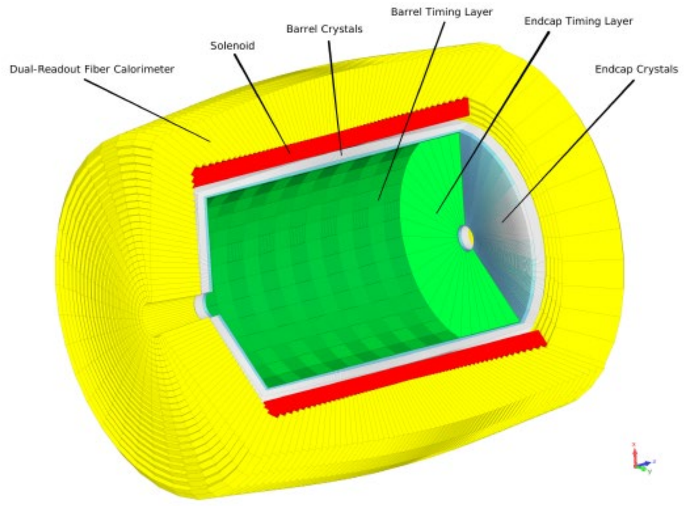
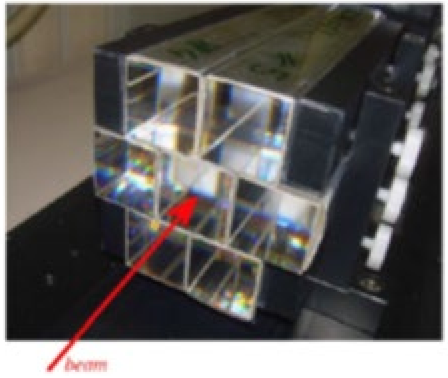
Dual readout calorimetry for electron positron colliders

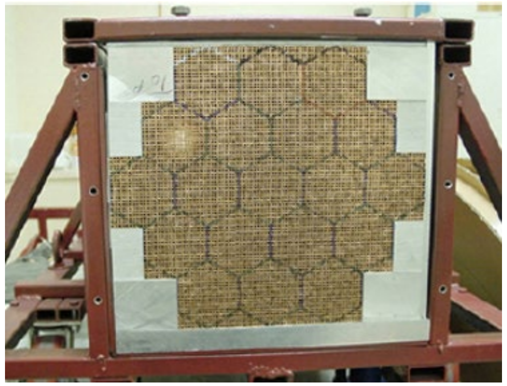
Sarah Eno, U. Maryland

Instrumentation Frontier: calorimetry

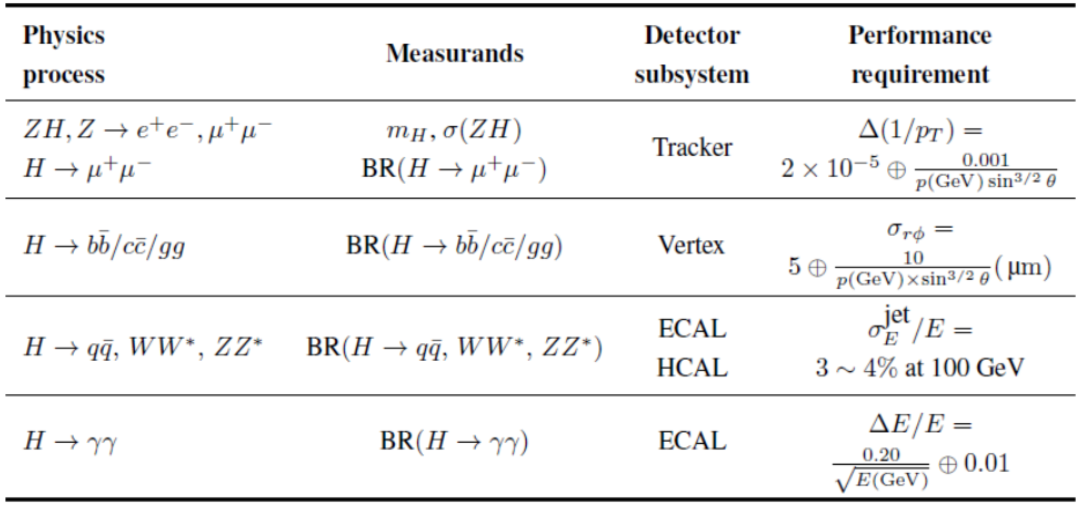
11 September 2020



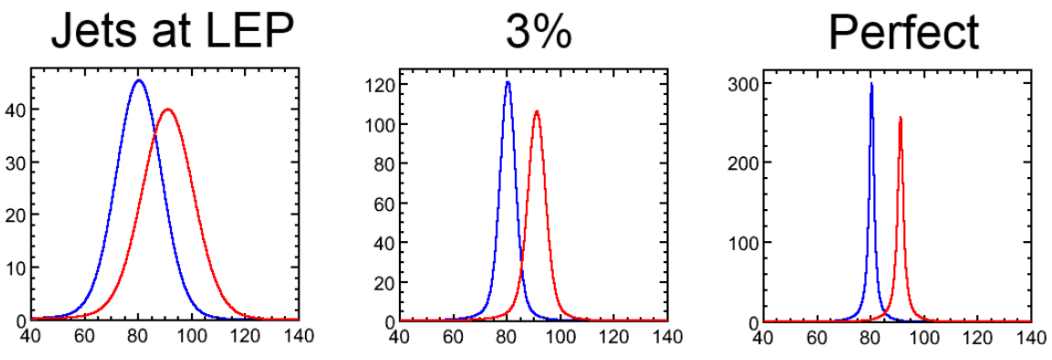




Detector specs for future electron positron colliders

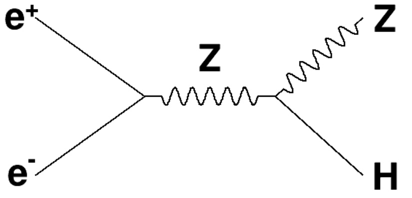


Physics process	Measurands	Detector subsystem	Performance requirement
$ZH, Z \to e^+e^-, \mu^+\mu^-$ $H \to \mu^+\mu^-$	$m_H, \sigma(ZH)$ $\mathrm{BR}(H \to \mu^+\mu^-)$	Tracker	$\Delta(1/p_T) =$ $2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$
$H \to b\bar{b}/c\bar{c}/gg$	$\mathrm{BR}(H \to b\bar{b}/c\bar{c}/gg)$	Vertex	$\sigma_{r\phi} =$ $5 \oplus \frac{10}{p(\mathrm{GeV}) \times \sin^{3/2}\theta} (\mu\mathrm{m})$
$H \to q\bar{q}, WW^*, ZZ^*$	$\mathrm{BR}(H \to q\bar{q}, WW^*, ZZ^*)$	ECAL HCAL	$\sigma_E^{\mathrm{jet}}/E =$ $3 \sim 4\%$ at 100 GeV
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\Delta E/E =$ $\frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$

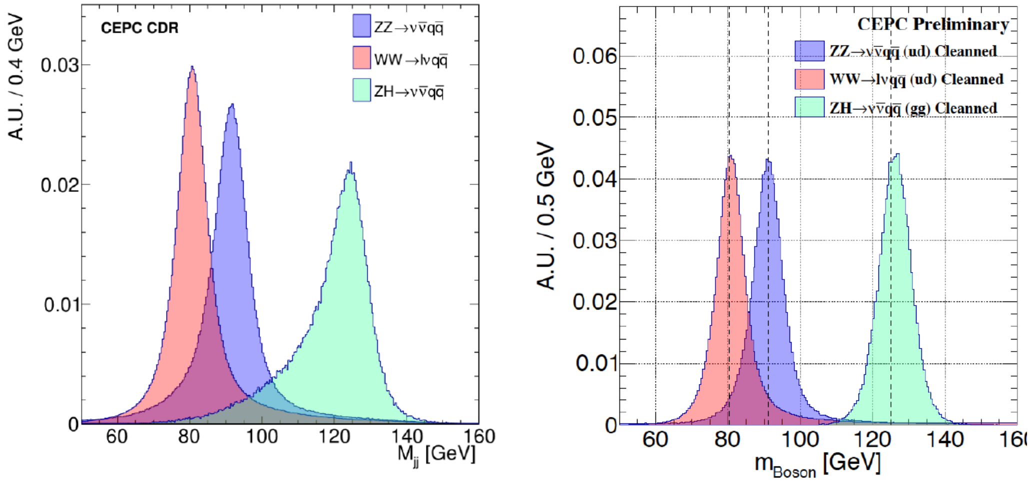


M. Thomson

Slide: F. Richard at International Linear Collider – A worldwide event



Massive Boson Separation



Peizhu Lai & CEPC CDR *WW sample: using μvqq sample,*
Plot: the visible mass without the muon

CEPC-RECO-2017-002 (DocDB id-164),
CEPC-RECO-2018-002 (DocDB id-171),
Eur. Phys. J. C (2018) 78: 426

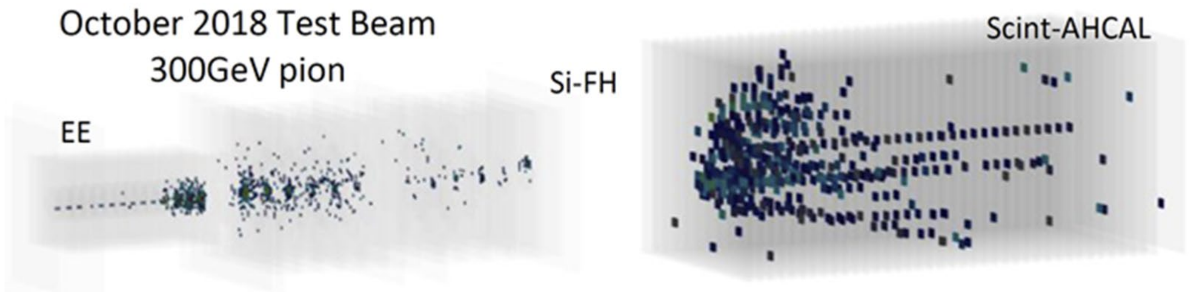
11/03/19 Topical Calo WS@IHEP 21

Challenging spec for hadronic calorimetry (3% at 100 GeV is a sampling term of about $30\%/\sqrt{E}$ with small constant term). Modest spec on EM calorimetry ($20\%/\sqrt{E}$).

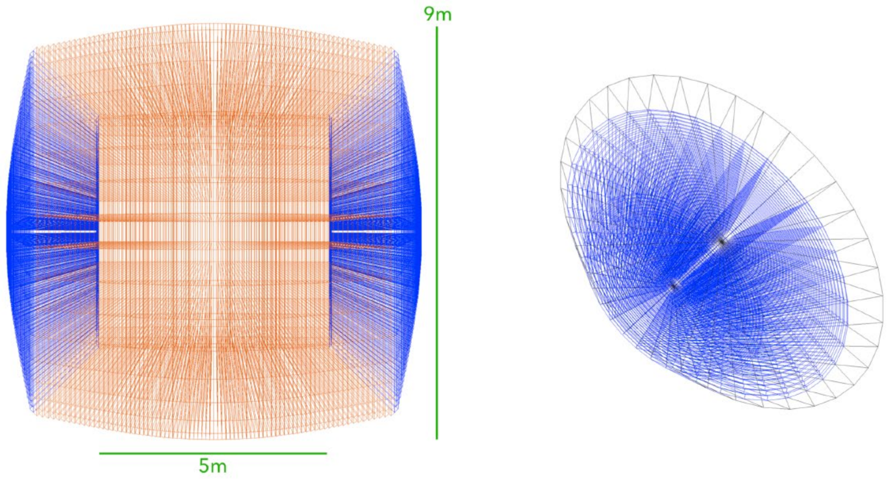
Modern approaches

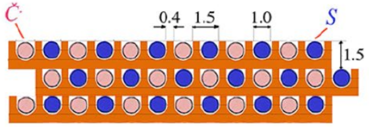
There are two approaches to achieving this resolution: using the calorimeter as little as possible (high granularity calorimetry) or through improvements to the calorimeter resolution (dual readout)

High granularity calorimetry



Dual readout



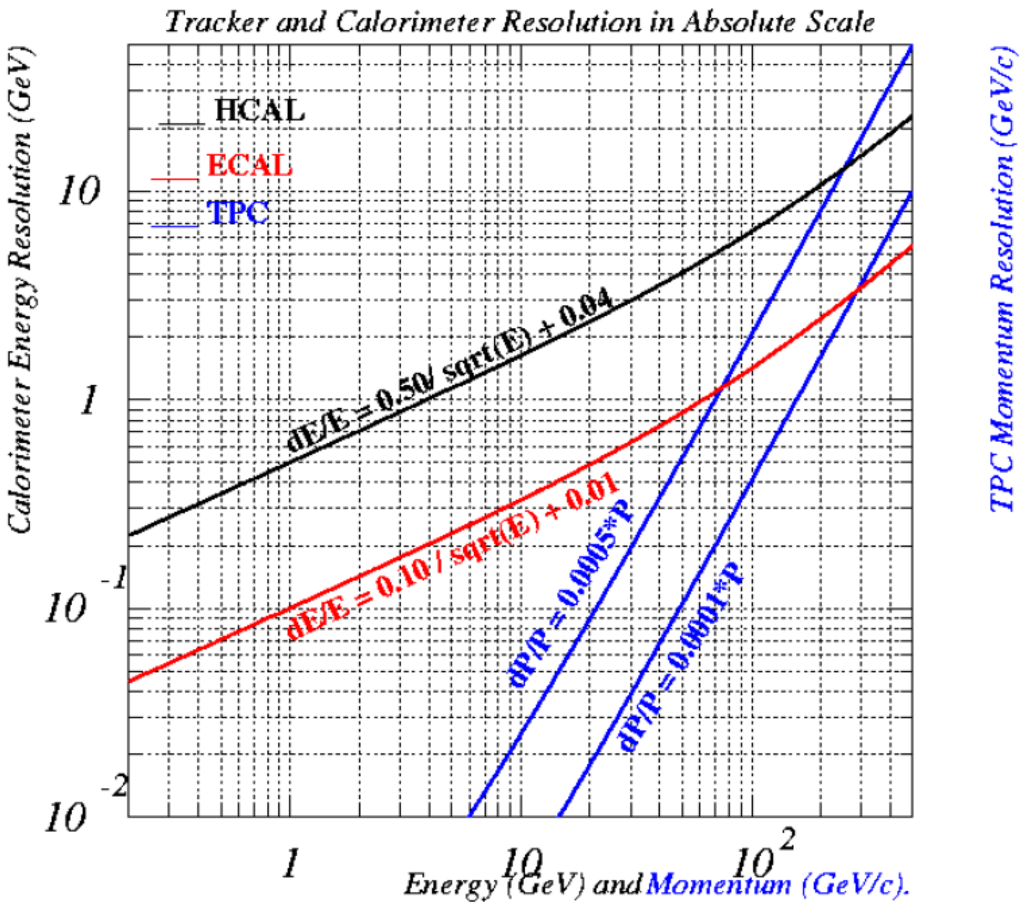


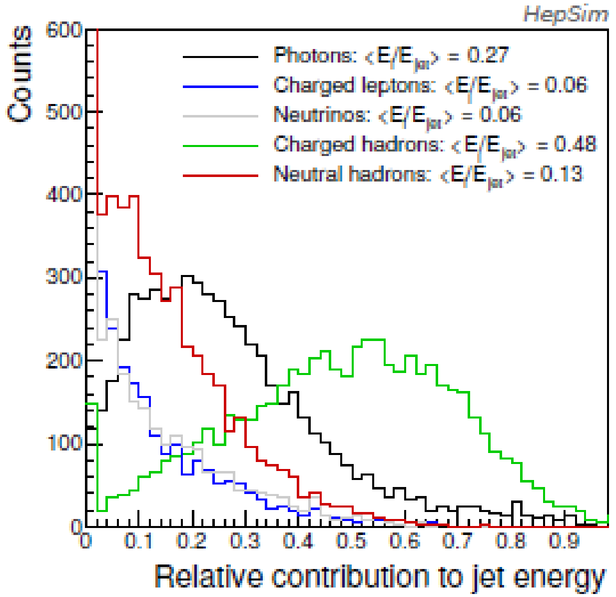
Copper + scintillating and Cherenkov fibers

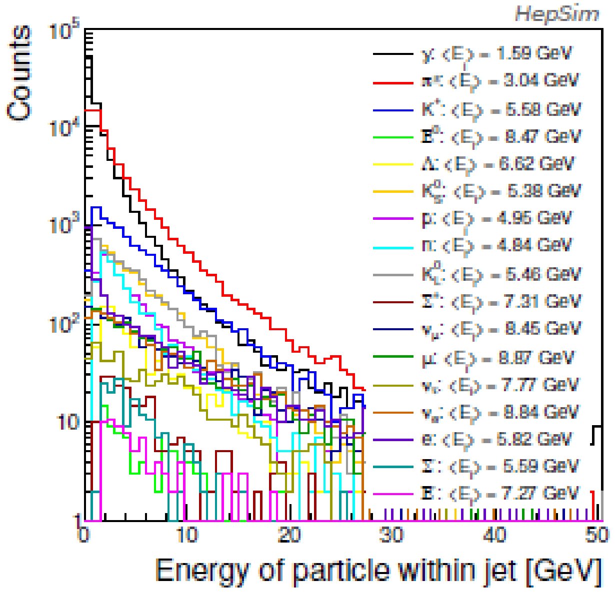
Because the approaches are very different, they are truly complementary.
At future facilities with multiple interaction points, such complementarity should be encouraged

HGC reminder:

Can live with a “mediocre” calorimeter resolution





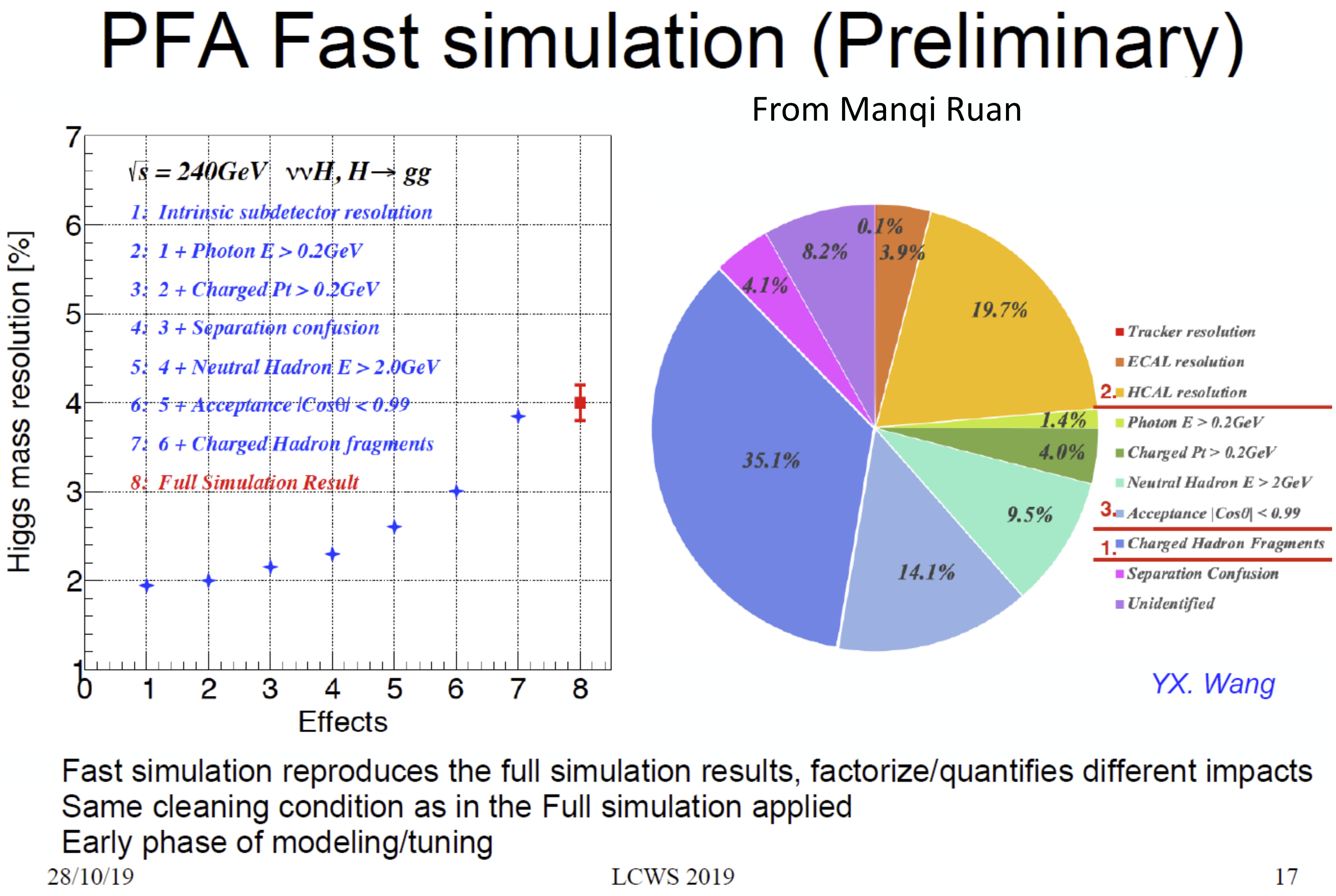


Calorimeter resolution requirements not that stringent. 50% HAD and 10% EM stochastic terms

Very well studied by a strong group with members from Europe, Asia, and the US See Jim Brau’s talk later in this series. Lots of work being done in CMS now (FSU, Texas Arlington, MN, UCSB, TT, NW, Pitt,…)

Pöschl https://indico.ihep.ac.cn/event/11938/

Pattern recognition



PFA Fast simulation (Preliminary)

From Manqi Ruan

Fast simulation reproduces the full simulation results, factorize/quantifies different impacts
Same cleaning condition as in the Full simulation applied
Early phase of modeling/tuning

28/10/19 LCWS 2019 17

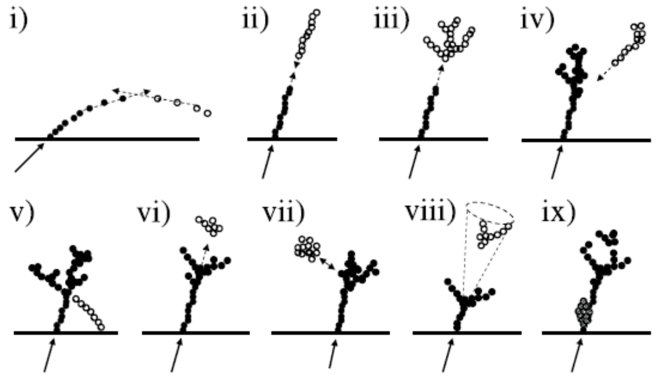


Figure 4: The main topological rules for cluster merging: i) looping track segments; ii) track segments with gaps; iii) track segments pointing to hadronic showers; iv) track-like neutral clusters pointing back to a hadronic shower; v) back-scattered tracks from hadronic showers; vi) neutral clusters which are close to a charged cluster; vii) a neutral cluster near to a charged cluster; viii) cone association; and ix) recovery of photons which overlap with a track segment. In each case the arrow indicates the track, the filled points represent the hits in the associated cluster and the open points represent the hits in the neutral cluster.

Of course, the pattern recognition is challenging. Hadronic resolution is also still a leading driver

Dual readout fundamentals

Contribution to hadronic resolution due to e/h

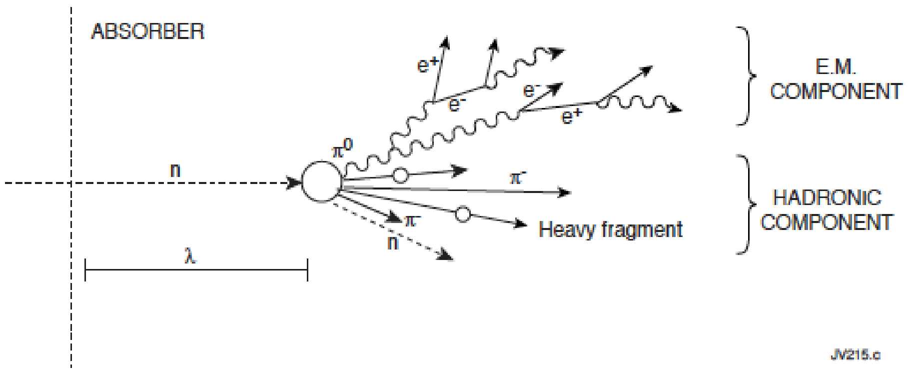
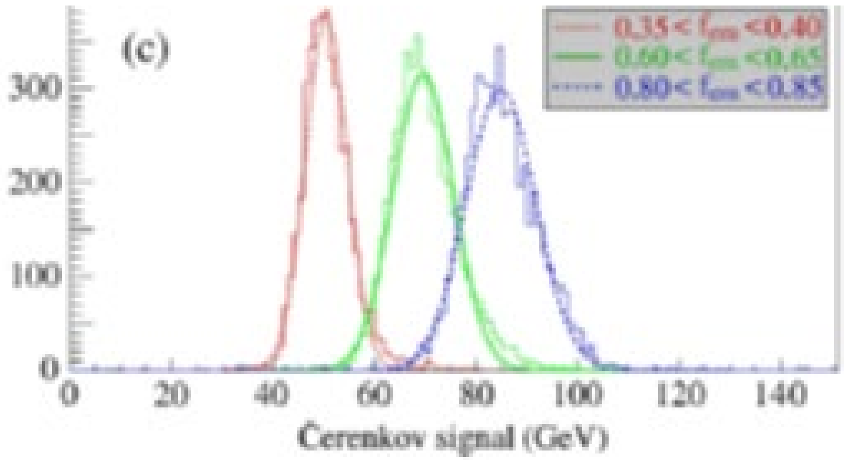


Fig. 9: Schematic of development of hadronic showers.



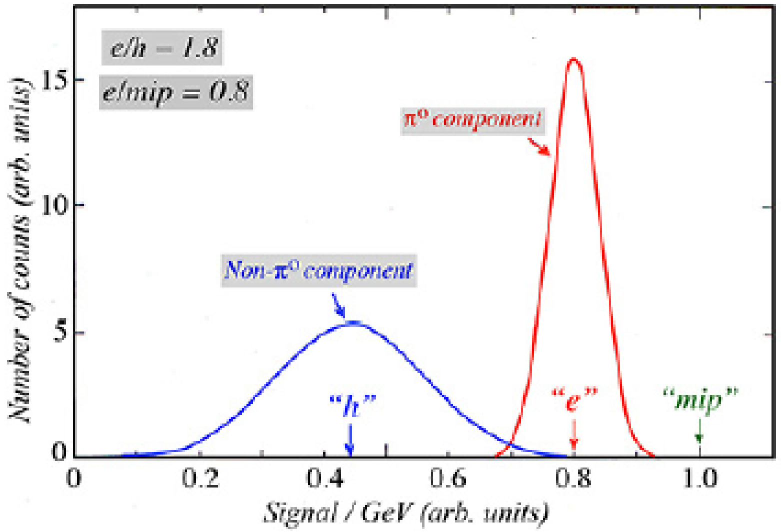


FIG. 2: Illustration of the meaning of the e/h and e/mip values of a (generic) calorimeter. Shown are distributions of the signal per unit deposited energy for the electromagnetic and non-em components of hadron showers. These distributions are normalized to the response for minimum ionizing particles ("*mip*"). The average values of the em and non-em distributions are the em response ("*e*") and non-em response ("*h*") , respectively.

If you could know shower by shower what fraction is pizeros, you could remove this resolution source

DREAM/RD52/IDEA

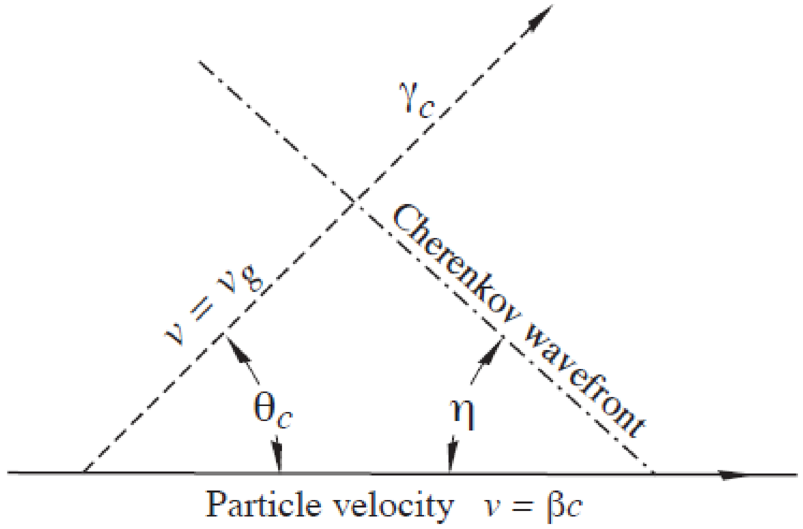
Use **Cherenkov light** to measure, shower-by-shower, the fraction of the shower energy in pizeros. Use **scintillation light** to measure all ionizing energy deposits. Apply a scale correction that depends on this ratio.

Using this, you can get sampling terms of 3% for electrons/photons and 30% for hadrons.

This is the DREAM or IDEA of the RD52 collaboration.

For an excellent review of their exhaustive work, see: Wigmans, New Developments in Calorimetric Particle Detection, **arXiv: 1807.03853**

Measurement 1: Cherenkov radiation



Can generate in

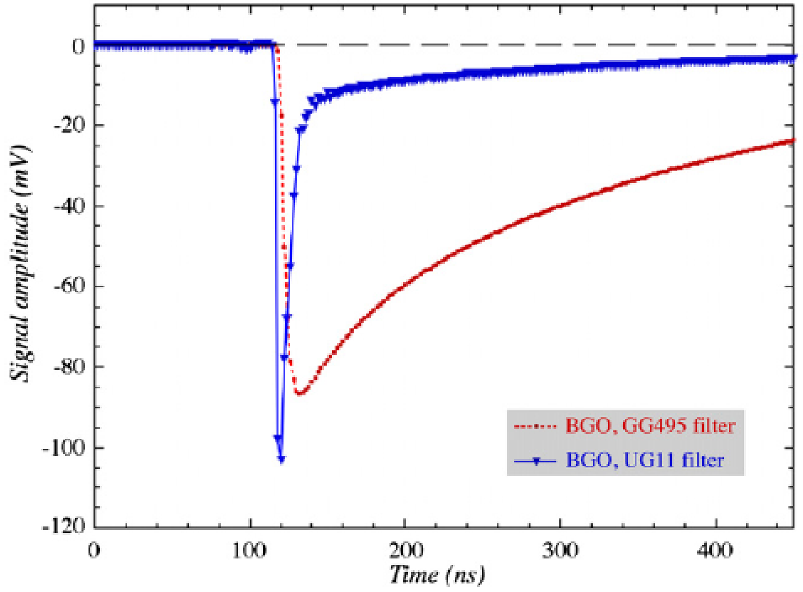
- Quartz
- Clear plastic fibers
- Crystals like BGO, PbWO4

(basically need some transparent material, the higher the n the better)

Can be identified by its

- Angle
- Wavelength
- timing

$$\frac{d^2N}{dx\,d\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right) .$$



f

Passage of particles through matter (pdg.lbl.gov)

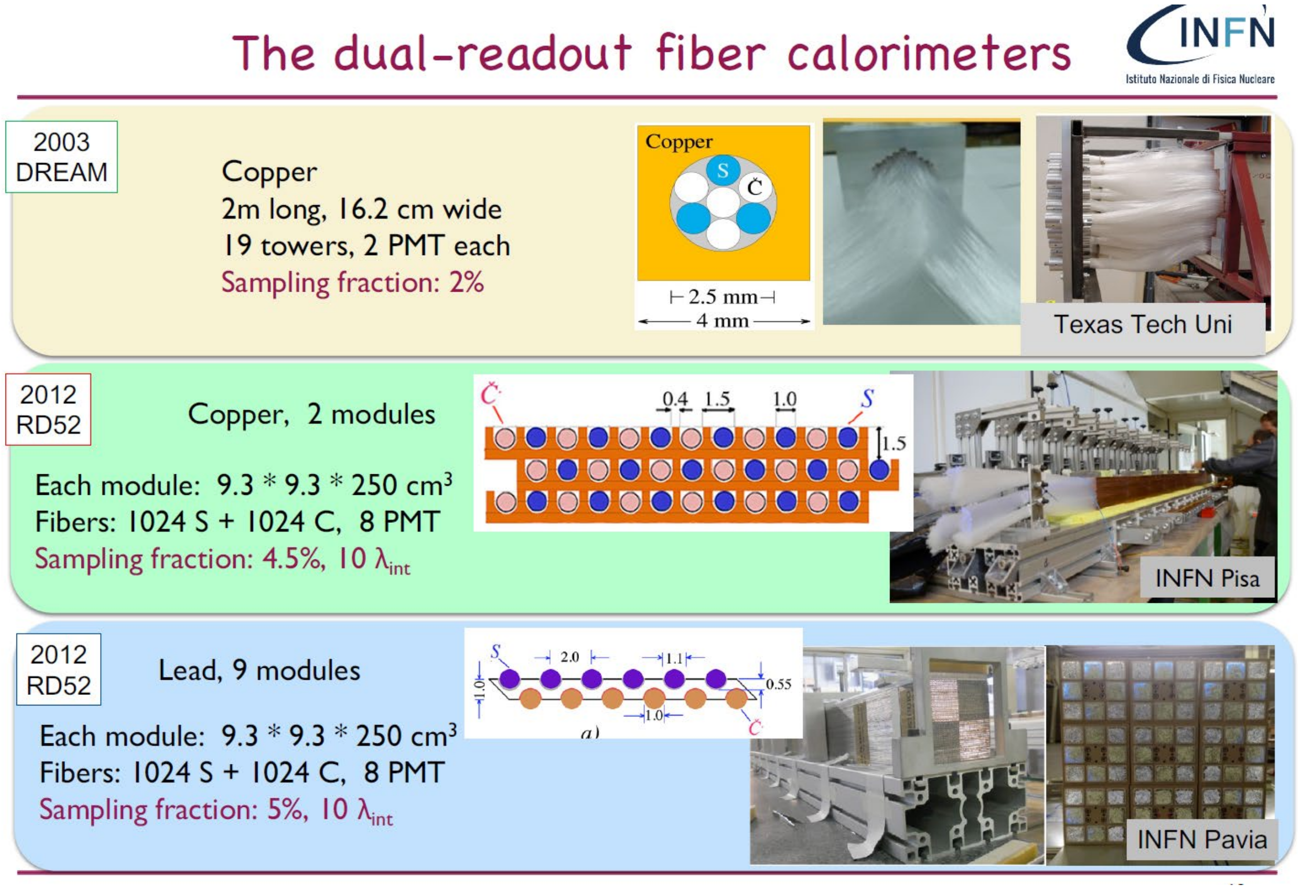
Measurement 2

But since this is only sensitive to the relativistic portion of the shower, need something else to generate signal from the entire energy deposit

- plastic scintillator (advantage of sensitivity to neutrons)
- Crystals like BGO, PbWO4 (advantage of excellent EM resolution)

RD52

RD52 started by studying dual readout in crystals. But then they moved to the following geometry



The dual-readout fiber calorimeters

INFN Istituto Nazionale di Fisica Nucleare

2003 DREAM

Copper
2m long, 16.2 cm wide
19 towers, 2 PMT each
Sampling fraction: 2%

2012 RD52

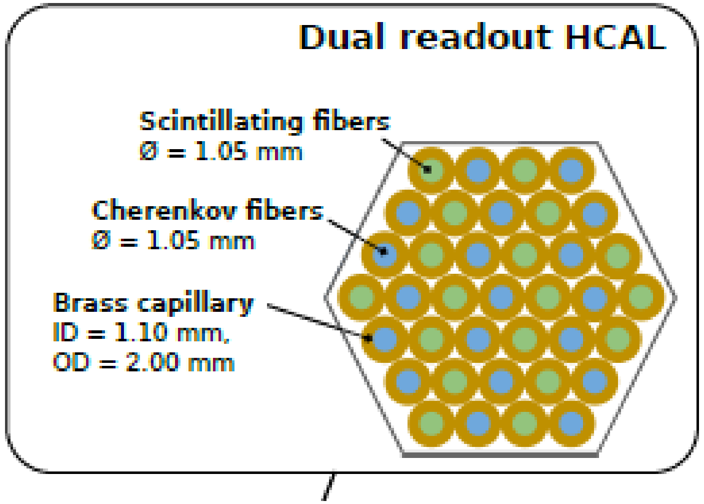
Copper, 2 modules

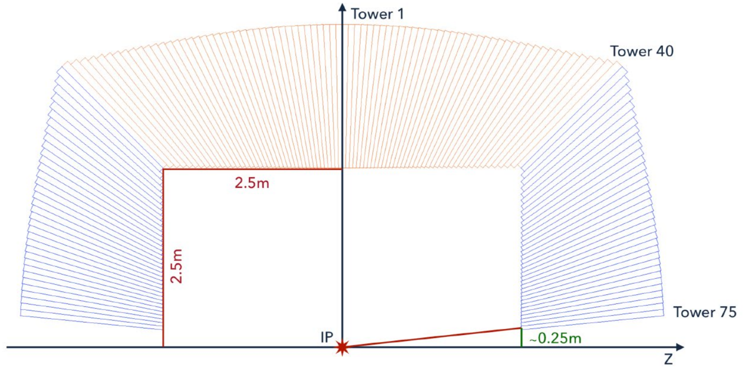
Each module: 9.3 * 9.3 * 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: 4.5%, 10 λ_{int}

2012 RD52

Lead, 9 modules

Each module: 9.3 * 9.3 * 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: 5%, 10 λ_{int}





75 projective elements x 36 slices

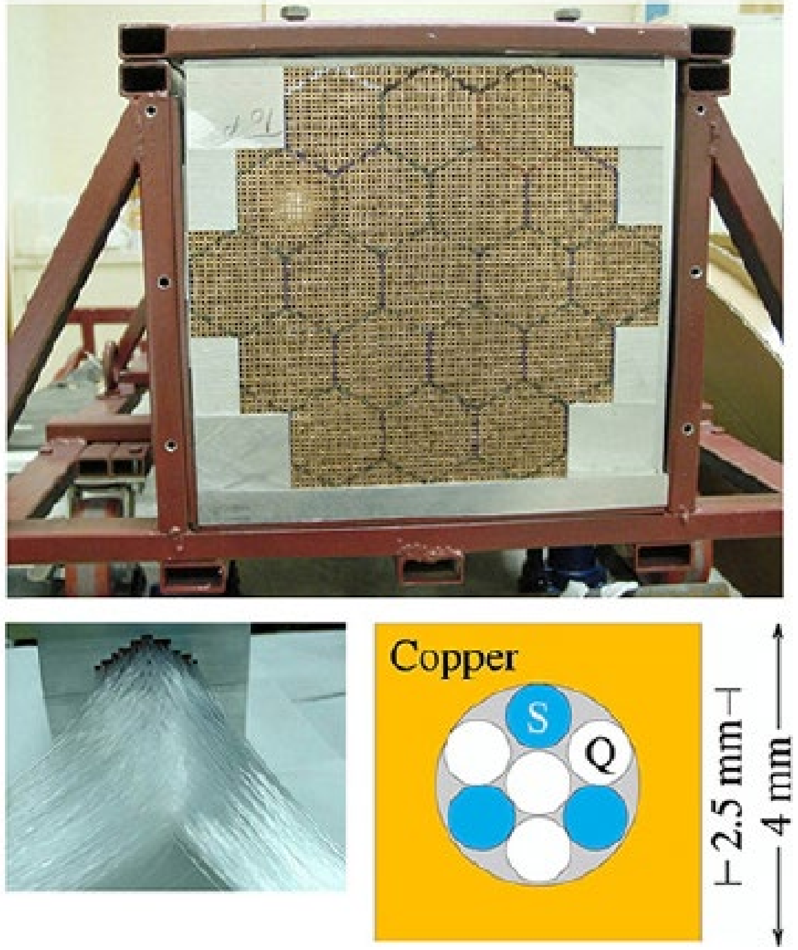
Read out the single fiber: 130 M channels

Tower size: $\Delta\theta = 1.125°$

$\Delta\phi = 10°$

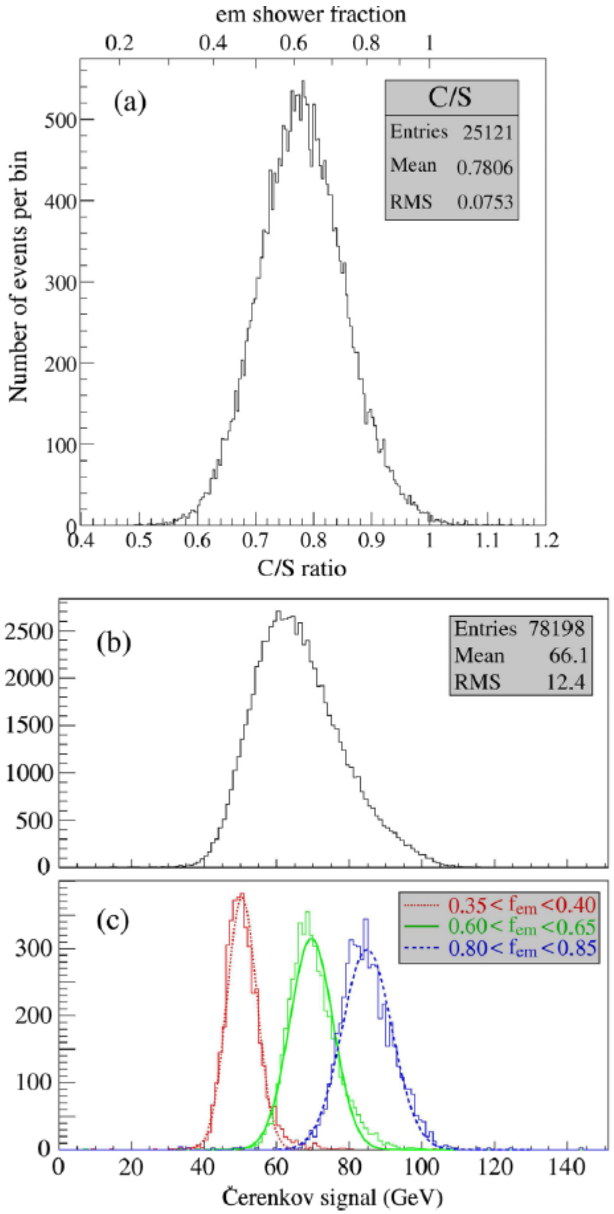
Test beam prototypes

has sampling media parallel to incident particle direction to uniformly sample the longitudinal shower.



