Status of the CEPC Crystal ECAL

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Outline

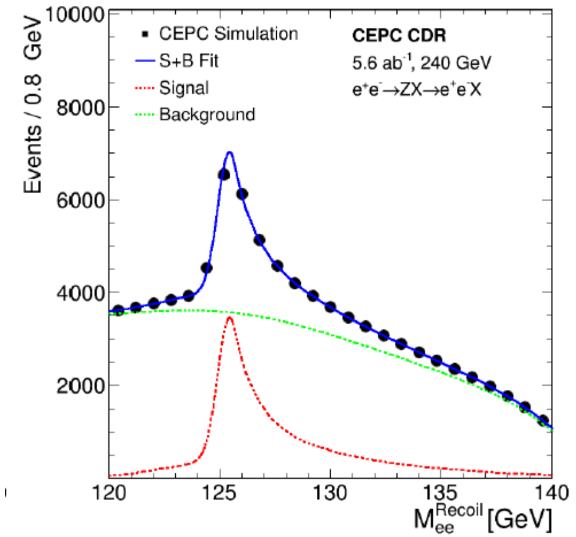
- Motivations

- 2 major designs in pursuit: recent progress
  - Design 1: short bars, single-ended readout
    - Impacts of threshold to linearity and resolution

  - Design 2: long bars, double-ended readout
    - Physics requirements
    - Digitisation, event display, and reconstruction

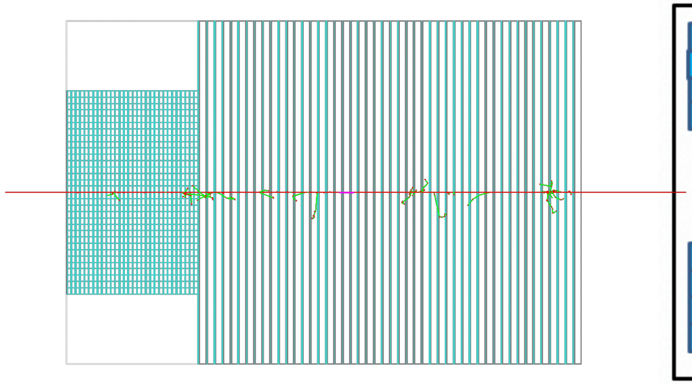
Motivations

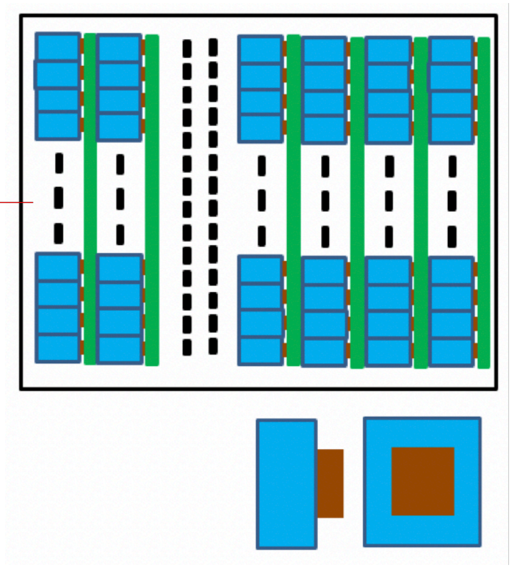
- Future lepton colliders: e.g. CEPC
  - Precision measurements with Higgs and Z/W
- Why highly granular crystal calorimeter?
  - Homogeneous structure
    - Optimal intrinsic energy resolution: ~3%/√E ⊕~1%
  - Energy recovery of electrons: to improve Higgs recoil mass
    - Corrections to the Bremsstrahlung of electrons
  - Capability to trigger with a single photon
    - Flavour physics at Z-pole
    - Potentials in search of new physics
- Fine segmentation
  - PFA capability for precision measurements of jets



Crystal calorimeter: 2 designs in pursuit

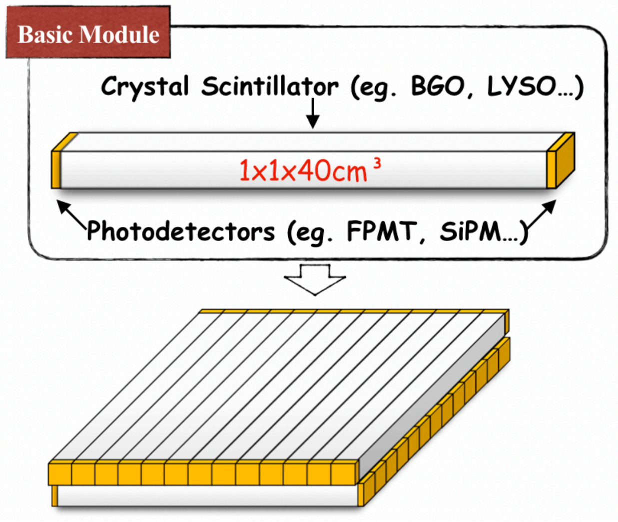
Design 1

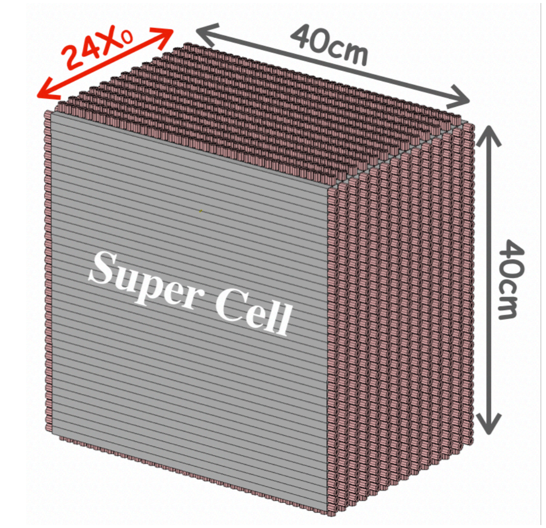




- Fine transverse segmentation: 1×1cm or 2×2cm cells
- Single-ended readout with SiPM
- Potentials with PFA

Design 2

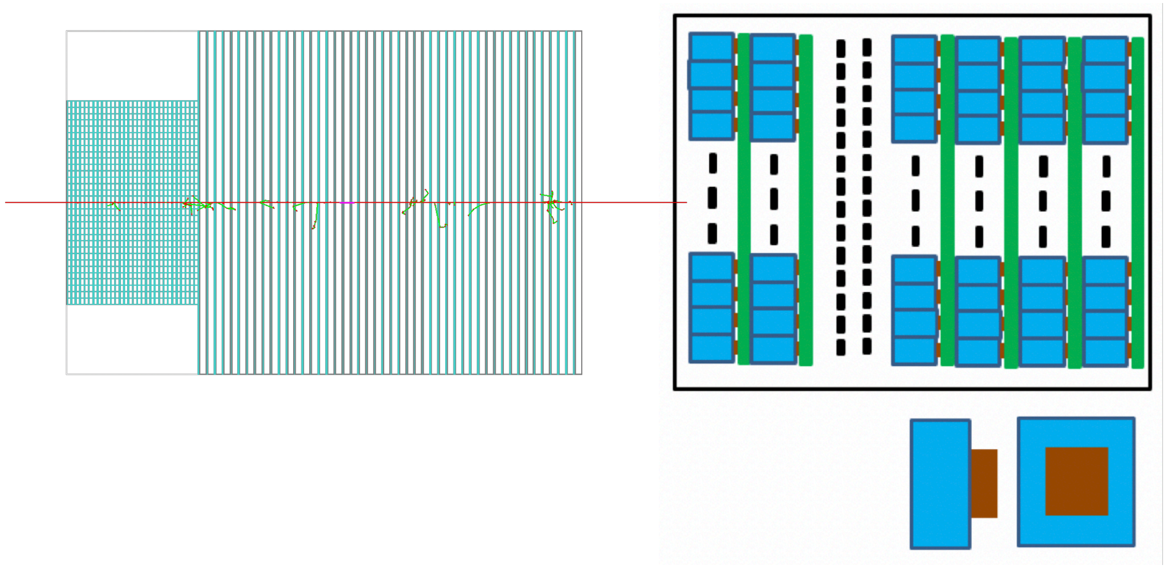




- Long bars: 1×40cm, double-sided readout
  - Super cell: 40×40cm cube
- Crossed arrangement in adjacent layers
- Significant reduction of #channels
- Timing at two sides: positioning along bar

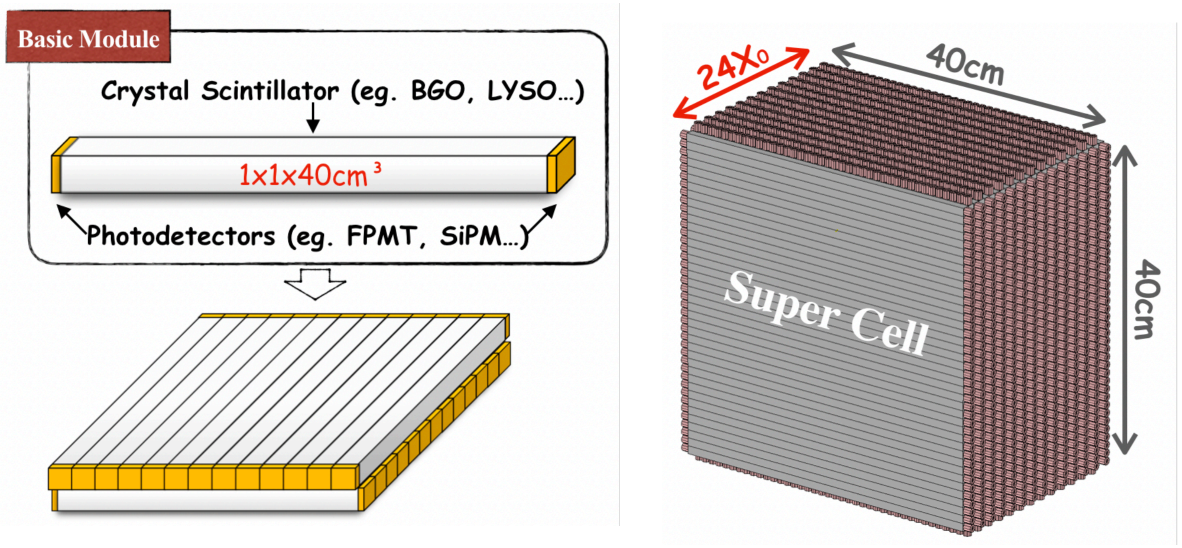
2 designs in pursuit: ongoing studies

Design 1



- Design optimisations
  - Transverse: separation power
  - Longitudinal: leakage correction
- Neutral pion reconstruction (in plan)

