Update on simulation studies for a crystal calorimeter option in IDEA

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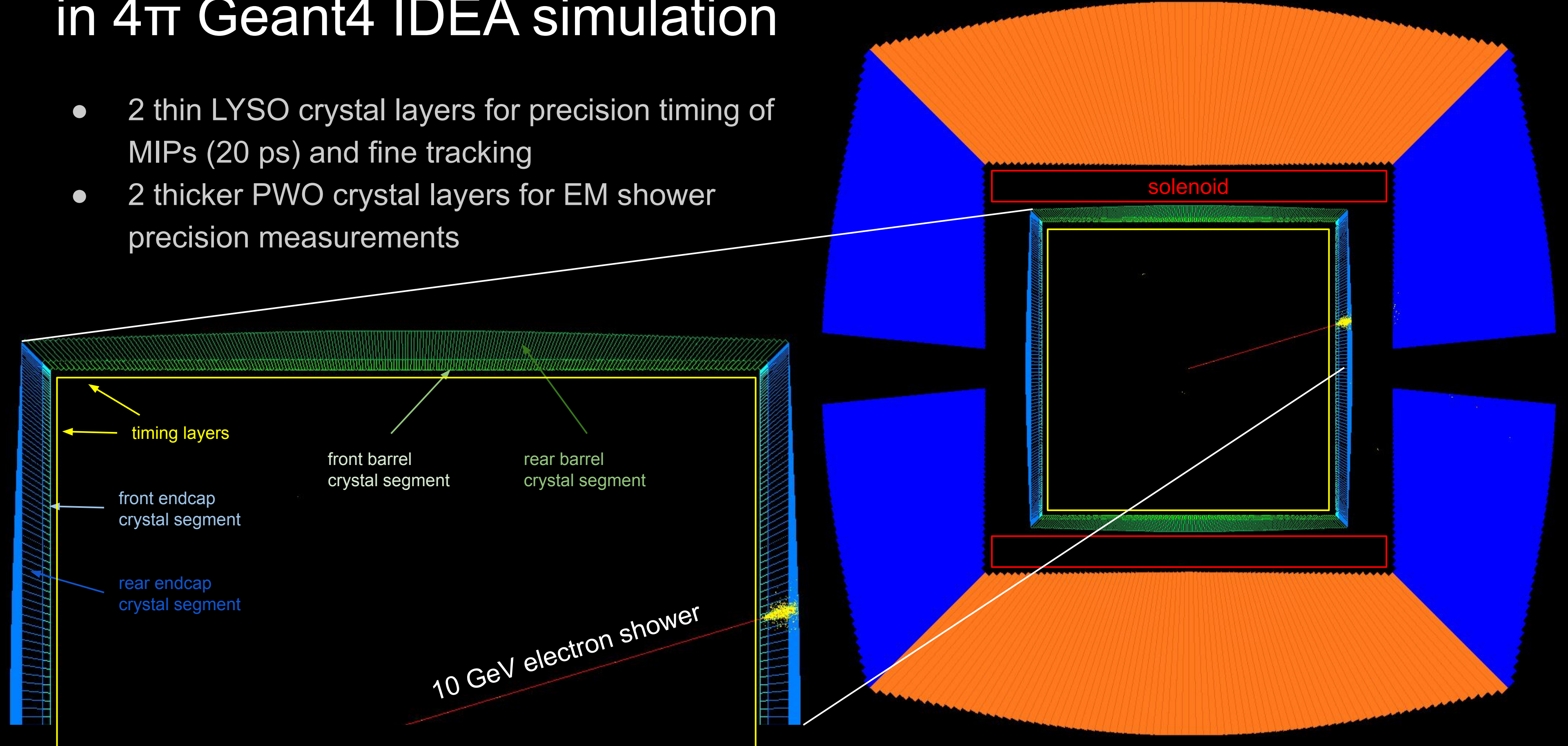
W.Chung, M.Lucchini, T.Shemma, C.Tully

