Geant4 simulations of sampling and homogeneous hadronic calorimeters with dual readout for FCC-ee

2nd Annual U.S. Future Circular Collider (FCC) Workshop

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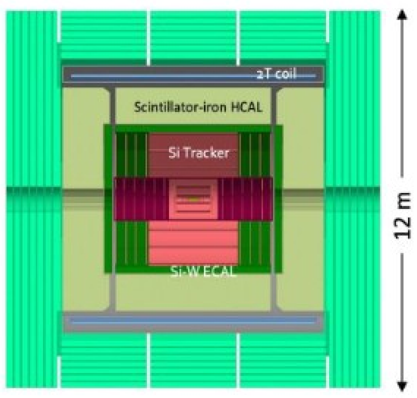
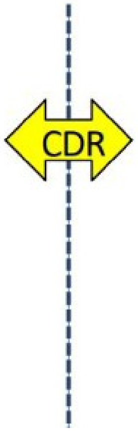
CALVISION

FCC-ee HCAL options

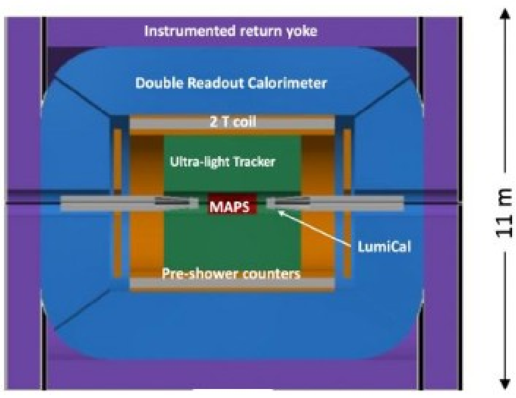
Credit to Nicolas Morange

CLD

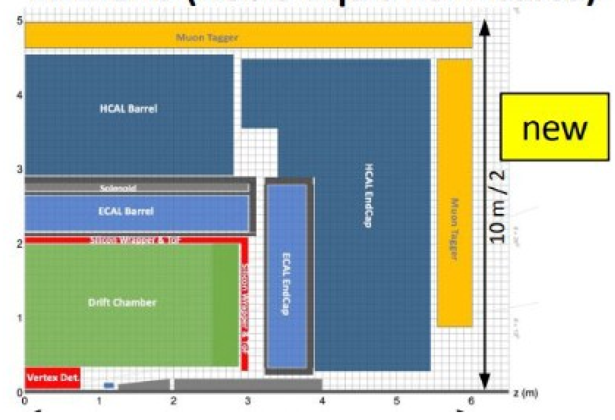




IDEA



ALLEGRO (Noble Liquid ECAL based)



Scintillator + Iron HCAL
- SiPMs directly on Scintillator or
- TileCal: WS fibres, SiPMs outside

~ similar to ILC, CLIC, CEPC

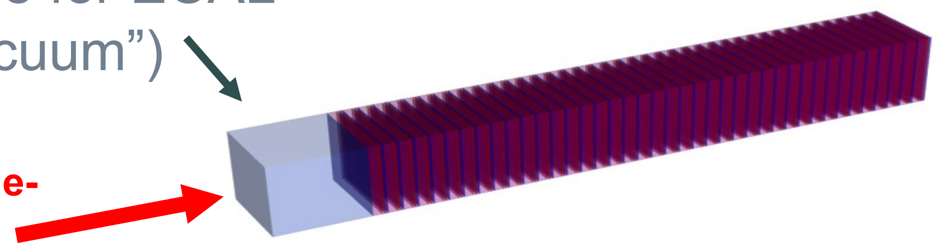
Dual readout HCAL:
Alternate:
Cherenkov fibers
Scintillating fibers

Scintillator + Iron HCAL:
- SiPMs directly on Scintillator or
- TileCal: WS fibres, SiPMs outside

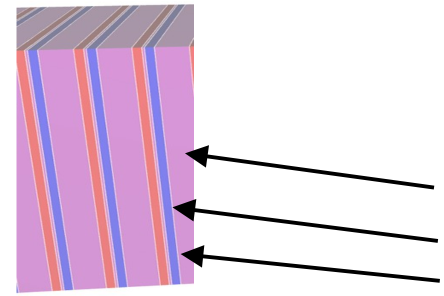
~ similar to ILC, CLIC, CEPC

Question: Can we add dual readout to CLD/ALLEGRO?
Modify active material and use Geant4 simulation to demonstrate this !

HCAL tower with dual readout (40L-PFQ)



20 cm x 20 cm ~ 1.2 λ_I



Simulate response to 1- 40 GeV single particles and analyze:

- Energy deposit
- Nr of Cherenkov photons
- Nr of Scintillation photons
- No photo-detection readout (100% efficiency)
- Count all photons at position (t,x,y,z)

