The ARC compact RICH detector: reconstruction and performance
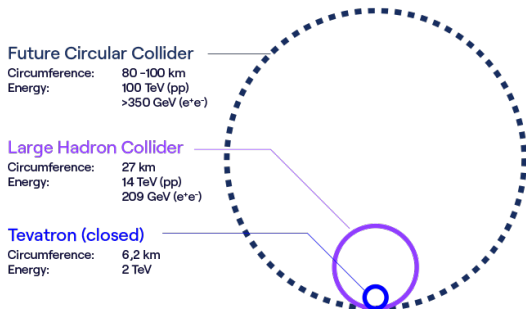
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on behalf of those
working on the ARC concept

Sep 16, 2025

Motivation

- FCC-ee will produce copious heavy flavour hadrons
- World class flavour physics programme is possible if one can have excellent **particle identification** (PID) and in particular hadron separation
- PID is crucial for B decay children (1-40 GeV), τ decays, and jet tagging in Higgs, top and W physics

Future Circular Collider
Circumference: 80 -100 km
Energy: 100 TeV (pp)
>350 GeV (e⁺e⁻)

Large Hadron Collider
Circumference: 27 km
Energy: 14 TeV (pp)
209 GeV (e⁺e⁻)

Tevatron (closed)
Circumference: 6,2 km
Energy: 2 TeV

The ARC concept

ARC (**A**rray of **R**ich **C**ells) is a proposed RICH detector for the FCC (or another Higgs factory)

- First presented by R. Forty at FCC week 2021
- Lightweight and compact solution for PID
- Specifically adapted for the CLD experiment, occupying 10% of the tracker volume:
  - Dimensions: 20 cm radial depth, 2.1 m radius, 4.4 m length
  - Material budget targeted below $0.1X_0$
- Cellular in design, with each cell functioning as an independent RICH detector cell
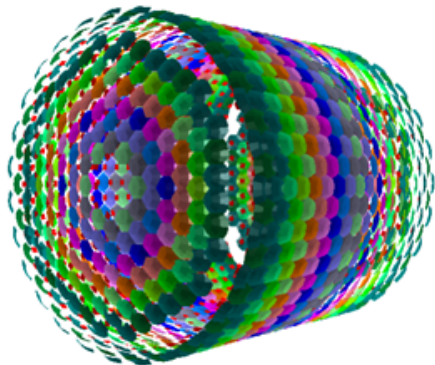
ARC single cell geometry
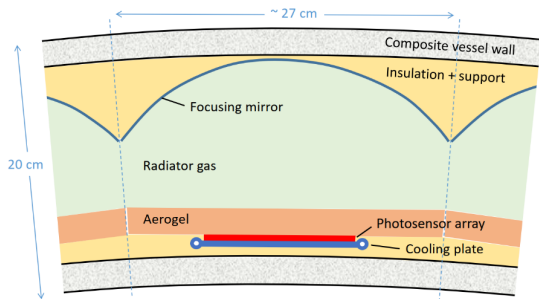
- Two radiators: C_4F_{10} (or a more eco-friendly alternative) + **aerogel** (for low **p** tracks)
- Spherical focusing mirror
- Photosensor array: most suitable candidates are Silicon Photomultipliers (SiPMs) arrays with cooling plates
- Aerogel also as thermal insulator between SiPM array and gas radiator

Goal: Construct prototype of single cell within the DRD4 collaboration

Simulation of a single cell

- Simulations performed inside Key4Hep framework
- Cherenkov photons are emitted in the two radiators and focused with a spherical mirror onto a photosensor plane (red volume)

- Each radiator produces a distinct pattern of Cherenkov light, resulting in **two separate rings**

Silicon Photomultipliers

INFN
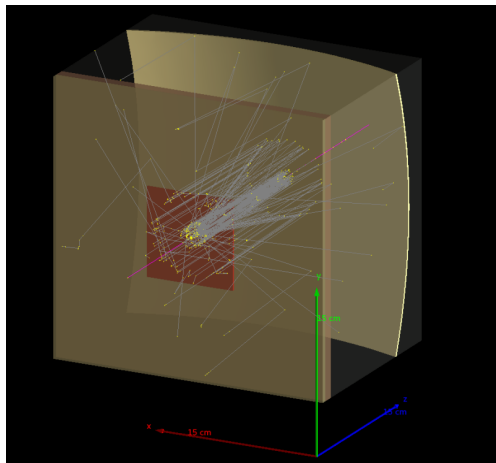
SiPMs: compact, highly sensitive light detectors capable of detecting single photons

