Combining Dual-Readout Crystals and Fibers in a Hybrid Calorimeter for future e^+e^- Higgs factories

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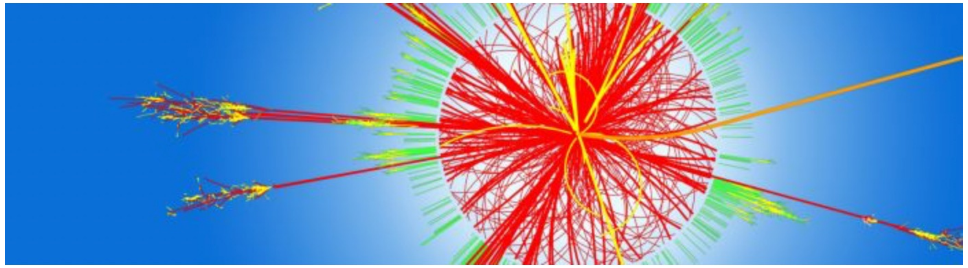

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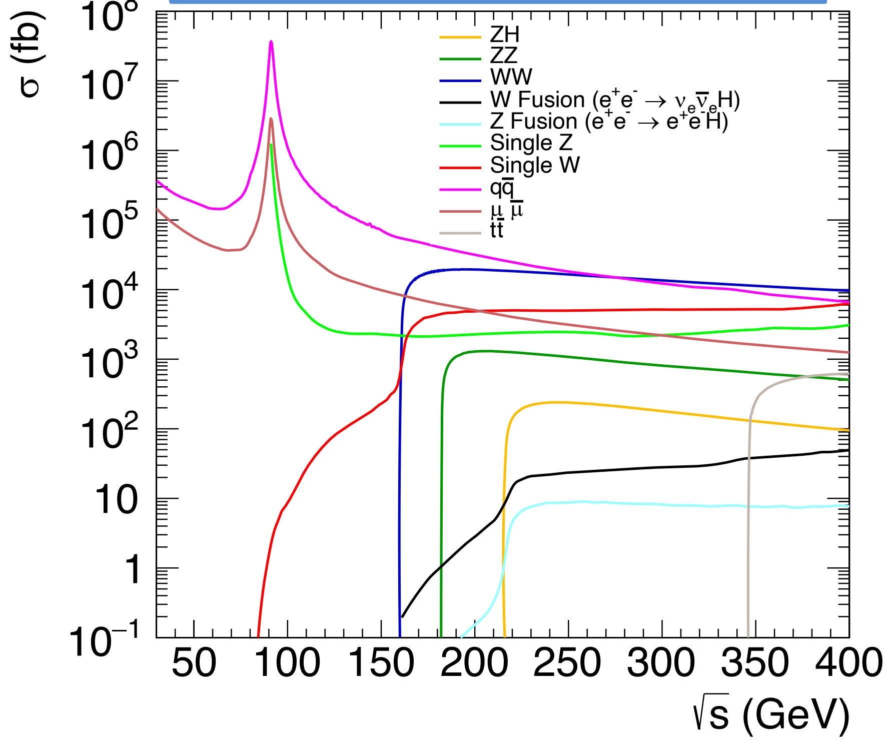
On behalf of the CalVision and IDEA collaborations

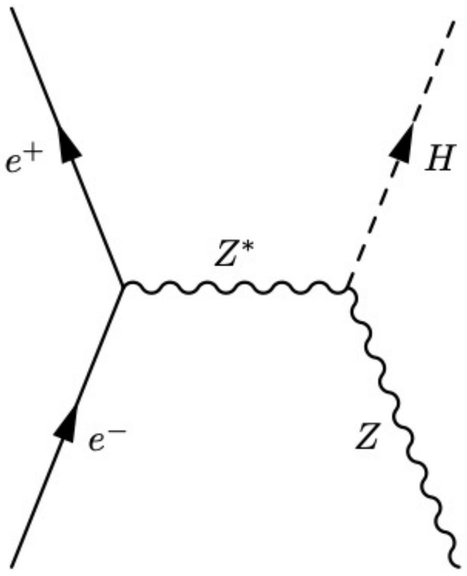
S. Eno, N. Akchurin, A. Belloni, S. Chekanov, M. Demarteau, J. Freeman, P. Harris, R. Hirosky, J. Hirschauer, A. Jung, S. Kunori, Y. Lai, M. Lucchini, S. Magill, H. Newman, J. Qian, C.G. Tully, H. Wenzel, B. Zhou, J. Zhu, R.-Y. Zhu

Motivation

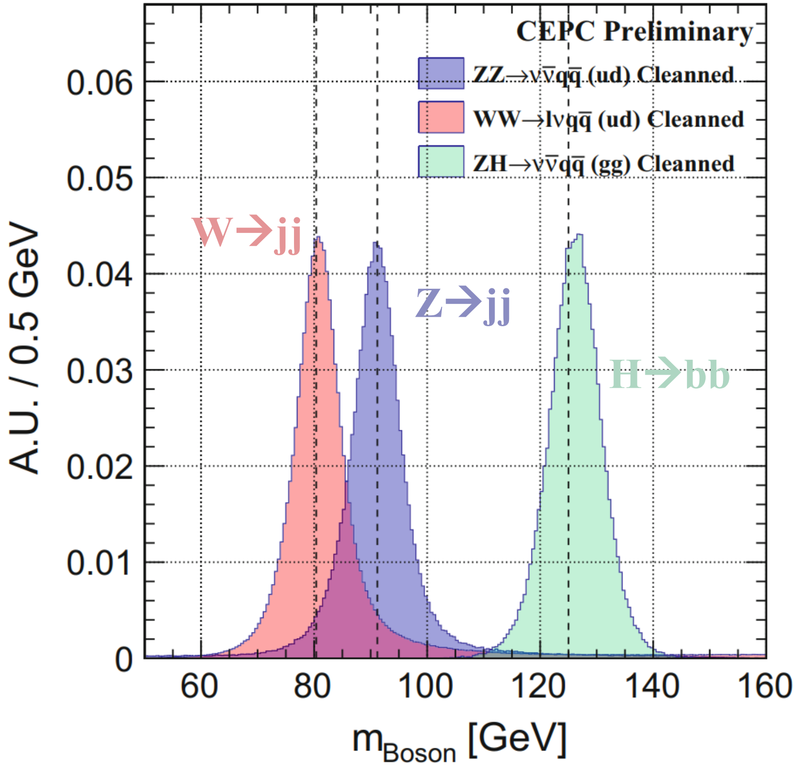
- Jet energy resolution is a key benchmark of the e^+e^- detector performance because 97% of the SM Higgsstrahlung signal has jets in the final states
- A critical metric is how well the hadronically-decayed W/Z bosons can be separated
  - 3~4% jet energy resolution ~100GeV gives decent W/Z separation ~2.5 σ
- Very hard to achieve with a traditional approach to calorimetry

Cross sections for various processes in e^+e^- collisions



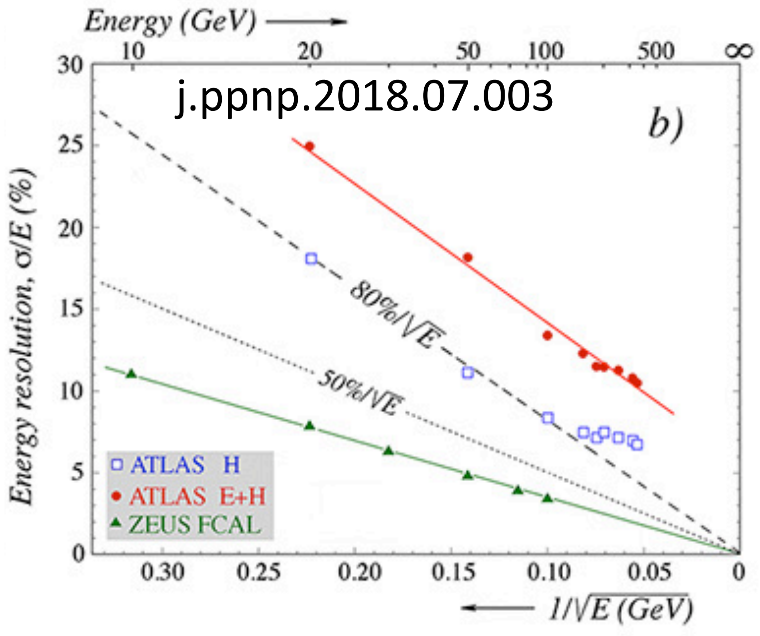


EPJC (2018) 78:426

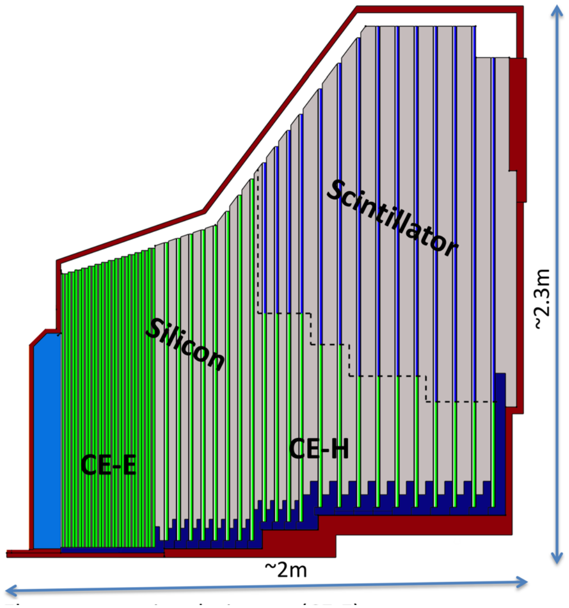


Motivation

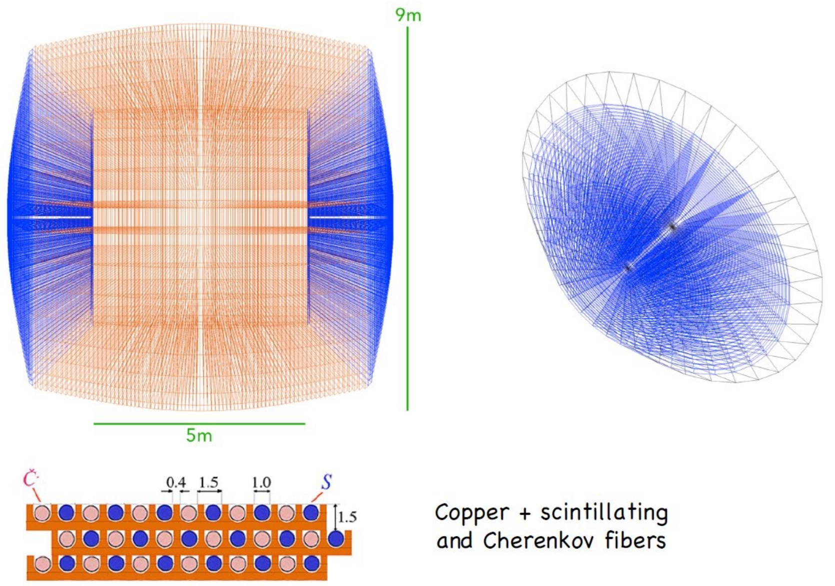
- A typical HCAL resolution of σ_{HAD}/E >50%/√E
- Two different but complementary approaches:
  - Particle Flow Algorithm (PFA) oriented, using High granularity calorimeter (HGC)
  - Dual Readout (DRO) calorimeter, improve the resolution by additional information from Cherenkov light and identify the EM fraction



ZEUS: 35%/√E



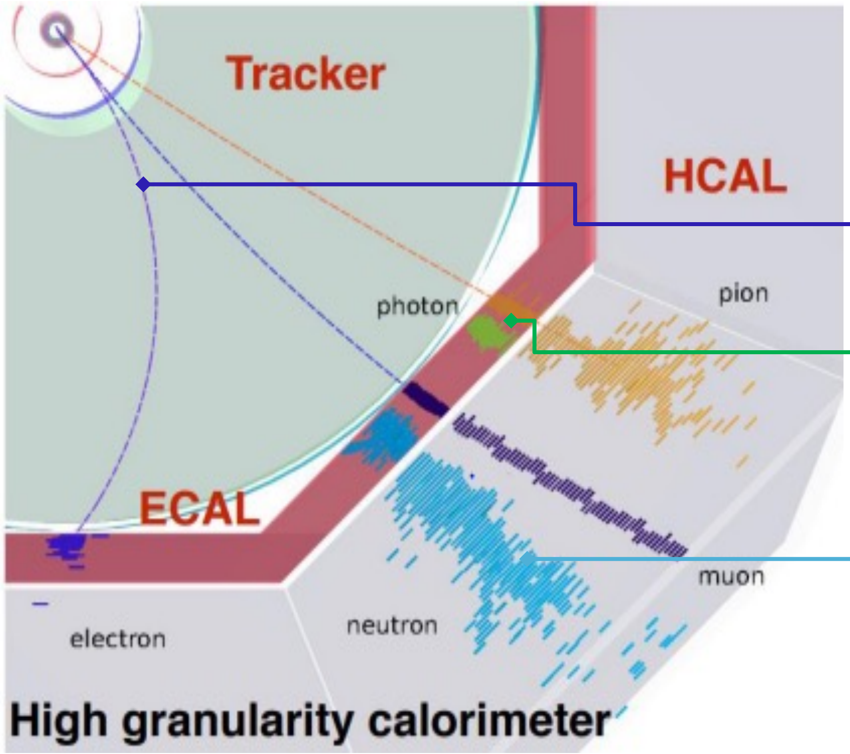
CMS High granularity calorimeter



Sketch of the IDEA calorimeter (left) and endcap geometry (right)

High Granularity Calorimetry

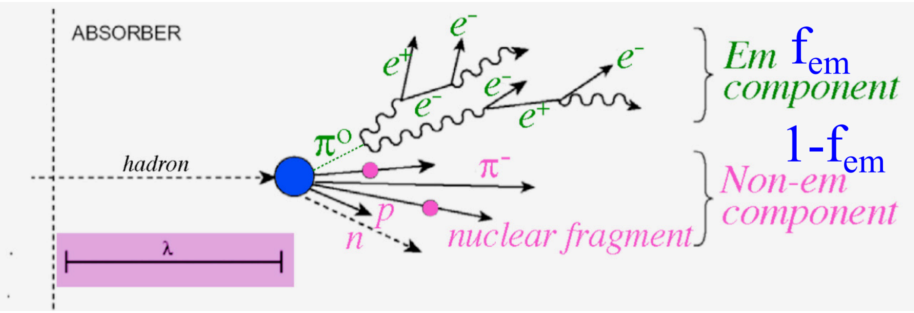
- HGCAL achieve excellent jet resolution by the tracker and shower pattern recognition
- Each individual particle in shower is reconstructed and identified with the subdetector providing the best energy resolution for that particle type
- Calorimeter resolution requirements not that stringent. EM ~ 15%/√E and HAD ~ 55%/√E

