Dual-readout calorimetry with homogeneous crystals

Bob Hirosky

for the Calvision Team

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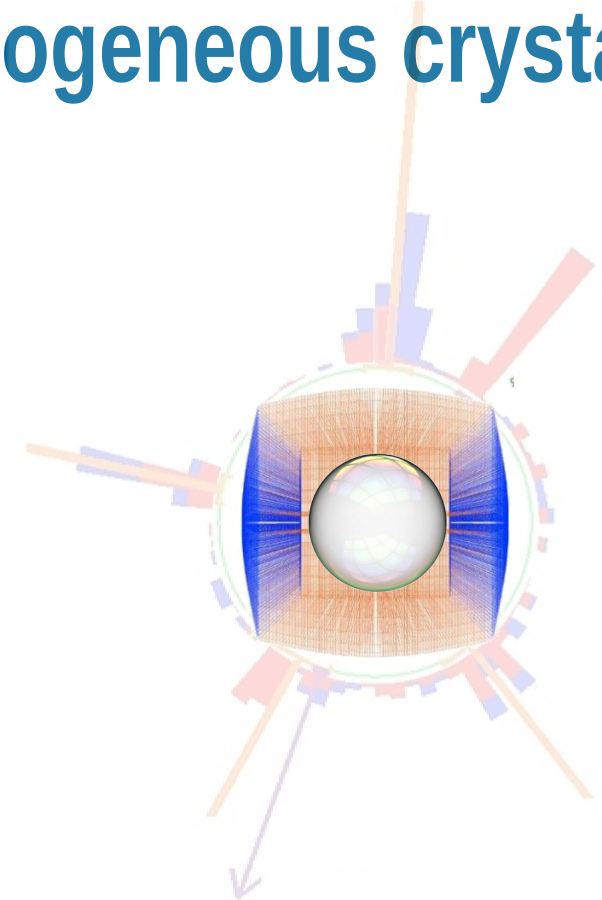
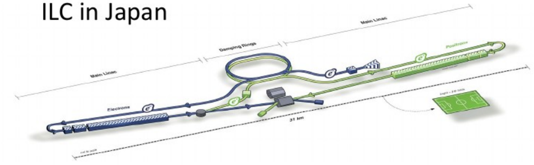


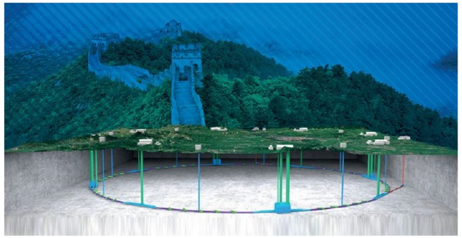
Future colliders and calorimetry

The next international collider will most likely be an e+e- collider, Higgs factory with capabilities of numerous precision measurements at the EW scale.

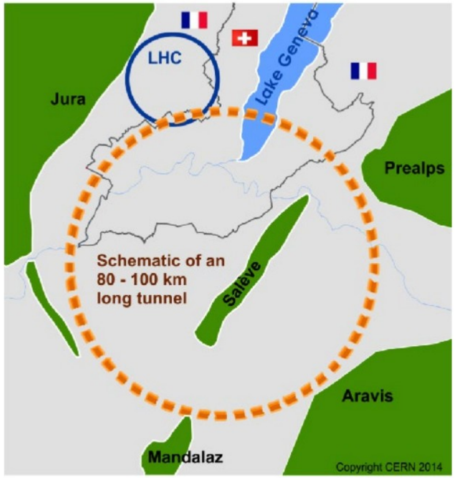
ILC in Japan



CEPC in China

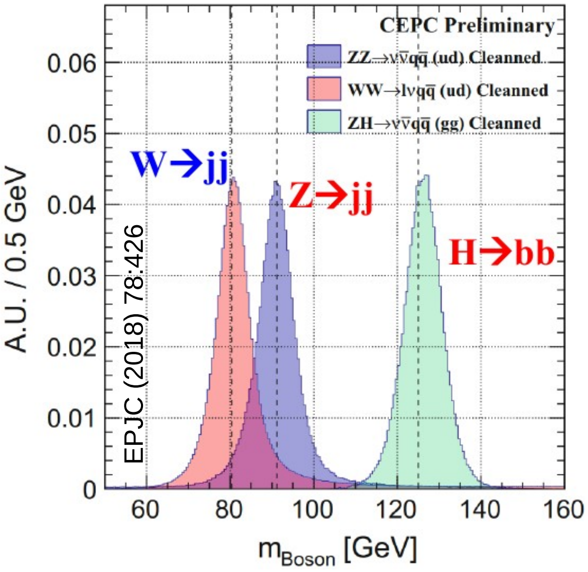


FCC-ee at CERN



Jet energy resolution is a key benchmark of e+e- detector performance

- eg, Need calorimeters w/ ΔE/E ~ 3-4% for jets ~100 GeV to separate hadronic W's Z's
- Very hard to achieve with traditional calorimetry, having HCAL resolution >~50%/√E



Complementary approaches to better calorimetry:

- **High granularity**
- **Dual Readout (DR)**

Future colliders and calorimetry

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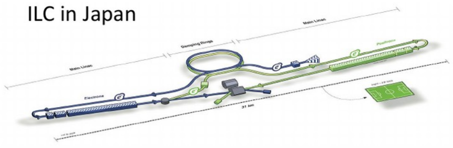
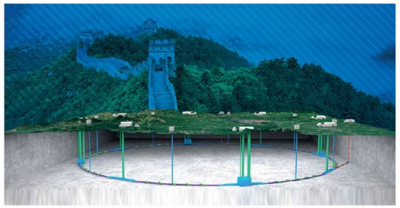
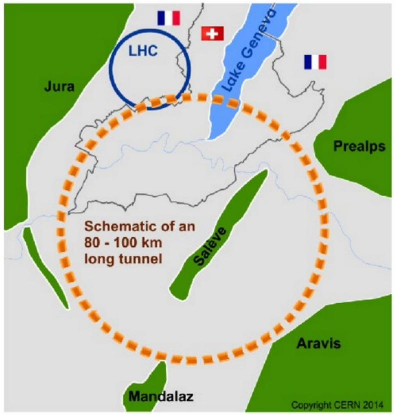
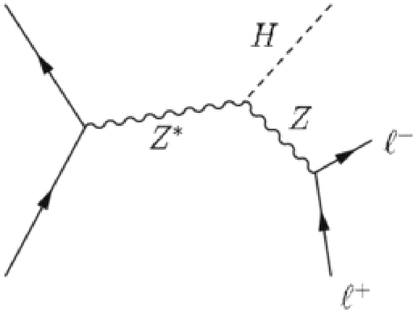




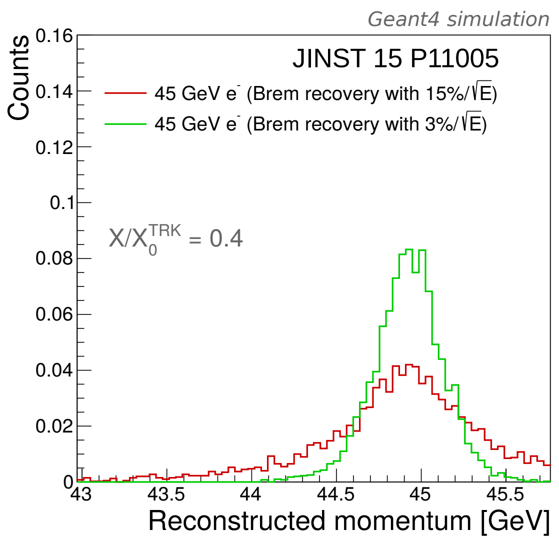


High resolution EM calorimetry equally important, eg



- Unexpected, even invisible, Higgs decay
- Precision W/Z-boson studies
- **Electron brem. recovery**
- π^0 reconstruction and jet matching

eg, brem. recovery important in electron energy resolution



Also see talk by M. Tornago

Future colliders and calorimetry

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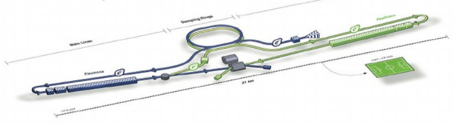
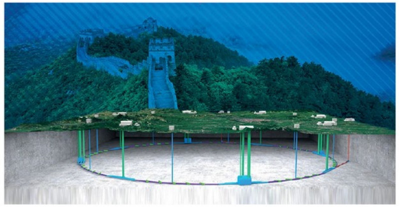
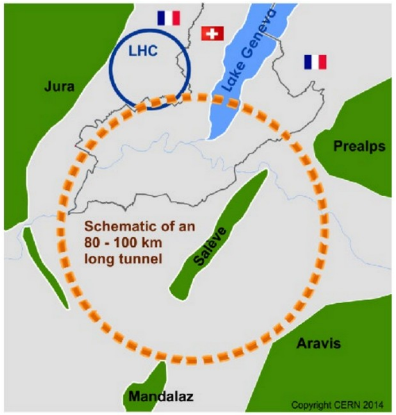
ILC in Japan



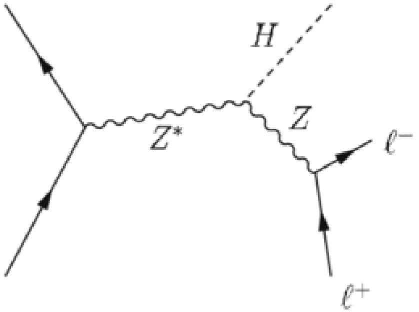
CEPC in China



FCC-ee at CERN



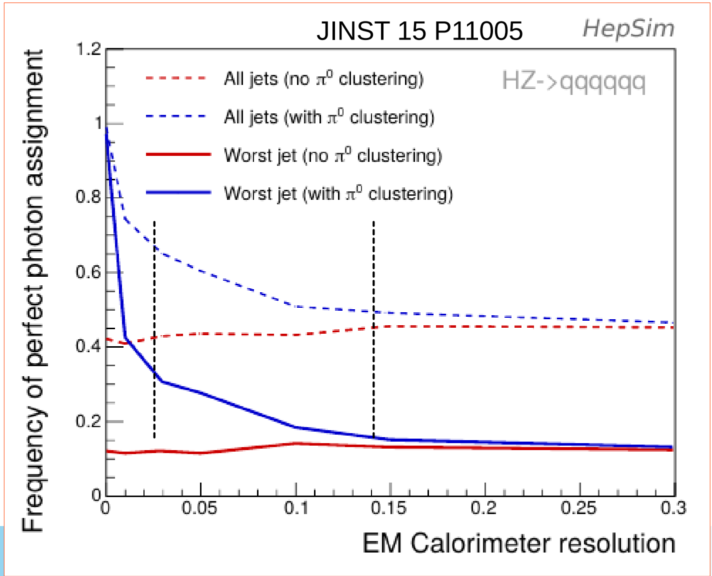
High resolution EM calorimetry equally important, eg