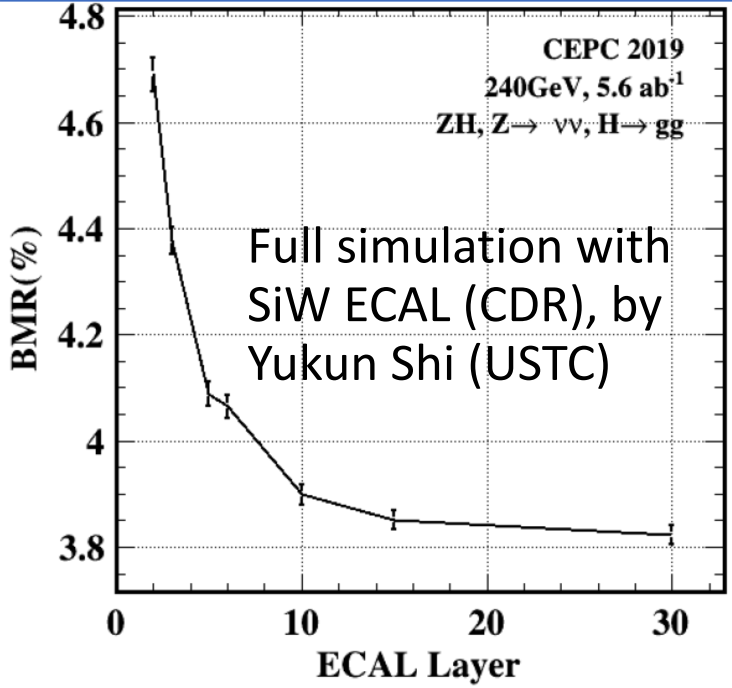
Design 2



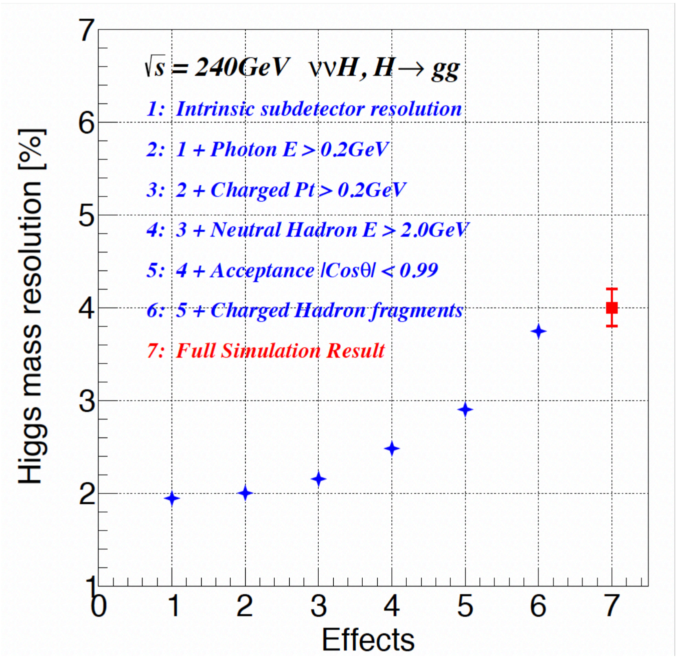
- Multiplicity of incident particles (jets)
  - Based on physics benchmarks
- Digitisation in each bar
  - Time stamps, #photons detected
- Event display and reconstruction

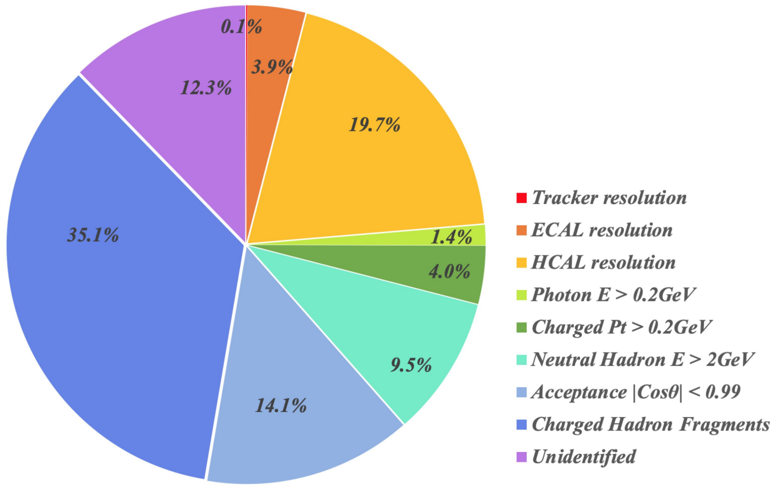
Longitudinal segmentation optimisation

Boson Mass Resolution vs #Layer in ECAL



PFA Fast Simulation (Yuexin Wang)

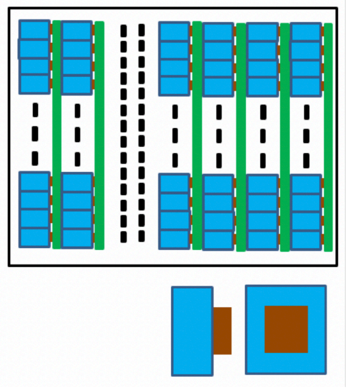


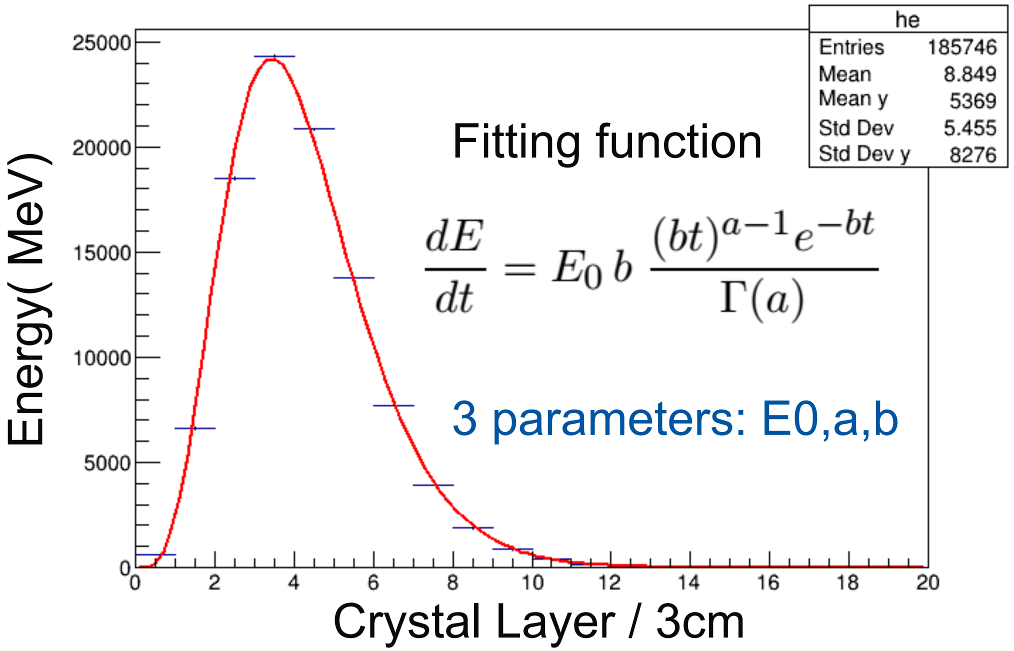


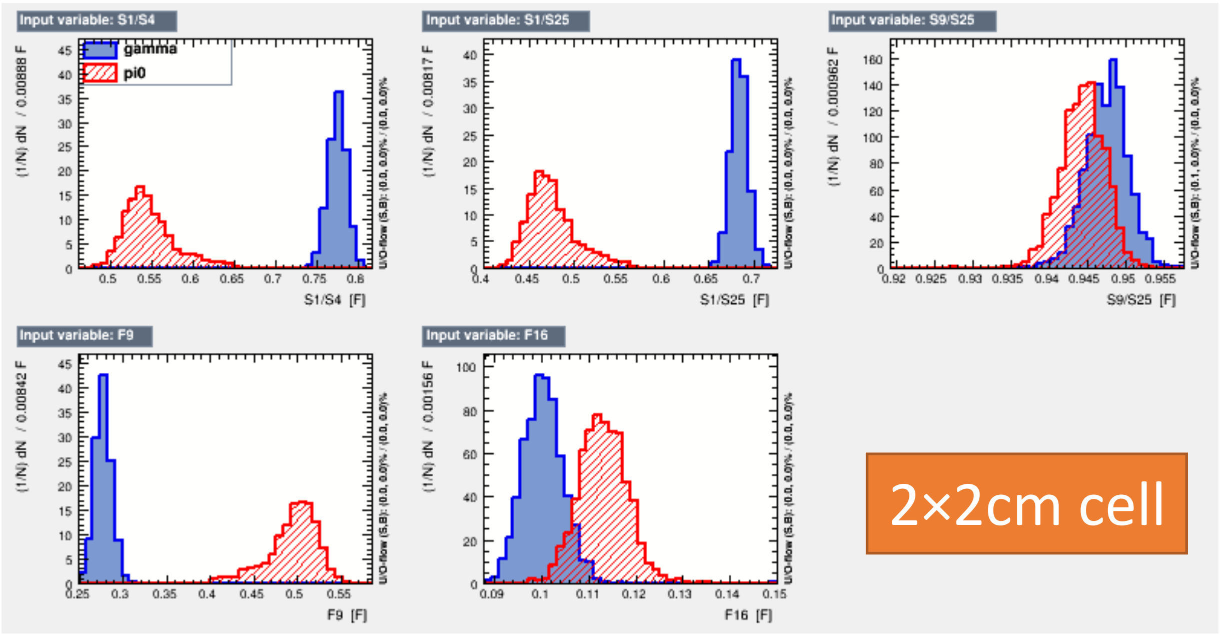
- Full simulation with SiW-ECAL via the benchmark Higgs to 2 gluons
  - 10 longitudinal layers or more in ECAL can help achieve better than 4% of BMR
  - Expect small impact from ECAL intrinsic energy resolution (PFA fast simulation)
- Guidance for the longitudinal segmentation

