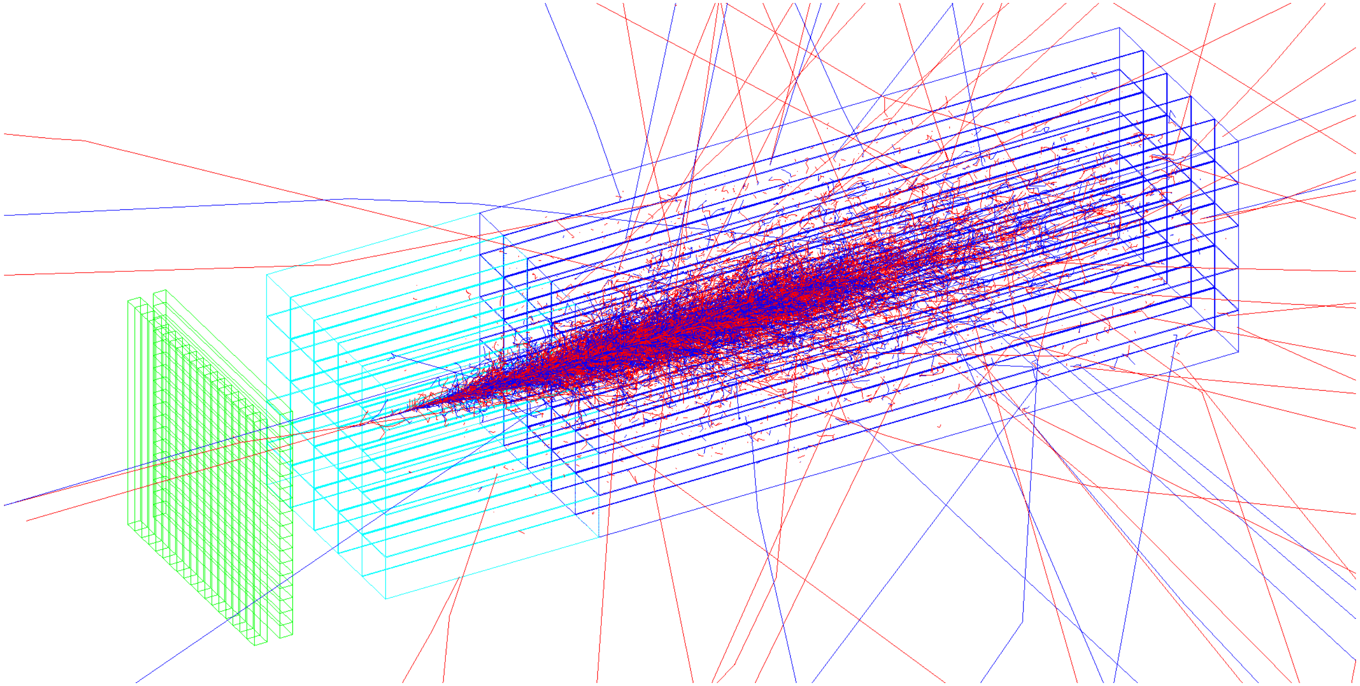


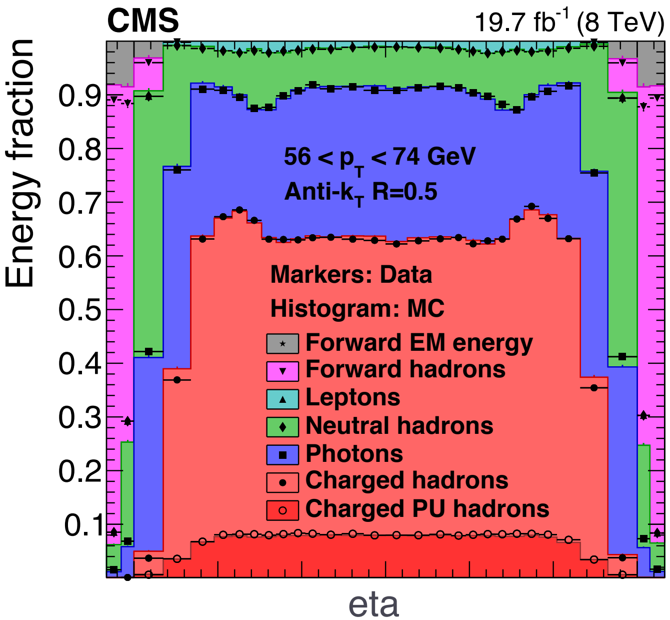
Segmented Crystal EM Calorimetry

January 16-18, 2019
HKUST Jockey Club IAS, Hong Kong, China

Sarah Eno (University of Maryland, College Park)
for
Marco Lucchini (Princeton), Chris Tully (Princeton)

Balancing Jets and EM particle resolutions

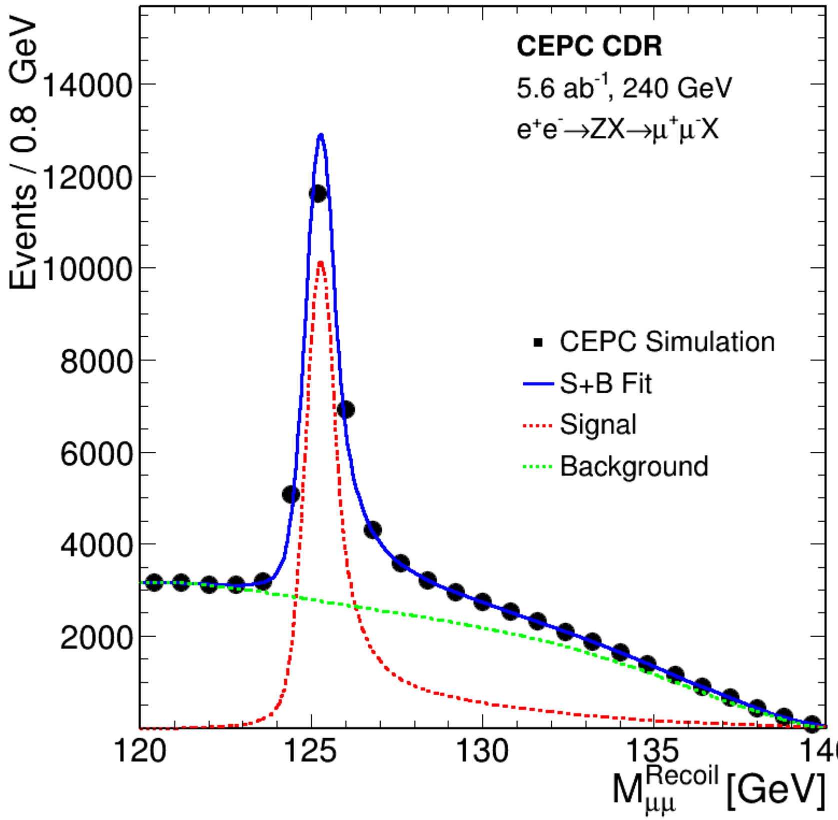
- **For HZ production, all Z recoils matter**
  - ~70% of Z decay are hadronic
- **Particle Flow Principle**
  - Optimal use of measurement information applied to each reconstructed particle
    - Charged hadrons (~65%)
      measured using track (~0.1%)
    - Neutral hadron (~10%)
      HCAL (~45%/√E)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



