ARC: A RICH detector proposal for FCC-ee

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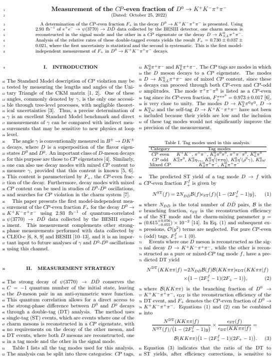
Analysis work summary

- For my PhD thesis I'm working on two related projects:
  - Measurement of $D^0 \to K^+K^-\pi^+\pi^-$ strong phases c_i and s_i at BESIII
  - Binned GGSZ analysis of γ in $B^\pm \to Dh^\pm$, $D \to K^+K^-\pi^+\pi^-$ at LHCb
- Over the summer I have worked on two papers:



Measurement of the CP-even fraction of $D^0 \to K^+K^-\pi^+\pi^-$

(Dated: October 25, 2022)

A determination of the CP-even fraction F_+ in the decay $D^0 \to K^+K^-\pi^+\pi^-$ is presented. Using 2.93 fb^{-1} of $e^+e^- \to \psi(3770) \to D\bar{D}$ data collected by the BESIII detector, one charm meson is reconstructed in the signal mode and the other in a CP eigenstate or the decay $D \to K^0_{S,L}\pi^+\pi^-$. Analysis of the relative rates of these double-tagged events yields the result $F_+ = 0.730 \pm 0.037 \pm 0.021$, where the first uncertainty is statistical and the second is systematic. This is the first model-independent measurement of F_+ in $D^0 \to K^+K^-\pi^+\pi^-$ decays.

I. INTRODUCTION

The Standard Model description of CP violation may be tested by measuring the lengths and angles of the Unitary Triangle of the CKM matrix [1, 2]. One of these angles, commonly denoted by γ, is the only one accessible through tree-level processes, with negligible theoretical uncertainties [3]. Thus, a precise determination of γ is an excellent Standard Model benchmark and direct measurements of γ can be compared with indirect measurements that may be sensitive to new physics at loop level.

The angle γ is conventionally measured in $B^\pm \to DK^\pm$ decays, where D is a superposition of the flavor eigenstates D^0 and $\bar{D}^0$. An important class of D-meson decays for this purpose are those to CP eigenstates [4]. Similarly, one can also use decay modes with mixed CP content to measure γ, provided that this content is known [5, 6]. This content is parameterized by F_+, the CP-even fraction of the decay. Furthermore, decay modes with mixed CP content can be used in studies of D^0-$\bar{D}^0$ oscillations, and searches for CP violation in the charm system [7].

This paper presents the first model-independent measurement of the CP-even fraction F_+ for the decay $D^0 \to K^+K^-\pi^+\pi^-$ using 2.93 fb^{-1} of quantum-correlated $\psi(3770) \to D\bar{D}$ data collected by the BESIII experiment. This measurement complements other strong-phase measurements performed with data collected by CLEO-c [6, 8, 9] and BESIII [10–13], and it is an important input to future analyses of γ and D^0-$\bar{D}^0$ oscillations using this channel.

II. MEASUREMENT STRATEGY

The strong decay of $\psi(3770) \to D\bar{D}$ conserves the $C = -1$ quantum number of the initial state, leaving the D-meson pair in an anti-symmetric wave function. This quantum correlation allows for a direct access to the strong-phase difference between D^0 and $\bar{D}^0$ decays through a double-tag (DT) analysis. The method uses single-tag (ST) events, which are events where one of the charm mesons is reconstructed in a CP eigenstate, with no requirements on the decay of the other meson, and DT events, where both D mesons are reconstructed, one in a tag mode and the other in the signal mode.

