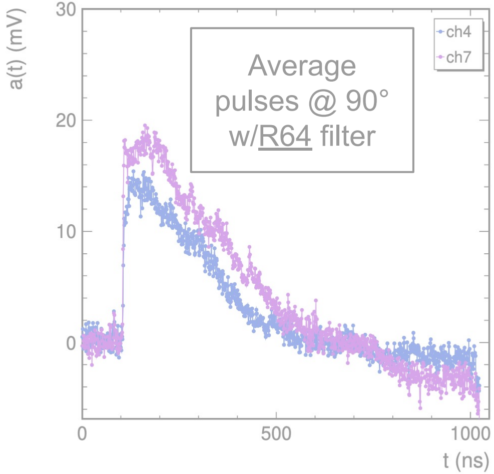

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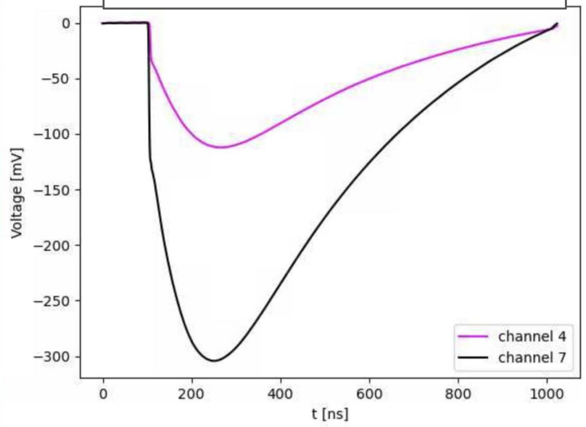
Average pulses for “rear” (unfiltered) channels @ 90°



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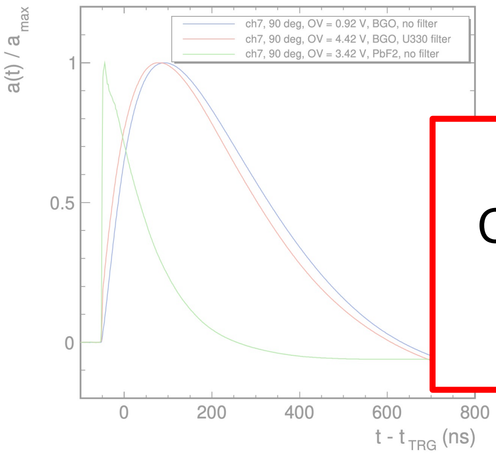
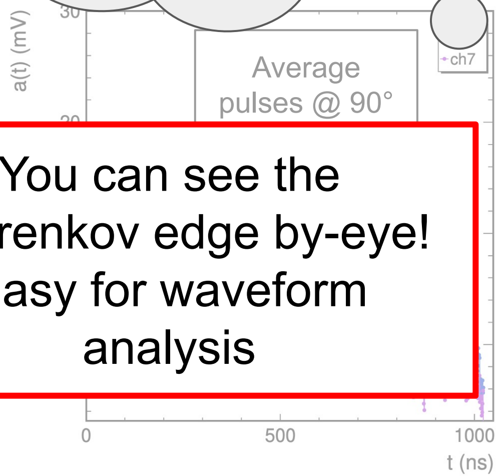


DSB Glass

lter
t-only

Analysis ongoing!



You can see the Cherenkov edge by-eye! Easy for waveform analysis

ABS Glass

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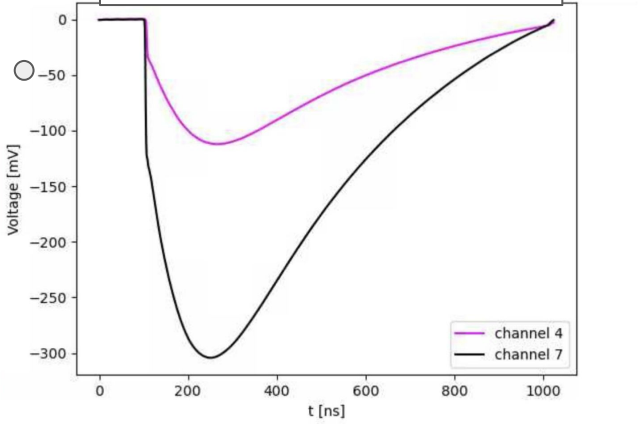

3 Results to showcase today

first time heavy glasses have been used in a beam test! Targets a homogenous HCAL

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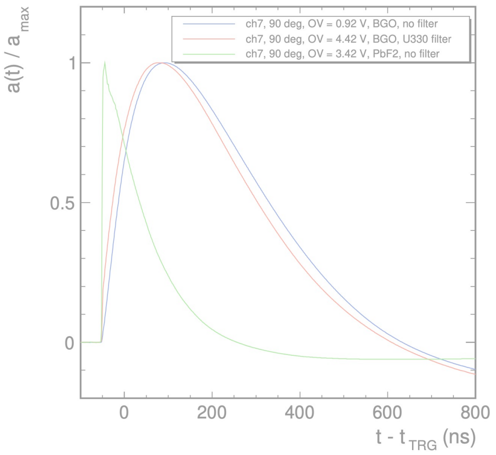

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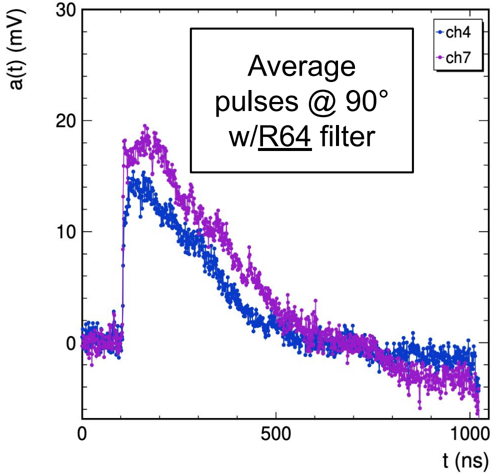

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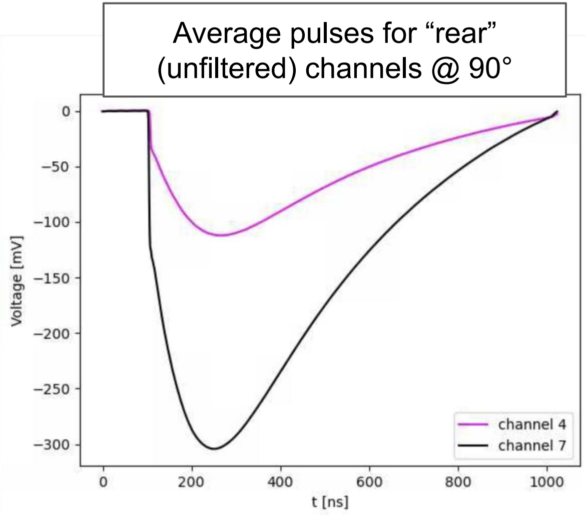
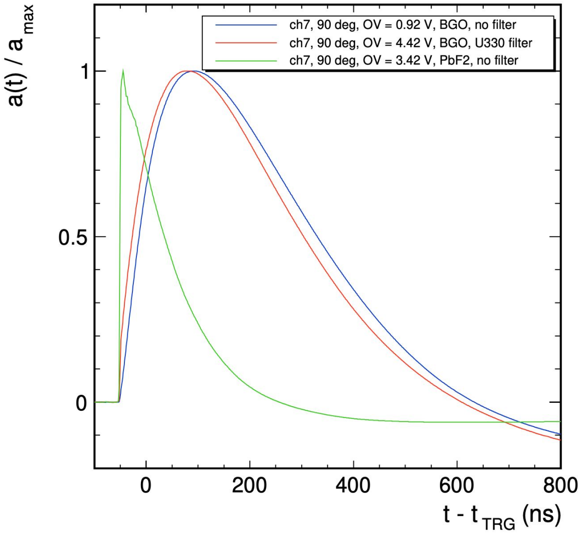
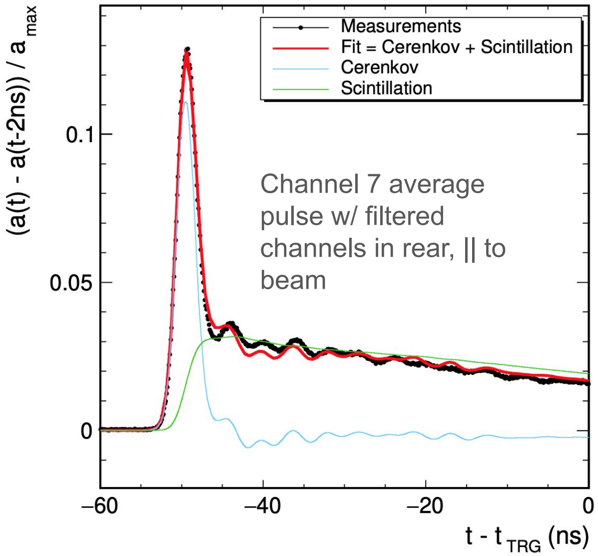