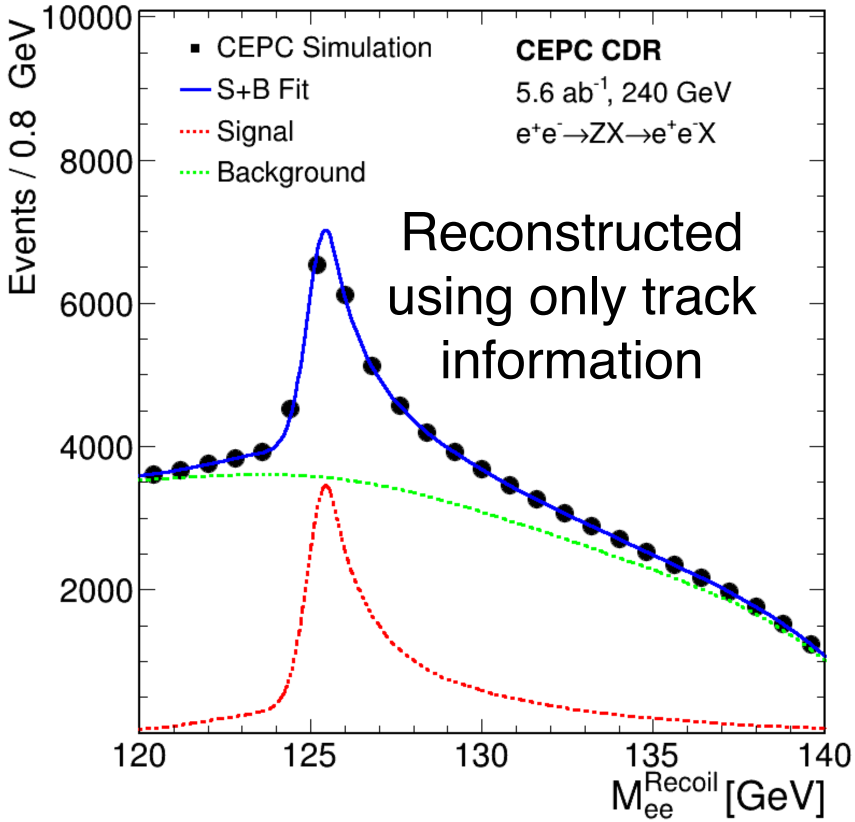
Z →Jets ~ 3.5 - 5.5% (Limited by HCAL & EM)