Design 1: optimisation studies

- Crystal longitudinal depth
  - Use shower profiles in segmented layers to correct for tails (energy leakage)
  - Aim for shorter crystal depth (cost), balance with performance (correction precision)
- Crystal transverse segmentation
  - Transverse size: separation of photons and neutral pions

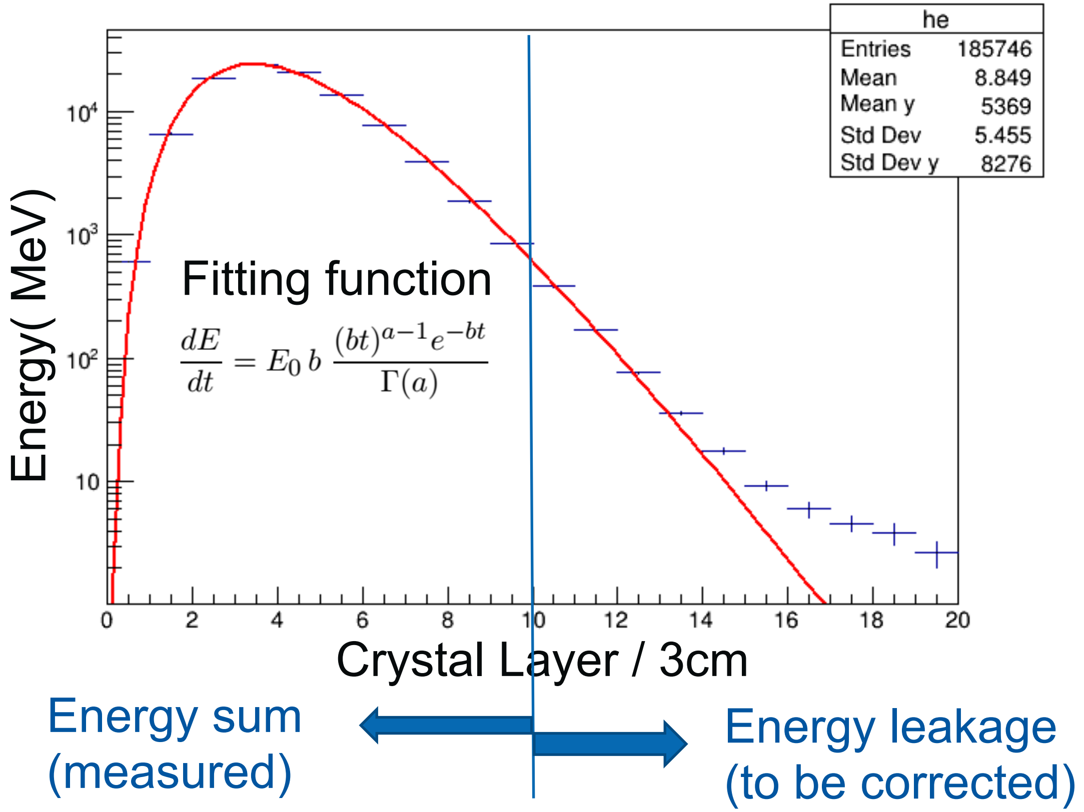


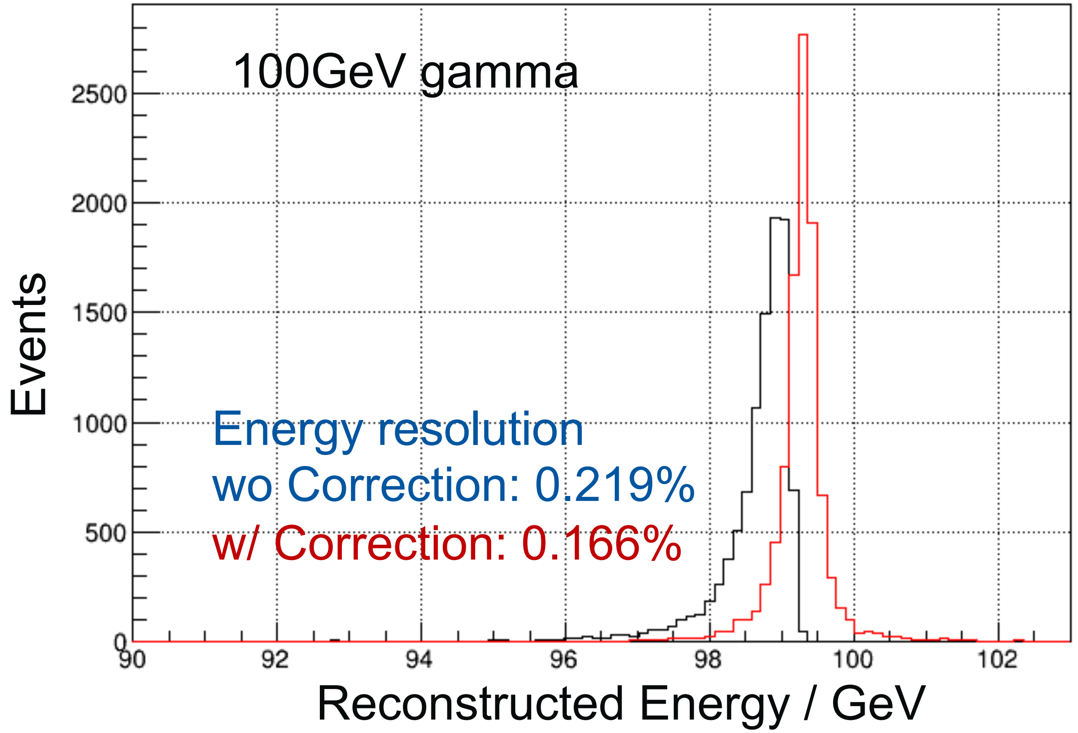




Crystal longitudinal depth: optimisation (reminder)

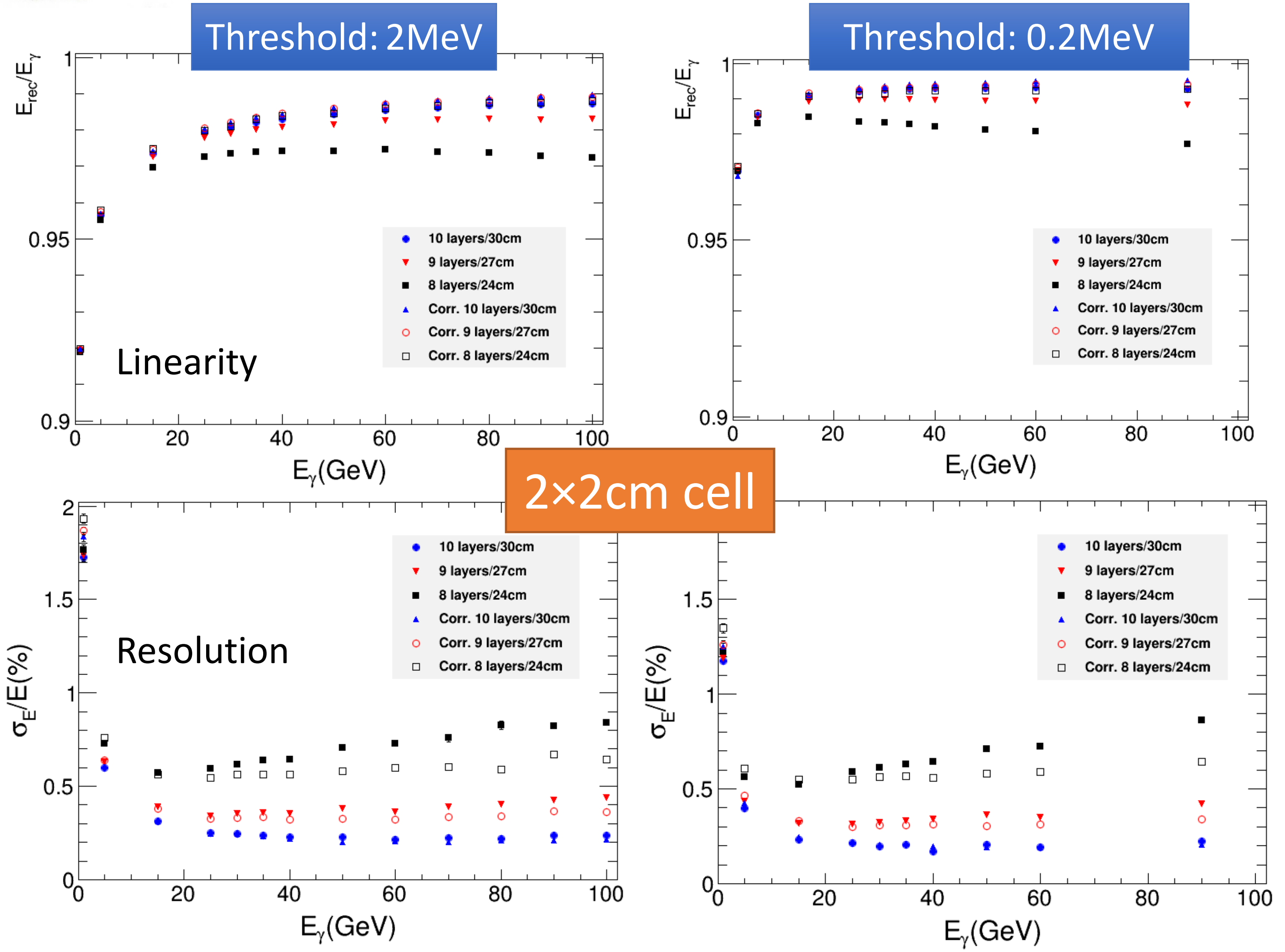
- Energy leakage correction using longitudinal shower profile
- Based on the fine segmentation in crystal length





