Particle Identification with the ARC in Key4hep

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on behalf of those
working on the ARC concept

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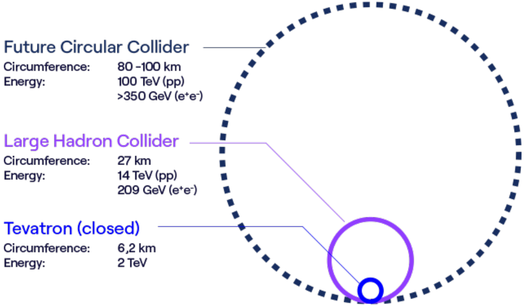
Motivation

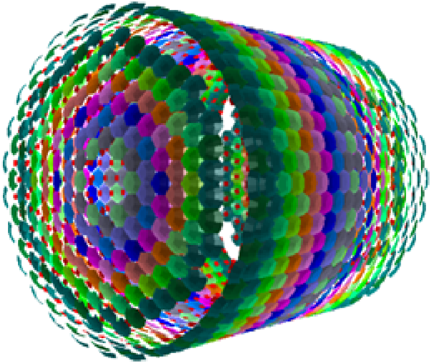
- FCC-ee will produce copious heavy flavour hadrons
- World class flavour physics programme is possible if one can have excellent **particle identification** (PID) and in particular hadron separation
- PID is crucial for B decay children (1-40 GeV), τ decays, and jet tagging in Higgs, top and W physics



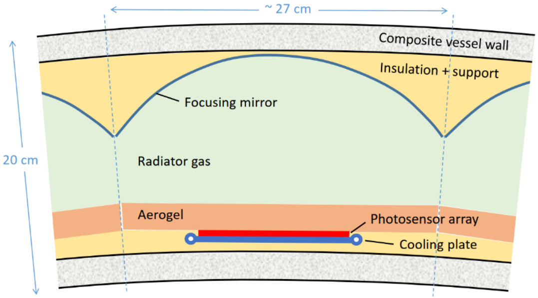
The ARC concept

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: $\mathbf{C_4F_{10}}$ (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

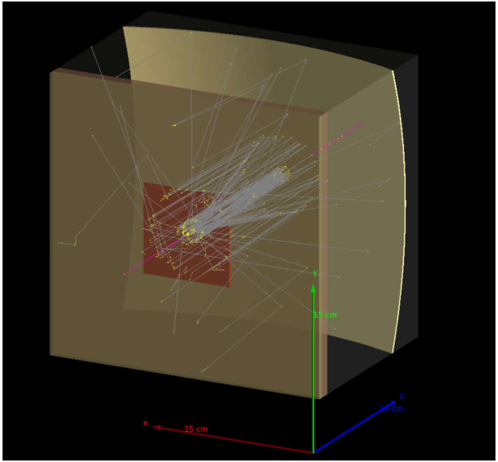
ARC Simulations performed inside **Key4Hep** framework. The tools used for a full simulation include:

- **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
- **Additional Tools**: Includes digitization, reconstruction, and more

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)

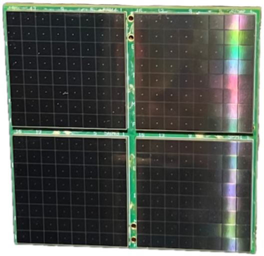
- Each radiator produces a distinct pattern of Cherenkov light, resulting in **two separate rings**



Silicon Photomultipliers

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

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



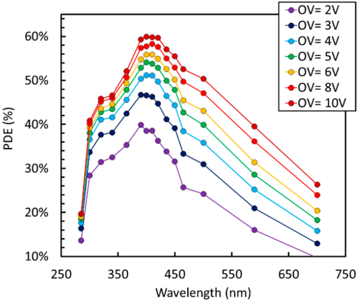


Figure: PDE vs Wavelength for FBK SiPMs
doi.org/10.3390/s19020308

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

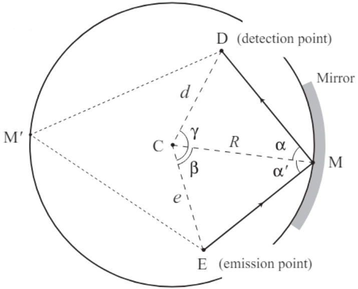


Figure: RICH pattern recognition - Forty, R W ; Schneider, O

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

- 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

ARC Reconstruction Algorithm in Key4hep

The reconstruction algorithm, **ARCalg**, is implemented within the Gaudi framework

