ARC - a novel RICH detector for a future e^+e^- collider
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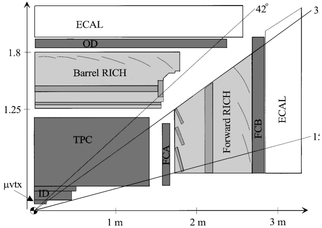
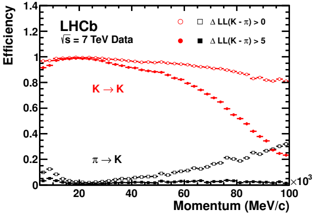
Introduction RICH detectors

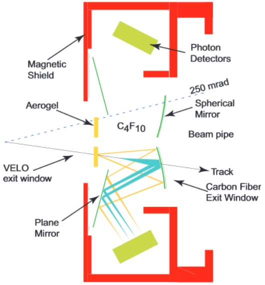
- Excellent hadron PID is crucial in flavour physics
  - Resolve combinatorics and seprate decay modes
- RICH detectors are very powerful for particle ID at high momentum
- At LHCb, π-K separation is excellent up to 100 GeV
- A 4π collider RICH layout was previously used at DELPHI and SLD
  - Challenging because of the space required



(a) DELPHI RICH layout



(b) LHCb RICH performance



(c) LHCb RICH layout

Motivation for RICH at FCC-ee

- FCC-ee will collect 3×10^{12} visible Z boson decays in 4 years
  - Allows for a world-leading flavour physics programme
  - Combined with excellent PID capabilities, FCC-ee will reach an unprecedented precision

- Good PID performance is also required for WW, Higgs and $t\bar{t}$ physics

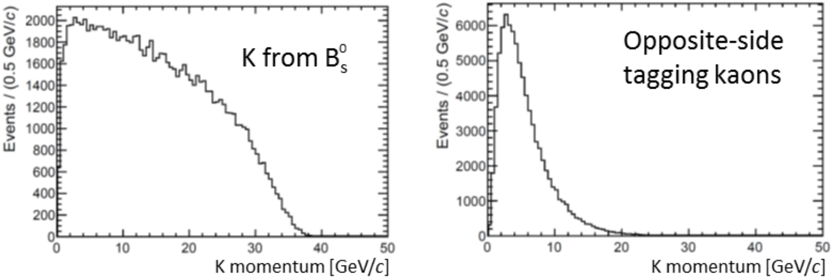


Figure 2: $B_s^0 \rightarrow D_s^{\pm} K^{\mp}$

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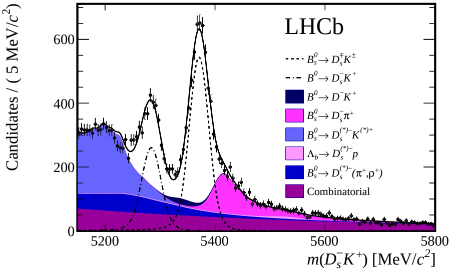


Figure 3: $B_s^0 \to D_s^{\pm} K^{\mp}$

Array of RICH Cells

- **A**rray of **RI**CH **C**ells (ARC): A novel RICH detector concept
  - First presented by R. Forty at FCC week 2021
  - Compact, low-mass solution for particle ID for FCC-ee
- Design based on current CLD experiment concept
  - Radial depth of 20 cm, radius of 2.1 m and a length of 4.4 m
- Concept inspired by the compound eyes of an insect
- Aerogel and gas radiators with a spherical mirror
  - Aerogel also acts as thermal insulation between gas and detector

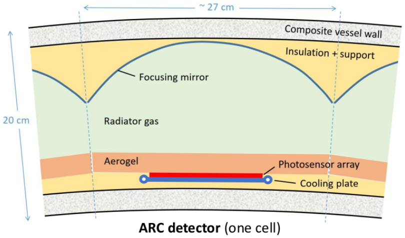


Figure 4: ARC has a cellular structure, similar to an insect's compound eyes

Array of RICH Cells

- All cells are the same size, organised on a hexagonal grid
  - Barrel (endcap) has 945 (384) cells in total, where 18 (21) are unique
  - Hexagonal shape avoids the corners, where performance is worse

