Geant4 studies on the IDEA Dual-Readout crystal option

Dual-Readout Meeting

02/12/20

W.Chung[1], S.Eno[2], M.Lucchini[1]*, C.Tully[1]

[1]Princeton University, [2]Maryland University

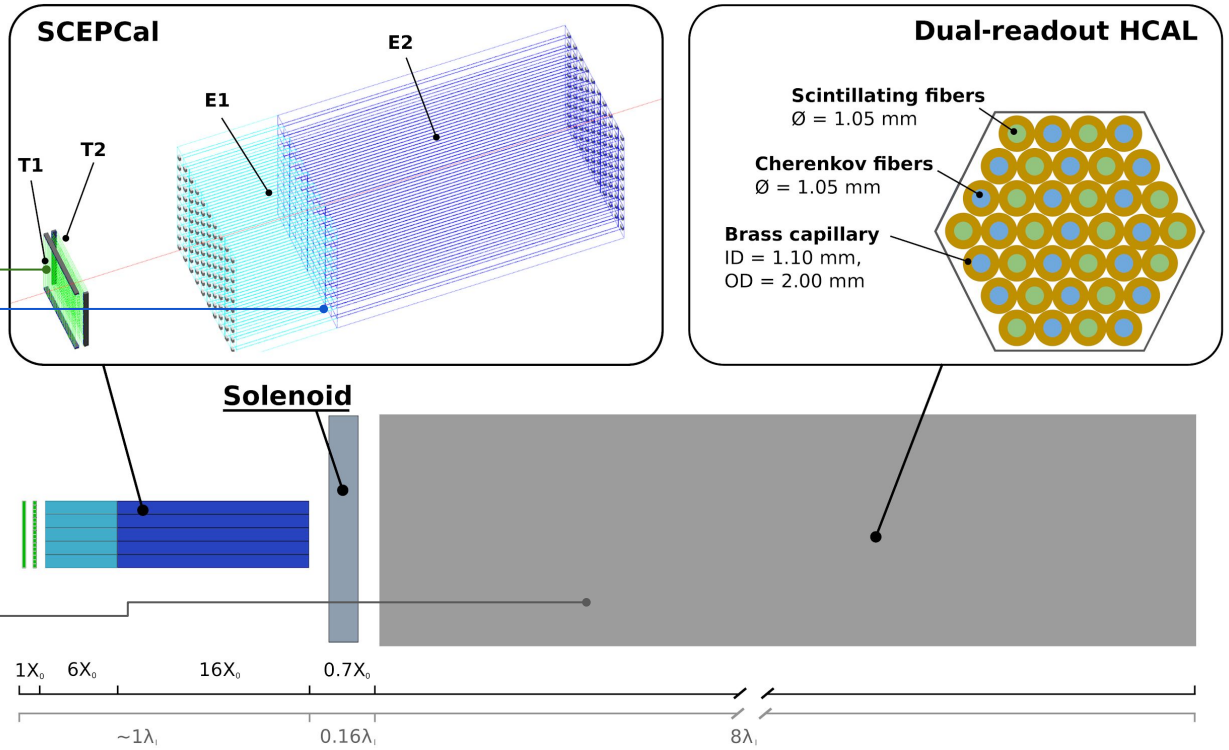
Context

- **Looking into a crystal EM calorimeter option to be integrated with the dual readout IDEA calorimeter** [see presentation at FCC workshop]
  - Maintain dual readout capabilities and good hadron resolution
  - Boost energy resolution for photons to improve
    - improve pi0 reconstruction → impact on jet reconstruction
    - enable recovery of Brem photons to enhance Z→ee recoil mass resolution
    - potential for B physics (R.Aleksen)
  - Exploit longitudinal segmentation to improve particle ID
  - Allow for overall detector cost optimization (e.g. decreasing sampling fraction of the fiber calorimeter by increasing brass tube diameter with limited impact on hadron resolution)

Layout overview

- **Transverse and longitudinal segmentations** optimized for particle identification and particle flow algorithms
- Exploiting **SiPM readout** for contained cost and power budget

- **Timing layers** — $\sigma_t \sim 20$ ps
  - LYSO:Ce crystals (~$1X_0$)
  - 3x3x60 mm³ active cell
  - 3x3 mm² SiPMs (15-20 um)
- **ECAL layers** — $\sigma^{EM}_E/E \sim 3\%/\sqrt{E}$
  - PWO crystals
  - Front segment (~$6X_0$)
  - Rear segment (~$16X_0$)
  - 10x10x200 mm³ crystal
  - 5x5 mm² SiPMs (10-15 um)
- **Ultra-thin IDEA solenoid**
  - ~$0.7X_0$
- **HCAL layer** — $\sigma^{HAD}_E/E \sim 27\%/\sqrt{E}$
  - Scintillating and quartz fibers inserted in brass capillaries
  - (similar to prototypes in A.Karadzhinova-Ferrer slides)



This talk **overview**

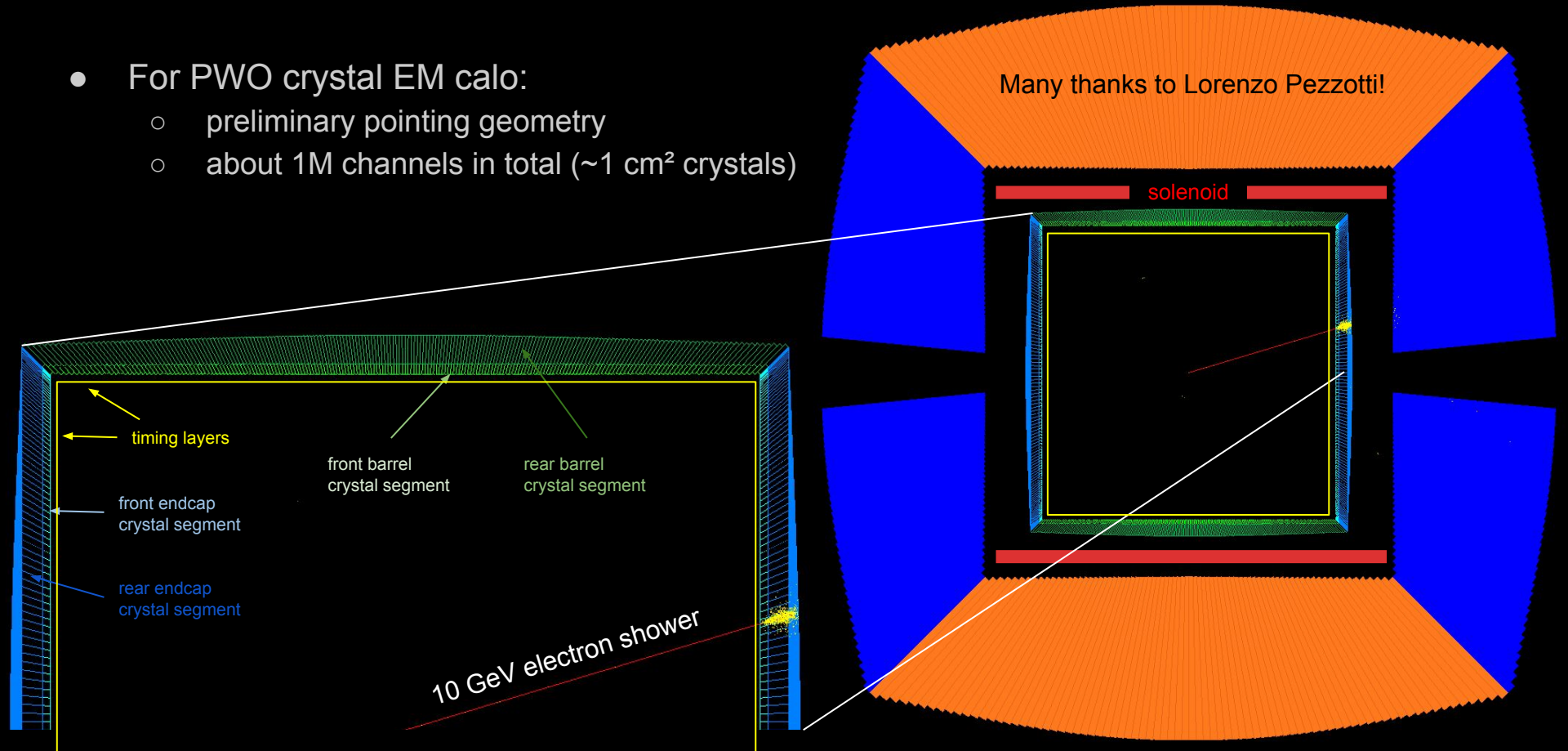
- **IDEA calorimeter Geant4 code forked from Lorenzo Pezzotti's repository**
  https://github.com/marco-toli/Git_IDEA_CALO_FIBER
- **Added 2-layer crystal em calorimeter segments**
  - PWO crystals with pointing geometry
  - Current radial envelope: [1800 < R < 2000] mm
- **Added 2-layer crystal timing segments**
  - LSO crystals with non-pointing geometry (wall grid)
  - Current radial envelope: [1775 < R < 1795] mm
- **Added SCEPCal information to ntuple**
  - Integrals of scintillation and cherenkov signals (rear and front) in SCEPCal
  - Hits in crystals (single hit signal and position)
  - Timing information from both ECAL and timing layers
- **First sanity checks**
  - Response uniformity
  - Spatial, time and energy resolutions

Geometry

Ongoing integration in 4π Geant4 IDEA simulation

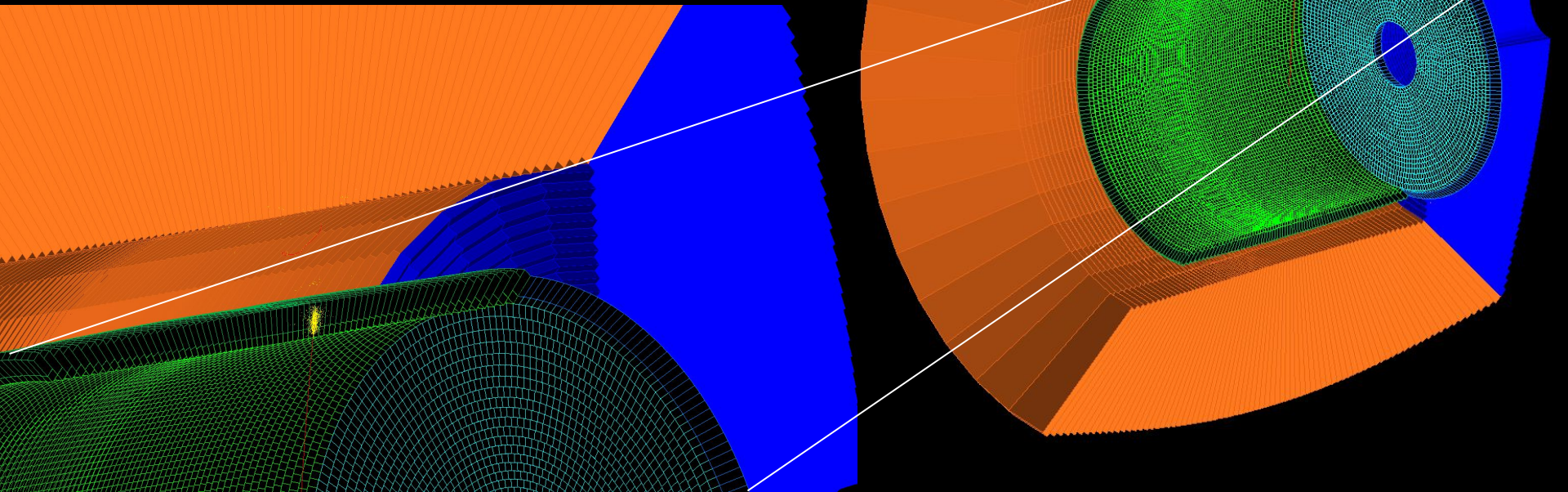
- For PWO crystal EM calo:
  - preliminary pointing geometry
  - about 1M channels in total (~1 cm² crystals)

Many thanks to Lorenzo Pezzotti!