Dual-Readout Calorimetry: arXiv:1712.05494
Lee, Livan, Wigmans Rev. Mod. Phys. 90 (2018) 40

Why it works



The top plot shows extracted C/S ratio.

The middle is the signal from the Cherenkov alone.

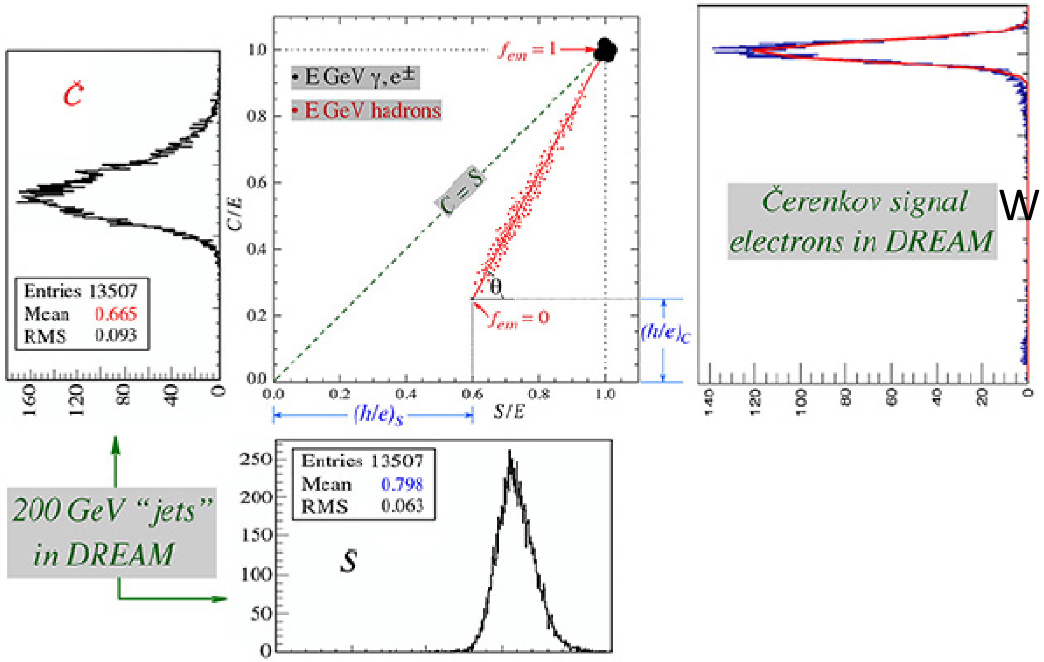
The bottom is the Cherenkov signal in bins of C/S.

Dual-readout moves the center of these individual gaussians to the same place, leading to better resolution

Dual-Readout Calorimetry: arXiv:1712.05494

In 2D

When you have a pure EM shower, both are calibrated to give a response of 1.
When you have a “pure hadron” shower (no pizero production), the Cherenkov response is low but the scintillator response, while lower than before, isn’t much lower.



When

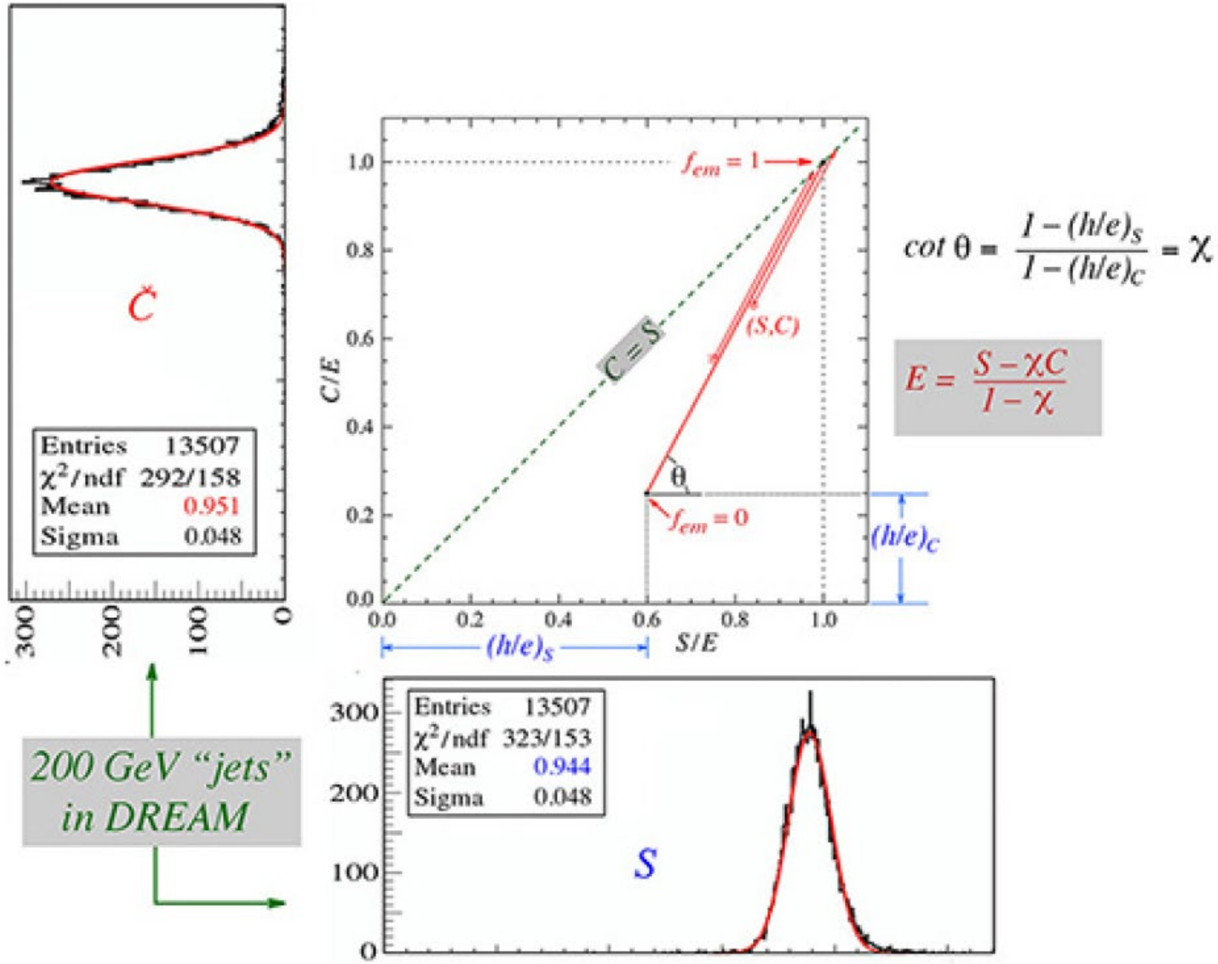
FIG. 8: The $S - C$ diagram of the signals from a (generic) dual-readout calorimeter [29]. The hadron events are clustered around the straight (red) line, the electron events around the point (1,1). Experimental signal distributions measured in the scintillation and Čerenkov channels for 200 GeV “jets” with the DREAM fiber calorimeter [30] are shown as well. Also shown is a typical (Čerenkov) response function measured for electrons in DREAM.

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

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

Two equations with two unknowns (E and f_{em}). Only two equations if $(e/h)_S$ and $(e/h)_C$ are different.

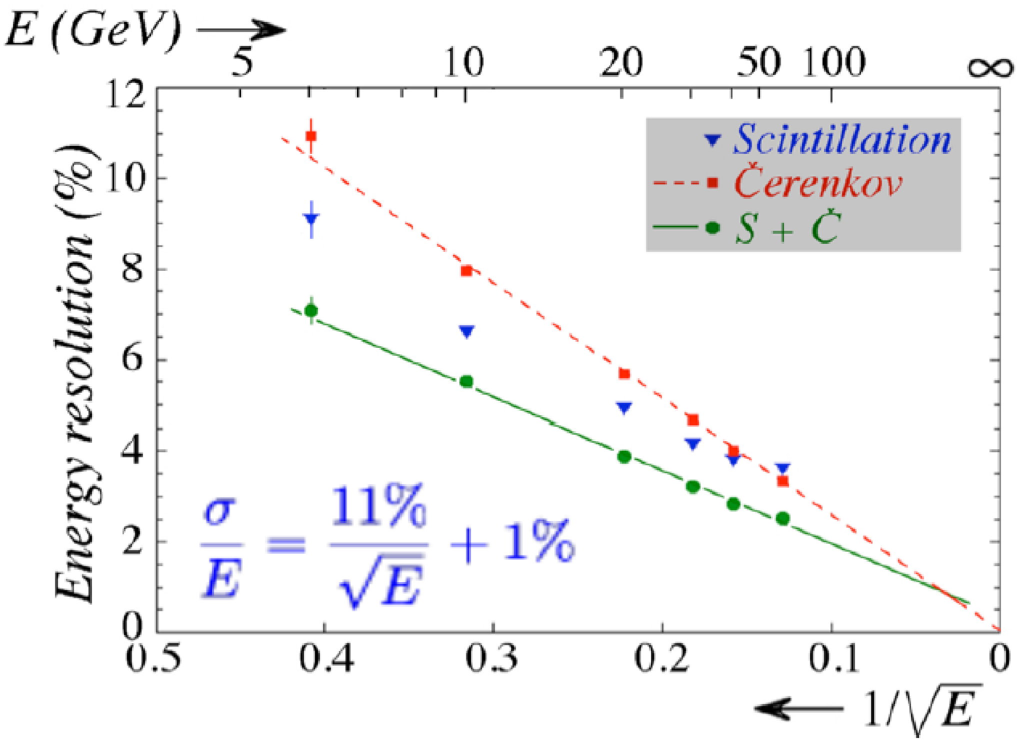
Dual-Readout Calorimetry: arXiv:1712.05494



Each point scattered alone the red line is moved up until it intersections C=S (note the arrows) then the projection of this onto each axis is combined.

IDEA

Measured EM resolution



Measured HAD resolution

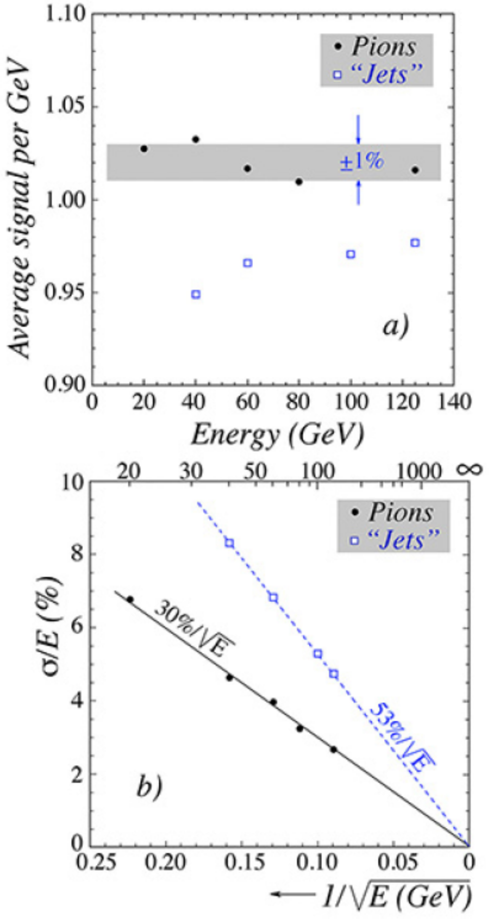


FIG. 44: The average calorimeter signal per GeV (*a*) and the fractional width of the signal distribution (*b*) as a function of energy, for single pions and multiparticle events ("jets"). Results are given for the RD52 dual-readout calorimeter signals, obtained with the rotation method [32].

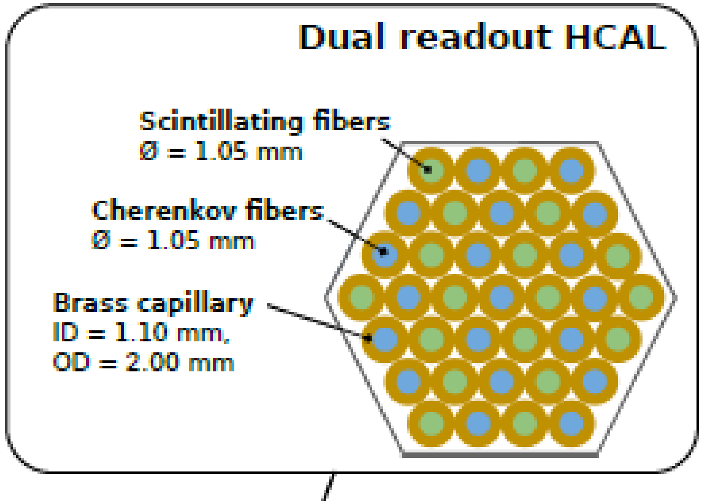
Just ignore the "jets" curves. They are a strange measurement. The single pion resolution has a stochastic term of 30%, even for this small calorimeter. Pretty good!

Our simulation (Lucchini)

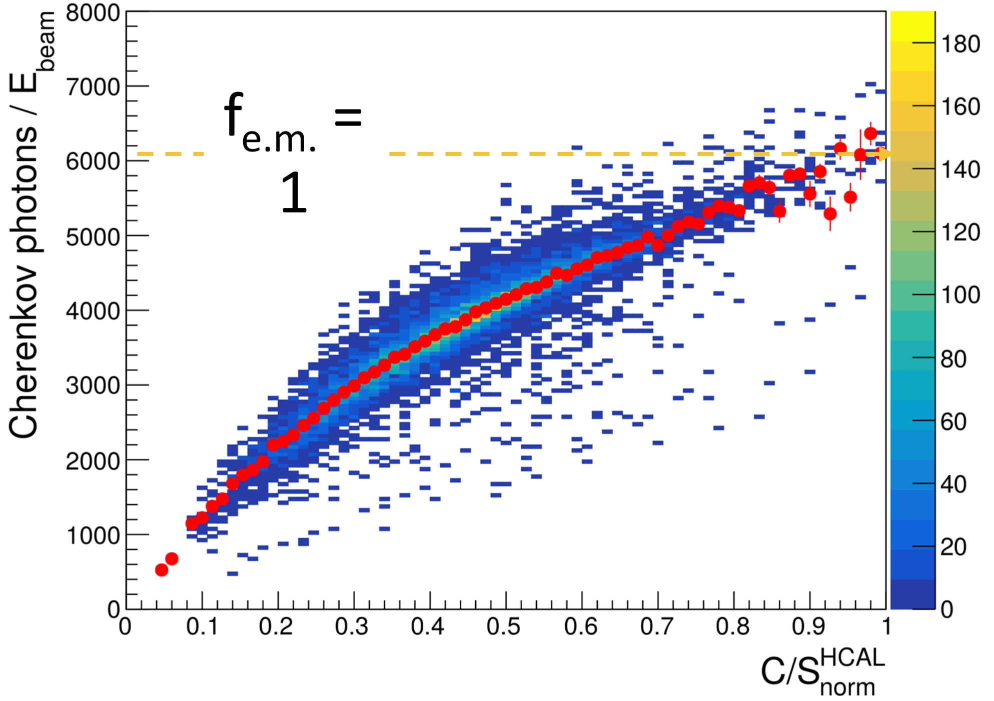
https://arxiv.org/abs/2008.00338

Dual readout correction works as expected,

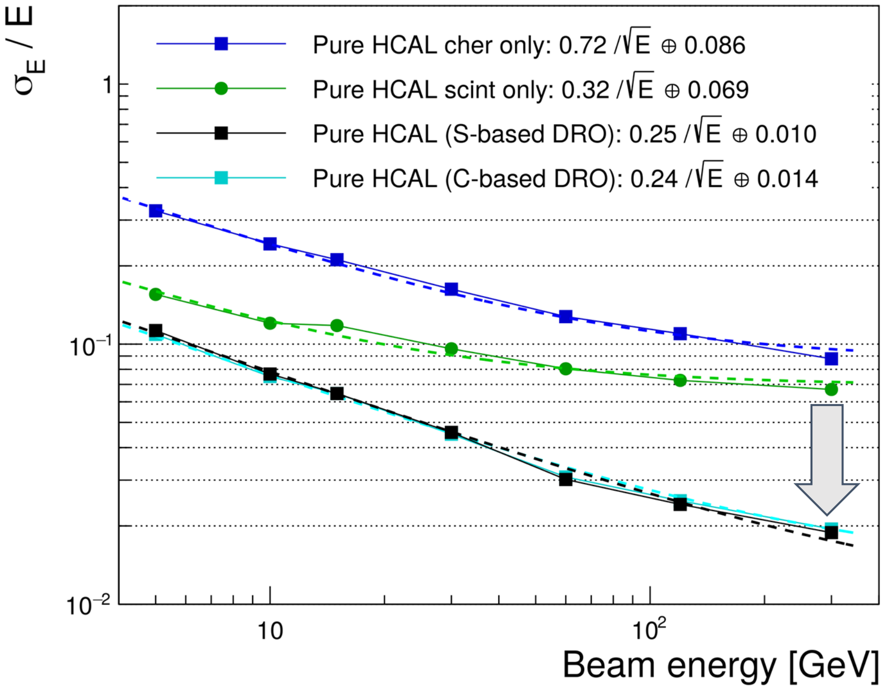
- ○ delivering ~25%/√E ⊕ 1% to hadrons for a large calorimeter
- ○ linearity and gaussian distributions are restored



DRO correction for C



energy resolution to $K^{0,L}$



← cher only

← scint only

← DRO corrected

However, this method also works in crystals

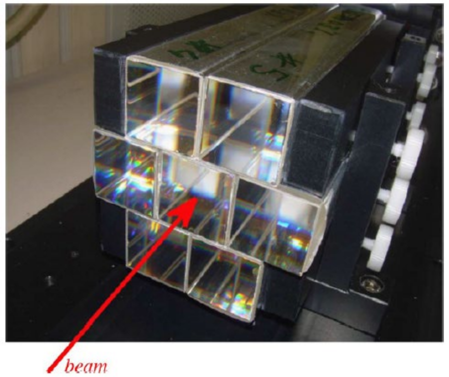


Fig. 2. The PWO matrix consisted of seven crystals with dimensions of 3 × 3 × 20 cm^3. These were arranged as shown in the figure and the beam entered the matrix in the central crystal. All crystals were individually wrapped in aluminized mylar. Both the upstream and downstream end faces were covered with filters. See text for details.

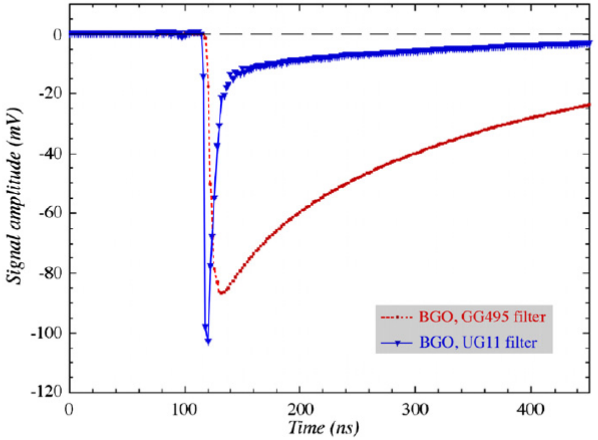


Fig. 3. The time structure of typical signals measured in a single BGO crystal, placed perpendicular to the beam line. The crystal was equipped on one side with a yellow filter, and on the other side with a UV filter, and read out with small, fast PMTs. The signals were measured with the sampling oscilloscope at a rate of 0.5 GHz, or 2.0 ns per sample.

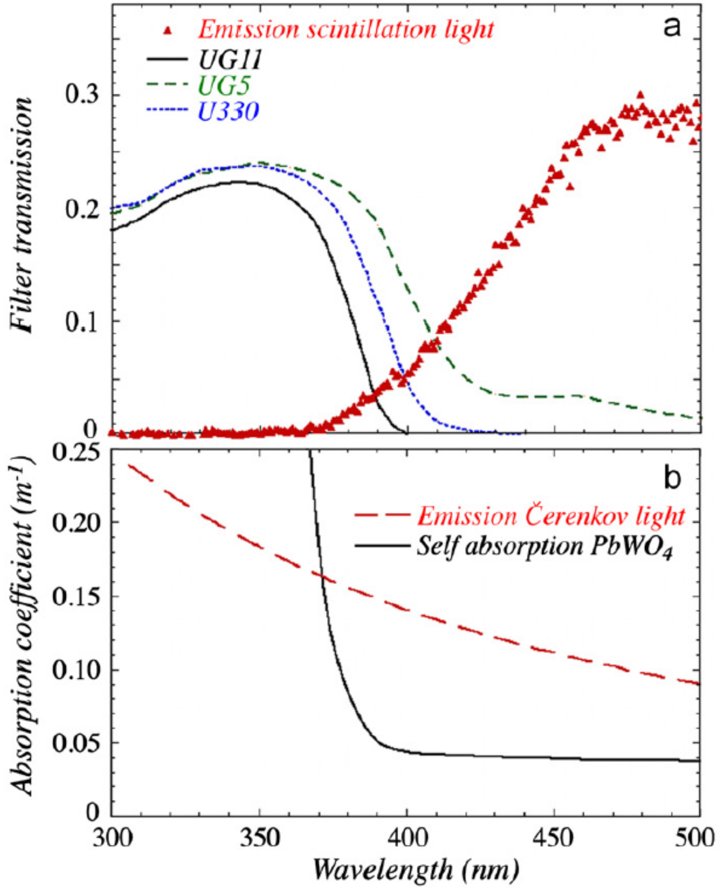


Fig. 5. Emission and absorption characteristics relevant to the PbWO$_4$ crystal matrix. Diagram (a) shows the emission spectrum of the scintillation light, as well as the transmission characteristics of three filters used to obtain the Čherenkov signals. In diagram (b), the Čherenkov spectrum is plotted, together with the self-absorption coefficient of the PbWO$_4$ crystals, as a function of the wavelength [5].

Detection of electron showers in dual-readout crystal calorimeters (https://www.sciencedirect.com/science/article/pii/S0168900212014520)

crystals

Why did they move away from crystals? Crystals would allow EM resolutions of $3\%/\sqrt{E}$?

- Not a compelling case for precision EM resolution
- At the time they did these studies, SiPMs were not well developed. PMTs are expensive, and they thought they could only afford one per crystal. But to see the small Cherenkov signal over the large scintillation signal, had to cut down the scintillation signal, ruining the precision EM resolution. All the cost of crystals and none of the benefits
- PMTs also had limited wavelength sensitivity, didn't go much below or above the scintillation region.
- Also because of the readout constraints, thought the calorimeter could not be high granularity with crystals

But Sipmms change this.

Lucchini/Tully/Eno/IDEA/RD52 proposal

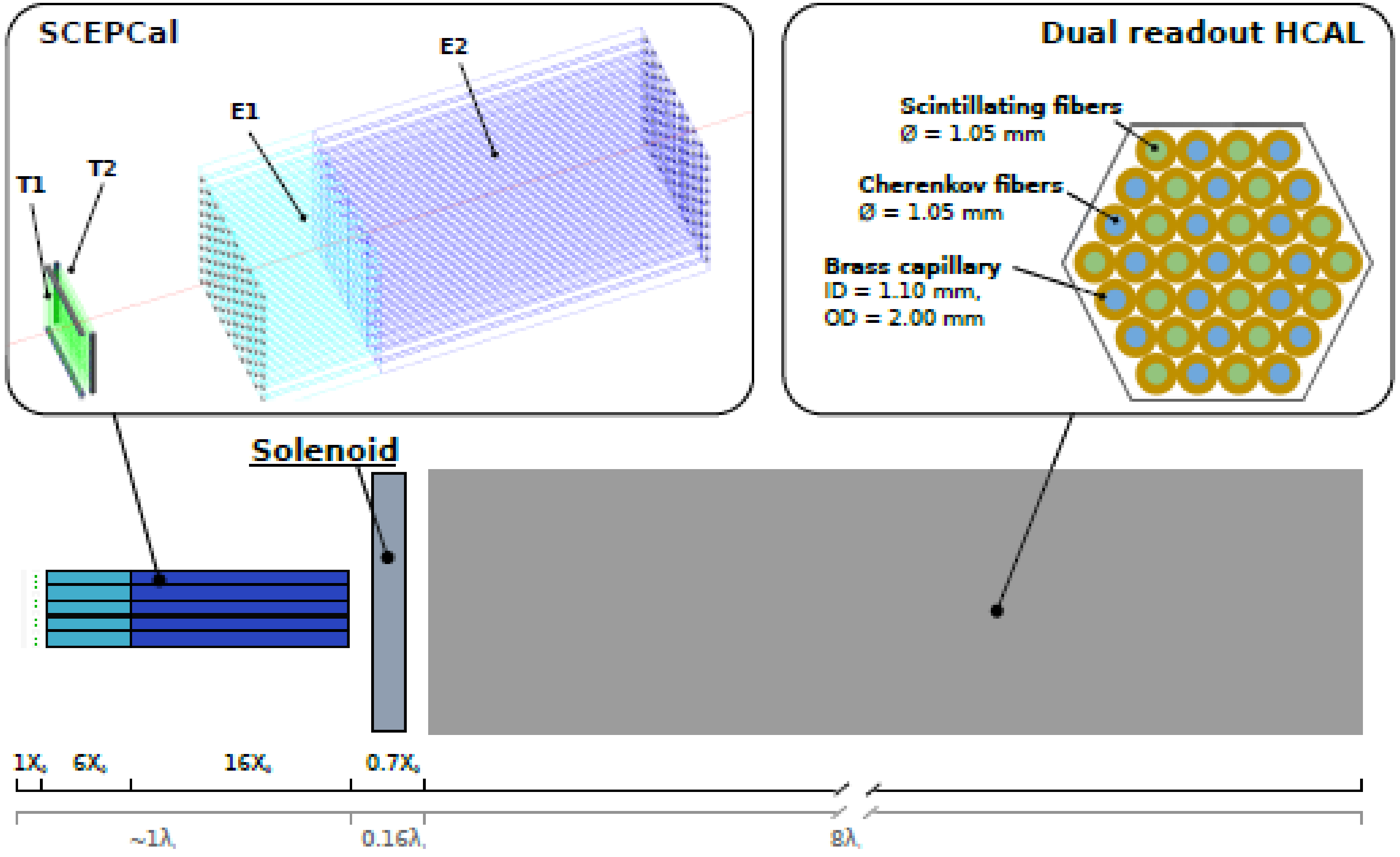
Drawing from the pioneering work of RD52, but upgrading for new developments in inexpensive, high-QE, tailored-wavelength sipmms See: https://arxiv.org/abs/2008.00338
Also see Snowmass LOI: SNOWMASS21-IF6-008.pdf

σ_t ~ 20 ps

- **Timing layer**
  - LYSO:Ce crystals (~$1X_0$)
  - 3x3x54 mm³ active cell
  - 3x3 mm² SiPMs (15-20 um)

σ_E/E ~ 3%/√E

- **ECAL layer**
  - PbWO crystals
  - Front segment (~$6X_0$ ~50 mm)
  - Rear segment (~$16X_0$ ~140 mm)
  - 10x10 mm² crystal
  - 5x5 mm² SiPMs (10-15 um)
  - 3 SiPMs (one on entrance, two on exit)



CMS ECAL crystals are 22x22x230 mm

Some crystal options

Also BSO: better in theory but cost unknown

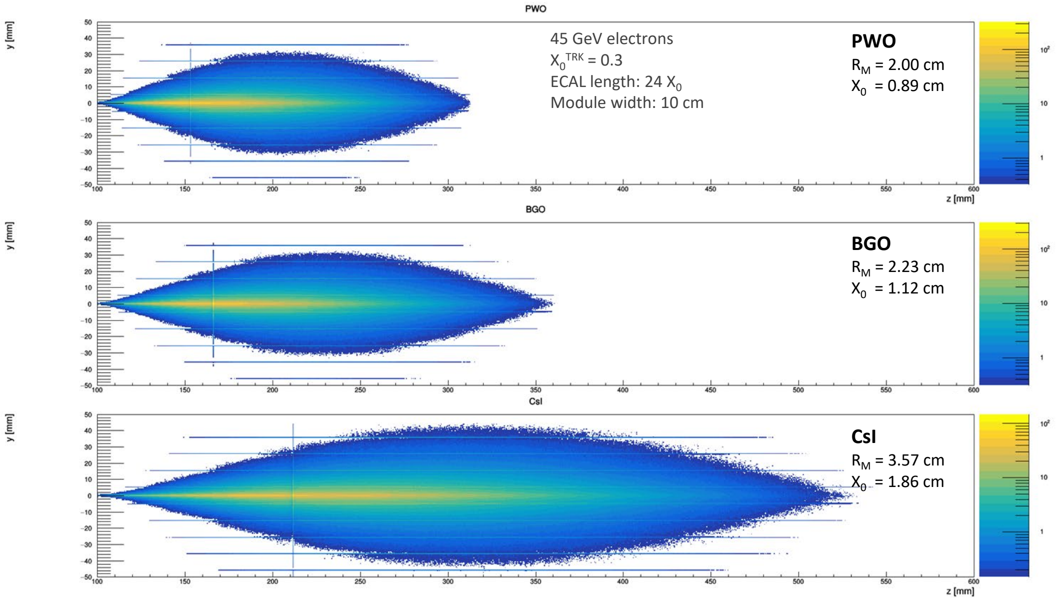
- **PWO**: the most compact, the fastest, the cheapest
- BGO: in between (potential for dual readout)
- CsI: the less compact, the slowest, the brightest

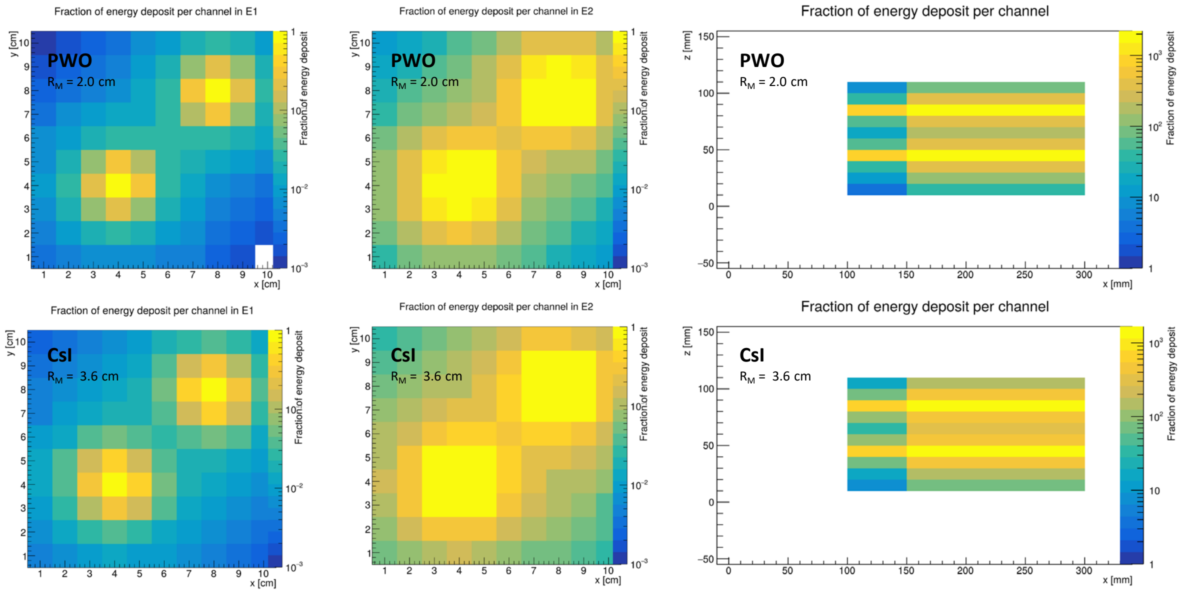
better for PFA

better stochastic term

Crystal	Density g/cm³	λ_I cm	X_0 cm	R_M cm	Relative LY @ RT	Decay time ns	Photon density (LY / τ_D) ph/ns	dLY/dT (% / °C)	Cost (10 m³) $/cm³	Cost*X_0 $/cm²
PWO	8.3	20.9	0.89	2.00	1	10	0.10	-2.5	8	7.1
BGO	7.1	22.7	1.12	2.23	70	300	0.23	-0.9	7	7.8
CsI	4.5	39.3	1.86	3.57	550	1220	0.45	+0.4	4.3	8.0

*Values from: Journal of Physics: Conference Series **293** (2011) 012004*





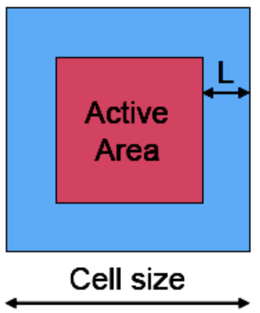
Technological advancements (**SiPMs**)

- Many technological advancements in the field of photodetectors
- Compact and robust SiPMs with small cell size (high dynamic range) extending and enhancing sensitivity in a broad range of wavelengths

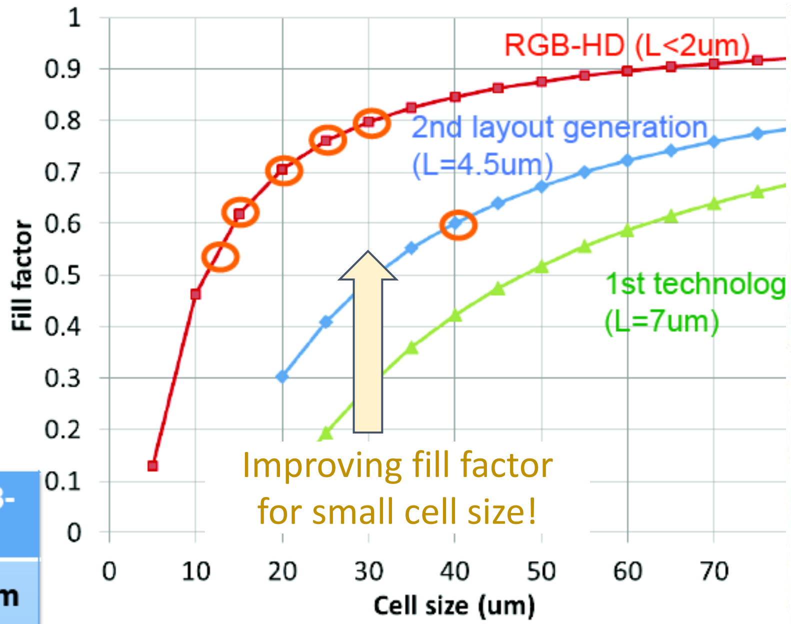
RGB-HD SiPM technology

FBK

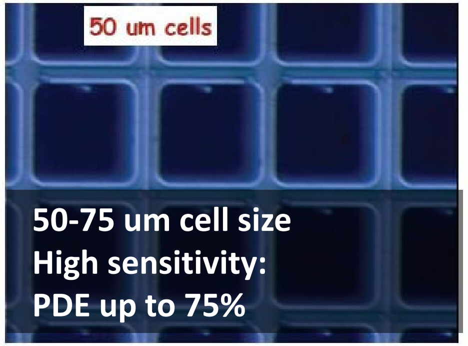
SiPM Cell, top view



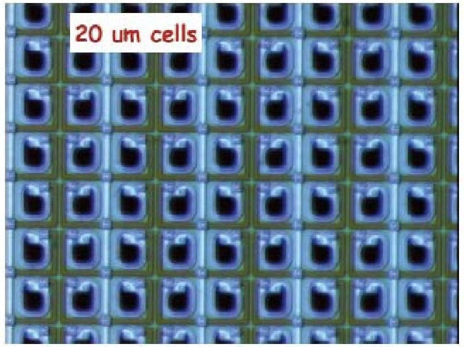
	Std. SiPM RBG	RGB-HD
CS	40 μm	15 μm
FF	60 %	62 %

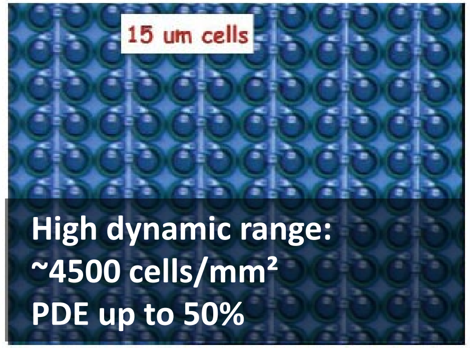


Improving fill factor for small cell size!