30cm long BGO (~27X0), 10 layers, 3cm per layer

First look at the impact of threshold

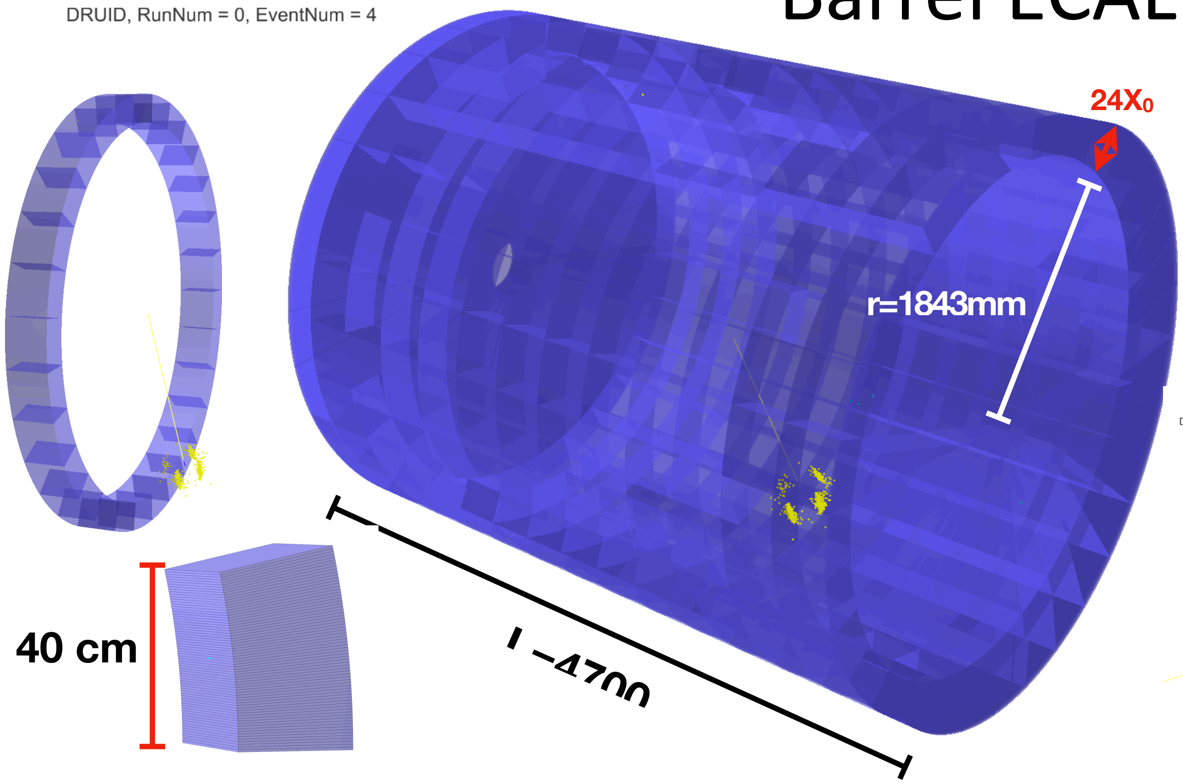


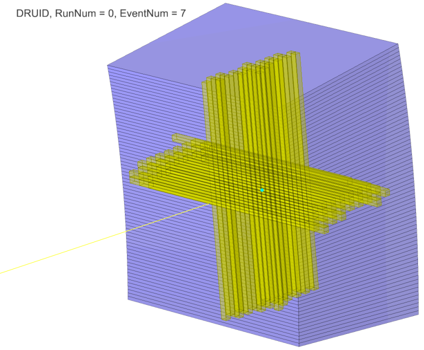
Energy fluctuations only; digitisation in the next step

- Threshold significantly impacts response linearity and energy resolution, esp. at lower energy
- Correction using shower profiles can partially recover the resolution degrade due to leakage fluctuations at higher energy
- Plan to quantify the impacts of threshold → provide guidance to the noise level requirement of crystal-SiPM and electronics

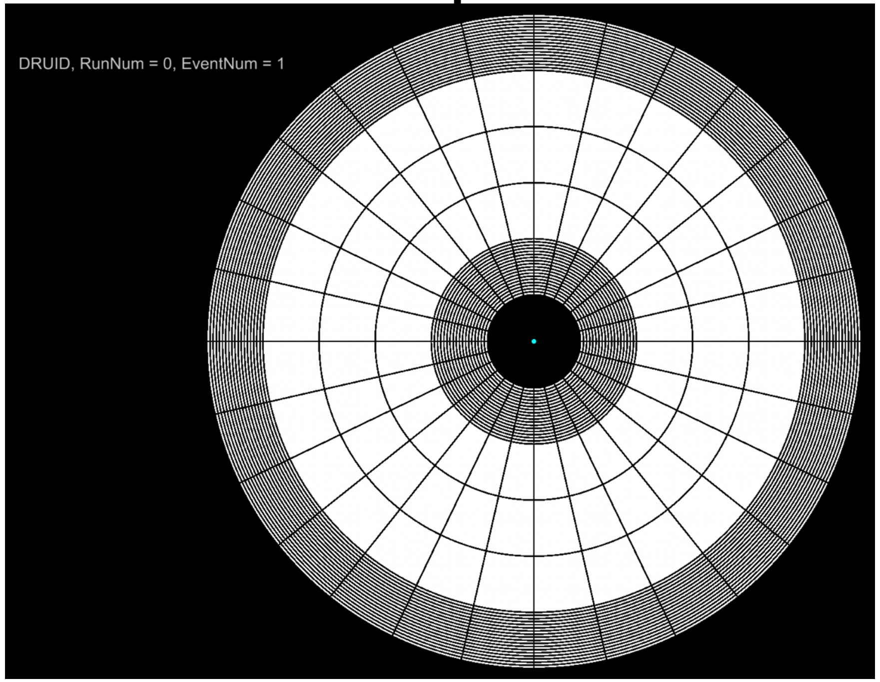
Design 2: implementation in CEPC detector geometry

Barrel ECAL





Endcap ECAL



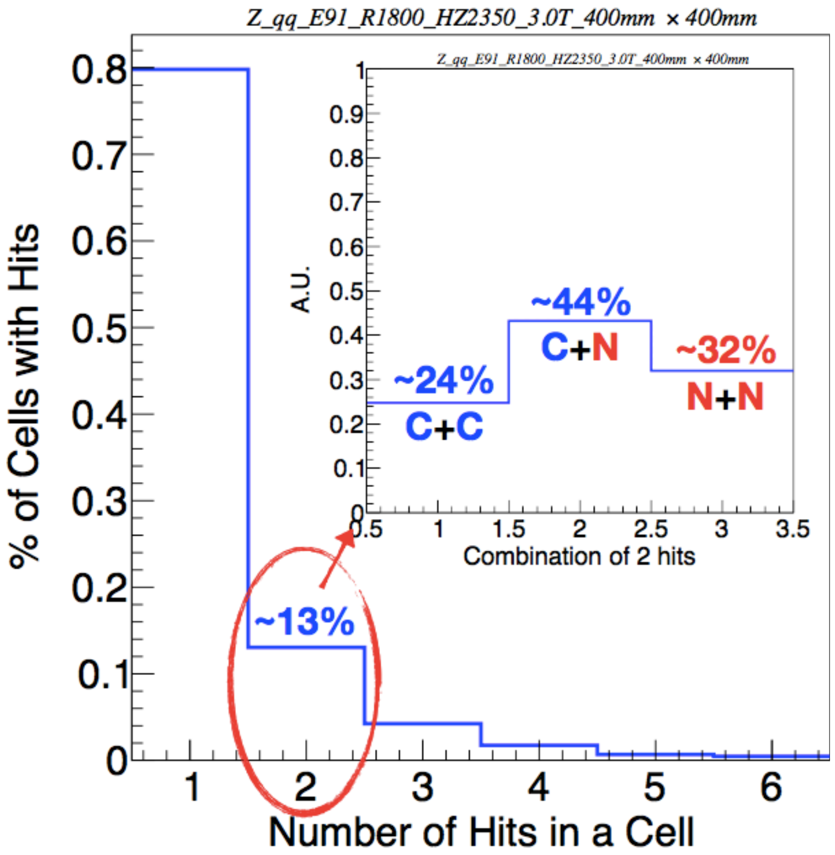
- Super cells with long bars: implemented in the full CEPC detector simulation
- Extract key information from physics benchmarks (details in the following pages)
- Digitisation and reconstruction with patterns in event display

