Simulation and performance study of the ARC concept for a compact RICH detector

Alvaro Tolosa-Delgado (CERN)

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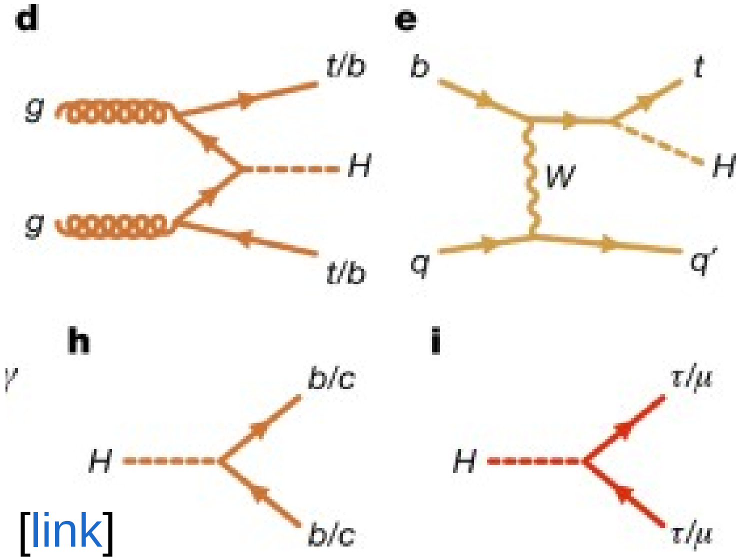
Motivation of PID in FCCee

- FCC-ee is expected to produce an unprecedented amount of Higgs, enabling precise studies of its properties and couplings
- Higgs physics, particularly flavor tagging, relies on hadron Particle Identification (PID) to identify decay products such as bb-jets and cc-jets with high accuracy
- Flavor physics studies, supported by the abundant Z bosons at FCC-ee, would also benefit from advanced PID capabilities. See V. Cairo [FCC22] and R. Forty [FCC23]
- RICH detectors are highly effective for particle identification at high momenta, as demonstrated by the LHCb experiment



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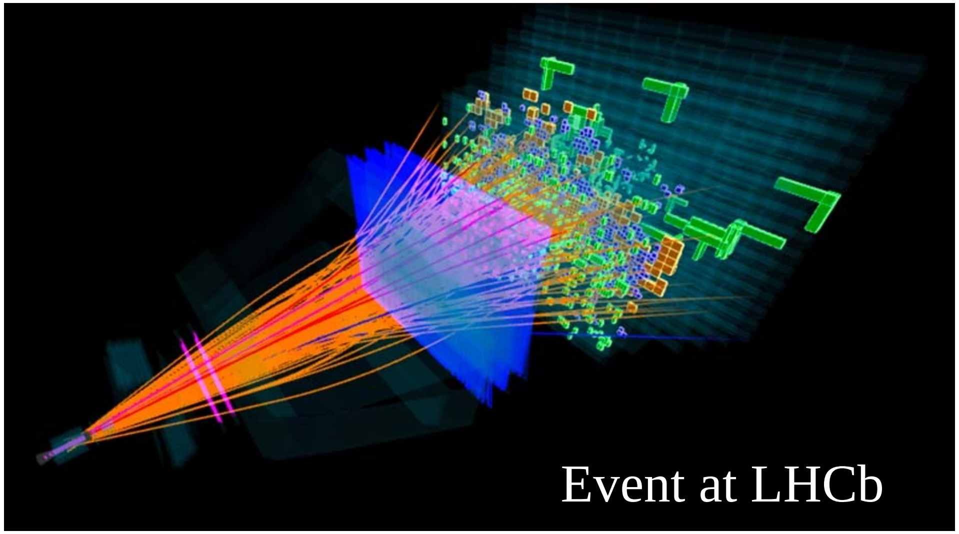


Introduction to ARC

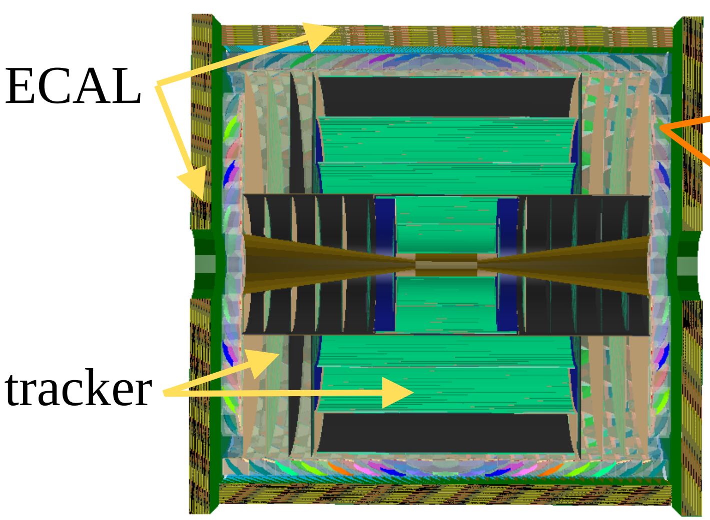
- The Array of RICH Cells (ARC) detector provide PID capabilities for FCC-ee detector with a small radial extent (20 cm) and a minimal impact on material budget ($<0.1X_0$)
- First presented by R. Forty at FCC Week 2021 and later by M. Tat at key workshops ECFA October 2022 and FCC physics 2023
- Updated description shared at FCC Week 2023, including a new CLD option with a smaller tracker to accommodate ARC
- **See S. Pezzulo's talk for insights on event reconstruction [link]**
- This talk includes contributions by S. Pezzulo, M. Tat, R. Cardinale, and R. Forty, summarized in a dedicated document [link]
- I also thank our colleagues for their collaboration, working on the physics motivation for the ARC concept and preparation of the hardware prototype: M. Basso, V. Cairo, S. Malde and G. Wilkinson