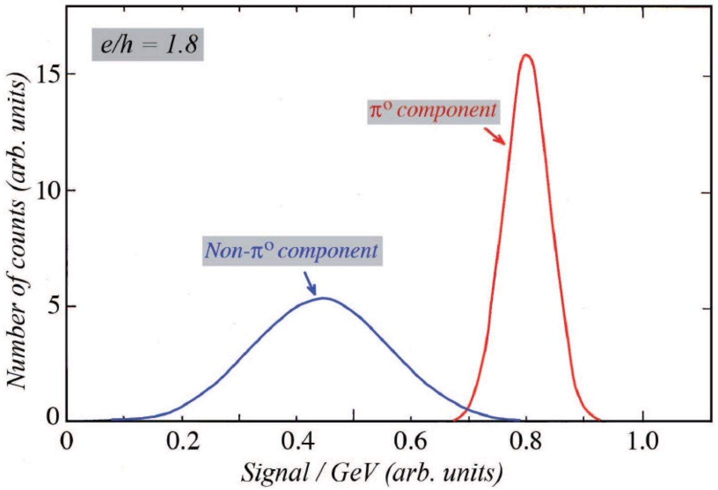


Particles	Energy fraction	Subdetector	Typical resolution
Charged particles	~65%	Tracker	$<5\times10^{-5}p_T$
Photons	~25%	ECAL	~15%/√E
Neutral hadrons	~10%	ECAL+HCAL	~55%/√E

Dual Readout Calorimetry

- Read out both scintillation and Cherenkov photons to measure the EM fraction (f_{em}) event-by-event, allowing for the corrections for different EM and hadronic responses
  - Scintillation (S) – sensitive to dE/dX energy loss ⇒ charged particles
  - Cherenkov (C) – only produced by relativistic particles, dominated by EM component





f_{em} fluctuations dominate the hadronic energy resolution

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

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

E: Total energy
h/e: Calo response to HAD/EM

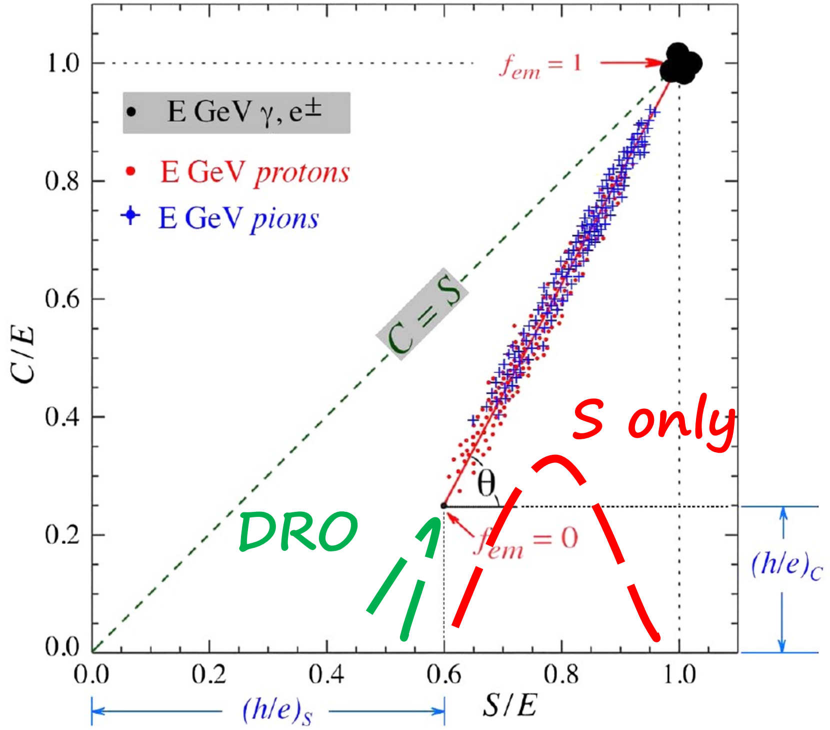
⇩

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

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

$$E = \frac{S - \chi C}{1 - \chi}$$

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



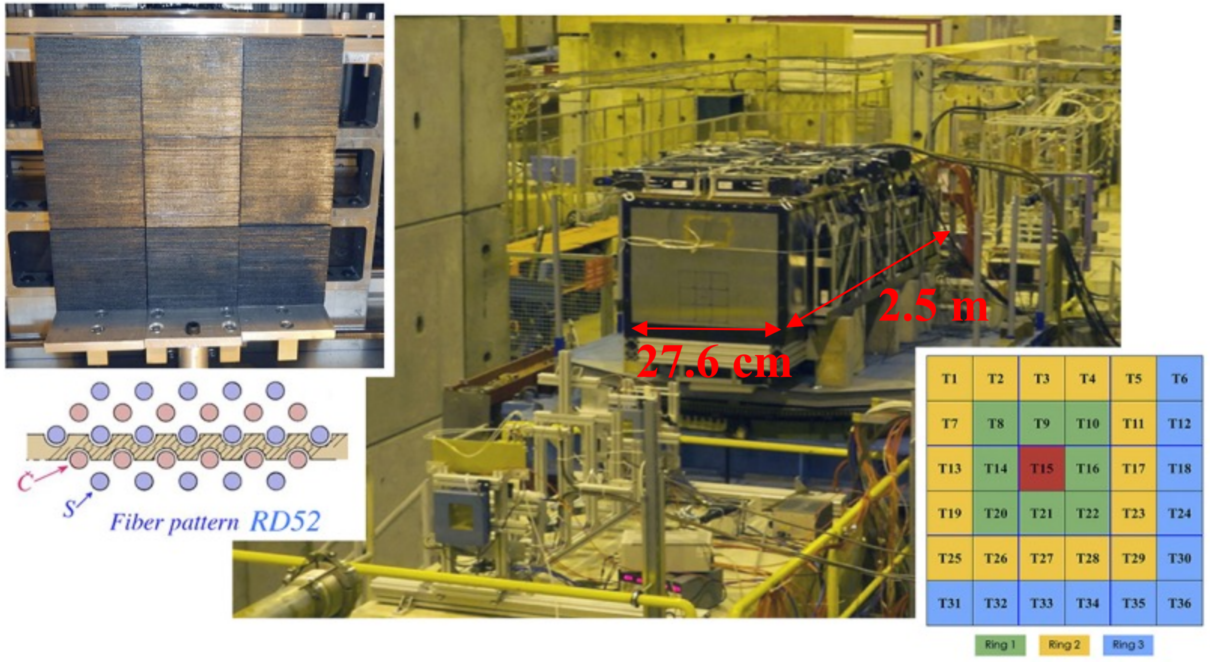
DRO calorimetry relies on the fact that h/e is different for Cherenkov and Scintillation readout

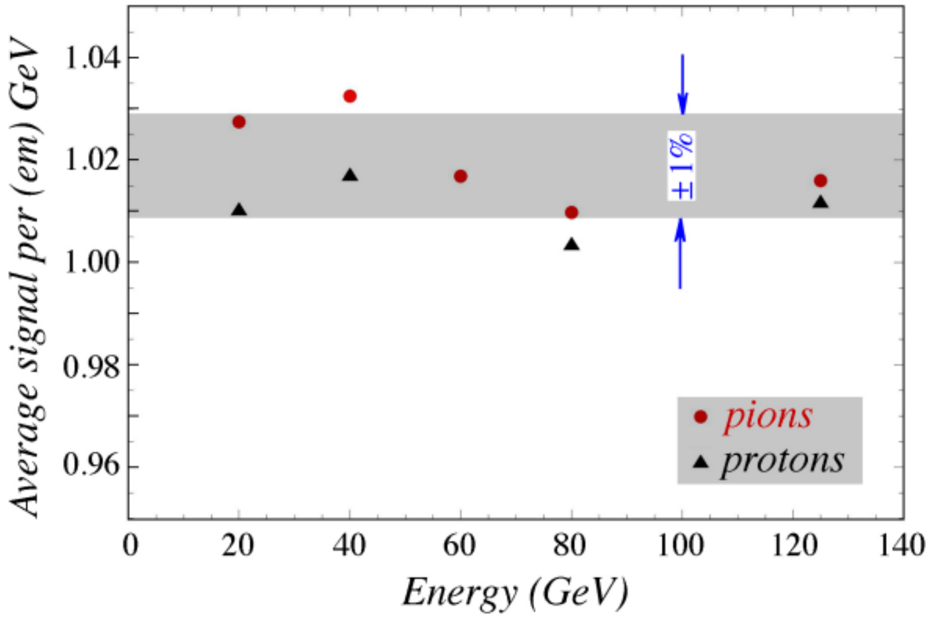
χ is independent of the incident hadron's energy

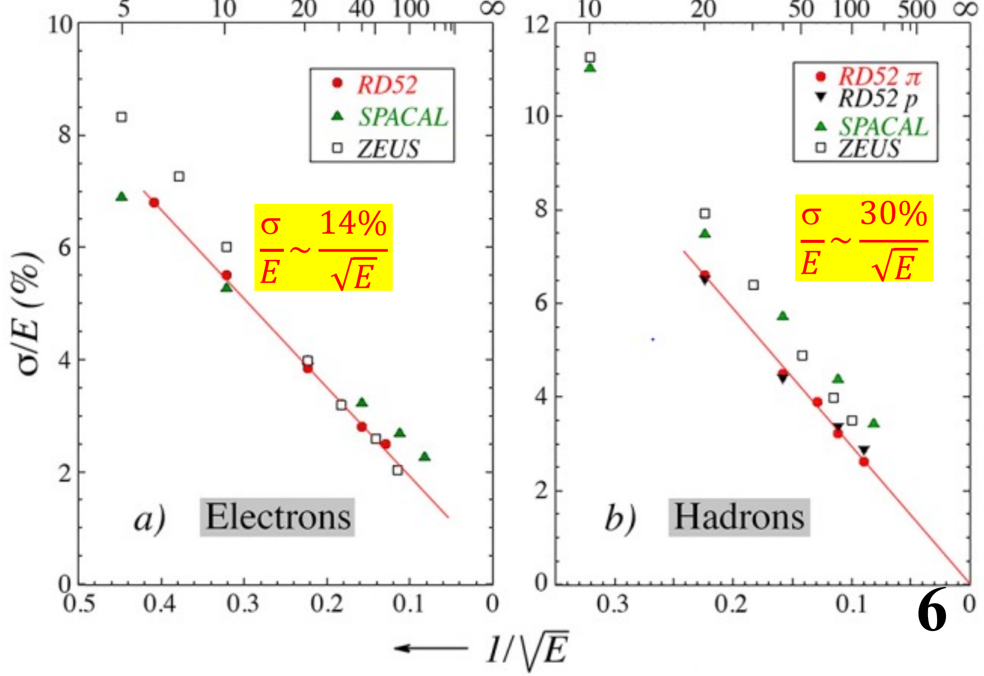
Dual Readout Calorimetry

- Extensive R&D by the DREAM/RD52/IDEA collaborations (Rev. Mod. Phys. Vol 90, April 2018):
  - Sampling calorimeter with lead or copper absorber
  - Clear plastic fibers and scintillation fibers for C/S readout
- Linearity and HAD energy resolution are excellent. While the EM resolution is good enough to achieve the W/Z separation goal, could it be better ?

Lead absorber, 9 modules with ~36k fibers

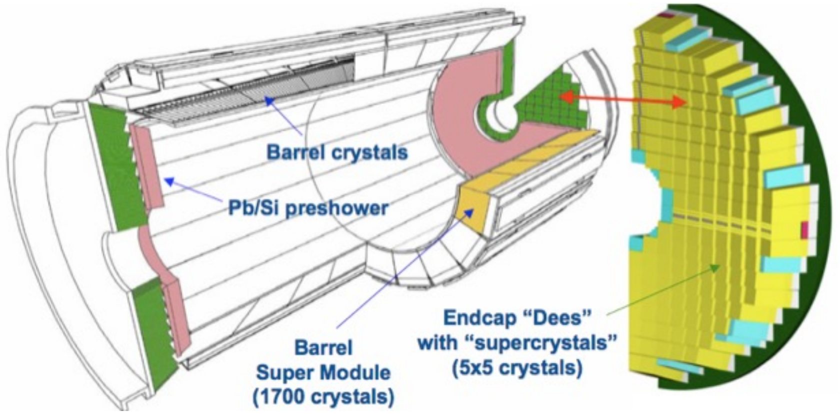




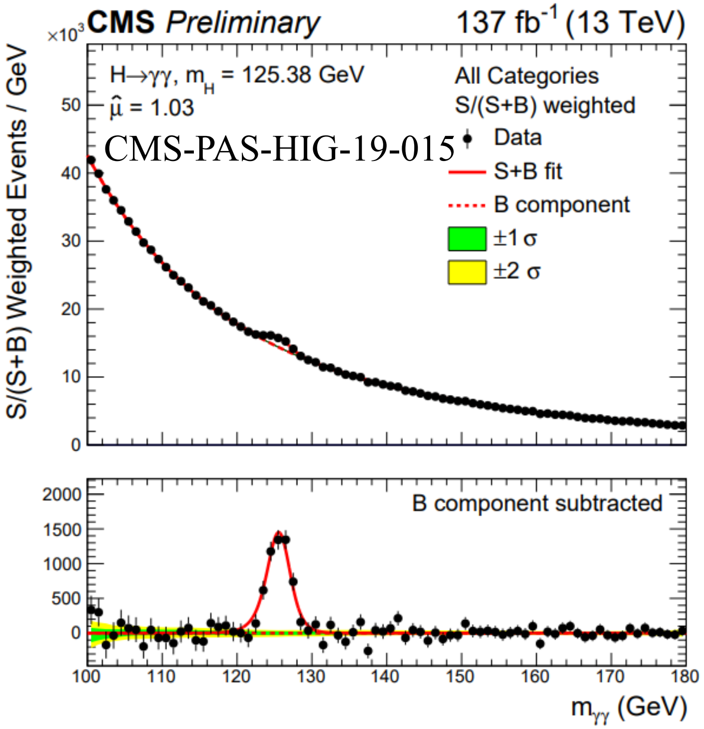


Crystal Calorimeters

- Crystal calorimeters are homogeneous detector, have **excellent EM energy resolutions, ~3%/√E or better**
- Traditional crystal calorimeters suffer from large non-uniform e/h responses so the HAD energy resolution and linearity are not good