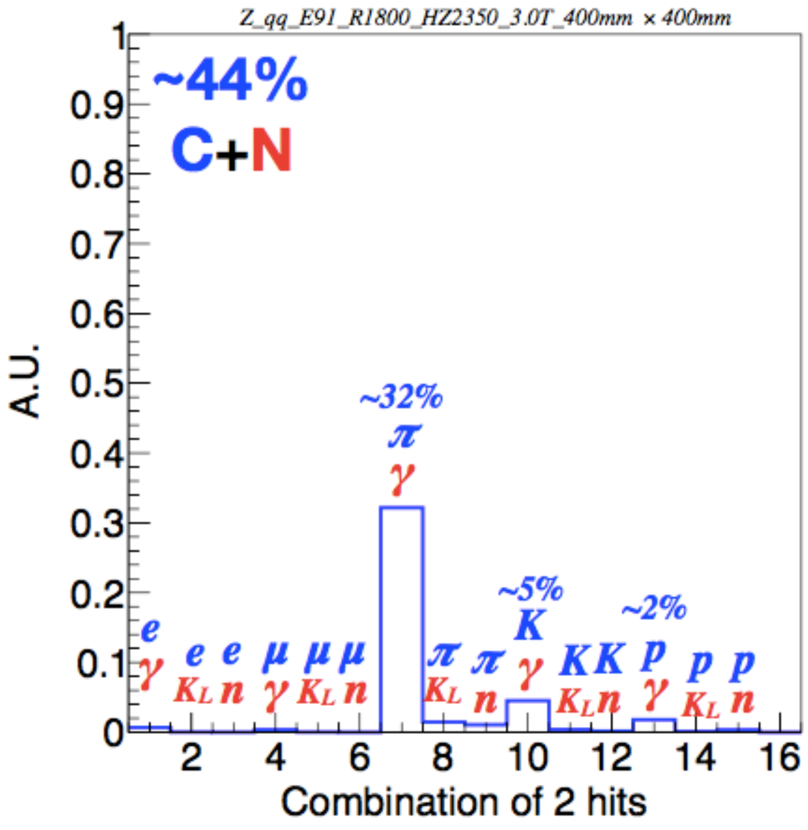
Selected physics benchmarks

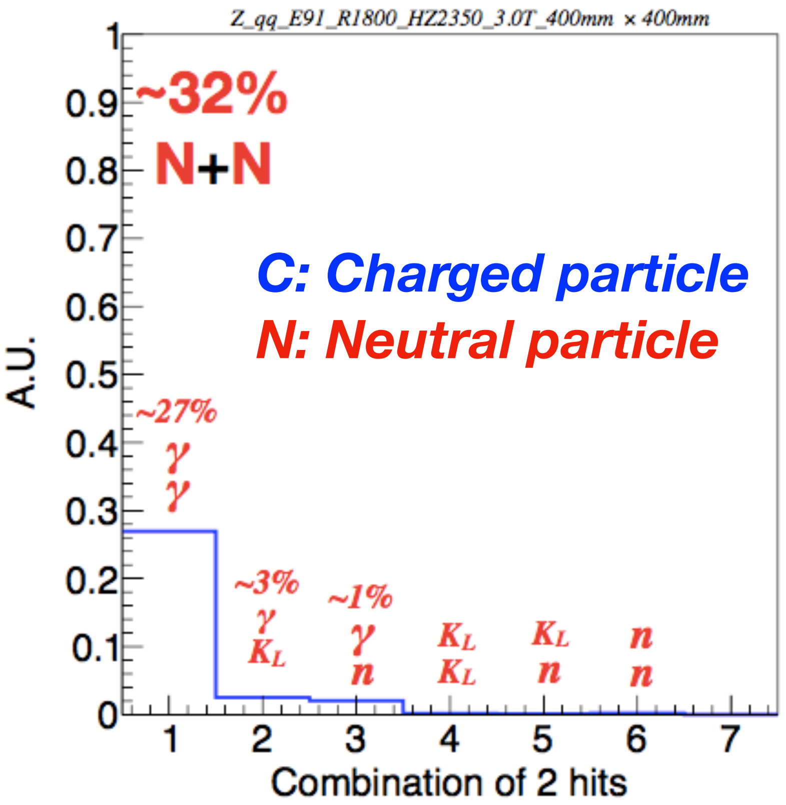
Center of Mass Energy	91.2 GeV	240 GeV	360 GeV
2 jets	Z→qq	Z→qq ννH, H→gg	Z→qq
4 jets	-	Z→qq, H→gg	Z→qq, H→qq
6 jets	-		tt → 6q

- Choose the "hottest" super cell: with maximum energy
- Focus on the multiplicity and energy of particles
- Size of the super cell: first fixed at 40×40cm as default, then scanned down to 1×1cm

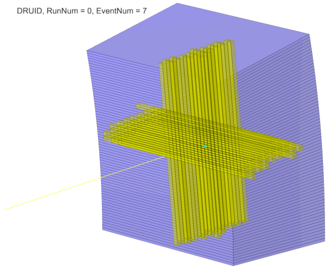
Multiplicity at 40cm×40cm entrance of a super cell





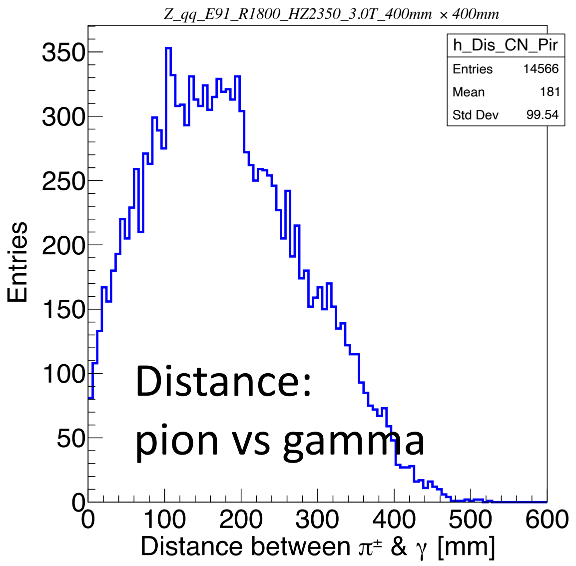


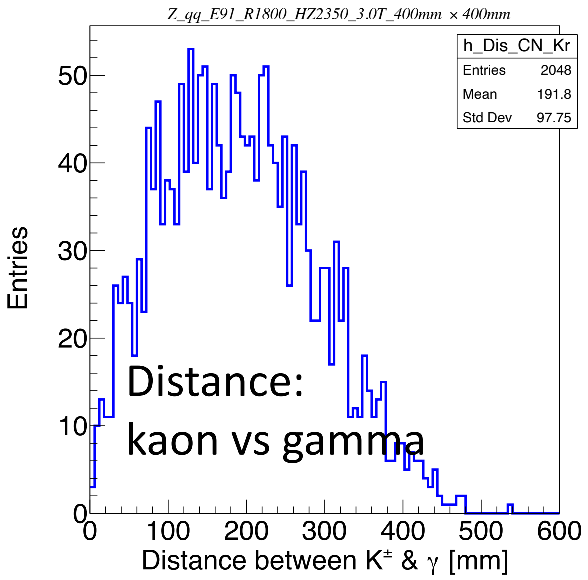
- Particles entering 40cm×40cm area (supercell front face)
  - Generator level with Z→qq events

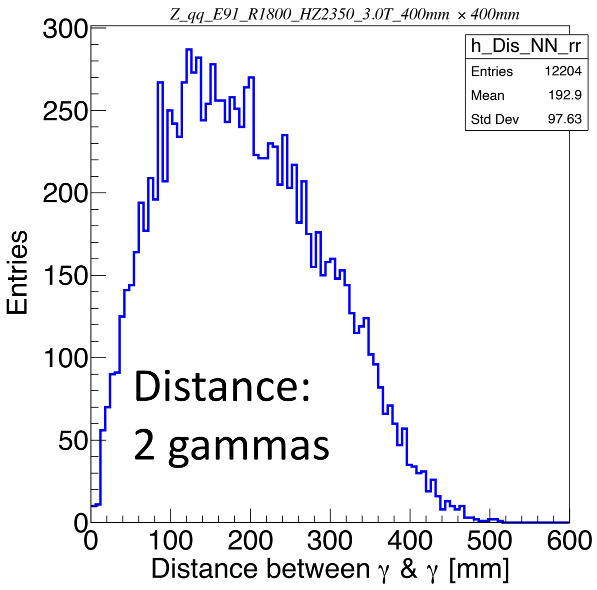


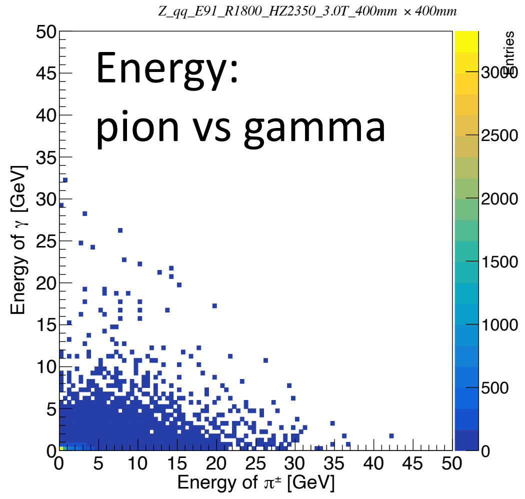
Z→qq
91.2GeV

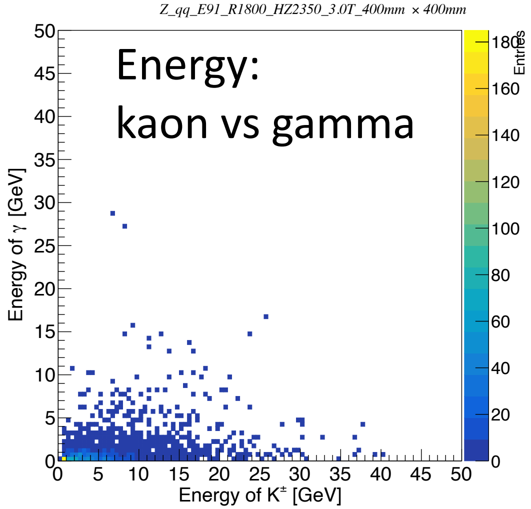
Distance of 2 close-by particles, energy spectra

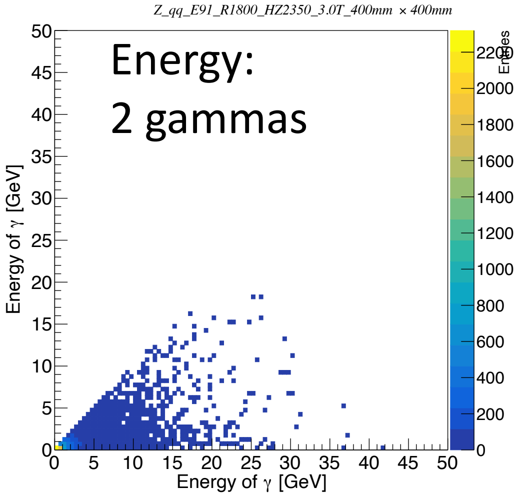












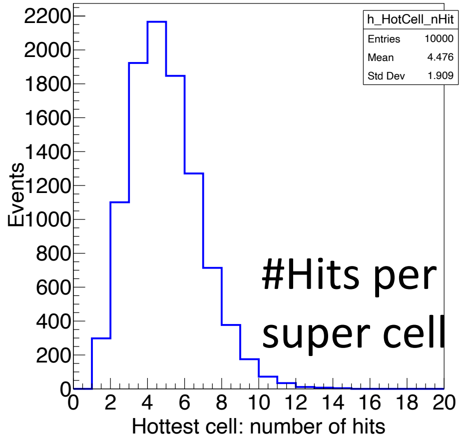
Z→qq 91.2GeV

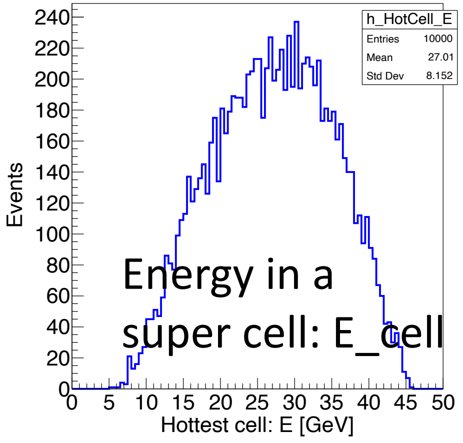
- Distance between two particles
  - Peak at ~20cm
- Energy spectra on the level of 10GeV
  - For charged pions, kaons and gammas