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

- **Muons**



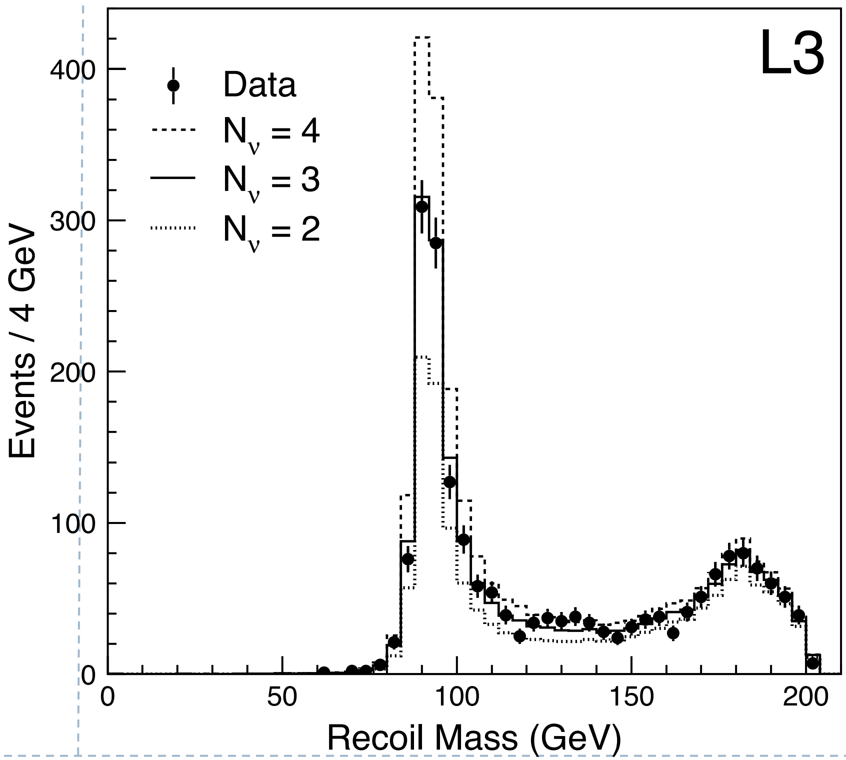
- **Electrons**

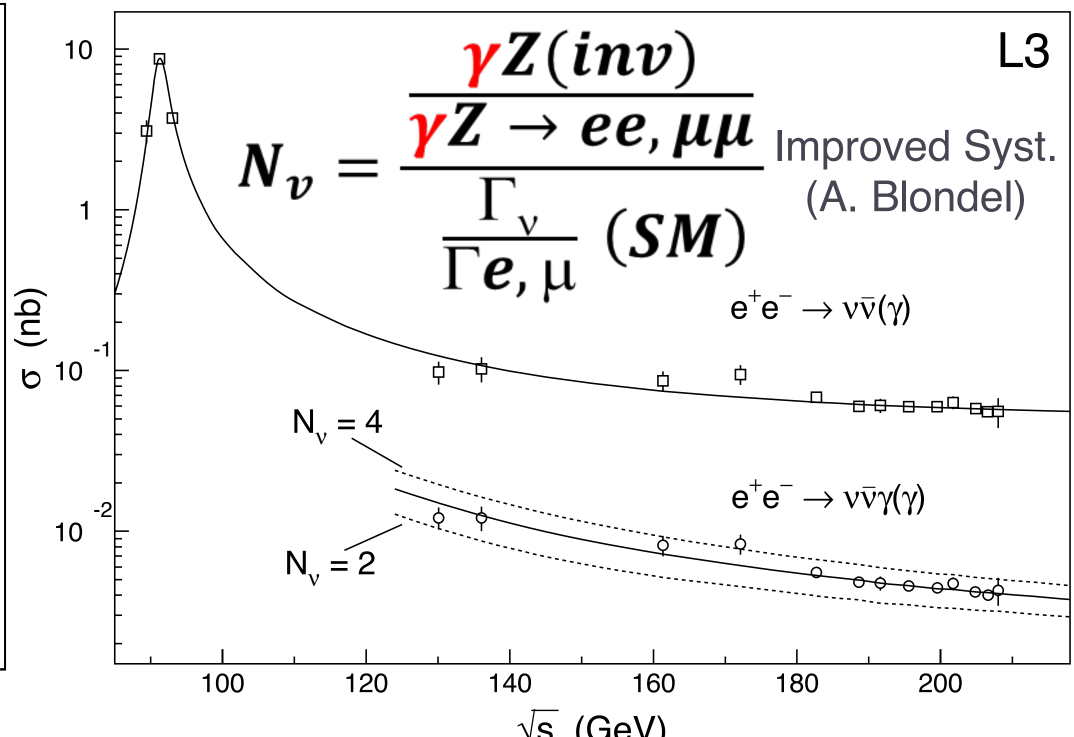


e's worse than μs w/ CDR reference design
(needs Brem. Recovery, but that has EM res.)
Broadening due to brem~2-4%
*15%/√E → ~0.3-0.6% (compare to 0.1-0.3% for muons)

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



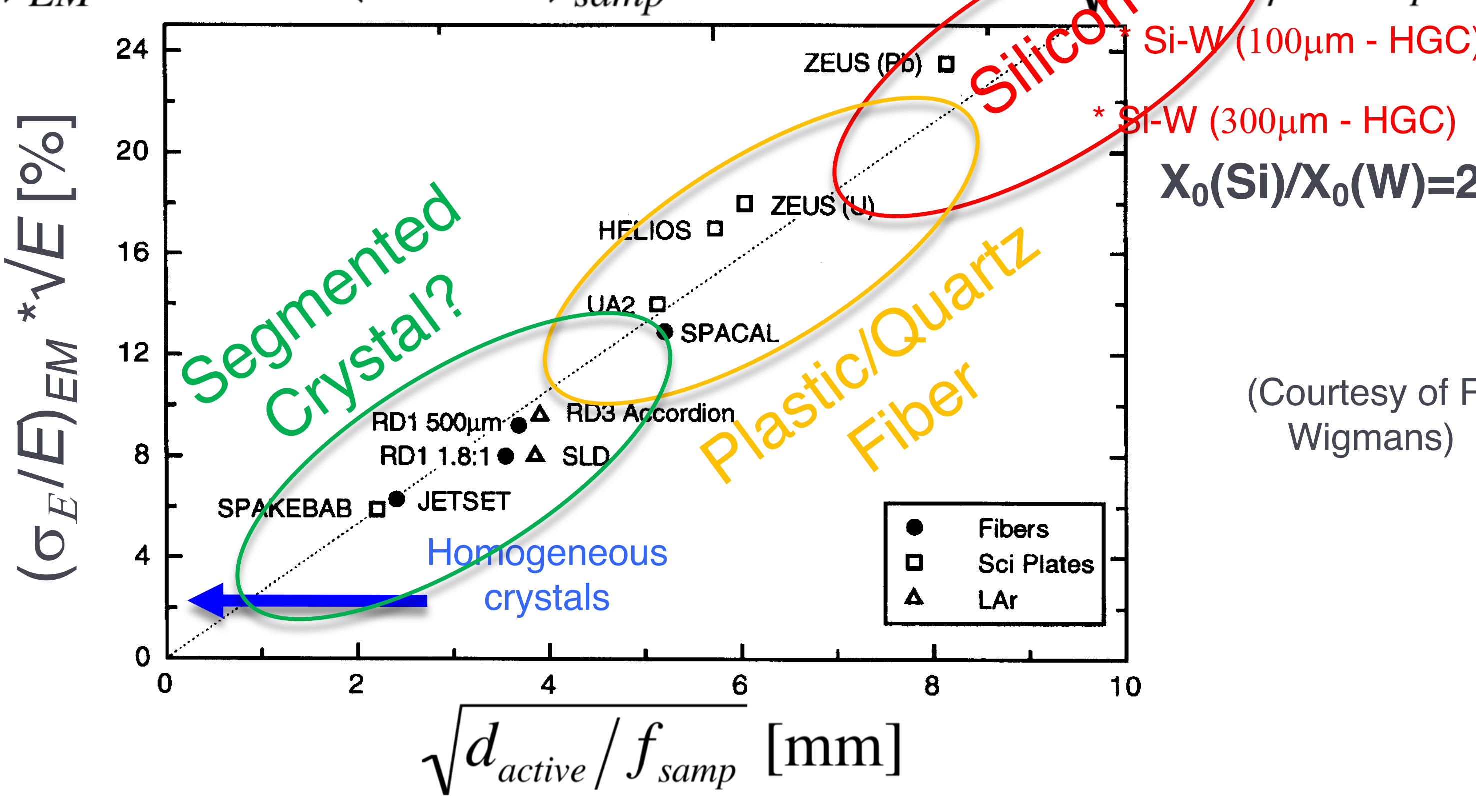


E. Bartos *et al*., "2γ **and** 3γ **annihilation as calibration processes for high energy** e+e– **colliders,"** https://arxiv.org/abs/0801.1592