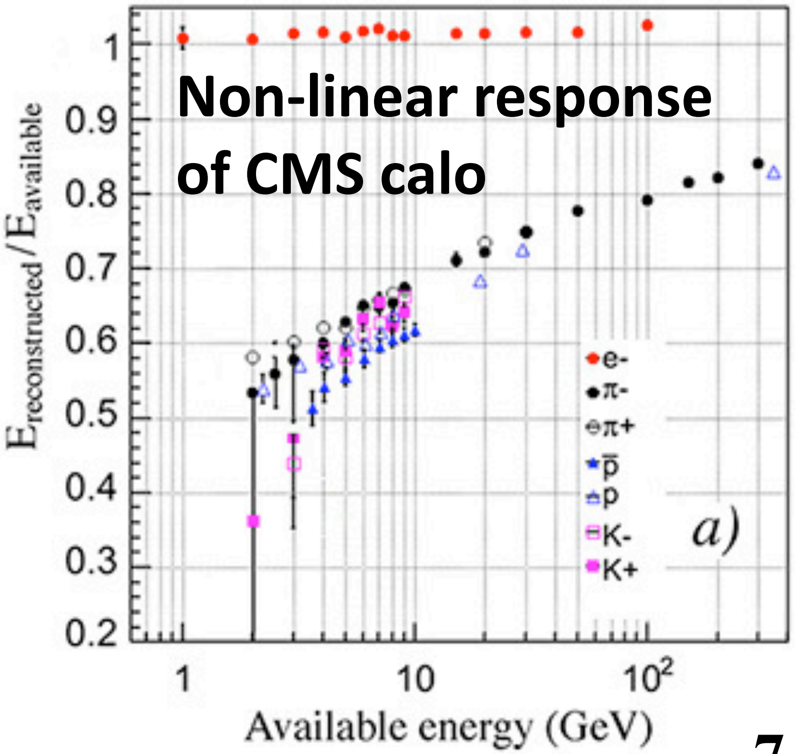


CMS barrel ECAL



CMS-PAS-HIG-19-015

Eur. Phys. J. C (2009) 60: 359–373

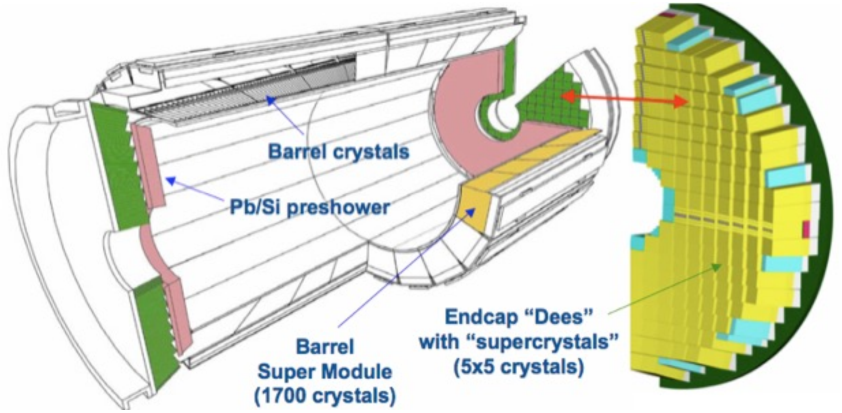


Non-linear response of CMS calo

Combine strengths from several calorimeter concepts

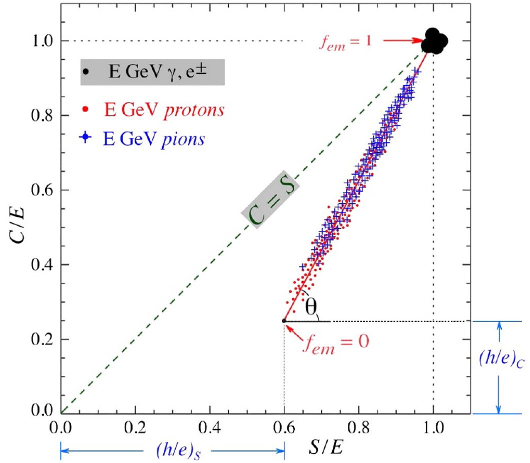
- Can we combine the strengths of a crystal ECAL with that of a DRO calorimeter?

Crystal Calorimeter



Excellent EM energy resolutions

DRO Calorimeter



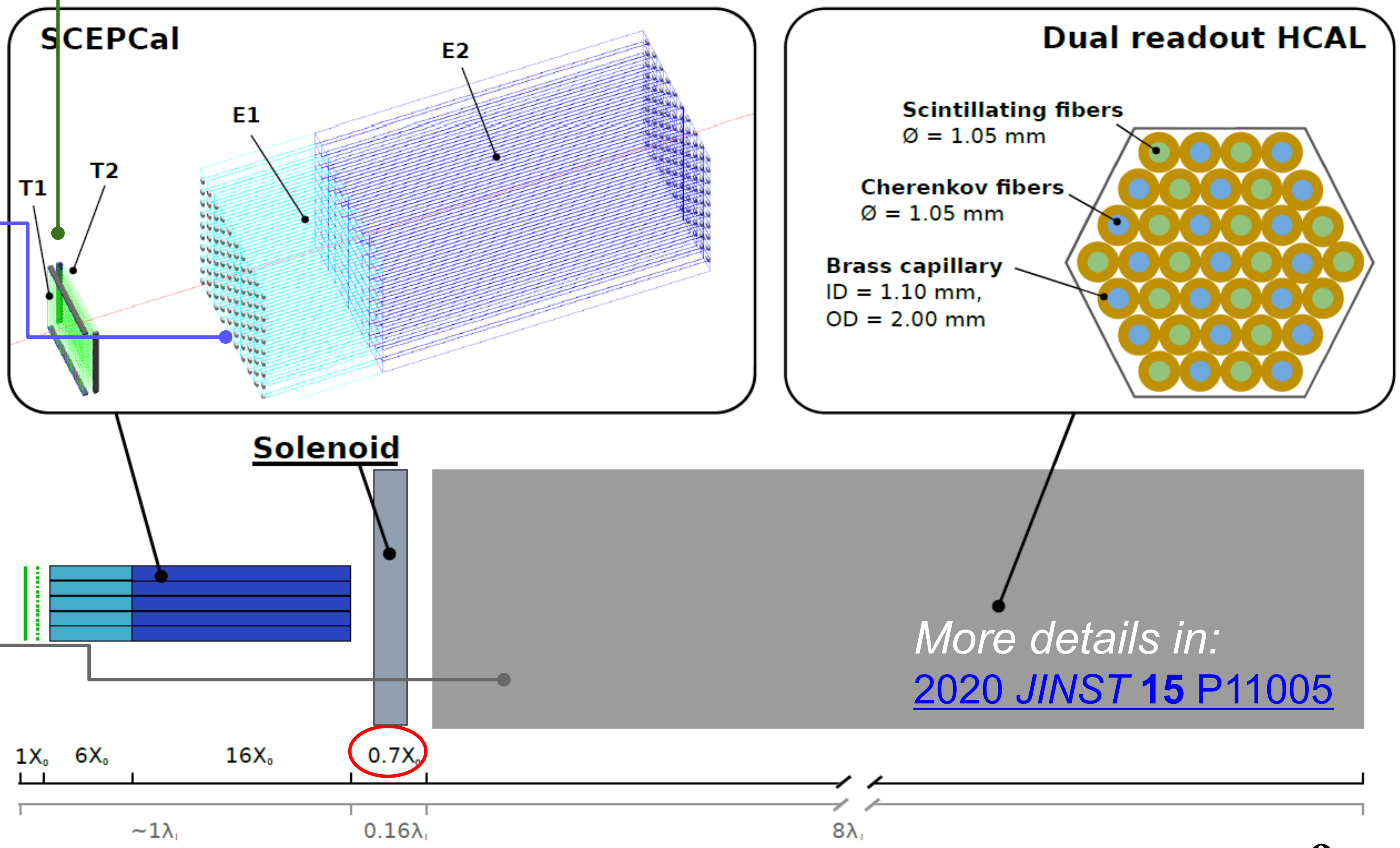
Excellent Linearity and HAD energy resolution

=> DRO crystal ECAL?

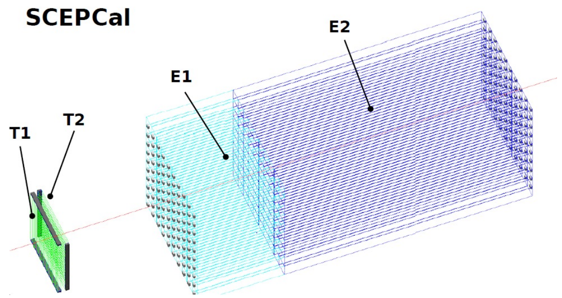
- Can a DRO crystal ECAL be combined with a DRO HCAL to have excellent energy resolution for both EM particles and hadrons?

A Segmented DRO Crystal ECAL with a DRO Fiber HCAL

- **Two Timing layers**
  - $\sigma_t \sim 20$ ps
  - LYSO:Ce scintillating crystals (~1 X_0)
  - $3\times3\times60$ mm^3 thin crystal bar
  - 3×3 mm^2 SiPM (15-20 µm cell size)
- **Two ECAL layers**
  - $\sigma_{EM}/E \sim 3\%/\sqrt{E}$
  - $PbWO_4$ crystals
  - Crystal cross-section: 10×10 mm^2
  - 5×5 mm^2 SiPM (10-15 µm cell size)
- **Ultra-thin IDEA solenoid**
  - ~ $0.7X_0$
- **HCAL layer**
  - $\sigma_{HAD}/E \sim 26\%/\sqrt{E}$
  - Scintillating and "clear" PMMA fibers inserted inside brass capillaries

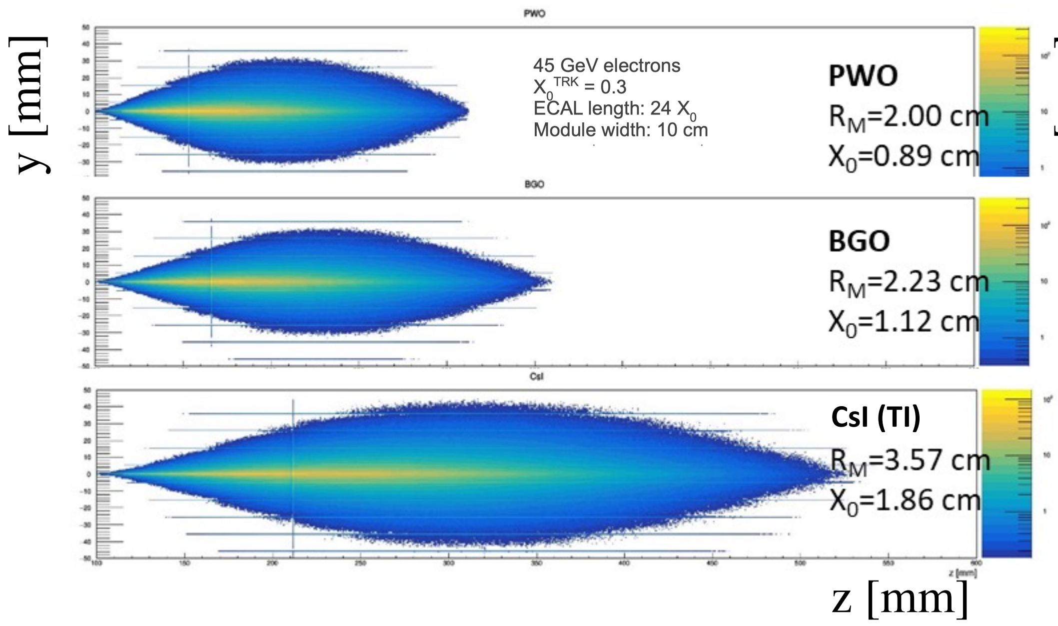


Segmented ECAL

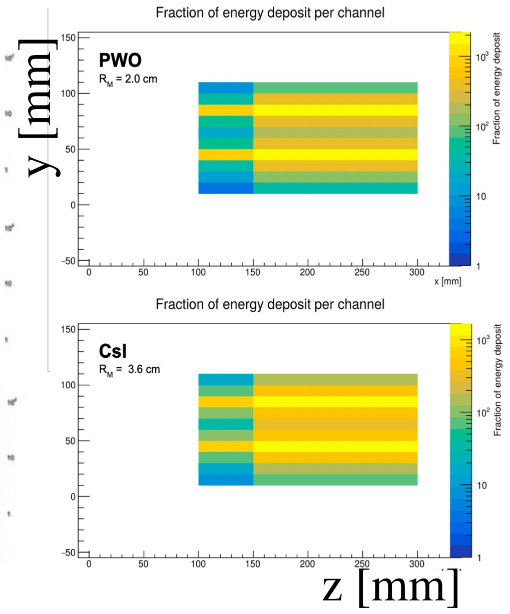


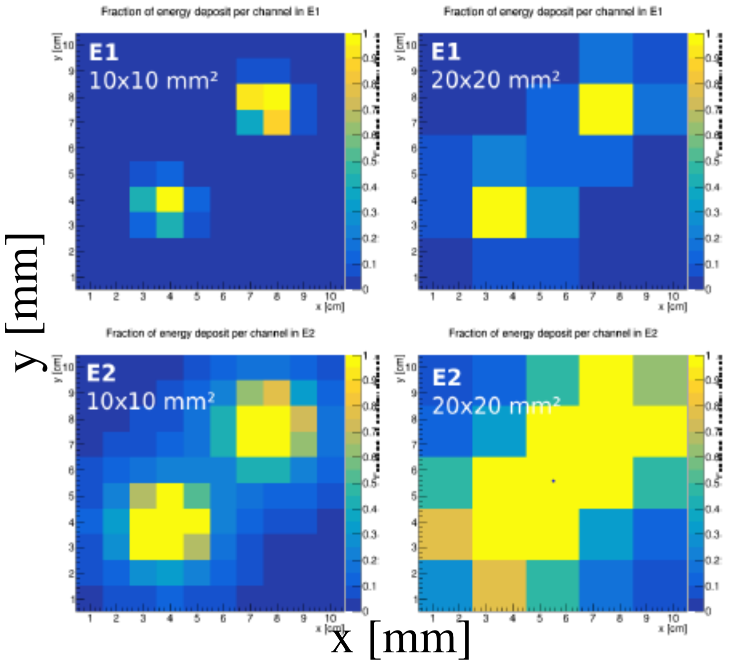
- Two layers with $PbWO_4$ crystals (high density, short radiation length, small Moliere radius, fast signal, reasonable C/S ratio (~30%), cost effective, relatively low light yield)
- Transverse and longitudinal segmentations beneficial to particle identification and particle flow algorithms
- BGO and BSO are also good candidates

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 (Tl)	4.5	1.86	39.3	3.57	550	1220	1.79



Longitudinal profile

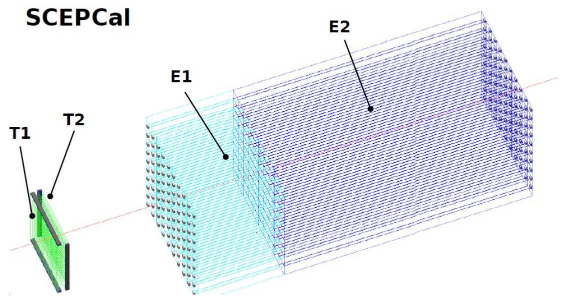




Reconstruction of two photons emitted with an angle of 3 degrees

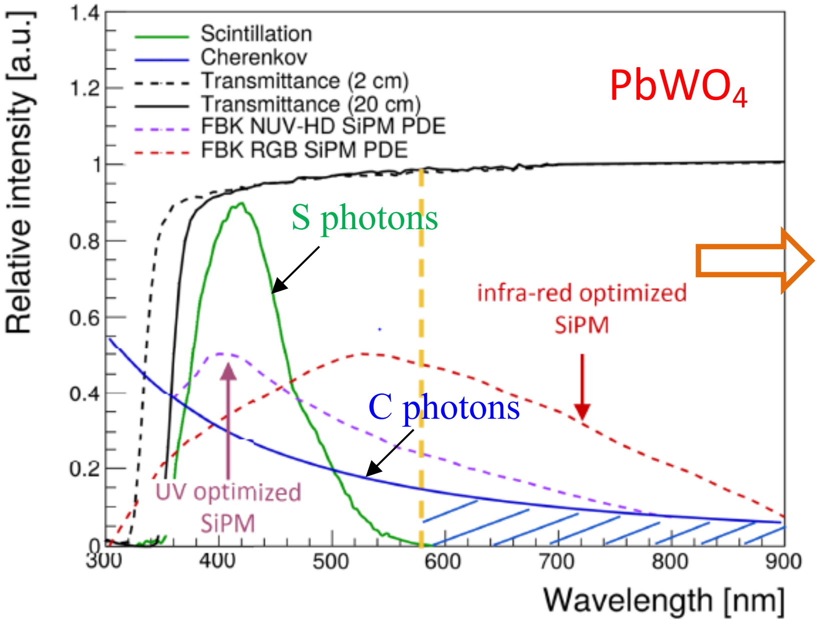
Segmented ECAL

- 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 Cherenkov light
- Different crystals require different optimization strategy for S and C detection