DSB and ABS Properties: Ren-Yuan Zhu's CPAD2023 talk

BGO (Bismuth Germanate)

- Electronics shaping poor → need to differentiate pulse to see Cherenkov peak
  - 2 ns Single Delay Line technique
- Can then fit Cherenkov and Scintillation contributions

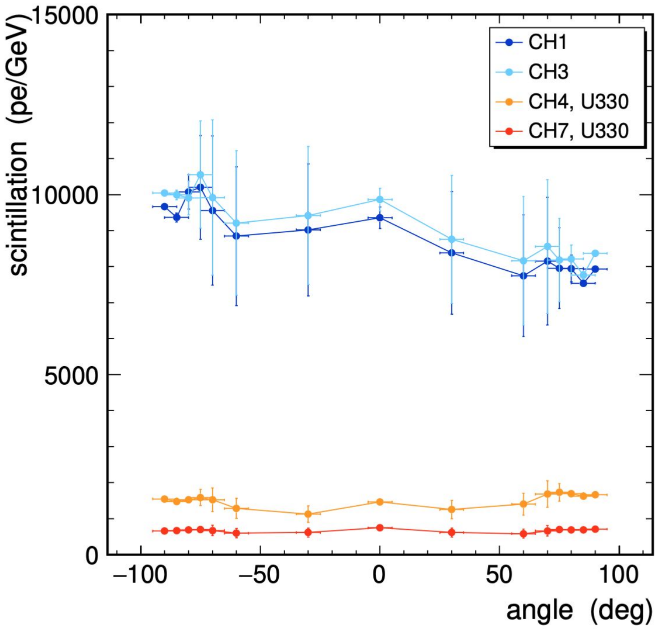


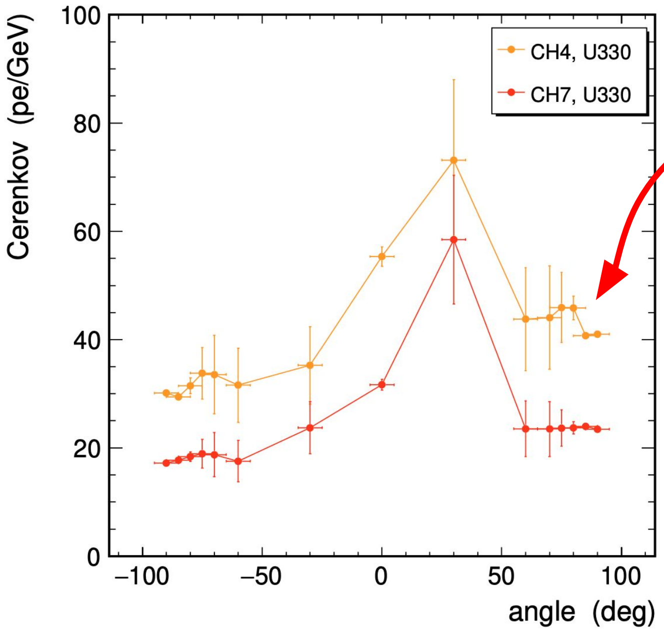


Channel 7 average pulse w/ filtered channels in rear, || to beam

BGO SDL Analysis

Light yield = (amplitude from fit * $a_{max,MPV}$) / (A1pe * $E_{deposit,MPV}$)





Let's be optimistic!

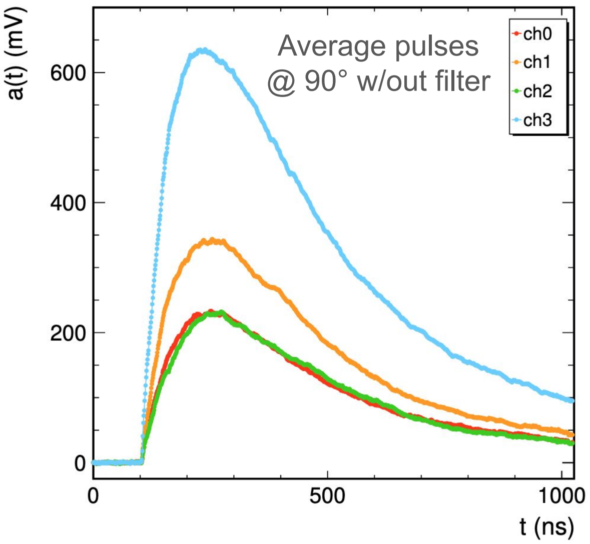
at 90°

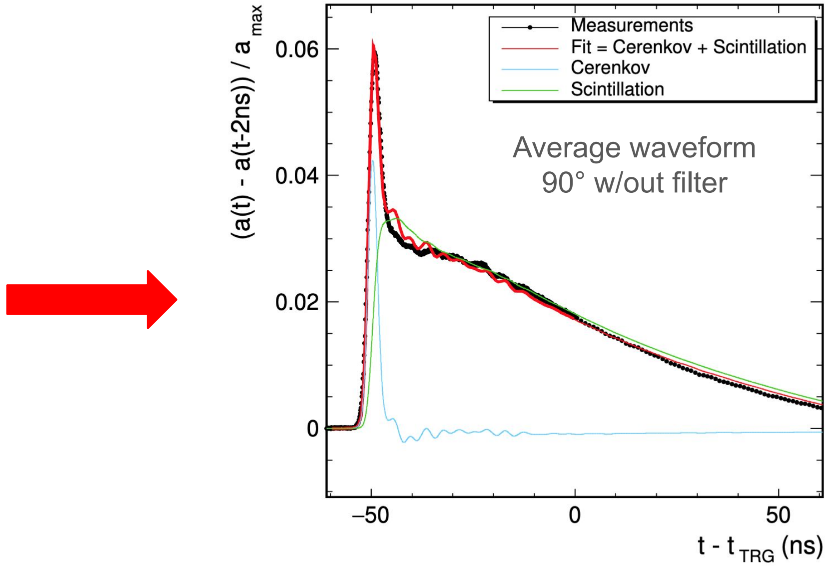
Ch4*4 = **160 pe/Gev**
(Ch4+Ch7)*2 = **120 pe/GeV**

DSB-3 (Barium Disilicate) Scintillating Glass

DSB Properties: Ren-Yuan Zhu's [CPAD2023 talk]

