A dual-readout crystal electromagnetic calorimeter for future e^+e^- Higgs factories

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On behalf of the CALVISION team

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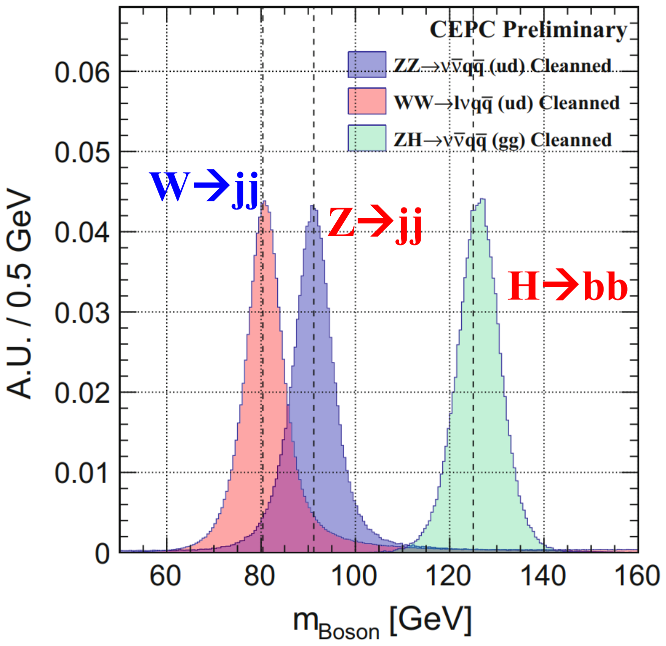
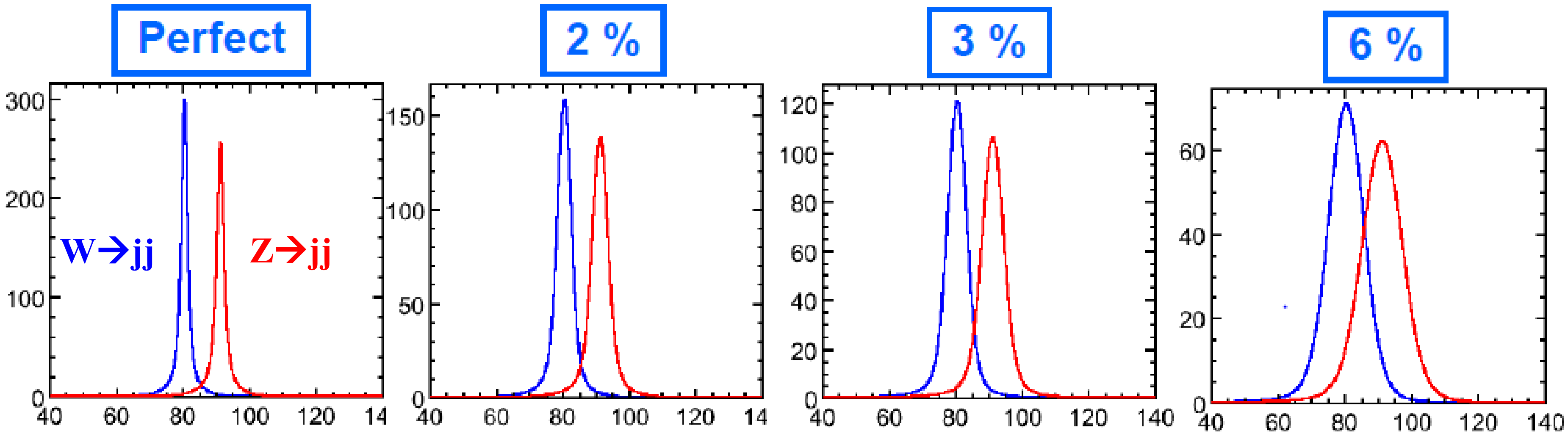
Introduction

EPJC (2018) 78:426

- Jet energy resolution is a key benchmark of the e^+e^- detector performance
- Important to build calorimeters that can achieve $\Delta E/E \sim$ 3-4% for jets at 100 GeV to separate hadronically-decayed W and Z bosons
- Very hard to achieve this with a traditional approach to calorimetry
  - Limited by a typical HCAL resolution of >50%/$\sqrt{E}$
- Two different but complementary approaches considered:
  - High granularity calorimeter
  - Dual Readout (DRO) calorimeter



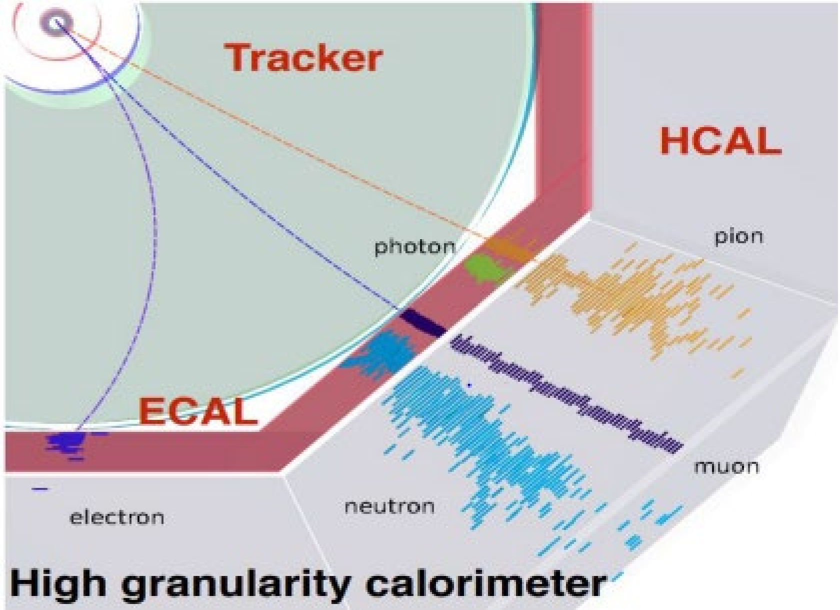


3-4% jet energy resolution gives decent W/Z separation ~2.5 σ

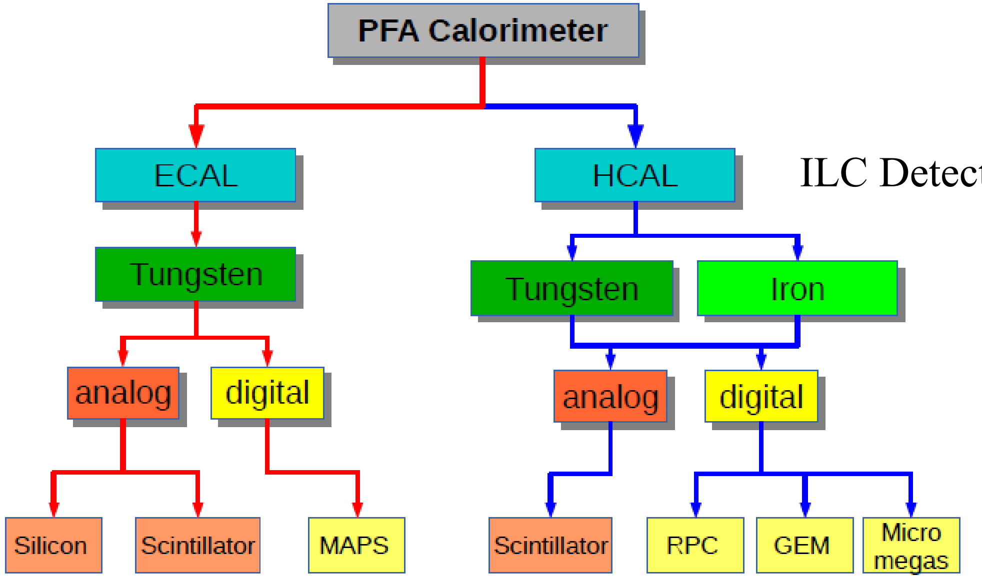
High Granularity Calorimetry

- Sampling calorimeter, reconstructing and identifying individual particles in showers, measuring the energy of each particle with the detector subsystem providing the best resolution for that particle type:

Particles	Energy fraction	Detector	Typical resolution
Charged particles	~65%	Tracker	$<5\times10^{-5}p_T$
Photons	~25%	ECAL	$\sim15\%/\sqrt{E}$
Neutral hadrons	~10%	ECAL+HCAL	$\sim60\%/\sqrt{E}$



Characteristics:
- High granularities $\Rightarrow$ large channel counts;
- relatively small sampling fractions



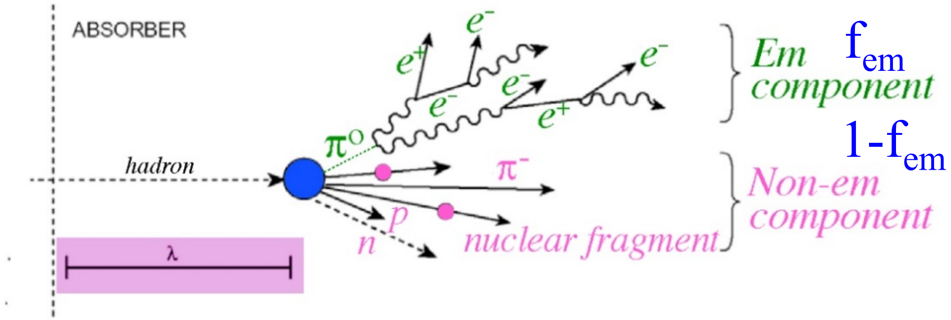
ILC Detector TDR

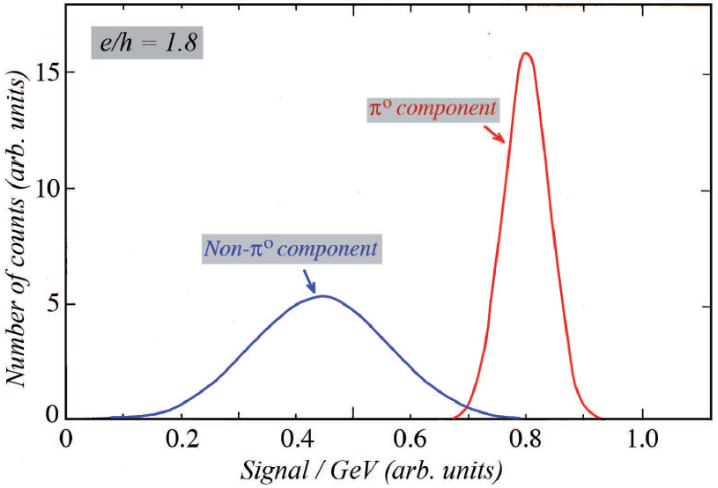
Dual Readout Calorimetry

- Read out both scintillation and Cerenkov photons to disentangle EM and hadronic components event-by-event, allowing for the corrections for different EM and hadronic responses

  Scintillation – sensitive to dE/dX energy loss ⇒ charged particles

  Cerenkov – relativistic charged particles, mostly electrons





f_{em} fluctuations dominate the hadronic energy resolution

$$S = E\left[f_{em} + \left(\frac{h}{e}\right)_S (1 - f_{em})\right]$$

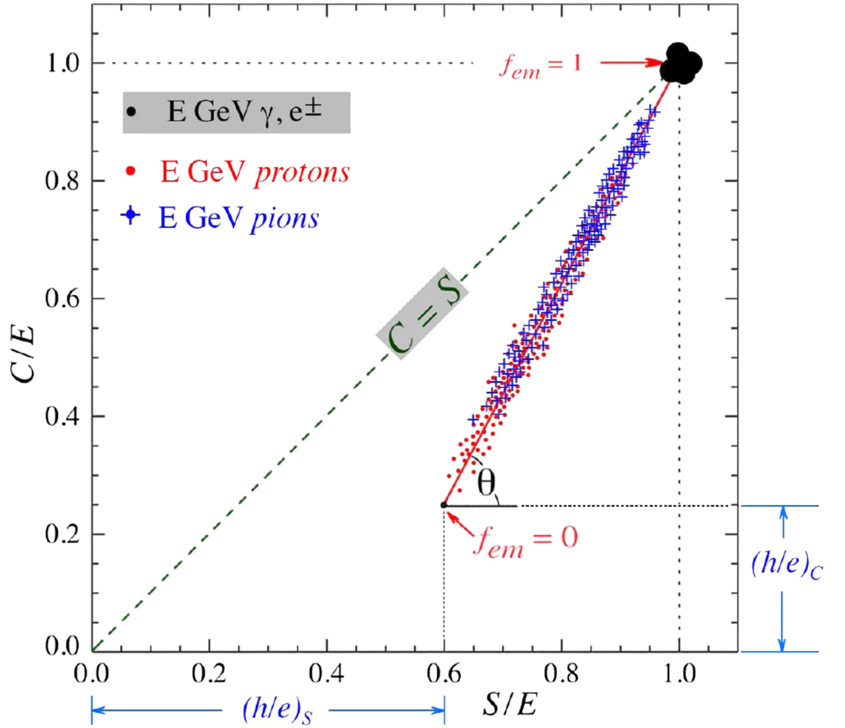
$$C = E\left[f_{em} + \left(\frac{h}{e}\right)_C (1 - f_{em})\right]$$

$$\Downarrow$$

$$\frac{S}{E} = \left(\frac{h}{e}\right)_S + f_{em}\left[1 - \left(\frac{h}{e}\right)_S\right]$$

$$\frac{C}{E} = \left(\frac{h}{e}\right)_C + f_{em}\left[1 - \left(\frac{h}{e}\right)_C\right]$$

$$E = \frac{S - \chi C}{1 - \chi} \qquad \chi = \frac{1-\left(\frac{h}{e}\right)_S}{1-\left(\frac{h}{e}\right)_C} = \cot\theta$$



