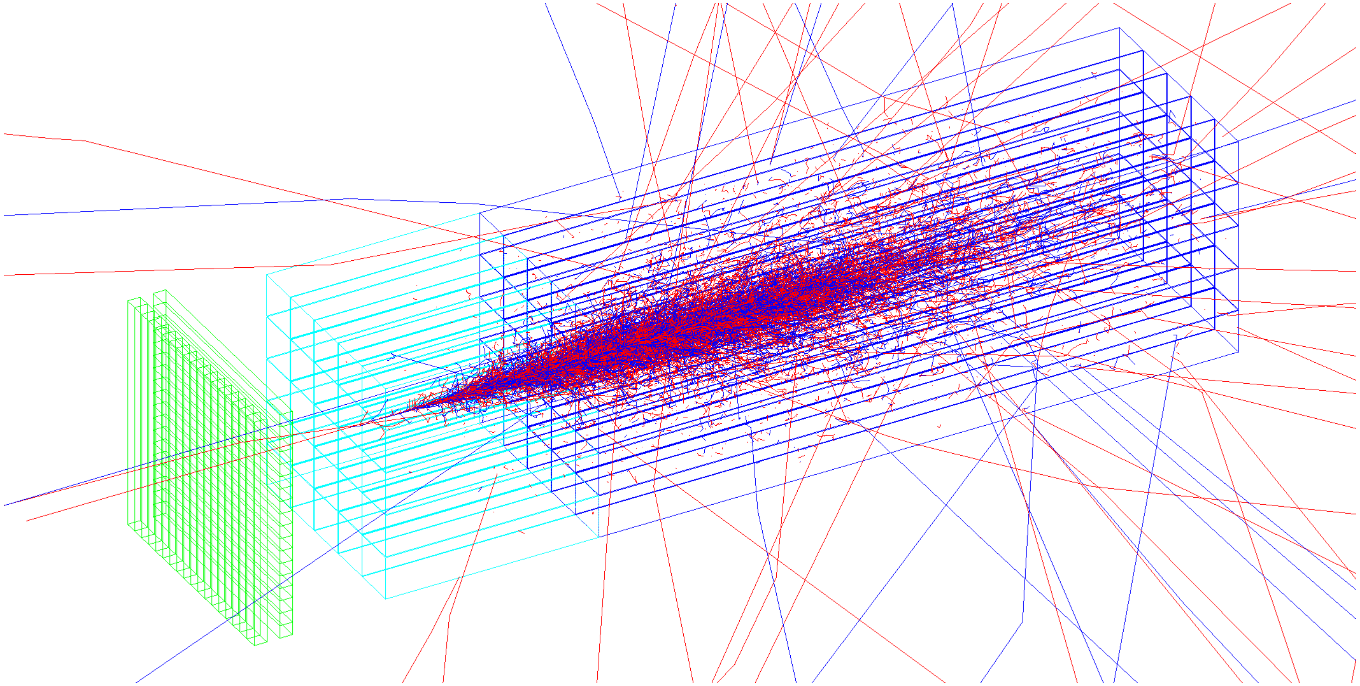


Segmented-Crystal Electromagnetic Precision Calorimeter (S-CEPCal)

12 March 2019

Calorimetry Workshop, IHEP, Beijing, China

Sarah Eno (University of Maryland, College Park)

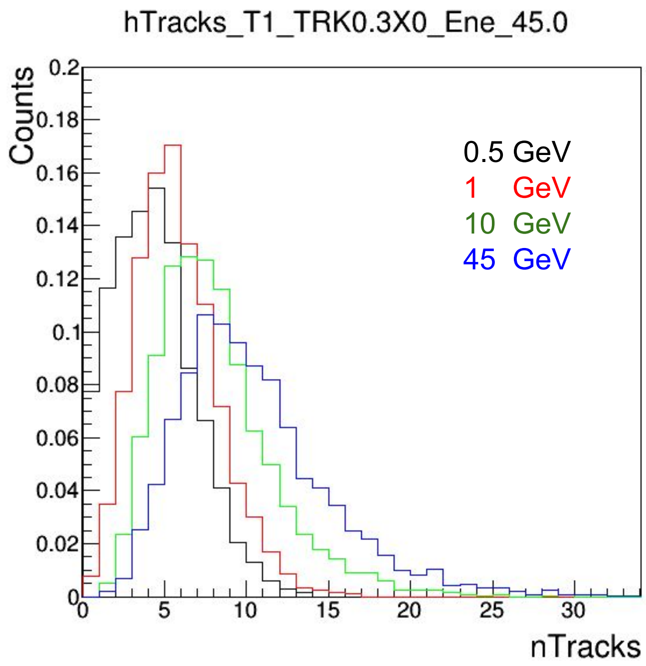
Marco Lucchini (Princeton), **Chris Tully** (Princeton)

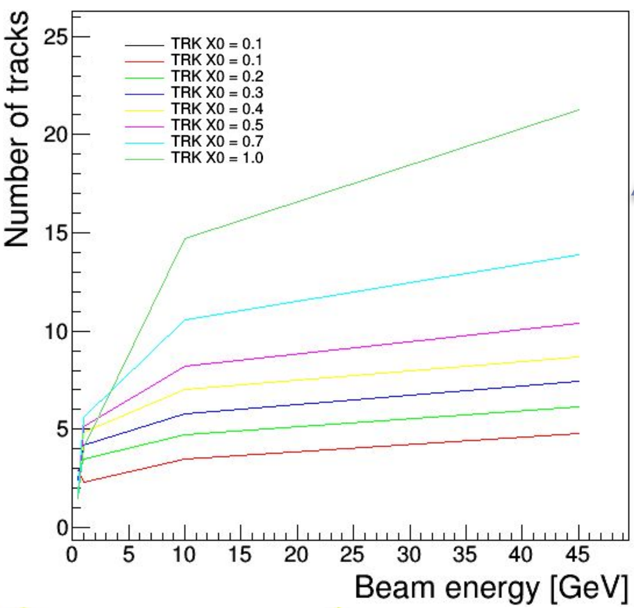
Performance Goals for Electromagnetic Precision Calorimeter

- **Put Z→ee on equal footing with Z→μμ recoil**
  - x3 improvement on electron Brem. energy measurement
- **Improve PFA EM shower imaging and separation**
  - x100 increase on EM shower sampling fraction (1/300 → ~1)
- **Incorporate Precision Time-of-Flight System**
  - ~20ps MIP/photon timing with high granularity (~3mm)
- **Include Dual-Readout capabilities for hadrons**
  - Dual wavelength filters for Cherenkov/Scint discr.
- **Extend Physics Program w/ EM Res. and Timing**
  - Neutrino counting ($Z\rightarrow\nu\nu\gamma/Z\rightarrow\mu\mu\gamma$), Long-lived Particles, Cosmics/Out-of-time background reduction for Emiss
- **Cost-effective solution**
  - Segmented crystals with SiPM readout

Electron Bremsstrahlung in Tracker

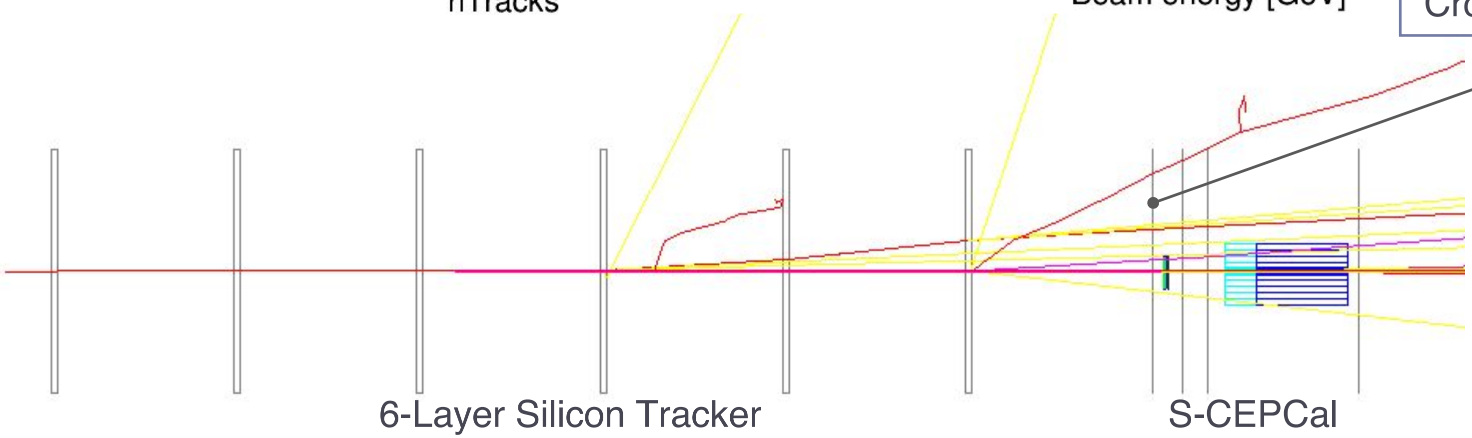
- counting number of tracks at the entrance of the timing layer (e+, e-, gamma)





