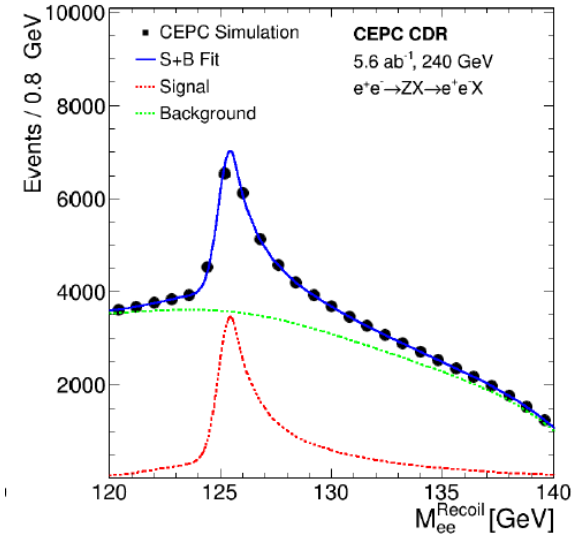
中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

Performance Studies of the New ECAL Concept with Crystal Bars

Yong Liu (Institute of High Energy Physics, CAS),
on behalf of the CEPC Calorimetry Working Group

International Workshop on High Energy Circular Electron-Positron Collider
Oct. 26-28, 2020

Motivations

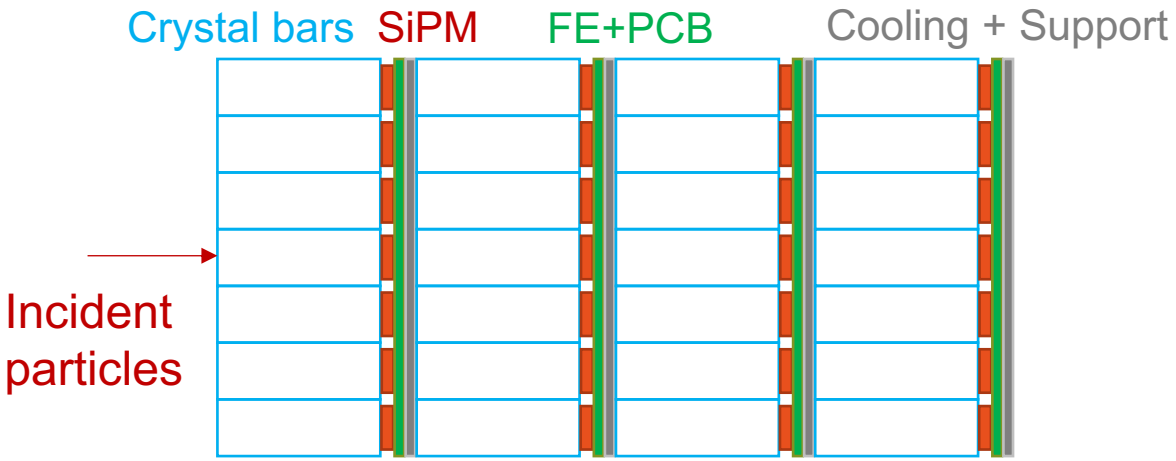


- Background: future lepton colliders (e.g. CEPC)
  - Precision measurements with Higgs and Z/W
- Why crystal calorimeter?
  - Homogeneous structure
    - Optimal intrinsic energy resolution: $\sim 3\%/\sqrt{E} \oplus \sim 1\%$
  - Energy recovery of electrons: to improve Higgs recoil mass
    - Corrections to the Bremsstrahlung of electrons
  - Capability to trigger single photons
    - Flavour physics at Z-pole, potentials in search of new physics, …
- Fine segmentation
  - PFA capability for precision measurements of jets

Studies on the High-Granularity Crystal ECAL, Y. Liu, Oct. 27, 2020, Calorimetry Session

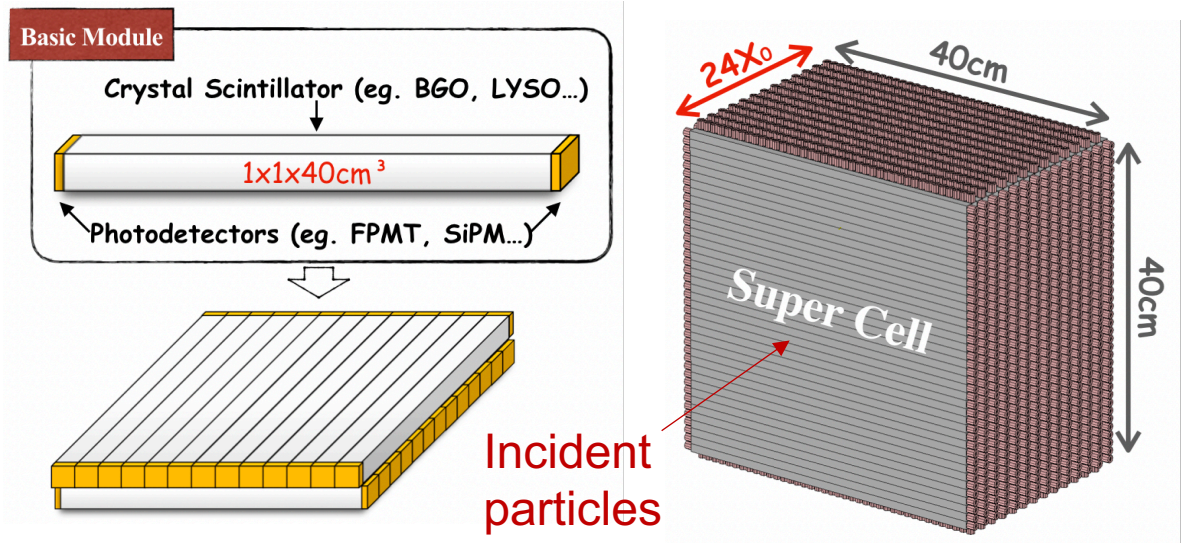
High-granularity crystal ECAL: 2 major designs

Design 1



- Longitudinal segmentation
- Fine transverse segmentation
  - 1×1cm or 2×2cm cells
- Single-ended readout with SiPM
- Potentials with PFA

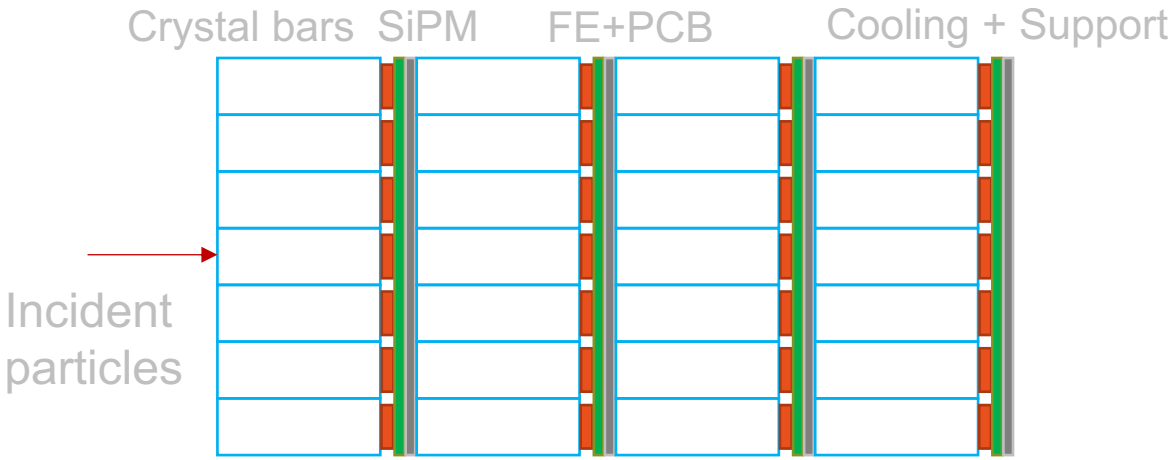
Design 2



- Long bars: 1×40cm, double-sided readout
  - Super cell: 40×40cm cube
- Crossed arrangement in adjacent layers
- Significant reduction of #channels
- Timing at two sides: positioning along bar