40 layers

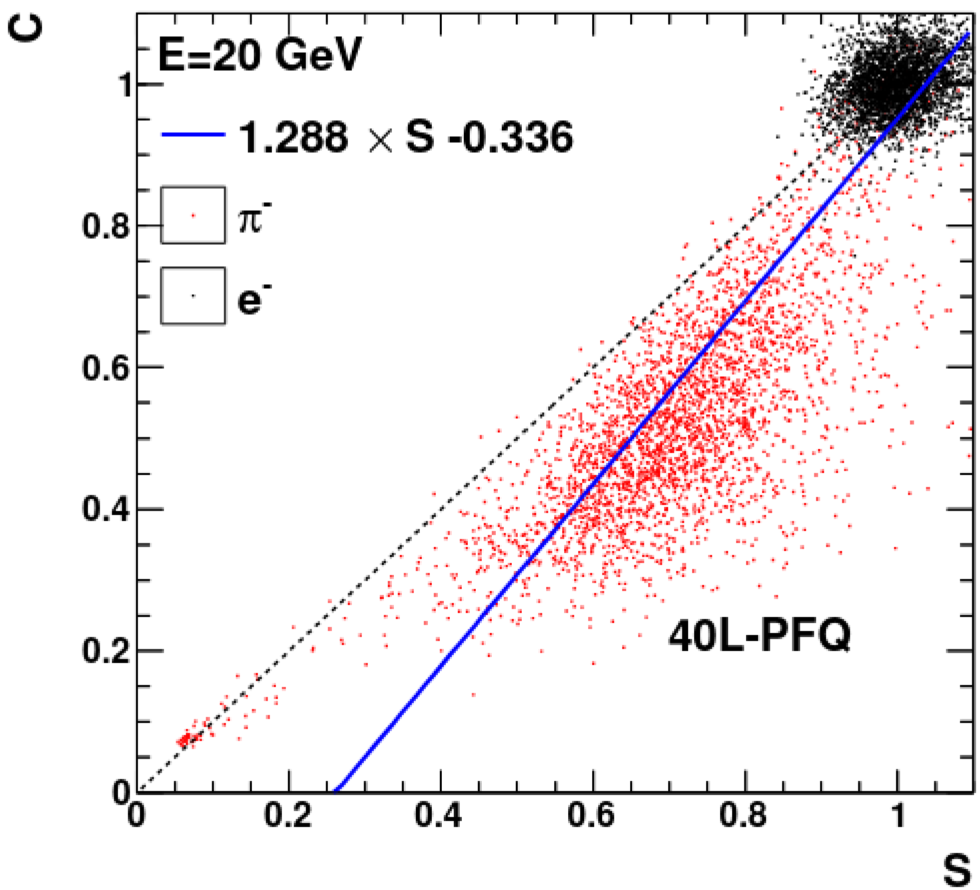
→ 4.7 λ_I for Fe only
→ 5.5 λ_I for Fe+active
→ >70% containment (>1 GeV)

Each layer has

- *2 cm steel (red color)*
- *0.5 cm of Quartz*
- *0.5 cm Polystyrene*
- *Sampling fraction ~10%*

Geant4 simulations are challenging!
20 GeV particles produces 4 million photons (on average)

Calibrated light response for 40-PFQ



S and **C** are Nr of scintillation and Cherenkov photons calibrated to electrons at the same energy

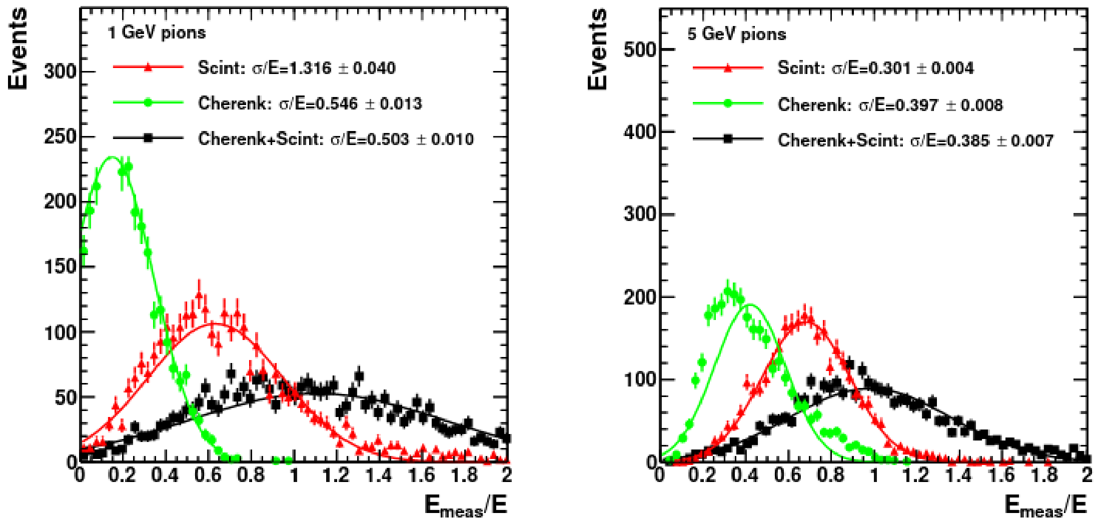
$$(h/e)_S = 0.71 \text{ (for the scintillation light)}$$

$$(h/e)_C = 0.52 \text{ (for Cherenkov light)}$$

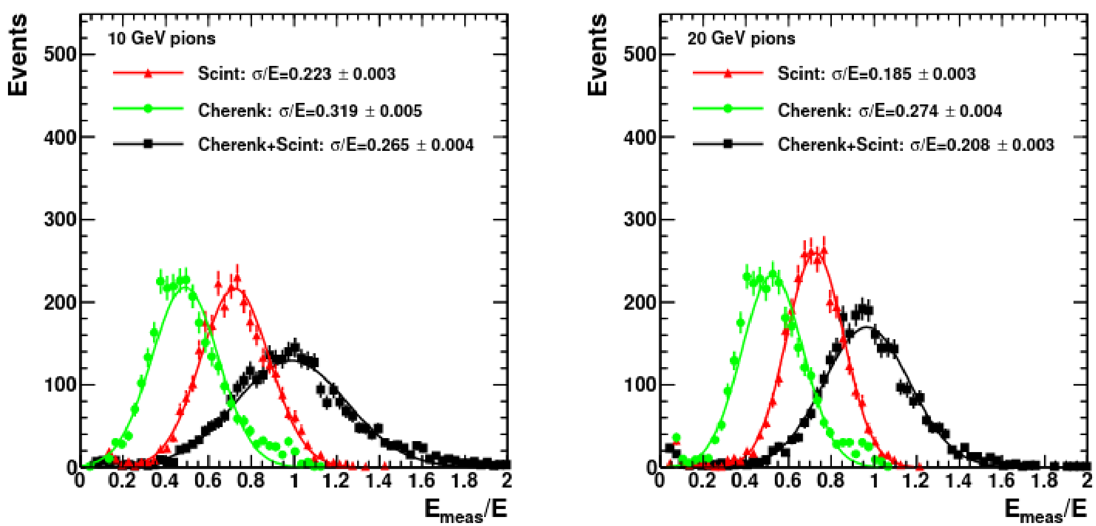
$$\kappa \equiv (1-(h/e)_S)/(1-(h/e)_C) = 0.6$$

