FERMILAB-SLIDES-25-0177-CMS

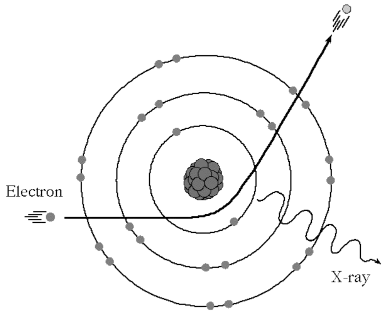
Dual readout in homogenous inorganic scintillators for precision calorimeters

Thomas Anderson, Andrea Benaglia, Karl Bue, *Grace Cummings*, Tim Edberg, Sarah Eno, Liang Guan, Yuxiang Guo, Bob Hirosky, Hayden Hollenbeck, Daniel Levin, Alexander Ledovskoy, Hui-chi Lin, Marco Lucchini, Christopher Martin, Sara Nabili, Mekhala Paranjpe, Jianming Qian, Junjie Zhu

US Muon Collider Workshop, 08 August 2025

Calorimetry in one slide

Electromagnetic Calorimetry



Electrons like to interact.

Whatever layer is first is your ECAL.

Hadron Calorimetry

Need a strong interaction →
need lots of stuff. And dense stuff if you are reasonable!

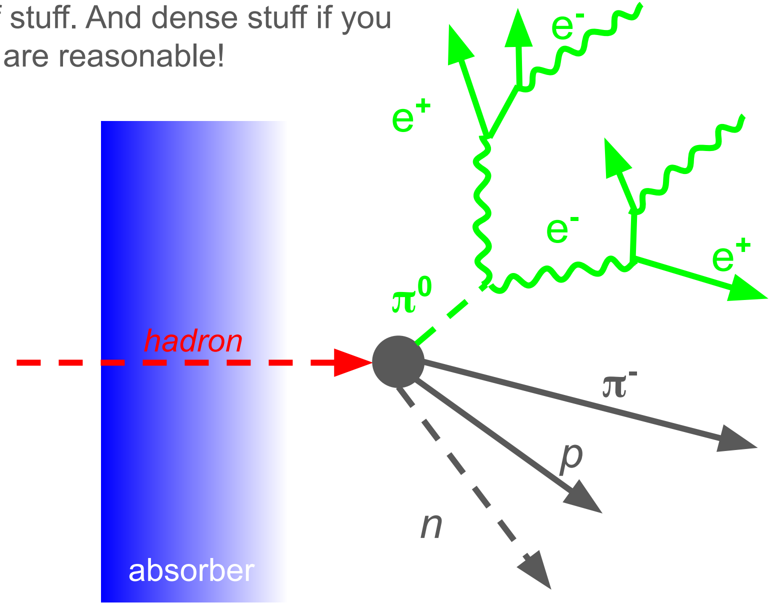
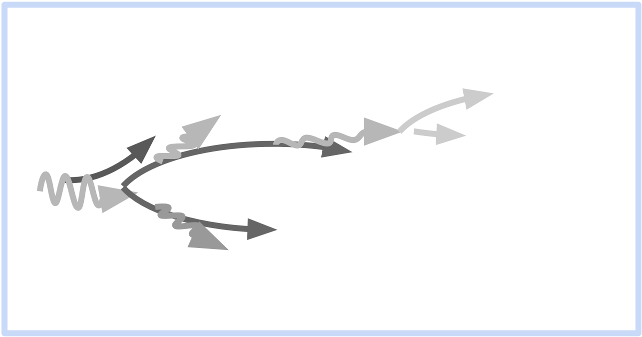


Figure adapted from Sehwook Lee 2019 *J. Phys.: Conf. Ser.* **1162** 012043

The two styles

Homogenous

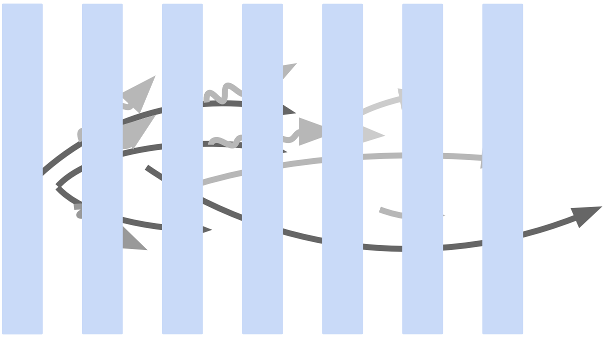
- Everything captured



Great for electrons and photons that deposit all readily deposit energy via ionization

Sampling

- Only get snapshots of the shower

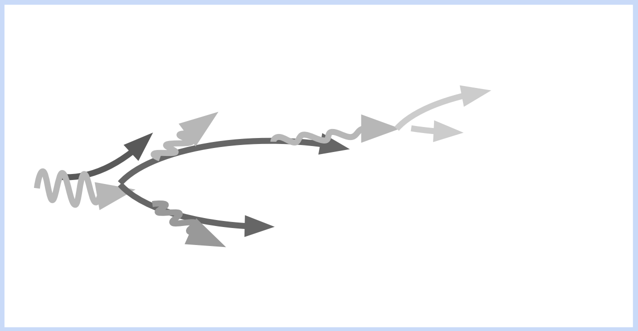


Great for hadrons because you can interleave really dense layers, and pay for a lot of them

Scintillating crystals for electromagnetic calorimetry

Homogenous

- Everything captured



Great for electrons and photons that deposit all readily deposit energy via ionization

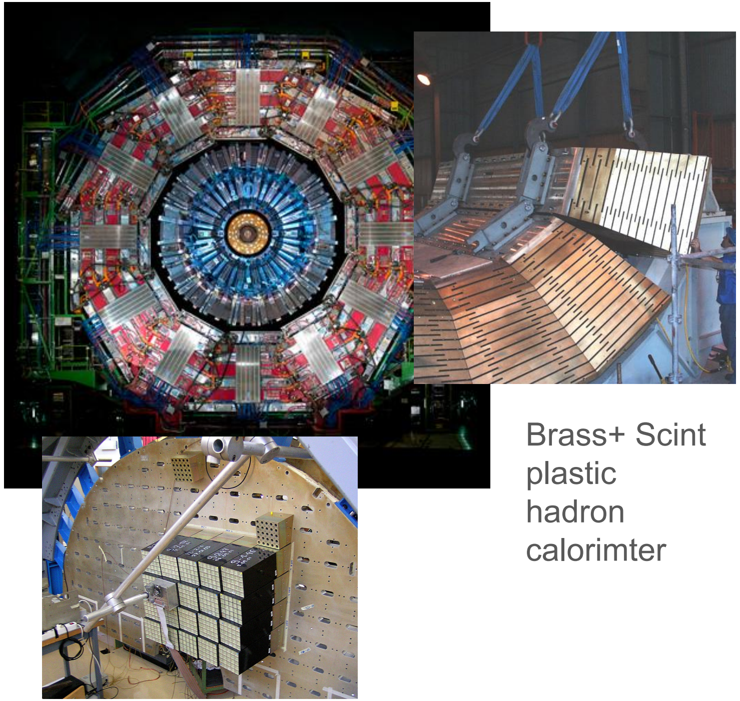
Electromagnetic Calorimeter Examples

Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/\mathrm{E}^{1/4}$	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

Scintillating crystals the way to go

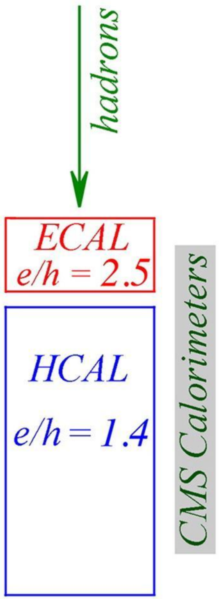
https://pdg.lbl.gov/2022/web/viewer.html?file=../reviews/rpp2022-rev-particle-detectors-accel.pdf

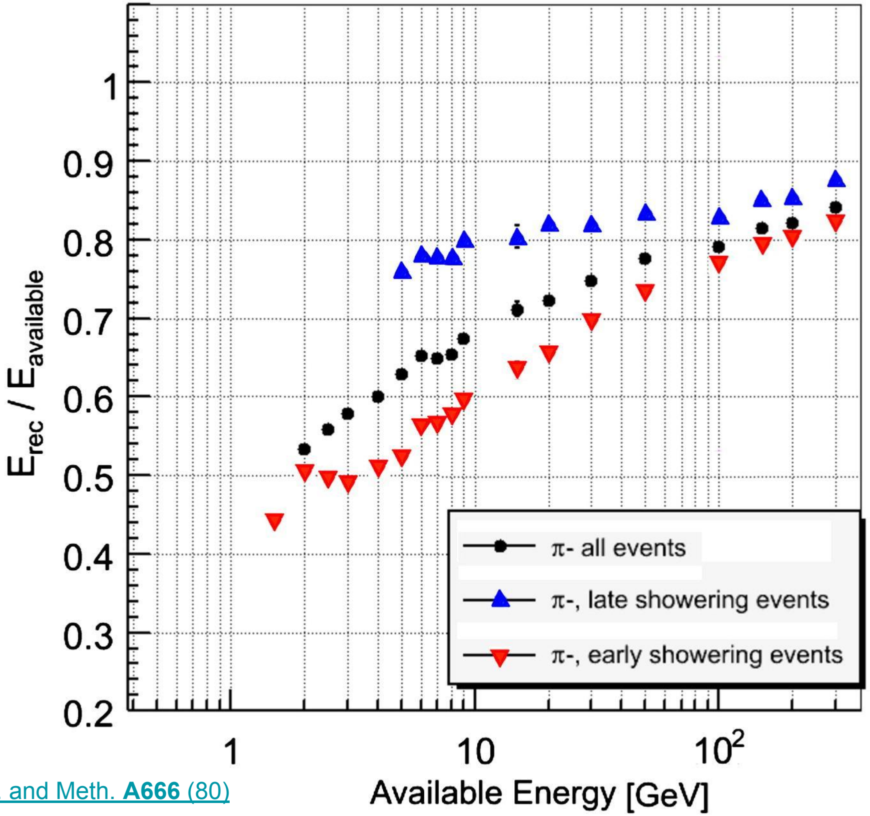
Scintillating Crystals for … hadron calorimetry