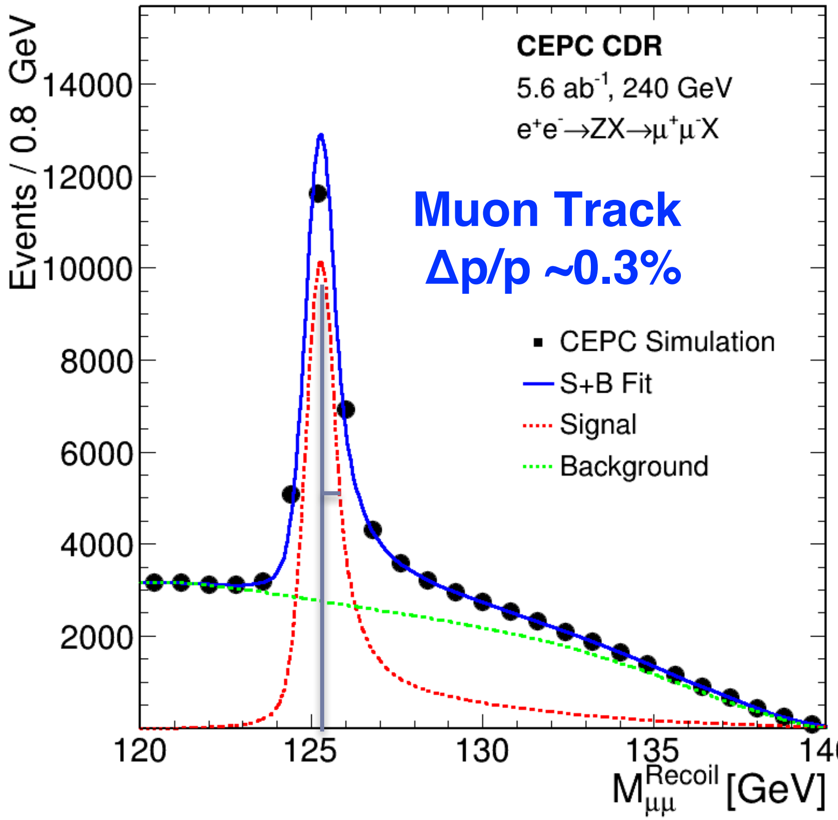
Tracker Material Increasing

Count Tracks (e+,e-, photons) Crossing Here

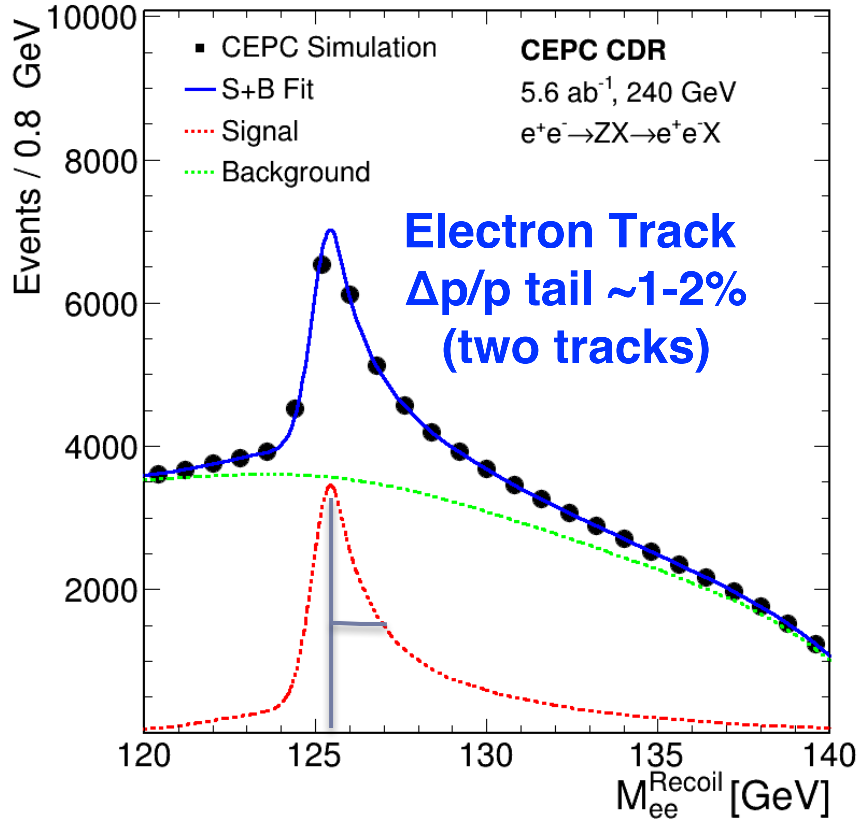


Electron should be done well at e^+e^- Collider

- **Muons**



- **Electrons**



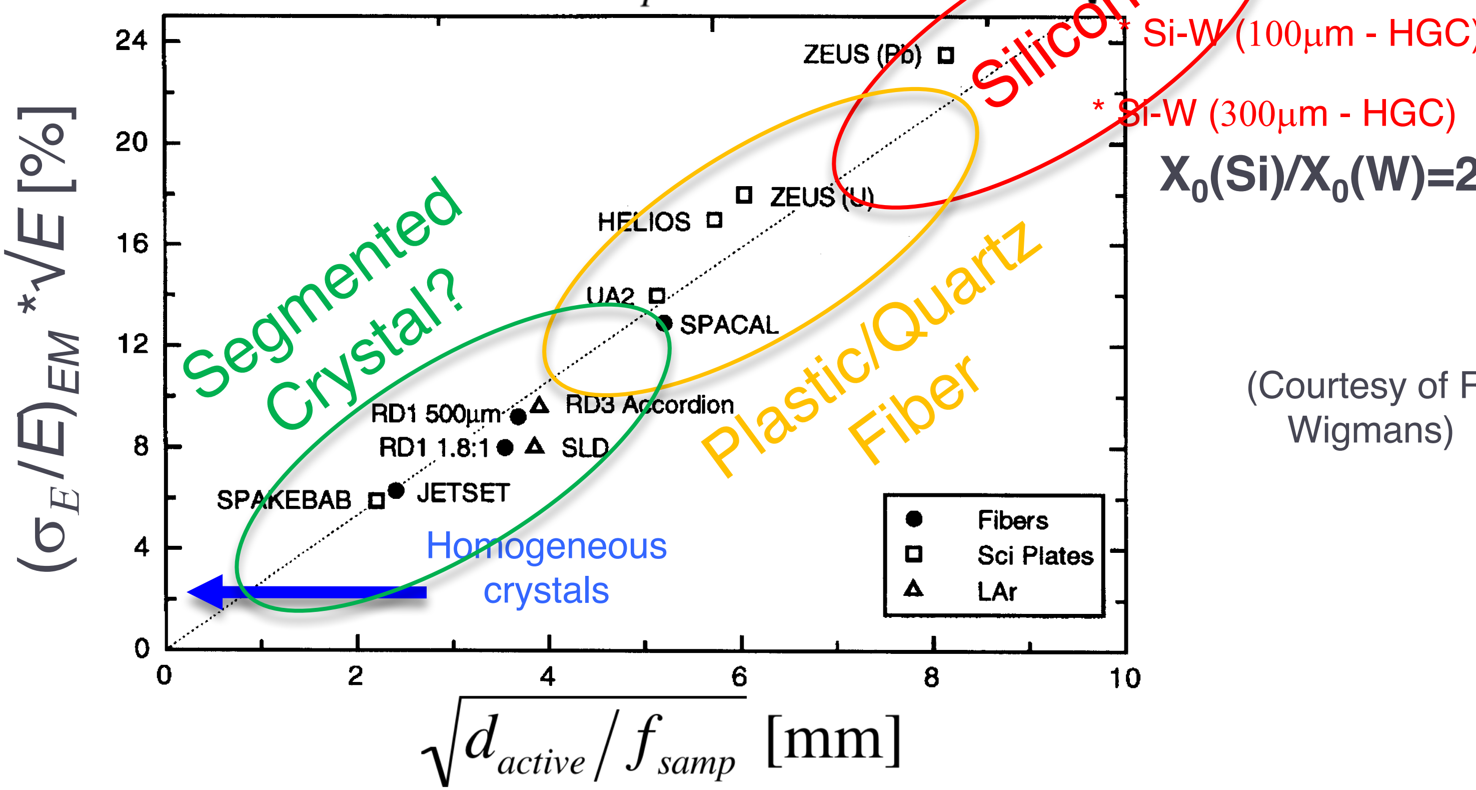
Not yet there w/ CDR reference design
(needs Brem. recovery w/ EM res.)

~1-2% @ $5\%/\sqrt{E_{loss}}$ → ~<0.3% in quadrature

Three Regimes of EM Resolution

- **For EM showers in a sampling calorimeter, the energy resolution is dominated by the sampling fluctuations:**

$$(\sigma_E/E)_{EM} \cdot \sqrt{E} \approx (\sigma_E/E)_{samp} \cdot \sqrt{E} = 2.7\% \sqrt{d_{active}/f_{samp}}$$



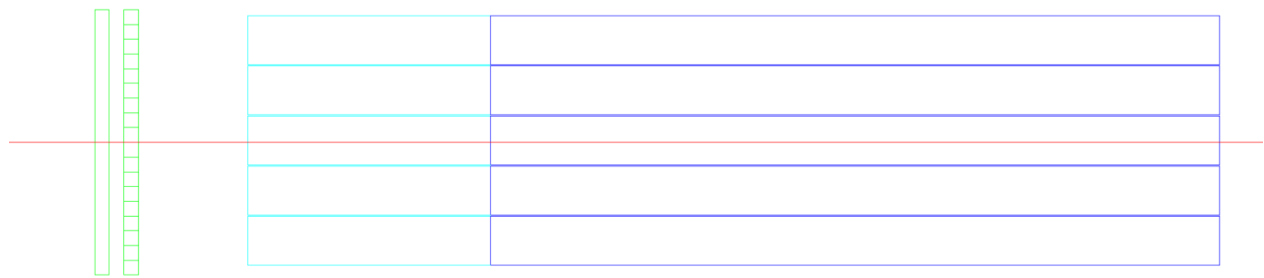
$X_0(Si)/X_0(W)=27$

(Courtesy of R. Wigmans)

Segmented Crystal Calorimeter Module

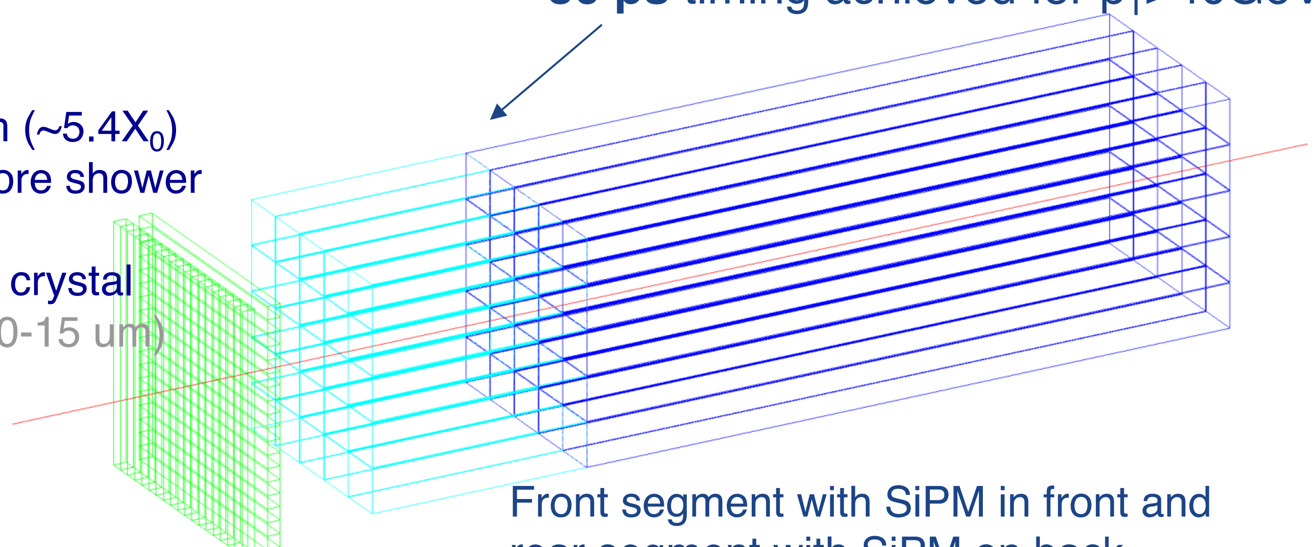
- **Timing layer:**
  - LYSO:Ce crystals
  - SiPMs
  - 3x3x54 mm³ active cell
  - 3x3 mm² SiPMs (15-25 um)

1 layer: **30 ps**
2 layers: **20 ps** + tracking



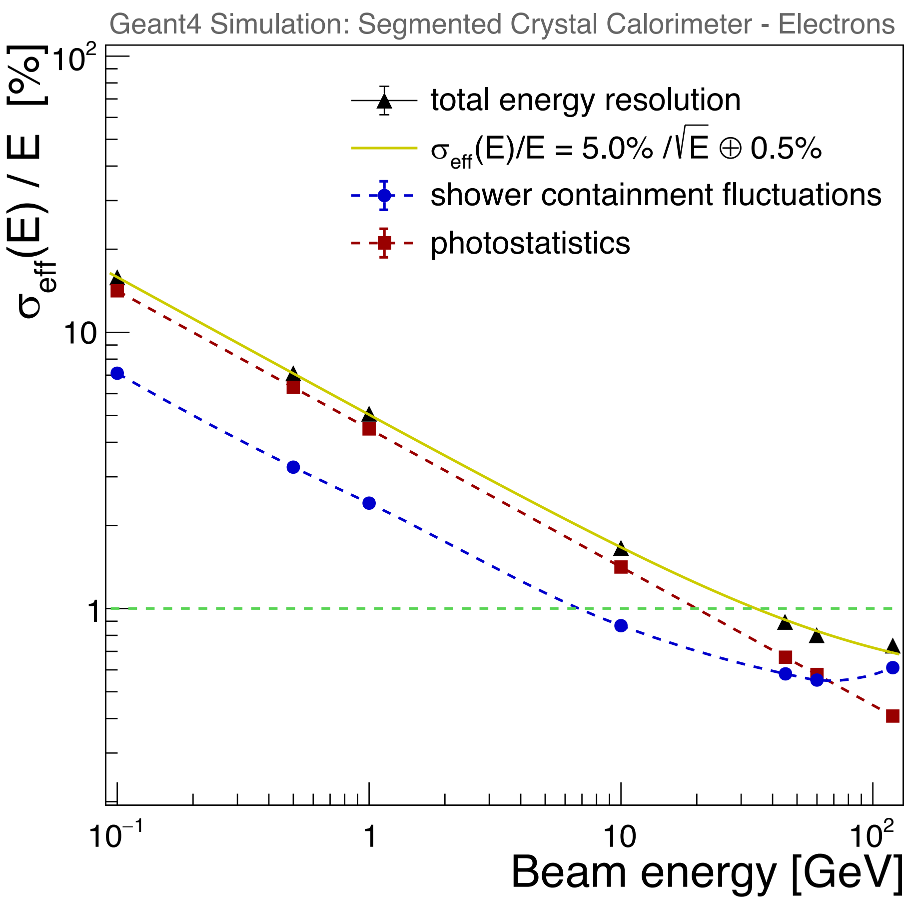
< **5%/sqrt(E) (+) 1%**
~30 ps timing achieved for p_T>40GeV

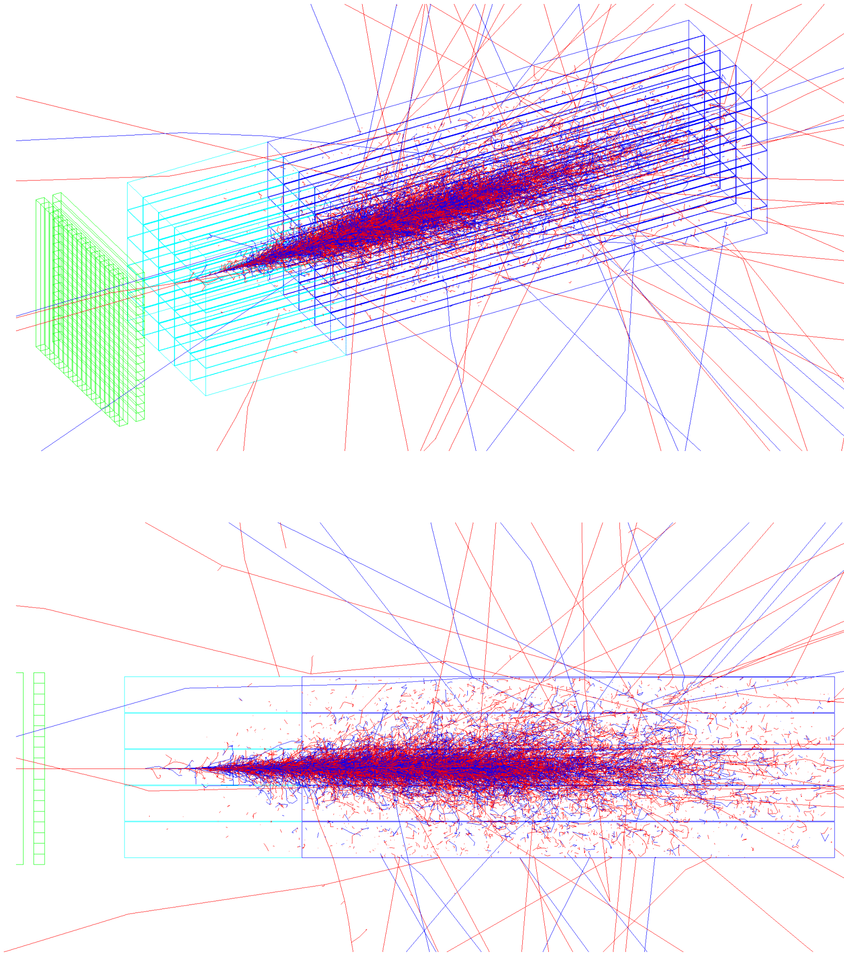
- **ECAL layer:**
  - PbWO crystals
  - front segment 5 cm (~5.4X_0)
  - rear segment for core shower
  - (15 cm ~16.3X_0)
  - 10x10x200 mm³ of crystal
  - 5x5 mm² SiPMs (10-15 um)



Front segment with SiPM in front and rear segment with SiPM on back
→ Avoids dead material at shower max

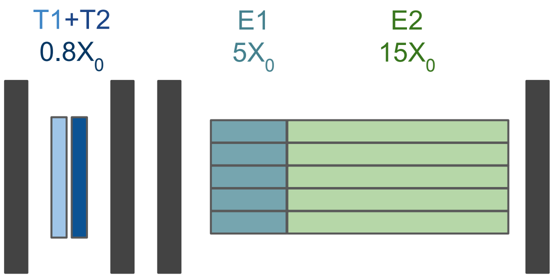
Electron Energy Resolution (no Dead Material)

