Dual-readout calorimetry with homogenous crystals and precision timing characterization

Grace Cummings on behalf of the CalVision Consortium

US FCC Meeting, 26 March 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

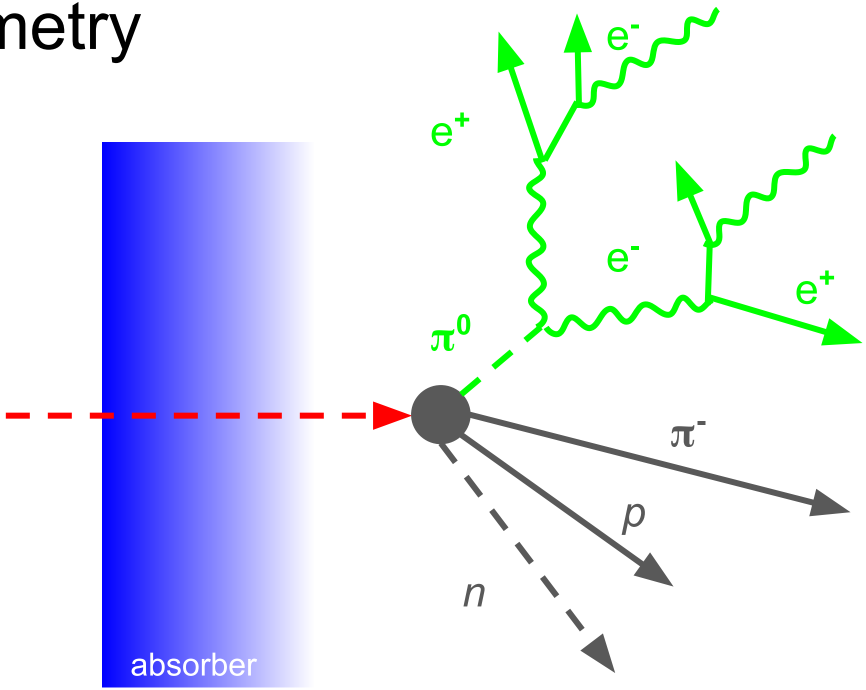
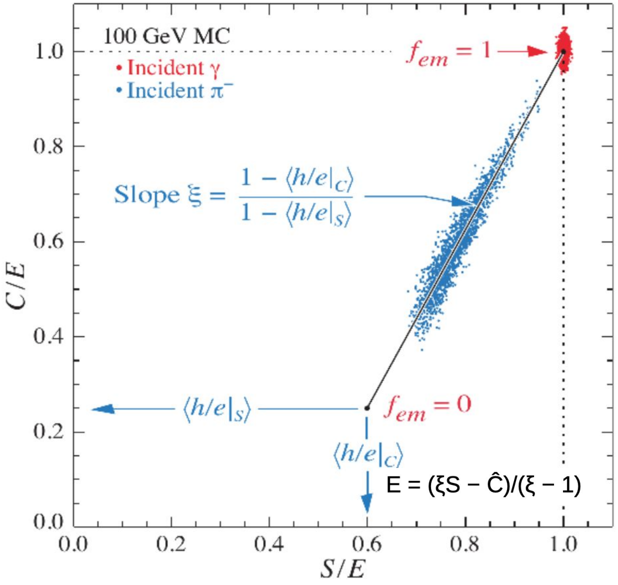


Figure adapted from Sehwook Lee 2019 *J. Phys.: Conf. Ser.* **1162** 012043

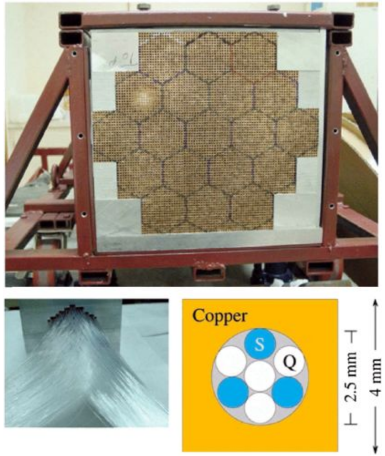
What is Dual Readout (DR)?

- 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)

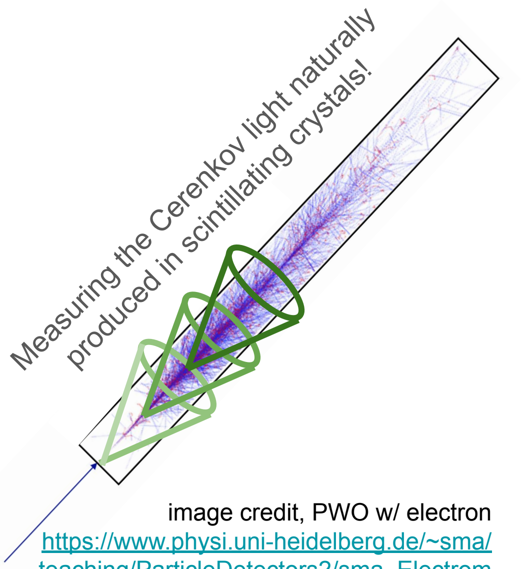


image credit, PWO w/ electron
https://www.physi.uni-heidelberg.de/~sma/teaching/ParticleDetectors2/sma_ElectromagneticCalorimeters.pdf

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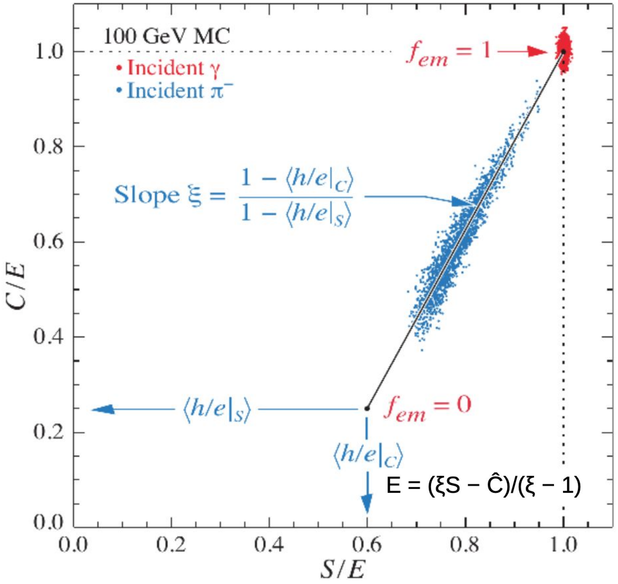

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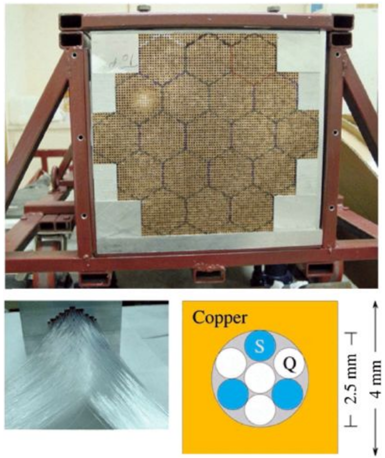

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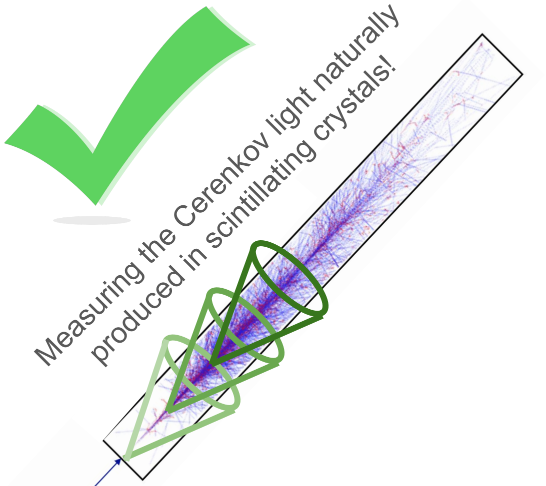

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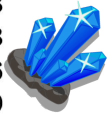
Why DR in Crystal Electromagnetic Calorimeters?