Brass+ Scint plastic hadron calorimter

CMS's Crystal electromagnetic calorimeter





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

Hadronic energy deposition

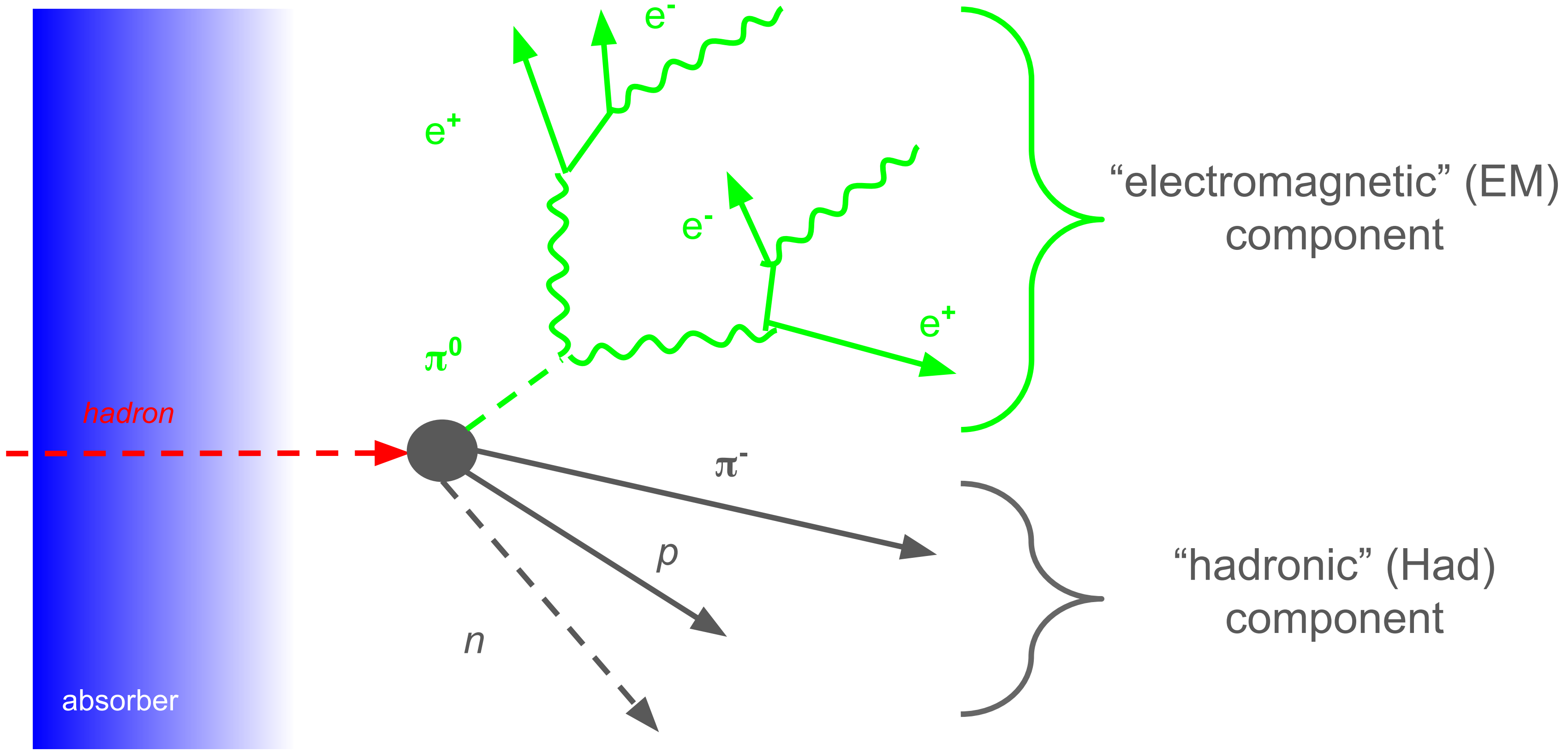


Figure adapted from Sehwook Lee 2019 *J. Phys.: Conf. Ser.* **1162** 012043

Hadronic energy deposition

EM/Had ratio fluctuates event-to-event

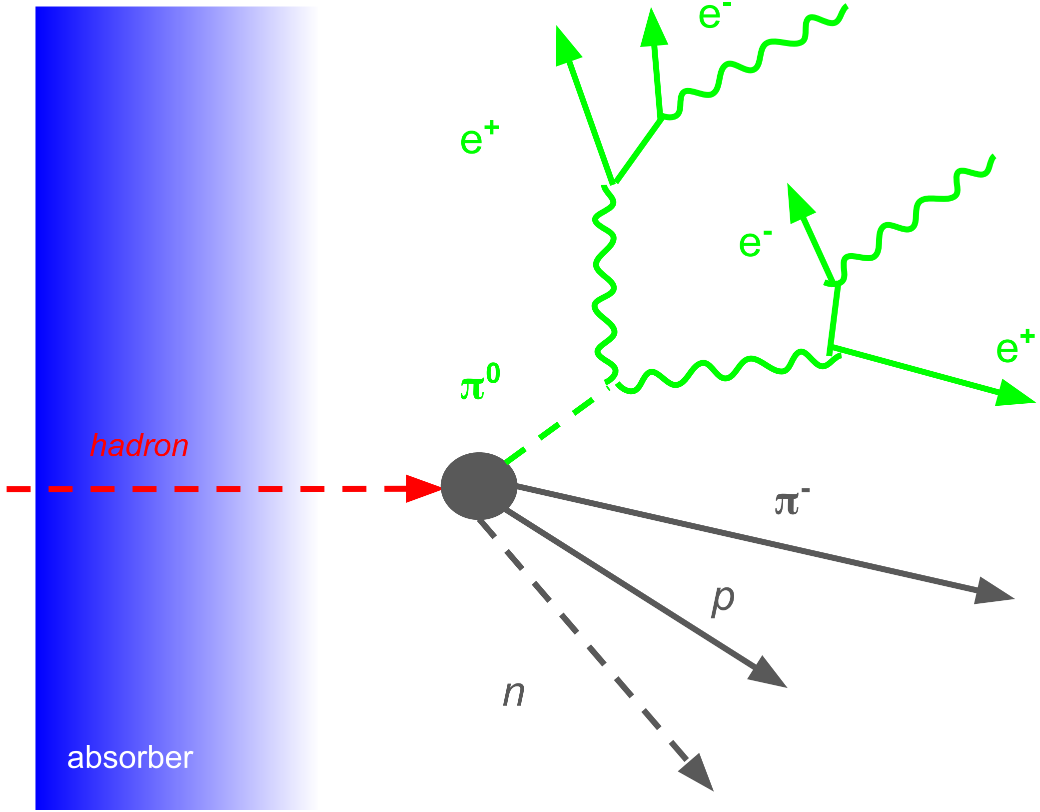
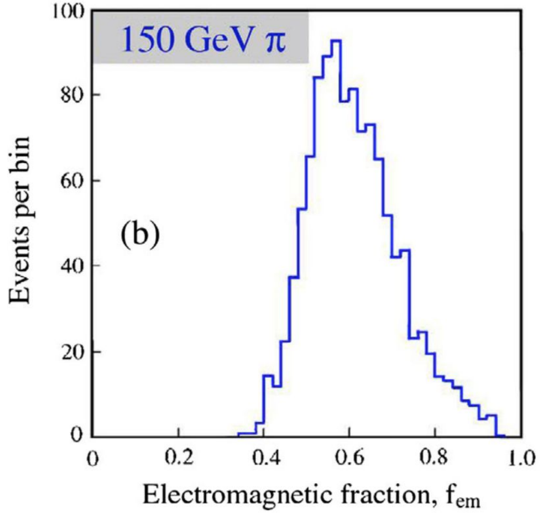


Figure adapted from Sehwook Lee 2019 *J. Phys.: Conf. Ser.* **1162** 012043



Rev. Mod. Phys. 90, 025002, NIM A316 (3-5)1992, 184-201

Hadronic energy deposition

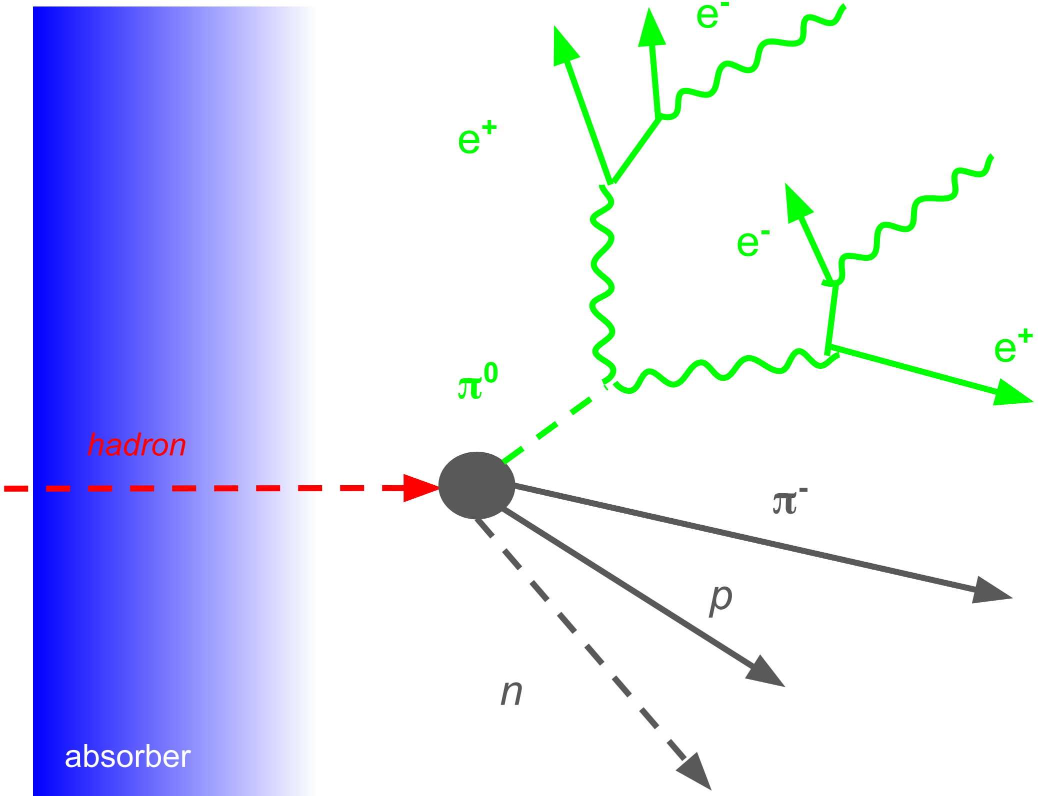
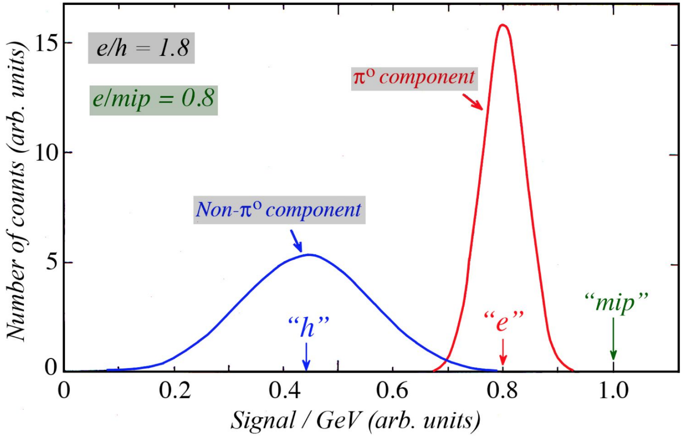


