# Particle Identification with ARC

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# Particle Identification with ARC

- Motivation of Particle Identification (PID) in FCCee

- Detector description of Array of RICH Cells (ARC)

- ARC reconstruction for Particle Identification

    - The local pattern recognition

    - Inverse ray-tracing of the Cerenkov photons (*with code*)

# Motivation of PID in FCCee

- FCC-ee is expected to produce an unprecedented amount of Z, opening possibility of world-class flavor physics program
- 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 for example
- Please refer to Roger Forty presentation during the FCC week 2023 for further motivation of PID in FCCee experiments design
- With these ideas in mind, the Array of RICH Cells (ARC) concept was developed by Roger Forty, Guy Wilkinson, and Martin Tat

# Motivation of PID in HEP

- ARC provide PID capabilities for FCC-ee detector with a small radial extent (20 cm) and a minimal impact on material budget (<$0.1X_0$)

- The detector was presented by Roger at FCC Week 2021 and the Kickoff Detector Concepts workshop June 2022, and later by Martin at ECFA October 2022 and Krakow January 2023

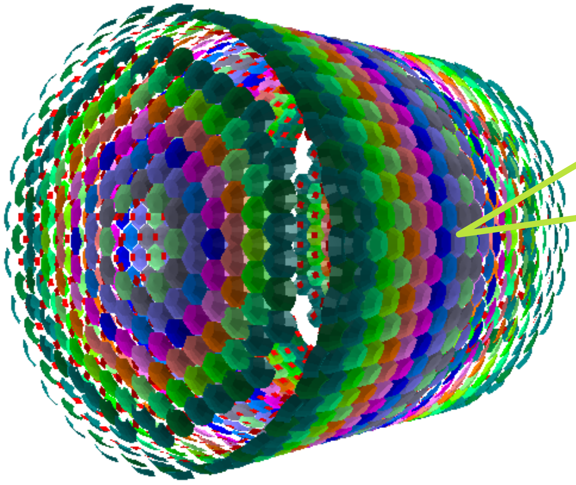
- The ARC detector description was presented at FCC Week 2023, and a new option of CLD with a smaller tracker to accommodate the ARC is ready. Please see G. Sadowski talk about the CLD tracker studies for further details, and B. Francois talk about the status of the different detector concepts

- I would like to thank Martin, Roger, Guy, the FCC software team and many others that participated in the discussions and followed and supported the work of the ARC geometry implementation

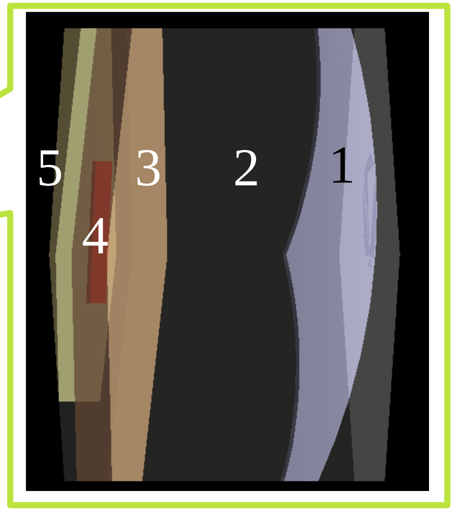
- This talk focuses on how to implement the PID algorithm of ARC in key4hep. For illustration, ARC has been added to the CLD experiment concept, as it currently lacks PID

# Detector description of ARC

- The detector geometry, material description (including optical properties) and sensor readout is fully implemented in DD4hep framework
- The **ARC** consist on an large array of **RICH cells** placed as in the picture below (only mirrors and sensors are visible for simplicity)
- Each RICH cell consist in an spherical mirror (1) which focus the light produced in the two Cerenkov radiators (2,3) into a light sensor (4)



ARC




RICH cell

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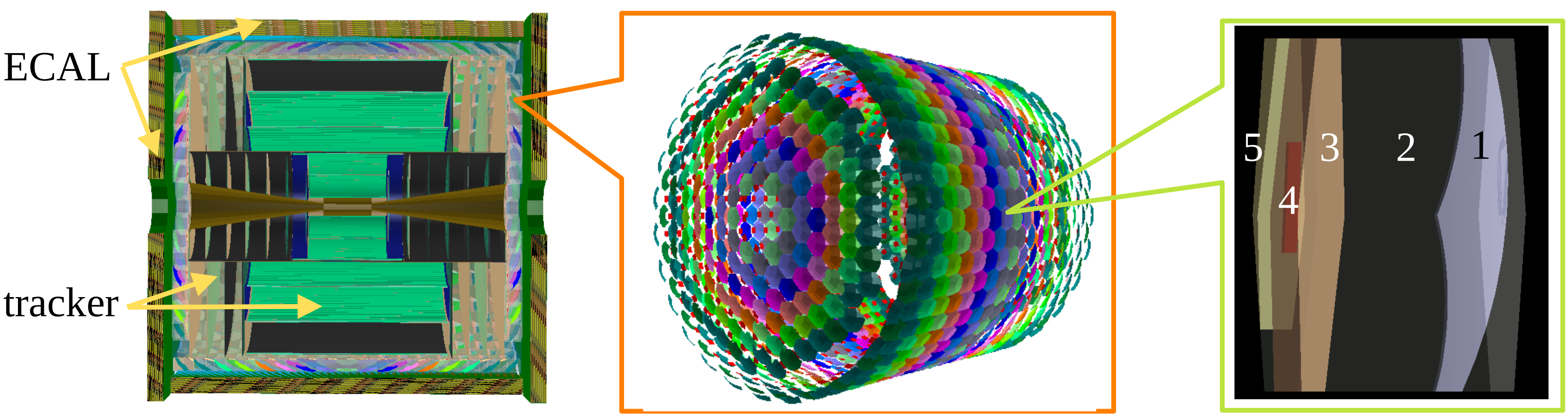
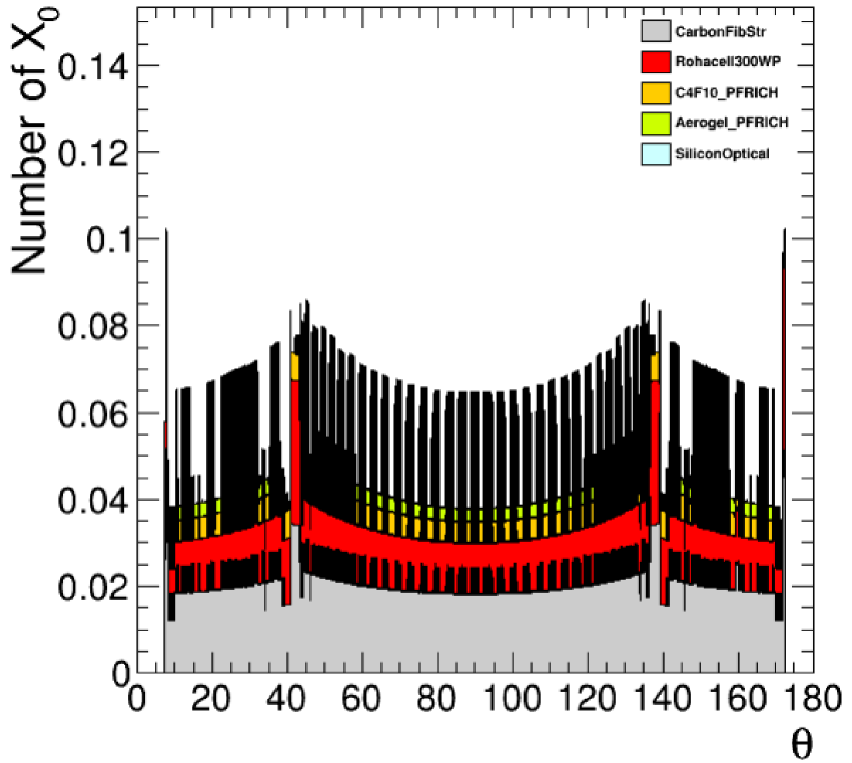
- Each RICH cell consist in an spherical mirror (1) which focus the light produced in the two Cerenkov radiators (2,3) into a light sensor (4)
- **CLD option 3** has a smaller tracker compared to option 2 to leave space for the ARC, which is placed between the tracker and the ECAL

