RICH full sim implementation in Key4hep

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RICH full sim implementation in Key4hep

- Motivation of PID in HEP
- Design of Array of RICH Cells (ARC)
- Detector description and physics simulation
  - How to simulate one ARC cell
  - ARC geometry for CLD detector
  - ARC reconstruction
- Summary

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- Flavour physics requires excellent hadron Particle Identification (PID) to resolve combinatorics and separate decay modes
- Higgs physics through flavor tagging would benefit as well
- RICH detectors are very powerful for particle identification at high momentum, as it is shown by LHCb experiment
- See Roger Forty presentation for further motivation of PID in FCCee experiments design

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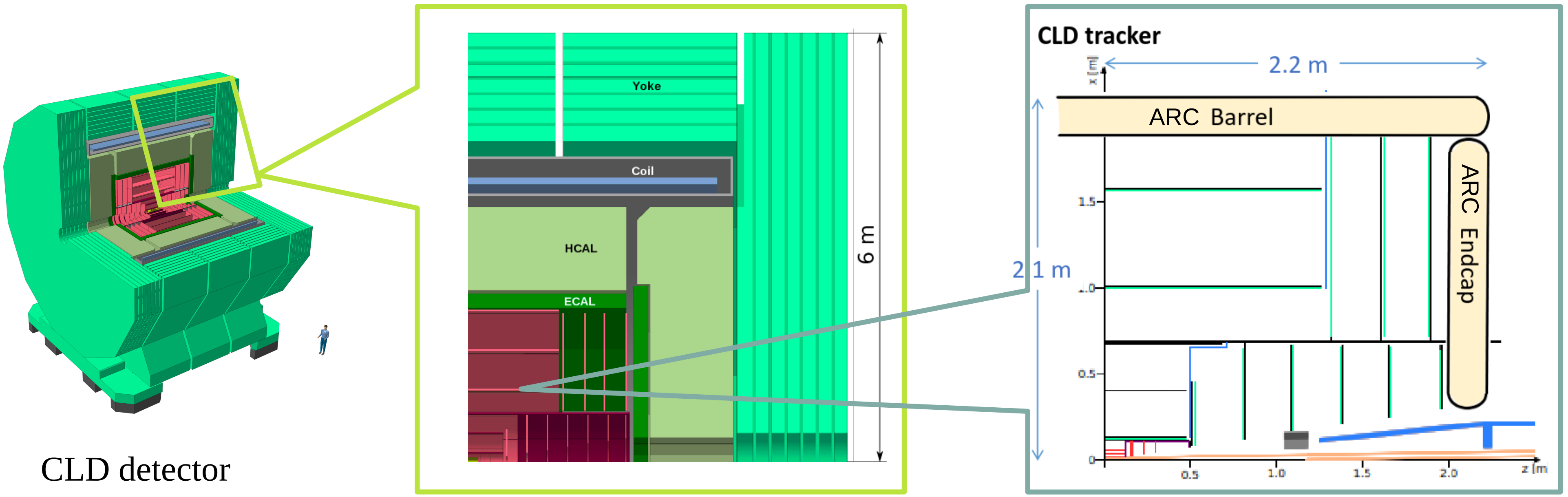
- This talk is a follow up of the previous ones

Design of Array of RICH Cells (ARC)

- The ARC was designed to be integrated with the CLD detector, between the tracker and the ECAL
- The ARC thickness is 20 cm, the barrel length is 4.4 m and the endcaps are placed as the bases of the barrel

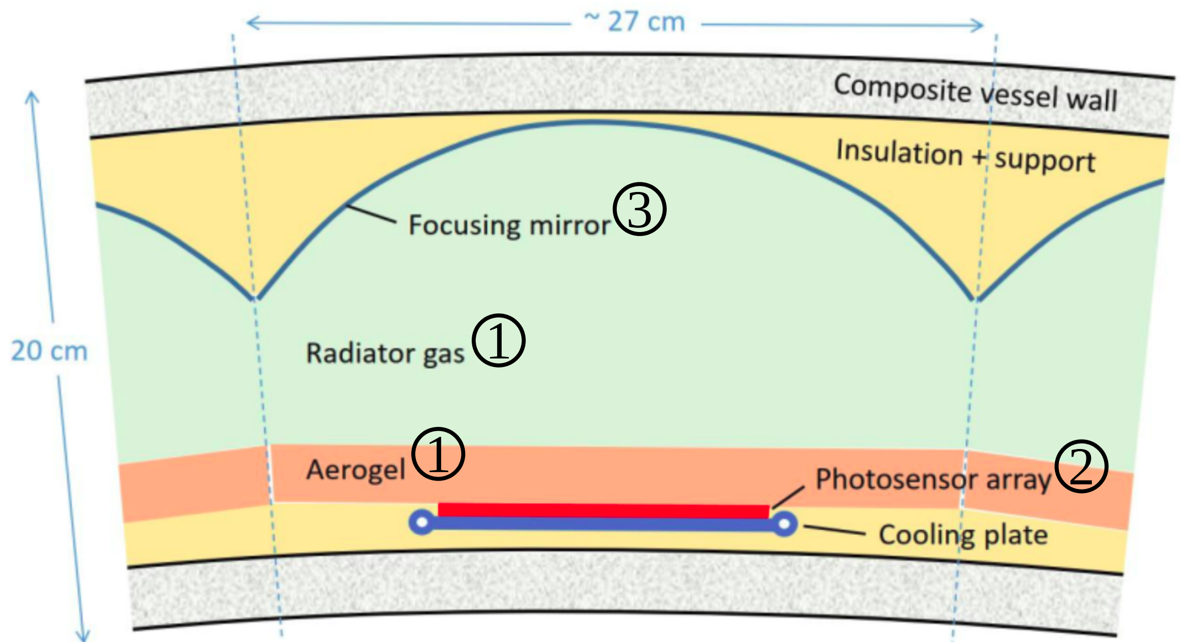


Design of Array of RICH Cells (ARC)

The detector geometry, material description and readout is implemented in DD4hep framework

Main elements of RICH detectors

1. radiators, to produce Cherenkov light
2. light sensor, to detect such light
3. mirror, to focus light on the sensor



ARC detector (one cell)

Detector description and physics simulation

The tools for a full simulation are

- DD4hep for detector description
- GEANT4 for physics simulation
  - Hadronic & EM physics
  - Optical physics
- MC generators / particle gun
- Others (digitization, reconstruction, etc)

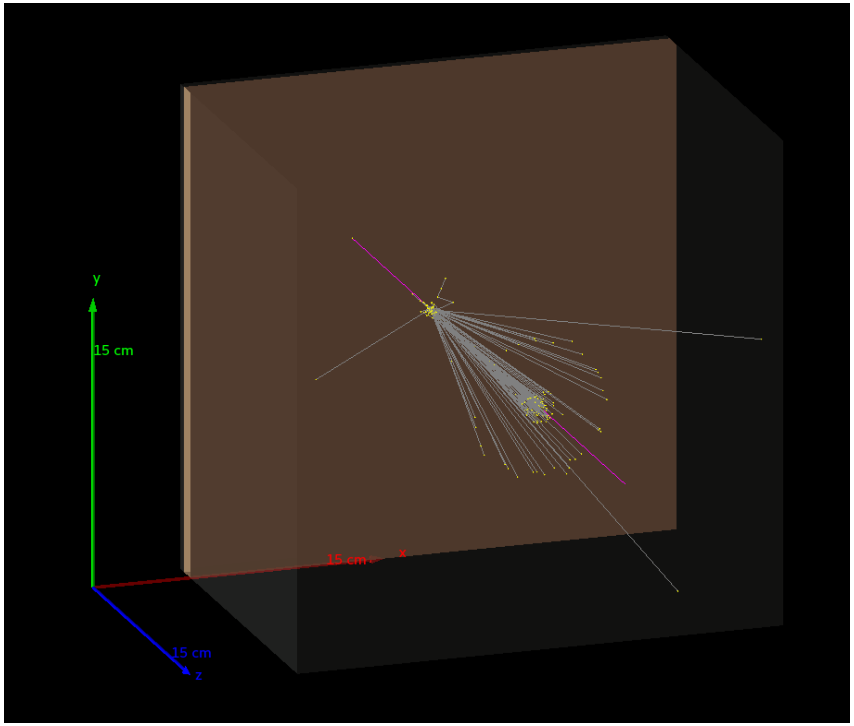
The physics processes have been validated extensively (e.g., by LHCb)

The processes are built according to the material properties, therefore a careful material characterization is required for a realistic simulation

The number of Cherenkov photons is ~10 per track, so fullsim is feasible

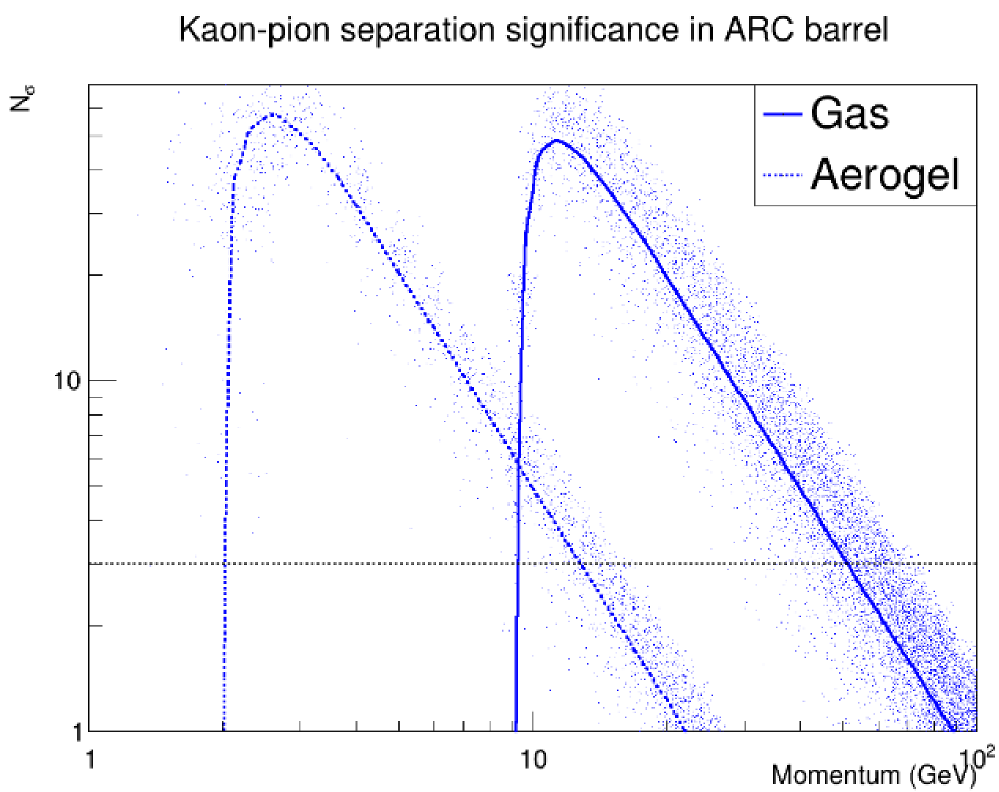
How to simulate one ARC cell (i)