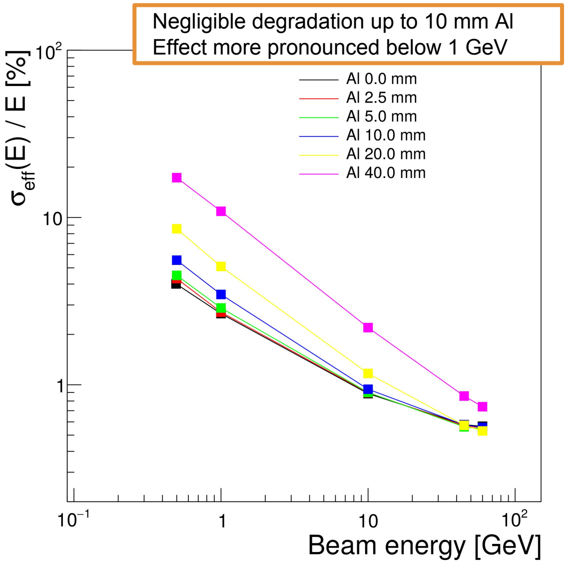




Dead Material between Layers

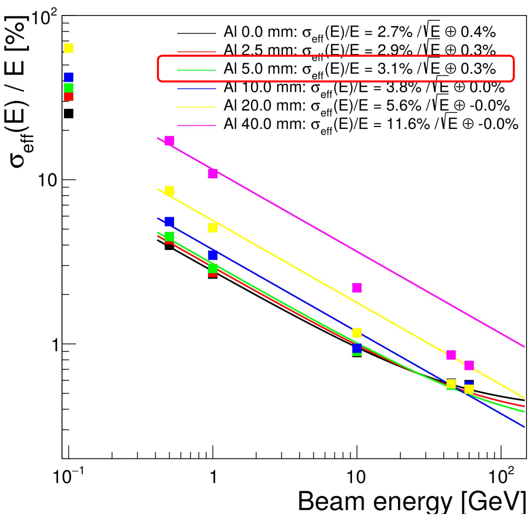
- Services required:
  - FE/ASIC for read-out → PCB material
  - Cooling plate
  - Cables
- Space allocated:
  - 5 cm in front of crystal timing layer T1 (for T1 read-out)
  - 10 cm in front of crystal ECAL E1
    - 5 cm for T2 and 5 cm for E1 → **cooling plate may be shared**
  - 5 cm in rear of crystal ECAL E2 (for E2 read-out)
- Material budget:
  - Realistic cooling plate ~ 3 mm Al → 0.035 X_0
  - PCB ~ 2 mm, + cables, etc
  - **total: 0.056 X_0** (5 mm Al equivalent) for each layer
  - Scan up to 0.5X_0 / layer



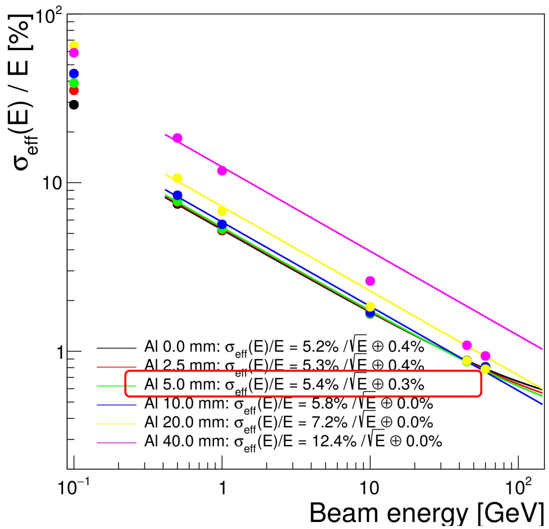


Impact of Dead Material between Layers

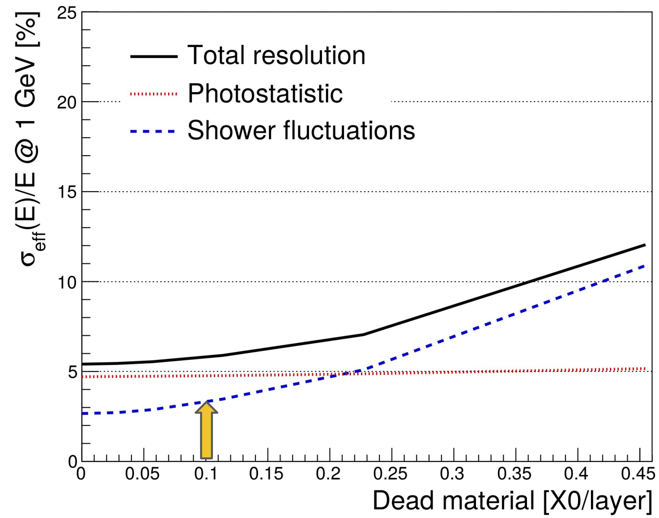
Shower fluctuations only



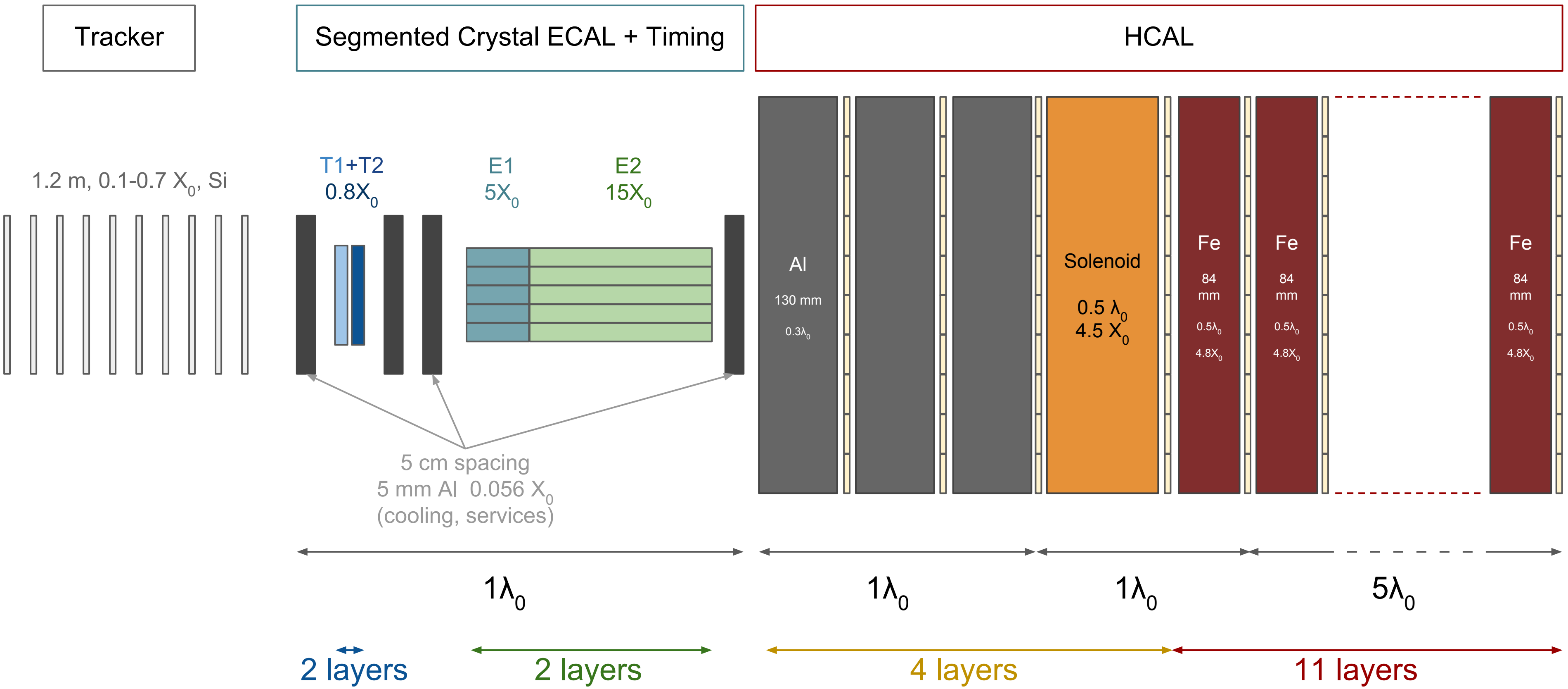
Total (including photostat.)



Stochastic term vs dead material

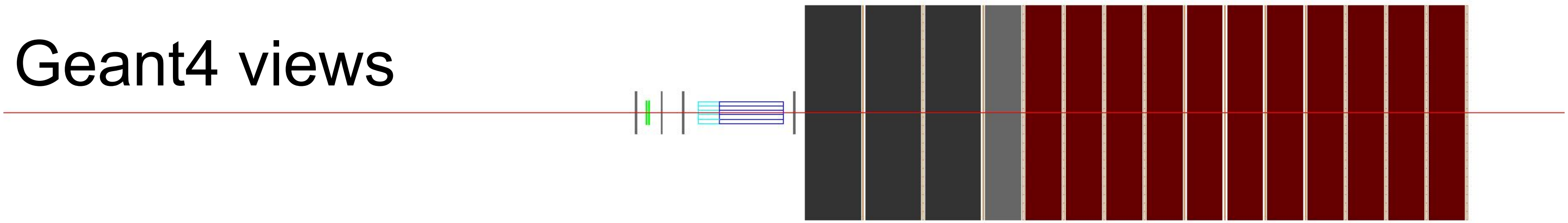


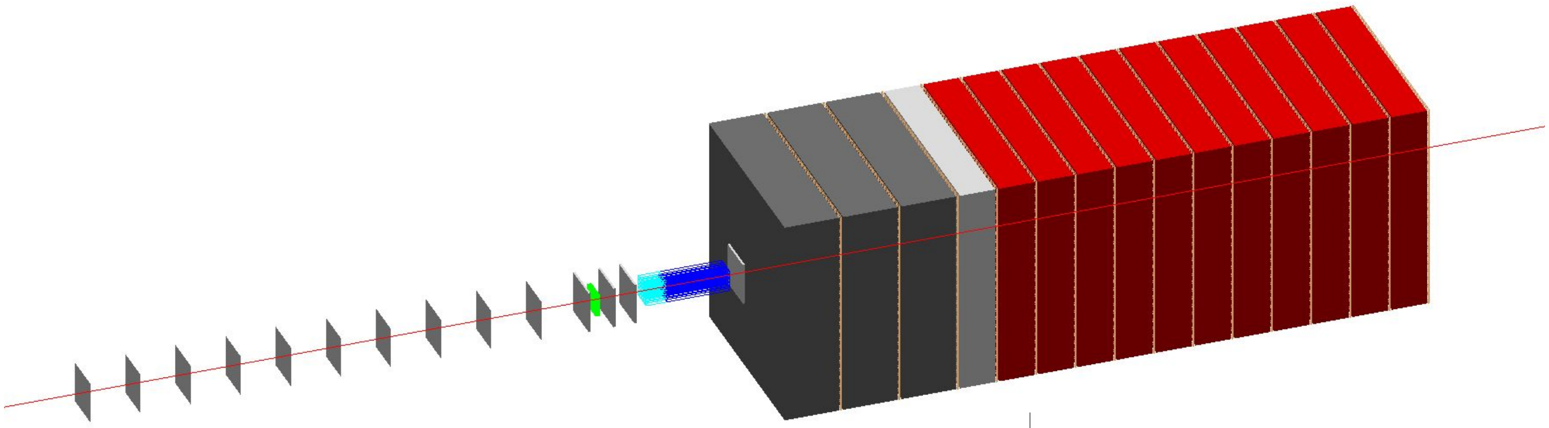
Dead Material including Tracker

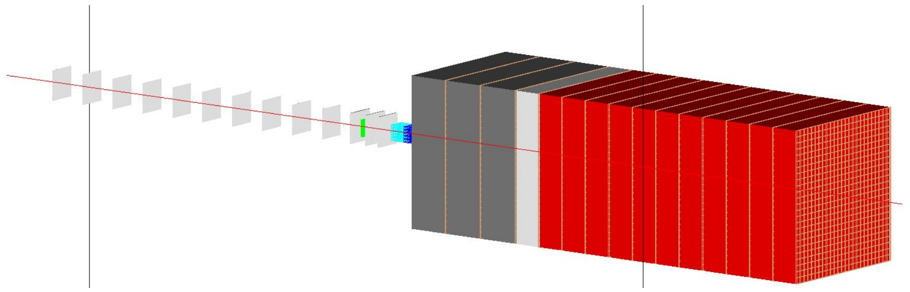


Additional Views

Geant4 views

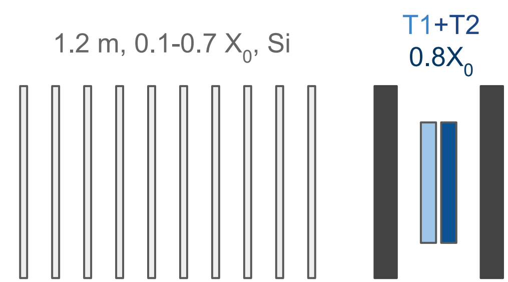


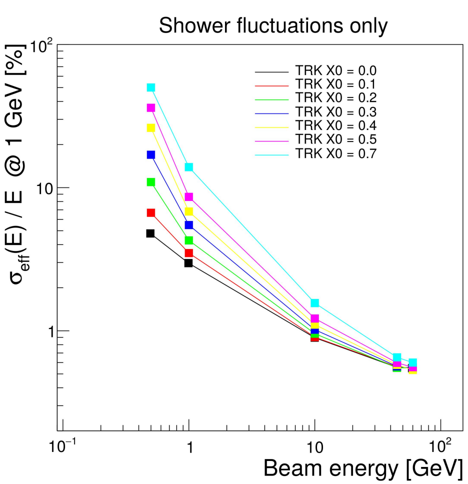


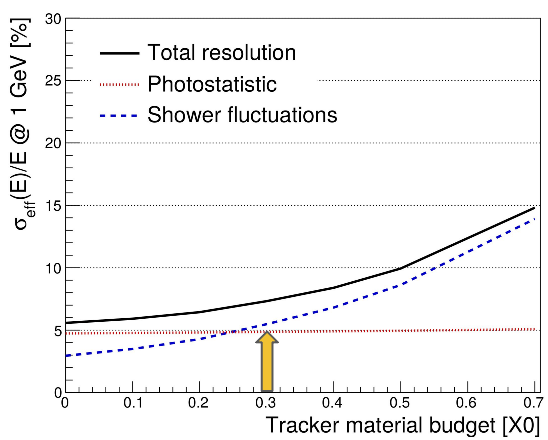


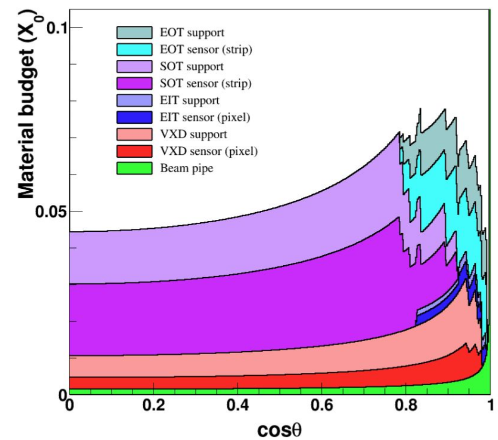
Impact of Tracker Material

- Study impact of tracker material budget in front of SC-E(P)CAL
- Material budget:
  - Realistic material budget ~$0.3X_0$ **?**
  - Scan up to **$0.7X_0$**
- Negligible impact on energy resolution

