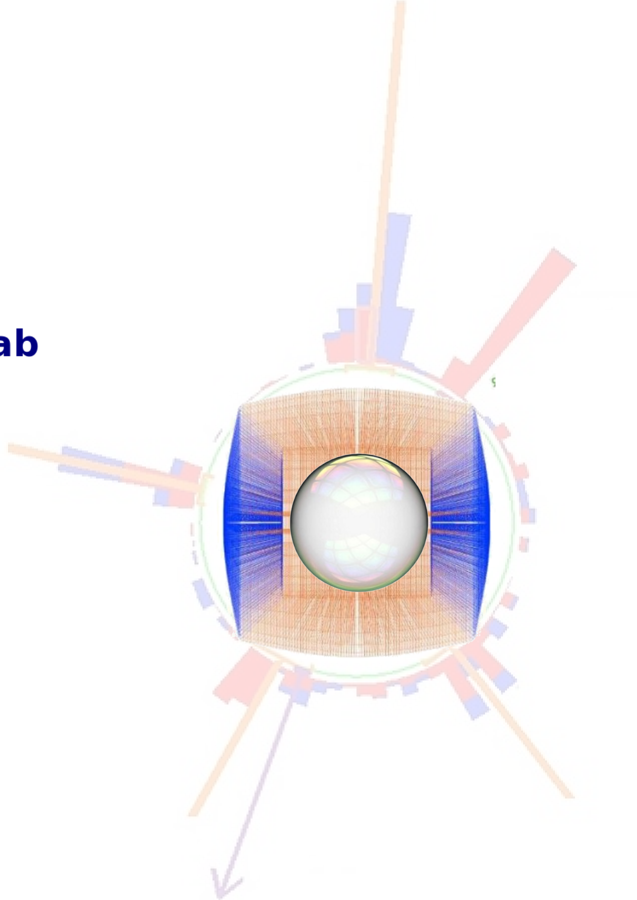
Dual Readout Calorimetry

Bob Hirosky and Grace Cummings

for the Calvision Team



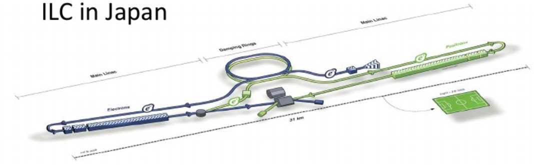
CALVISION co-PIs

Alberto Belloni	Harvey Newman	Andreas Jung
Chris Tully	Ren-Yuan Zhu	Marcel Demarteau
Sarah Eno	Jim Hirschauer	Phil Harris
Bob Hirosky	Hans Wenzel	Jim Freeman
Sergei Chekanov	Jianming Qian	Shuichi Kunori
Steve Magill	Bing Zhou	
Nural Akchurin	Junjie Zhu	

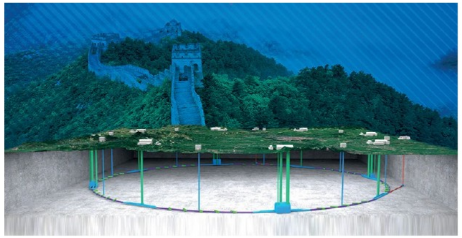
Future colliders and calorimetry

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

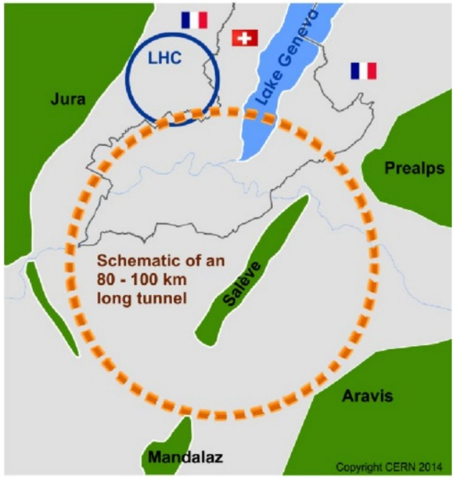
ILC in Japan



CEPC in China

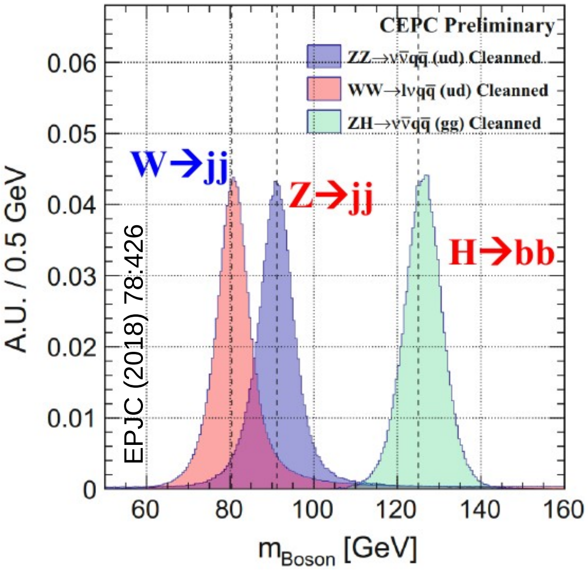


FCC-ee at CERN



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



EPJC (2018) 78:426

Complementary approaches to better calorimetry:

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

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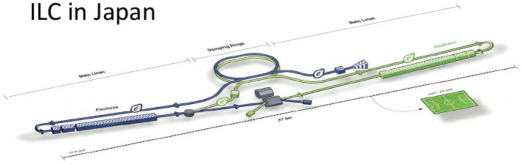

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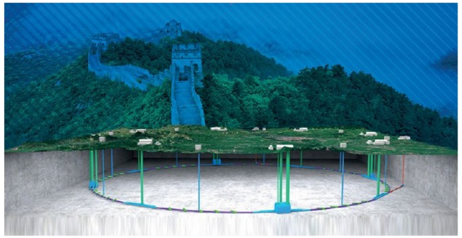

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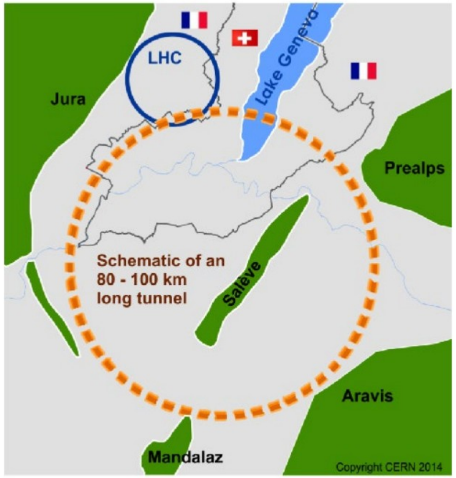
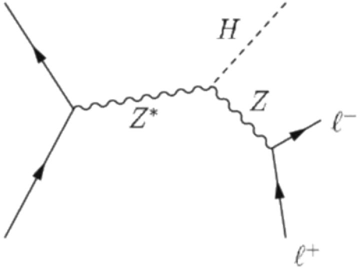
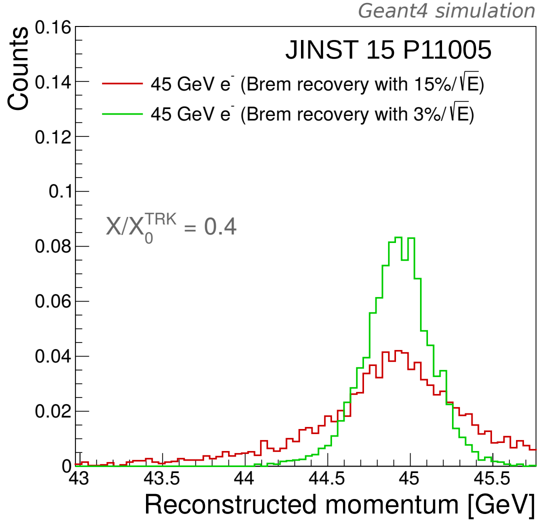


High resolution EM calorimetry equally important, eg



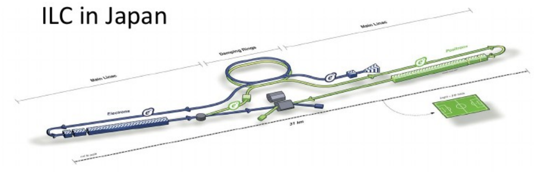
- Unexpected, even invisible, Higgs decay
- Precision W/Z-boson studies
- **Electron brem. recovery**
- π^0 reconstruction and jet matching