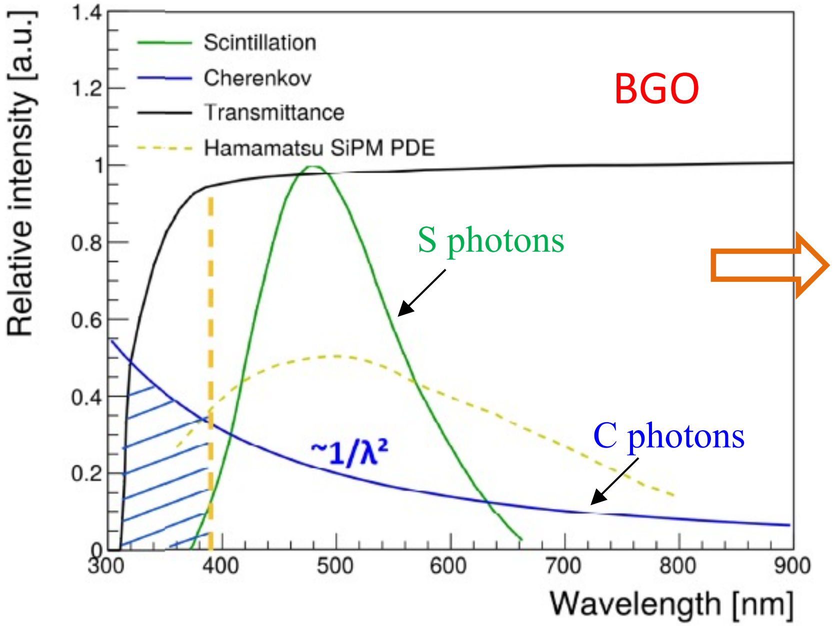


$PbWO_4$	Scintillation [photons/GeV]	f_S [%]	Cherenkov [photons/GeV]	f_C [%]
Generated	200000	100	56000	100
Collected	10000	5.0	2130	3.8
Detected by NUV SiPM #1 ($\lambda < 550$ nm)	2000	1.0	140	0.25
Detected by RGB SiPM #2 ($\lambda > 550$ nm)	< 20	< 0.01	160	0.3

~50 C photons/GeV is enough to achieve 3% energy resolution



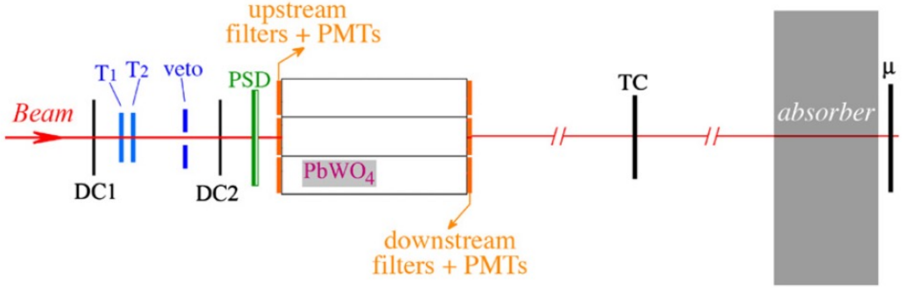
Cherenkov photons above the scintillation peak are much less affected by self-absorption

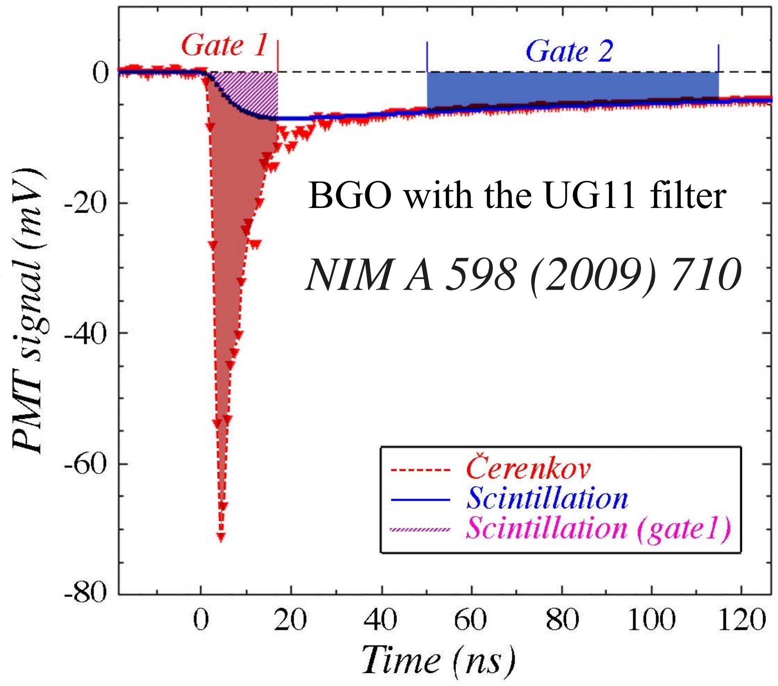


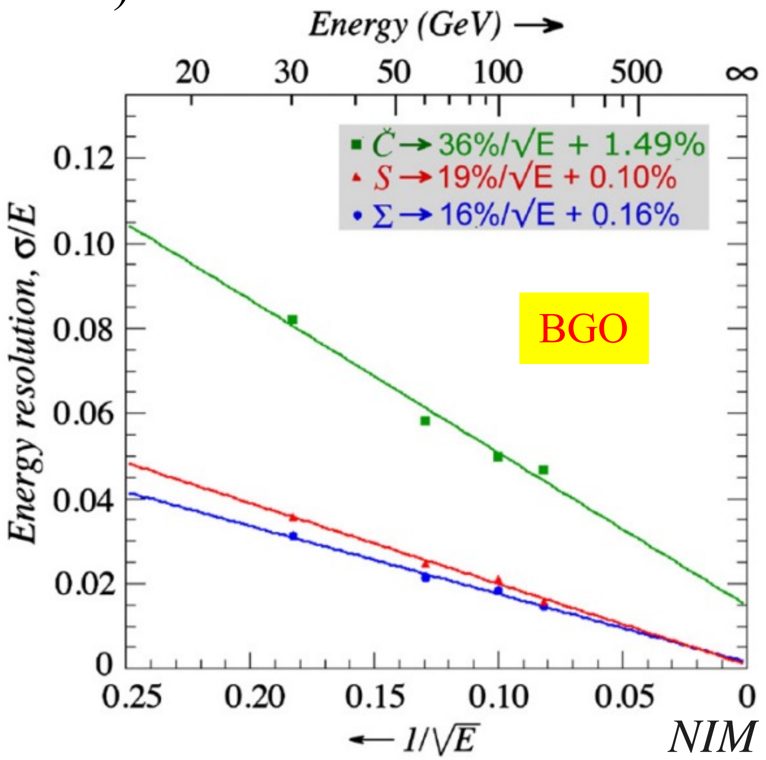
Larger detection window for Cherenkov photons below the scintillation peak

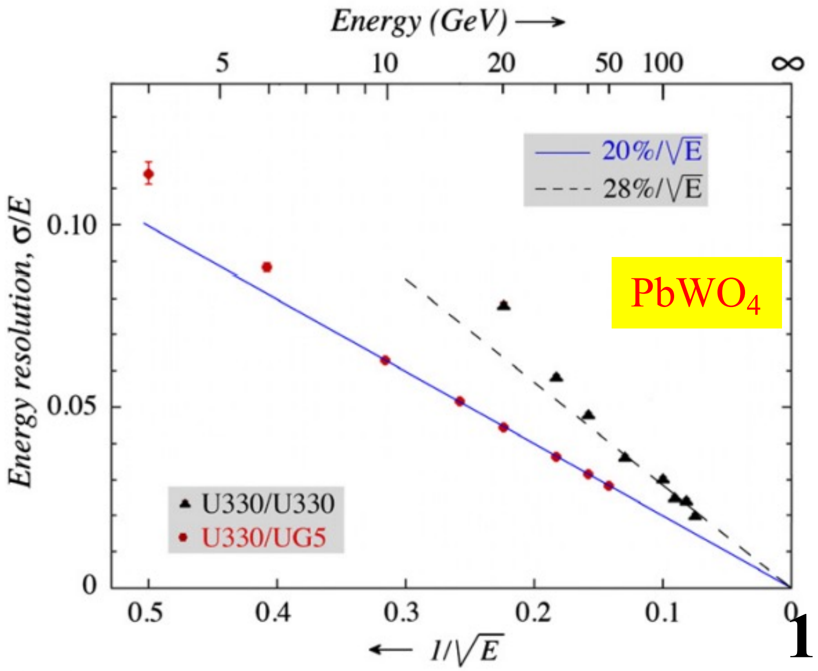
Previous DREAM/RD52 Work on the DRO Crystal Calorimeter

- DREAM/RD52 has investigated DRO of crystals with PMTs to separate C and S signals with the following properties:
  - Optical spectra
  - Time structure
  - Angular distribution
  - Polarization
- Worse electron energy resolution compared to 3%/√E
- Resolution dominated by limited statistics for # of photons detected (only a small fraction of C and S photons are selected)









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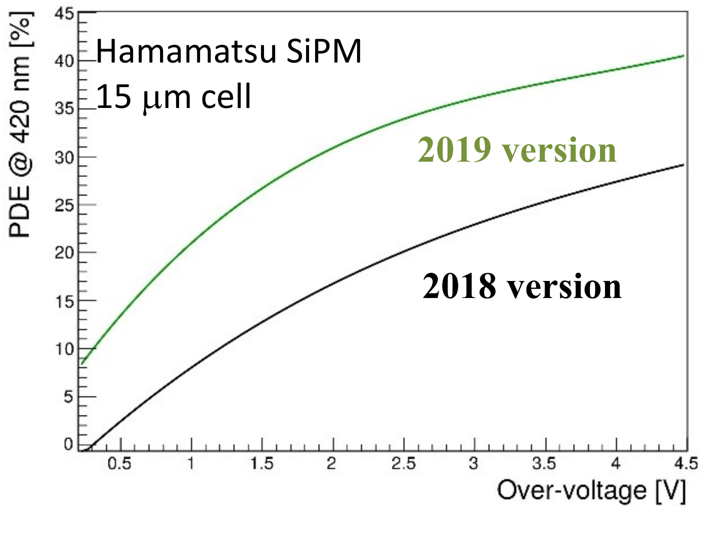
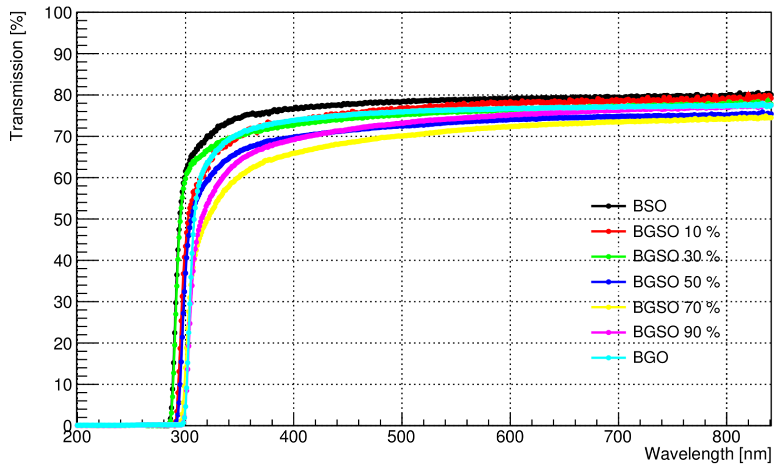
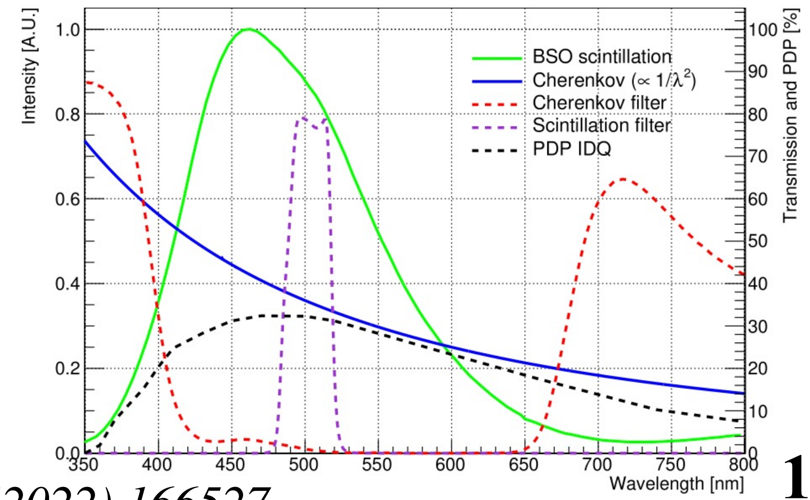
Previous DREAM/RD52 Work on the DRO Crystal Calorimeter

- A proof of principle that combined DR crystal ECAL and fiber HCAL can hold both good EM and HAD resolutions
- Not pursued further by the DREAM/RD52 collaboration for various reasons:
  - Cost with PMT readout (SiPMs were not well developed at that time)
  - Limited wavelength sensitivity for PMT, did not go much below or above the scintillation region
  - DRO fiber calorimeter achieved a respectable EM resolution ~ 10%/√E
- Advancements in photodetector field could overcome limitation on DRO crystals (Higher PDE, compact size, sensitivity to a broad range of wavelengths)!
- Development of crystal material, e.g. using mixed crystals to tune the scintillating properties
- New optical filters enable separating the Cherenkov and scintillation light efficiently, or use nanoparticle to enhance the UV detection