- **Inputs**: `SimTrackerHits`, `MCParticles`
- **Output**: `ParticleID` collection
- Utilizes geometric data provided by the **GeoSvc** service and powered by **DD4hep**

Key Features:

- `k4FWCore::MultiTransformer` is used to process collections
- `initialize()`, `operator()`, and `finalize()` methods allow for a modular design

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:

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

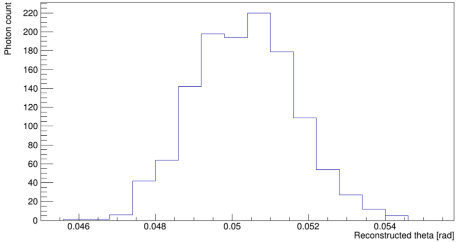
  where σ_1 and σ_2 are the total errors relative to the Cherenkov reconstructed angles while N_1 and N_2 are the average number of detected photons per track

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

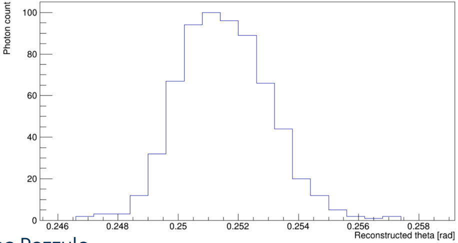
$$N_\sigma \approx \frac{m_1^2 - m_2^2}{2p^2 \sigma_{\theta_c} \sqrt{n^2 - 1}}$$

Results - C_4F_{10} + aerogel

Total error gas



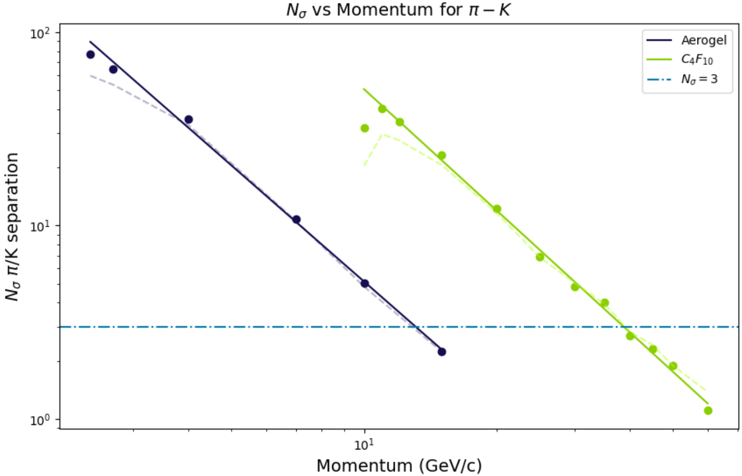
Total error aerogel



	Total error [mrad]	Photon yield
Gas	1.3	14
Aerogel	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}

Conclusions

- **SiPMs** are good photosensor candidates for their high sensitivity and compact design
- Particle separation power was investigated for C_4F_{10} and aerogel, demonstrating good performance in the momentum range of approximately 2 GeV/c to 40 GeV/c
- Alternative **environmentally friendly** radiators have been investigated [ECFA '24]
- **Next Steps**:
  - Extend simulations to the entire ARC detector
  - Include the **magnetic field** to study its effect on particle tracks
  - Develop and implement a **global PID likelihood approach**
- For more details, see the **supporting note** $\rightarrow$ "Simulation and performance study of the ARC concept: a compact RICH for future collider experiments" [10.17181/6g0gs-7kw30]

Thank you for the attention!