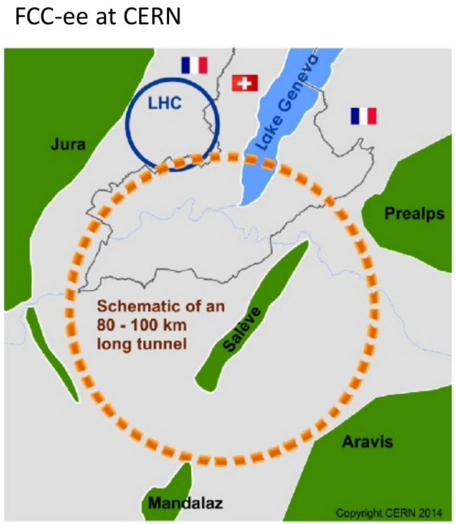
JINST 15 P11005

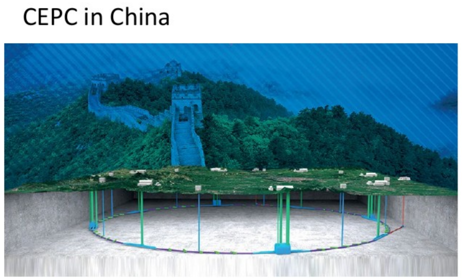


Future colliders and calorimetry

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







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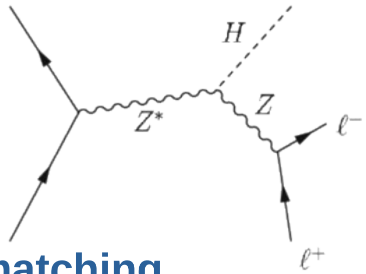
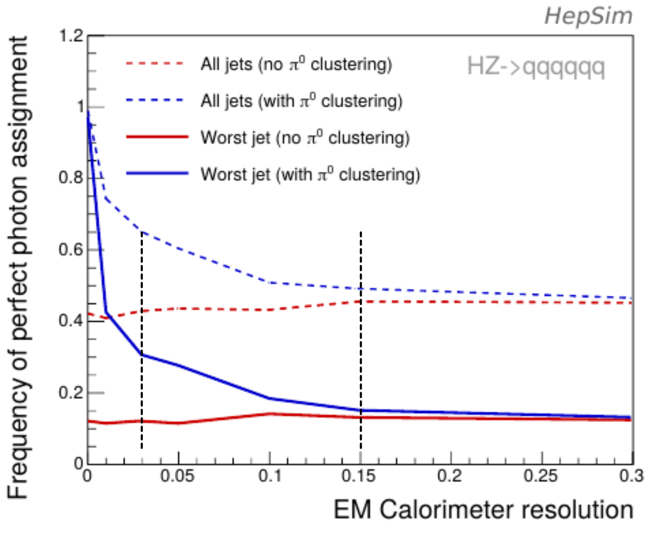


eg, photon matching in 6 jet event:

w/ π^0 clustering
w/o π^0 clustering



Brief overview of Calvision

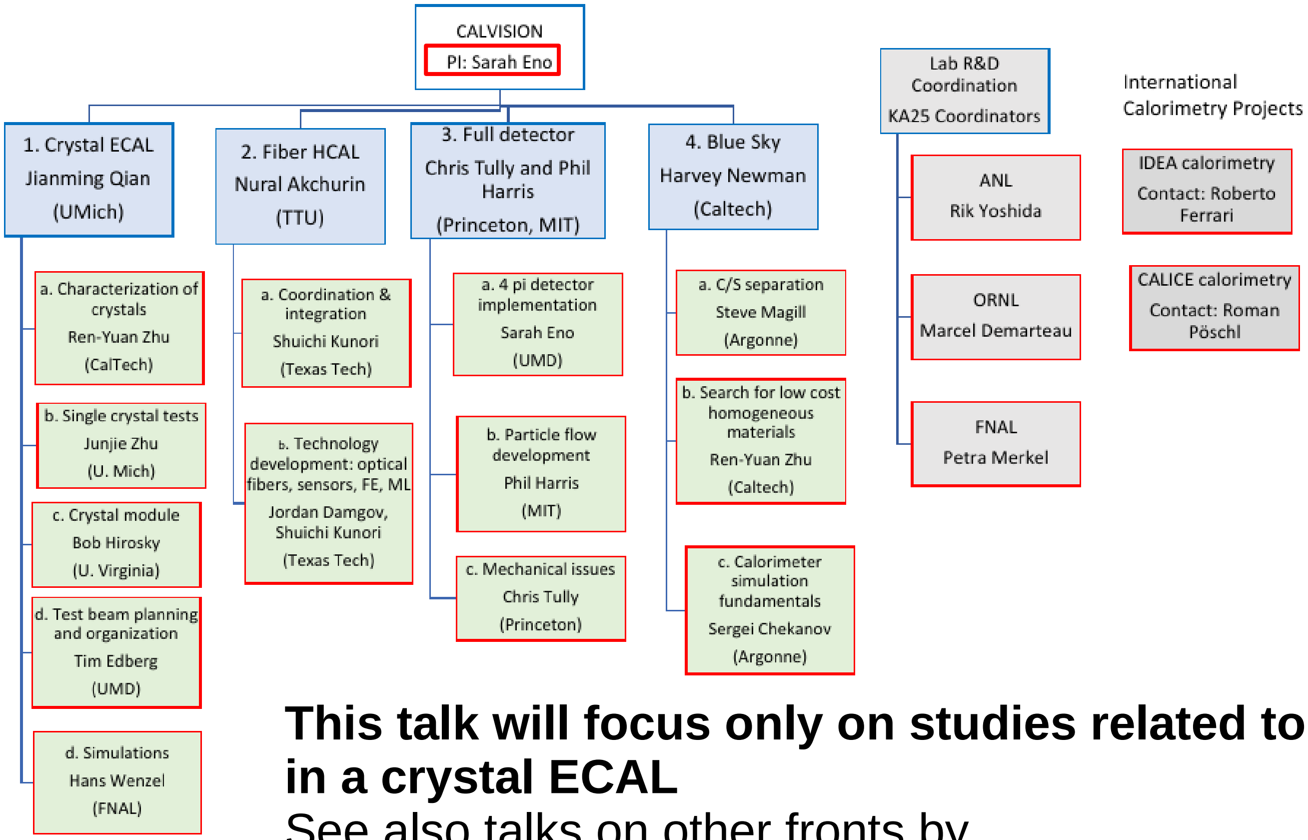
CALVISION formed to pursue calorimetry efforts on <u>multiple fronts</u>:

- Crystal DR ECAL
- Fiber DR HCAL
- Full Detector studies (sim.)
- New RECO algorithms
- BlueSky R&D (materials, sensors, R/O, ...)

Multi-year efforts proposed in each area.

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

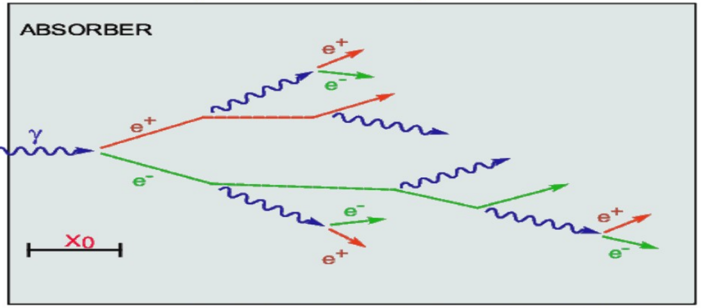
Scale up modules in next phase



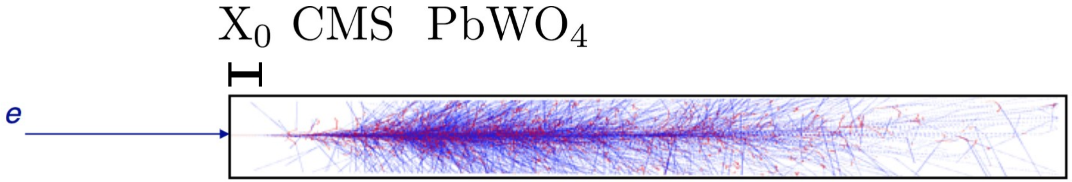
This talk will focus only on studies related to DR in a crystal ECAL

See also talks on other fronts by
- R. Zhu on Scintillator R&D
- S. Chekanov on DR Calorimetry Simulation

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



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



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

Achieved resolutions in the range:

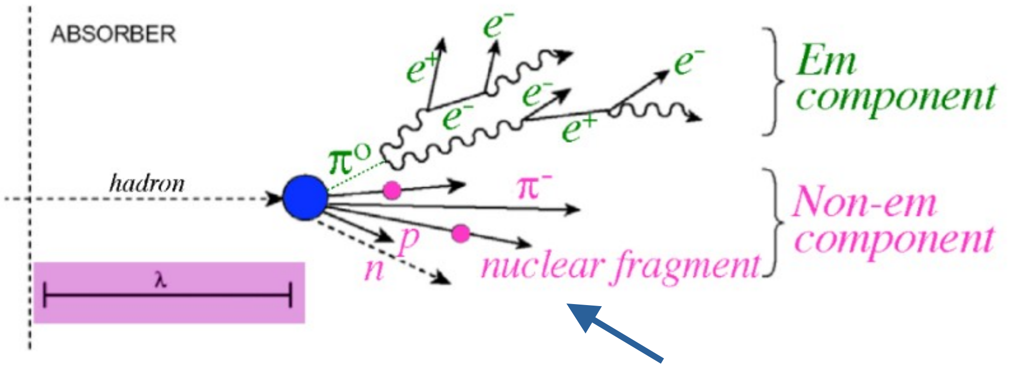
Homogeneous:
~ few %/sqrt(E)