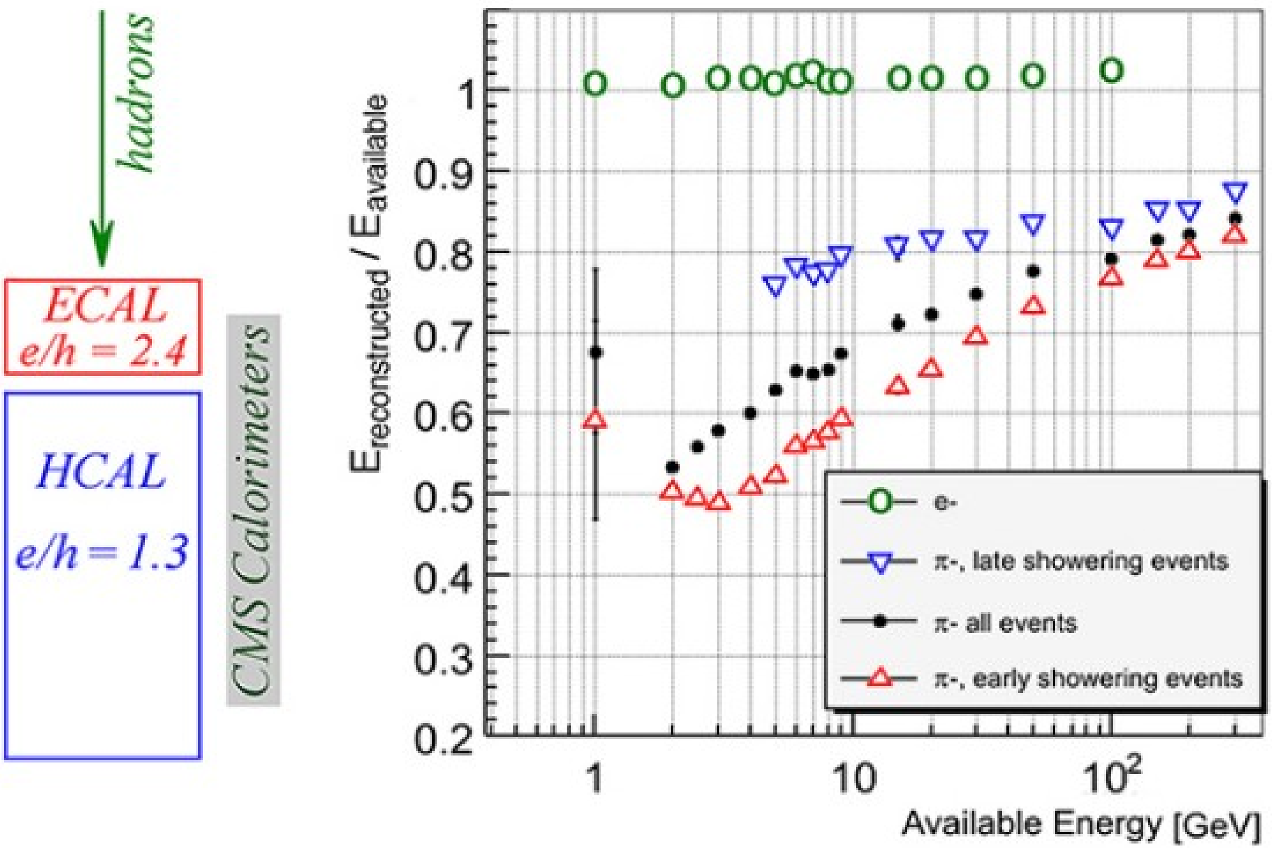
- Unexpected, even invisible, Higgs decay
- Precision W/Z-boson studies
- Electron brem. recovery
- **π^0 reconstruction and jet matching**

eg, photon matching in 6 jet event:

w/ π^0 clustering
w/o π^0 clustering



Effect of an optimized EM section in traditional calorimetry



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

Large dispersion in E^{vis} and non-linearity for hadrons

Strong dependence on location of interactions if layers have non-uniform e/h

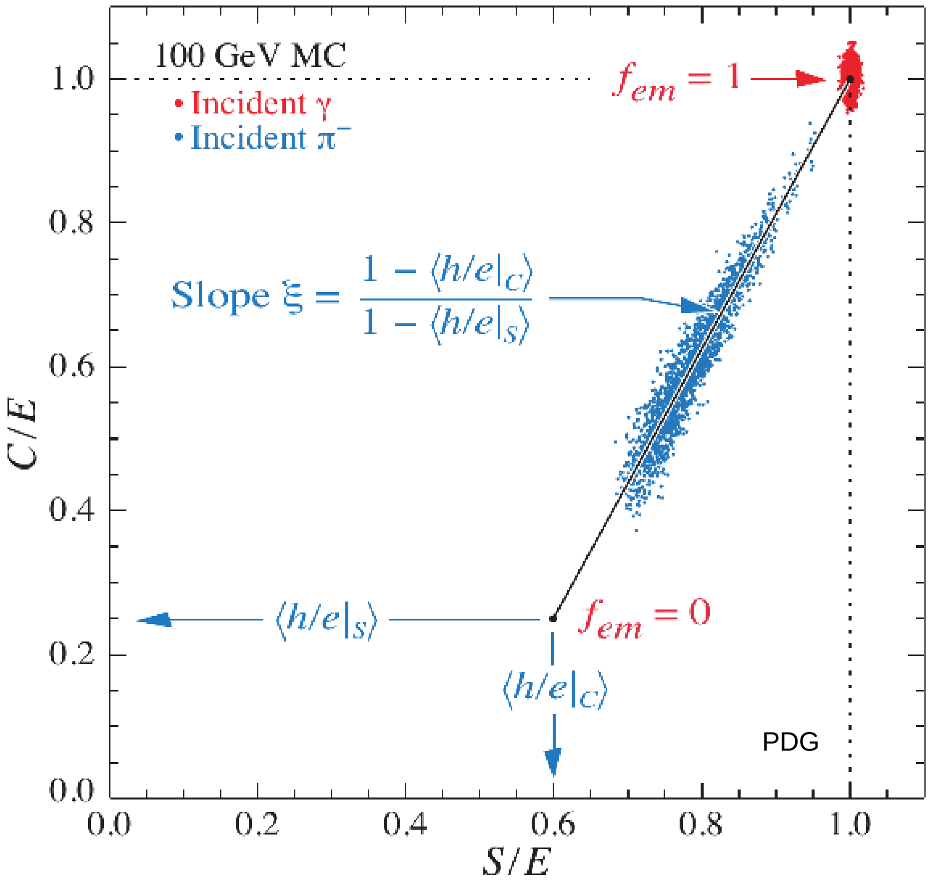
Improving jet resolutions

Taking state of the art EM calorimeter energy resolution as sufficient for future physics needs, a goal is to simultaneously improve hadron performance

Two general approaches

- **Particle-flow**: use track info to measure charged jet fragments and calorimeter data mainly for the measurement of neutral particles.
  - Requires fine (transverse) granularity to separate showers
  - “Confusion term” for co-linear particles/showers important at high energy
- **Dual-readout**: use proxy for invisible E component of hadron showers
  - Effectively use an evt-by-evt proxy for EM fraction of hadronic showers
  - More moderate requirements on granularity
  - **Complimentary** to (also **compatible** with) PF methods
  - Apply to **BOTH** EM and hadronic layers to optimize resolution

Dual Readout (DR) Calorimetry



$E = (\xi S - \hat{C})/(\xi - 1)$

Hadronic event (π^- here) can be seen to scatter about the fixed slope

Slope depends only on e/h values and is energy and species independent

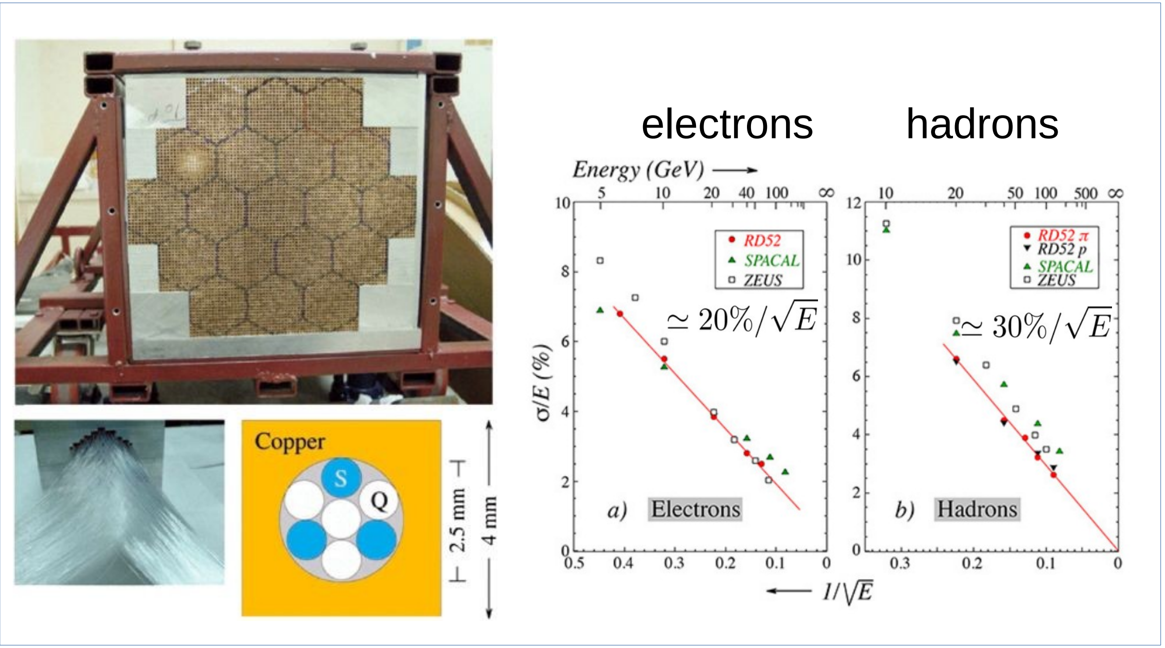
$\hat{C}$,S measurements effectively determine f_{em} and allow a shower-by-shower correction => proxy to correct for invisible energy

Nice review: RevModPhys.90.025002

Previous DREAM/RD52 results on DR Crystal Calorimeter

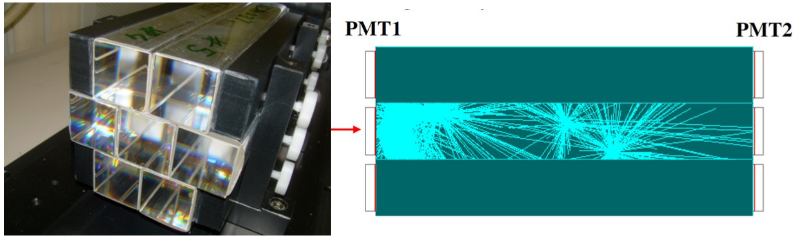
DREAM/RD52 previously investigated DR w/ crystals and PMTs readout using BOTH optical filters and timing to separate Ĉ and S signals

Excellent hadron performance demonstrated, reasonable EM



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

Proof of principle for DR crystal calorimeter



- Ĉ/S filters, PMT readout
- Resolution O(10%/√E), dominated by photon detection statistics
- Improvements needed on efficiency, λ range of light collection to increase Ĉ signal for DR application
- Need B-field compatible readout

NIM 686 (2012) 125

Calvision

CALVISION formed to pursue calorimetry efforts on <u>multiple fronts</u> and in collaboration with other projects, particularly IDEA/MaxiCC

Interests in:
- Crystal DR ECAL
- Fiber DR HCAL
- Full Detector studies (sim.)
- Event Reconstruction
- BlueSky R&D (materials, sensors, R/O, ...)

Multi-year efforts planned in each area.

1st phase:
- Lower level R&D
- Single modules, small arrays
- Materials/technology evaluations
- Building up simulation program
- Scale up modules in next phase

This talk will focus on studies related to DR in a crystal ECAL

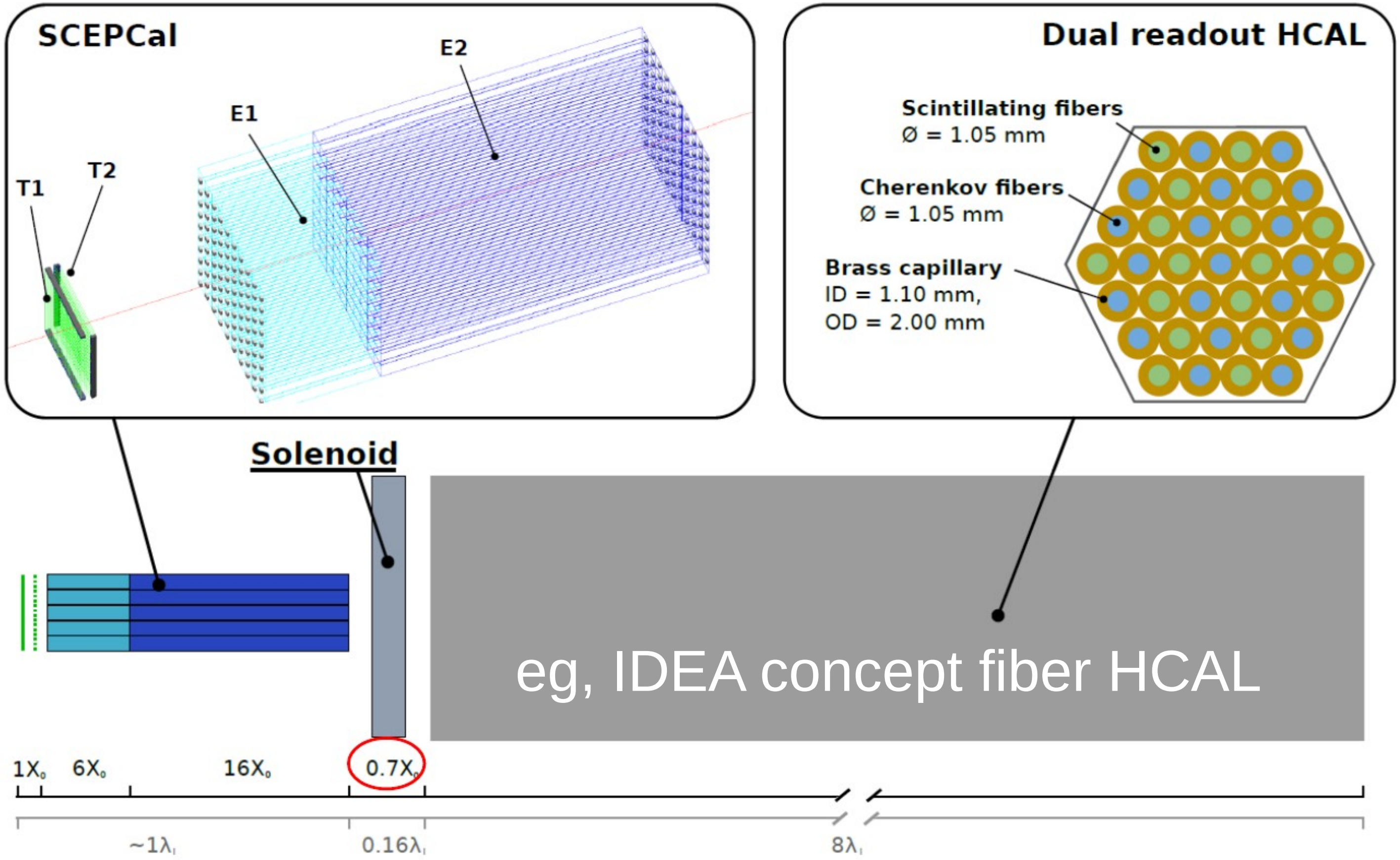
See also talks on other fronts by
- Wonyong Chung: DR Calorimetry Simulation
- Renyuan Zhu: Progress of Inorganic Scintillators
- Nural Akchurin: US Perspective, High-granularity DR
- And many related topics all week!