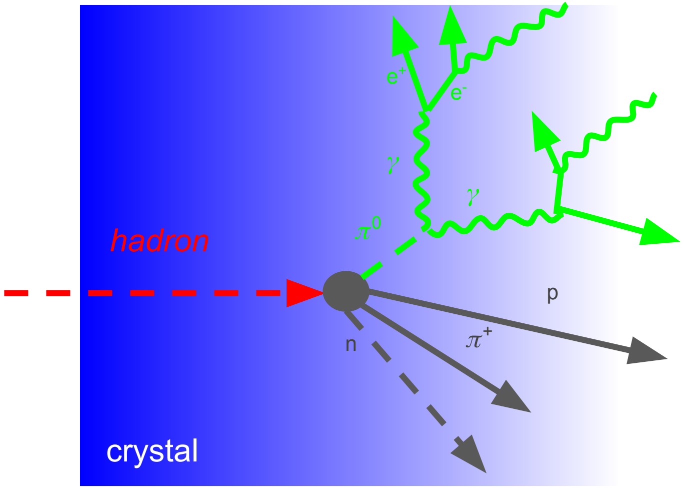
Figure adapted from Sehwook Lee 2019 *J. Phys.: Conf. Ser.* **1162** 012043

Detector response differs for each component



Rev. Mod. Phys. 90, 025002

Hadronic showers in crystals



Both components produce scintillation light!

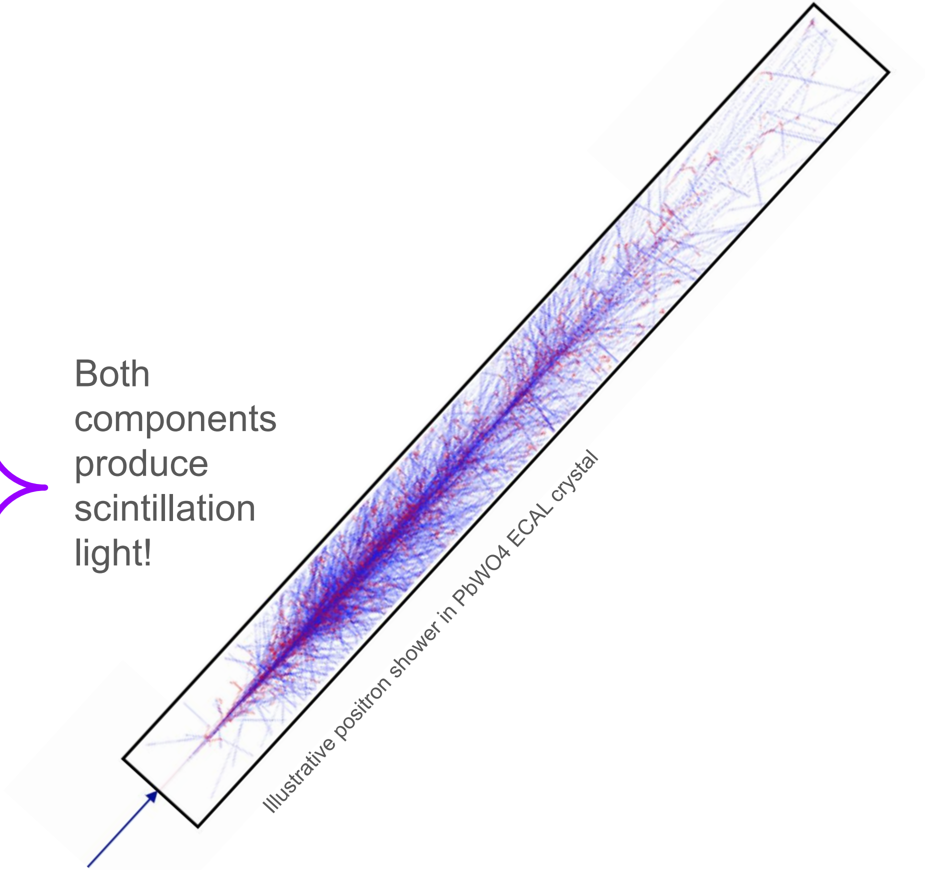
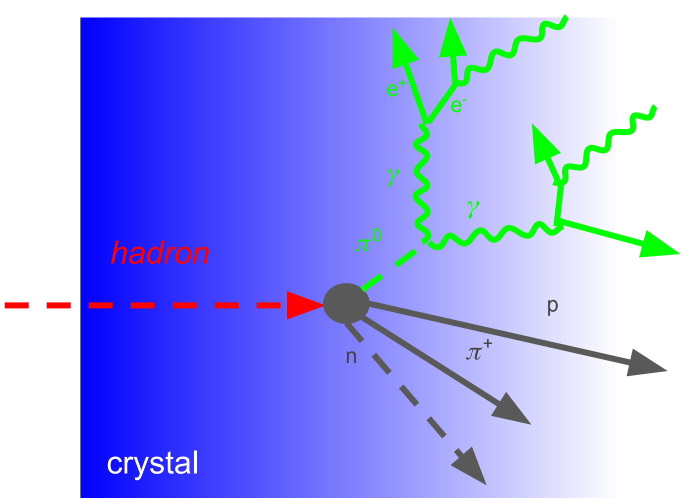


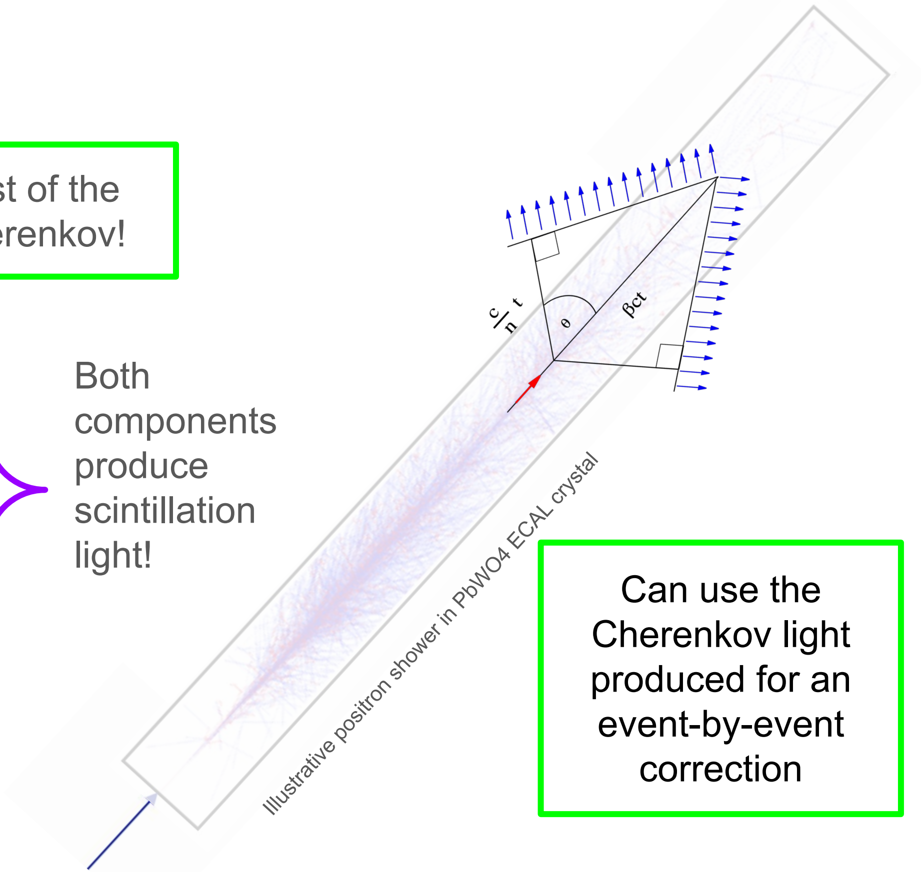
image credit:
https://www.physi.uni-heidelberg.de/~sma/teaching/ParticleDetectors2/sma_ElectromagneticCalorimeters.pdf

Hadronic showers in crystals



Most of the Cherenkov!

Both components produce scintillation light!