Note:
Significant part of non-compensation comes from large lateral leakage of the hadronic shower (to be discussed later)

Resolution for 40L sandwich-style HCAL



(a) 1 GeV (b) 5 GeV

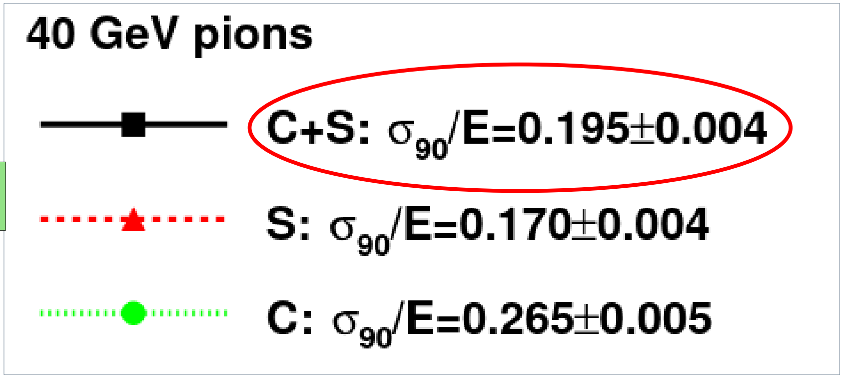


(c) 10 GeV (d) 20 GeV

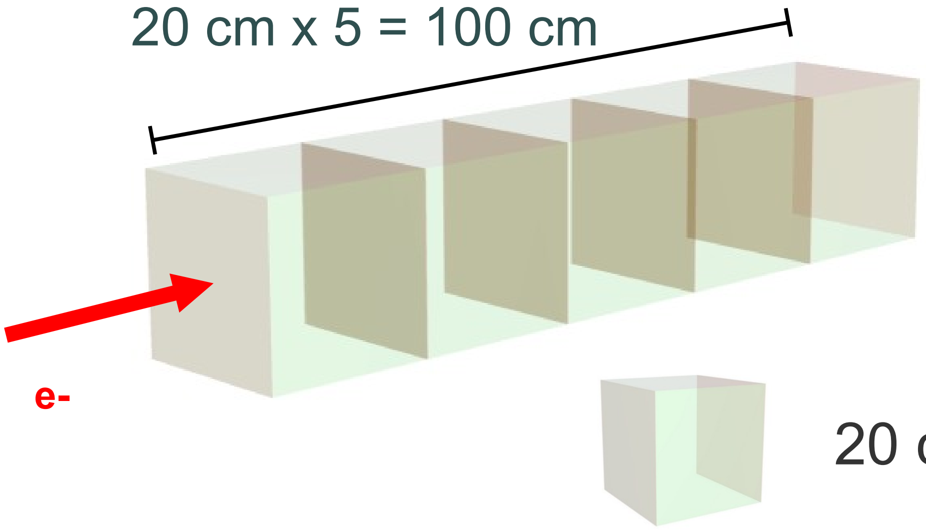
$$E = \frac{S - \kappa \cdot C}{1 - \kappa}$$