- Scintillating glass
  - Some admixture of $BaO+SiO_2+Ce_2O_3+Gd_2O_3$





DSB-3 SDL analysis

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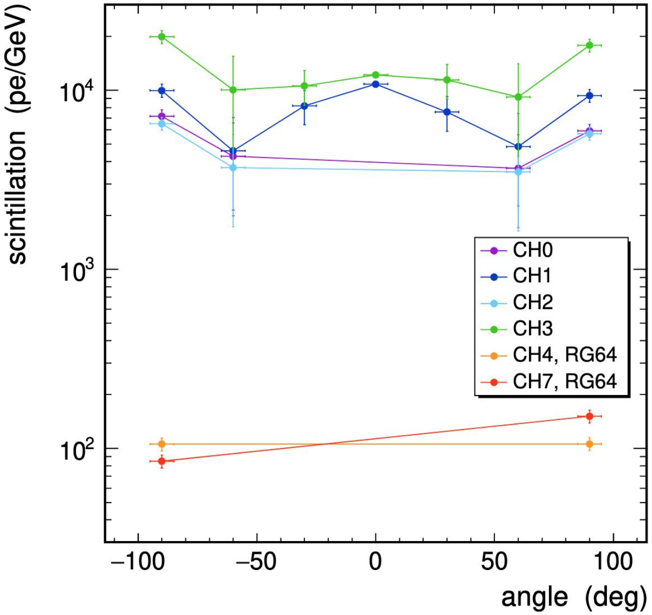
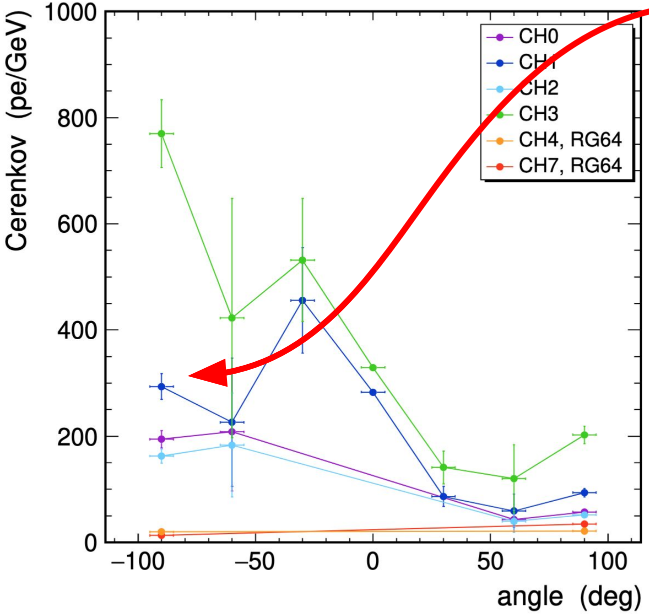


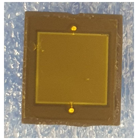


~1000 Cherenkov pe/GeV (if our Geant model of DSB is correct)!

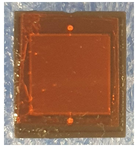
First time this glass has been put in beam!

CERN MaxiCC Test beam setup 1

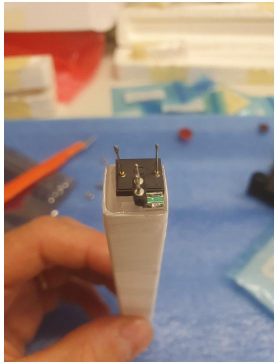
- Beams tested
  - mixed hadrons 120 GeV
  - electrons 10 GeV (E scan up to 100 GeV)
  - Muons 120 GeV
- PWO 1.3 cm x 1.3 cm x 15 cm
- 2 SiPMs on "rear"
  - small 3 mm x 3 mm for Scint (no filter)
  - 6 mm x 6 mm for Cherenkov w/ filter
- Kodak thin film 8 and 24 filters
- SCEPCAL prototype run
  - 2 crystals -- segmentation
- straight light yield interpretation

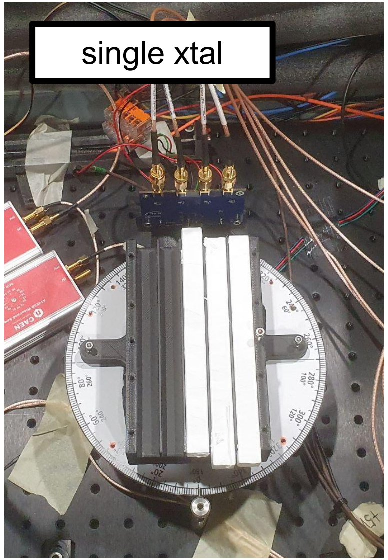


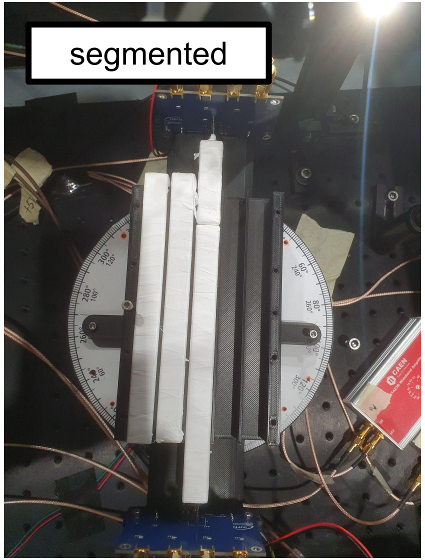
Kodak-8: 490 nm long pass



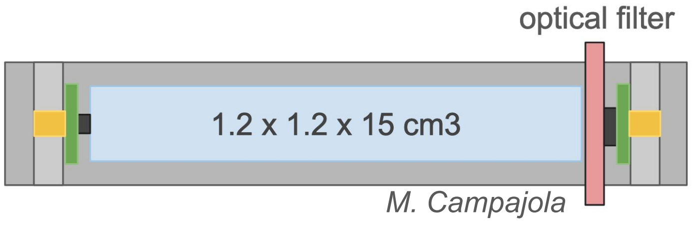
Kodak-24: 590 nm long pass (< 1% scint transmission)



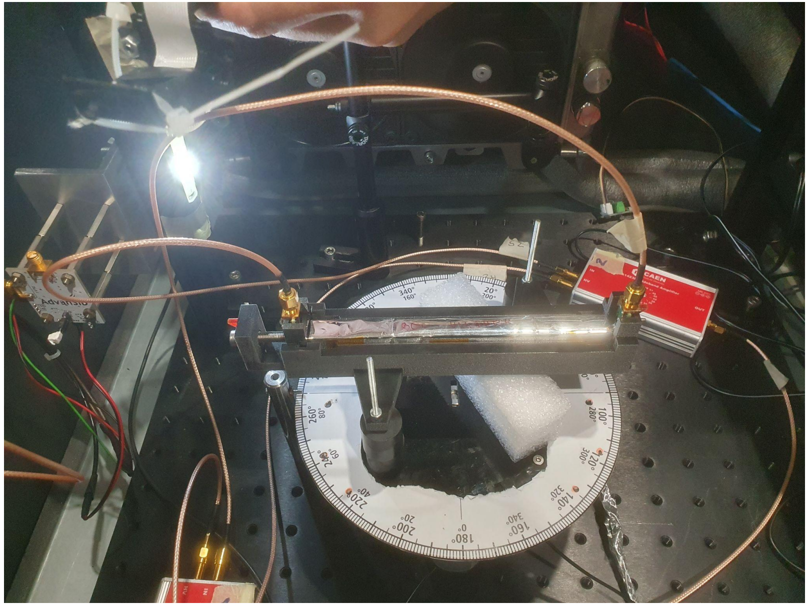




CERN MaxiCC Test beam setup 2



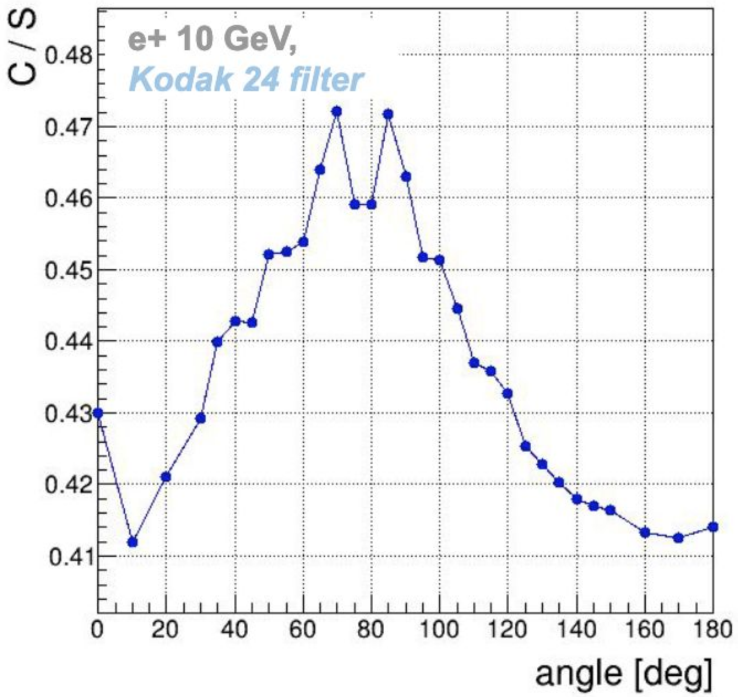
- Beams tested
  - electrons 10 GeV /20 GeV
  - Muons 120 GeV
- Multiple crystals/filters
  - 1.2 cm x 1.2 cm x 15 cm crystals
  - BGO w/ Schott UG11
  - BSO w/ Schott UG11
  - PWO w/ many different long-pass
  - CsI (Ti) w/ Schott UG11
- Dual ended HPK SiPM readout
  - “front” 3 mm x 3 mm for scintillation
  - “back” 6 mm x 6 mm for Cherenkov
- direct yield AND waveform analysis