- 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)	$16–18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	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)	$20–30X_0$	$12\%/\sqrt{E} \oplus 1\%$	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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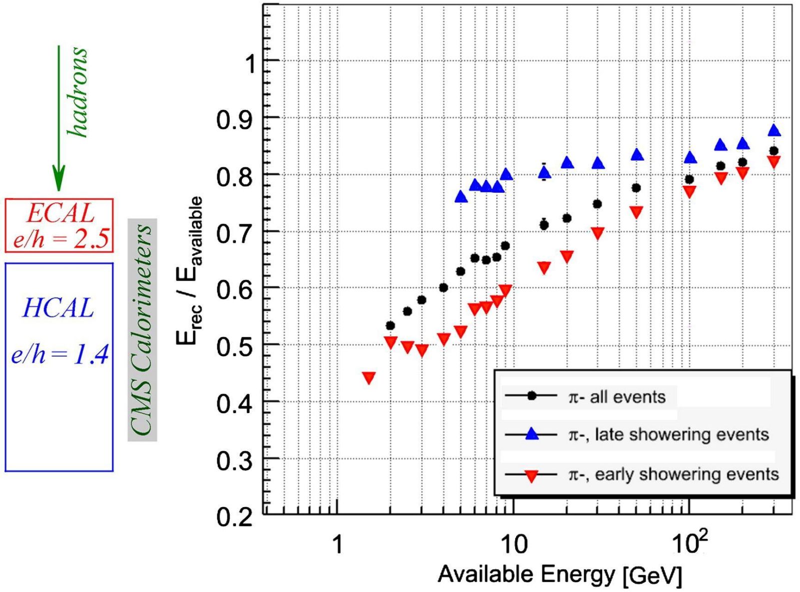
Great ECALs can degrade good HCALs



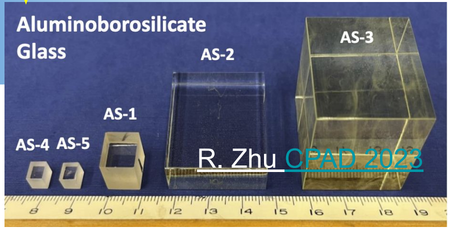
N. Akchurin, R. Wigmans, (2012) Nucl. Instr. and Meth. **A666** (80)

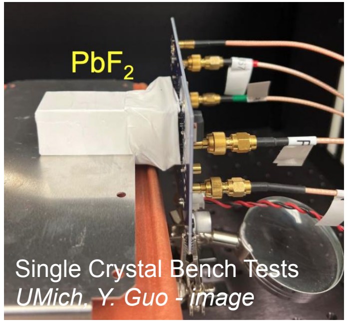
CalVision - Overview

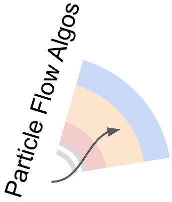
Joined w/ MaxiCC!

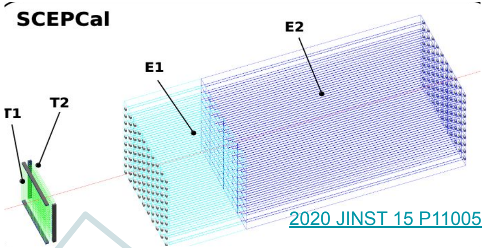
Technologies → Detector Implementation

Heavy Glasses for Homogenous HCAL

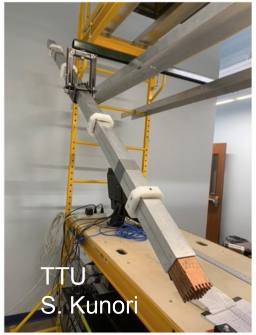


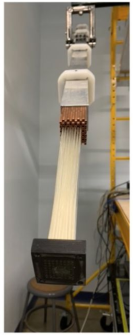


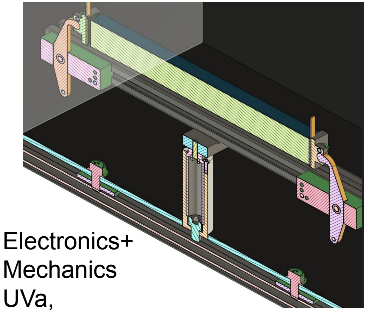




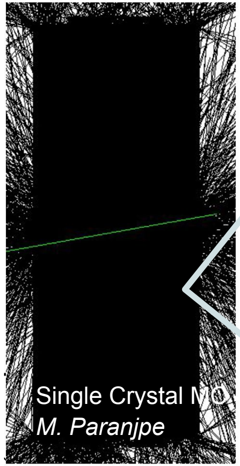
DR Fiber HCAL



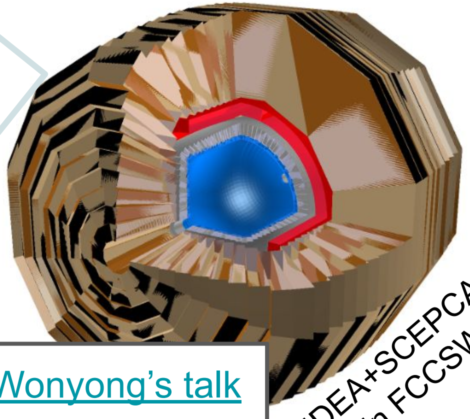




Electronics+
Mechanics
UVa,
E. Fernandez- image



Simulation Fundamentals-
See Sergei's talk

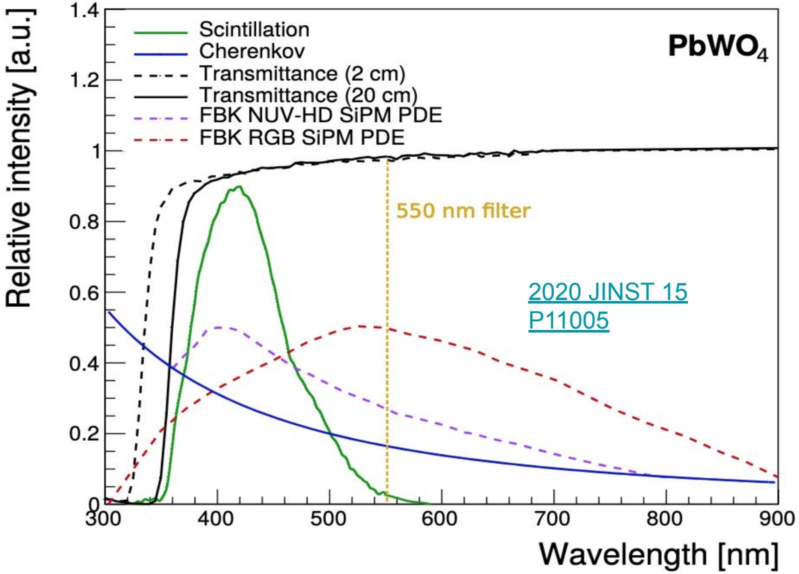


See Wonyong's talk

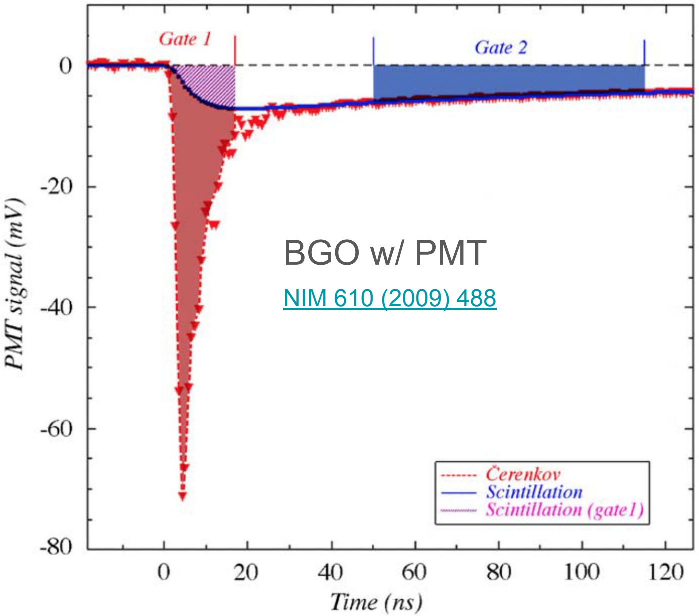
IDEA+SCEPCAL in FCCSW

CalVision - R&D in Crystals + Readout for DR

- Variety of media → PWO, BGO, PbF2 + heavy glasses
- Cerenkov and Scint Separation using timing and wavelength
- SiPMs for readout