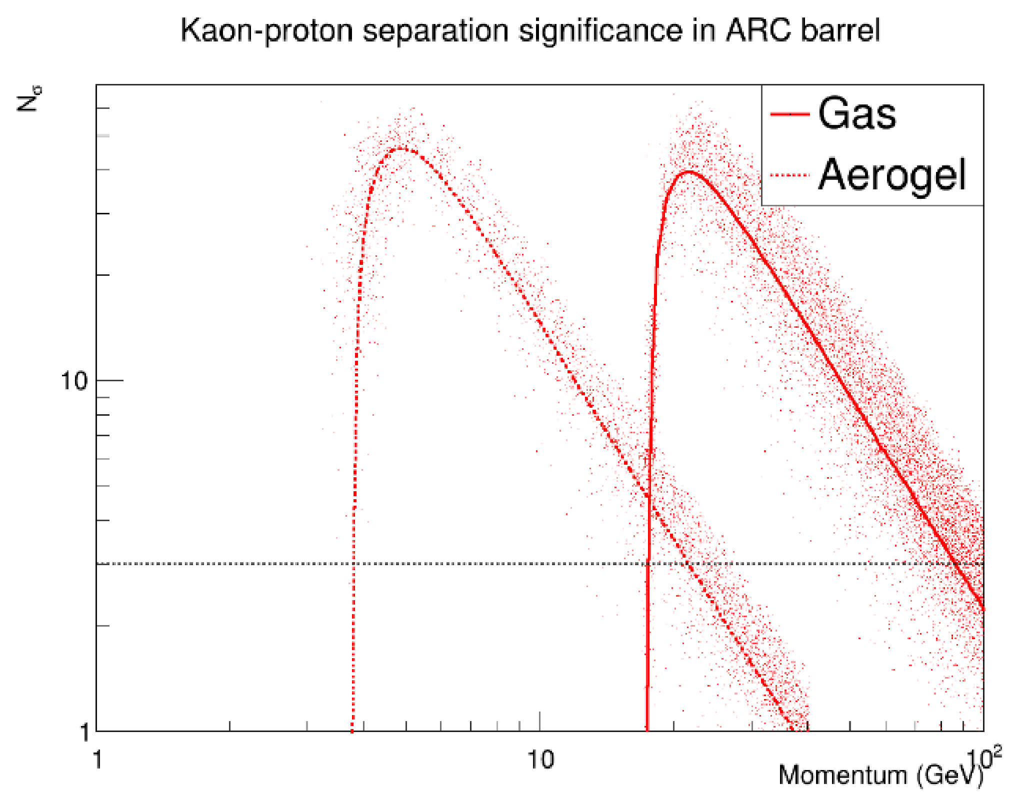
- The key materials of the ARC are the Cherenkov radiators: an aerogel layer and a gas volume (C4F10)
- The two rings of Cherenkov light are produced, one for each radiator
- The picture shows a track of a 50 GeV pion moving along z-axis
- The gray tracks correspond to the Cherenkov photons



How to simulate one ARC cell (ii)

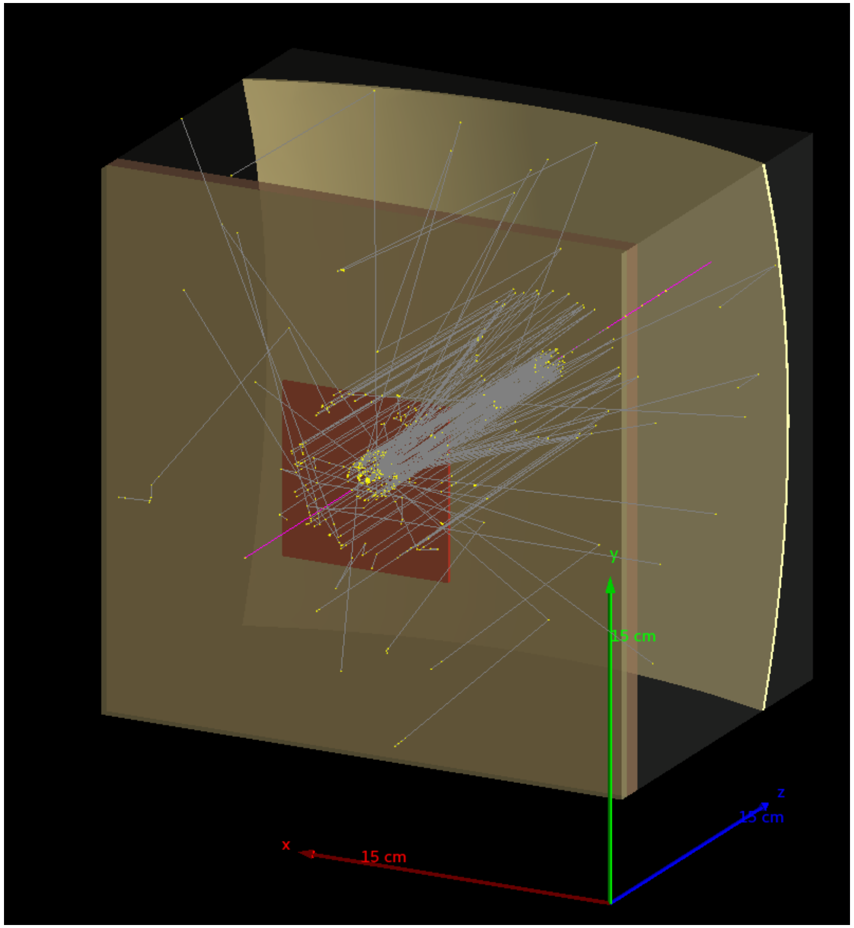
- Two radiators provide sensitivity at different energy ranges
- Gas (aerogel) provides over 3σ pion-kaon separation in the range 10-50 GeV (2-10 GeV). [M. Tat slides at EFCA workshop 2022]





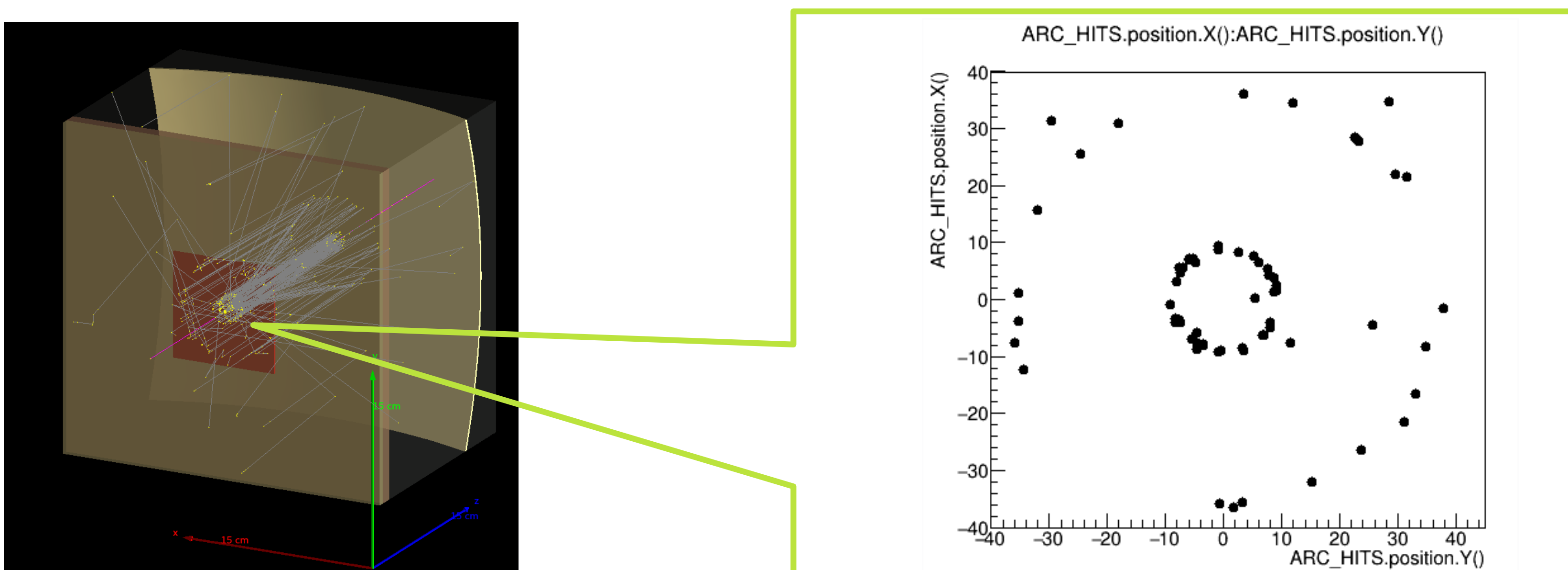
How to simulate one ARC cell (iii)

- A 2 mm thick spherical mirror (yellow) focus the photons on a smaller area
- Surface properties must be defined in order to be reflective during the simulation
- The red volume where the photons are focused corresponds to a light sensor
- The best candidate for the light sensor is a SiPM



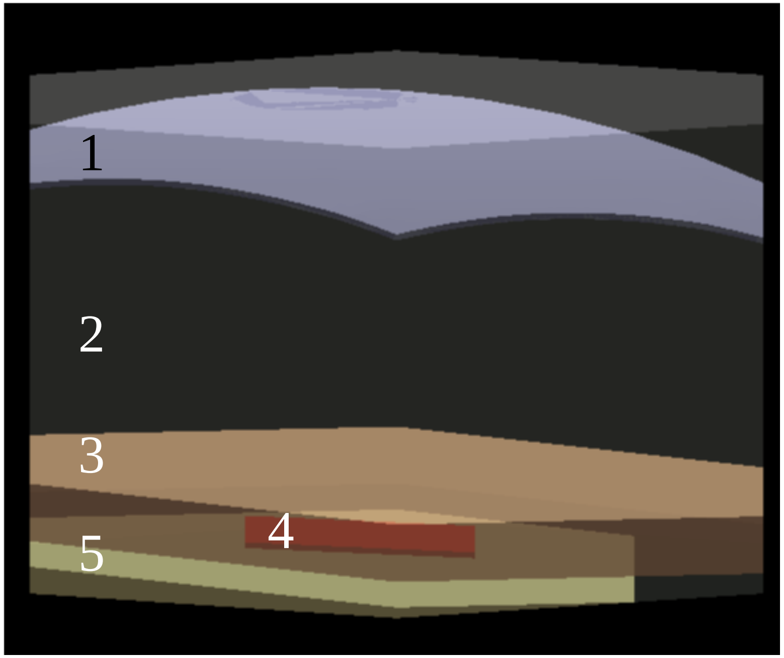
How to simulate one ARC cell (iv)

- The light sensor is associated with a type of sensitive detector, e.g. tracker, in order to register the deposited energy
- The read-out object takes care of generating the output data associated to the light sensor
- The read-out object can take a segmentation pattern, which later is used to link the global hit position with a sensor pixel, and viceversa