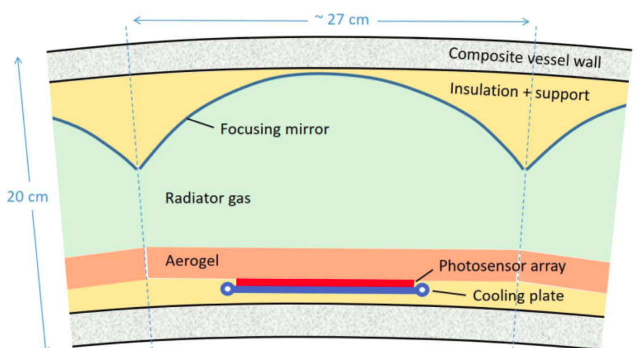



CLD option 3 | ARC | RICH cell

# Detector description of ARC

- A critical feature for the ARC design to be accepted in an experiment is to minimize the material budget: the current design checked in simulation is only 5% $X_0$ (on average)
- To make this a reality, R&D will be needed on the lightweight composite vessel and the photosensor; the baseline gas radiator is unpressurized $C_4F_{10}$, but alternatives are under study (e.g. Novel gas mixtures, or xenon)
- Development of the ARC concept is one of the work packages in new R&D Collaboration on Photon detectors and Particle ID —see task 4.3.4 in the DRD4 proposal
- DRD4 was set up last month, further participation welcome (Coordinator: Massimiliano Fiorini, CB chair: Guy Wilkinson)

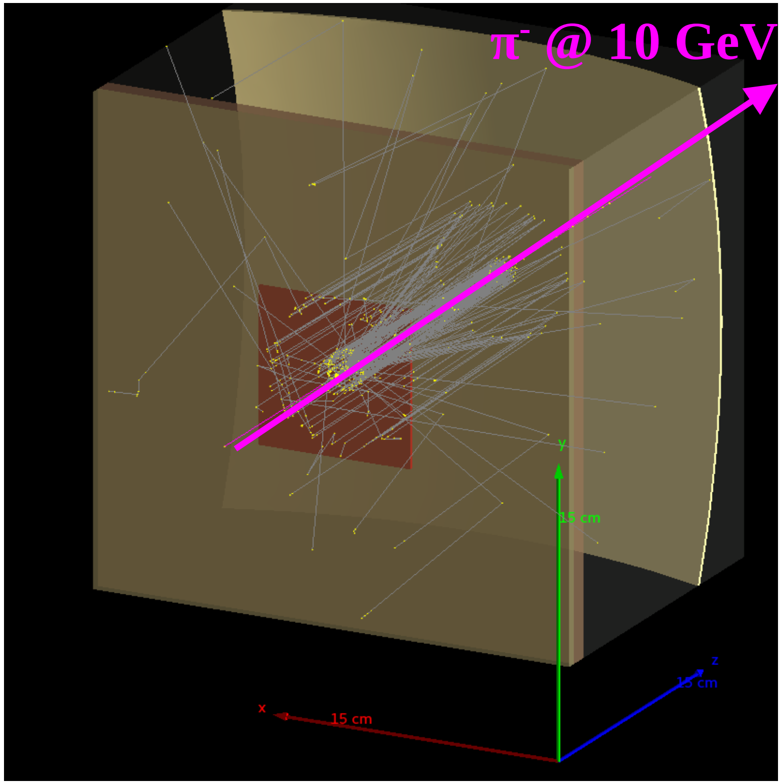


ARC detector (one cell)

# Detector response of ARC

- There are two Cerenkov radiators inside each RICH cell
- When a charged particle crosses a cell, two cones of Cerenkov photons are created. The detected photon energy is in the range of (2, 6) eV, or (200, 600) nm