2020 JINST 15 P11005

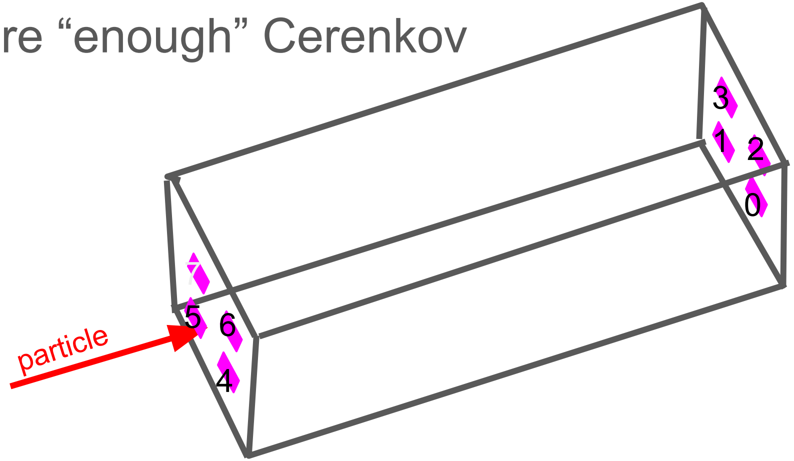


BGO w/ PMT

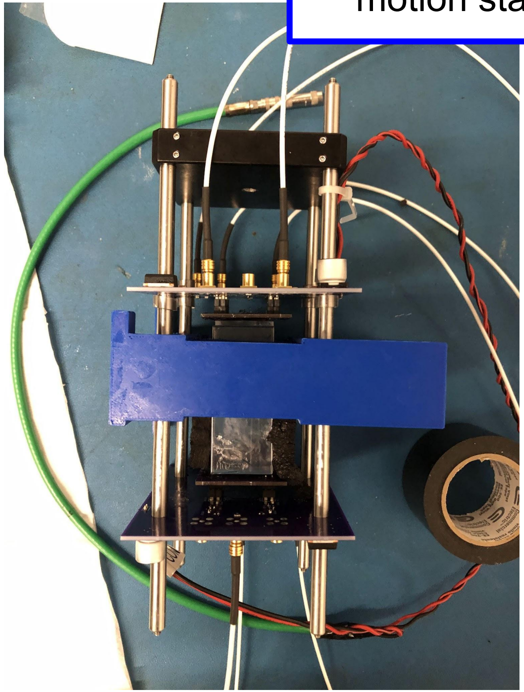
NIM 610 (2009) 488

CalVision Single Crystal Module - Phase 0

- 4 Hamamatsu S14160-6050HS 6x6 mm SiPMs per end
  - single amplifier stage
  - ~0.5 mV per photon electron
- Optical coupling by grease or silicone cookie
- 2.5 x 2.5 x 6.0 cm crystal
  - **will not contain a shower**
- Goal: Measure “enough” Cerenkov



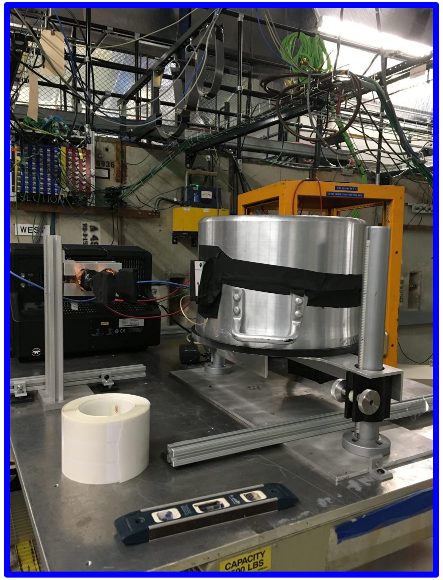
Can mount to a motion stage



Dual-ended single crystal test beams

Test beam at Fermilab, April 24th - 26th

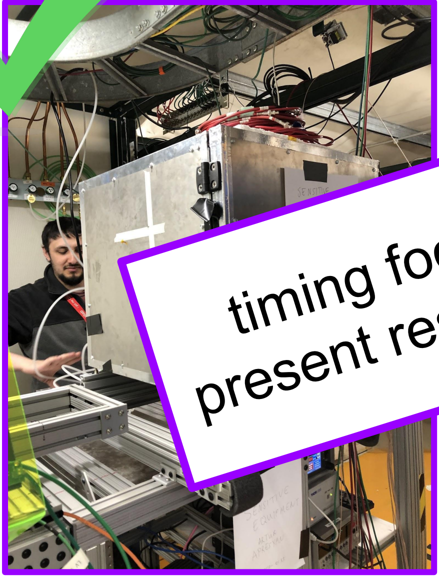
Test beam at Fermilab, May 31st - June 7th

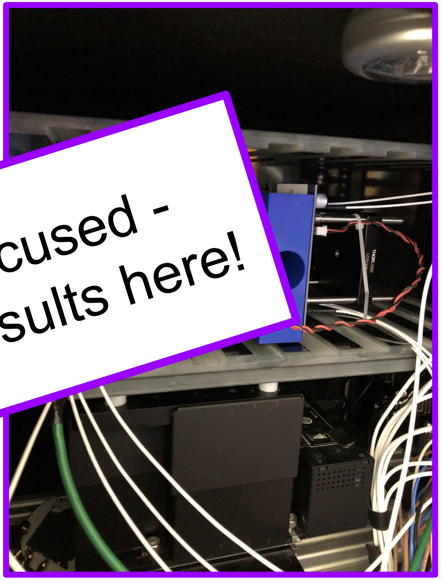


2 test beams with 120 GeV protons @ Fermilab in 2023

Dual-ended single crystal tests ongoing

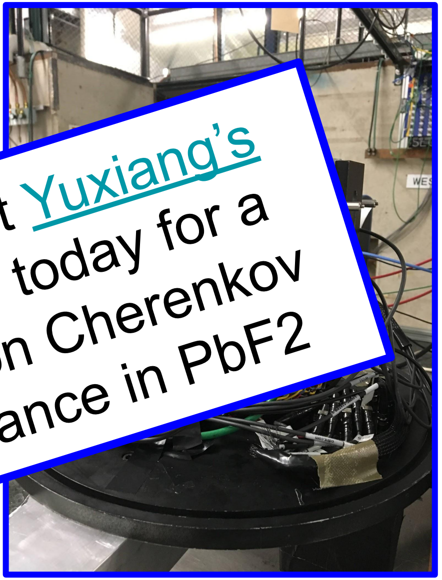
Test beam at Fermilab, April 24th - 26th





timing focused - present results here!

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

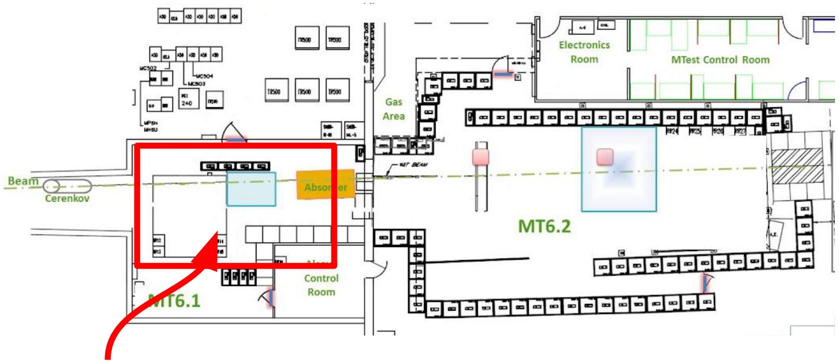


Check out Yuxiang's talk later today for a results on Cherenkov acceptance in PbF2