A Segmented DRO Crystal ECAL + DRO Fiber HCAL

SCEPCal:
Segmented
Crystal
Electromagnetic
Precision
Calorimeter

Concept:

- (Optional) timing layer
- Segmented ECAL
- Thin solenoid
- DREAM/RD52 style HCAL



Enhance physics program with precision ECAL + DR hadron performance

Initial studies for crystal+SiPM DR ECAL

Initial bench and beam tests for xtal ECAL, focus on understanding photon collection in various materials (PWO, BGO, PbF, BSO, etc.)

Each have different advantages/challenges for performance criteria

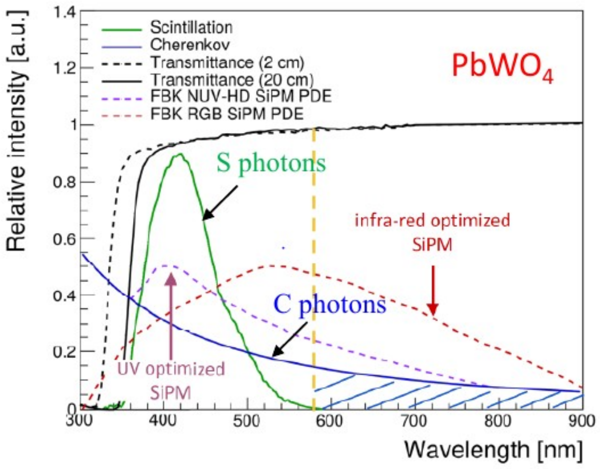
- acquire data for tuning simulation
- guide choices for a ‘phase 2’ ECAL module sufficient in size to contain an electron shower
- Gain experience with FE electronics, readout and beam interfaces to run efficient beam tests

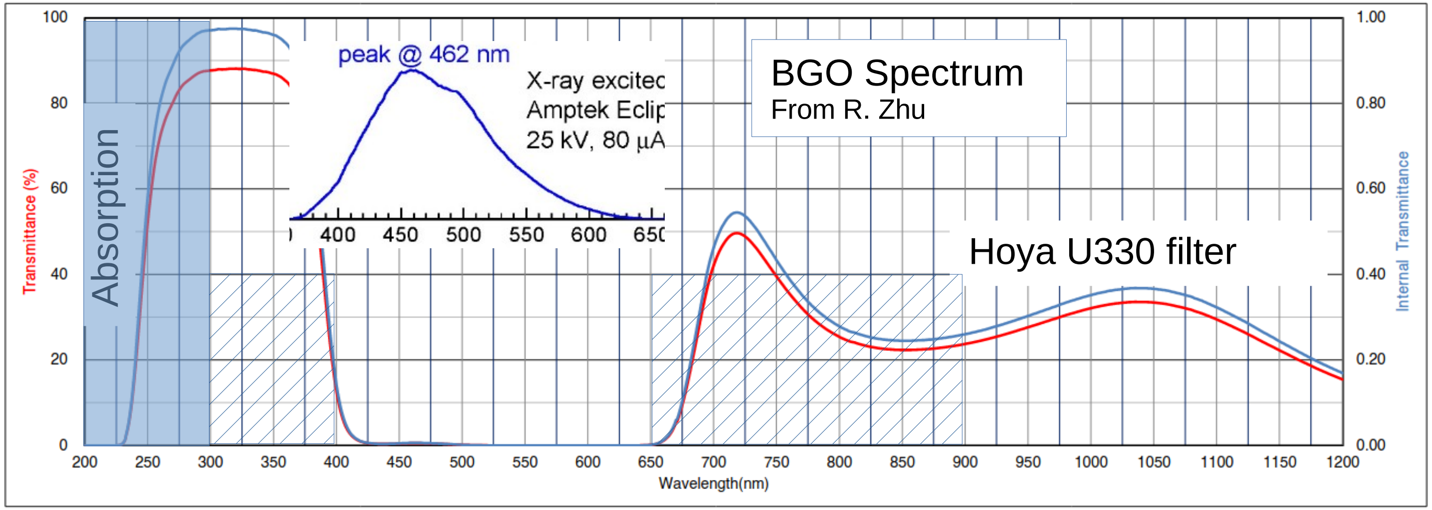
‘Phase 3’ is planned to develop a larger ECAL, sufficient to use with single hadrons in ECAL+HCAL resolution studies in collaboration with IDEA

Performance/feasibility of concept strongly depends on:

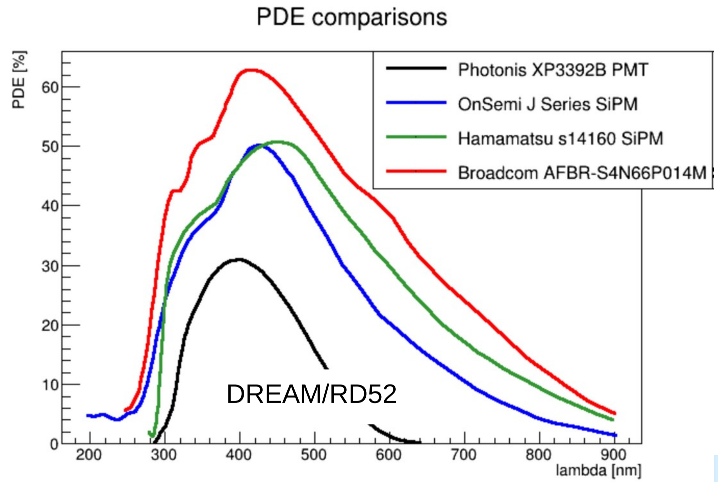
- **Adequate sampling statistics of Č light (>~50 photons/GeV)**
  - **Need large area sensors; good PDE, λ sensitivity**
- **Sufficient separation of Č from S light to avoid washing out signal**
  - **Wavelength, timing/pulse shape discriminators**
- **For state of art ECAL resolution, reasonably large S is desirable. May require some care to address saturation effects in SiPMS/readout**
  - **Eg small cell, fast recovery devices**

Challenge of Light Detection and Separation





Detection regions for Ĉ light



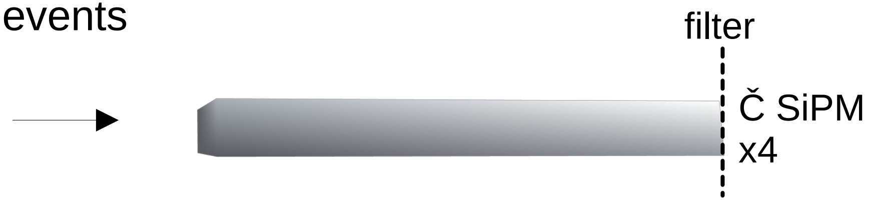
n.b. Crystal transparency is poor at NUV where Ĉ light is most intense => use longer λ's beyond scint spectrum

Modern SiPMs are promising, but improvements in deep Red/NIR sensitive devices are very desirable

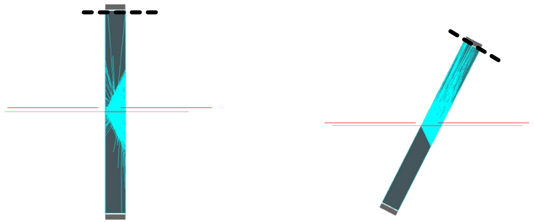
Test beam efforts 2023/2024

Test beam 1: 120 GeV proton beam (FNAL)
- PWO/BGO,interference/absorption filters
- Concentrated on beam on long axis, MIPs + showering events
- Study light collection and S,Ĉ components, timing
- Lecroy scope 10GS/s

Baseline bar configuration



Test beam 2: 120 GeV proton beam (FNAL)
- PWO/BGO/PbF, absorption filters
- Concentration on angular dependence of light collection
- Aim to tune MC and identify Ĉ/S signal+variations
- Readout: 5GS/s DRS



Test beam 3: 2-4 GeV e- beam (DESY)
- PWO/BGO/BSO/PbF/scint glasses
- Material and filter scan, longer crystals
- Readout: 1-5GS/s DRS

Test beam 4: various beams (CERN)
- Coming in July

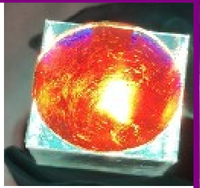
SiPM evaluations

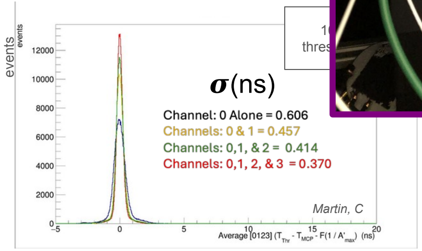
Hamamatsu
S14160-6050HS
Large area 6x6 mm SiPMs

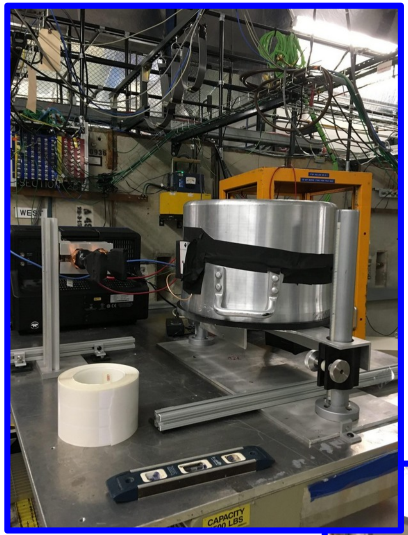
Broadcom
AFBR-S4N66C013-ND
Large area 6x6 mm SiPMs

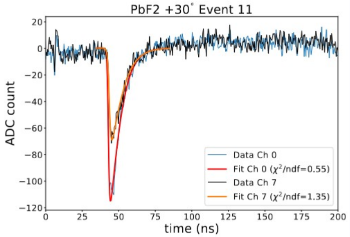
OnSEMI
MICROFJ-60035-TSV-TR
Large area 6x6 mm SiPMs