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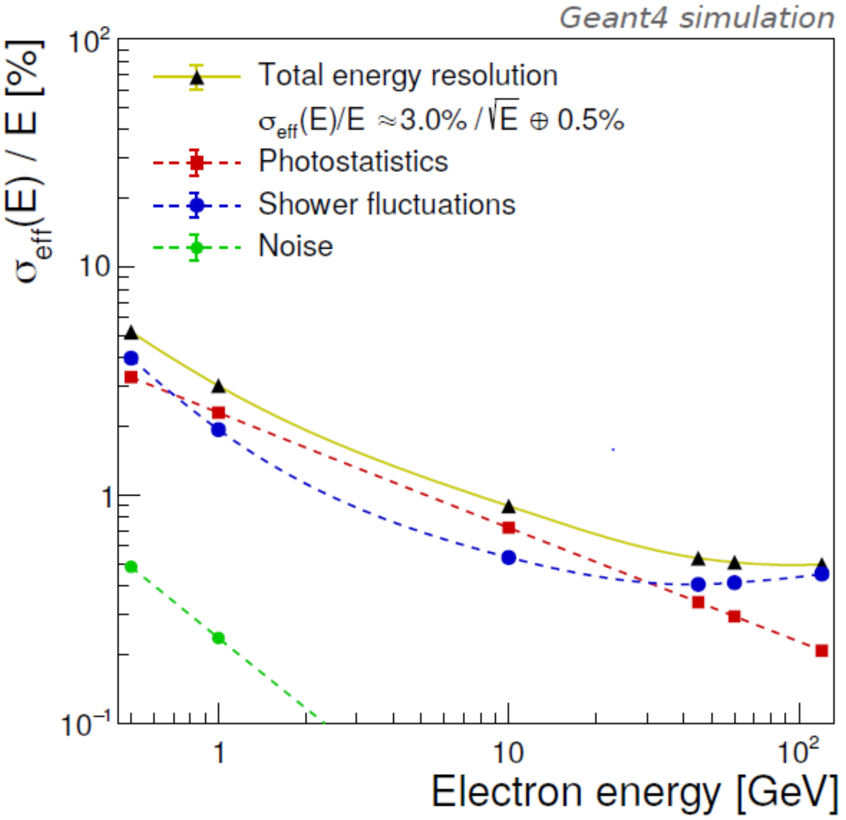
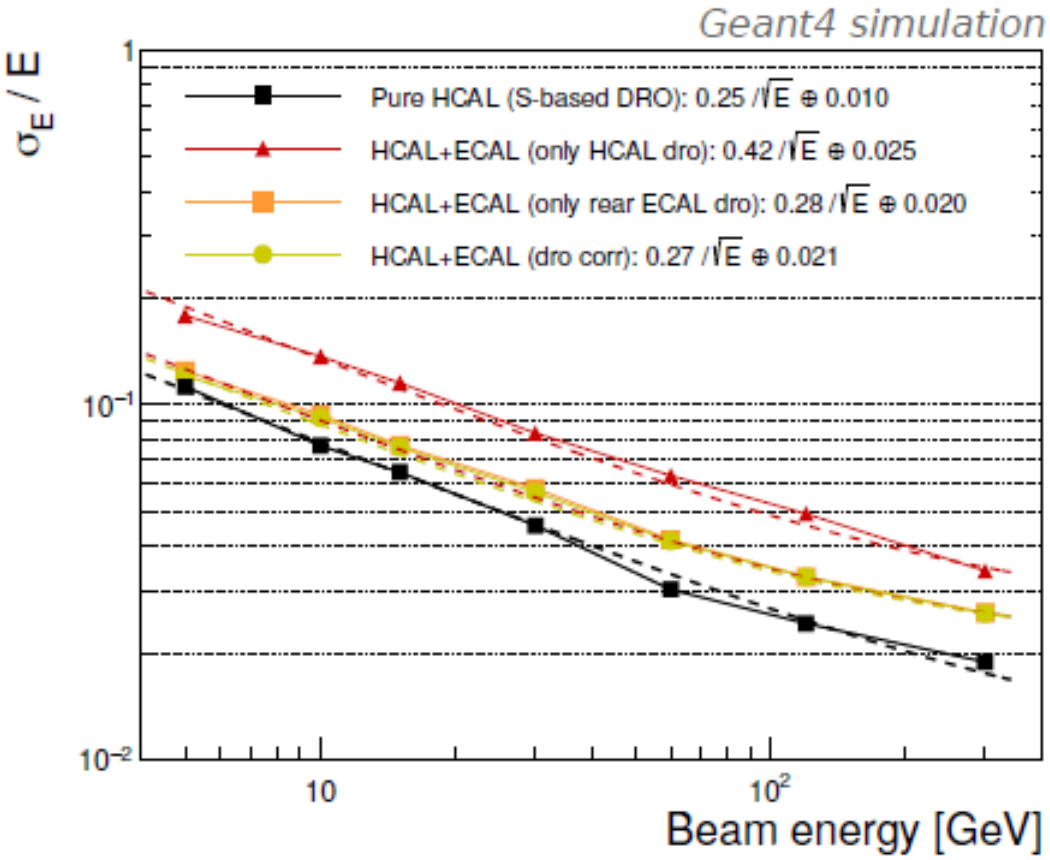
Energy Resolution

- Great EM and HAD resolution, 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
- Can we apply PFA to this hybrid calorimeter and further improve the resolution?

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



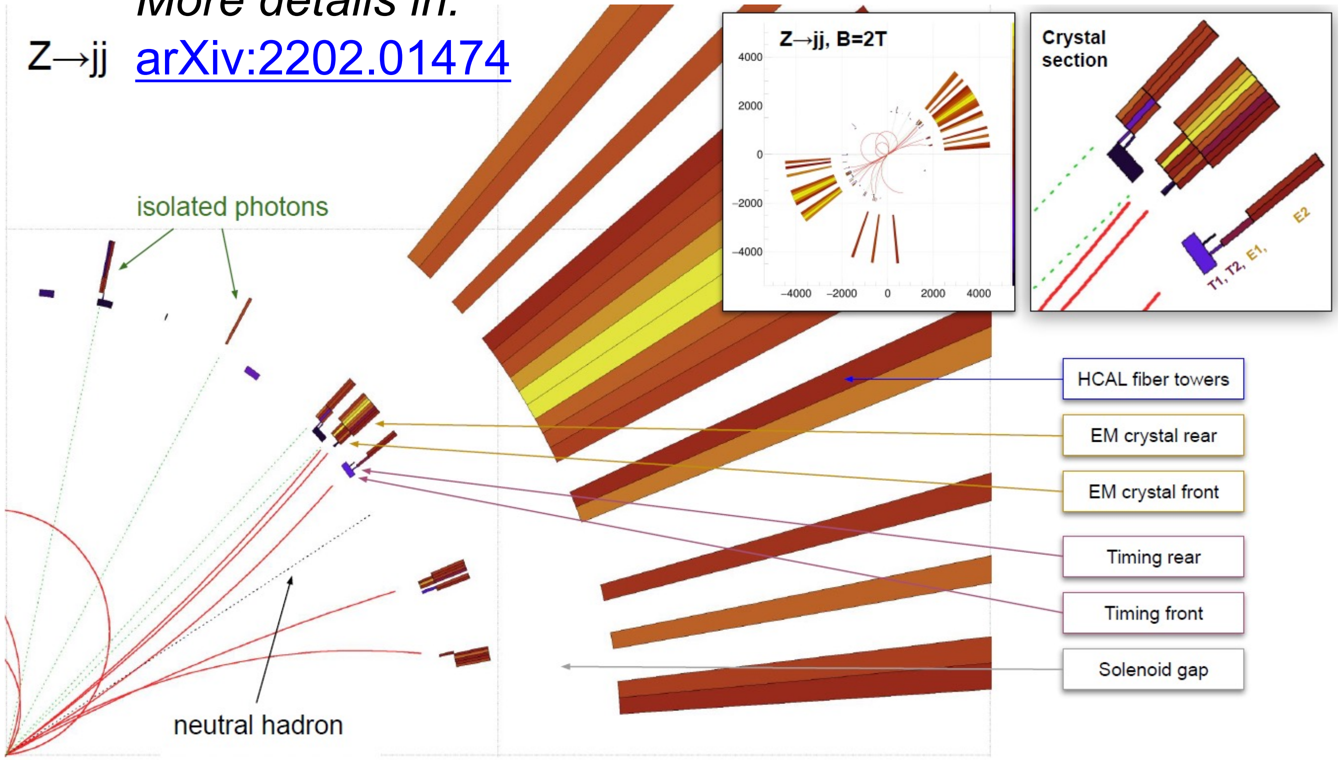
HAD: $\sigma_E/E \sim 27\%/\sqrt{E} \oplus 2\%$

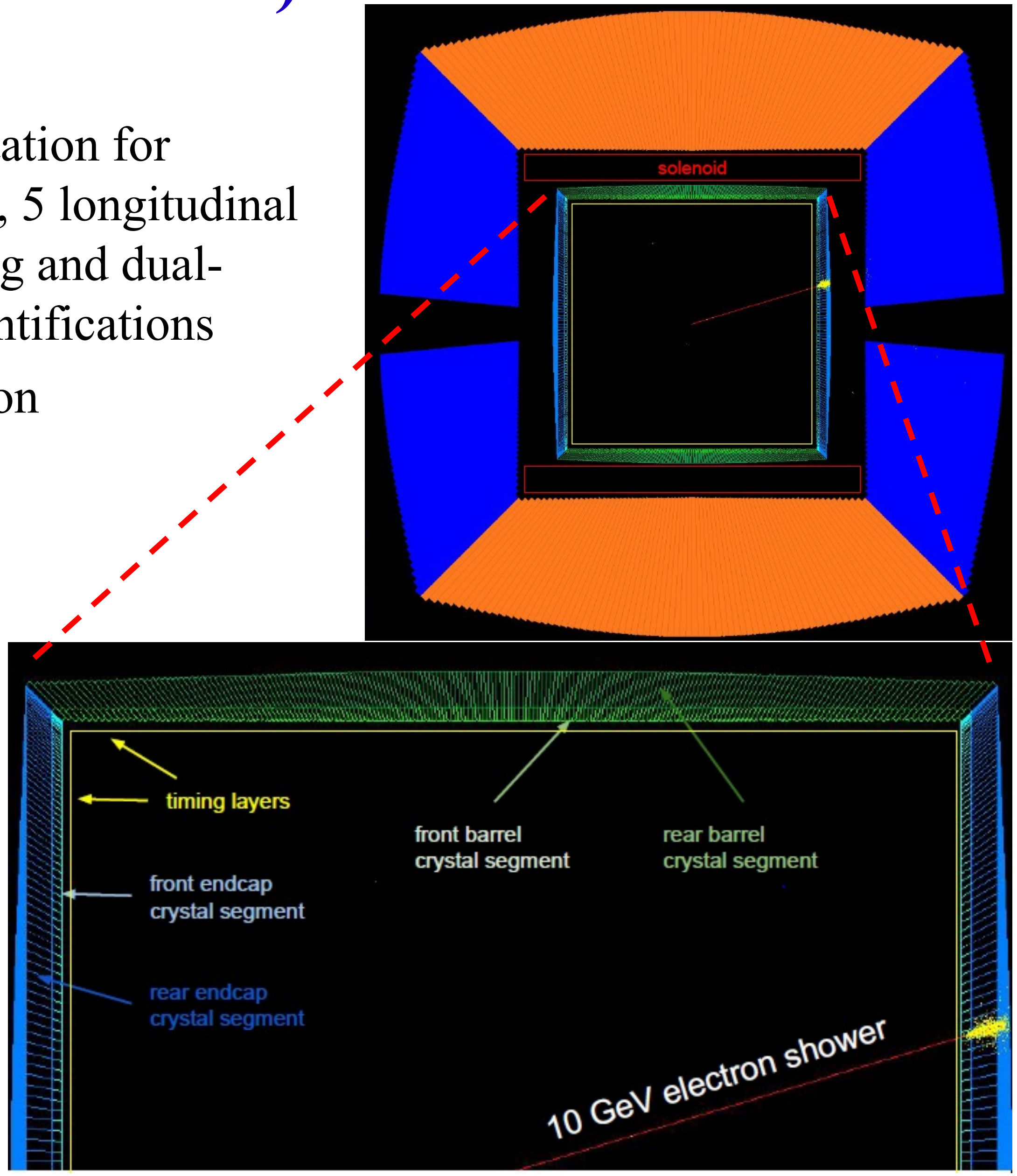


Dual-Readout Particle Flow Algorithm (DR-PFA)

- The segmented 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
- Integration of crystal calo option in 4π Geant4 IDEA simulation

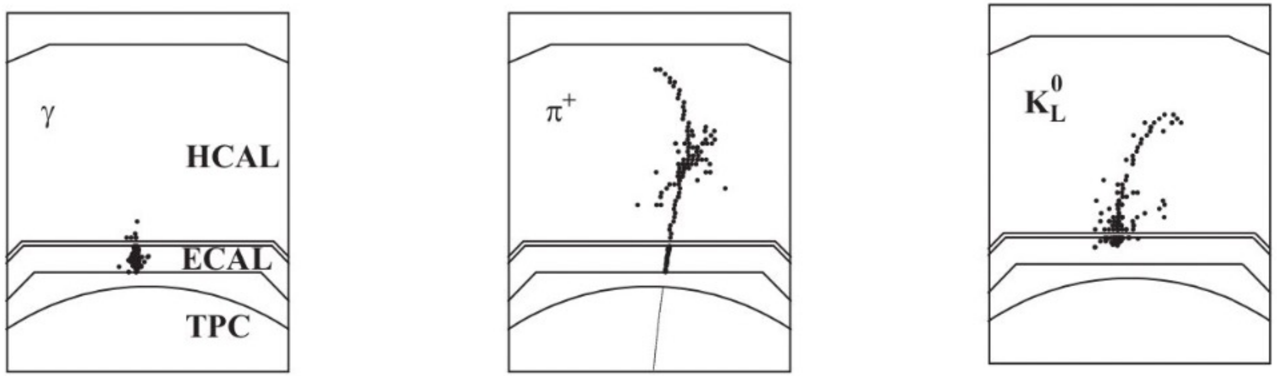
More details in: arXiv:2202.01474



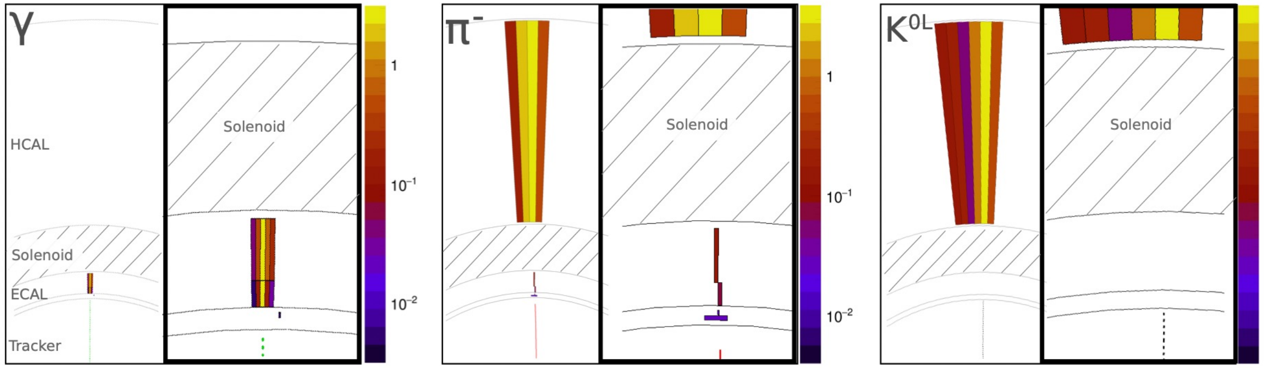


Dual-Readout Particle Flow Algorithm (DR-PFA)