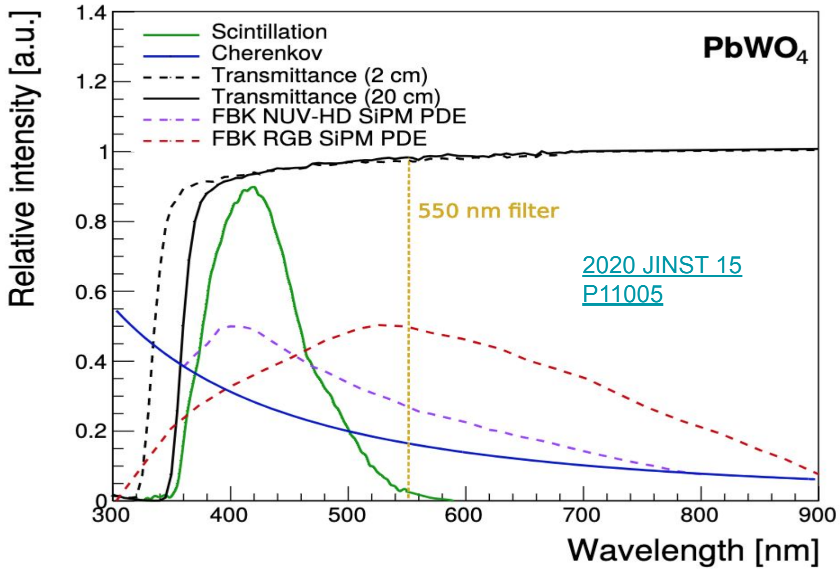


Can use the Cherenkov light produced for an event-by-event correction

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

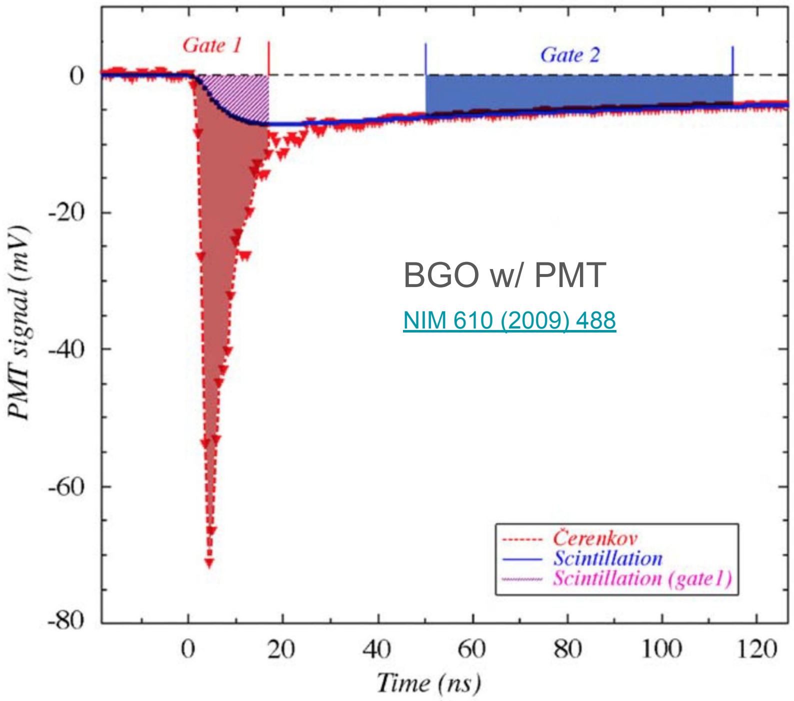
How to separate Cherenkov and Scintillation light

Wavelength Filters



2020 JINST 15 P11005

Time structure

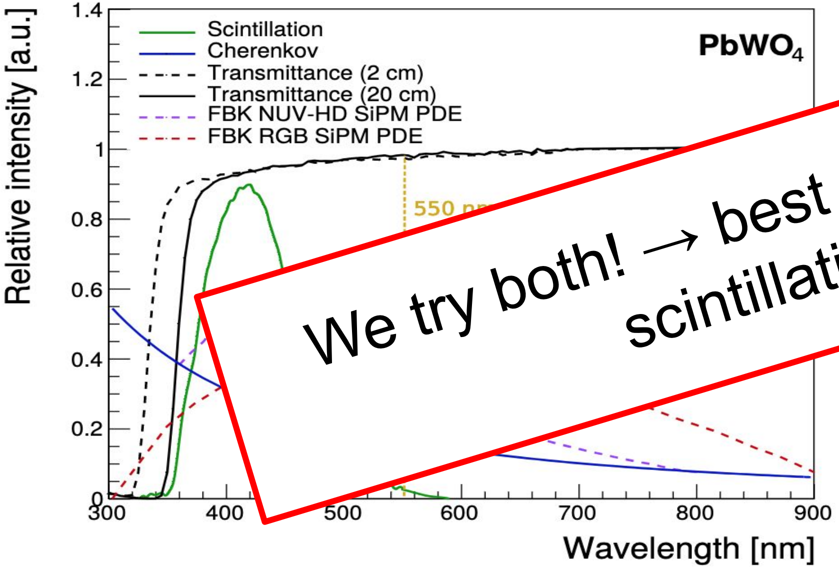


BGO w/ PMT

NIM 610 (2009) 488

How to separate Cherenkov and Scintillation light

Wavelength Filters



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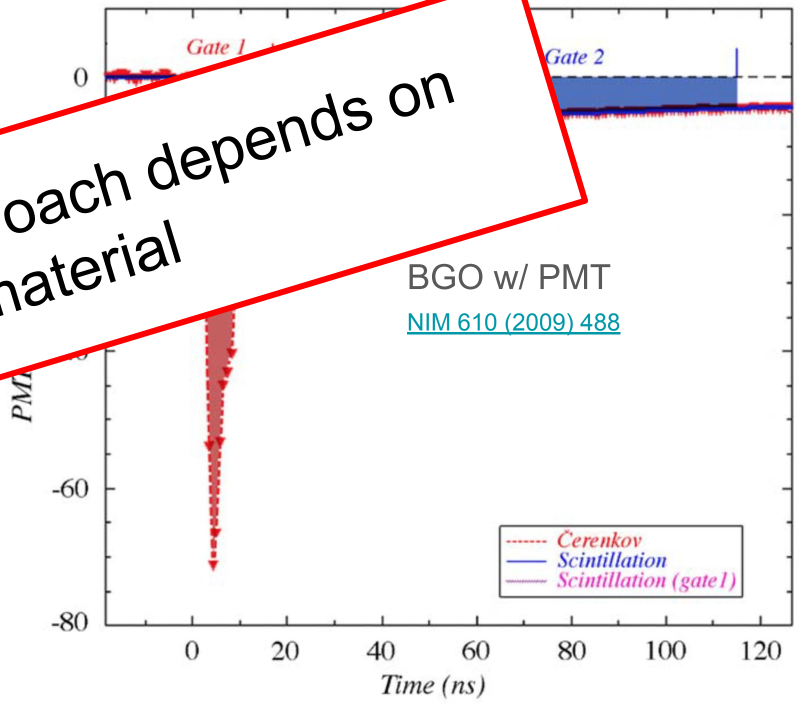


BGO w/ PMT

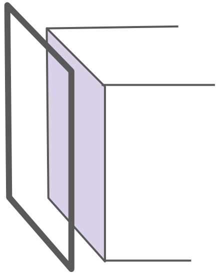
[NIM 610 (2009) 488]

We try both! → best approach depends on scintillating material

DESY CalVision: Dual-end 4 SiPM Readout

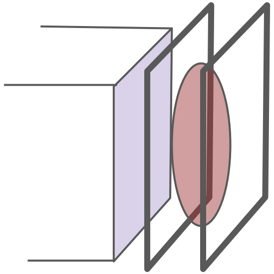
- 2 GeV Electron Beam
- **4** Broadcom 6x6 mm SiPMs **per end**
- Prioritized configurability
  - tested many crystal/filter combinations
  - used same SiPMs for each

“front” → Scint Channels



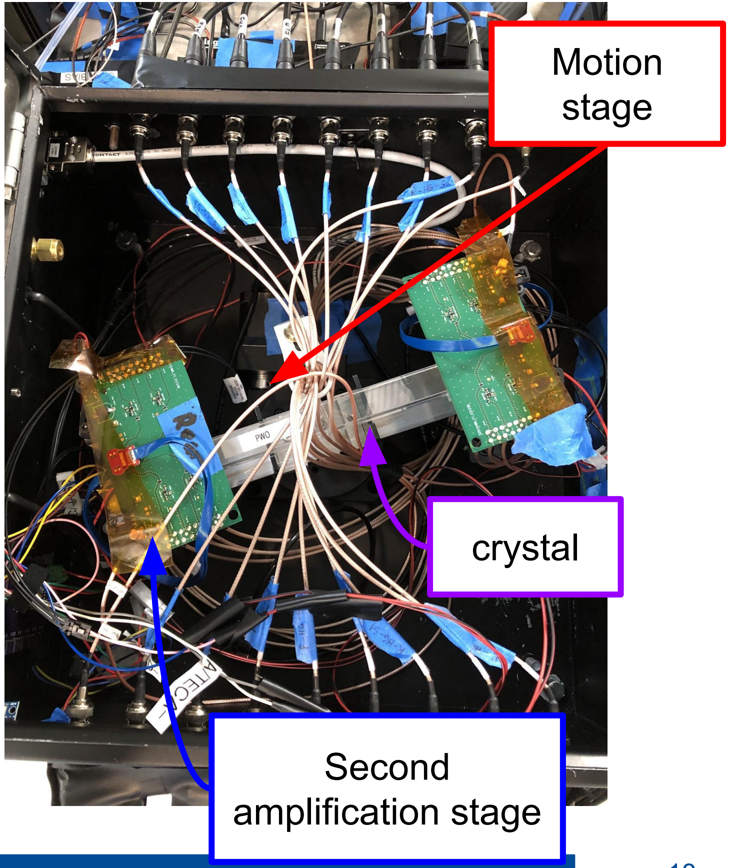
Crystal → cookie → SiPMs (not pictured)