2 test beams with 120 GeV protons @ Fermilab in 2023

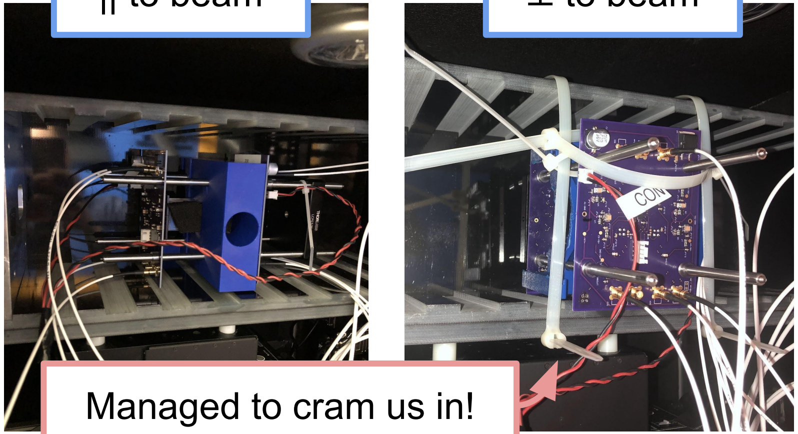
April ‘23 Test Beam

- Partnered with CMS Endcap Timing Layer
  - Thanks to C. Madrid + A. Apresyan
  - Used there DAQ + MCP+ box
  - 8 channel LeCroy scope readout
    - 7 SiPM readout + MCP for trigger
- 120 GeV Protons
  - Fermilab Test Beam Facility
  - 4s spills, 1 spill a minute
  - ~60,000 events per spill
  - 3 cm x 3 cm beam spot
  - pixel telescope for position
- 1.5 days of data ~30 hours of work



|| to beam

⊥ to beam

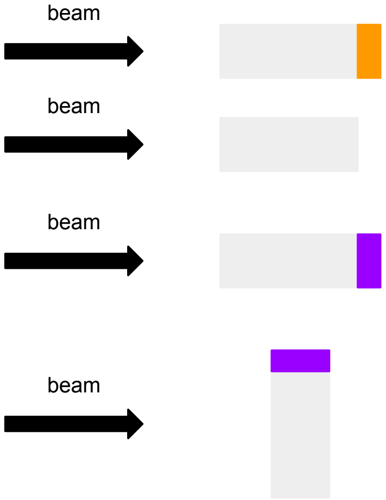


Managed to cram us in!

April ‘23 Test Beam

4 orientations

$PbW0_4$



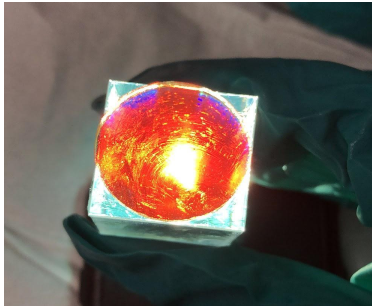
w/ scintillation filter

w/out scintillation filter

BGO

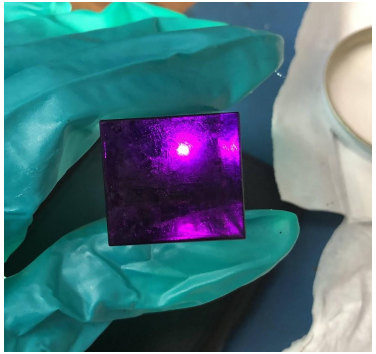
w/ scintillation filter

w/out scintillation filter



660 nm long-pass on PWO

Interference filter!



U330 notch- filter on BGO

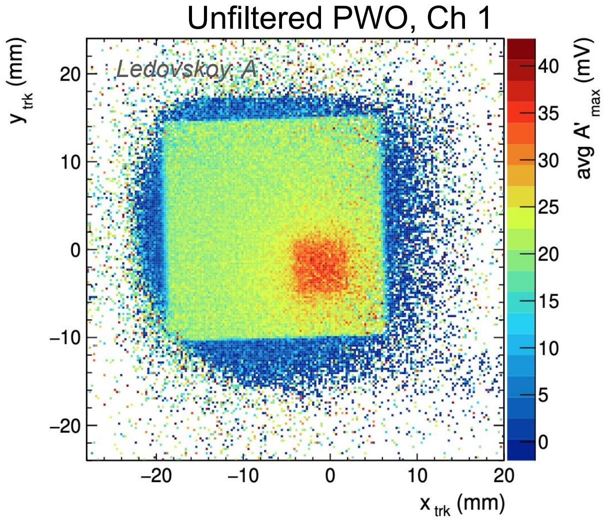
Just stuck on with thin layer of grease

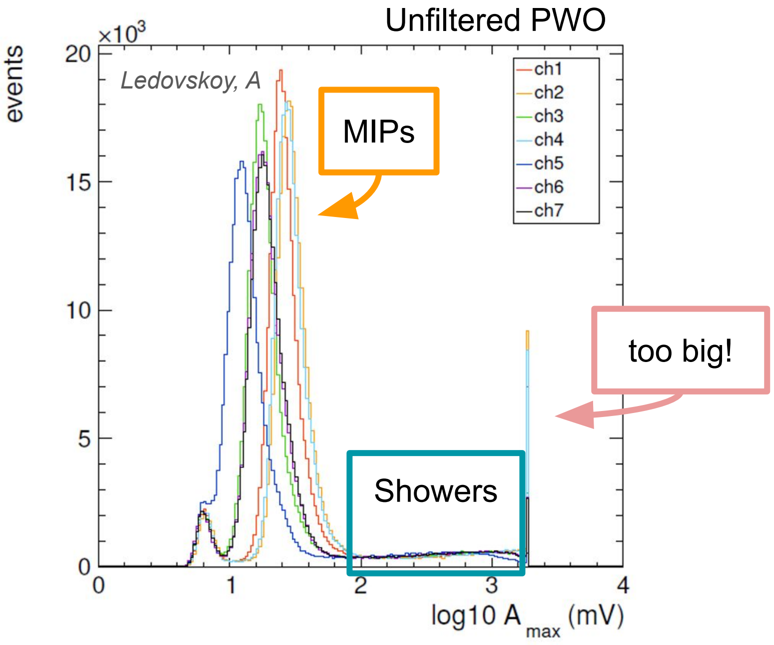
Really all we had time for!

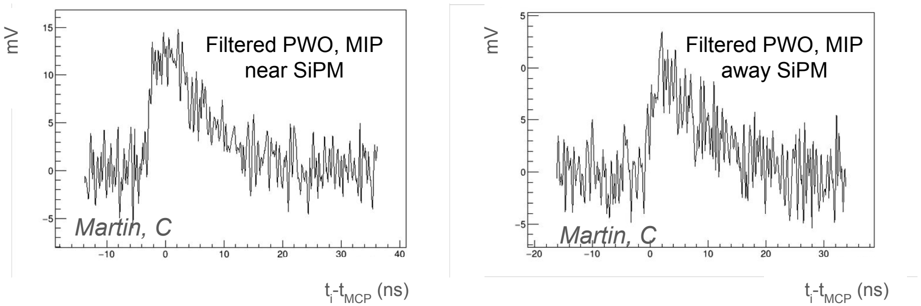
Poor position control (may be ok for timing)

What did we see?