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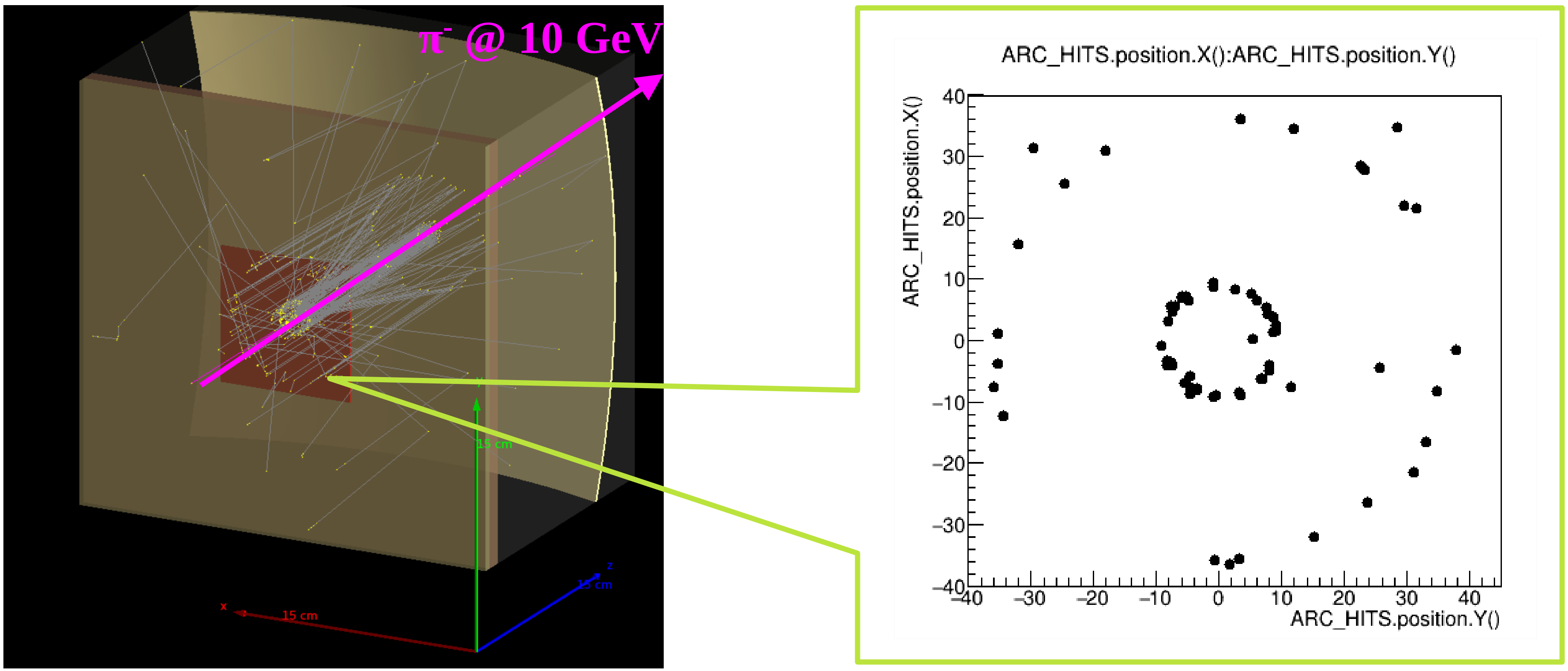
- When a charged particle crosses a cell, two cones of Cerenkov photons are created. The detected photon energy is in the range of (2, 6) eV, or (200, 600) nm
- The hit pattern in the sensor corresponds to two concentric rings
- DD4hep and Geant4 are used to simulate the behavior of the ARC detector

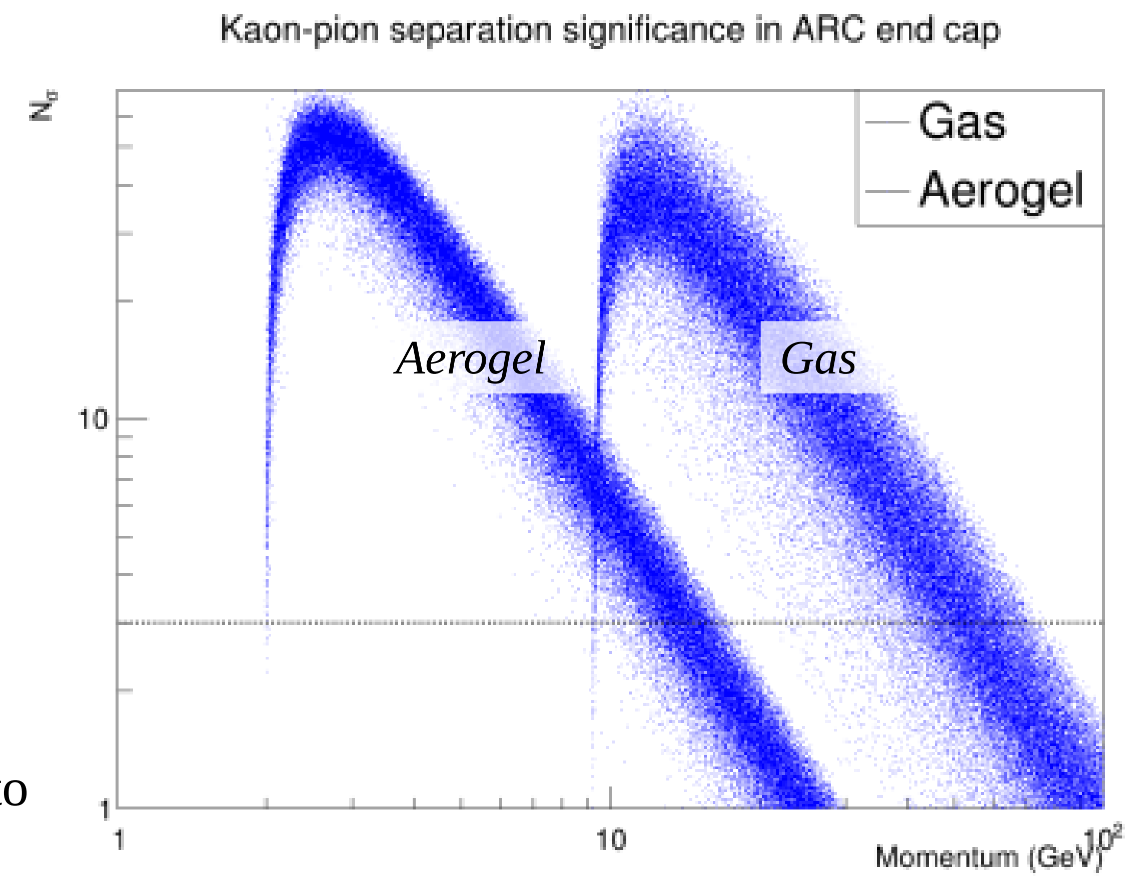


# Detector response of ARC

- The expected performance of ARC has been studied so far with a stand-alone ray tracing approach: e.g. see the plots presented by Martin Tat at the Krakow meeting

- Note that this is for *positive* identification (where both kaon and pion are above threshold) - there is also **information *below* the kaon Cherenkov thresholds** (2 GeV in aerogel, 9 GeV in gas): there pions will produce light but kaons will not, so the detailed performance *vs* momentum should come from full simulation

- Now the full simulation of ARC in CLD is available, the current work is to implement reconstruction for particle ID in those events, including the affect of scattering and background




*Gas (aerogel) provides over 3σ pion-kaon separation in the range 10-50 GeV (2-10 GeV)*

# ARC reconstruction for Particle Identification

The particle identification is based on the pattern recognition of the Cerenkov rings projected into the photon sensor of the RICH cell

The reconstruction implementation road map is the following:

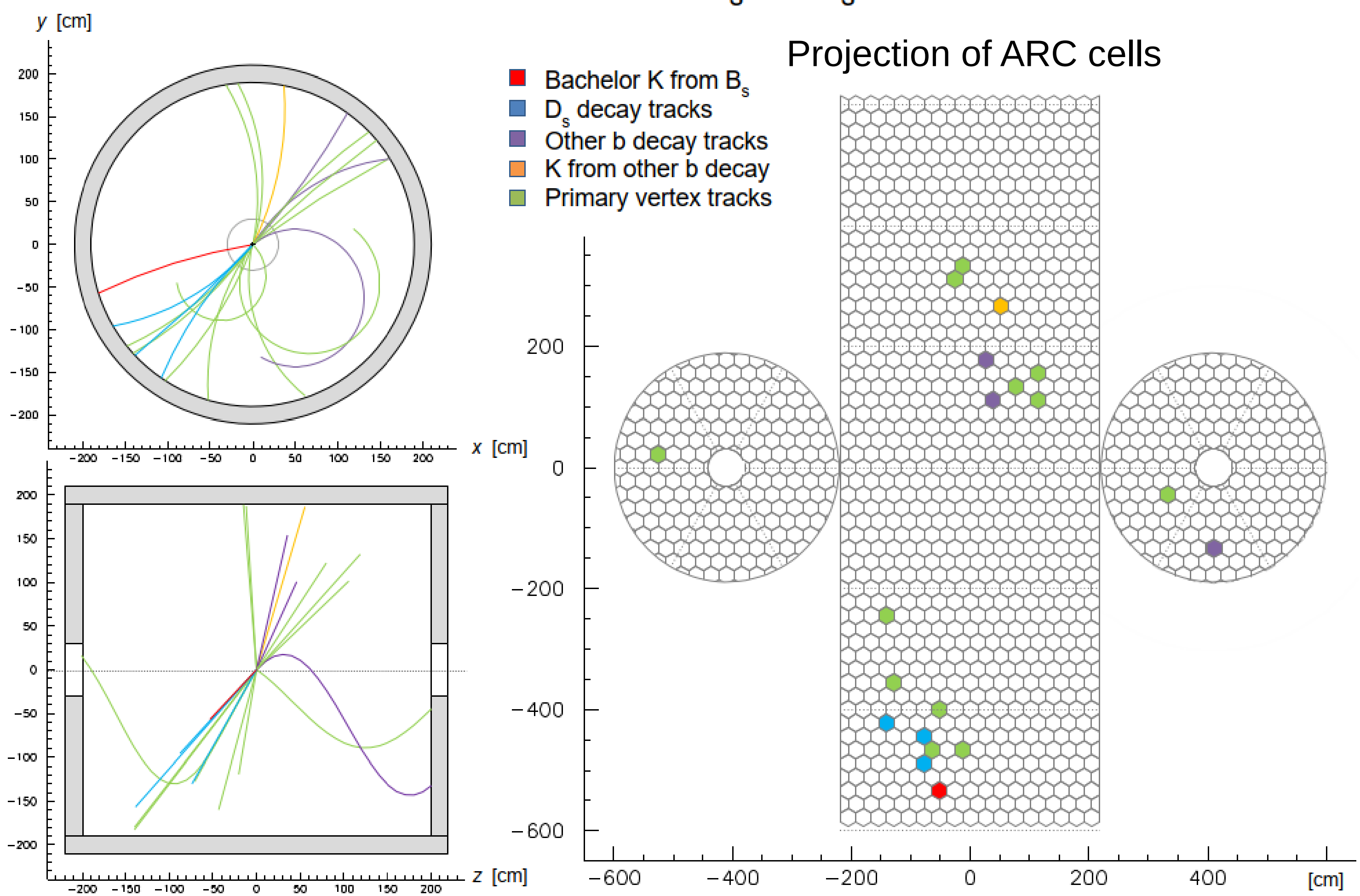
1) Local method: the pattern recognition of individual ring images are treated independently. A local likelihood function is used to distinguish between different particle hypothesis. [LHC-B/97-018]

This method assumes that the photons registered in a RICH cell are created by a single track, and therefore it is expected to work for ARC since a low occupancy of the detector is expected during the FCCee runs [see next slide]

# ARC reconstruction for Particle Identification

Preliminary simulations show low track occupancy of ARC in Z decay events

Display of a simulated $B_s \rightarrow D_sK$ event in ARC




*M. Tat, R. Forty*

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2) Global method: each photon is explicitly assigned to a reconstructed ring image using a global likelihood function. [LHCB/98-040]

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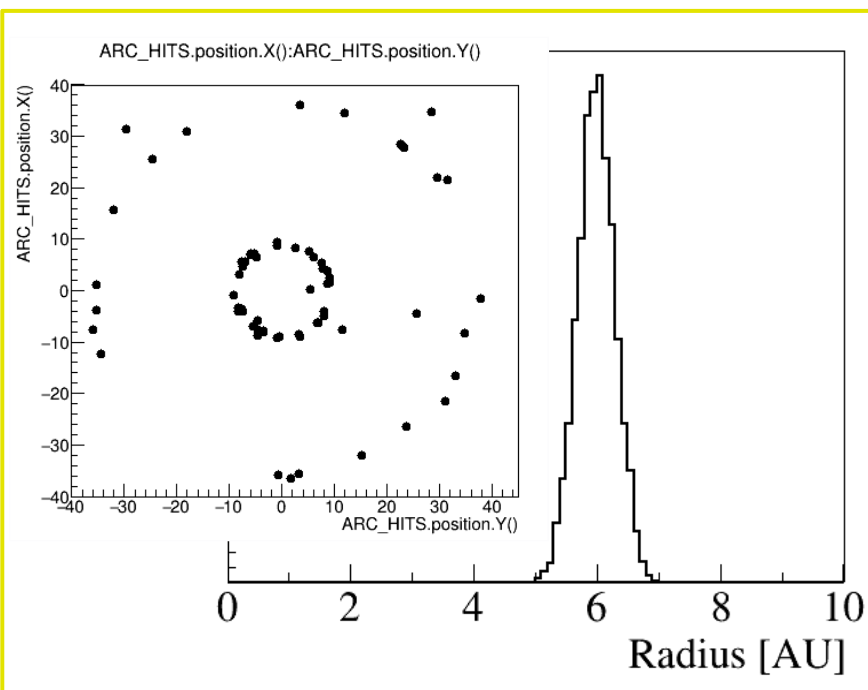
For both methods the performance of the pattern recognition relies on the knowledge of the track parameters measured in the tracking system

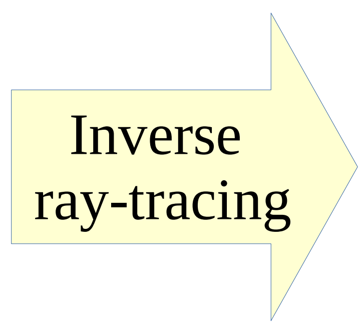
# ARC reconstruction for PID. The local method