Three Regimes of EM Resolution

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

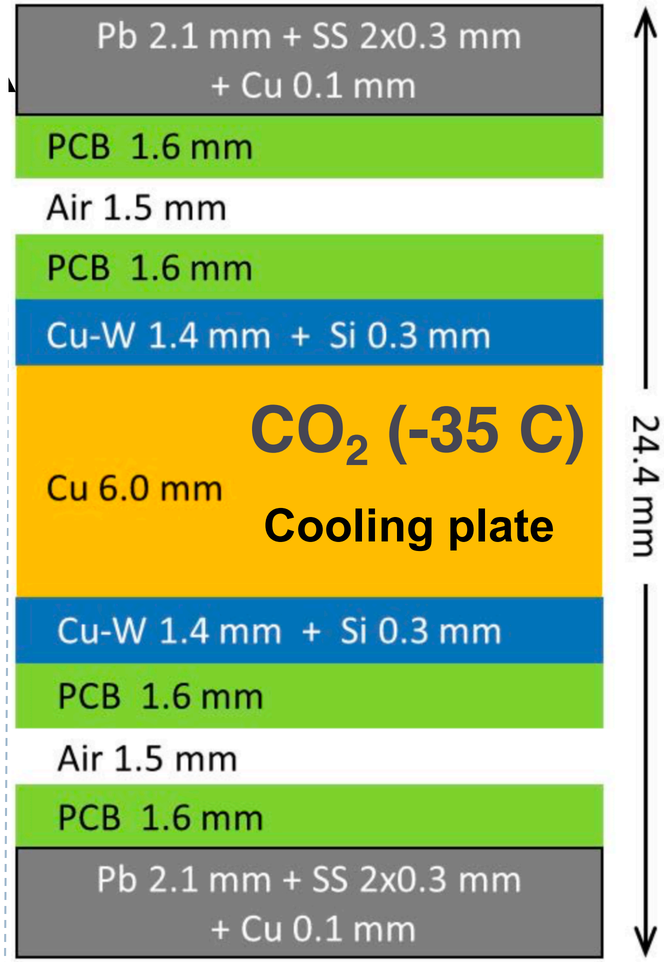
$$(\sigma_E/E)_{EM} \cdot \sqrt{E} \approx (\sigma_E/E)_{samp} \cdot \sqrt{E} = 2.7\% \sqrt{d_{active}/f_{samp}}$$

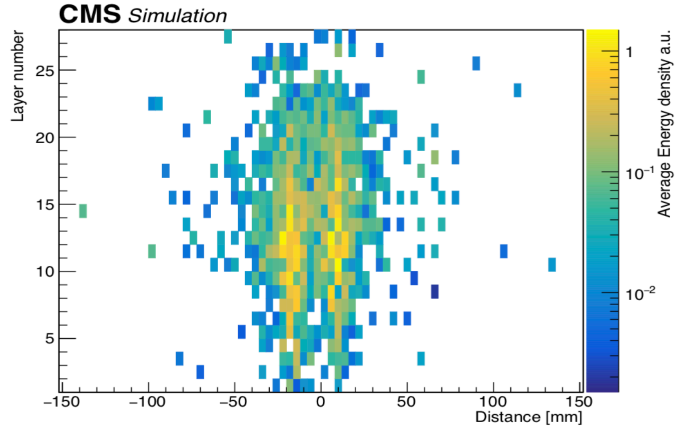


$X_0(Si)/X_0(W)=27$

(Courtesy of R. Wigmans)

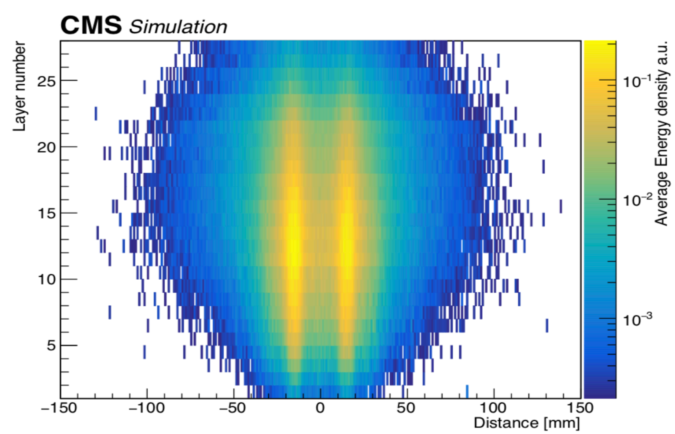
Imaging Capabilities of High Granularity





One event

Fluctuations driven by
Low Sampling Fraction(~1/300)
High SF → is like average over many low SF showers