Sampling
~10-15%/sqrt(E)

Hadron calorimetry

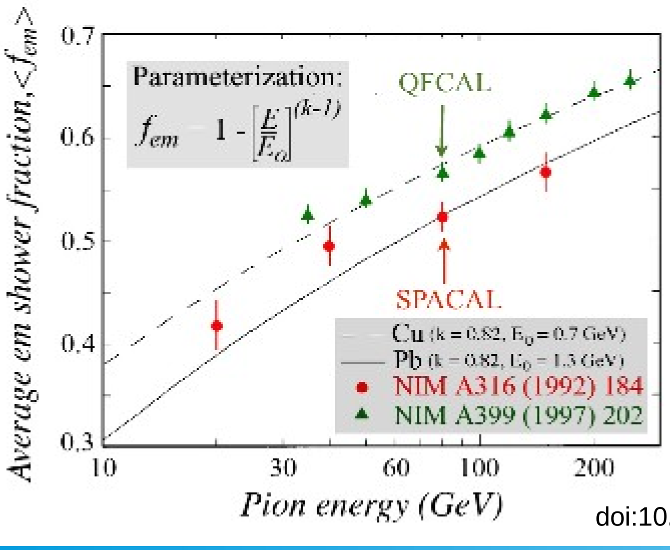
Much more challenging to precisely measure E deposition by hadrons

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



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

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



Also dependence on materials

doi:10.1088/1742-6596/1162/1/012043

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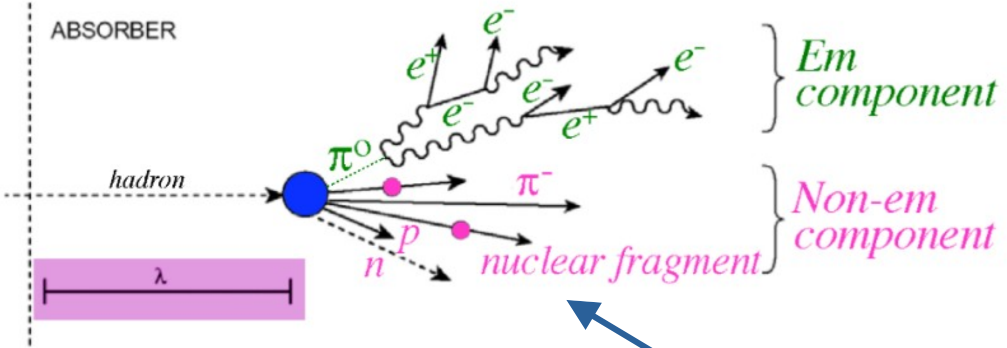

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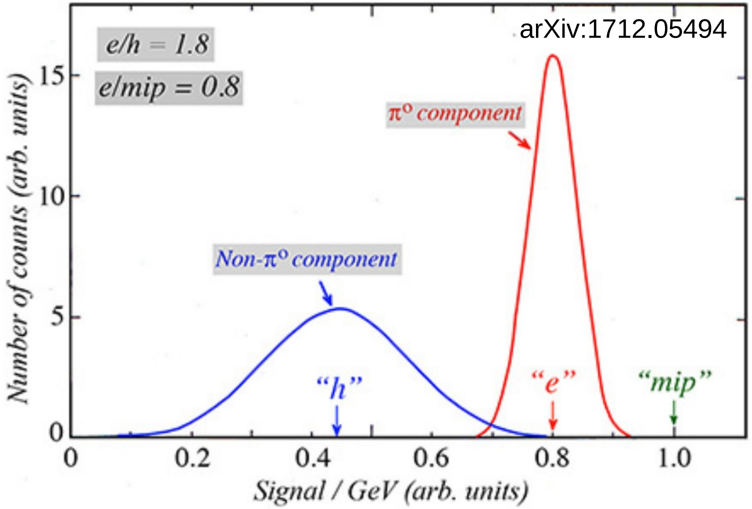
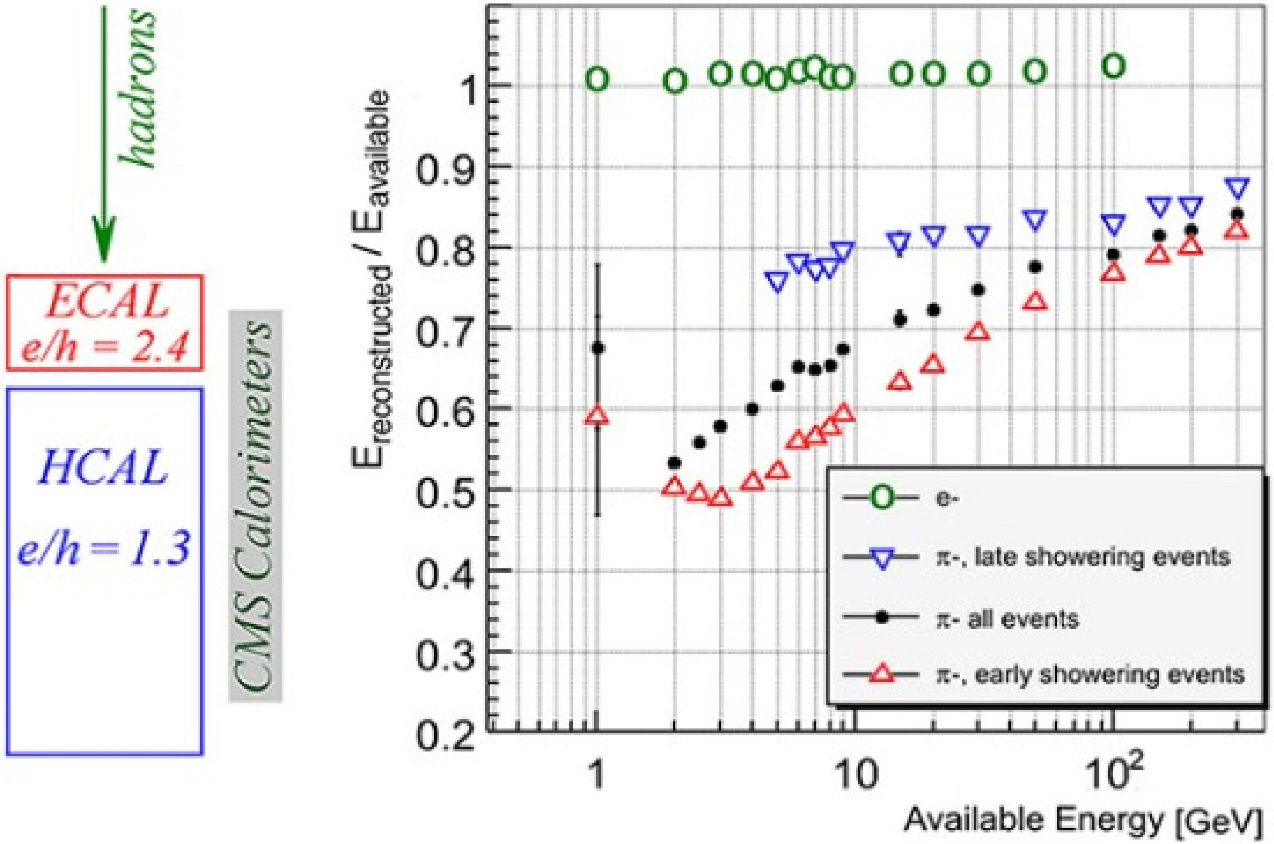


Examples of e/h		hadronic resolution
CMS:	2.4 (1.3) ECAL (HCAL)	~ 85%/√E
ATLAS	1.37	~ 52%/√E