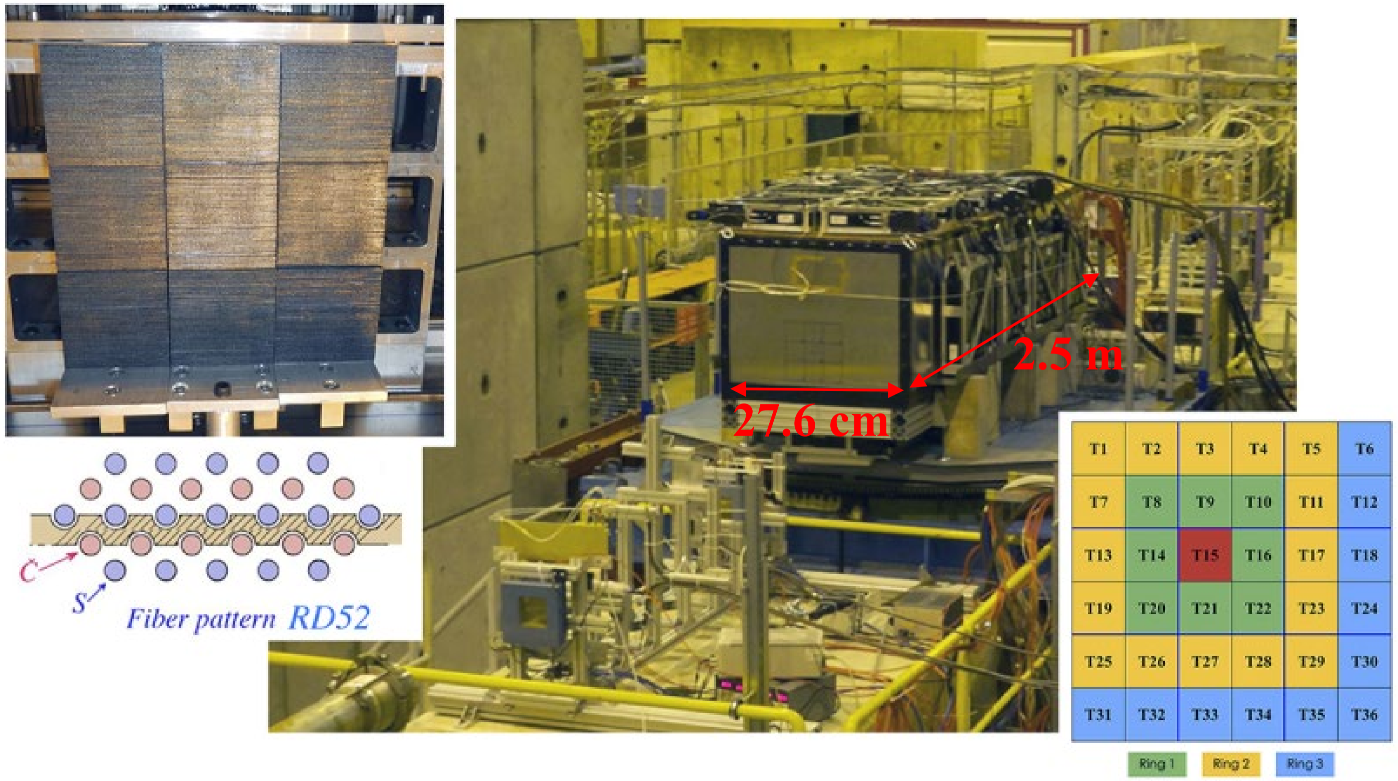
DRO calorimetry relies on the fact that e/h is different For Cerenkov and Scintillation readout

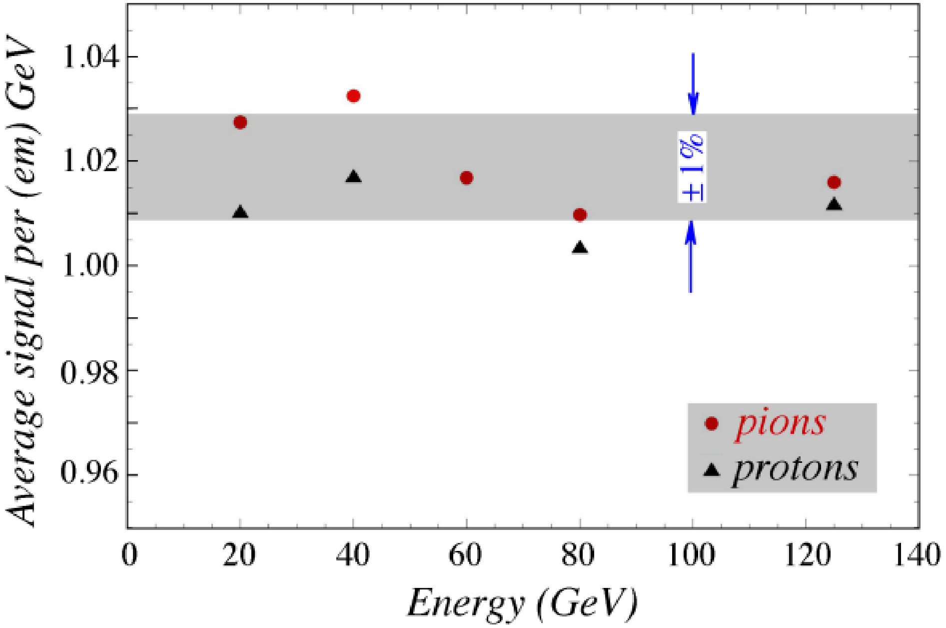
χ is independent of the incident hadron's energy

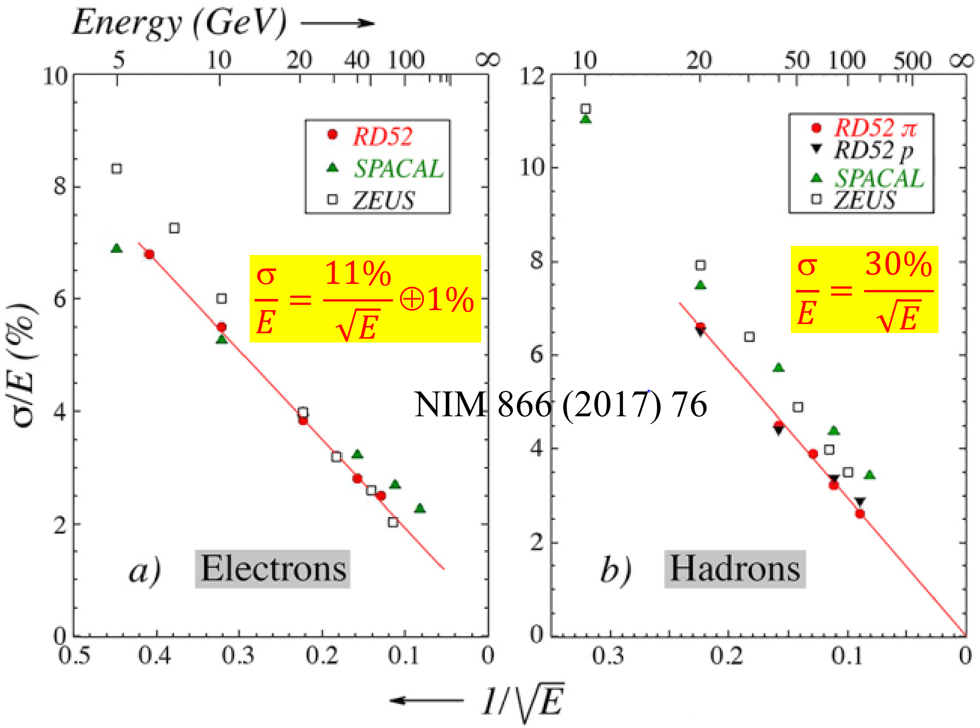
Dual Readout Calorimetry

- Extensive R&D by the DREAM/RD52/IDEA collaborations (Rev. Mod. Phys. Vol 90, April 2018):
  Sampling calorimeter with lead or copper absorber
  Clear and scintillation fibers for C/S readout.

Lead absorber, 9 modules with ~36k fibers



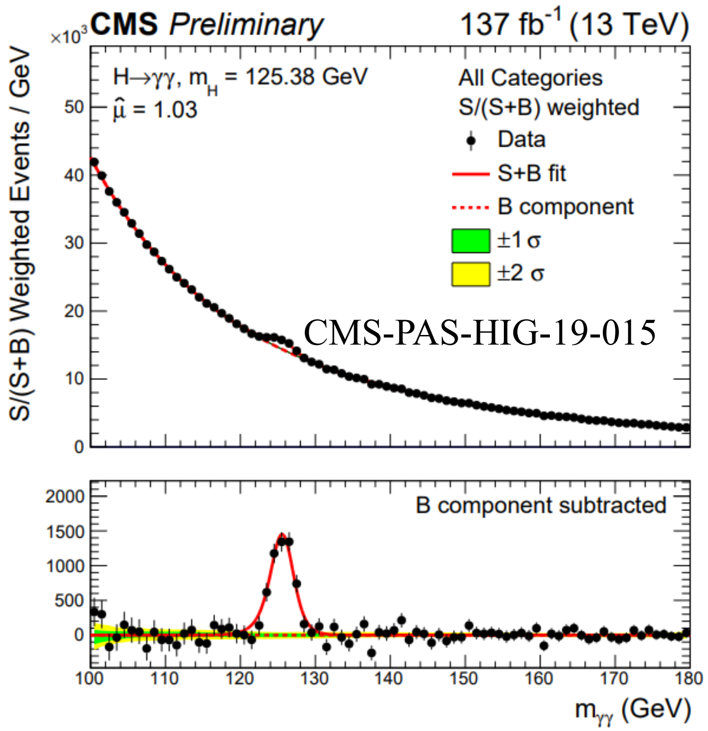




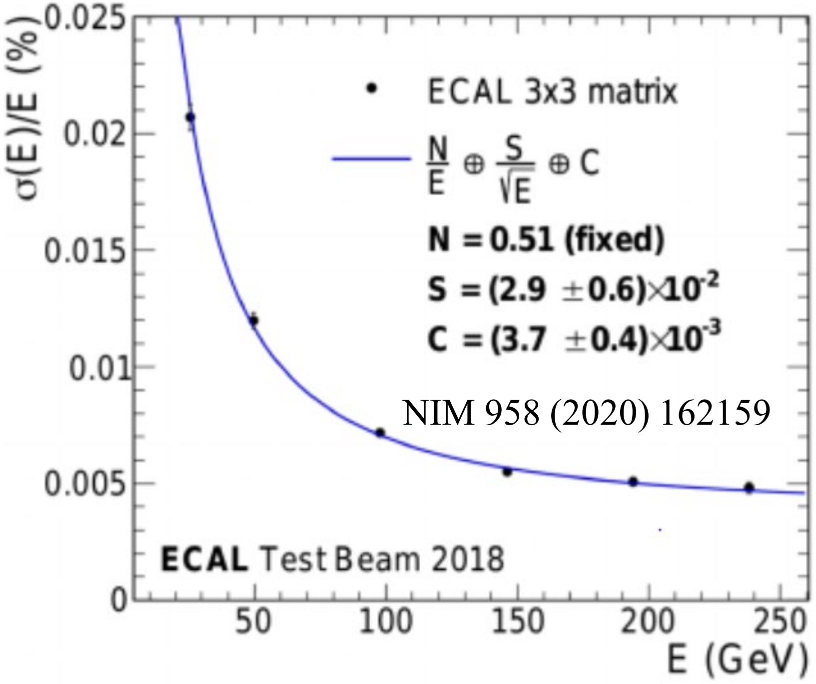
NIM 866 (2017) 76

Crystal Calorimeters

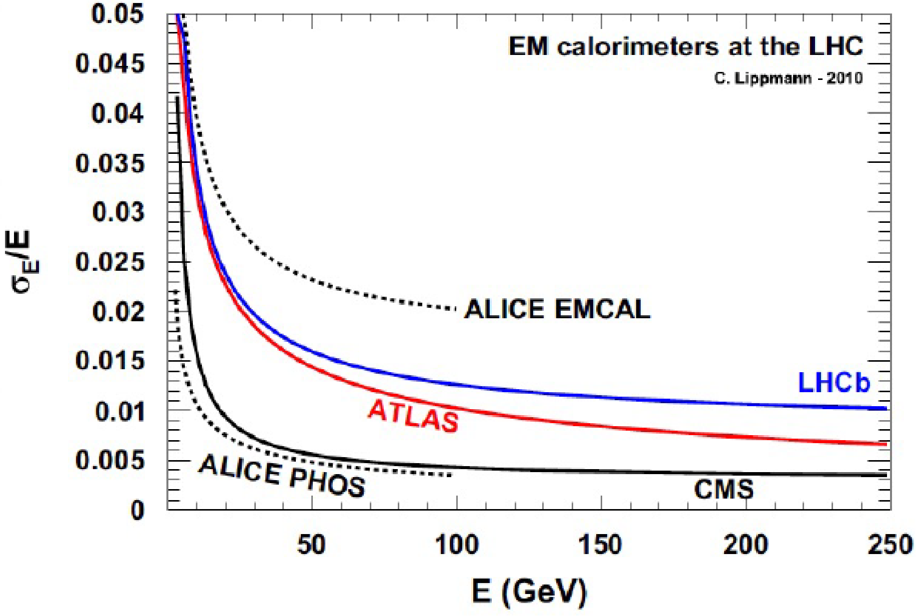
- Crystal calorimeters are homogeneous detector, have excellent EM energy resolutions, ~3%/√E or better