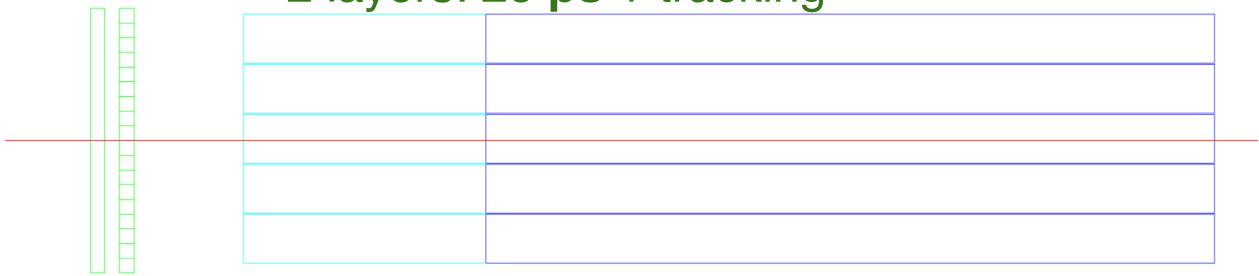


Several thousand events

Segmented Crystal Calorimeter Module

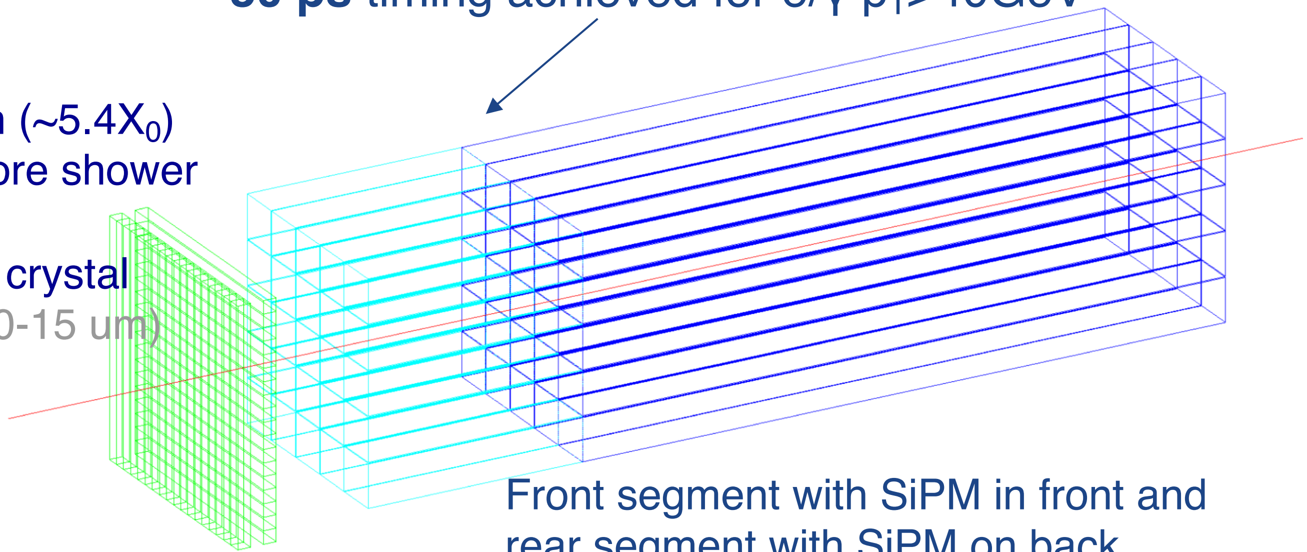
- **Timing layer (2 layers):**
  - LYSO:Ce crystals
  - SiPMs
  - 3x3x54 mm³ active cell
  - 3x3 mm² SiPMs (15-25 um)

For all MIPS
1 layer: **30 ps**
2 layers: **20 ps** + tracking



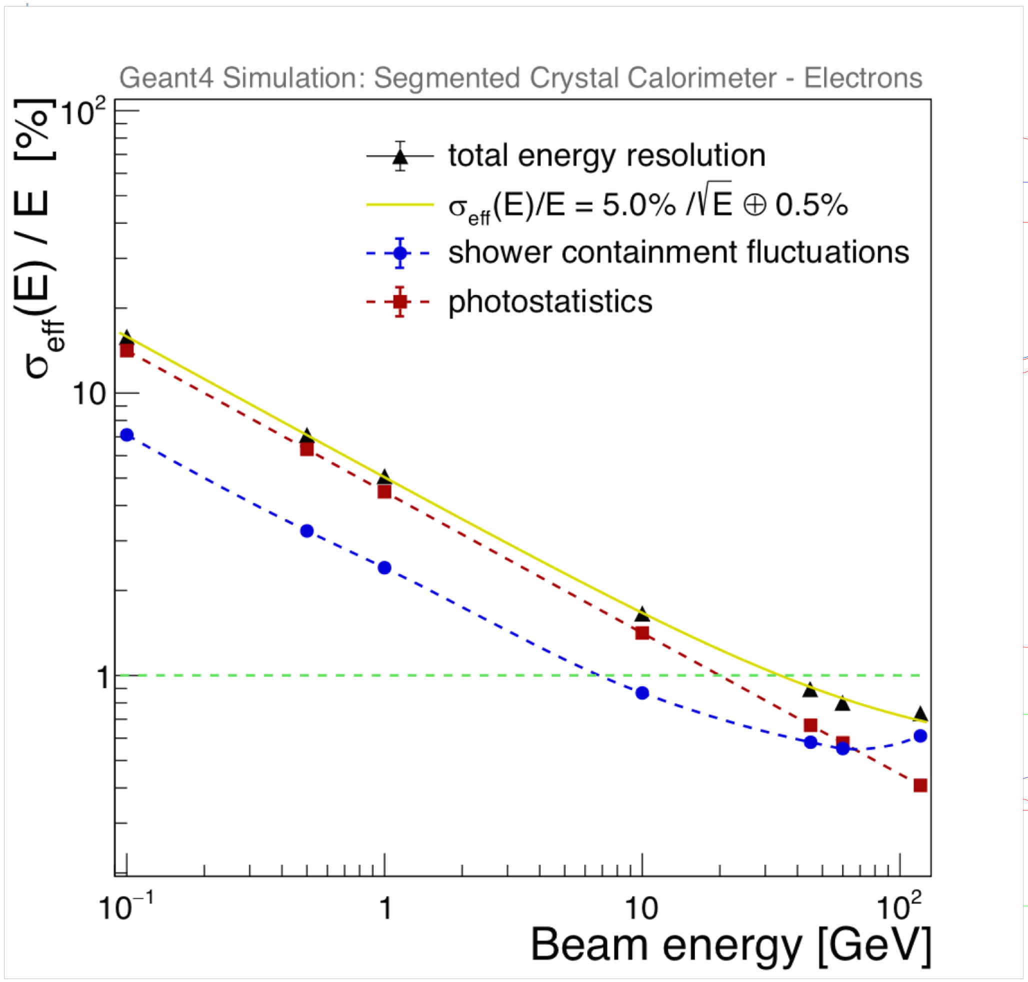
< **5%/sqrt(E) (+) 1%**
~30 ps timing achieved for e/γ p_T>40GeV