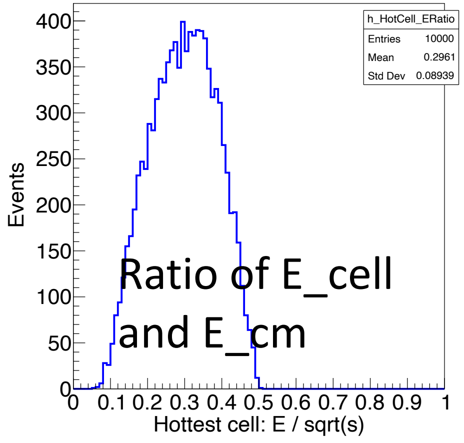
“Hottest” super cell: generator vs Geant4

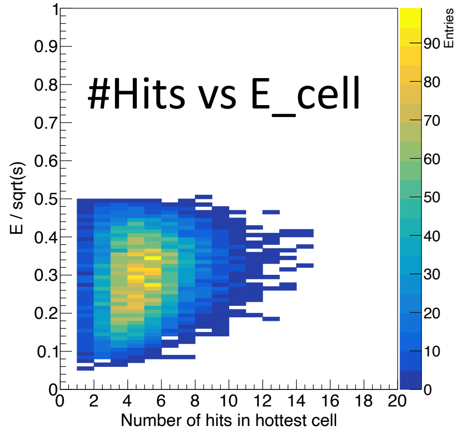
Generator-level results

Z→qq 91.2GeV



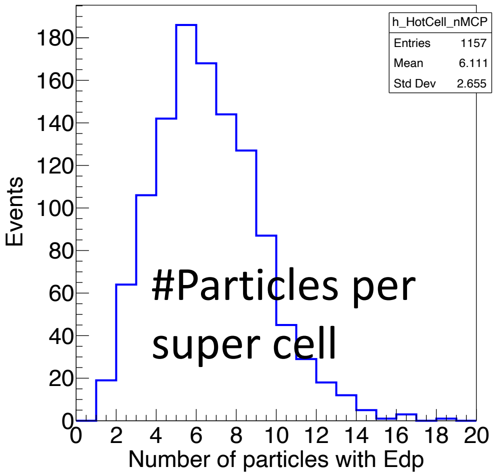


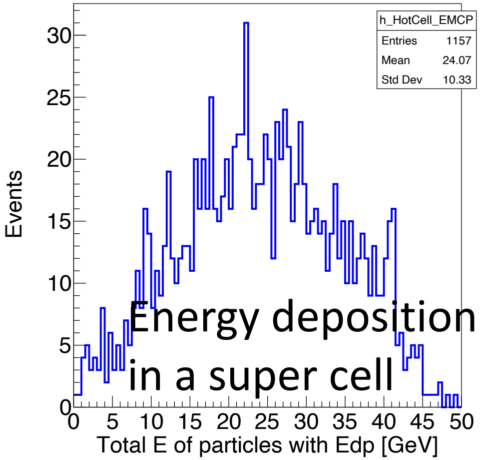


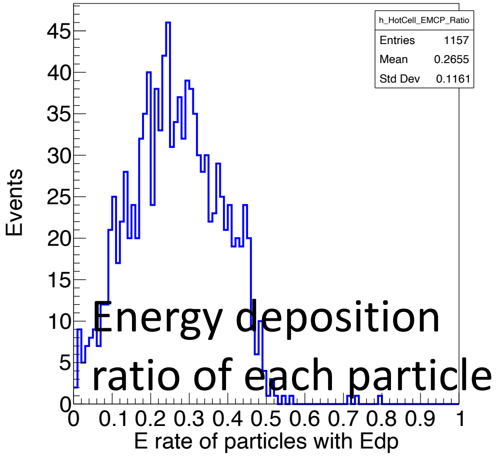


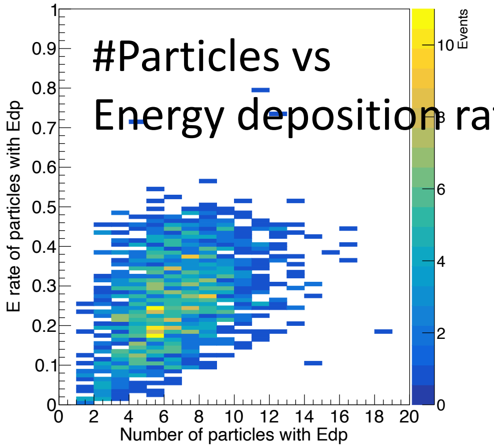
Geant4 simulation results

“Hottest” super cell: max. energy

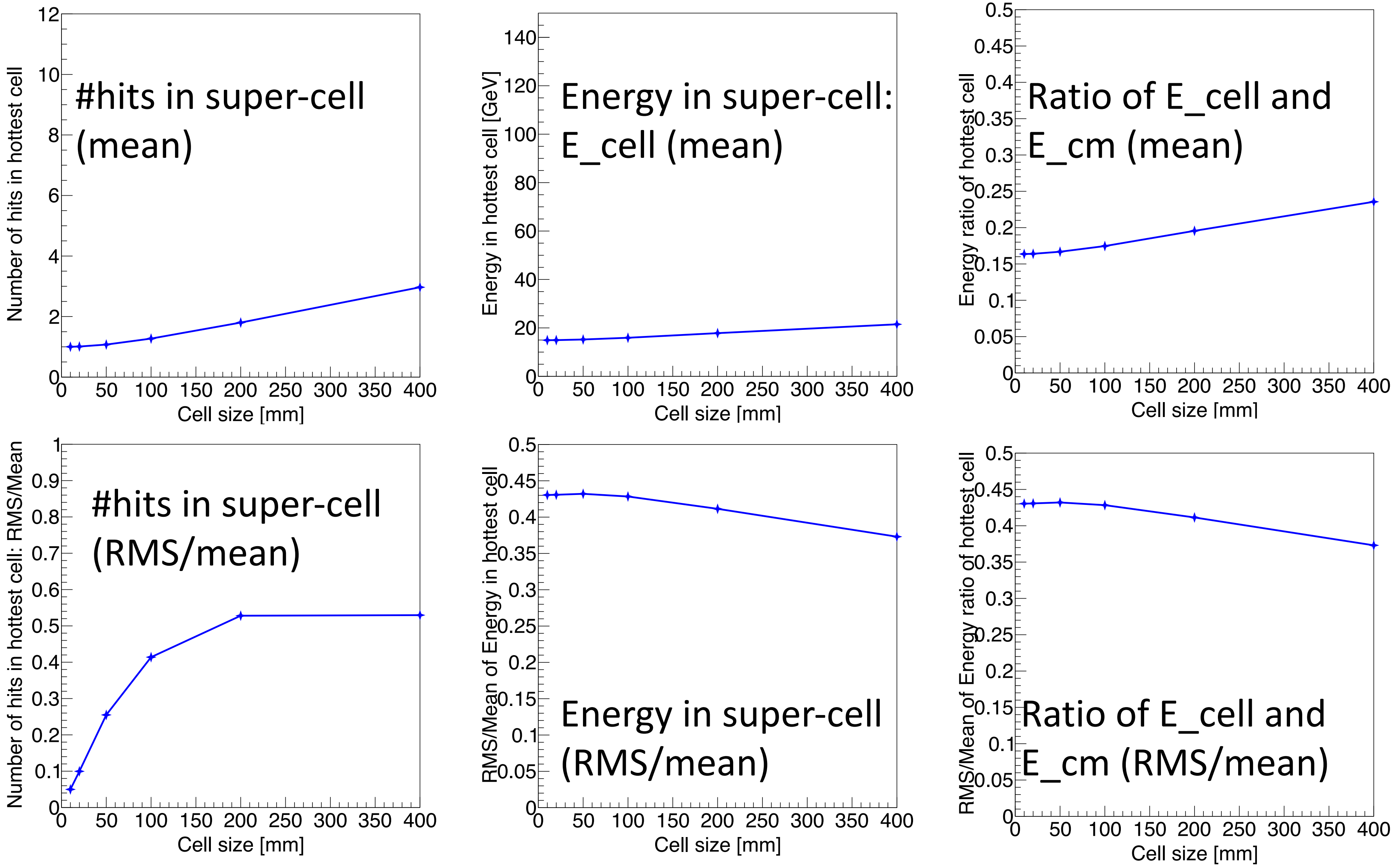








Varying the size of “hottest” super-cell: 1×1cm→40×40cm

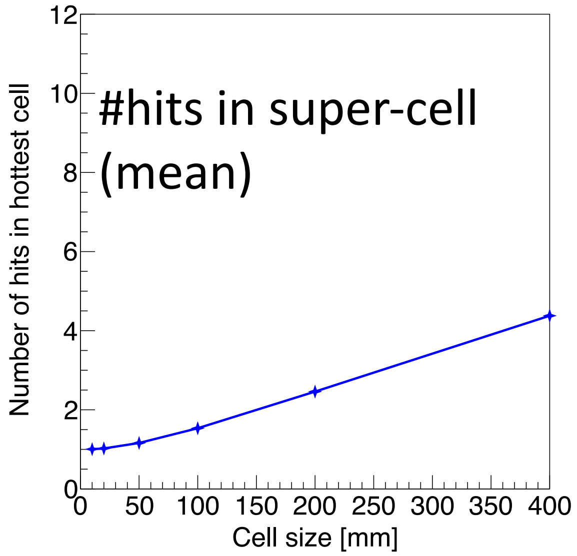


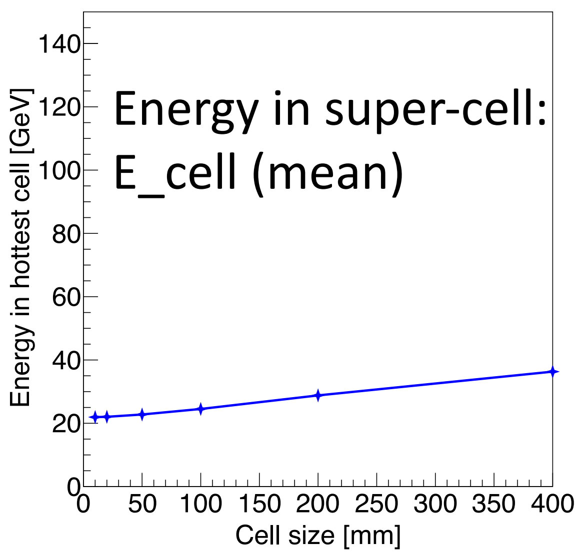
Z→qq 91.2GeV

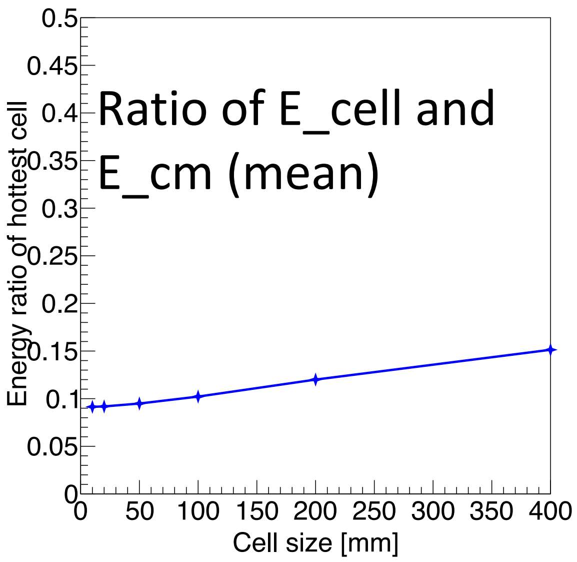
- Mean #hits in the hottest cell: vary in the range of 1 and less than 3
- RMS/mean #hits can go up to 50%
- Mean energy of each particle: on the level of 10GeV or less