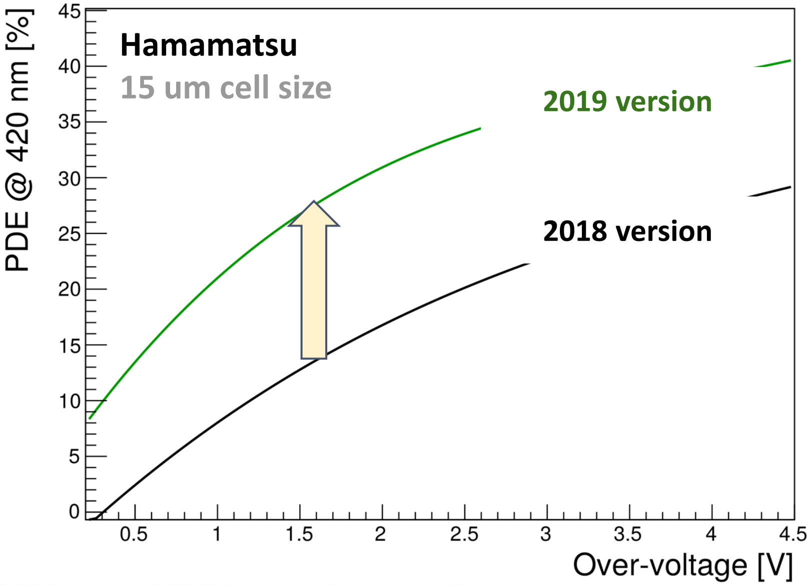


50-75 um cell size
High sensitivity:
PDE up to 75%





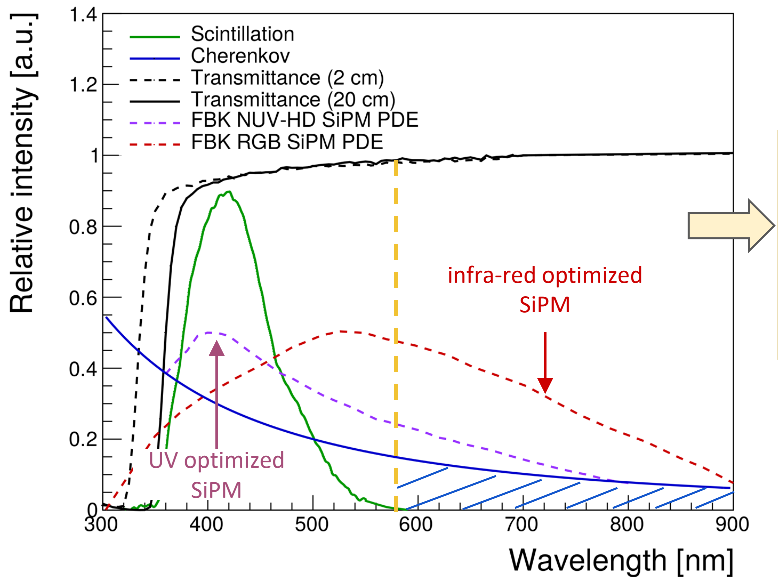
High dynamic range:
~4500 cells/mm^2
PDE up to 50%



Cherenkov detection in PWO and BGO

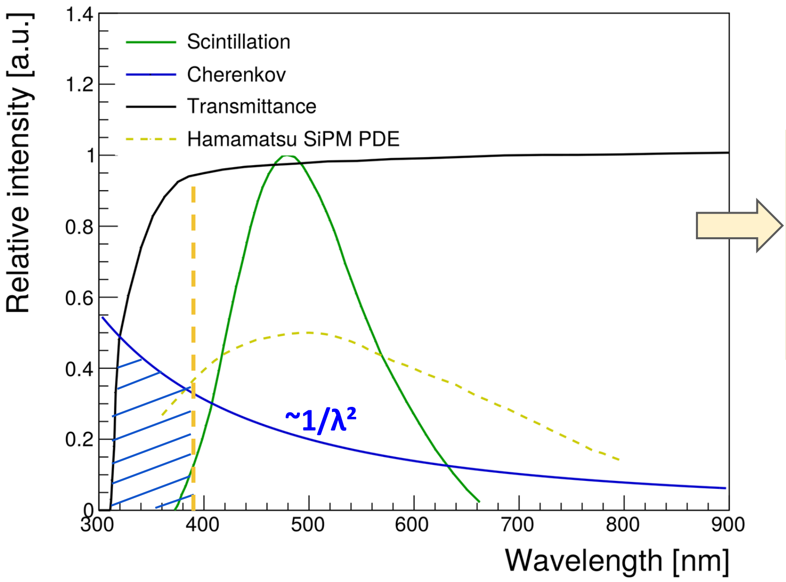
- Sensitivity in both the UV and infrared region with Silicon Photomultipliers
- At least two crystal candidates for a compact, cost-contained ECAL with DRO capabilities:
  - **PWO** (e.g. CMS) and **BGO** (e.g. L3)
  - Detect Cherenkov photons in either the UV (BGO) or infrared region (PWO)

PWO



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

BGO



BGO has a larger stokes shift, wider range of transparency for UV Cherenkov

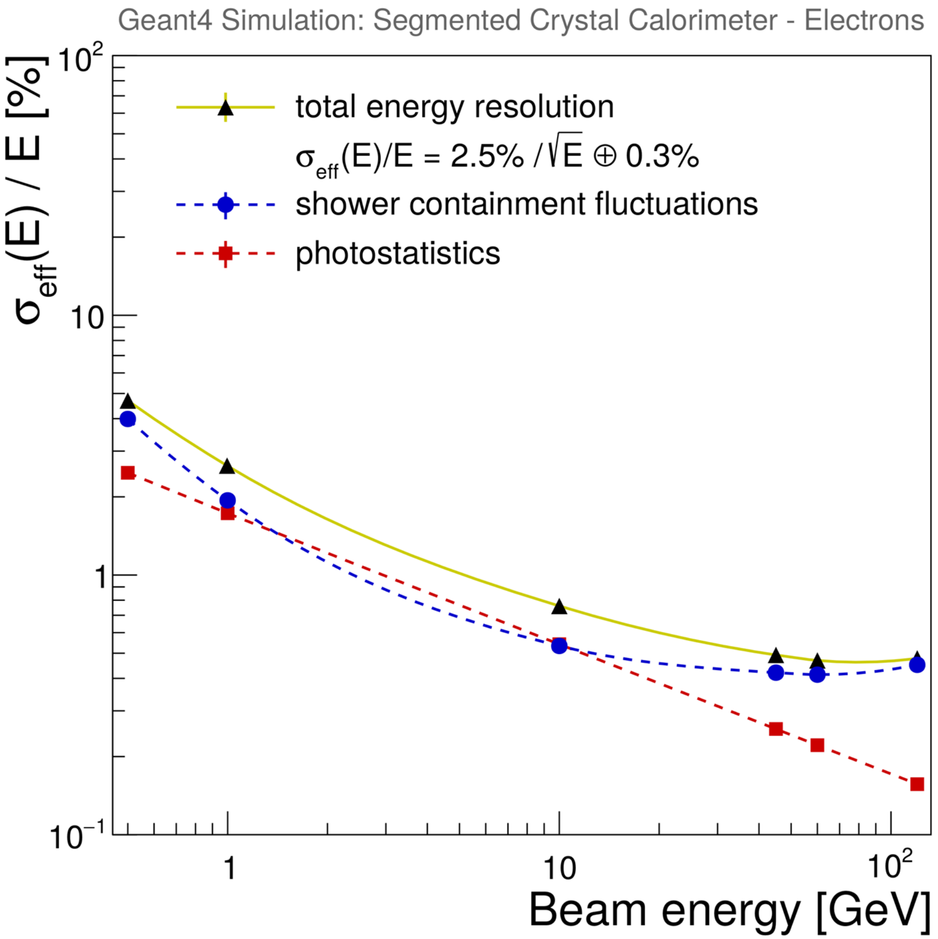
~10% of signal from Cherenkov in CMS ECAL (N Akchurin et al.) increasing due to radiation damage that filters out the UV scintillation component!

Cherenkov signal detected and exploited for timing applications even for electrons from 511 keV ɣ-rays!
Stefan Gundacker et al., 2020 Phys. Med. Biol.65 025001

SCEPCAL e.m. resolution

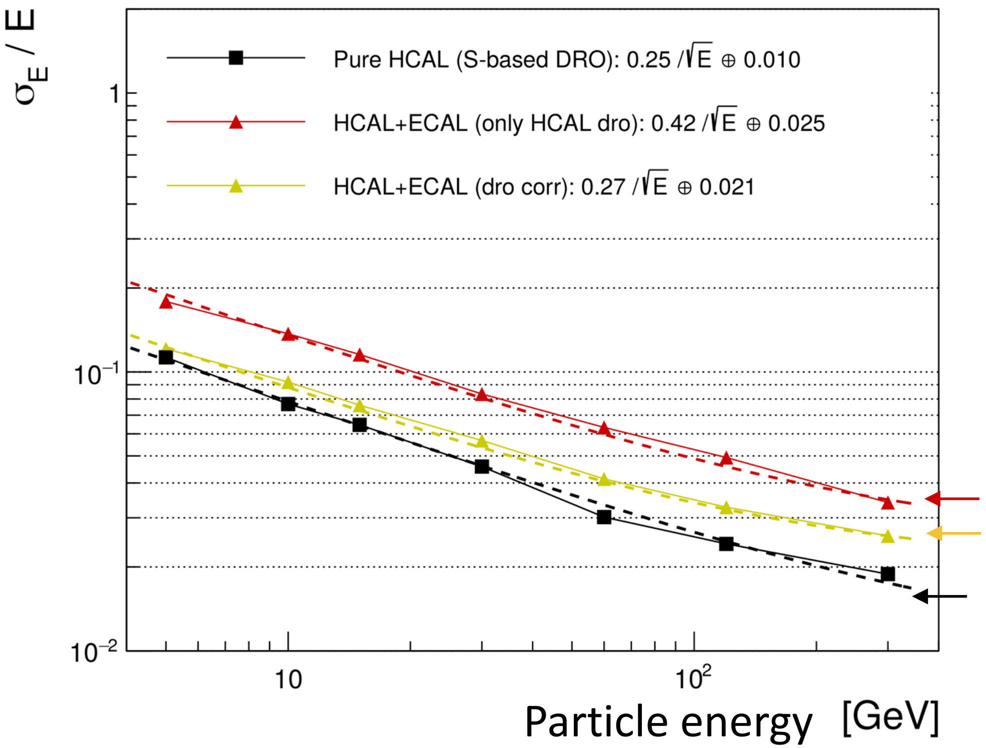
- Contributions to energy resolution:
  - Shower containment fluctuations
    - Longitudinal leakage
    - Tracker material budget
    - Services for front layer readout
  - Photostatistics
    - Tunable parameter depending on:
      - SiPM choice
      - Crystal choice
  - Noise
    - Negligible with SiPMs
      - low dark counts, high gain
  - Channels intercalibration
    - ~0.5% constant term (not in the plot)

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



Hadronic resolution

1. Correct the energy deposit in the HCAL with DRO
2. Correct the energy deposit in the back section of the ECAL with DRO
3. Calibrated sum of ECAL+HCAL



adding raw ECAL energy

adding DRO corr ECAL

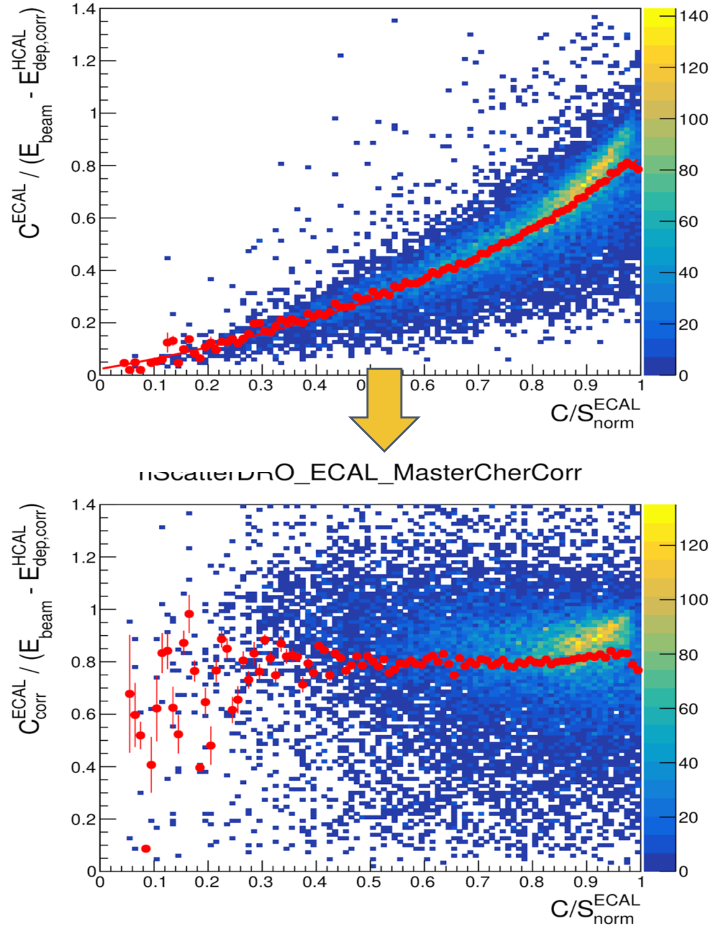
pure HCAL

~27%/√E ⊕ 2%

Good stochastic term recovered with ECAL Dual Readout!

DRO correction for the energy deposit in the ECAL

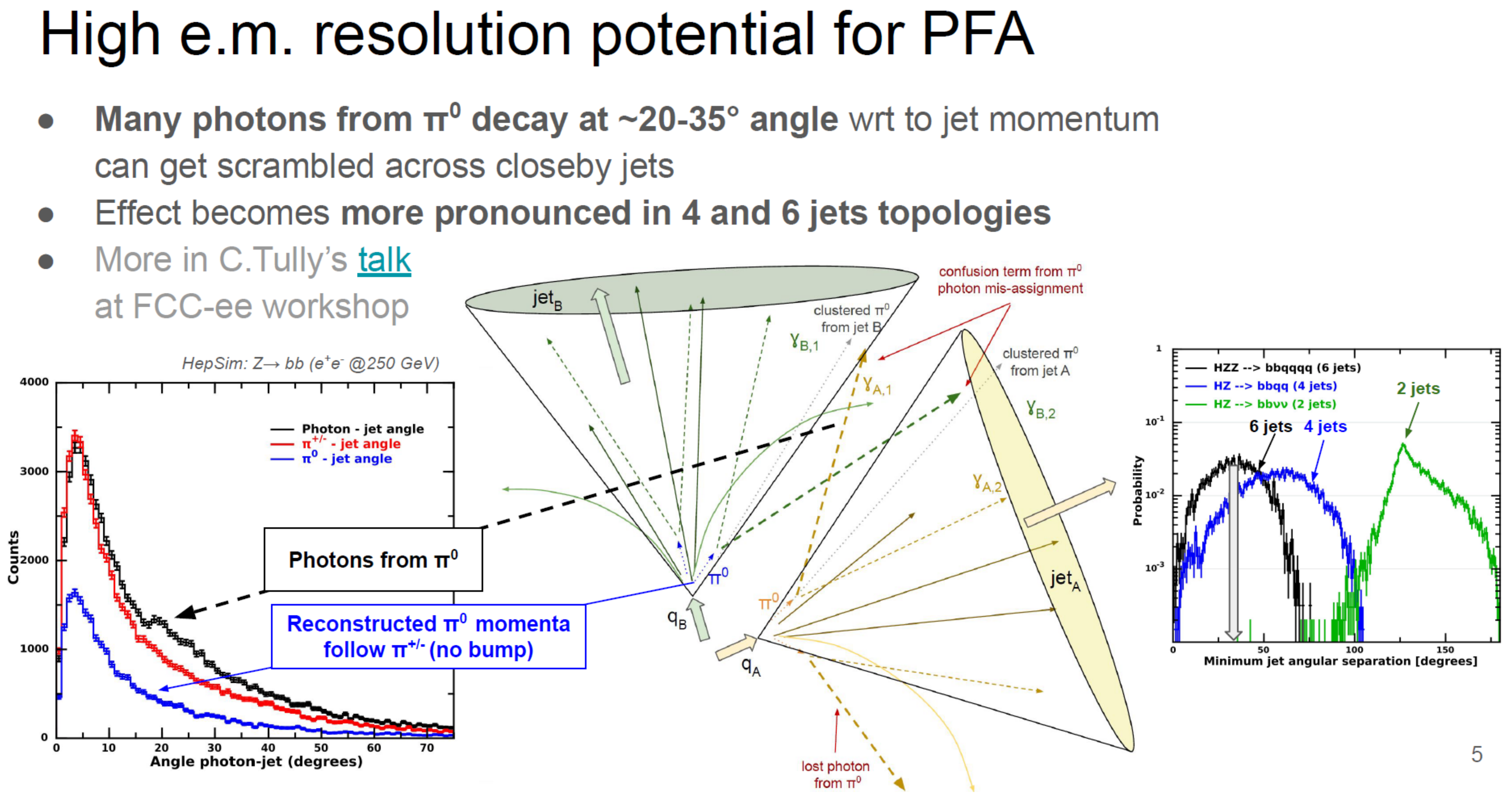
before correction



after correction

PFA benefits

See Marco's work in our paper on this



High e.m. resolution potential for PFA

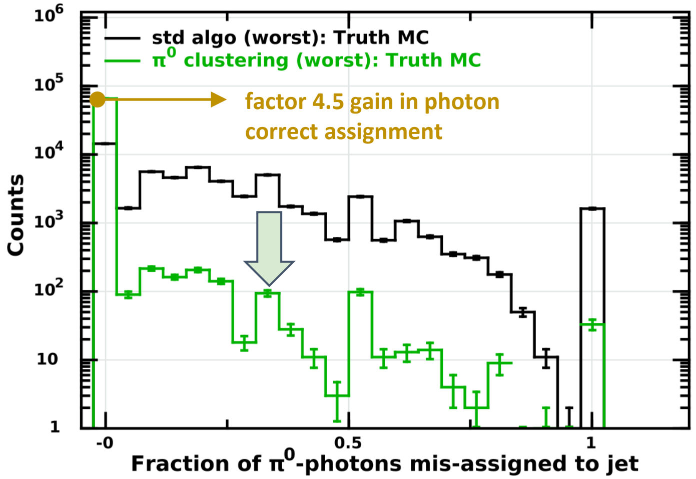
- **Many photons from π^0 decay at ~20-35° angle** wrt to jet momentum can get scrambled across closeby jets
- Effect becomes **more pronounced in 4 and 6 jets topologies**
- More in C.Tully's talk at FCC-ee workshop

Improvements in photon-to-jet assignment

- **High e.m. resolution enables** photons **clustering into π⁰'s** by reducing their angular spread with respect to the corresponding jet momentum
- **Improvements in the fraction of photons correctly clustered to a jet** sizable only for e.m. resolutions of ~3-5%/√(E)

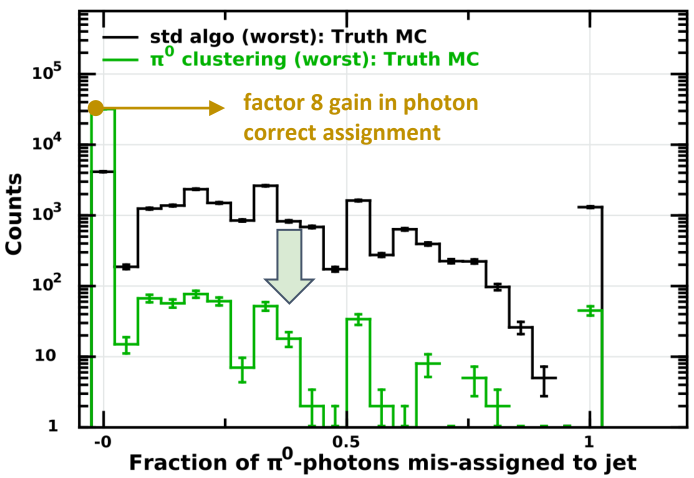
ideal e.m. resolution

worst jet in a 4-jets topology



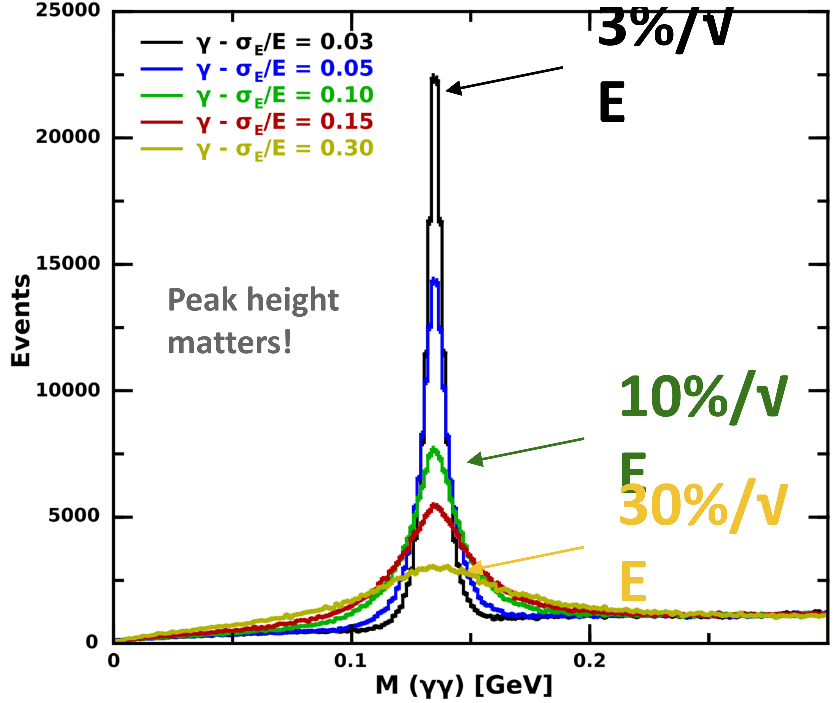
factor 4.5 gain in photon correct assignment

worst jet in a 6-jets topology



factor 8 gain in photon correct assignment

HepSim: Z→ bb (e⁺e⁻ @250 GeV)



3%/√E

Peak height matters!

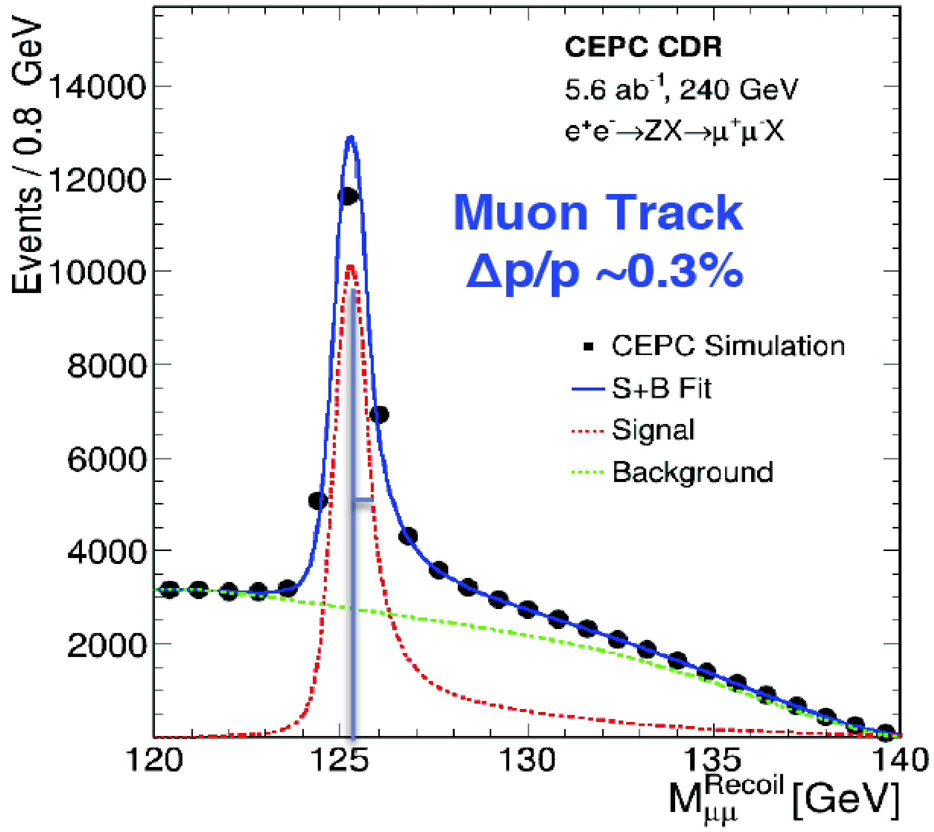
10%/√E

30%/√E

Z to e^+e^- Brem recovery

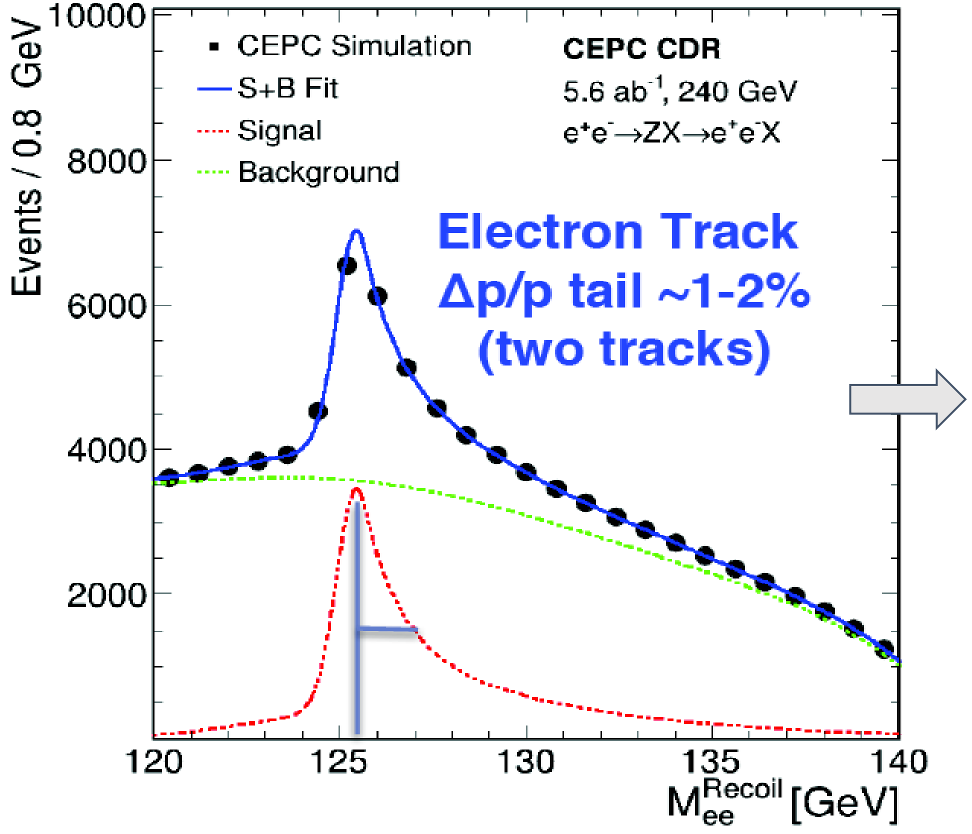
Example from CEPC CDR reference design
(electron tracks with no Bremsstrahlung recovery)

Z→$\mu^+\mu^-$ Recoil



Muon Track
Δp/p ~0.3%

Z→e^+e^- Recoil

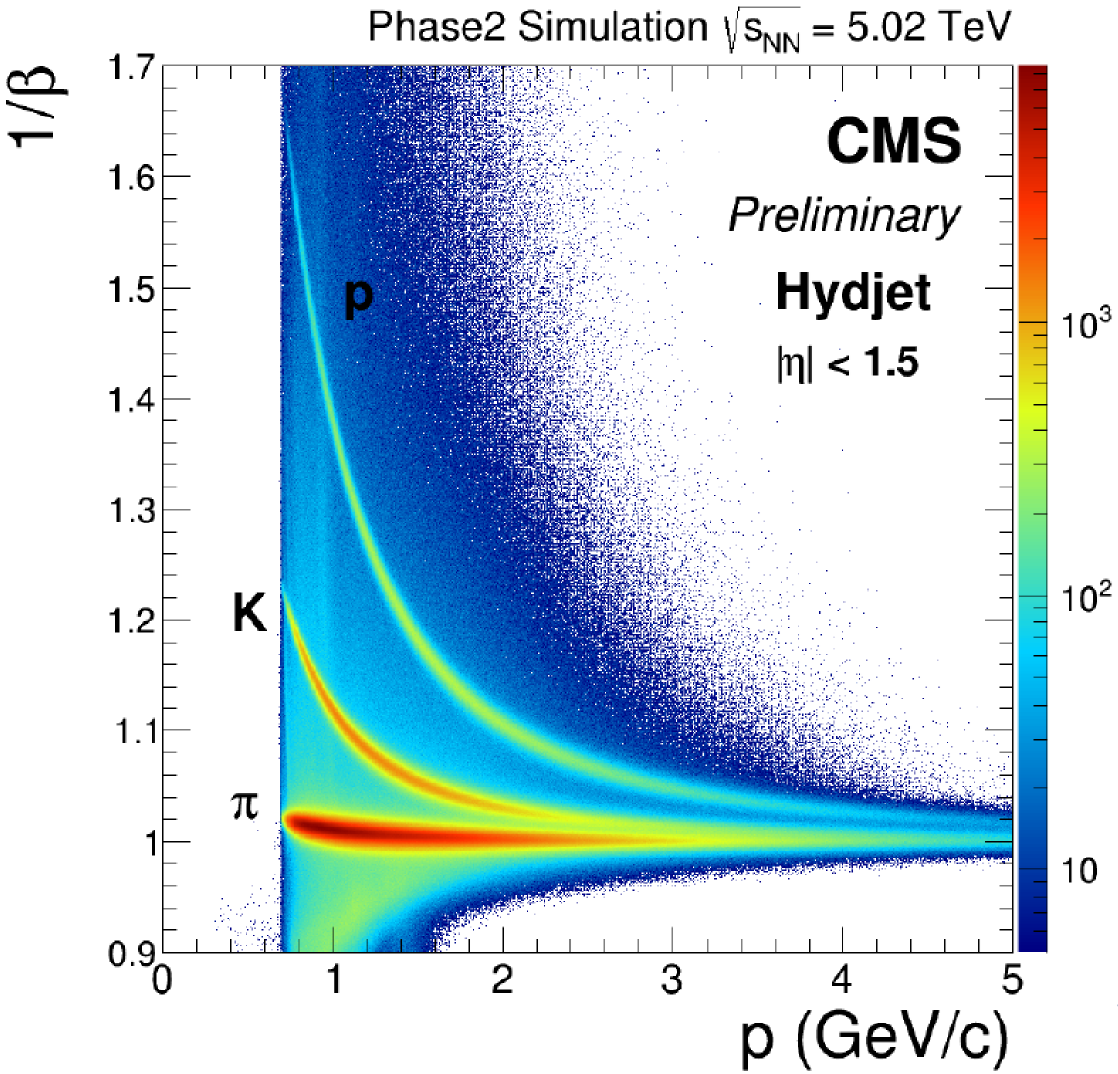


Electron Track
Δp/p tail ~1-2%
(two tracks)

~80% of resolution recovery with 3%/√(E)

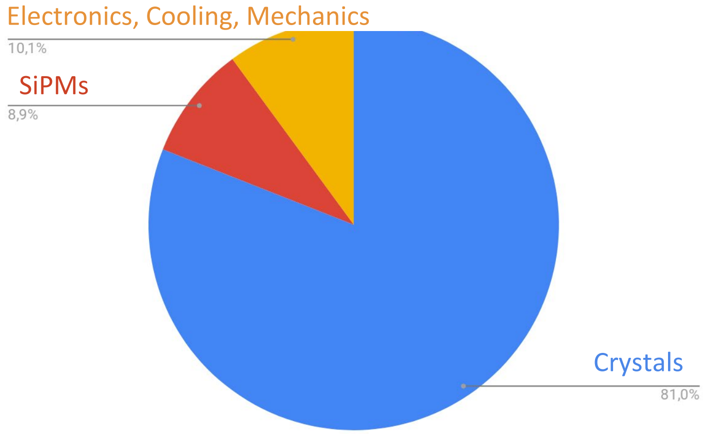
Flavor physics

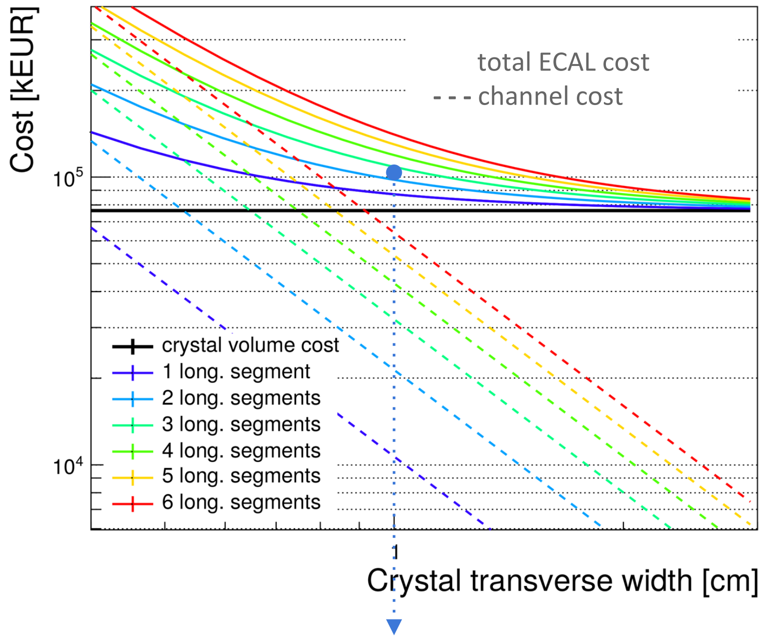
Precision EM resolution and timing could benefit flavor physics program



Cost-power drivers and optimization

- **Channel count** in **SCEPCal** is limited to **~2.5M**
  - 625k channels/layer (2 “timing layers” + “ECAL layers”)
- Cost drivers in **ECAL** layers (tot ~95M€):
  - **~81% crystals**, **9**% SiPMs, **10**% (electronics+cooling+mechanics)
  - **~19% of cost scales with channel count**
- Power budget driven by electronics: ~74 kW
  - 18.5 kW/layer
- Room for fine tuning of the segmentation and of the detector performance/cost optimization (see backup)





Reference design:
1 cm², 2 segments
cost ~ 95M€

Active members

Italy: actively working on testbeam work on the HCAL part

- Pisa
- Cagliari
- Roma la Sapienza
- Pavia
- Calabria

South Korea: simulation of the HCAL part

- Kyungpook

China: crystals and contact with Shanghai crystal

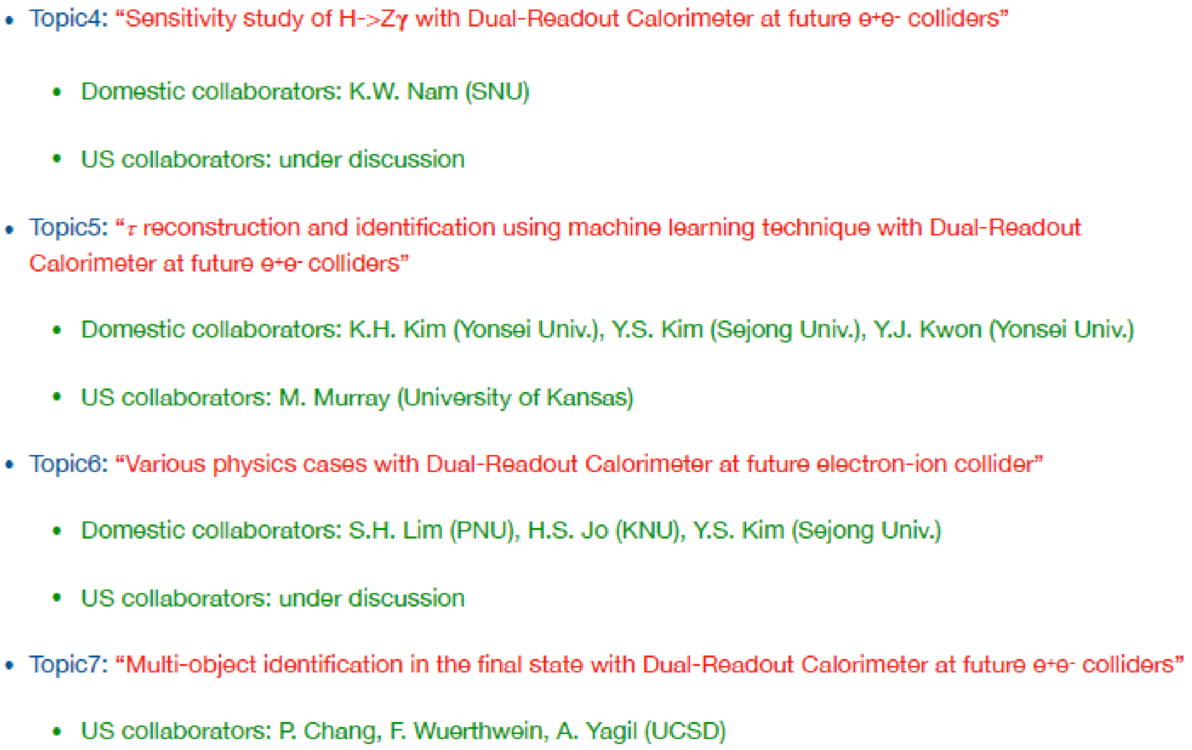
- IHEP (Liu and Ruan)

USA: in our copious spare time, working on simulations of the ECAL part and thinking about crystals

- Sarah Eno, Chris Tully, Marco Lucchini, Jianming Qian, Ren-Yuan Zhu, Sunanda Banerjee, Bob Hirosky, Harvey Newman, Nural Akchurin, John Hauptman, Toyoko Orimoto

Other US interest (gathered by Hwidong Yoo of Yongsei University)

- Totally seven topics are in pipeline
- Topic1: “Feasibility study of merging the MIP Timing Detector and Dual-Readout Calorimeter at future e^+e^- colliders”
  - Domestic collaborators: C.S. Moon (KNU), J.H. Yoo (Korea Univ.)
  - US collaborators: David Stuart (UCSB)
- Topic2: “Fast optical photon transport at GEANT4 with Dual-Readout Calorimeter at future e^+e^- colliders”
  - US collaborators: S.Y. Jun (Fermilab) & GEANT4 collaboration under discussion
- Topic3: “Heavy flavour tagging using machine learning technique with silicon vertex detector and Dual-Readout Calorimeter at future e^+e^- colliders”
  - Domestic collaborators: S.H. Lim (PNU)
  - US collaborators: Jin Huang (BNL), Qipeng Hu (LLNL)



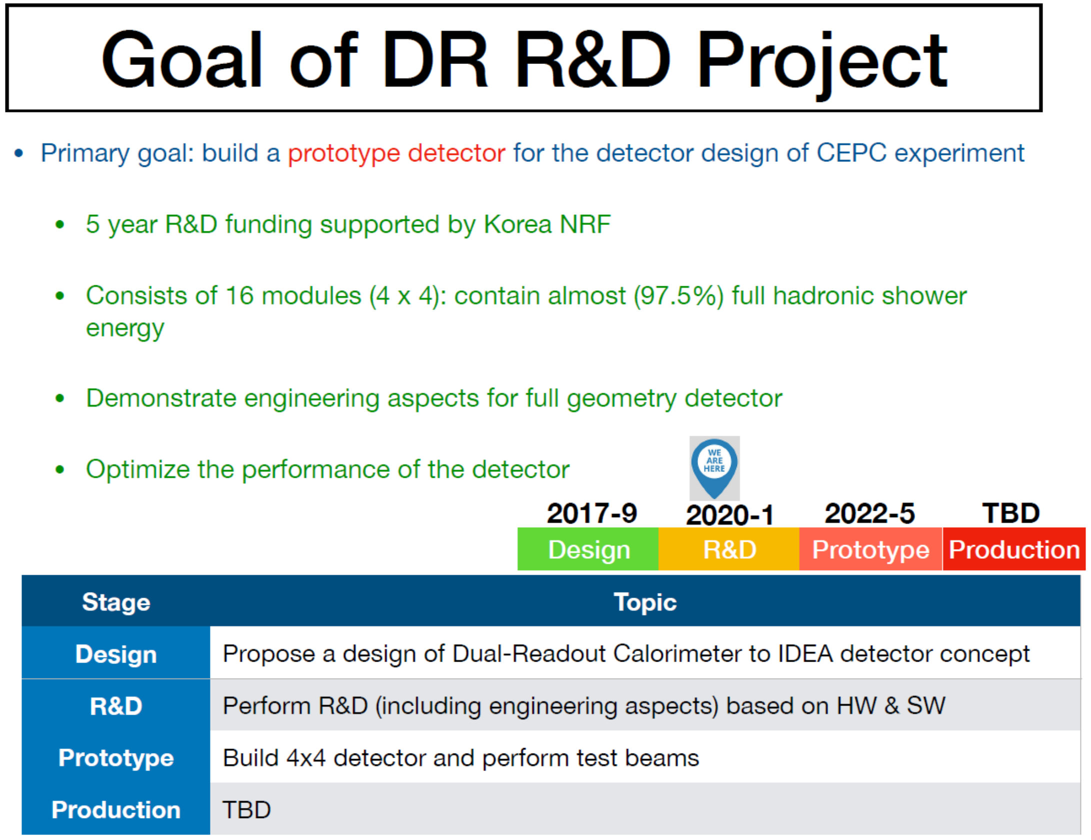
- Topic4: “Sensitivity study of H->Zγ with Dual-Readout Calorimeter at future e^+e^- colliders”
  - Domestic collaborators: K.W. Nam (SNU)
  - US collaborators: under discussion
- Topic5: “τ reconstruction and identification using machine learning technique with Dual-Readout Calorimeter at future e^+e^- colliders”
  - Domestic collaborators: K.H. Kim (Yonsei Univ.), Y.S. Kim (Sejong Univ.), Y.J. Kwon (Yonsei Univ.)
  - US collaborators: M. Murray (University of Kansas)
- Topic6: “Various physics cases with Dual-Readout Calorimeter at future electron-ion collider”
  - Domestic collaborators: S.H. Lim (PNU), H.S. Jo (KNU), Y.S. Kim (Sejong Univ.)
  - US collaborators: under discussion
- Topic7: “Multi-object identification in the final state with Dual-Readout Calorimeter at future e^+e^- colliders”
  - US collaborators: P. Chang, F. Wuerthwein, A. Yagil (UCSD)

