7th FCC Physics Workshop

Laboratoire d'Annecy de physique des particules

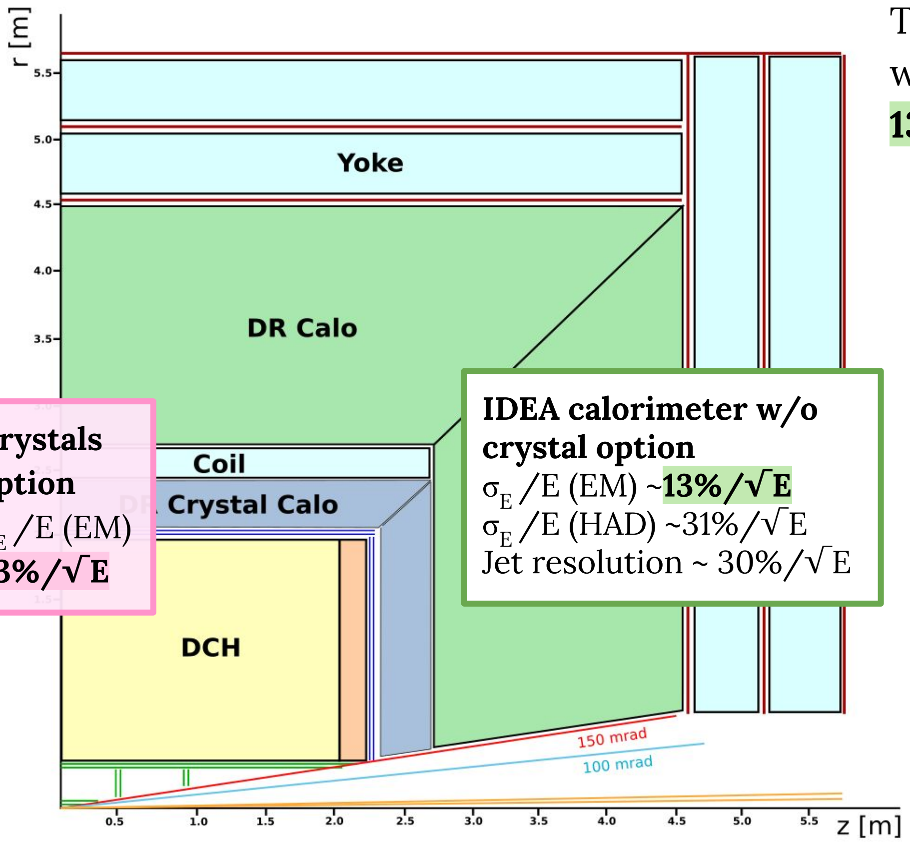
Towards Dual Readout Crystal Reconstruction

Flavia Cetorelli[2,3], Wonyong Chung[4], Marco Lucchini[1,2], Chris Tully[4]

1. Università degli Studi di Milano - Bicocca
2. INFN Milano-Bicocca
3. CERN
4. Princeton University

01/02/2024

IDEA detector with crystals option



Crystals option
σ_E/E (EM) ~**3%/√E**

IDEA calorimeter w/o crystal option
σ_E/E (EM) ~**13%/√E**
σ_E/E (HAD) ~31%/√E
Jet resolution ~ 30%/√E

The addition of a dual readout crystals calorimeter will **improve** the **EM energy resolution** from **13%/√E** to **3%/√E:**

- Enhance the **reconstruction** of physics objects and expand the **FCCee physics program:**
  - CP violation studies with Bs decay to **low energy photons** arXiv:2107.05311
  - Clustering of π0 's photons to **improve jet clustering** algorithm JINST 15 P11005
  - Enhance collection of bremsstrahlung photons to improve the **resolution** of **Z→ee** decays arXiv:1811.10545

The crystals calorimeter will be inserted **before the coil** [2.1-2.4] m:

- Preshower removed.
- Fiber calorimeter reduced by 20 cm.
- Muon and tracker systems untouched.