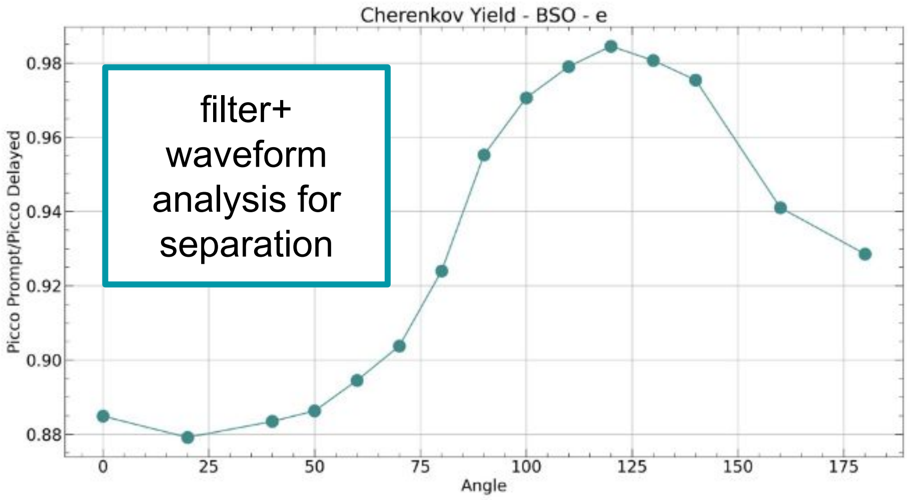
CERN Test beam analysis results

Both show clear Cherenkov acceptance!

setup 1



setup 2



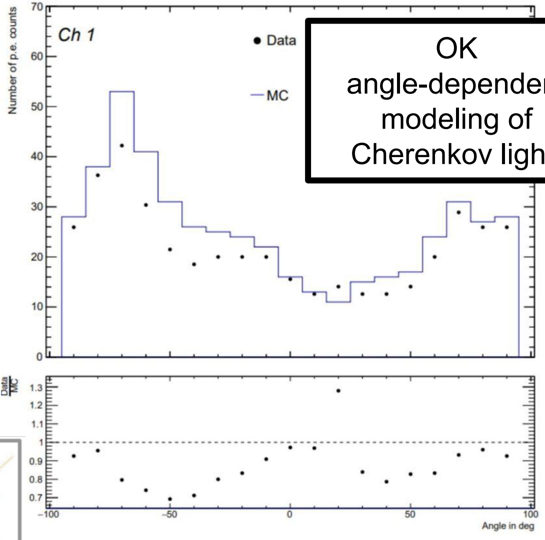
filter+ waveform analysis for separation

Simulation

Test Beam setup simulation

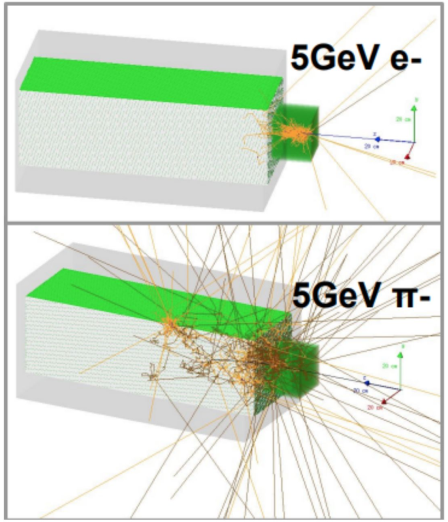
- Extensive single-crystal development
  - PbF_2 modeling paper for Cherenkov acceptance
  - Position dependence in BGO
- Moving to crystal matrix + Dual Readout HCAL
  - segmented crystal front
  - different crystals
  - fiber or sandwich DR HCAL back
- In DD4HEP framework

arXiv:2407.08033v1

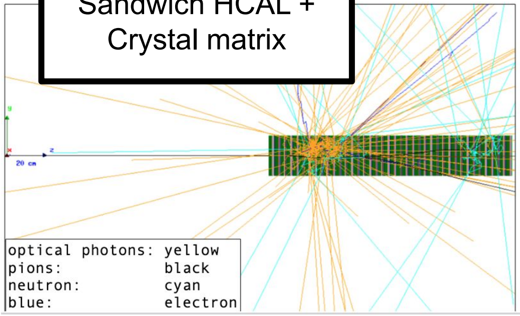


OK angle-dependent modeling of Cherenkov light!