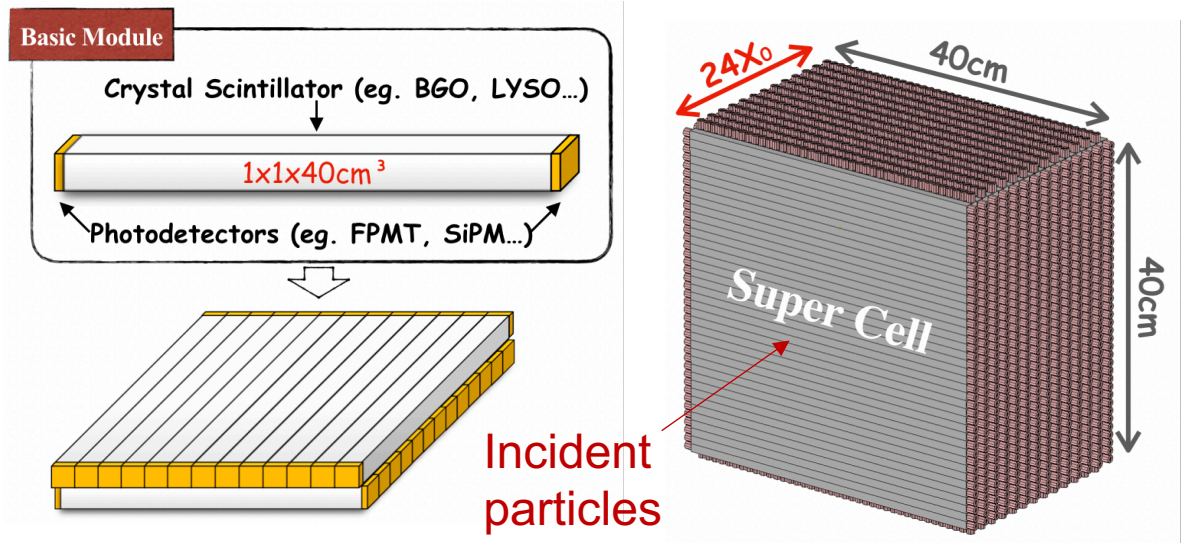
High-granularity crystal ECAL: 2 major designs

Design 1: short bars



- Longitudinal segmentation
- Fine transverse segmentation
  - 1×1cm or 2×2cm cells
- Single-ended readout with SiPM
- Potentials with PFA

Design 2: long bars



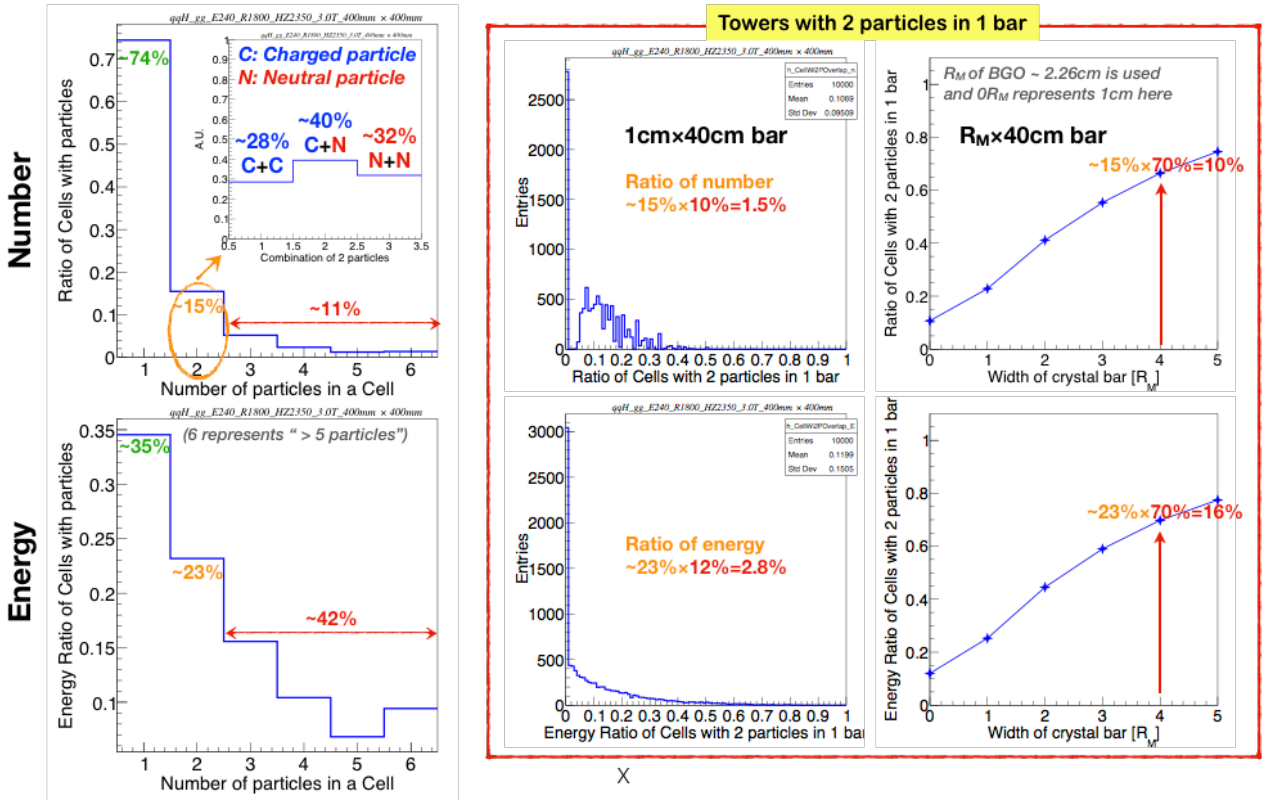
- **Advantages**
  - Longitudinal granularity: 24 layers, 1X0/layer
  - Save #channels, ~15 times less
  - De facto 3D calorimeter: timing for hit positions for transverse granularity
- **Key issues**
  - Ambiguity: multiple incident particles within one super cell
  - Separation of nearby showers
  - Impact on the Jet Energy Resolution (JER)

Reminder: physics requirements

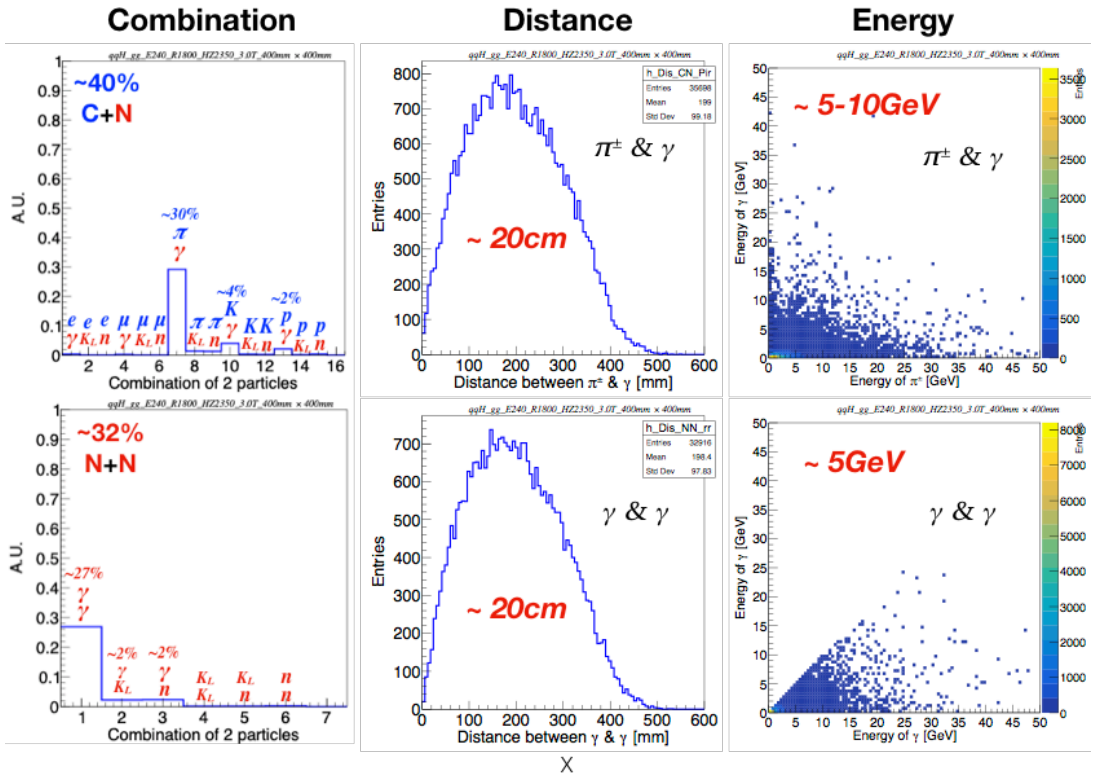
Yuexin Wang (IHEP)

Z→qq, H→gg at 240GeV

Multiplicity in a 40cm×40cm tower



Tower with 2 particles: distance & energy distribution

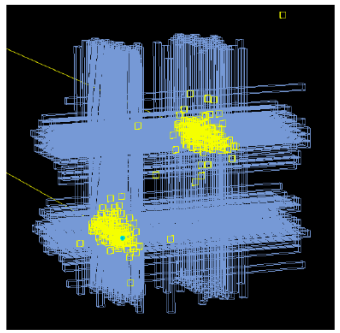


- Estimate the multiplicity level of jets: fast simulation
  - First studies with 2 incident particles (from a jet): hitting the hottest tower