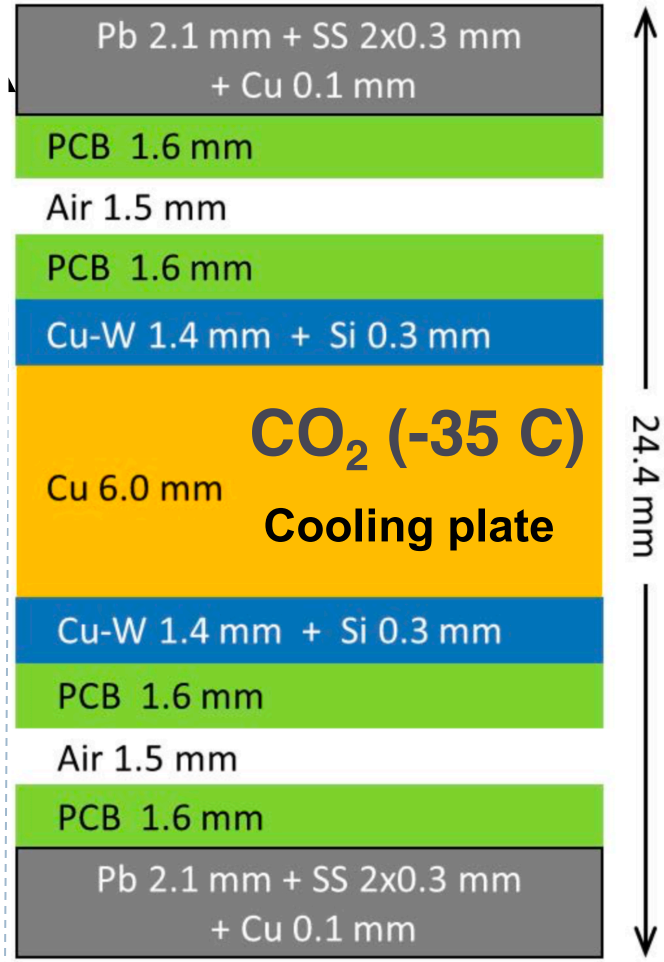


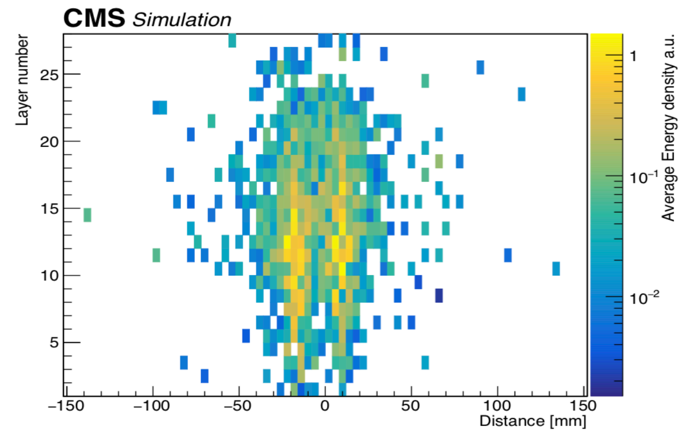






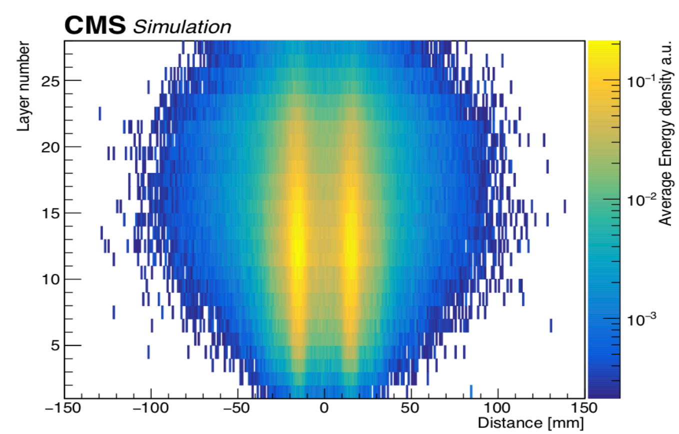
Imaging Capabilities of Silicon (~1/300)





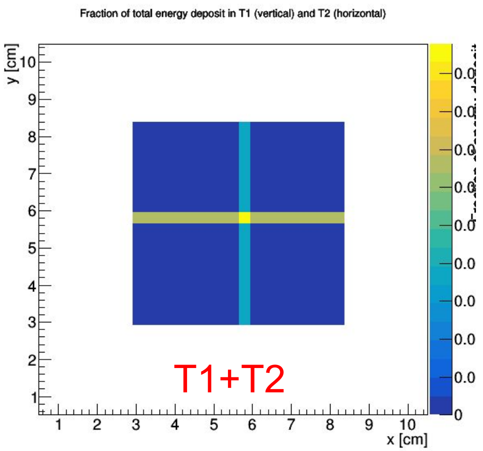
One event

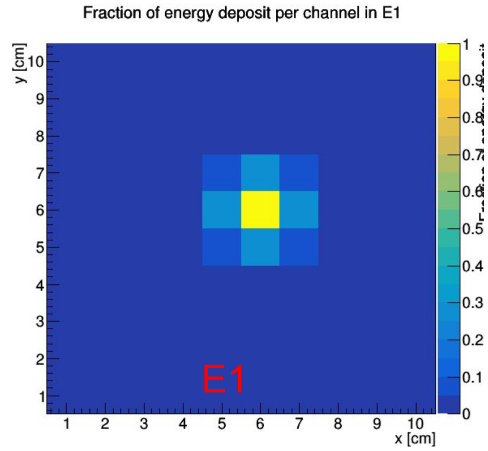
Fluctuations driven by
Low Sampling Fraction(~1/300)
High SF → one shower looks like many

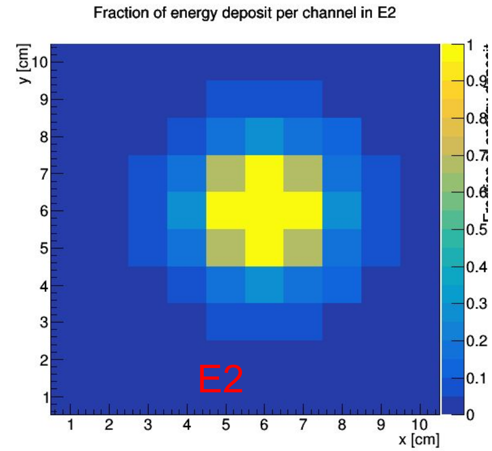


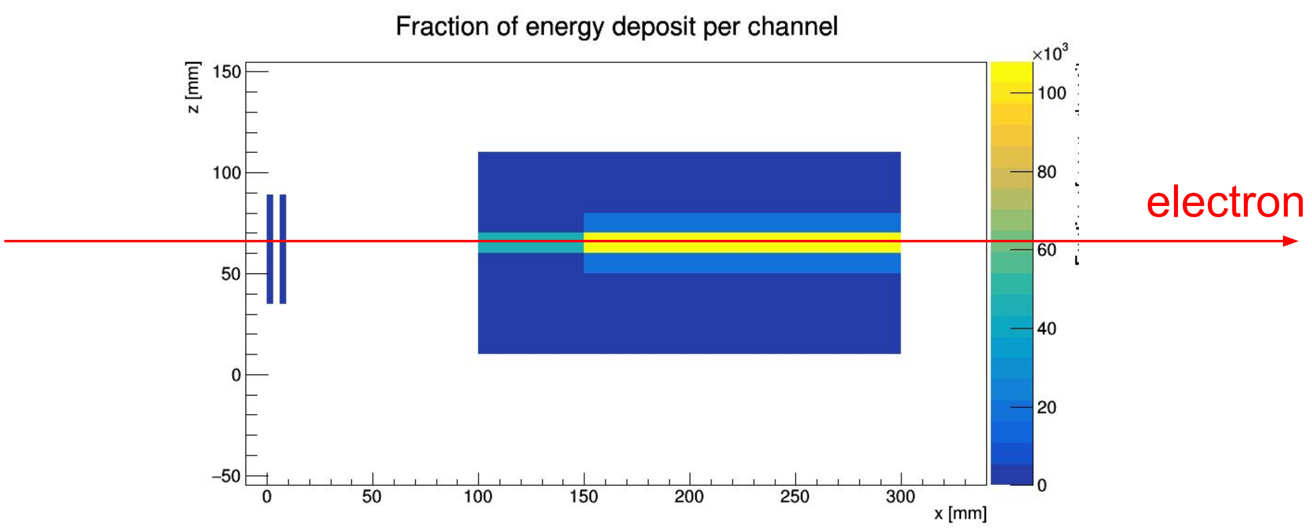
Several thousand events

S-CEPCal Single EM Shower (High Stat)