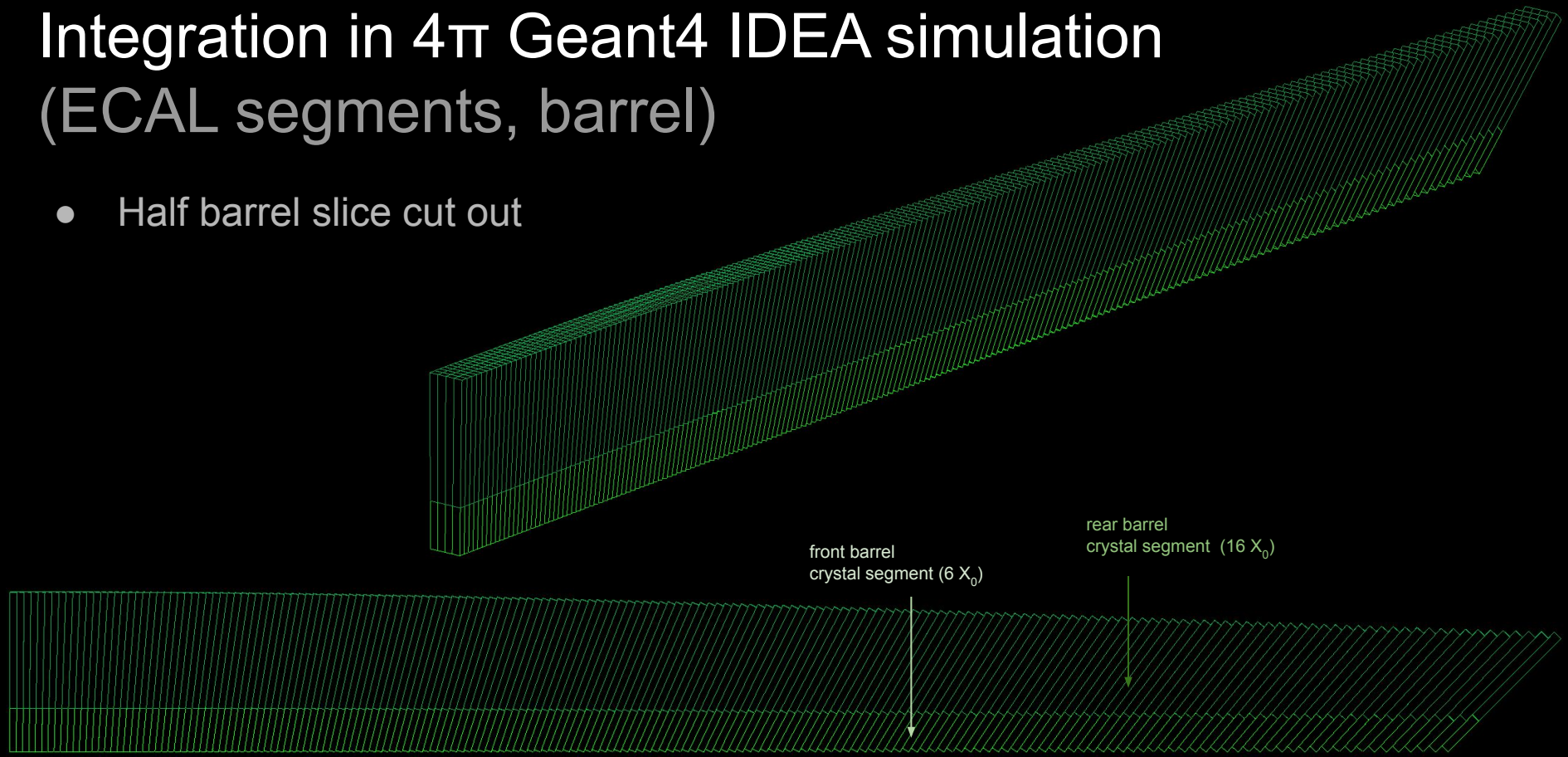
Integration in 4π Geant4 IDEA simulation (side view)

- Inner radius: 2000 mm
- Outer radius: 2200 mm
- Crystal length: 20 cm (~22 X_0)



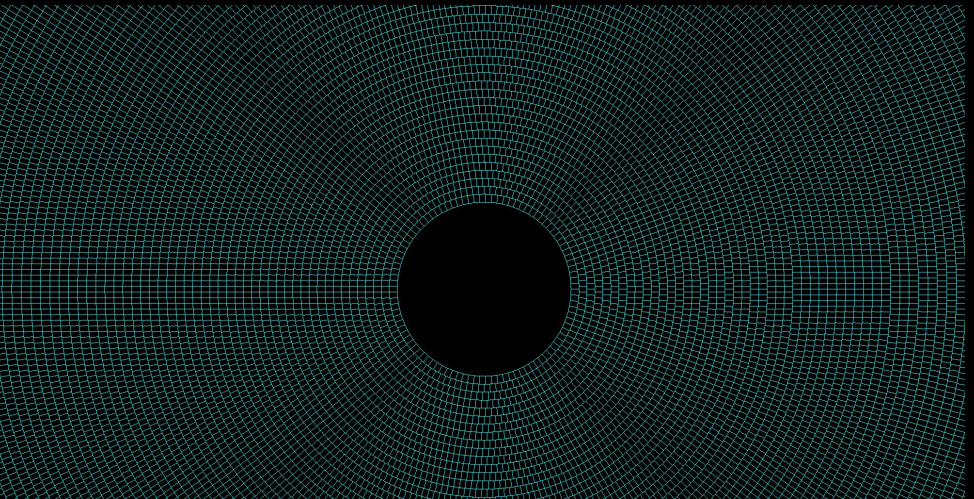
Integration in 4π Geant4 IDEA simulation (ECAL segments, barrel)

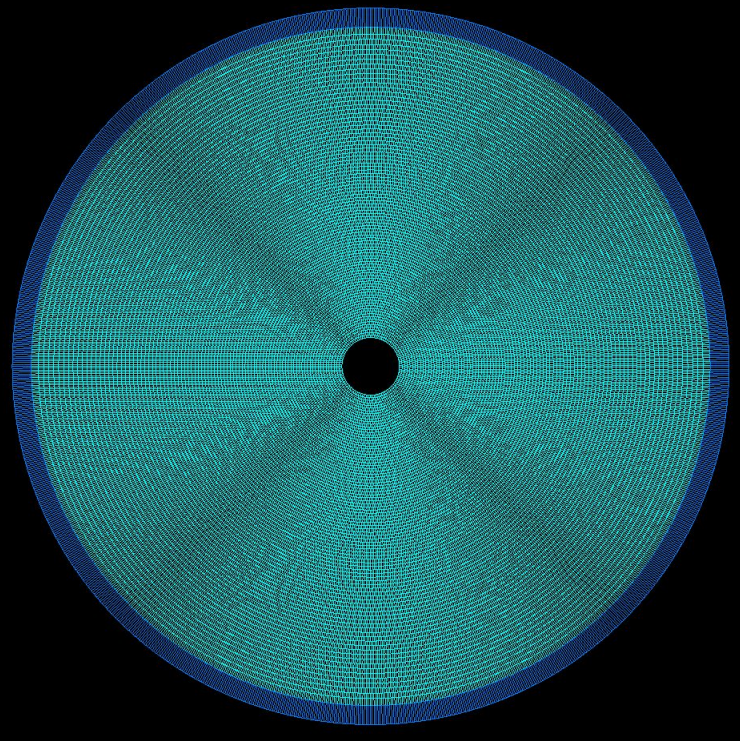
- Half barrel slice cut out



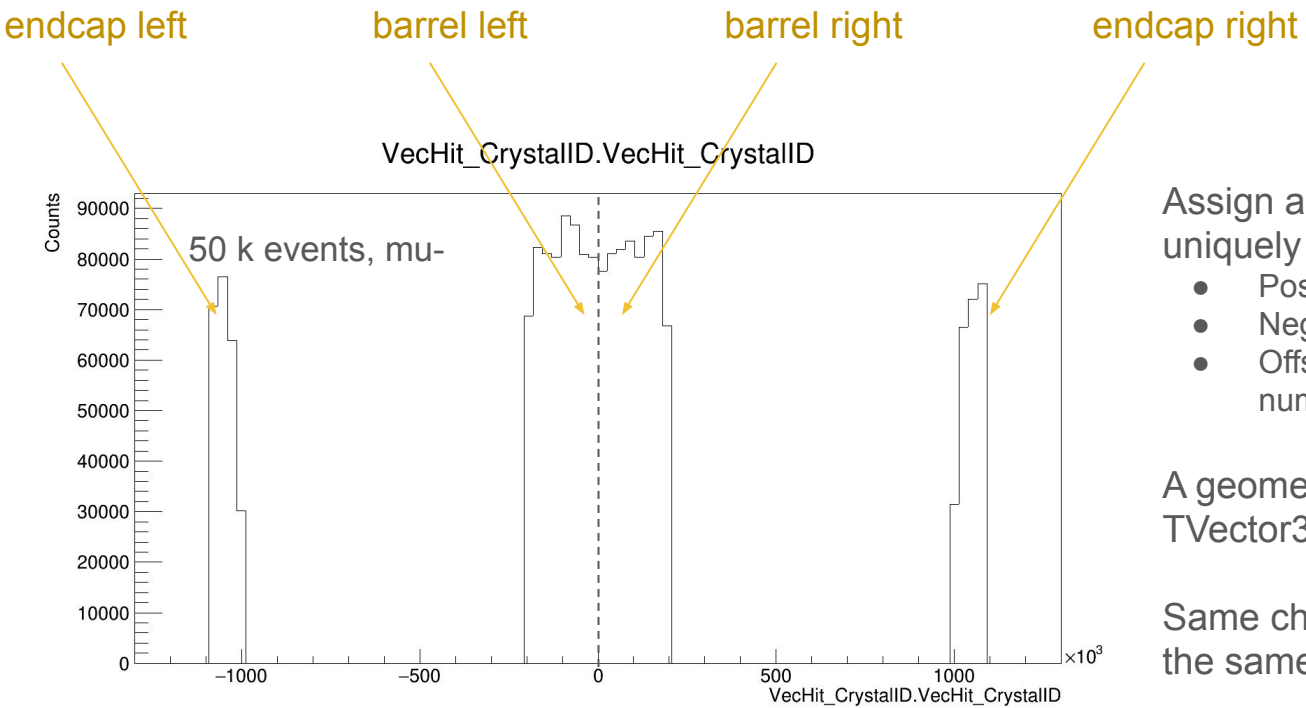
Integration in 4π Geant4 IDEA simulation (ECAL segments, endcap)

- Concentric pointing rings
- Each ring divided in replicas to yield similar crystal dimensions





Crystal numbering (ECAL segments)