Reconstruction with 2 incident photons

Yuexin Wang (IHEP)

Event patterns in event display

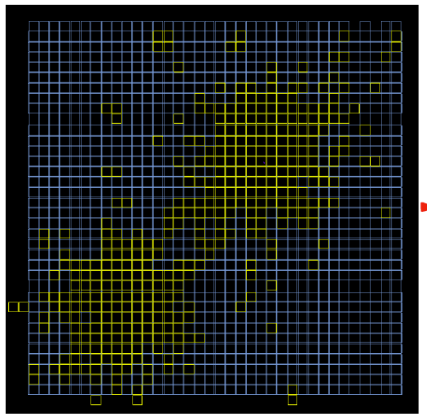


2 parallel 5GeV γ

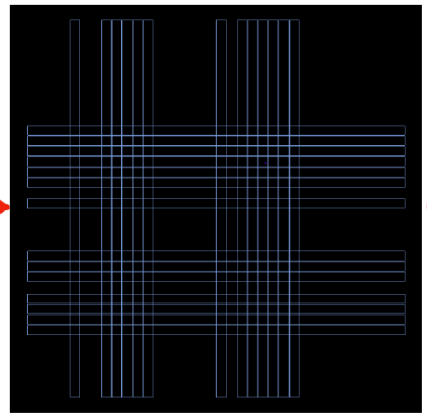
distance ~20cm along the diagonal

→ can be separated.

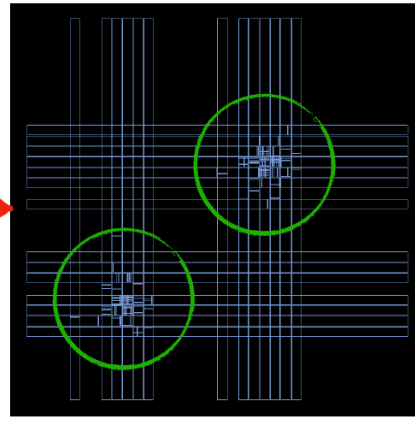
Simulated Hits (yellow cells)



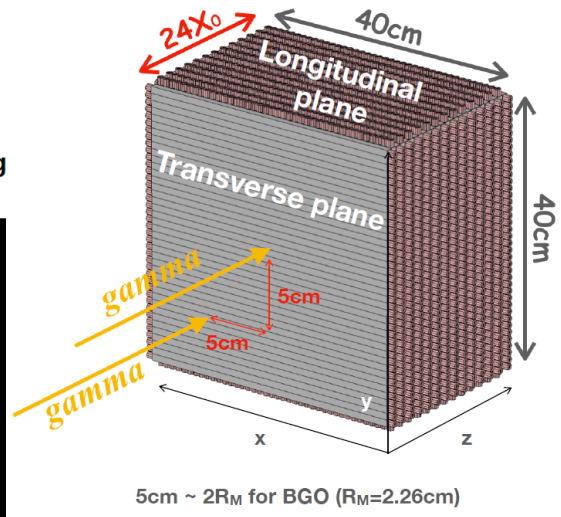
Digitized Long Bar Hits (E_{dep} > 1 MIP)



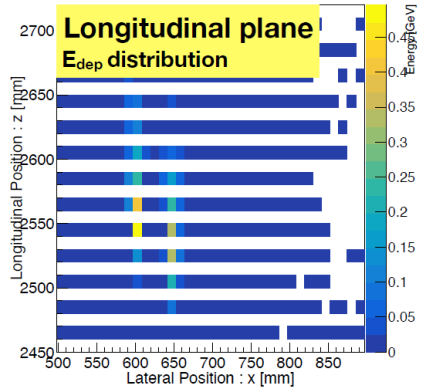
Reconstructed positions using time difference of 2 ends

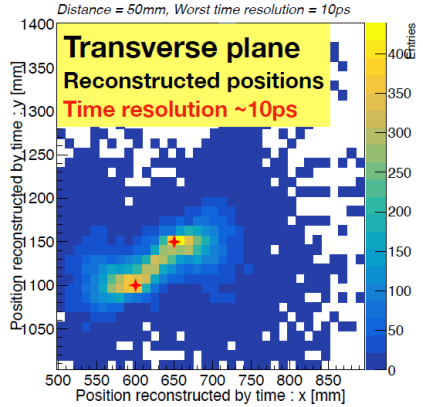


Shower profiles in 2 planes



5cm ~ $2R_M$ for BGO (R_M=2.26cm)





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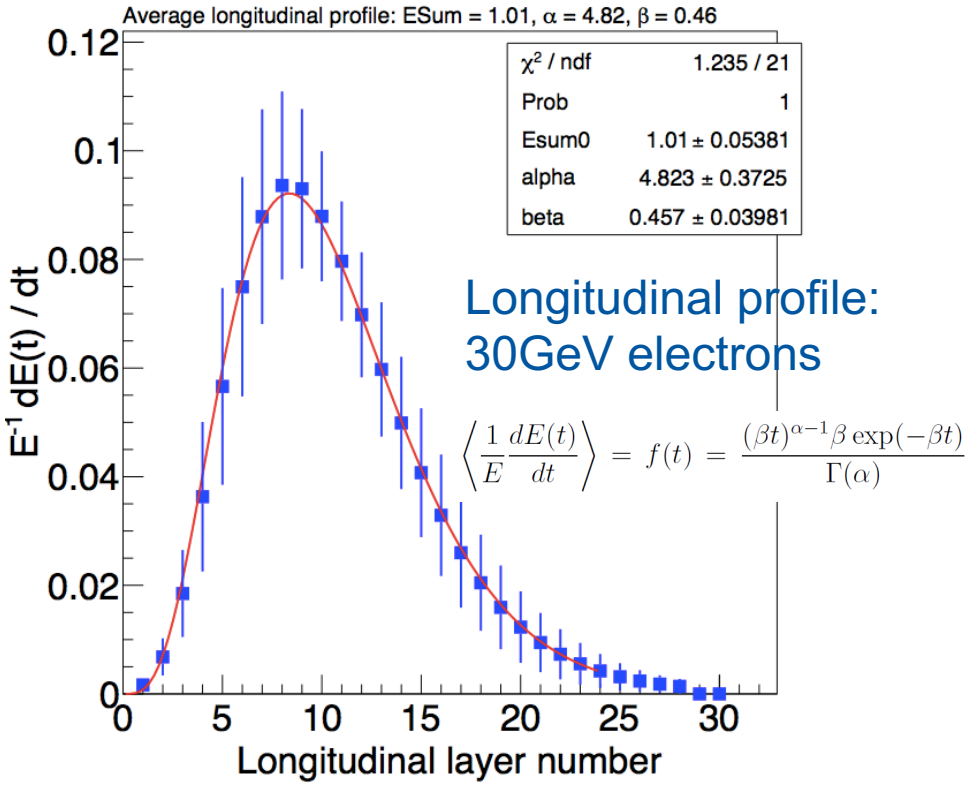
Timing information can help resolve ambiguity

Reconstruction with 2 incident particles

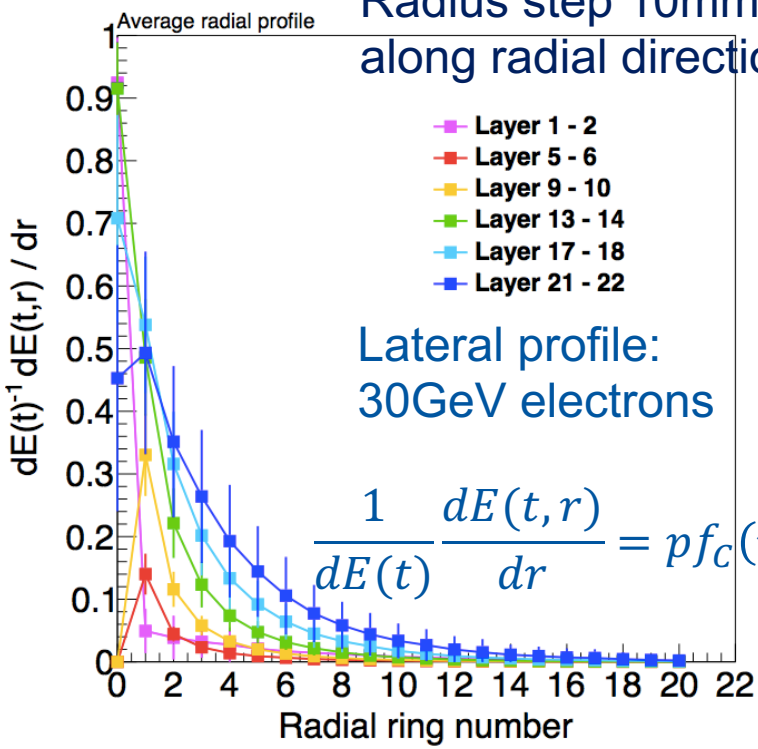
Yuexin Wang, YL (IHEP)