The DR crystal calorimeter option

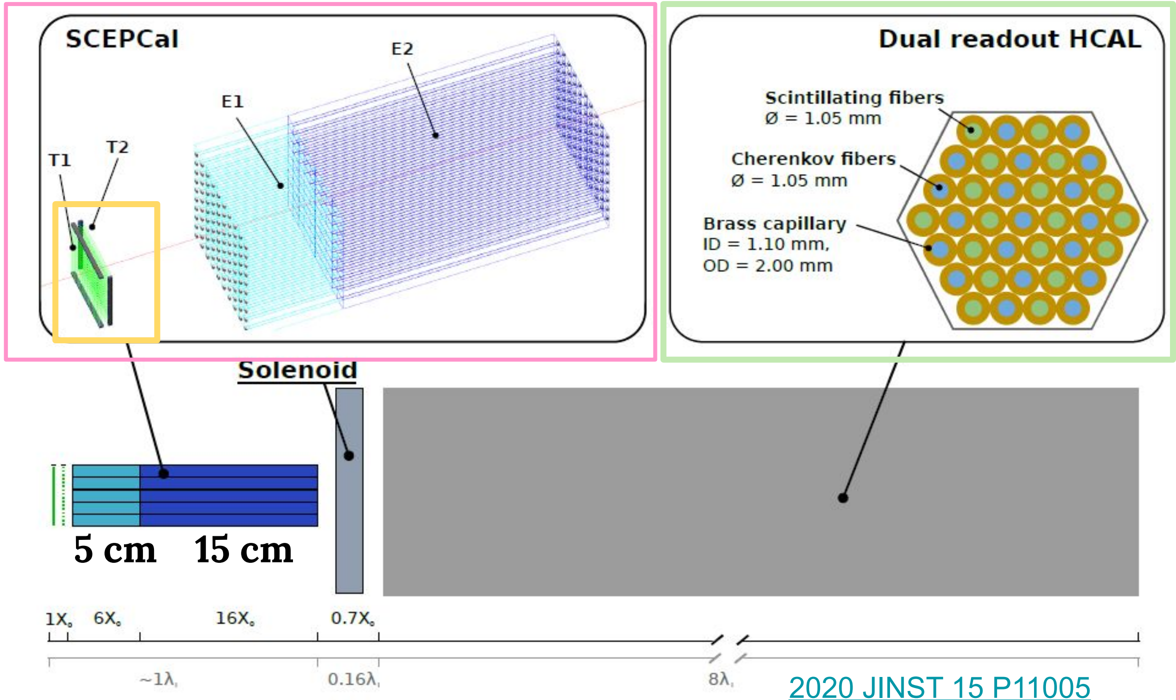
Two layers of $PbWO_4$ (baseline) crystals:

- **longitudinal** segmentation: 5 cm (**6 X_0**) + 15 cm (**16 X_0**) ,
- **transverse** segmentation: 1x1 cm^2 - 1.5x1.5 cm^2

Provide more info to **particle flow** algorithms and improve **PID**

Reading out from the crystals:

- Time information
- Position information (x,y,z)
- Energy deposited **scintillation light**
- Number of **Cherenkov photons**



Possible addition of **timing layers** → to achieve a time resolution **~20 ps** for MIPs

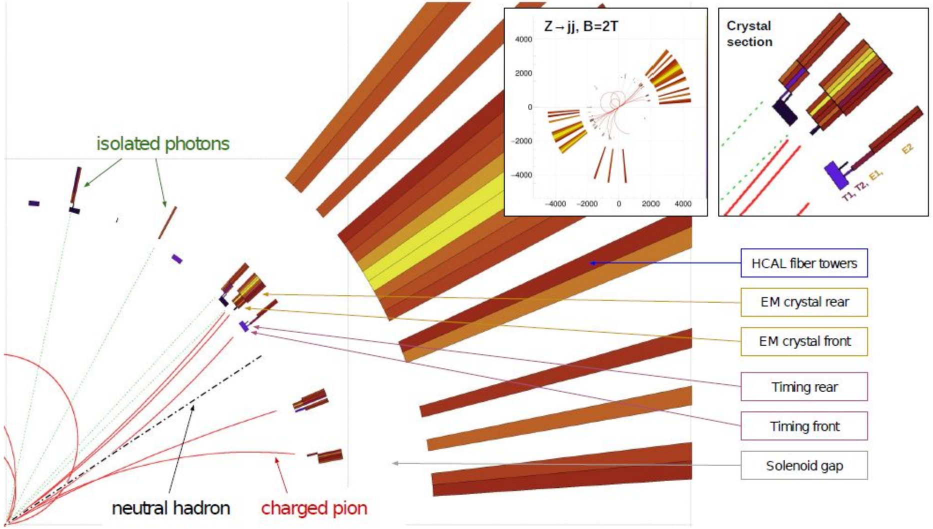
2020 JINST 15 P11005

SCEPCal: simulation in Geant4

More details in:
2022 JINST 17 P06008

Geant4 **4π standalone** simulation of **hybrid segmented crystal** and **fiber dual-readout** calorimeter:

- Performance of crystals option assessed:
  - Excellent **electromagnetic 3%/√E** and **hadron** resolution **26%/√E**
- Proto DR-oriented **particle flow** algorithm developed and tested:
  - demonstrated the potential of exploiting dual-readout information.



Starting point for more sophisticated implementation:

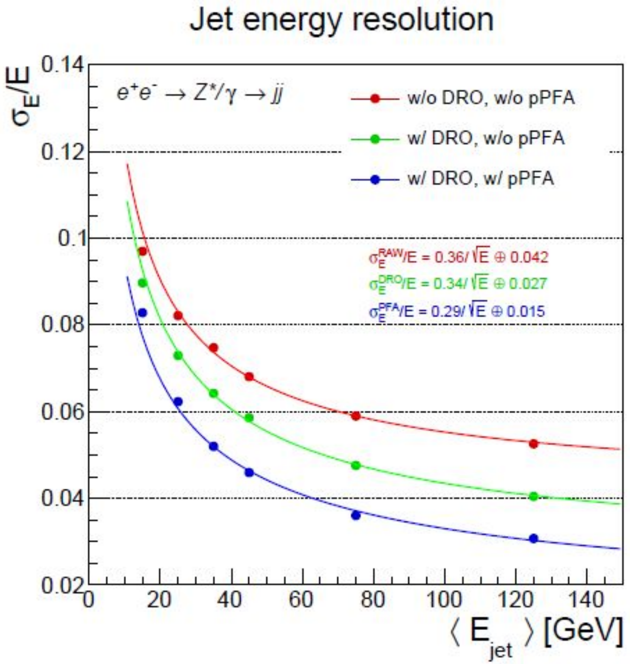
- **neural networks, graph-theory** approaches to optimize the exploiting of the additional information provided by dual-readout approach + longitudinal/transversal segmentation
- **Goal**: improve tracker-calorimeter matching in the reconstruction of objects to enhance the particle identification and final physics performance.

DR-PFA algorithm

More details in:
2022 JINST 17 P06008

Dual-Readout Particle Flow Algorithm (DR-PFA):

1. **Identification photons** calorimeter hits to remove from them from hit collection.
2. Association of **calorimeter hits to charged tracks** by exploiting the dual-readout corrected response of the hybrid calorimeter.
3. **Jet clustering**: matched charged tracks, tracks that do not reach the ECAL surface, and unmatched calorimeter hits (photons or neutral hadrons).
4. **Dual-readout correction** on the fraction of jet energy from unmatched hits.



Sensible **improvement in jet resolution: 3-4%** for jet energies above 50 GeV

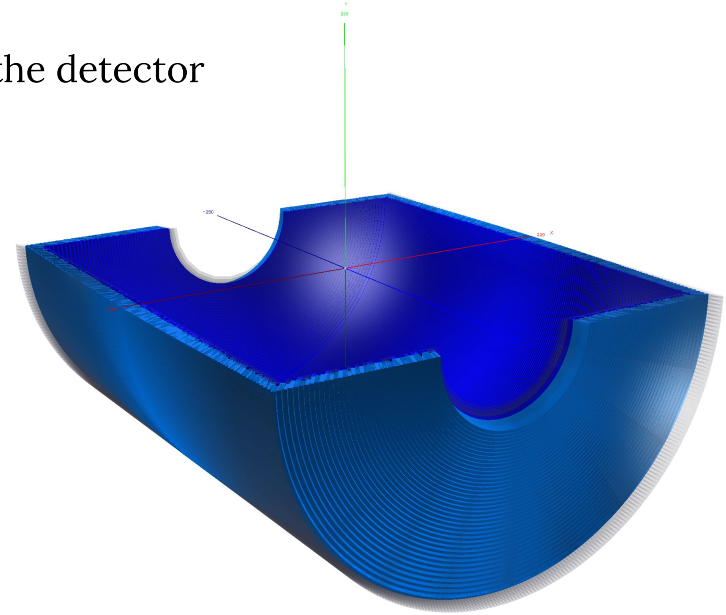
SCEPCal simulation in Key4Hep

★ Moving to **Key4Hep** framework to have a coherent FullSimulation of the IDEA Detector:

- Why Key4HEP?
  - **Easier maintenance:** common software package chosen by future colliders experiments
  - **Modularity:** it allows to test different scenarios combining different subdetectors

- Why a Full Simulation of IDEA?
  - run **cost/performance** optimization studies of the detector
  - design **dedicated particle flow algorithm**
  - assess the potential of FCCee **physics program**

- Status of the SCEPCal simulation in Key4Hep:
  - **Geometry implemented** in DD4HEP (debugging ongoing) and **simulation** in k4SimGeant running (ddsim transition ongoing)
  - Next steps:
    - DIGI, reconstruction, PFA.



Sanity checks of the geometry

Ongoing work to produce performance plots of SCEPCal to **validate the simulation**:

- Correlation between deposited energy and number of cherenkov photons produced
- Multiplicity of hits of both scintillation and cherenkov VS hit thresholds, energy of particle gun, crystal face width
- Total reconstructed energy vs phi and eta
- Reconstructed energy resolution and linearity vs particle energy
- Comparison of energy deposits in front and rear segments
- Angular resolution (weighted eta of hits vs eta of MCtruth, and same for phi)
- …

Some **very preliminary** results in the next slides: Particle gun of **photons** of 10 GeV.