Effect of an optimized EM section in traditional calorimetry



10.1088/1748-0221/15/11/P11005

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

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

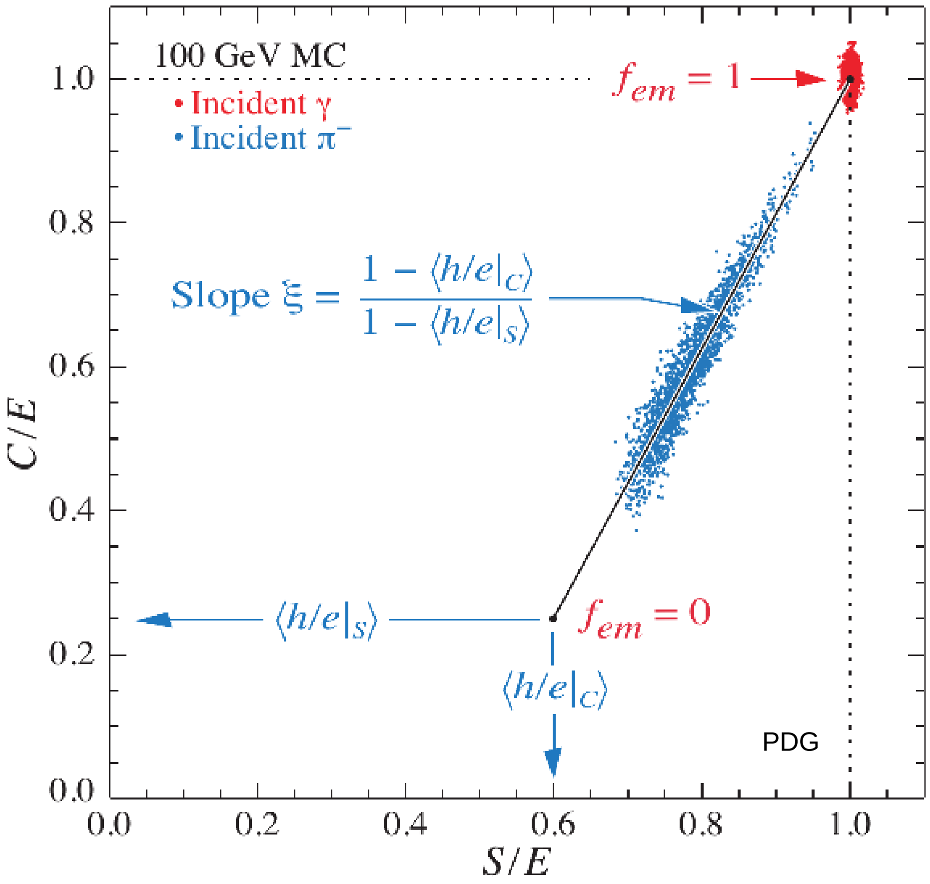
Improving jet resolutions

Taking state of the art EM calorimeter energy resolution as sufficient for future physics needs, the focus is (simultaneously) improving 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 measure of 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

How/why DR works



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

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

Slope depends only on e/h values and is therefore 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

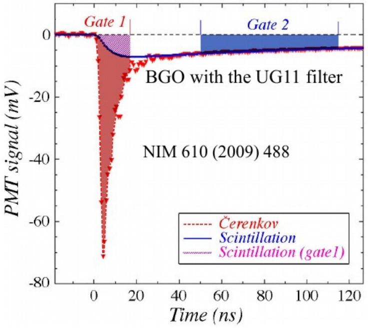
Previous DREAM/RD52 results on DR Crystal Calorimeter

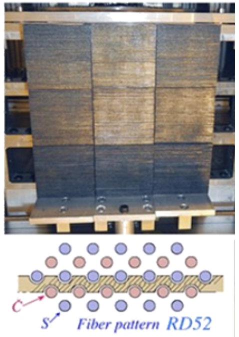
DREAM/RD52 previously investigated DR of crystals with PMTs using BOTH optical filters and timing to separate Ĉ and S signals

A proof of principle for a DR crystal calorimeter, but

- Resolution dominated by limited statistics for # of photons detected (only a small fraction of Ĉ and S photons selected)
- Improvements needed on efficiency, λ range of light collection
- Not pursued further:
  - Cost with PMT readout
  - Limited wavelength sensitivity
  - ‘acceptable’ EM resolution demonstrated in fiber calorimeter for goals of the day

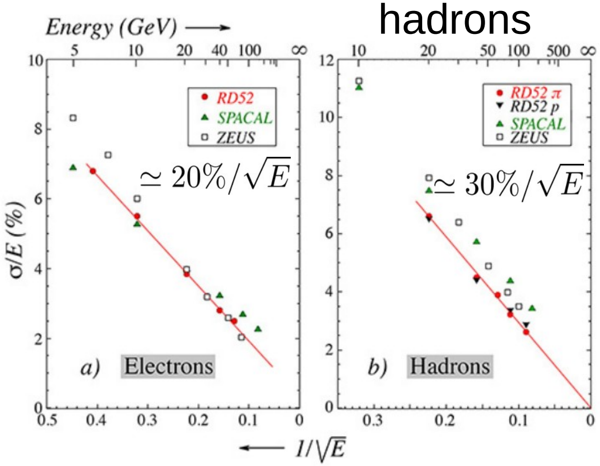
NIM 686 (2012) 125
Rev. Mod phys. 90 (2018) 40



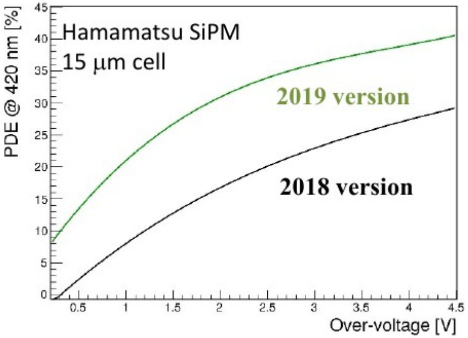


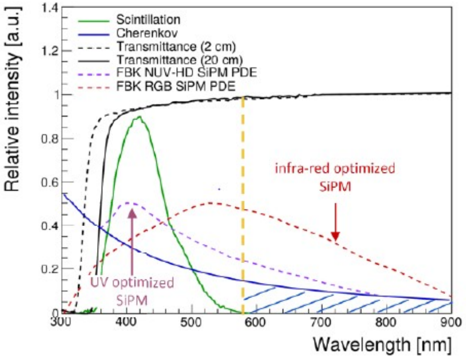
electrons

hadrons



Vast improvement in SiPMs ===> in past decade can significantly improve DR EM+HAD detector performance





Fast, affordable, tunable λ sensitivity

Calvision: initial studies for DR ECAL

Initial bench and beam tests for xtal ECAL focusing 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

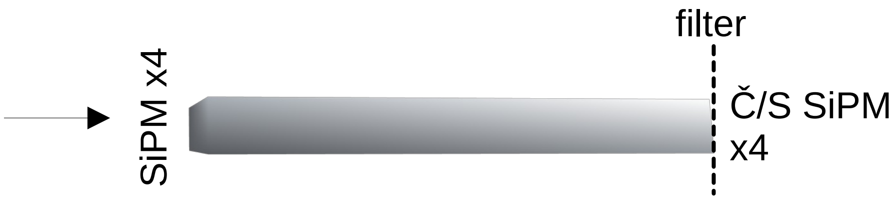
Performance/feasibility of concept strongly depends on:

- Adequate sampling statistics of Č light (>~50 photons/GeV)
  - **Need large area sensors**
- 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**

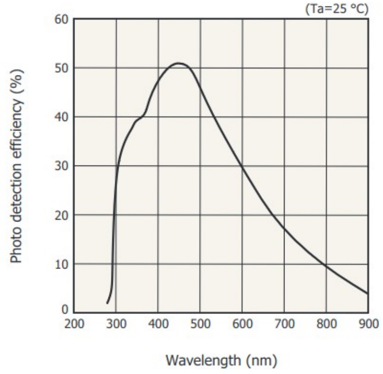
Two main test beam efforts @FNAL in 2023

- **Test beam 1: 120 GeV proton beam**
  - PWO/BGO,interference/absorption filters
  - Concentrated on beam on long axis
  - MIPs + showering events
  - Study light collection and S,Ĉ components
  - Readout: homemade front end + Lecroy scope 10GS/s
  - **Qualitative results today**

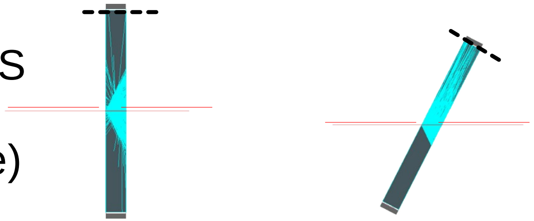
Baseline bar configuration



Hamamatsu
S14160-6050HS
Large area 6x6 mm SiPMs*



- **Test beam 2: 120 GeV proton beam**
  - PWO/BGO/PbF
  - absorption filters
  - Concentration on angular dependence of light collection
  - Aim to tune MC and identify Ĉ/S signal+variations (consistent w/ Ĉ emission cone)
  - Readout: homemade front end + 5GS/s DRS
  - **Stay tuned for future reports**



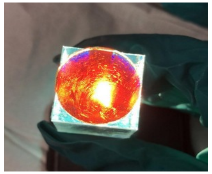
*Also planning tests for devices w/ similar specs from Broadcom