CMS-PAS-HIG-19-015



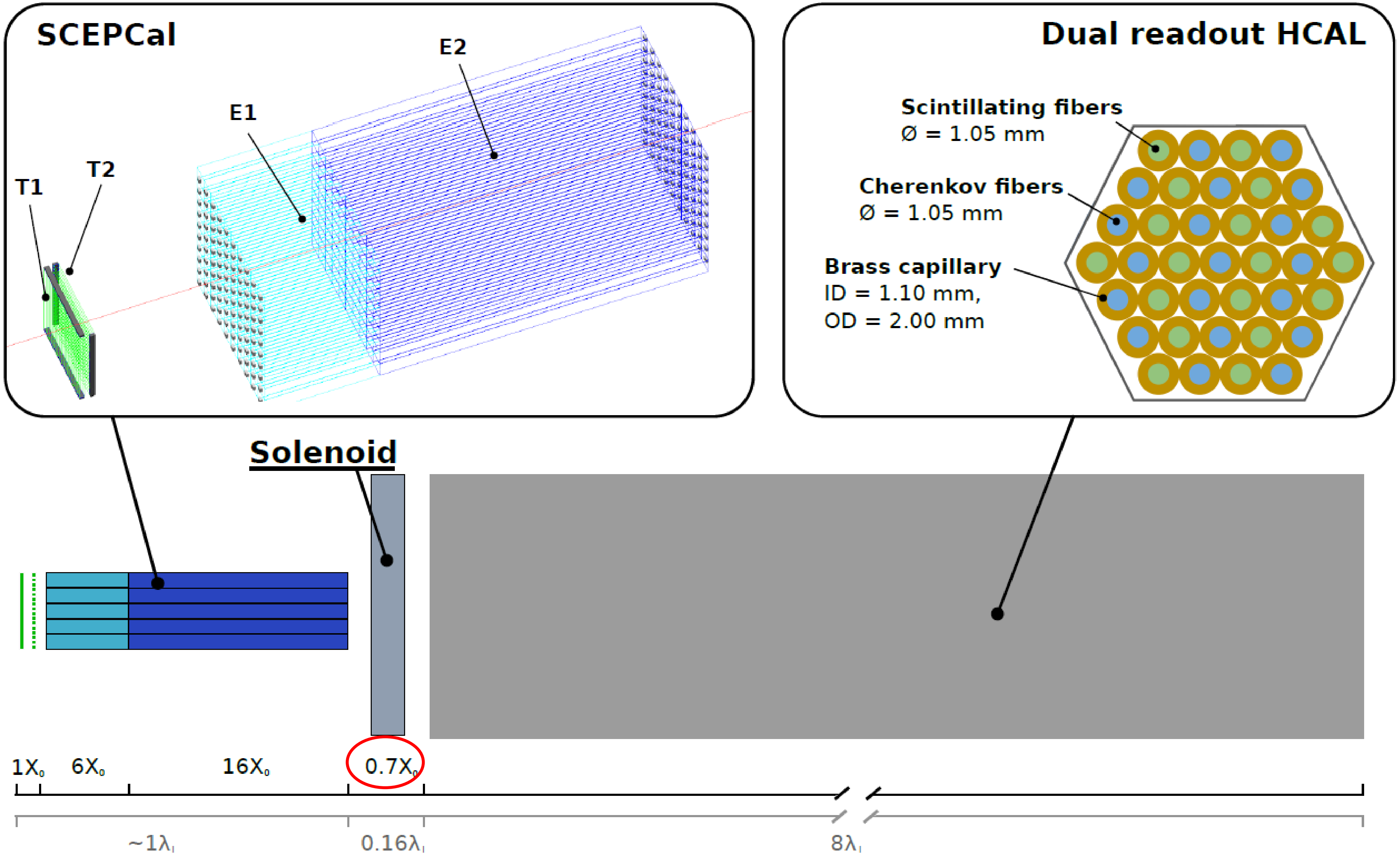
NIM 958 (2020) 162159



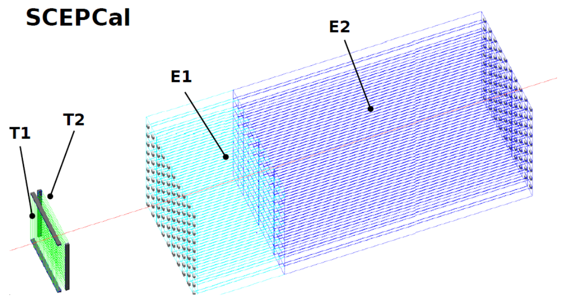
- Traditional crystal calorimeters suffer from large non-uniform e/h responses
- Can we combine the strengths of a crystal ECAL with that of a DRO calorimeter?
- Can a DRO crystal ECAL be combined with a DRO HCAL to have excellent energy resolution for both EM particles and hadrons?

A Segmented DRO Crystal ECAL with a DRO Fiber HCAL

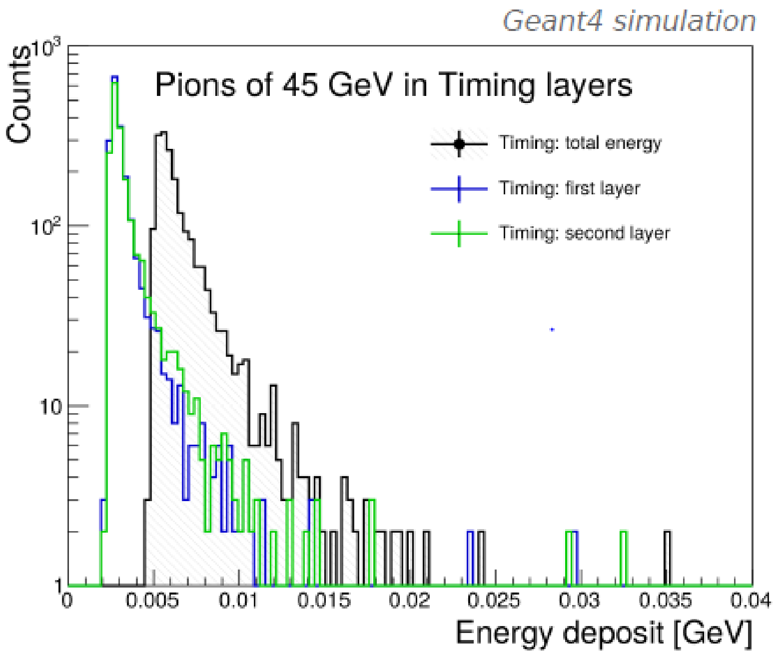
arXiv:2008.00338

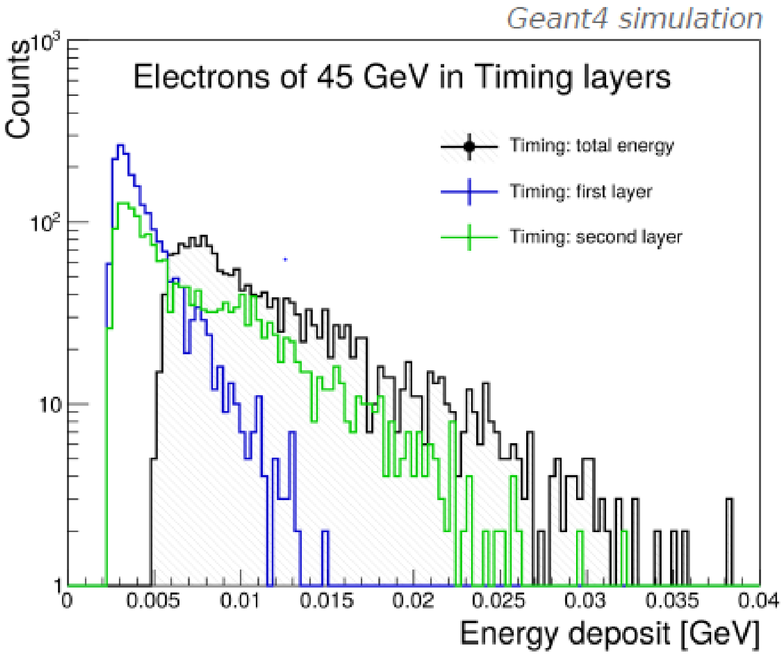


Timing Layers (Optional)



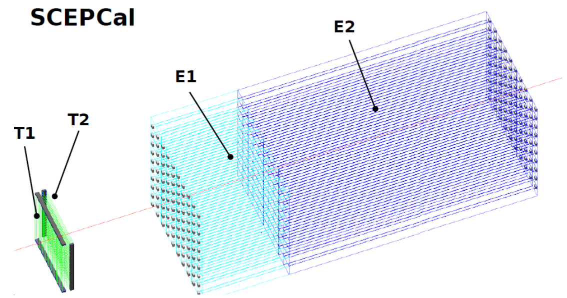
- Two timing layers (σ_t~20 ps)
- Similar timing performance as the CMS barrel MIP Timing detector
- LYSO:Ce scintillating crystals (~0.8 X_0)
- 3×3×100 mm^3 thin crystal bar
- 3×3 mm^2 SiPM (15-20 μm cell size)
- Two layers are orthogonal to each other → position resolution ~ 1 mm in x-y directions
- Excellent timing resolution will be useful for searches of long-lived particles, and for providing new possibilities for identifications of charged hadrons through TOF



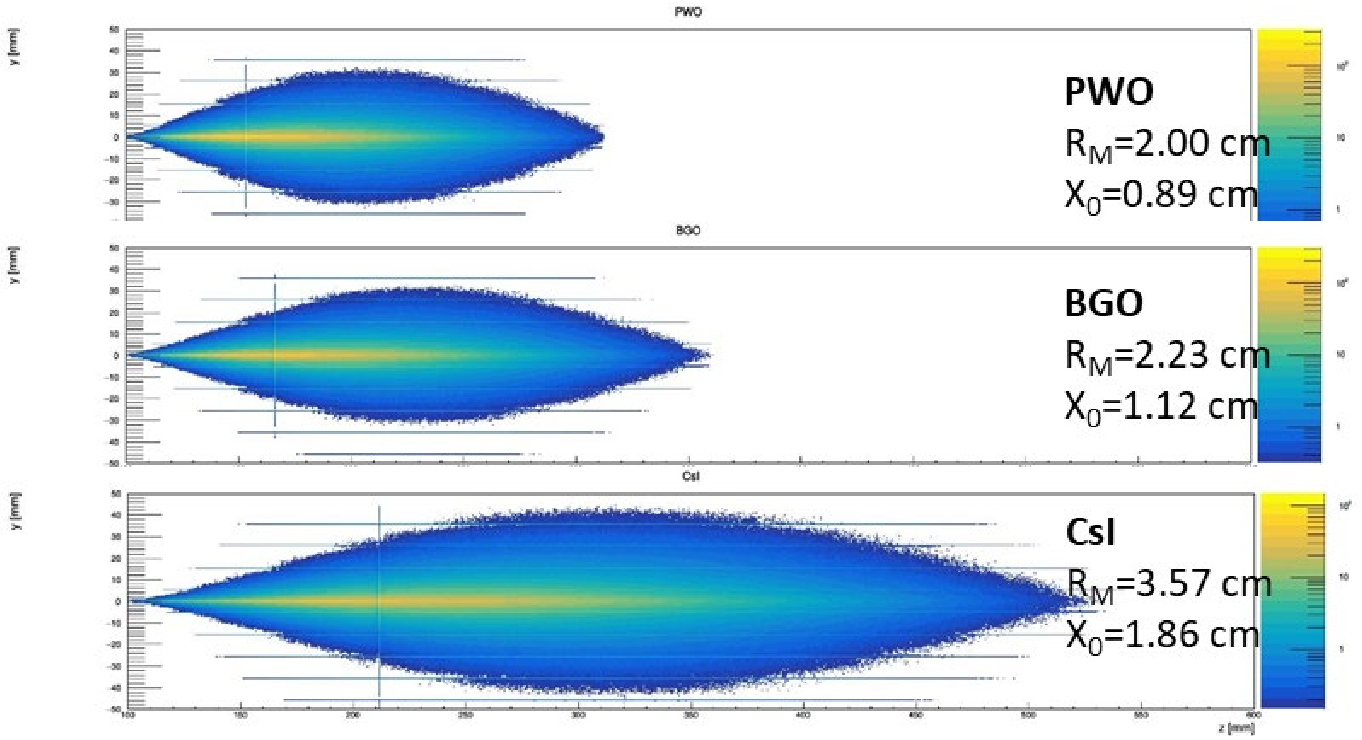


Segmented ECAL

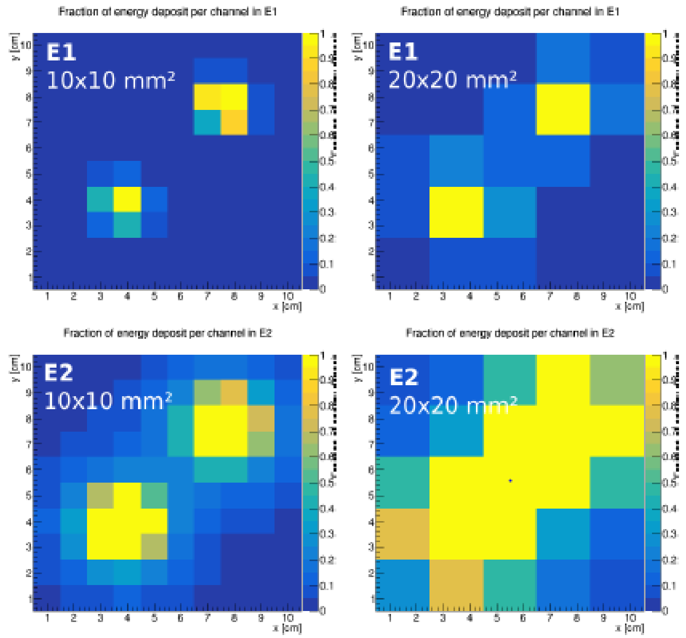
- Two layers with $PbWO_4$ crystals (high density, short radiation length, small Moliere radius, fast signal, reasonable C/S ratio (~30%), cost effective, relatively low light yield)
- BGO and BSO are also good candidates
- Crystal cross-section: 10×10 mm^2