Table I lists all the tag modes used for this analysis. The analysis can be split into three categories: CP tags, $K^0_S\pi^+\pi^-$ and $K^0_L\pi^+\pi^-$. The CP tags are modes in which the D meson decays to a CP eigenstate. The modes $D \to K^0_{S,L}\pi^+\pi^-$ are of mixed CP content, since these decays can proceed through both CP-even and CP-odd amplitudes. The mode $\pi^+\pi^-\pi^0$ is listed as a CP-even tag since its CP-even fraction, $F_+^{\pi\pi\pi^0} = 0.973 \pm 0.017$ [6], is very close to unity. The modes $D \to K^0_L\pi^0\pi^0$, $D \to K^0_L\omega$ and the self-tag $D \to K^+K^-\pi^+\pi^-$ have not been included because their yields are low and the inclusion of these tag modes would not significantly improve the precision of the measurement.

Table I. Tag modes used in this analysis.

Category	Tag modes
CP even	K^+K^-, $\pi^+\pi^-$, $K^0_S\pi^0\pi^0$, $\pi^+\pi^-\pi^0$, $K^0_L\pi^0$
CP odd	$K^0_S\pi^0$, $K^0_S\eta_{\gamma\gamma}$, $K^0_S\eta'(\pi\pi\eta)$, $K^0_S\eta'(\rho^0\gamma)$, $K^0_S\omega$
Mixed CP	$K^0_S\pi^+\pi^-$, $K^0_L\pi^+\pi^-$

The predicted ST yield of a tag mode $D \to f$ with CP-even fraction F_+^f is given by

$$N^{\rm ST}(f) = 2N_{D\bar{D}}\mathcal{B}(f)\epsilon_{\rm ST}(f)\big(1 - (2F_+^f - 1)y\big), \quad (1)$$

where N_{DD} is the total number of $D\bar{D}$ pairs, $\mathcal{B}$ is the branching fraction, $\epsilon_{\rm ST}$ is the reconstruction efficiency of the ST mode and the charm-mixing parameter $y = (0.615^{+0.056}_{-0.055}) \times 10^{-2}$ [14]. In Eq. (1) and subsequent expressions, $\mathcal{O}(y^2)$ terms are neglected. For pure CP-even (odd) tags, $F_+^f = 1$ (0).

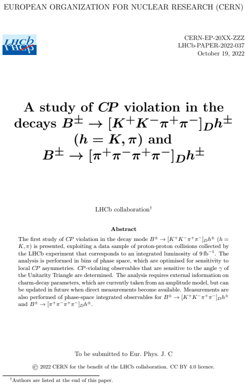
Events where one D meson is reconstructed as the signal decay $D \to K^+K^-\pi^+\pi^-$, while the other is reconstructed as a pure or mixed-CP tag mode f, have a predicted DT yield

$$\begin{aligned} N^{\rm DT}(KK\pi\pi|f) =& 2N_{D\bar{D}}\mathcal{B}(f)\mathcal{B}(KK\pi\pi)\epsilon_{\rm DT}(KK\pi\pi|f) \\ & \times\big(1 - (2F_+^f - 1)(2F_+ - 1)\big), \end{aligned} \quad (2)$$

where $\mathcal{B}(KK\pi\pi)$ is the branching fraction of $D^0 \to K^+K^-\pi^+\pi^-$, $\epsilon_{\rm DT}$ is the reconstruction efficiency of the DT event, and F_+ denotes the CP-even fraction of $D^0 \to K^+K^-\pi^+\pi^-$. Equations (1) and (2) can be combined into

$$\frac{N^{\rm DT}(KK\pi\pi|f)}{N^{\rm ST}(f)/\big(1 - (2F_+^f - 1)y\big)} \times \frac{\epsilon_{\rm ST}(f)}{\epsilon_{\rm DT}(KK\pi\pi|f)} = \mathcal{B}(KK\pi\pi)\big(1 - (2F_+^f - 1)(2F_+ - 1)\big). \quad (3)$$

Equation (3) indicates that the ratio of the DT to ST yields, after efficiency corrections, is sensitive to