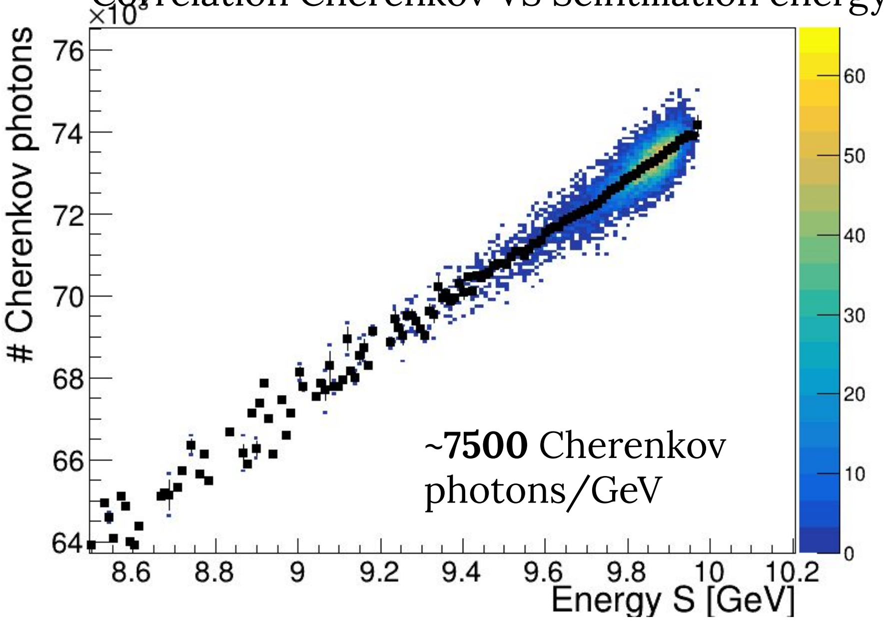
First results with baseline crystal face width of **1x1 cm^2 - Barrel only.**

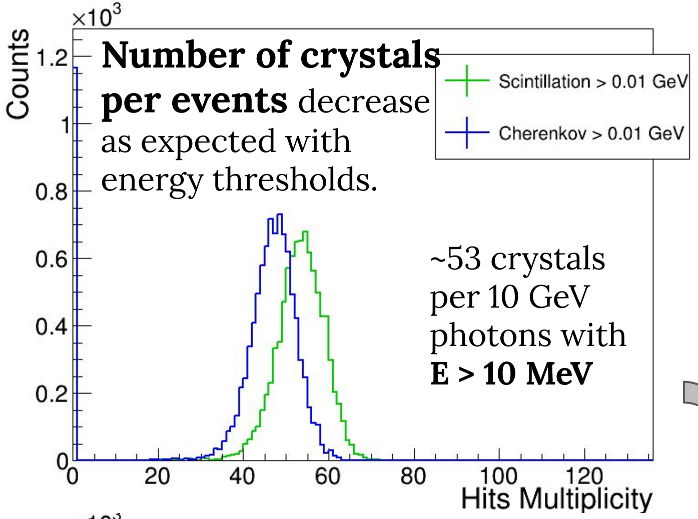
Hits Multiplicity: C and S

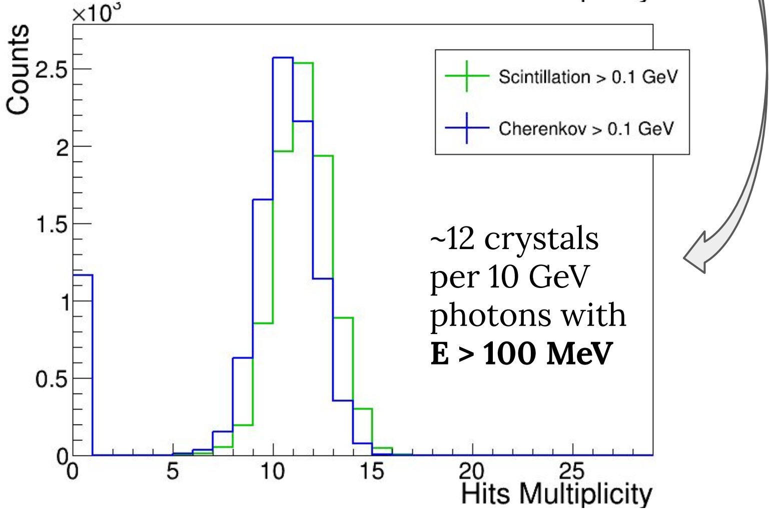
Saving both the energy deposited in the crystals and the number of Cherenkov.