Assign a channel ID to the hit that uniquely identify the crystal position

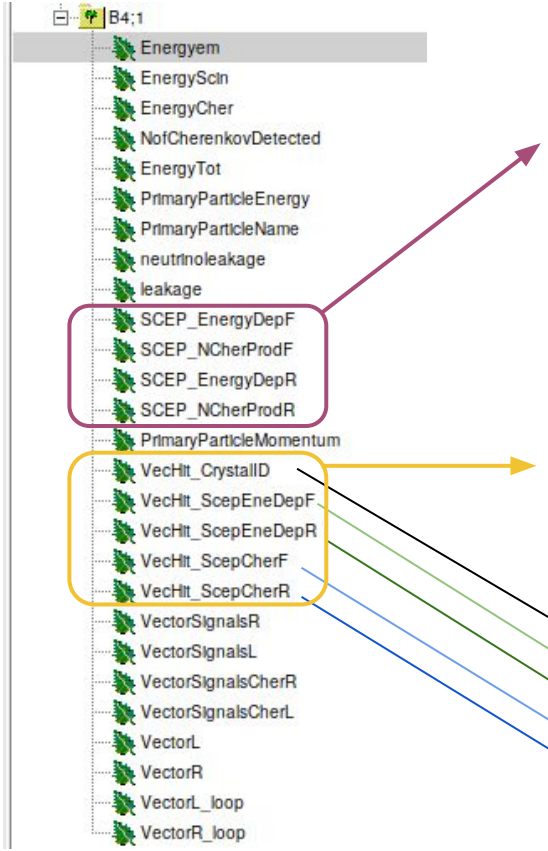
- Positive IDs for right side
- Negative IDs for left side
- Offset of 1e6 between endcap and barrel numbering

A geometry helper function to retrieve the TVector3 corresponding to a given chID

Same chID for front and rear crystals at the same position

Readout (ECAL segments)

Ntuple variables



- Total energy deposited via ionization in the SCEPCal front layer
- Total number of Cherenkov photons produced in the SCEPCal front layer
- Total energy deposited via ionization in the SCEPCal rear layer
- Total number of Cherenkov photons produced in the SCEPCal rear layer

A hit for a given chID is created whenever either a Cherenkov photon or some energy is deposited in either the front or rear segment of a given crystal

An std::vector is created containing all hits in the event

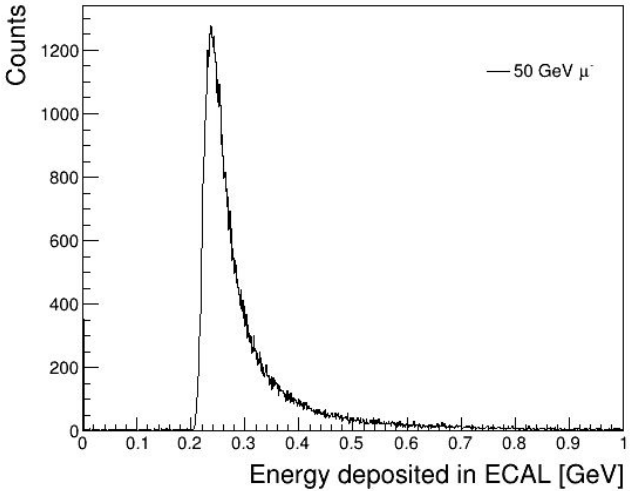
For each hit the following information is saved:

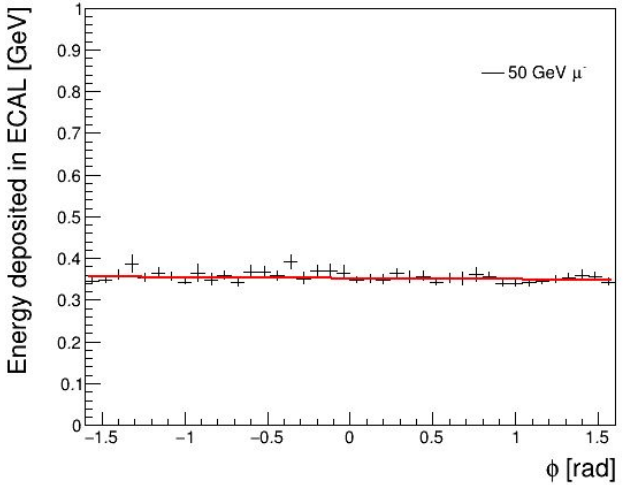
- Channel ID of the corresponding hit
- Total energy deposited via ionization in the SCEPCal front crystal
- Total energy deposited via ionization in the SCEPCal rear crystal
- Total number of Cherenkov photons produced in the SCEPCal front crystal
- Total number of Cherenkov photons produced in the SCEPCal rear crystal

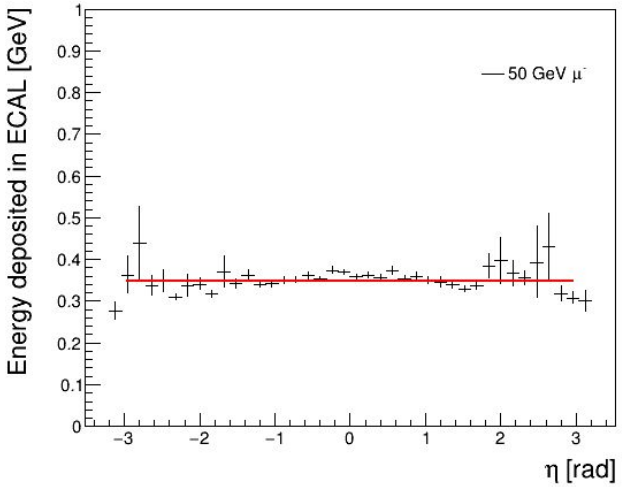
Sanity checks (ECAL segments)

Response to MIPs

- 50 GeV mu- particle gun
- Very uniform MIP peak across entire detector, as expected at about 250 MeV

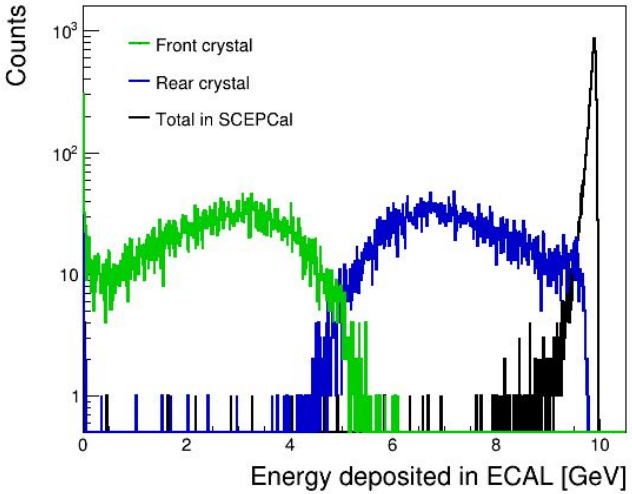


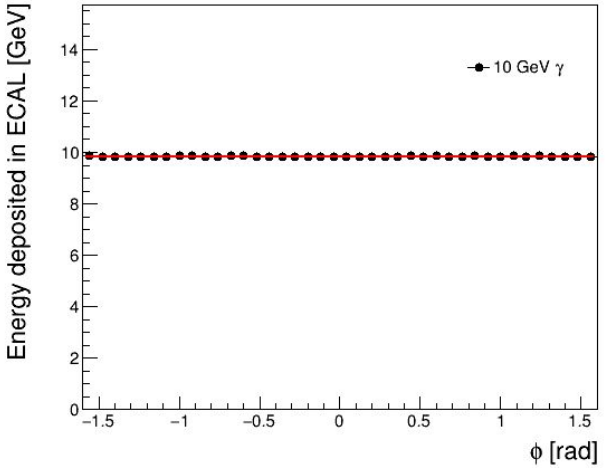


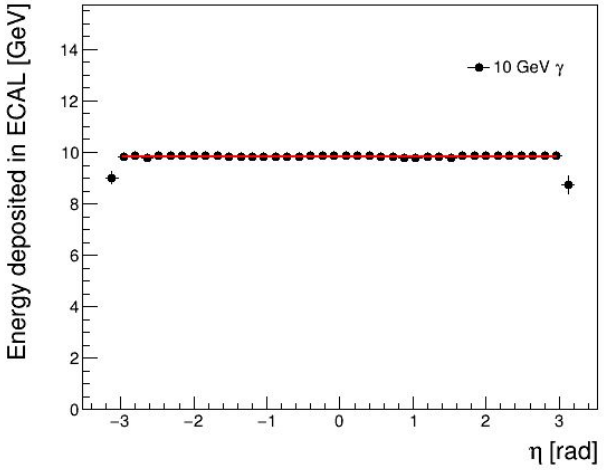


Response to photons

- 10 GeV gamma particle gun





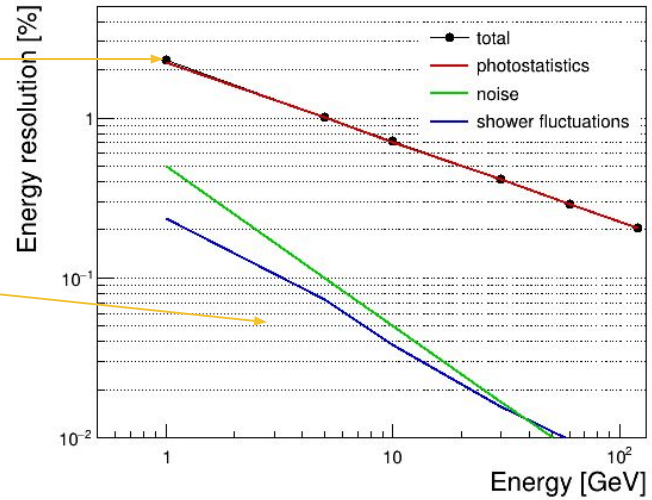


Energy resolution to electrons

- From simulation just get the contribution from shower fluctuations
- Adding noise and photostatistic terms afterwards as a parameterization of the energy deposited in the crystal segments

2000 phe/GeV → ~2.5%/sqrt(E)

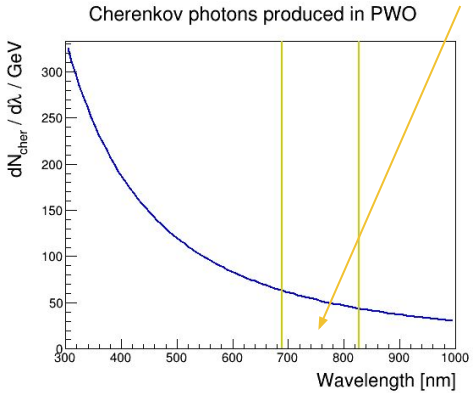
No material budget in front of ECAL → smaller contribution from shower fluctuations than standalone Geant4 in our paper

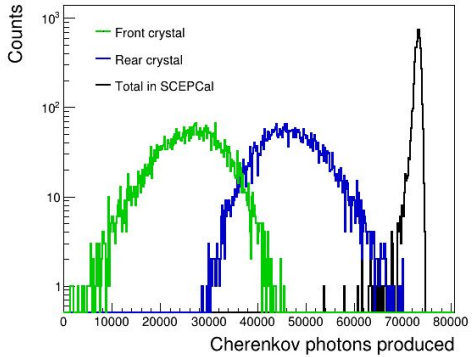


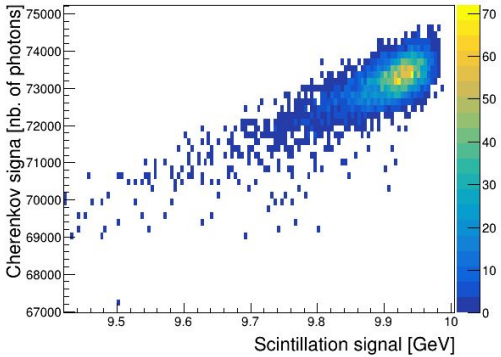
Cherenkov signal in PWO

- Count only a “small” fraction of the Cherenkov photons produced in PWO
  - Amount of cherenkov produced in [300-1000] nm ~ 70000/GeV
  - Amount of cherenkov produced in [690-830] nm ~ 7300/GeV
  - Still large enough to yield negligible stochastic term at 1 GeV
  - Further downscaling factor to account for “optics” can be applied afterwards (LCE, PDE, filters, etc.)