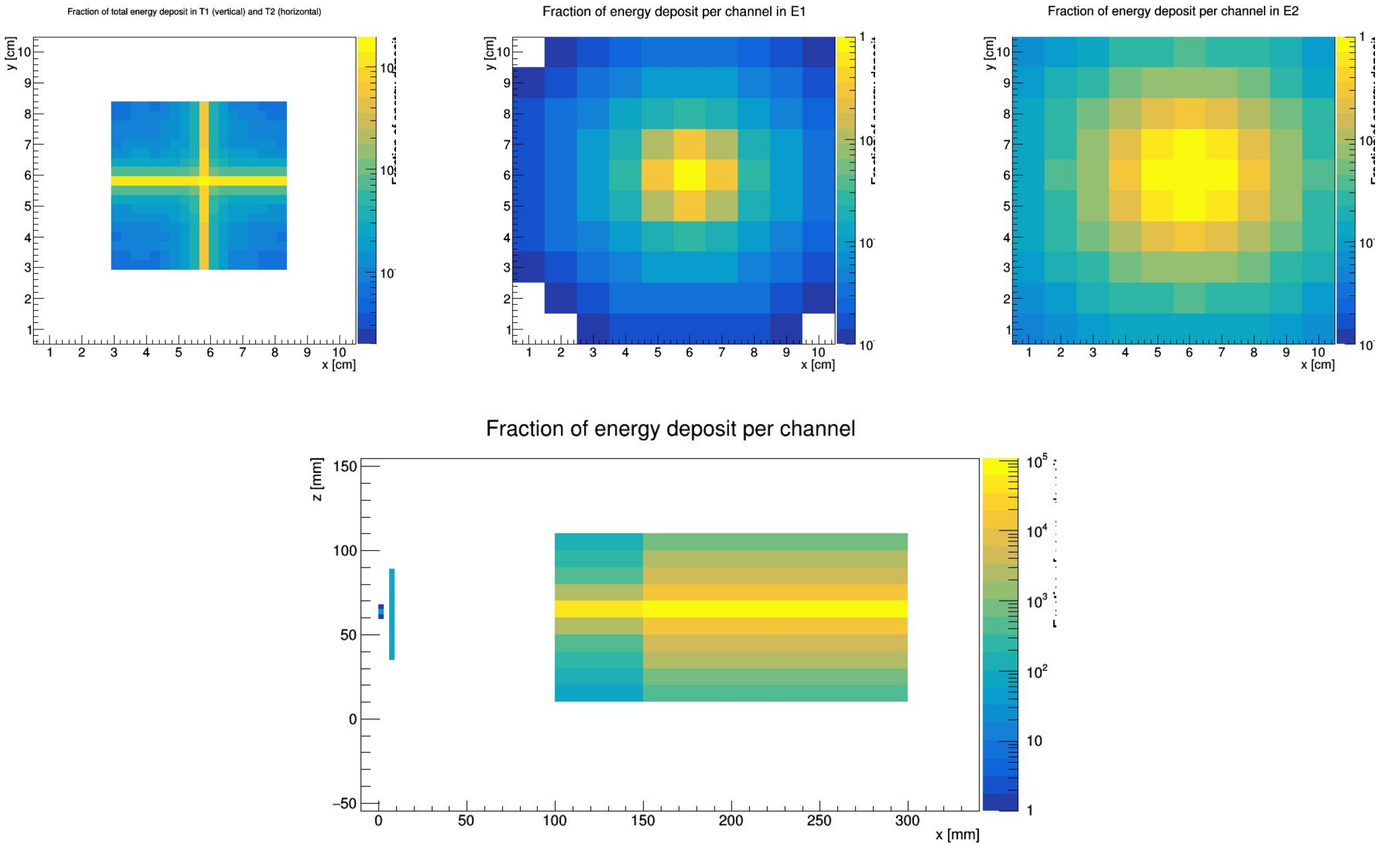




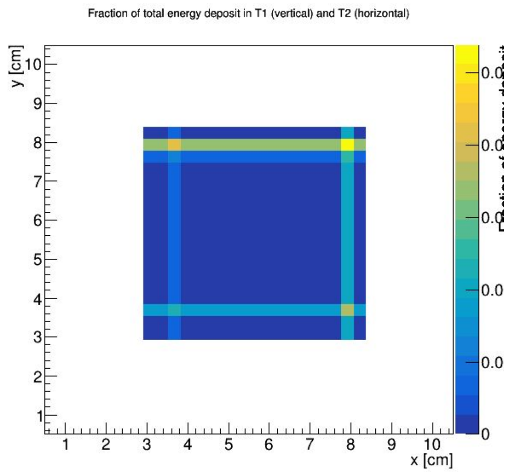


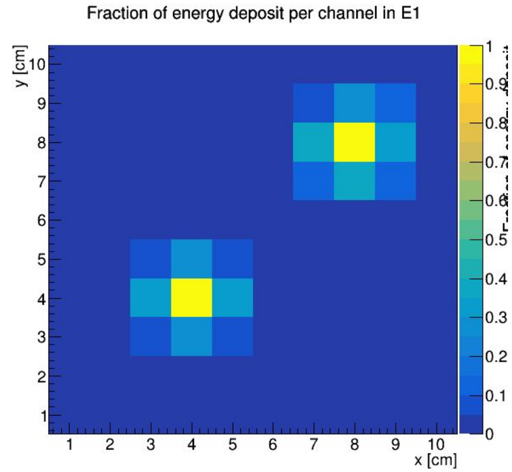


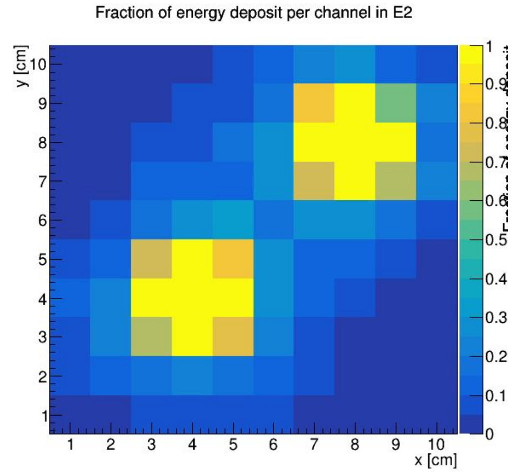
S-CEPCal Single EM Shower (High Stat- Log)

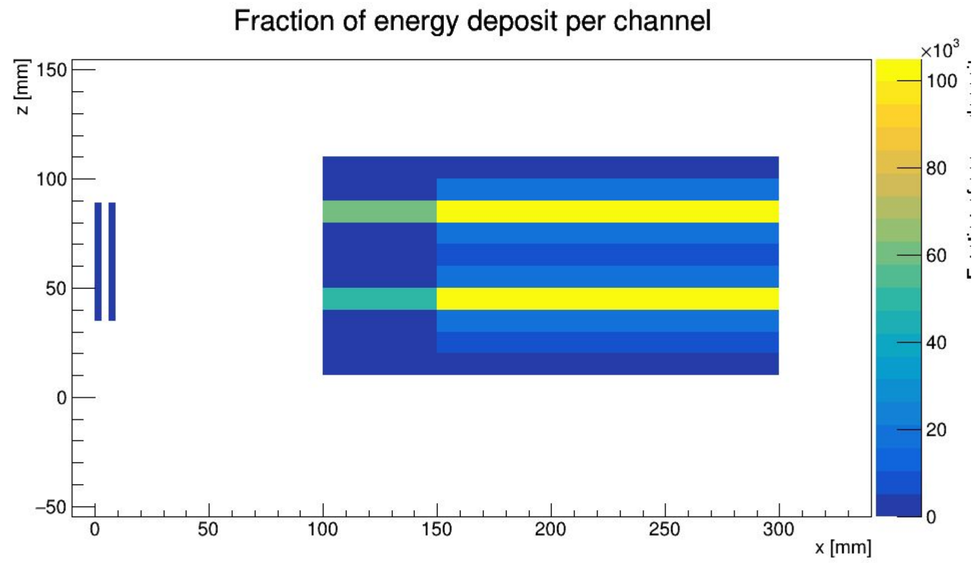


S-CEPCal Pair of EM Showers (High Stat)

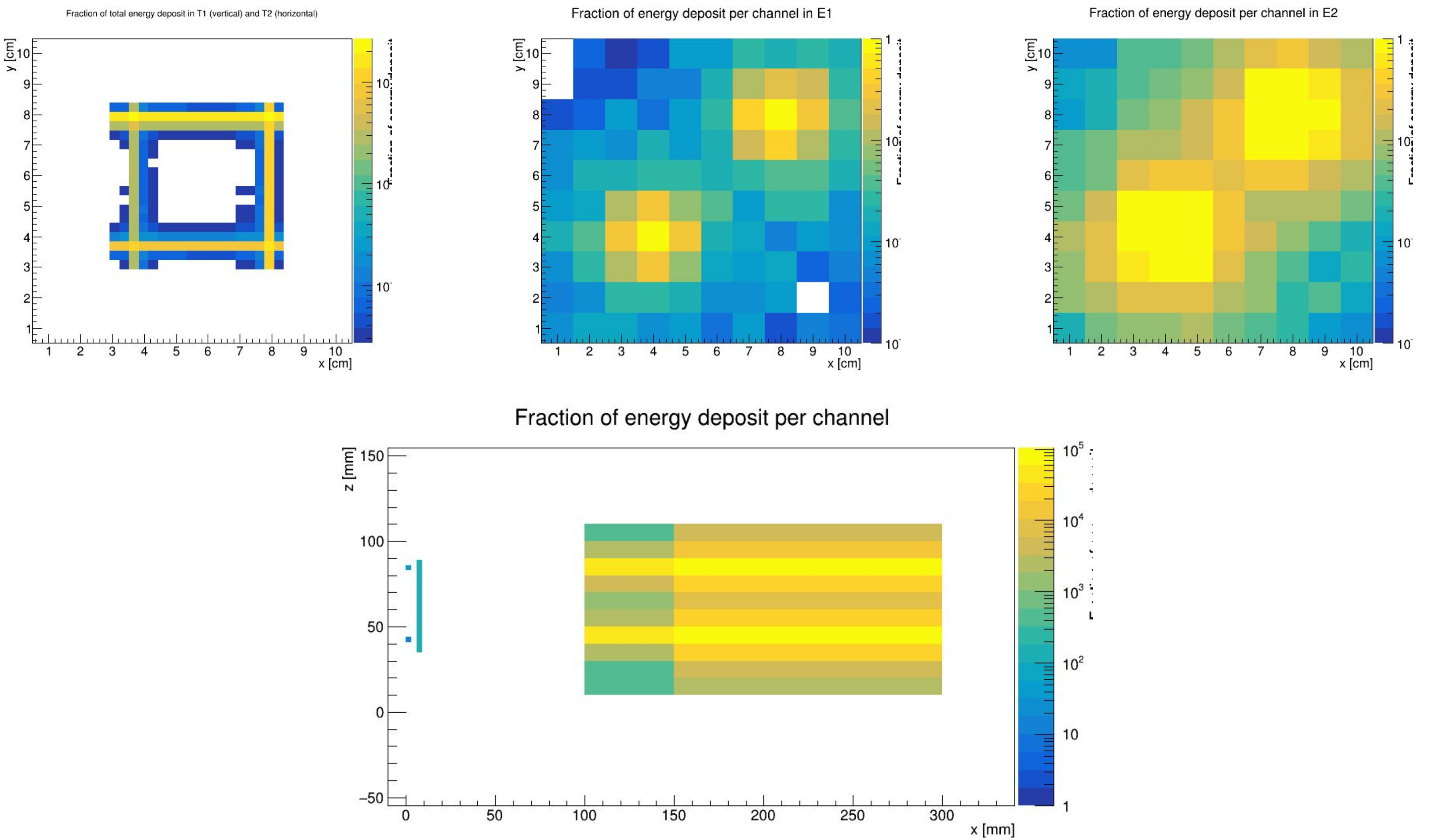




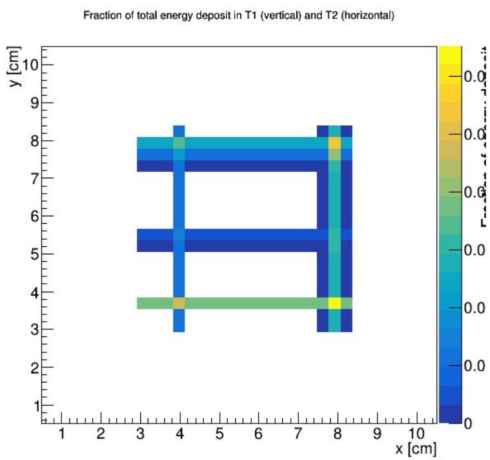


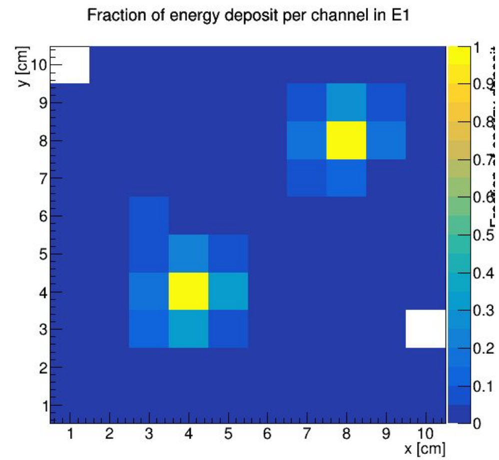


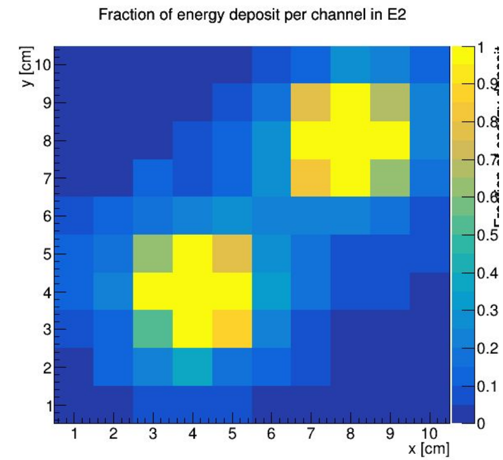
S-CEPCal Pair of EM Showers (High Stat - Log)

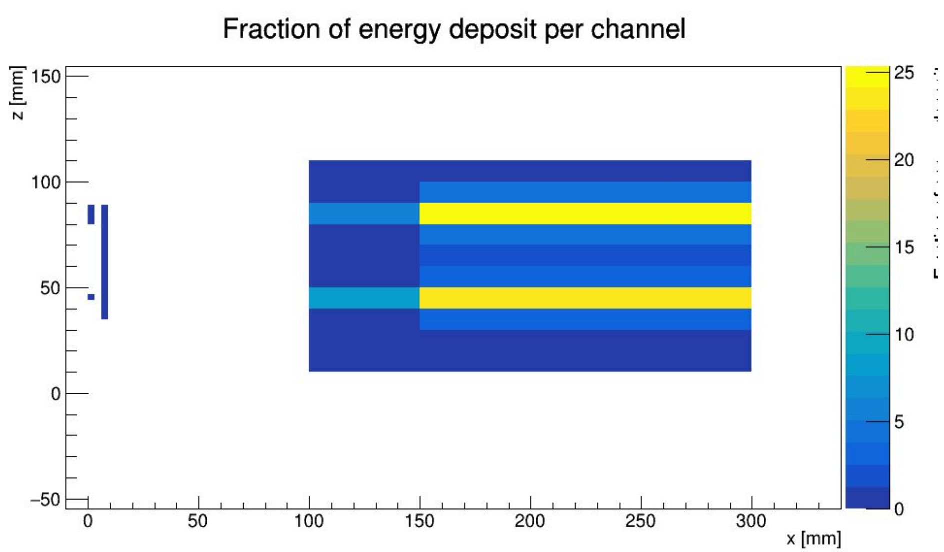


S-CEPCal Pair of EM Showers (Single Event)