- SiPM array with 0.5 mm $\times$ 0.5 mm pixel
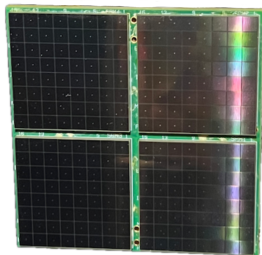- PDE curve at Overvoltage=10V is considered

Figure: SiPMs matrix, 3 mm x 3 mm pixels
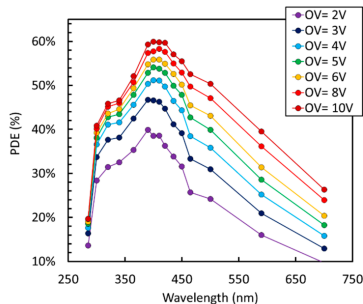

Figure: PDE vs Wavelength for FBK SiPMs
doi.org/10.3390/s19020308

Cherenkov angle reconstruction

The local pattern recognition method, originally described by R. Forty and O. Schneider [LHCB/98-040] is implemented in a **Gaudi algorithm (ARCalg)**

- Cherenkov angle reconstruction for each photon relies on track information provided by the tracking system
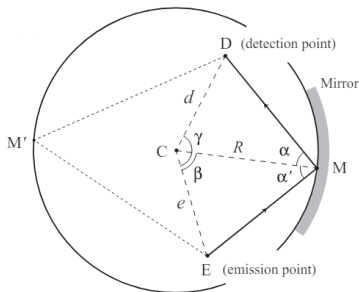

Figure: RICH pattern recognition - Forty, R W ; Schneider, O

$$4e^2 d^2 \sin^4 \beta - 4e^2 d_y R \sin^3 \beta +$$
$$+ (d_y^2 R^2 + (e + d_x)^2 R^2 - 4e^2 d^2) \sin^2 \beta +$$
$$+ 2e d_y (e - d_x) R \sin \beta + (e^2 - R^2) d_y^2 = 0$$

- Emission point (**E**) is approximated at the midpoint of the track in the radiator

- The equation has two real solutions corresponding to **M** and **M'**

$$\rightarrow \mathbf{p} = EM/|EM| \, , \, \cos \theta_c = \mathbf{p} \cdot \mathbf{t}$$

Cherenkov Angle Reconstruction

- Currently using a **local approach** on a single cell:
  - Fast, identifies hits per track via θ_c peaks
  - might be limited by background contamination from other tracks

- For the entire detector, a **global approach** may be needed (implementation in the ARCalg on-going):
  - Fits θ_c of all tracks simultaneously
  - Handles cross-contamination but involves complex multi-parameter fits
  - Uses a **PID likelihood function** to combine Cherenkov angle measurements across multiple tracks

π/K/p particle separation

Estimated the number of standard deviation of separation between π and K (also p/K and p/π)

- **Number of standard deviations (estimated from simulations)** of separation between two different particle types:

$$N_\sigma = \frac{|\theta_1 - \theta_2|}{\sqrt{\left(\frac{\sigma_1}{\sqrt{N_1}}\right)^2 + \left(\frac{\sigma_2}{\sqrt{N_2}}\right)^2}}$$
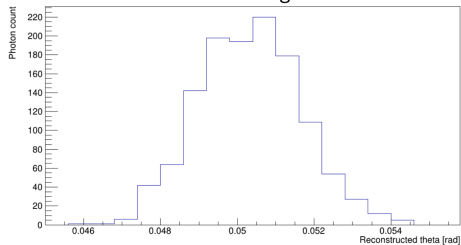
  where σ_1 and σ_2 are the total errors relative to the Cherenkov reconstructed angles while N_1 and N_2 are the average number of detected photons per track
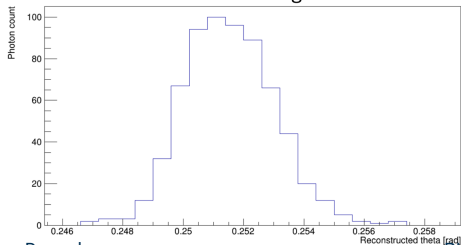
- **Number of standard deviations (expected)**:

$$N_\sigma \approx \frac{m_1^2 - m_2^2}{2p^2 \sigma_{\theta_c} \sqrt{n^2 - 1}}$$

Results – C_4F_{10} + aerogel

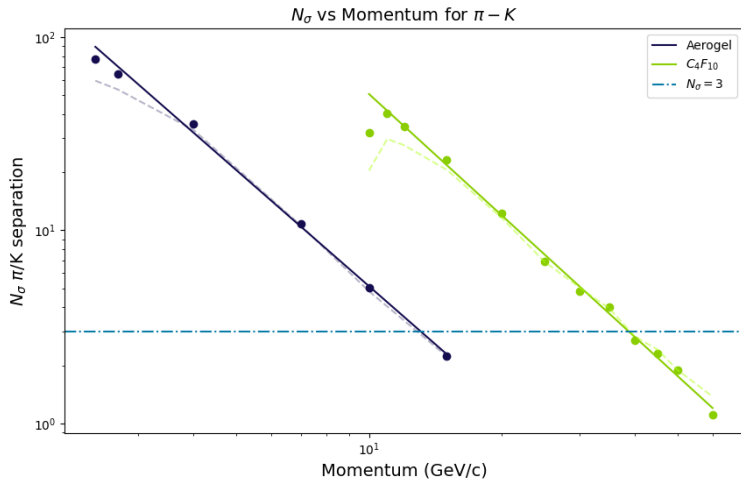Total error gas

Total error aerogel

	Total error [mrad]	Photon yield
Gas	1.3	14
Aerogel [a]	1.5	7

Kaon particle gun @ 45 GeV

[a] 1 cm layer, n= 1.03

π/K particle separation – C_4F_{10} + aerogel

N_σ vs Momentum for $\pi - K$

Separation above the threshold ($N_\sigma = 3$) up to 13 GeV/c for aerogel and 40 GeV for C_4F_{10}

Reconstruction with Track Multiplicity
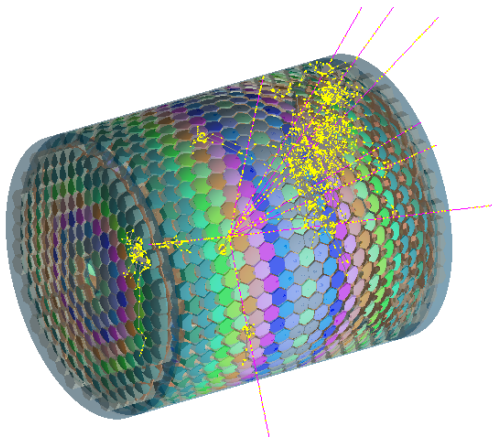
- The reconstruction algorithm has not been extended yet to the whole detector but **preliminary full simulations** are ongoing
- Occupancy studies based on $H \to s\bar{s}$

Reconstruction with Track Multiplicity

- Preliminary studies show that approximately 80% of cells are crossed by a **single track** per bunch crossing
- A non-negligible fraction of cells are crossed by **multiple tracks**, which introduces potential reconstruction ambiguities

Distribution of number of charged tracks per cell [avg/event]
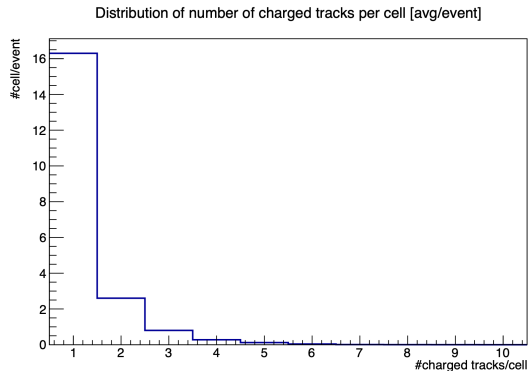
Two-Track Scenarios – preliminary

