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ARC Detector: Particle ID with Magnetic Field and Multi-Track Scenarios

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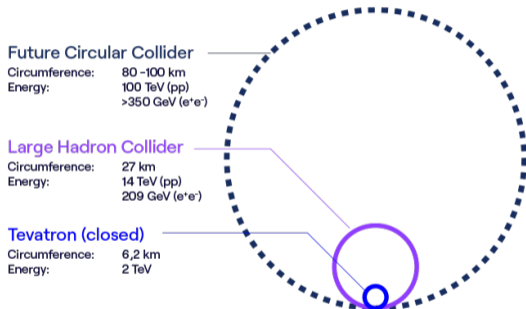
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on behalf of those
working on the ARC concept

May 20, 2025

Motivation

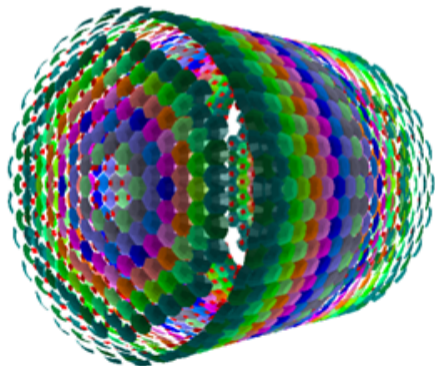
- FCC-ee will produce copious heavy flavour hadrons
- World class flavour physics programme is possible if one can have excellent **particle identification** (PID) and in particular hadron separation
- PID is crucial for B decay children (1-40 GeV), τ decays, and jet tagging in Higgs, top and W physics



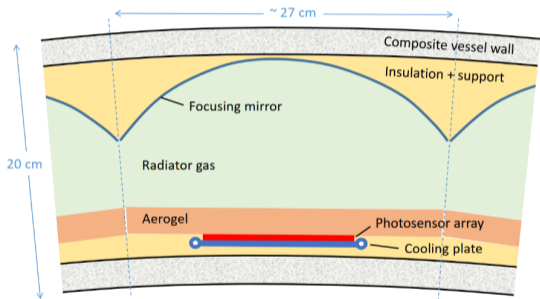
The ARC concept

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 in 3 years (fostered by DRD4 Collaboration)

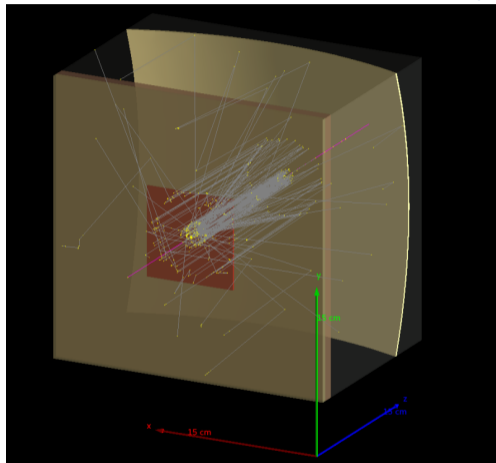
Simulation Framework

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

Simulation of a single cell

- 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

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

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

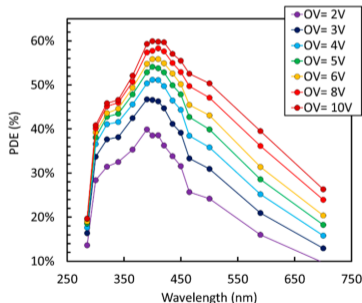
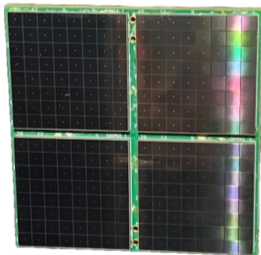


Figure: PDE vs Wavelength for FBK SiPMs

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

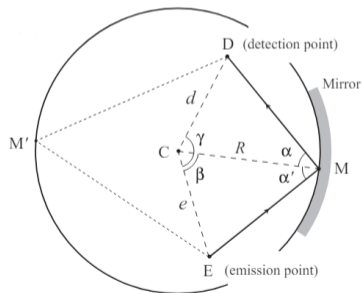


Figure: RICH pattern recognition - Forty, R W ; Schneider, O

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

- 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

$\pi/K/p$ 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:

$$N_\sigma = \frac{|\theta_1 - \theta_2|}{\sqrt{\left(\frac{\sigma_1}{\sqrt{N_1}}\right)^2 + \left(\frac{\sigma_2}{\sqrt{N_2}}\right)^2}}$$