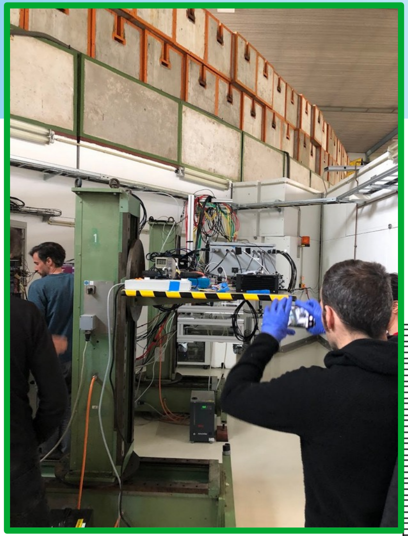
Test Beams

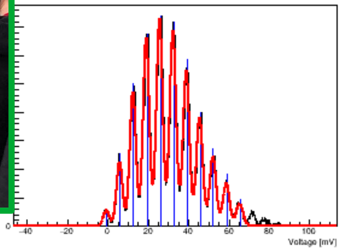


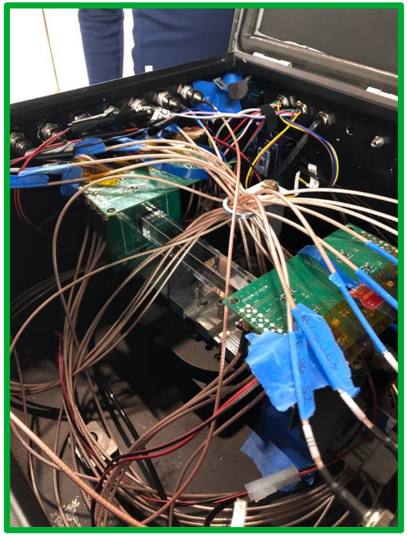

events
σ(ns)
Channel: 0 Alone = 0.606
Channels: 0 & 1 = 0.457
Channels: 0,1, & 2 = 0.414
Channels: 0,1, 2, & 3 = 0.370
Martin, C
Average [0123] (T_{Thr} - T_{MCP} - F(1 / A'_{max})) (ns)




PbF2 +30° Event 11
ADC count
time (ns)
Data Ch 0
Fit Ch 0 (χ^2/ndf=0.55)
Data Ch 7
Fit Ch 7 (χ^2/ndf=1.35)



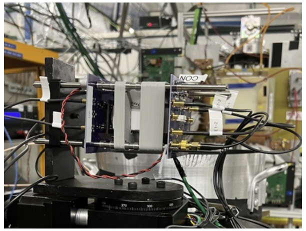

Voltage [mV]

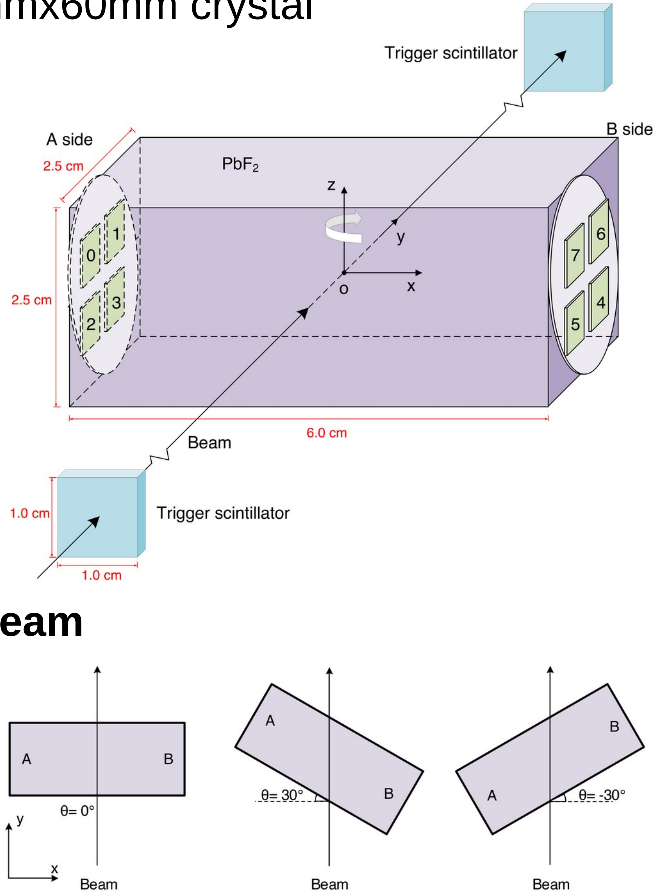


Study PbF2 crystals to test modeling of Cerenkov light collection

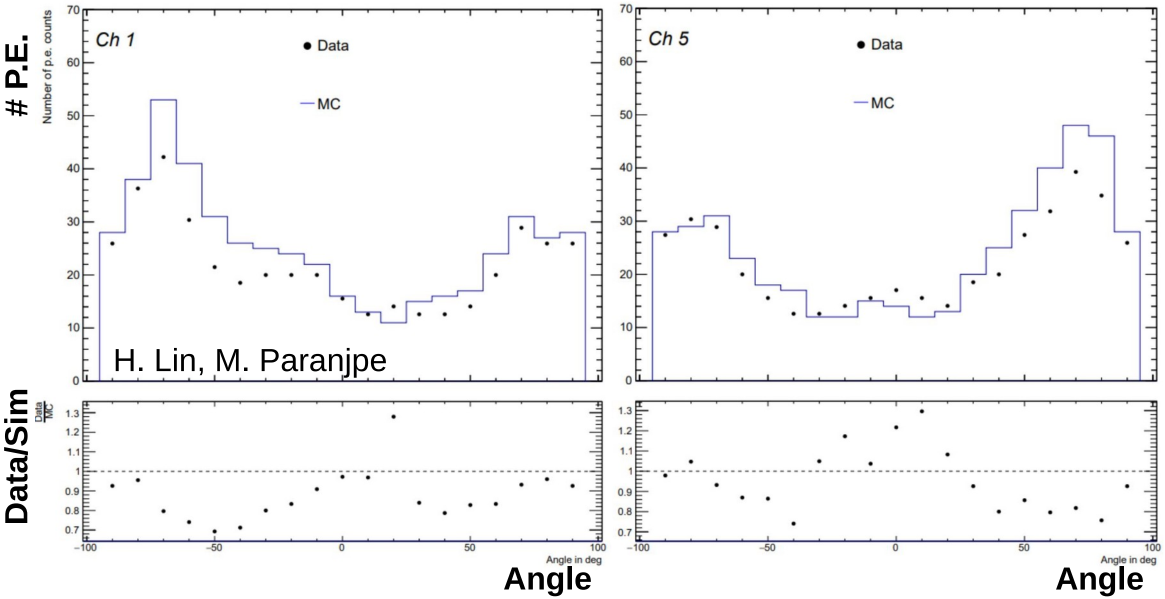
- Geant4 model normalized to response @ 90°
- Tune reflection model for surface conditions
- **Good O(<20%) modeling precision of Ĉ photon statistics – shape structure determined by Cherenkov cone, Z matching, internal reflection, surface reflections, ...**

25mmx25mmx60mm crystal



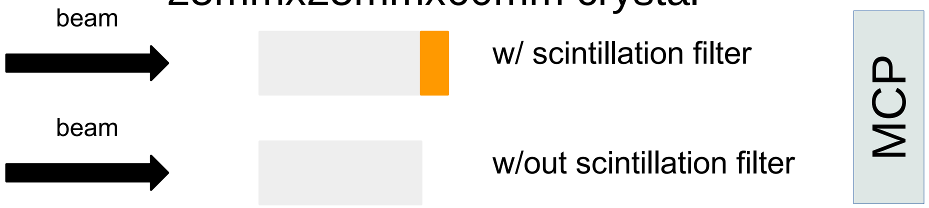


120 GeV proton beam

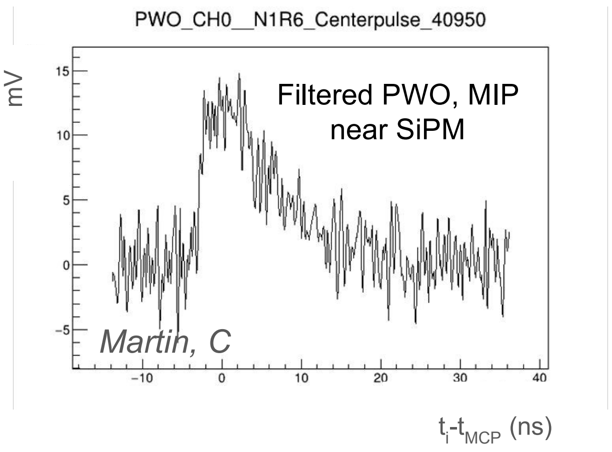


PbWO4 signals, 120 GeV protons

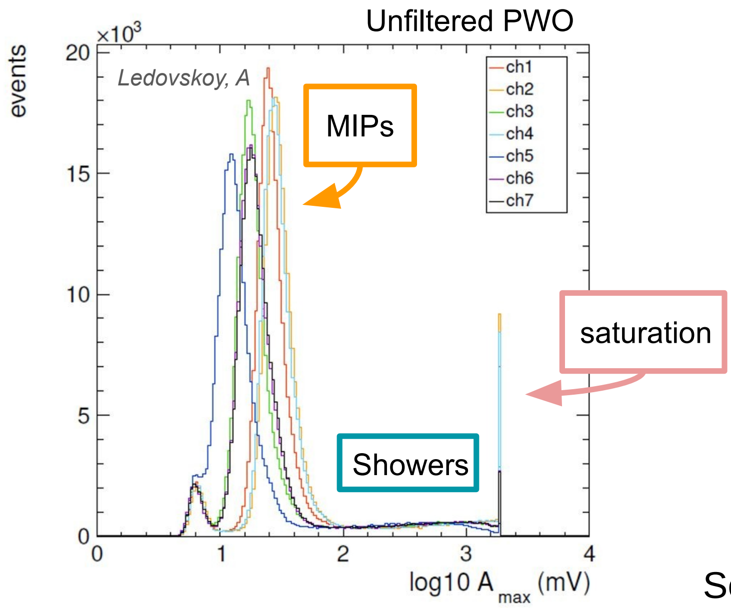
25mmx25mmx60mm crystal



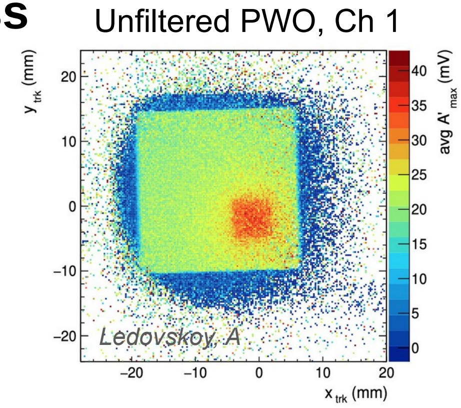
~Good signal-to-noise for MiPs
(improved for test beam3)



Collect MIP and showering events



Position dependence evident in readout
=> good coverage of crystal cross section is important



See also G. Cummings slides at US FCC Workshop

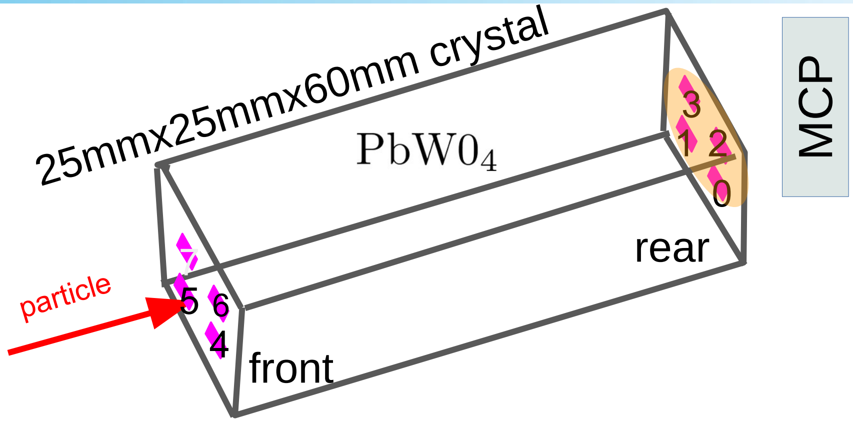
MIP Timing Resolution – Filtered PWO

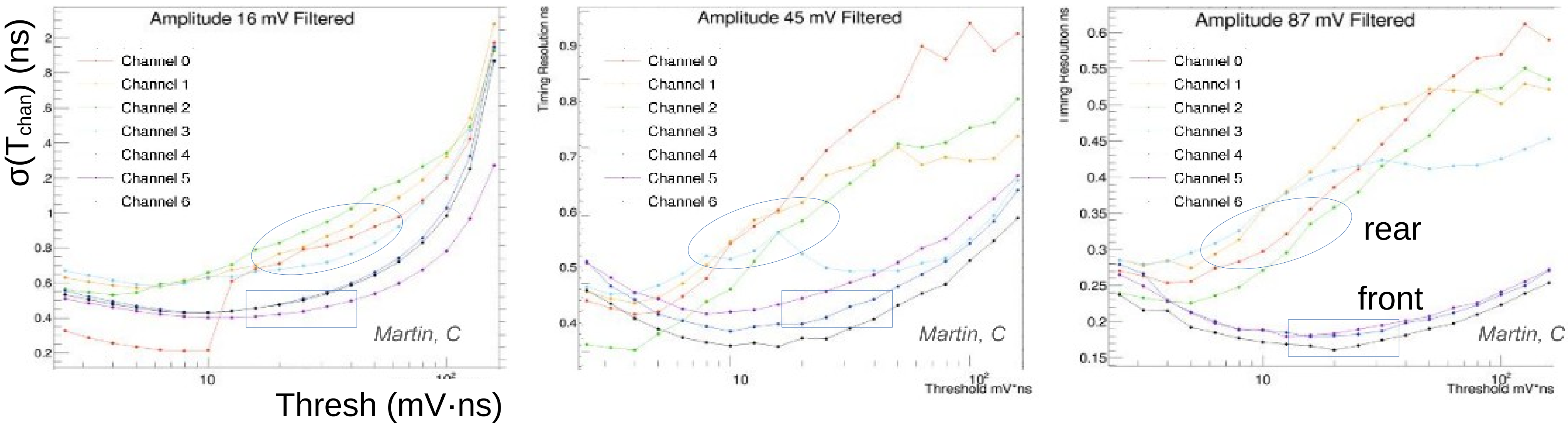
660 nm interference filter on rear SiPMs