Count only photons
produced in small window
(~7300 C photons / GeV)

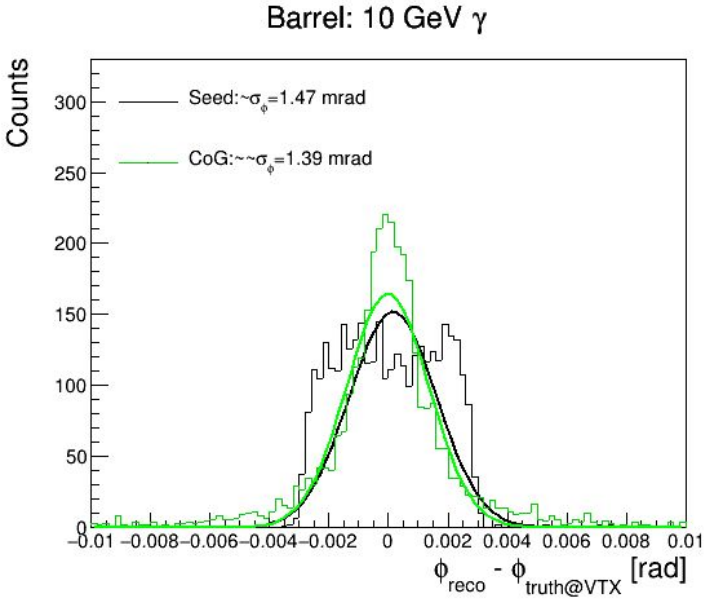


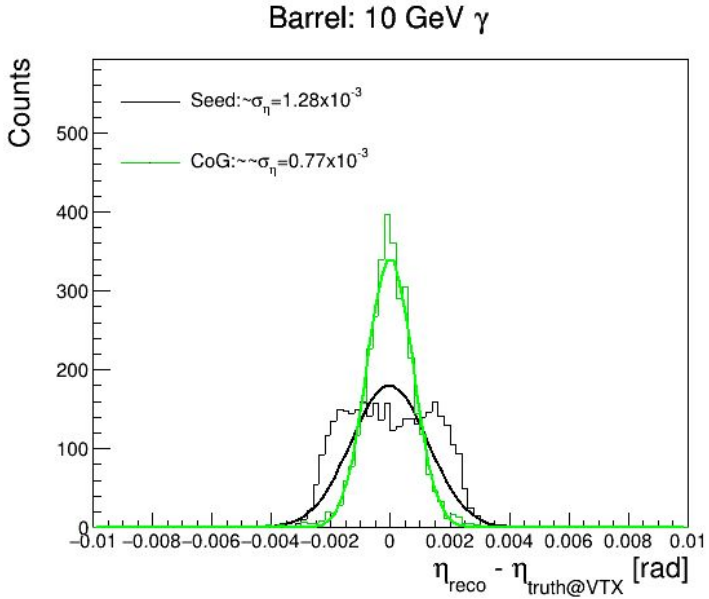




Angular resolution (barrel)

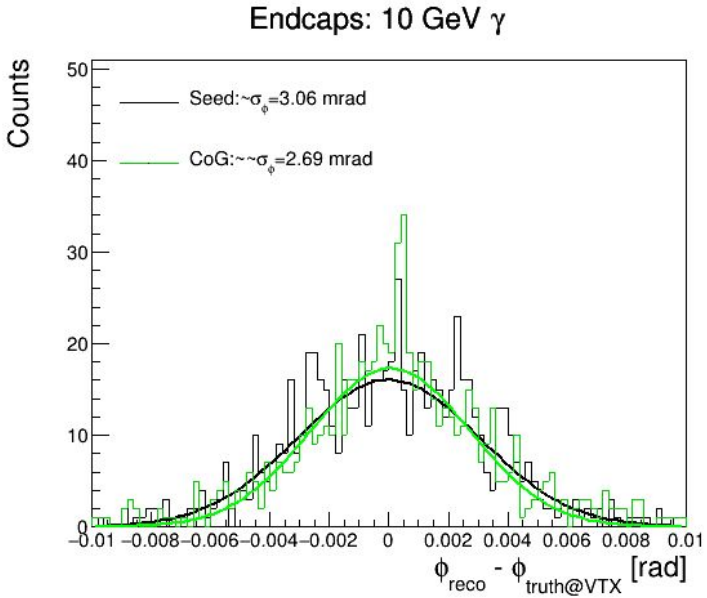
- Spatially uniform photons @ 10 GeV are generated
  - Seed: just using the hit with maximum energy deposition to reconstruct position (precision driven by crystal granularity)
  - Center of Gravity of the shower

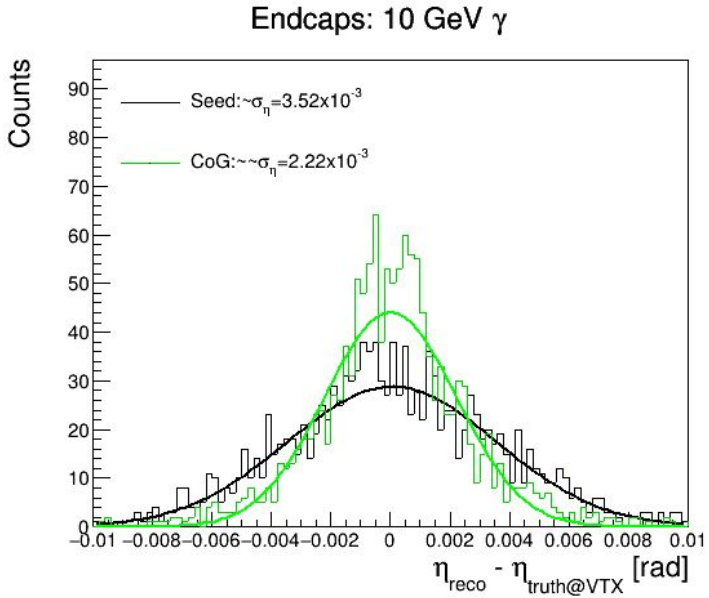




Angular resolution (endcap)

- Spatially uniform photons @ 10 GeV are generated
  - Seed: just using the hit with maximum energy deposition to reconstruct position (precision driven by crystal granularity)
  - Center of Gravity of the shower

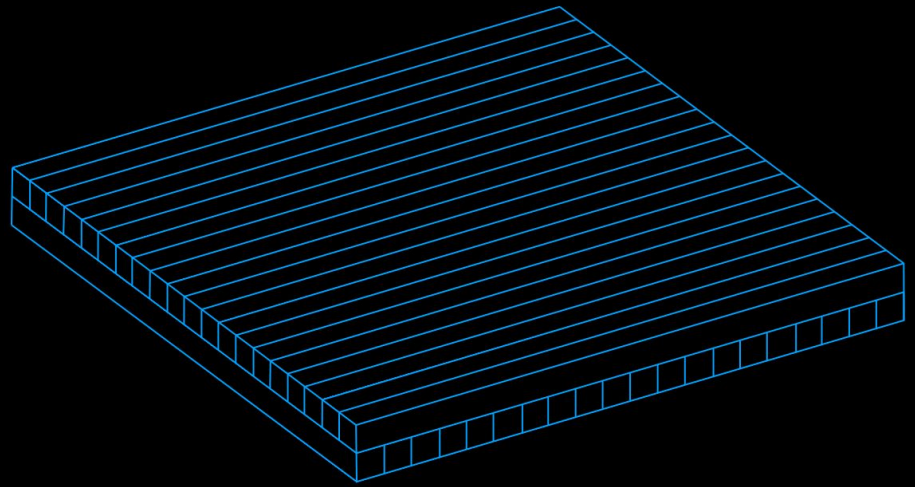


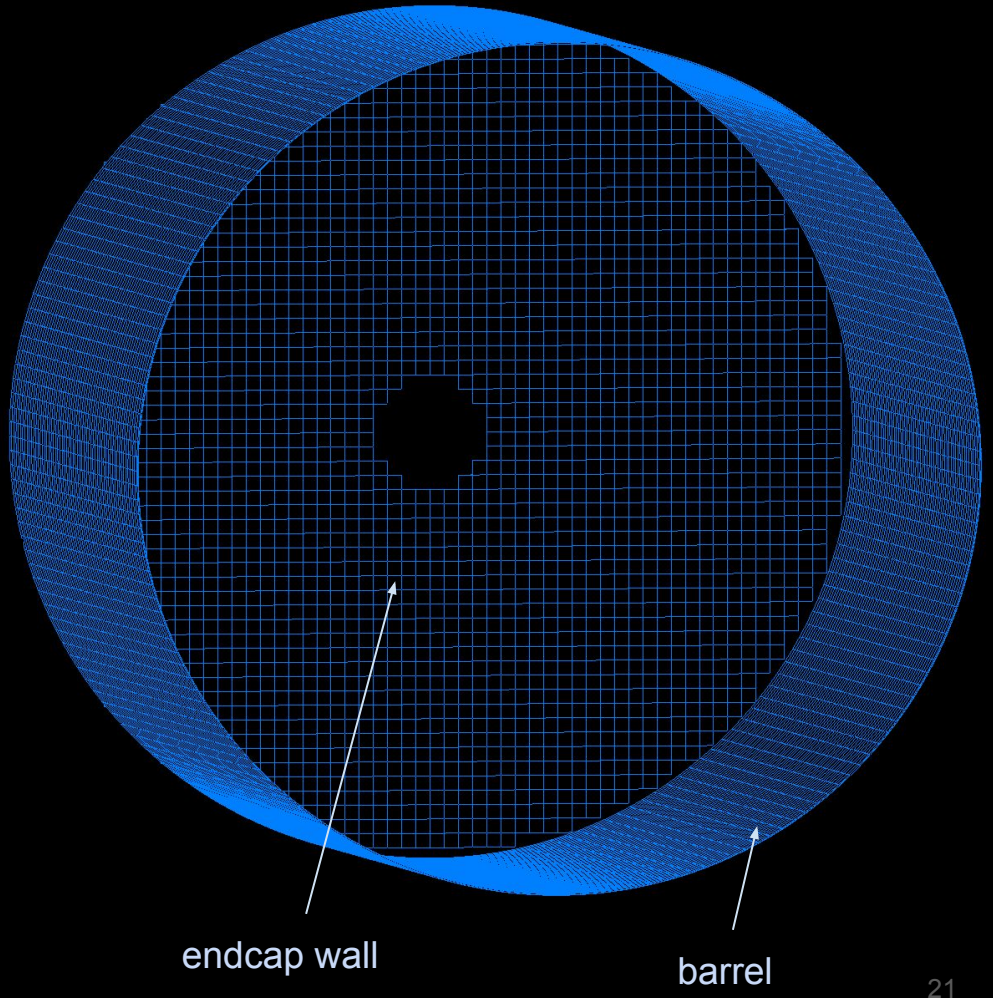


Geometry (Timing layers)