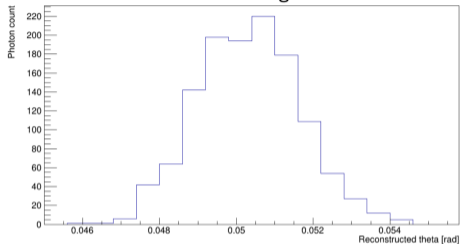
where σ_1 and σ_2 are the total errors relative to the Cherenkov reconstructed angles while N_1 and N_2 are the average number of detected photons per track

- **Number of standard deviations (expected):**

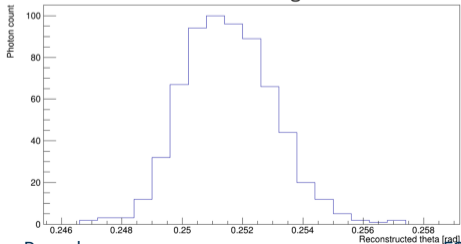
$$N_\sigma \approx \frac{m_1^2 - m_2^2}{2p^2 \sigma_{\theta_c} \sqrt{n^2 - 1}}$$

Results - C₄F₁₀ + aerogel

Total error gas



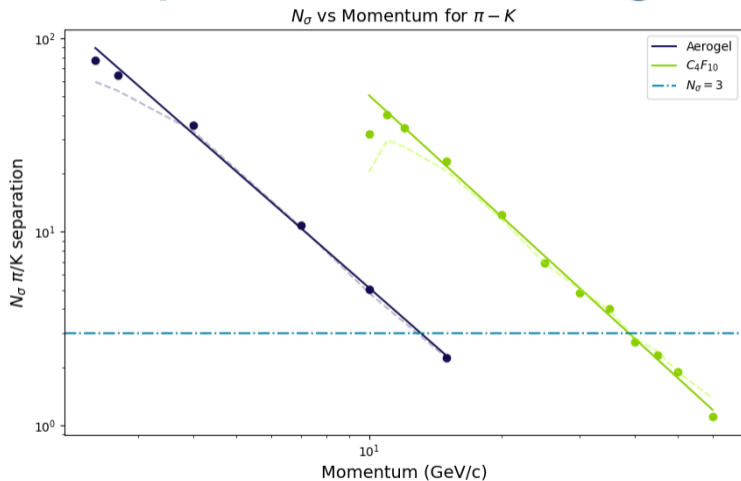
Total error aerogel



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

Kaon particle gun @ 45 GeV

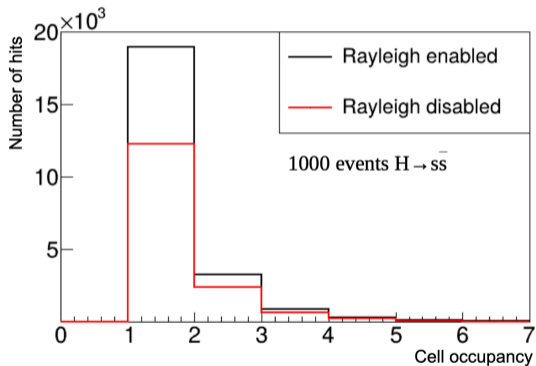
π/K particle separation - C_4F_{10} + aerogel



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

- Preliminary full simulation of $H \rightarrow s\bar{s}$ by A. Tolosa Delgado [8th FCC workshop] shows 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