Fiber HCAL + Crystal matrix



Sandwich HCAL + Crystal matrix

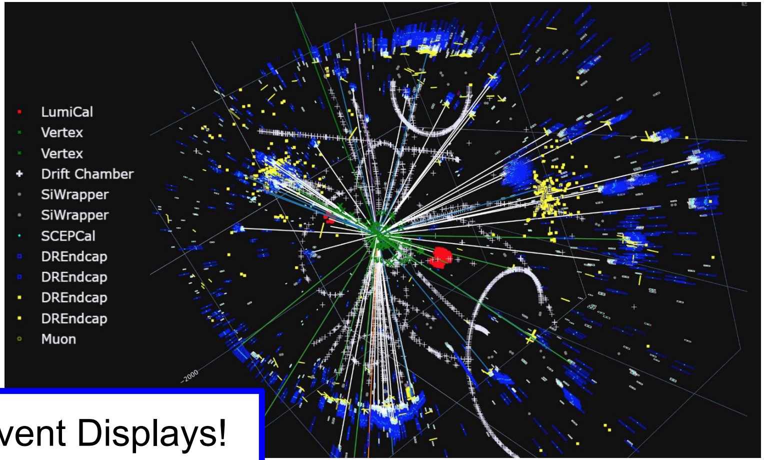


Full Detector Simulation

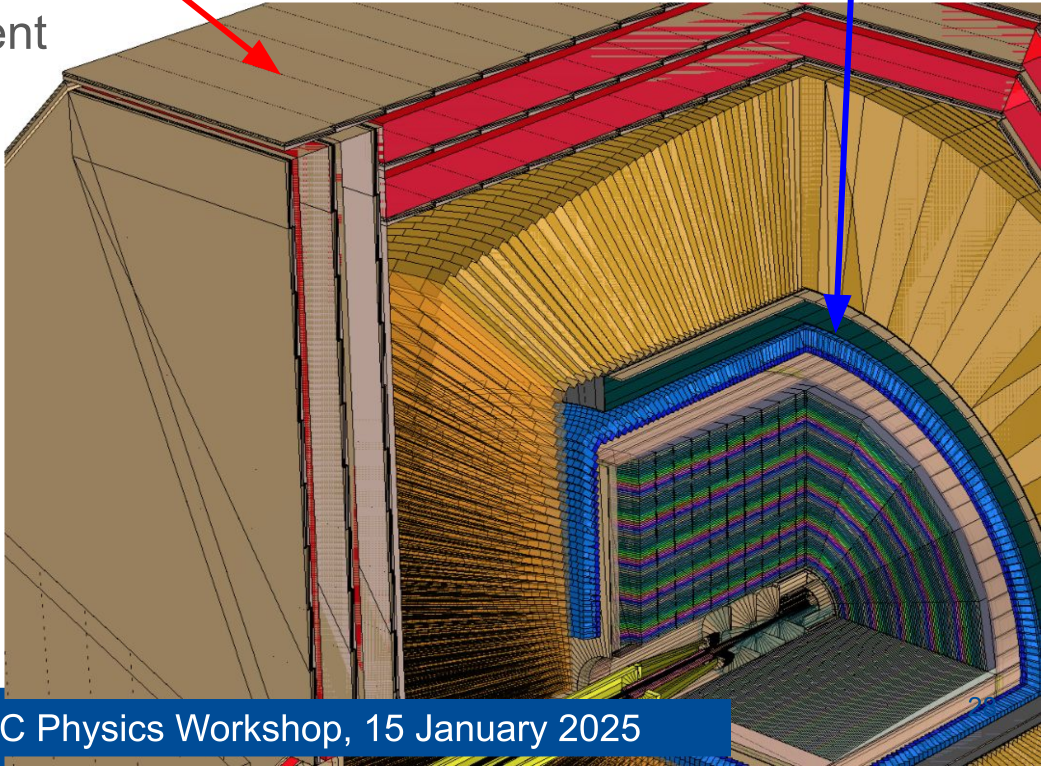
arXiv:2408.11027

- Fully differentiable crystal ECAL **implemented in key4HEP**
  - integrated into the **IDEA detector** concept
  - working on fleshing out DR capabilities
- Lots of reconstruction development
  - Particle Flow
  - ML photon energy regression

Crystal ECAL!

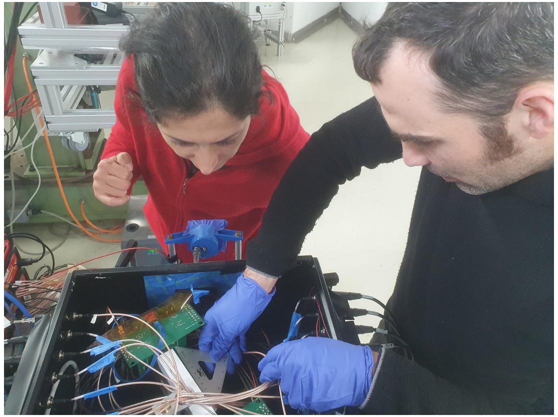


Event Displays!



Summary and future plans

- Test beams promising!
  - DESY test beam comfortably surpasses goal of > 50 Cherenkov photoelectrons / GeV
    - BGO
    - DSB glass for homogenous HCAL
  - CERN test beams pioneering segmentation and guiding SiPM choices for matrix prototype
- Matrix tests for full containment - 2025 is the start!
  - CalVision building a BGO matrix with 4 SiPM readout
    - more granular front segment than rear
  - MaxiCC building a PWO matrix w/ improved SiPMs from test beam results
- Simulation maturing
  - crystal ECAL integrated into Key4HEP
  - Full DR test beam modules implemented in GEANT4

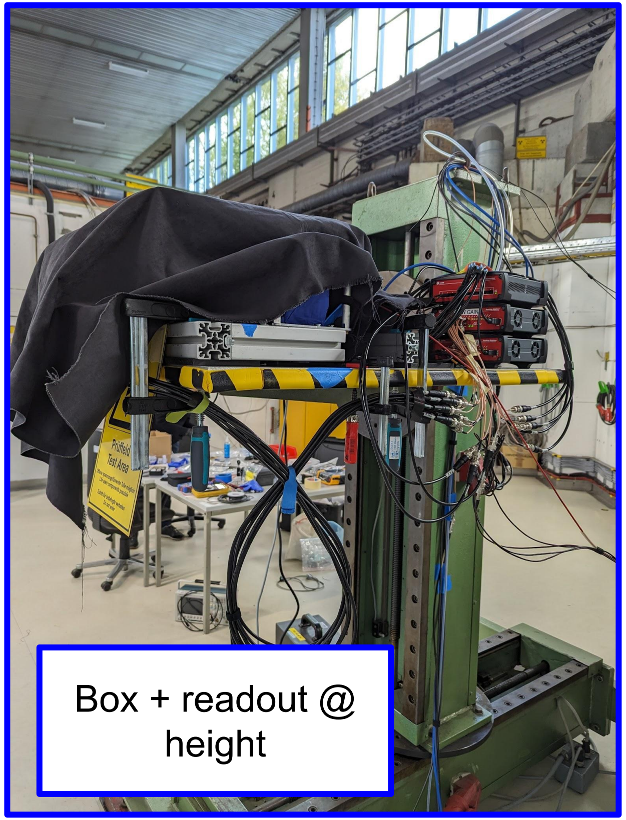


back-up

DESY Test beam campaign parameters

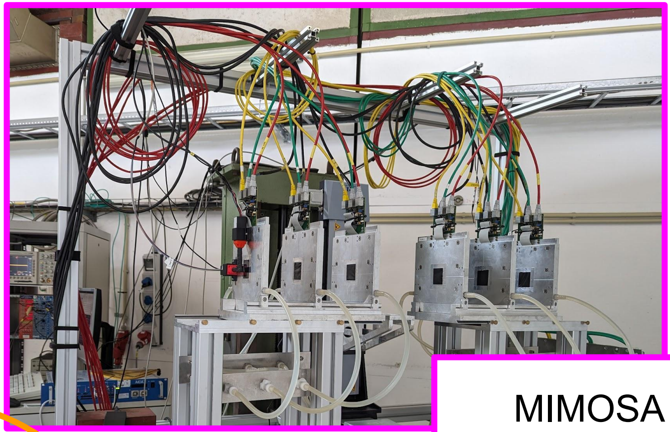
- Electron beam
  - most data taken @ 2 GeV (highest rate)
- ~60,000 events per measurement (w/ telescope)
  - ~3 minutes
  - ~400 Hz DAQ rate
- DRS-based readout
  - 1 GHz sampling (1000 ns)
- Angle Scans
- Integrated with Silicon telescope

DESY Test beam setup

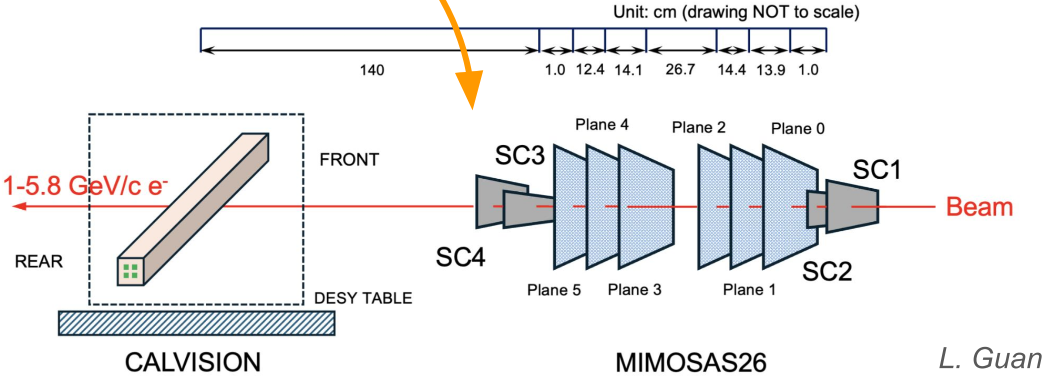


Box + readout @ height

Trigger scint panels (1 cm x 1.5 cm)



MIMOSA Si telescope

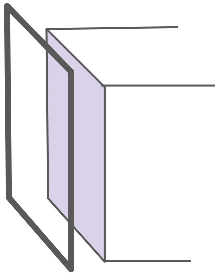


L. Guan

DESY CalVision: Dual-end 4 SiPM Readout

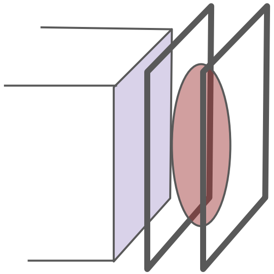
- 2 GeV Electron Beam
- **4** Broadcom 6x6 mm SiPMs **per end**
- Prioritized configurability
  - tested many crystal/filter combinations
  - used same SiPMs for each