Detector description of ARC

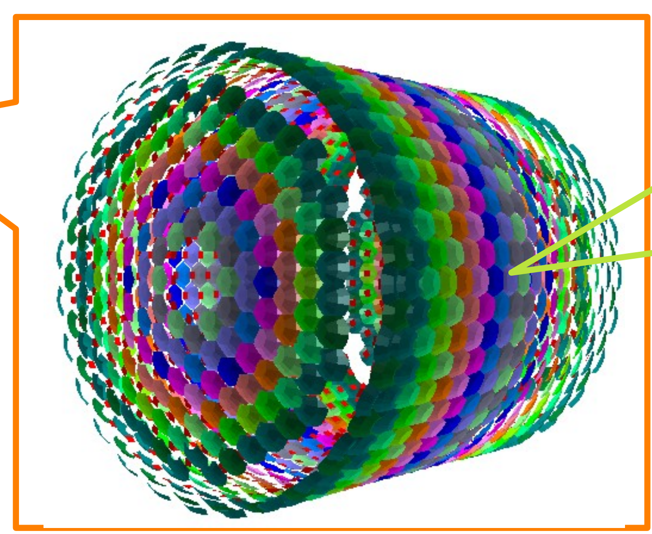
- The **ARC** consists of an large array of independent **RICH cells** placed as in the picture below (only mirrors and sensors are visible for simplicity)

- Each RICH cell consists of an spherical mirror (1) which focuses the light produced in the two Cerenkov radiators (2,3) into a light sensor (4)

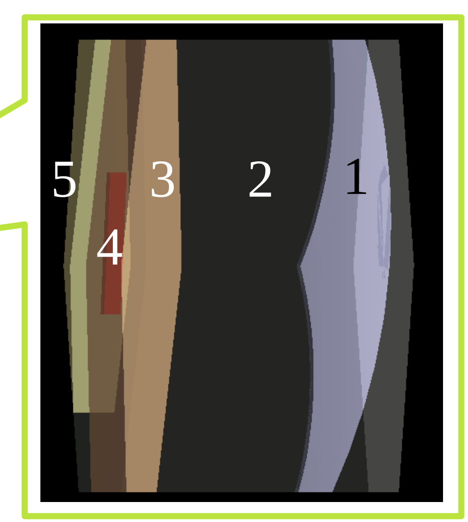
- **CLD option 3** has a smaller tracker to fit ARC. See G. Sadowski study about the tracking performance of this CLD option (EPJ-WoC)