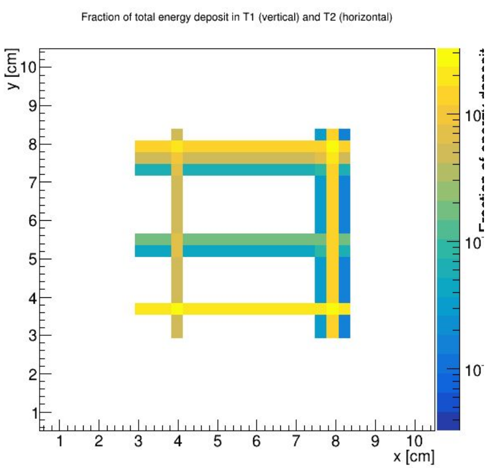


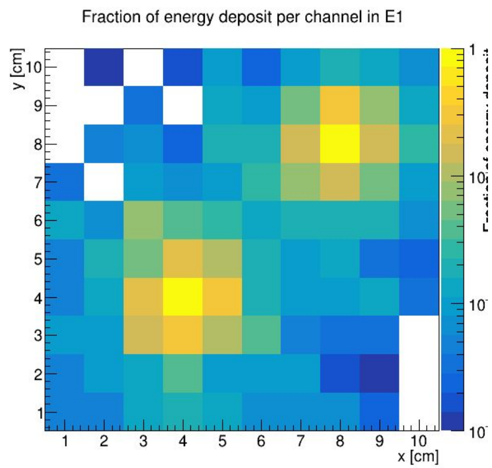


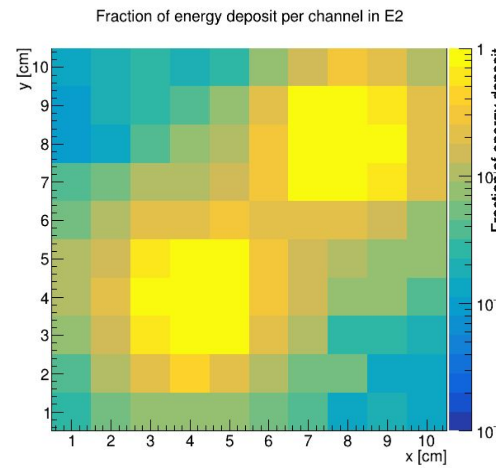


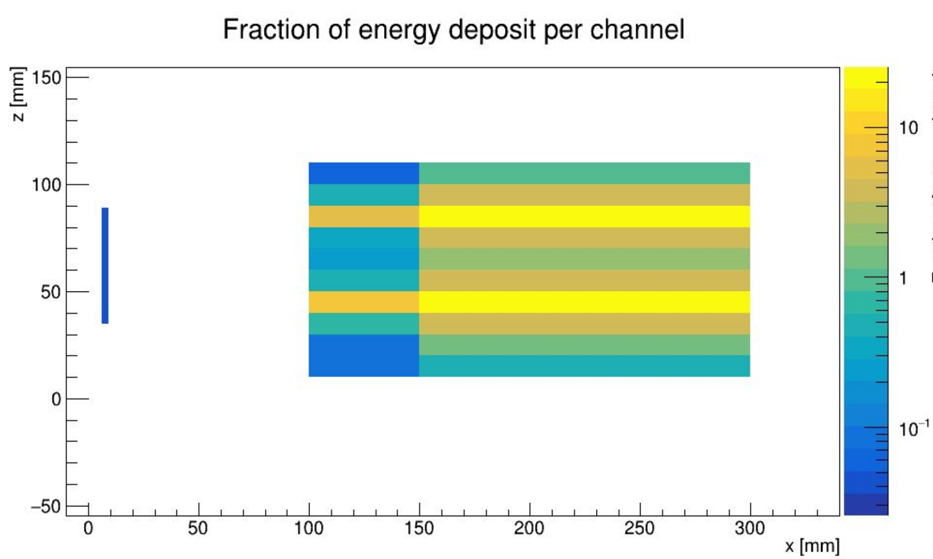


S-CEPCal Pair of EM Showers (Single Event - Log)

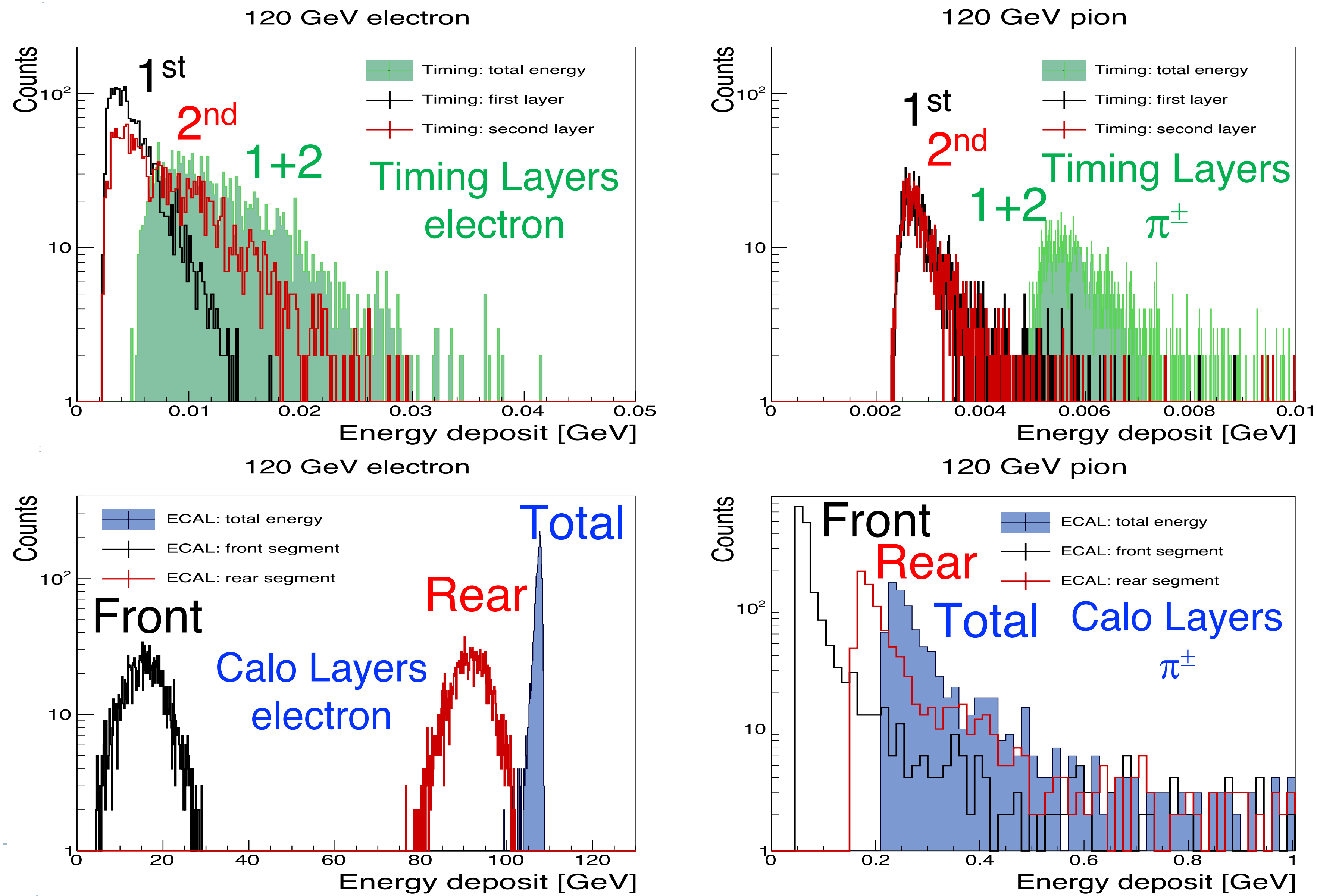




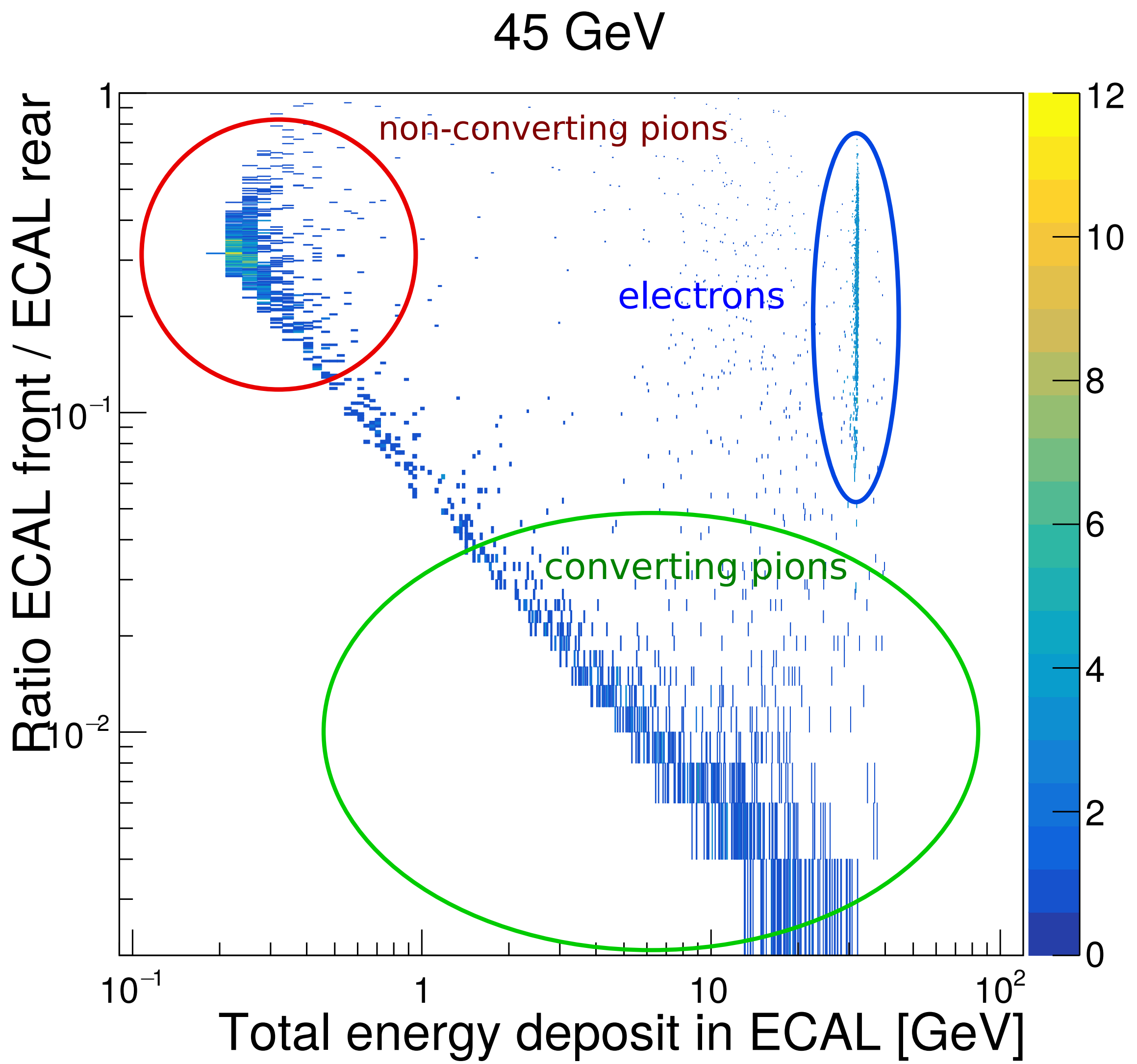




Electron/$\pi^{\pm}$ Discrimination



Electron/$\pi^{\pm}$ Discrimination

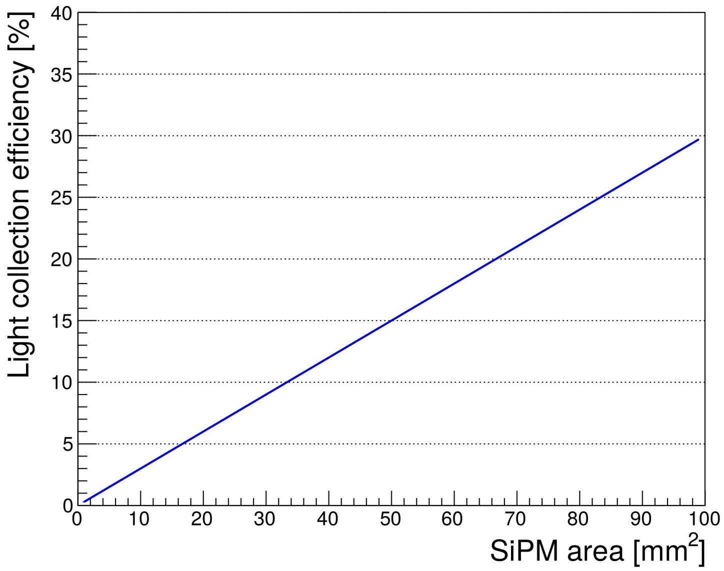


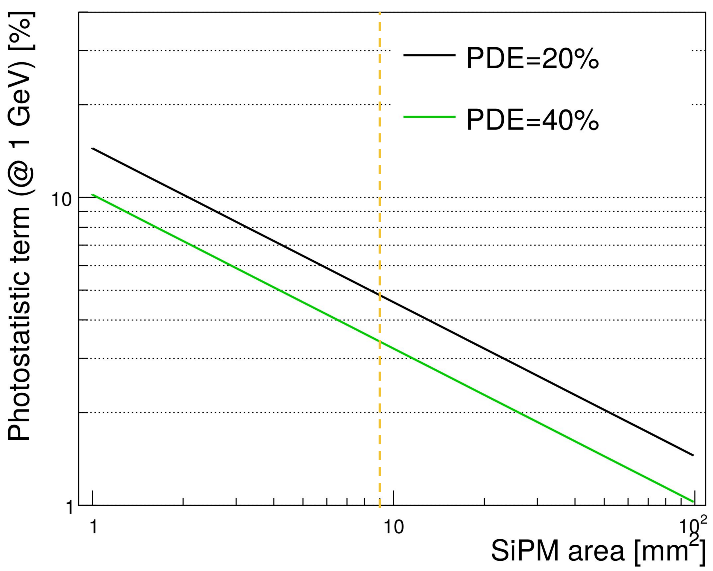
Energy Resolution and Dynamic Range

- **5%/sqrt(E) → LO>400 phe/GeV → LO>0.4 phe/MeV**
  - at LCE~2.5%, PDE ~ 20% → LY>80 ph/MeV
  - Ok for PWO (~100 ph/MeV)
- **Maximum energy deposit in single crystal for 120 GeV e.m. shower ~60%**
  - ~ 35000-70000 phe for ~72 GeV (at PDE~20-40% resp.)
- **SiPM 5x5 mm^2 on a 10x10 mm^2 crystal is sufficient**
  - LCE~2.5%
  - if cell size: 15 um → cells / SiPM ~110,000 and PDE up to 40%
  - if cell size: 10 um → cells / SiPM ~250,000 and PDE up to 25%
- **Sensitivity for 0.1 GeV particles**
  - 40 phe signal
  - Noise from SiPM within 30 ns integration gate negligible (DCR<10MHz → noise<1 phe)

