ARC - progress update and plans towards full simulation
FCC Workshop, Kraków

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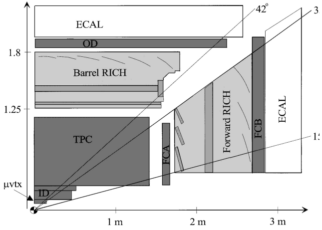
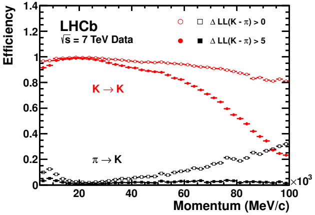
Introduction RICH detectors

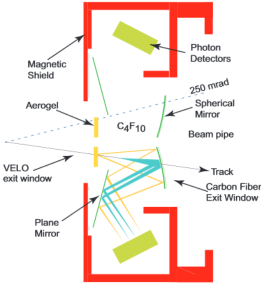
- Excellent hadron PID is crucial in flavour physics
  - Resolve combinatorics and separate decay modes
- RICH detectors are very powerful for particle ID at high momentum
- At LHCb, π-K separation is excellent up to 100 GeV
- A 4π collider RICH layout was previously used at DELPHI and SLD
  - Challenging 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 5×10^{12} 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 Higgs, WW and $t\bar{t}$ physics
  - In particular, kaon ID is crucial for $H \to s\bar{s}$

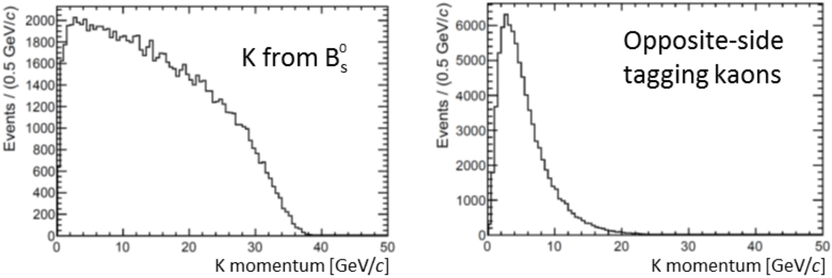


Figure 2: $B_s^0 \to D_s^{\pm} K^{\mp}$

B physics requires pion-kaon separation from low momentum up to 40 GeV

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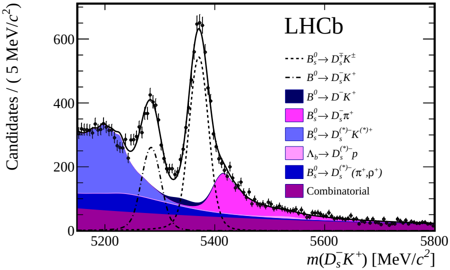


Figure 3: $B_s^0 \to D_s^{\pm} K^{\mp}$

The $B_s^0 \to D_s^{\pm} \pi^{\mp}$ background would be 10 times larger without PID capabilities!

Array of RICH Cells

- **A**rray of **R**I**C**H **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
  - Concept inspired by the compound eyes of an insect
- Adapted to fit into the CLD experiment concept, taking 10% from the tracker volume
  - Radial depth of 20 cm, radius of 2.1 m and a length of 4.4 m
  - Aim to keep material budget below $0.1X_0$
- Aerogel and gas radiators with a spherical mirror
  - Aerogel also acts as thermal insulation between gas and detector

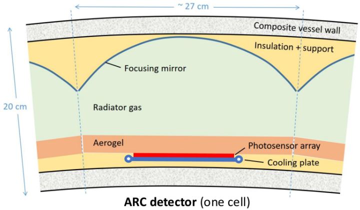


Figure 4: ARC has a cellular structure, similar to an insect's compound eyes

Array of RICH Cells

- All cells are the same size, organised on a hexagonal grid
  - Barrel (endcap) has 945 (402) cells in total, where 18 (23) are unique
  - Hexagonal shape avoids the corners, where performance is worse