April ‘23 proton test beam at Fermilab

4 orientations

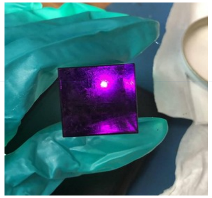
beam

$PbW0_4$	→	w/ scint filter
	→	w/o filter
BGO	→	w/ scintfilter
	→	w/o filter

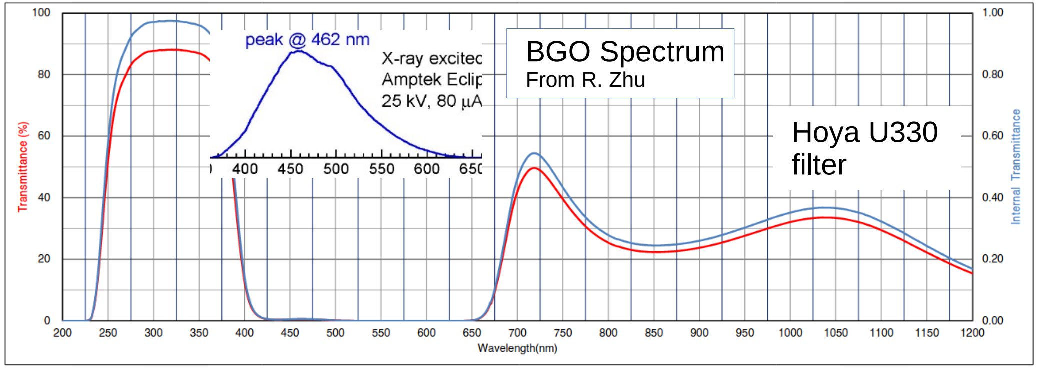


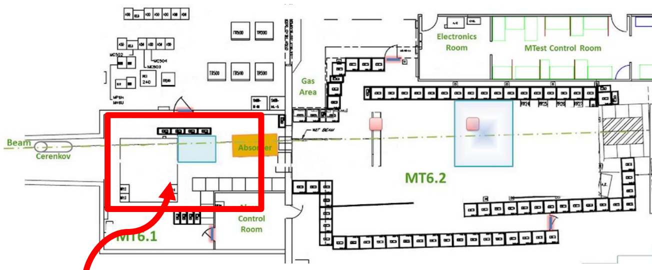
660 nm long-pass interference filter on PWO

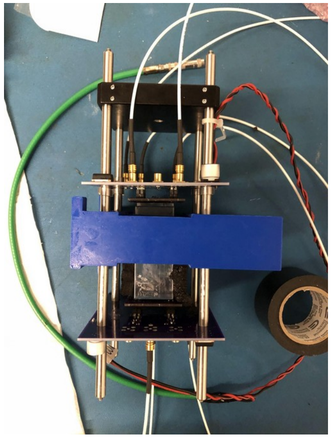
Results shown here



U330 absorptive notch- filter on BGO







Readout (fast scope)

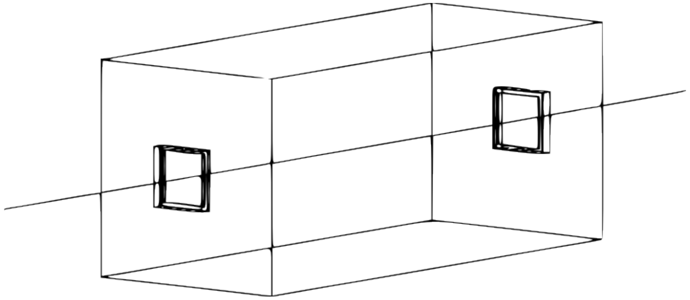
n.b. Crystal transparency is poor at NUV where Ĉ light is most intense => use longer wavelengths beyond scint spectrum.
Improvements in NIR sensitive GAPDs very desirable

Thanks to Chris Madrid and Artur Apresyan for their support and opportunity use this beam time.

Preliminary analysis of proton on BGO data

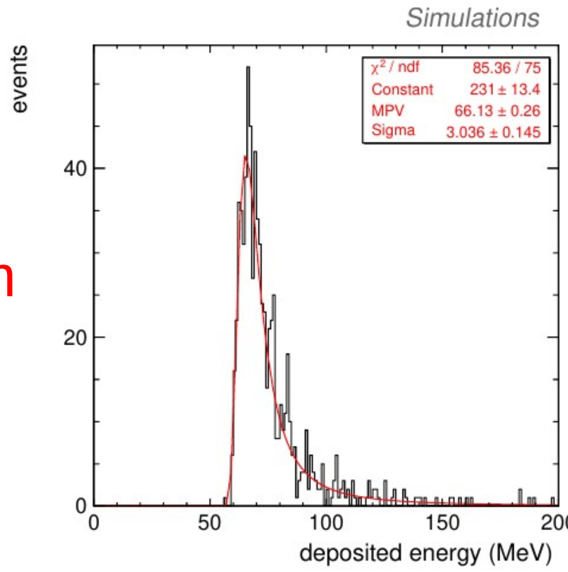
Simulation:
MPV = 66 MeV
Select tracks with deposited energy 50–100 MeV

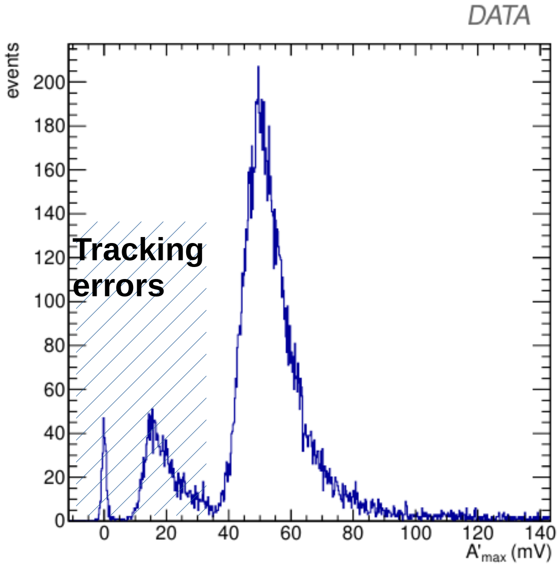
DATA:
MPV = 50 mV
Select tracks with reconstructed amplitude 35–100 mV



Simplified Geant4 model

MIP spectrum





Good S/N in data

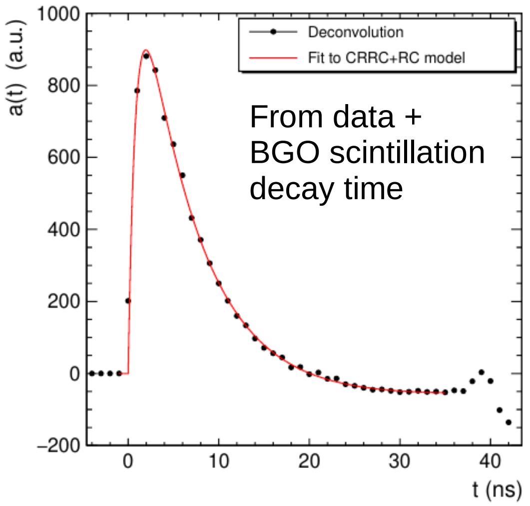
Signal analysis (BGO)

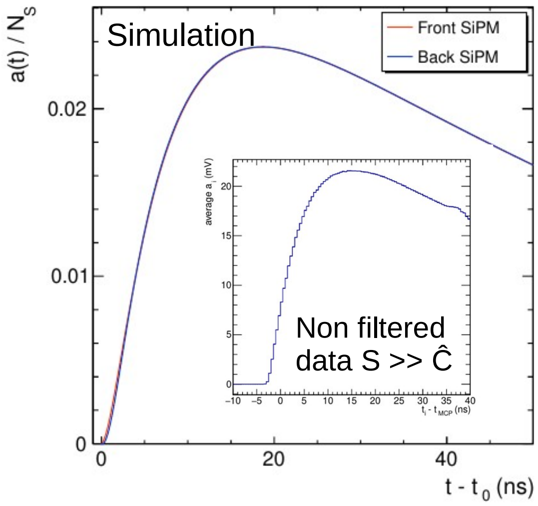
Modeling of signal shapes using data + photon tracing in Geant4

Single photon response (SPR) SiPM + Amplifier

Scint signal, integrating over photon production/arrival times

Ĉ signal, integrating over photon prod./arrival times





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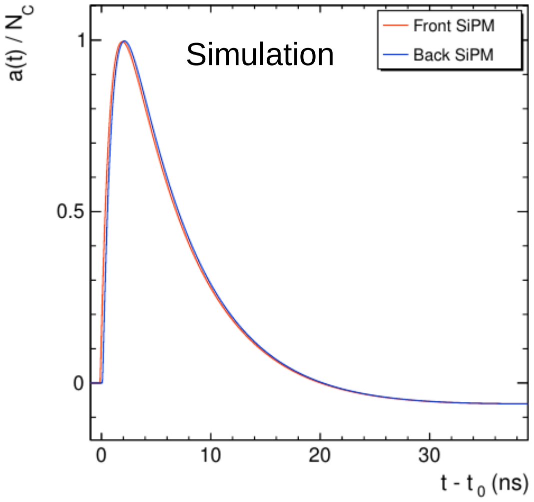
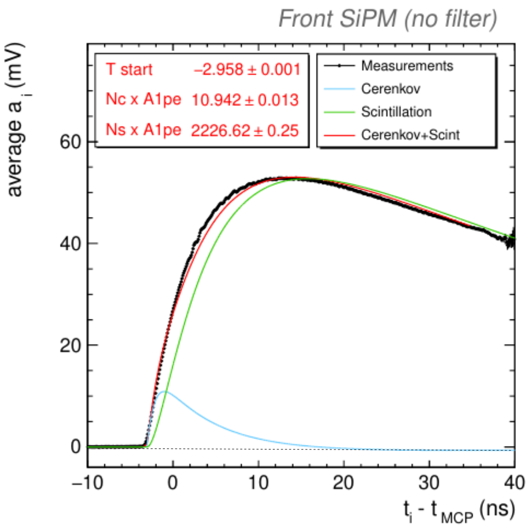