“front” → Scint Channels



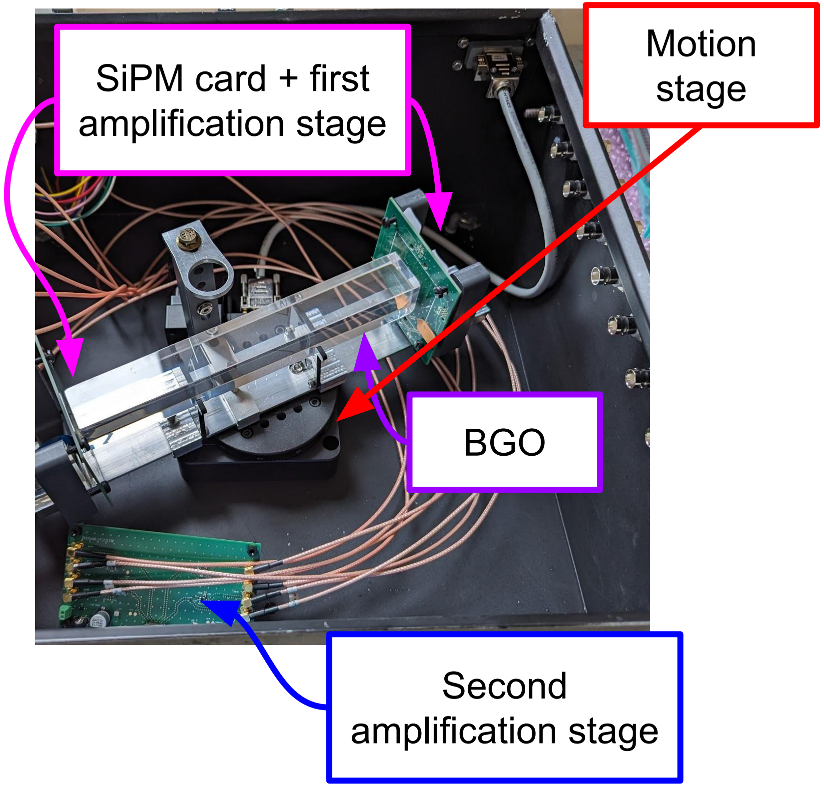
Crystal → cookie → SiPMs (not pictured)

“rear” → Cherenkov Channels

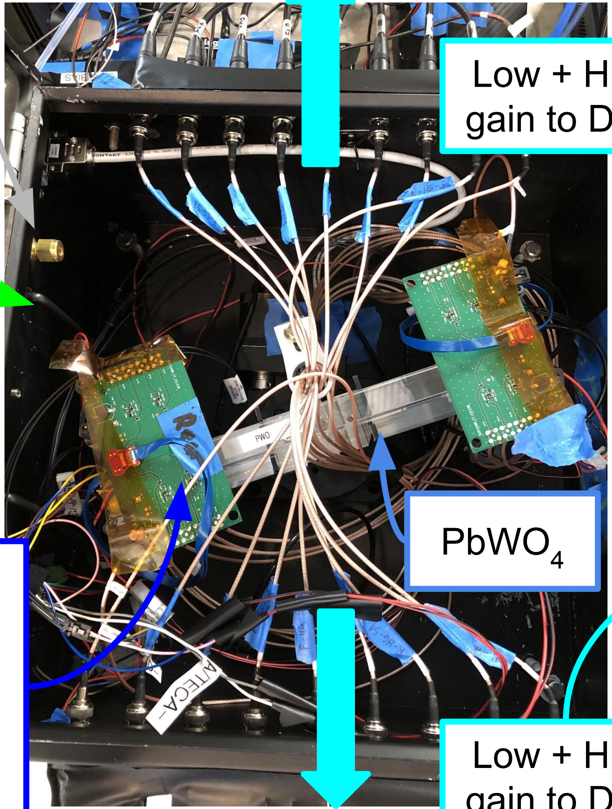


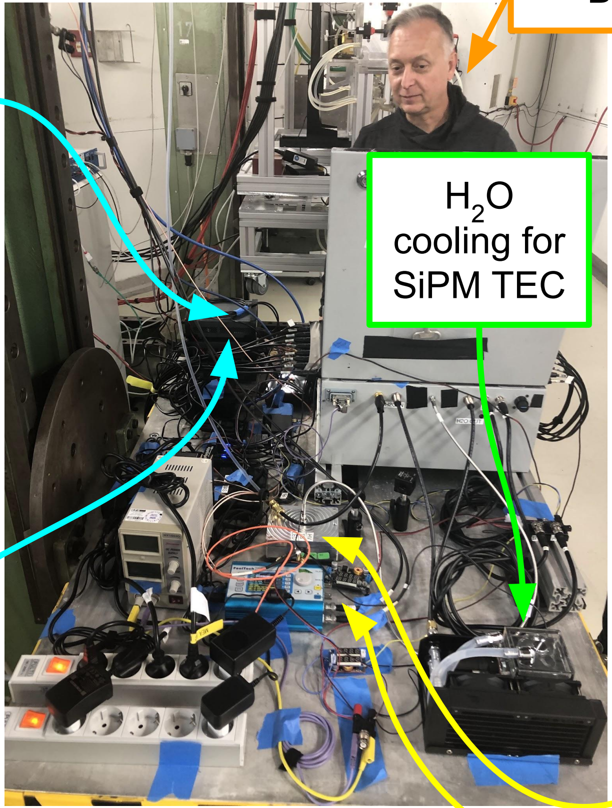
Crystal → cookie → filter → cookie → SiPMs (not pictured)

All SiPMs covered



Support structures





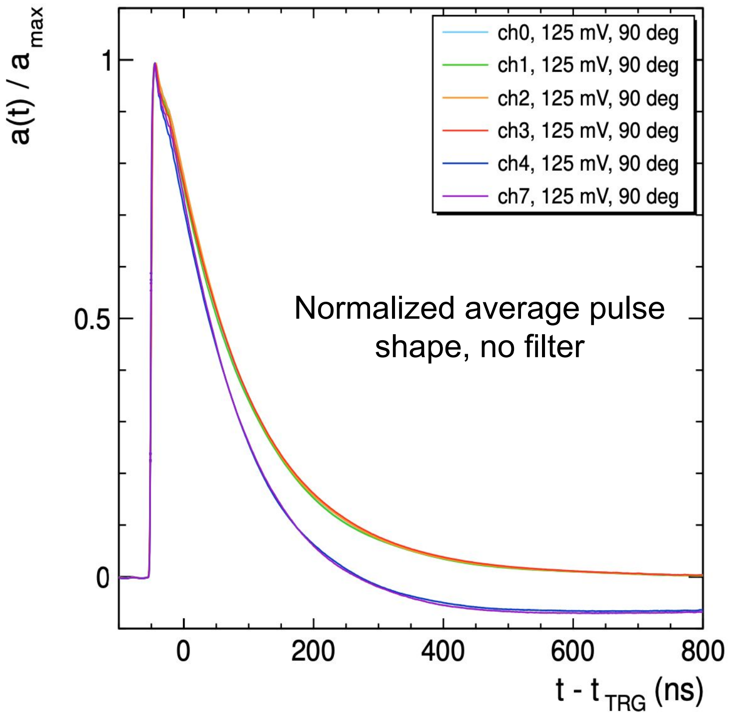
PbF_2

- directly measure Cherenkov acceptance and signal shape
- 36 $V_{bias} \rightarrow$ 3.5 V_{over}

ch0	ch1	ch2	ch3	ch4	ch7
0.512	0.430	0.473	0.406	0.465	0.565

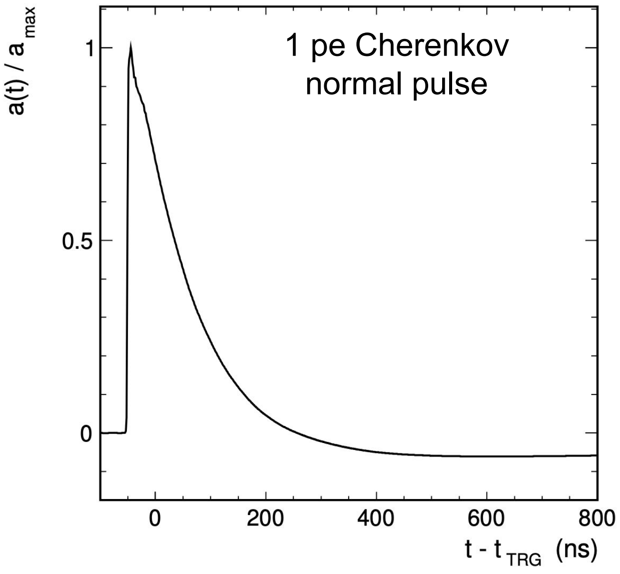
Table 3.1: Amplitude of 1 pe in mV at bias voltage of 36 V