[1]Princeton University

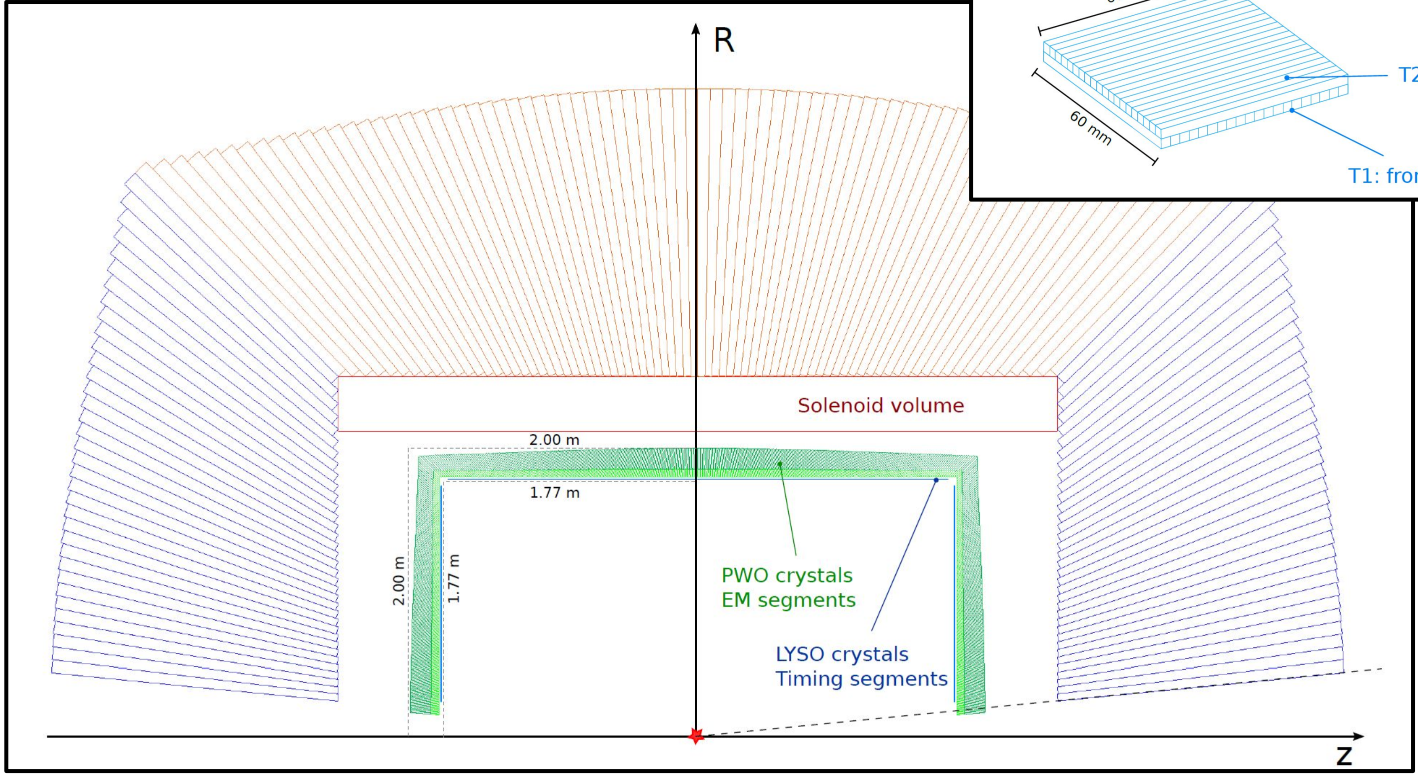
PRINCETON UNIVERSITY

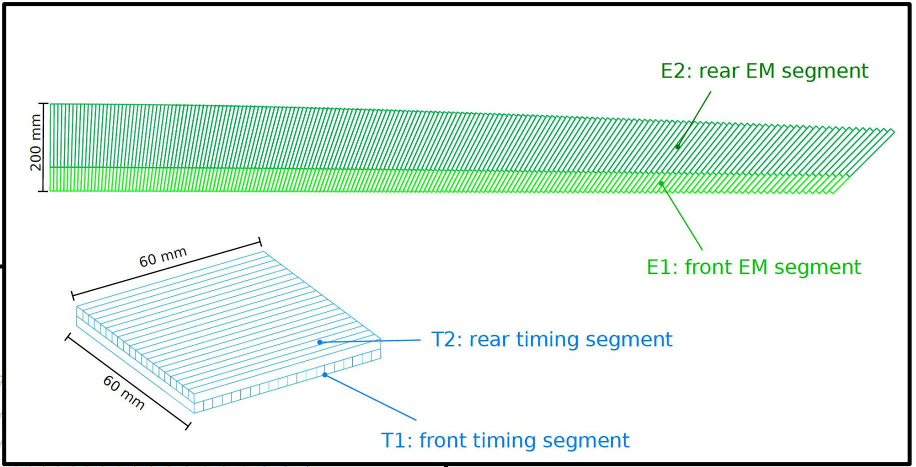
Integration of crystal calo option in 4π Geant4 IDEA simulation

- 2 thin LYSO crystal layers for precision timing of MIPs (20 ps) and fine tracking
- 2 thicker PWO crystal layers for EM shower precision measurements



Geometry





- Just inside the solenoid
  ~22 cm of radial space
  ~22 X_0 ~ 1 λ_I

- 2 MIP timing layers as a planar XY grid
- 2 EM shower layers with projective geometry

Signals

- Hits in MIP timing layers:
  - t1, t2, E1, E2

Scintillation signal and time stamp from both layers

- Hits in EM shower layers:

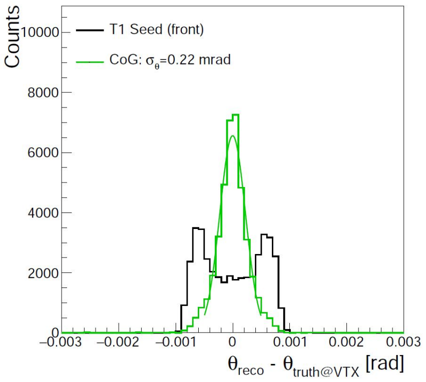
$$S_F = \mathcal{P}(E_{dep,F} \cdot LY \cdot \epsilon_S)$$
$$S_R = \mathcal{P}(E_{dep,R} \cdot LY \cdot \epsilon_S)$$
$$S = S_F + S_R$$
$$C = C_R = \mathcal{P}(N_{cher,prod,R} \cdot \epsilon_C)$$

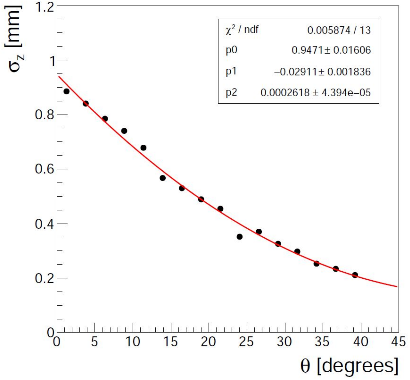
Scintillation signal from both front and rear segments

Cherenkov signal from only the rear segment

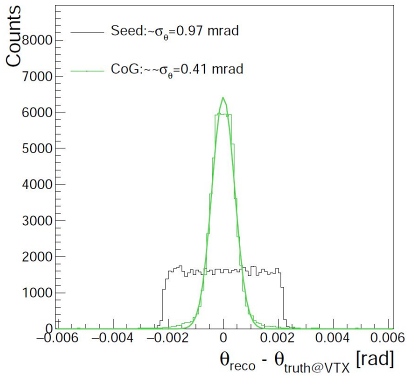
Angular resolution

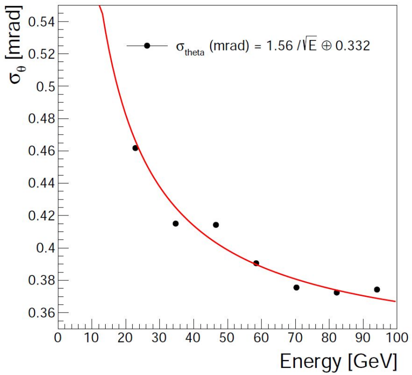
- **T1+T2:** 0.3-1.0 mm spatial resolution along z with the MIP timing layer grid (muons)





- **E1+E2:** 0.3-0.45 mrad angular resolution for EM particles using center of gravity of the shower (photons)