Threshold on pulse integral, amplitude walk correction

MIP Timing resolution ~200 - 400 ps / single channel

- Upstream channels - no filter, mostly scintillation
- Worse resolution on channels w/ Cherenkov selection filter

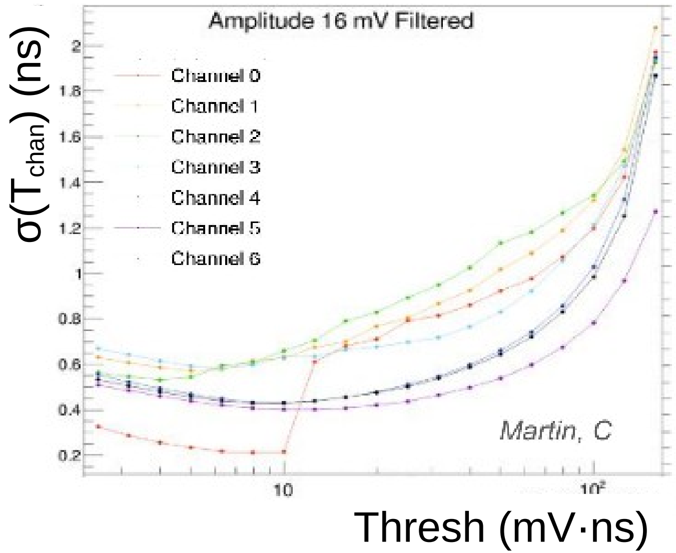


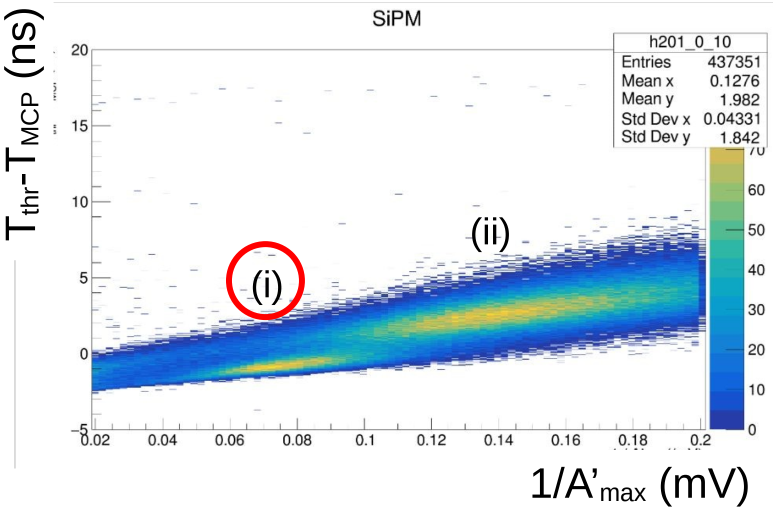


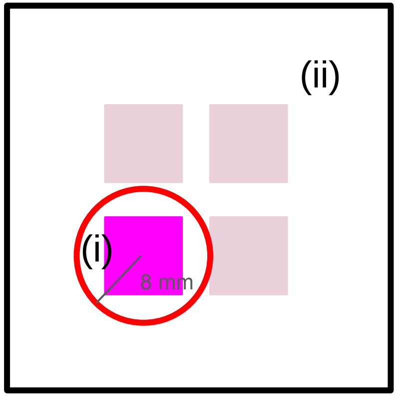
MIP Timing Resolution – Filtered PWO

Two “peak” structure correlated with track location wrt SiPM (absent in unfiltered data)

- Visible on filtered channels, correlated with track location wrt SiPM



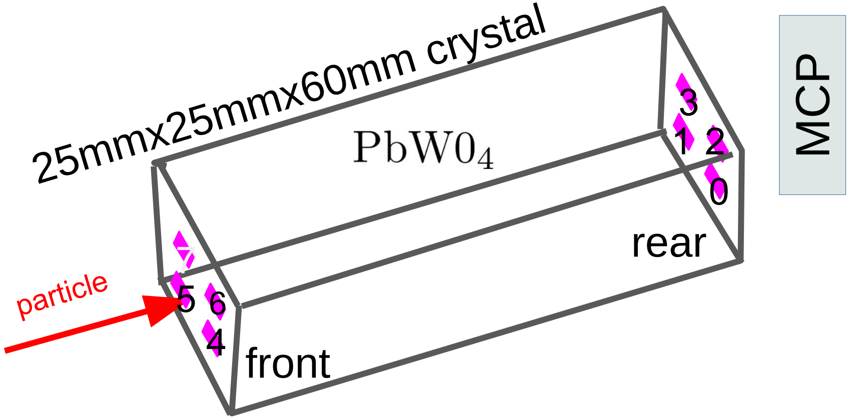




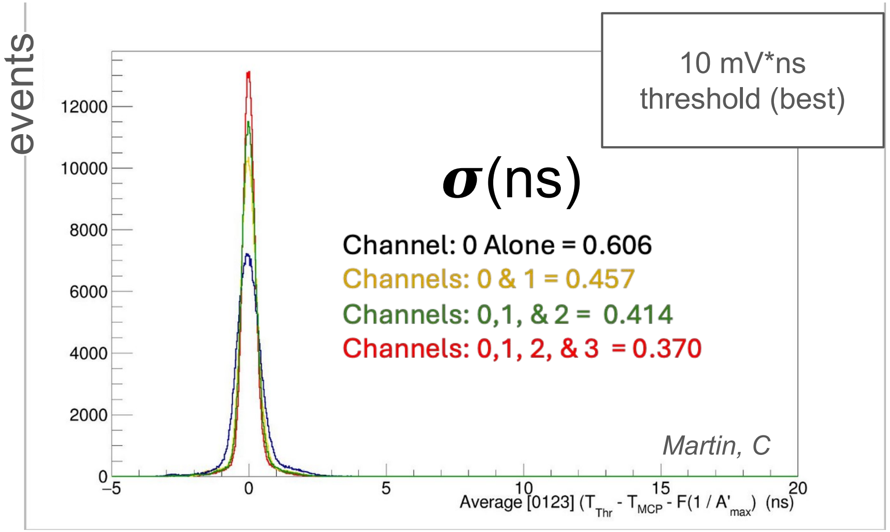
Hypothesized as a combined effect of interference filter and Cerenkov directionality

MIP Timing Resolution – Unfiltered PWO

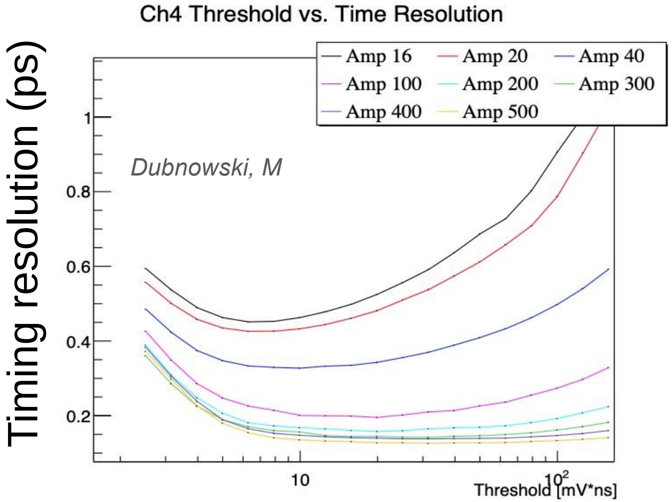
- No “double peak” structure in unfiltered data
- Simple combination of channels yields improved timing resolution



Rear channels



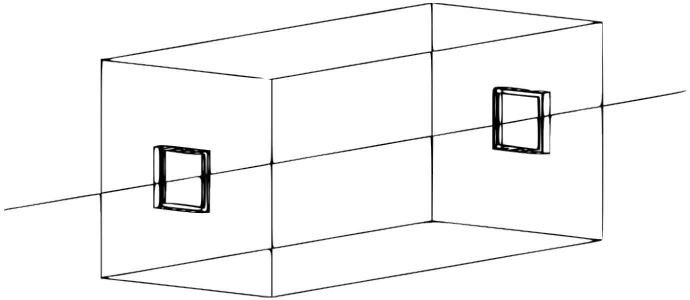
Upstream / front channels even better => <200ns



Analysis of 120 GeV Protons on BGO

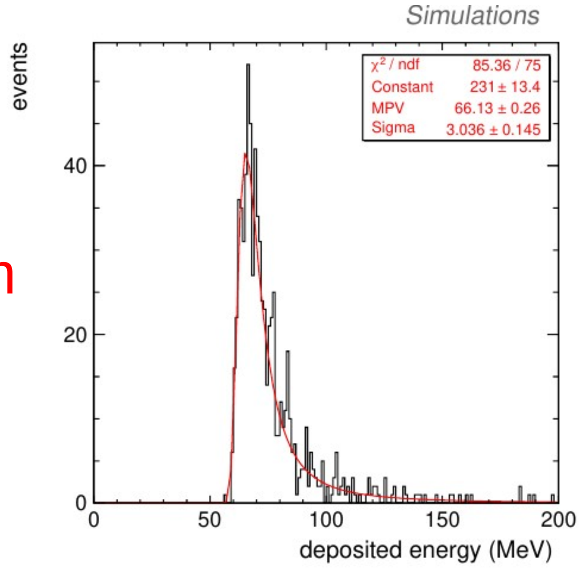
Simulation:
MPV = 66 MeV
Select tracks with deposited energy 50–100 MeV

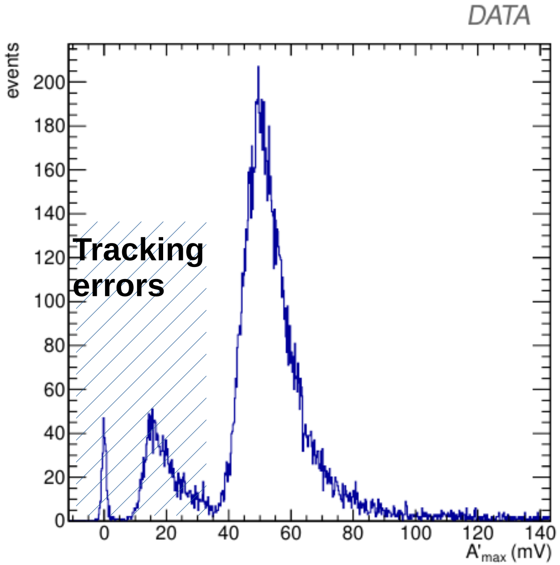
DATA:
MPV = 50 mV
Select tracks with reconstructed amplitude 35–100 mV