- Traditional PFA exploit mainly the topological information of hits (rather than their energy) to reconstruct showers and possibly match them to a charged track
- DR-oriented PF algorithm exploit **object identification, high resolution and linear response provided by the crystal ECAL** to improve the tracker-calorimeter hit matching



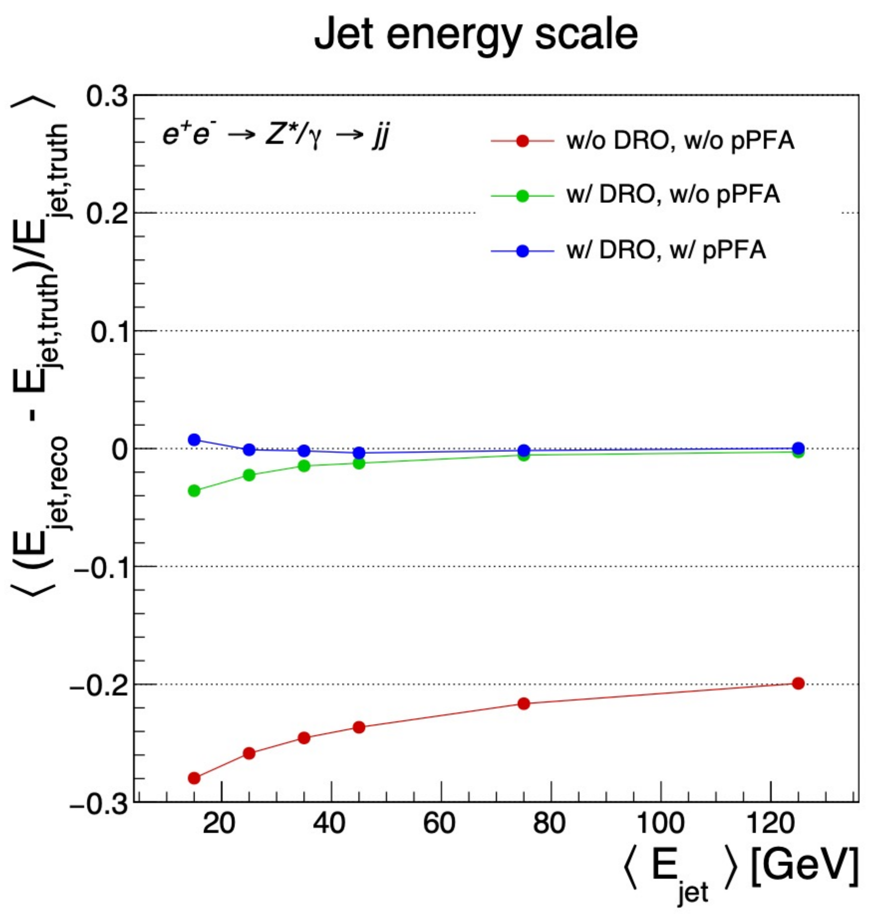
Typical PFA with Si-W high granularity calorimeter

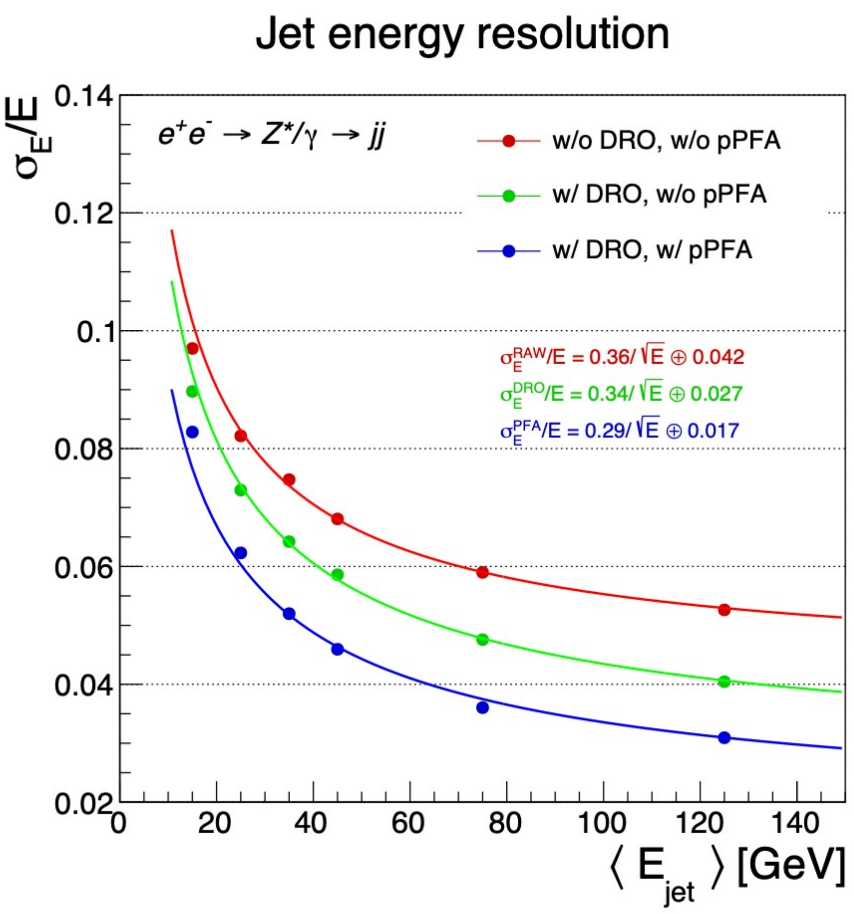


DR-PFA with high resolution DRO calorimeter

Jet Energy Linearity and Resolution

- Jet energy linearity and resolution as a function of jet energy in off-shell $e^+e^- \rightarrow Z^* \rightarrow jj$ events (at different center-of-mass energies):
- Prominent improvement in jet resolution when the PFA is combined with DR information

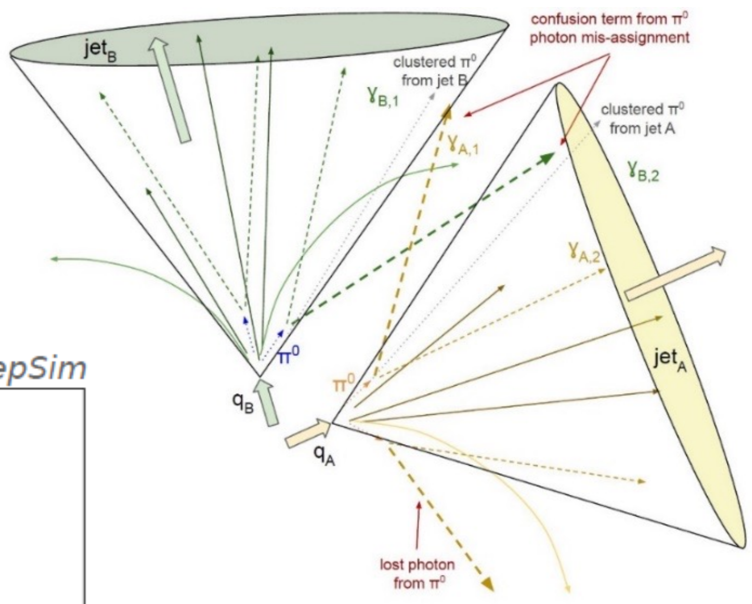


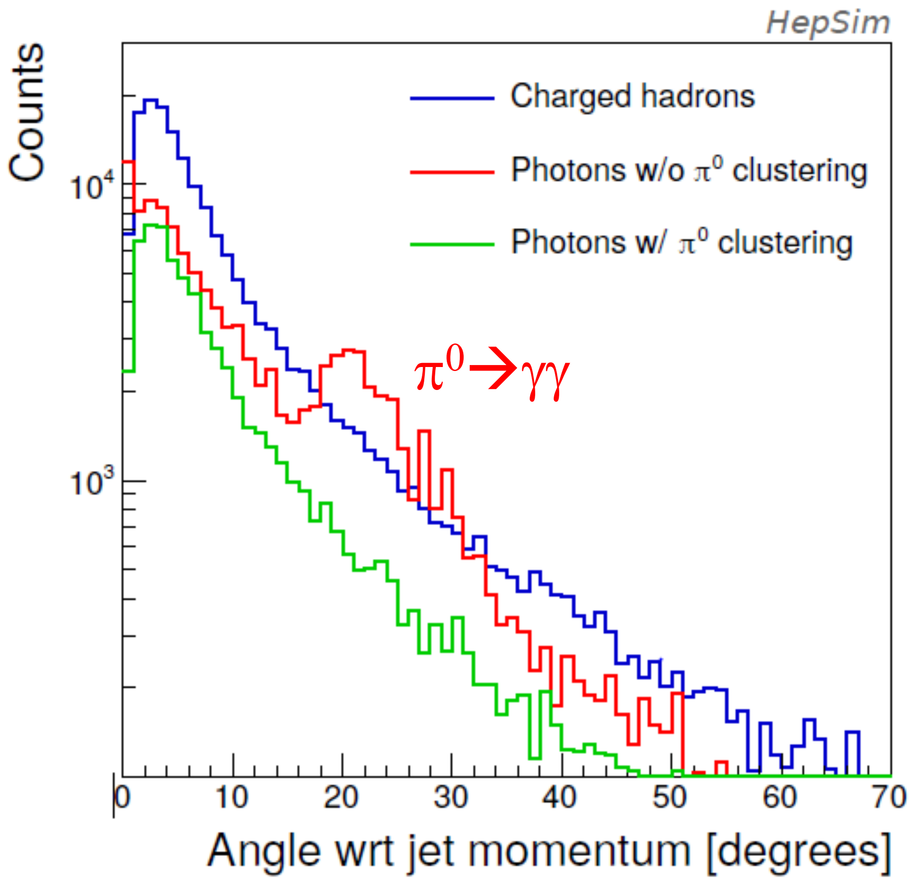


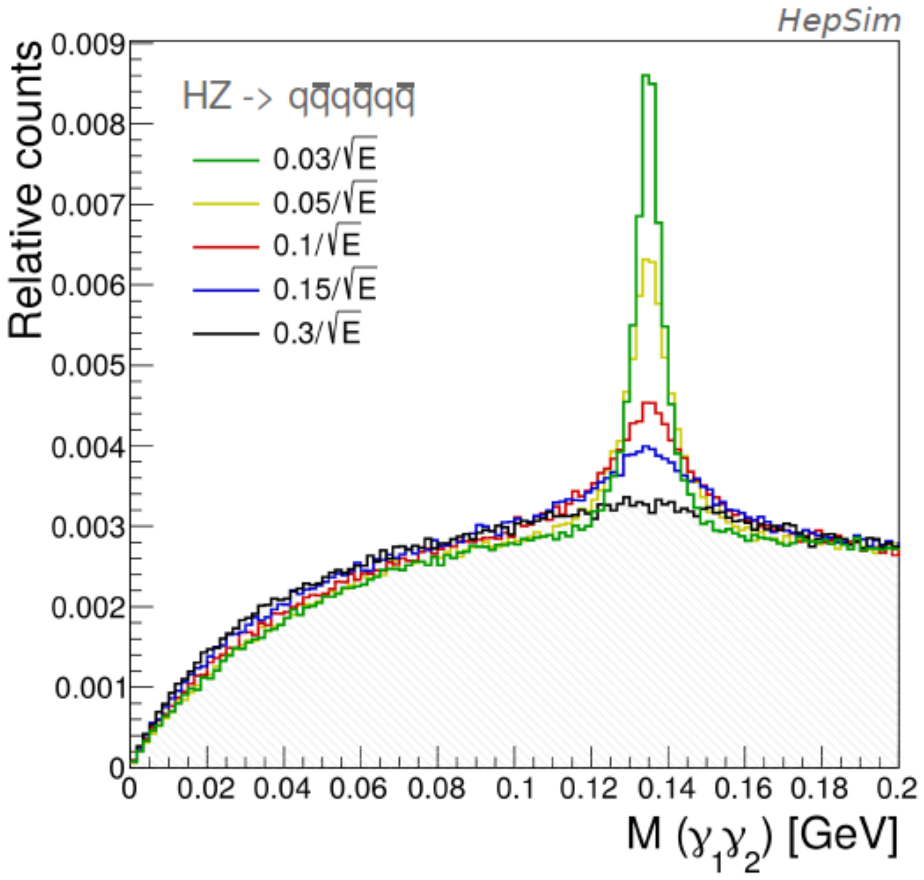
More details in:
arXiv:2202.01474

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 particular for event topologies featuring 4 or 6 jets.

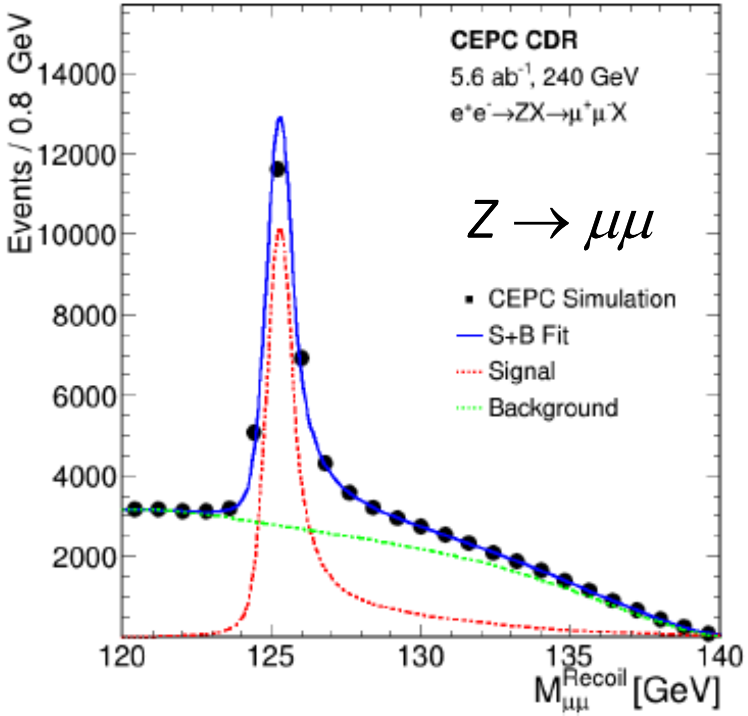


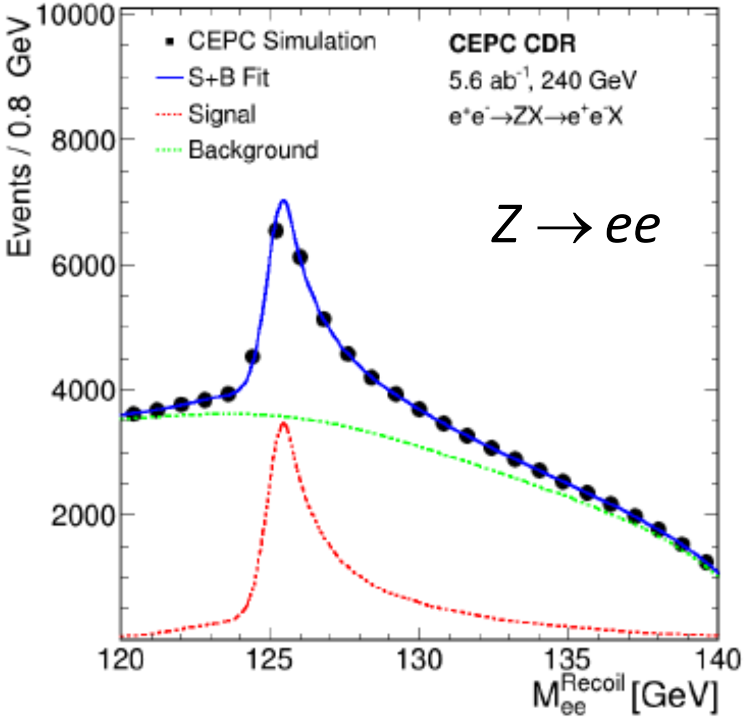


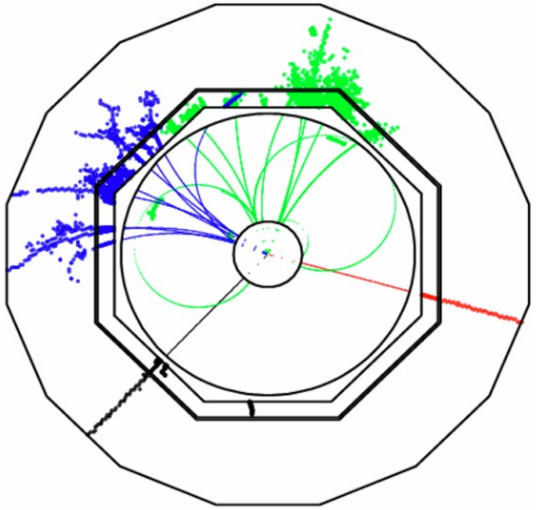


Advantages with a High-resolution EM Calorimeter

- 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 $Z \rightarrow e^+e^-$ channel due to bremsstrahlung radiation, need to have good EM resolution for the radiation recovery