10 GeV photons 10k events 1x1 cm² crystal size

Correlation Cherenkov VS Scintillation energy



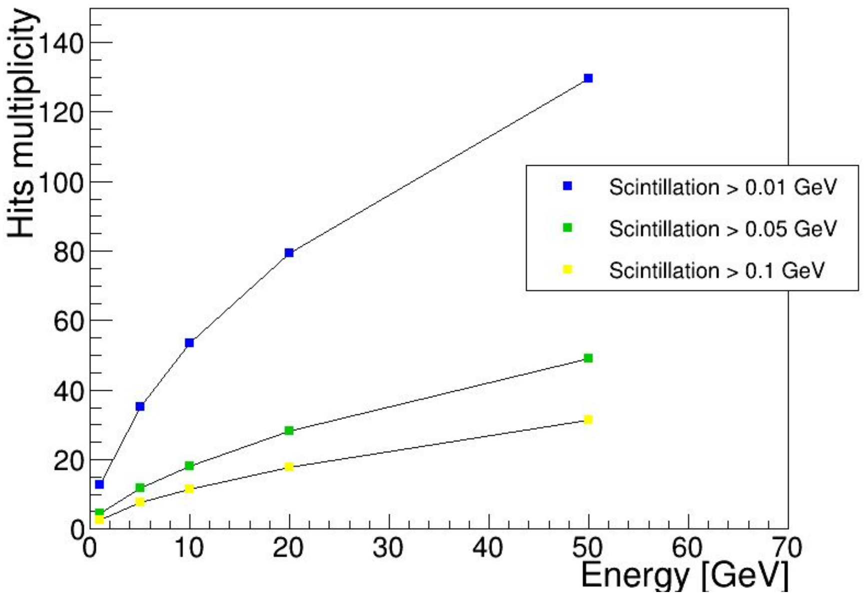


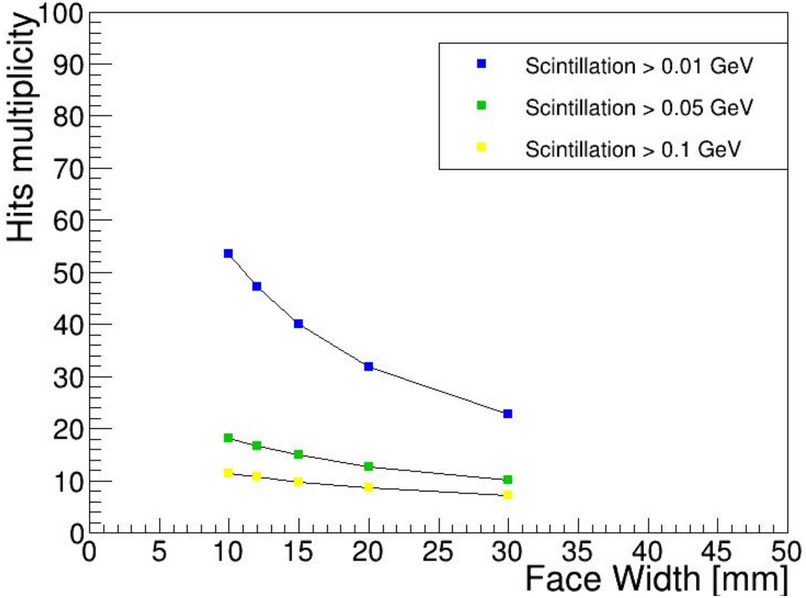


Hits multiplicity VS energy/crystal size

Particle gun photons

Investigating the **number of crystals** with an energy deposit > threshold for **different energies** of particle gun and **different granularities** of crystals.



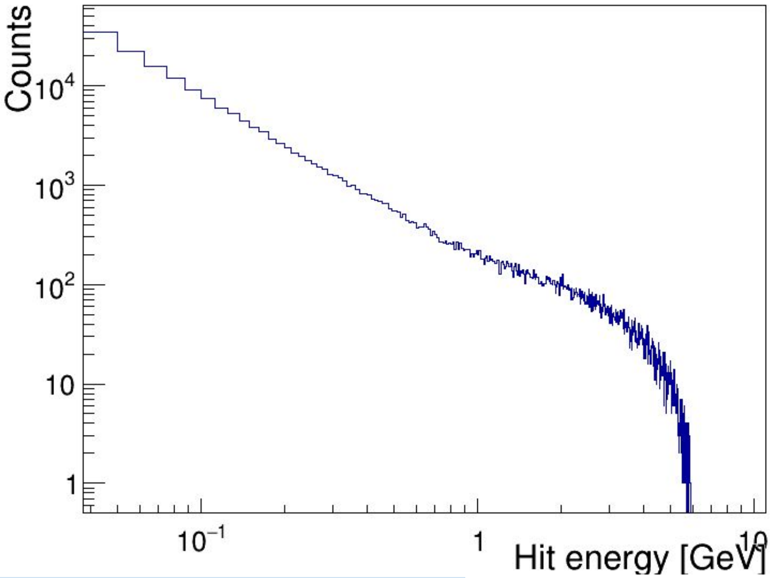


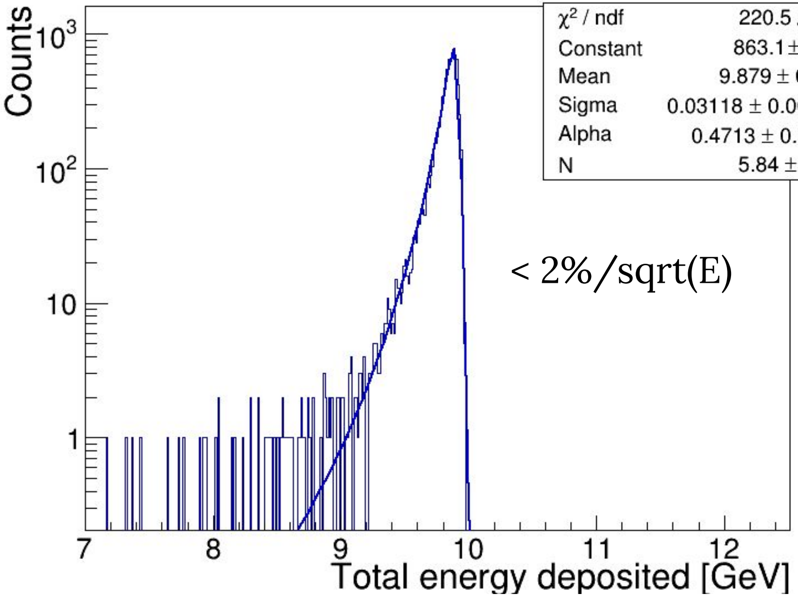
Simulation used to **optimize** crystal granularity and segmentation of the detector.