Open questions

Almost everything

- How to support it mechanically?
- What is the jet as opposed to single particle resolution?
- How does upstream material affect the jet reconstruction?
- What is the best tracking system to go with this calorimeter? (current proposal is TPC, but this doesn’t work really for high intensity Z running)
- Can cms-style particle flow improve event reconstruction?
- How would segmentation affect tau reconstruction?
- Scintillation/Cherenkov separation can be achieved by wavelength filtering, timing, polarization. The default plan is wavelength separation. But can inexpensive electronics that includes timing help? Can pulse shape measurements in the readout help ()?
- The crystal dual readout hasn’t been done with modern photodetectors. But only those (according to simulation) allow this to work. We need to purchase crystals and do test beam measurements.
- Which crystal should we use? $PbWO_4$, BGO, BSO?
- Would the timing layer solve the beam background problems at muon colliders?
- Assembly needs to be understood

Other countries

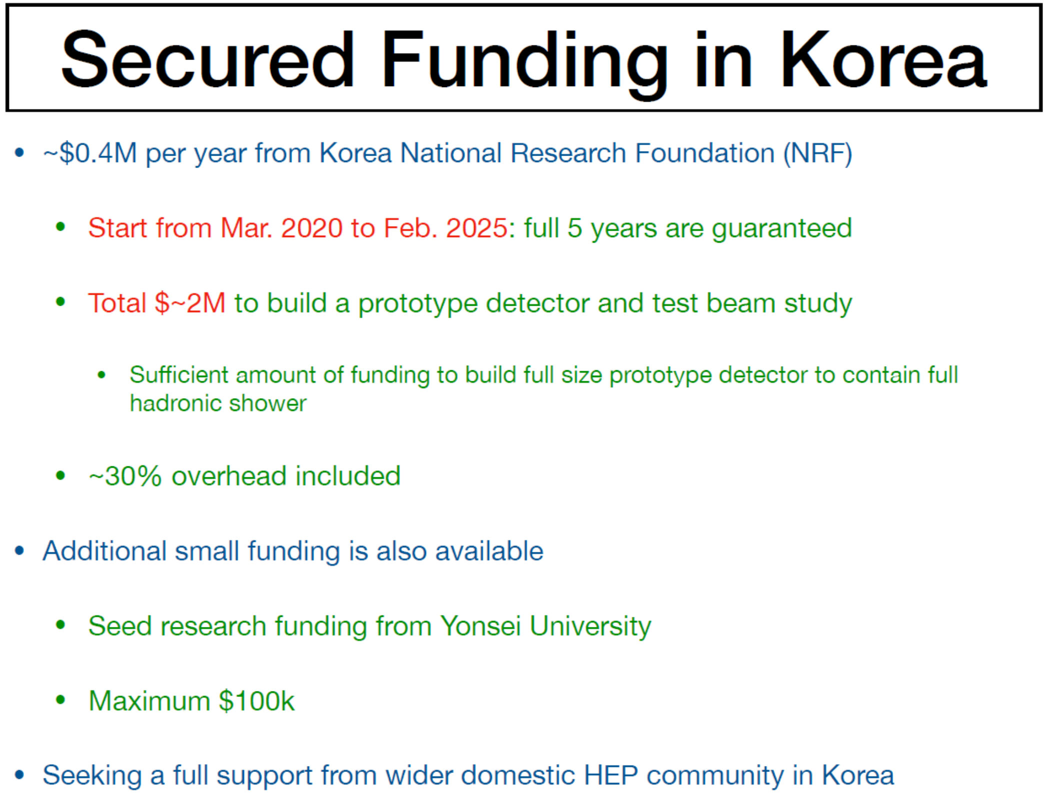


Goal of DR R&D Project

- Primary goal: build a prototype detector for the detector design of CEPC experiment
  - 5 year R&D funding supported by Korea NRF
  - Consists of 16 modules (4 x 4): contain almost (97.5%) full hadronic shower energy
  - Demonstrate engineering aspects for full geometry detector
  - Optimize the performance of the detector

2017-9	2020-1	2022-5	TBD
Design	R&D	Prototype	Production

Stage	Topic
Design	Propose a design of Dual-Readout Calorimeter to IDEA detector concept
R&D	Perform R&D (including engineering aspects) based on HW & SW
Prototype	Build 4x4 detector and perform test beams
Production	TBD



Secured Funding in Korea

- ~$0.4M per year from Korea National Research Foundation (NRF)
  - Start from Mar. 2020 to Feb. 2025: full 5 years are guaranteed
  - Total $~2M to build a prototype detector and test beam study
    - Sufficient amount of funding to build full size prototype detector to contain full hadronic shower
  - ~30% overhead included
- Additional small funding is also available
  - Seed research funding from Yonsei University
  - Maximum $100k
- Seeking a full support from wider domestic HEP community in Korea

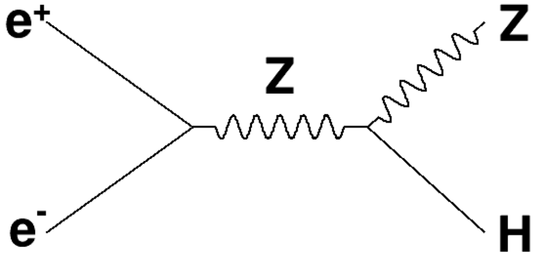
Is the US funding any area of future detector R&D this well? Sad!

Conclusion

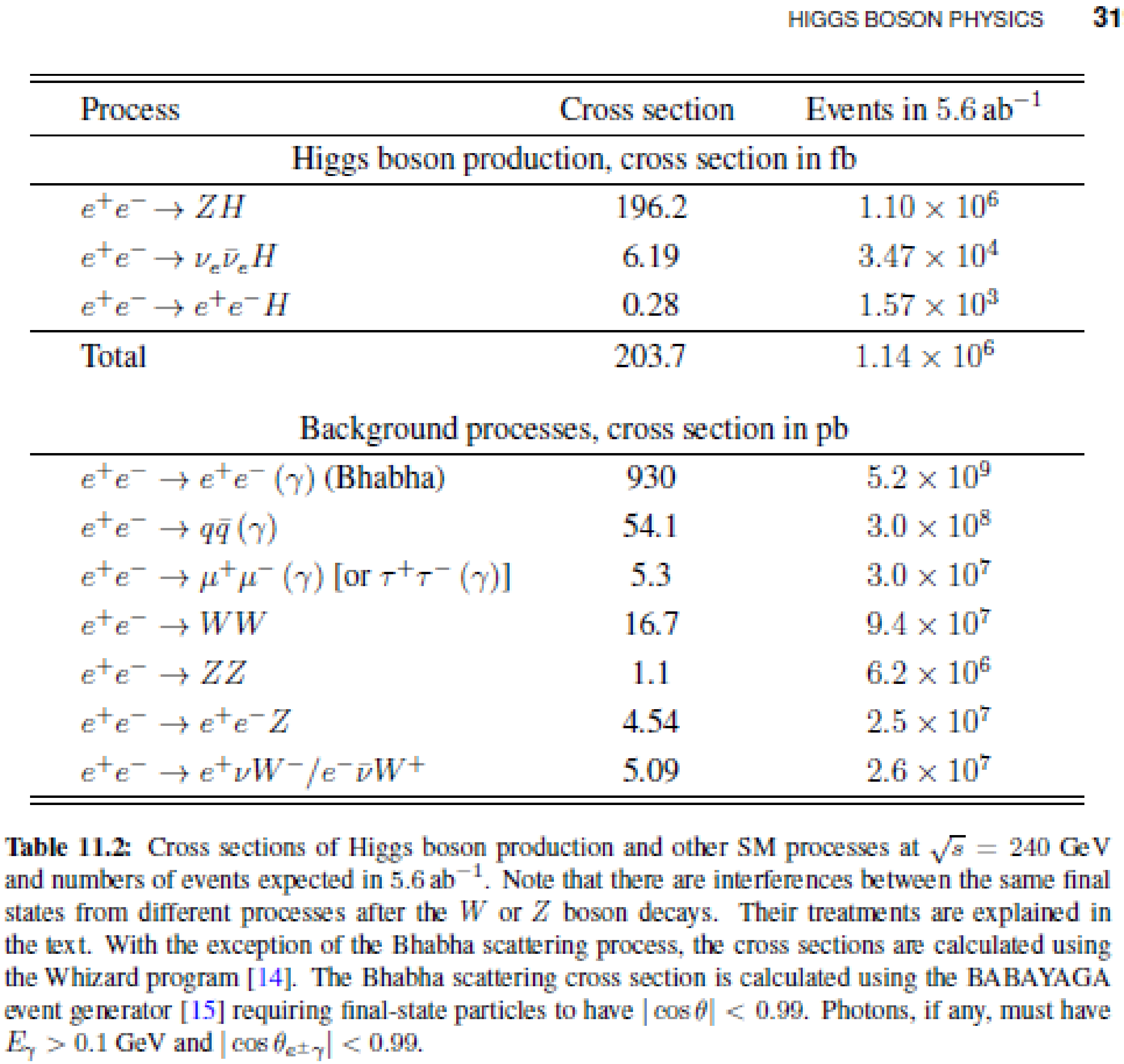
- Dual readout is an exciting complementary technology that can deliver the needed calorimeter behavior
- It can also allow precision EM calorimetry
- SiPM advances have been crucial to extended the possibilities
- Lots of work to do! Come join us!

BACKUP

Calorimetry for future e^+e^- Higgs and Z factories



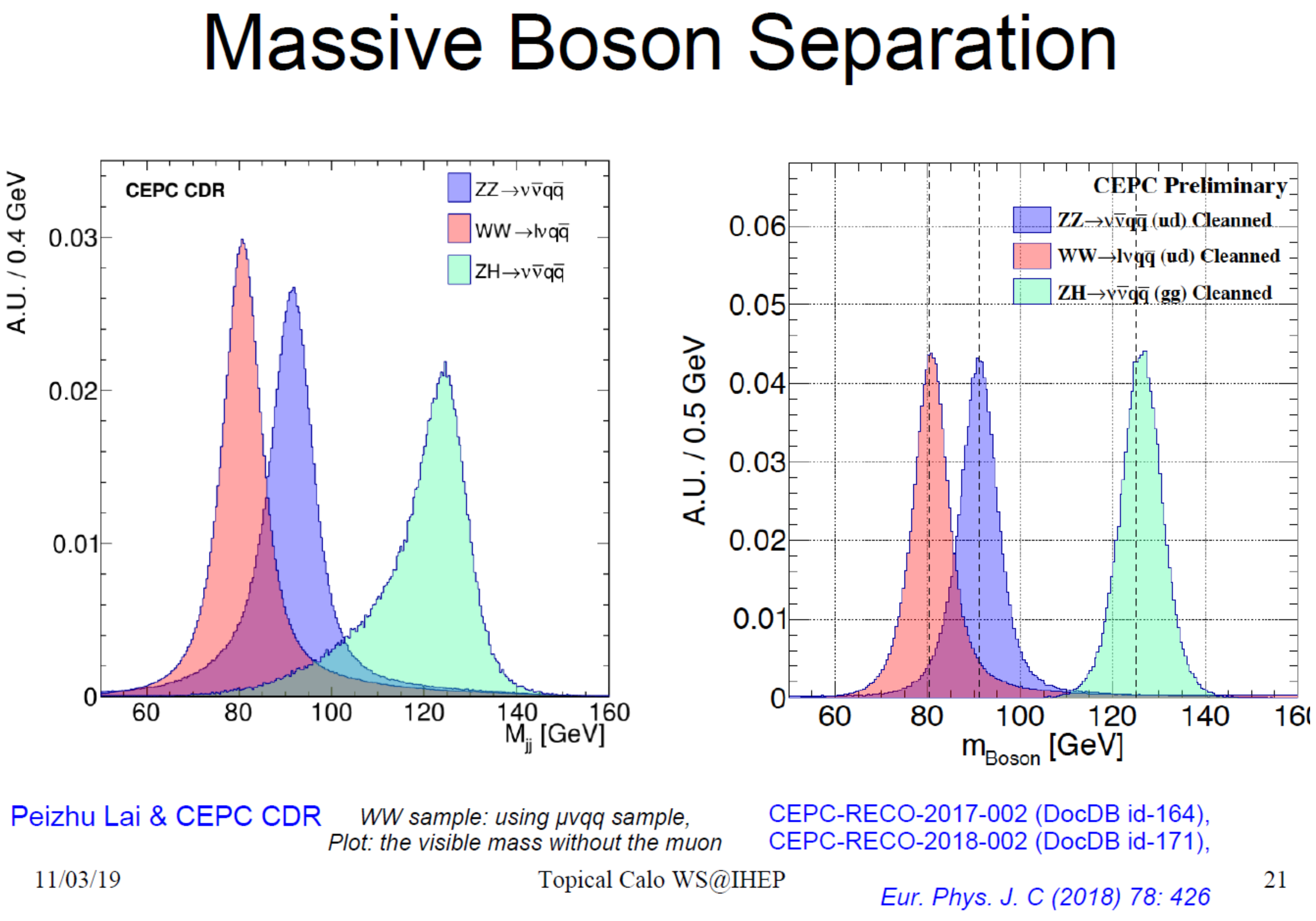
Higgs can be identified independent of decay mode using the “missing mass “ or “boson recoil mass” method, where you identify the Z and use its 3-momentum as the 3-momentum of the recoil particle and the center-of-mass collision energy minus the visible energy as the energy, requiring that to be consistent with the Higgs mass. Mass peak can distinguish ZH from WW, ZZ.


HIGGS BOSON PHYSICS 319

Process	Cross section	Events in 5.6 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	196.2	1.10×10^6
$e^+e^- \to \nu_e\bar{\nu}_e H$	6.19	3.47×10^4
$e^+e^- \to e^+e^- H$	0.28	1.57×10^3
Total	203.7	1.14×10^6
Background processes, cross section in pb		
$e^+e^- \to e^+e^- (\gamma)$ (Bhabha)	930	5.2×10^9
$e^+e^- \to q\bar{q} (\gamma)$	54.1	3.0×10^8
$e^+e^- \to \mu^+\mu^- (\gamma)$ [or $\tau^+\tau^- (\gamma)$]	5.3	3.0×10^7
$e^+e^- \to WW$	16.7	9.4×10^7
$e^+e^- \to ZZ$	1.1	6.2×10^6
$e^+e^- \to e^+e^- Z$	4.54	2.5×10^7
$e^+e^- \to e^+\nu W^-/e^-\bar{\nu}W^+$	5.09	2.6×10^7

Table 11.2: Cross sections of Higgs boson production and other SM processes at $\sqrt{s} = 240$ GeV and numbers of events expected in 5.6 ab^{-1}. Note that there are interferences between the same final states from different processes after the W or Z boson decays. Their treatments are explained in the text. With the exception of the Bhabha scattering process, the cross sections are calculated using the Whizard program [14]. The Bhabha scattering cross section is calculated using the BABAYAGA event generator [15] requiring final-state particles to have $|\cos\theta| < 0.99$. Photons, if any, must have $E_\gamma > 0.1$ GeV and $|\cos\theta_{e^\pm\gamma}| < 0.99$.

Separate EWK bosons



Massive Boson Separation

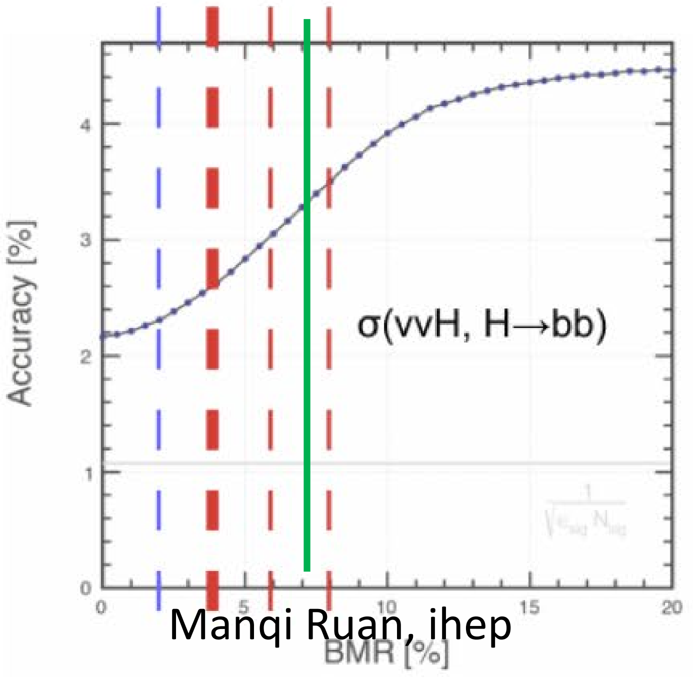
Peizhu Lai & CEPC CDR

WW sample: using μvqq sample,
Plot: the visible mass without the muon

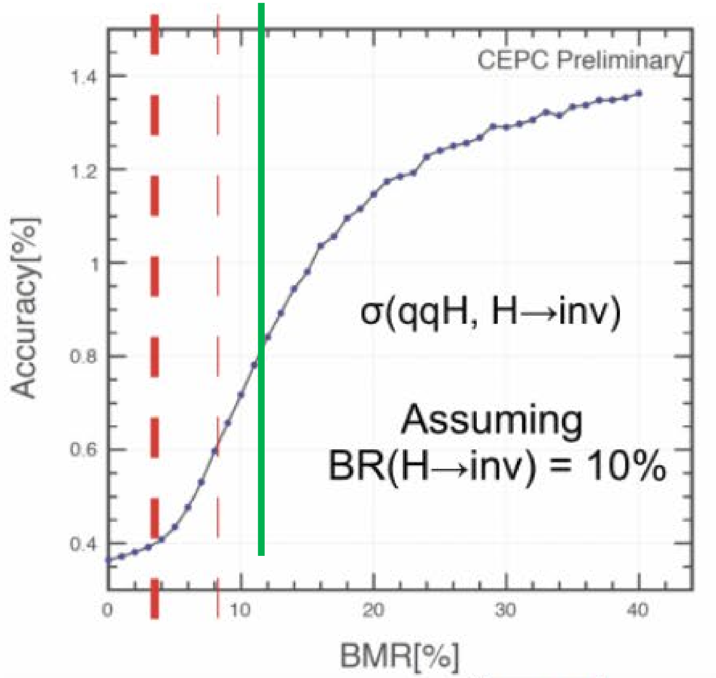
CEPC-RECO-2017-002 (DocDB id-164),
CEPC-RECO-2018-002 (DocDB id-171),
Eur. Phys. J. C (2018) 78: 426

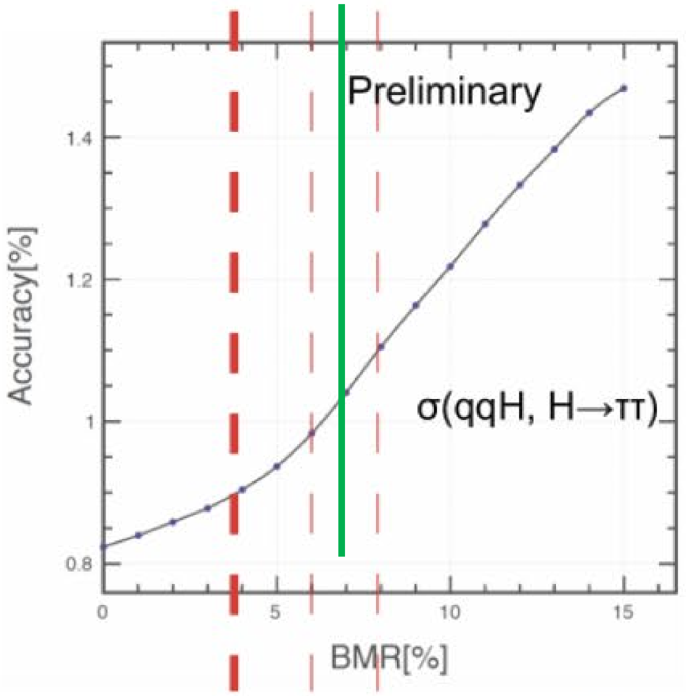
Jet resolution is essential to $e^+ e^-$ Higgs factory calorimetry

Boson Mass Resolution (BMR)



Manqi Ruan, ihep





$$\text{Accuracy}=\frac{\sqrt{S+B}}{S}$$

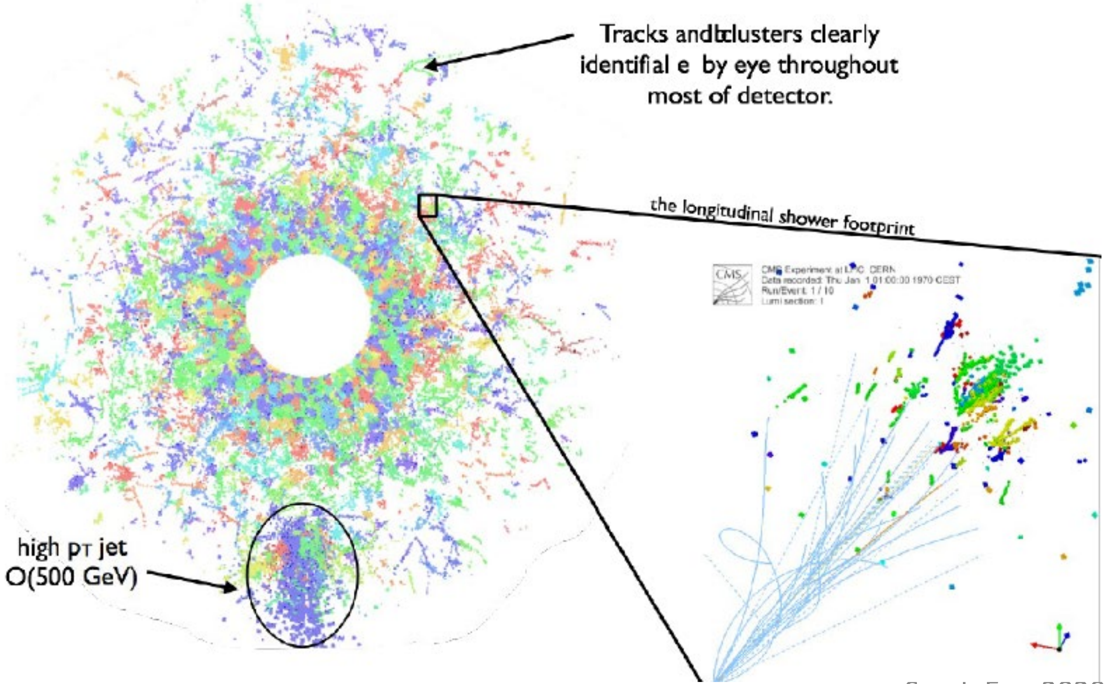
3

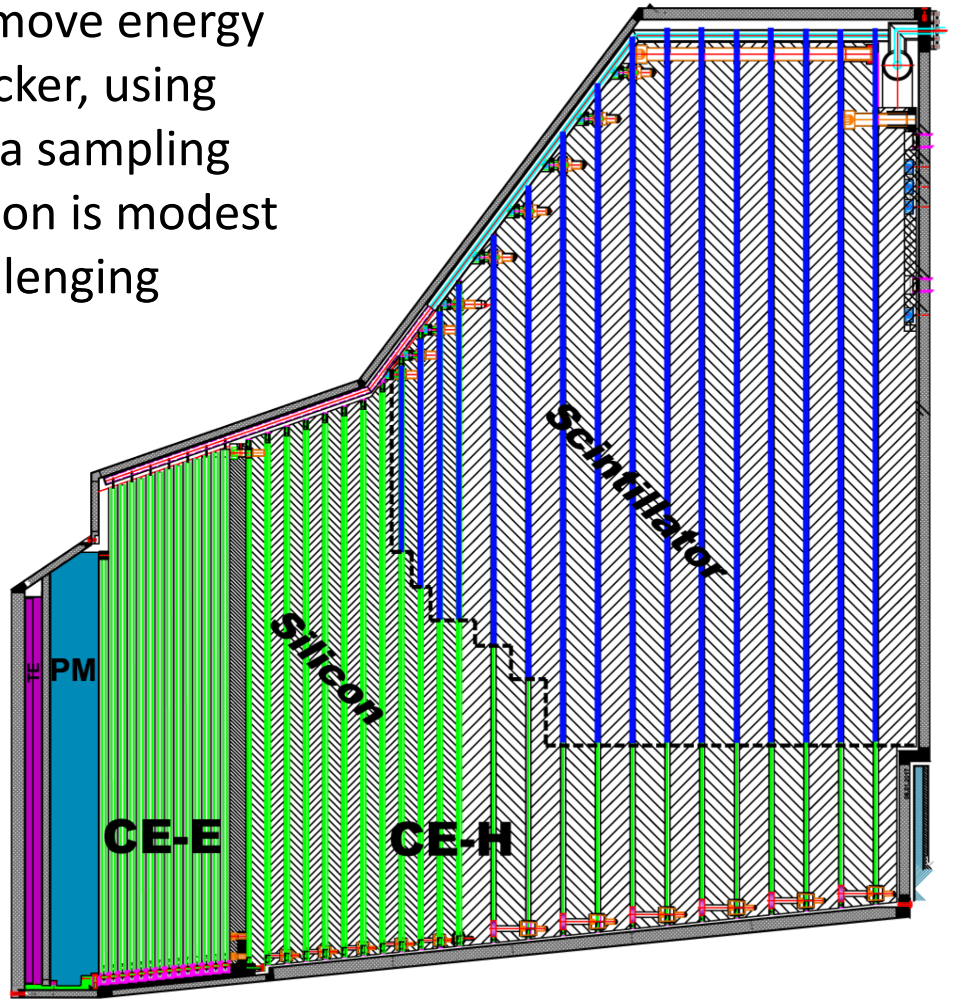
hadronic calorimetry ($30\%/\sqrt{E}$).

The precision for many of the key measurables are steepish functions of the resolution

High granularity

In high granularity calorimetry, you use pattern recognition to remove energy deposits from charged hadrons that are well measured in the tracker, using the calorimetry only for photons and neutral hadrons. Since it is a sampling calorimeter and doesn't have compensation, calorimeter resolution is modest (15% EM, 50% hadron). High granularity is needed to do the challenging shower pattern recognition.





Particle flow

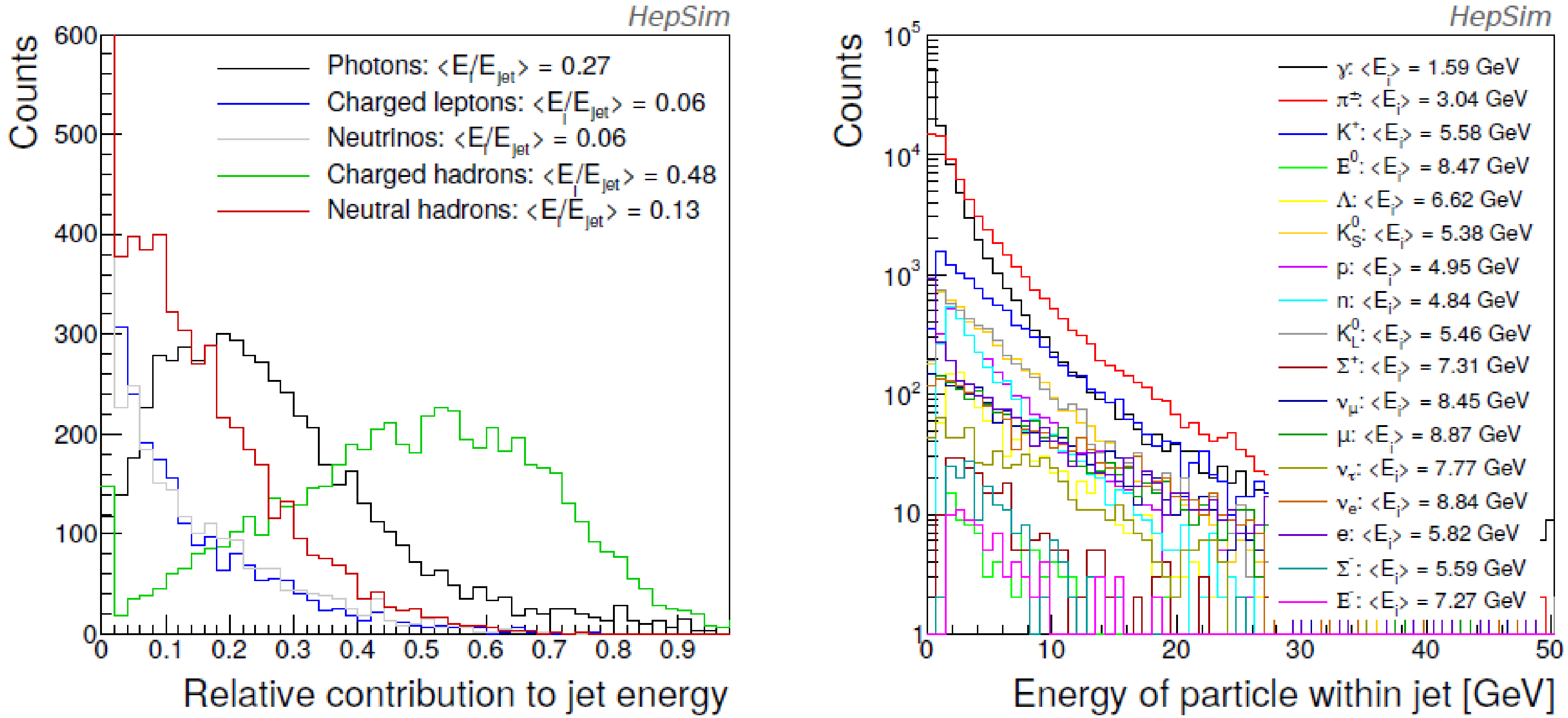


Figure 1. Left: relative contribution of different particles (photons, neutrinos, leptons, neutral hadrons, charged hadrons) to the jet energy. Right: energy distribution of different particle types clustered within jet.

eta

Particle Flow Calorimetry and the PandoraPFA Algorithm (https://arxiv.org/abs/0907.3577)

Marco Lucchini studies using hepsim https://arxiv.org/abs/2008.00338

A Segmented Crystal Electromagnetic Precision Calorimeter (SCEPCal) for future colliders

29/05/20

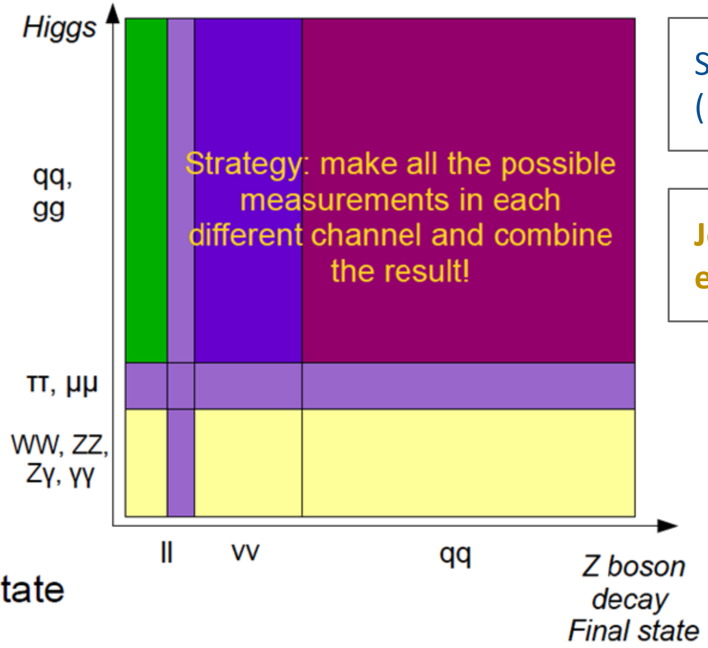
S.Eno[2], Y.Lai[2], M.Lucchini[1], C.Tully[1]

[1]Princeton University, [2]University of Maryland

PRINCETON UNIVERSITY

Final States of e^+e^- Higgs Physics @~246 GeV

- SM Higgs
  - ***0 jets: 3%:*** *Z→ll, νν (30%); H→0 jets (~10%, ττ, μμ, γγ, γZ/WW/ZZ→leptonic)*
  - ***2 jets: 32%***
    - *Z→qq, H→0 jets. 70%*10% = 7%*
    - *Z→ll, νν; H→2 jets. 30%*70% = 21%*
    - *Z→ll, νν; H→WW/ZZ→semi-leptonic. 3.6%*
  - ***4 jets: 55%***
    - *Z→qq, H→2 jets. 70%*70% = 49%*
    - *Z→ll, νν; H→WW/ZZ→4 jets. 30%*15% = 4.5%*
  - ***6 jets: 11%***
    - *Z→qq, H→WW/ZZ→4 jets. 70%*15% = 11%*



Strategy: make all the possible measurements in each different channel and combine the result!

Slide borrowed from Manqi Ruan (LCWS 2019, Sendai, Japan)

Jet resolution is a key benchmark for e^+e^- detectors performance

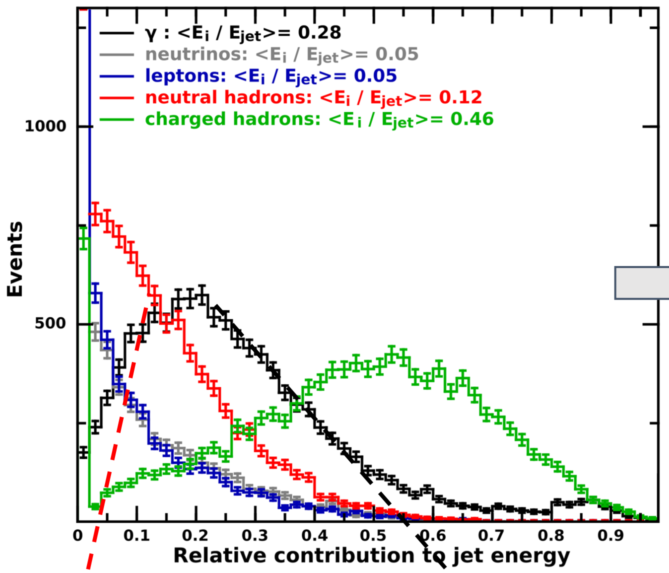
- **97%** of the SM Higgsstrahlung Signal has Jets in the final state
- **1/3** has only 2 jets: include all the SM Higgs decay modes
- **2/3** need color-singlet identification: grouping the hadronic final sate particles into color-singlets
- Jet is important for EW measurements & jet clustering is essential for **differential** measurements

Role of calorimeters on PFA jet performance

- Baseline jet performance depends on particle composition and the relevant sub-detector resolutions

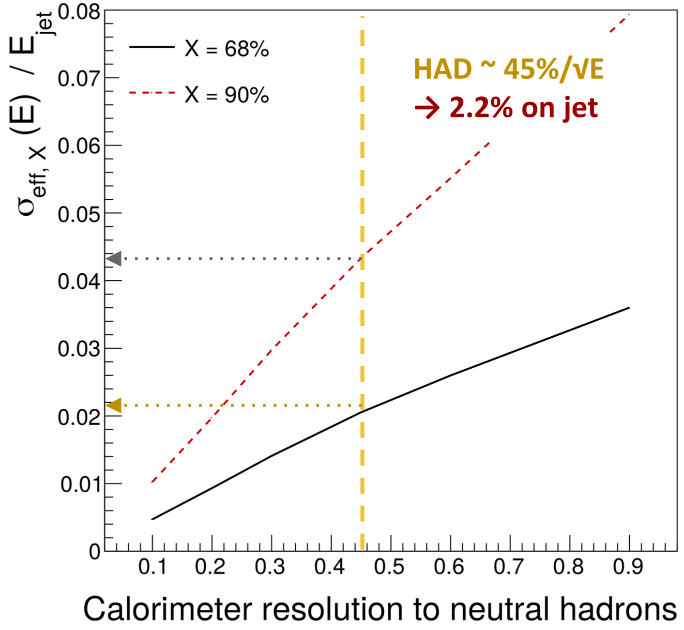
- Calorimeter resolution requirements to achieve target jet resolution of ~3%
  - EM (photons) better than 20%/√E
  - Neutral hadrons (mostly $K^{0,L}$ of <E>~5 GeV) better than 45%/√E

HepSim: Z→ bb (e^+e^- @250 GeV)

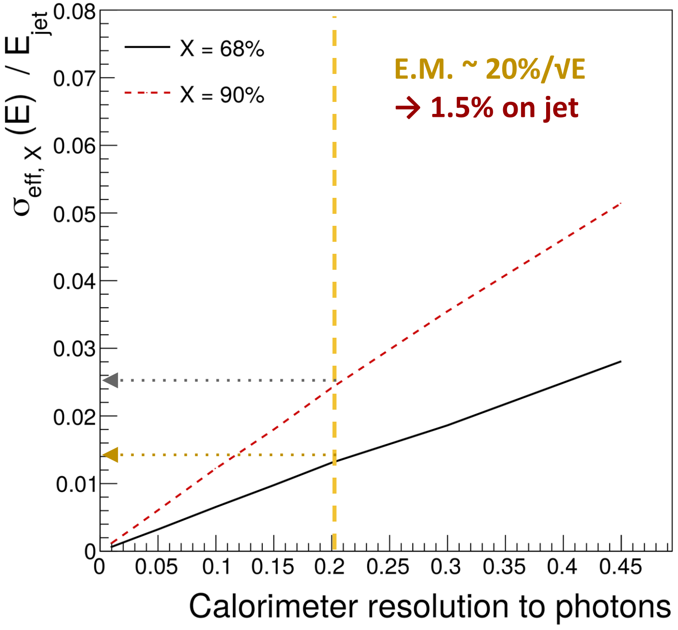


~2.7% contribution to jet resolution from calorimeters (added in quadrature)

HepSim: Z→ bb (e^+e^- @250 GeV)



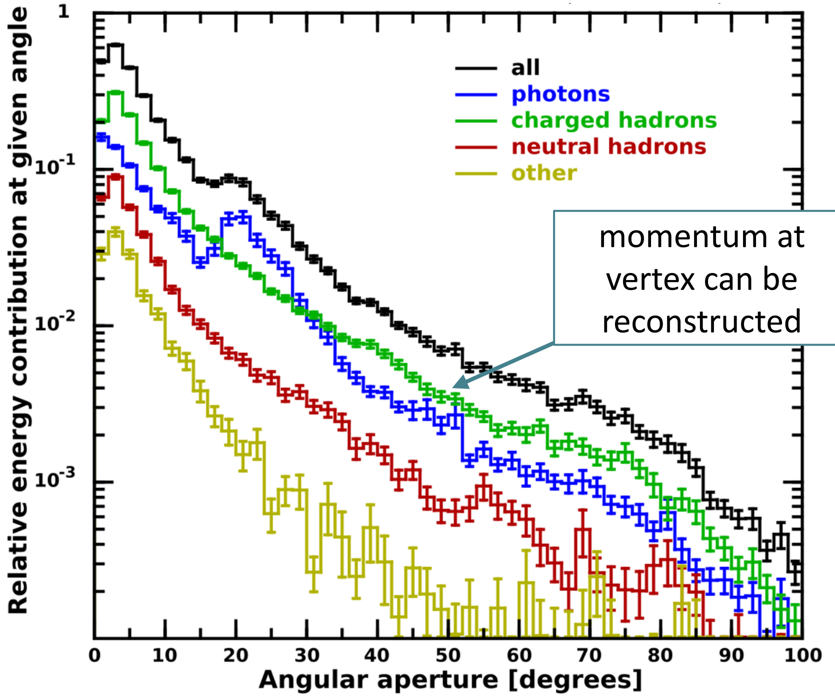
HepSim: Z→ bb (e^+e^- @250 GeV)