“rear” → Cherenkov Channels



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

All SiPMs covered



Support structures

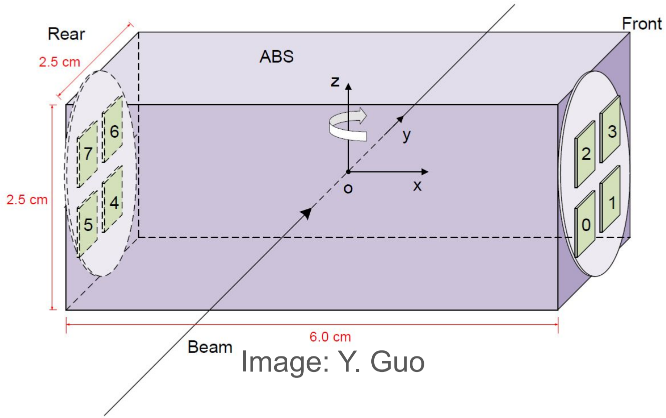
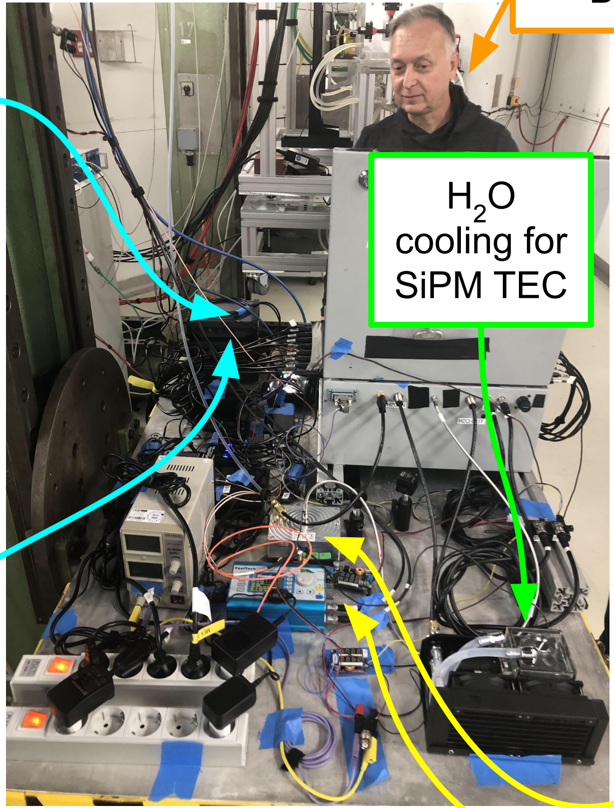


Image: Y. Guo

Low + High gain to DRS



Bob

H_2O cooling for SiPM TEC

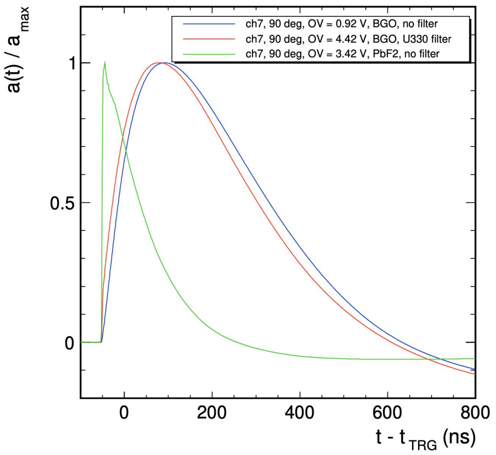
Pulser and LED for Calibration system

Low + High gain to DRS

2.5 Results to showcase today

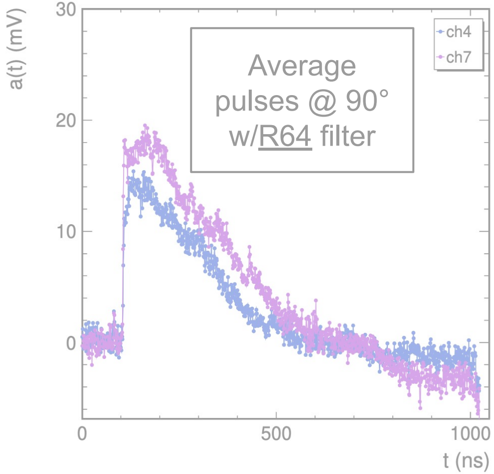
BGO

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



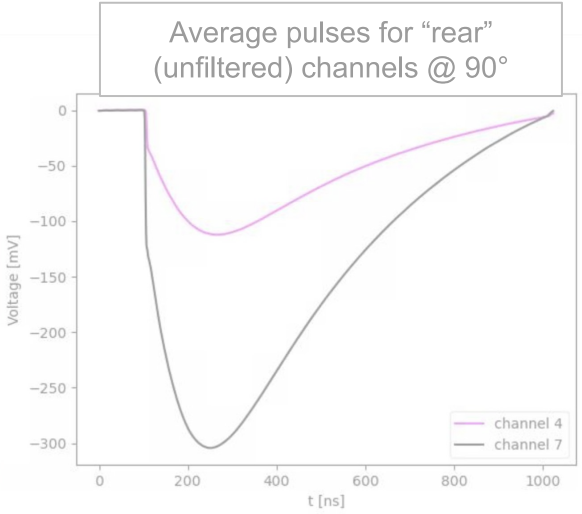
DSB Glass

- $BaO+SiO_2+Ce_2O_3+Gd_2O_3$
- 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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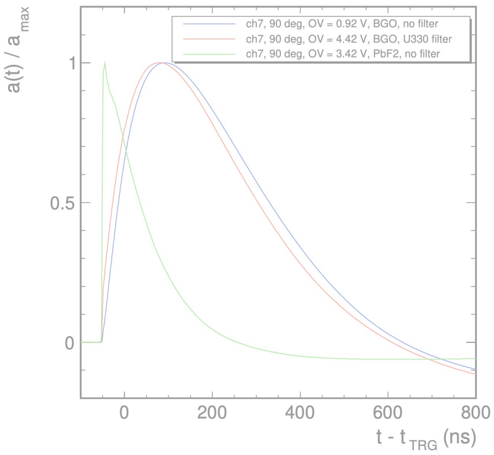

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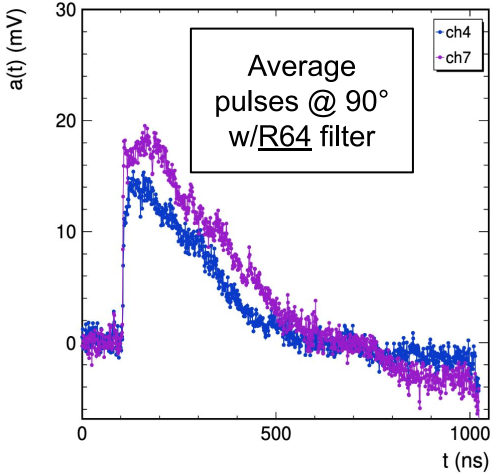

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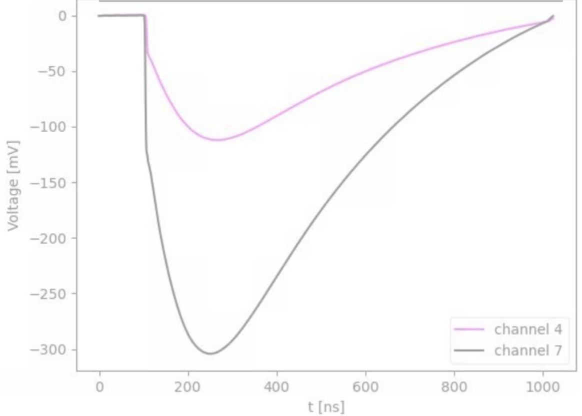
Average pulses for “rear” (unfiltered) channels @ 90°



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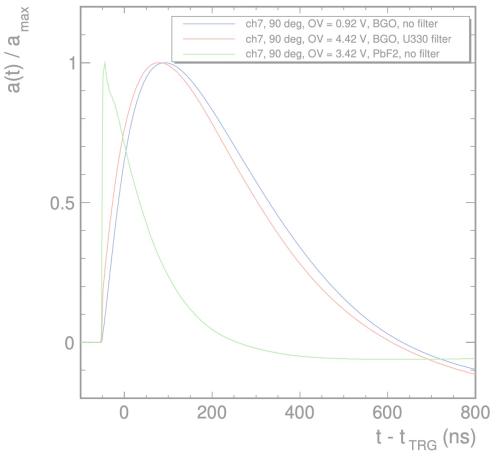

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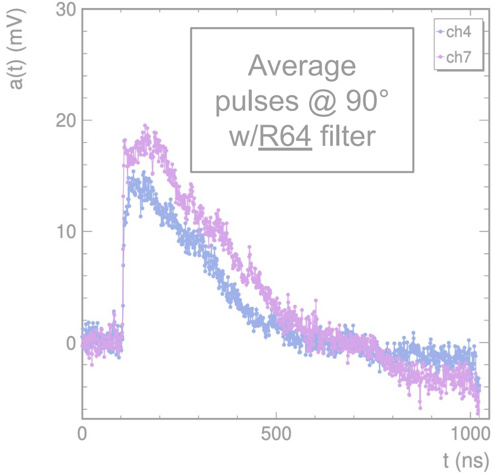

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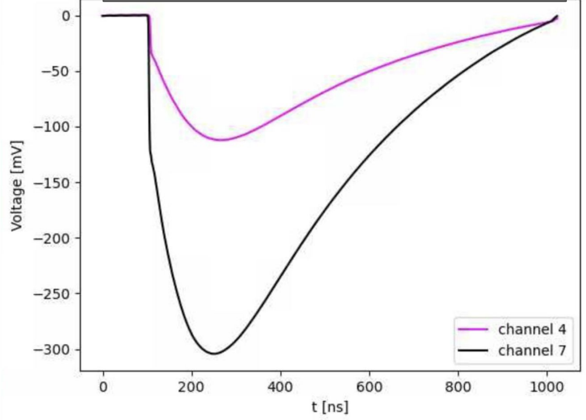