L.Lee, M.Livan,R.Wigmans, Rev.Mod.Phys. 90 (1918) 025002

Inclusion of Cherenkov signal does not improve resolution

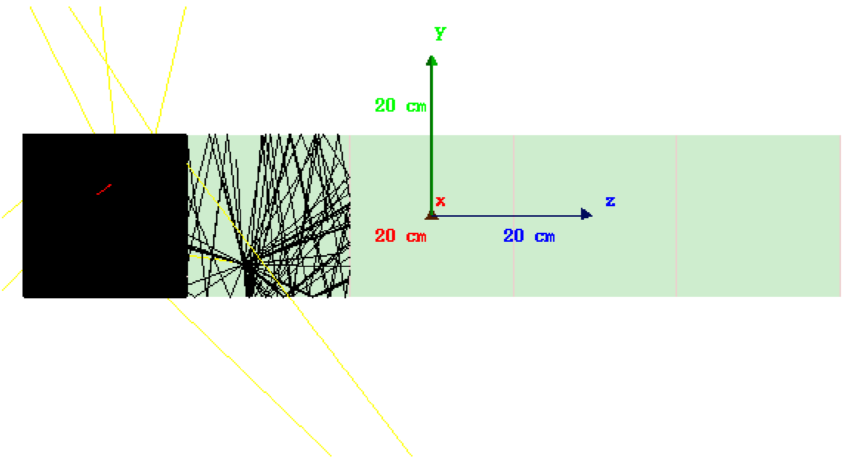


Simulation of a simple HCAL tower using PbWO4



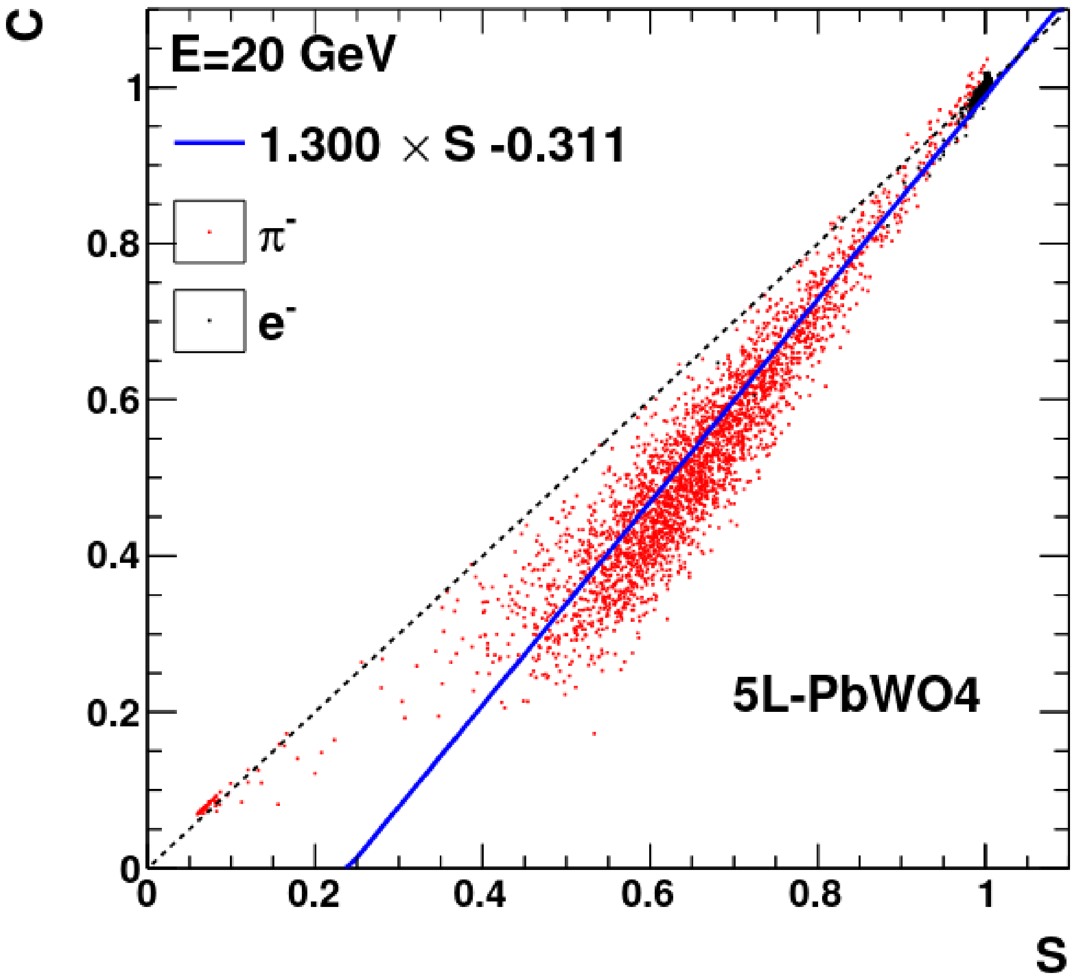
- 5 interaction lengths
- 98% longitudinal containment
- 65% lateral containment for 1 GeV (goes up with energy)

20 cm x 20 cm ~ 21 X_0 ~ 1 λ_I



5 GeV pion
(black lines – optical photons)

Calibrated light response for 5L-PbWO4



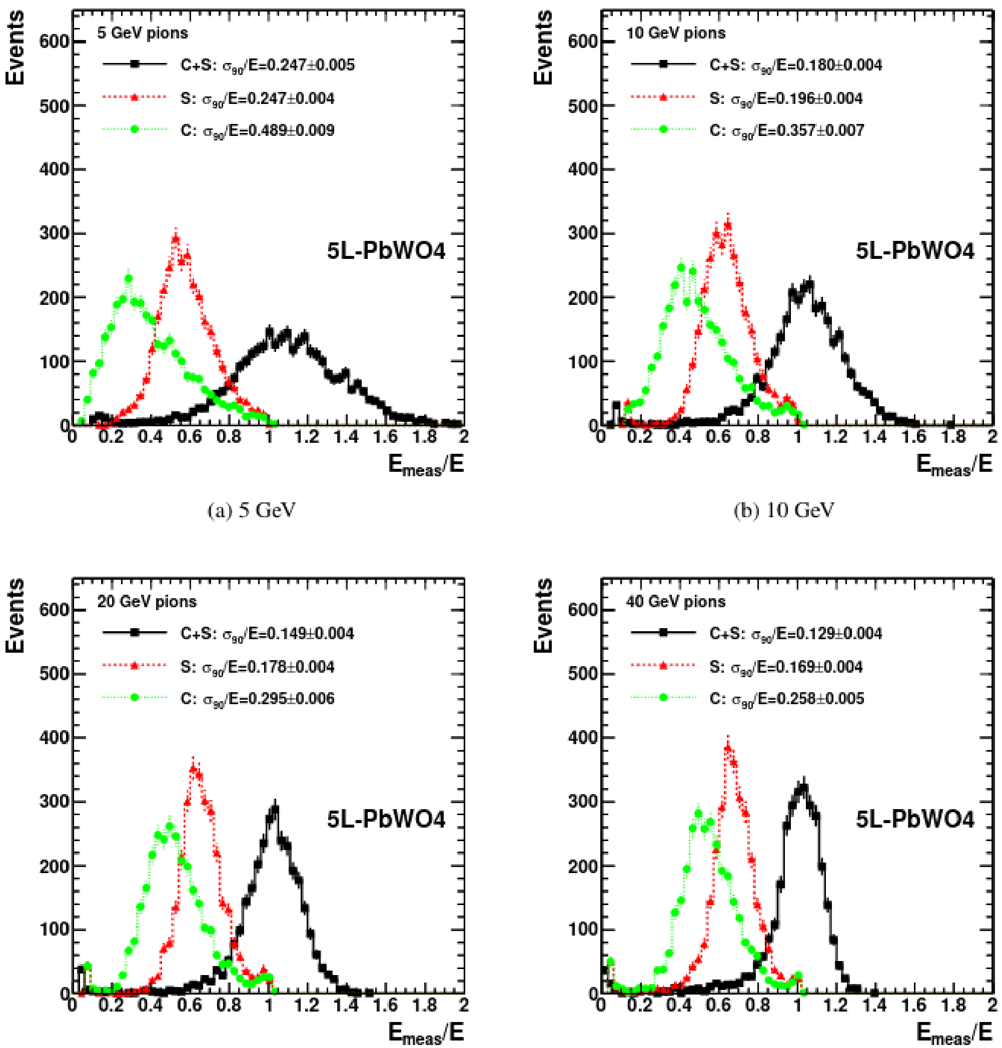
S and **C** are Nr of scintillation and Cherenkov photons calibrated to electrons at the same energy