Crystal	Density g/cm^2	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



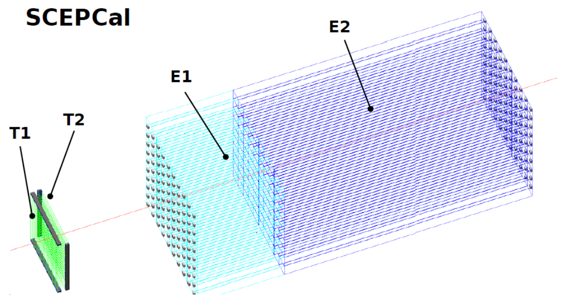
Longitudinal profile

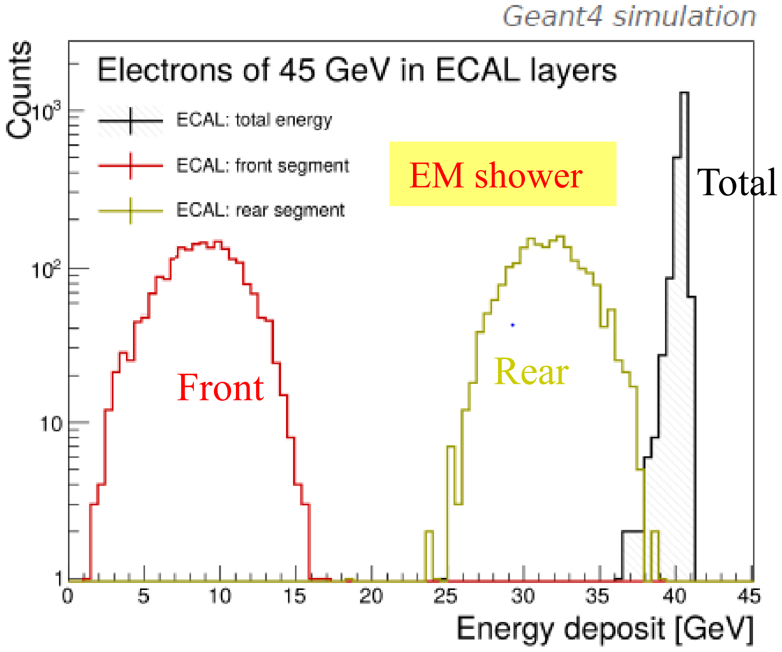


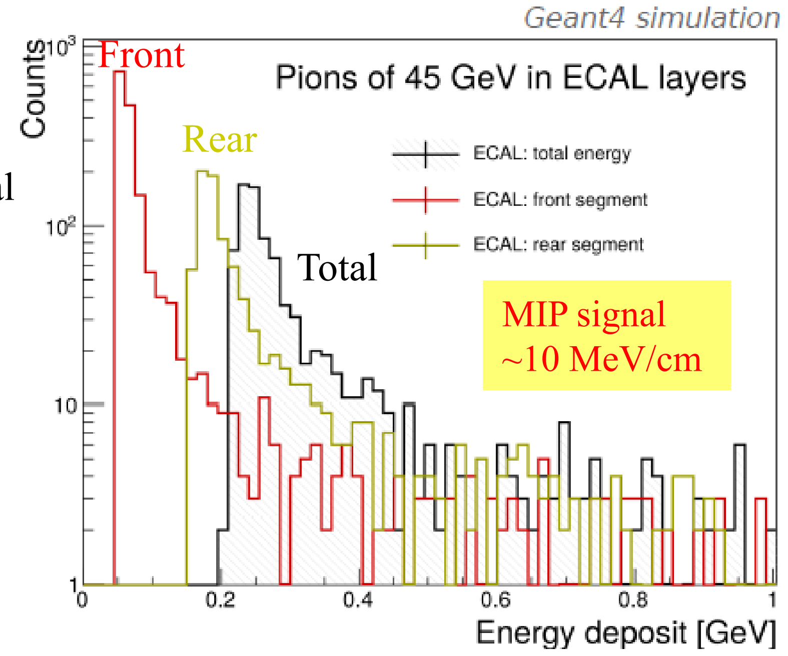
Reconstruction of two photons emitted with an angle of 3 degrees

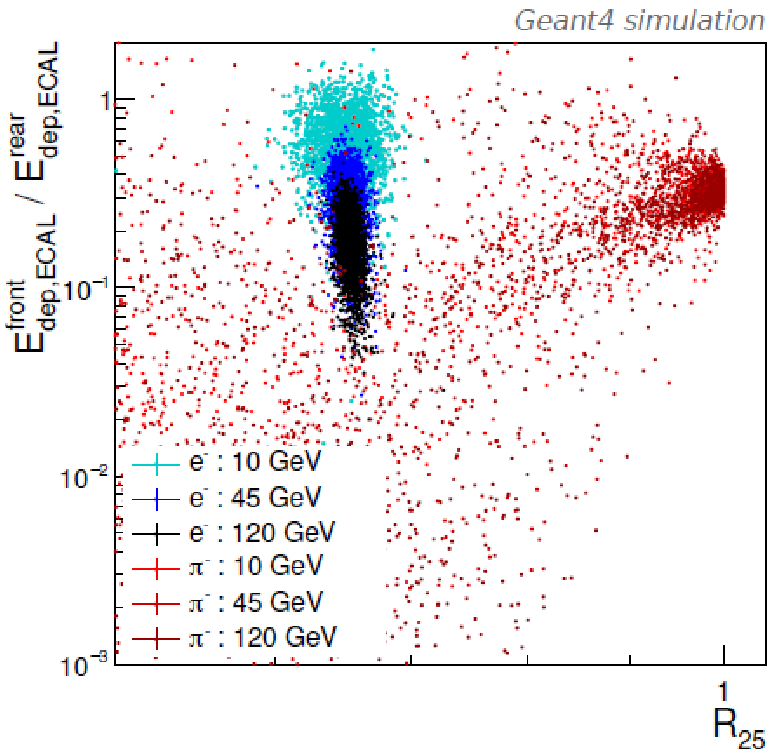
Segmented ECAL

- Two segmented layers:
  - Front segment (~6 X_0, ~50 mm)
  - Rear segment (~16 X_0, ~140 mm)
- The longitudinal segmentation will be useful for the separation of electrons and pions





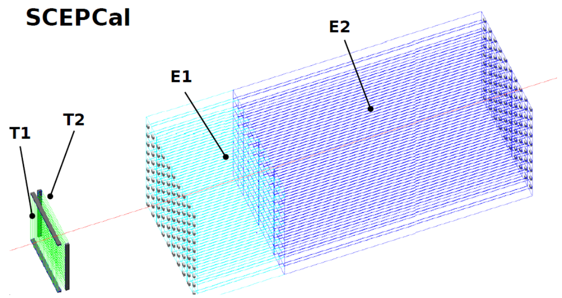




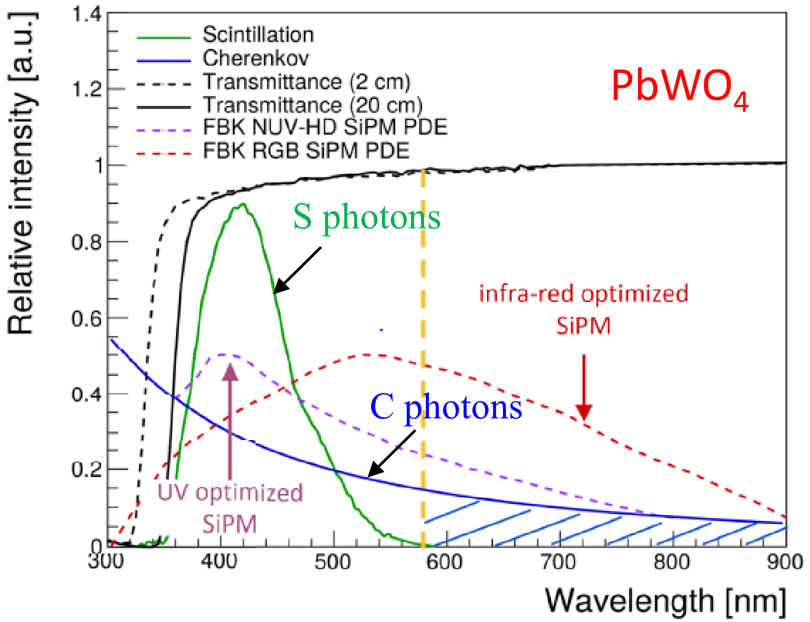
Ratio of energy deposited in front and rear segments
vs
Ratio of energy deposited in the central crystal and the total energy deposited in a 5×5 crystal matrix

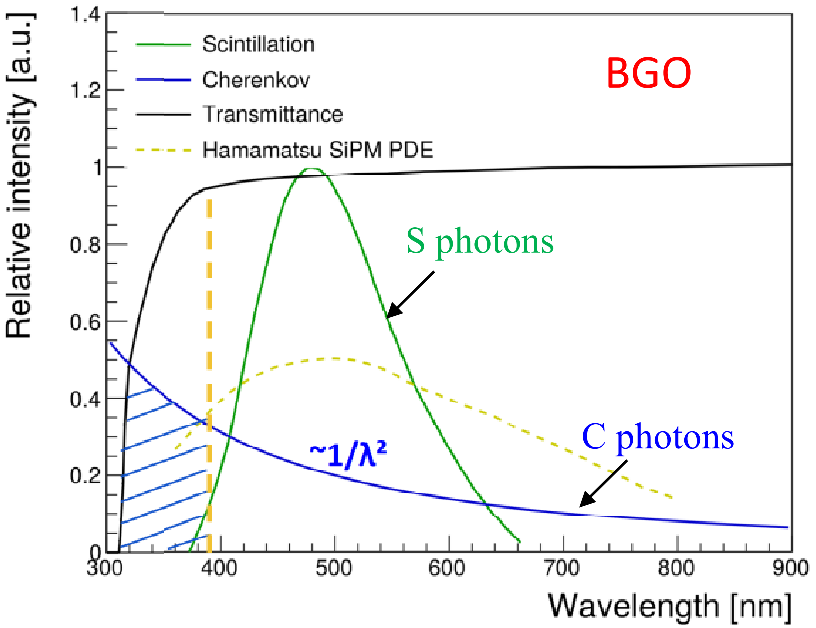
Segmented ECAL

- 5×5 mm^2 SiPM (10-15 μm cell size)
  - Rely on optical filters to separate S and C
- 3 SiPMs (one on entrance, two on exit)
  - Front: optimized for scintillation light
  - Rear: two SiPMs optimized for scintillation and Cerenkov light



	Scintillation [photons/GeV]	f_S [%]	Cherenkov [photons/GeV]	f_C [%]
Generated	200000	100	56000	100
Collected	10000	5.0	2130	3.8
Detected by NUV SiPM #1 ($\lambda < 550$ nm)	2000	1.0	140	0.25
Detected by RGB SiPM #2 ($\lambda > 550$ nm)	< 20	< 0.01	160	0.3