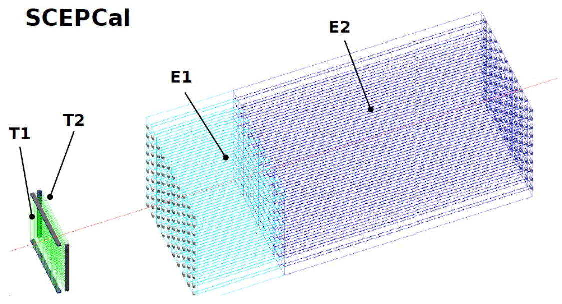
Summary

- With the advancement in SiPM technologies, the highly performant DRO hybrid calorimeter system is suitable for future Higgs factories
  - Excellent EM, HAD and jet resolution and high energy linearity by combining the DRO information from different calorimeter segments (homogeneous crystals + sampling fibers)
  - Enhanced particle identification capabilities by the moderate longitudinal segmentation
  - Further 3-4% improvement for $E_{jet} > 50$ GeV combining DRO with particle flow algorithm

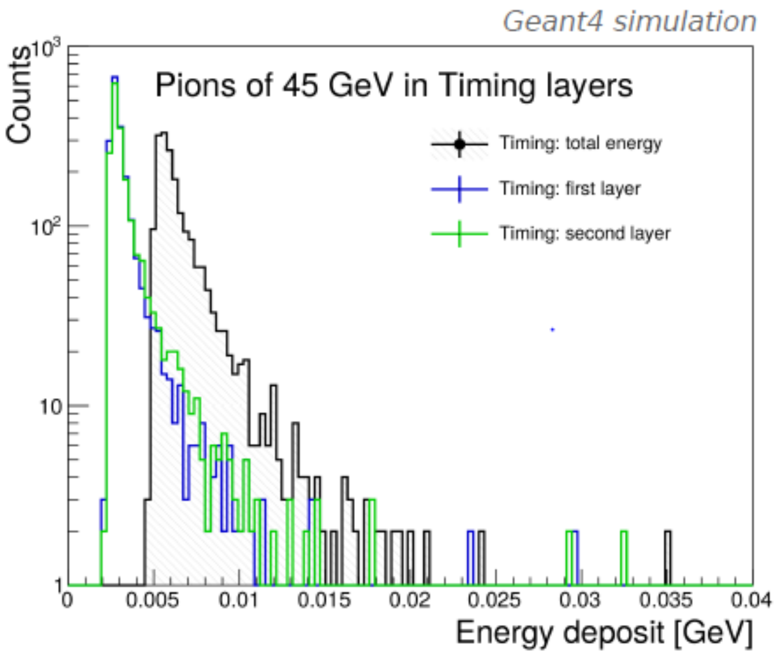
	High granularity Si/W ECAL + scintillator-based HCAL	Fiber-based DRO calo	Hybrid DRO crystal and fiber
# longitudinal layers	>40	1	5
ECAL cell cross-section HCAL cell cross-section	25-100 mm² 100-900 mm²	2-144 mm²	100 mm² 400-2500 mm²
EM energy resolution HAD energy resolution	15–25%/√E 45–55%/√E	10–15%/√E 25–30%/√E	~3%/√E 25–30%/√E

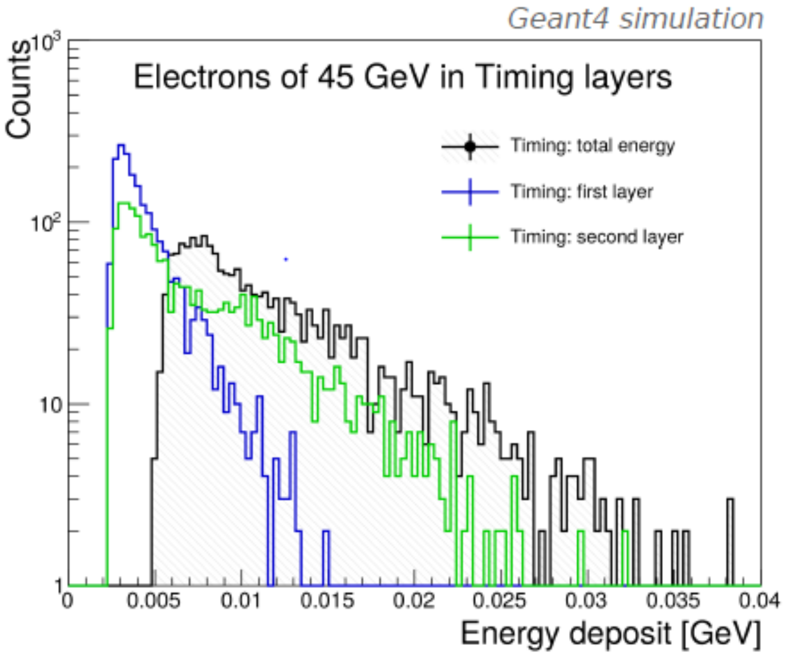
Additional material

Timing Layers



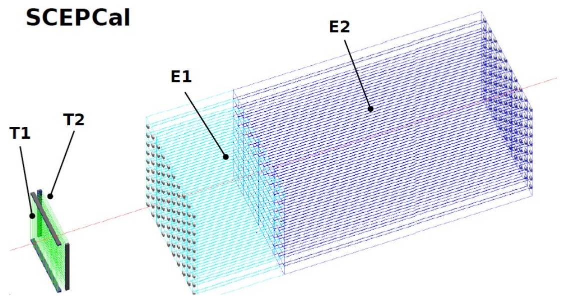
- Two timing layers (σ_t~20 ps)
- Similar timing performance as the CMS barrel MIP Timing detector
- LYSO:Ce scintillating crystals (~0.8 X_0)
- 3×3×100 mm^3 thin crystal bar
- 3×3 mm^2 SiPM (15-20 μm cell size)
- Two layers are orthogonal to each other → position resolution ~ 1 mm in x-y directions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

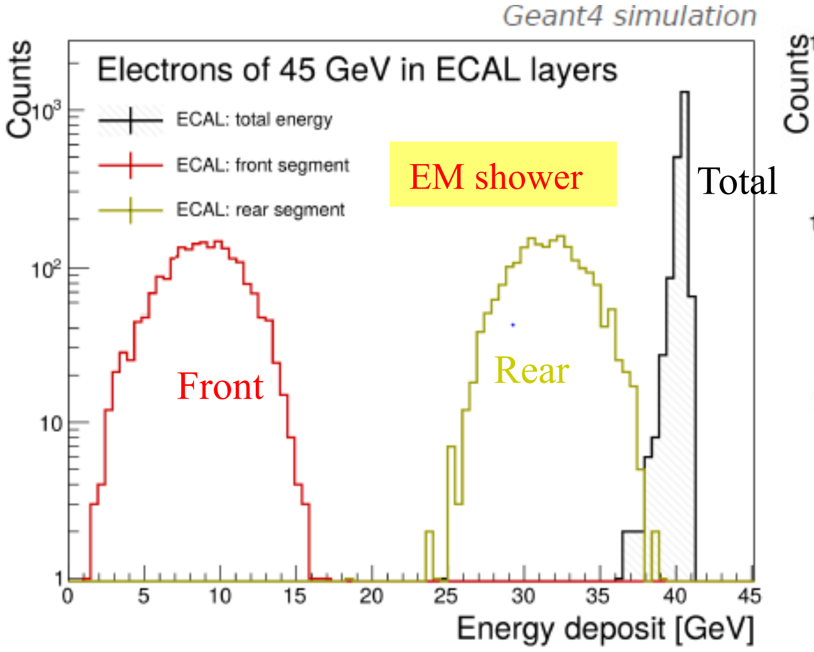


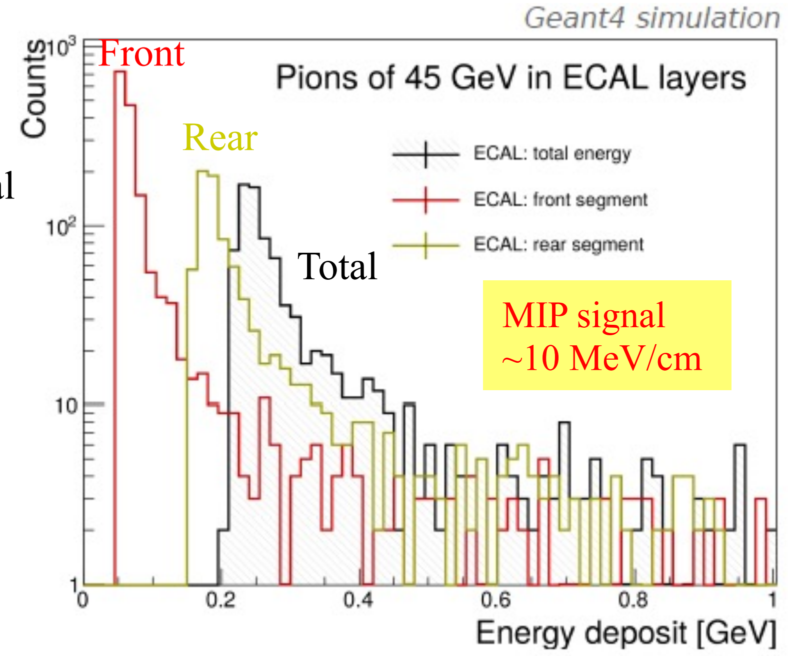


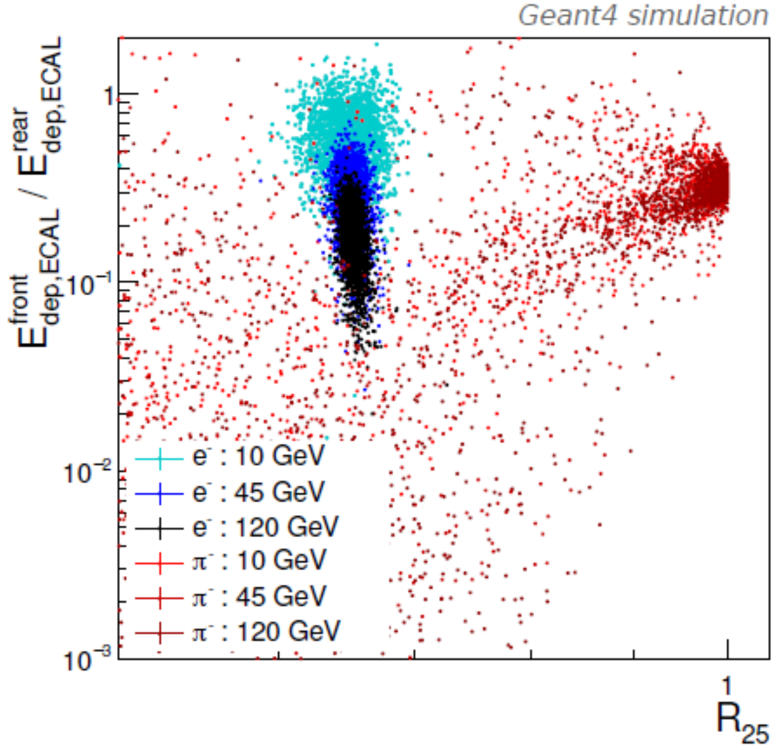
Segmented ECAL

- Two 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









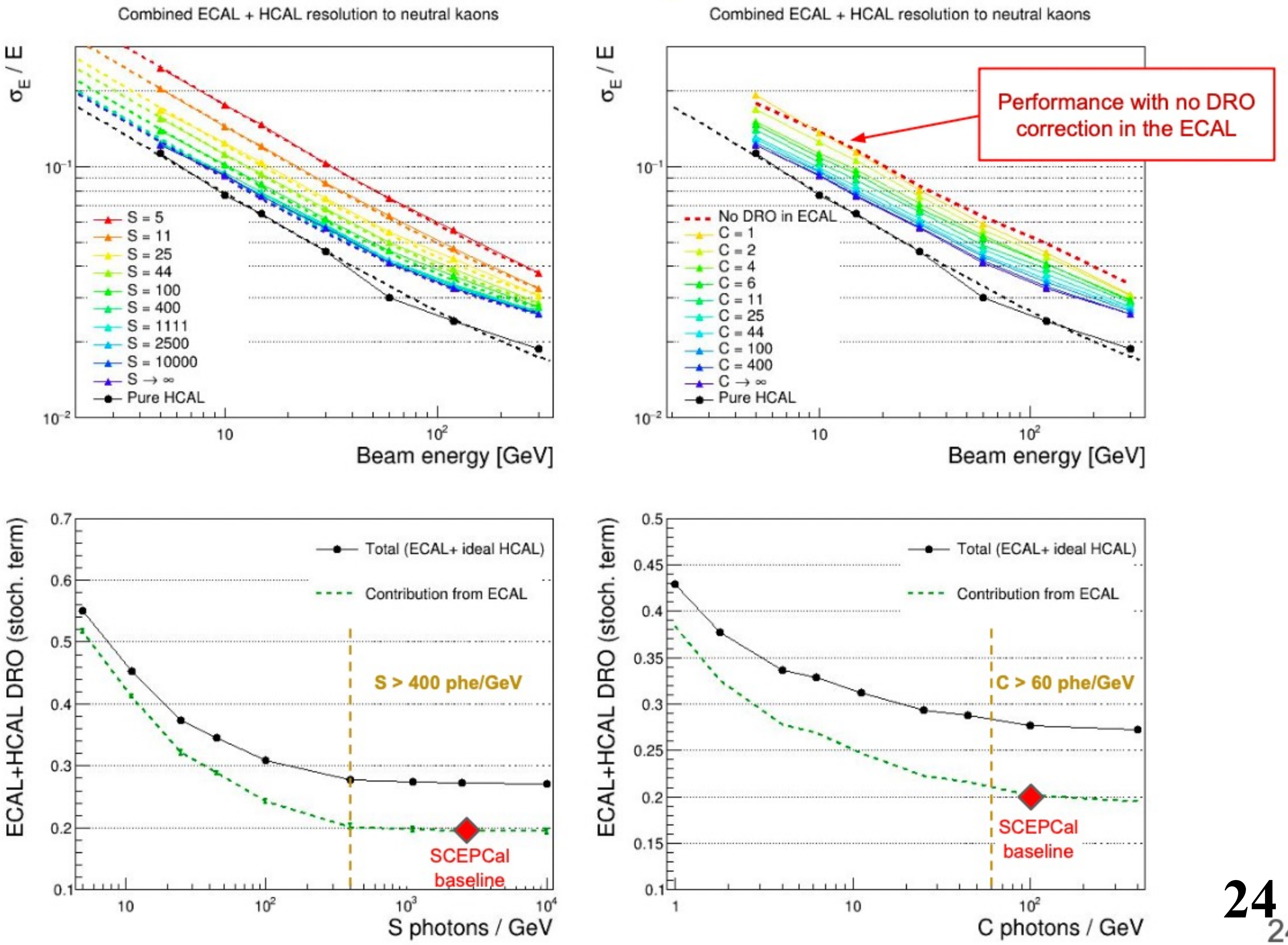
Ratio of energy deposited in front and rear segments
vs
Ratio of energy deposited in the central crystal and the total energy deposited in a 5×5 crystal matrix