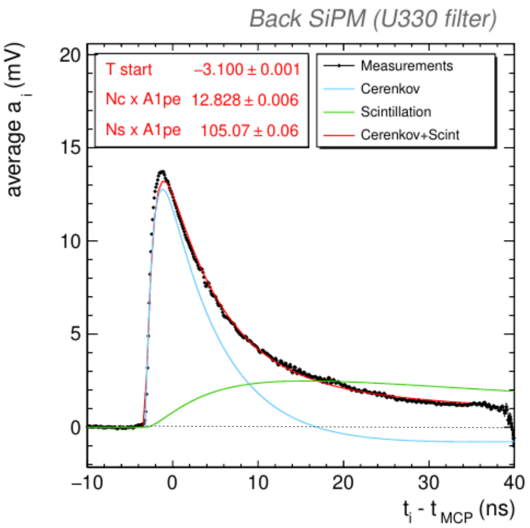
SPR from (de)convolution of average measured signal w/o filter + BGO decay time.

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

Signal analysis data (BGO)

Fits to average MIP signal using two components

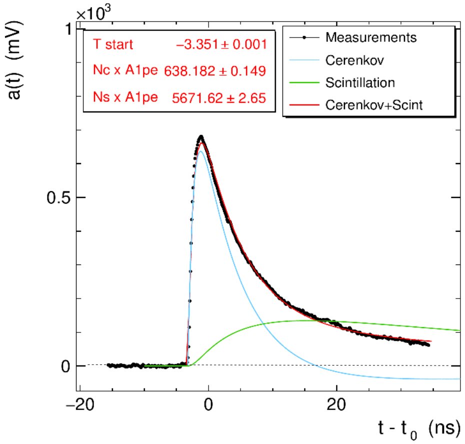




Correcting for 1PE amplitude ~0.6mV yields Order of <20>PE/MIP

Example of showering event

- ~50 MIPs
- Order of a few GeV E loss
- Best fit result ~1k photons in Ĉ component of fit



Very encouraging!

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**
- More results to follow, including angular dependence of S/Ĉ collection in 2nd test beam. Strong verification of modeling and light collection performance, additional filter studies.
- Also timing performance studies in progress

Future test beam plans to improve quantitative results:

- Explore additional crystal and filter combinations
- Enhance test stand with better noise rejection, user friendly mechanics, and SiPM temperature control
- Include an in-situ calibration system for test beams
- Study/improve linearity of readout over range of interest for test beam
- Additional consistency checking of signal modeling and cross check on nonscintillating crystal
- Continued tuning of simulation to match measured material properties and performance
- …
- Prepare for stage 2 (mechanics, electronics) to test ~8x8 ECAL matrix

Supported via:
DE-SC0022045

More slides

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Future test beam plans to improve quantitative results:

- Explore additional crystal and filter combinations
- Enhance test stand with better noise rejection, user friendly mechanics, and SiPM temperature control
- Include an in-situ calibration system for test beams
- Study/improve linearity of readout over range of interest for test beam
- Additional consistency checking of signal modeling and cross check on nonscintillating crystal
- Continued tuning of simulation to match measured material properties and performance
- …
- Prepare for stage 2 (mechanics, electronics) to test ~8x8 ECAL matrix

CALVISION

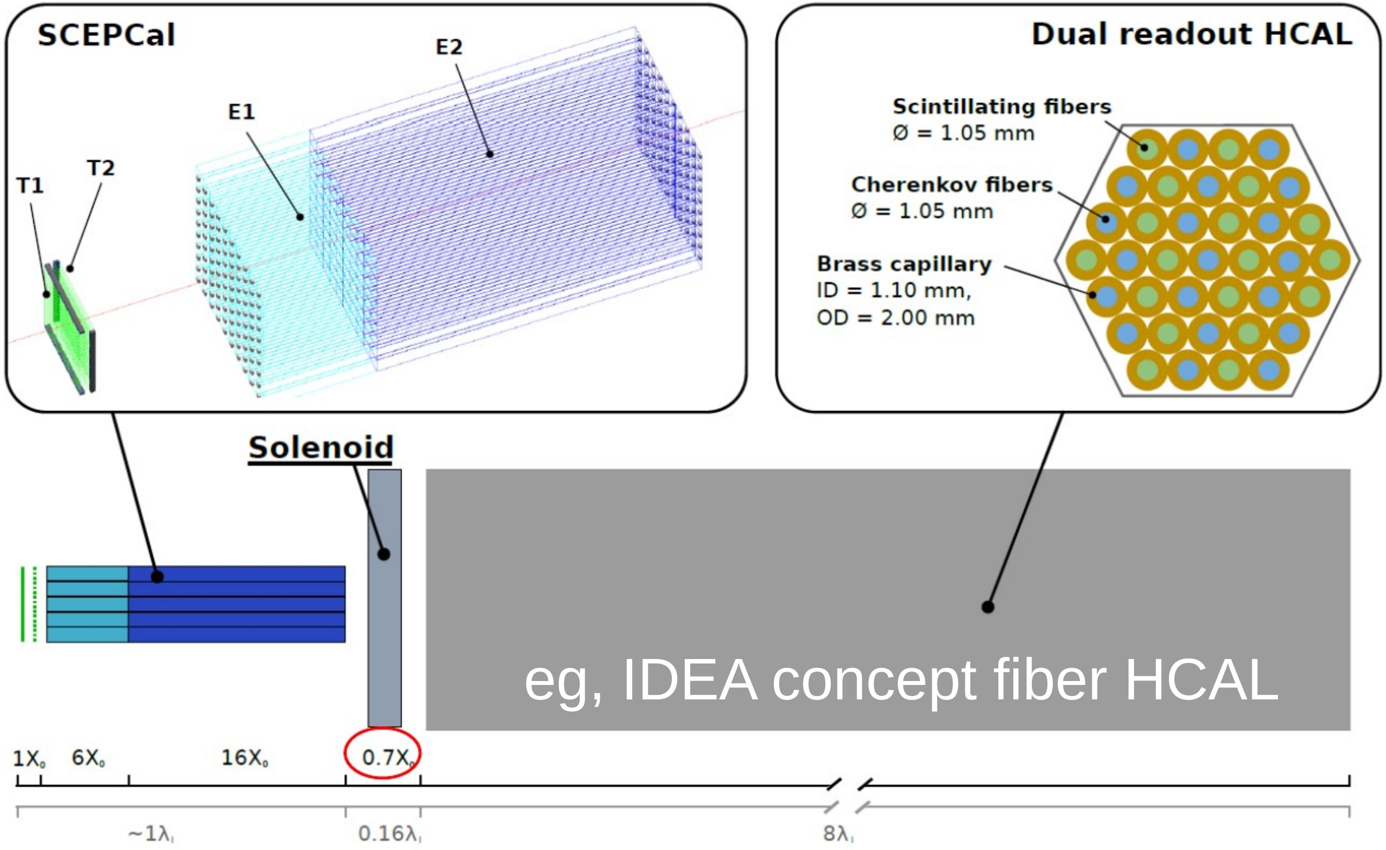
R&D consortium dedicated to detector R&D future colliders, emphasis on detector to meet physics requirements for next lepton collider.