Simplified Geant4 model

MIP spectrum



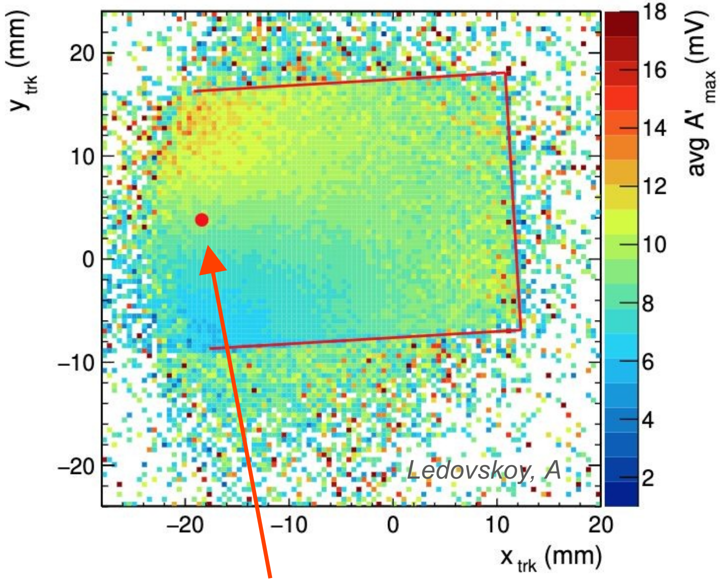


Good S/N in data

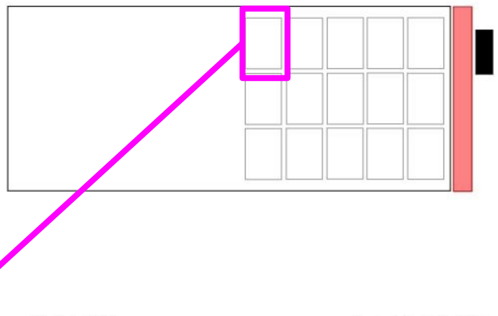
BGO Modeling

Modeling of scintillation and Cherenkov photon collection for BGO crystal

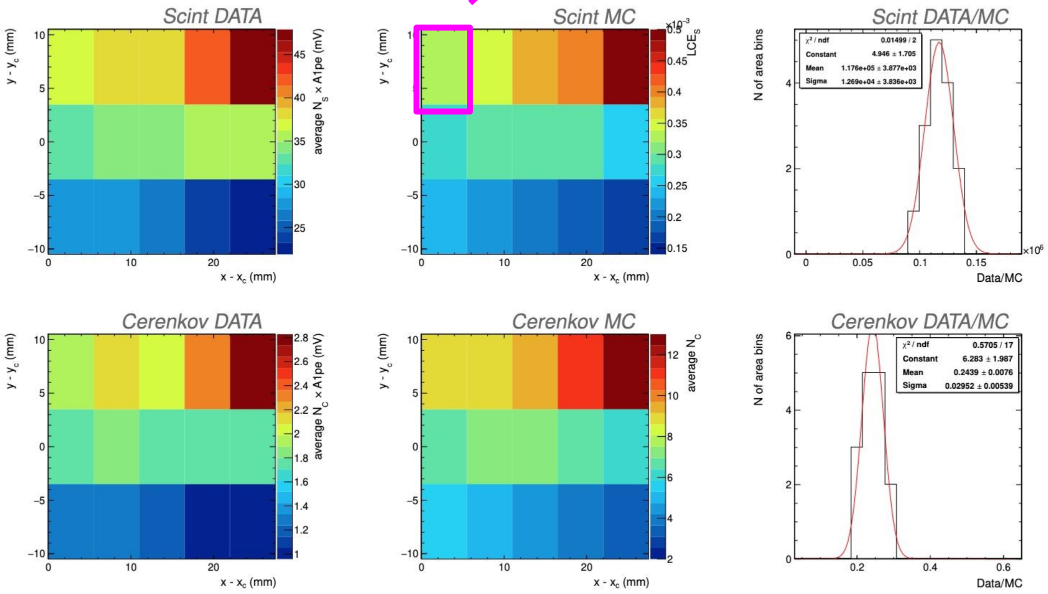
- Simulation only tuned for average amplitude over the scan
- Data/simulation agreement to 10% level



Center of crystal



Beam position x,y

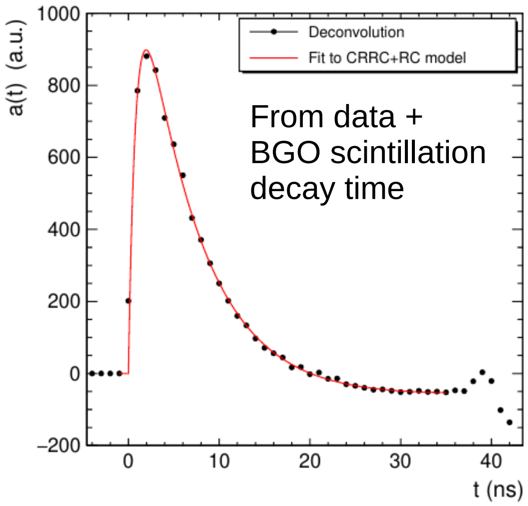


Measure of light collection in channel 5 vs beam position

Signal analysis (BGO)

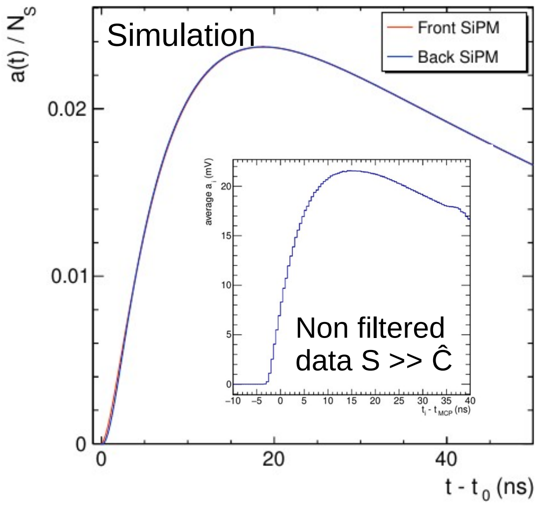
Modeling of signal shapes using data + photon tracing in Geant4

Single photon response (SPR) SiPM + Amplifier



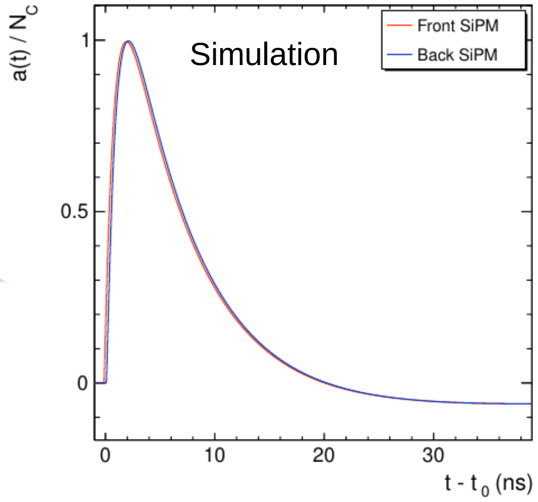
SPR from (de)convolution of average measured signal w/o filter + BGO decay time.

Scint signal, integrating over photon production/arrival times



&

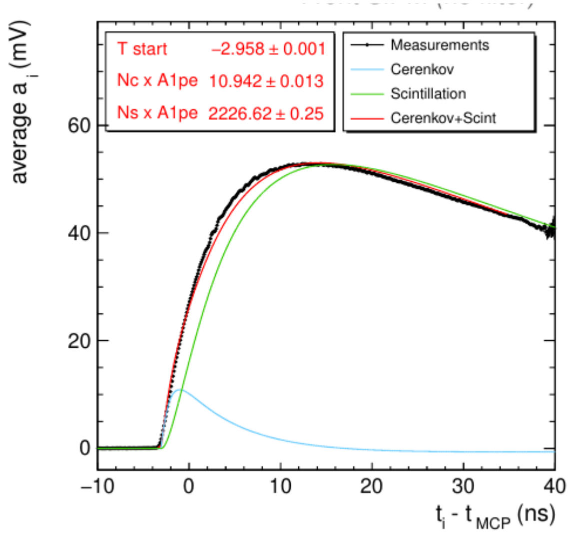
Ĉ signal, integrating over photon prod./arrival times



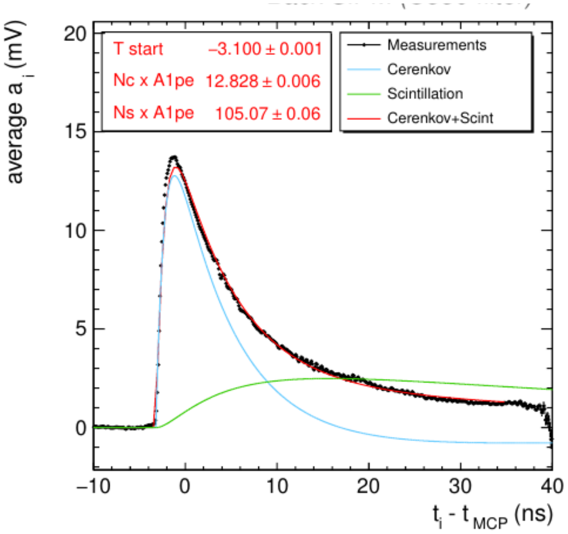
Light production models ⊗ propagation ⊗ electronics response function
Used as templates for fitting pulse components

S/Ĉ Signal Analysis in Data (BGO)

Front SiPM (no filter)



Back SiPM (U330 filter)

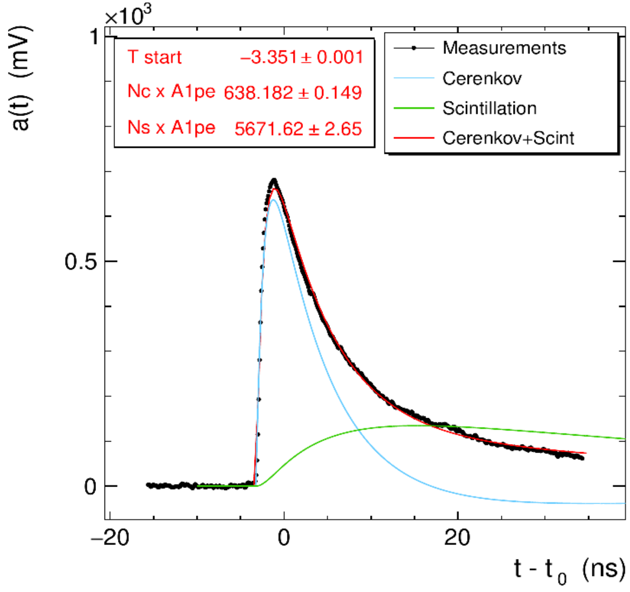


Fits to <u>average</u> MIP signal using two components

Accounting for 1PE amplitude ~0.6mV yields Order of <20>PE/MIP

Example of a <u>single</u> showering event

- Signal ~50 MIPs
- Order of a few GeV E loss
- **Very encouraging S/N and component separation**



Conclusions

Analysis of first test beam data is in progress

- **Preliminary analysis suggests the presence of a significant detected Ĉ signal component in filtered data from hadrons (protons) on BGO => our main requirement for implementing DR**
- Good progress in modeling details of light collection
  - Angular dependence of S/Ĉ collection
  - Dependence of light collection on track location
- Preliminary MIP timing performance in 200-400 ps range / single channel
  - Interesting features to study in up/downstream differences, filter effects
  - Future results will examine up/down stream timing correlations

Much work/analysis in progress:

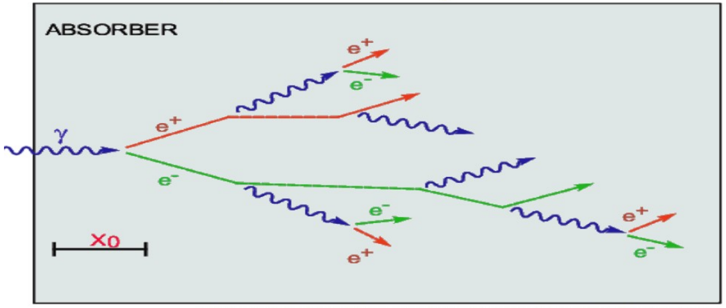
- Continue S/Ĉ separation in PWO, BGO, BSO, heavy glasses, filter optimizations
- Optimal use of combined SiPM signals for timing, S/Ĉ separation
- Select candidate crystal(s) for matrix test sufficient to contain EM showers
- Primary goals: validate EM resolution and application of DR in combined tests with IDEA HCAL

Supported via:
DE-SC0022045

More slides

EM calorimetry

Showers relatively* uniform. Excellent energy resolution has been realized in numerous EM calorimeters over the past few decades.