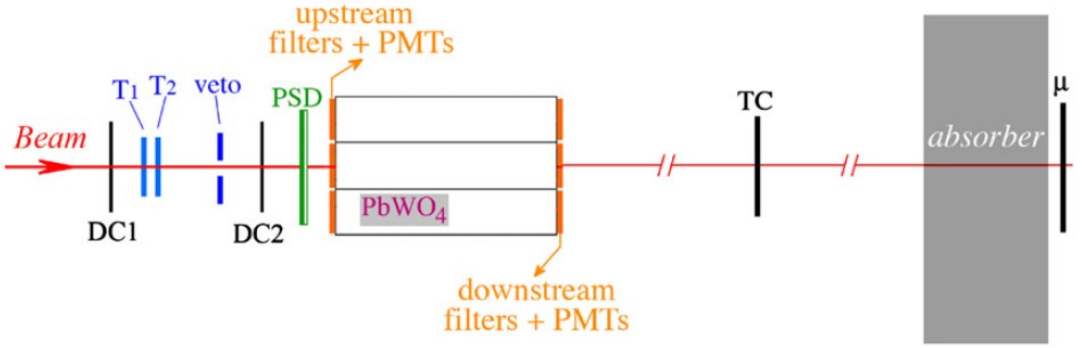


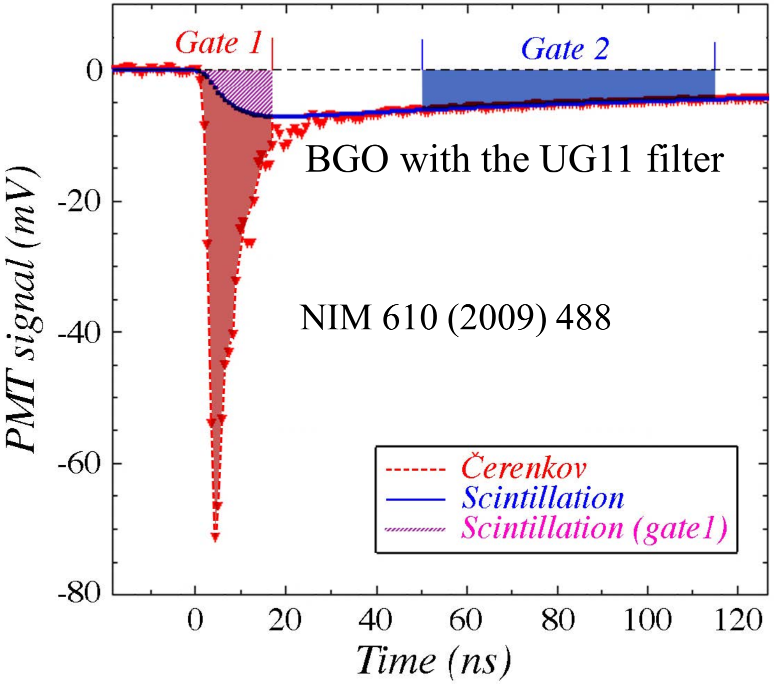


Light yield: ~200 S and ~56 C photons/MeV
Local collection eff: ~5% assumed
Photon detection eff: ~20% assumed

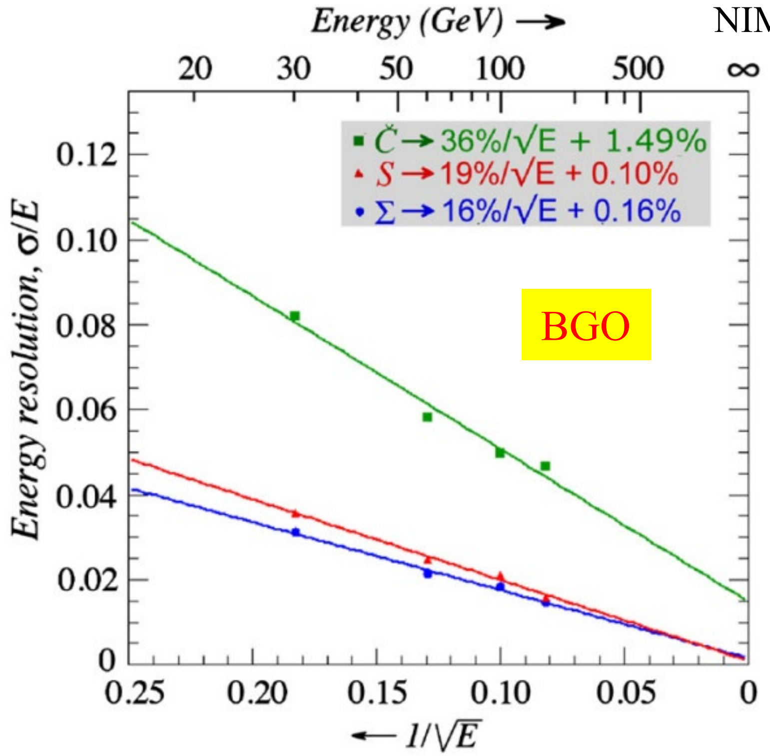
Previous DREAM/RD52 Work on the DRO Crystal Calorimeter

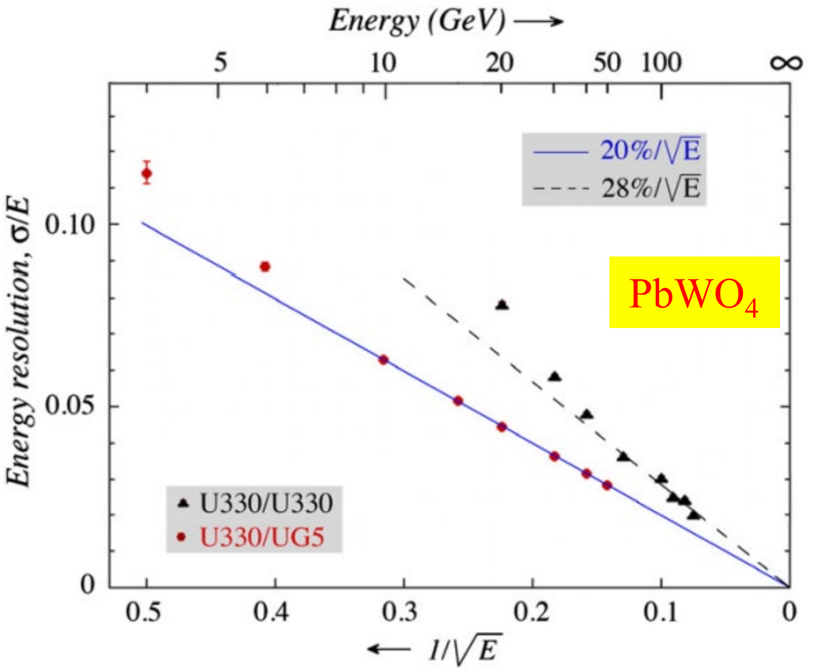
- DREAM/RD52 has investigated DRO of crystals with PMTs using optical filters and timing to separate C and S signals (NIM 686 (2012) 125)
  - BGO: GG495 filter (λ>495 nm) for S photons, UG11 UV filter (λ<400 nm) for C photons
  - $PbWO_4$ (w/ or w/o Mo-doped): U330 (λ<410 nm) or UG5 (λ<400 nm)





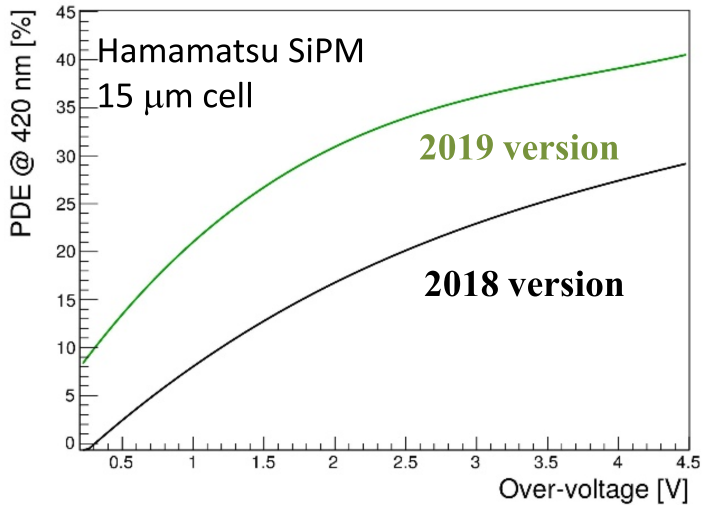
NIM 686 (2012) 125

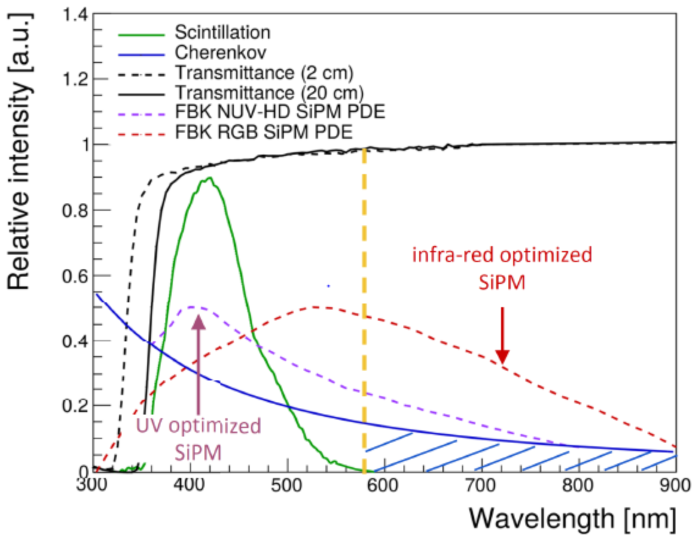




Previous DREAM/RD52 Work on the DRO Crystal Calorimeter

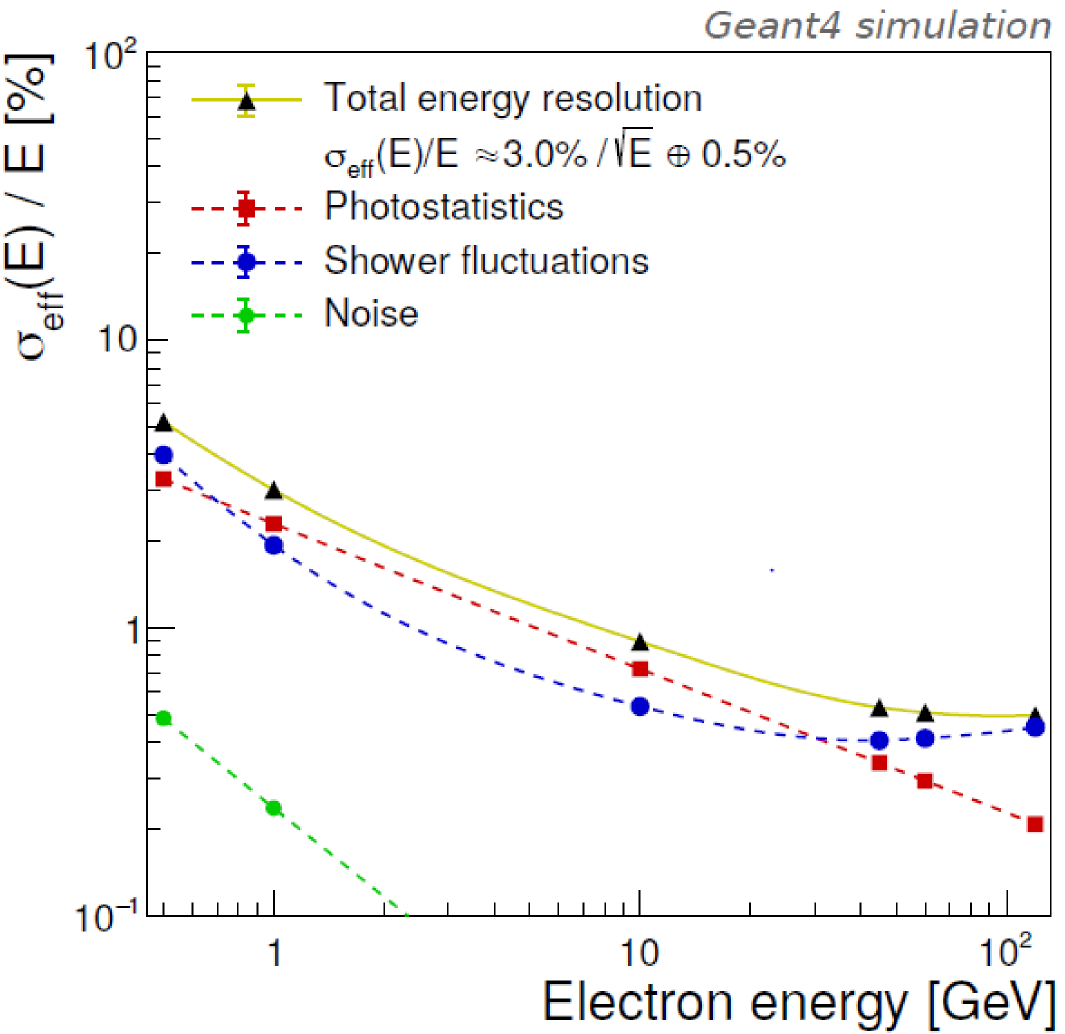
- A proof of principle for a DRO crystal calorimeter:
  - Worse electron energy resolution (15-30%/√E) compared to that provided by normal crystal calorimeters (3%/√E)
  - Resolution dominated by limited statistics for # of photons detected (only a small fraction of C and S photons are selected)
- Not pursued further by the DREAM/RD52 collaboration for various reasons:
  - Cost with PMT readout (SiPMs were not well developed at the time they performed these studies)
  - Limited wavelength sensitivity for PMT, did not go much below or above the scintillation region
  - DRO fiber calorimeter achieved a respectable EM resolution
- SiPMs change this picture