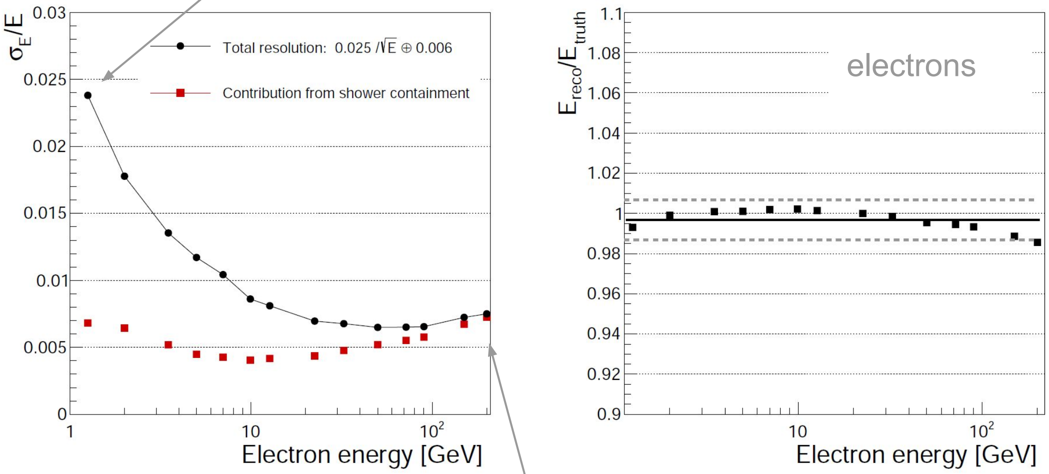
Energy resolution for EM particles

- Energy resolution:

$$\frac{\sigma_E}{E} \sim \frac{2.5\%}{\sqrt{E}} \oplus 0.6\%$$

- Linearity within ±1%

Driven by photostatistics as no tracker/dead material currently in simulation



Some shower leakage beyond 200 GeV

The dual readout method for a hybrid calorimeter

1. Apply the DRO correction on the energy deposits in the crystal and fiber segments first

2. Sum up the corrected energy from both segments

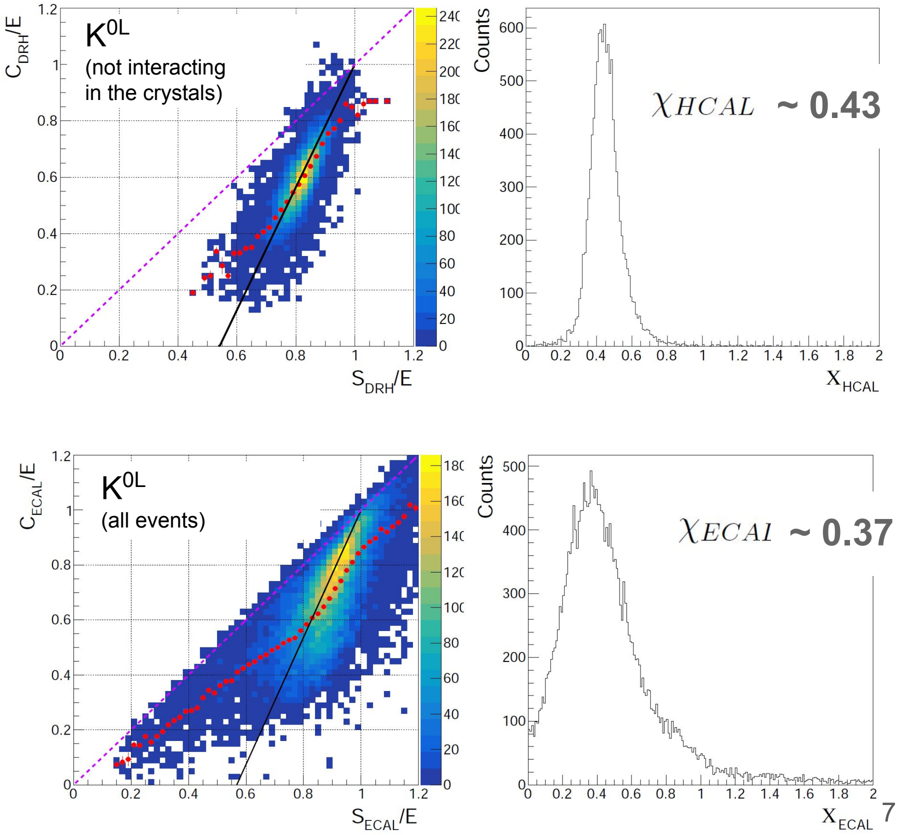
$$E_{HCAL} = \frac{S_{HCAL} - \chi_{HCAL} C_{HCAL}}{1 - \chi_{HCAL}}$$

$$E_{ECAL} = \frac{S_{ECAL} - \chi_{ECAL} C_{ECAL}}{1 - \chi_{ECAL}}$$

$$E_{total} = E_{HCAL} + E_{ECAL}$$

$$\chi_{HCAL} = \frac{1 - (h/e)_s^{HCAL}}{1 - (h/e)_c^{HCAL}}$$

$$\chi_{ECAL} = \frac{1 - (h/e)_s^{ECAL}}{1 - (h/e)_c^{ECAL}}$$

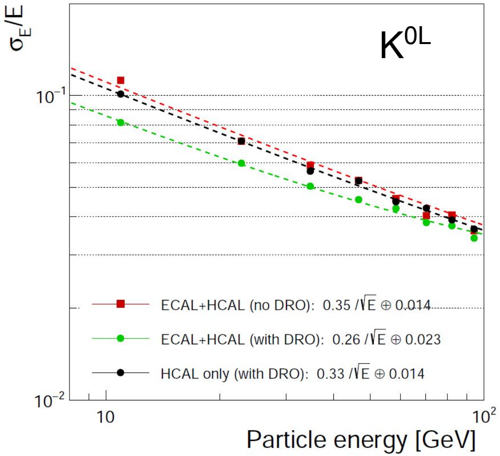


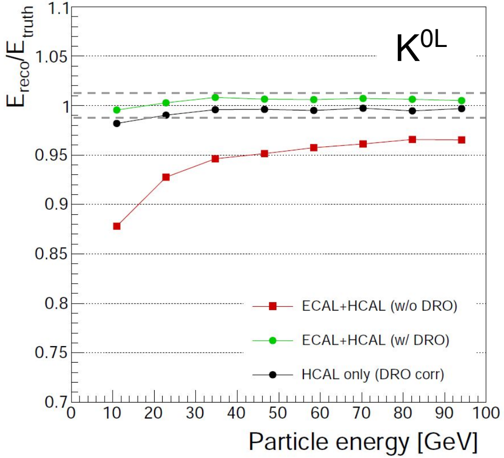
Energy resolution for neutral hadrons

- Energy resolution comparable to that of the fiber-only IDEA calorimeter:

$$\frac{\sigma_E}{E} = \frac{26\%}{\sqrt{E}} \oplus 2.3\%$$

- Linearity within ±1%



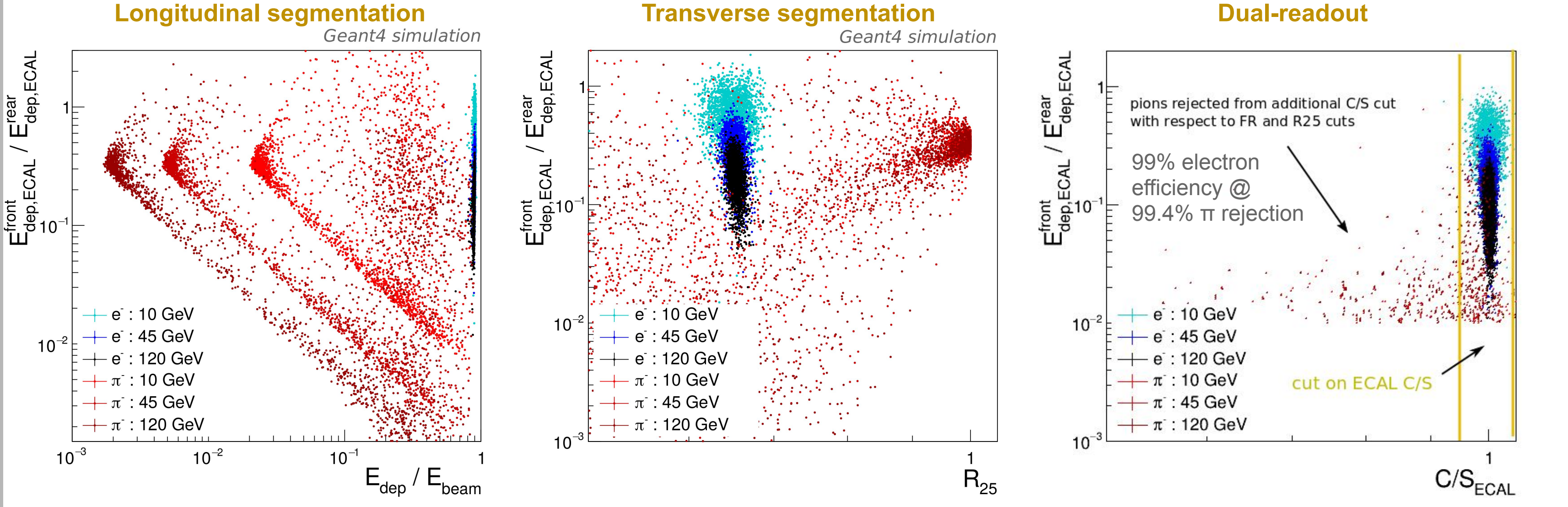


Results comparable with standalone Geant4 simulation published in:
[M.Lucchini et al, JINST 2020 15 P11005]

Particle ID with crystal segmentation

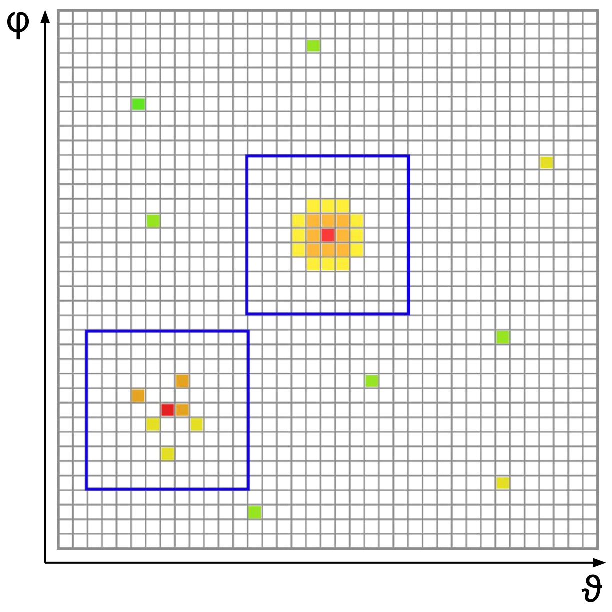
Standalone Geant4 study from
[M.Lucchini et al, JINST 2020 15 P11005]

- Topology of longitudinal/transverse energy deposits in crystals provides a **clear $e^{+/-}/\pi^{+/-}$ discrimination**→better than 99% electron efficiency at 99% pion rejection (with simple cuts)
- **Large potential for improvement with the addition of dual-readout information** and use of more sophisticated pattern recognition algorithm



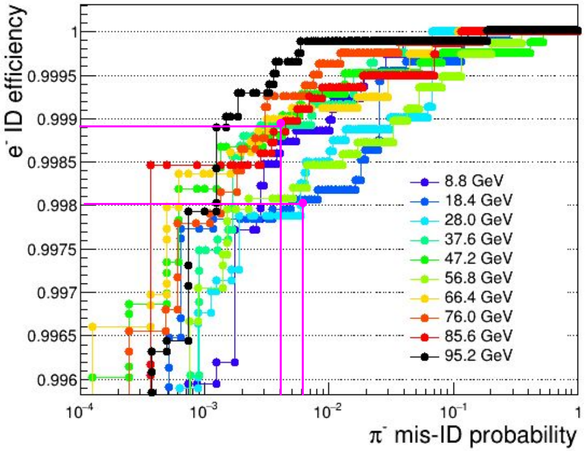
Exploiting CNN for particle ID (4π detector)

- Single particle gun events **(e^-, ɣ, π^0, π^-, K^{0L}) isotropically**
- Flat energy distribution in **1-100 GeV range**
- Process data to:
  - Find '**seed ECAL crystal'** in the full calorimeter (i.e. crystal with the highest energy deposit)
  - Select a square image of **45x45 pixels** (=crystals) around the seed crystal (→ **45x45** cm²)
  - 10 MeV energy cut on ECAL hits (hits in ECAL crystals with total energy lower than 10 MeV are not used to build the images)
- **Train a convolutional neural network for particle discrimination:**
  - **e^- / π^-**
  - **ɣ / π^0**
  - **ɣ / K^{0L}**