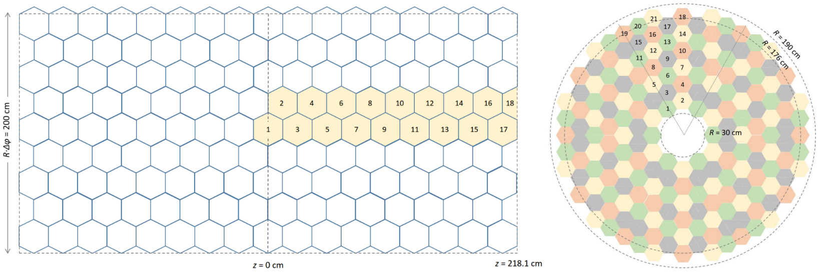


Figure 5: Barrel (left) and endcap (right) cells

Array of RICH Cells

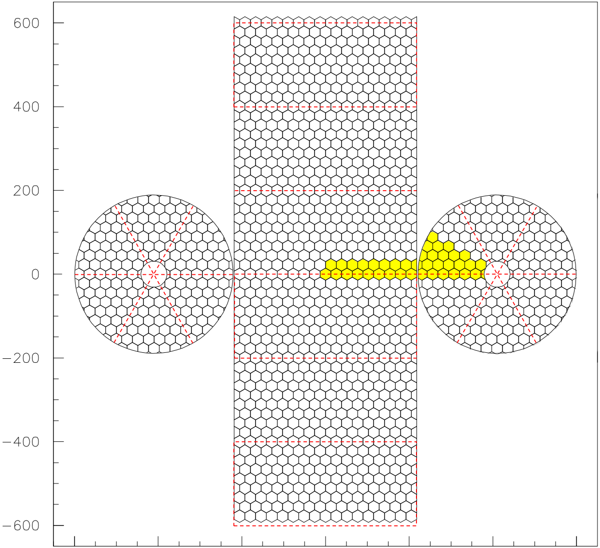
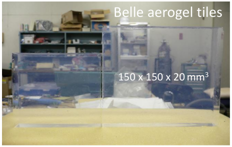


Figure 6: Barrel and endcap cells

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, plan to replace with suitable Novec gas, such as $C_5F_{10}O$
- Aerogel:
  - Well known as a RICH radiator, e.g. from ARICH at Belle II
  - $n = 1.01\text{-}1.10 \implies \theta_c = 141\text{-}430\,\text{mrad}$, 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



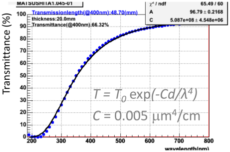


Figure 7: Belle aerogel tiles (left) and aerogel transmission function (right).