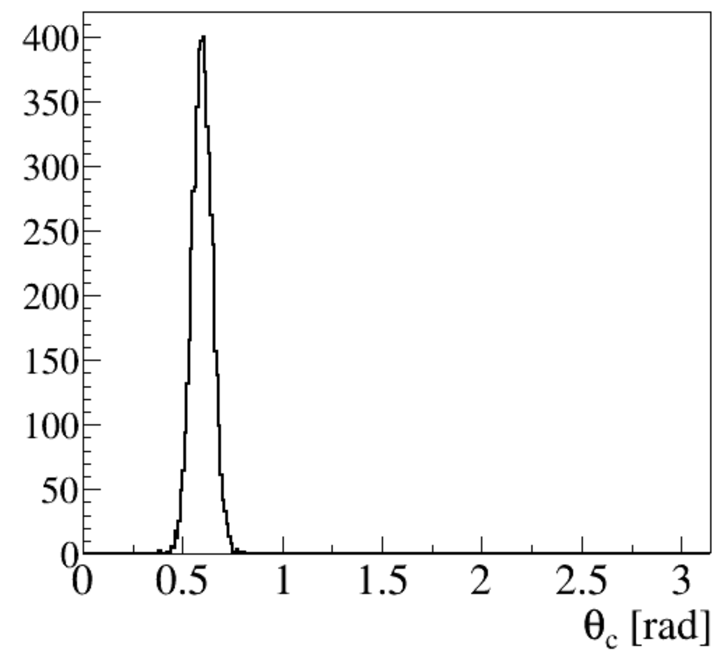
The local method is applied for each RICH cell independently

It consist in the following steps:

a) Perform an inverse ray-tracing of the optical photons, to convert the ring distribution in the light sensor into a distribution on theta, with theta the angle of the photons with respect the charged particle track



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b) Calculate the likelihood of each particle hypothesis (electron, muon, pion, kaon, proton, and background), as described in this note LHC-B/97-018. This corresponds to fitting the peak with a Gaussian, and comparing its mean and area to the expectations for each hypothesis

$$\mathcal{L} = \frac{1}{N}\sum_{hits\ i}\log\left(1+\frac{1}{\sqrt{2\pi}\sigma_\vartheta\varepsilon}e^{-\frac{(\vartheta_i-\vartheta_{hypo})^2}{2\sigma_\vartheta^2}}\right)$$

$$N = \log\left(1+\frac{1}{2\sqrt{\pi}\sigma_\vartheta\varepsilon}\right),$$

# ARC reconstruction for PID. The local method

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The ARC has two types of Cerenkov radiators, the gas filling most of the volume of the cell and a layer of aerogel on top of the light sensor. The implementation of the code will start by taking into account just the optical photons generated in the gas; later it will evolve to take into account also the photons generated in the aerogel.

It assumes that the photons hitting the sensor are produced by 1 track. A global method will be implemented if required, and corrections added for tracks that cross two cells

# ARC reconstruction for PID. The local method

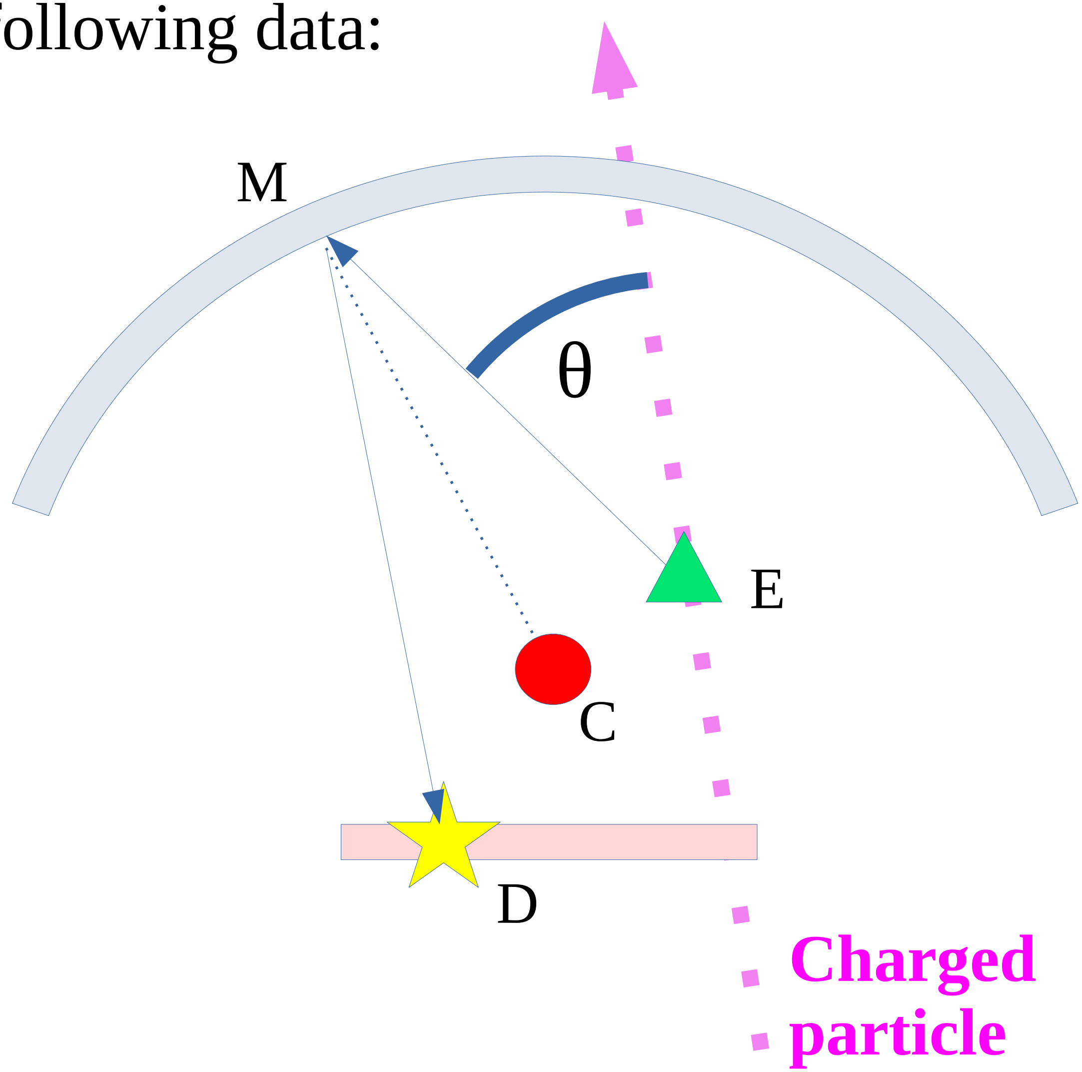
- The ARC reconstruction method(s) can be implemented as Gaudi algorithms
- To be discussed what is the best way to connect the PID from ARC with other reconstruction algorithms
- Sketch of the local method implementation as Gaudi functional

```
class RICH_PID :
public TransformAlgorithm<ReconstructedParticle(const Track&, const TrackerHitCol&)> {
    ...
ReconstructedParticle operator()(const Track& tr, , const TrackerHitCol& RICH_hit) const {
    auto e_point        = extrapolate_track_to_emission_point(tr, geoSvc);
    auto d_point        = convert_to_global_coordinates(RICH_hit);
    auto mirror_ptr     = get_mirror_properties(tr, geoSvc);
    auto Cerenkov_theta = solve_raytracing_equation(e_point,d_point,mirror_ptr, tr);
    auto PID_likelihood_map = calculate_PID_likelihood(Cerenkov_theta);
    auto reco_particle  = ReconstructedParticle(tr, PID_likelihood_map)
    return reco_particle;
}
```