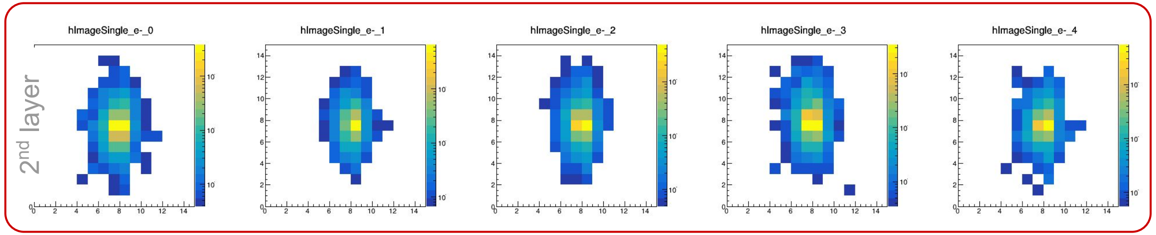
$\pi^{\pm}$ / $e^{\pm}$ identification with CNN

- Crystal calo only performance comparable to fiber calo only
- Further improvement by combining both calorimeter segments

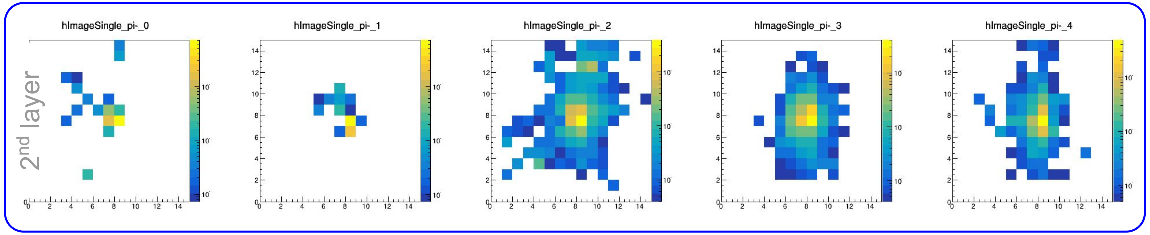


	IDEA Pb only		Crystal calo only	
	e^- ID	π^- mis-ID	e^- ID	π^- mis-ID
20 GeV	99.4%	0.8%	99.8%	0.6%
60 GeV	99.8%	0.4%	99.9%	0.4%