Photostatistics

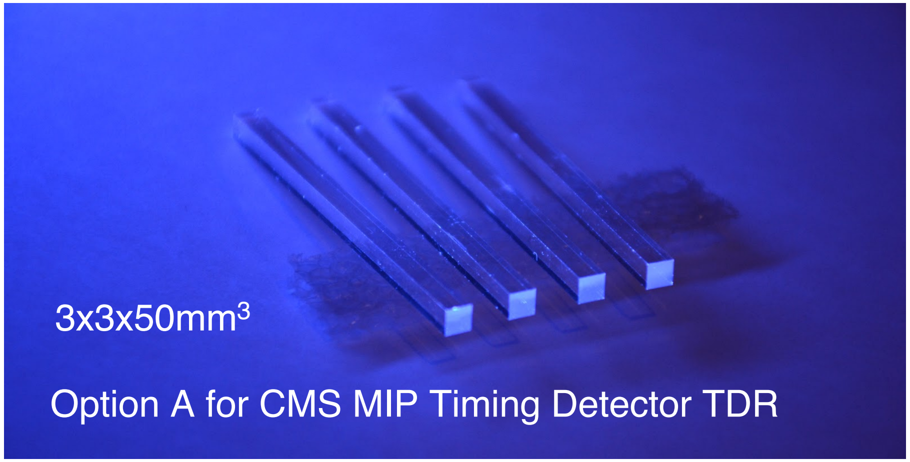
- 5%/sqrt(E) → LO>0.4 phe/MeV
  - for LCE~2.5% (9 mm² SiPM), PDE ~ 20% → The crystal must have a LY>80 ph/MeV
- SiPM 3x3 mm² on a 10x10 mm² crystal is sufficient
  - with SiPM area = crystal end face → LCE~30%



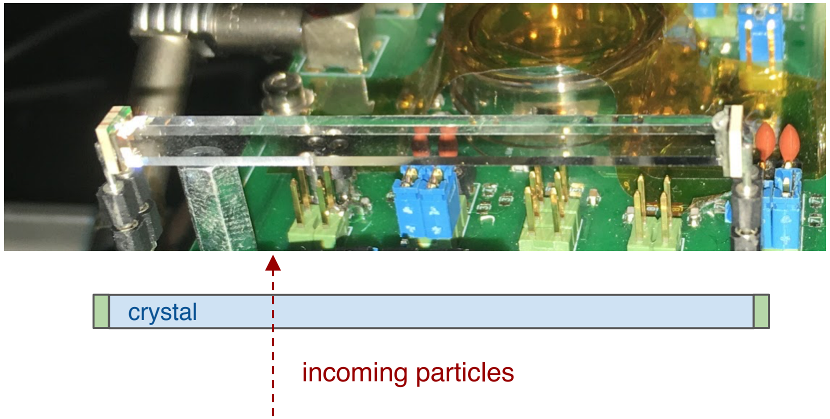


Small Crystal Geometries for Timing Detectors

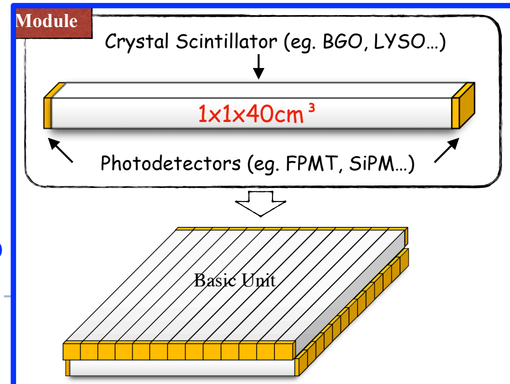
- **Tiles and Bars (few mm thick w/ area of ~1cm^2)**
  - CMS MTD: Single layer ~330,000 channels
  - Stereo readout for bars (L/R) ~25ps timing resolution



Non-wrapped crystal bar with 2 SiPMs attached at each end

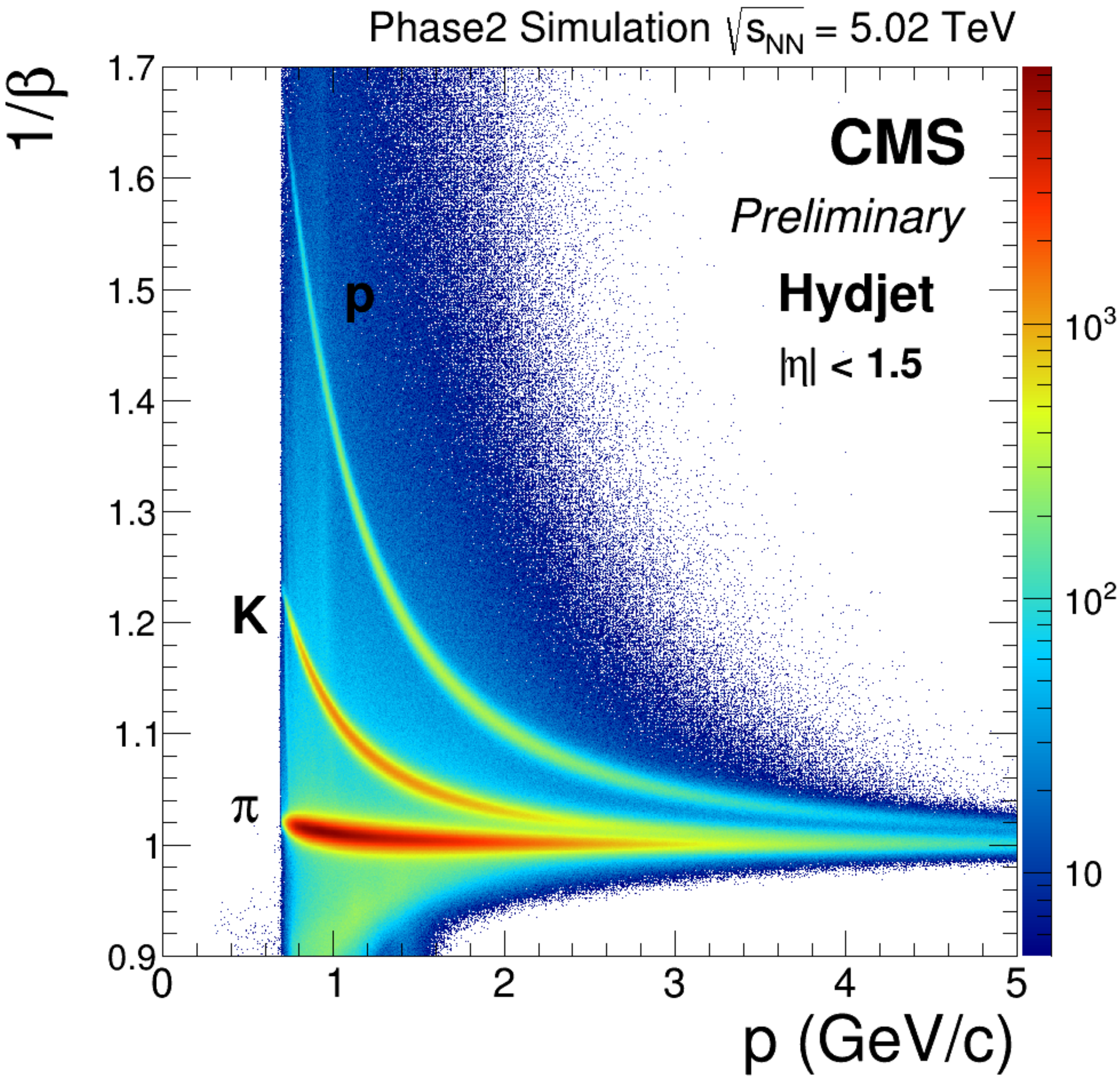


Low occupancy timing layer timing for ~1 X0
Transverse orientation w/ stereo readout



Similar study at IHEP
by Yuexin Wang

Time-of-Flight Particle ID (R=1.2m)

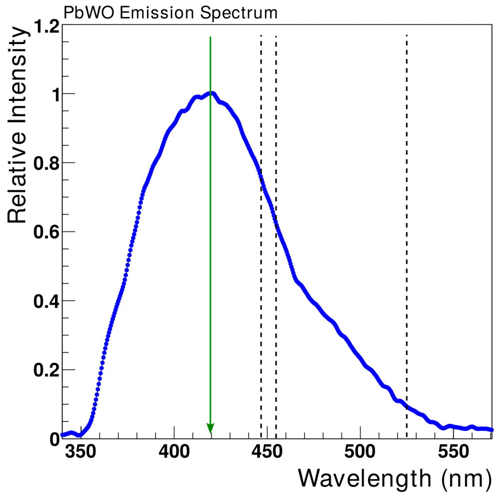


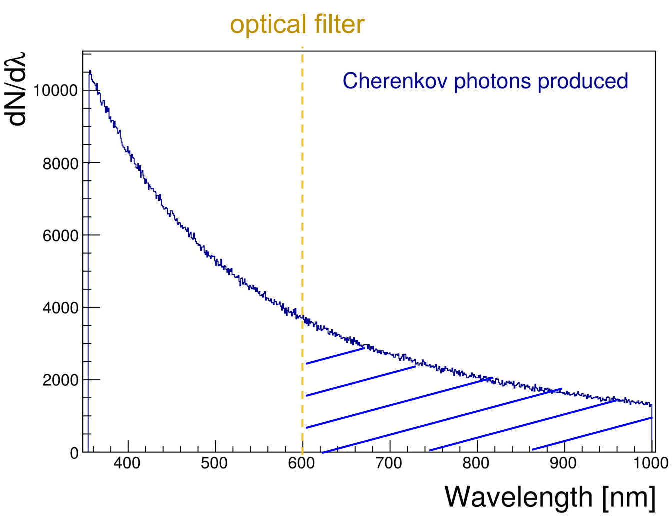
Single Layer (30 ps)

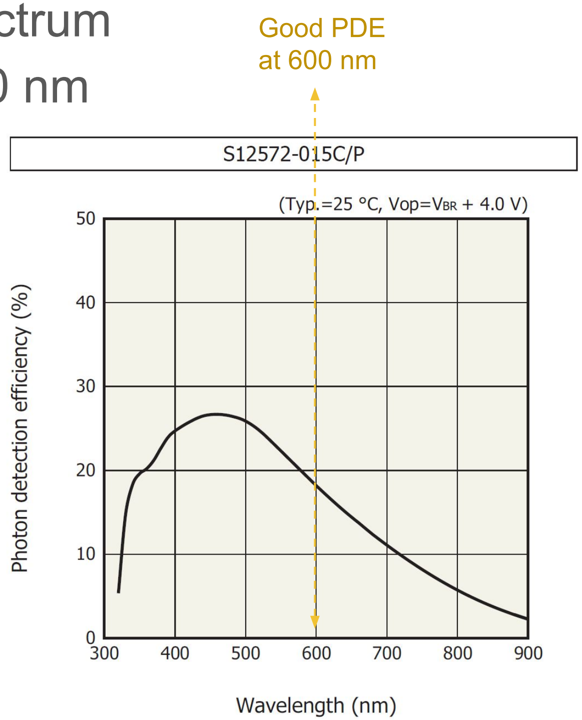
Improves by 1/√2 w/Dble Layer

Dual-Readout Capability

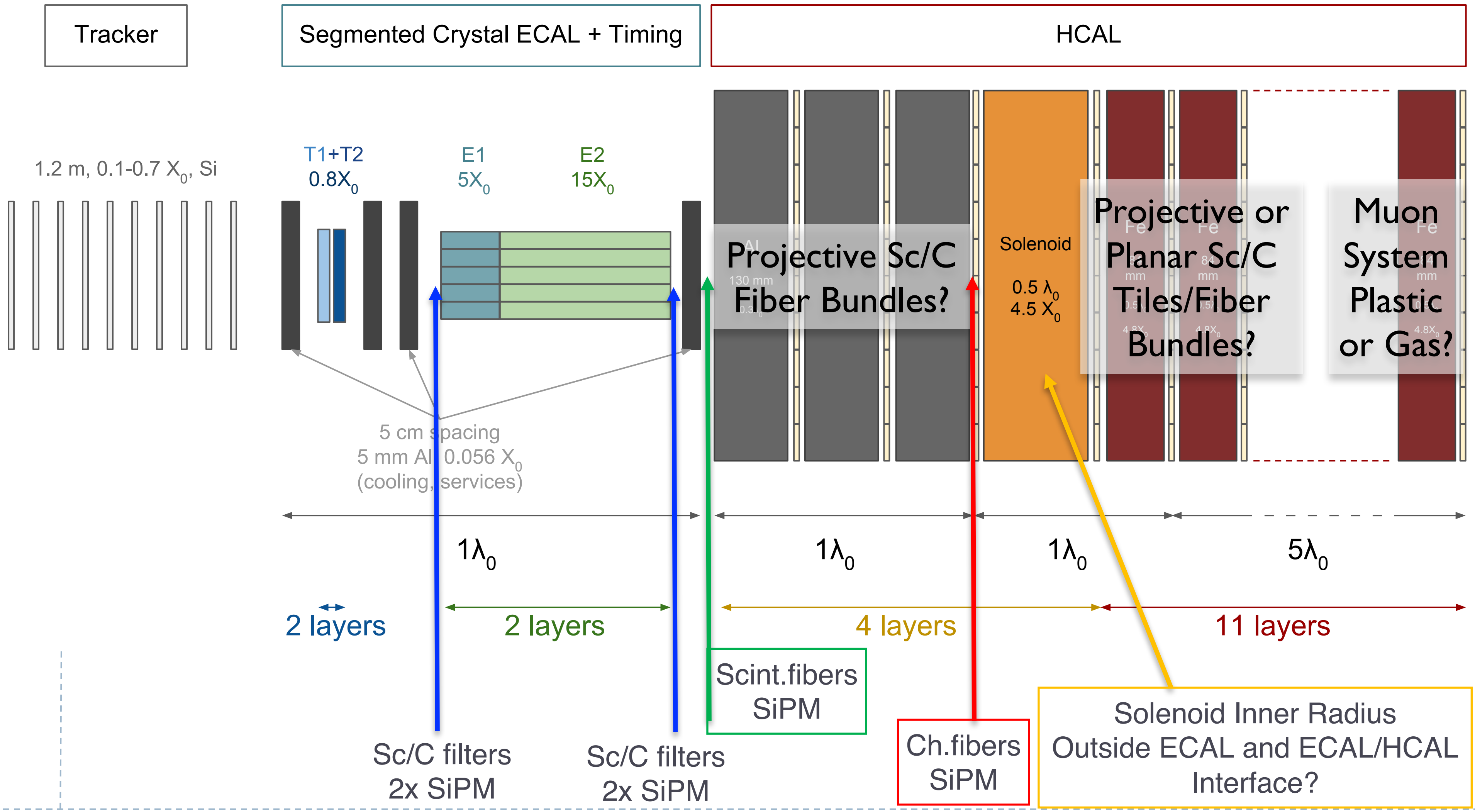
- PWO - excellent Cherenkov radiator (transparency cut off at 350 nm)
- Exploit Cherenkov photons **above** PWO emission spectrum
- 2 SiPMs, one with optical filter > 600 nm, another <600 nm