ARC geometry for the CLD detector

- Cell shape is hexagonal to improve light collection in the corners



1. Spherical mirror
2. Radiator gas C4F10
3. Aerogel
4. Light sensor
5. Cooling plate

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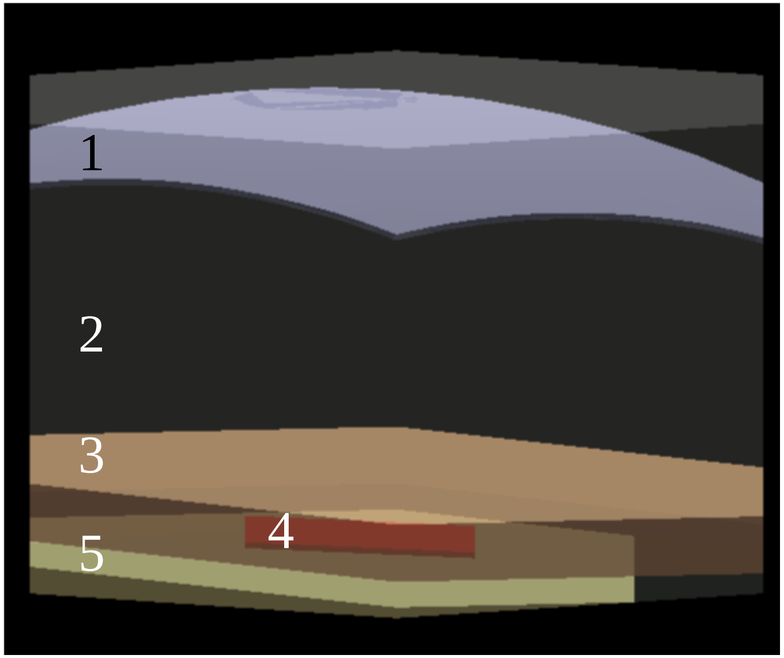
- Cell shape is hexagonal to improve light collection in the corners
- The geometry of mirror and sensor is modeled by a set of parameters, optimized for each cell by dedicated ray-tracing software (done by Martin Tat)
- Re-optimization of such parameters is required if the detector geometry changes (e.g., radius of the barrel)



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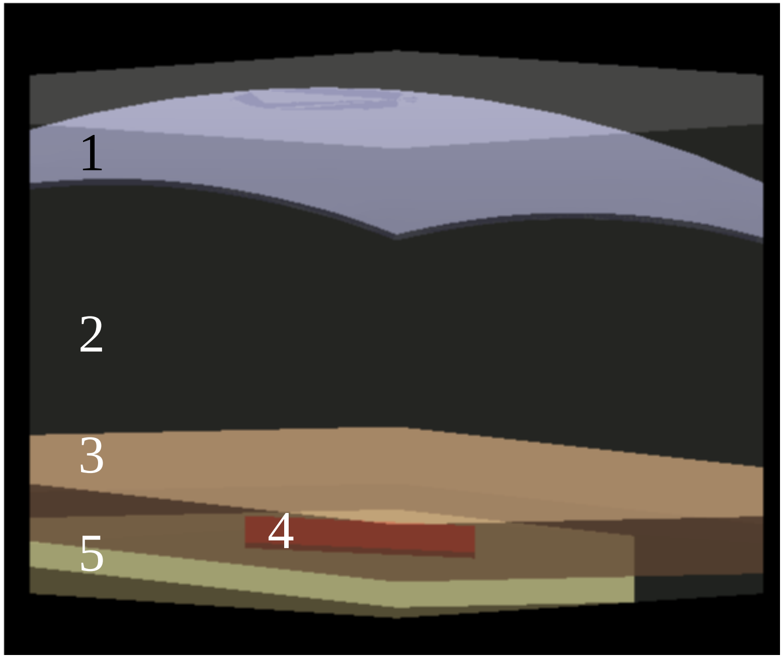
- Re-optimization of such parameters is required if the detector geometry changes (e.g., radius of the barrel)
- Geometrical arguments restrict the optimization to 18 singular cells in the barrel and 21 in the endcap. The full geometry results from the repeated placement of these singular cells



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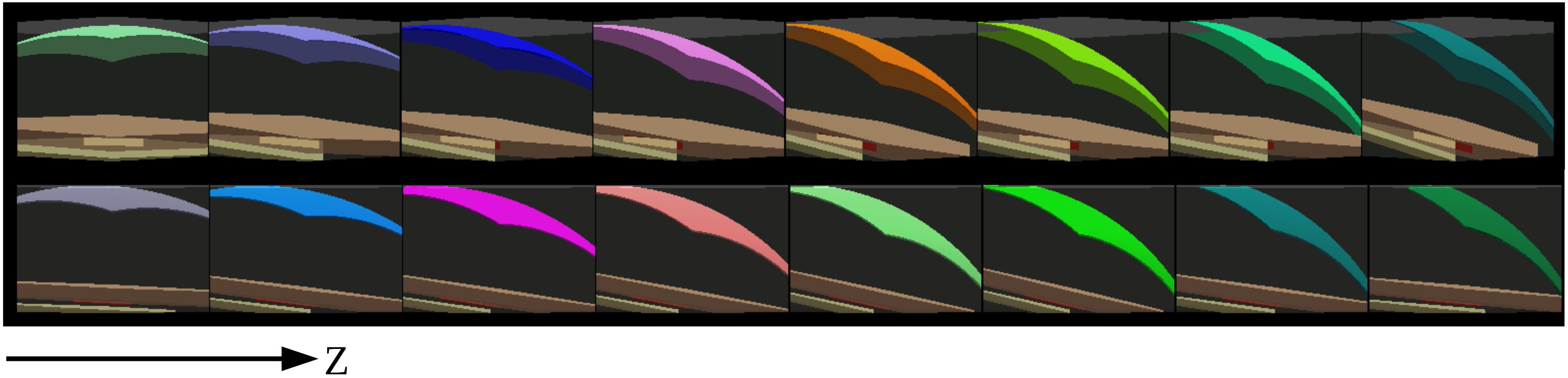
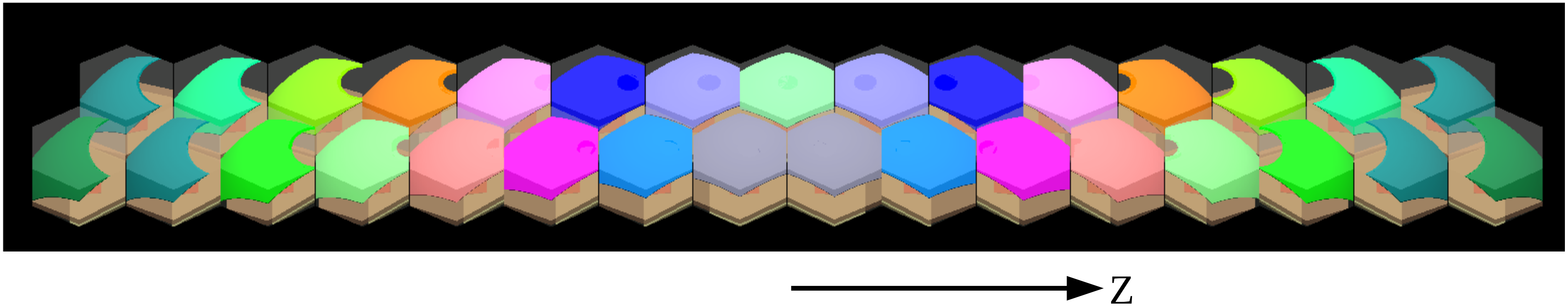
ARC geometry for the CLD detector

The barrel is made of the following 16 singular cells

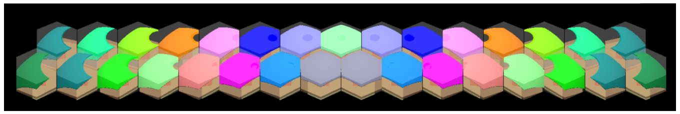


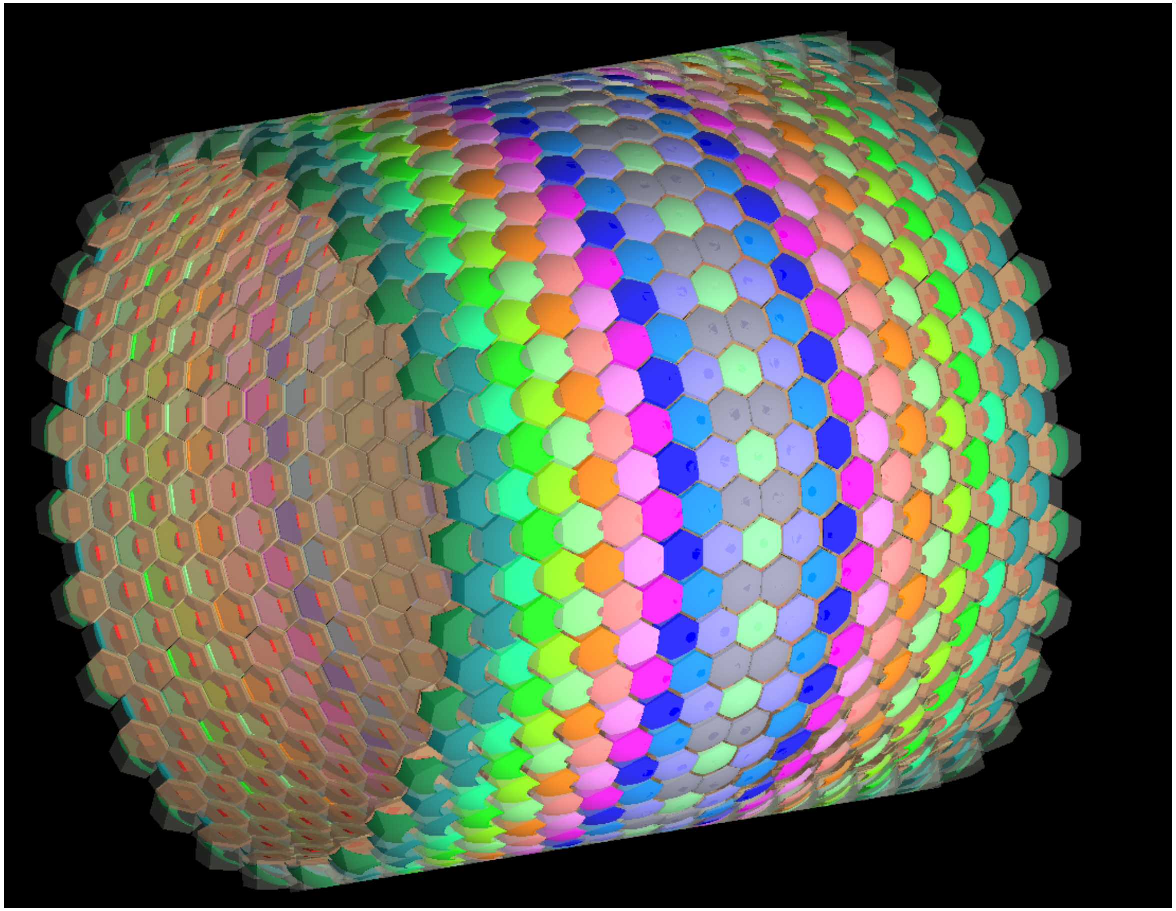
The cell geometry is mirrored when placed at positions with z<0