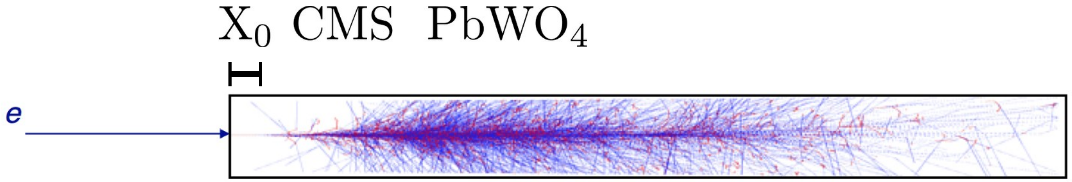


Image source: PWO w/ electron

$$X_0\ [\mathrm{cm}] = \frac{716.4\ [\mathrm{g\,cm^{-2}}]}{\rho\ [\mathrm{g\,cm^2}]}\frac{\mathrm{A}}{\mathrm{Z(Z+1)ln}\frac{287}{\sqrt{\mathrm{Z}}}}$$

Homogeneous EM Calorimeters

Technology (Experiment)	Depth	Energy resolution	Date
$Bi_4Ge_3O_{12}$ (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
$PbWO_4$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
Liquid Kr (NA48)	$27X_0$	$3.2\%/\sqrt{E} \oplus 0.42\% \oplus 0.09/E$	1998

2022 Review of Particle Physics

Achieved resolutions in the range:

Homogeneous:
~ few %/sqrt(E)

vs

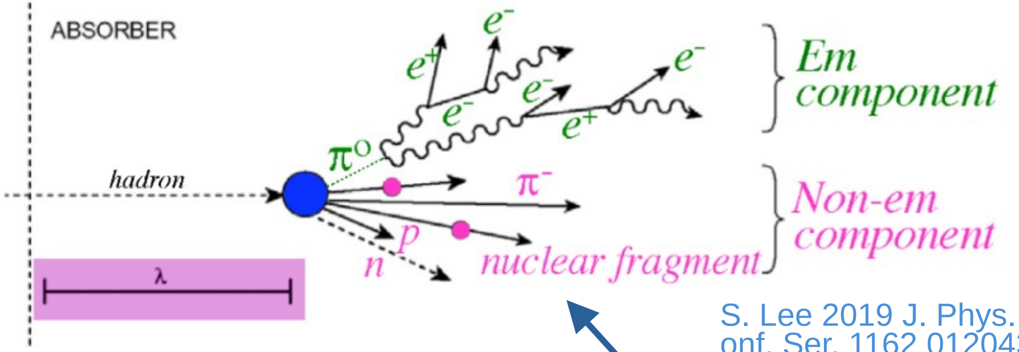
Sampling:
~10-15%/sqrt(E)

Hadron Calorimetry is Challenging

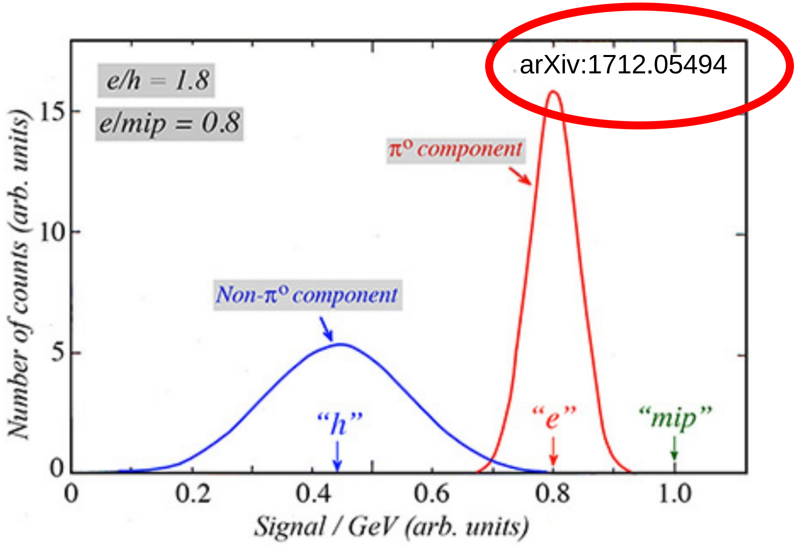
Much more challenging to precisely measure E deposition by hadrons

$$\lambda_I\ [\mathrm{cm}] \simeq \frac{35.00\ [\mathrm{g\,cm^{-2}}]\sqrt[3]{A}}{\rho\ [\mathrm{g\,cm^3}]}$$

Showers include a pure EM component with large E dependence and fluctuations
=> different response,e/h>1, degrades resolution



S. Lee 2019 J. Phys.: Conf. Ser. 1162 012043



Purely hadronic component can result in significant amount of *invisible* energy (eg ~8 MeV/nucleon release, neutrons interacting late wrt integration times, ...)

Examples of e/h		hadronic resolution
CMS:	2.4 (1.3) ECAL (HCAL)	~ 85%/√E
ATLAS	1.37	~ 52%/√E

CALVISION

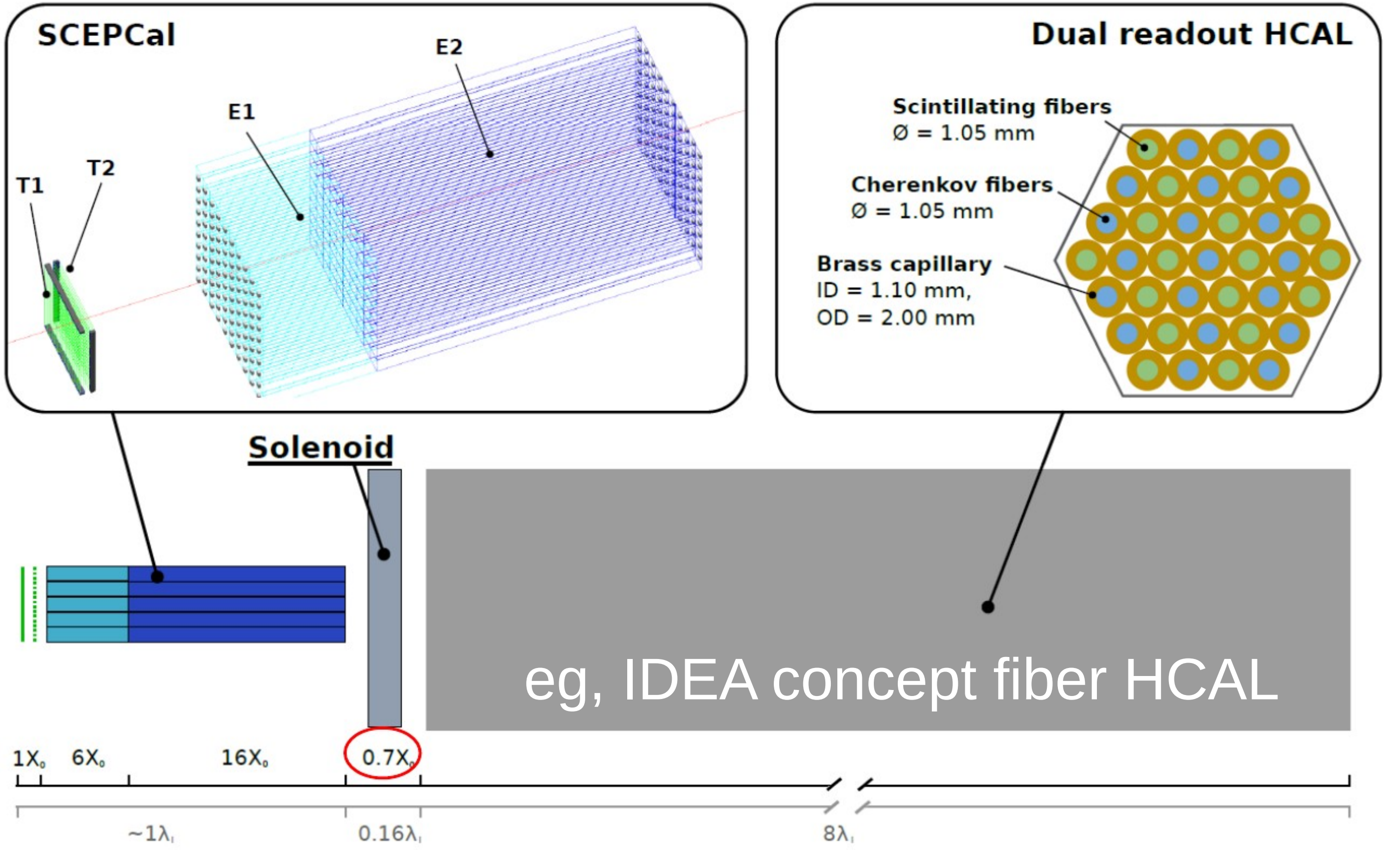
R&D consortium dedicated to detector R&D future colliders, emphasis on detector to meet physics requirements for next lepton collider.

- Precise measurements of the Higgs boson properties, and
  - W and Z bosons physics as critical tests of Standard Model
  - and their use in exploration of new physics beyond the SM
- Develop complimentary technologies to typical PFA approaches
- Explore (moderately) high granularity calorimetry with:
  - Intrinsic dual readout capabilities
  - State of art EM resolution (homogeneous crystal)
  - Hadron performance comparable to fiber-based DR
- Bluesky R&D on materials, sensors, readout, techniques
- Collaborate in international efforts on best detector solutions

A Segmented DRO Crystal ECAL + DRO Fiber HCAL

Concept:

- (Optional) timing layer
- Segmented ECAL
- Thin solenoid
- DREAM/RD52 style HCAL



SCEPCal:
Segmented
Crystal
Electromagnetic
Precision
Calorimeter

Concept highlights advantages for physics program with precision ECAL

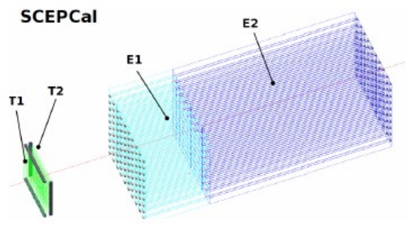
10.1088/1748-0221/15/11/P11005

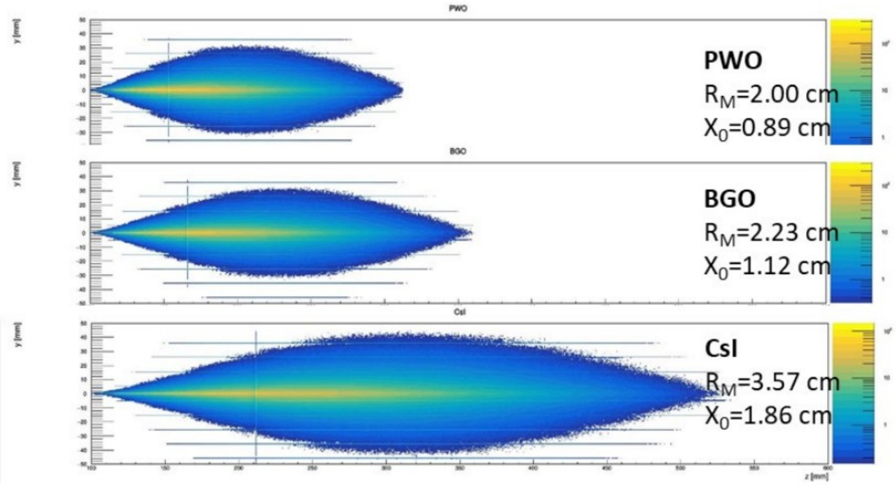
Segmented ECAL

Two layers w/ high density (short X_0, small R_M)

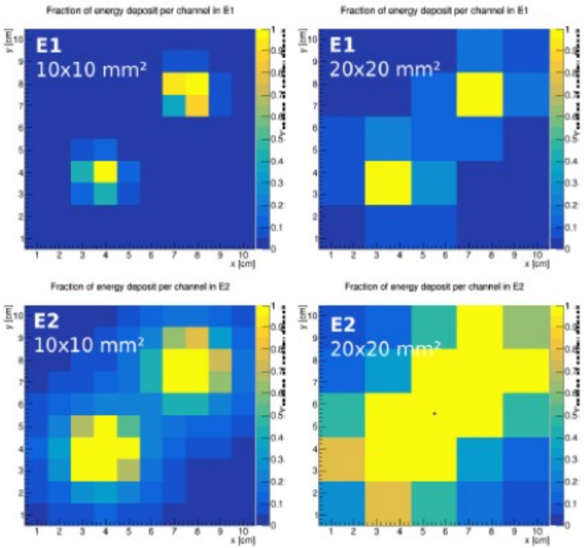
- Fast signal, reasonable Ĉ/S ratio, cost effective
- **$PbWO_4$**, BGO and BSO are good candidates