# ARC reconstruction for PID. Inverse ray-tracing

The theta angle θ between the Cerenkov photon and the charged particle can be calculated as described in this note LHCB/98-040 by Roger Forty and Olivier Schneider from the following data:

1. Hit position in the light sensor of a RICH cell (D)
2. The radius and center of the mirror M of that particular RICH cell
3. Estimated emission point (E) of the Cerenkov photon



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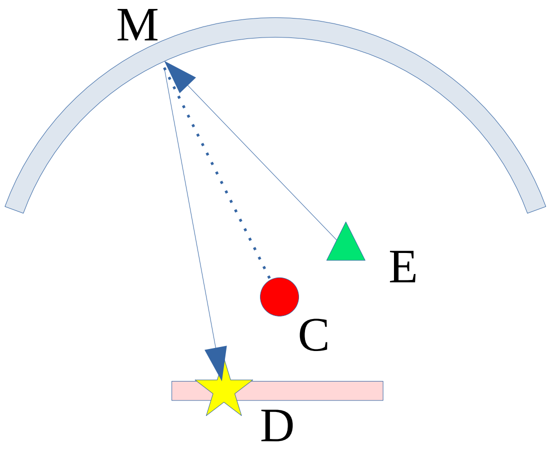
ARC data coming from the simulation (or experiment) contain a cell ID for each hit, that identifies the position of the sensor pixel where the photon was detected. We can use DD4hep machinery to convert the cell ID into a 3D position in the global coordinate system




```
Detector& description = Detector::getInstance();
          description.fromCompact( “ARC_detector.xml” );
CellIDPositionConverter     idposConv( description )  ;
Position pointFromDecoder = idposConv.position( cell_id ) ;
```

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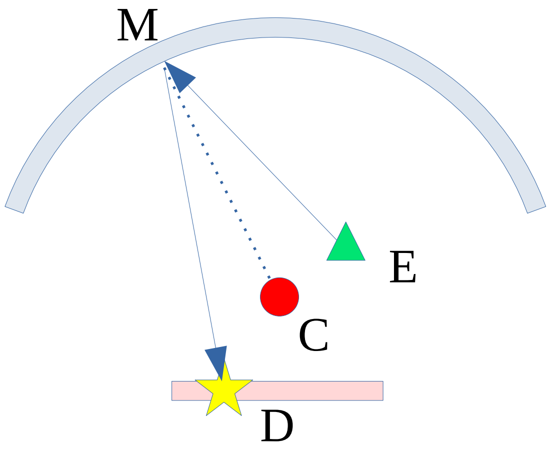


The mirrors are spherical caskets, built as intersection of a semi-sphere and the shape of the corresponding RICH cell. The mirrors are off-centered differently for each cell, so it is necessary to first calculate what cell was crossed by a given track, and then use the code in the following slide to retrieve the mirror properties.

# ARC reconstruction for PID. Inverse ray-tracing

## Retrieving the geometrical properties of the mirror of that RICH cell

```
int ncell = 1, reflected = 0, nphi = 1; // based on the track information

/// retrieve pointer to the mirror shape
auto barrelDE = description→detector("ARCBARREL");
auto cellDE_name = Form("ARCBARREL_cell%d_ref%d_phi%dDE", ncell, reflected, nphi);
auto cellDE = barrelDE.child( cellDE_name );
auto mirrorDE_name = Form("ARCBARREL_mirror%d_ref%d_phi%dDE", ncell, reflected, nphi);
auto mirrorDE = cellDE.child( mirrorDE_name );
auto mirrorSolid = mirrorDE.solid();
auto m = (TGeoCompositeShape*)mirrorSolid.access();

/// Retrieve the center of the sphere
//-- this is just the matrix for building the intersection, translation
auto matrix_boolean = m->GetBoolNode()->GetRightMatrix();
//-- matrix for placing the cell
auto matrix_cellvol = cellDE.nominal().worldTransformation();
double local_coord [3] = {0.,0.,0.};
double global_coord[3] = {0.,0.,0.};
(matrix_cellvol**matrix_boolean).LocalToMaster(local_coord, global_coord);
/// global_coord contains now the XYZ global coordinates of the center of the mirror

/// Retrieve the inner radius of the spherical mirror
TGeoSphere * spherical_mirror_shape = (TGeoSphere*)m->GetBoolNode()->GetRightShape()
double mirror_r_min = spherical_mirror_shape->GetRmin();
```

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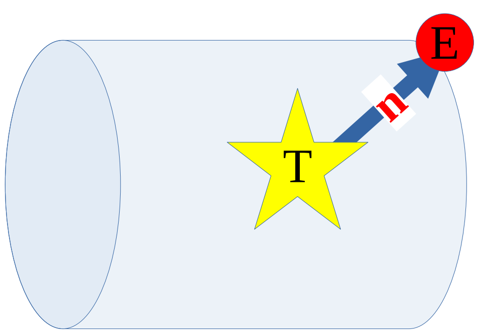
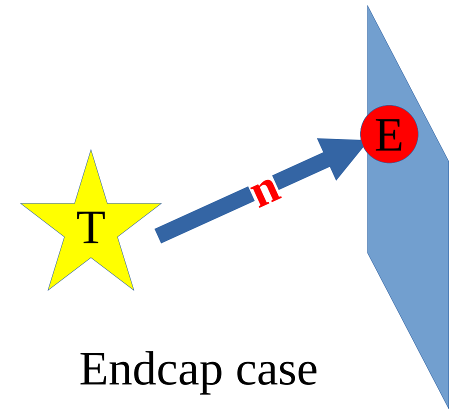
   As a first approximation, we can consider that the emission point lies on a surface that is in the middle of the ARC radiator. The emission point is determined as intersection of an extrapolation of the track and this surface.