Timing layers

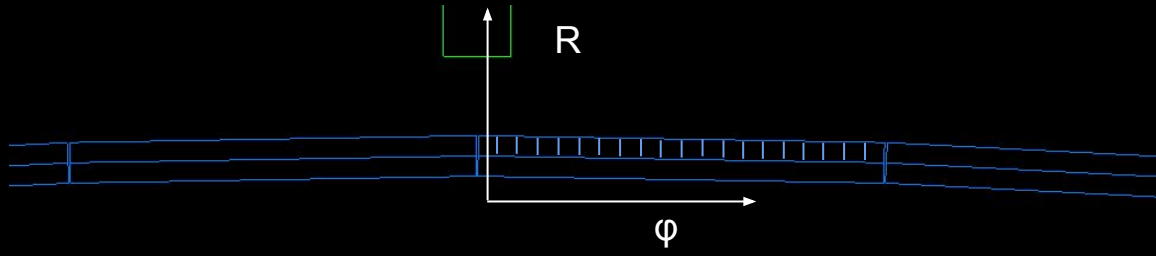
- Inner radius: 1775 mm
- Outer radius: 1795 mm
- Module size: 60x60x6 mm^3
- Crystal size: 60x3x3 mm^2

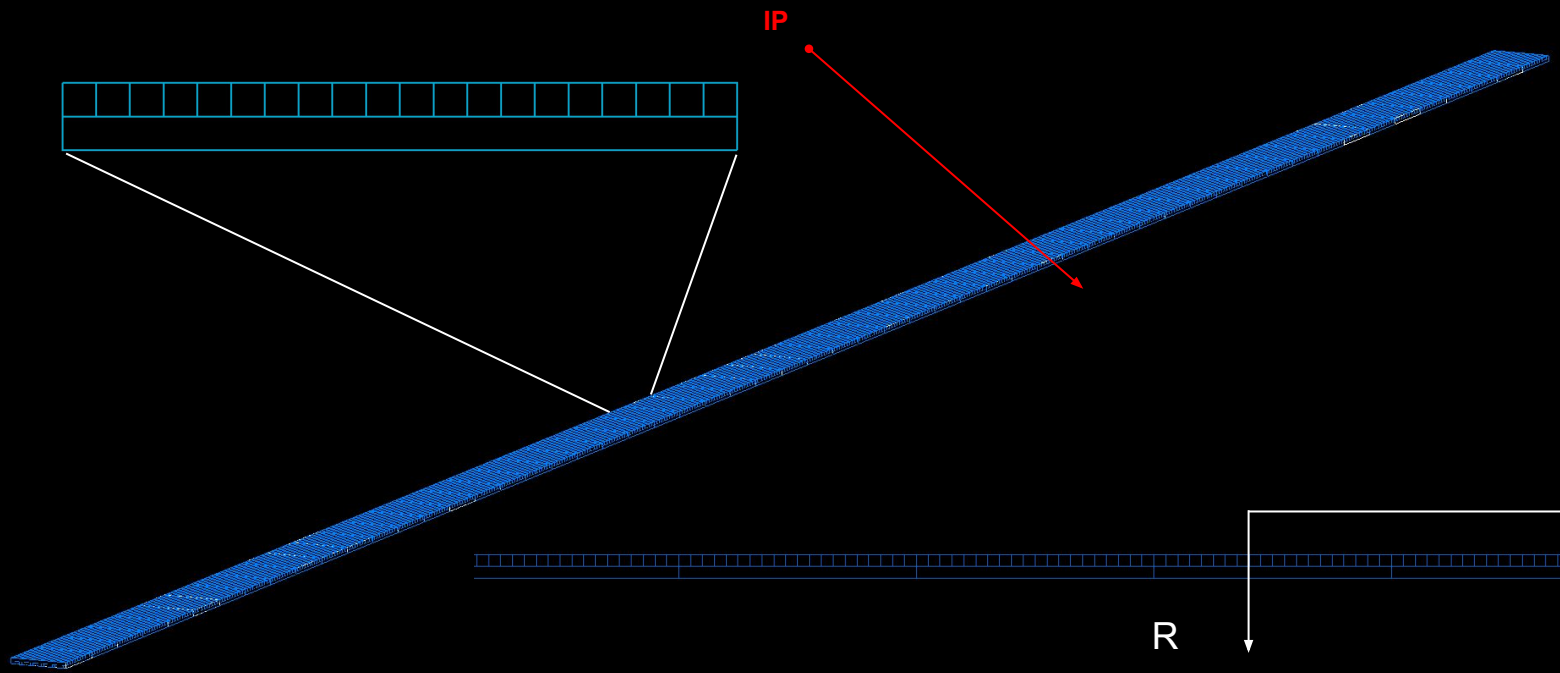




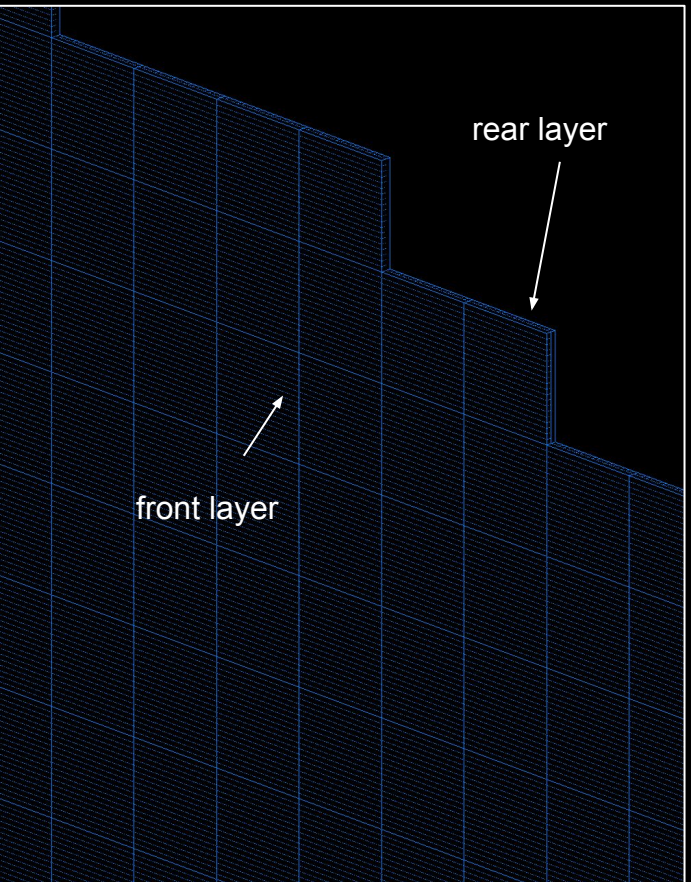
Timing layer barrel

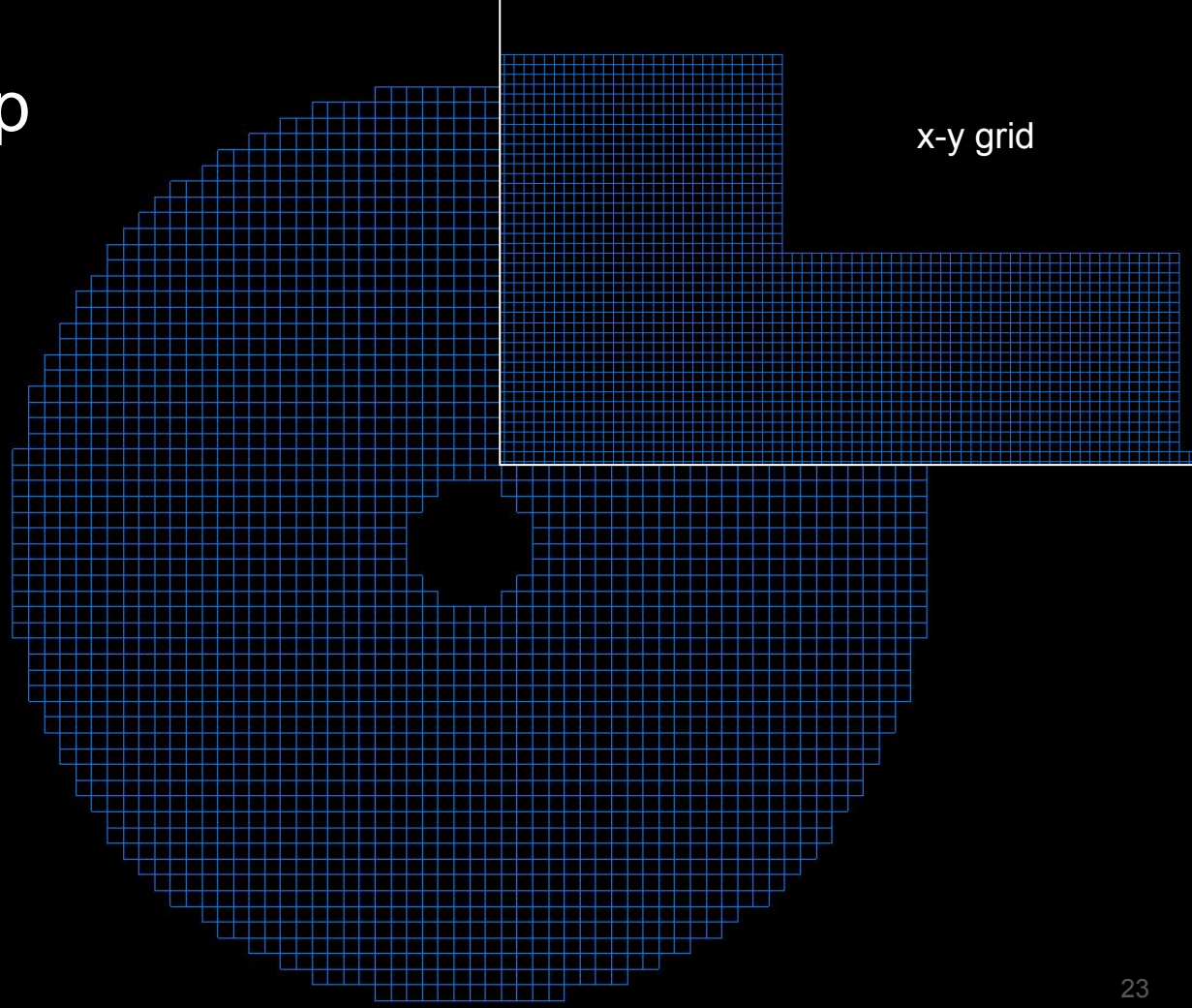
- Trays of modules running along z





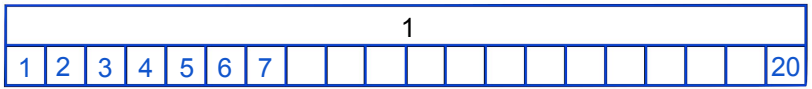
Timing layer endcap





Timing crystal numbering

crystal_ID, module_ID, tray_ID

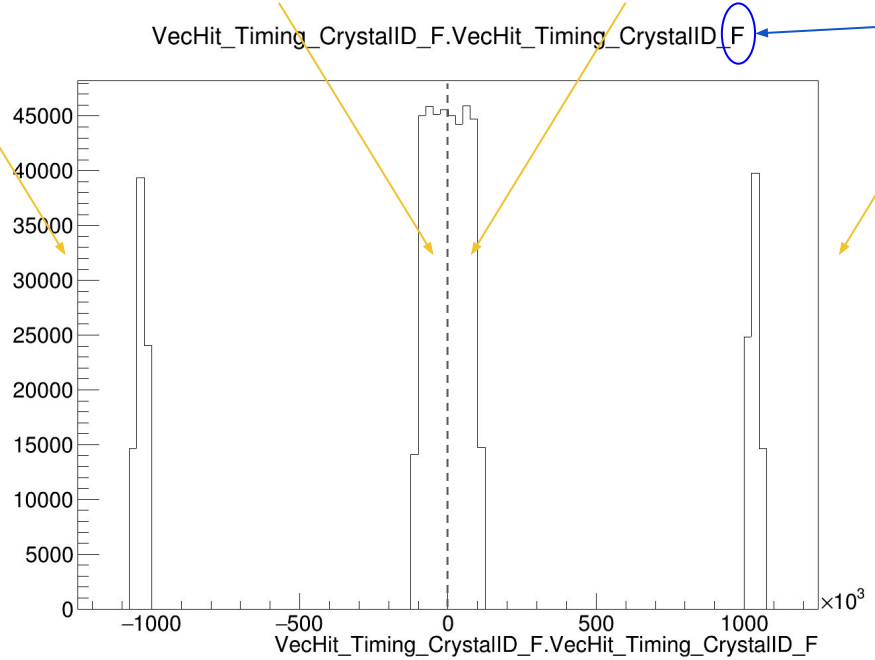


endcap left

barrel left

barrel right

endcap right



Independent vectors for front and rear layer!

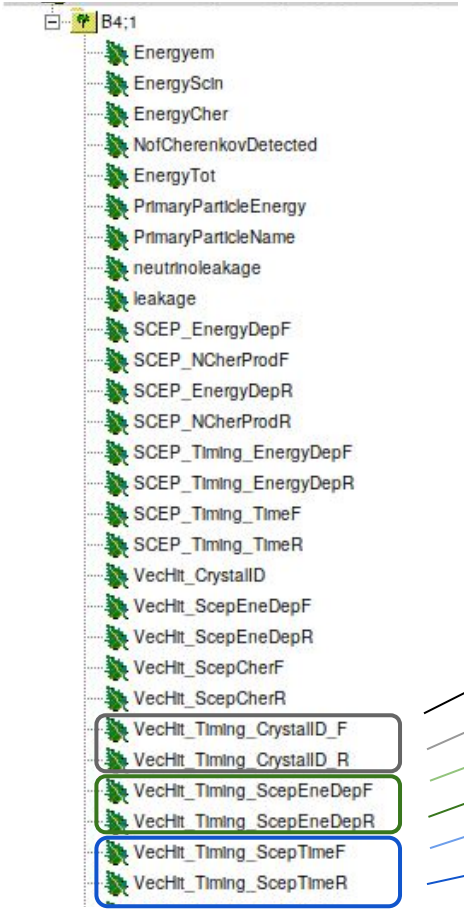
Assign a channel ID to the hit that uniquely identify the crystal position

- Positive IDs for right side
- Negative IDs for left side
- Offset of 1e6 between endcap and barrel numbering

A geometry helper function to retrieve the TVector3 corresponding to a given chID

Same chID for front and rear crystals at the same position

Ntuple variables (timing layers)



A hit for a given chID is created whenever some energy is deposited in either the front or rear segment (front and rear layers treated independently)

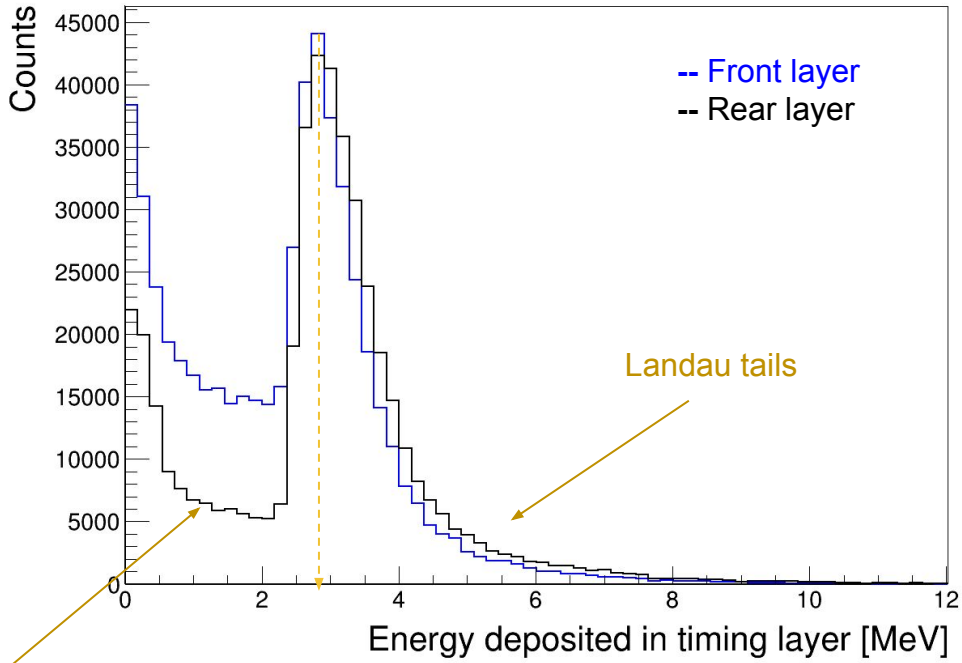
An std::vector for the front (or rear) layer is created containing the following information:

- Channel ID of the corresponding hit in the front layer
- Channel ID of the corresponding hit in the rear layer
- Total energy deposited via ionization in the timing front crystal
- Total energy deposited via ionization in the timing rear crystal
- Time stamp in timing front crystal (*E_dep)
- Time stamp timing rear crystal (*E_dep)

Sanity checks (Timing layers)