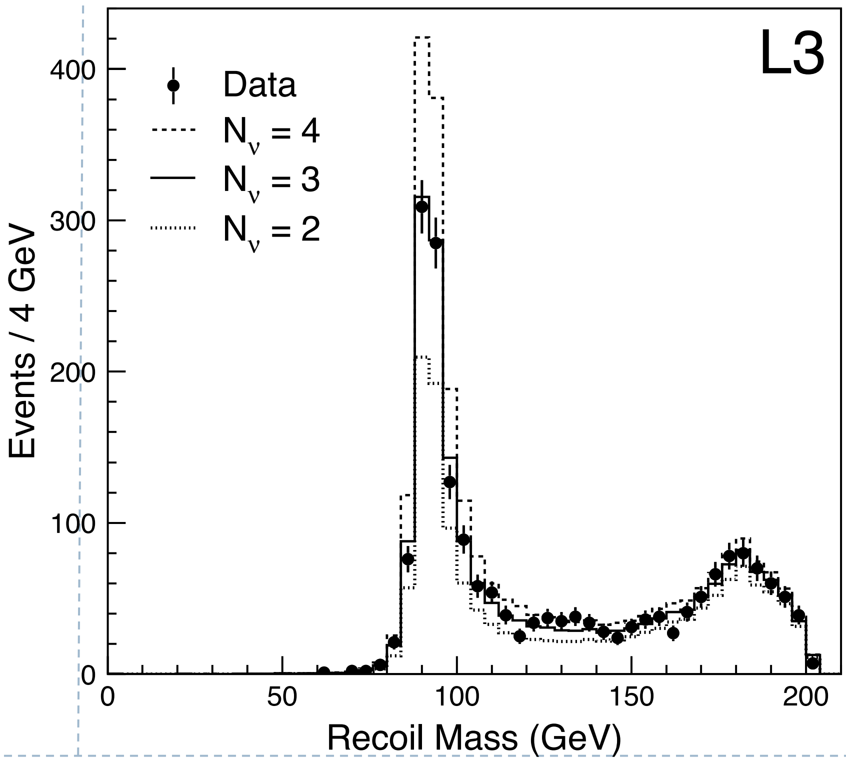


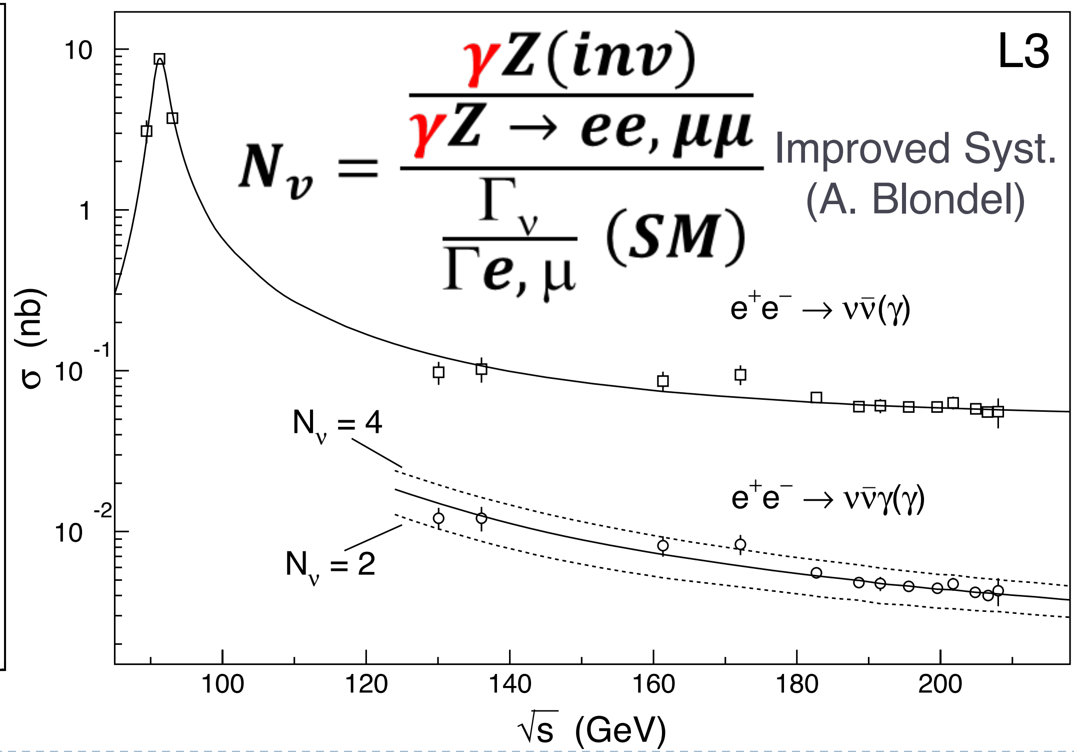
Dual-Readout ECAL+HCAL Compatibility



EM Resolution and Photon Counting

- **EM Resolution also improves angular measurements and resolves Nγ counting**
- **Recoil photons (~8% of full √s collision rate)**
  - New Physics Searches and Neutrino Counting





E. Bartos *et al.*, "2γ **and** 3γ **annihilation as calibration processes for high energy** e+e– **colliders,"** https://arxiv.org/abs/0801.1592

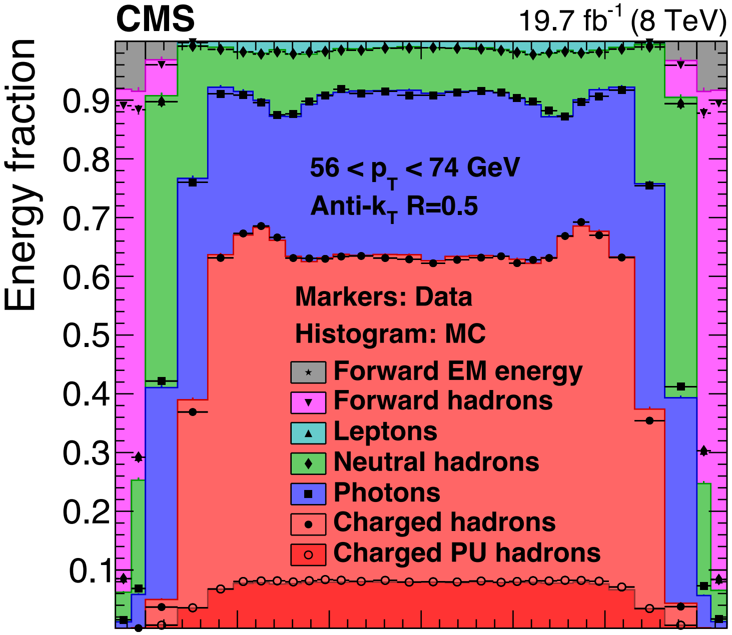
Conclusions

- **Physics case at e^+e^- colliders calls for high resolution ECAL**
  - $Z \rightarrow e^+e^-$ recoil resolution w/ Brem. recovery methods
  - Highly resolved PFA clustering from high sampling fraction
  - 20ps Resolution Time-of-Flight Particle ID for π/K/p
  - Photon counting with high fidelity/angular resolution
- **Homogenous and segmented crystal calorimeters can provide outstanding energy resolution in the energy range 0.1-120 GeV**
- **Calorimeter design can capitalize on the expertise from previous HEP crystal calorimeters**
- **Recent progress in the fields of crystals and SiPMs enables a flexible, compact and lower cost solution for a high resolution ECAL**
- **A highly segmented calorimeter in transverse and longitudinal direction combined with 20 ps timing capabilities extends the physics program for particle ID, long-lived particles and improves out-of-time background rejection**

Additional slides

Balancing Jets and EM particle resolutions

- **For HZ production, all Z recoils matter**
  - ~70% of Z decay are hadronic
- **Particle Flow Principle**
  - Optimal use of measurement information applied to each reconstructed particle
    - Charged hadrons (~65%)
      - Replaced by track (~0.1%)
    - Neutral hadron (~10%)
      - HCAL (~45%/√E) ~4.5%/√E
    - Photons/EM (~25%)
      - ECAL (~15%/√E) ~3.8%/√E



Z Jets ~ 3.5 - 5.5% (Limited by HCAL & EM)

Comparisons with CMS and PANDA ECALs

- **LY (PWO) ~ 100 ph/MeV**
- **CMS EE:**
  - QE_{VPT} ~22%,
  - LCE ~ 9% (1 VPT: size~ 11 mm radius - area: 380 mm²)
  - PbWO, crystal end face size: ~30x30 mm²
- **CMS EB:**
  - QE_{APD}~75%,
  - LCE~9% (2xAPDs, size: 5x5 mm²)
  - PbWO crystal size: ~22x22 mm²
- **Resolution measured in test beam: ~3-6% stochastic + 0.3-0.6% constant**

http://iopscience.iop.org/article/10.1088/1748-0221/2/04/P04004/pdf
https://arxiv.org/pdf/1306.2016.pdf

PANDA ECAL
PWO-II development:
→ factor 4 higher LO at -25°C wrt to +25°C
→ ~20 phe/MeV @PDE=20%
→ <2% stochastic term

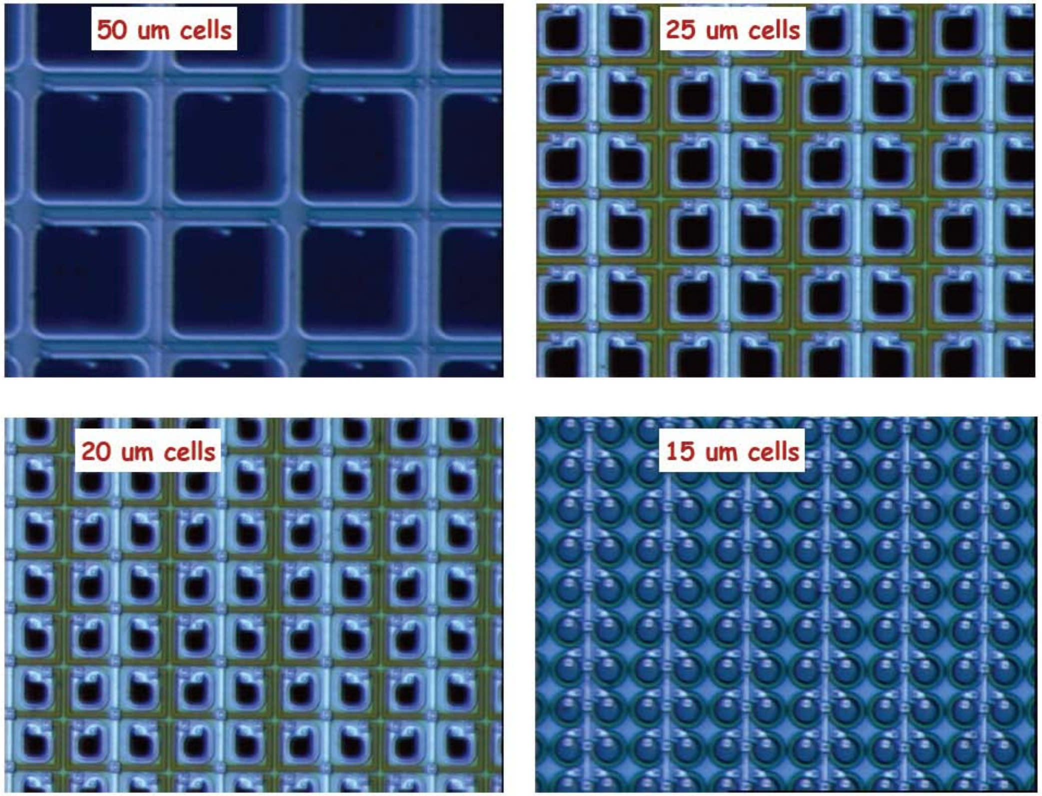
https://arxiv.org/pdf/0810.1216.pdf

Silicon Photomultiplier (SiPM) Cells

- **Typical dynamic range customization for SiPM**
  - More (small) SPADS to count more photons (50→15µm)
  - Bright crystal (LYSO, GAGG) and high photodetection efficiency (PDE) and light collection efficiency (LCE)

Currently:
Large device ~6x6mm^2
CMS MTD ~4.5 m^2 of SiPMs (of 3x3mm^2)

Segmented Crystal ECAL:
~200 m^2 of crystal surface (3-4 layers)
Which SiPM device?



Further Possibilities for SiPMs with High Dynamic Range and Packing Density

- **Large pixel count w/ large gain leads to current output limitations for large area devices**
  - Multiple analog outputs per device
    - Regional lumped analog sums - split output currents per region and sum (1/128, 1/32,1/8,1/2)
    - Multi-gain SPADs (5, 15, 50µm) for different cell sizes and fill factors – dynamic range built into SPAD layout
  - On-chip ADC with regional serializers
  - Commercial market for LIDAR advances is growing rapidly – many new developments expected