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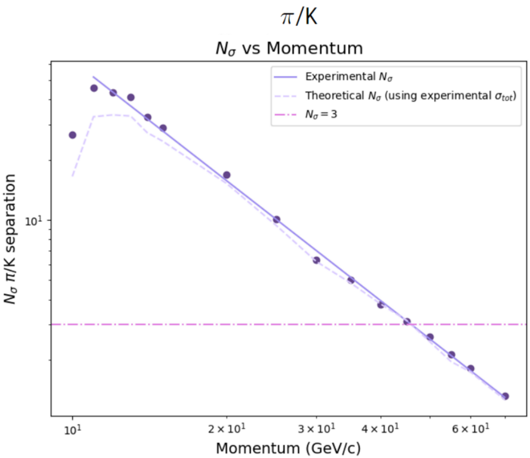
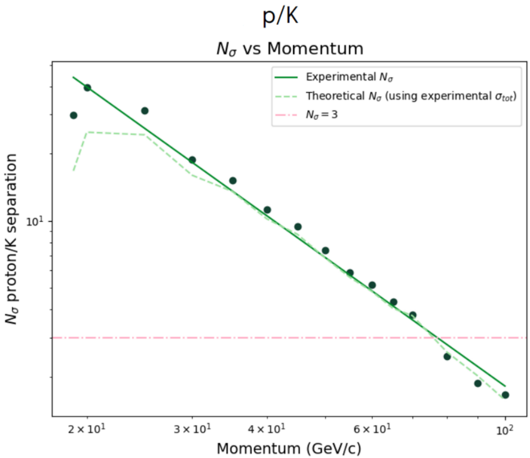
π/K/p particle separation - C_4F_{10}





Separation above the threshold ($N_\sigma = 3$) up to 45 GeV/c for π-K and 80 GeV for p-K

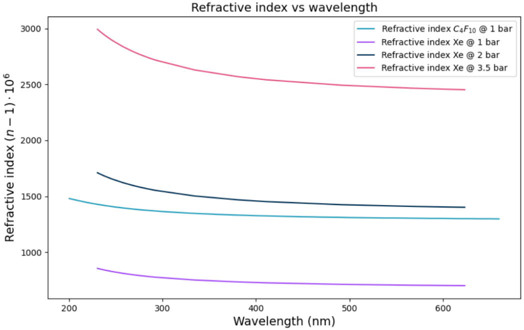
Alternative Radiator gas

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

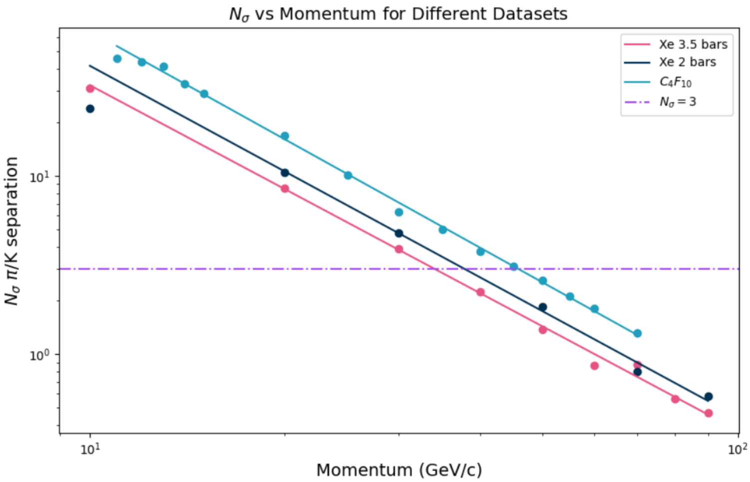
- Xenon could be suitable, but must be pressurized to achieve sufficient photon yield → higher total error, the vessel needs to be reinforced

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



π/K separation - Xe



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