single e^- events



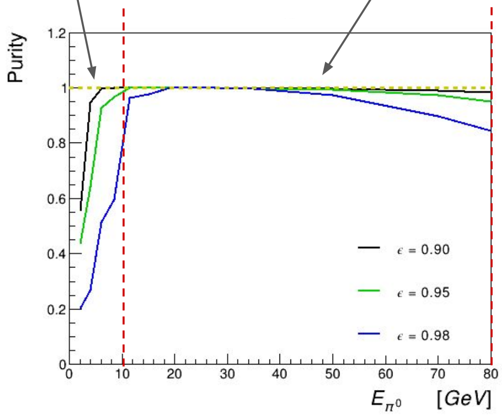
single π^- events

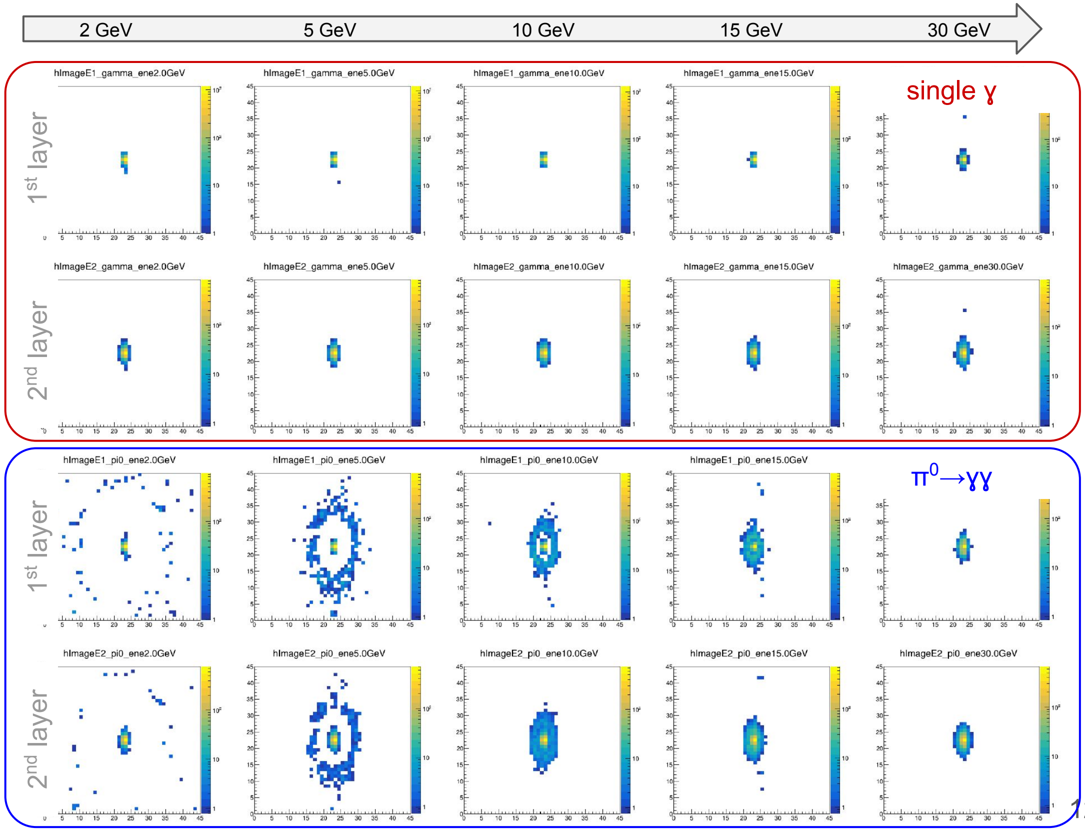


π^0 / γ identification with CNN

One photon with very low energy can be missed

Good separation in range 10-80 GeV





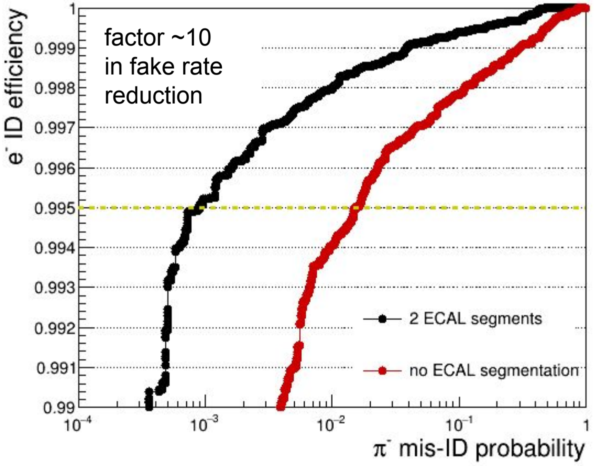
- In CEPC CDR requirement:

over all solid angle. To identify the τ-leptons in the different decay modes, the photons should be distinguishable from π^0's with an efficiency and purity higher than 95% measured in the $Z \to \tau^+\tau^-$ event sample at the CEPC Z factory operation.

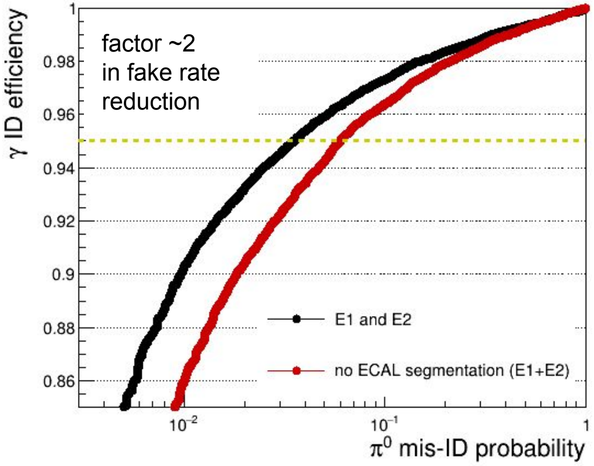
Crystal longitudinal segmentation matters

- Tangible improvements in particle ID with longitudinal ECAL segmentation (2 layers wrt to 1)
-

$\pi^{\pm} / e^{\pm}$



π^{0} / γ



For all events in range
1-100 GeV energy

Jets (event display)

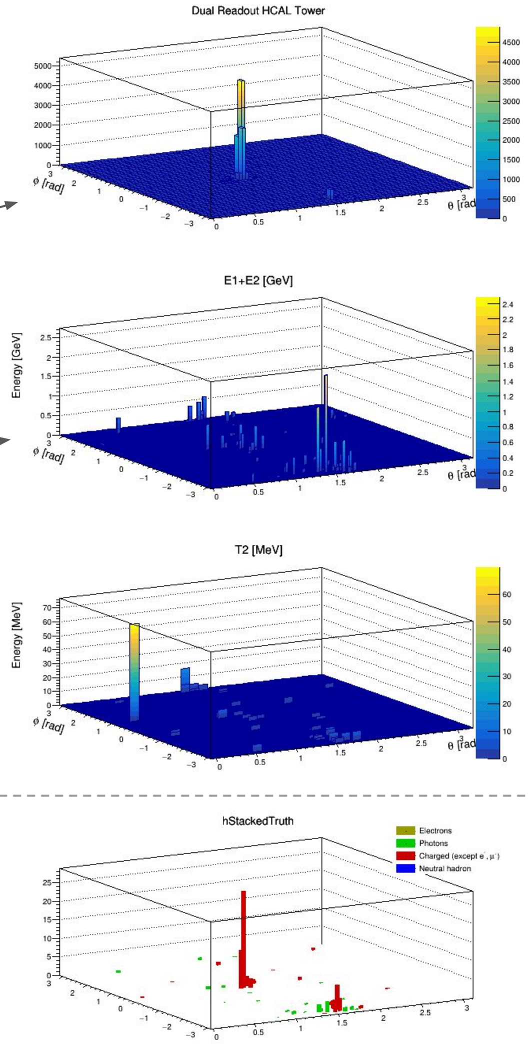
WW→jjμν

Hadron showers

Mainly **photon** and **electron** showers but also half of the **hadrons start showering**

All MIPs leave a track here

- Charged hadrons (mainly $\pi^{\pm}$)
- Neutral hadrons (mainly K^{0L})
- Photons (mainly from π^{0})
- Electron
- (Muons and neutrinos not displayed on truth graph)



Fiber calo towers

Crystal EM shower layers (E1+E2)

Crystal timing layer (T1)

MC truth

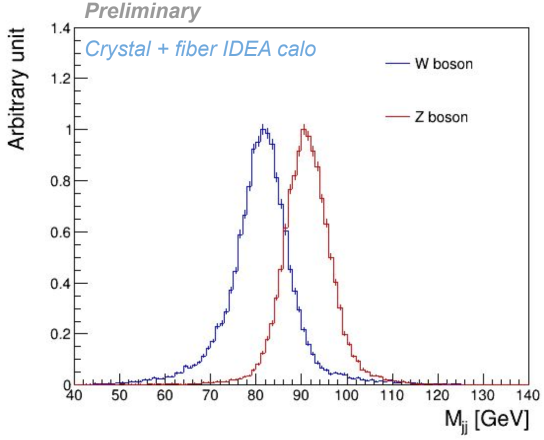
Hybrid dual-readout in jets

Running on same hepmc files from L.Pezzotti

- Run jet clustering algorithm using all crystal and fiber calo hits
- For each jet create a sub-jet with the contribution from the:
  - Fiber calo scintillation hits only
  - Fiber calo Cherenkov hits only
  - Crystal calo scintillation hits only
  - Crystal calo Cherenkov hits only

- Reconstruct the dual readout corrected jet energy by correcting the crystal and fiber jet component based on the respective DRO signals (as for single hadrons)

- **Room to improve the jet DRO correction algorithm**
  + expected improvement by exploiting PFA
  (identify single particles belonging to the jet)



- **ee→WW→jjμν**
- **ee→HZ**
  →□□jj

Summary and outlook

- Progress on **integration of a crystal calorimeter option** in front of the IDEA fiber calo within the Geant4 simulation framework of L.Pezzotti