Two-Track Scenarios - preliminary

GPS: π @ 30 GeV + k @ 10 GeV

Pixel ID

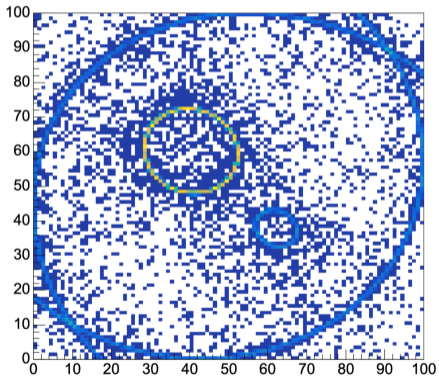
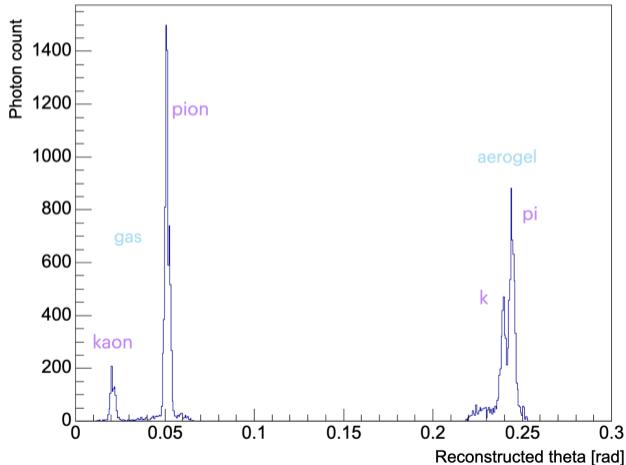


Figure: Photon hits on the photosensors in the x-y plane

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Reconstructed Theta



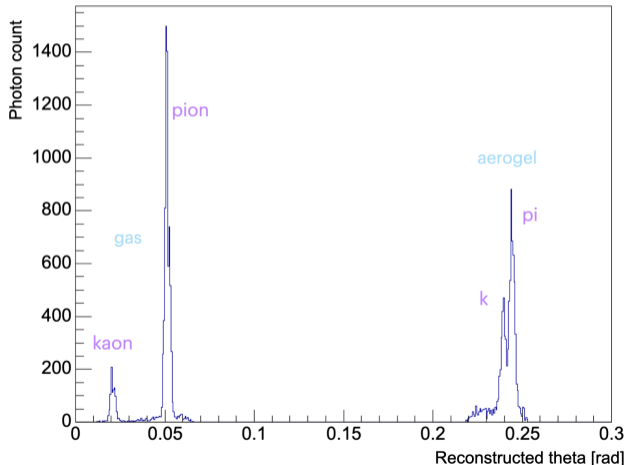
FCC week 2025

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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

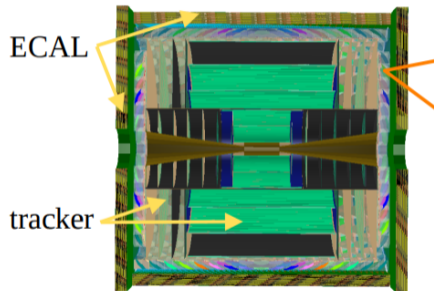
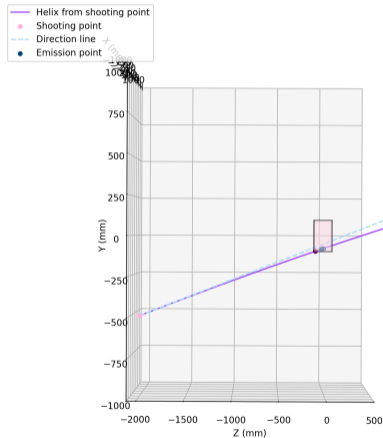


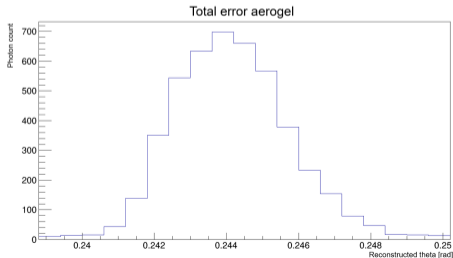
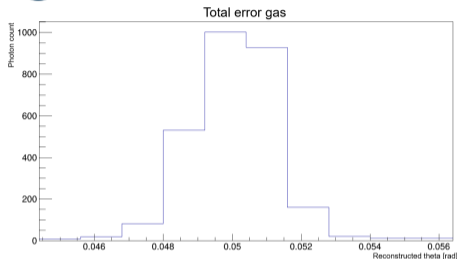
Figure: CLD option 3: ARC between the tracker and ECAL

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



Magnetic field - results



| | Total error [mrad] | | |
|----------------|--------------------|-----|-------------------|
| | 2 T | 3 T | No magnetic field |
| Gas | 1.3 | 1.3 | 1.3 |
| Aerogel | 1.6 | 1.6 | 1.5 |

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

Conclusions

- 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](#)]
- **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**
- For more details, see the **supporting note** → "Simulation and performance study of the ARC concept: a compact RICH for future collider experiments" [[10.17181/6g0gs-7kw30](#)]



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Thank you for the attention!