Photon hits

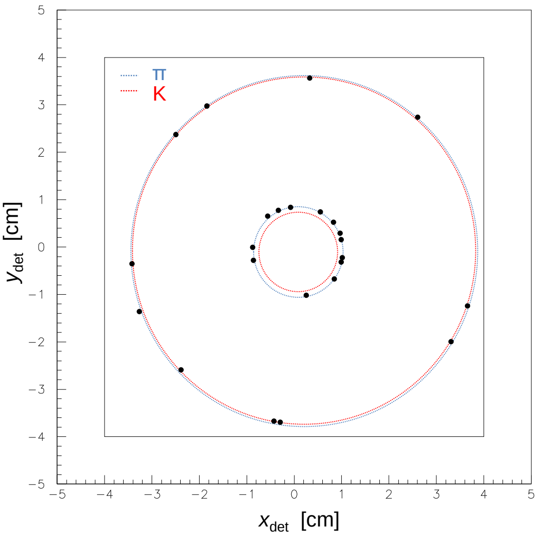


Figure 8: Photon hits on photodetector

Event display

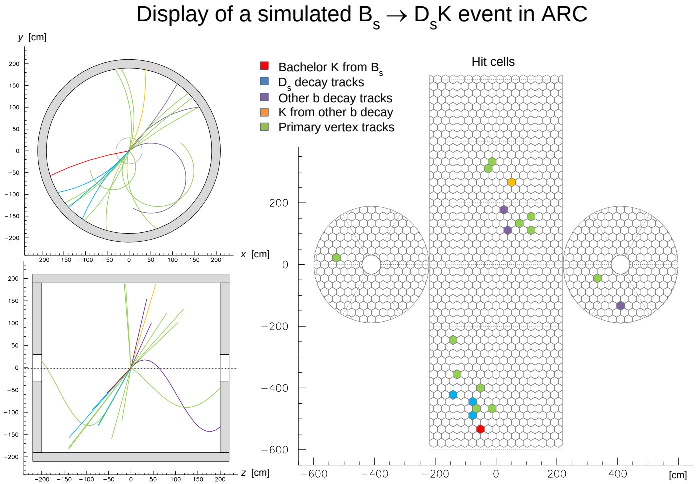


Figure 9: $B_s \to D_s K$

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
- Three 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 on refractive index
  3. Pixel size: Will be chosen so that it does not limit the performance

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 through optimised layout

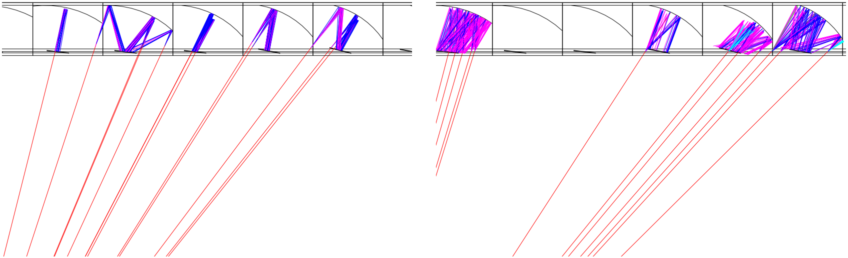


Figure 10: Tracking of photons from gas radiator (left) and aerogel radiator (right) through the ARC optics

- Parameters that are optimised:
  - Mirror curvature
  - Mirror vertical and horizontal position
  - Detector horizontal position and tilt

Performance of optimised ARC

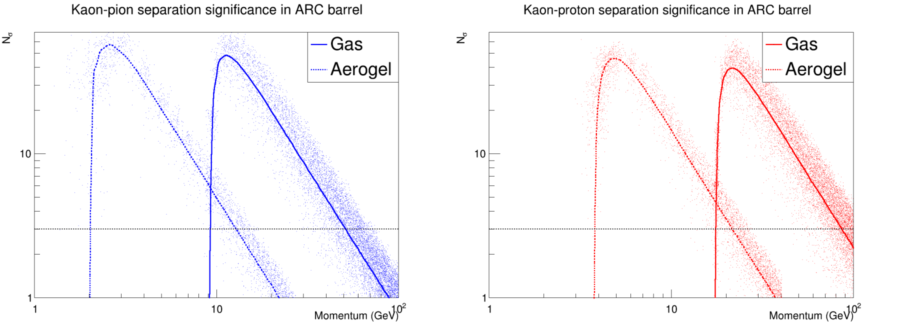
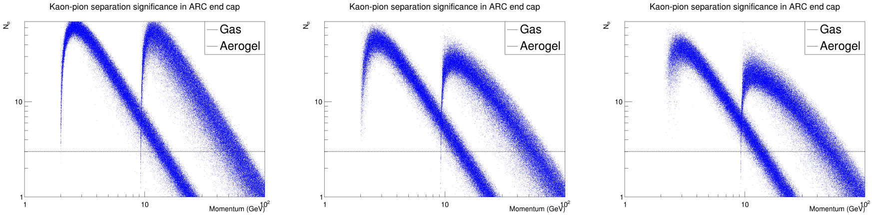