- **Single particle studies to validate geometry** show consistent results
  - Angular resolution
  - EM Energy resolution
  - Hadron energy resolution

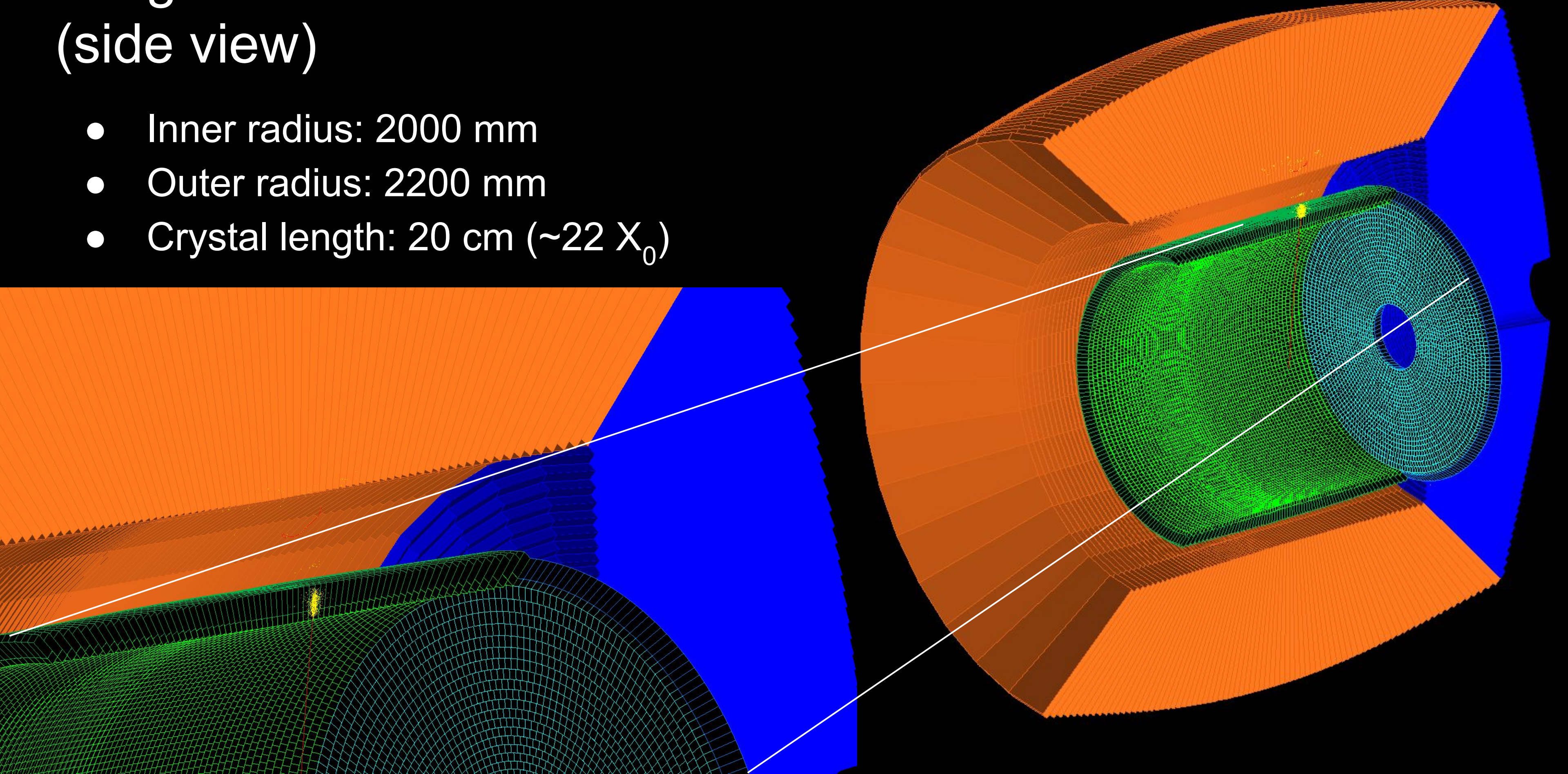
- **Jet studies** ongoing → preliminary results comparable with fiber calo only

- Ongoing work to **study** the **particle identification potential of the crystal calorimeter using Convolutional Neural Networks**