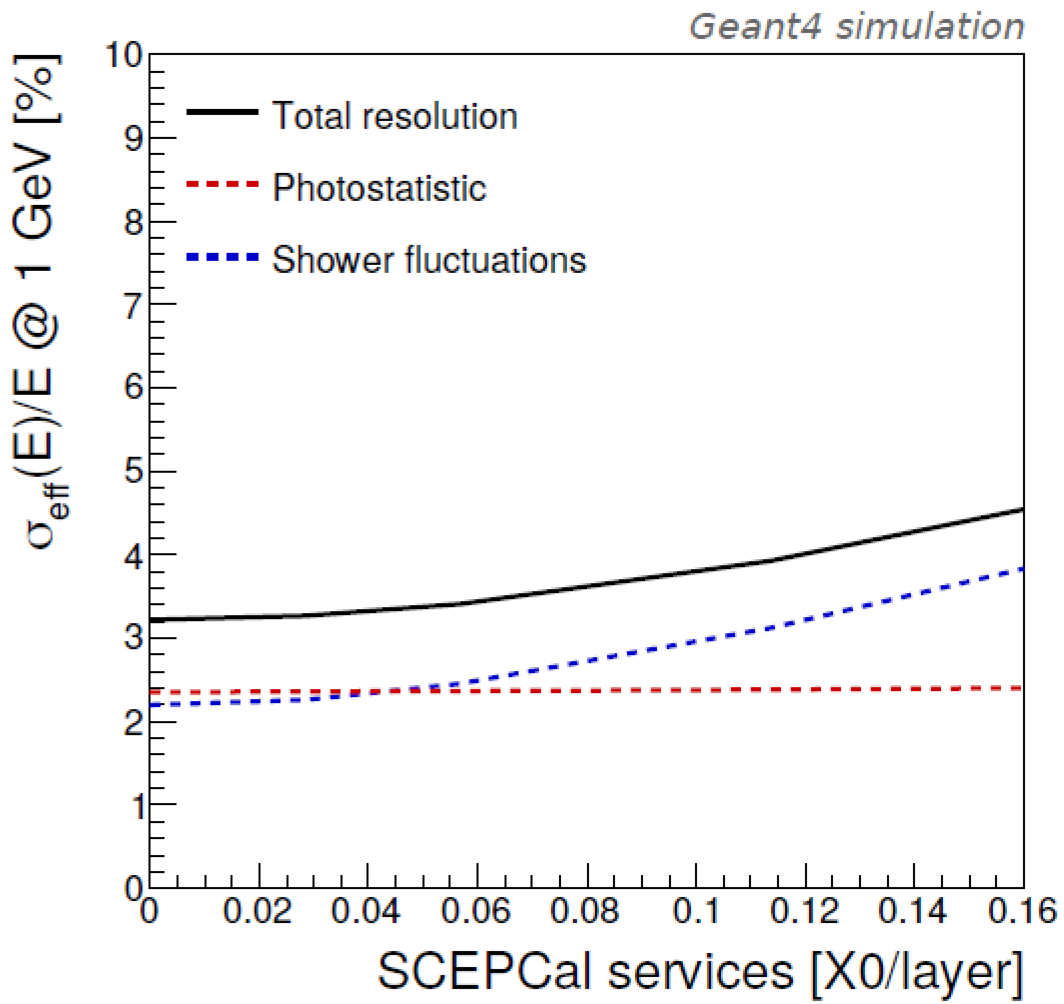




EM Energy Resolution

$\sigma_E/E \sim 3\%/\sqrt{E} \oplus 0.5\%$

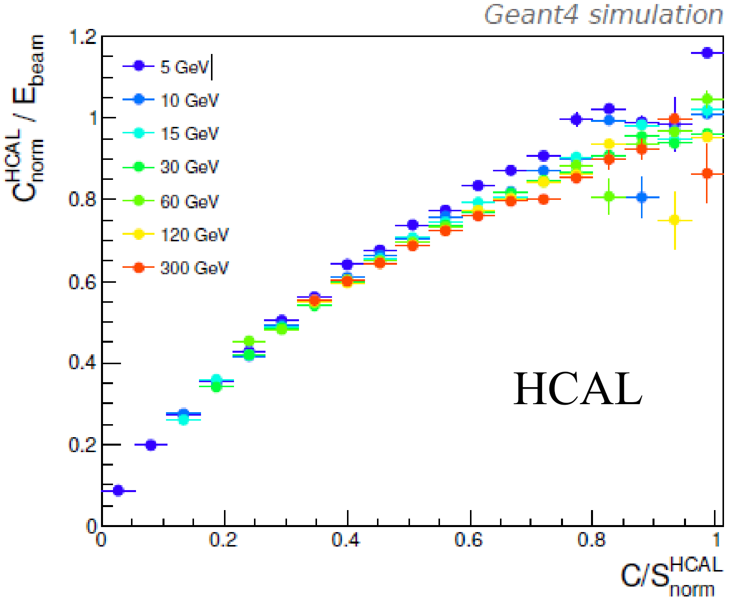


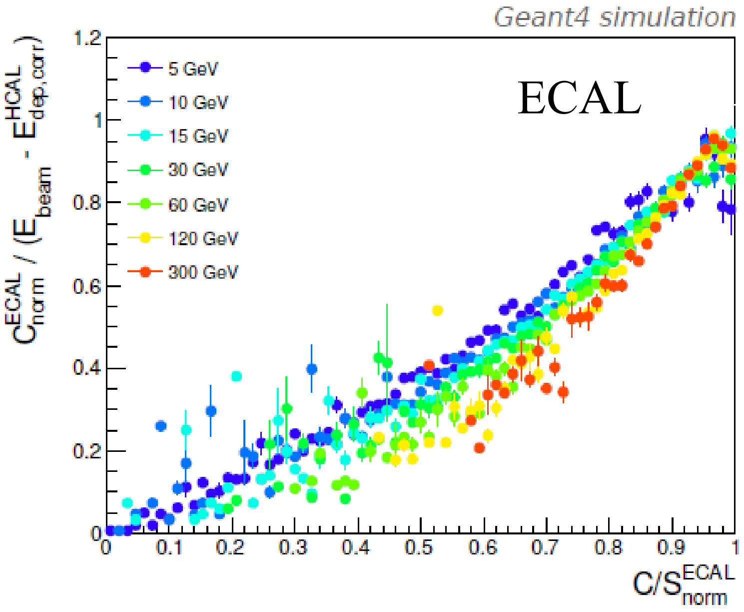


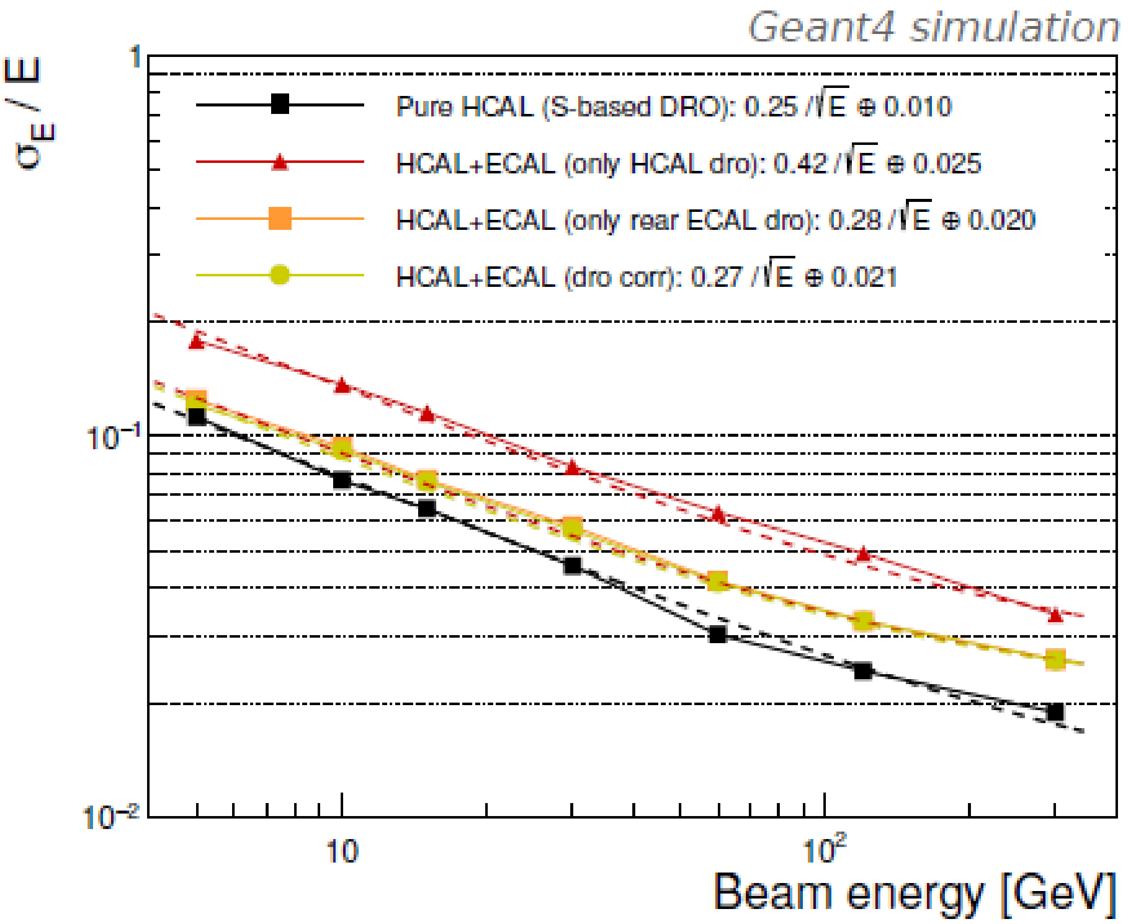
Impact of dead material between layers on energy resolution

Neutral Hadron Energy Resolution

$\sigma_E/E \sim 27\%/\sqrt{E} \oplus 2\%$







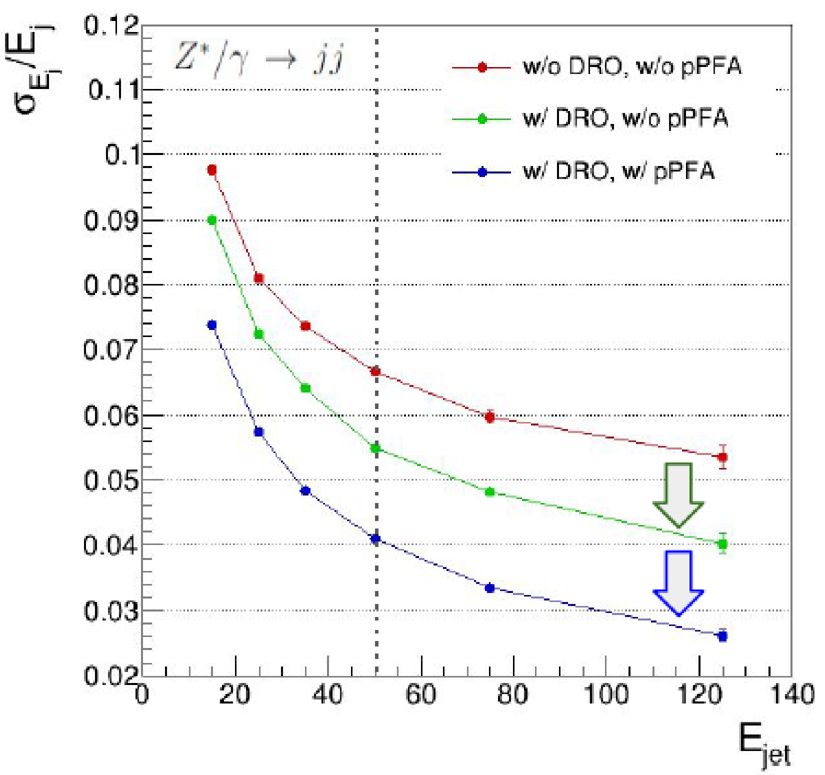
- Similar sampling term as that of a pure DRO HCAL
- Larger constant term due to the intrinsic limitation of a system that combines segments with different e/h ratios, and to the material budget from the ECAL services and the solenoid

Jet Energy Resolution and Linearity

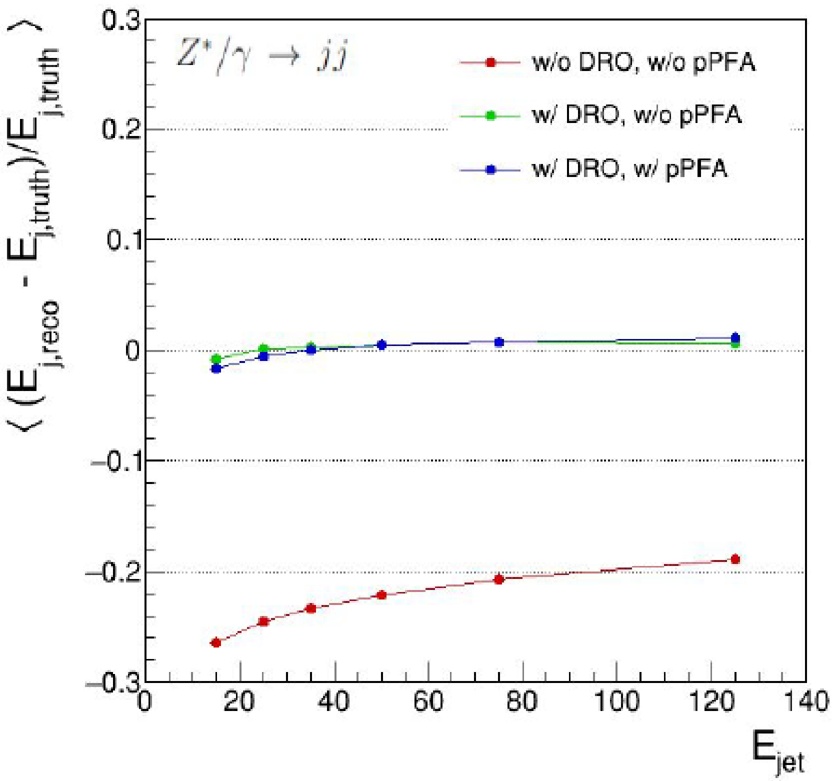
- The crystal ECAL is "particle-flow friendly"
  - Relatively compact showers, O(1 mm) transverse segmentation for timing layers, O(1 cm) transverse segmentation for ECAL, 5 longitudinal segmentations, high EM resolution for π^0 clustering, timing and dual-readout information for additional handling of particle identifications
- Maximally exploit object identification, high resolution and linear response provided by the crystal ECAL to improve the tracker-calorimeter hit matching in PFA