- 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

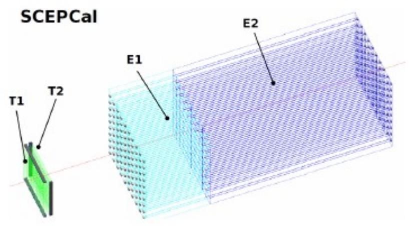
10.1088/1748-0221/15/11/P11005

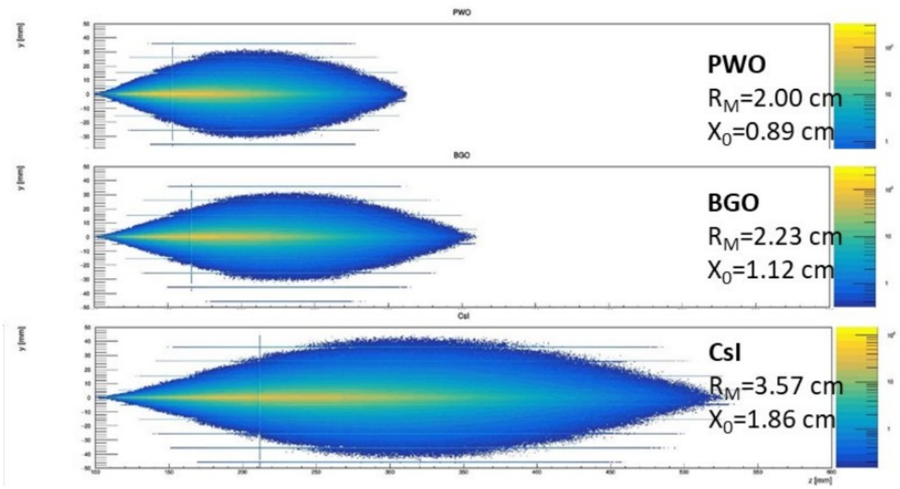
Segmented ECAL

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

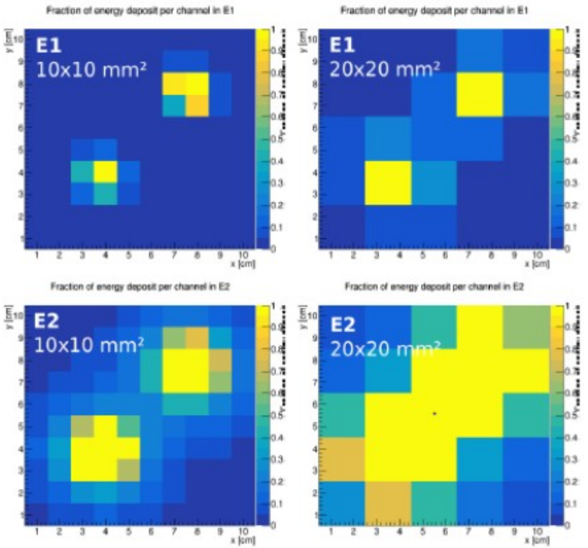
- Fast signal, reasonable Ĉ/S ratio, cost effective
- **$PbWO_4$**, BGO and BSO are good candidates

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



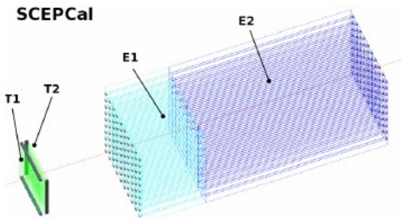
Separation of photons w/ 3° opening angle

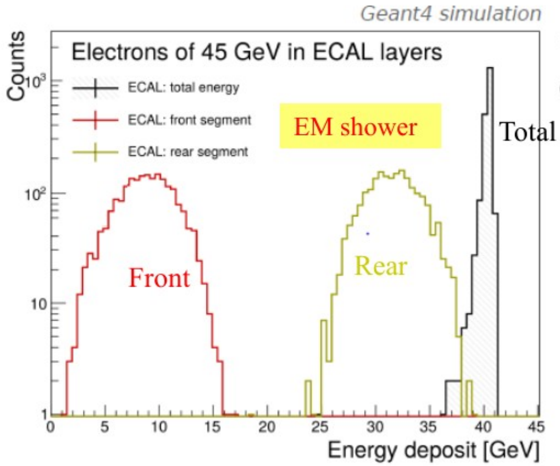
10.1088/1748-0221/15/11/P11005

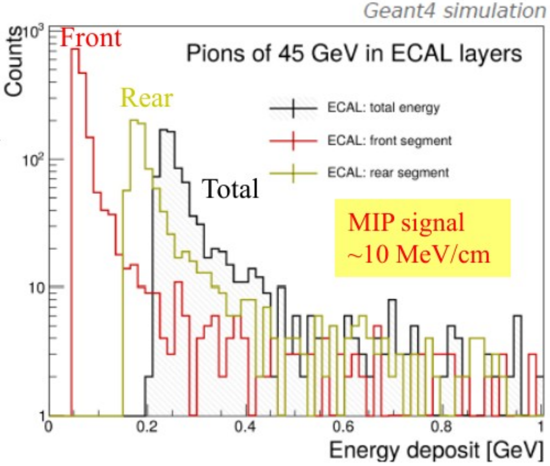
Segmented ECAL

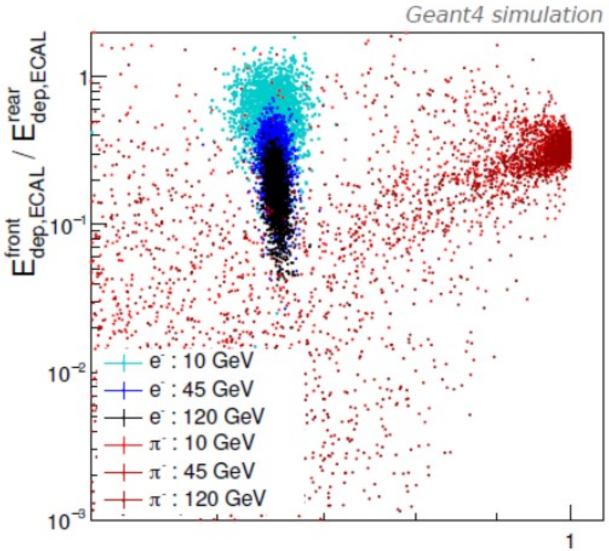
Two segmentation layers

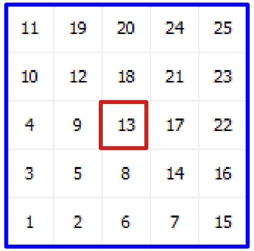
- Front segment (~6 X_0, ~50 mm)
- Rear segment (~16 X_0, ~140 mm)
- Longitudinal segmentation useful for the separation of electrons and pions (can also be included in e/γ/π±, separation methods)











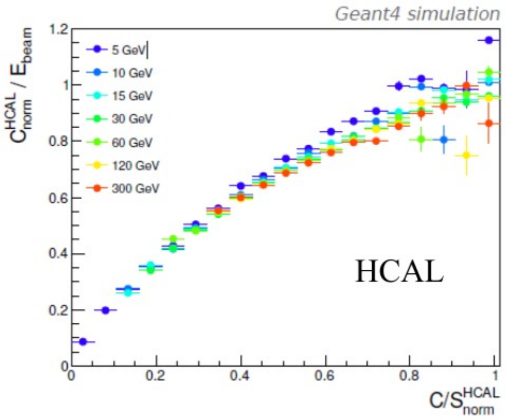
$$R_{25} = \frac{\text{cell 13}}{5\text{x}5}$$

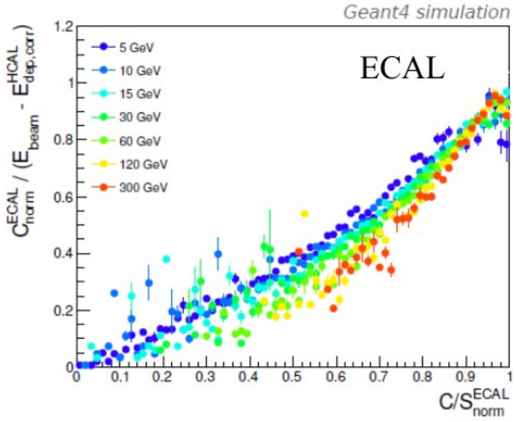
Front to rear energy vs transverse distribution

10.1088/1748-0221/15/11/P11005

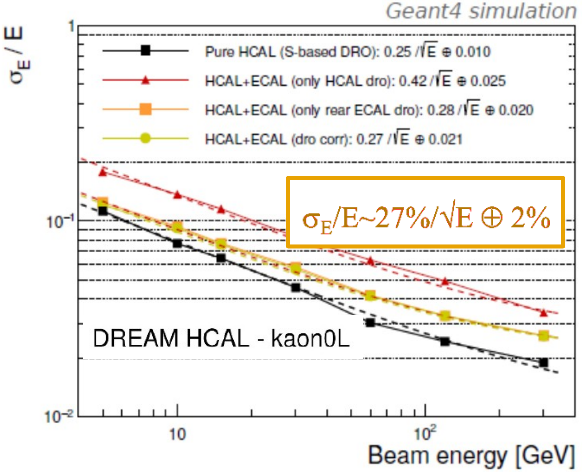
SCEPCal +DRO HCAL performance studies

DRO corrections





Neutral hadron E resolution



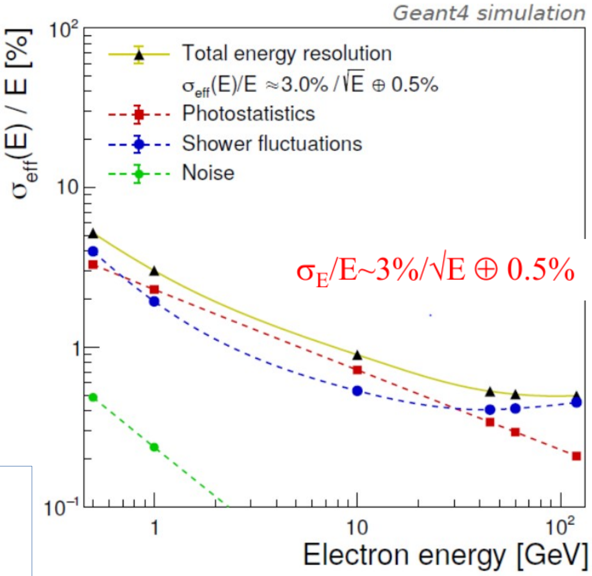
Similar sampling term as that of a pure DRO HCAL