CLD option 3



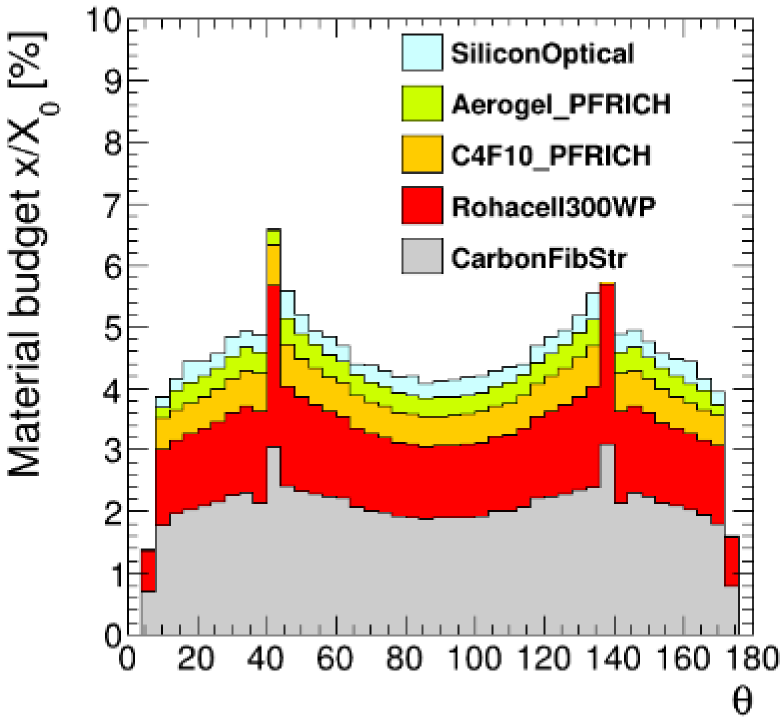
ARC

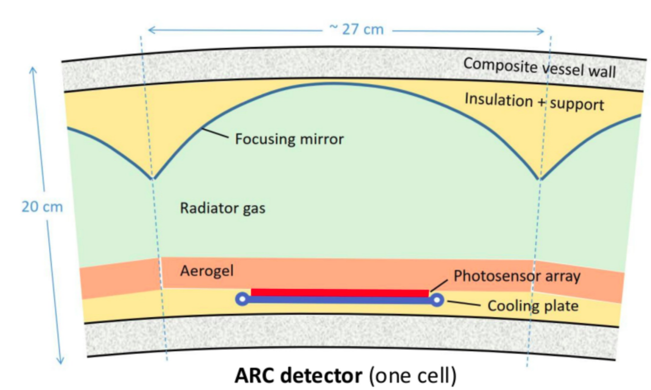


RICH cell

Detector description of ARC

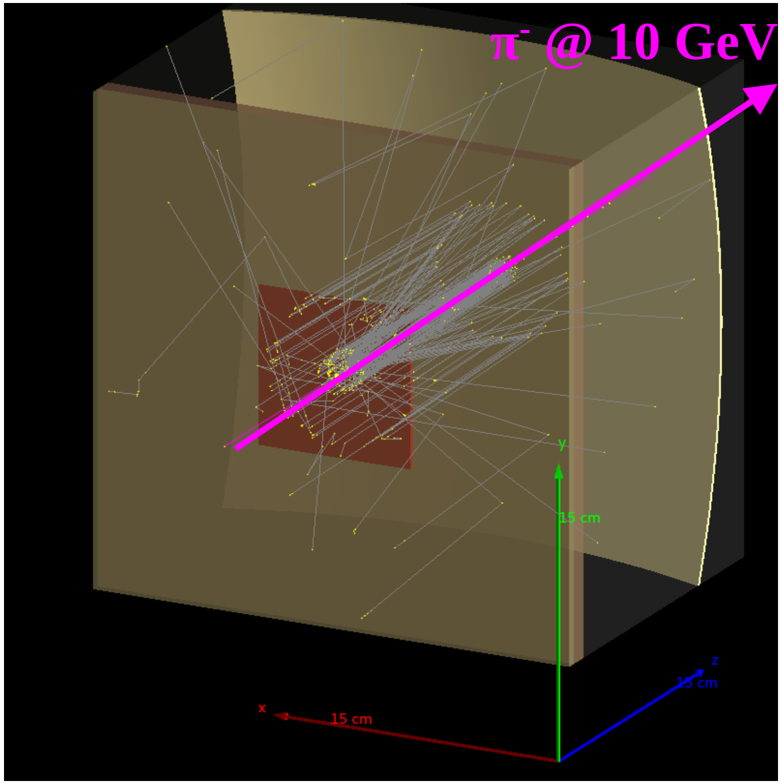
- A key requirement for the ARC design to be accepted in an experiment is having a minimal material budget. Current design averages 5% X_0
- To achieve this, R&D will be needed on the lightweight composite vessel and the photosensor; the baseline gas radiator is unpressurized C_4F_{10}, but alternatives are under study
- 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 in 2024, further participation is welcome!
(Coordinator: Massimiliano Fiorini, CB chair: Guy Wilkinson)