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

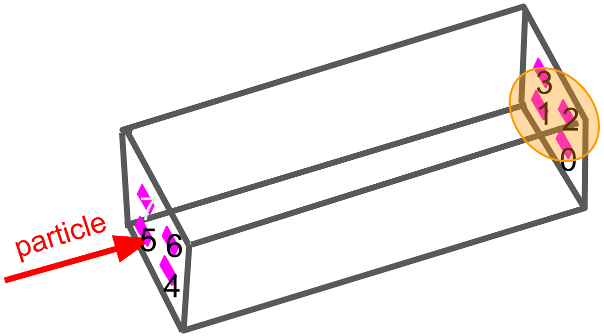




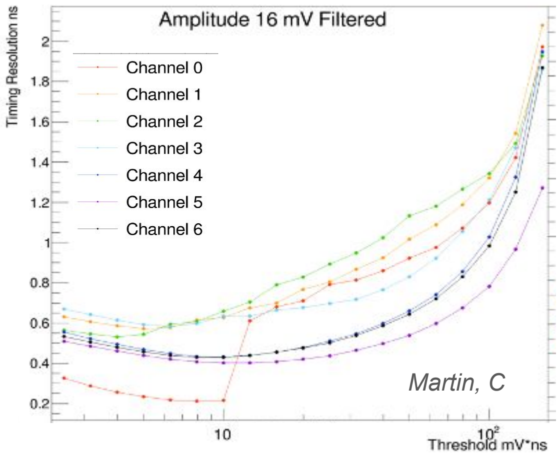


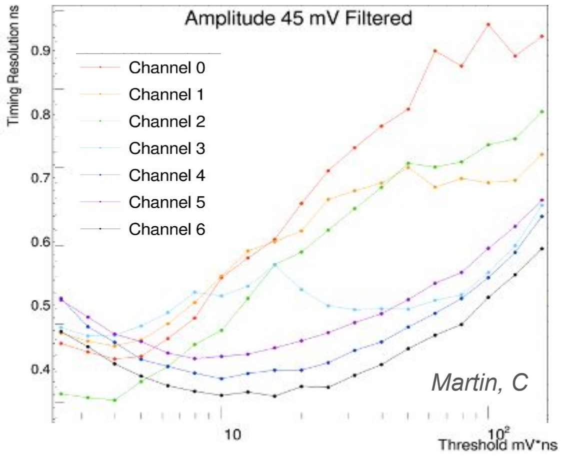
Preliminary Performance - Filtered PWO

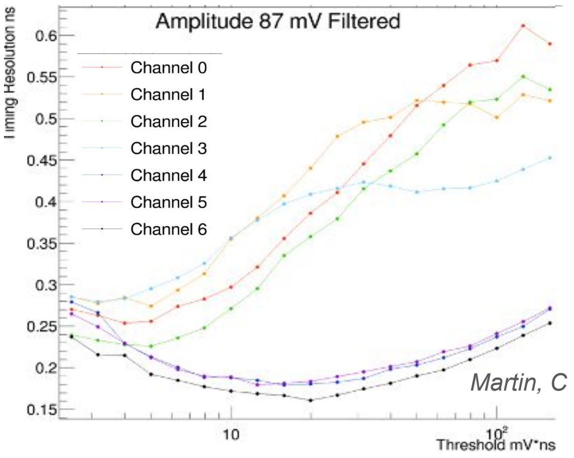
660 nm interference filter between Crystal and SiPMs on back



- ~MIP Timing resolution 200 - 400 ps / channel
  - Upstream channels - no filter, mostly scintillation
  - Cerenkov Channels worse
  - Integral method
    - (threshold for time place on waveform integral)







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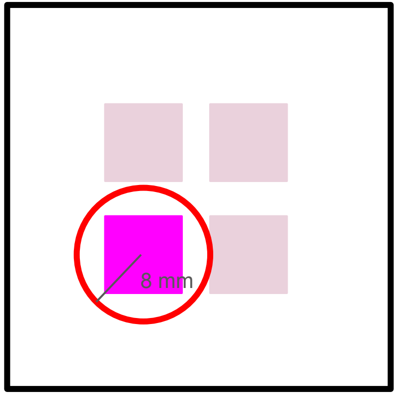

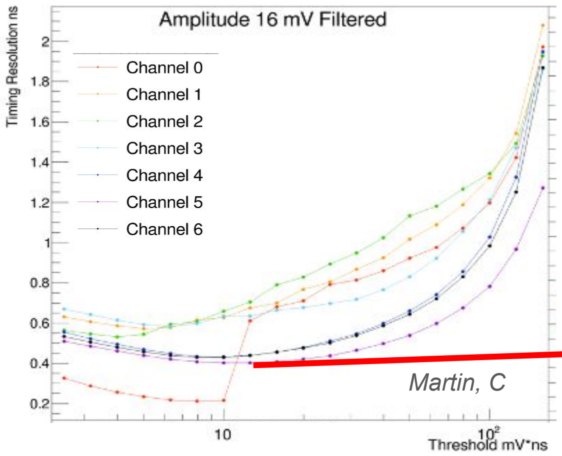

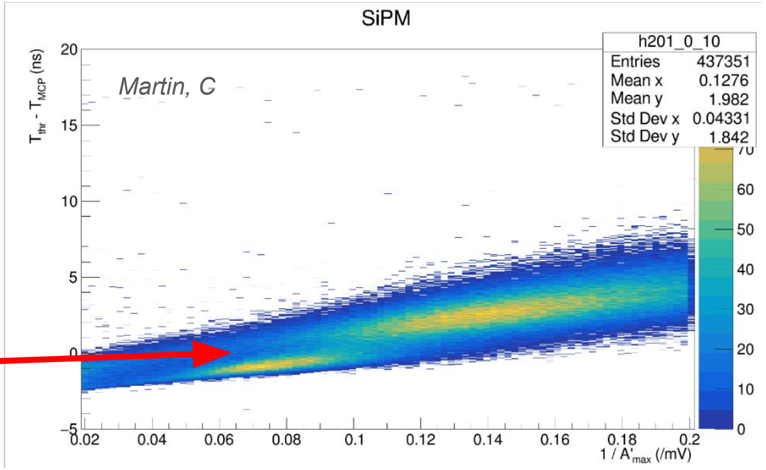

Two peak structure (absent in unfiltered data)

Combination of interference filter effects and Cerenkov Directionality

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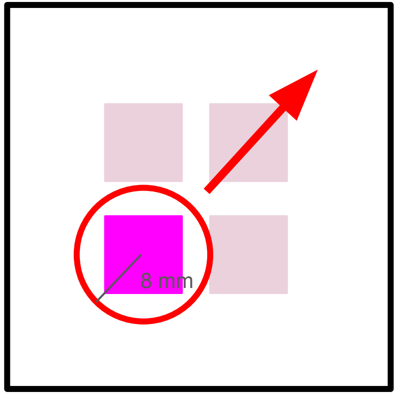

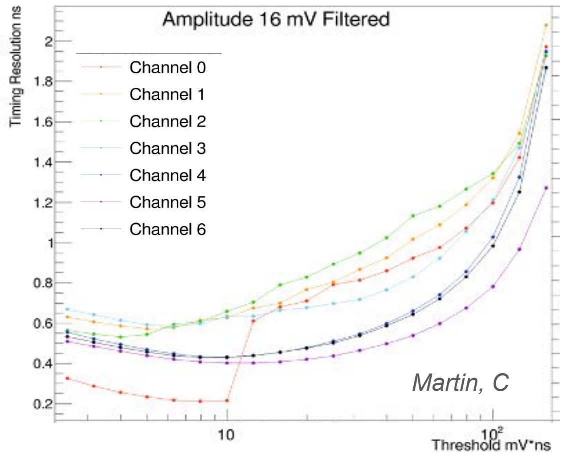

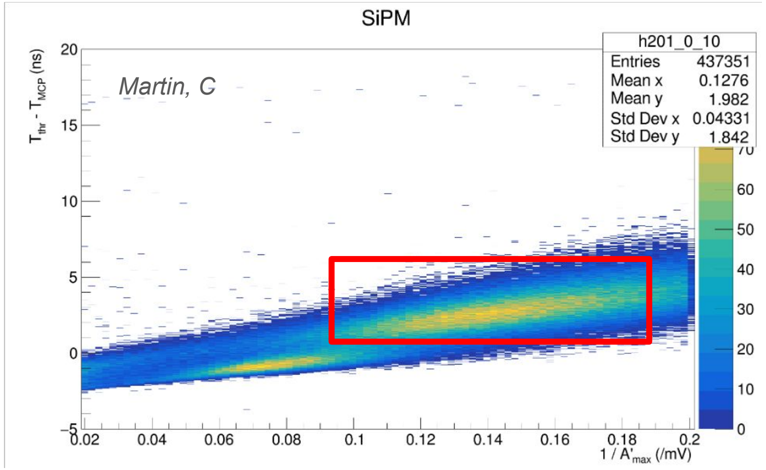

> 8 mm away from center of channel

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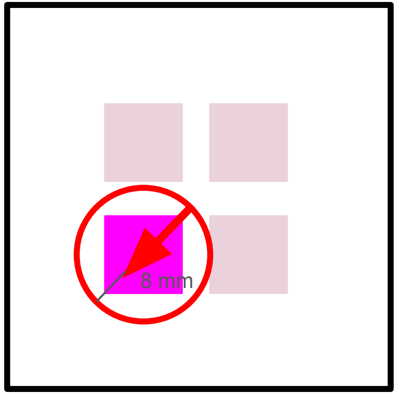