ARC geometry for the CLD detector

Then place this row 27 times around the Z axis

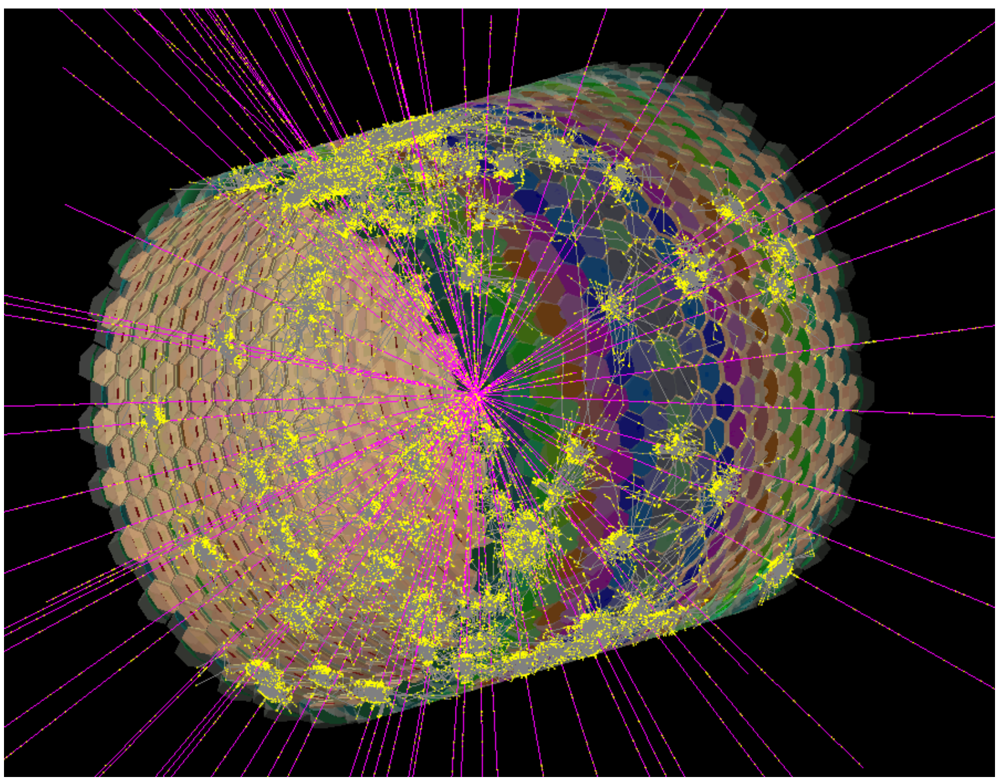


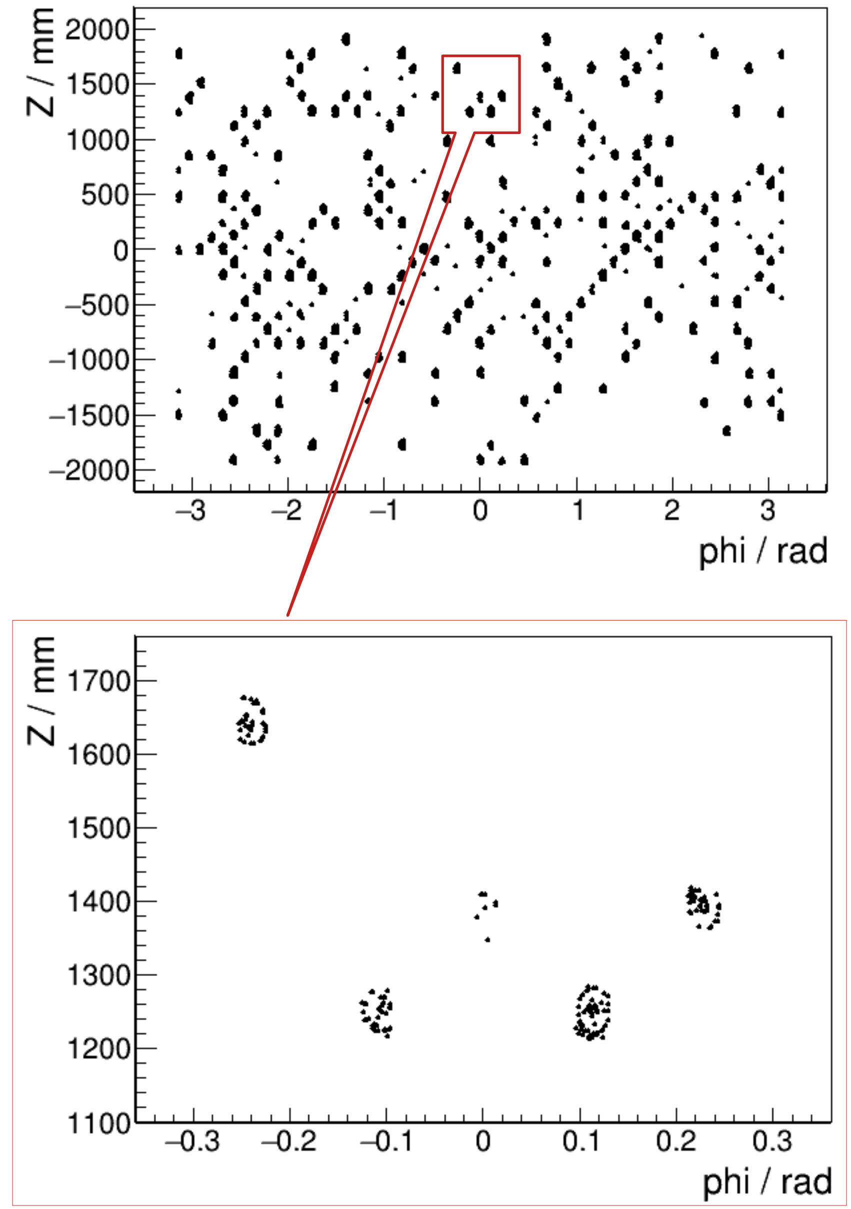


Final geometry of the ARC barrel
It can be used in physics simulations

ARC geometry for the CLD detector

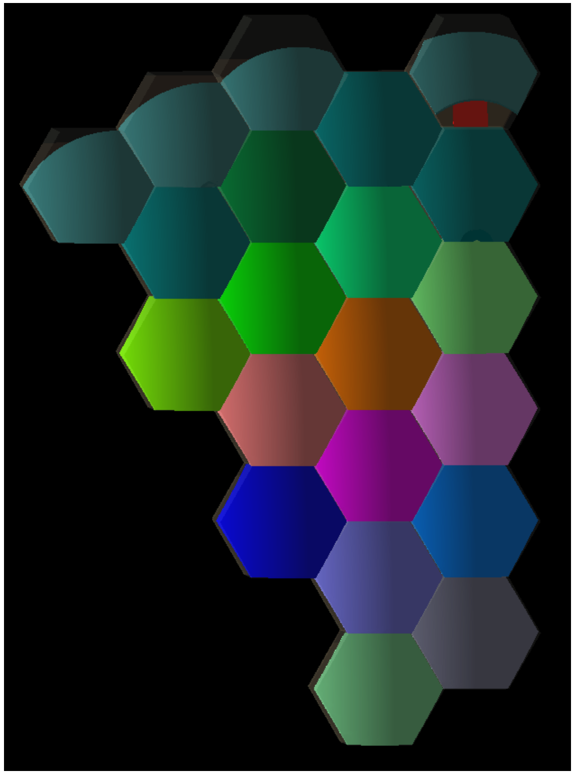
The image below corresponds to 100 π^+ @ 50 GeV (pink), and the corresponding Cherenkov photons (hits in yellow). Secondaries are not displayed for simplicity

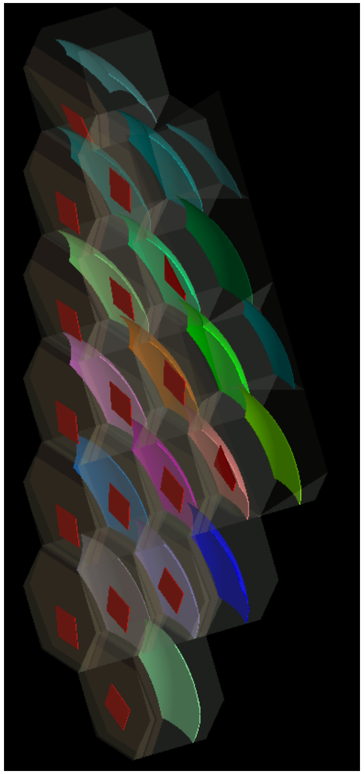




ARC geometry for the CLD detector

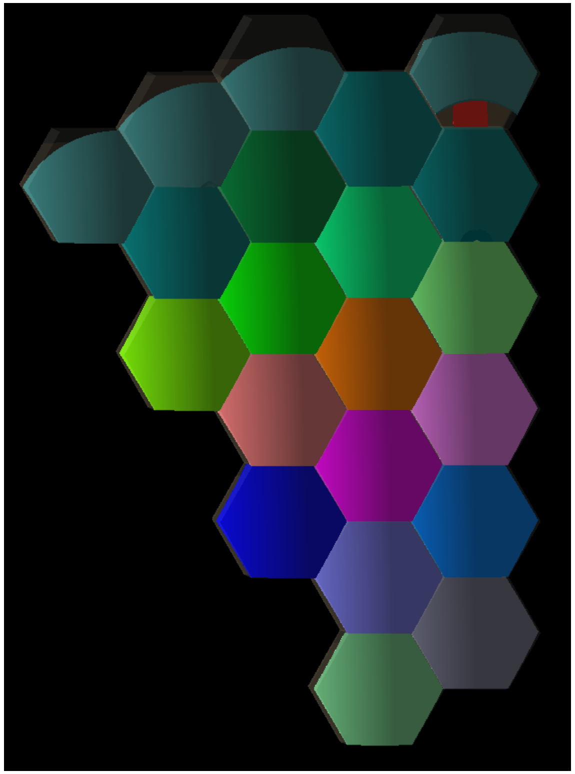
- The endcap is made of the following 21 singular cells