Working principles of ARC

- There are two Cerenkov radiators inside each RICH cell, a gas and an aerogel
- 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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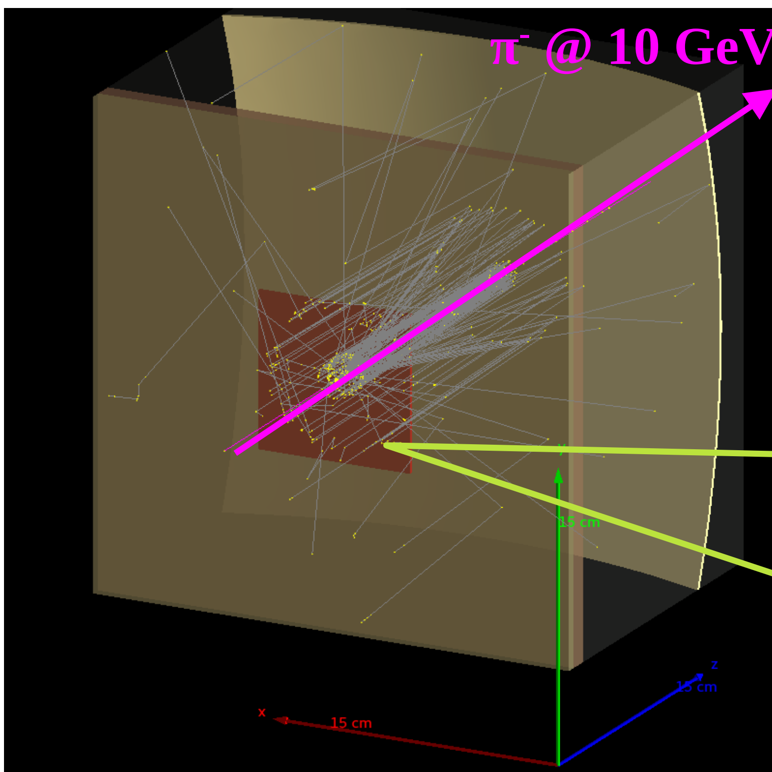
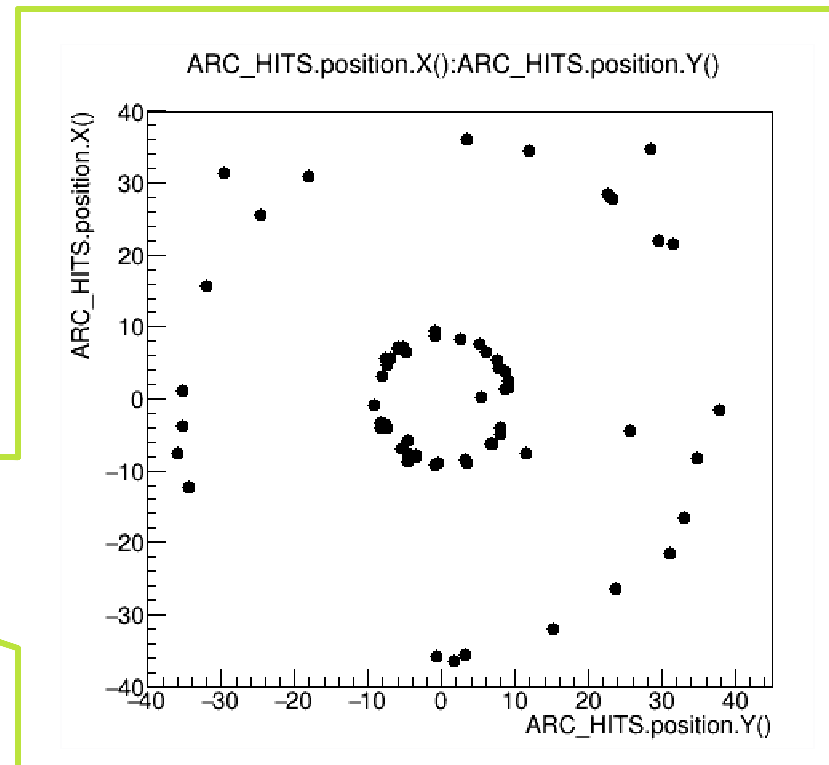
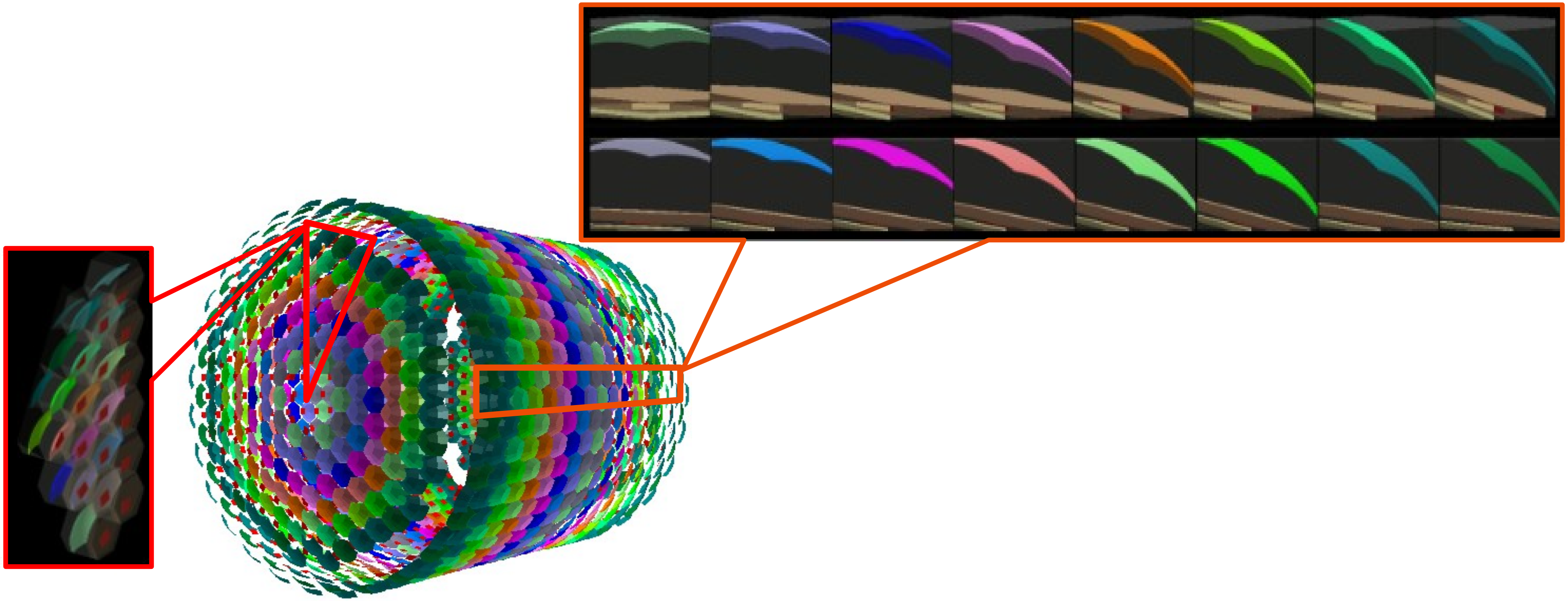
- The hit pattern in the sensor corresponds to two concentric rings
- DD4hep and Geant4 are used to simulate the behavior of the ARC detector