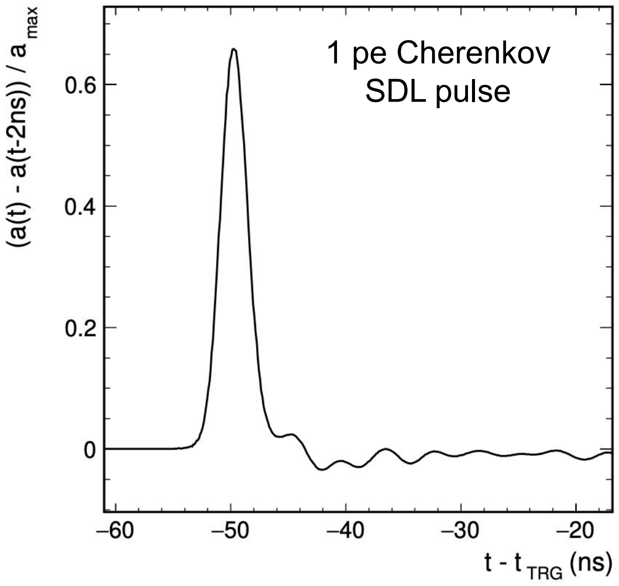
$$Npe = A_{max}/A_{1pe}$$



The Single Delay Line (SDL) method - take a derivative

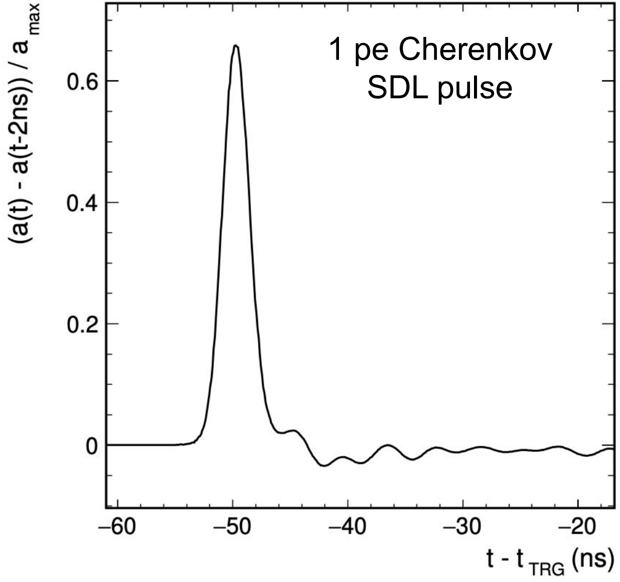
- 2 ns delay
- Cherenkov 1 PE shape from PbF_2

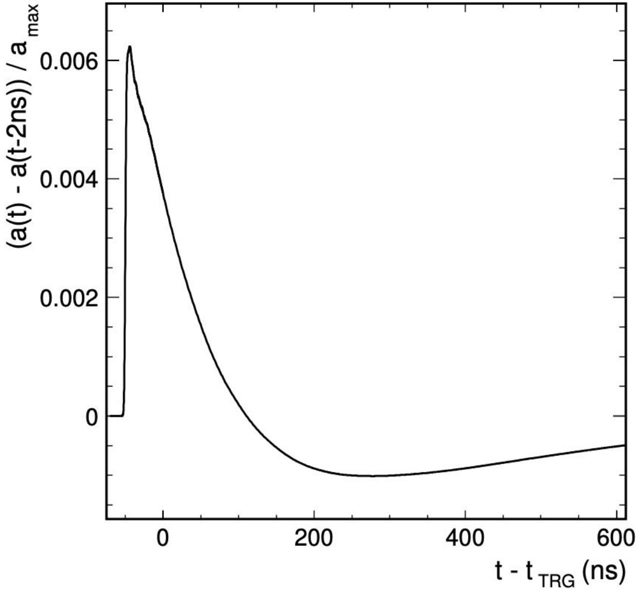




The Single Delay Line (SDL) method - take a derivative

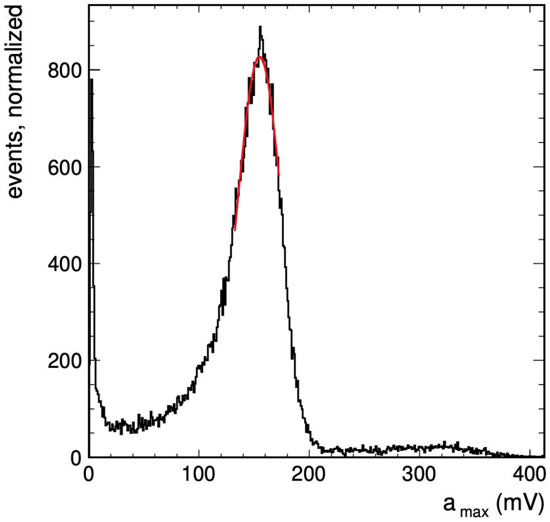
- 1 pe scintillation shape → convolute 1 pe Cherenkov w/ $y = \frac{1}{\tau}\exp\left(-\frac{t}{\tau}\right)$
  - w/ τ = 314 ns → decay time of BGO





BGO SDL Analysis

- Build average SDL pulse at most probable amplitude for rear channels to extract photoelectrons per energy



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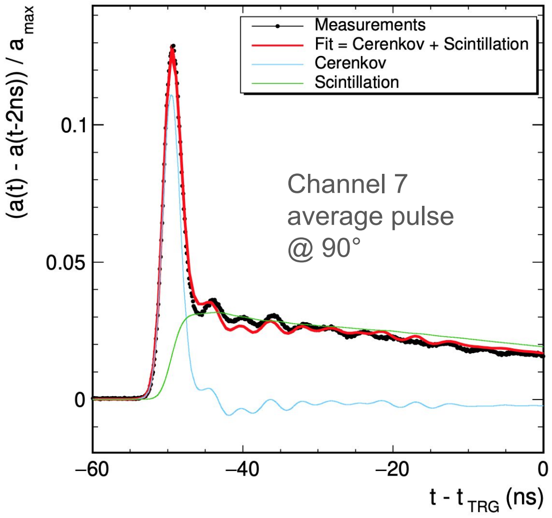