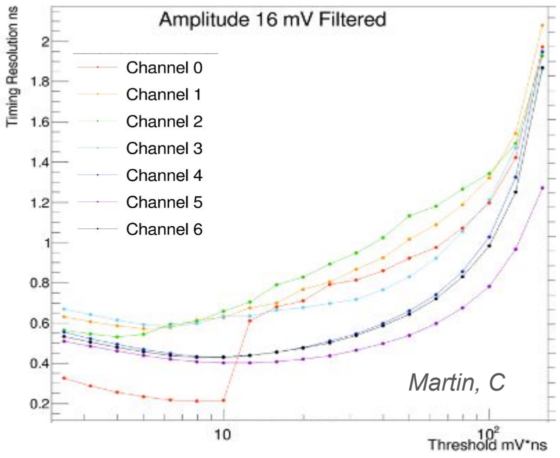

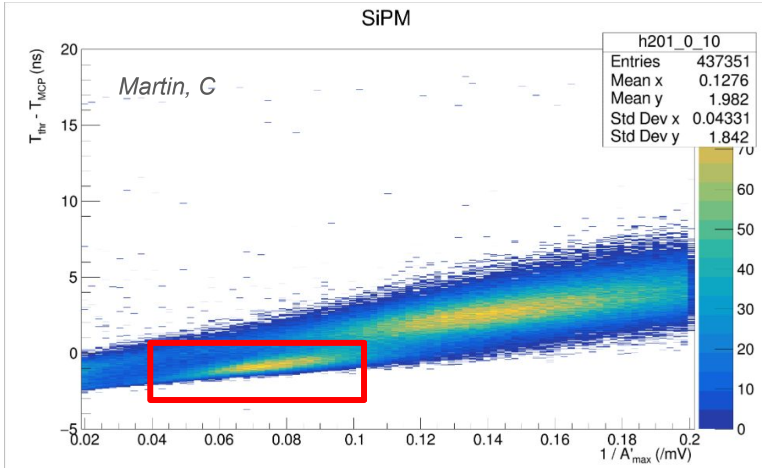

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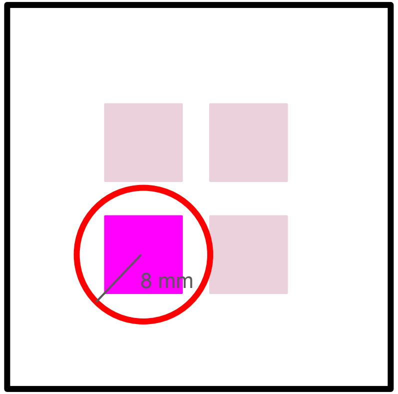
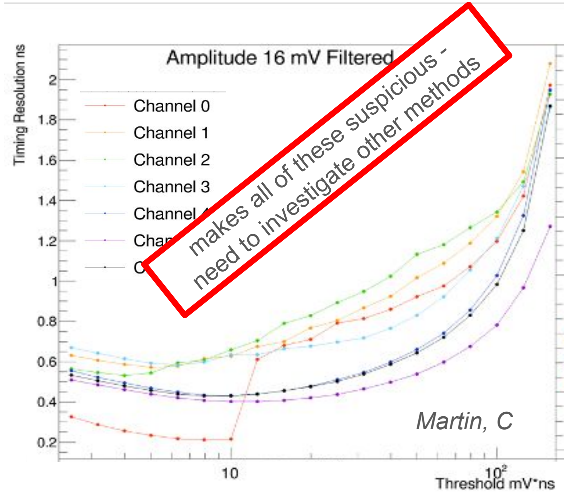
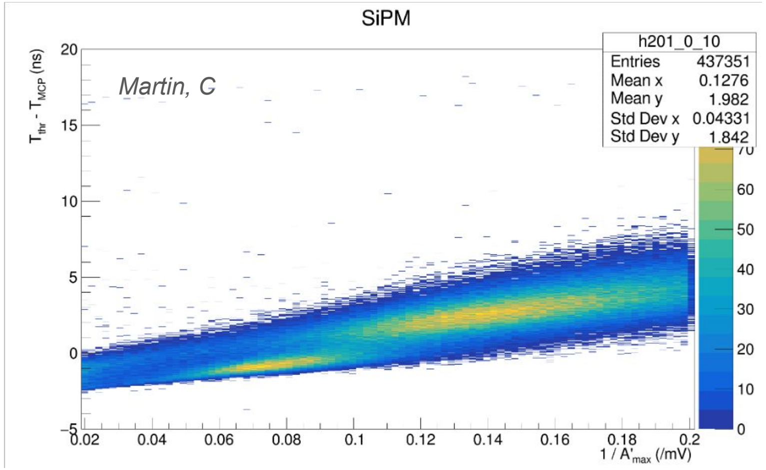




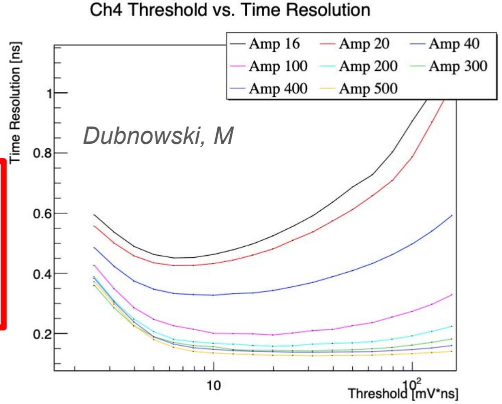


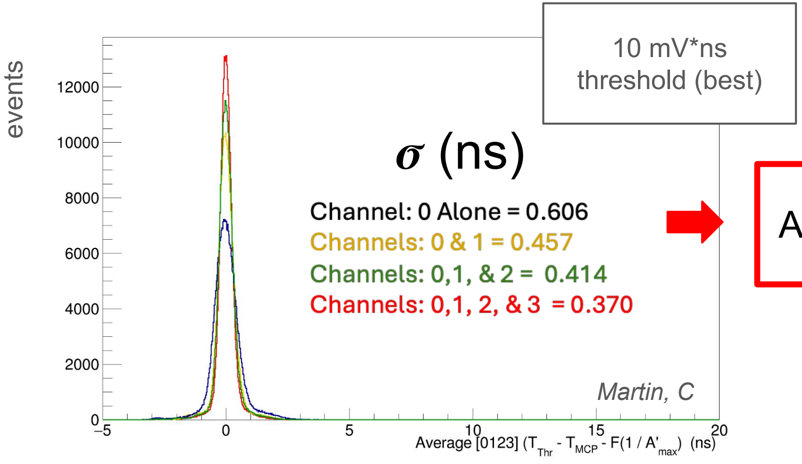
Position dependence will degrade performance in downstream channels

Preliminary Performance - **Un**filtered PWO

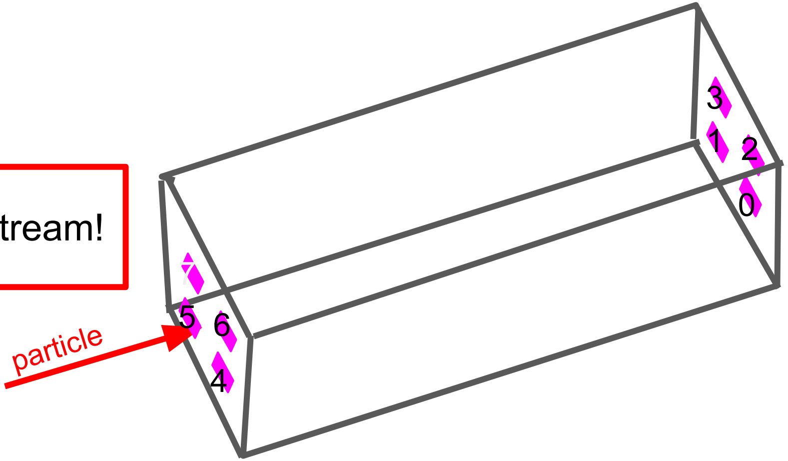
- More stable
  - no double peaks
  - *reduced* sensitivity to Cerenkov (but still there)
- Can combine channels
  - channels amplitude walk corrected

Upstream better





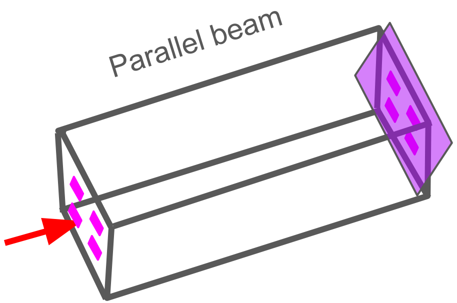
All downstream!