Geometry design

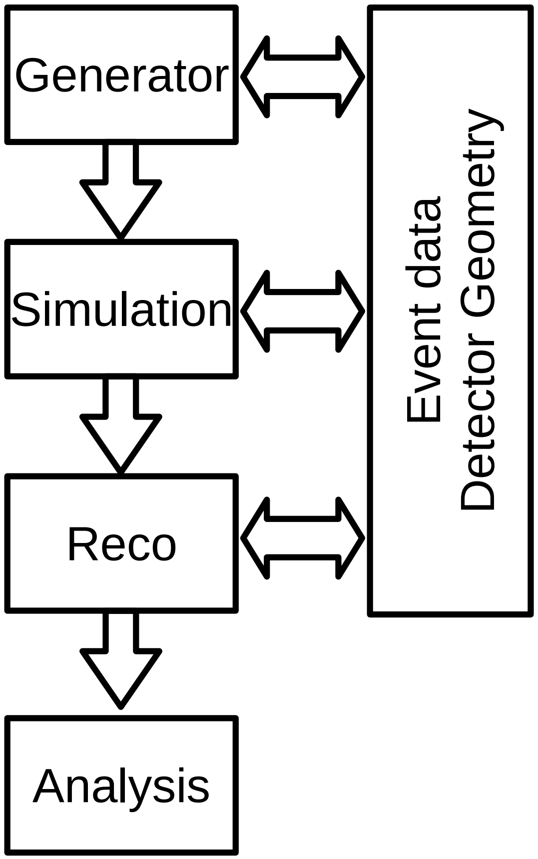
- The position of the mirror and photon sensor is optimized for each cell in a certain sequence starting from the center
- A dedicated software performs an inverse ray-tracing simulation of the Cherenkov photons, and adjust the geometry of the cells in order to optimize the angular resolution of the reconstructed angle [Tat23]



Simulation framework

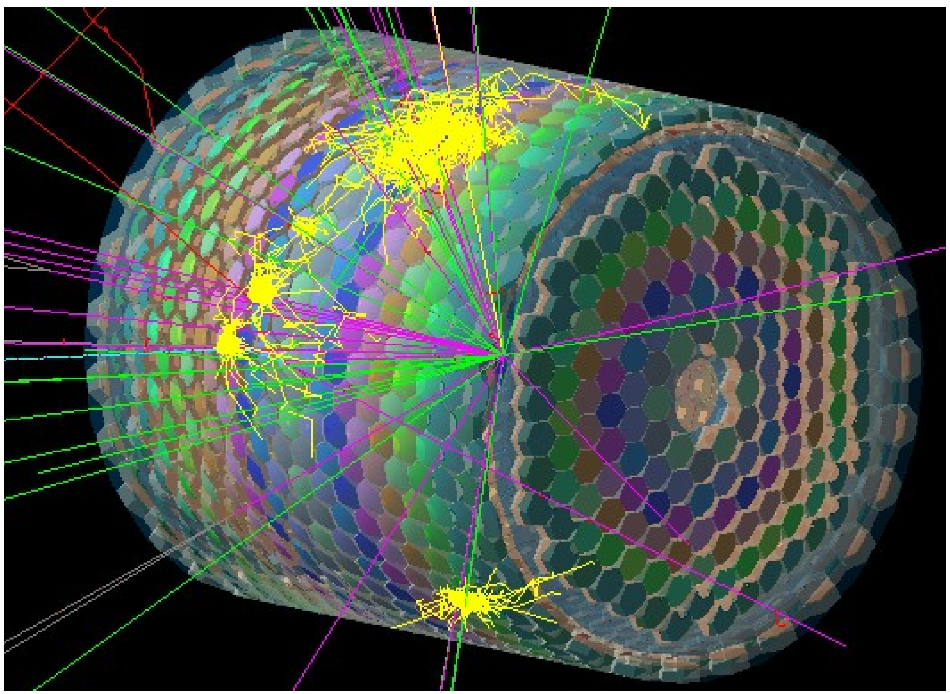
Software tools:

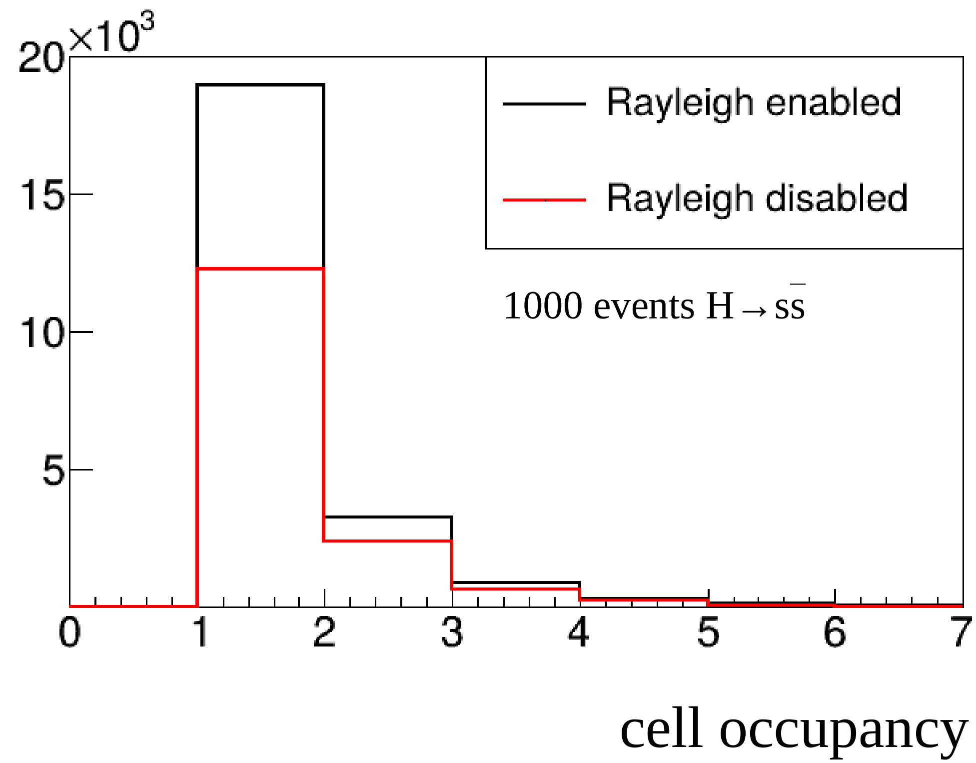
- Detector description, including optical properties in DD4hep format
- Geant4 is used to simulate the physics
- Digitization and Cherenkov angle reconstruction are implemented as Gaudi functional algorithms
- The sim hits are represented by tracker hits in EDM4hep, the outputs of the ARC reconstruction algorithm are a collection of PID objects associated to the corresponding track