GPS: π @ 30 GeV + k @ 10 GeV

Pixel ID

Reconstructed Theta
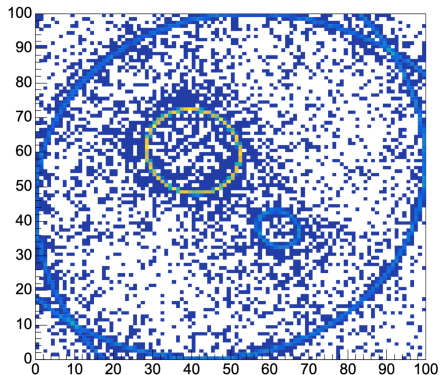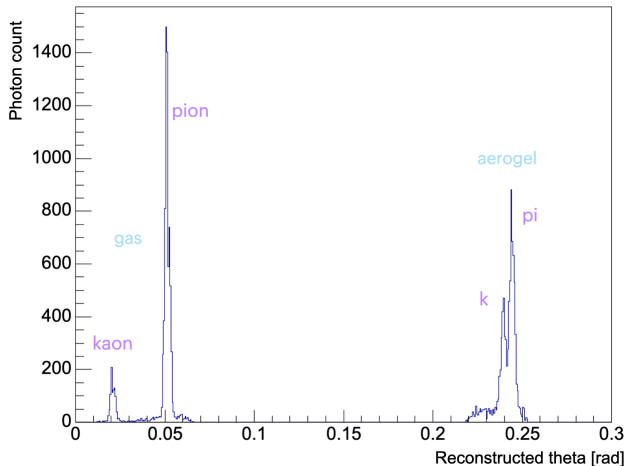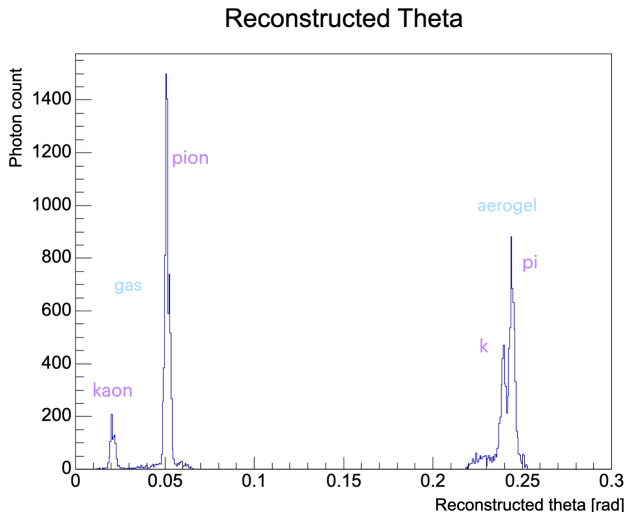

Figure: Photon hits on the photosensors in the x-y plane

Two-Track Scenarios - preliminary

- The algorithm successfully identifies the Cherenkov peaks
- The **angular resolution** is comparable to that in the single-track case
- Next steps: test the algorithm in varied multi-track scenarios, evaluate the **peak separation power**

Reconstructed Theta

Magnetic field implementation

- The ARC was adapted for **CLD**, which features a magnetic field of **2–3 T**
- The first iteration of the reconstruction algorithm assumes **straight tracks**, which breaks down in the presence of a magnetic field
- Must be updated to reconstruct **helical trajectories**, especially important at low momentum where curvature effects are more pronounced
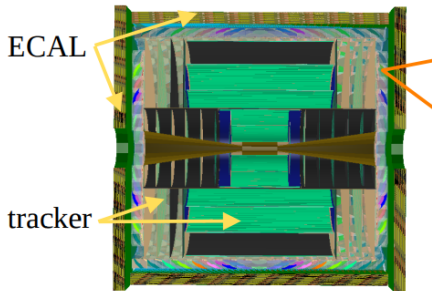