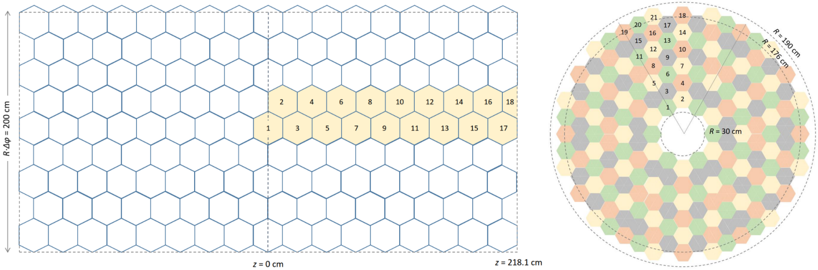


Figure 5: Barrel (left) and endcap (right) cells

- Original idea by R. Forty was a vessel with pressurised gas
  - Higher photon yield in smaller radial space
- However, a non-pressurised gas was found to have better performance, and also simplify the vessel design

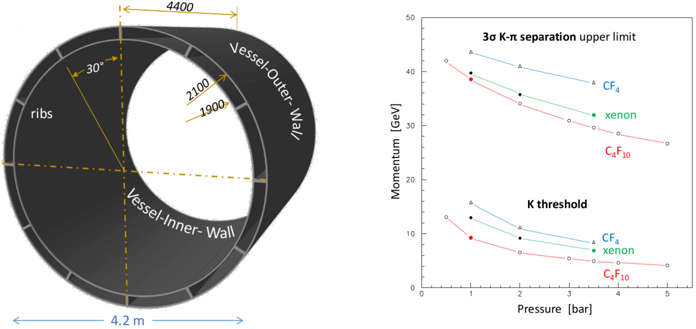


Figure 6: Layout of original carbon fiber vessel (left) and the performance at different pressures (right)

ARC radiators

- C_4F_{10}:
  - Baseline assumption, well known from LHCb RICH1
  - $n = 1.0014 \implies \theta_c = 53\,\text{mrad}$, suitable for high momentum particles
  - C_4F_{10} is a greenhouse gas, substitution with xenon is possible
- Aerogel:
  - Well known from ARICH at Belle
  - $n = 1.01\text{-}1.10 \implies \theta_c = 141\text{-}430\,\text{mrad}$, suitable at low momentum
  - Very low thermal conductivity
    - Suitable to separate gas from detector, which must be cooled
    - Cherenkov photons come for “free” and are focused by the same mirror
  - Drawback: Some loss of photons from scattering

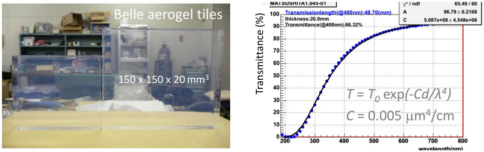


Figure 7: Belle aerogel tiles (left) and aerogel transmission function (right).