Jet reconstruction in PFA

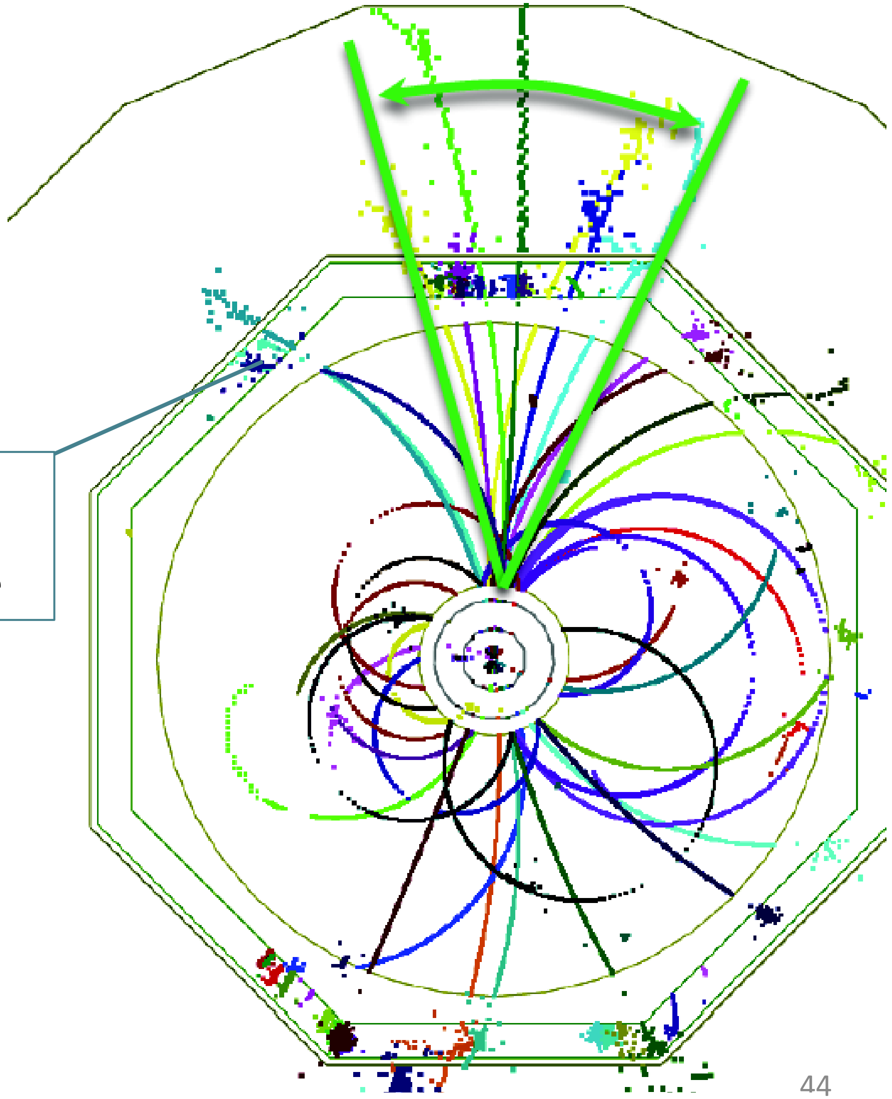
- Key features of PFA in Jet reconstruction:
    - **Swaps out hadronic resolution for tracks** (charged hadrons)
    - **Corrects momentum direction at the vertex**

HepSim: Z→ bb (e^+e^- @250 GeV)



momentum at vertex can be reconstructed

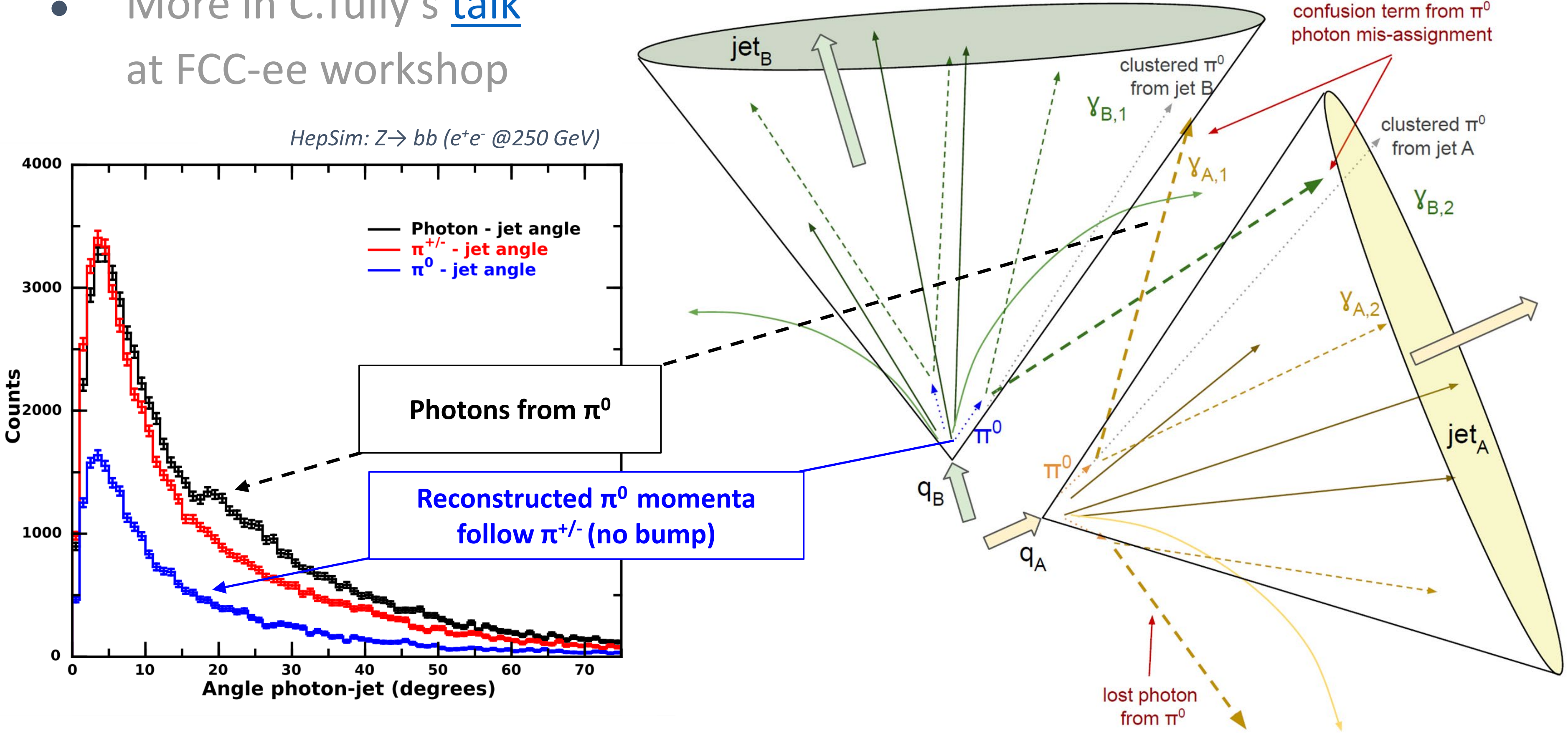
$\pi^{+/-}$ from jet bending outside the calo jet cone

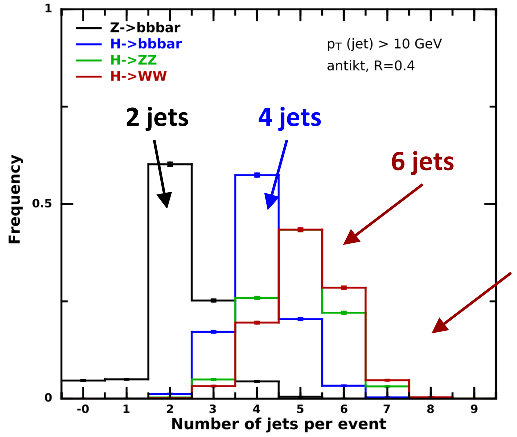


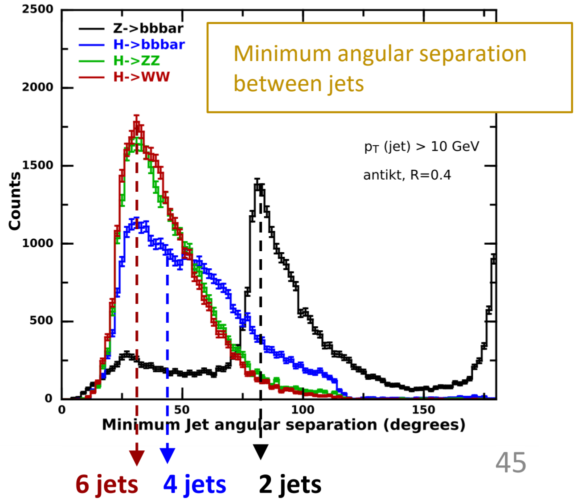
Picture borrowed from Marcel Vos

High e.m. resolution potential for PFA

- **Many photons from π^0 decay at ~20-35° angle** wrt to jet momentum can get scrambled across closeby jets
- Effect becomes **more pronounced in 4 and 6 jets topologies**
- More in C.Tully's talk at FCC-ee workshop





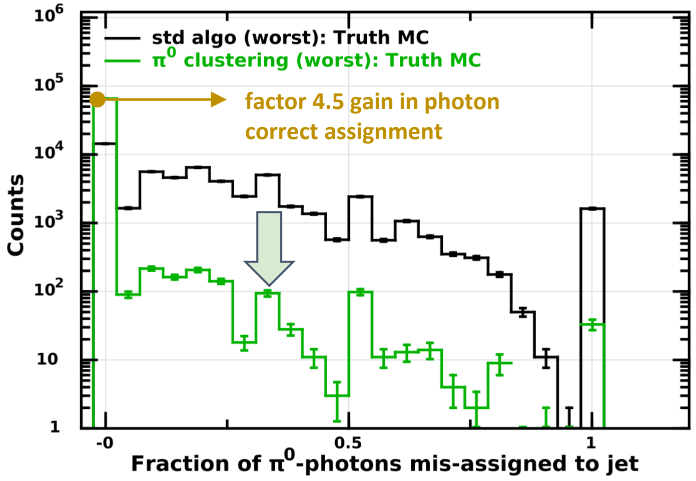


Improvements in photon-to-jet assignment

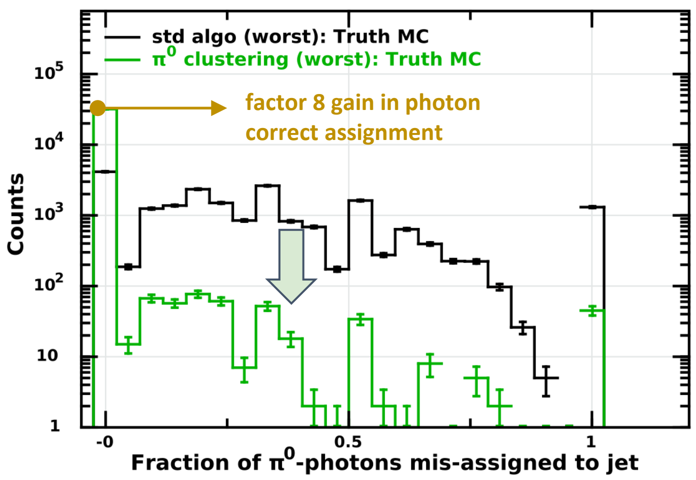
- **High e.m. resolution enables** photons **clustering into π^0's** by reducing their angular spread with respect to the corresponding jet momentum
- **Improvements in the fraction of photons correctly clustered to a jet** sizable only for e.m. resolutions of ~3-5%/√(E)

ideal e.m. resolution

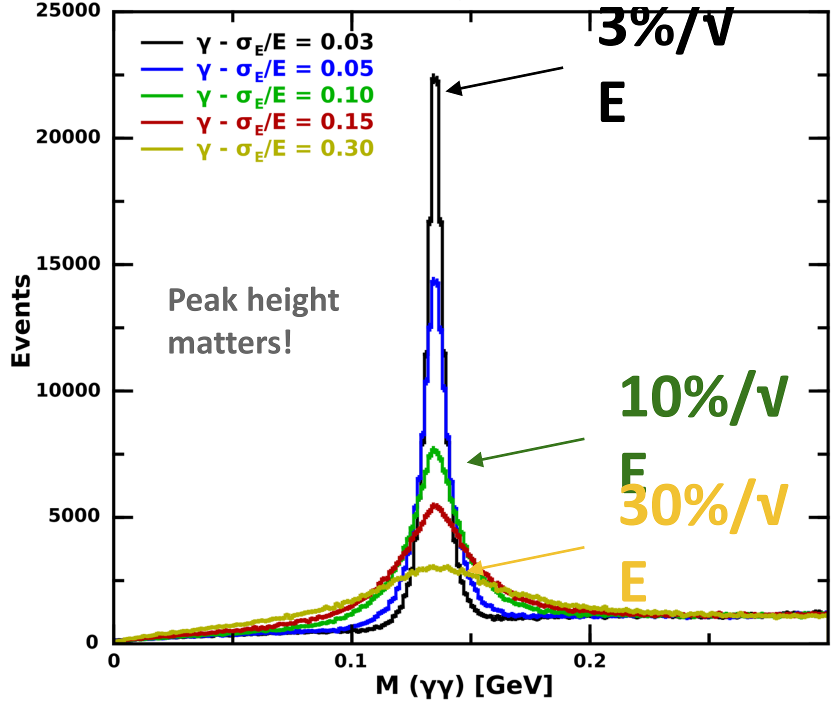
worst jet in a 4-jets topology



worst jet in a 6-jets topology



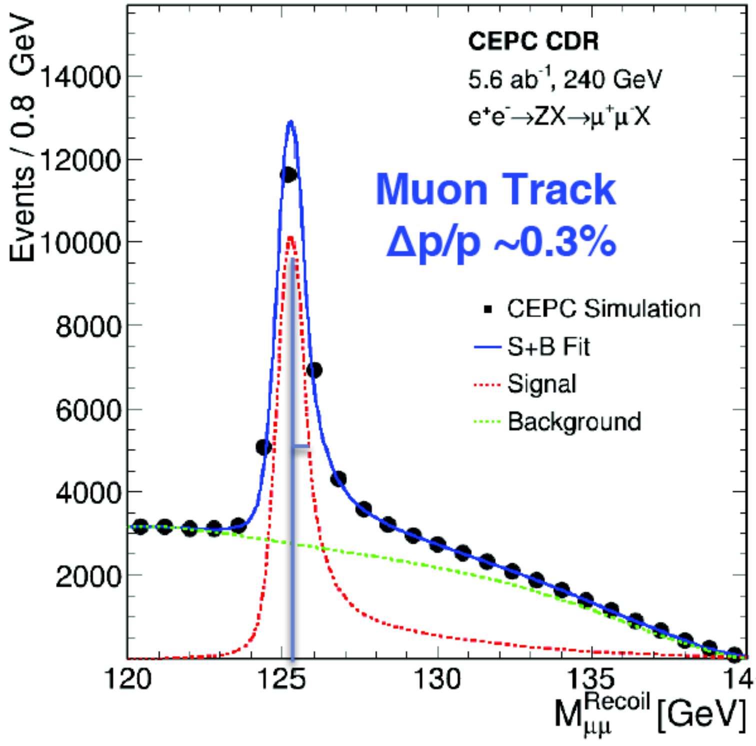
HepSim: Z→ bb (e$^+$e$^-$ @250 GeV)



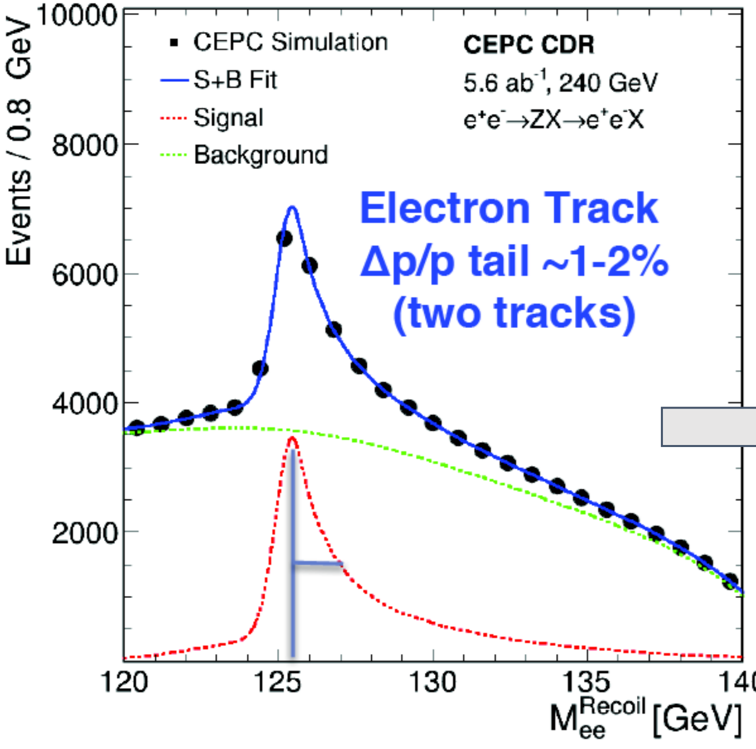
Brem recovery

Example from CEPC CDR reference design
(electron tracks with no Bremsstrahlung recovery)

- **$Z \rightarrow \mu^+\mu^-$ Recoil**



- **$Z \rightarrow e^+e^-$ Recoil**



~80% of resolution recovery
with 3%/√(E)

The combination of
a high precision ECAL with an excellent HCAL
would be *IDEA*L to take up the challenge of precision physics at future e^+e^- colliders

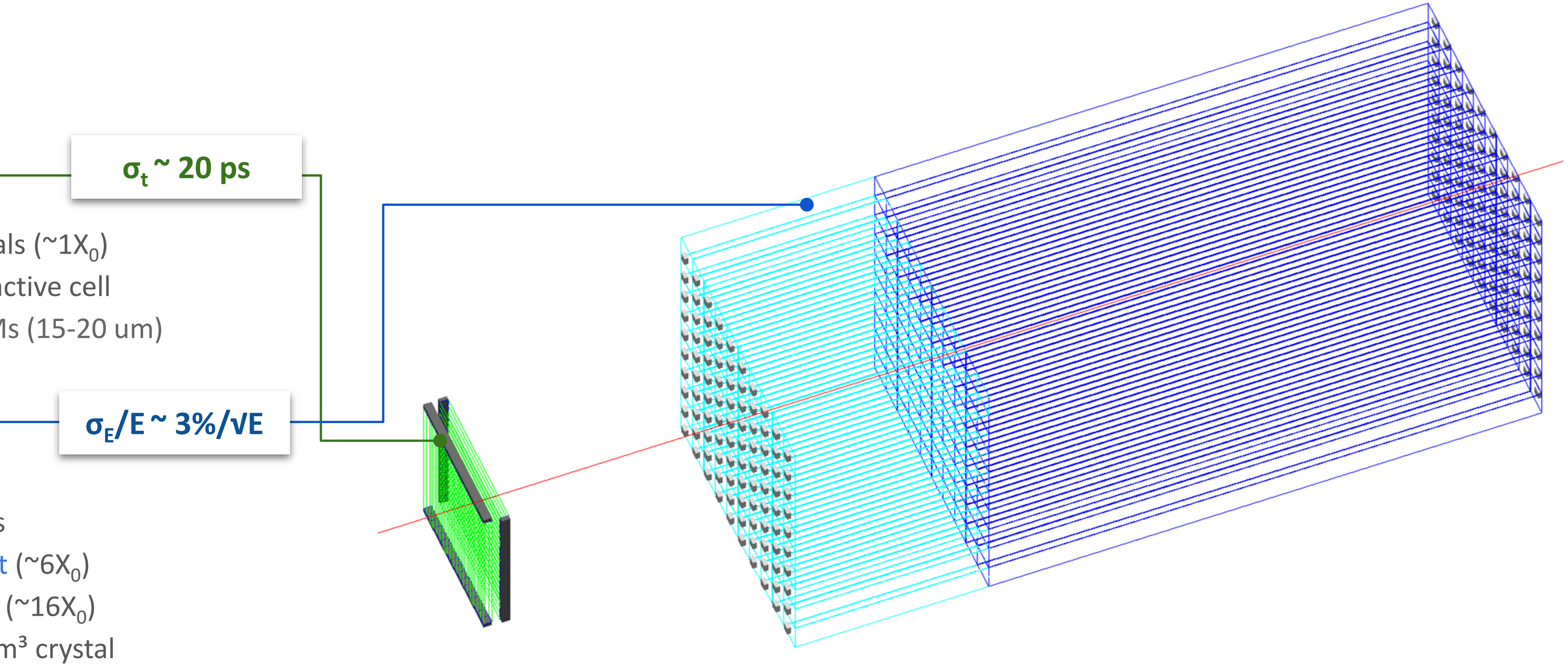
---

- Design optimization of a segmented crystal ECAL
- Integration of crystal ECAL with a Dual ReadOut HCAL
- Optimization of Dual ReadOut in crystal ECAL

Overview of a SCEPCal module

- ***SCEPCAL:*** a **S**egmented **C**rystal **E**lectromagnetic **P**recision **C**alorimeter
- **Transverse and longitudinal segmentations** optimized for particle identification, shower separation and performance/cost
- Exploiting **SiPM readout** for contained cost and power budget

- **Timing layer**
    - LYSO:Ce crystals (~1X_0)
    - 3x3x54 mm³ active cell
    - 3x3 mm² SiPMs (15-20 um)
- **ECAL layer**
    - PbWO crystals
    - Front segment (~6X_0)
    - Rear segment (~16X_0)
    - 10x10x200 mm³ crystal
    - 5x5 mm² SiPMs (10-15 um)



$\sigma_t \sim 20$ ps

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

Some crystal options

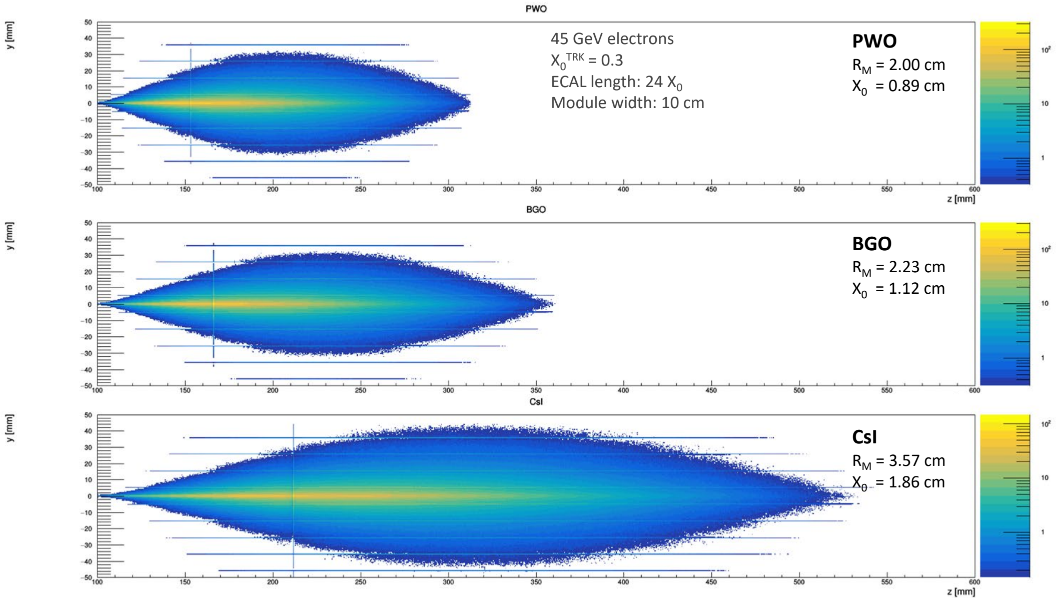
- **PWO**: the most compact, the fastest, the cheapest
- BGO: in between (potential for dual readout)
- CsI: the less compact, the slowest, the brightest

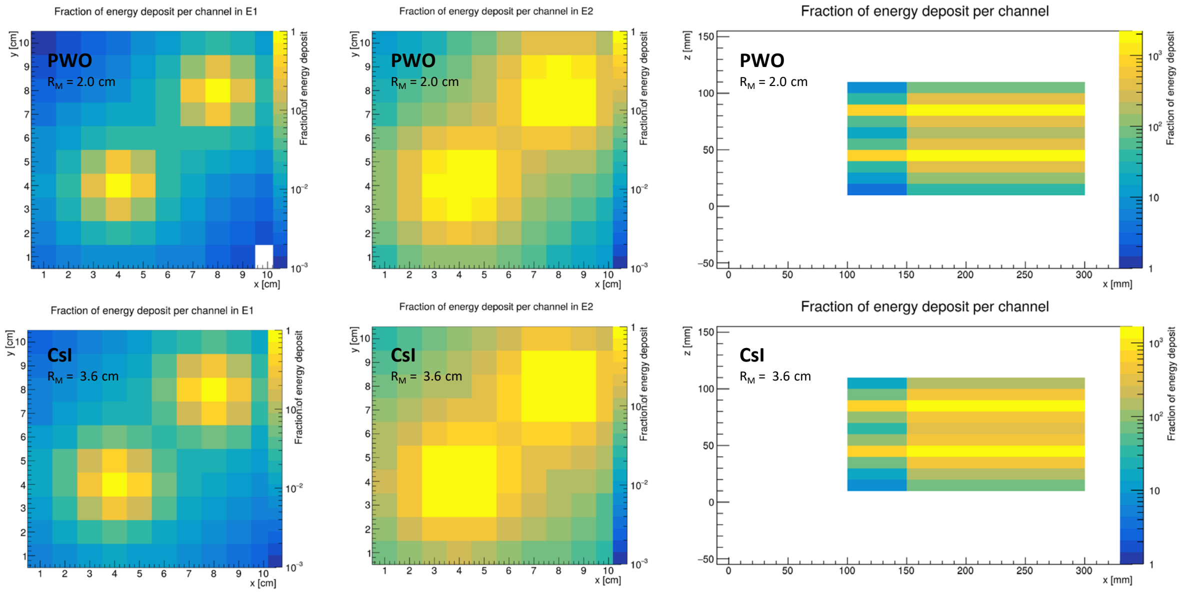
better for PFA ⇧

⇩ better stochastic term

Crystal	Density g/cm³	λ_I cm	X_0 cm	R_M cm	Relative LY @ RT	Decay time ns	Photon density (LY / τ_D) ph/ns	dLY/dT (% / °C)	Cost (10 m³) $/cm³	Cost*X_0 $/cm²
PWO	8.3	20.9	0.89	2.00	1	10	0.10	-2.5	8	7.1
BGO	7.1	22.7	1.12	2.23	70	300	0.23	-0.9	7	7.8
CsI	4.5	39.3	1.86	3.57	550	1220	0.45	+0.4	4.3	8.0

*Values from: Journal of Physics: Conference Series **293** (2011) 012004*

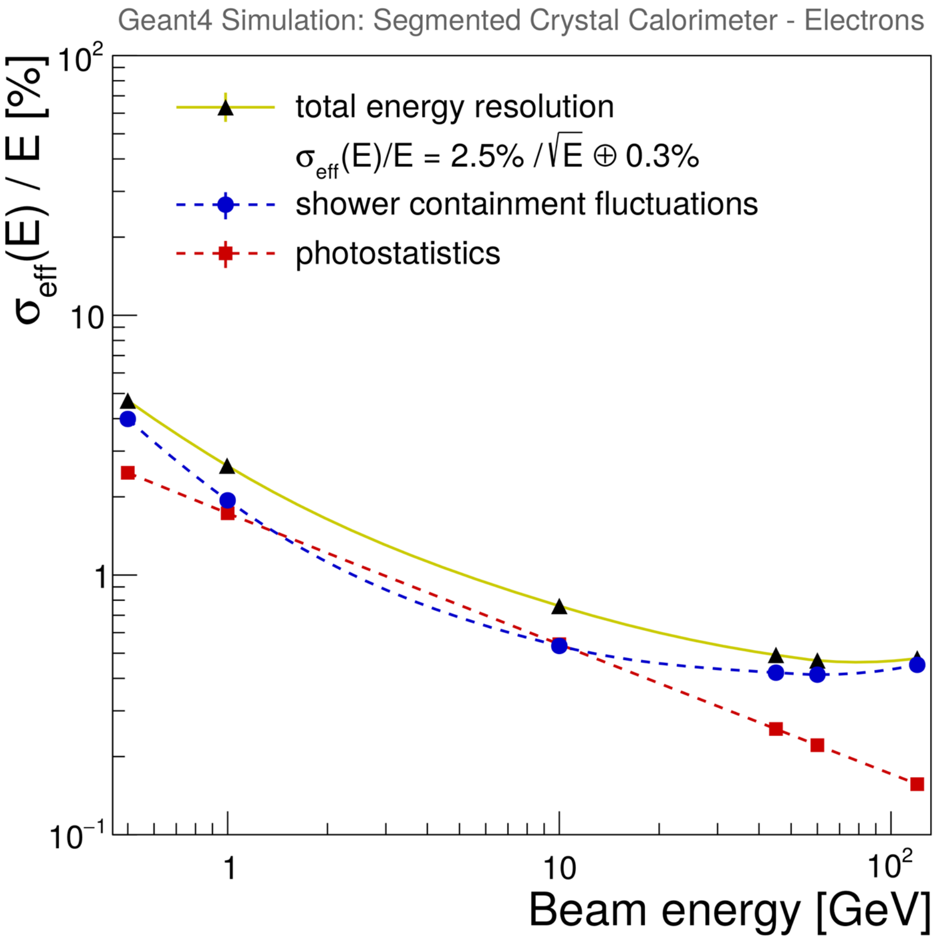




SCEPCAL e.m. resolution

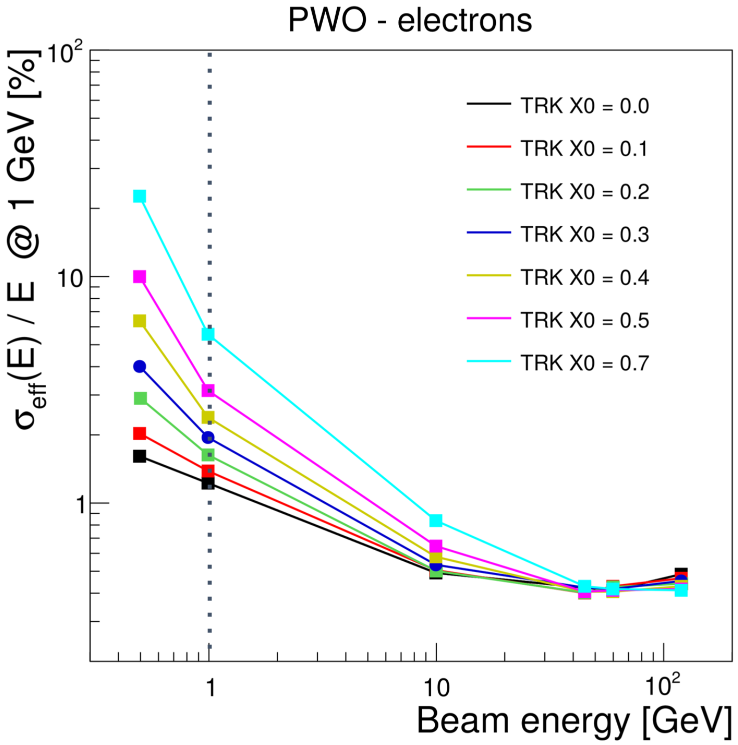
- Contributions to energy resolution:
  - Shower containment fluctuations
    - Longitudinal leakage
    - Tracker material budget
    - Services for front layer readout
  - Photostatistics
    - Tunable parameter depending on:
      - SiPM choice
      - Crystal choice
  - Noise
    - Negligible with SiPMs
      - low dark counts, high gain
  - Channels intercalibration
    - ~0.5% constant term (not in the plot)

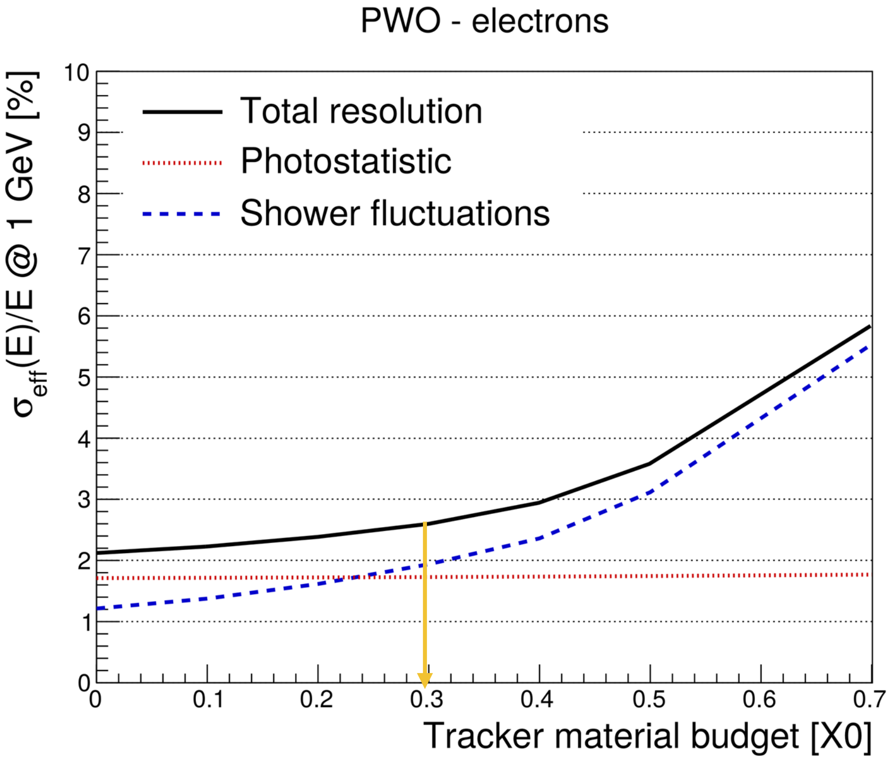
$\sigma_E/E \sim 3\%/\sqrt{E} \oplus 0.5\%$



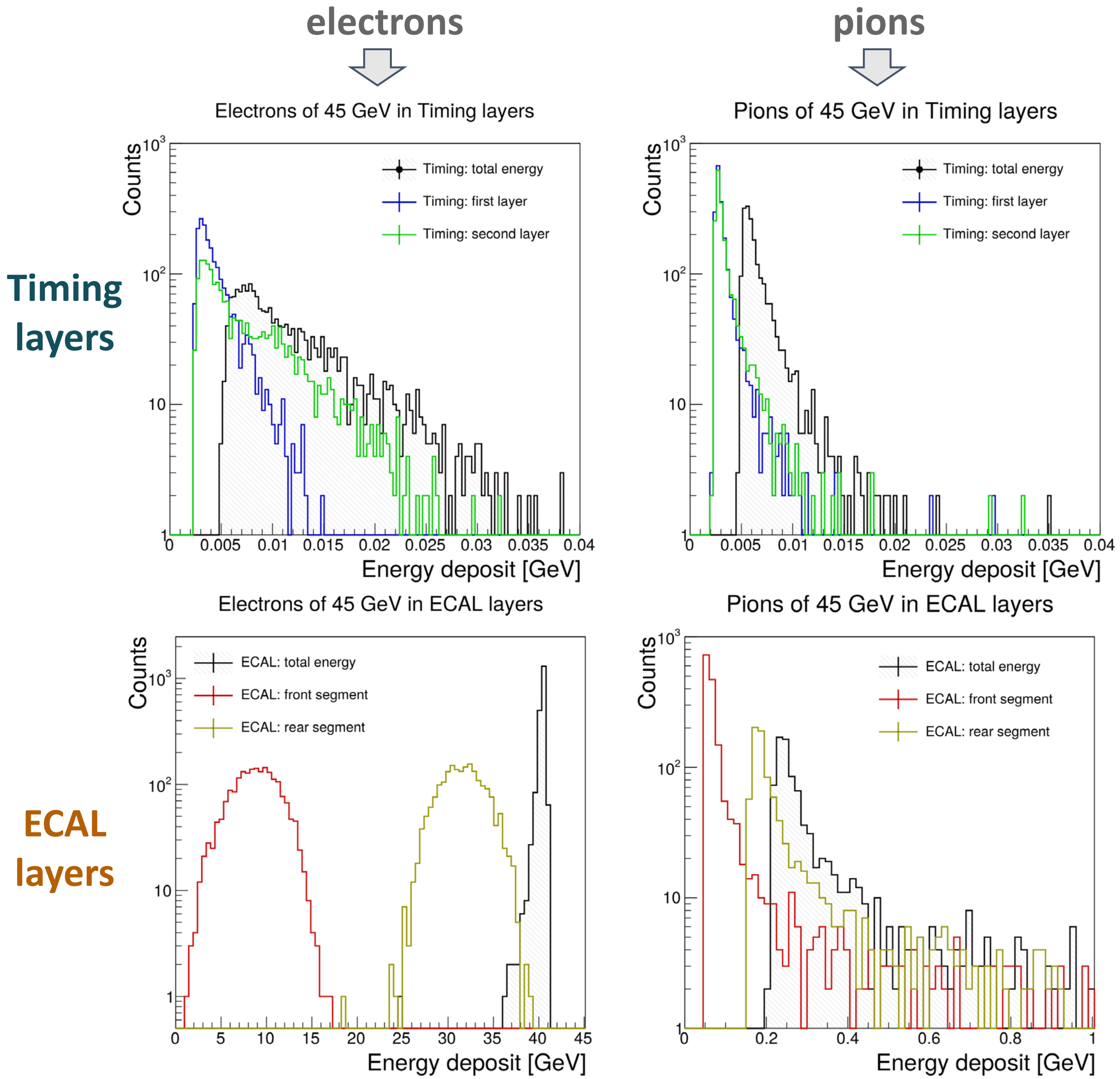
Impact of tracker and dead **material budget**

- Tracker material budget <0.3X_0 for <2% impact on stoch. term
  - Well within the target of the CEPC and IDEA reference tracker designs
- Dead material for services <0.3X_0 for impact on stoch. term < 2%
  - Compatible with estimated material budget from cooling (5 mm Al plate) and readout electronics