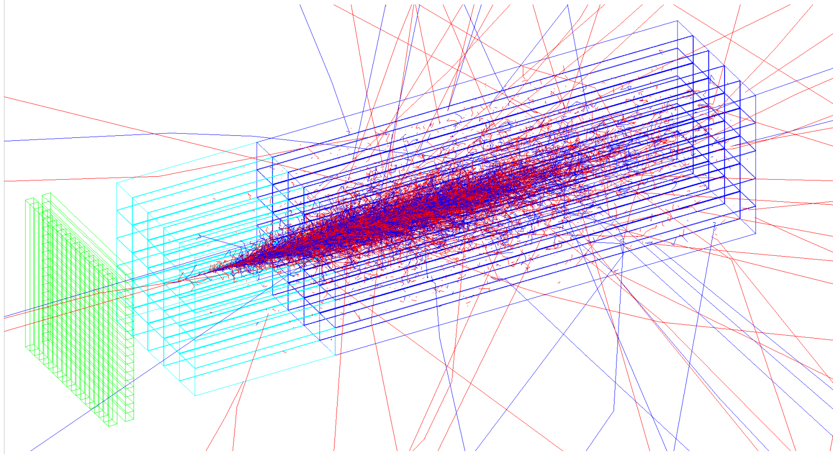
- **ECAL layer:**
  - PbWO crystals
  - front segment 5 cm (~5.4X_0)
  - rear segment for core shower
  - (15 cm ~16.3X_0)
  - 10x10x200 mm³ of crystal
  - 5x5 mm² SiPMs (10-15 um)

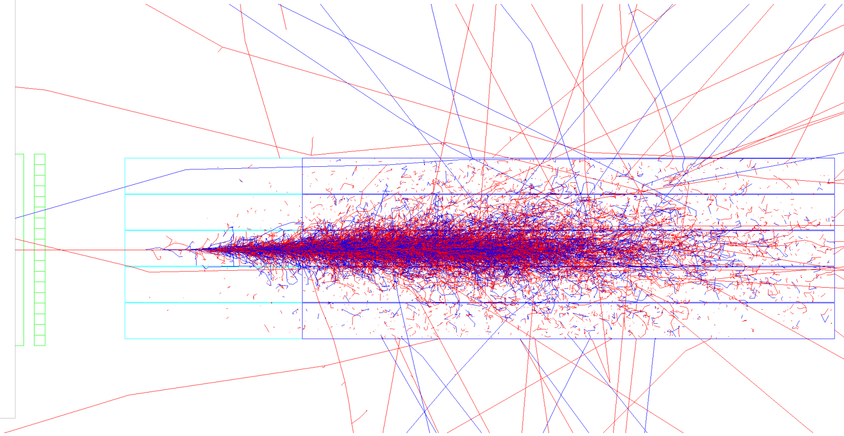


Front segment with SiPM in front and
rear segment with SiPM on back
→ Avoids dead material at shower max