- 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

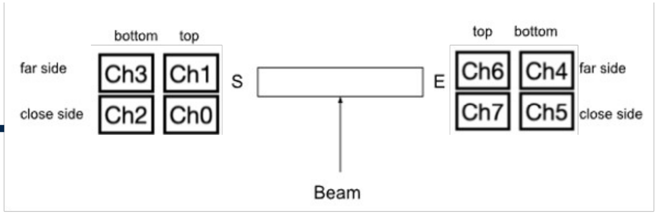
June 2023 Test Beam @Fermilab Datasets

Non scintillating, Ĉ only

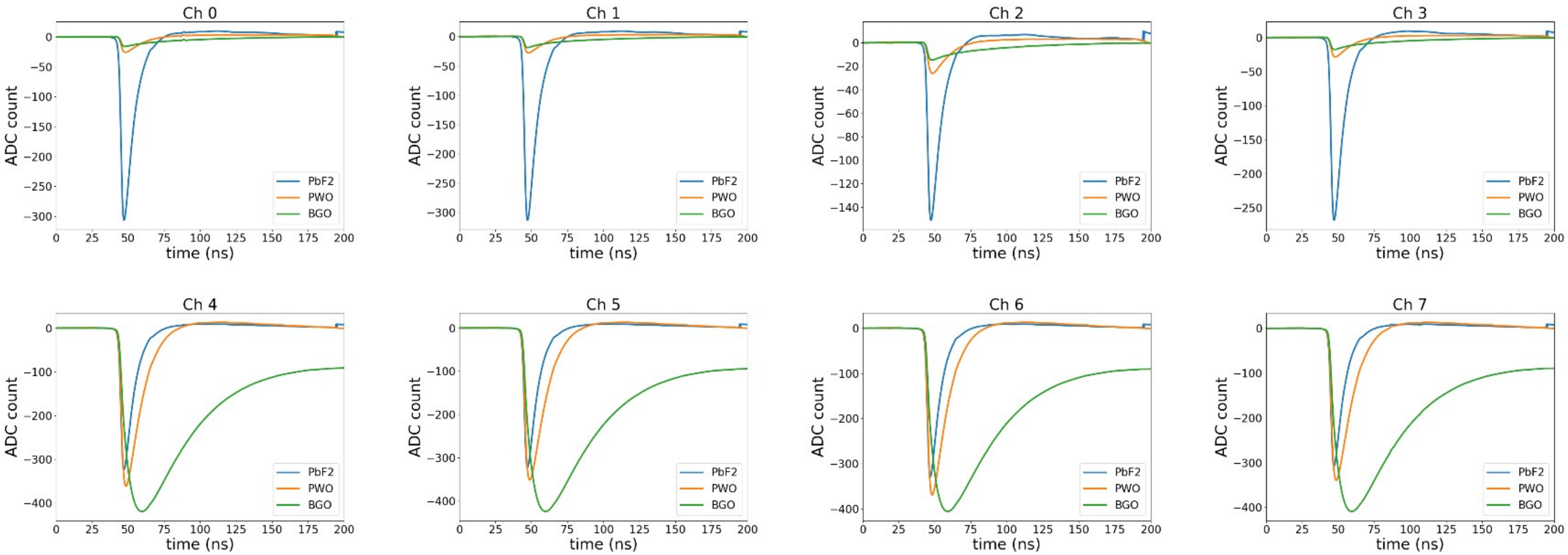
Crystal	Size	Filter (S side only)	Run #	Angle (°)	# of events	Satuarated-event rate (%)
PbF2	6x2.5x2.5 cm^3	No filter	11-29	0 to ±90 (10° interval)	~40k-70k	|θ|<30°: 2% 30°<|θ|<60°: 10% 60°<|θ|: 30%
PWO		R60	31-66	0 to ±90 (5° interval, except ±85°)	~30k-70k	|θ|<30°: 2% 30°<|θ|<60°: 15% 60°<θ: 20% θ<-60°: 35%
		No filter	103-121	0 to -50 (5° interval), 0 to +25 (5° interval), ±90	~20k-40k	|θ|<30°: 5% 30°<|θ|<60°: 15% 60°<|θ|: 45%
BGO		U330	68-101	0 to -45 (5° interval), 0 to +50 (5° interval), -55, -65, -75, ±90	~50k-60k	|θ|<30°: 7% 30°<|θ|<60°: 20% 60°<|θ|: 40%

June 2023 Test Beam @Fermilab Datasets

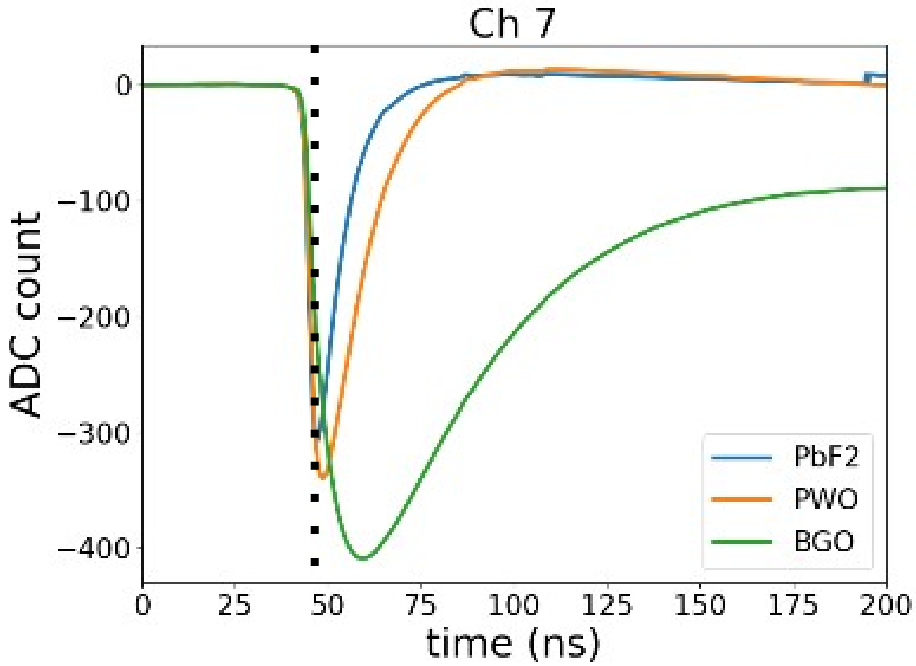
Average Time Spectrum (θ=0°)



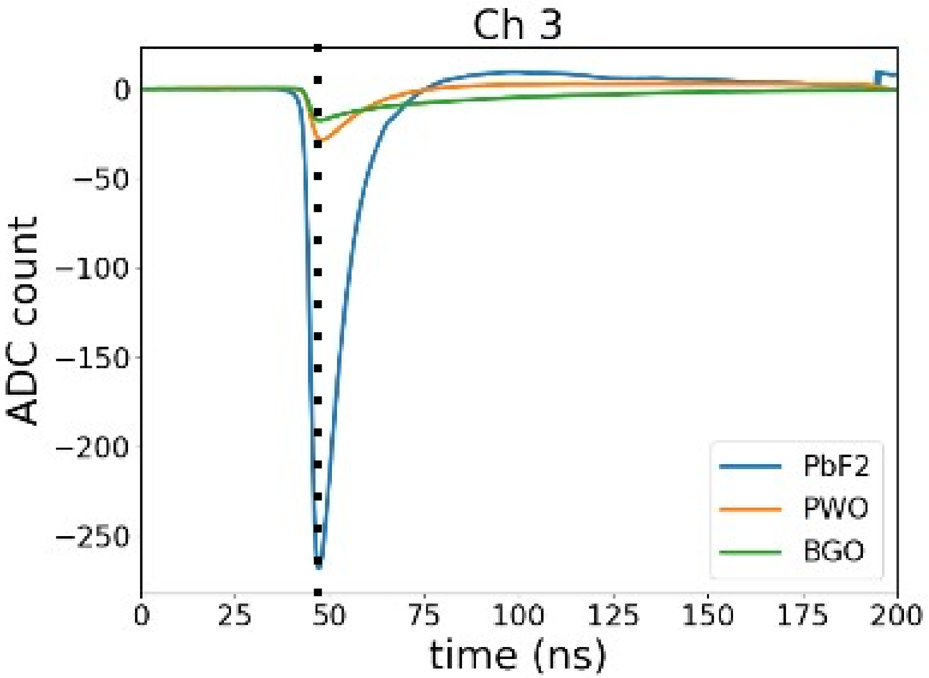
- The spectra are averages over events.
- PbF2: no filter for all channels; PWO and BGO: w/ fiter for ch 0-3, w/o filter for ch 4-7



June 2023 Test Beam @Fermilab Datasets



without filter



with filter