- How can we separate two close-by electrons/photons?
- EM shower profiles in 3D: ongoing studies
  - Input to the weights for energy splitting



Longitudinal profile:
30GeV electrons

$$\left\langle \frac{1}{E}\frac{dE(t)}{dt} \right\rangle = f(t) = \frac{(\beta t)^{\alpha-1}\beta \exp(-\beta t)}{\Gamma(\alpha)}$$



Radius step 10mm
along radial direction

Lateral profile:
30GeV electrons

$$\frac{1}{dE(t)}\frac{dE(t,r)}{dr} = pf_C(r) + (1-p)f_T(r)$$

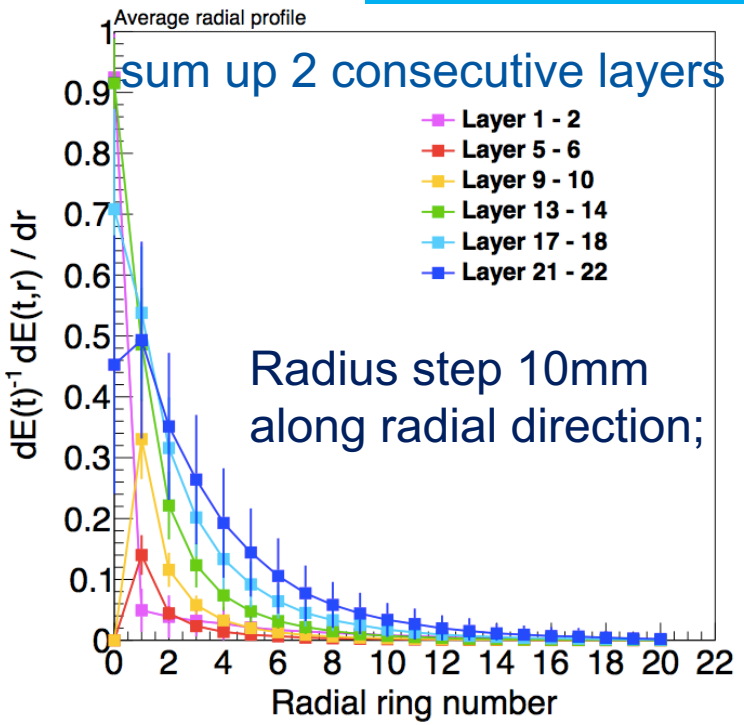
Reconstruction with 2 incident particles

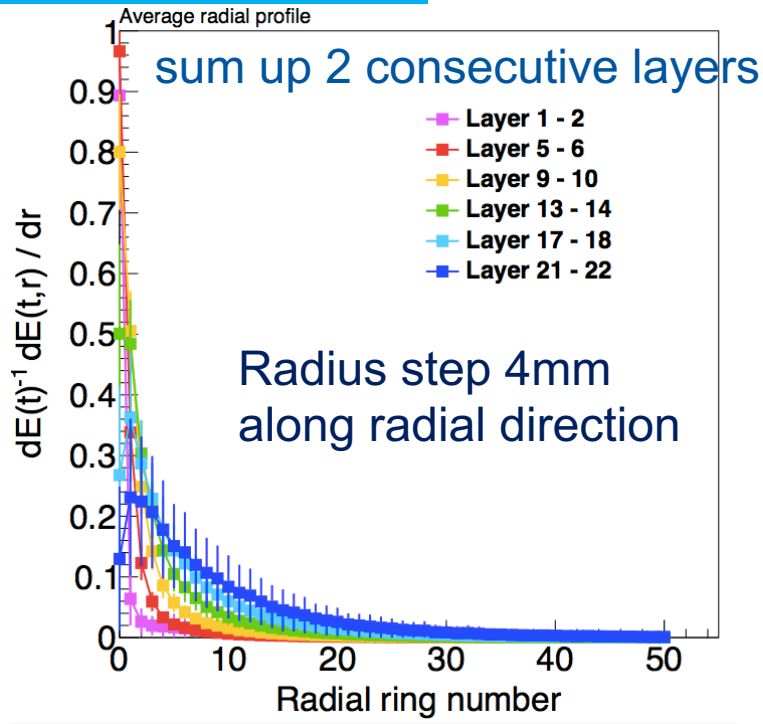
Yuexin Wang, YL (IHEP)

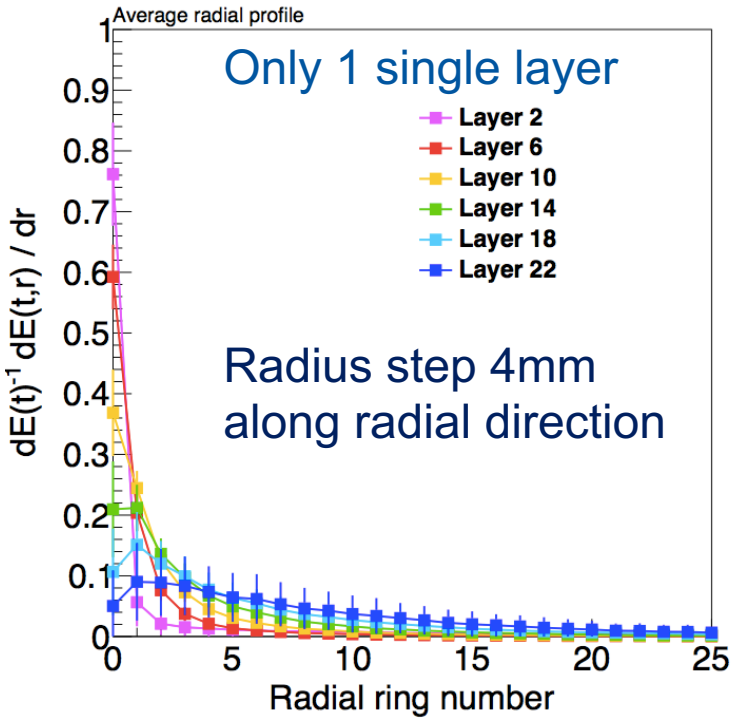
- How can we separate two close-by photons?
- EM shower profiles in 3D: ongoing studies
  - Input to the weights for energy splitting