$$\kappa \equiv (1-(h/e)_S)/(1-(h/e)_C)$$

$$(h/e)_S = 0.58 \text{ and } (h/e)_C = 0.39$$

$$\kappa = 0.67$$

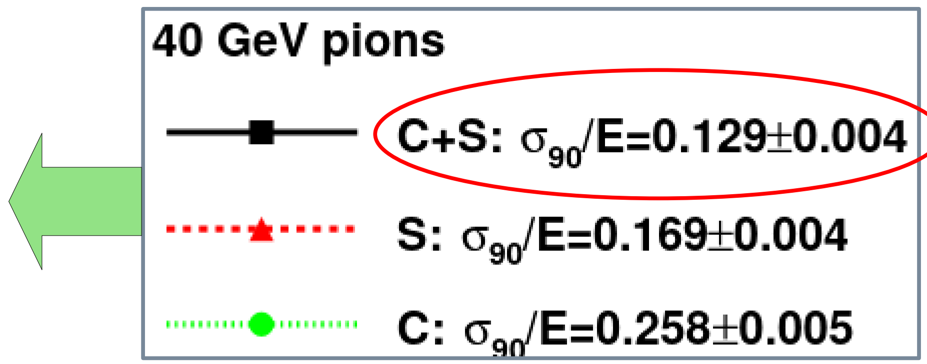
Pions: Calibrated light response



$$E = \frac{S - \kappa \cdot C}{1 - \kappa}$$

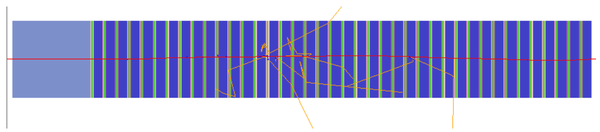
L.Lee, M.Livan,R.Wigmans, Rev.Mod.Phys. 90 (1918) 025002

Inclusion of Cherenkov signal improves resolution up to 30%



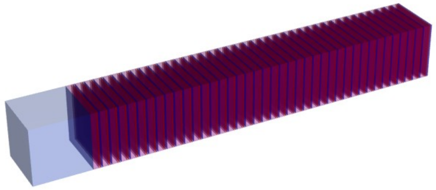
Other checks for sampling calorimeter

- **250L-PQ**
  - 250 layers with polystyrene (0.5cm) and quartz (0.5cm)
  - Longitudinal size: ~5.6 λ_I
  - Lateral size ~1 λ_I



$$\kappa = 0.73, \ (h/e)_S = 0.65 \text{ and } (h/e)_C = 0.52$$

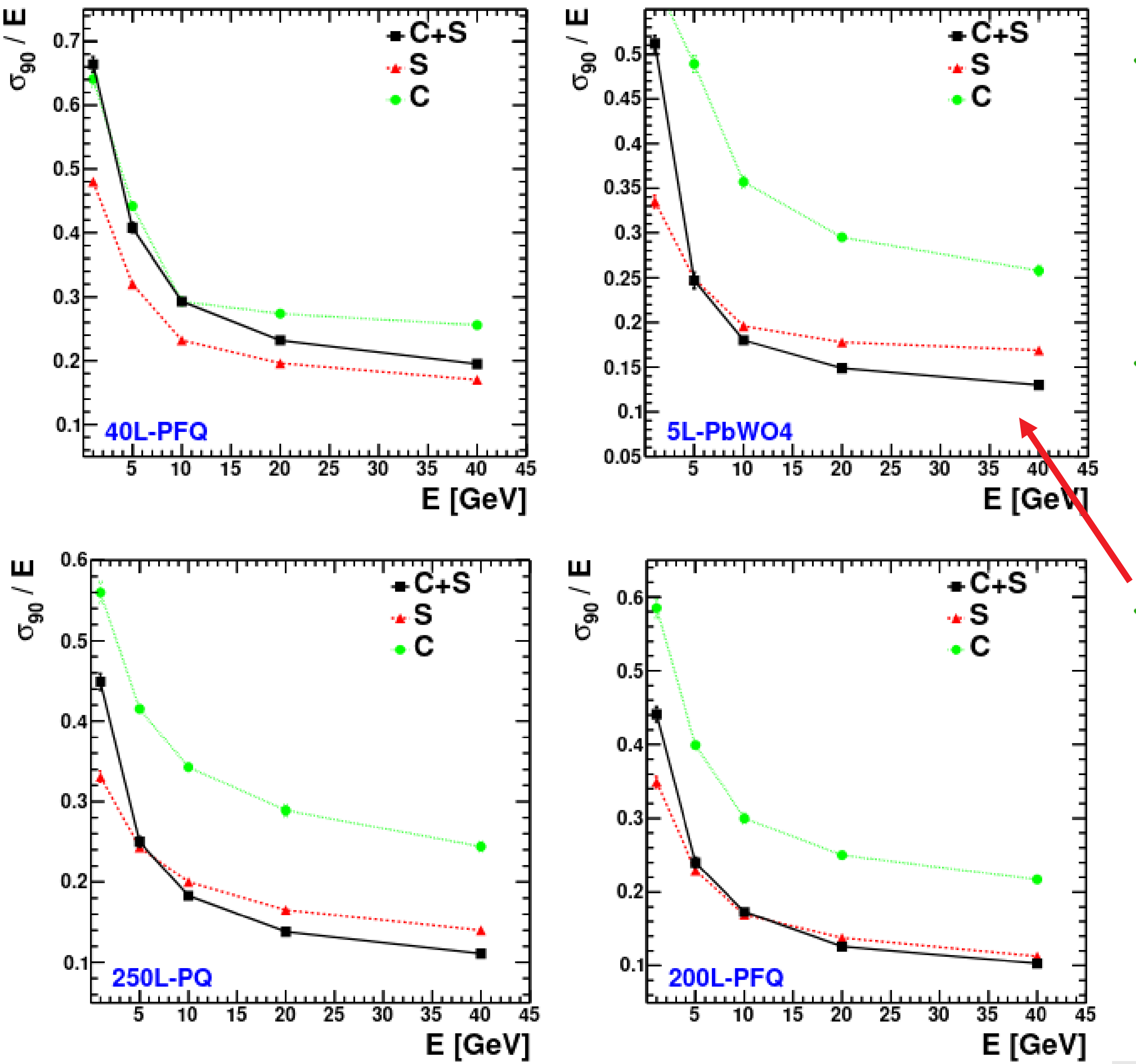
- **200L-PFQ**
  - 200 layers with polysterene, steal (passive), quartz
  - Longitudinal size: ~5.6 λ_I
  - Lateral size ~1 λ_I



$$\kappa = 0.52, \ (h/e)_S = 0.77 \text{ and } (h/e)_C = 0.56$$

Both calorimeters will not fit to the HCAL envelope for CLD, ILD, SiD, CLIC..
Need to use denser materials with smaller interaction length (W, for example)