Additional material

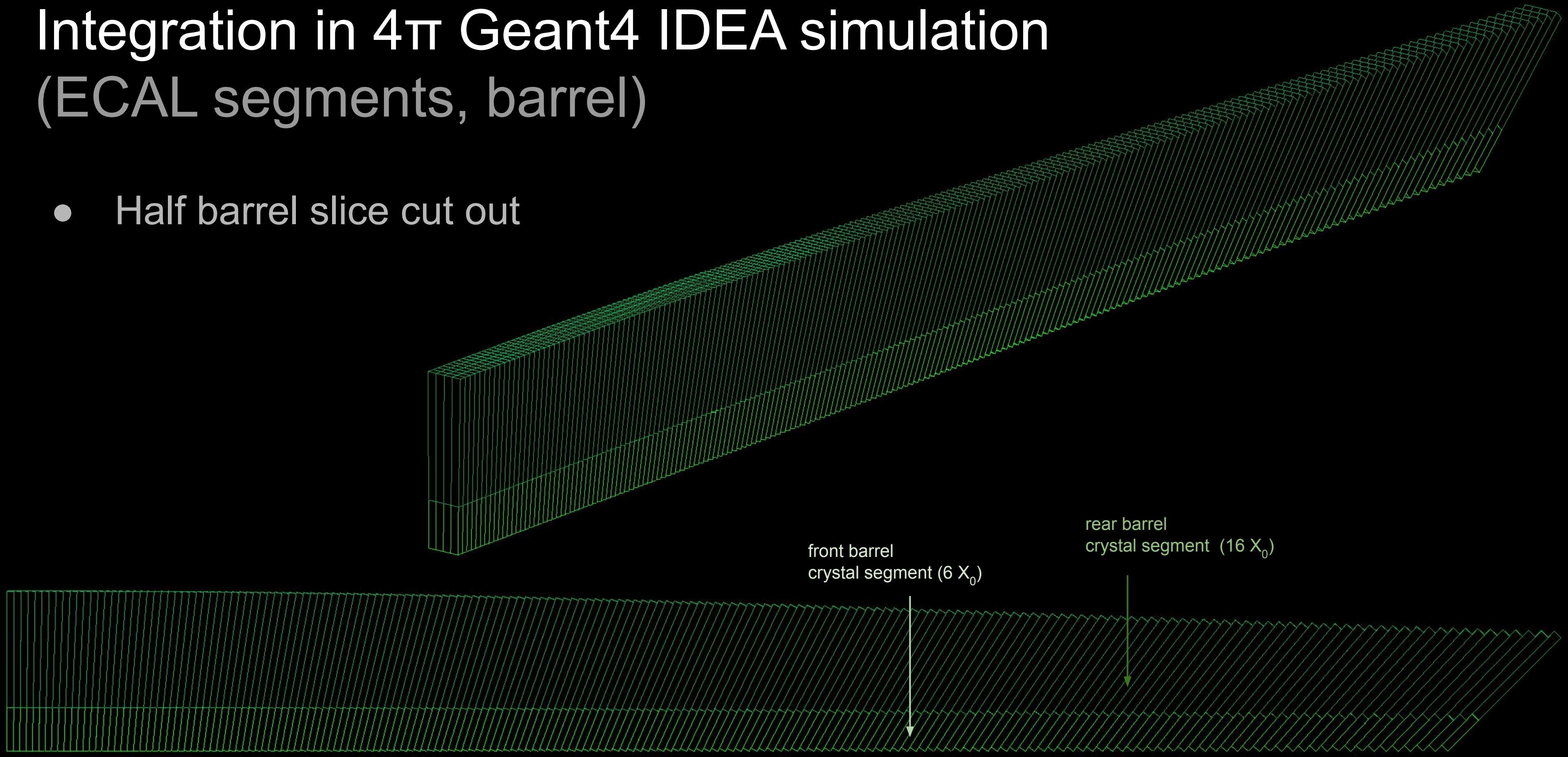
Integration in 4π Geant4 IDEA simulation (side view)

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



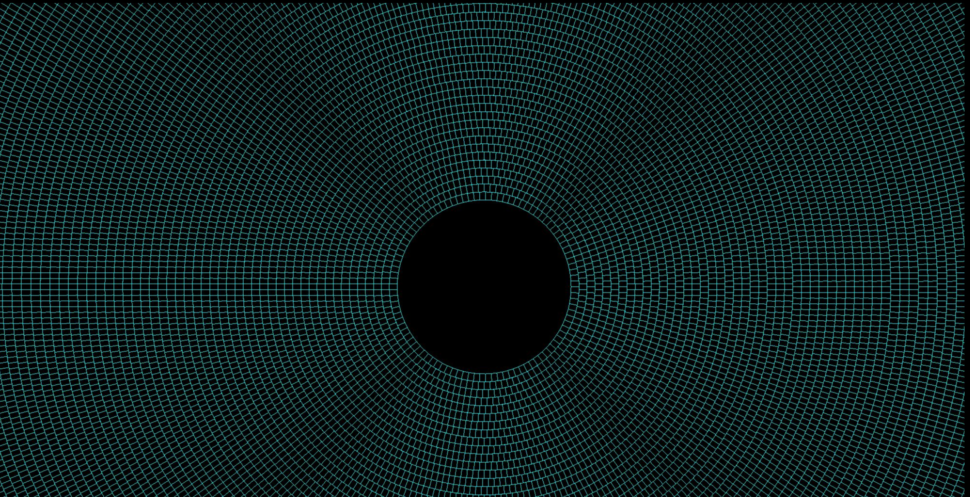
Integration in 4π Geant4 IDEA simulation
(ECAL segments, barrel)

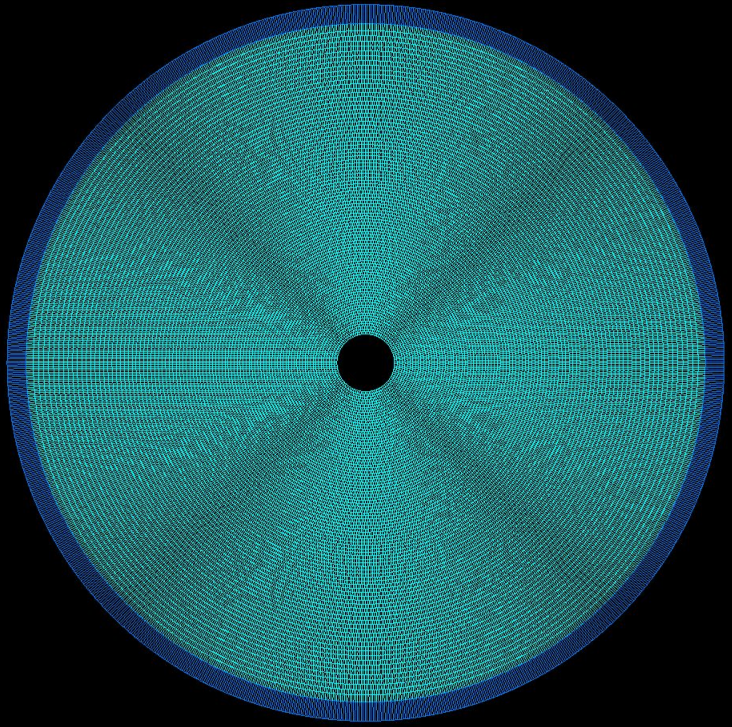
- Half barrel slice cut out

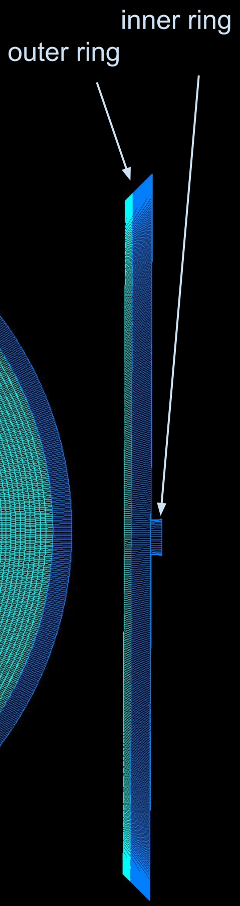


Integration in 4π Geant4 IDEA simulation
(ECAL segments, endcap)

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







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)