$$\frac{1}{dE(t)}\frac{dE(t,r)}{dr} = pf_C(r) + (1-p)f_T(r)$$

Lateral profile: 30GeV electrons

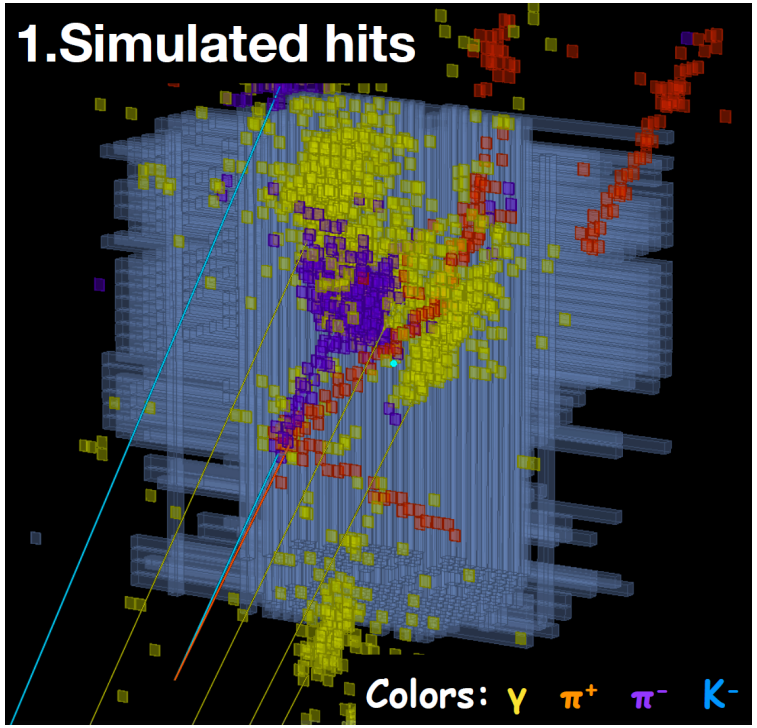


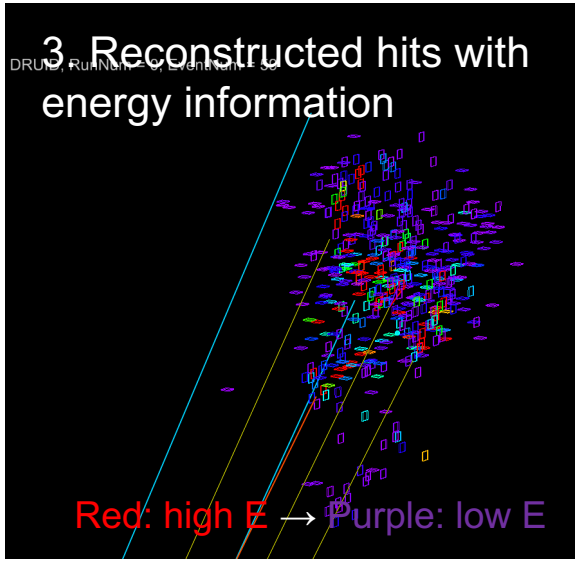


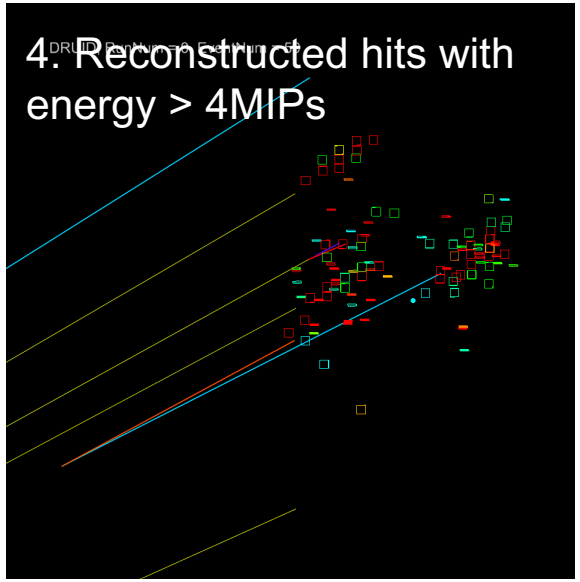


Pattern studies using Event Display

- Complex patterns
- Need further studies on positioning and energy splitting





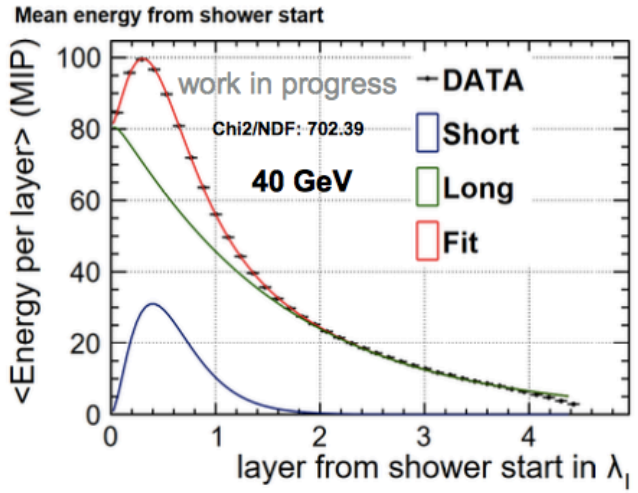


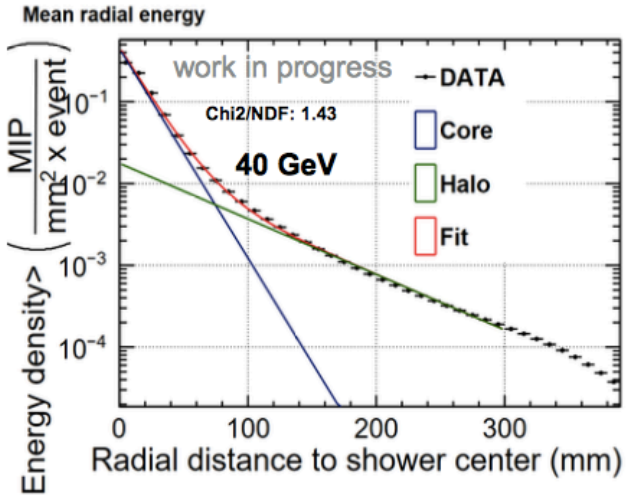
- Next steps: hadronic shower profiles in the crystal ECAL

Hadronic shower profiles: CALICE AHCAL studies

Fits to longitudinal and Radial profiles

- → 38 points are available for the longitudinal fit up to a depth of ~4.4λ_I. Each bin in longitudinal direction corresponds to ~0.11λ_I
- → The "long" component of the longitudinal profile which dominates in the shower tail, is accompanied around shower maximum by the "short" component
- → For the radial fit, the fine transverse granularity provides 39 points in the range from 0 to 390 mm. Each bin width corresponds to one third of the transverse size of the 30×30 mm^2 cell
- → The data set includes statistical uncertainties only





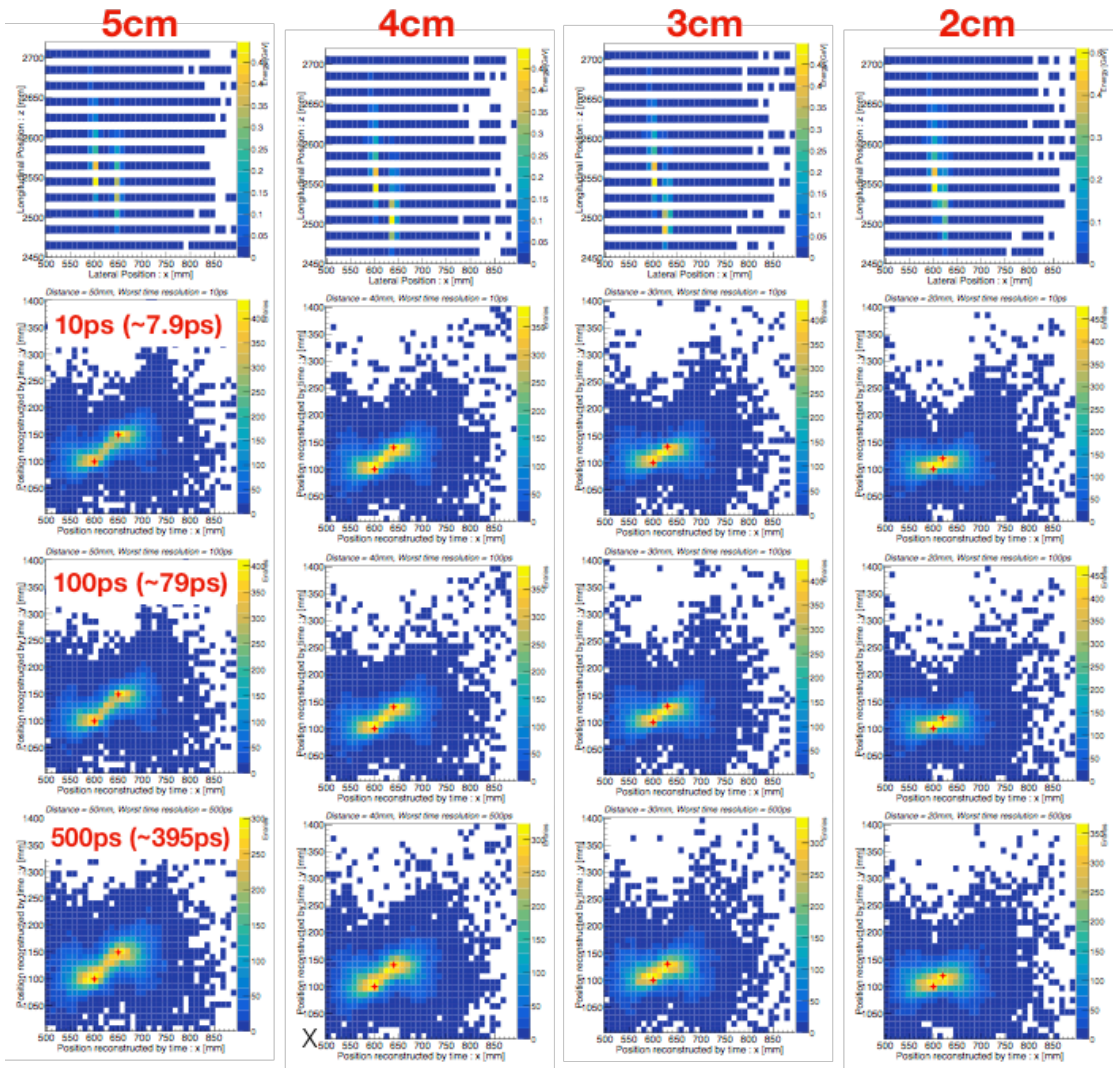
Test-beam data for AHCAL and hadronic shower profile parameterizations