Figure 11: Separation significance per track for π-K (left) and p-K (right)

- Gas (aerogel) provides over 3σ pion-kaon separation in the range 10-50 GeV (2-10 GeV)
  - These plots do not include (small) effects of the magnetic field
- Combined, the aerogel and gas ensure excellent PID performance over the whole range of interest to flavour physics

Magnetic field effects

- Magnetic field will degrade the performance in two ways:
  1. Tracks will be displaced in azimuthal direction, so aerogel photons may miss the sensor.
  2. The emission point uncertainty will be larger because particles will change direction as it travels through the radiator.



(a) No B-field　　**(b)** $B = 2\,\mathrm{T}$　　**(c)** $B = 3\,\mathrm{T}$

Figure 12: Comparison of kaon-pion separation in the barrel in the presence of a magnetic field

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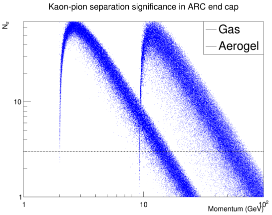
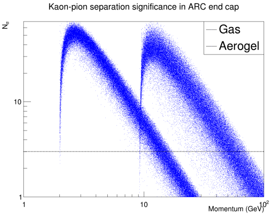
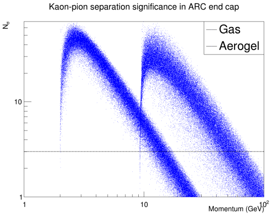


(a) No B-field



(b) $B = 2\,\mathrm{T}$



(c) $B = 3\,\mathrm{T}$

Figure 13: Comparison of kaon-pion separation in the end cap in the presence of a magnetic field

DD4hep implementation

- We have finished the optimised layout
- We wish to implement our layout in DD4hep
  - More general detector description
  - Full Geant4 simulation
  - Most importantly: Make ARC available to detector projects that wish to include ARC in their design!
- We would like to thank the FCC Software team for providing support and man power for the DD4hep implementation

DD4hep progress

A single cubic cell with gas, aerogel, cooling plate, vessel walls and mirror has been implemented, and it passed the overlap check!

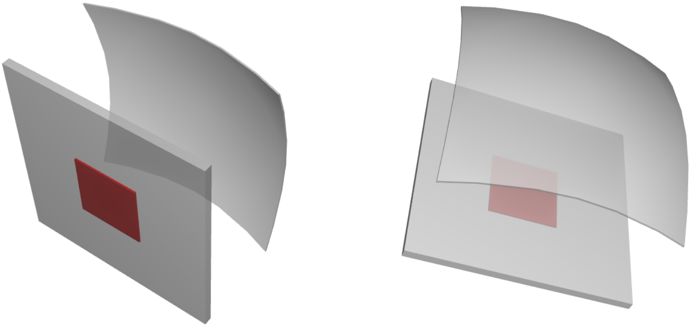


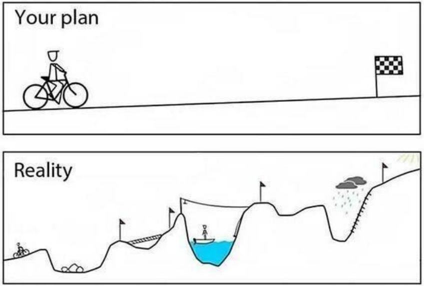
Figure 14: Graphical display of a single cubic ARC cell. Vessel walls and cooling plate have been removed for easier visualisation.

Special thanks to Alvaro Tolosa Delgado for providing the code!