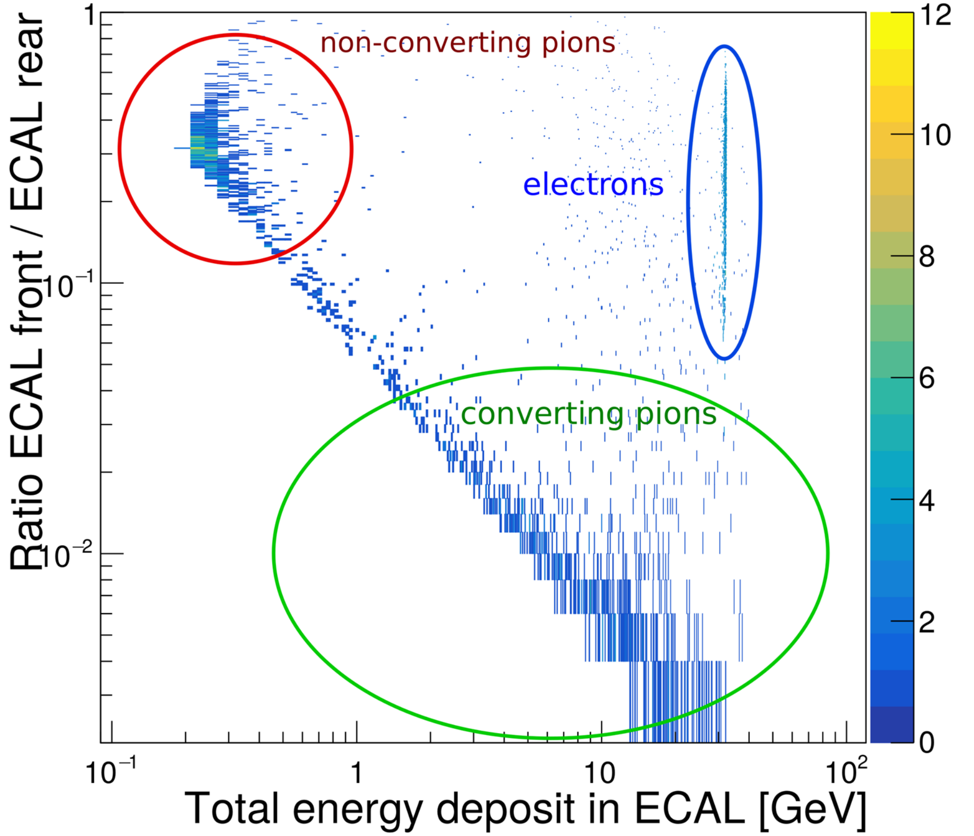




Particle ID with longitudinal segmentation

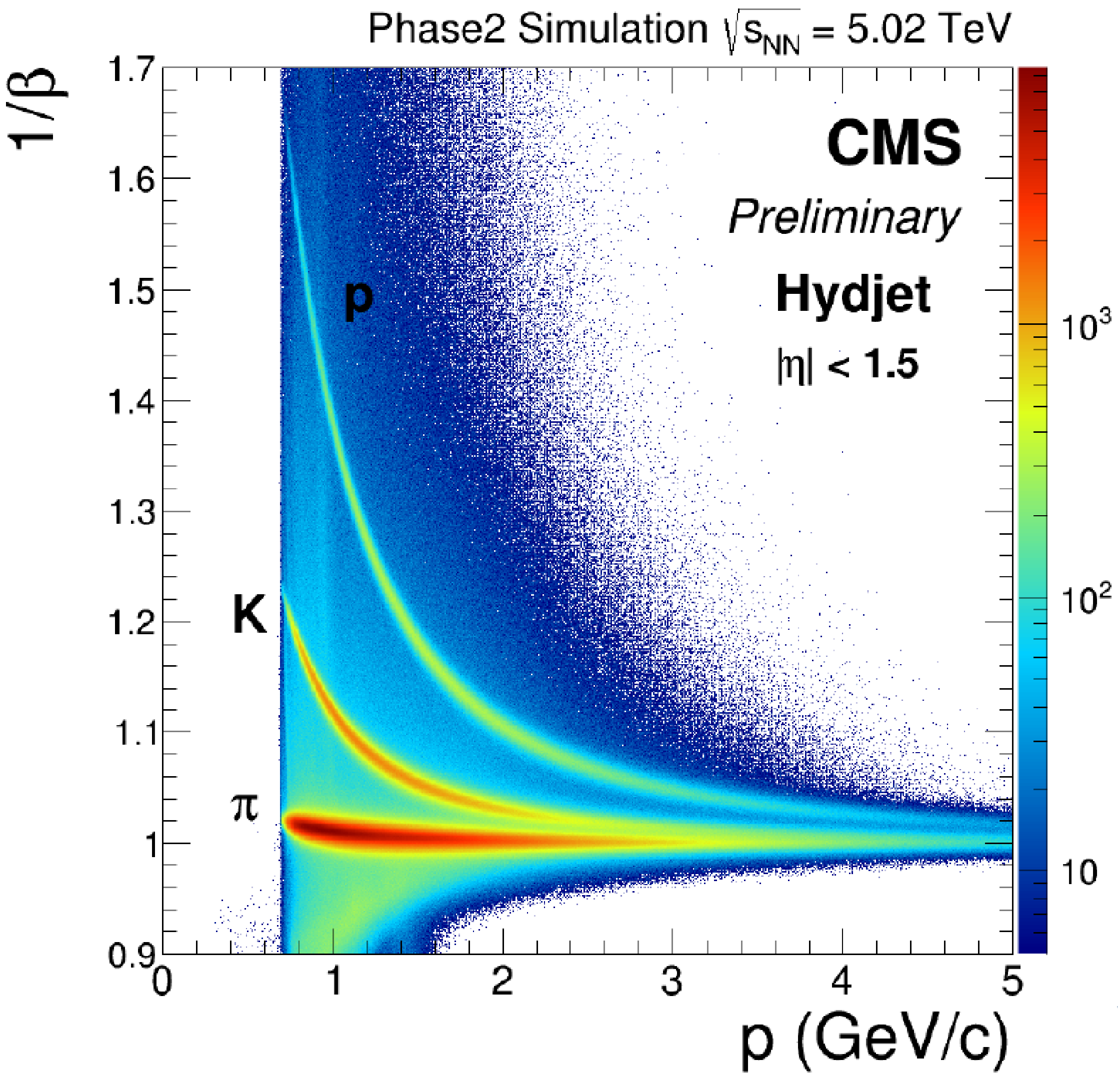


- Topology of longitudinal energy deposits in different layers provides clear **electron / π$^{+/-}$ discrimination**



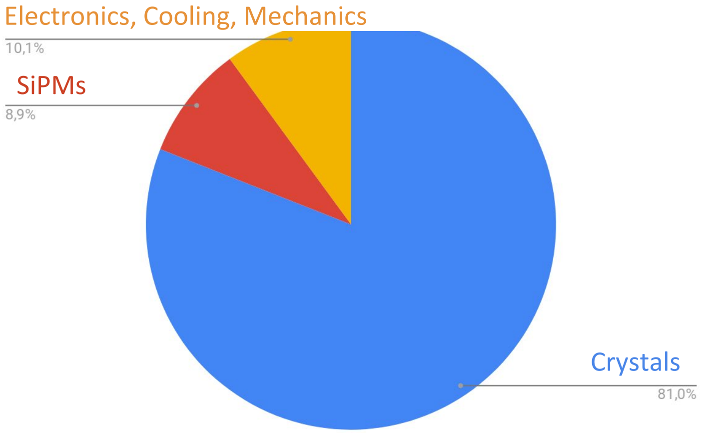
Particle ID with **time-of-flight**

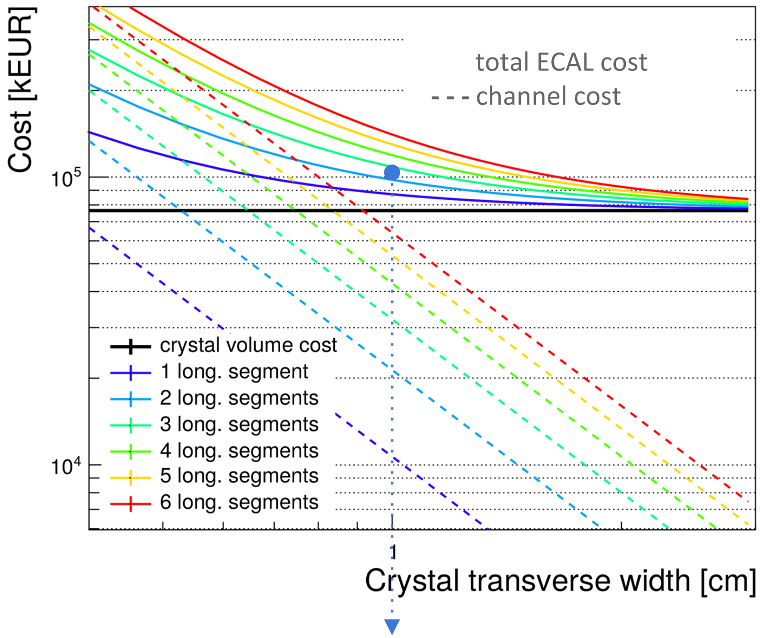
- Excellent time-of-flight capabilities for particle identification:
  - Time tagging of **MIPs with ~30 ps** time resolution with single layer
    - See [MTD in CMS Phase 2 upgrade]()
  - Time resolution of **30 ps to e.m. showers** with E >20 GeV with the ECAL (rear) segment(s)
    - See [Phase 2 CMS ECAL Upgrade]()



Cost-power drivers and optimization

- **Channel count** in **SCEPCal** is limited to **~2.5M**
  - 625k channels/layer (2 “timing layers” + “ECAL layers”)
- Cost drivers in **ECAL** layers (tot ~95M€):
  - **~81% crystals**, **9**% SiPMs, **10%** (electronics+cooling+mechanics)
  - **~19% of cost scales with channel count**
- Power budget driven by electronics: ~74 kW
  - 18.5 kW/layer
- Room for fine tuning of the segmentation and of the detector performance/cost optimization (see backup)

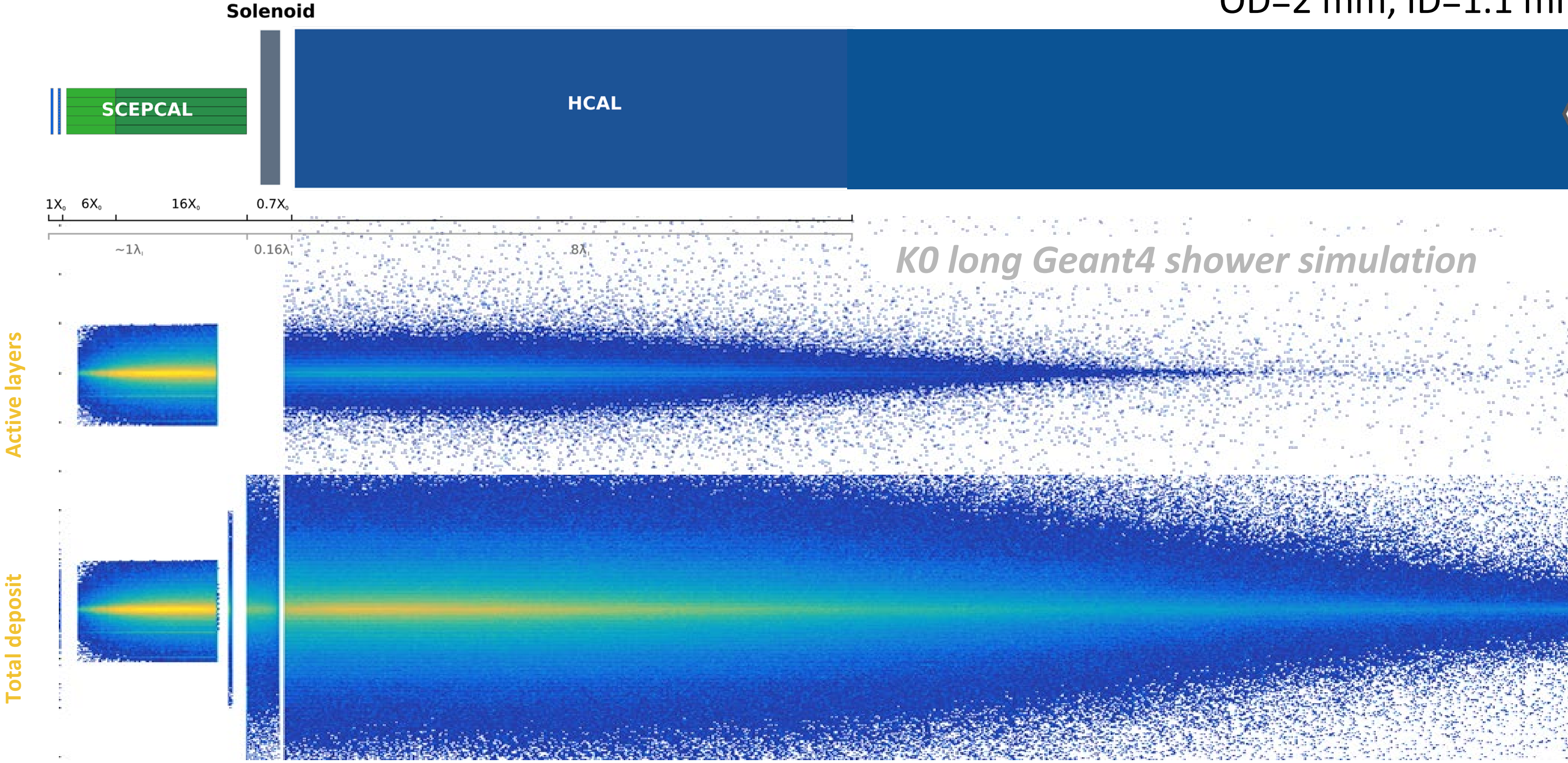




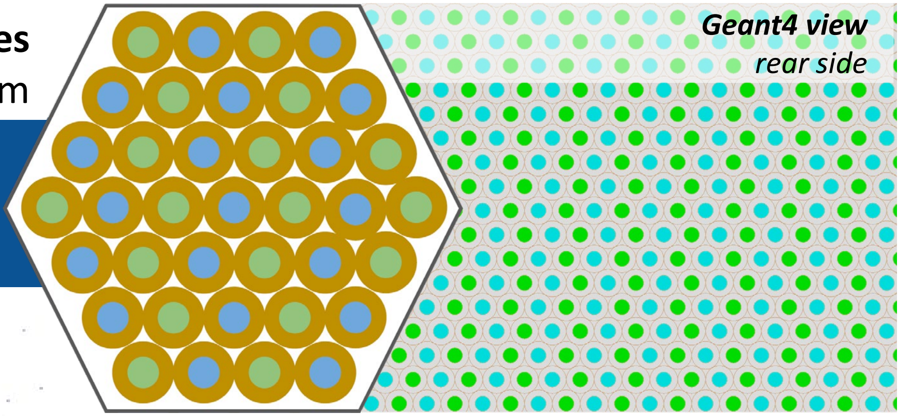
Reference design:
1 cm², 2 segments
cost ~ 95M€

Integrating excellent ECAL with excellent HCAL

- Ultra-thin solenoid (~0.6X_0) between ECAL and HCAL
- Ease the HCAL design (cost/performance) from the ‘burden’ of e.m. resolution



Brass capillaries
OD=2 mm, ID=1.1 mm

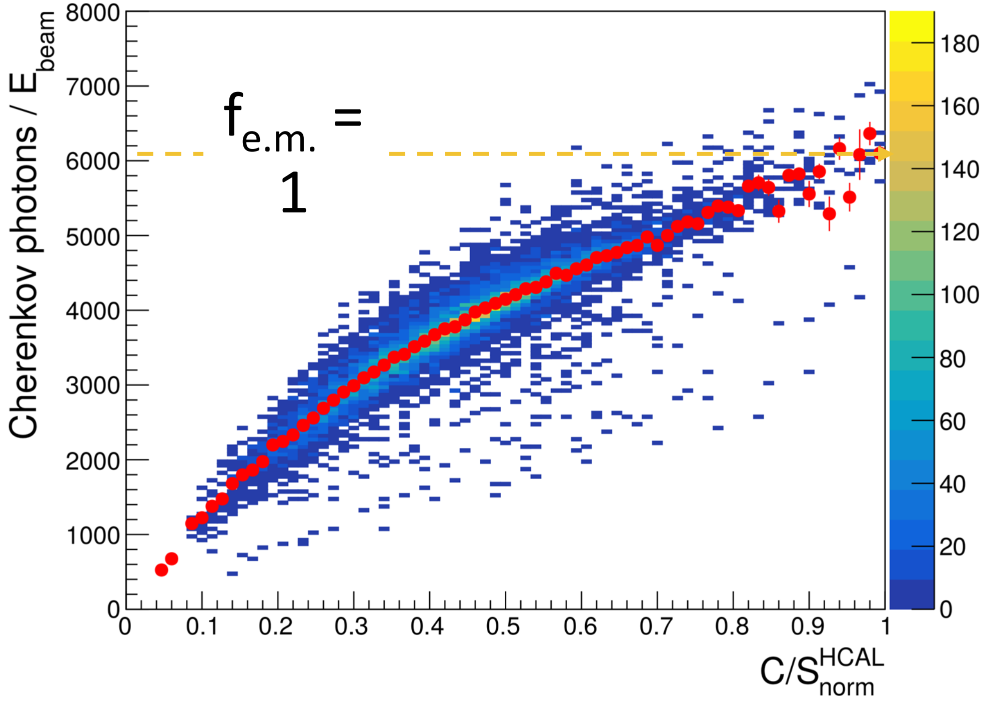


Geometry inspired by the presentation of V.Chmill at FCC-ee workshop

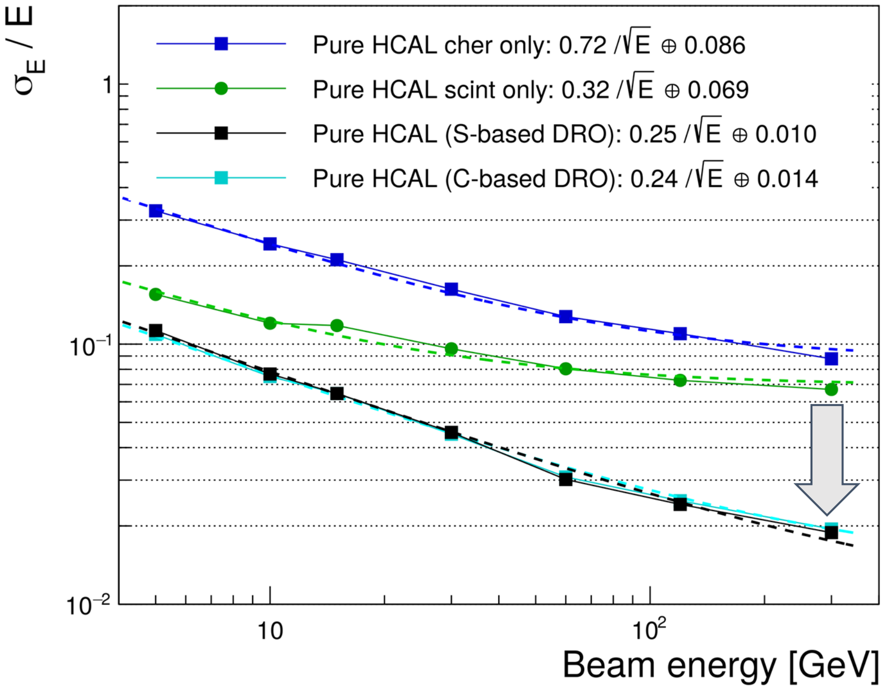
Reference dual readout HCAL

- HCAL-only performance studied by selecting events that do not interact in the ECAL
- **Dual readout correction works as expected,**
  - delivering ~25%/√E ⨁ 1% to hadrons
  - linearity and gaussian distributions are restored

DRO correction for C



energy resolution to $K^{0,L}$



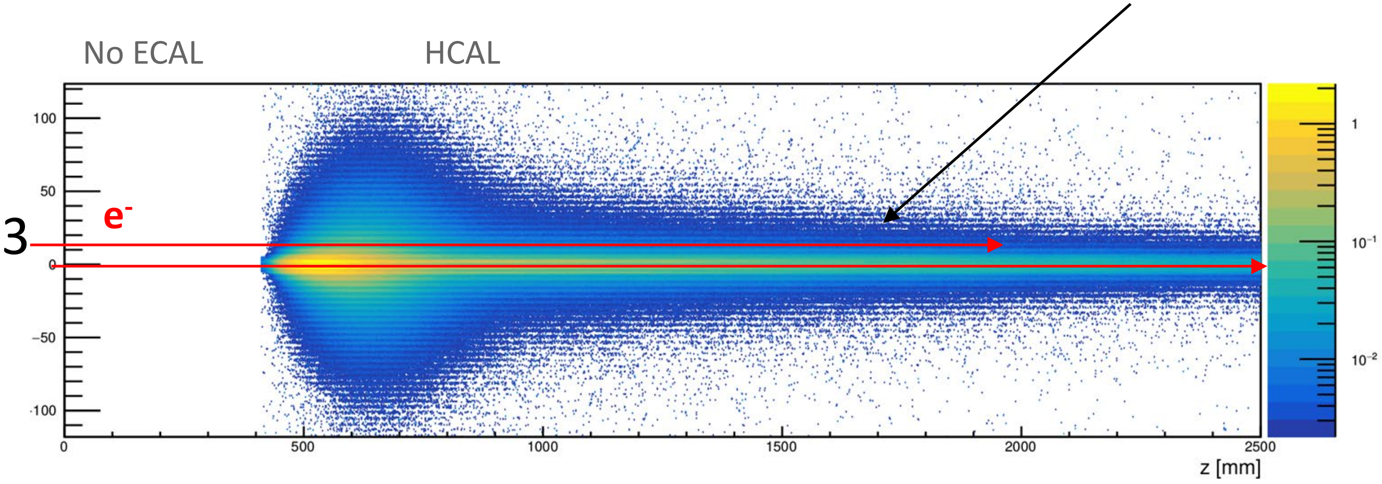
← cher only

← scint only

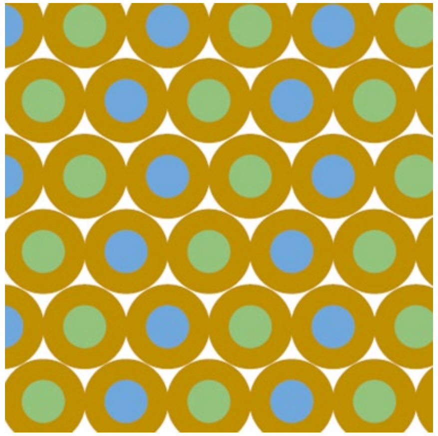
← DRO corrected

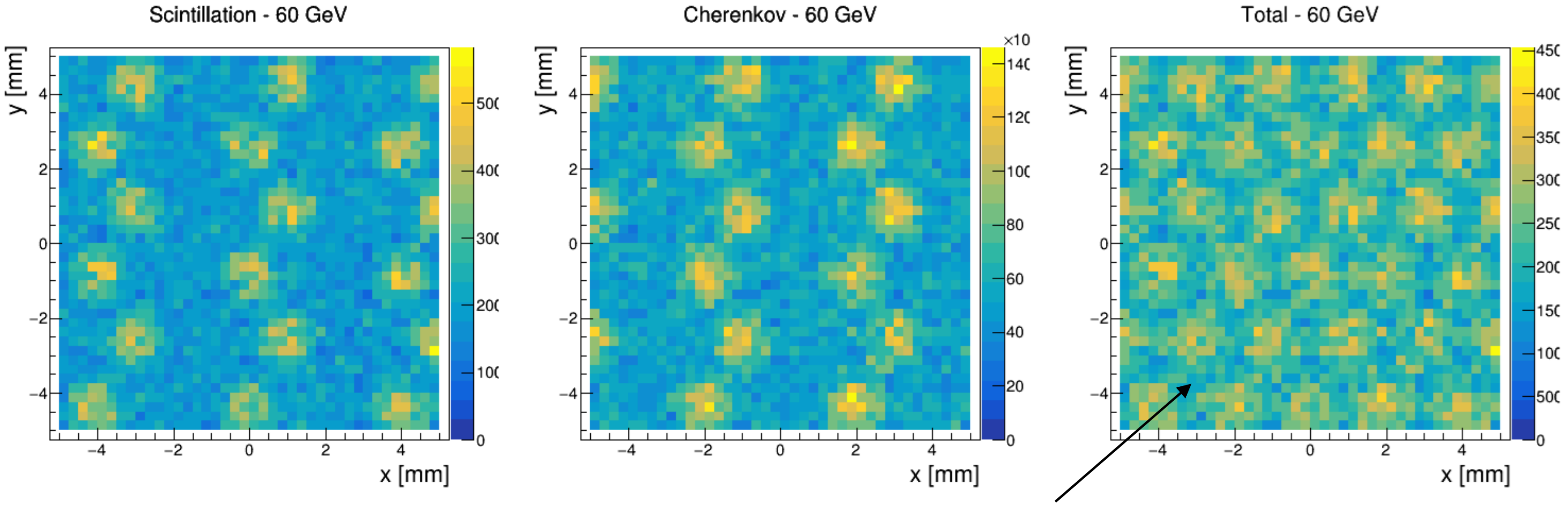
Response to e.m. showers

- Energy resolution:
  ~17%/√(E) ⊕ 2% (at 0 deg angle)
- Non-uniformities for impact angles <~3 deg
  (requires non-pointing design?)



channelling at 0 deg

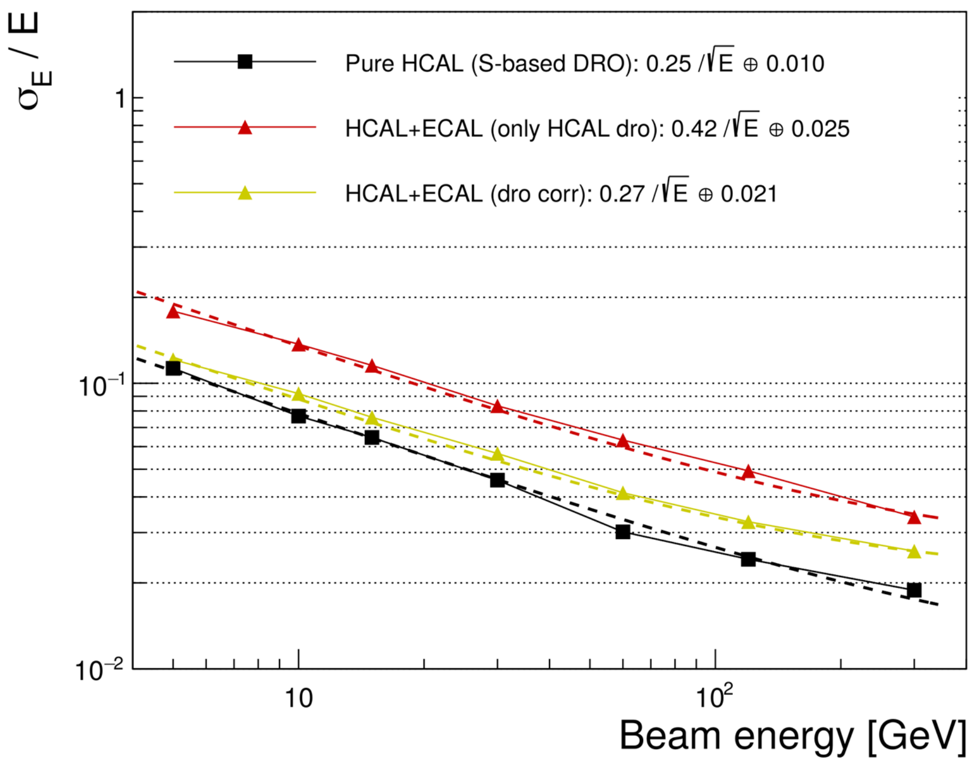




response drop in brass tubes and air gaps

Combining ECAL&HCAL dual readout

1. Correct the energy deposit in the HCAL with DRO
2. Correct the energy deposit in the ECAL with DRO
3. Calibrated sum of ECAL+HCAL



~27%/√E ⊕ 2%

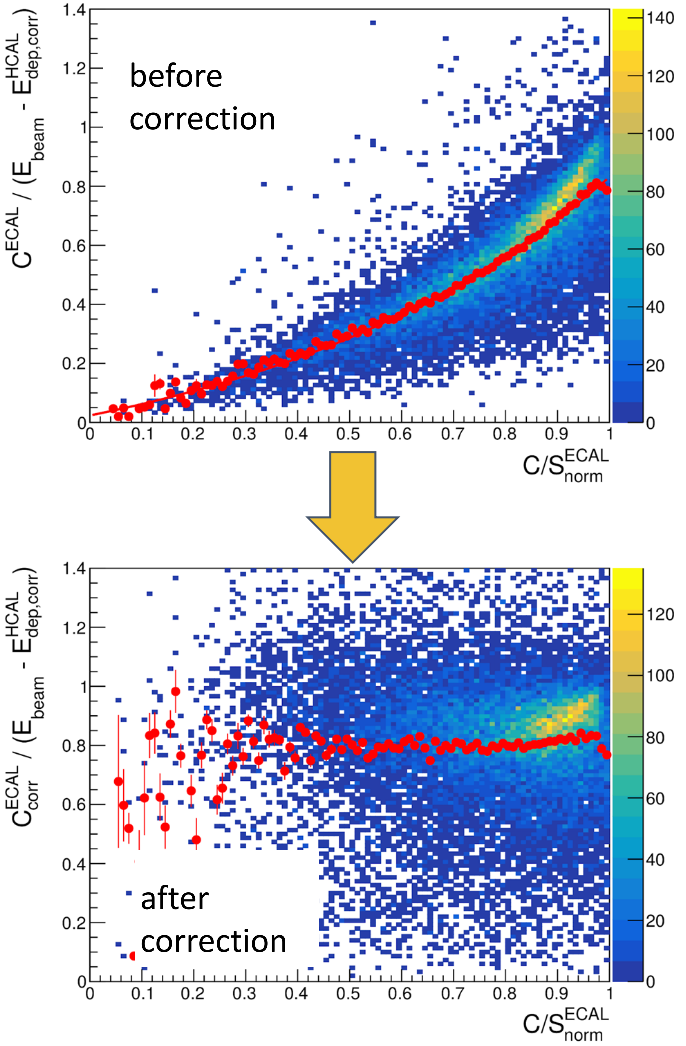
Good stochastic term recovered with ECAL Dual Readout!

← adding raw ECAL energy

← adding DRO corr ECAL

← pure HCAL

DRO correction for the energy deposit in the ECAL



Implementing dual readout in crystal ECAL

- First test of combination of a DRO crystal ECAL with DREAM HCAL back in 2009 with BGO modules (N.Ackurin et al., NIM A 610 (2009) 488-501)

Successful demonstration that DRO principles also apply to a hybrid calorimeter system (despite many experimental limitations!)

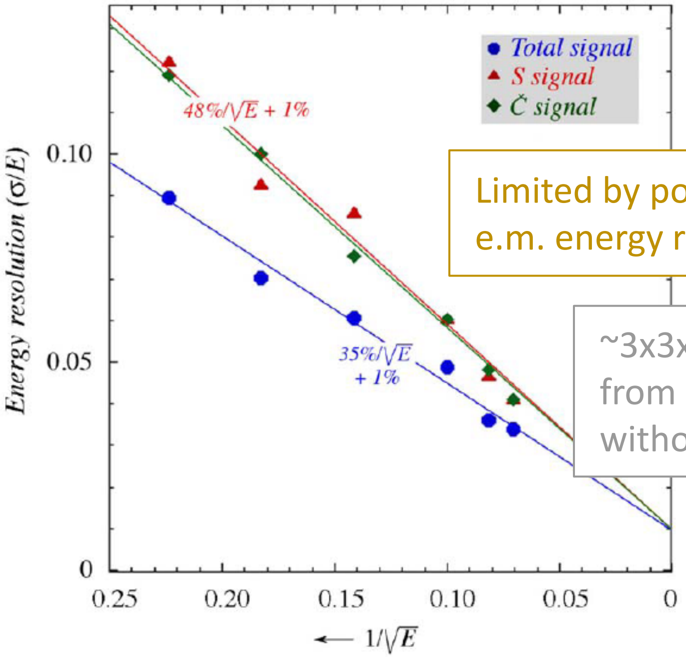
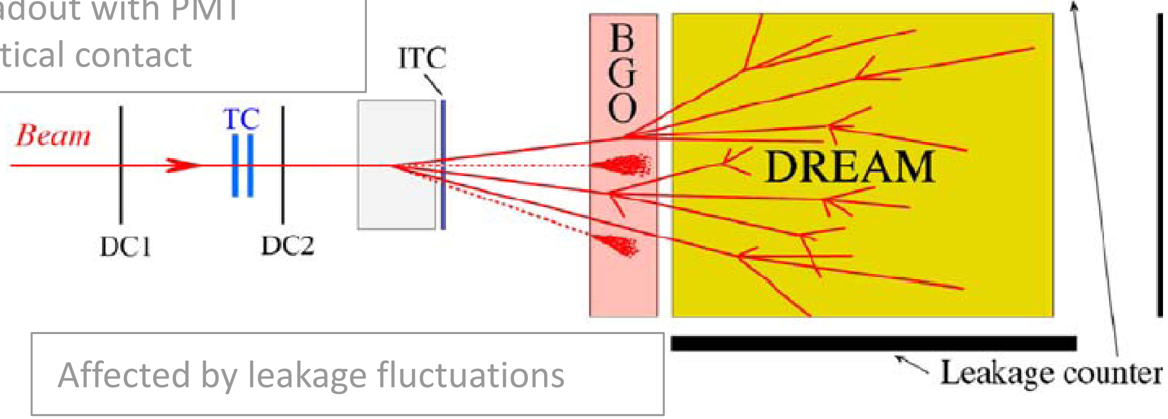


Fig. 8. The energy resolution of the BGO ECAL as a function of energy, for electrons with energies ranging from 20 to 200 GeV. The relative width of the distribution, σ/mean, is plotted versus the beam energy, separately for the scintillation and Cherenkov components of the signals, and for the total signal, integrated over the first 115 ns. See text for details.

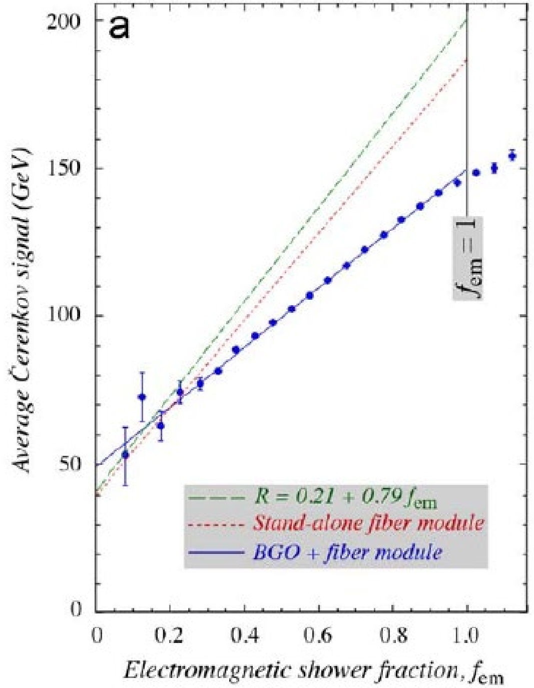
Limited by poor ECAL e.m. energy resolution

~3x3x24 cm³ tapered crystals from L3 readout with PMT without optical contact

N. Akchurin et al. / Nuclear Instruments and Methods in Physics Research A 610



Affected by leakage fluctuations



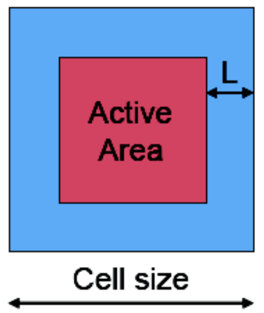
Technological advancements (**SiPMs**)

- Many technological advancements in the field of photodetectors
- Compact and robust SiPMs with small cell size (high dynamic range) extending and enhancing sensitivity in a broad range of wavelengths

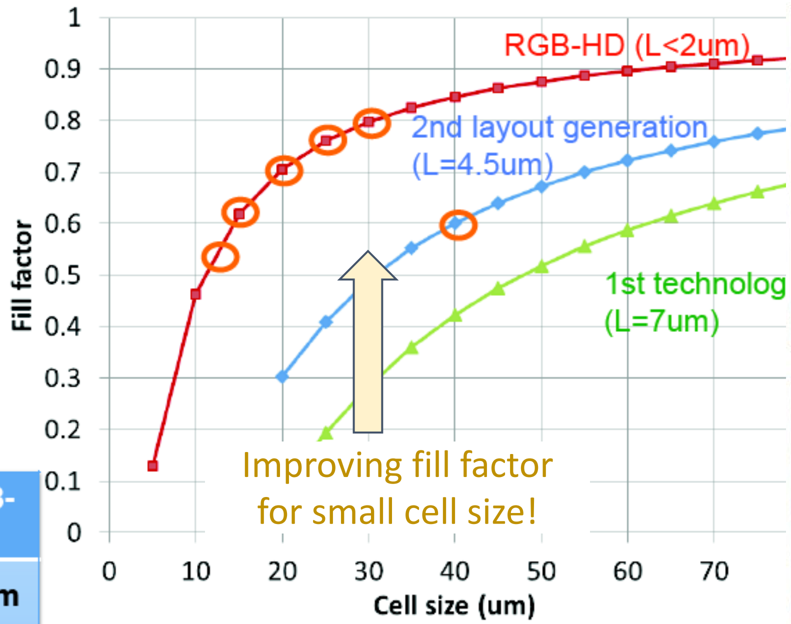
RGB-HD SiPM technology

FBK

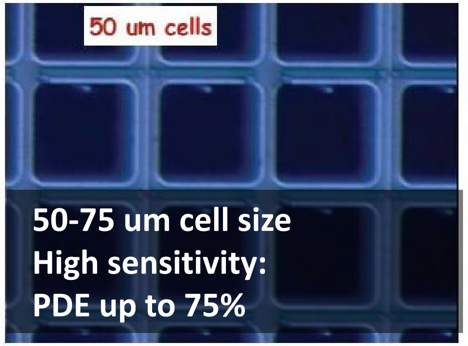
SiPM Cell, top view



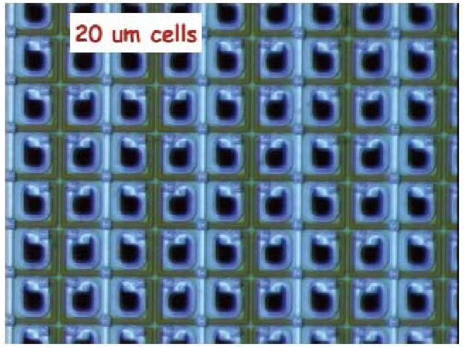
	Std. SiPM RBG	RGB-HD
CS	40 *μm*	15 *μm*
FF	60 %	62 %

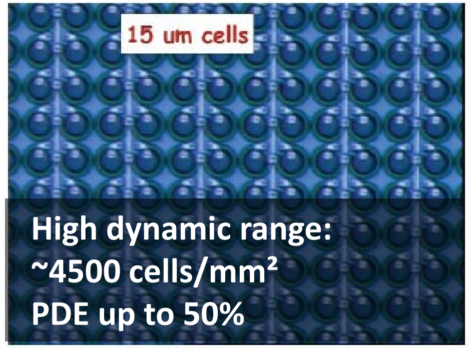


Improving fill factor for small cell size!