Simulation framework

- ARC **cell occupancy** is expected to be low [Tat23]
  - This idea is supported by preliminary full simulation of $H\to s\bar{s}$
- Rayleigh scattered photons in the aerogel may be detected by neighboring cells

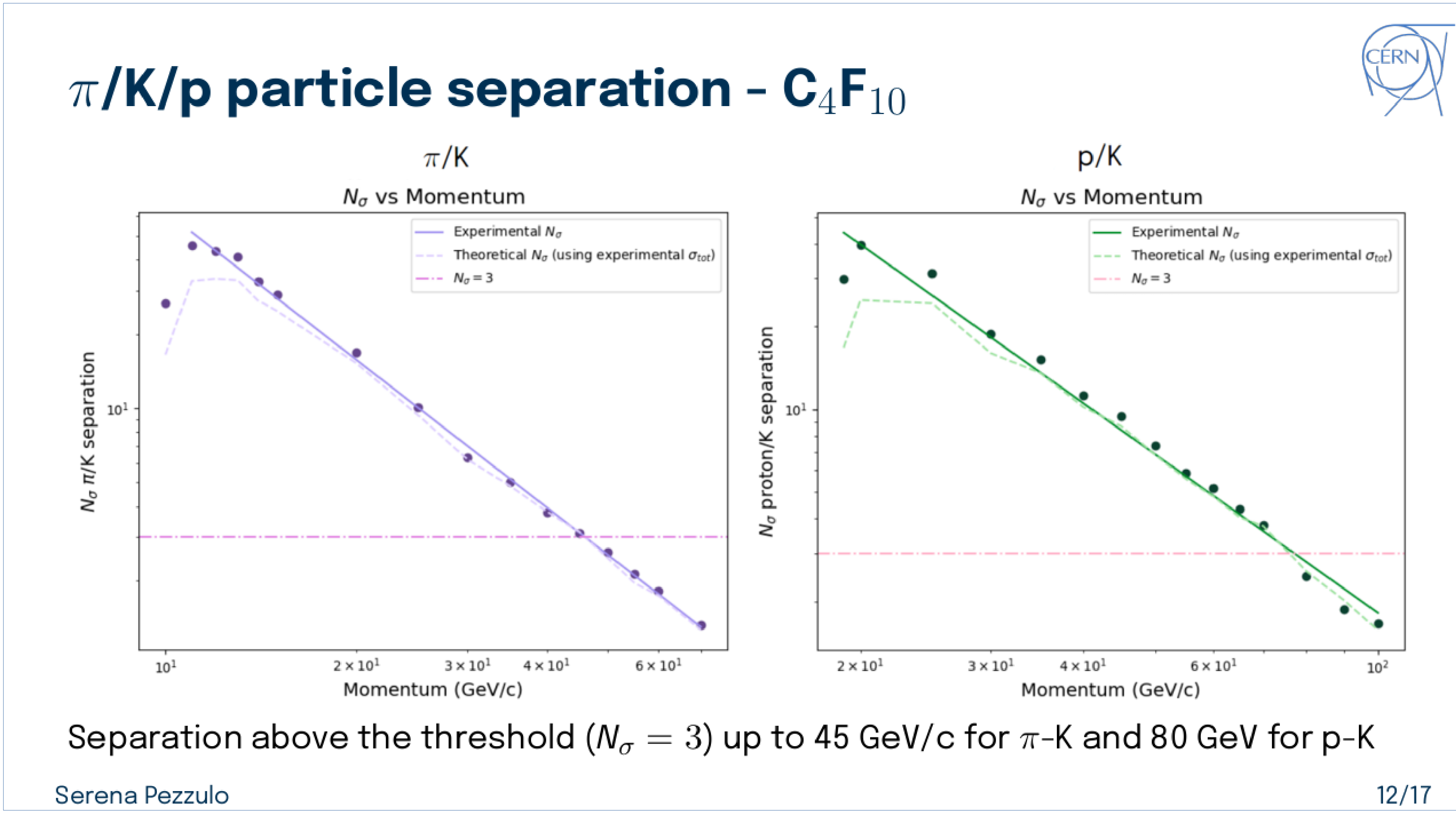




*__Cell occupancy__: number of charged particles responsible for producing photons that are detected by that specific cell