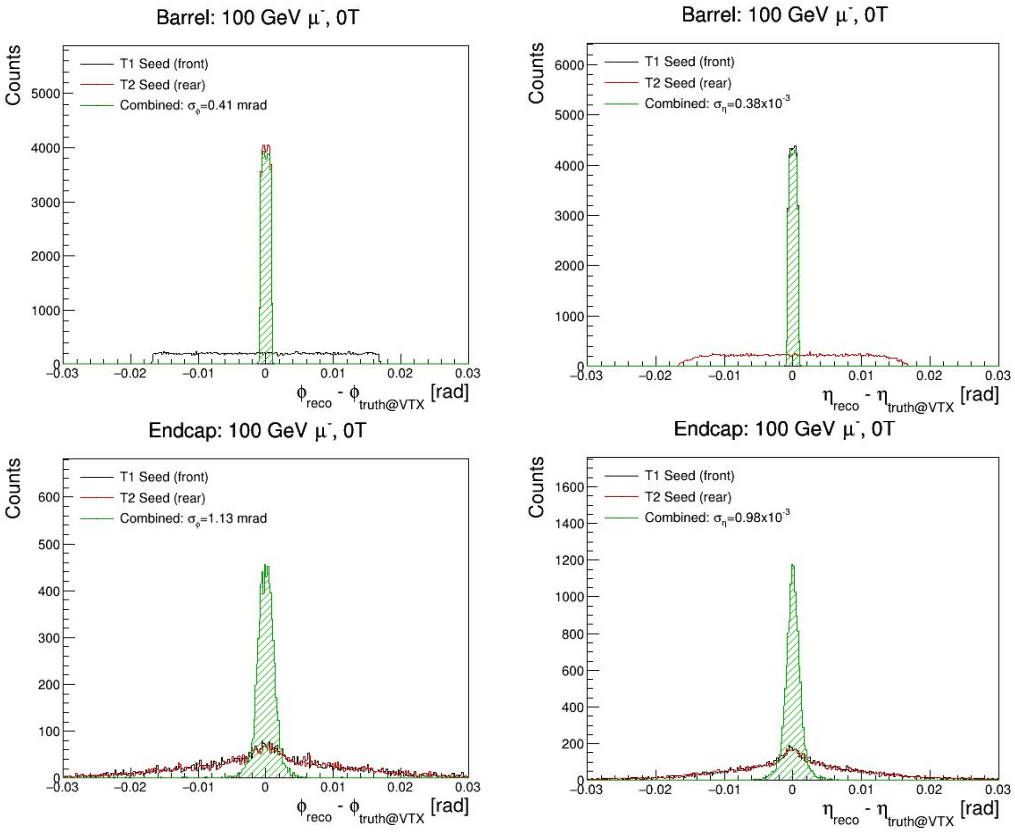
Response to MIPs

- 100 GeV mu- particle gun
- MIP peak at 2.86 MeV as expected for 3 mm LYSO



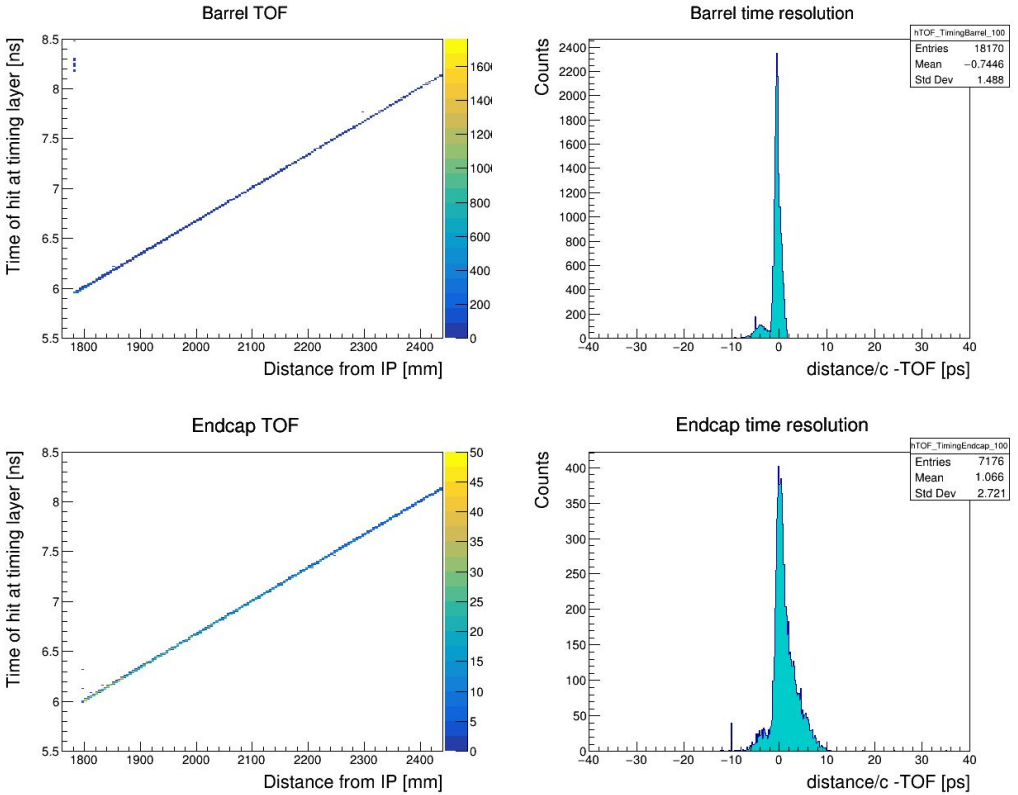
Spatial resolution of timing layer

- 100 GeV muon, 0T field to check geometry and position resolution



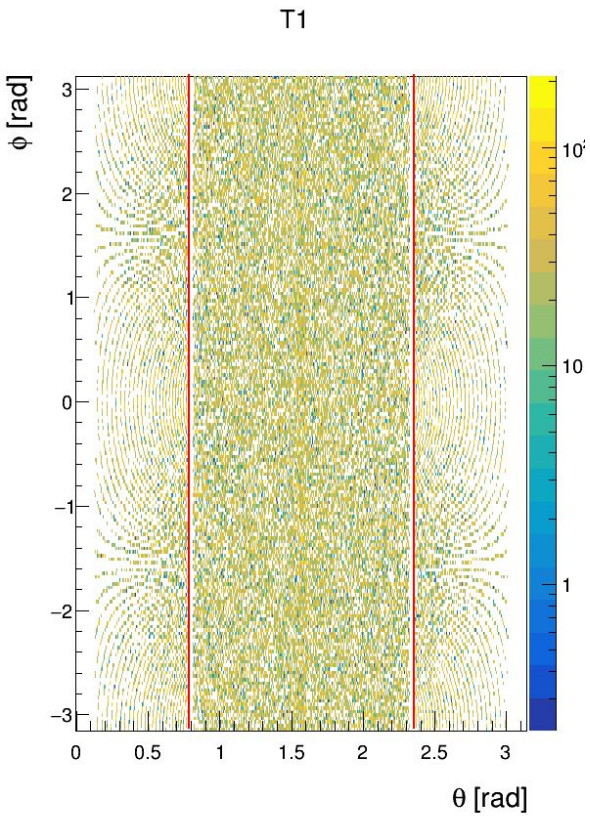
Time of flight resolution

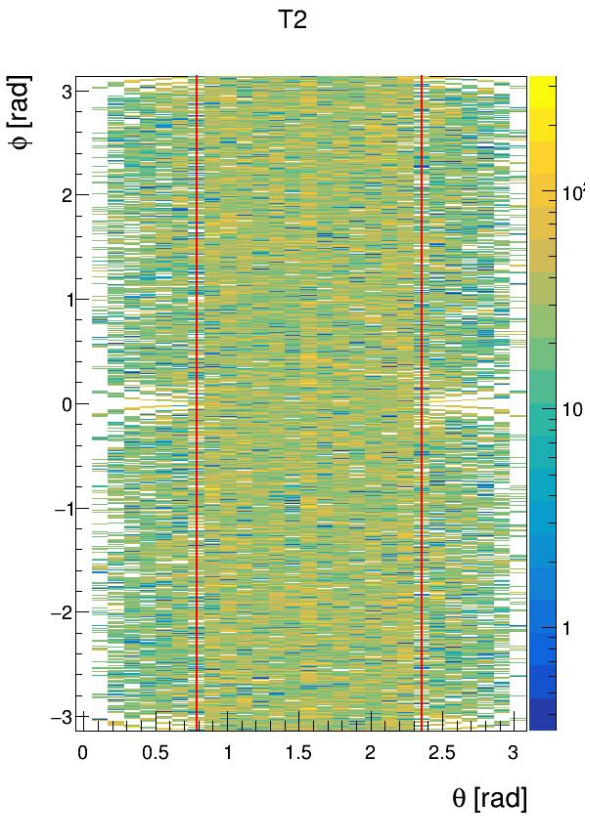
- 100 GeV muon, 0T field to check geometry and time of flight resolution

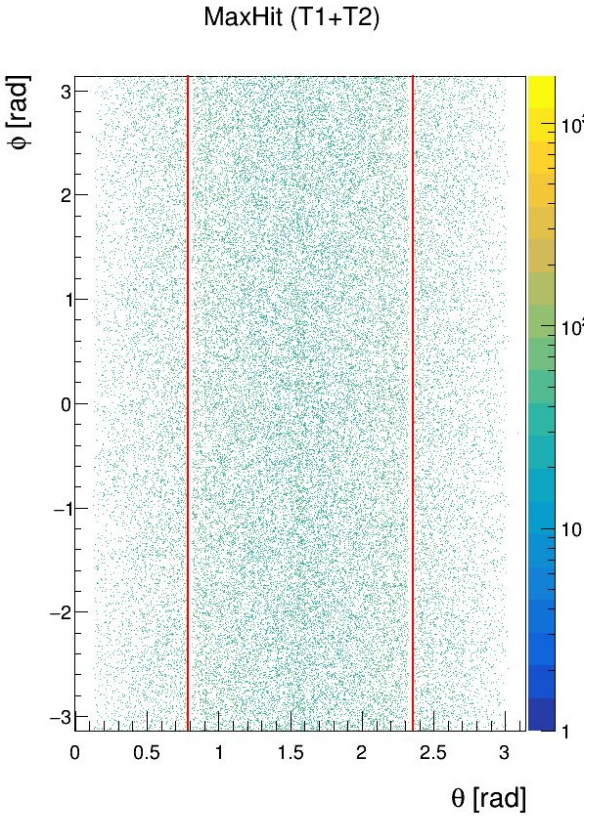


θ-φ Grids (exploiting segmentation)