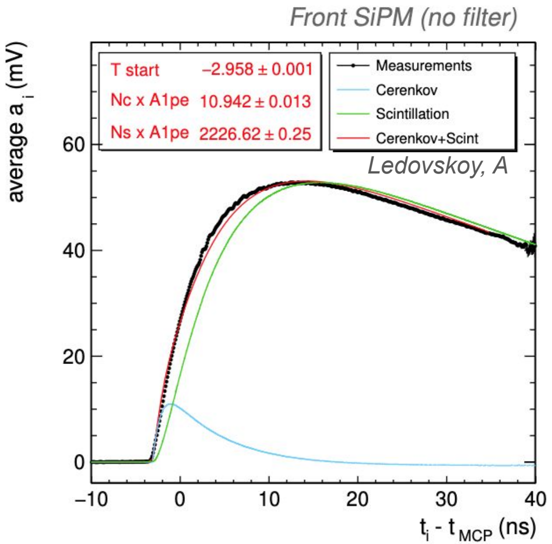
Preliminary Performance -BGO

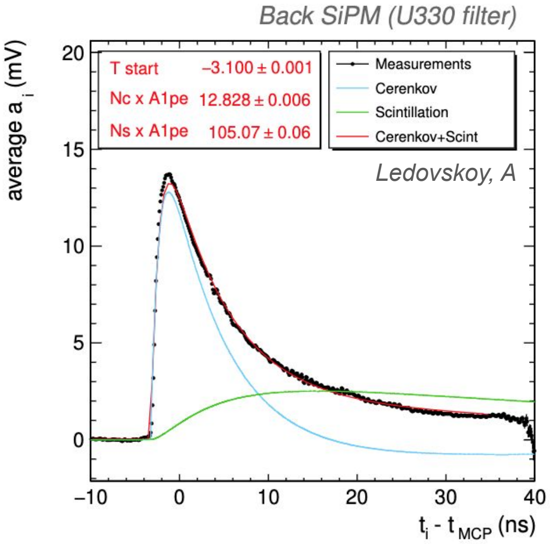
- Pulse shape analysis to extract # of Cherenkov and Scint
  - take Scintillation shape from unfiltered channels
    - deconvolute with BGO scint function to get Cherenkov
  - Cherenkov shape fit with CR-RC Shaper + RC Differentiator model

Hoya U330 notch filter between Crystal and SiPMs on back



Central MIP signals



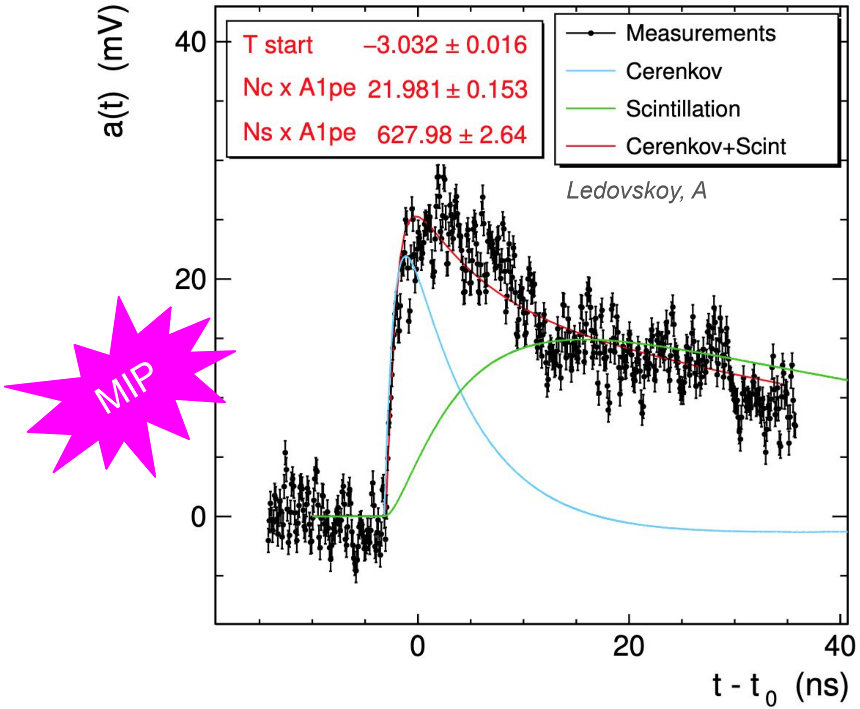


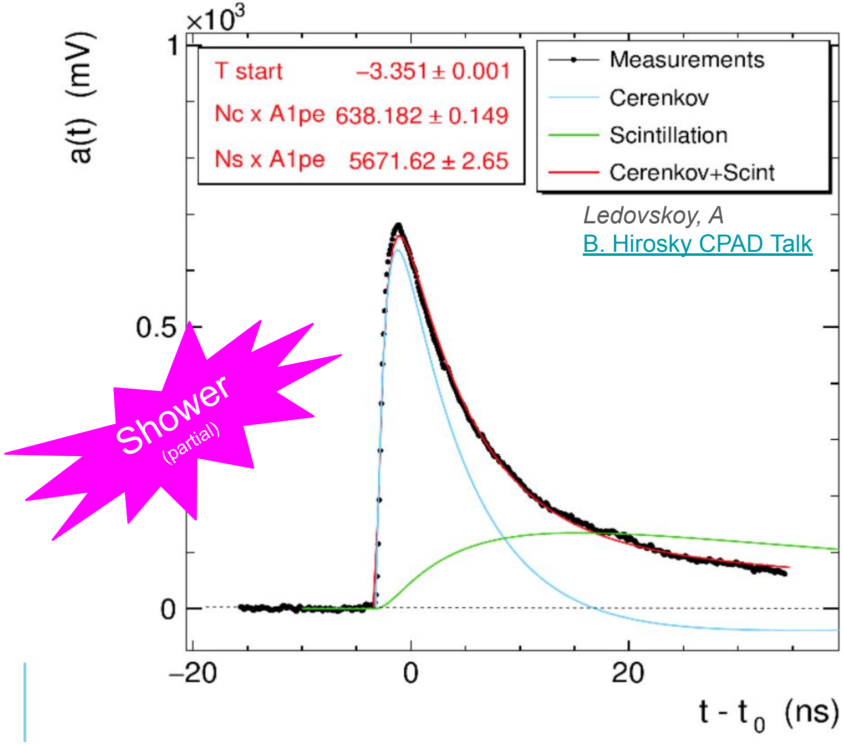
Assume single photon electron peak of ~0.6 mV