O. Pinto, Classical study of Shower Shapes IN AHCAL, CALICE Collab. Meeting, Sep. 28-30, 2020

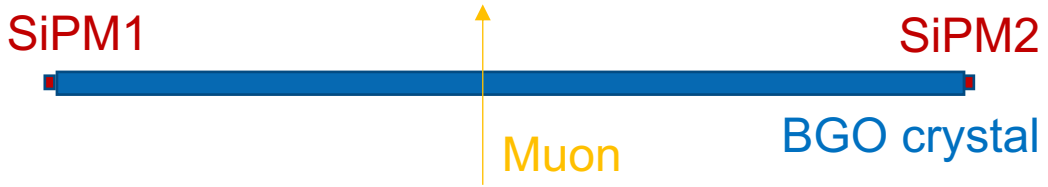
Separation of two photons: timing resolution

Yuexin Wang, YL (IHEP)

- Vary the timing resolution:
  - Maintain the dependence on hit position
  - Change the slope to vary time resolution of single end from 10ps to 500ps.
- Critical separation distance (with the help of energy info.):
  - ~3cm along the bar (~4cm along the diagonal), mainly limited by the Moliere radius.
- Separation power: seems not so sensitive to time resolution.
  - Only preliminary results of simple digitization, need to check and further understanding

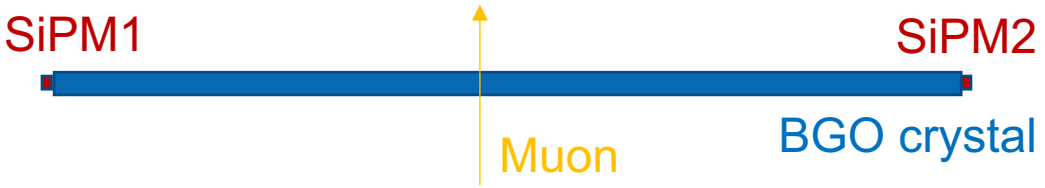


Single crystal bar simulation studies: timing performance



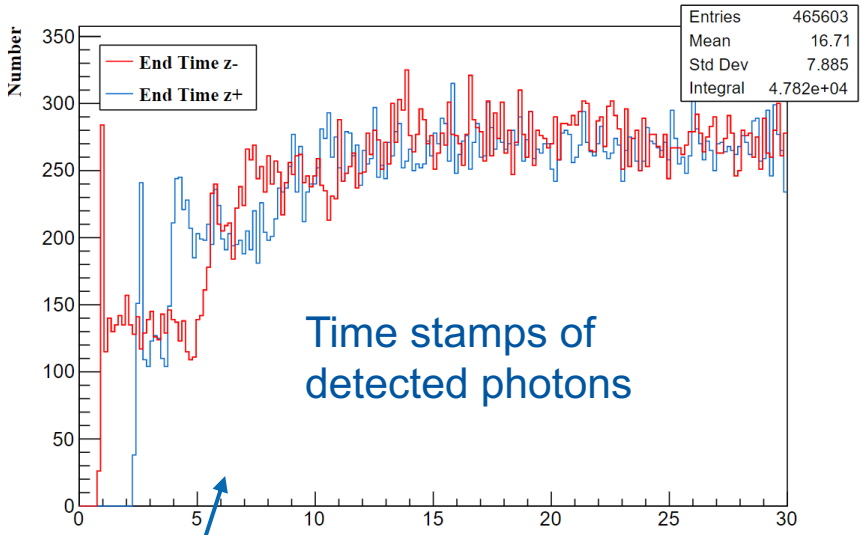
- Geant4 full simulation
  - Geometry
    - A 40cm long crystal bar, 1x1 cm² transverse size
    - Read out by two SiPMs at both ends
  - Properties
    - BGO: light yield, decay times (fast and slow), refractive index, transmission (absorption length)
    - Wrapping: ESR foil (~99% reflectivity) with air gaps (total reflections)
    - SiPM: 6x6 or 10x10 mm² sensitive area, Photon Detection Efficiency (PDE), realistic SMD package
  - Primary particle: 1GeV muon (for MIP calibration)
  - Optical photon processes:
    - Scintillation, Cherenkov, absorption, refraction/reflection at boundaries

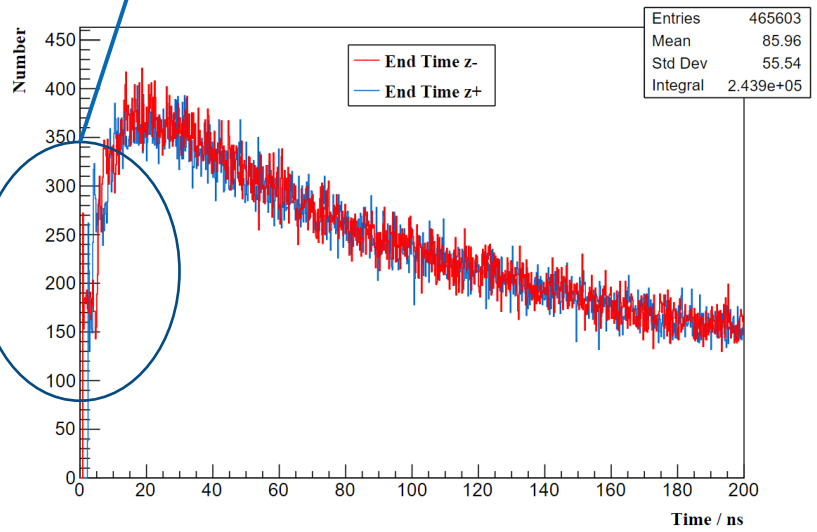
Single crystal bar simulation studies: timing performance

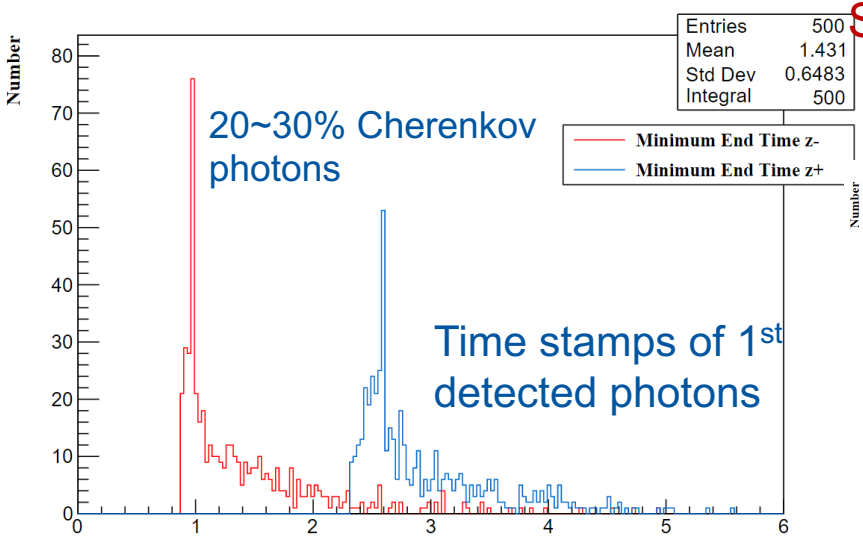


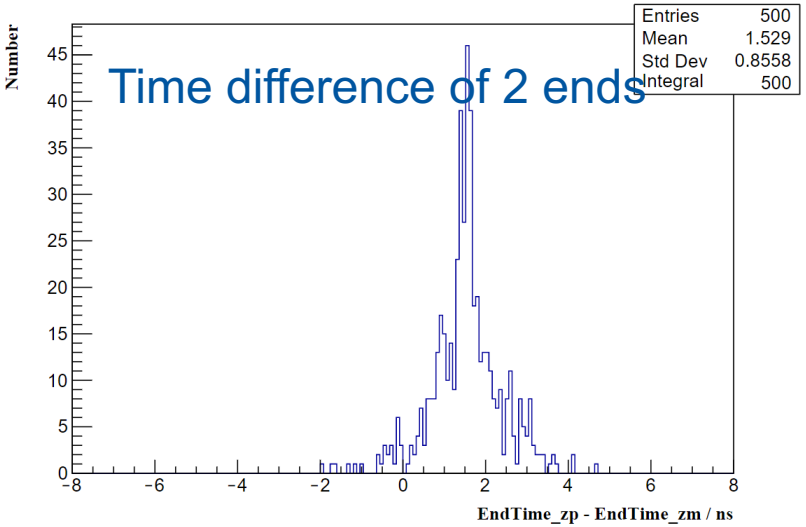
- Information extracted from G4
  - Energy deposition: mean ~10 MeV/MIP, determined by crystal thickness
  - #scintillation photons, #detected photons at either SiPM
  - Time stamp of each detected photon
    - T0: shooting of the primary particle (muon)
    - Included: scintillation time (~hundreds ns), propagation time (a few ns) within the crystal bar
    - **Excluded: timing uncertainties from SiPMs and electronics**
- Digitization
  - Timing: Choose the time stamp of the 1st photon detected at each SiPM
  - #detected photons : proportional to energy deposition
- Crystal measurements in plan to validate the full simulation