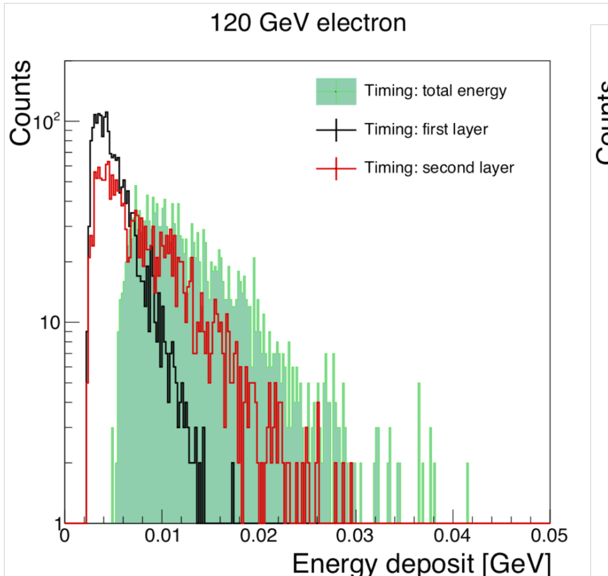
Electron Energy Resolution

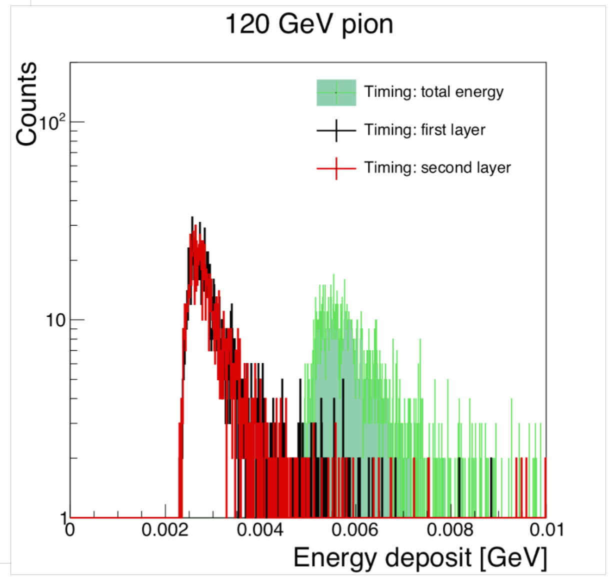


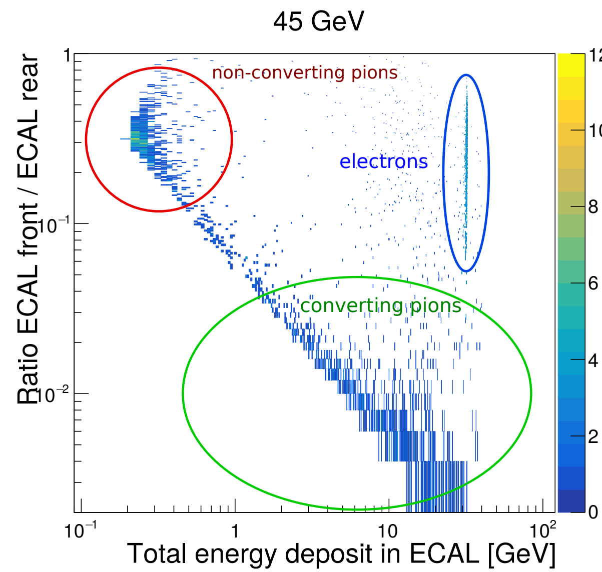


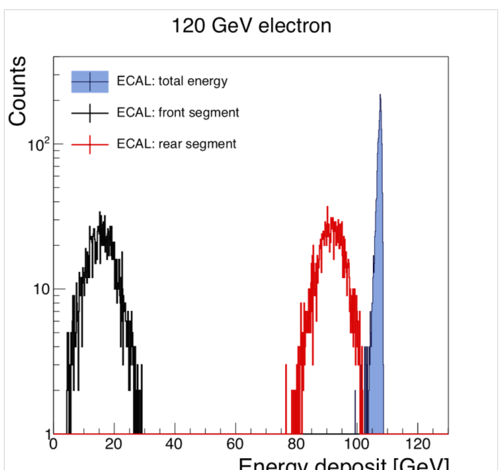


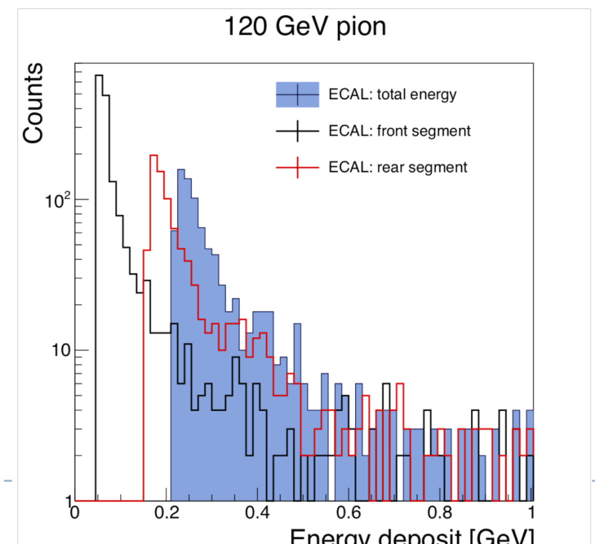
Electron/$\pi^{\pm}$ Discrimination

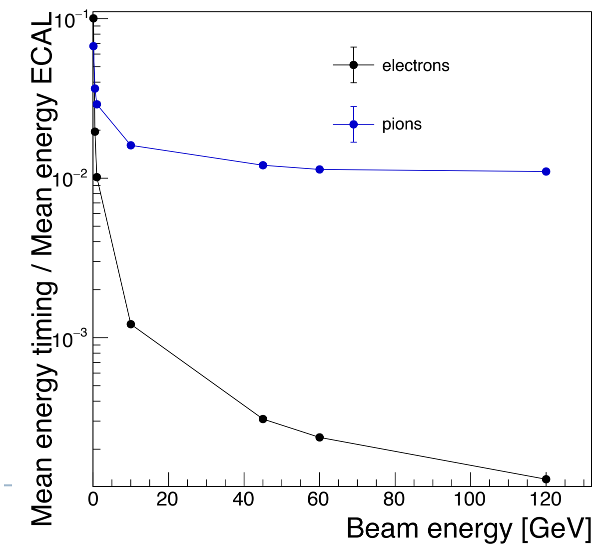






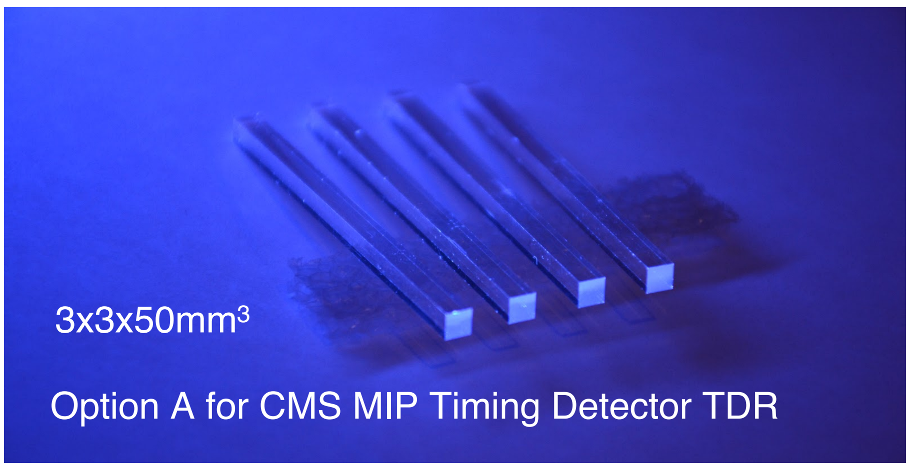




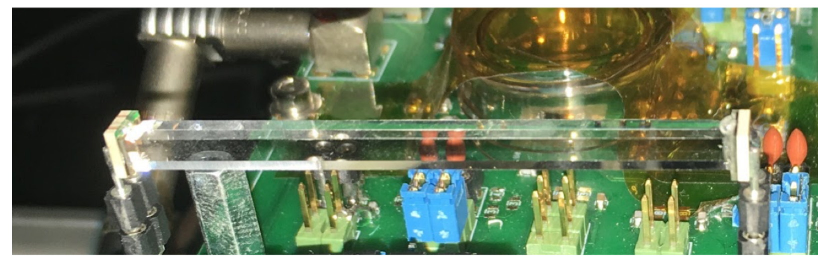


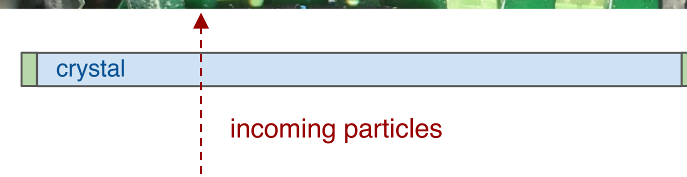
Small Crystal Geometries for Timing Detectors

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

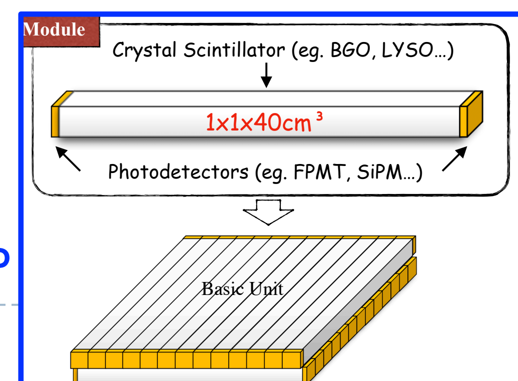


Non-wrapped crystal bar with 2 SiPMs attached at each end



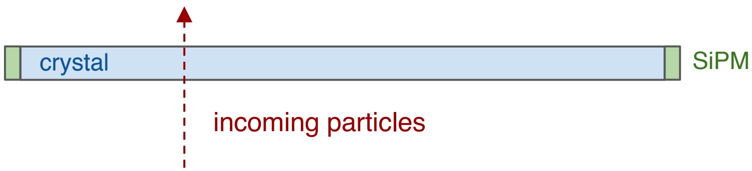


Low occupancy timing layer timing for ~1 X0
Transverse orientation w/ stereo readout