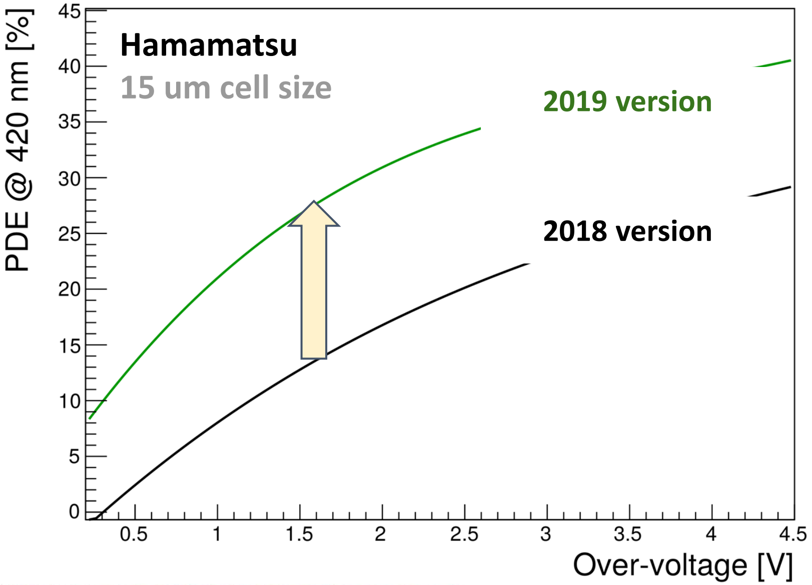


50-75 um cell size
High sensitivity:
PDE up to 75%



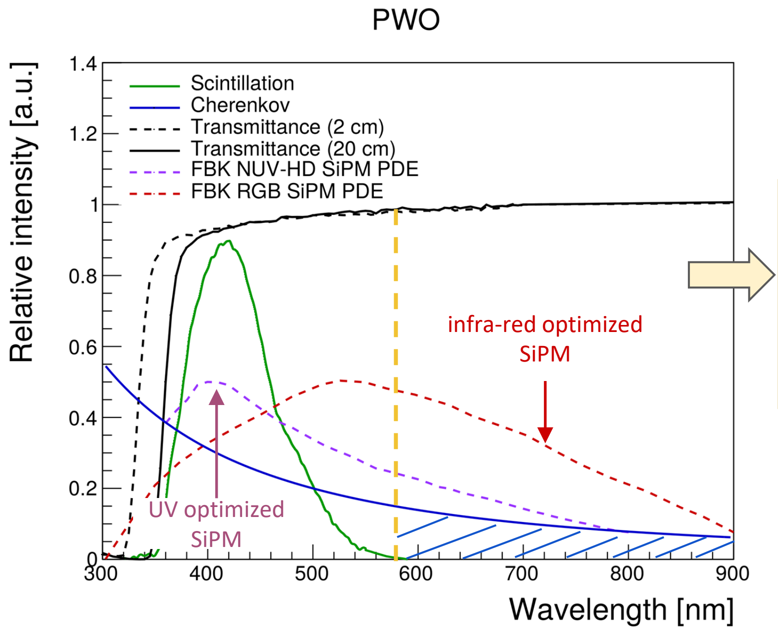


High dynamic range:
~4500 cells/mm^2
PDE up to 50%



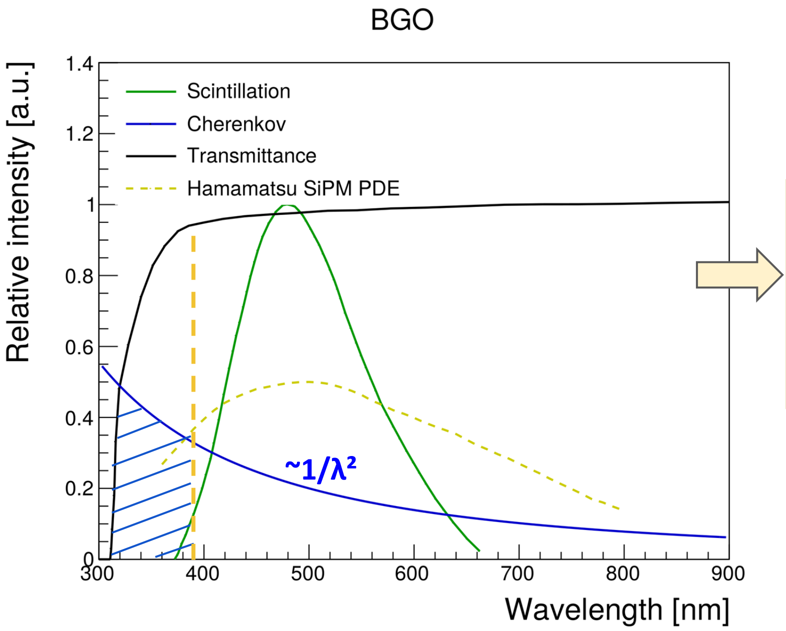
Cherenkov detection in PWO and BGO

- Sensitivity in both the UV and infrared region with Silicon Photomultipliers
- At least two crystal candidates for a compact, cost-contained ECAL with DRO capabilities:
  - **PWO** (e.g. CMS) and **BGO** (e.g. L3)
  - Detect Cherenkov photons in either the UV (BGO) or infrared region (PWO)



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

~10% of signal from Cherenkov in CMS ECAL ([N Akchurin et al.](#)) increasing due to radiation damage that filters out the UV scintillation component!



BGO has a larger stokes shift, wider range of transparency for UV Cherenkov

Cherenkov signal detected and exploited for timing applications even for electrons from 511 keV ɣ-rays! [Stefan Gundacker et al., 2020 Phys. Med. Biol.65 025001](#)

Validation of Geant4 **ray-tracing** simulation

- Geant4 simulation for ray-tracing of Cherenkov photons validated
- **Reproducing experimental results from test beam**

(thanks to G.Gaudio for help in retrieving details of the setup!)

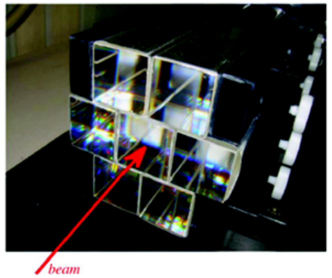
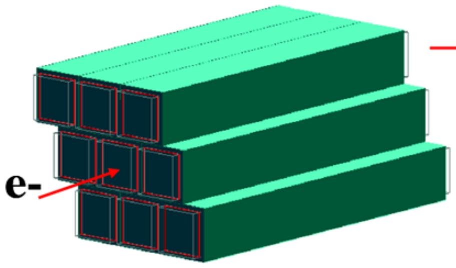


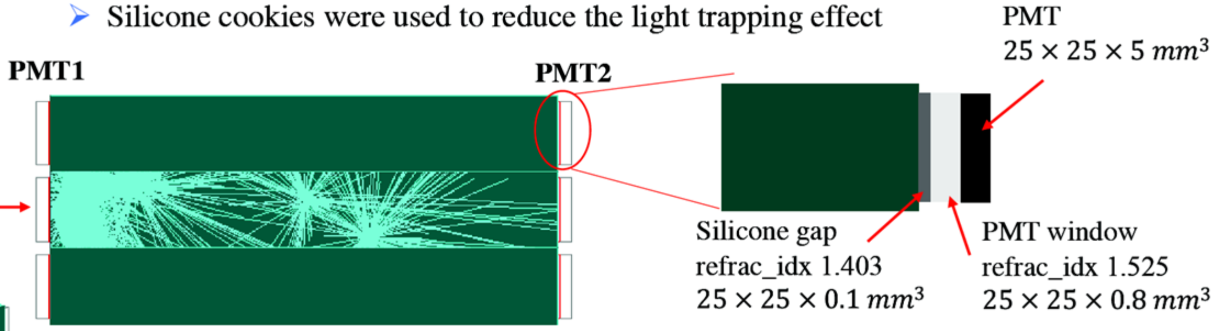
Fig. 2. The PWO matrix consisted of seven crystals with dimensions of 3 × 3 × 20 cm^3. These were arranged as shown in the figure and the beam entered the matrix in the central crystal. All crystals were individually wrapped in aluminized mylar. Both the upstream and downstream end faces were covered with filters. See text for details.

F. Bedeschi, G. Gaudio, et al. https://www.sciencedirect.com/science/article/pii/S0168900212014520

Geometry and material description in the paper

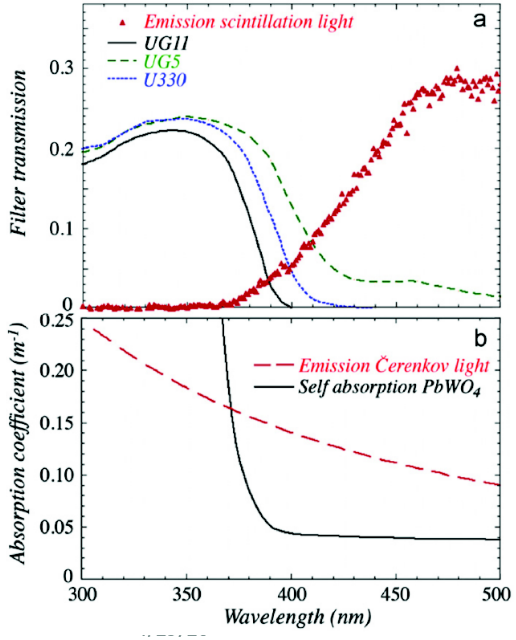
- 7 crystals with dimensions of $30 \times 30 \times 200\ mm^3$
- All crystals were individually wrapped in aluminized mylar.
- Hamamatsu R8900-100 tubes
- Both the upstream and downstream end faces of the matrix were covered with a large optical transmission filter (U330 or UG5)
- Silicone cookies were used to reduce the light trapping effect





- Crystal wrapped with aluminum sheet of 0.985 reflectivity
- 0.1 mm silicone gap between crystal and PMT Borosilicate glass window
- Interface between gap and PMT window is set as the filter
- PMT surface is set as sensitive

Simulation of optical filters and PWO optical properties

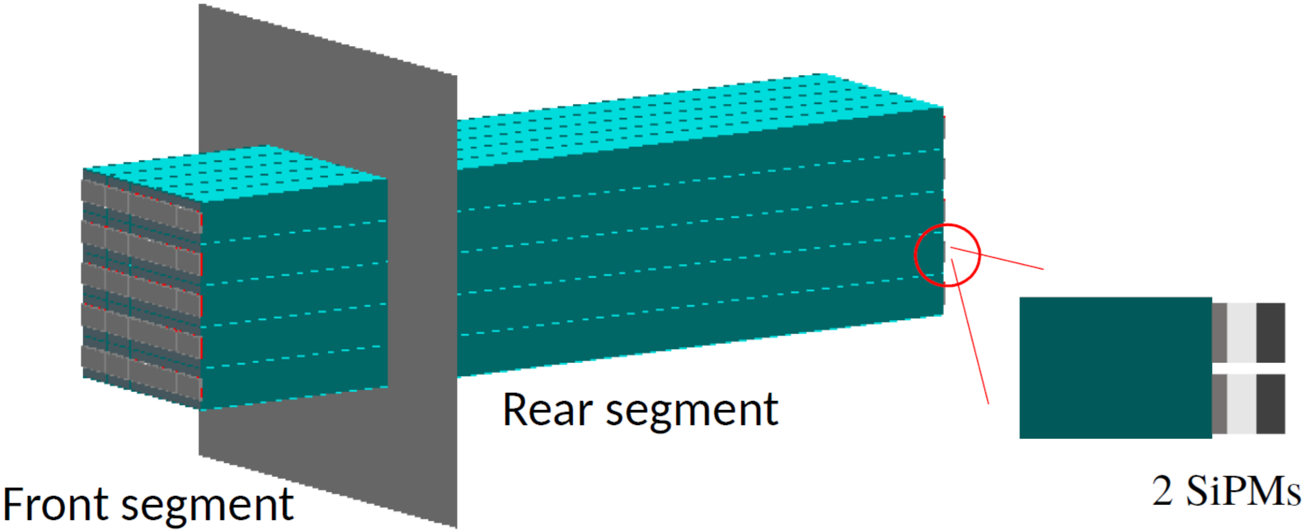


MC to data comparison: simulation predicting ~40% more Cherenkov photons (fine tuning ongoing)

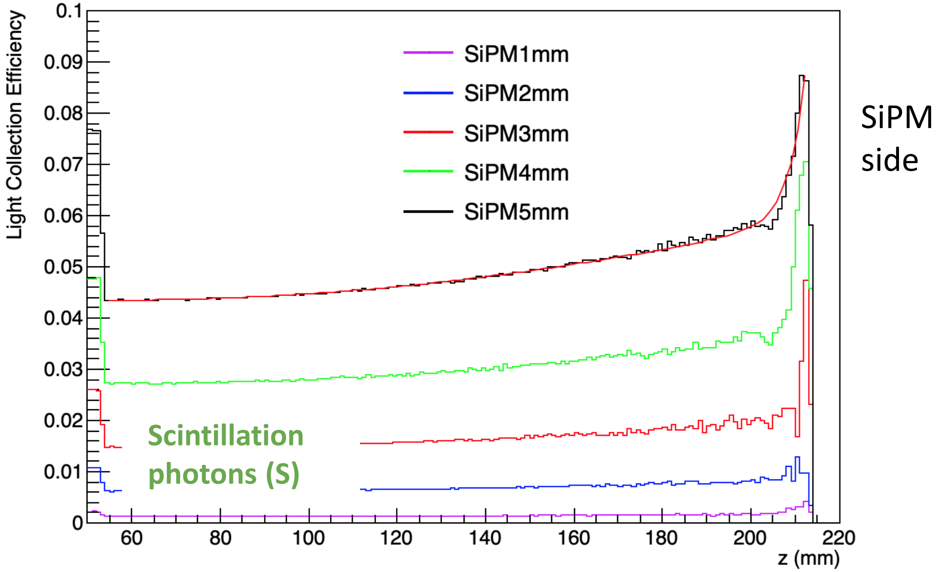
	Detected photons (50 GeV e-)		Number in paper (50 GeV e-)
Filters	Upstream	downstream	
No filter /No filter	9950	14860	
No filter/U330	9146	781	
No filter/UG5	9199	1278	
U330/U330	517	774	650
U330/UG5	513	1246	1250

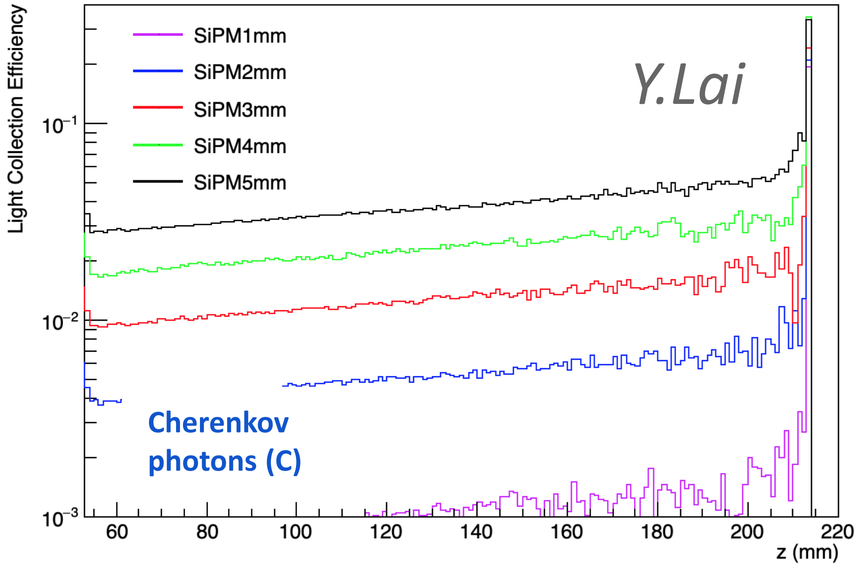
Ray-tracing in the SCEPCal

- Study impact of various parameters on light collection efficiency for both S and C:
  - LCE grows linearly with SiPM active area
  - LCE grows with shorter crystals



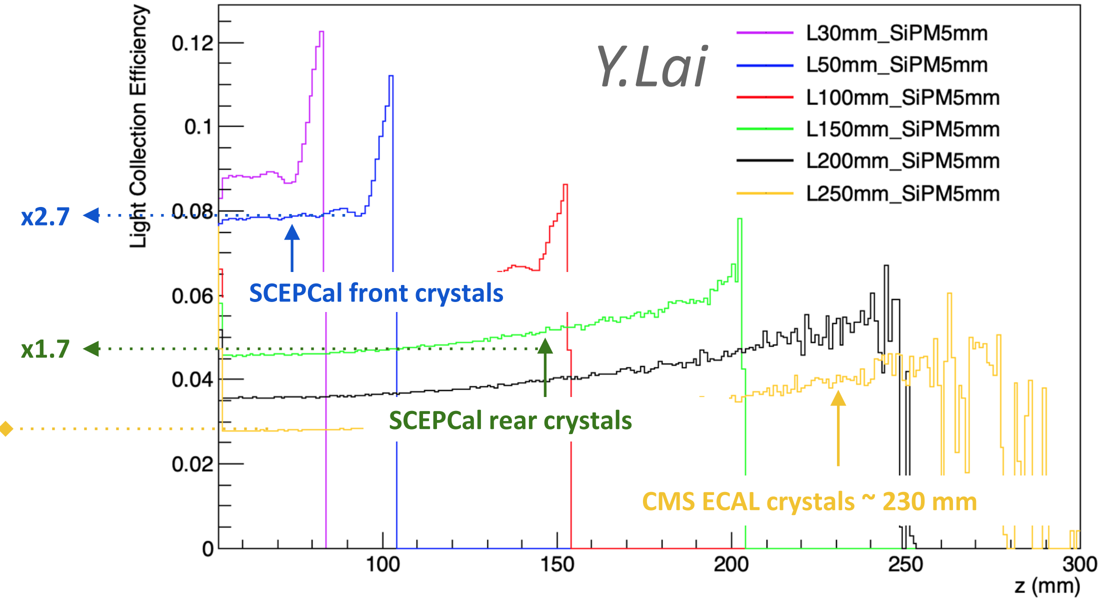
Light collection efficiency for rear SCEPCal crystal





SCEPCal key features for **DRO optimization**

- **High granularity increases light collection efficiency** (both C and S)
  - 1 cm^2 cross section compared to ~ 3 cm^2 in L3/CMS
  - crystal length reduced by ~2x
- **SiPM active area can be tuned** to achieve target resolution (stoch. term)
  - light collection efficiency increasing linearly with SiPM area
- SiPM with smaller dynamic range but high PDE can be selected for C-detection



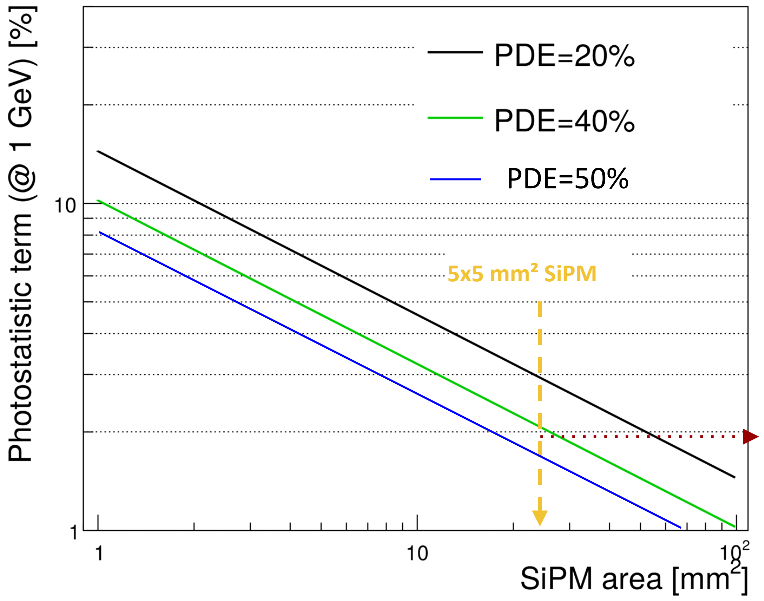
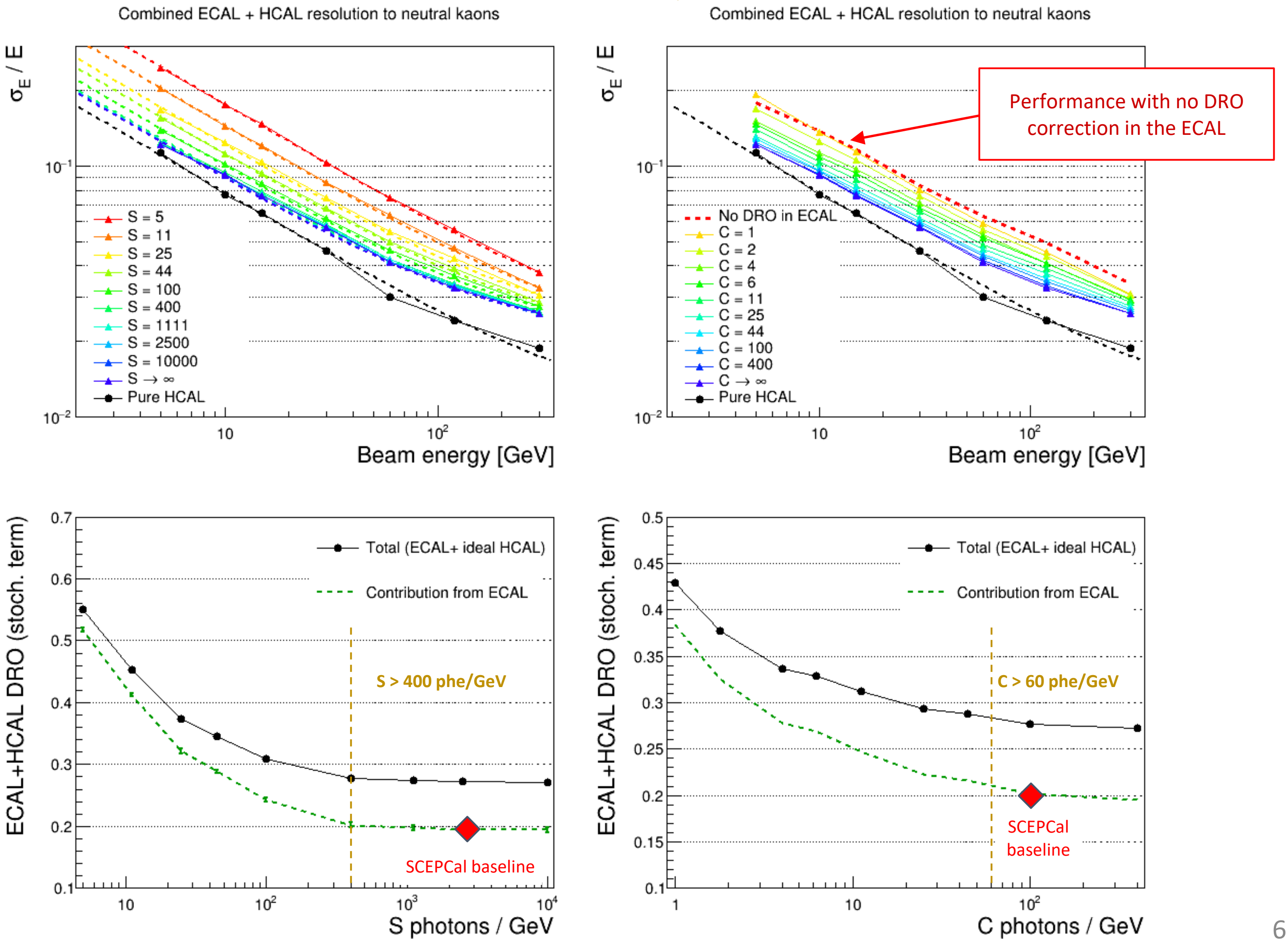


Photo-statistics term for S can be tuned by increasing the SiPM active area down to <**2%**

Photo-statistic requirements for S and C

Smearing according to Poisson statistics

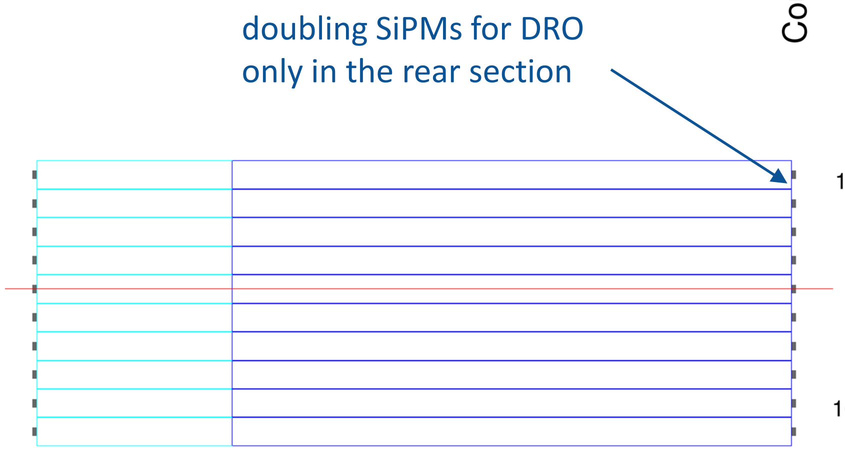
- Poor S directly impact the ECAL resolution stochastic term
  (even without DRO):
  - S > 400 phe/GeV to limit the contribution to HCAL stoch. term below 20%
- A limited resolution to C (photostatistics) impacts the C/S and thus the precision of the event-by-event DRO correction
  - C > 60 phe/GeV to limit the

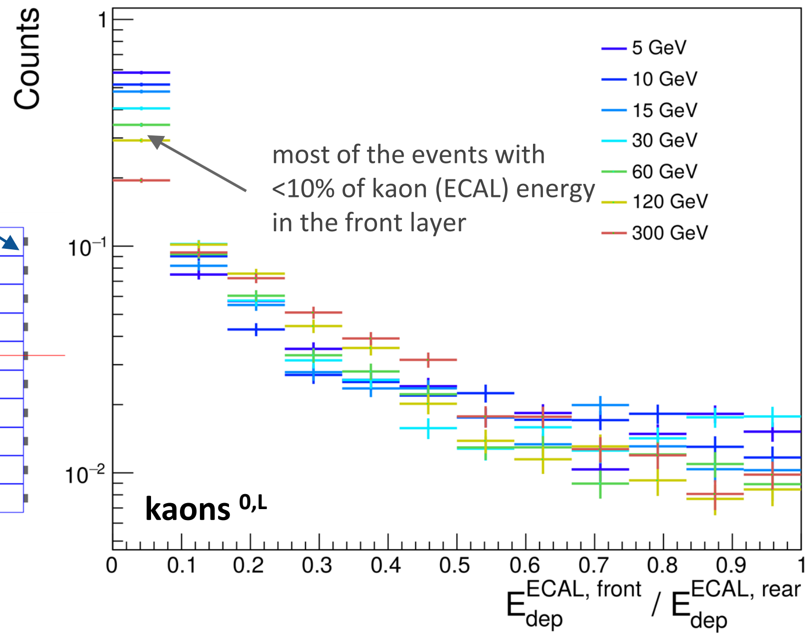


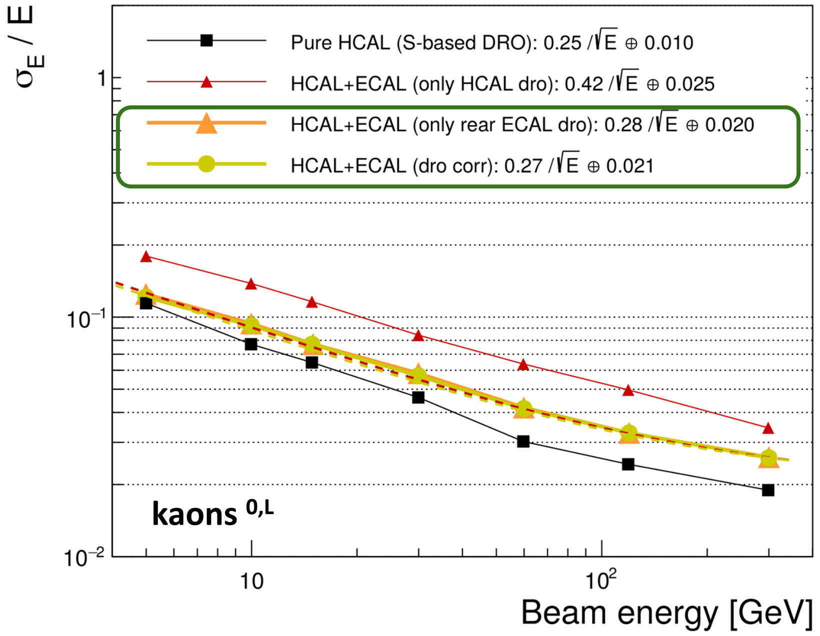
Performance with no DRO correction in the ECAL

DRO in the **rear** SCEPCal segment **only**

- Majority of the energy deposit from hadron is in the rear ECAL section
- **Dual readout can be implemented in the rear section only**
  - No degradation in performance wrt a full (front+rear) DRO ECAL
  - +50% in channel count wrt to non-DRO ECAL can be mitigated by decreasing granularity in the rear compartment where shower radius is larger


doubling SiPMs for DRO only in the rear section


most of the events with <10% of kaon (ECAL) energy in the front layer



Summary

- **Highlights of a segmented crystal ECAL (SCEPCal):**
    - **Excellent DRO hadron calorimetry** with 27%/√(E) ⨁ 2% is achieved with a segmented crystal EM calorimeter in front of the thin solenoid in the IDEA detector
    - **Addition of ~3%/√(E) ⨁ 1% EM resolution** for photons and brem recovery for electrons
    - Enables **efficient pre-clustering of pizero photons**, shown to reduced photon misassignment in the 4th jet by a factor of 4.5 and the 6th jet by a factor of 8 - impacting 2/3 of all HZ events.
- **Optimization of DRO capabilities**:
    - Methods to extract C from rear crystals significantly improved with SiPMs and shorter crystals, relative to previous tests (2009 DREAM+BGO, 2013 BGO/PWO DRO studies)
    - Option for interleaved pure-C radiating crystals with PWO also being studied.
- Combination of DRO ECAL and DRO HCAL allows for **separate optimizations of channel count,**

Additional slides

Outlook

- Progress on standalone simulation for further cost/performance optimization of the SCEPCal layout and its integration with a DRO HCAL

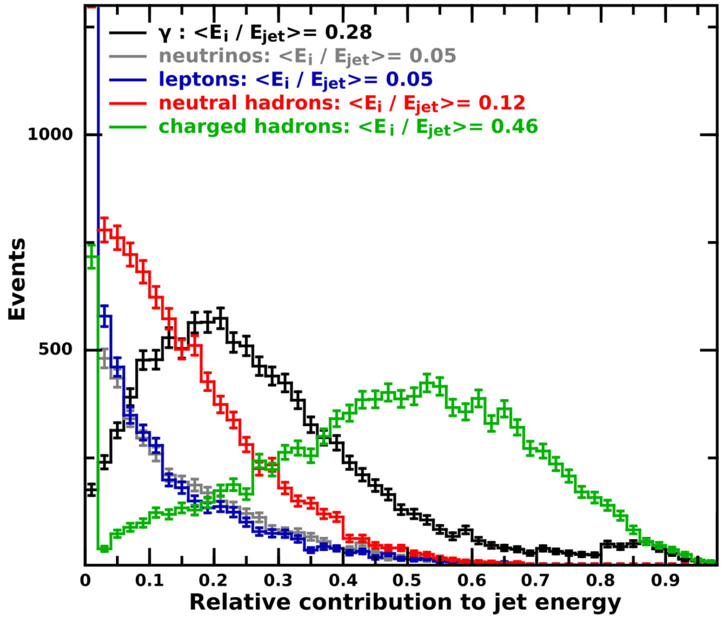
- Experimental (beam) tests to consolidate parameters

- Looking forward to a more quantitative PFA benchmark for a comparison of calorimeter designs

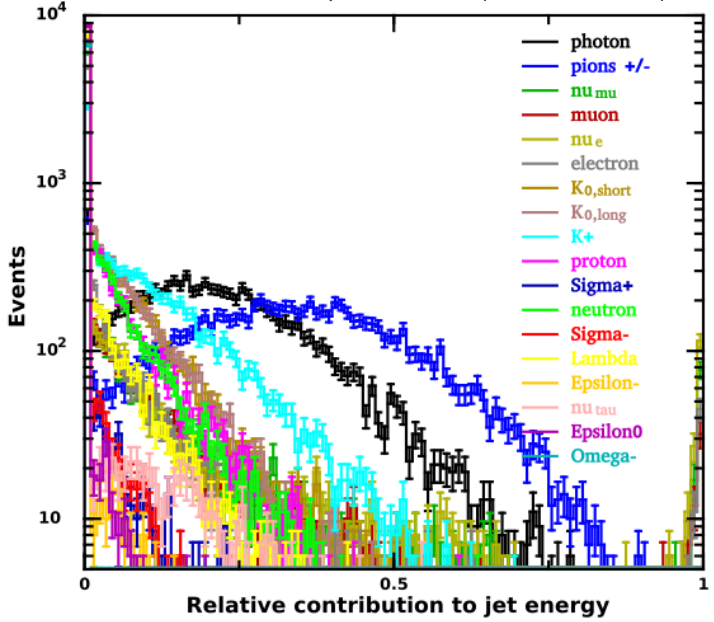
Jet composition

- 30% photons, 50% charged hadrons, 10% neutral hadrons
- Neutral hadrons are mainly kaons with mean energy of ~5 GeV

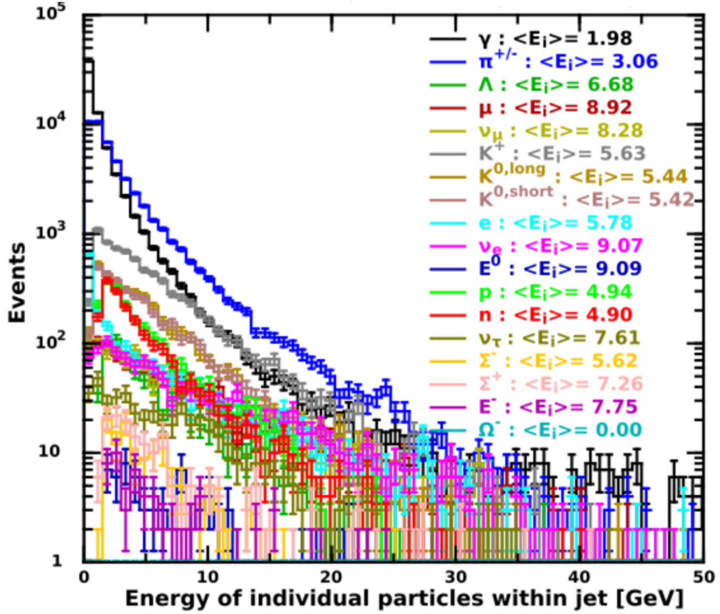
HepSim: Z→ bb (e^+e^- @250 GeV)



HepSim: Z→ bb (e^+e^- @250 GeV)



HepSim: Z→ bb (e^+e^- @250 GeV)

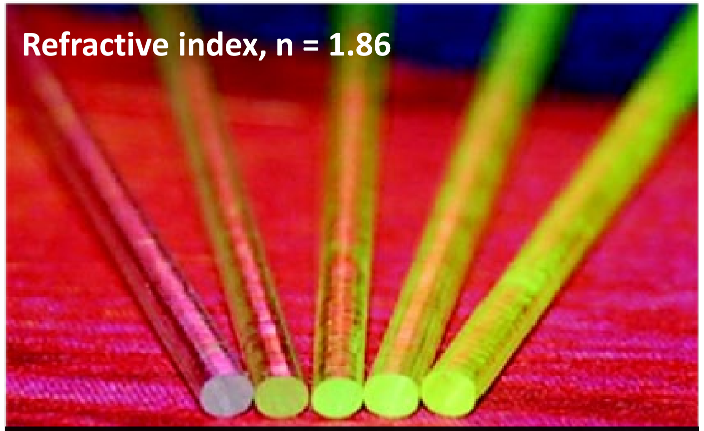


Crystal based Spaghetti Calorimeters

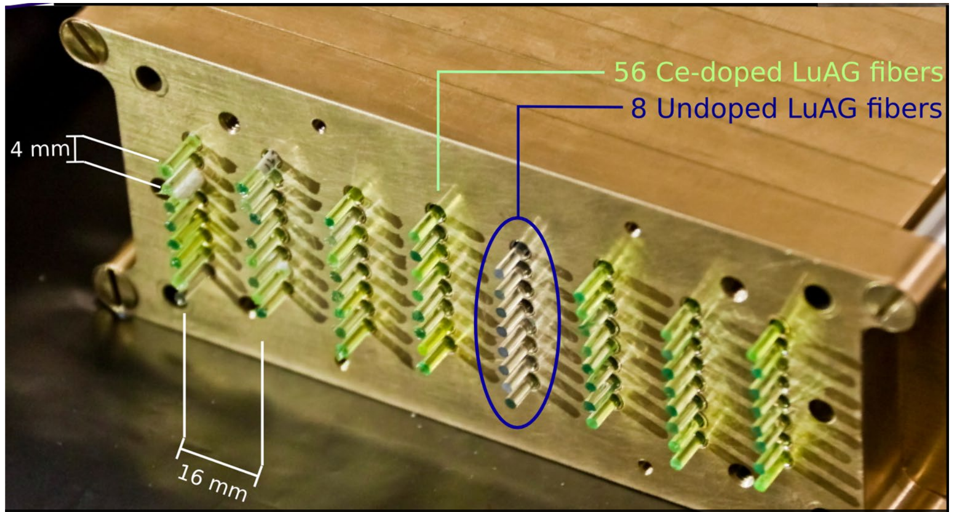
- Technology wise, a lot of progress in high granularity crystal calorimeters
  - **New materials and new production processes**
  - **Undoped LuAG crystals as excellent cherenkov radiators**
  - Crystal based SPACAL being studied for LHCb HL-LHC upgrade

$Lu_3Al_5O_{12}$
ρ = 6.73 g/cm^3
X_0 = 1.41 cm
λ_I = 23.3 cm

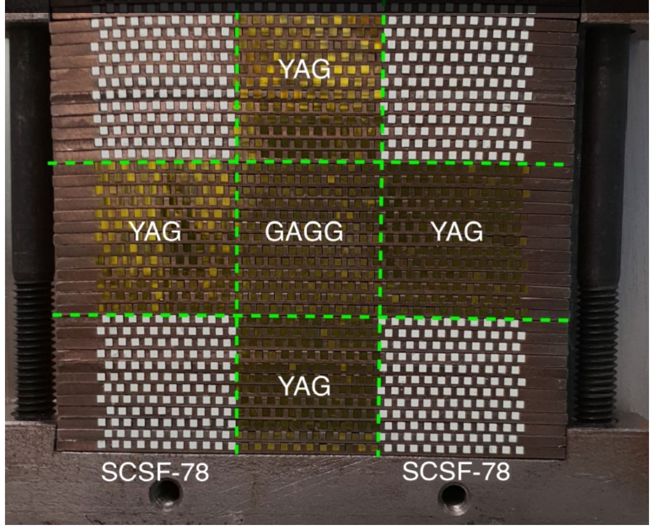
Undoped:
Cherenkov radiator
Cerium-doped:
Good scintillator


Refractive index, n = 1.86

Formerly proposed for "Studies on sampling and homogeneous dual readout calorimetry with meta-crystals"



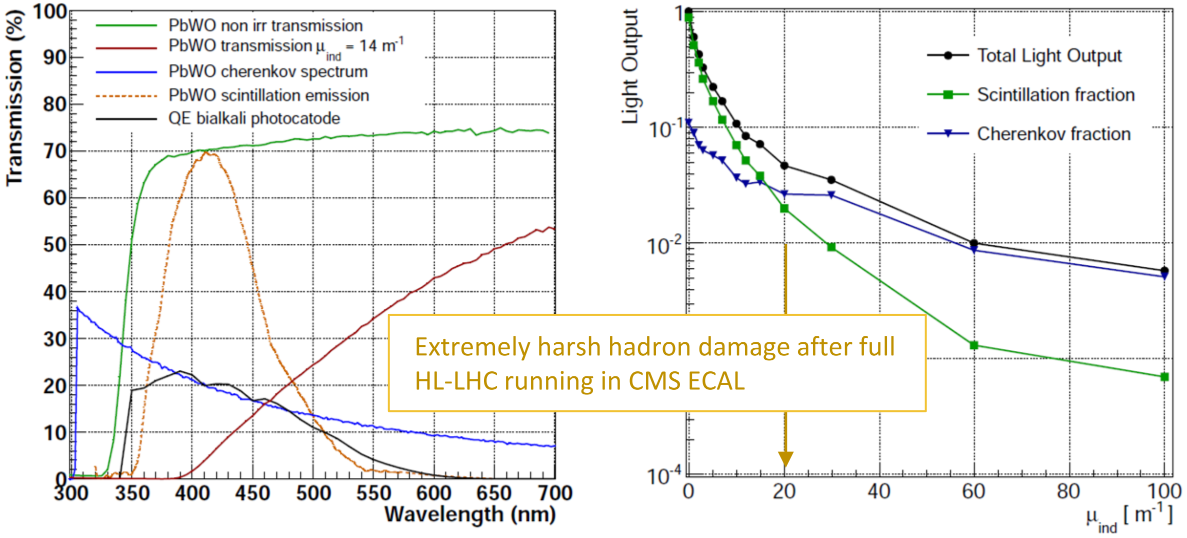
Test beam results of a high granularity LuAG fibre calorimeter prototype (A.Benaglia et al.)



The Phase II upgrade of the LHCb calorimeter system (M.Pizzichemi, et al.)