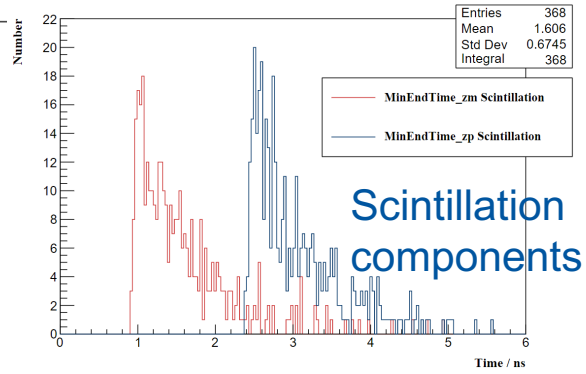
Single crystal bar simulation studies: timing performance

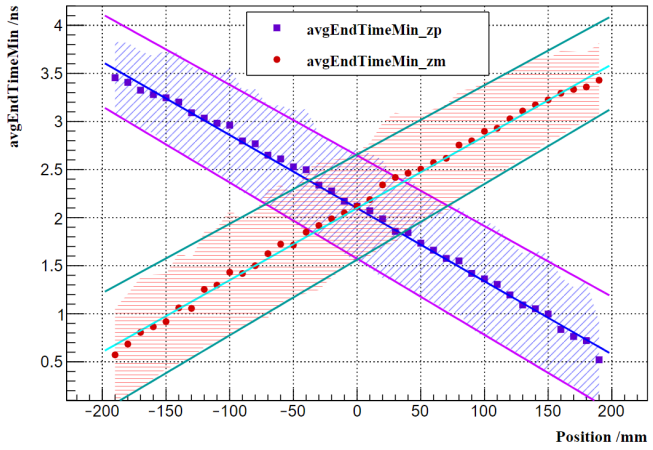








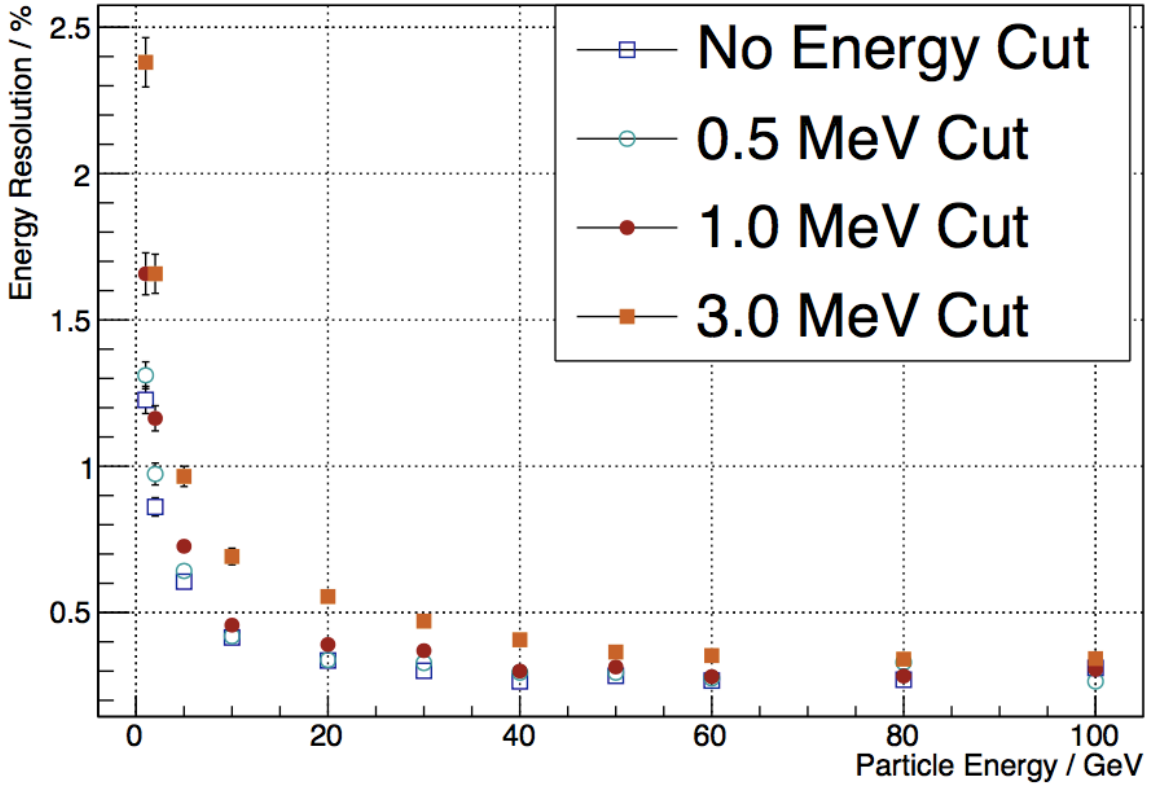




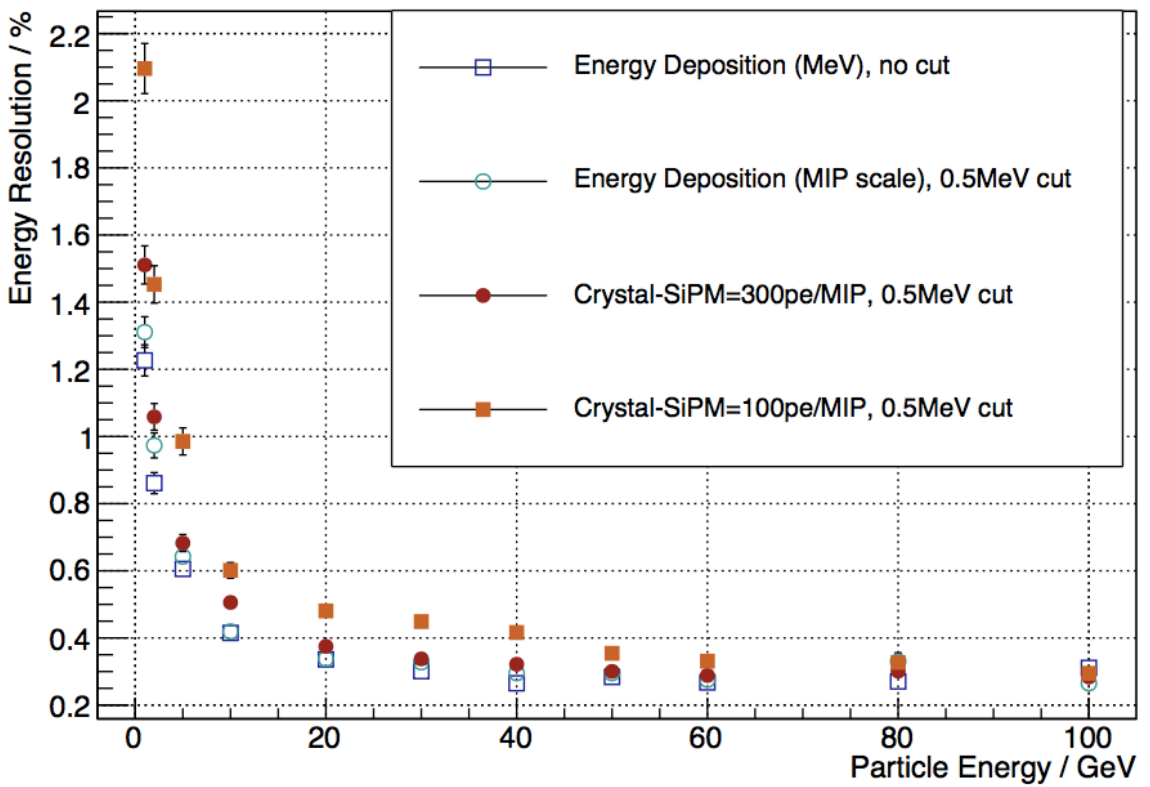
Impact from upstream materials: ongoing studies

- Ideal scenario as reference: no upstream materials
  - 1-MIP response ~10MeV per cm in BGO/PWO crystal