Lucchini, EPS-HEP Conf 2021

Jet resolution

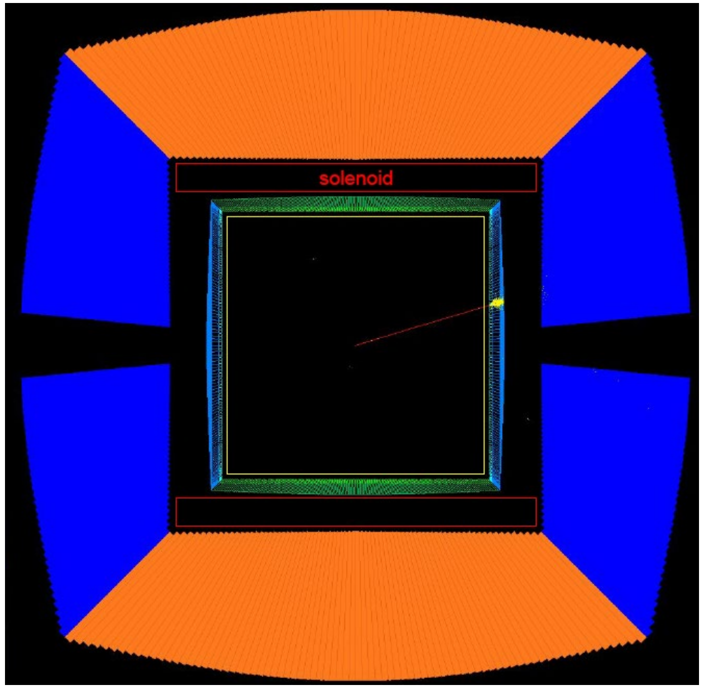


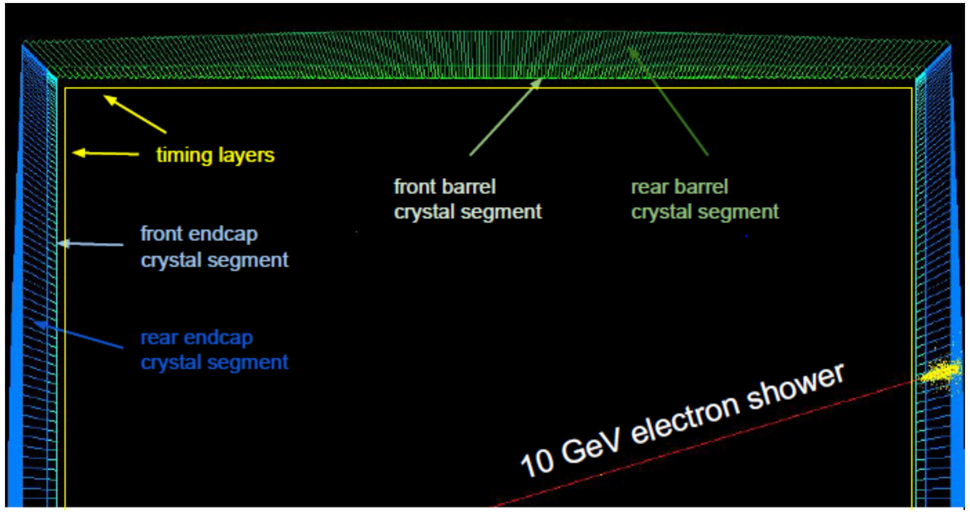
Linearity

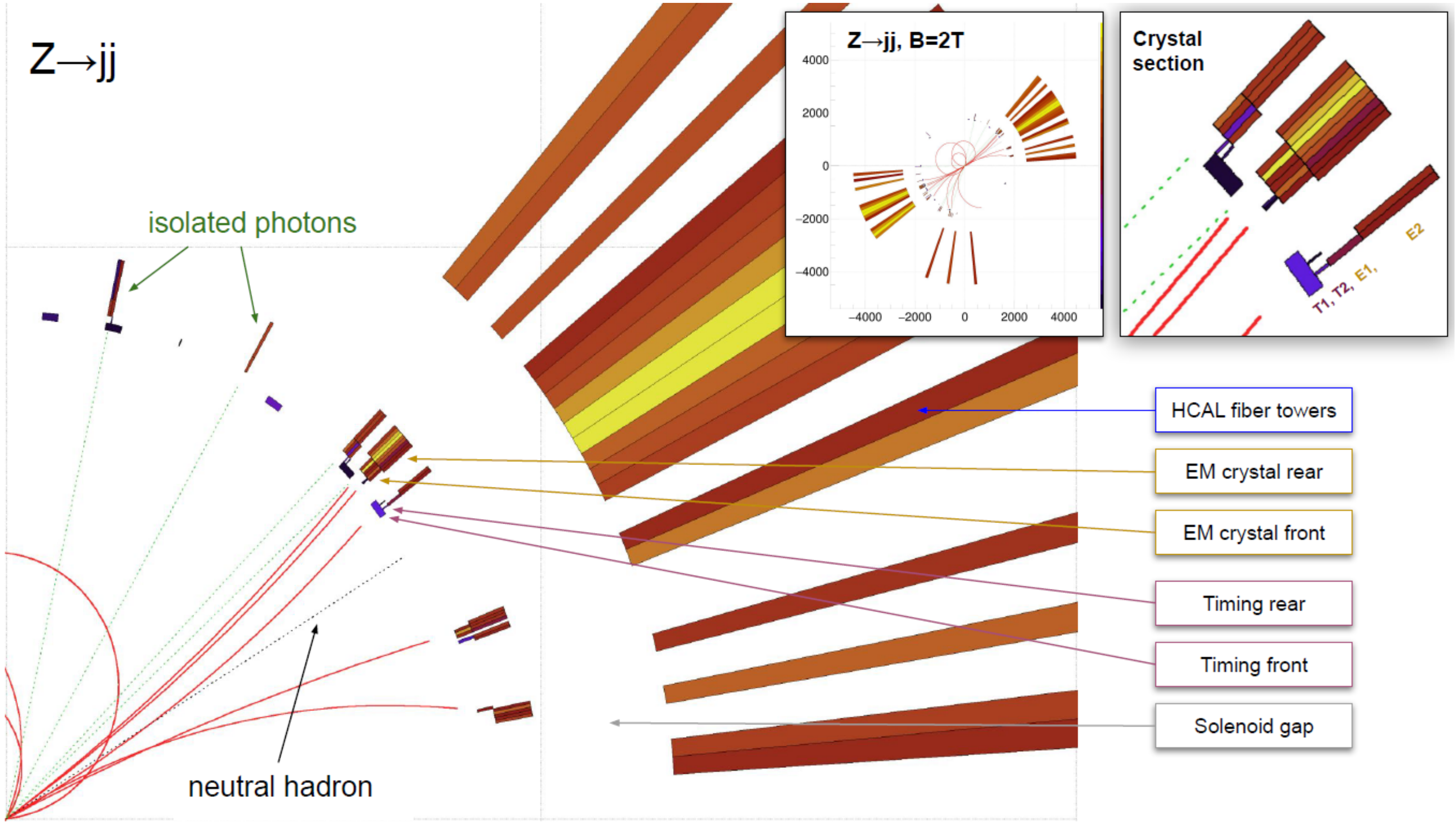


GEANT Simulation: A Z→jj Event Display

Lucchini, EPS-HEP Conf 2021

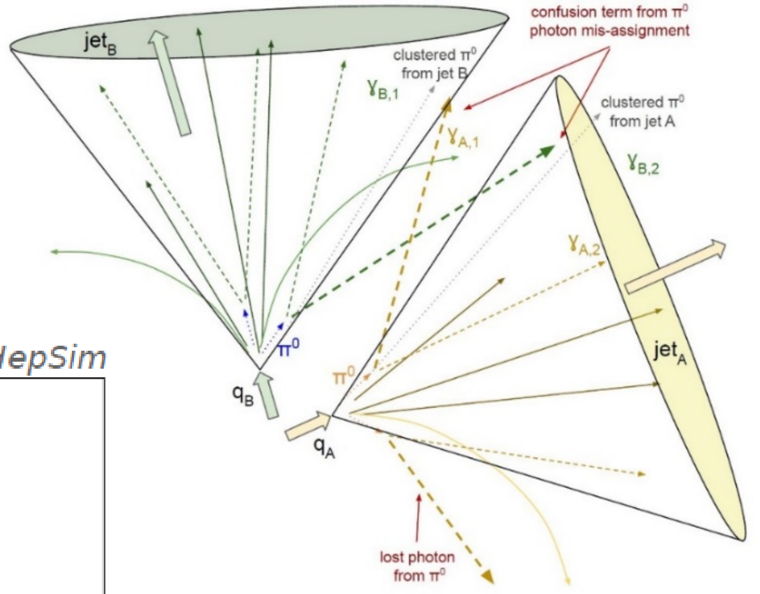


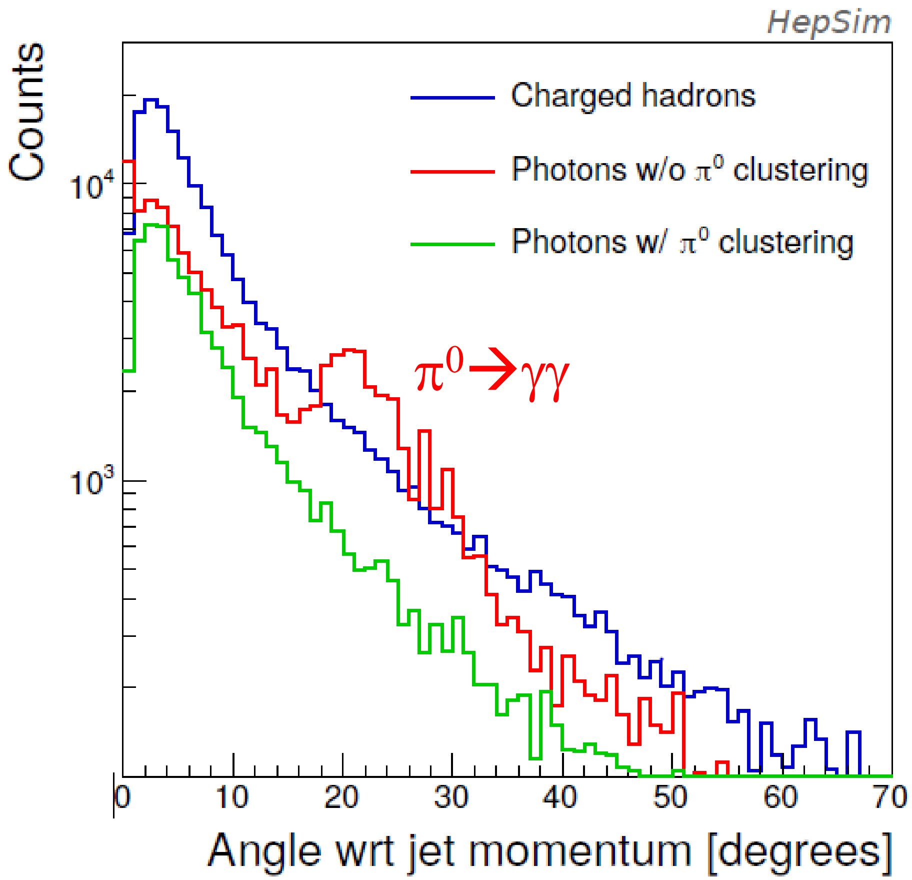


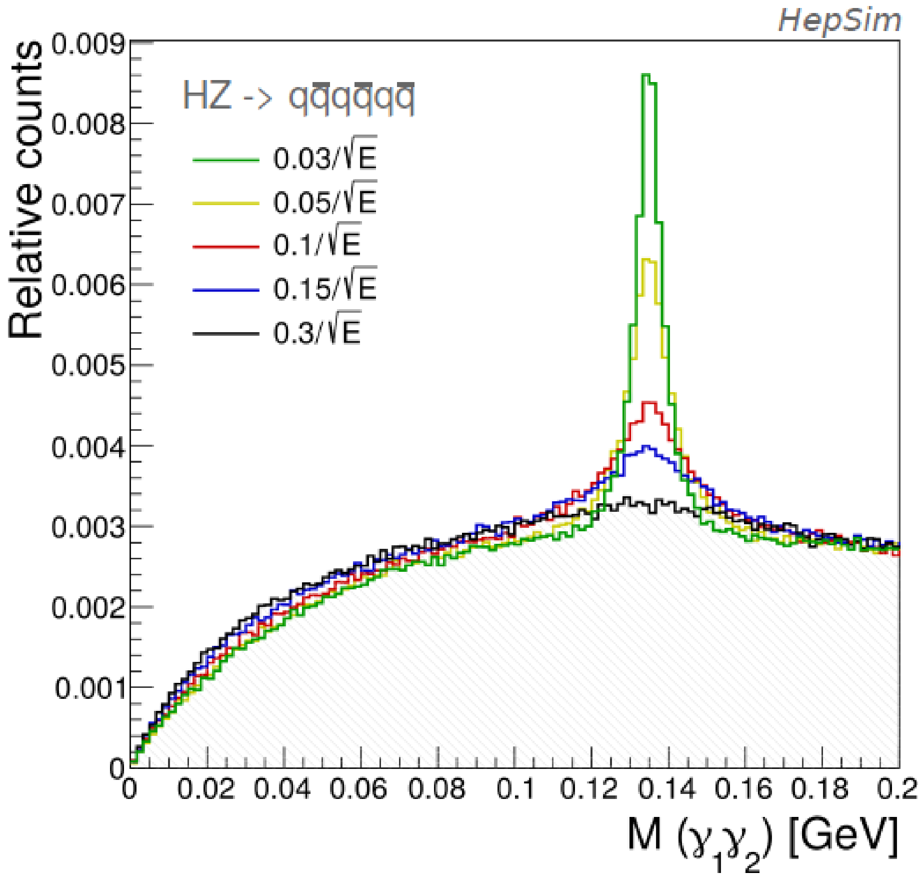


Advantages with a High-resolution EM Calorimeter

- In hadronic showers, π^0 is a significant component of neutral particles. Good EM resolution is critical for the π^0 reconstruction and therefore is important for correctly clustering γ's into the right jets