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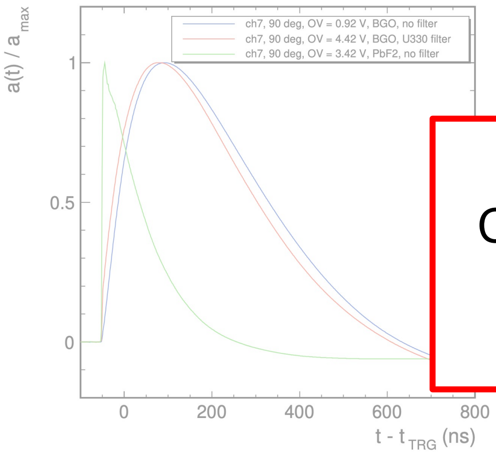
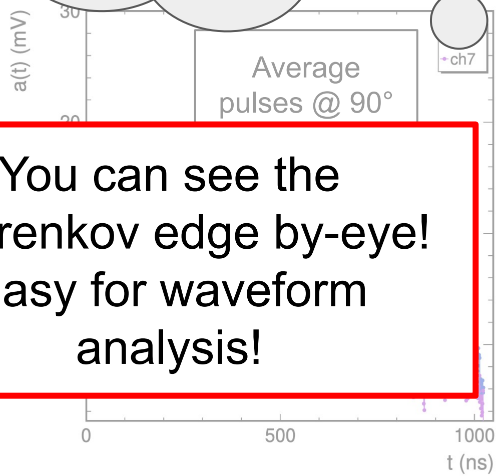


DSB Glass

Analysis ongoing!
(this is the 0.5)



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

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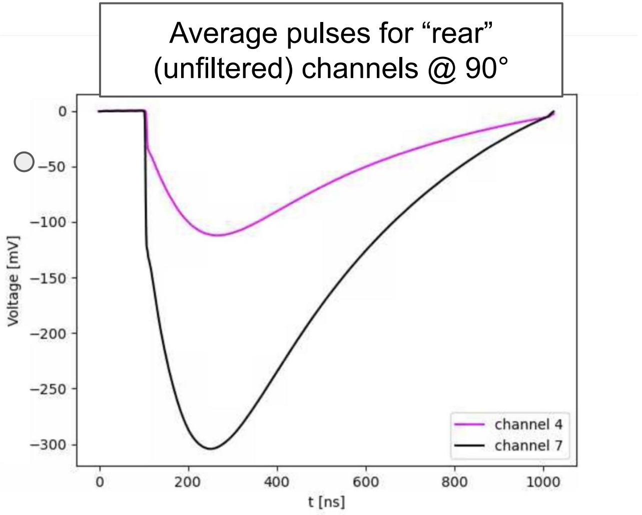

2.5 Results to showcase today

first time these heavy glasses have been used in a beam test!

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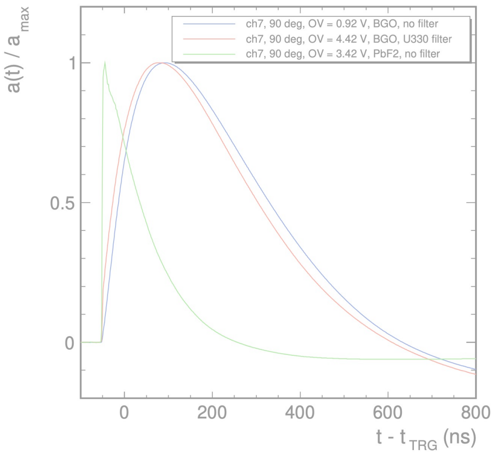

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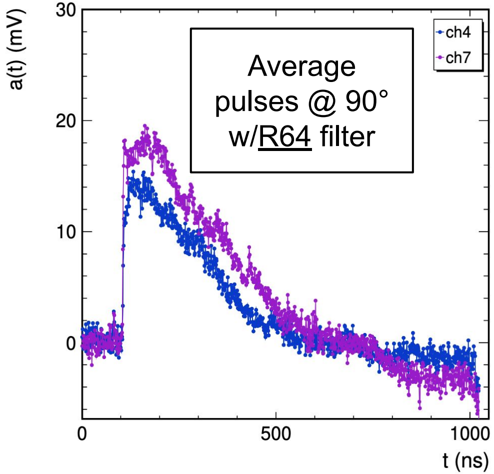

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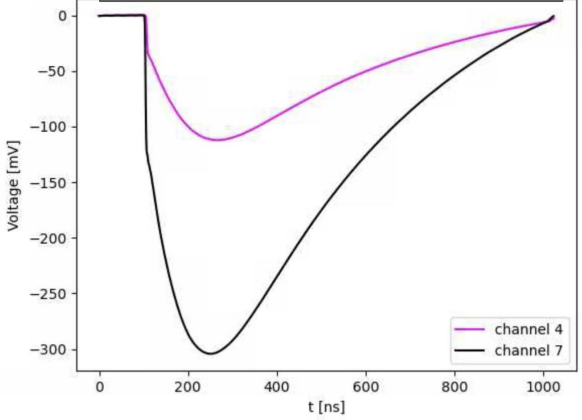
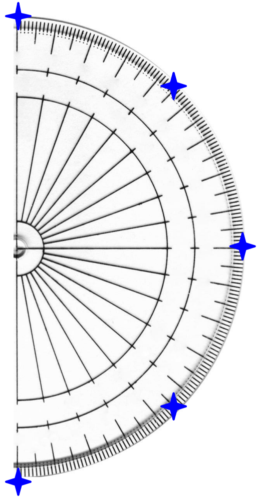


DSB and ABS Properties: Ren-Yuan Zhu's CPAD2023 talk

Angle Scans - All crystals and glasses

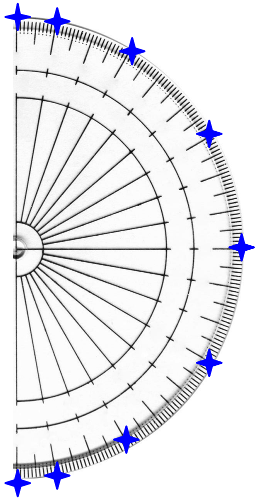
FILTERLESS

-90
-45
0
45
90



WITH A FILTER

-90
-80
-60
-30
0
30
60
80
90



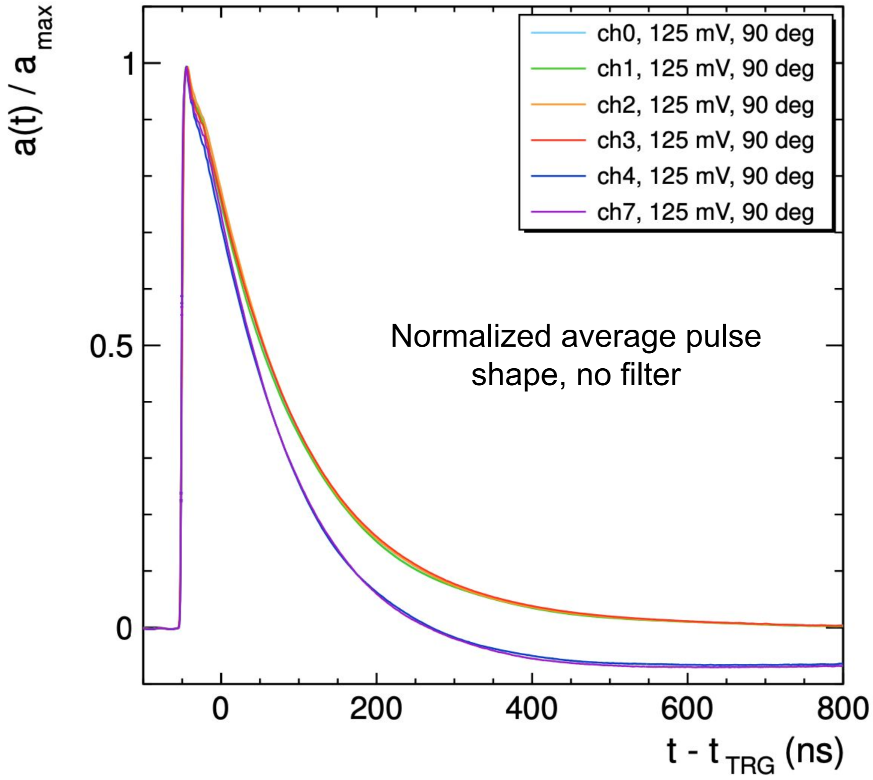
Why angle scans?
Cherenkov is directional → another handle for separation!

Why *these* angles?
Only really meaningful w/ full sweep, cut down on angles for time.

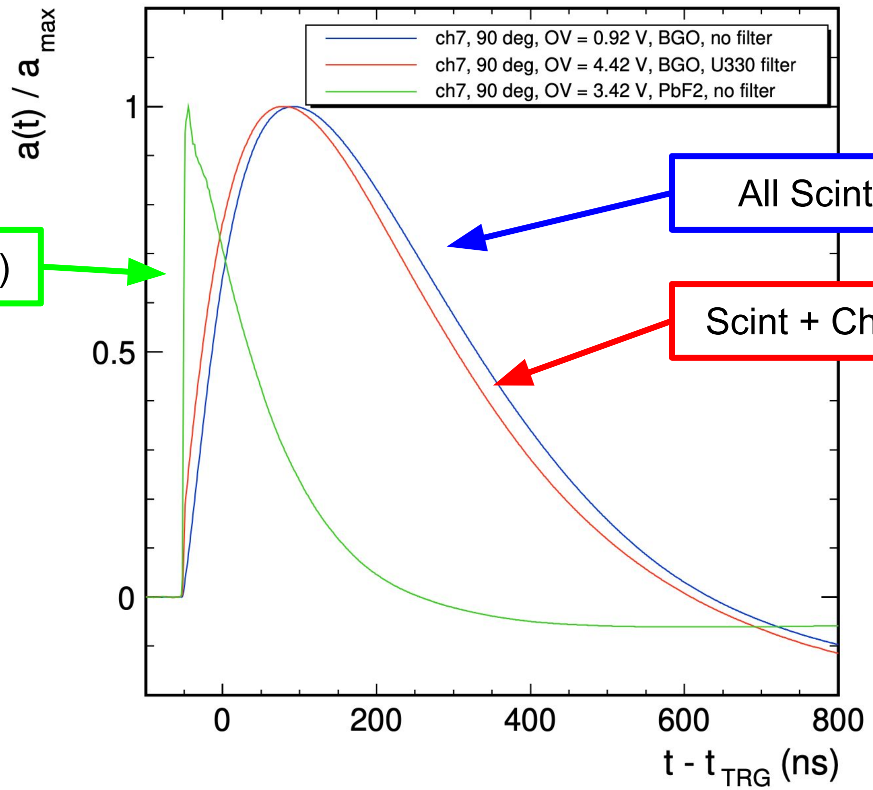
PbF_2 - The Control

- ~22 X_0
- 20 cm long

Serves as Cherenkov shape in fits!