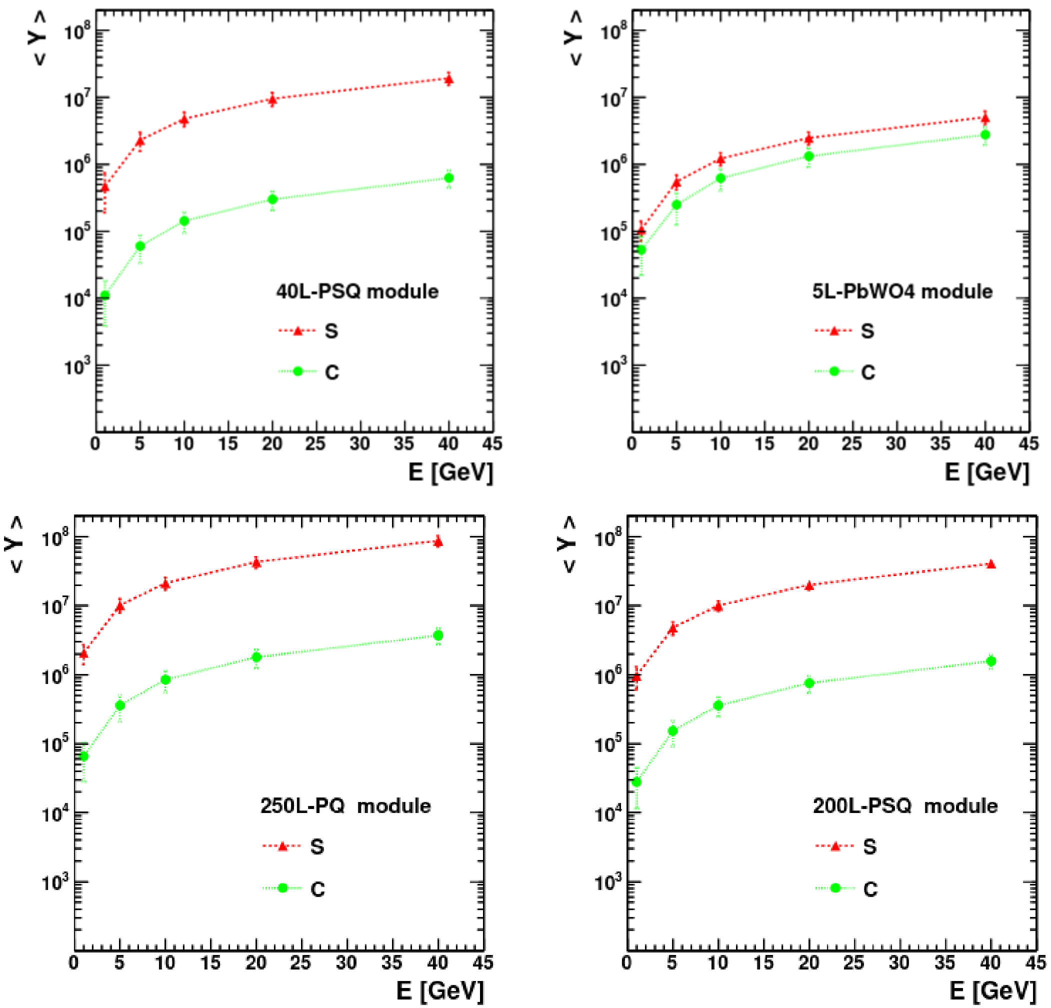
Summary of resolution studies



- 40 layer tower design do not show improvement in resolution for S+C (vs S)
- 200 and 250 layer towers show some improvements > 10 GeV
- 5-blocks of PbWO4 shows ~30% improvement after inclusion of C signal

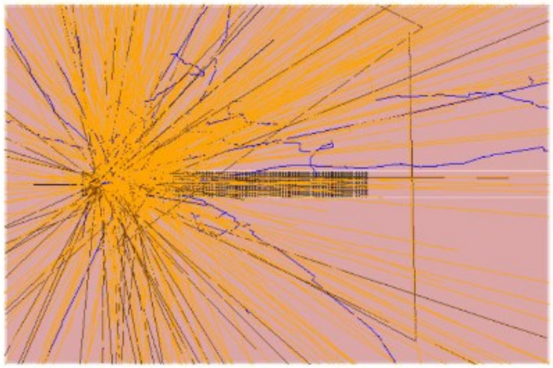
Note on CPU usage

- Previously, most simulations were done for energy deposits, which are then related to photon counts (need to know details from beam tests)
- Simulations with single-photon precision of optical photons from the first Geant4 physics principles are very CPU and data intensive

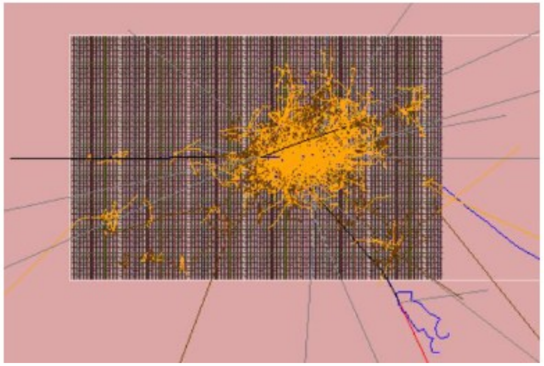


- According to average yield of optical photons, we need to create ~10^7 photons for a single tower
- Xeon(R) CPU E5-2650 require ~30 min per single collision of pion with with a tower
- Simulations of real collision events in a full HCAL brings us to exascale computing (GPU?)