Event displays

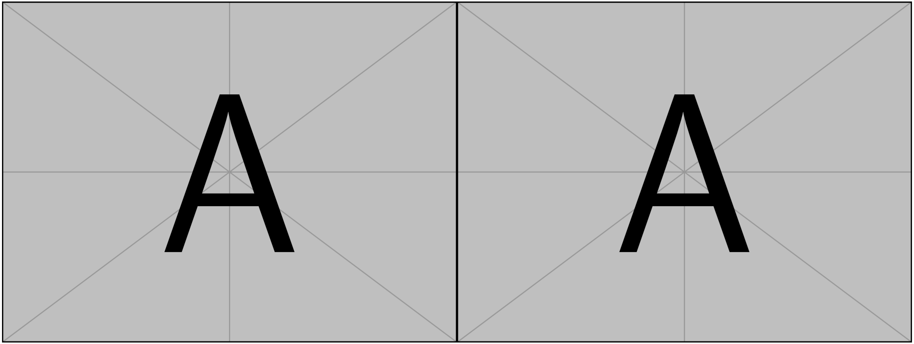


Figure 8: Some event displays from Roger

Optimisation of ARC layout

- The following procedure is used to evaluate the ARC performance:
  1. Generate straight particle track from IP and trace it through ARC
  2. Generate Cherenkov photons from gas radiator
  3. Track photons through the optics and to detector
  4. Reconstruct Cherenkov angles and calculate standard deviation
- Two sources of uncertainty are considered:
  1. Emission point uncertainty: Emission point is assumed to be the mid-point of the track inside the gaseous radiator
  2. Chromatic dispersion uncertainty: Spread in Cherenkov angle due to wavelength dependence in refractive index

Minimise the Cherenkov angle uncertainty:

$$\Delta\theta = \frac{1}{\sqrt{N}} \times \frac{1}{1-N} \times \sum_{i=0}^{N-1} (\theta - \bar{\theta})^2$$

Examples of photon tracking

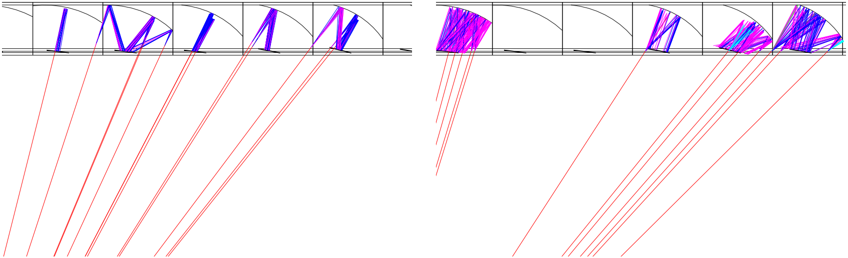
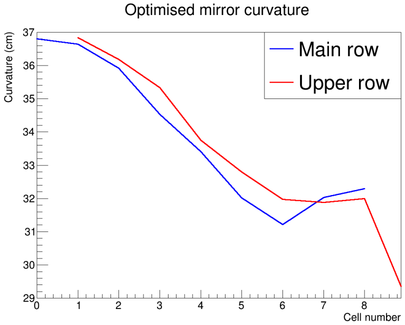
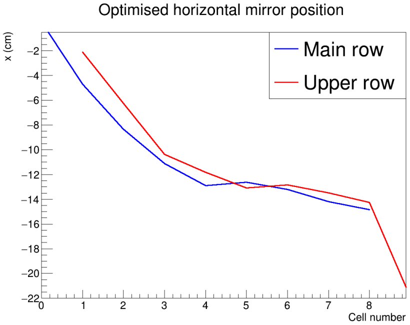


Figure 9: Tracking of photons from gas radiator (left) and aerogel radiator (right) through the ARC optics