Crystal	Density g/cm²	X_0 cm	λ_I cm	R_M cm	Relative Yield	Decay time ns	Refractive index
$PbWO_4$	8.3	0.89	20.9	2.00	1.0	10	2.20
BGO	7.1	1.12	22.7	2.23	70	300	2.15
BSO	6.8	1.15	23.4	2.33	14	100	2.15
CsI	4.5	1.86	39.3	3.57	550	1220	1.94





Longitudinal profiles



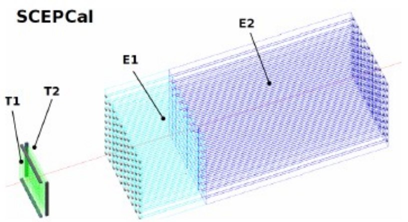
Separation of photons w/ 3° opening angle

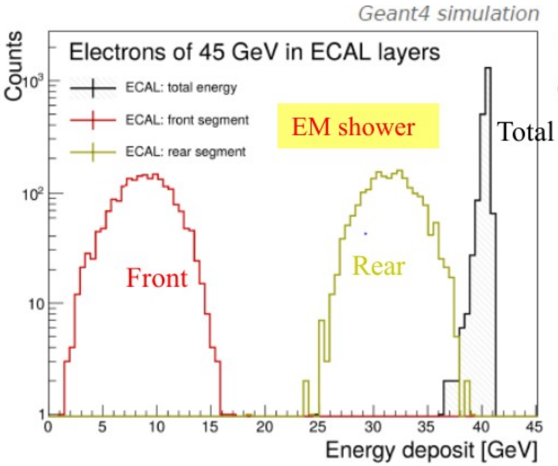
10.1088/1748-0221/15/11/P11005

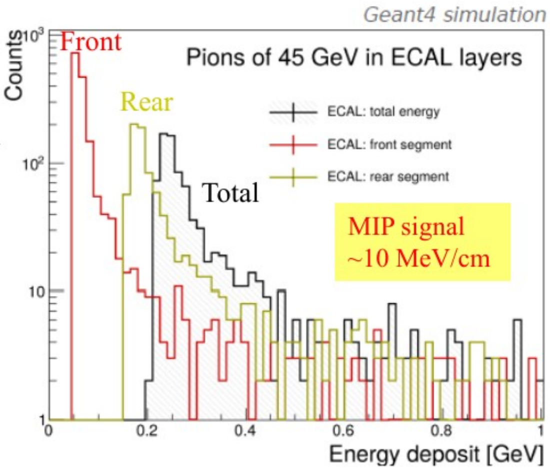
Segmented ECAL

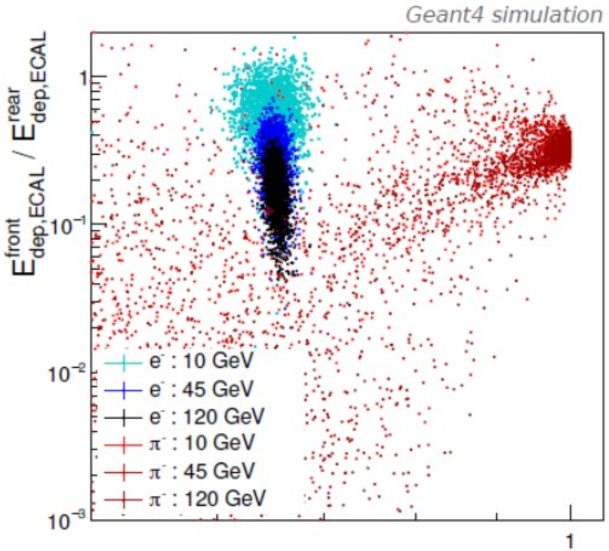
Two segmentation layers

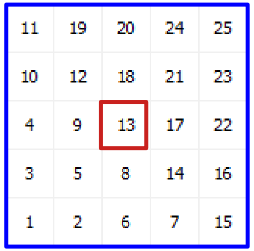
- Front segment (~6 X_0, ~50 mm)
- Rear segment (~16 X_0, ~140 mm)
- Longitudinal segmentation useful for the separation of electrons and pions (can also be included in e/γ/π$^{\pm}$, separation methods)











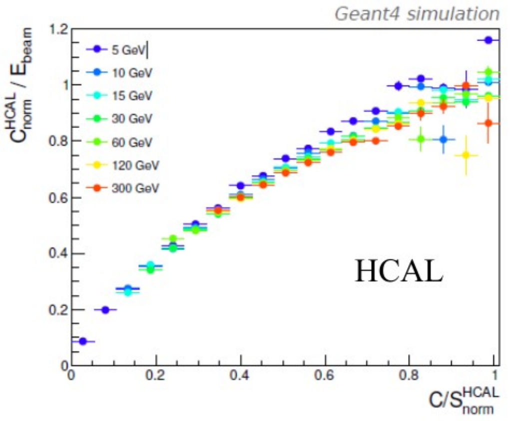
$$R_{25} = \frac{\text{cell 13}}{5\text{x}5}$$

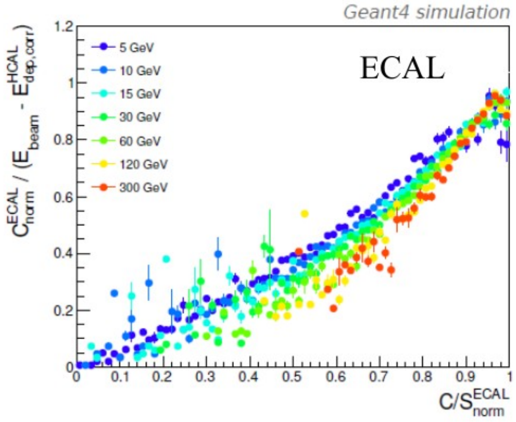
Front to rear energy vs transverse distribution

10.1088/1748-0221/15/11/P11005

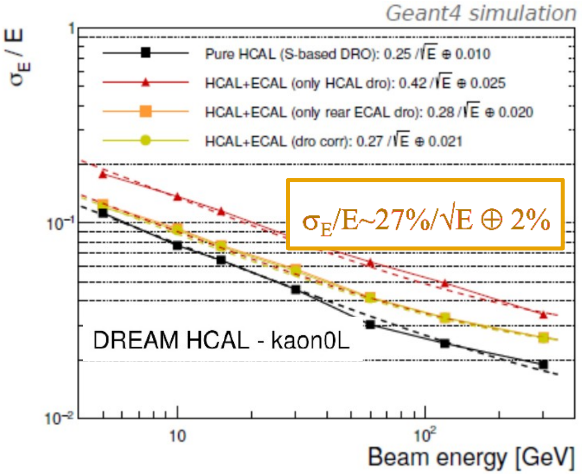
SCEPCal +DRO HCAL performance studies

DRO corrections





Neutral hadron E resolution



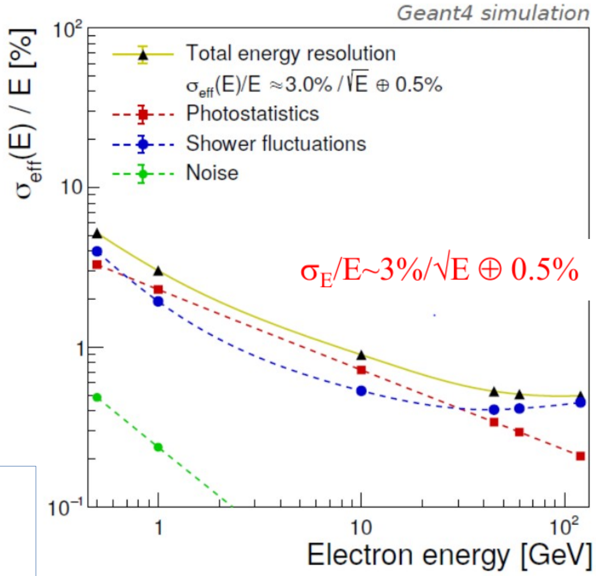
Similar sampling term as that of a pure DRO HCAL

- DR in EM + hadron sections

Slightly larger constant term:

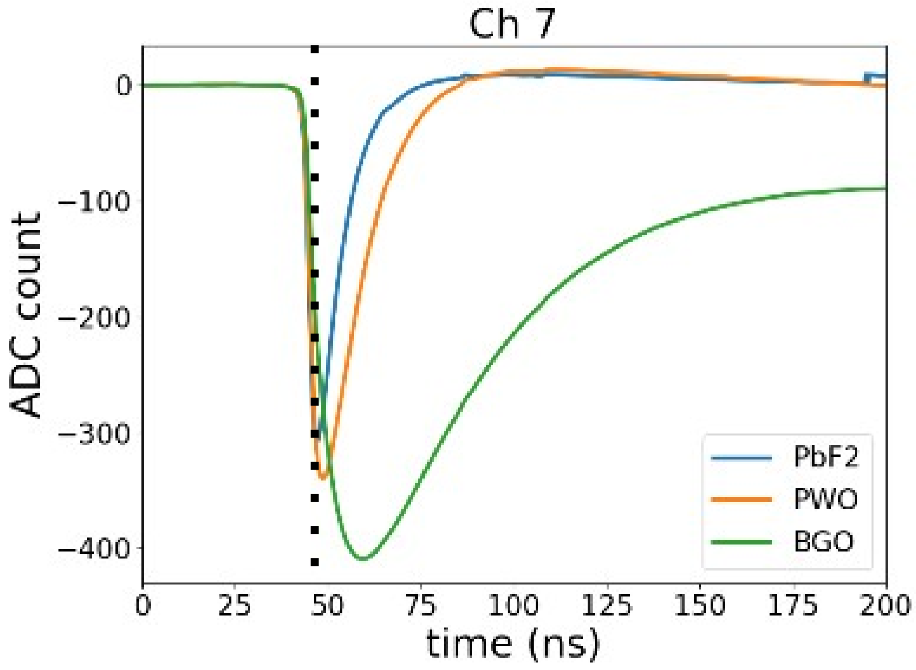
- intrinsic limitation in system combining segments with different e/h ratios
- material budget from the ECAL services and the solenoid

Electron E resolution

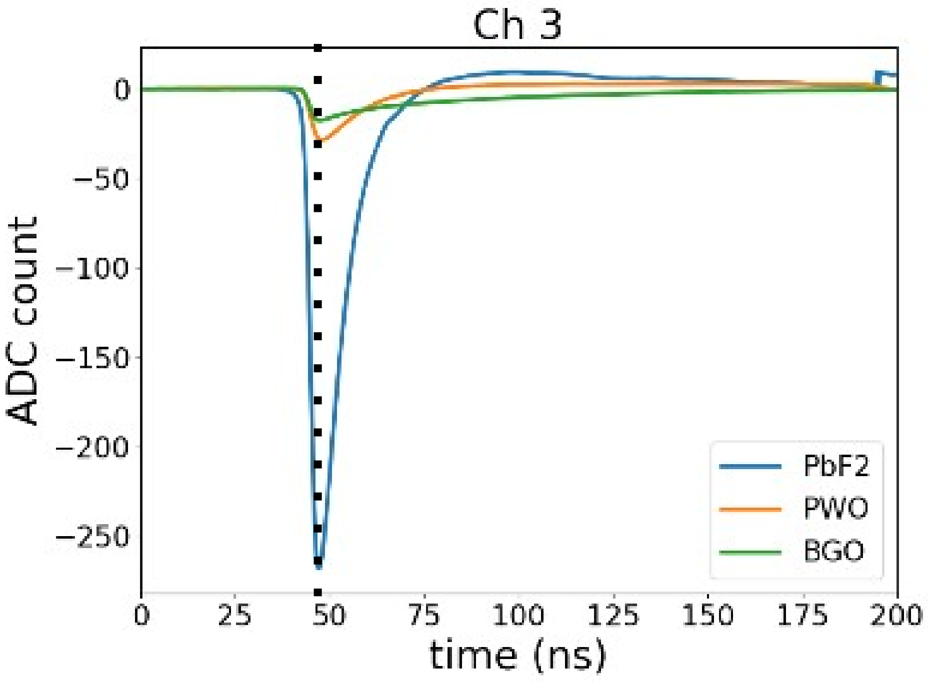


Electron energy resolution maintained at level of best crystal calorimeters

June 2023 Test Beam @Fermilab Datasets



without filter



with filter