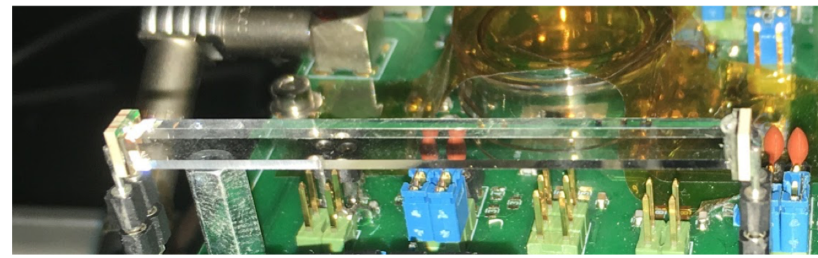


Similar study at IHEP
by Yuexin Wang

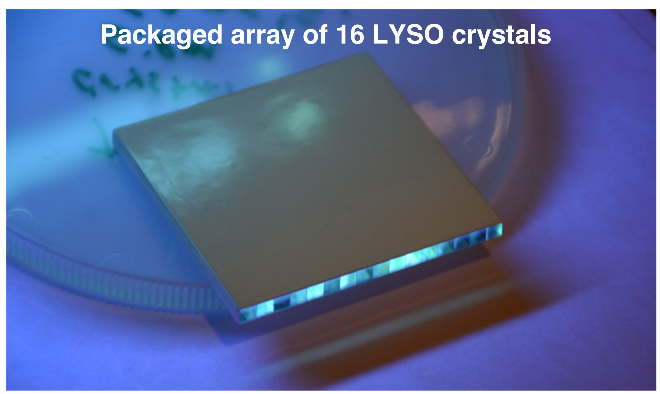
Crystal + SiPM timing layer (CMS MTD)



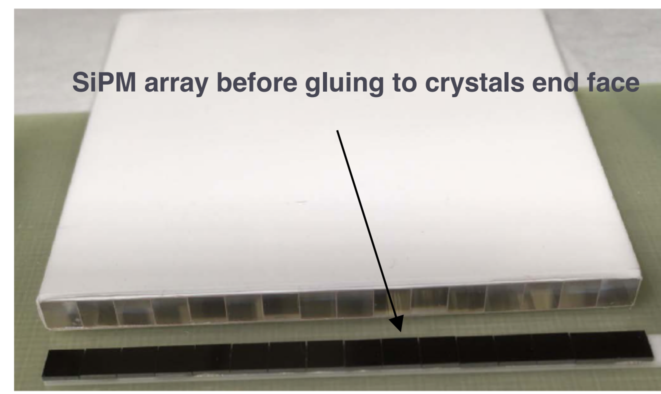
Non-wrapped crystal bar with 2 SiPMs attached at each end



Teflon wrapped crystal bar with 2 SiPMs attached at each crystal end face



Packaged array of 16 LYSO crystals



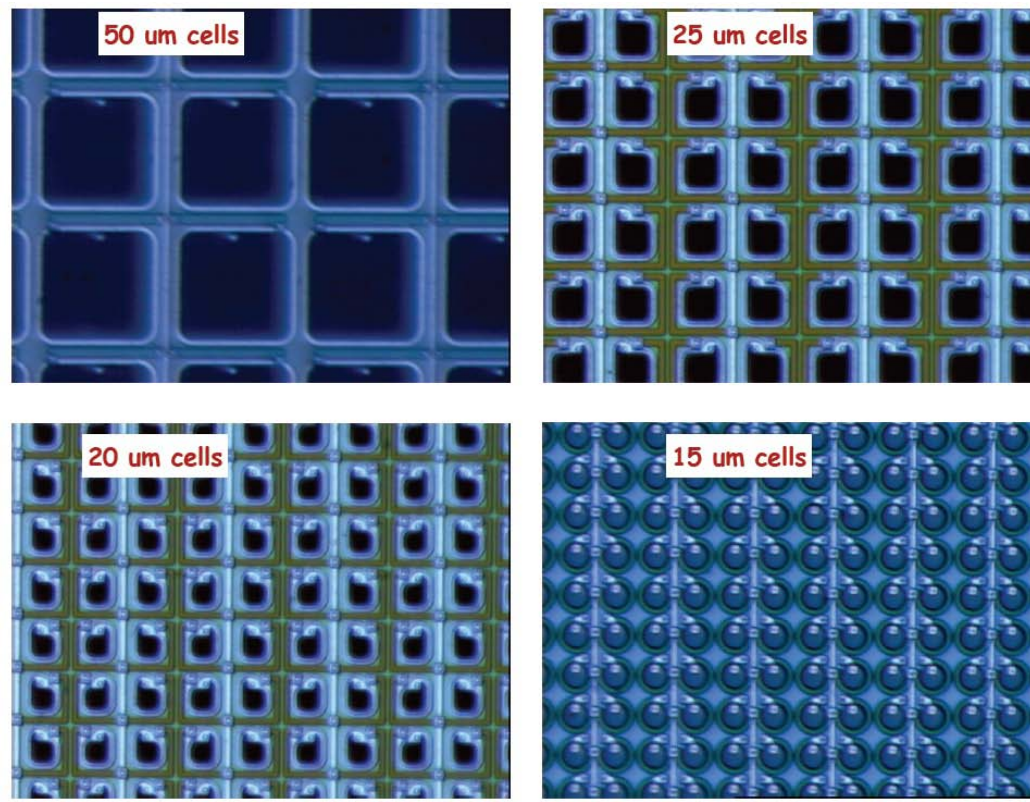
SiPM array before gluing to crystals end face

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?



Energy Resolution and Dynamic Range

ly=light yield of crystal, lce=light collection efficiency, pde= number of photoelectrons per photon, phe==number of photoelectrons,

- **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)

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

Conclusions

- **Physics case at e^+e^- colliders calls for high resolution ECAL**
  - Z Jet resolution not limited by EM resolution
  - Z→e^+e^- recoil resolution w/ Brem. recovery methods
  - Sampling fraction statistics for PFA shower separation
  - 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 the expertise from previous HEP detectors (CMS / PANDA ECALs)**
- **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 enables novel 4D algorithms for PFA**

Additional slides

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