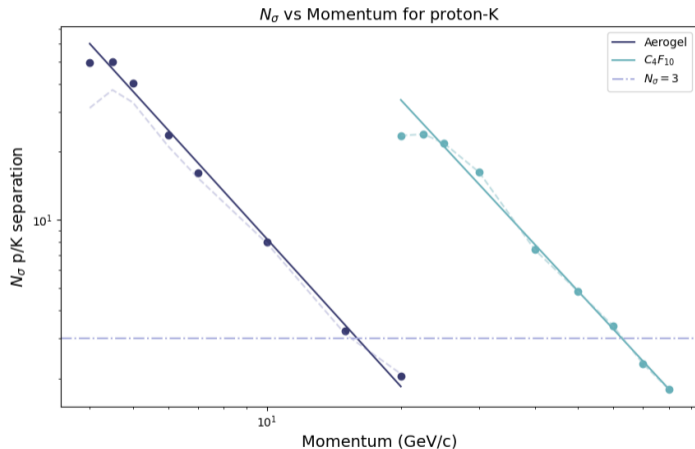
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K/p particle separation - C_4F_{10} + aerogel



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

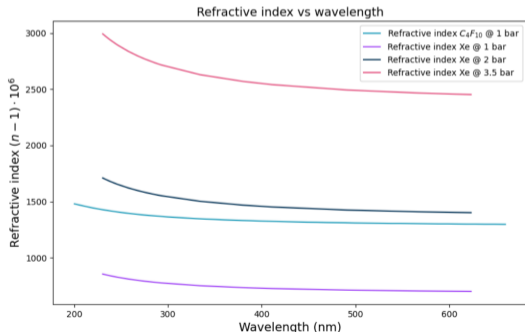
Alternative Radiator gas

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

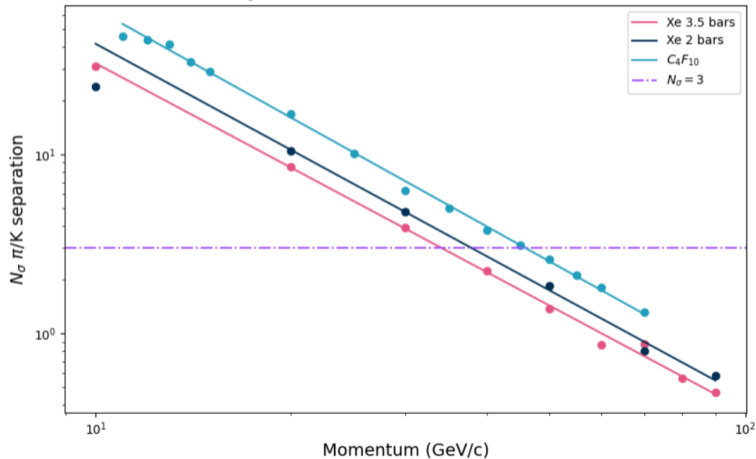
| Radiator | Photon yield | Total error [mrad] ^a |
|--|--------------|---------------------------------|
| C ₄ F ₁₀ @ 1 bar | 19 | 1.2 |
| Xe @ 1 bar | 10 | 1.2 |
| Xe @ 2 bar | 20 | 1.5 |
| Xe @ 3.5 bar | 35 | 1.9 |

^aconsidering 0.5 mm × 0.5 mm pixels



π/K separation - Xe

N_σ vs Momentum for Different Datasets



| Radiator | Max p [GeV/c] |
|--|---------------|
| C ₄ F ₁₀ @ 1 bar | 45 |
| Xe @ 2 bar | 38 |
| Xe @ 3.5 bar | 33 |