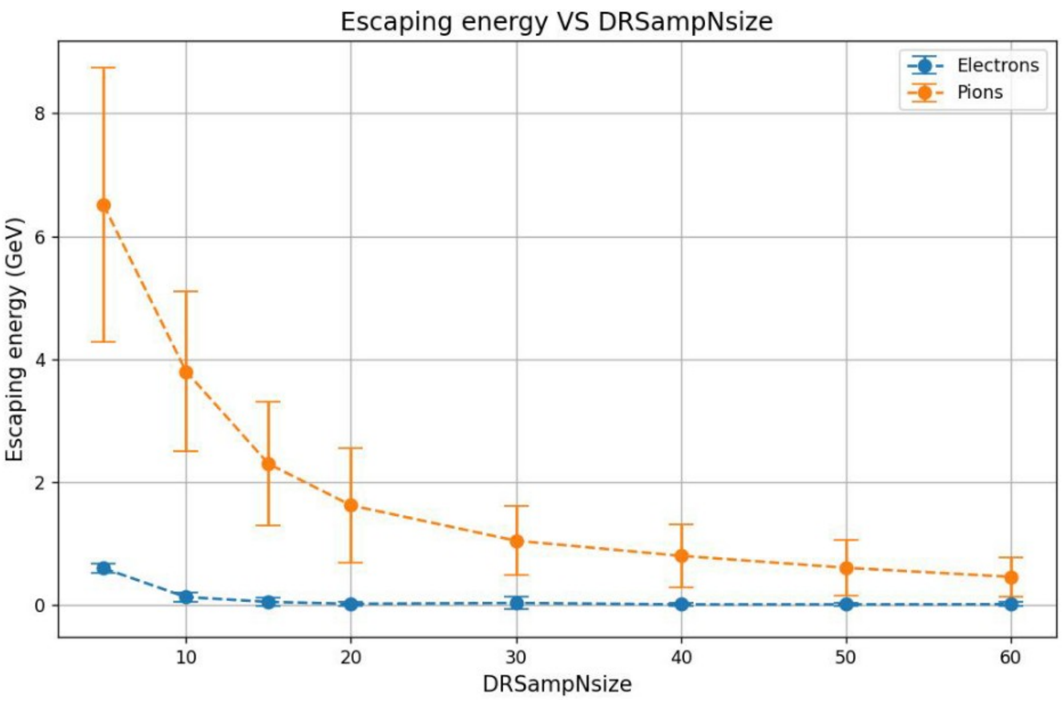
Using towers with ~95% lateral containment



DRSampNsize=5
20GeV Pion

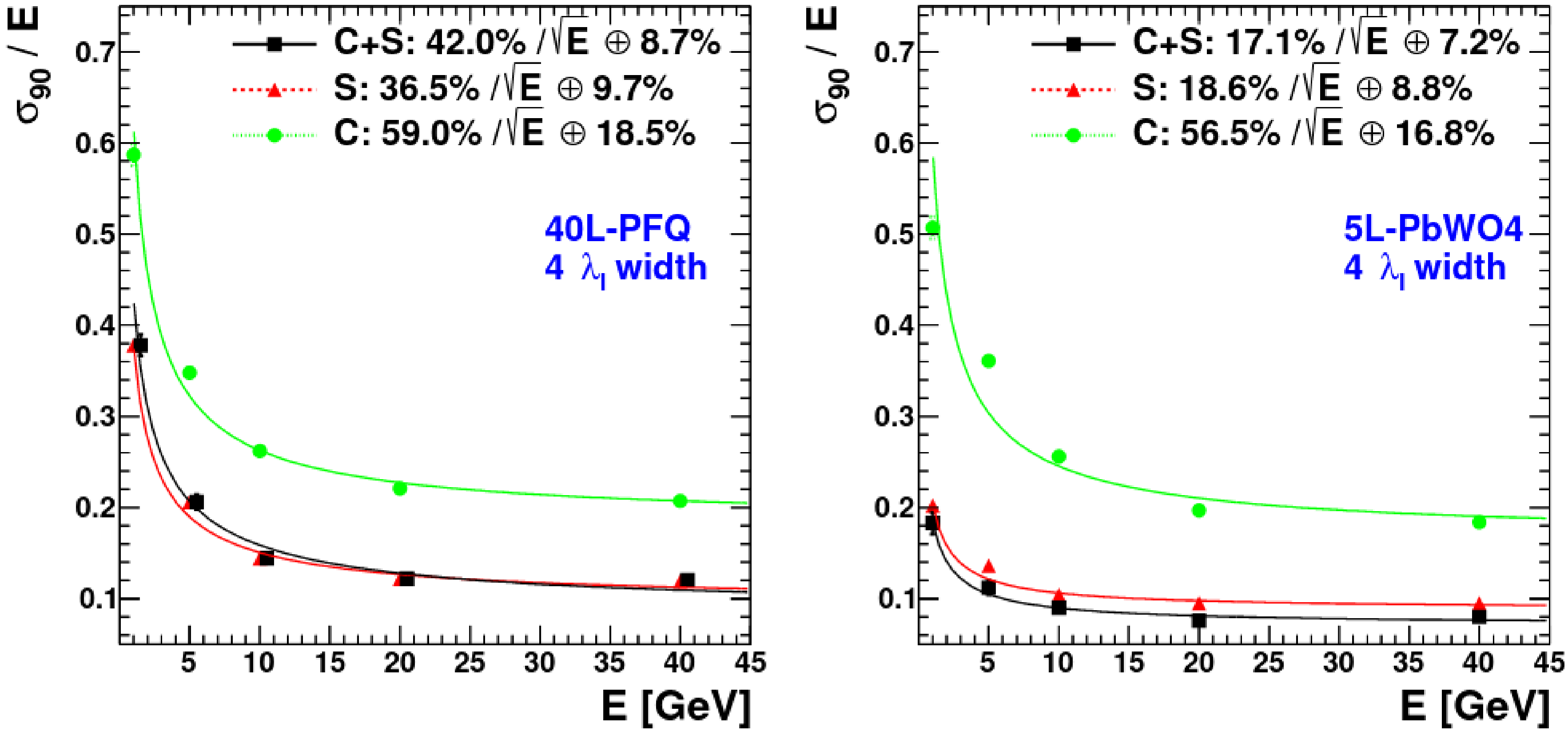


DRSampNsize=40
20GeV Pion



- Current simulations have ~30% lateral leakage for showers for 20 GeV
- Simulations repeated to 4 λ_I to reduce shower leakage to ~3-5%