BGO (Bismuth Germanate)

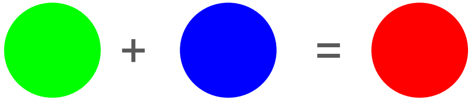


Cherenkov (from PbF_2)

All Scintillation

Scint + Cherenkov

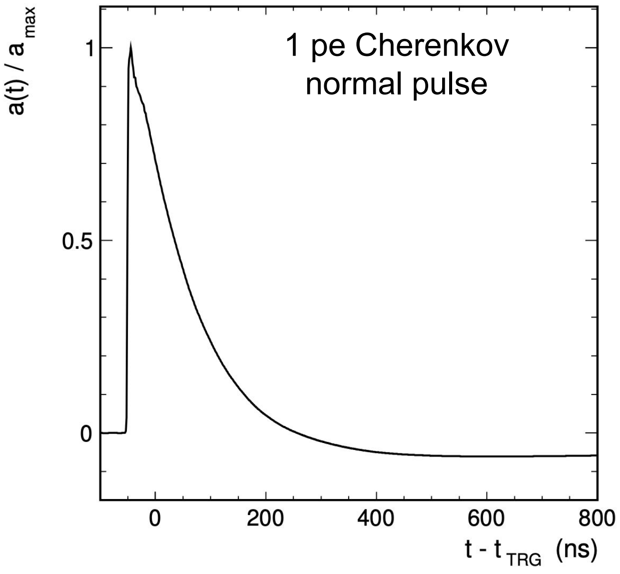
In principle…

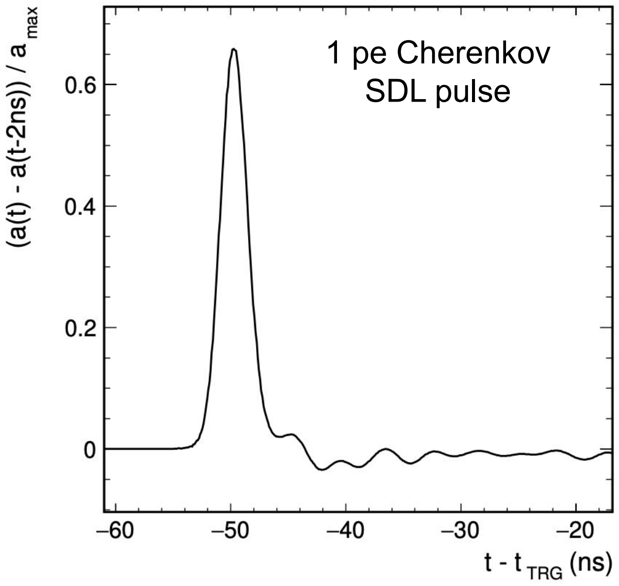


… but these are really similar.

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

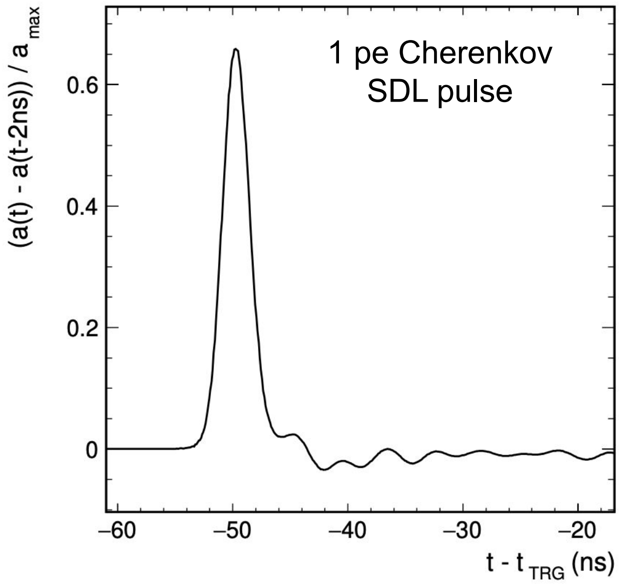
- 2 ns delay
- Cherenkov 1 PE shape from PbF_2

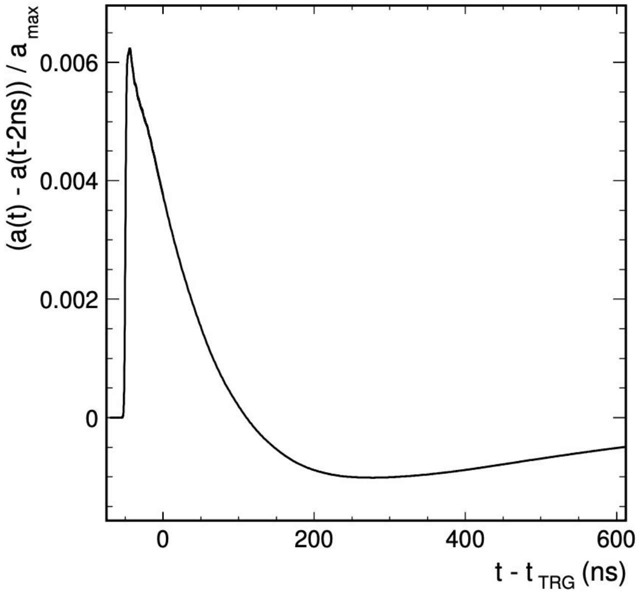




The Single Delay Line (SDL) method - take a derivative

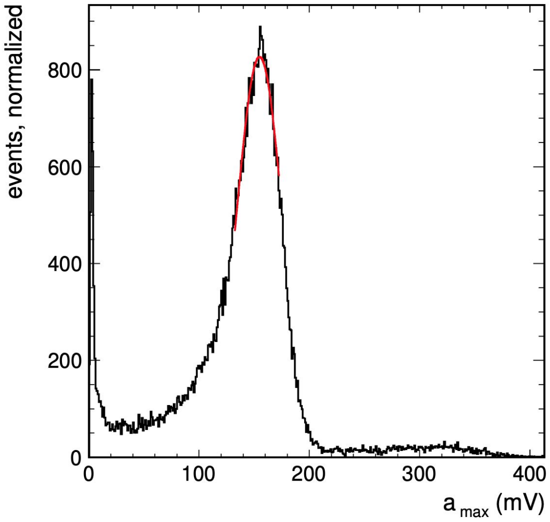
- 1 pe scintillation shape → convolute 1 pe Cherenkov w/ $y = \frac{1}{\tau}\exp\left(-\frac{t}{\tau}\right)$
  - w/ τ = 314 ns → decay time of BGO





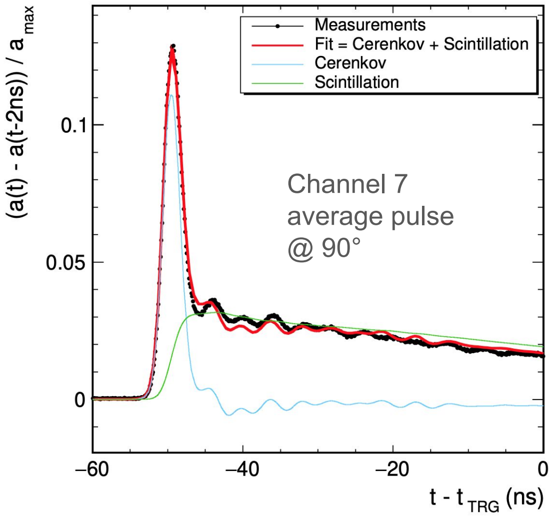
BGO SDL Analysis

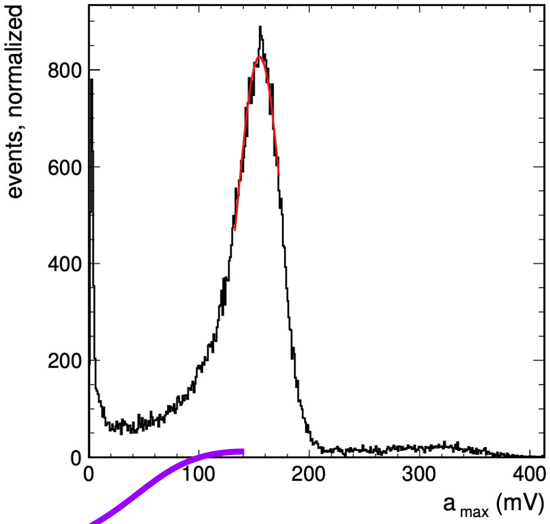
- Build average SDL pulse at most probable amplitude for rear channels to extract photoelectrons per energy