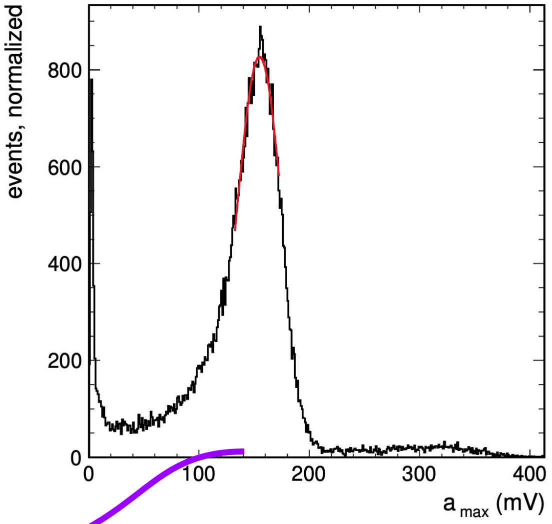

BGO SDL Analysis

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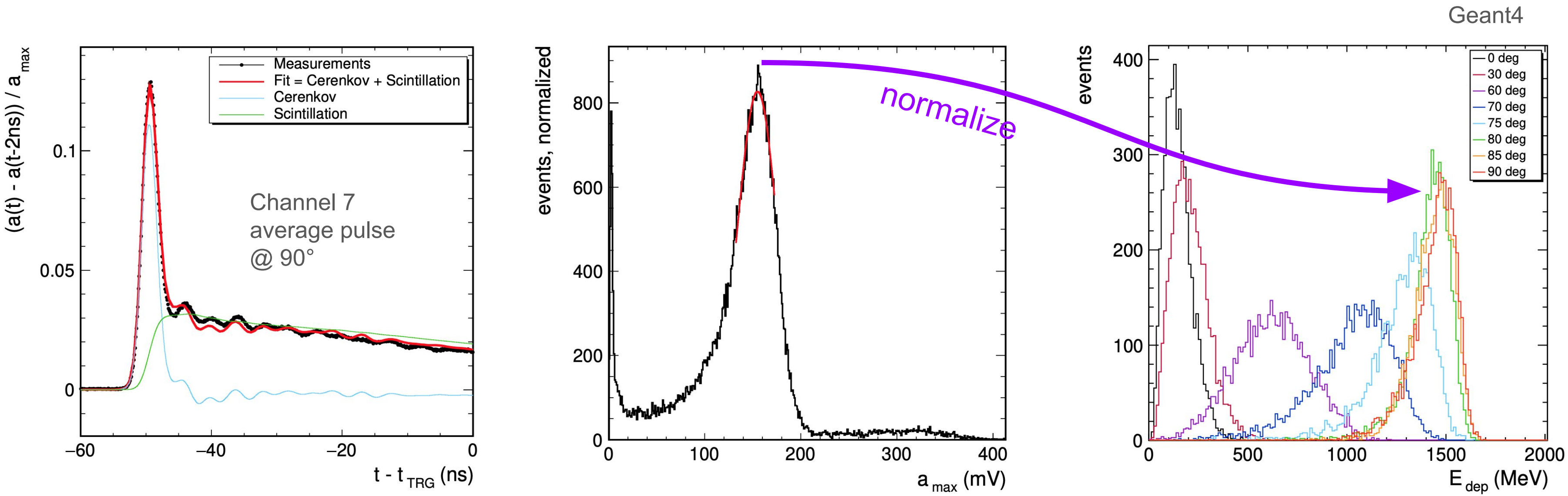
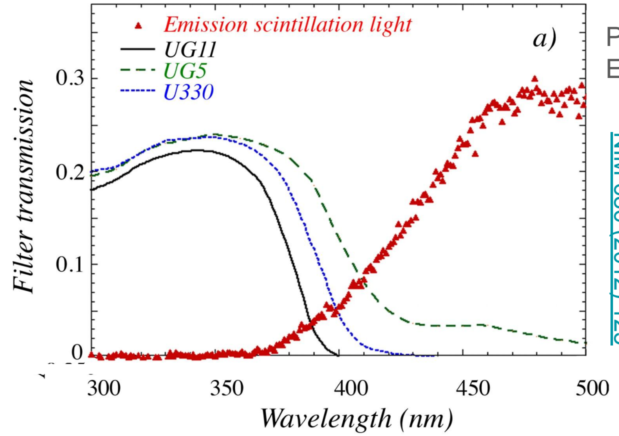


Previous homogenous DR attempts

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



PWO Scint Emission

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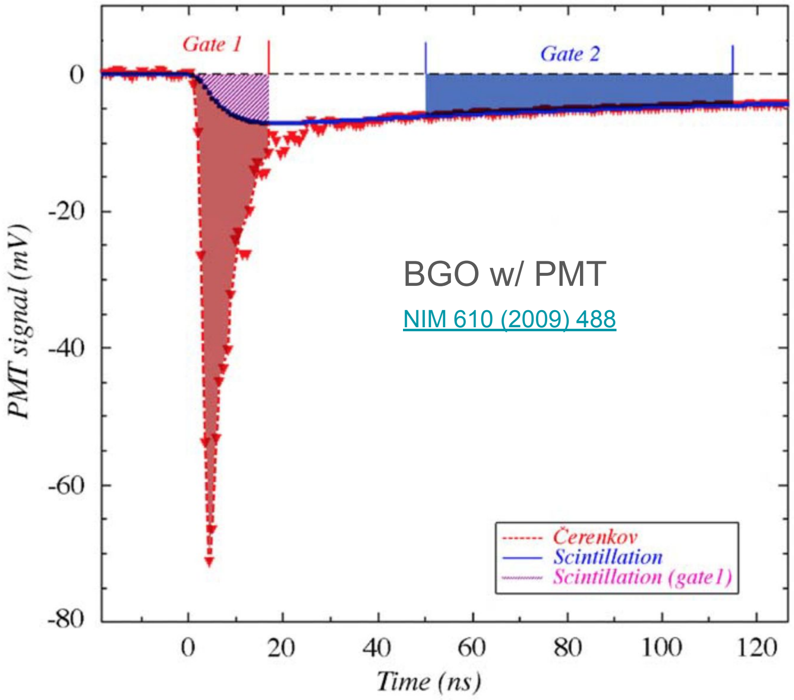
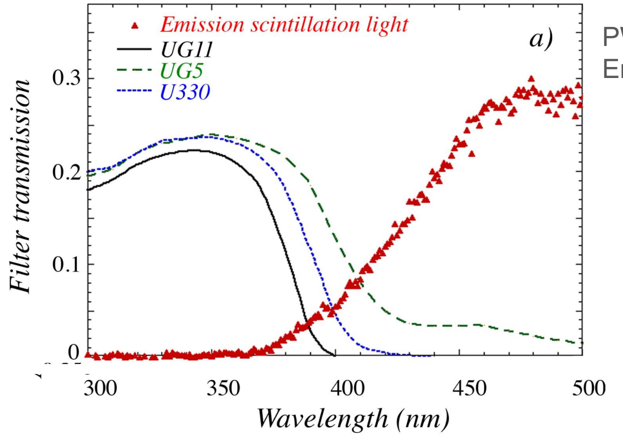
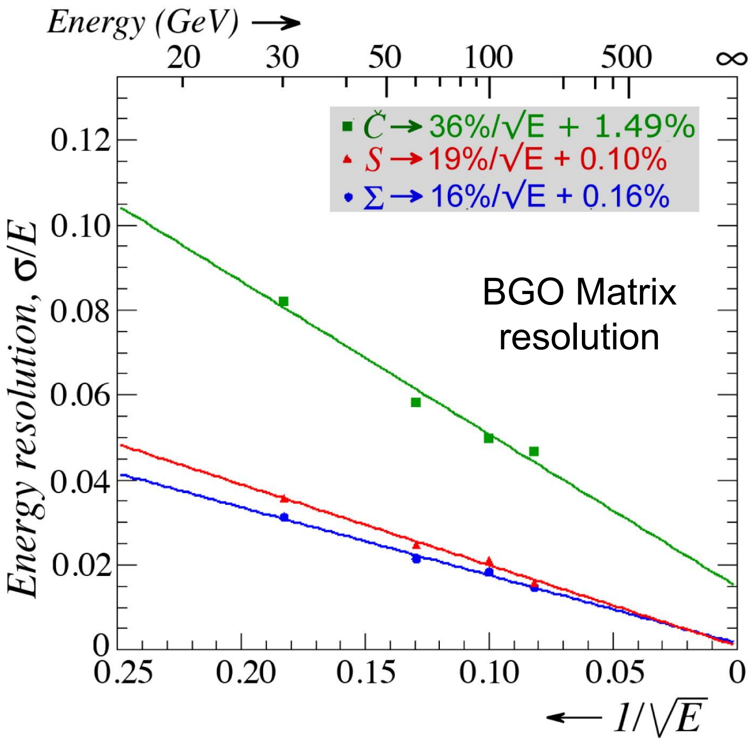


Previous homogenous DR attempts

- 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



PWO Scint Emission



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