Energy - per Hits and Total

10 GeV photons, 10k events
1x1 cm² crystal size

- ★ Sum all the energy hits of an event → **total reconstructed energy compatible with 10 GeV**
- ★ Very good preliminary energy resolution <~2%/sqrt(E) -- another 2%/sqrt(E) will be added by photostatistics term.

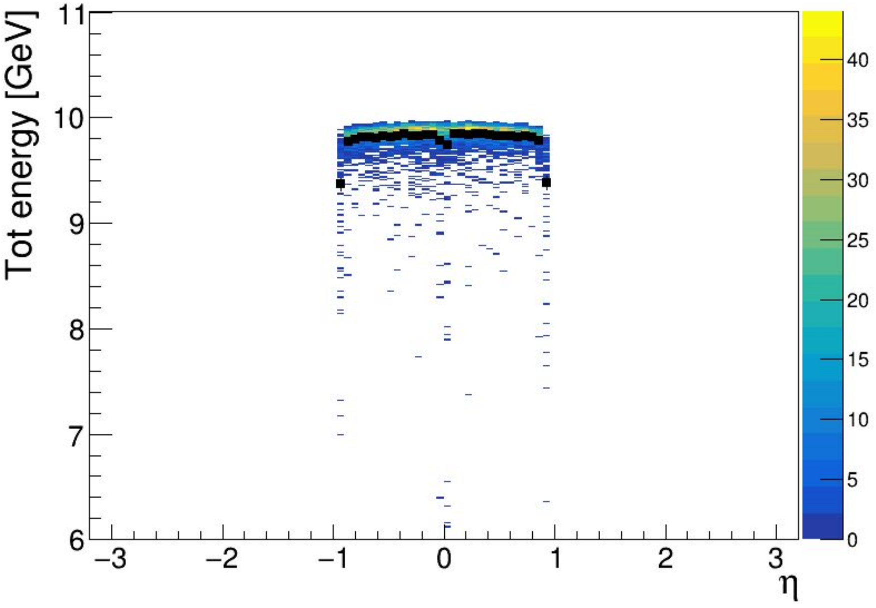


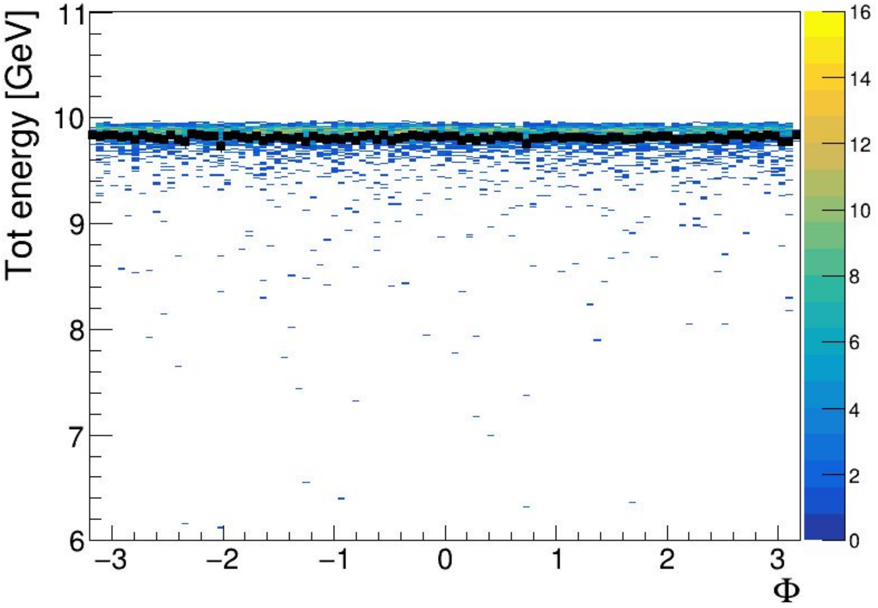


Total energy VS eta and phi

10 GeV photons 10k events
1x1 cm² crystal size

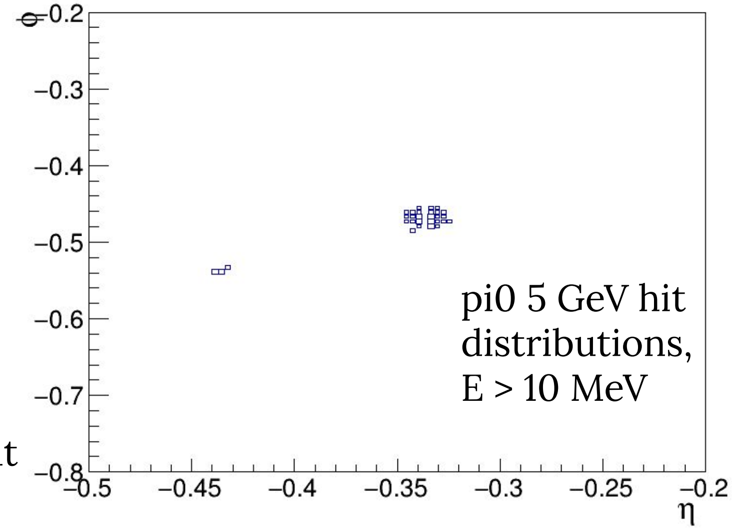
- Looking at total **reconstructed energy** (sum of all hits) as a function of **eta(phi)** of the hit with maximum energy ("seed")
- The **uniformity** of the **total reconstructed energy** along eta and phi looks **good**.





Next steps towards reconstruction

- Adapting the algorithms used for **Geant4** simulation, migrating the output to an edm4hep format.
  - More **sophistication** of the algorithm can be added on top.
- Clustering algorithms already implemented can be exploit:
  - as an eg. Key4hep **CLUE** algorithm
- The work on clustering can be **run in parallel** with geometry finalization, once we have settled the output DIGI format:
  - We can use E deposited and N Cherenkov with a scale factor (and Poisson smearing) as a starting point while implementing the SiPM response.



Summary