Barrel case



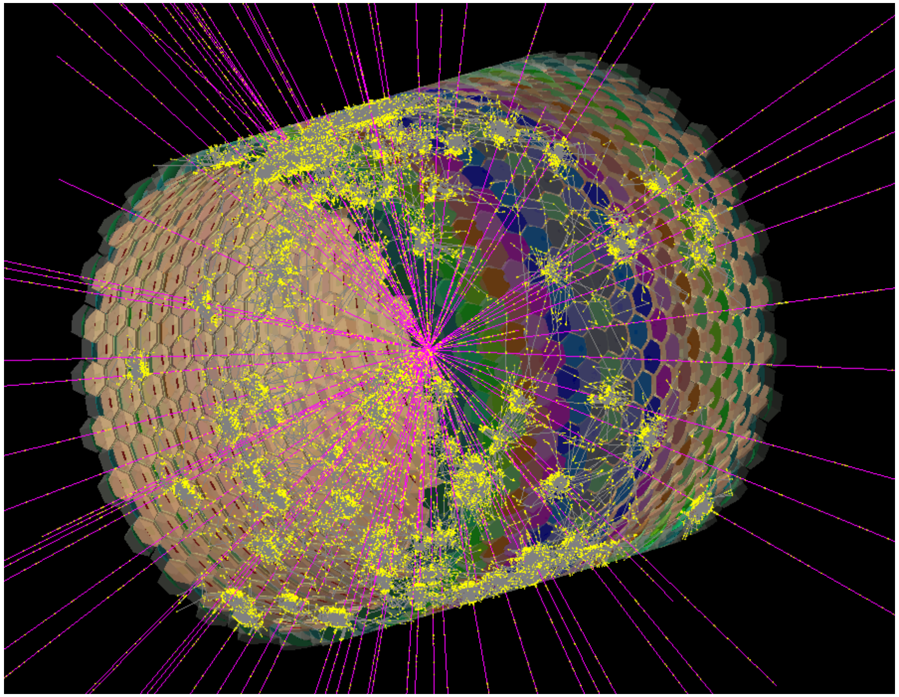

T: Last tracker position
**n**: particle direction




Endcap case

# Summary

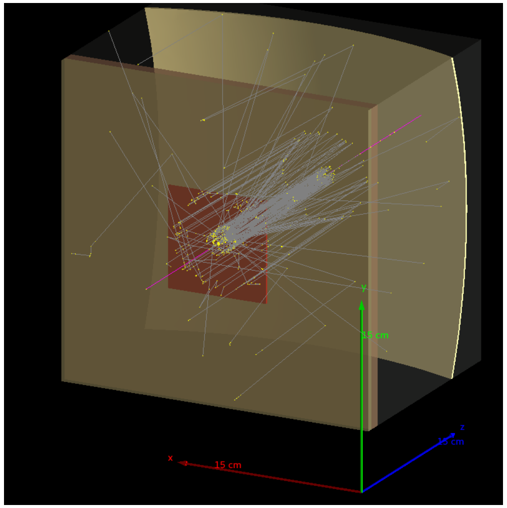
- The ARC geometry, material description (including optical properties) and sensor readout is fully implemented in DD4hep framework
- CLD detector option 3 has a modified tracker to accommodate the ARC, and it is ready to be used
- The implementation of ARC particle identification in key4hep as Gaudi algorithm is ongoing



# Appendix

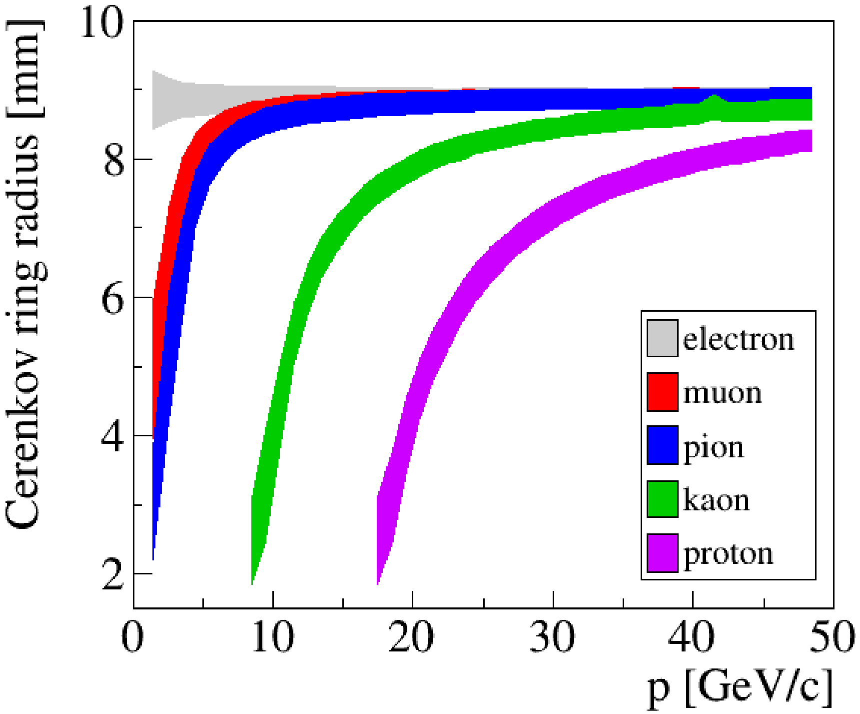
# Cerenkov ring radius resolution

The cubic RICH cell is taken as starting point for reconstruction code development. For further simplification, the aerogel is removed temporally for the sake of simplicity.



The Cerenkov photon hits are distributed as a ring shape in the sensor. The plot on the right shows the radius (and width 1 sigma) for different momentum of each particle hypothesis. There are two key points that are disregarded here and will make the radius distribution broader:

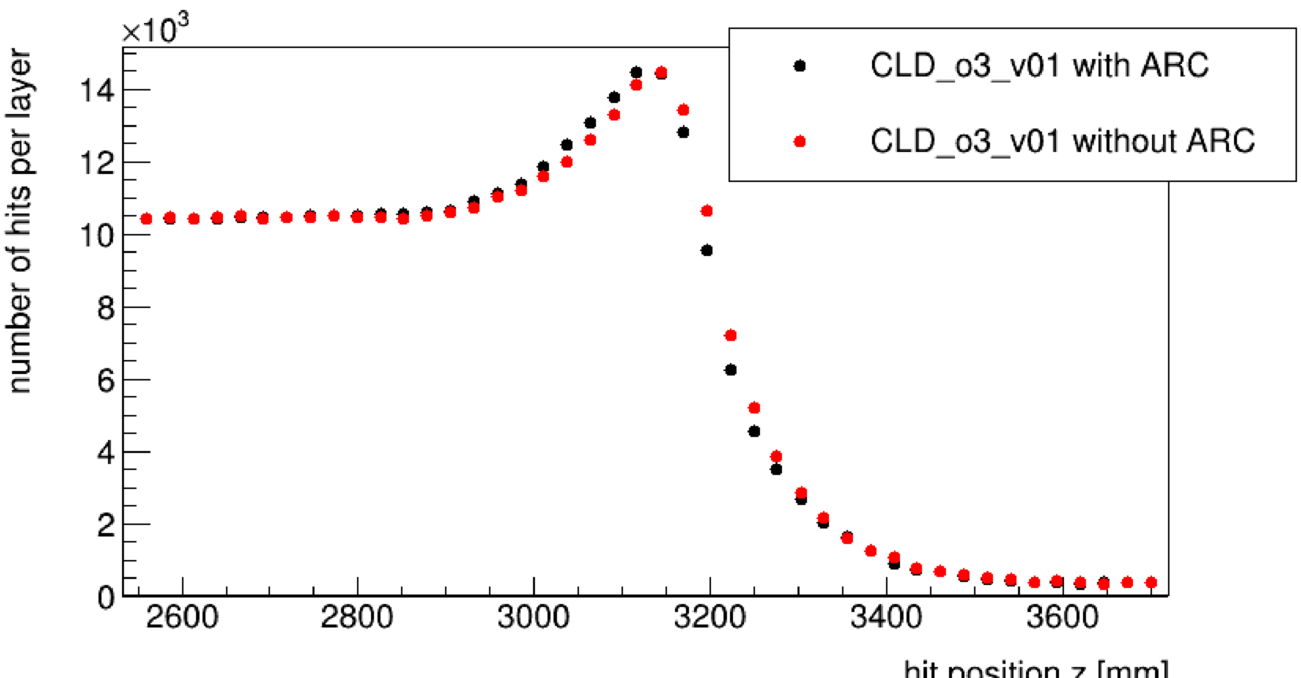
- Aerogel is not present. The Rayleigh scattering in the aerogel will affect the hit distribution
- Aberrations of the mirror. For this plot, particles have a trajectory following the symmetry axis of the cell, but that will not be the general case

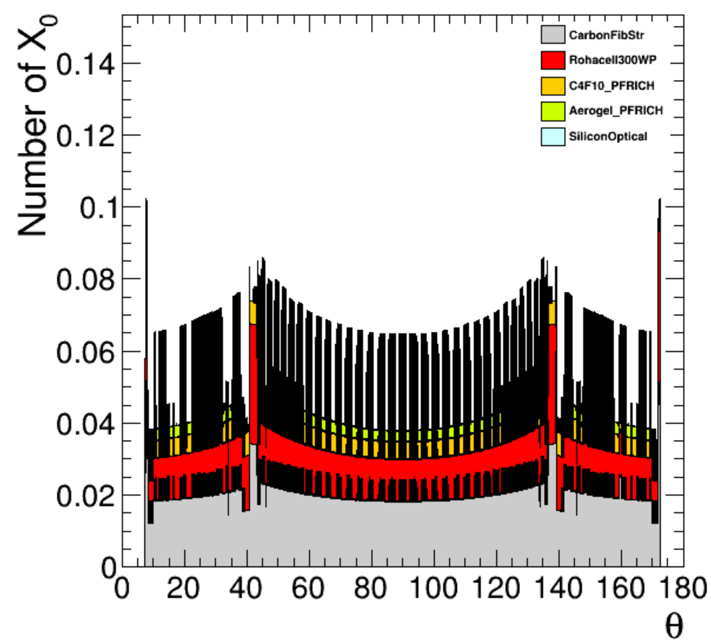


# Impact of presence of ARC in CLD

The number of hits per layer of the H-Cal Endcap is shown below. The detector concept is in both cases the option 3 of CLD. The difference is the presence/absence of the ARC detector.

**The Bragg peak shifts 1 layer because of the presence of the ARC**



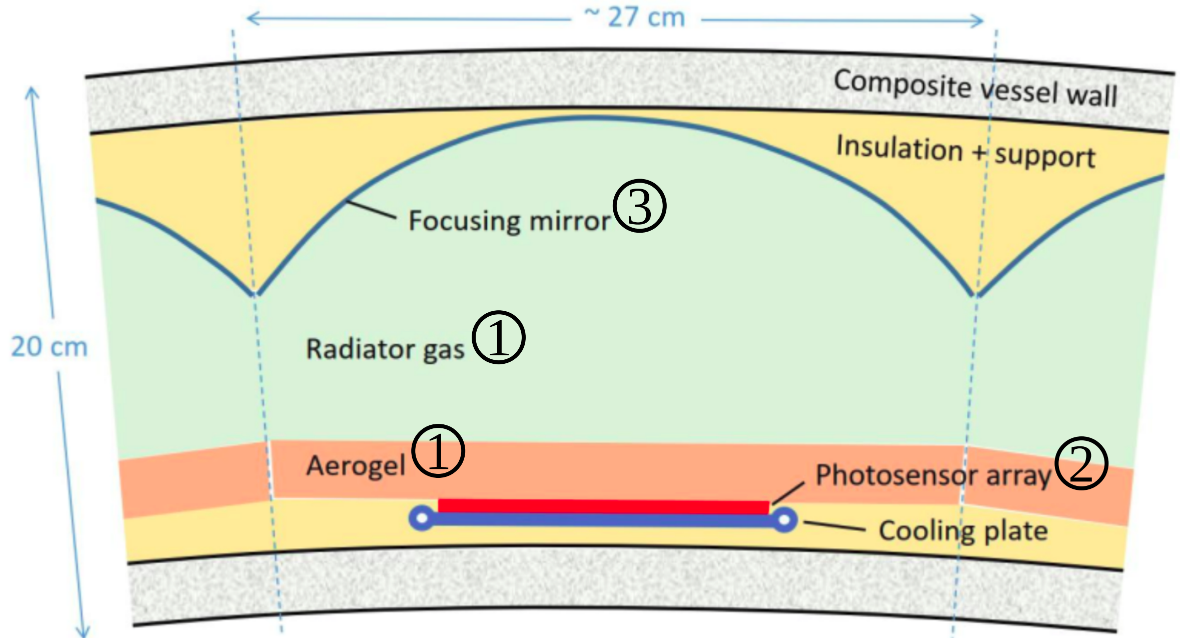

Particle gun: 10k $\mu^-$ @ 1GeV @ θ=10°

# Detector description of 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)