courtesy of M.Lucchini

Photo-statistic requirements for S and C

Smearing according to Poisson statistics

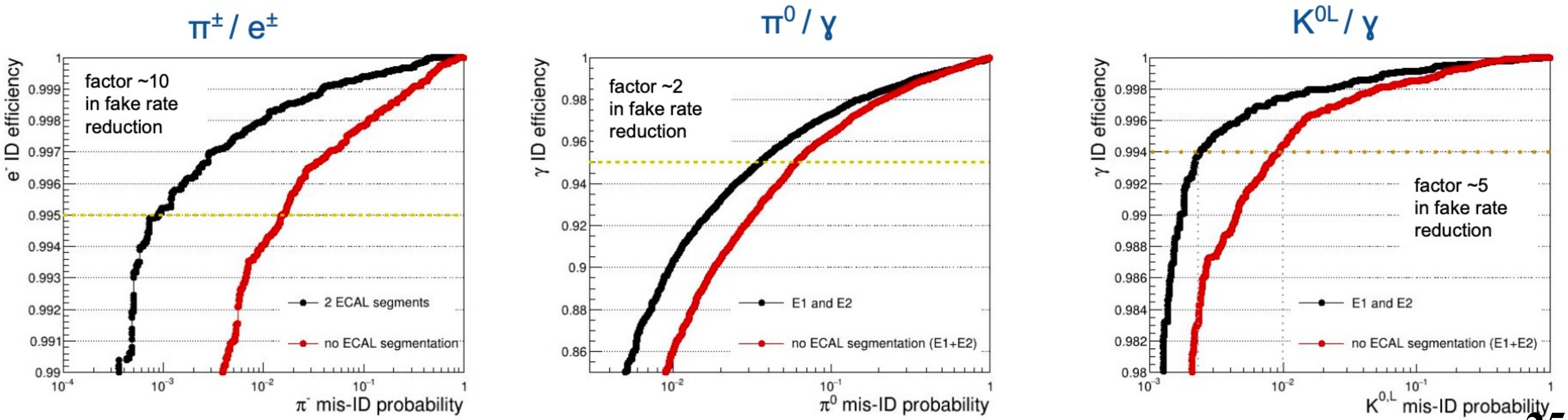
- A poor S (scintillation signal) impacts the hadron (and EM) resolution stochastic terms:
  - S > 400 phe/GeV
- A poor C (Cherenkov signal) impacts the C/S and thus the precision of the event-by-event DRO correction
  - C > 60 phe/GeV
- **SCEPCal layout choices** (granularity and SiPM size) **provide sufficient light collection efficiency**
  - Need experimental validation with lab and beam tests



Crystal longitudinal **segmentation matters**

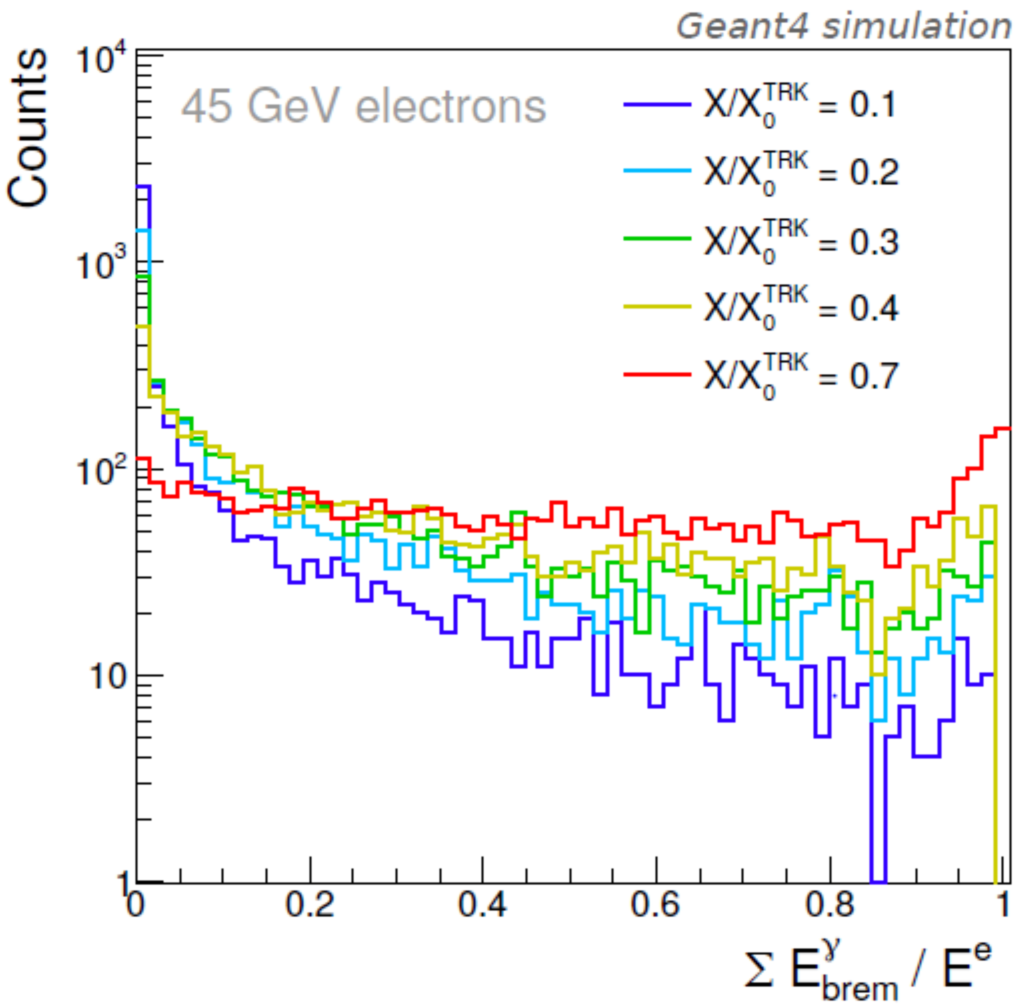
- Tangible improvements in particle ID from the longitudinal ECAL segmentation, i.e. **two crystal segments** (front and rear) instead of a single crystal cell

Single particle gun events with uniform energy distribution in the range 1-100 GeV, 100k events for each type of particle

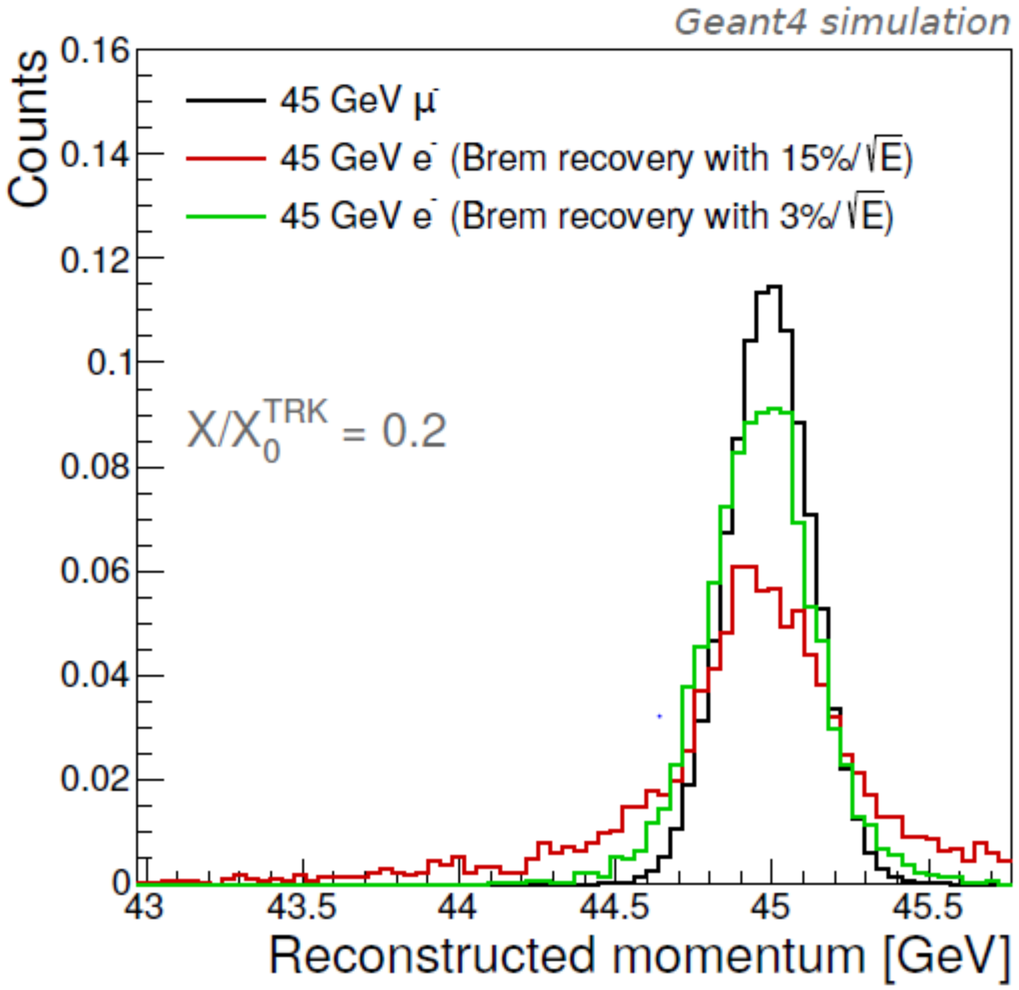


Advantages with a High-resolution EM Calorimeter

- Recovery of photons from bremsstrahlung



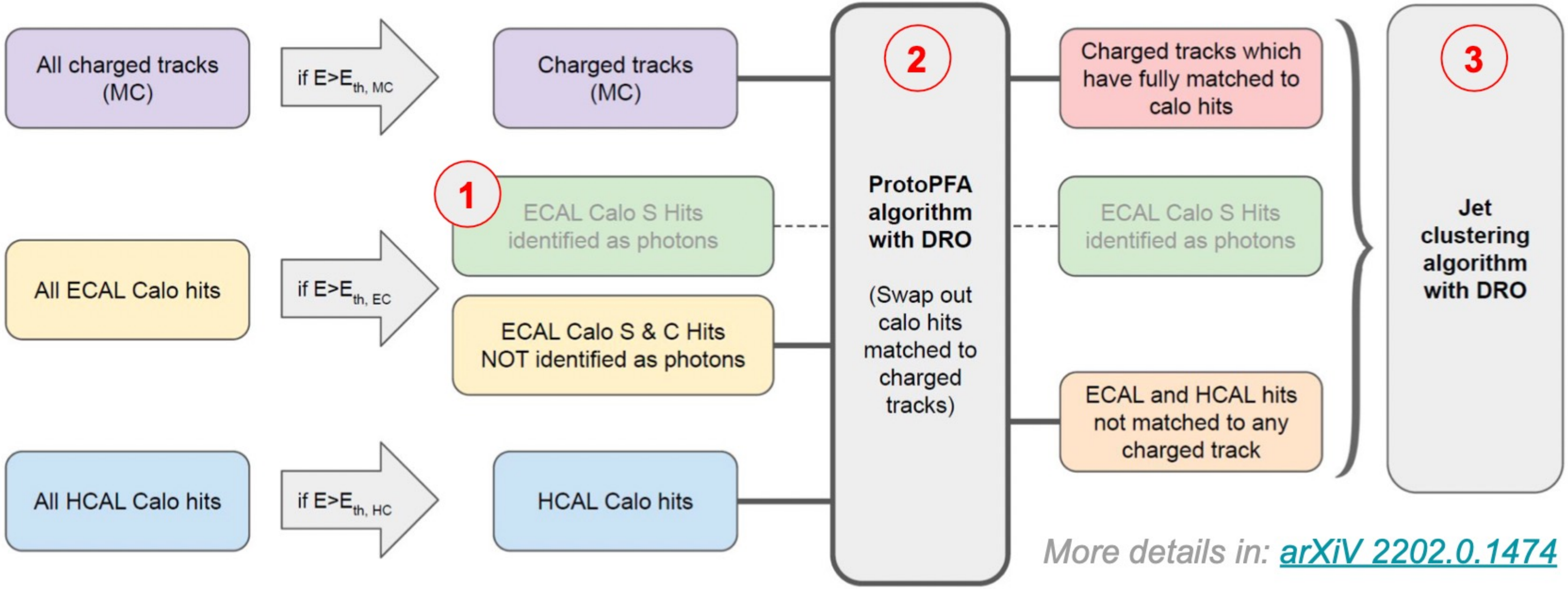
Energy lost through bremsstrahlung



Electrons: tracker measurement + photons courtesy of M.Lucchini

Dual-Readout Particle Flow Algorithm for jet reconstruction

- Maximally exploit the information from the **crystal ECAL** for classification of EM clusters and use it **as a linchpin** to provide stronger criteria in matching to the tracking and hadron calorimeter hits
- Exploit the **high resolution and linear response** of the hybrid **dual-readout** calorimeter to improve precision of the track-calo hits matching in a particle flow approach



More details in: arXiV 2202.0.1474