- We have in place the **simulation of the SCEPCal**, with 2 layers of PbWO crystal dual readout:
  - Debugging of the newly implemented detector geometry with particle gun ongoing
    - Barrel looks fine, endcaps are being fixed
  - In parallel, put some basis to have the simulation running with ddsim.
  - We are in contact with **key4hep experts** at **CERN** and **CalVision group**.
- Next steps:
  - Finalize the **geometry constructor** and validate it
    - produce more physics performance plots
  - **Integration** with other subdetectors:
    - dual-readout HCAL ...
    - .. tracker ...
    - ... towards the full simulation of the IDEA detector.
- **Documentation** of the IDEA Crystal option:
  - https://fcc-ee-detector-full-sim.docs.cern.ch/IDEA/IDEA_crystals/

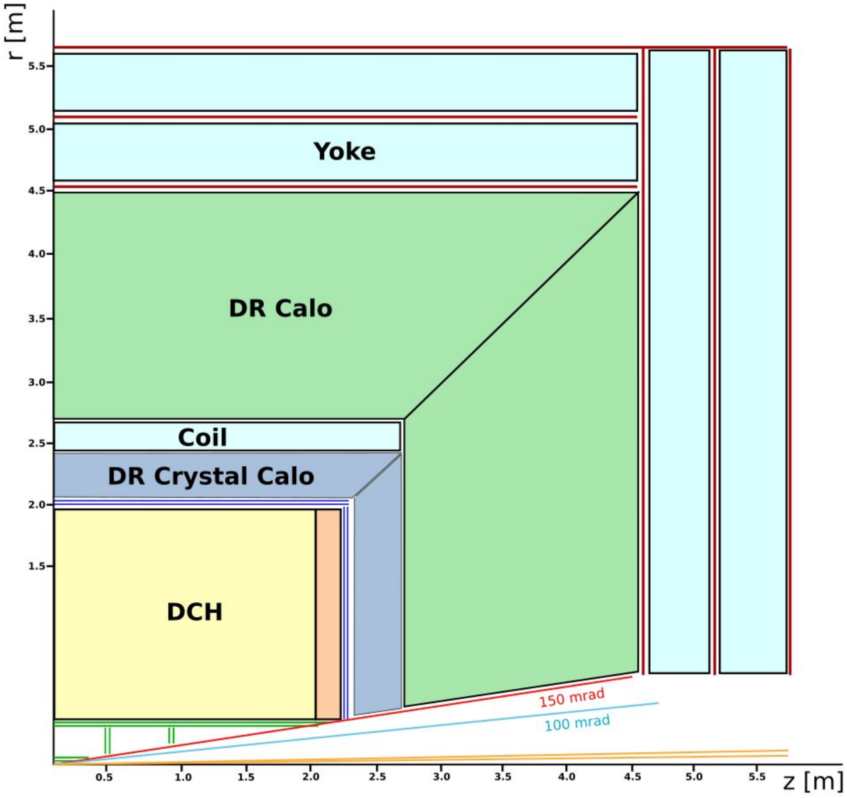
Backup

IDEA detector concept

IDEA detector for future e+e- circular colliders:

- Silicon pixel detector
- Drift chamber
- Layer of silicon micro-strip detectors
- ~~Preshower detector~~
- **DR Crystal calorimeter: SCEPCal [2.1-2.4 m]**
- Solenoidal magnet
- **Sampling fiber calorimeter** exploiting the **dual-readout** of scintillation and Cherenkov light
  → **excellent** energy resolution for **hadrons** and jets
  → **BUT** moderate energy **EM** resolution
- Muon spectrometer within the magnet return yoke.