PID Performance: Key Metrics

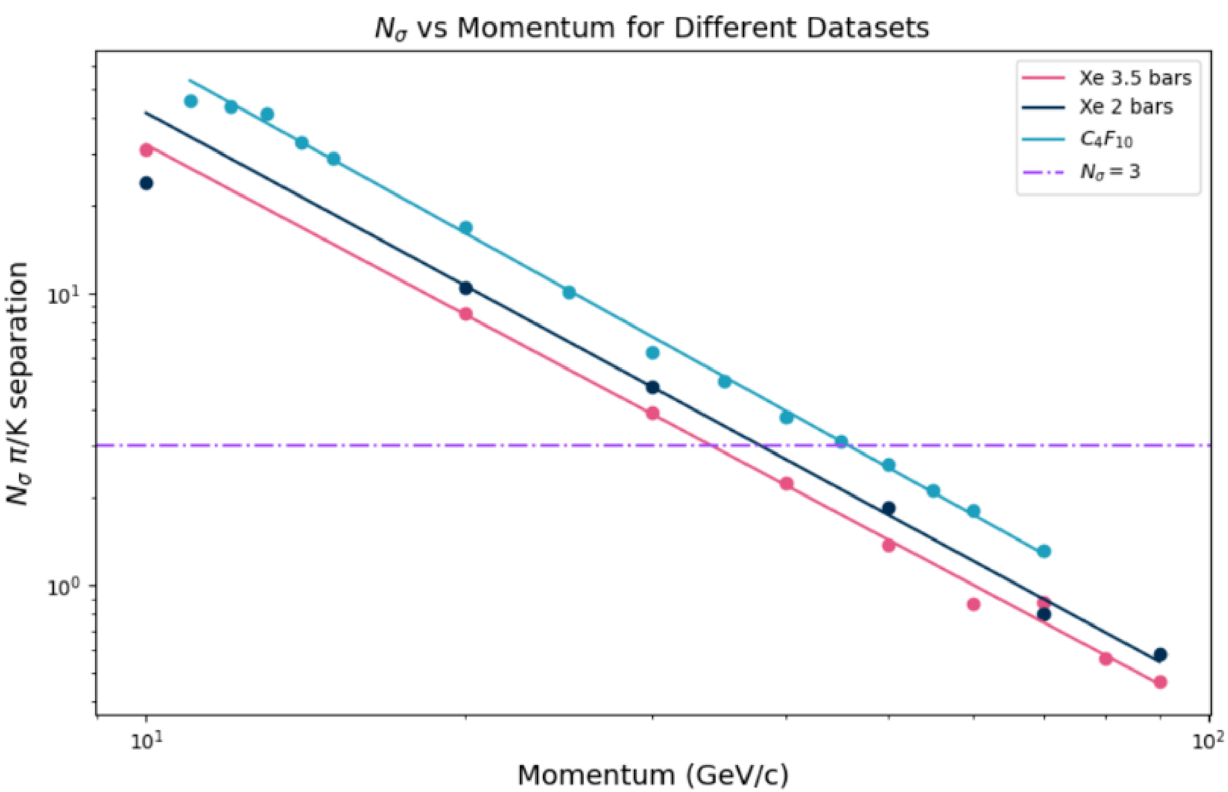
- First performance results using Geant4 were obtained by S. Pezzulo and presented at the 3rd ECFA workshop [Pezzulo24]



PID Performance: Radiator Comparison

- Pressurized Xenon can be an alternative to C_4F_{10} [Pezzulo24]

π/K separation - Xe



Radiator	Photon yield	Total error [mrad][a]
C_4F_{10} @ 1 bar	19	1.2
Xe @ 1 bar	10	1.2
Xe @ 2 bar	20	1.5
Xe @ 3.5 bar	35	1.9