Optimised mirror curvature and mirror position



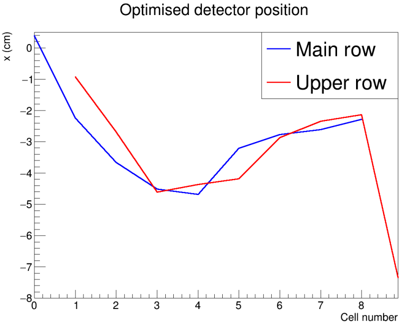
(a) Mirror curvature



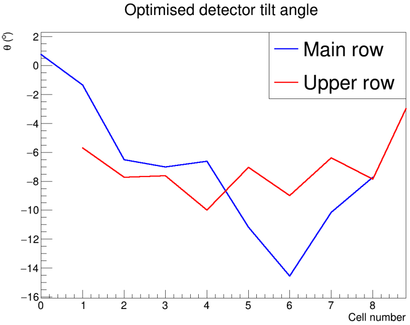
(b) Mirror position

Figure 10: Optimised mirror parameters

Optimised detector position and detector tilt angle



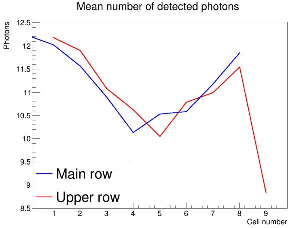
(a) Detector position



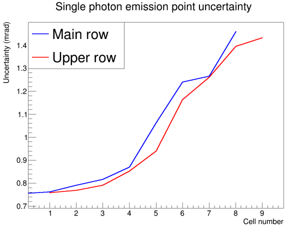
(b) Detector tilt angle

Figure 11: Optimised detector parameters

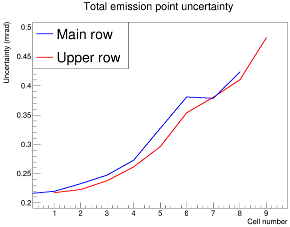
Emission-point uncertainties, mean number of photons



(a) Mean number of photons detected



(b) Single photon emission point uncertainty



(c) Total emission point uncertainty

Performance of optimised ARC

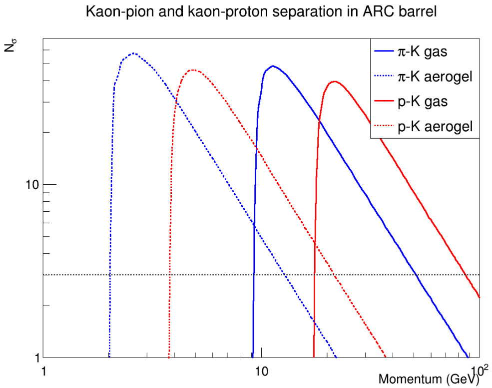


Figure 13: The pion-kaon (blue) and proton-kaon (red) separation significance in the gas radiator (solid) and aerogel radiator (dashed).

- Aerogel provides over 3σ pion-kaon separation in the range 2-10 GeV, while gas radiator ensures 3σ separation in the range 10-50 GeV

Performance of optimised ARC

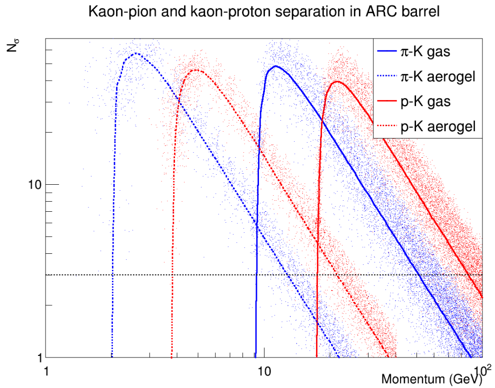


Figure 14: The pion-kaon (blue) and proton-kaon (red) separation significance in the gas radiator (solid) and aerogel radiator (dashed).

- Combined, the aerogel and gas ensure great PID performance over the whole range of interest to flavour physics

Summary and next steps

- ARC is a low mass cellular PID detector that fits inside a detector for FCC-ee
- We have developed an optimised layout that satisfies the requirements of flavour physics at the Z-pole
- Plenty of room for further work, including better optimisation, R&D of photodetectors and studies of magnetic field effects
- Opens up the possibility of a wide range of flavour physics measurements at FCC-ee!

Thanks for your attention!

Backup: Technical details about minimisation

- $f(\vec{x})$ is not easily to calculate analytically
- Approximate by simulating a large number of charged tracks
- Finite number of photons $\implies f(\vec{x})$ is not differentiable
  - Cannot be minimised using conventional methods (Minuit, etc)
- I have experimented with a new type of minimisation algorithms: Stochastic optimisation
  - Differential evolution
  - Start with a population of possible solutions, form new solutions by combining (mutating) existing solutions
  - Advantage: Doesn't require initial guess, robust against functions that a not continuous, noisy, change over time, etc
  - Disadvantage: No way to tell if optimal solution has been found, so it requires many iterations