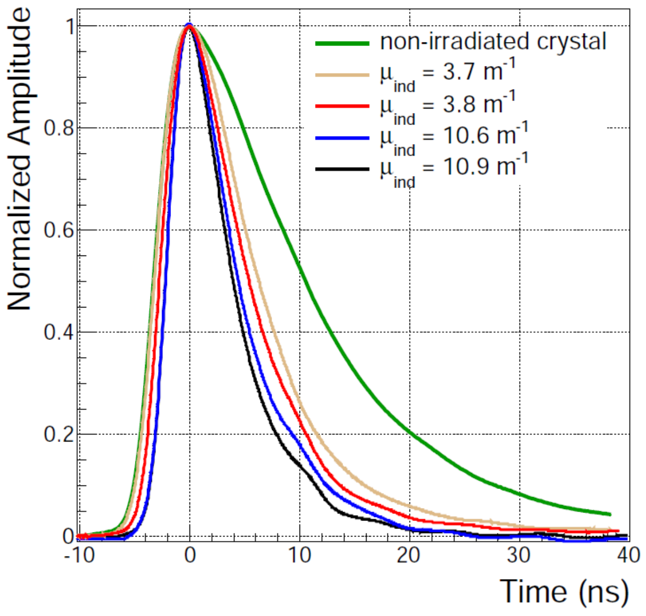
Increase of C/S ratio in irradiated PWO crystals

- **An example of high wavelength Cherenkov detection**
  - Radiation damage in PWO crystals filtering out the scintillation and enhancing the relative contribution of C photon (with lambda>500 nm) to the signal
  - Pulse shapes also get faster



Extremely harsh hadron damage after full HL-LHC running in CMS ECAL

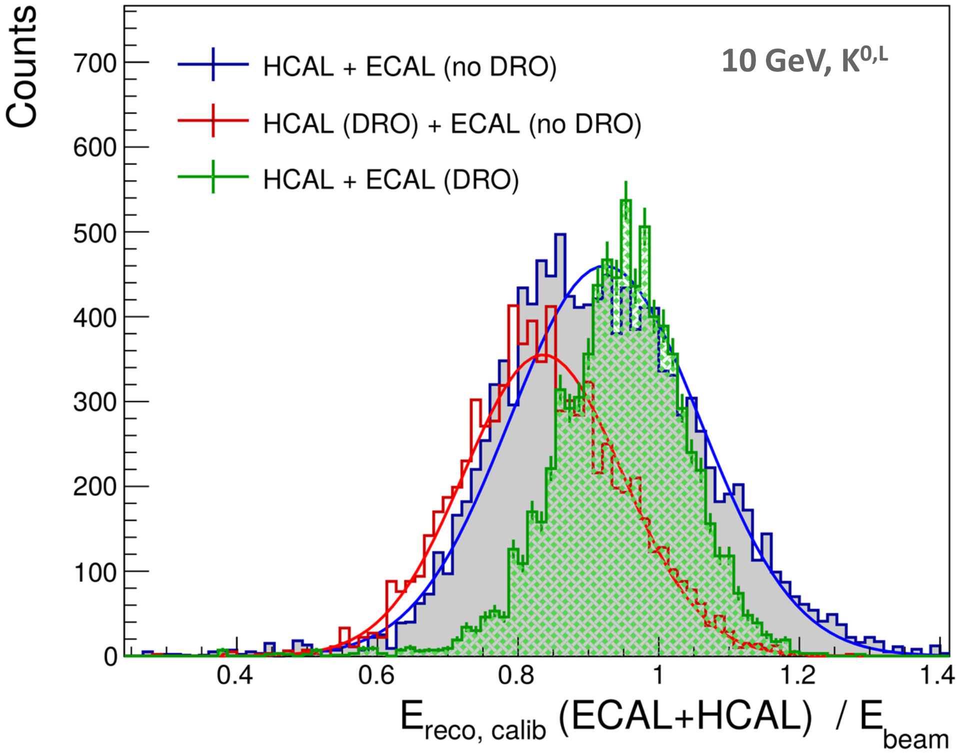
Figure 4.5: Left: wavelength dependence of Cherenkov and scintillation light compared with the transmission of hadron damaged crystals and the quantum efficiency (QE) of the photodetector. Right: contribution of scintillation and Cherenkov signal to the total light output at different μ_{ind}.

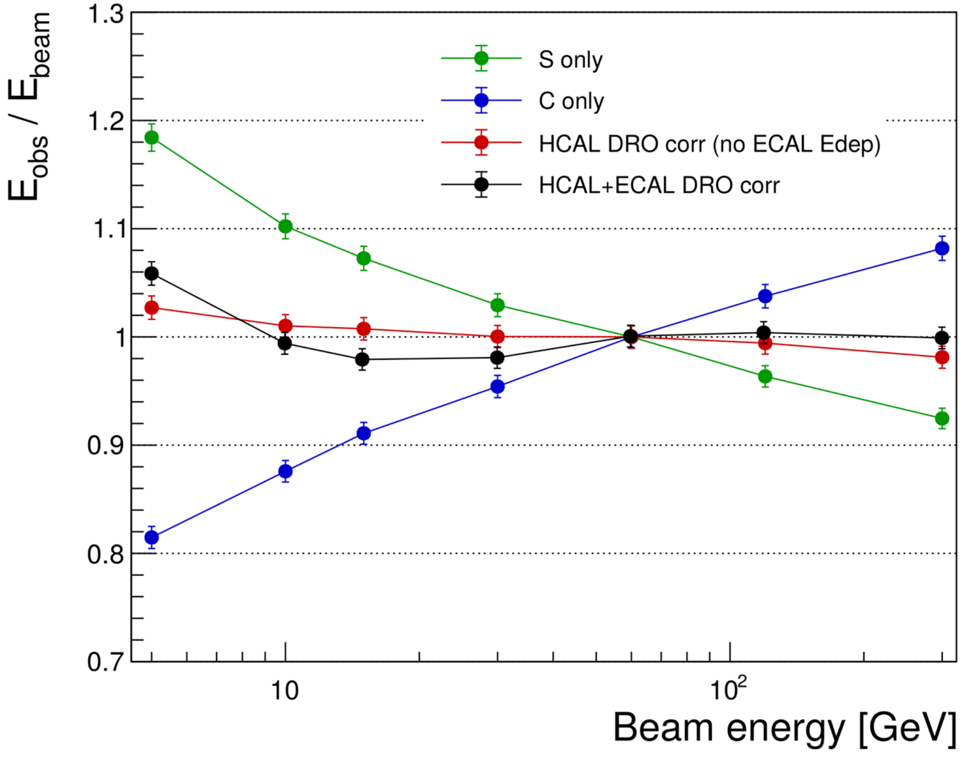


From "Evolution of the CMS ECAL Performance and R&D Studies for Calorimetry Options at High Luminosity LHC", M.Lucchini

Linearity (SCEPCal + DRO HCAL)

- Gaussian distributions and response linearity restored



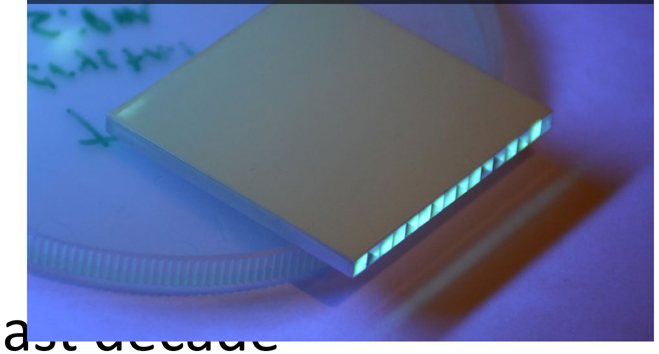


More on performance/cost optimization

Detector **cost** drivers

- **Crystal** options
  - LYSO:Ce for timing layer (optimal choice for the CMS MTD)
  - PWO (very compact - CMS and PANDA ECALs preferred choi
  - Many other crystals on the market may allow further optimi
- Crystal costs used as reference
  - Quotes from crystal vendors
    - **PWO: ~7€ /cc** (for 10 m^3, cut and polished)
    - **LYSO: ~30€ /cc** (for cut, polished and wrapped elements)
- **SiPMs**
  - Recent estimates from CMS Upgrade experience:
    - **~6€/SiPM** (9x9 mm^2 active area)
    - can embed a LED for monitoring: additional ~1€/channel
  - Cost constantly dropping and technology improving in the la
    - can aim at a factor ~2-4 reduction in the next decade


CMS ECAL PWO crystals


Array of LYSO crystal bars

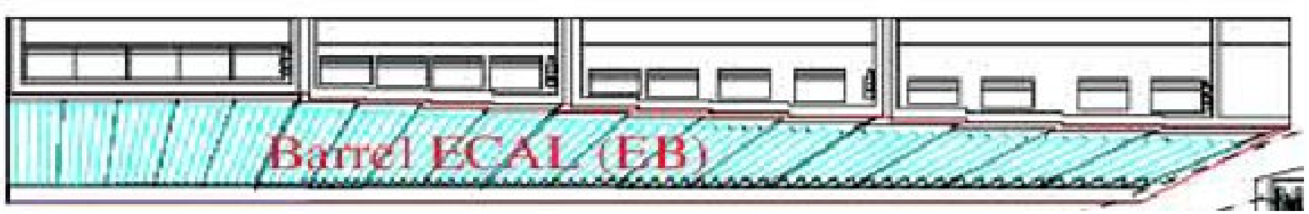
Cost and **power** breakdowns for SCEPCal

	T1+T2 (TIMING)	**E1+E2 (ECAL)**
Area barrel	53	53
Area endcap	19	19
Total area (barrel+endcaps)	**72 m²**	**72 m²**
# Channels barrel	977k	859k
# Channels endcaps	344k	374k
Total # of channels (barrel + endcaps)	**1.3 M**	**1.2 M**
Crystal cost	10 M€	78 M€
SiPM cost (+monitoring for ECAL only)	8 M€	8.5 M€
Electronics cost	5 M€	4.5 M€
Cooling+power+mechanics cost	5 M€	5 M€
Sub-total cost (barrel+endcaps)	28 M€	**96 M€**
Total cost (barrel+endcaps)	~124 M€	

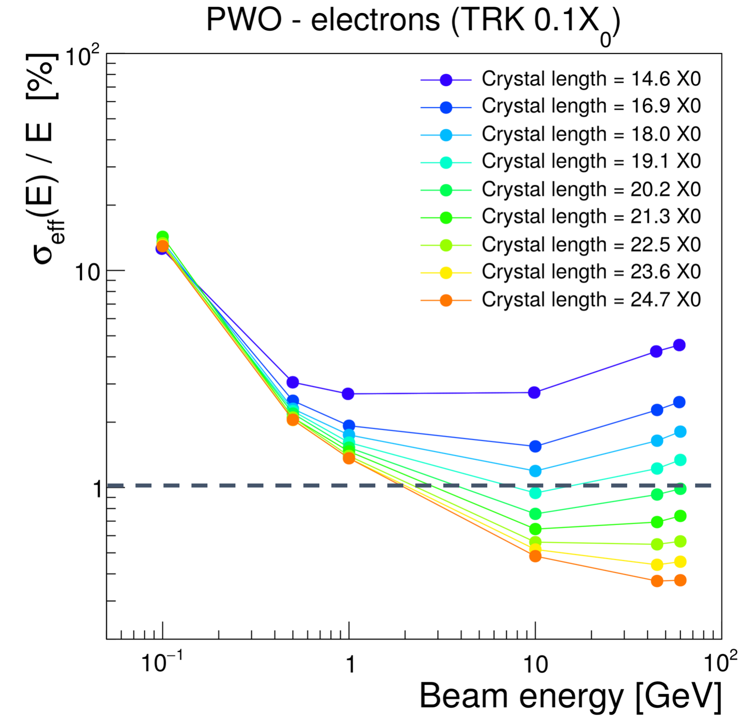
	T1+T2 (TIMING)	**E1+E2 (ECAL)**
# of readout channels	~1.3M	~1.2M
SiPMs (kW)	2.7	2.5
Electronics (kW)	34.3	33.5
Sub-total (kW)	**38**	**36**
Total (kW)	**~74 kW**	

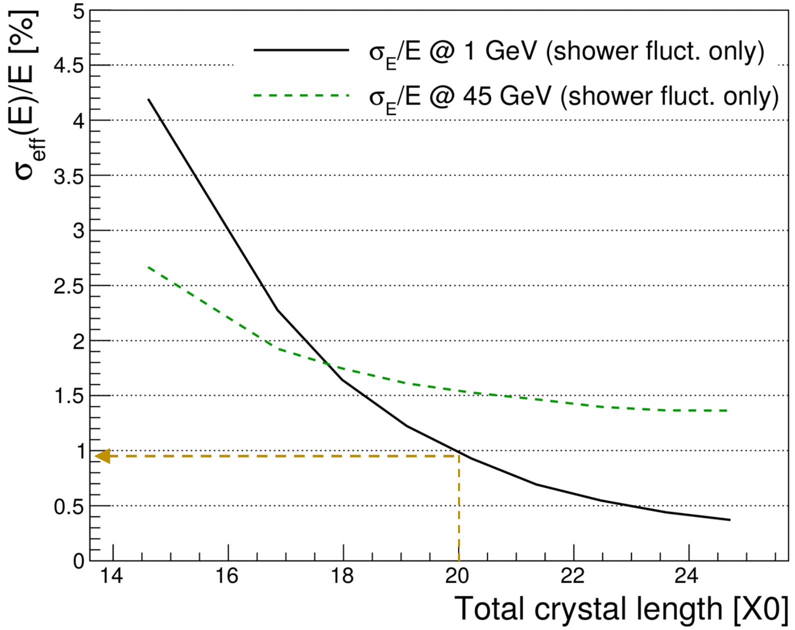
Optimization of crystal volume

- Crystal pointing geometry
  →reduce by ~20% crystal volume and channel count



- Optimizing crystal length vs energy resolution
  - with 20 X_0 contribution to constant term from shower leakage comparable to intercalibration precision: O(1%)
  - no substantial impact on stochastic component (negligible wrt photo-statistics term of ~4-5%)



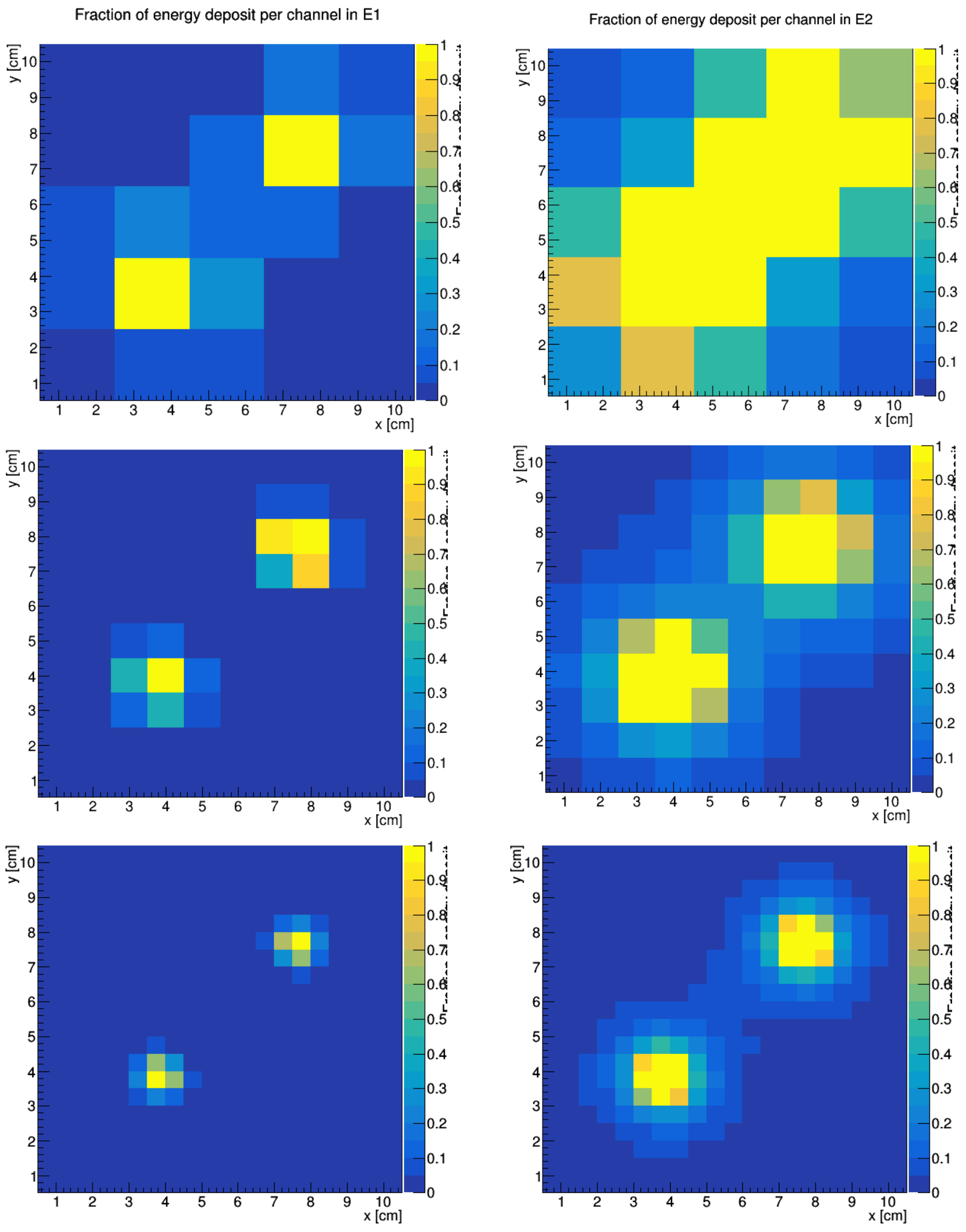


Transverse segmentation (visual impact)

cell size: 2x2 cm²

cell size: 1x1 cm²

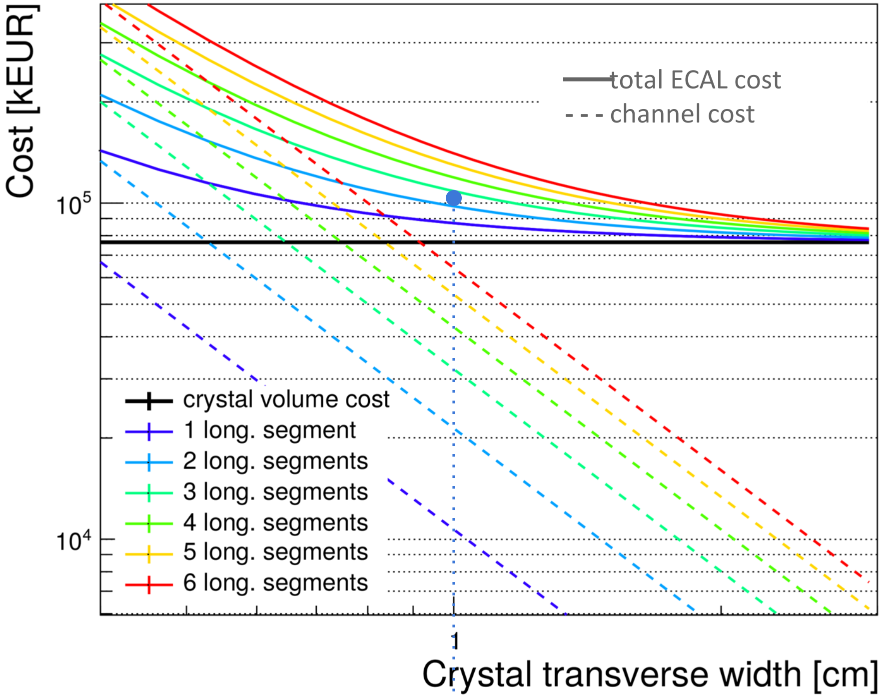
cell size: 0.5x0.5 cm²



Optimization of segmentation

- Segmentation optimized for performance/cost:
  - **Transverse** segmentation:
    → 1 cm ~ R_M / 2 (half Molière radius)
  - **Longitudinal** segmentation: 2 segments
    →particle ID with no dead material at shower max
    →simple for readout and services (front and rear)

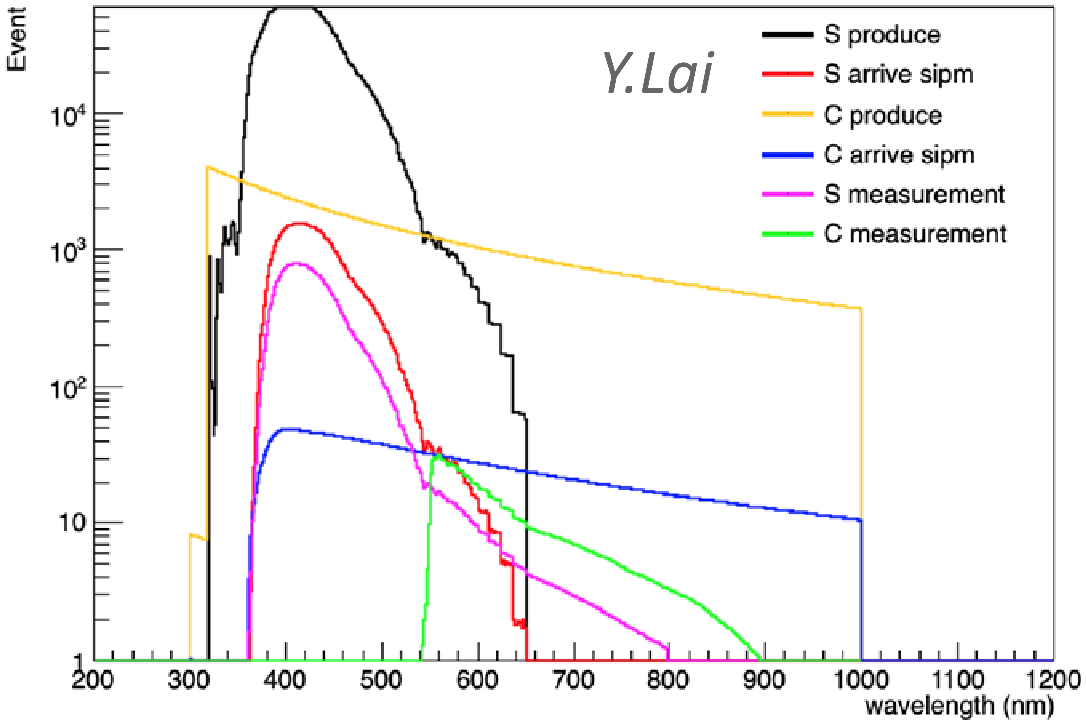
- Impact of ch. count on overall detector cost <20% for baseline segmentation choice
- Total cost ~ 95 M€

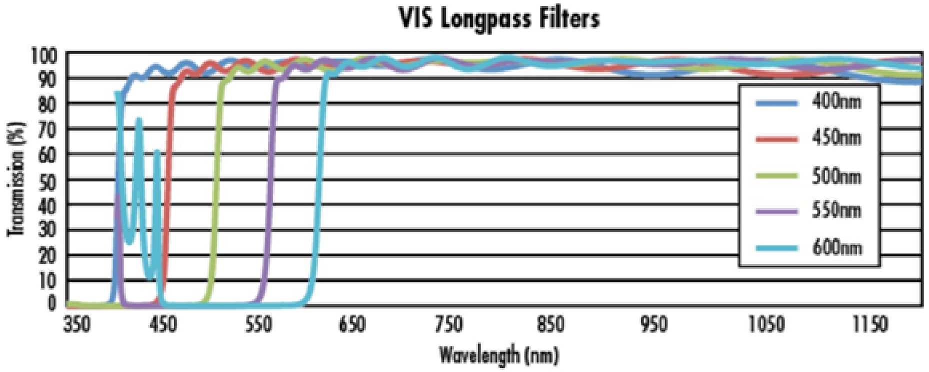


Reference design:
1 cm², 2 segments
cost ~ 95M€

More on SiPM readout

Fraction of S and C photons detected with dual SiPM





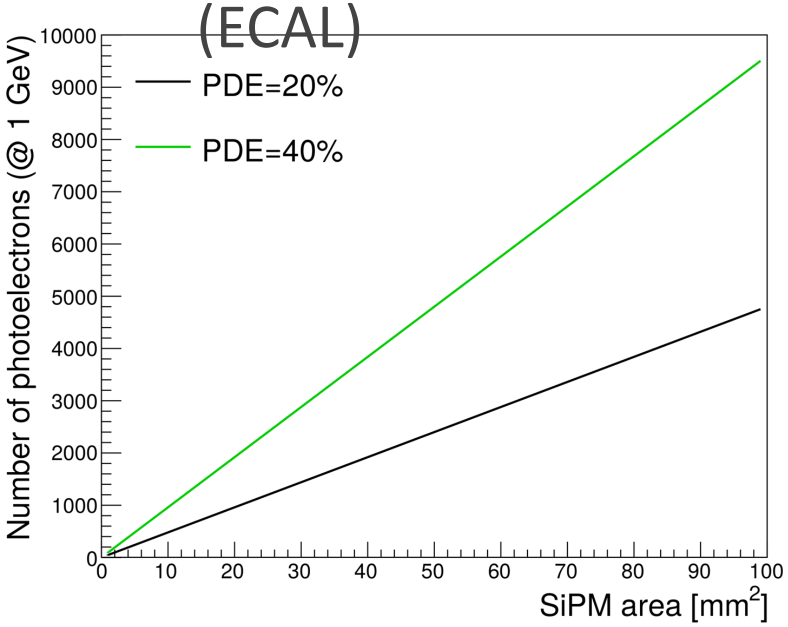
- RGB and UV SiPM are used to detect Cherenkov and scintillation photons
- All the photons detected by UV SiPM are considered as S
- The 550nm filter is added to RGB SiPM, so only photons with wavelength > 550nm could be detected. In this region, C is dominant
- The left plot shows spectrum of S and C when they are produced, arrived at the end and collected by SiPM
- The number of photons at different stages are shown in the table below, but it is a rough estimate, as the scintillation spectrum we are using is clearly rough up when wavelengths > 550nm.

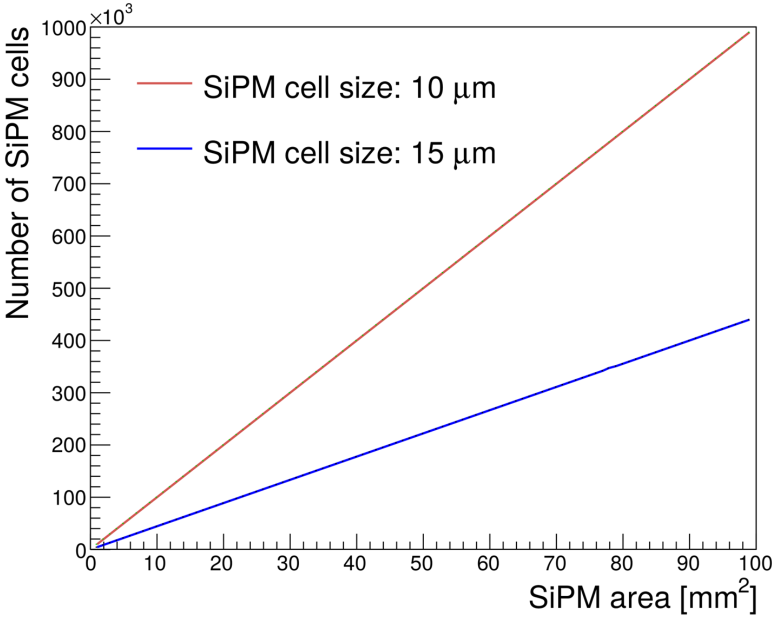
	S	**C**
Generate	4.5×10^5/GeV	5.655×10^4/GeV
Arrive at the End	5%	3.8%
Detected by SiPM	UV (1.1%) RGB (0.014%)	UV (0.49%) RGB (0.28%)

Misidentification as C

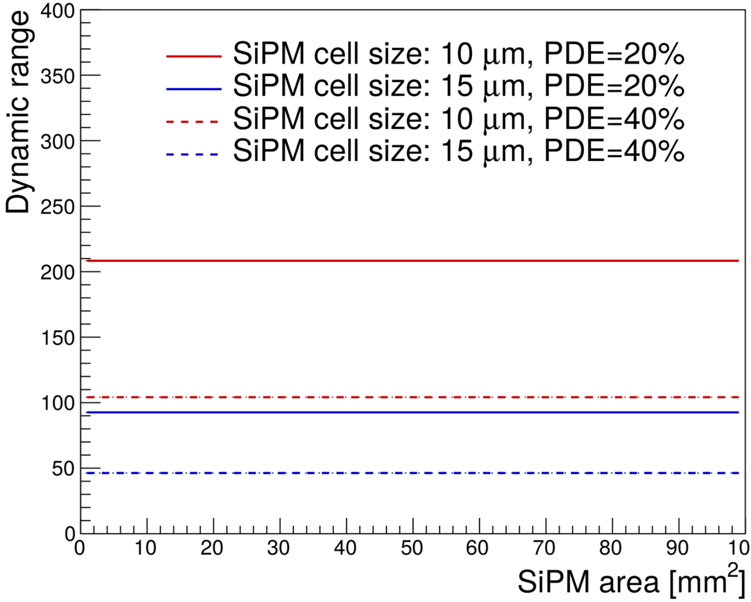
Dynamic range with SiPM

- 15 um cell pitch has high PDE (up to 50%) → optimal for T1 and T2 (timing)
- 10 um cell pitch has larger dynamic range → possibly better for E1, E2 (ECAL)





Ratio of number of photoelectrons at 1 GeV over SiPM available cells



More Geant4 simulation

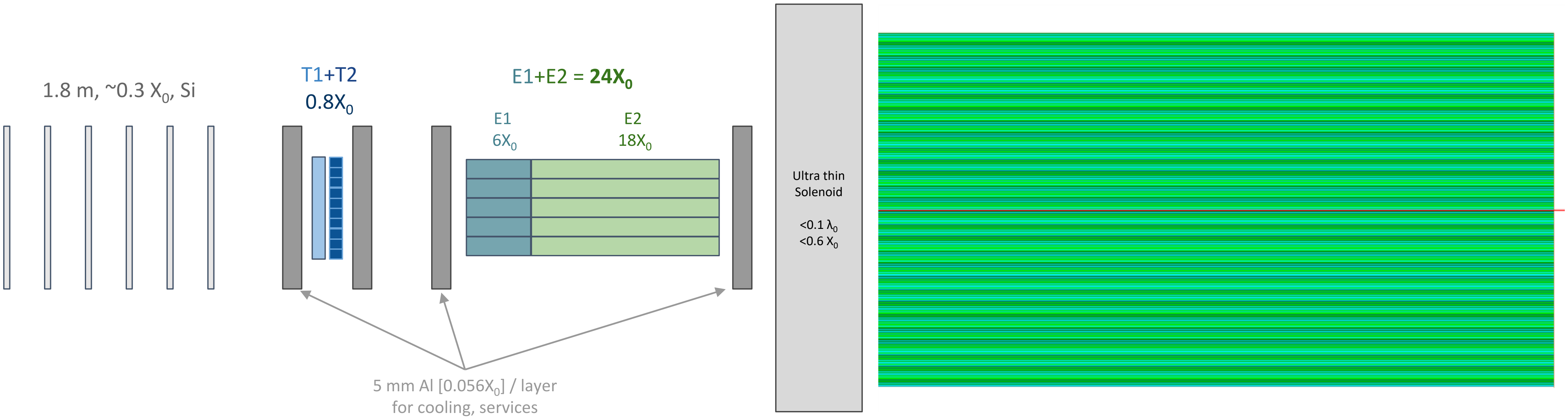
SCEPCal layout overview

Tracker

Timing
Crystal grid

SCEPCal
Segmented Crystal ECAL

HCAL
(dual readout)



1.8 m, ~0.3 X_0, Si

T1+T2
0.8X_0

E1+E2 = **24X_0**

E1
6X_0

E2
18X_0

5 mm Al [0.056X_0] / layer
for cooling, services

Ultra thin
Solenoid

<0.1 λ_0
<0.6 X_0

$1\lambda_0$

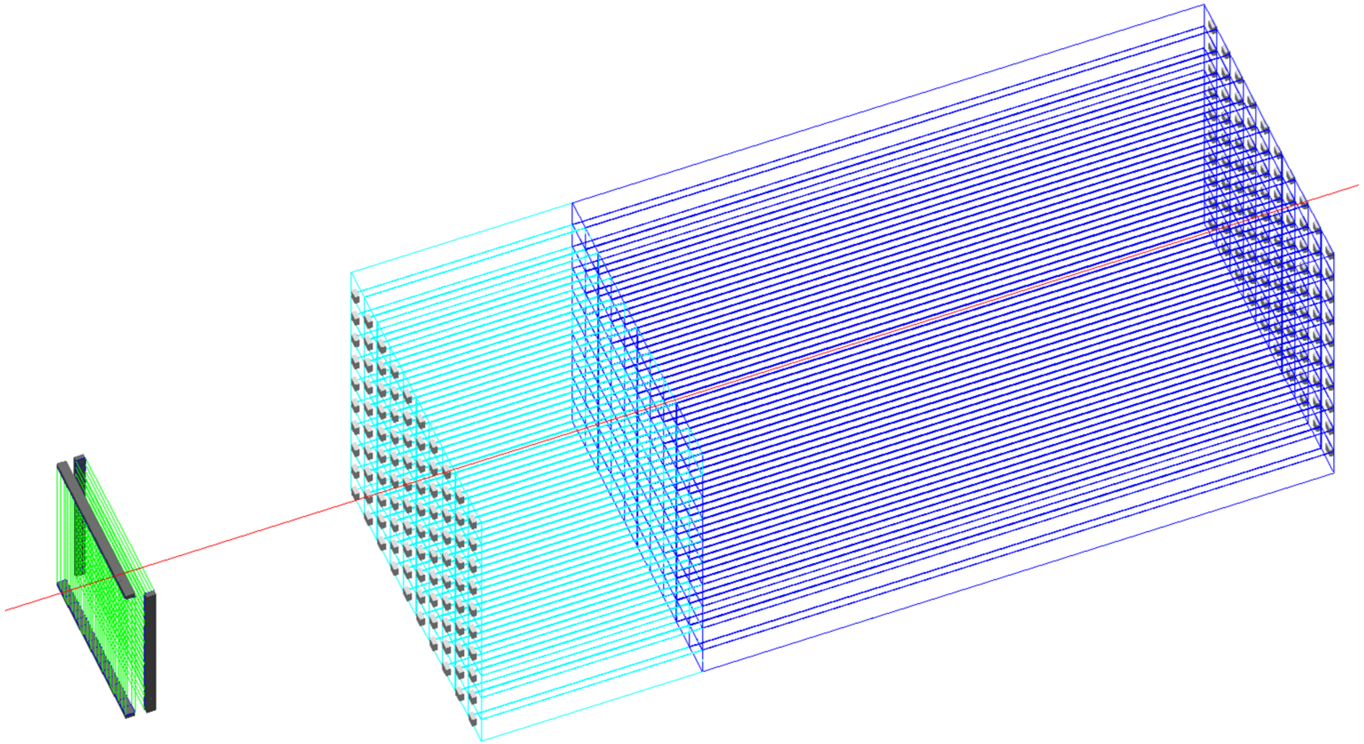
$\sim8\lambda_0$

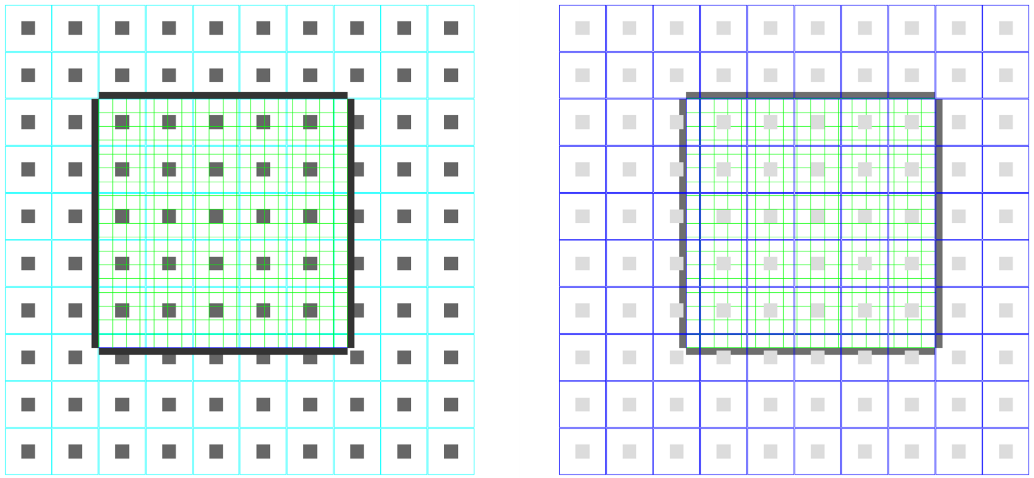
2 layers

2 layers

no longitudinal

S-CEPCal Geant4

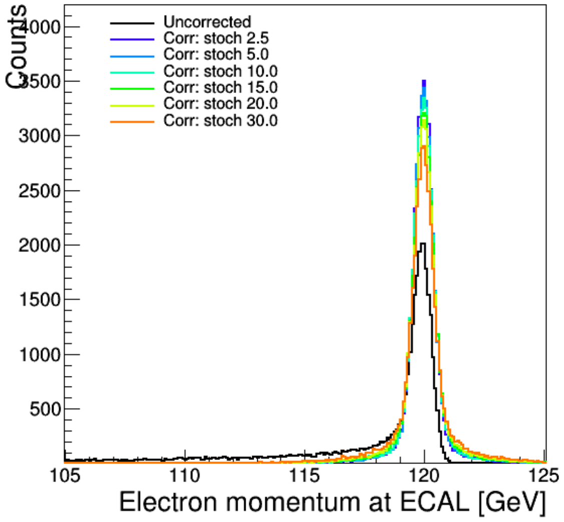




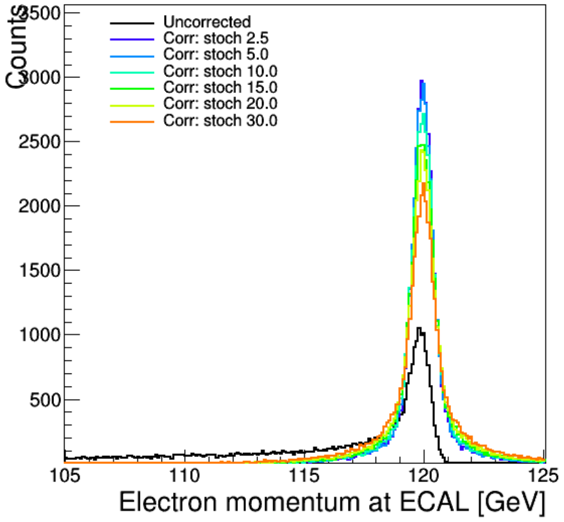
Electron momentum at ECAL

- Electron momentum at the entrance of ECAL smeared by 0.3 %
- 120 GeV electrons
- Adding back brem photons with ECAL resolution

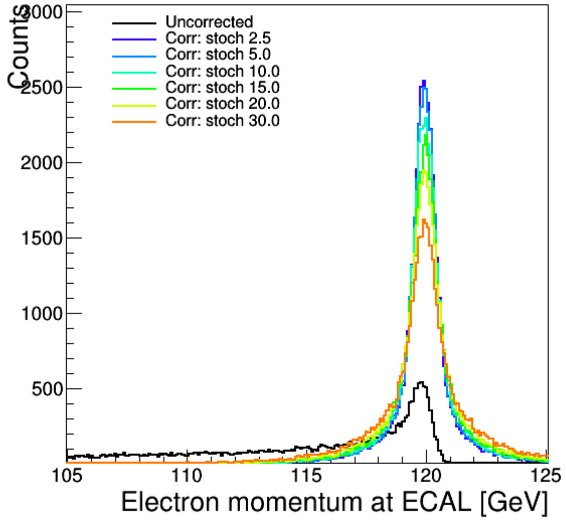
0.1 X_0



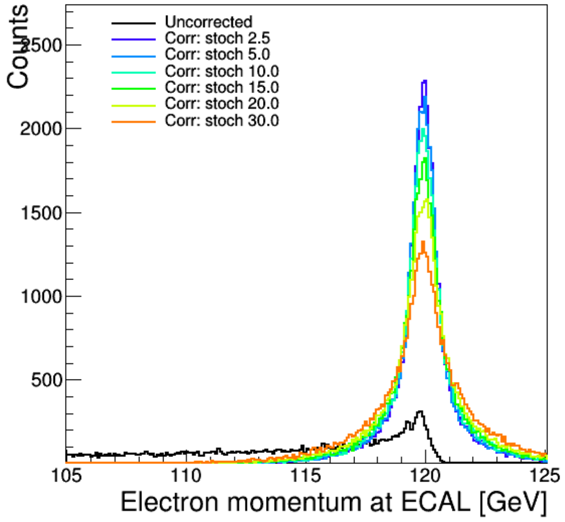
0.2 X_0



0.3 X_0



0.4 X_0



10 GeV $\pi^0 \rightarrow \gamma\gamma$ (Geant4 events display)