Discrimination driven by time profile

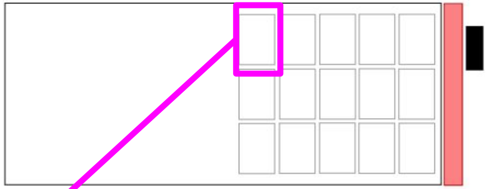
B. Hirosky CPAD Talk

Preliminary Performance - BGO single pulses

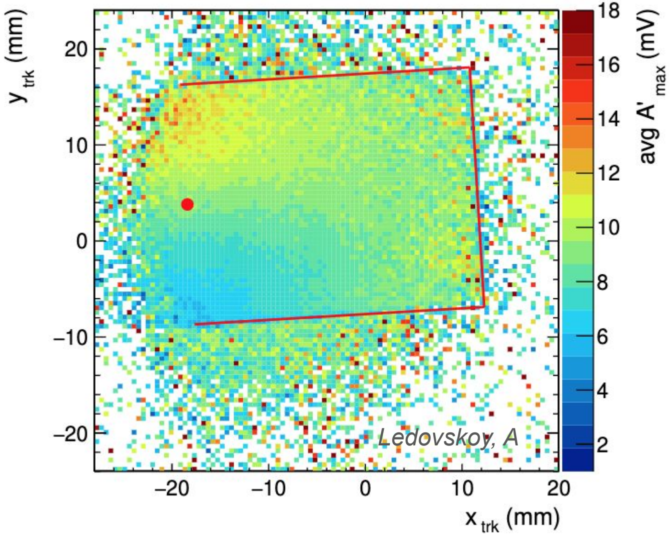




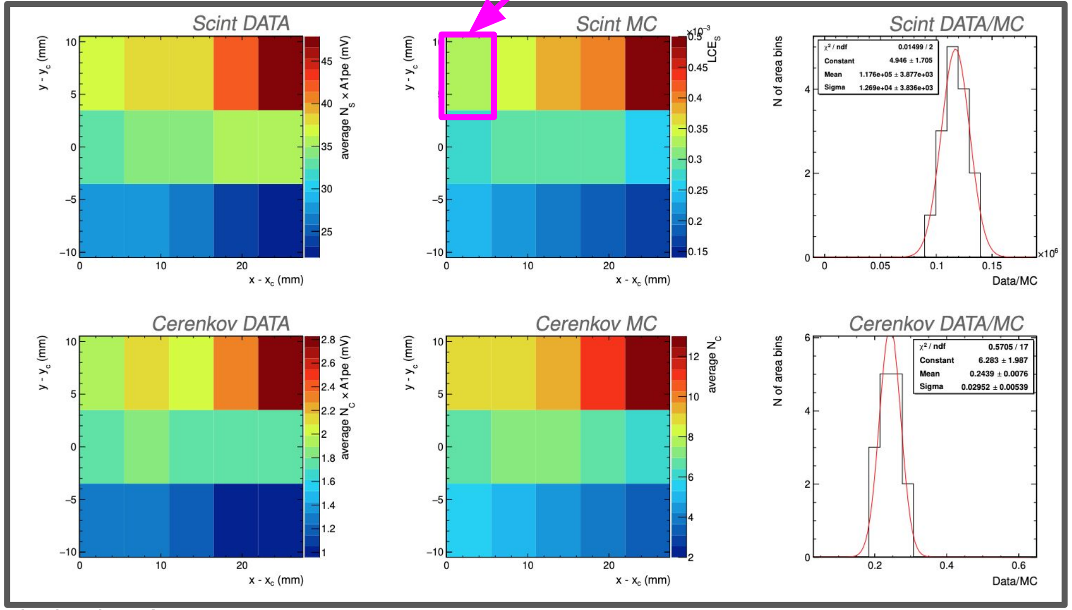
BGO Modeled well in MC ~ 10% level



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



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

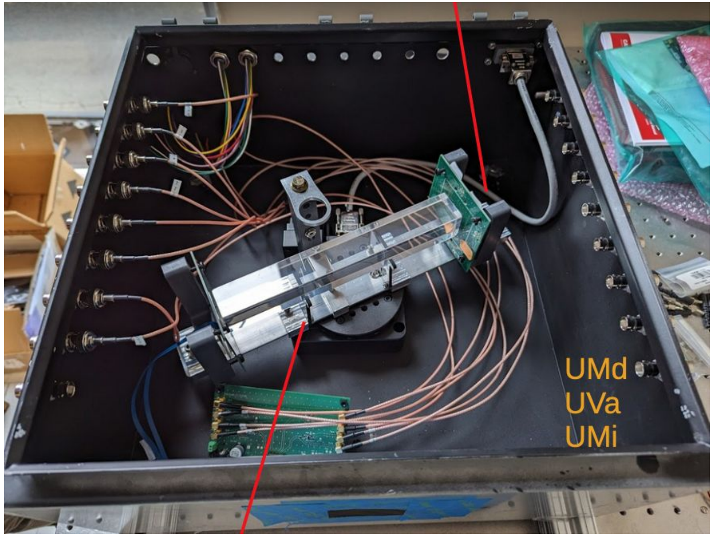


Ledovskoy, A

*LCE = N_detected/N_Generated

Summary

- PWO Timing - moderate
  - Variability of Cerenkov degrades the timing
  - Scintillation light will be Landau gitter limited
    - need a crystal large enough
      - improvement tracks with photostatistics
  - Improvements expected
    - Better methods for timing calculation
    - Better geometries
    - better electronics
- Separation Promising
  - BGO works!
  - PWO is harder
    - Scintillation light also fast
    - Needs better filters than those in April Test Beam



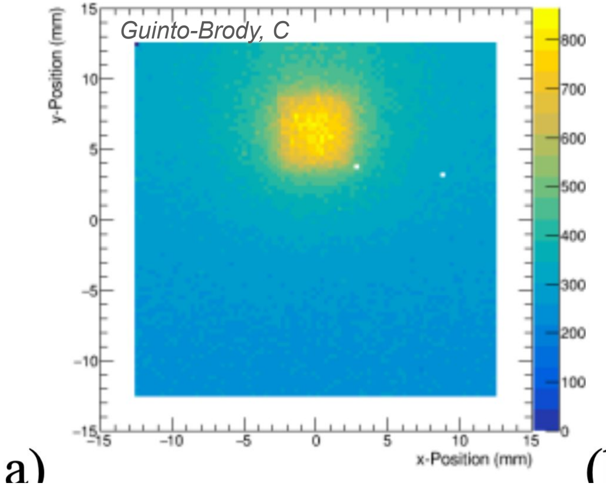
Upcoming DESY testbeams with quieter box, more crystals/glasses, better positioning and coupling!

back-up

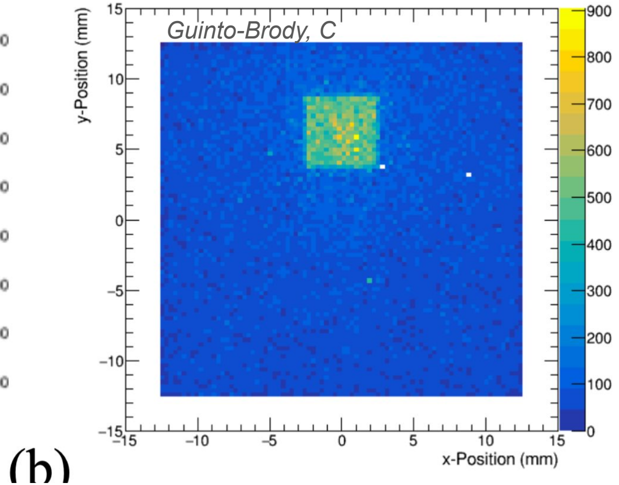
MC verification of extreme position dependence

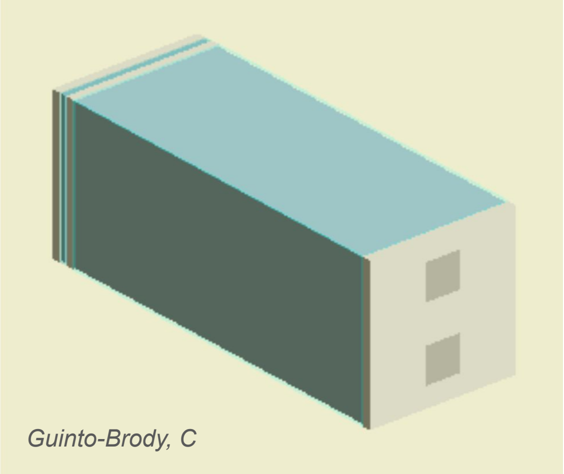
- Sharp edges confirmed in MC
  - 120 GeV protons on PWO, 88k events

Scint photons detected



Cerenkov photons detected

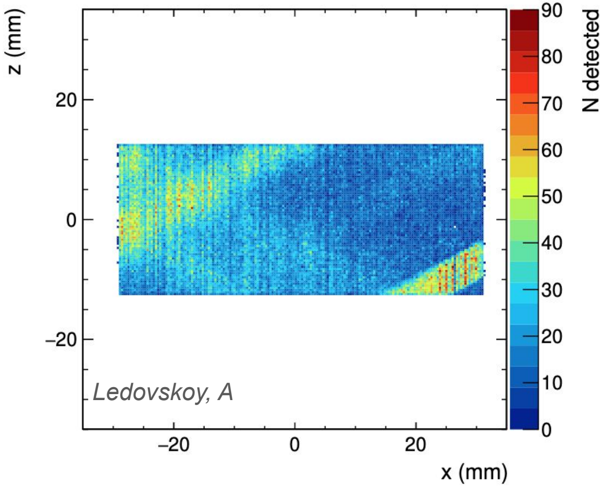




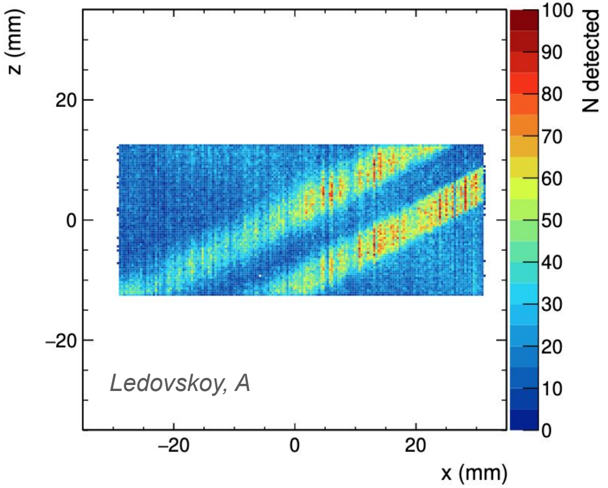
Also due to Cerenkov photons being created in the grease/SiPM window

MC validation of extreme position dependence

- Uniform illumination of perpendicular bar with 120 GeV protons



Upstream Channels



Downstream Channels