DD4hep implementation plan

Our preliminary plan for implementing ARC in DD4hep is:

1. Run simulation of single cubic cell and get Cherenkov rings
2. Change to hexagonal cell
3. Assemble full endcap
4. Do the same with the barrel



Summary and next steps

- ARC is a low mass and compact cellular PID detector designed to occupy minimum space (20 cm in the radial dimension) in a 4π detector at an e^+e^- collider such as FCC-ee
- We have developed an optimised layout that should achieve a 3σ kaon-pion separation in the range 2-50 GeV
  - With ARC, FCC-ee detectors can complement their current physics programme with a rich flavour physics programme
  - Will also enhance the capabilities in Higgs, WW and top physics
- DD4hep implementation is currently work in progress

Thanks for your attention!

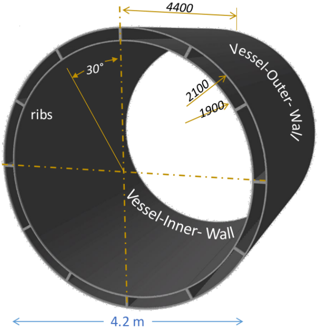
Backup: Estimated material budget breakdown

Units of radiation length X/X_0

Detector component	Pressurised	Non-pressurised
Vessel walls	5%	1%
Photosensor array/electronics	1%	1%
Cooling plate (3 mm CF)	1%	1%
Aerogel ($n = 1.03$)	1%	0.5%
C_4F_{10} gas	1%	0.5%
Focusing mirror	1%	1%
Total	10%	5%

Backup: Original pressurised ARC

- Original idea was for 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



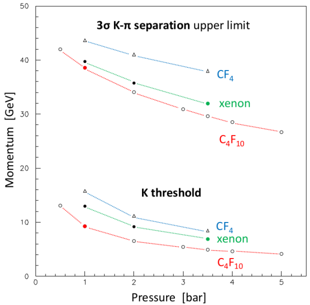
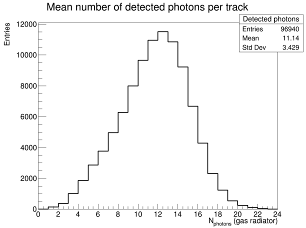


Figure 15: Layout of original carbon fiber vessel (left) and the performance at different pressures (right)

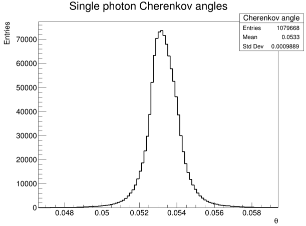
Backup: Technical details about minimisation

- $f(\vec{x})$ 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

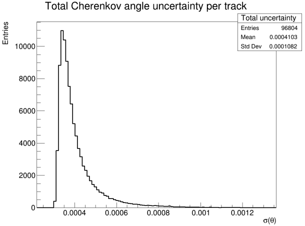
Backup: Cherenkov angle uncertainty for gas radiator



(a) Mean number of photons detected



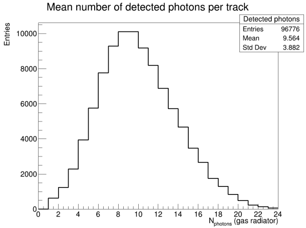
(b) Single photon uncertainty: 1.0 mrad



(c) Total uncertainty: 0.4 mrad

Figure 16: Gas radiator performance averaged over all barrel cells

Backup: Cherenkov angle uncertainty for aerogel radiator



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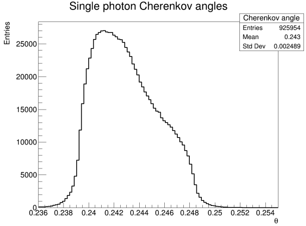
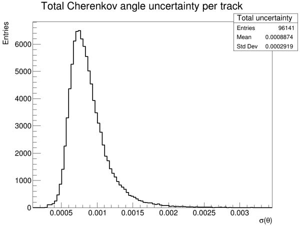


(b) Single photon uncertainty: 2.5 mrad



(c) Total uncertainty: 0.9 mrad

Figure 17: Aerogel radiator performance averaged over all barrel cells