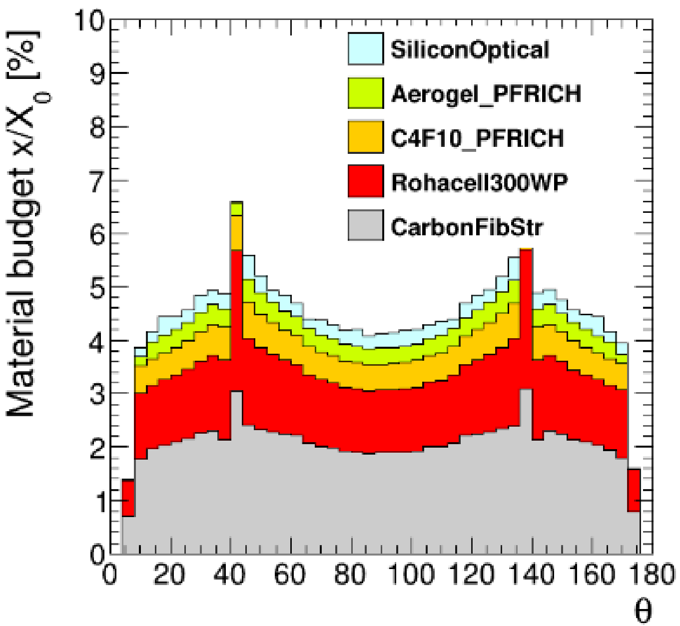
[a] considering 0.5 mm × 0.5 mm pixels

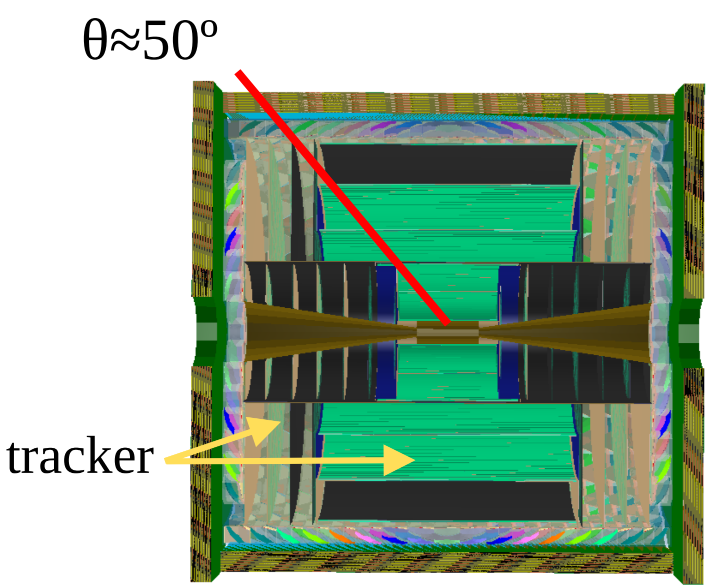
Radiator	Max p [GeV/c]
C_4F_{10} @ 1 bar	45
Xe @ 2 bar	38
Xe @ 3.5 bar	33

Serena Pezzulo 15/17

Challenges and Mitigation Strategies

- Magnetic Field Impact. Analytical calculations indicate minimal effects, full simulations are ongoing to confirm
- Engineering Optimizations:
  - Minimize material budget at θ≈40º caused by barrel-endcap transition
  - Improve tracker coverage near θ≈50º for CLD option 3 (red line)





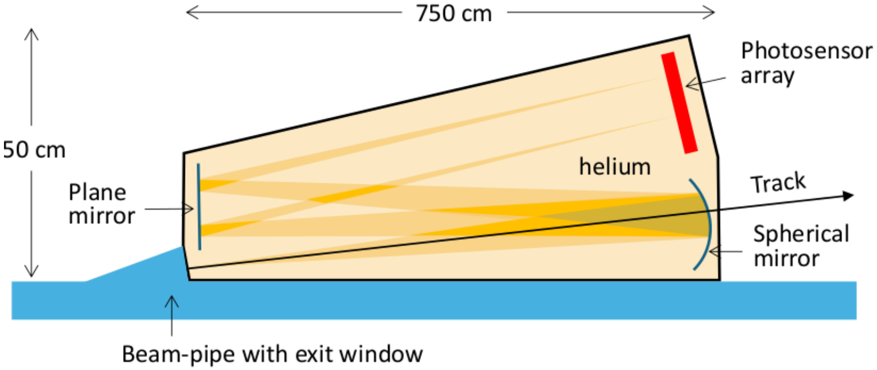
CLD option 3

Next steps

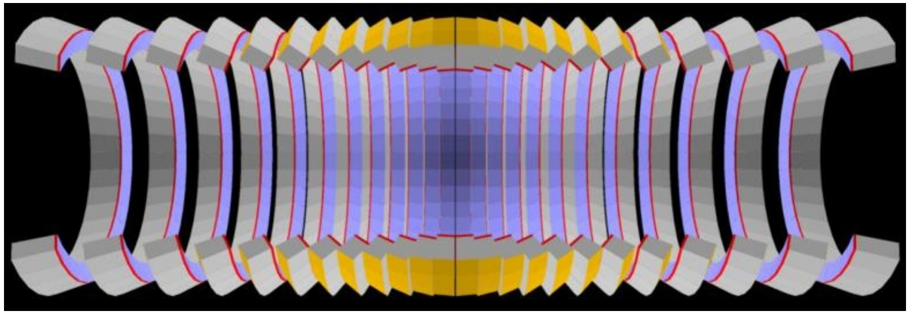
- Integrate ARC into the CLD full simulation chain
  - See S. Pezzulo's talk for insights on event reconstruction [link]
- Evaluate ARC impact on Particle Flow:
  - Tune algorithms for a bigger tracker-calorimeter gap
  - Develop PID-aware Particle Flow algorithms
- Conduct physics analyses with ARC
- Explore ARC integration into other detector concepts

Current R&D and Prototyping Efforts

- Development of ARC is one of the tasks of DRD4
  - Full conceptual design within one year
  - Prototype of a single ARC cell within three years, serving as testbed for
    - Radiator gas and aerogel new materials
    - Lightweight mirrors and vessels
    - SiPM developments: smaller pixellization, minimal dark count rate, radiation hardness, integrated readout electronics
- DRD4 ensures synergies with other projects:
  - Common prototype effort with ALADDIN and aerogel RICH for ALICE3



RICH detector for ALADDIN



RICH detector for ALICE

Summary and Conclusion

- ARC is a compact and modular RICH detector which provides accurate particle identification to the FCCee detector concepts
- Integration of ARC in into CLD full sim chain is ongoing
  - A lot of work ahead, collaboration is welcome!
- ARC is recognized as task by DRD4
  - synergies with other projects at CERN
  - Prototype to be delivered in 3 years