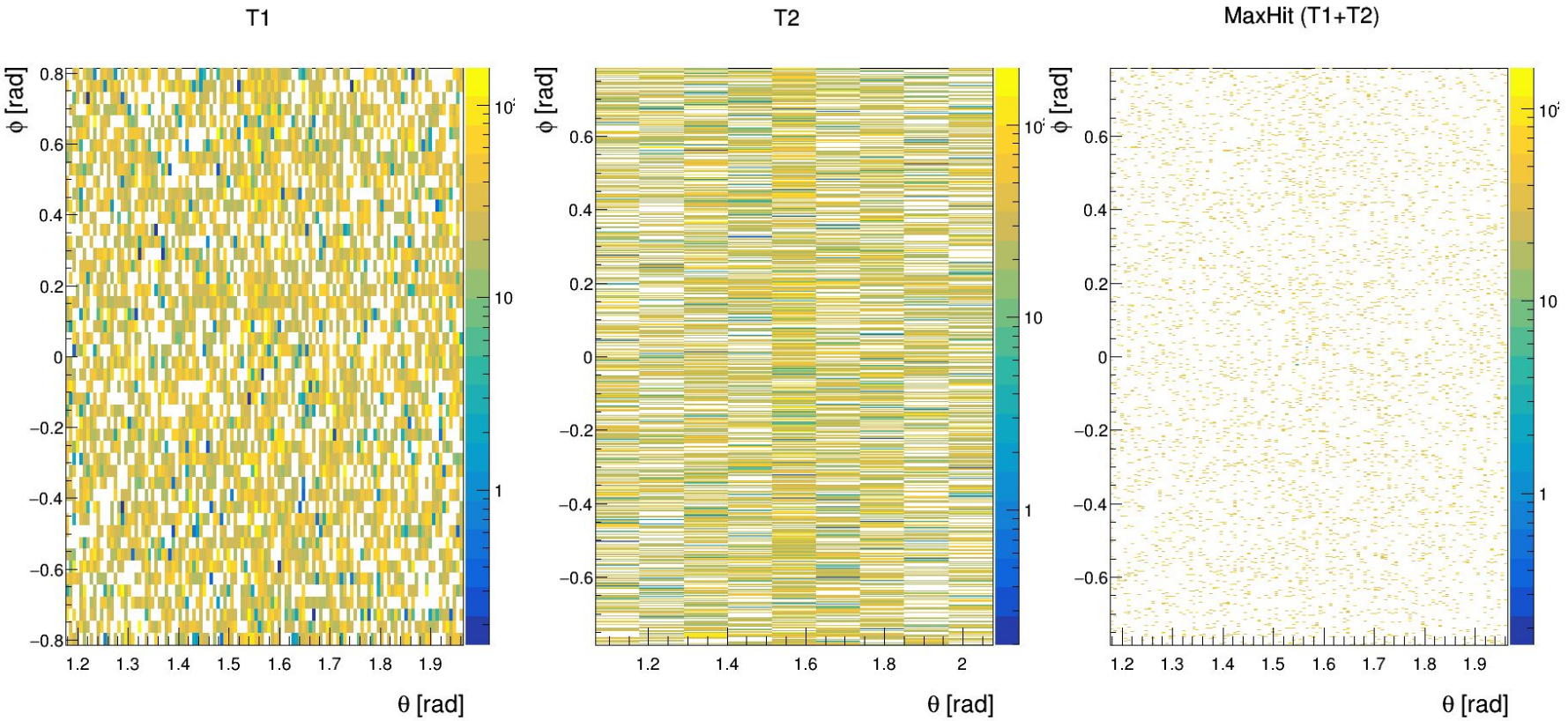
Timing layers - isotropic muon gun



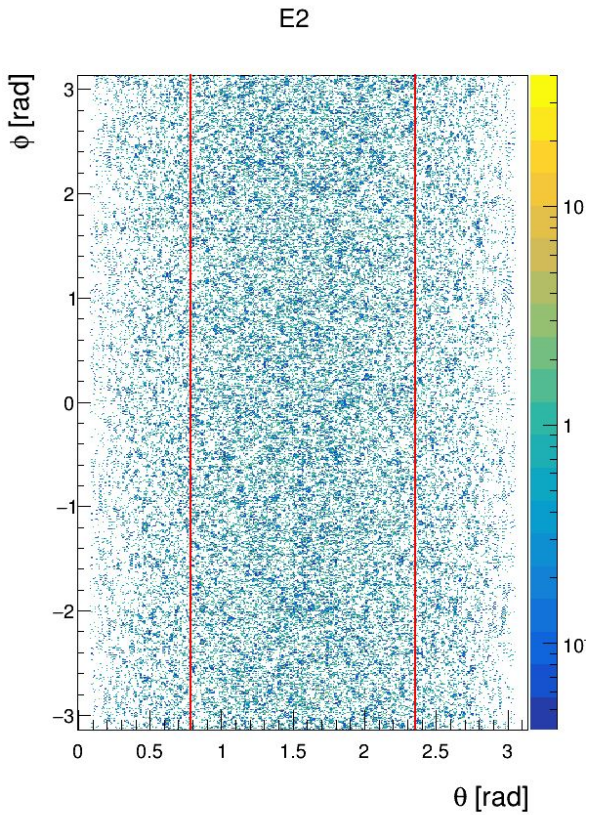


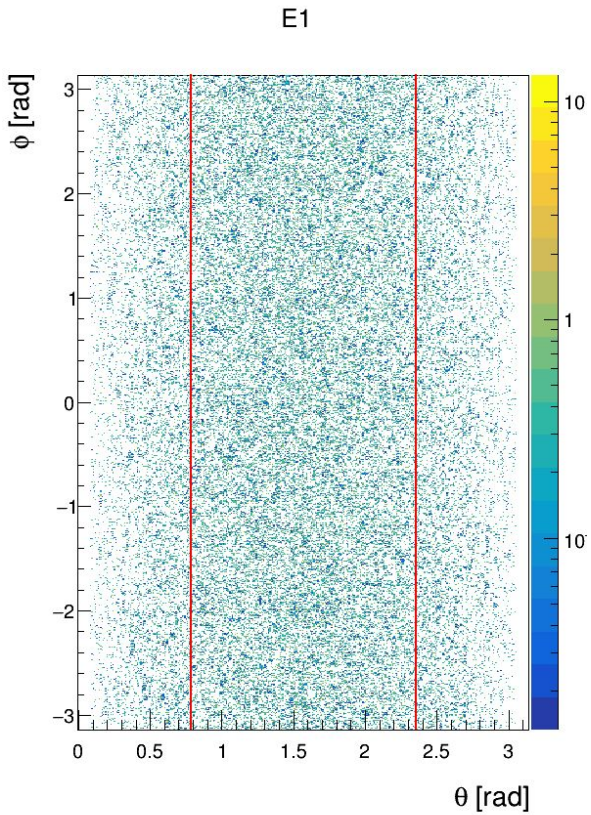


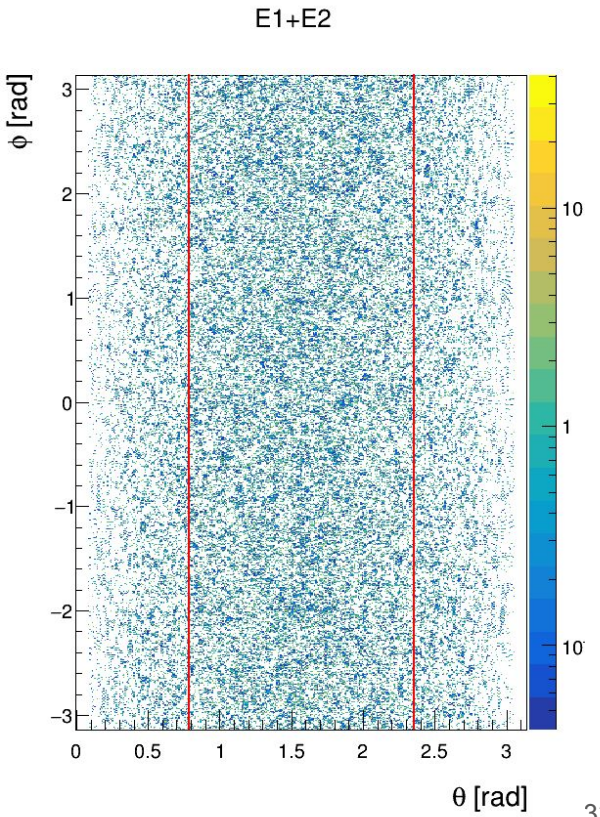
Timing layers - isotropic muon gun (zoom in)



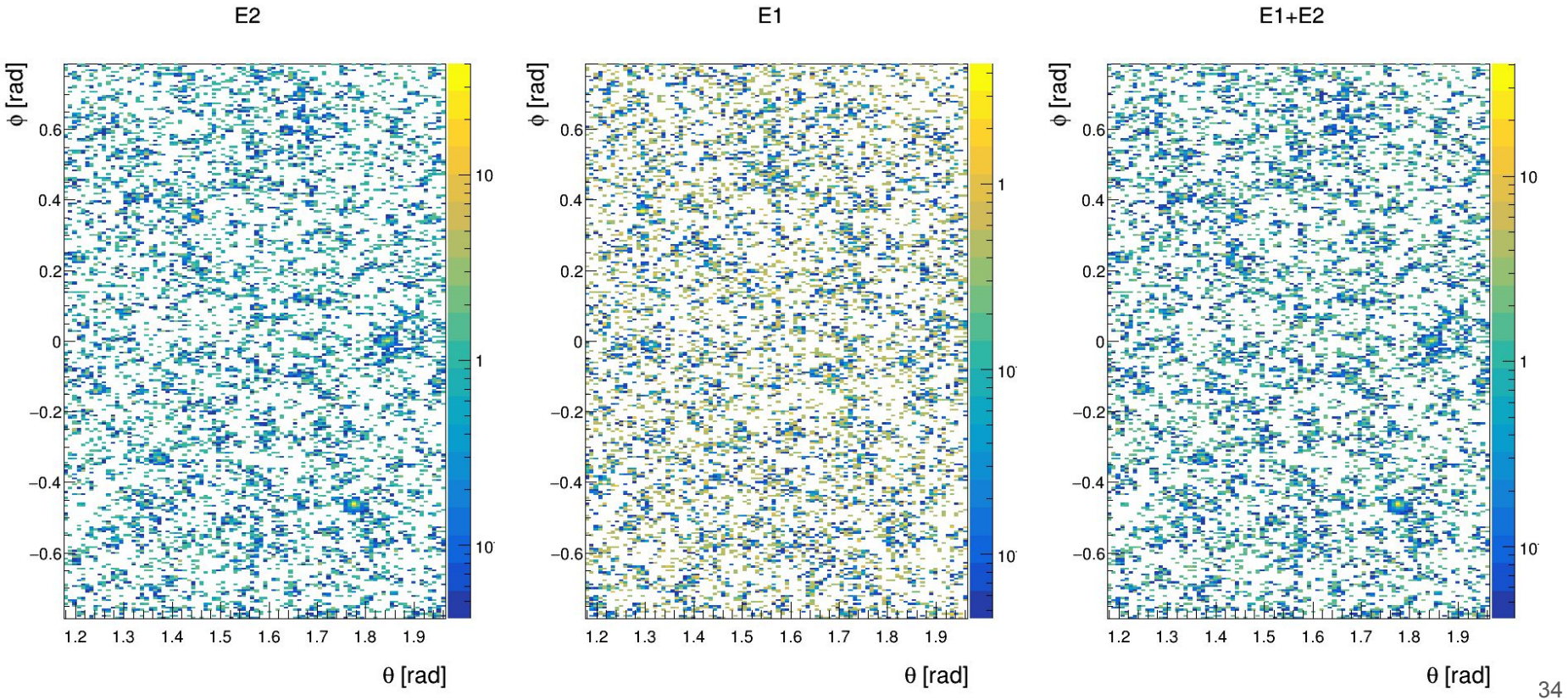
SCEPCal layers - isotropic muon gun



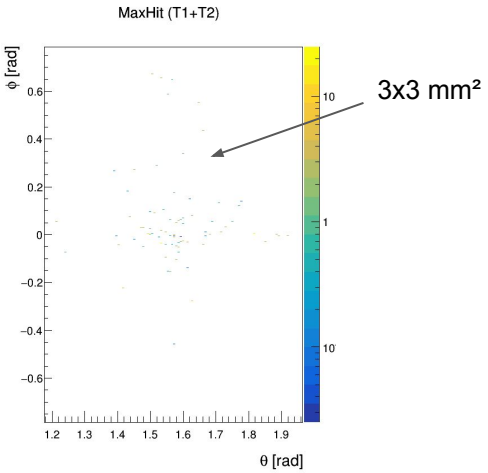


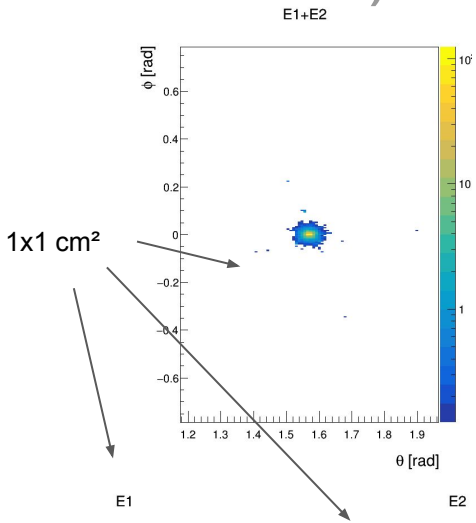


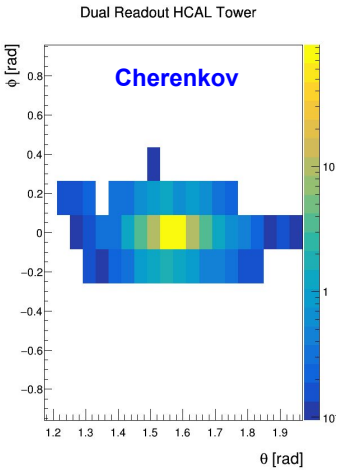
SCEPCal layers - isotropic muon gun (zoom in)

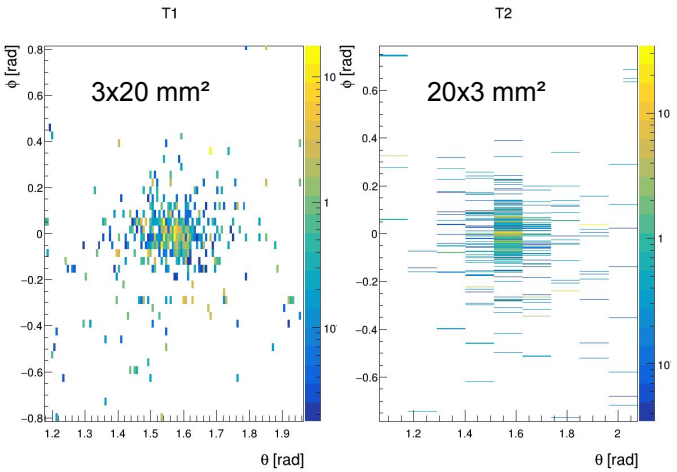


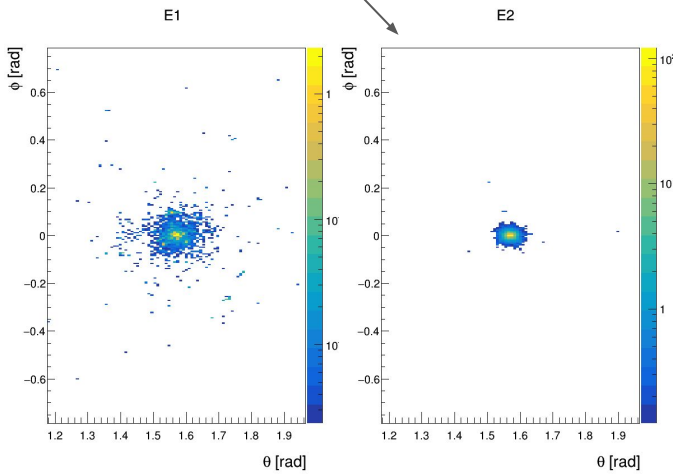
10 GeV neutral kaons (500 events)

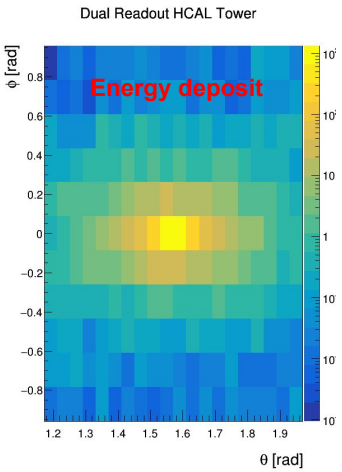












Future developments

Future developments

- A preliminary geometry for the IDEA DR crystal option available on github
- Geometry seems reasonable for first studies:
  - **Need to define a reasonable radial envelope** (currently within the drift chamber volume)
  - Some possible refinement of the geometry
    - PWO endcaps from cone to polycone
    - Granularity, uniform crystal front face dimensions?
    - Add dead material?
- Evaluate energy resolution to hadrons and jets
- Assess benefits from longitudinal segmentation for PID through CNN
- Consider migration to EDM4hep (and later in DD4HEP?)