ECAL

tracker

Figure: CLD option 3: ARC between the tracker and ECAL

Magnetic field implementation

- The Cherenkov angle is calculated as $cos\theta = \mathbf{p} \cdot \mathbf{t}$, where $\mathbf{p}$ is extrapolated from the quartic equation and $\mathbf{t}$ is the direction of the emitting particle

- The vector $\mathbf{t}$ is no longer taken as the initial shooting direction, but is instead evaluated as the **tangent to the helix** at the estimated emission point
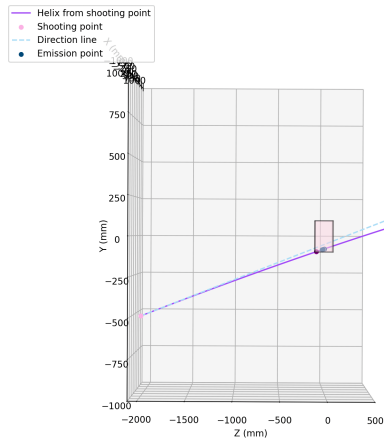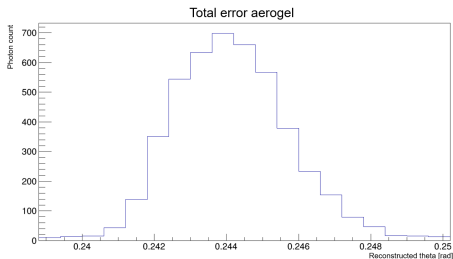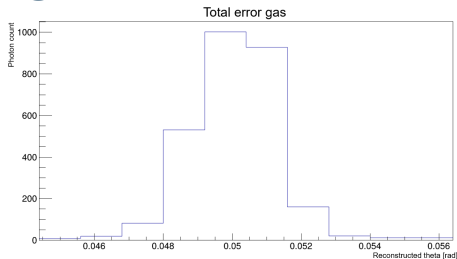

Figure: π @ 10 GeV crossing an ARC cell

Magnetic field - results

Total error gas

Total error aerogel

Total error [mrad]

	2 T	3 T	No magnetic field
Gas	1.3	1.3	1.3
Aerogel	1.6	1.6	1.6

Pion particle gun @ 10 GeV, $\sim 25°$ angle with respect to the MF direction

Conclusions

INFN

- Particle separation power was studied for C_4F_{10} and aerogel, showing good performance in the 2–40 GeV/c range for $\pi - K$ separation
- Performance was evaluated for **magnetic fields** between 2 and 3 T, showing minimal or no degradation
- Alternative **environmentally friendly** radiators have been investigated [ECFA '24]
- The Genova group is also developing a prototype of the module with the integrated cooling that will host the SiPM (See Roberta's talk on Friday)
- **Next Steps**:
  - Extend simulations to the entire ARC detector
  - Test the algorithm in **multi-track scenarios** with varied configurations and track angles and evaluate the peak separation power with the **magnetic field** enabled
  - Develop and implement a **global PID likelihood approach**

Thank you for the attention!

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SiPMs housing module

Prototype module is designed to house SiPMs, featuring **integrated active cooling**: collaboration with LHCb-RICH and under DRD4 collaboration

- Build on the LHCb-RICH Elementary Cell (EC) [arXiv:2305.10515]
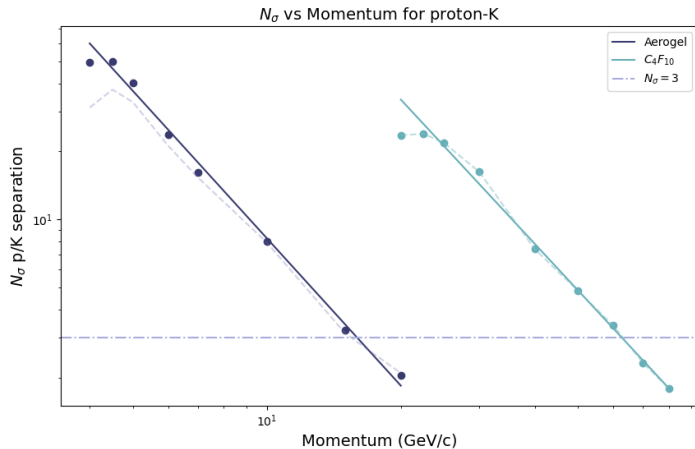- Integrated active cooling using Ceramic PCB with fluid coolant circulation
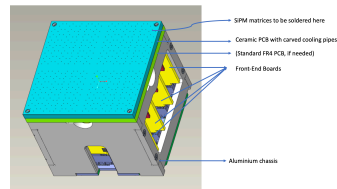
Readout by **ALCOR v2** (32 channels), collaboration with INFN-TO and INFN-BO under the DRD4 Collaboration