IDEA calorimeter w/o crystal option
σ_E/E (EM) ~**13%/√E**
σ_E/E (HAD) ~31%/√E
Jet resolution ~ 30%/√E



10.1393/ncc/i2020-20027-2

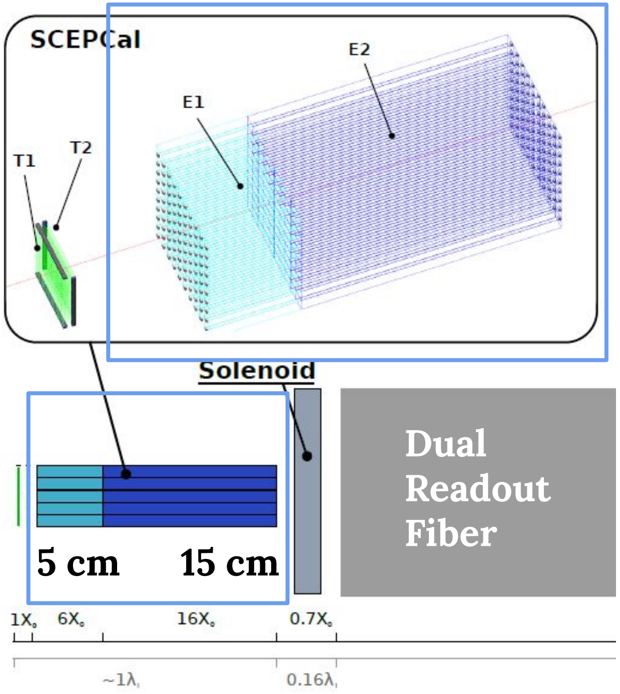
Geometry

★ Implemented a geometry with **2 layers of $PbWO_4$ crystals**:

- **Face width** of crystals = **1x1 cm^2** → **Nominal geometry tested!**
- **Front** crystal length = 5 cm
- **Rear** crystal length = 15 cm
- Barrel **length** / 2 = 2.25 m
- Barrel **inner radius** = 2.1 m

★ To be implemented: **2 timing layers**

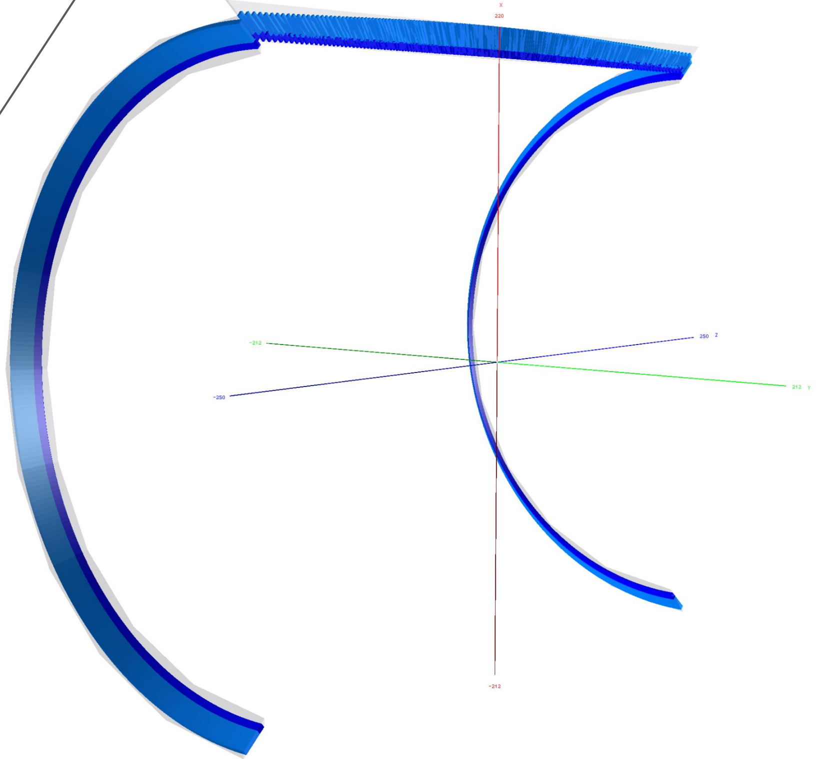
Two separated edm4hep collections for Cherenkov and Scintillation: cellID, energy (or #of cherenkov), position stored



Detector constructor

- In the detector constructor **intermediate envelope volumes** with around 1000 or less daughter volumes:
  - **Barrel:** envelope volumes are trapezoids slices
  - **Endcaps:** envelope volumes are concentric rings of dd4hep::Cone volumes

The **endcap rings** are still to be carefully checked as their geometrical implementation is **more challenging** than barrel.



Envelopes speed up the geometry construction process:

- 10x10 mm^2 crystals, 1000 events with photons/electrons of 10 GeV runs in about **15 min**.

Without envelopes: Issues of memory consumption.