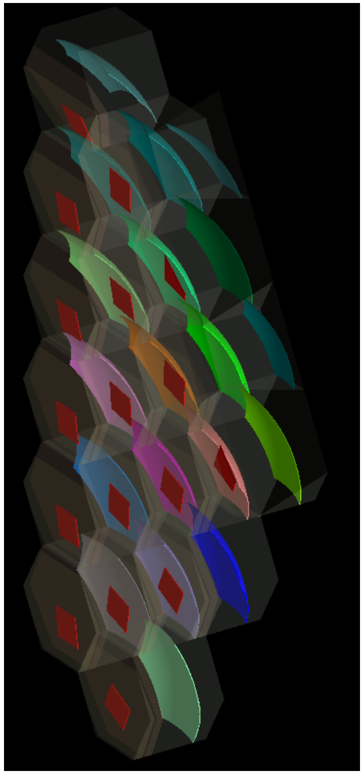


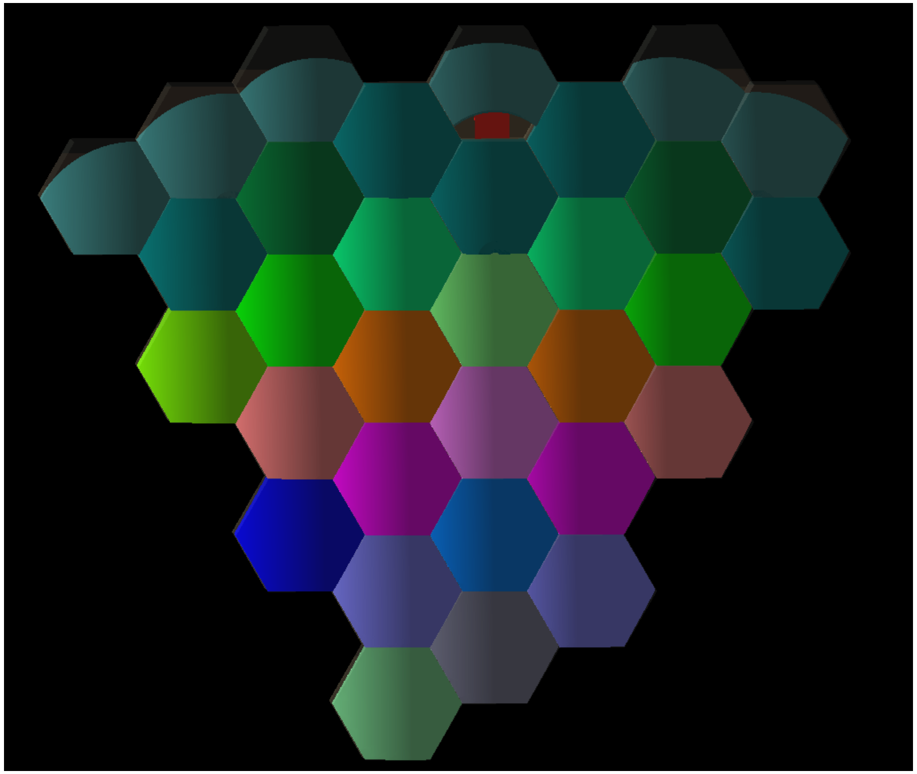


ARC geometry for the CLD detector

- The endcap is made of the following 21 singular cells
- Some have to be mirrored with respect to the vertical axis (x-axis) to make a sector of the endcap

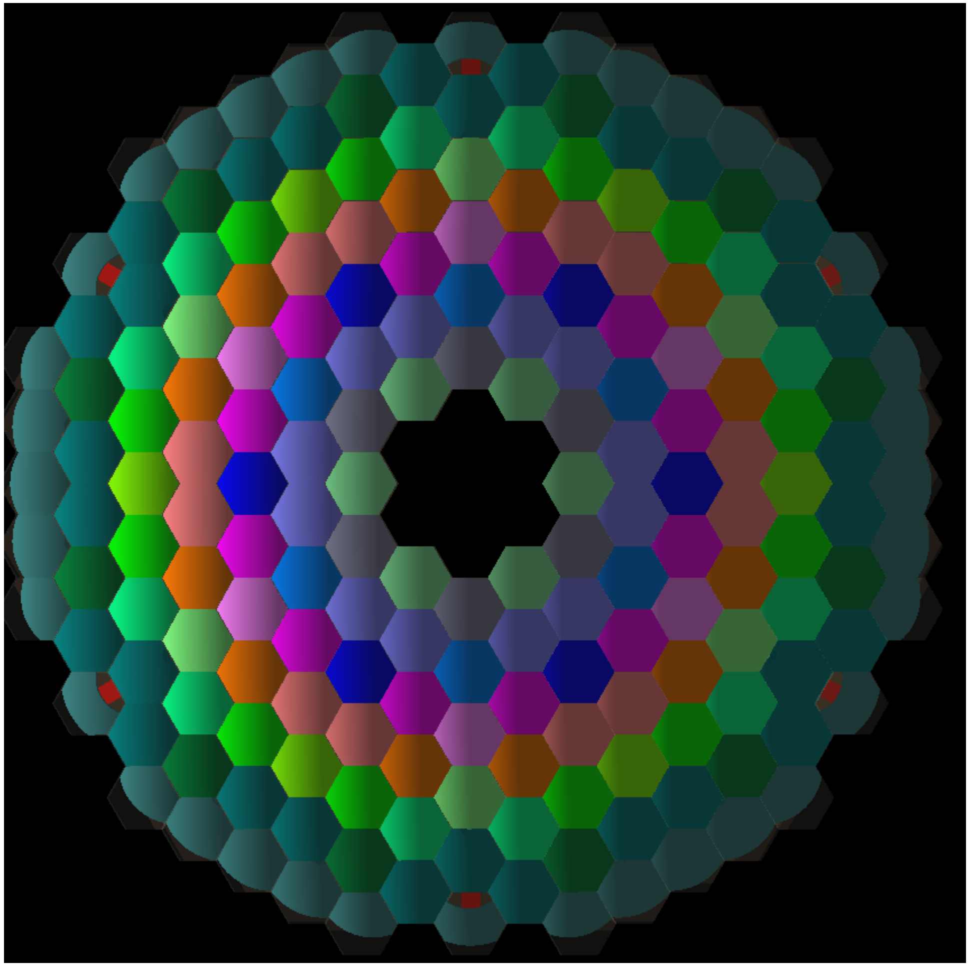


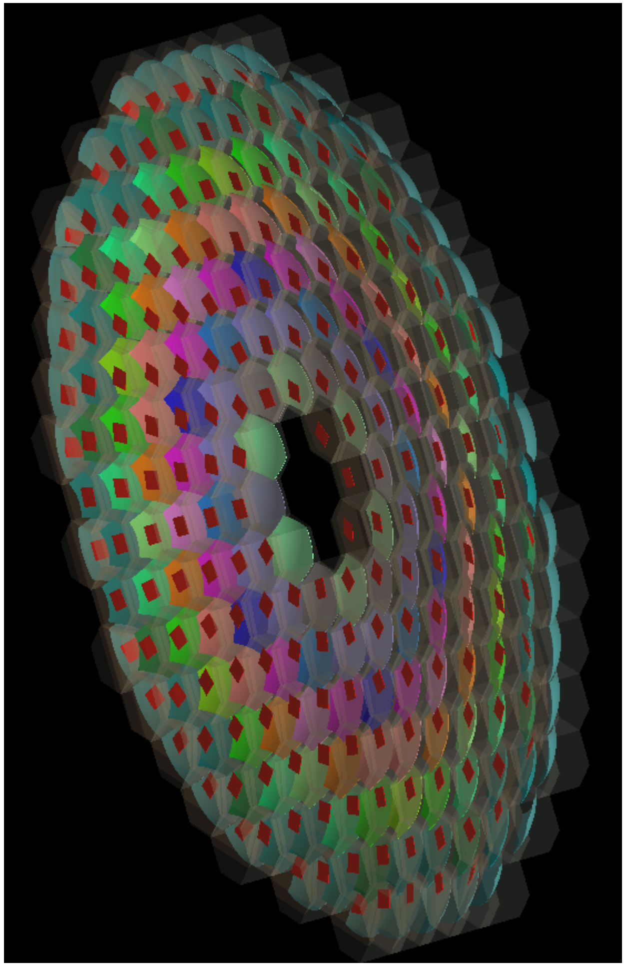




ARC geometry for the CLD detector

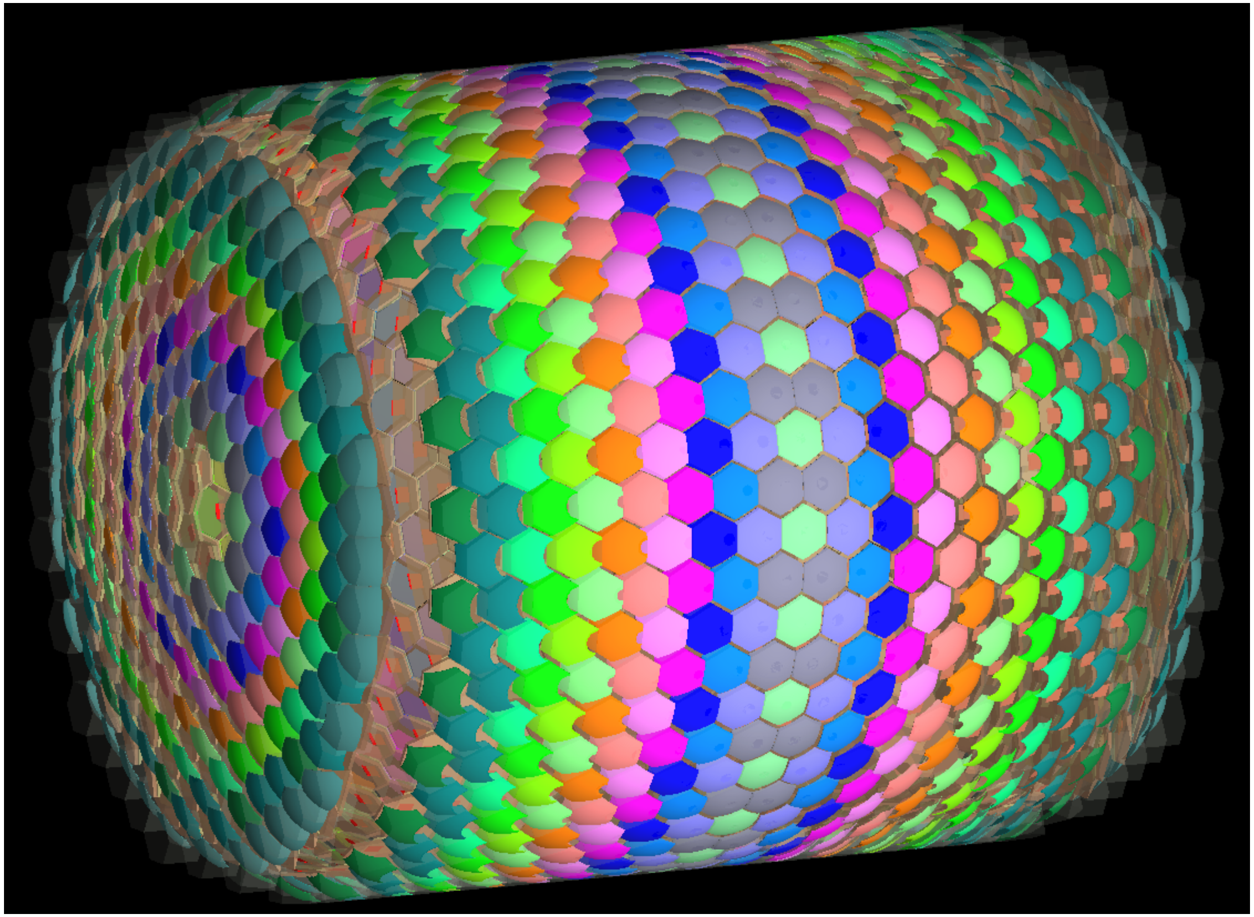
The endcap results by placing 6 times the sector around the Z-axis