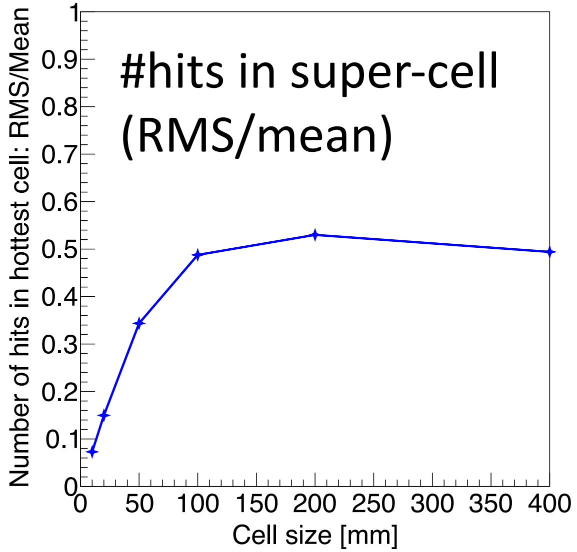
Varying the size of “hottest” super-cell: 4-jet events

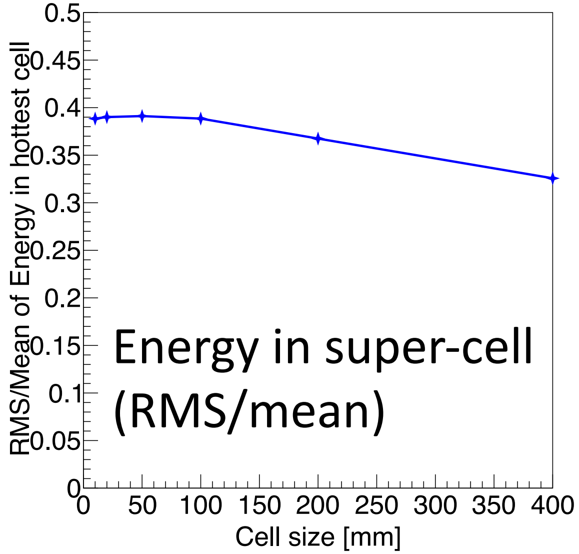
qqH→gg
240GeV

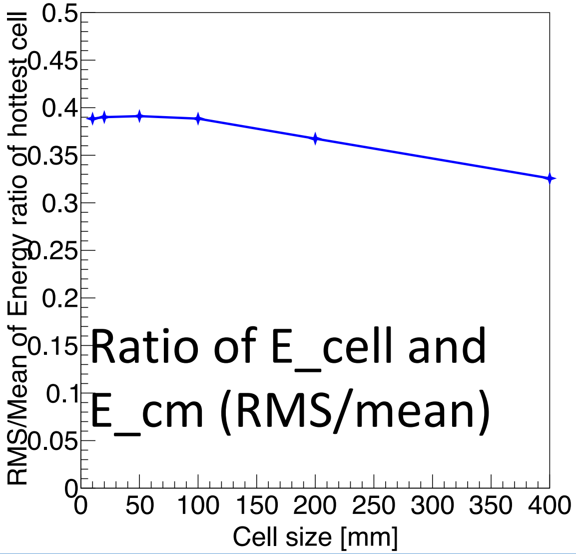






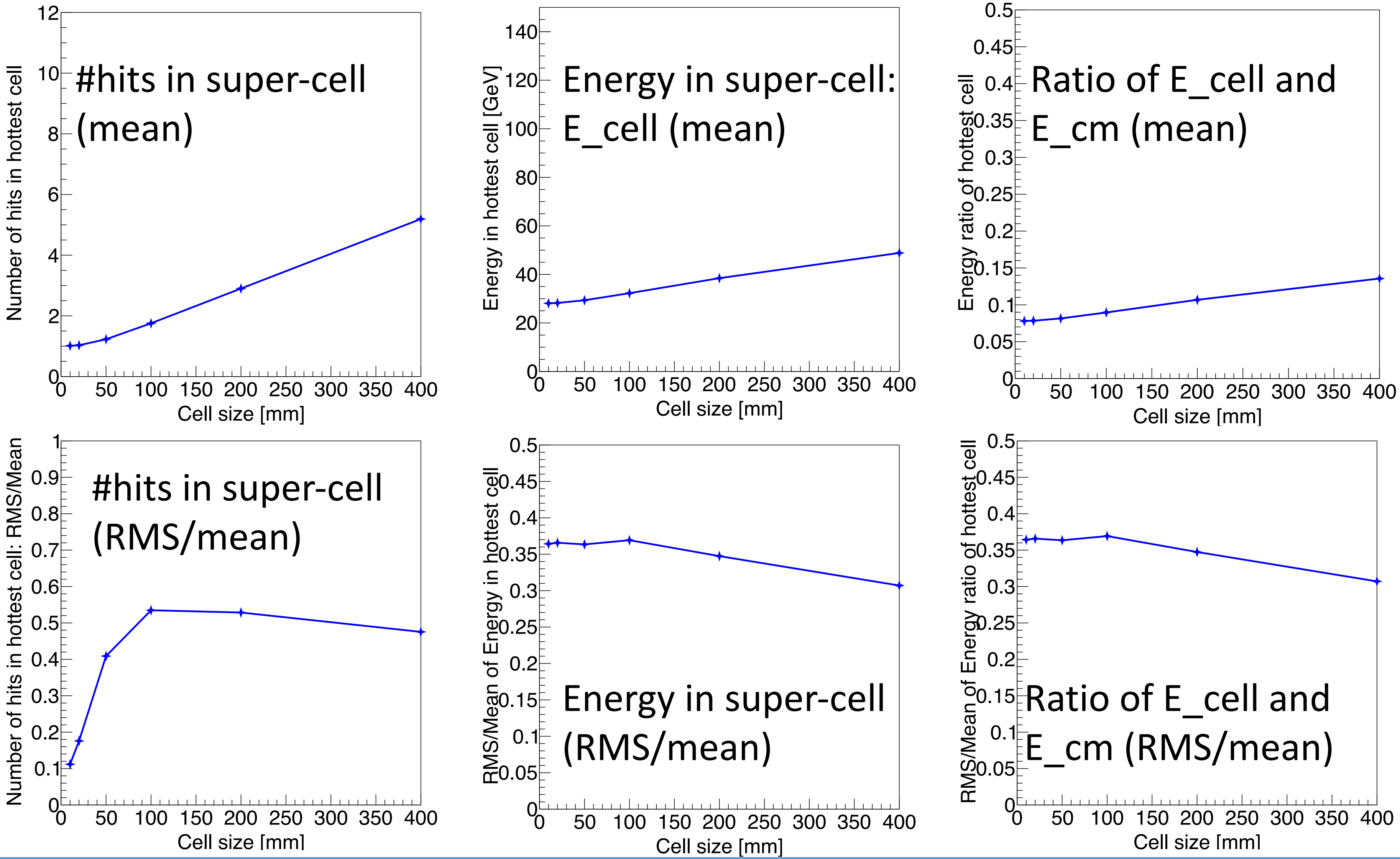






- Mean #hits in the hottest cell: vary in the range of 1 and 4
- RMS/mean #hits can go up to 50%
- Mean energy of each particle: on the level of 20GeV or less

Varying the size of “hottest” super-cell: 6-jet events

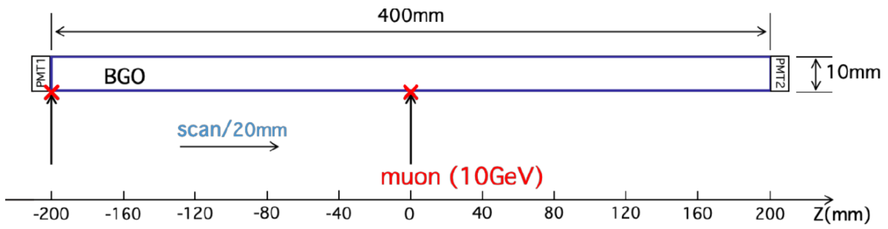


tt→6q
360GeV

- Mean #hits in the hottest cell: vary in the range of 1 and 5
- RMS/mean #hits can go up to 50%
- Mean energy of each particle: on the level of 30GeV or less

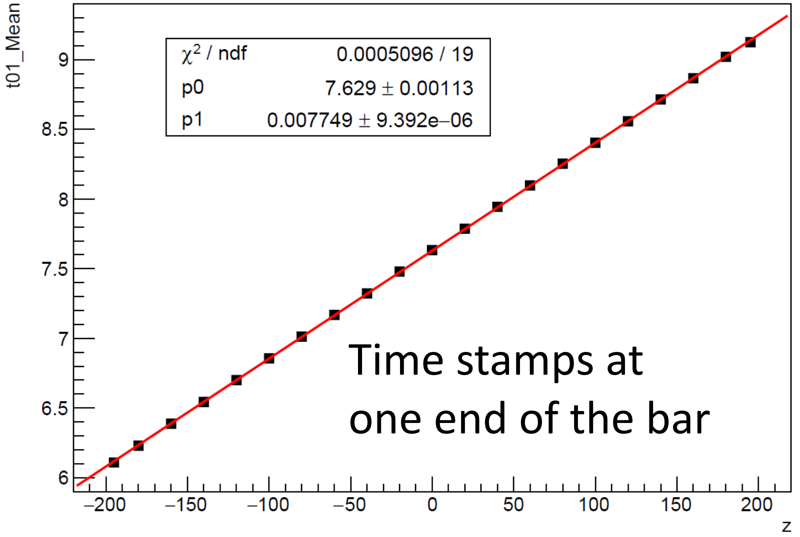
Digitisation of crystal bars

- (First) Focus on the time digitisation
  - 2 time stamps at each end of a crystal bar: dependent on the hit positions
  - Based on the stand-alone Geant4 full simulation of a single bar with complete optical processes