Impact from threshold of each channel

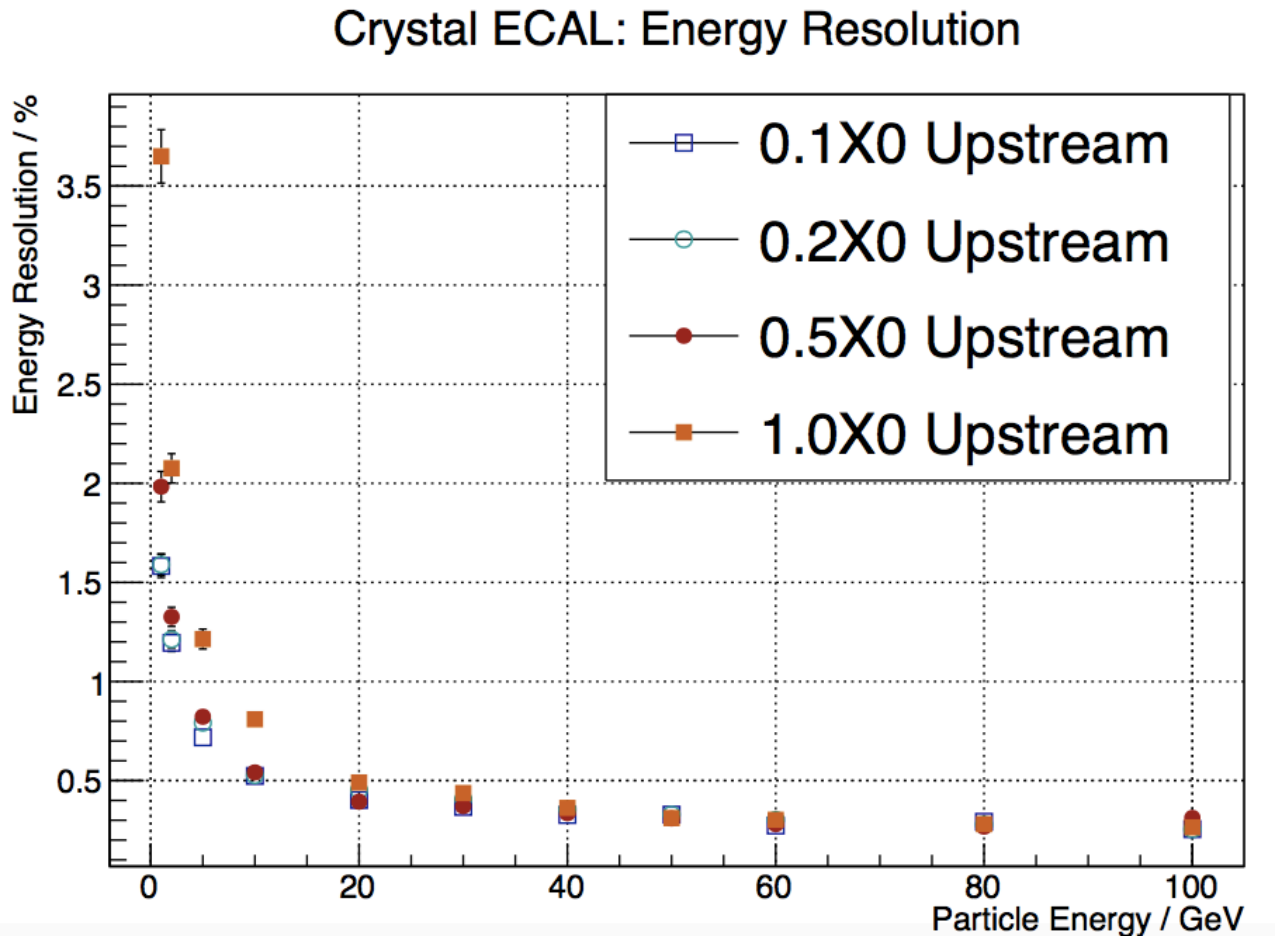


Impact from digitization (photon statistics + FE resolution)



Impact from upstream materials: ongoing studies

- Varying thickness of upstream material: an aluminum slab



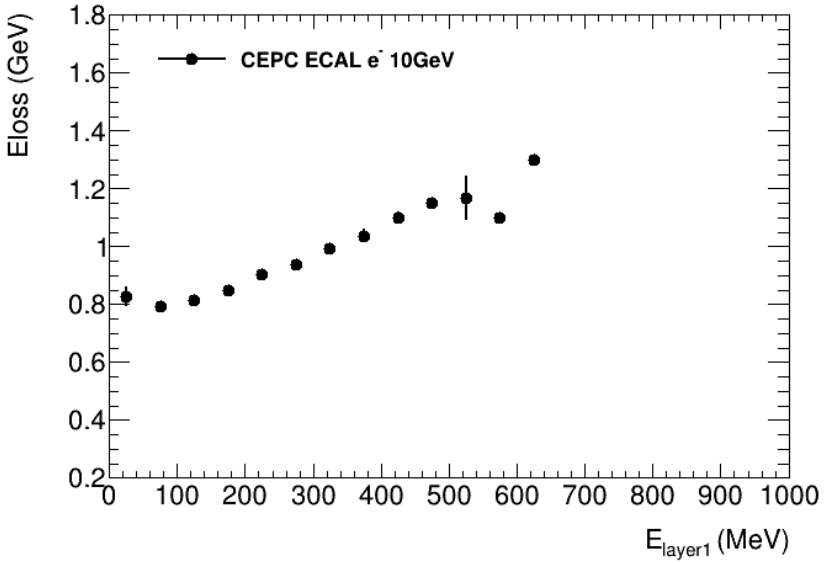
For each channel:
1MeV energy threshold
300 p.e./MIP

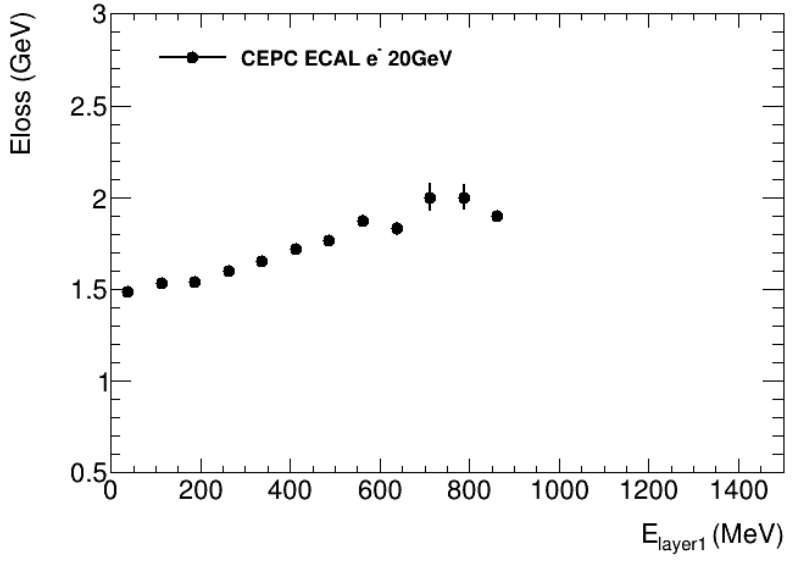
Impact from upstream materials: ongoing studies

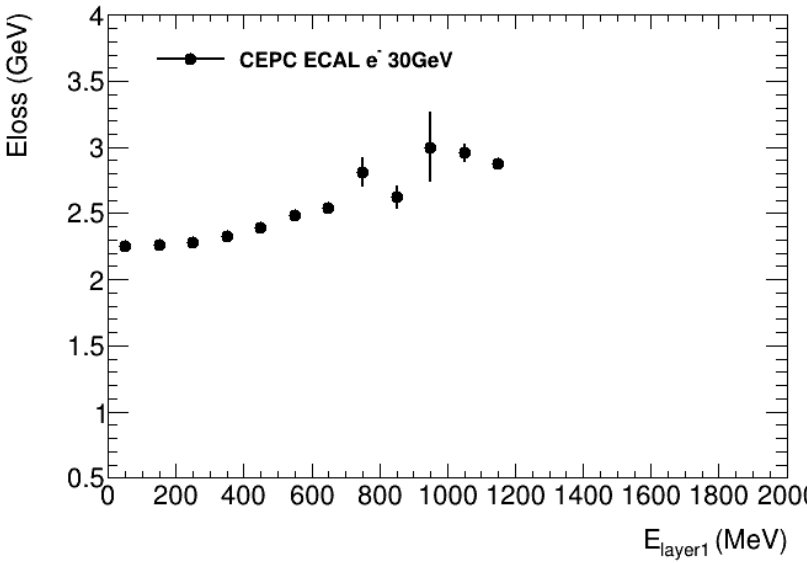
Stathes Paganis (NTU)

- Correlation of energy loss in upstream and first layer (as pre-shower)
  - Profiles dependence on particle energy
  - Hints for energy corrections

Fixed thickness of upstream (an aluminum slab): 1.5X0







Summary: ECAL performance with crystal bars

- Ongoing studies
  - Separation of two incident particles, EM shower profile studies
  - Single crystal bar simulation studies: timing performance
  - Focus on EM resolution: generic studies
    - Digitization and its effects
    - Upstream materials: deterioration and correction
- Plans
  - Separation power and energy splitting of near-by particles
  - Measurements of crystals: esp. timing performance
  - Impact from ECAL options on the hadronic energy resolution
    - Samples ready and calibration needed first

Backup slides