ARC geometry for the CLD detector

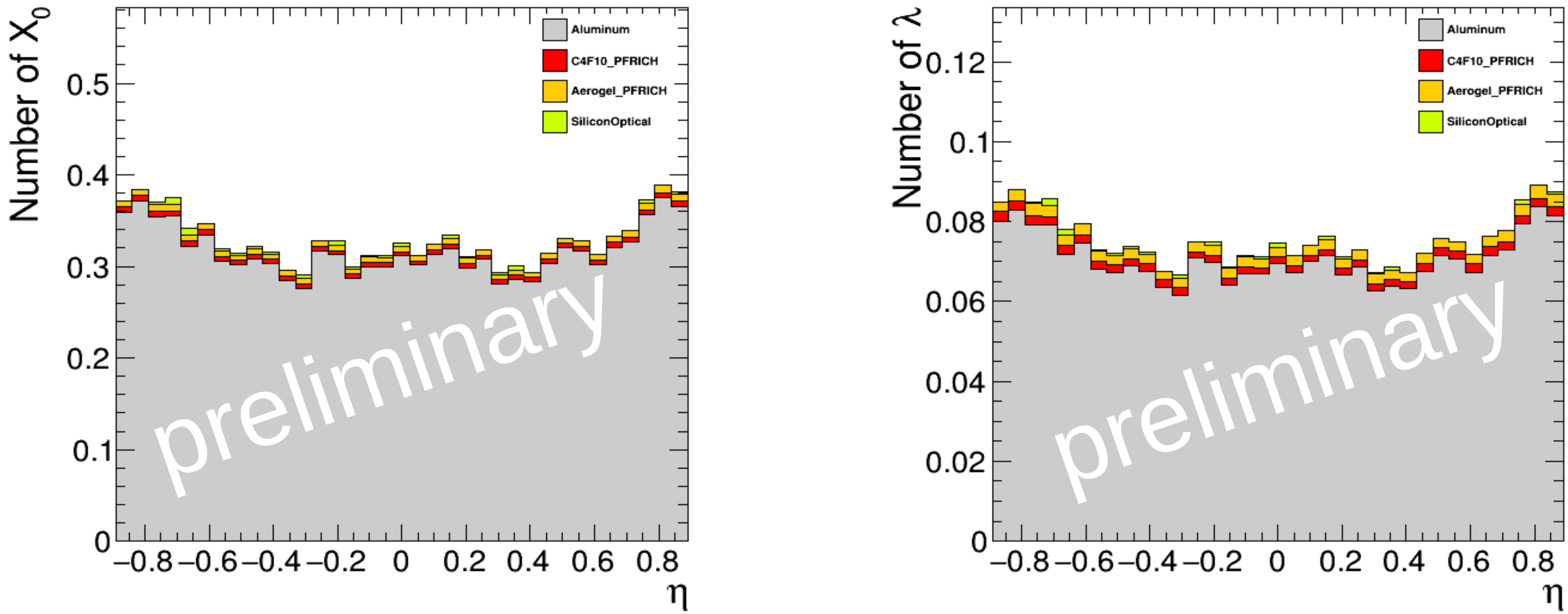
The image below shows the barrel and the endcap in their proper positions



The geometry of the ARC is ready to be used in Key4hep

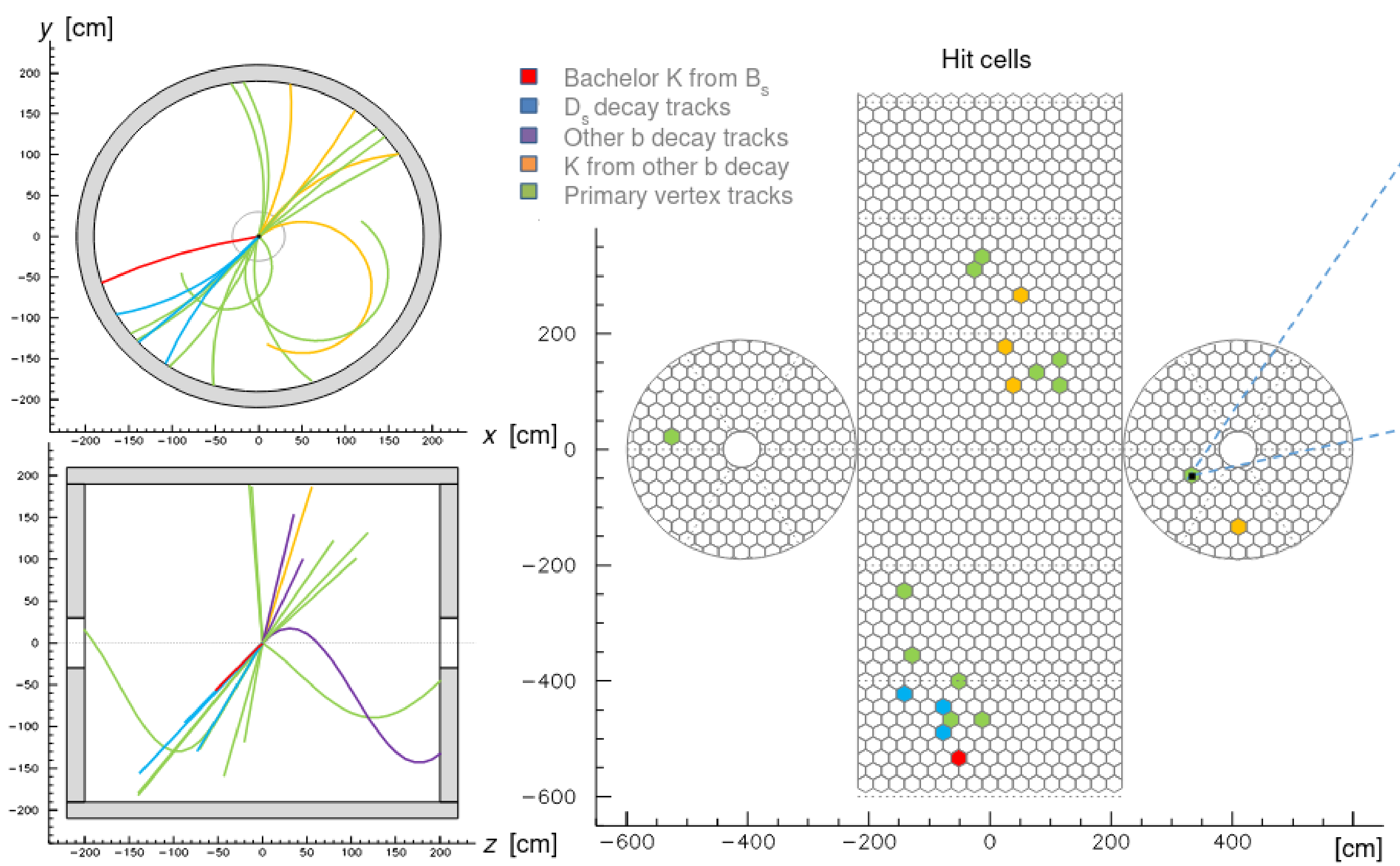
ARC geometry for the CLD detector

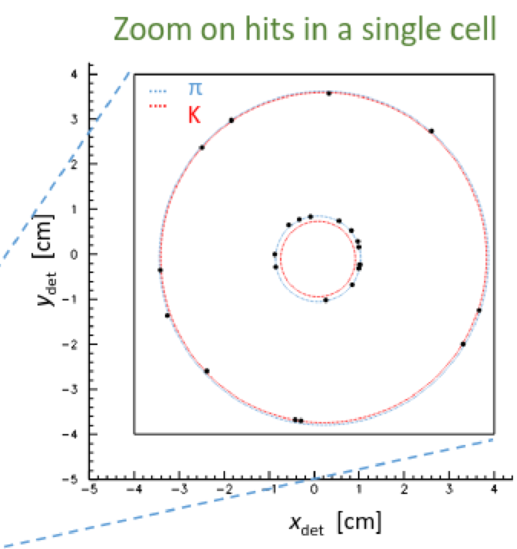
- The plots below show a preliminar estimation of the material budget
- Vessel walls, mirrors and the cooling services of the light sensor (Aluminum) are responsible for most of the material budget
- The use of aluminum is a temporary measure in the simulation, and it will be replaced by a lightweight carbon-fibre construction
- The target for the final material budget of the detector is < 10% of X0

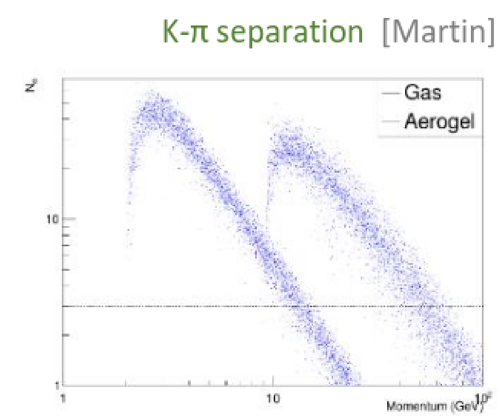


ARC reconstruction

- Display of a simulated Z event containing a $B_s \rightarrow D_s K$ decay







<u>Note</u>: this results do not come from a full simulation [Martin Tat. ECFA October 2022]

ARC reconstruction

Local pattern recognition method was originally described by Roger Forty and Olivier Schneider on the reference note LHCB/98-040

The method works as follows:

1. Reconstruct the Cherenkov angles for each photon detector hit, calculation based on information of the track (external to ARC)

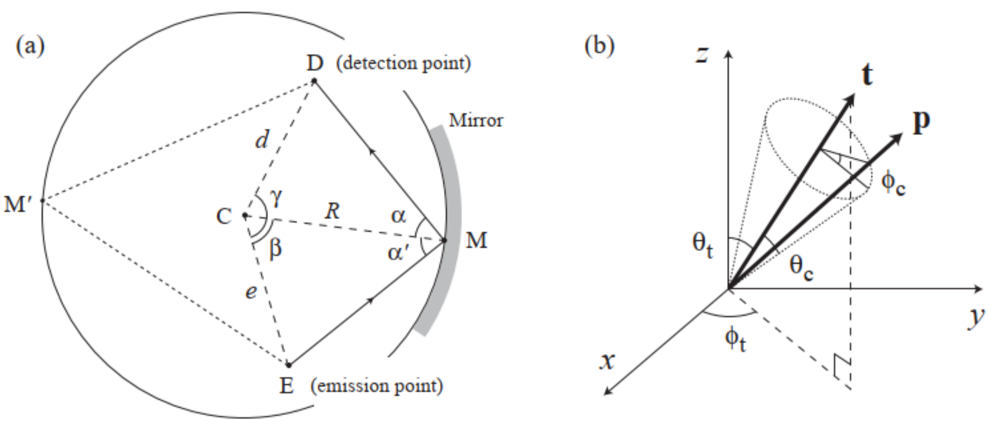


Figure 3: (a) Definition of parameters used in the reconstruction of the Cherenkov angles, for a photon emitted from point E, reflected in a spherical mirror at M and detected at D. (b) Definition of the angles describing the direction of a track **t** in the lab frame, and a photon **p** emitted by the track.