- PCB adapter to integrate the EC with ALCOR v2 (developed in Genova)
- Setup is functional and tests are ongoing
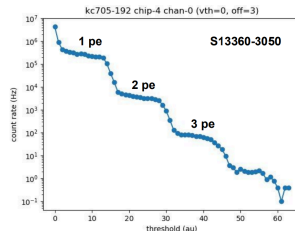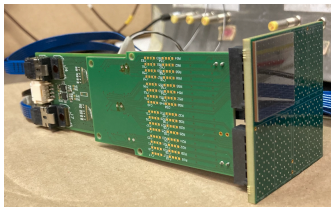
K/p particle separation – C_4F_{10} + aerogel

Separation above the threshold ($N_\sigma = 3$) up to 16 GeV/c for aerogel and 63 GeV for C_4F_{10}

Simulation Framework

ARC Simulations performed inside **Key4Hep** framework. The tools used for a full simulation include:

- **DD4hep**: Defines the detector geometry and material properties
- **Geant4**: Simulates interactions with the detector, including optical photon interactions
- **Monte Carlo Generators / Particle Gun**: Used for generating events
- **Gaudi functional algorithms**: Used for digitization and reconstruction

Alternative Radiator gas

With HFCs set to be banned by 2050, it is crucial to explore more environmentally friendly alternatives

- Xenon could be suitable, but must be pressurized to achieve sufficient photon yield → higher total error, the vessel needs to be reinforced
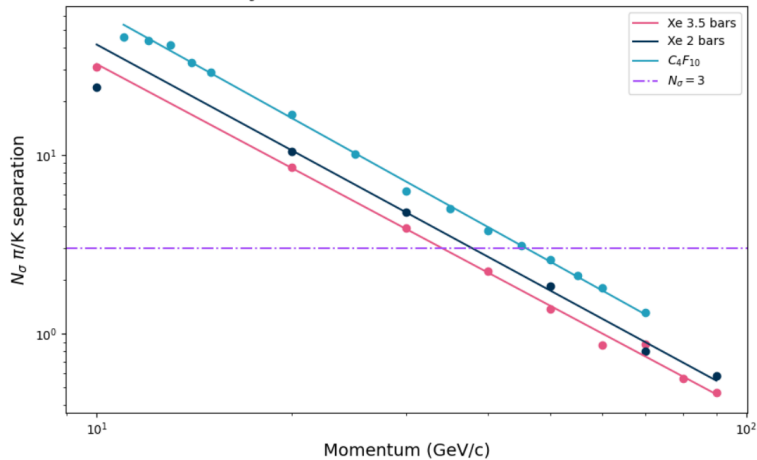
Radiator	Photon yield	Total error [mrad][a]
C_4F_{10} @ 1 bar	19	1.2
Xe @ 1 bar	10	1.2
Xe @ 2 bar	20	1.5
Xe @ 3.5 bar	35	1.9

[a]considering 0.5 mm × 0.5 mm pixels

Refractive index vs wavelength
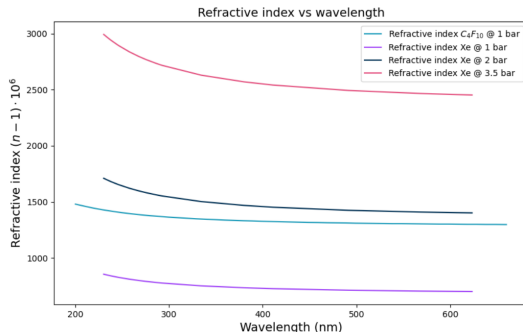
π/K separation - Xe

N_σ vs Momentum for Different Datasets

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