BGO SDL Analysis

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





BGO SDL Analysis

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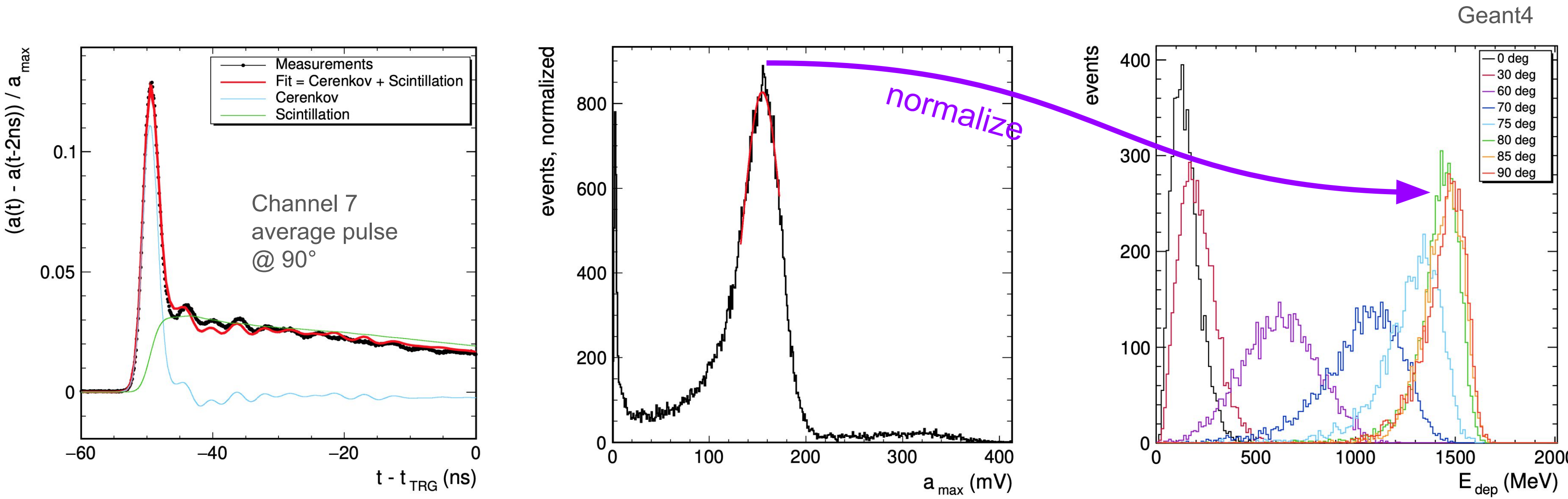
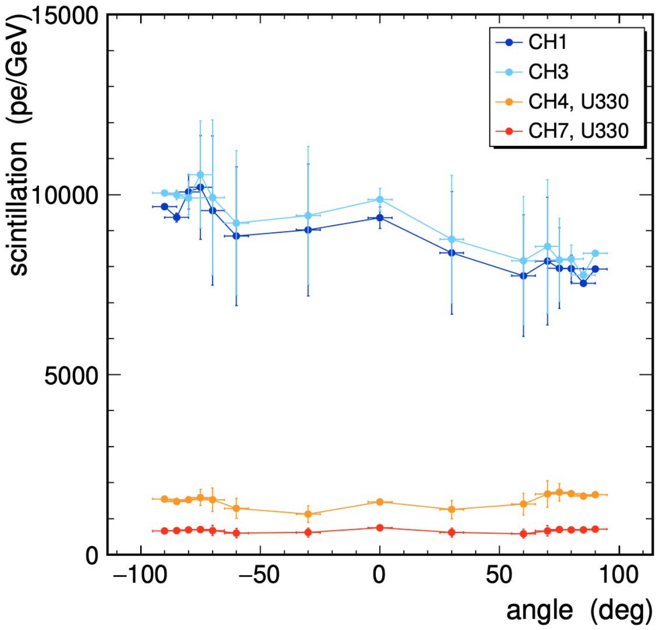
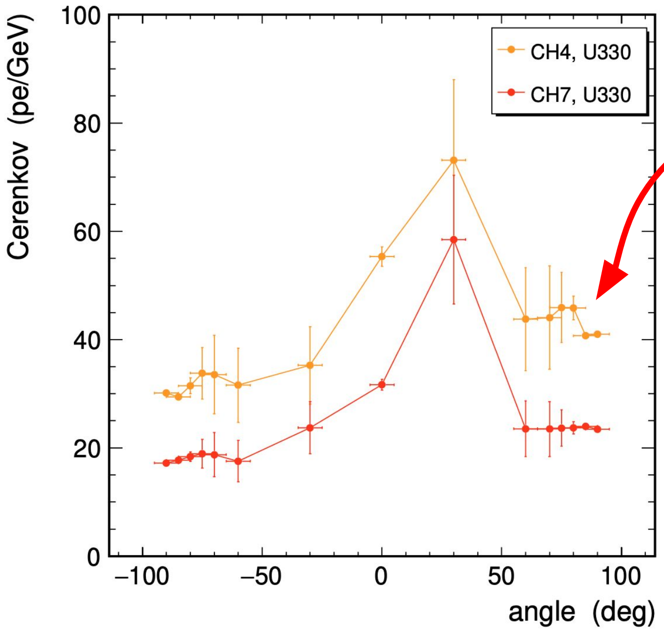


BGO SDL Analysis

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





Let's be optimistic!

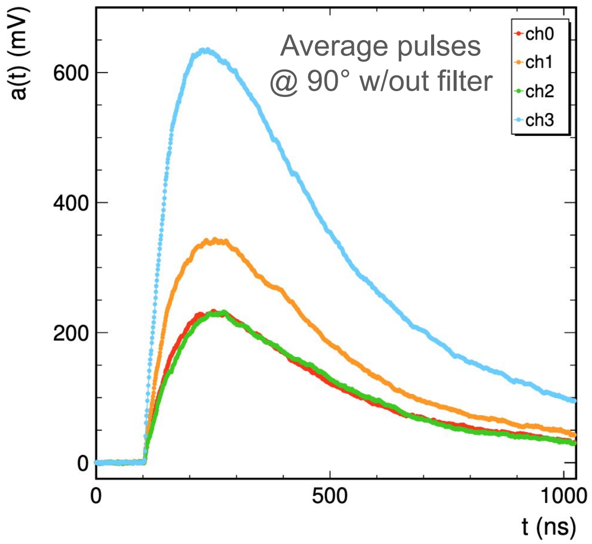
at 90°

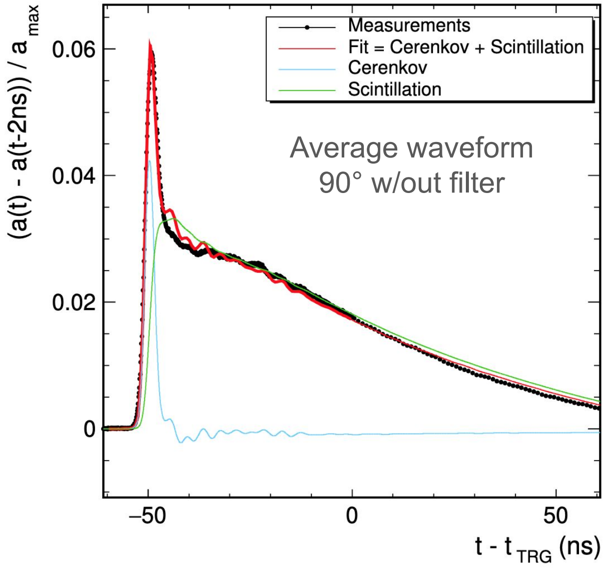
Ch4*4 = **160 pe/Gev**
(Ch4+Ch7)*2 = **120 pe/GeV**

DSB-3 (Barium Disilicate) Scintillating Glass

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

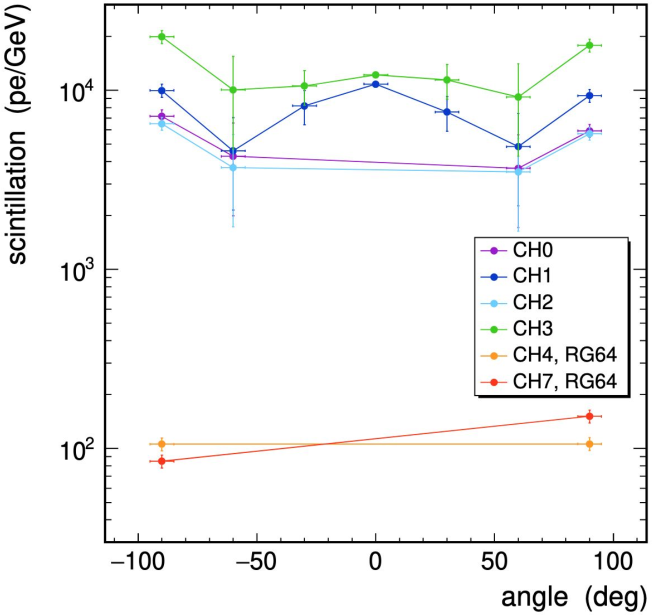
- Scintillating glass
  - Some admixture of $BaO+SiO_2+Ce_2O_3+Gd_2O_3$

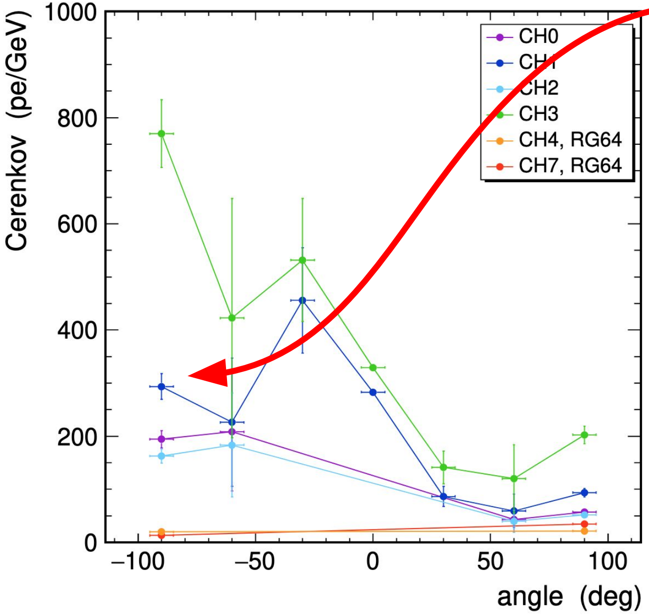




DSB-3 SDL analysis

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





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

First time this glass has been put in beam!

Summary and future plans

- Test beams promising!
  - DESY test beam comfortably surpasses goal of > 50 Cherenkov photoelectrons / GeV
    - BGO
    - DSB glass for homogenous HCAL
- 5 x 5 BGO crystal matrix → lateral + transverse containment
  - 22 X_0
  - Segmented – higher granularity in the front
- Joint test beam w/ DR hadron calorimeter
  - The *system* performance is what matters
- Simulation maturing
  - crystal ECAL integrated into Key4HEP
  - Full DR test beam modules implemented in GEANT4