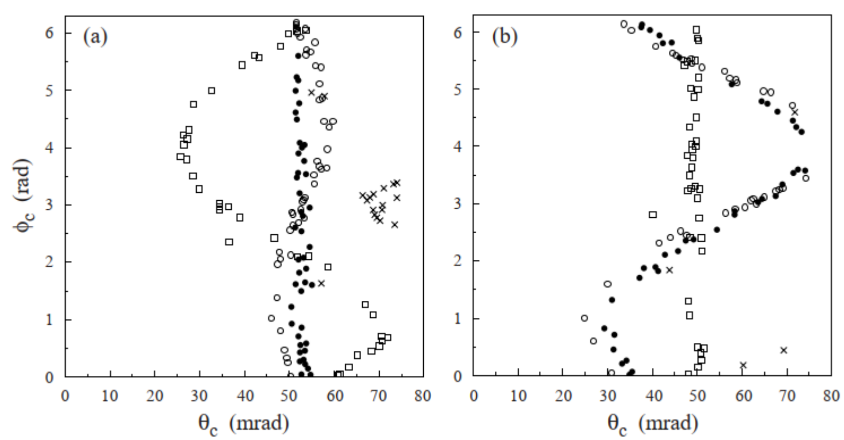


Figure 4: Reconstructed Cherenkov angles (θ_c, ϕ_c) for the hits in the event of Fig. 2, when calculated assuming that the photons were emitted from the gas radiator of RICH-1, from two tracks in turn: (a) from the track that gave the right-most ring in the dashed box of Fig. 2, and (b) from the track that gave the left-most ring in the same box. The symbol indicates which track the hit truly originated from: solid points for the track that gave the right-most ring, open points for the tracks that gave the other two rings, and crosses for hits from any other track.

ARC reconstruction

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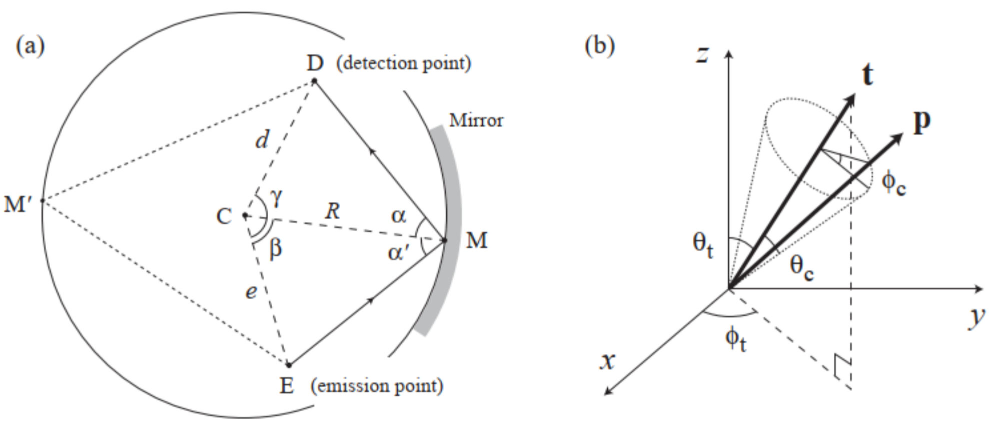
1. Reconstruct the Cherenkov angles for each photon detector hit
2. Plot the Cherenkov angles for all hits in the cell. Hits that come from the proper track will line up at a given θ_C (within the resolution)



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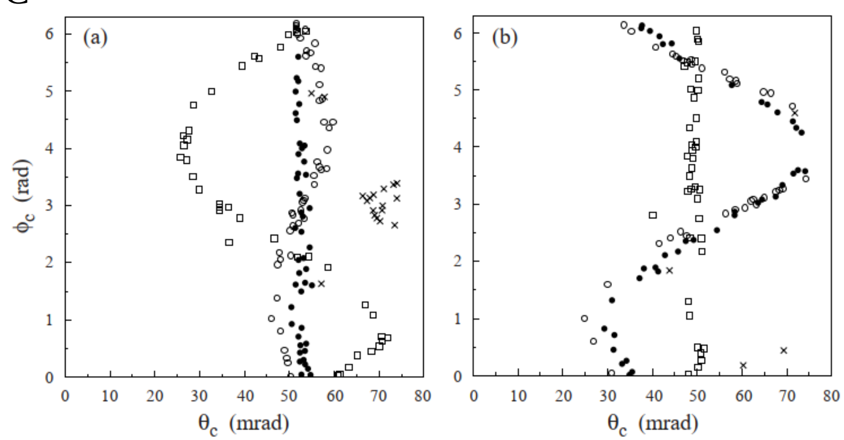

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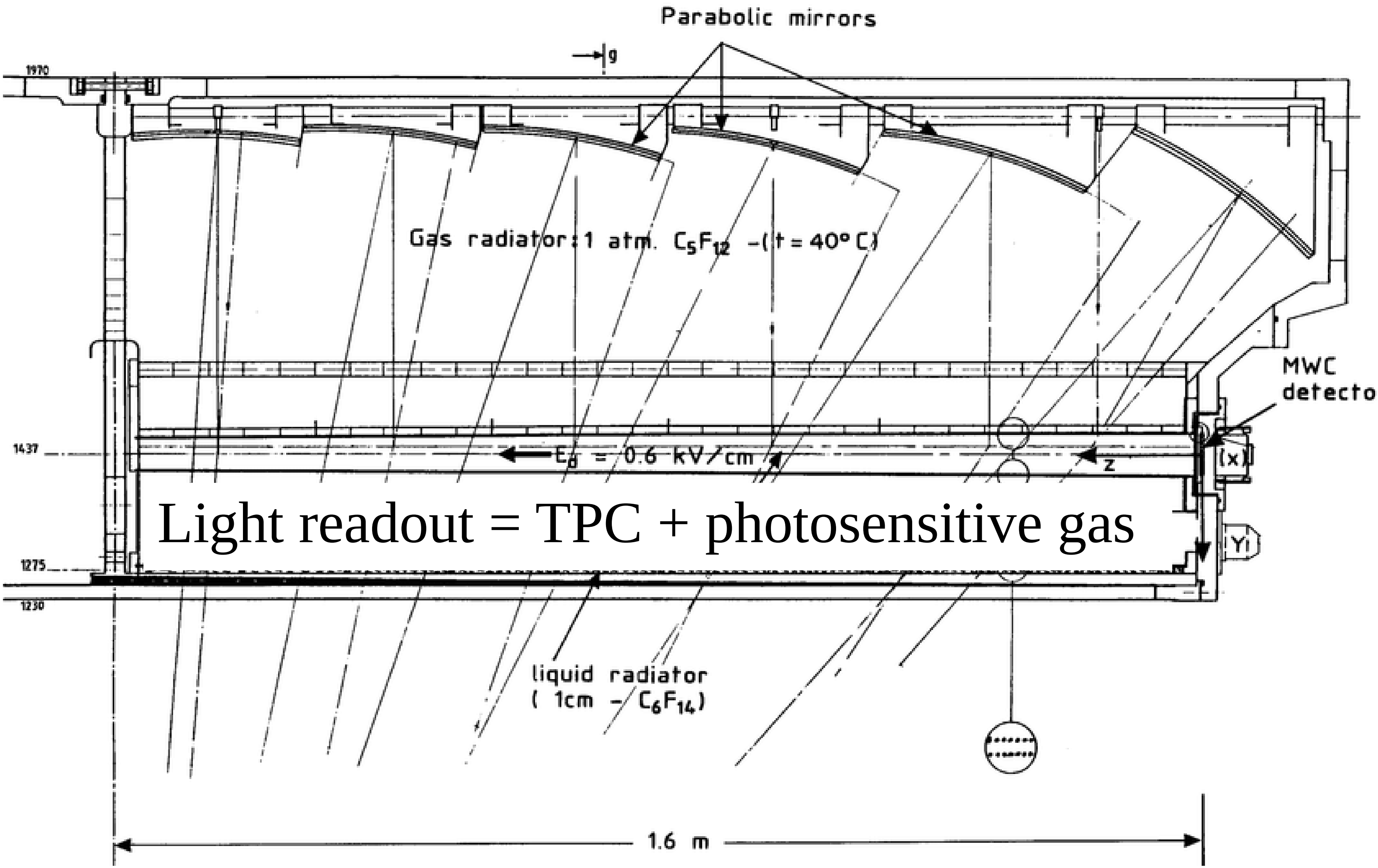
Summary

- ARC RICH detector description available in official FCC repository k4geo, PR#271
- The implementation of ARC in DD4hep facilitates
  - Fast evolution of the detector description
  - Easy integration with other detectors
  - Use in key4hep, the FCC software framework
- Dedicated reconstruction algorithms are being developed by Matt Basso @ TRIUMF
- FCC software team always happy to provide support

DELPHI RICH detector



Light readout = TPC + photosensitive gas

DELPHI RICH detector

Hit pattern in DELPHI RICH detector

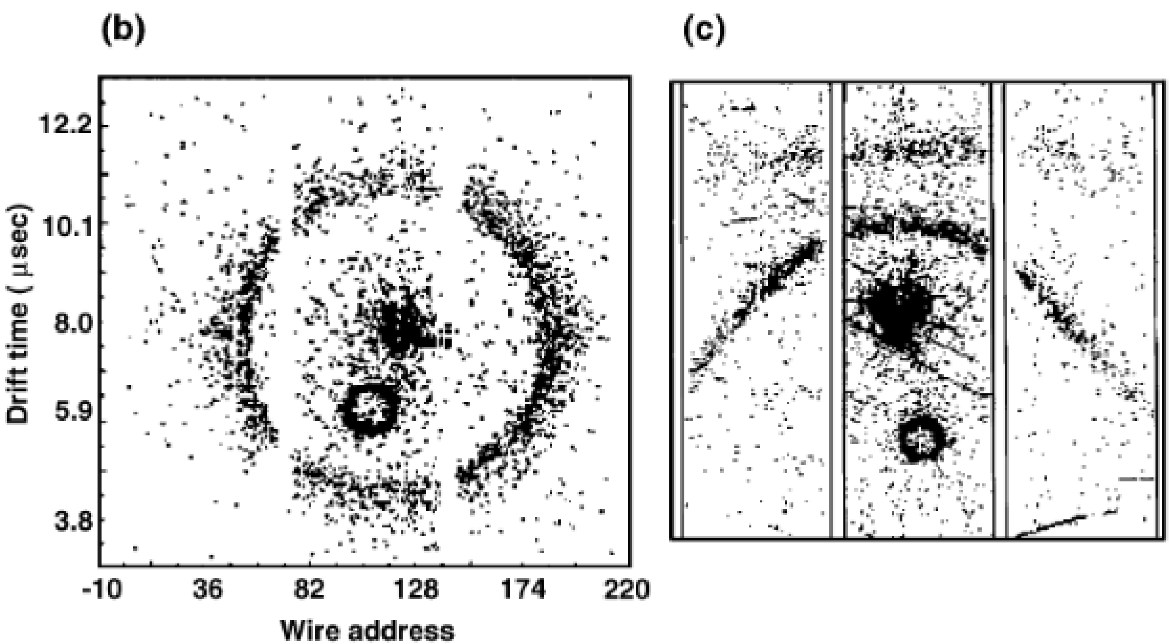
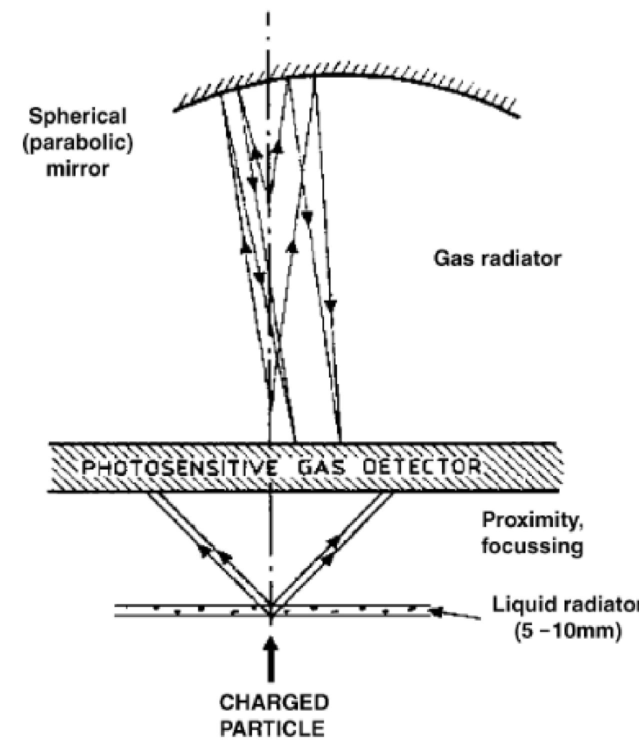