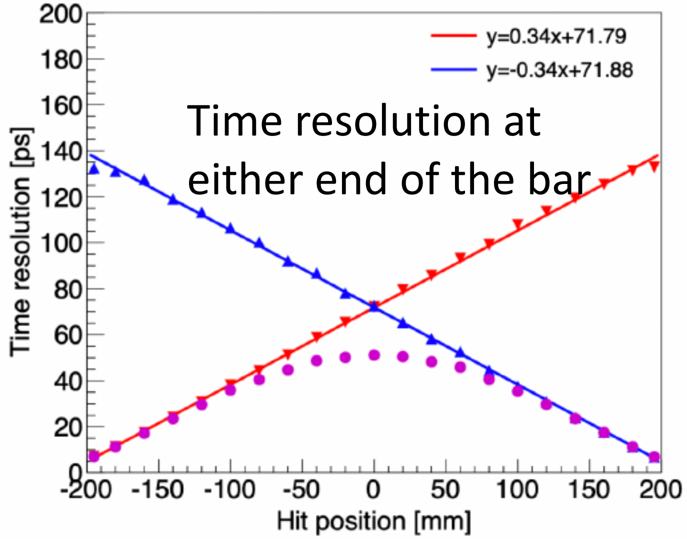


Including scintillation, light propagation, attenuation → realistic modelling of time stamps and #photons detected at both ends

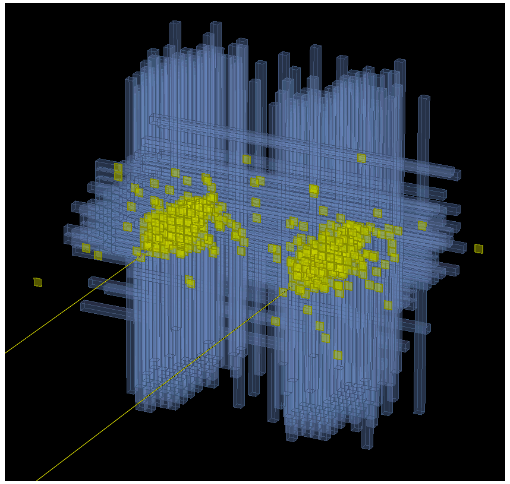
Time stamp (mean) vs hit positions



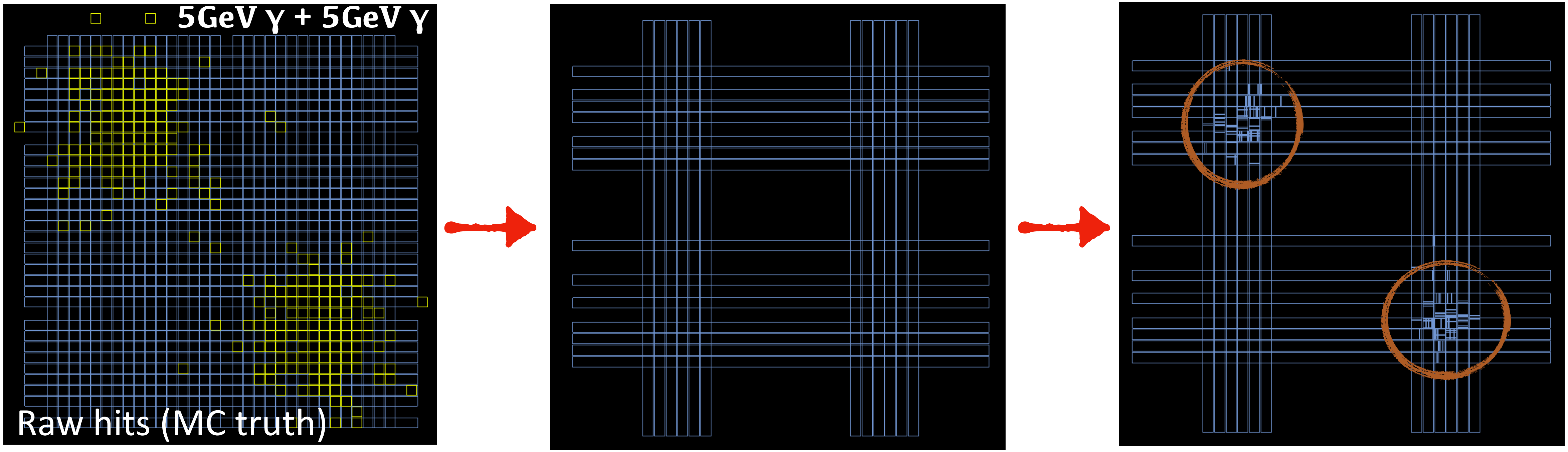
Time resolution vs hit positions



Event display of two 5GeV gammas (20cm away) hitting at the very same bar

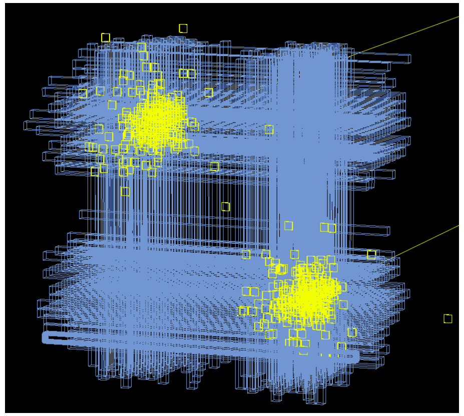


Reconstruction: patterns in event display



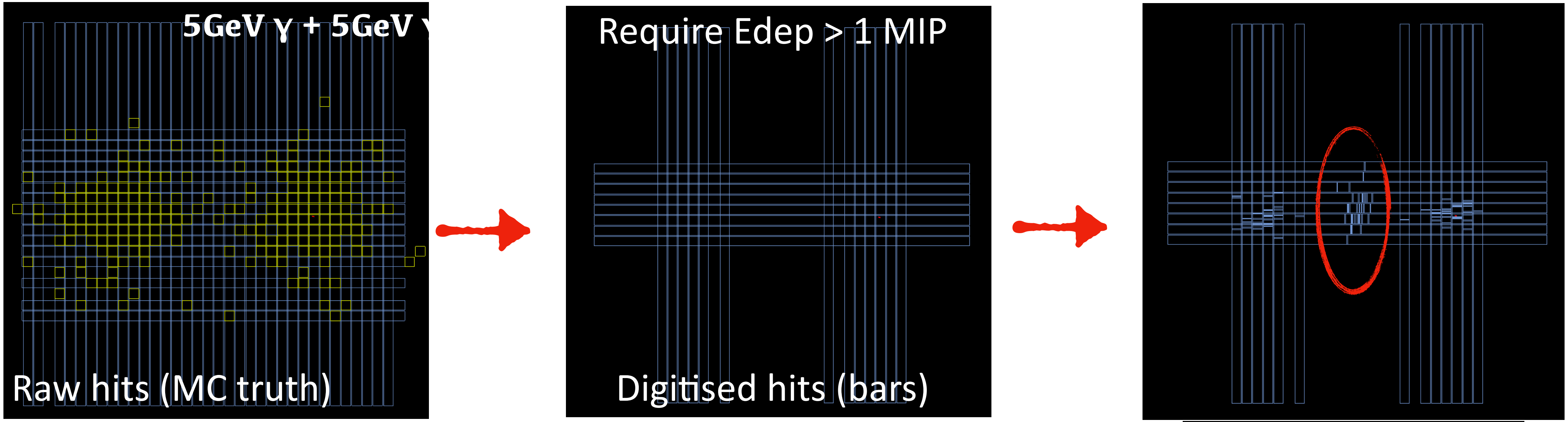
After digitisation and require Edep > 1 MIP

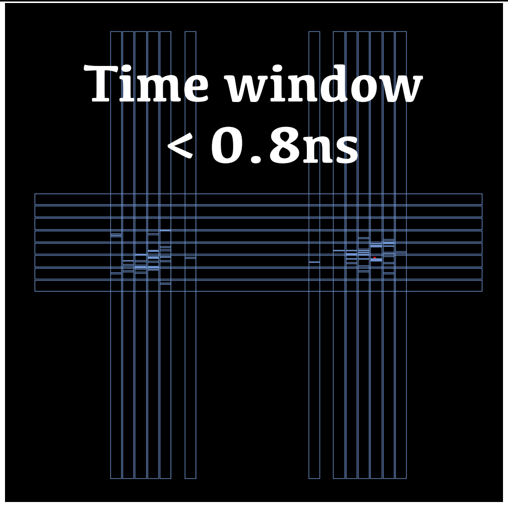
Reconstruction of hit positions using time stamps at two ends



- Two incident 5GeV gammas: in diagonal, separated by ~34 cm
  - Can be resolved

Reconstruction: patterns in event display





- Two 5GeV gammas: hit the same bar, 20 cm away
  - With timing at 2 ends, reconstructed fake hits (i.e. zero time difference, equal time stamps at each end)
  - Assuming two gammas with the same T0, 0.8 ns time window can help remove the fake hits

Summary

- Highly segmented crystal calorimeter: simulation studies with two major designs
  - Design 1: short crystal bars, single-ended readout
    - First look at impacts of threshold (linearity and resolution)
    - Plans
      - Quantify the noise requirement with the digitisation tool
      - Start to work on the reconstruction of neutral pion
  - Design 2: long crystal bars, double-ended readout
    - Key information extracted from physics benchmarks at different energy points
    - Developed digitisation tools
    - Reconstruction: shower patterns in event display (a powerful tool)
    - Plans
      - Quantify the separation power: e.g. critical distance of near-by showers
      - Explore more complex situations >2 particles in a super cell and multi-jet events