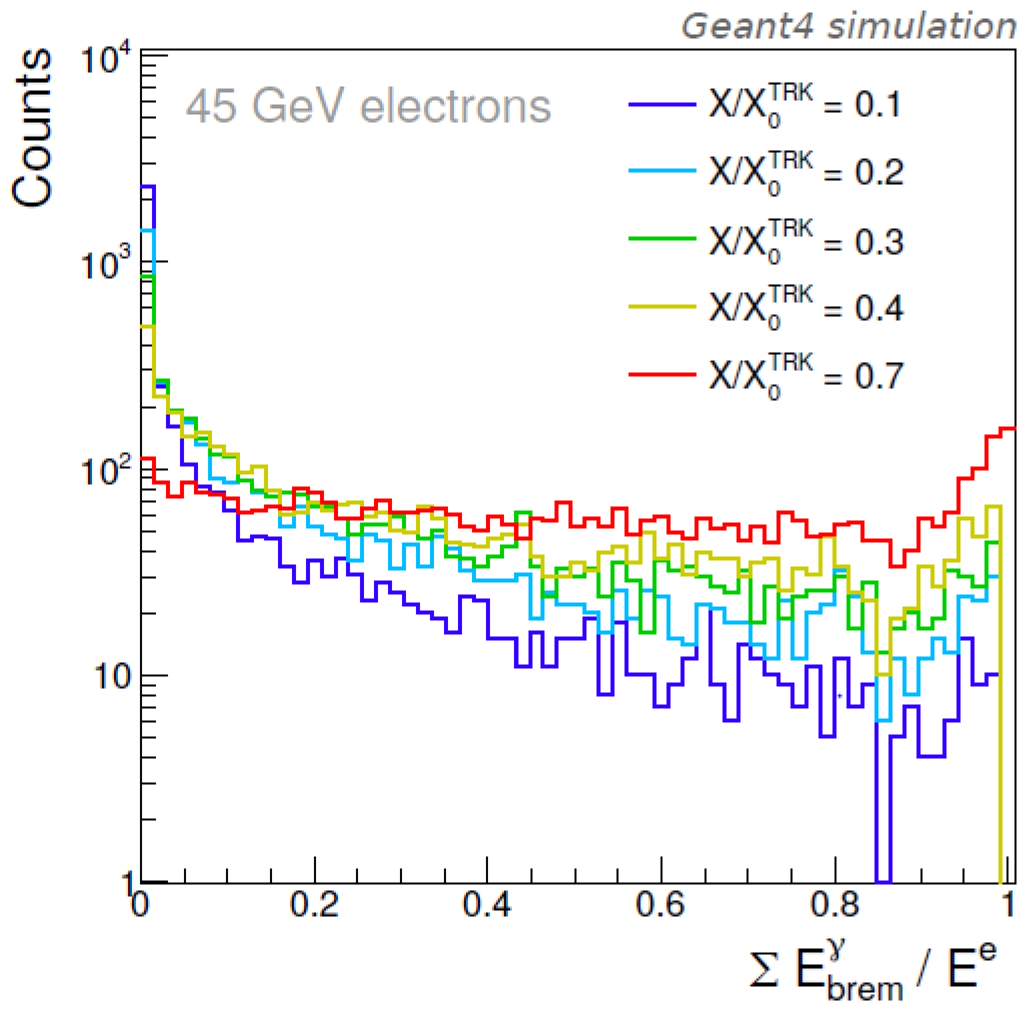


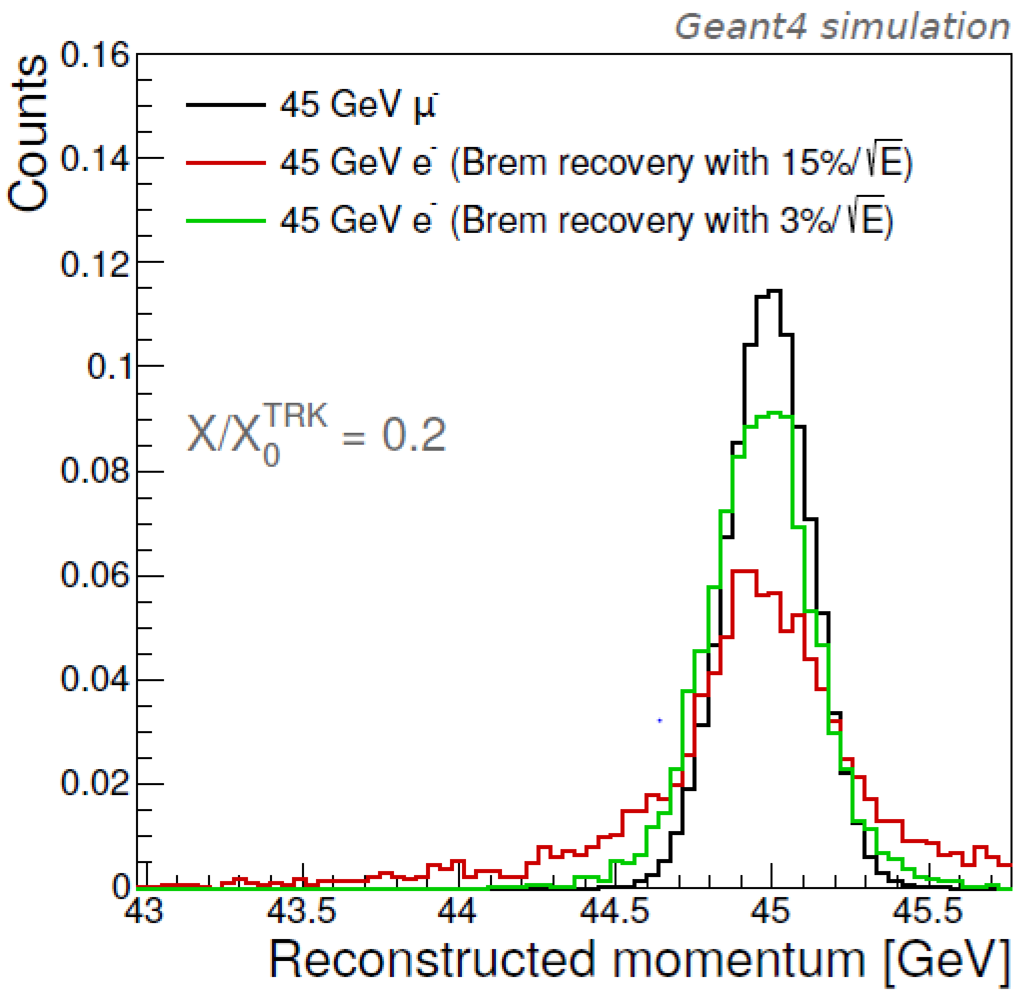




Advantages with a High-resolution EM Calorimeter

- Recovery of photons from bremsstrahlung

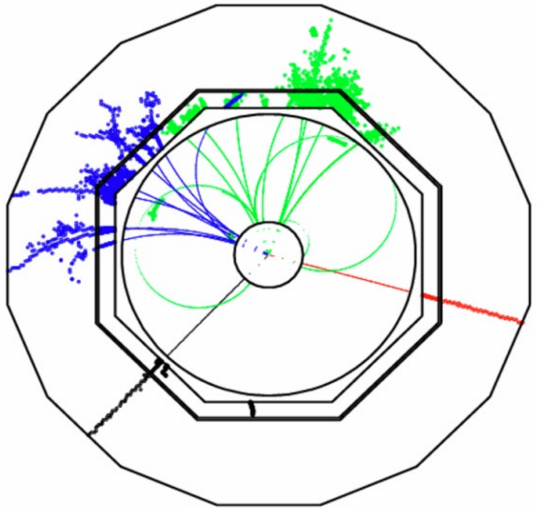


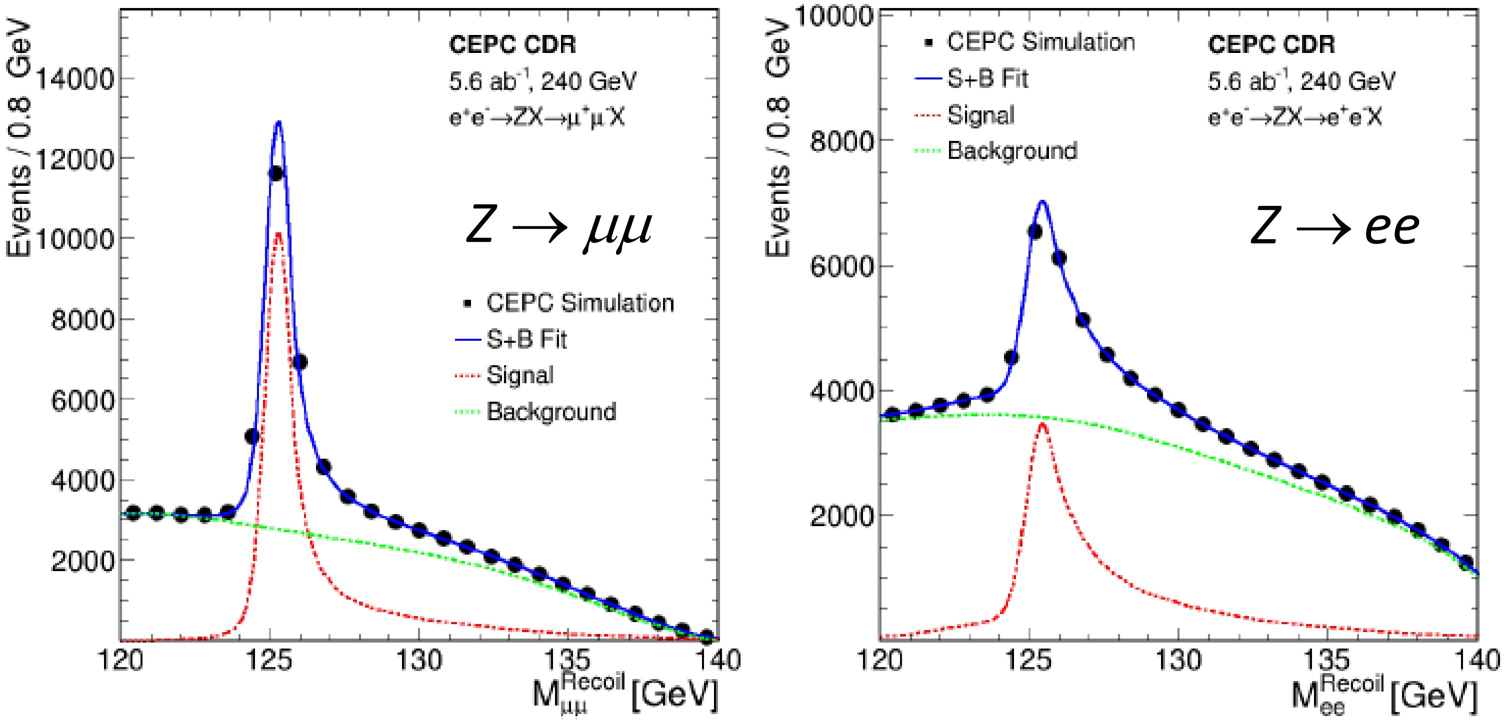


Electrons: tracker measurement + photons

Advantages with a High-resolution EM Calorimeter

- Improve Higgs tagging: the Higgs boson from the $e^+e^- \rightarrow ZH$ process can be identified through the recoil mass of the Z boson → identify the Higgs boson without looking at the Higgs boson





Much worse recoil mass resolution in the Z → ee channel due to bremsstrahlung radiation, need to have good EM resolution for the radiation recovery

Conclusions

- With the advancement in SiPM technologies, a dual-readout segmented ECAL using DRO becomes an attractive option for future Higgs factories
- When combined with the DRO fiber HCAL, the EM energy resolution can be significantly improved (~3%/√E) while the neutral hadron energy resolution is not expected to be adversely affected (~27%/√E)
- Significant R&D effort is needed to demonstrate DRO capability of a segmented crystal ECAL through simulation, cosmic ray and beam tests
- Integration with the IDEA detector concept in the simulation to optimize the design of the crystal ECAL
- The DRO crystal ECAL could also be combined with a high-granularity HCAL
- The CALVISION team plans to carry out of these R&D (if funded)