Using towers with ~97% lateral containment

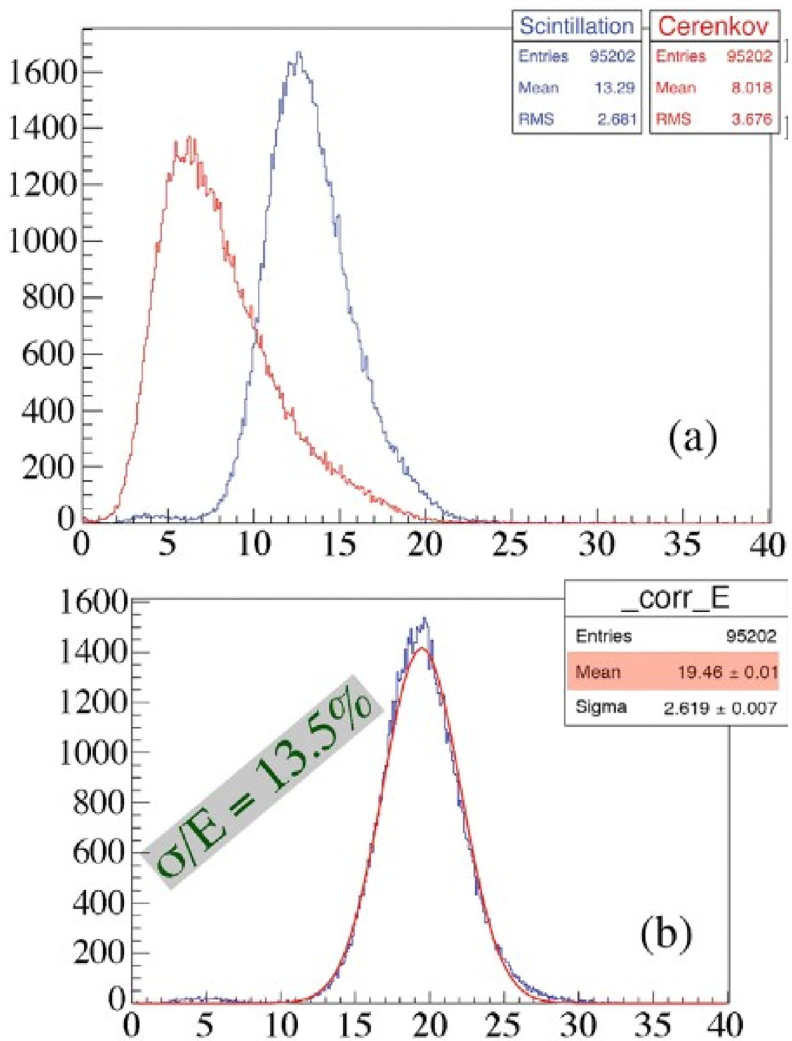


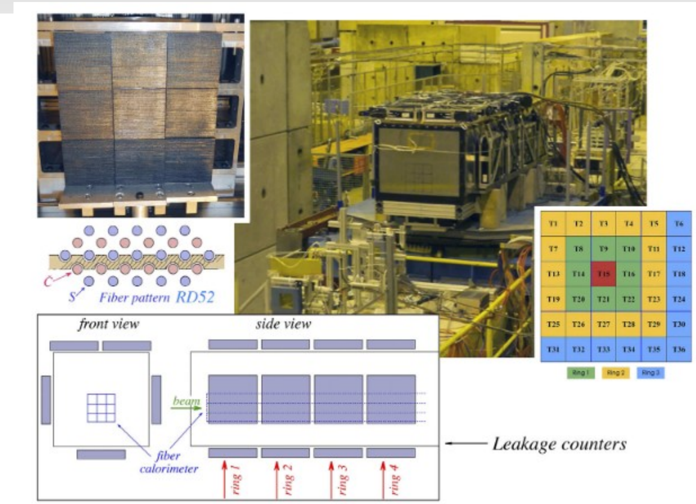
(a) 40L-PFQ ($4\lambda_I$ tower width) (b) 5L-PbWO4 ($4\lambda_I$ tower width)

- 40L-PFQ becomes almost fully compensating, while PbWO4 is not
- Homogeneous calorimeter shows best sampling term (17%) for C+S, as well as improvements in both sampling and constant terms.

Comparison with the RD52 lead-fiber dual-readout calorimeter

S.Lee, M.Livan, R. Wigmans
Rev. Mod. Phys. 90, 025002





- RD52 reports **σ/E=13.5%** for 20 GeV

Our simulations after taking into account lateral shower leakage:

- 40L-PSQ: **σ/E = 15.2%** (same for S and S+C)
- 5L-PbWO4 homogeneous:
  - σ/E = **12%** for S
  - σ/E = **9.5%** for S+C
- 200L and 250L are expected to be similar to RD52 but the exact values are too difficult to simulate for the used CPU.

Summary

- First realistic Geant4 simulations of optical photons in a sandwich-style tower designed for traditional HCAL (ILC, CLIC, FCC-ee)
- Inclusion of Cherenkov signal does not improve resolution for 40 layer sandwich design
  - Close to full compensation (assuming 95% lateral containment)
- Increasing the number of longitudinal layers to 200 -250 leads to small improvement in resolution for > 20 GeV
- Homogeneous 5L-PbWO4 tower gives the best resolution for scintillation lights. Adding Cherenkov signal decreases the resolution by 30%
  - Improvements best seen for E>10 GeV
- Comparing with RD52:
  - 40 layer design gives worse resolution
  - PbWO4 gives significantly better resolution (especially for S+C) than RD52

Available as: https://arxiv.org/abs/2311.03539 arXiv:2311.03539, ANL-HEP-186226