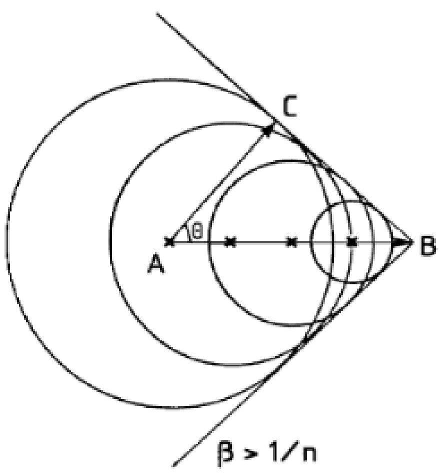
Fig. 17. – Dual radiator geometry (a) and related images formed by a perpendicularly incident particle (b) and by a particle traversing the radiators with an inclined direction (c), respectively [49].

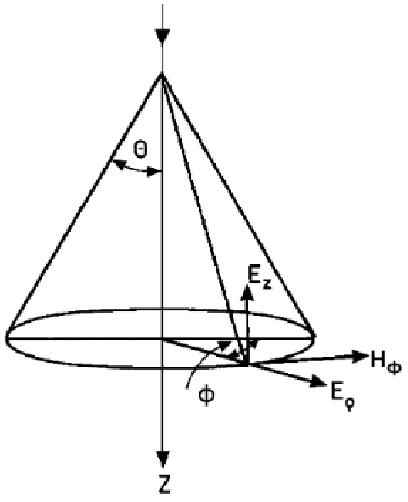


Design of Array of RICH Cells (ARC)

What is the Cherenkov radiation?

- A charged particle crossing a media causes a rapid electrical polarization. The atomic relaxation produces an EM pulse
- If the speed of the charged particle is larger than the phase velocity of light, a constructive interference wavefront is produced





Courtesy of F. Molina (CCHEN)

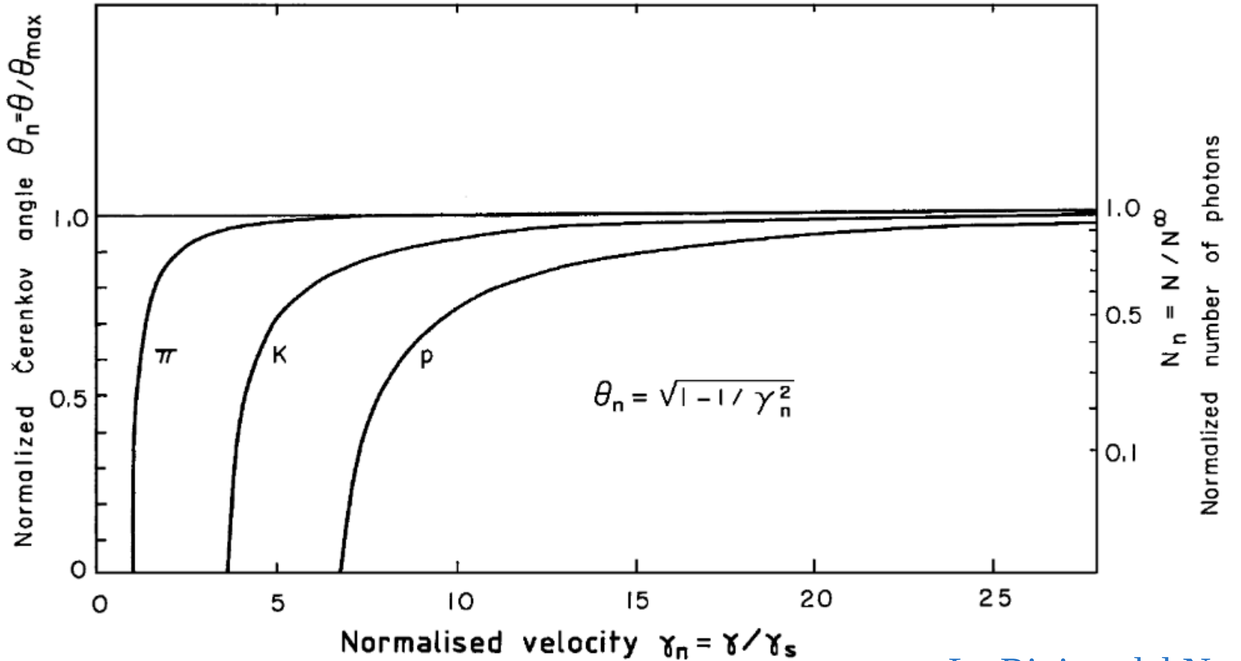
$$\cos\theta = AC/AB = (ct/n)/(\beta ct) = 1/\beta n.$$

$$\beta = \frac{v}{c}$$

Design of Array of RICH Cells (ARC)

How is the Cherenkov radiation used for PID?

- PID is derived from the speed of the particle and its momentum
- Cherenkov angle depends on the particle speed as: $\theta_c = \arccos \frac{1}{n\beta}$
- The threshold in momentum help in PID as well



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Detector description and physics simulation

- Full simulation is needed to have reliable performance estimation and to evaluate how this detector will integrate with the others (e.g. the effect of the additional material budget)

- The detector geometry, material description and readout is implemented within DD4hep framework

- Physics simulation is based on GEANT4

- Everything is orchestrated by the Key4hep framework

- See Brieuc Francois presentation about FCC Software

Detector description and physics simulation

The detector geometry, material description and readout is implemented in DD4hep framework

DD4hep separates the building of the detector element, as a C++ function, from a compact file which provides at run time definition of a number properties

Compact file(s) contain

-Material properties

-Magnetic fields

-Regions/limits/cuts

-Readout of sensitive volumes

-Call to detector element constructors

Detector element constructor:

-Builds the volume/detector tree

-Some volumes are associated with a sensitive detector (1 per constructor)

-Detector tree is used for later calibration/alignment

How to simulate one ARC cell

- The light sensor is associated with a type of sensitive detector, e.g. tracker, in order to register the deposited energy
- The read-out object takes care of generating the output data associated to the light sensor
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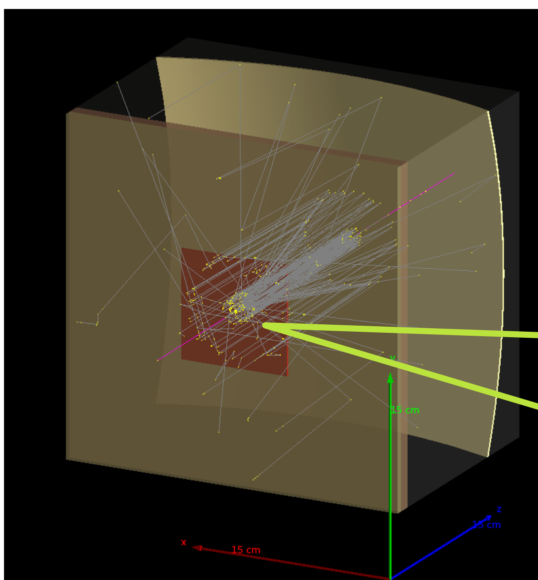

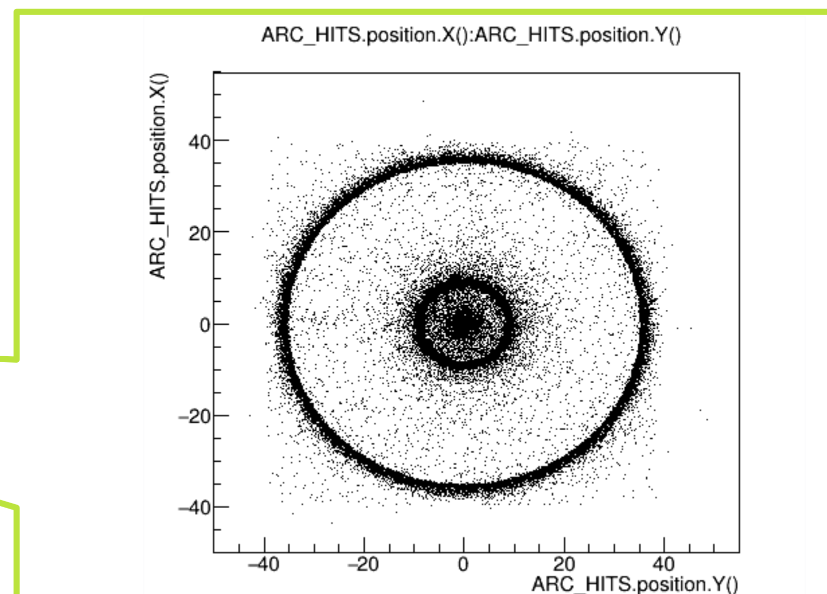

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Effect of magnetic field

For any practical purpose, the spectral dependence of the radiation must be taken into account. Frank and Tamm's equation describes the energy E radiated per unit path length $\mathrm{d}x$ by a particle of charge Ze:

$$\frac{\mathrm{d}^2E}{\mathrm{d}x\mathrm{d}\omega} = \frac{Z^2e^2\omega}{c^2}\left(1 - \frac{1}{\beta^2 n^2(\omega)}\right) , \tag{2.4}$$

where, because of the chromatic dispersion of the optical medium, n is a function of the radiation frequency ω. When integrated over the particle's path, of length L, in the

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