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

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LHCb-PAPER-2022-037
October 19, 2022

A study of CP violation in the decays $B^\pm \to [K^+K^-\pi^+\pi^-]_D h^\pm$ $(h = K, \pi)$ and $B^\pm \to [\pi^+\pi^-\pi^+\pi^-]_D h^\pm$

LHCb collaboration[†]

Abstract

The first study of CP violation in the decay mode $B^\pm \to [K^+K^-\pi^+\pi^-]_D h^\pm$ $(h = K, \pi)$ is presented, exploiting a data sample of proton-proton collisions collected by the LHCb experiment that corresponds to an integrated luminosity of 9 fb^{-1}. The analysis is performed in bins of phase space, which are optimised for sensitivity to local CP asymmetries. CP-violating observables that are sensitive to the angle γ of the Unitarity Triangle are determined. The analysis requires external information on charm-decay parameters, which are currently taken from an amplitude model, but can be updated in future when direct measurements become available. Measurements are also performed of phase-space integrated observables for $B^\pm \to [K^+K^-\pi^+\pi^-]_D h^\pm$ and $B^\pm \to [\pi^+\pi^-\pi^+\pi^-]_D h^\pm$.

To be submitted to Eur. Phys. J. C

[†]Authors are listed at the end of this paper.

Analysis work summary

- BESIII paper: Measurement of the CP-even fraction of $D^0 \to K^+K^-\pi^+\pi^-$
  - Has gone through all BESIII reviews, except for Spokesperson approval
  - We were unfortunately assigned the spokesperson with a backlog of 5 papers, expect 2-3 months delay...

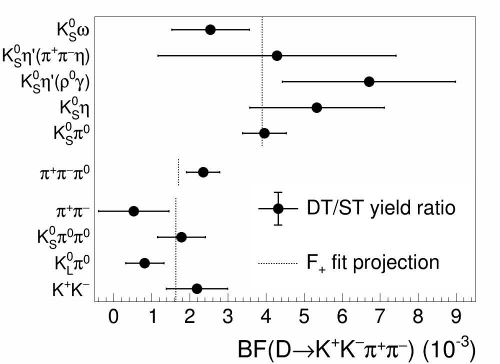


Figure 2: CP-even and CP-odd branching fractions of $D \to K^+K^-\pi^+\pi^-$

Analysis work summary

- LHCb paper: A study of CP violation in the decays $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D h^{\pm}$ $(h = K, \pi)$ and $B^{\pm} \to [\pi^+\pi^-\pi^+\pi^-]_D h^{\pm}$
  - Binned model dependent GGSZ analysis of $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D h^{\pm}$
  - Phase space integrated GLW analysis of $B^{\pm} \to [h^+h^-\pi^+\pi^-]_D h^{\pm}$
  - Paper has just been through 1st collaboration wide circulation, currently waiting for RC and EB to review the new draft

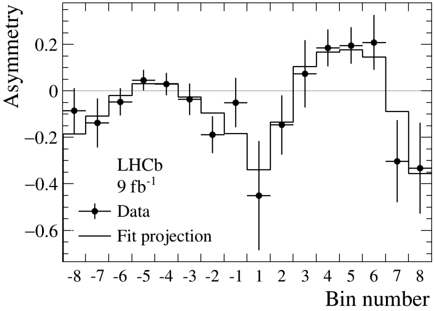


Figure 3: $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D K^{\pm}$ bin asymmetries

ARC: A solution for PID at FCC-ee

Array of **R**ICH **C**ells

A side project I've worked on while my BESIII and LHCb papers go through review

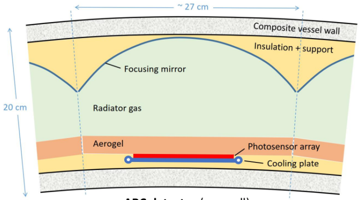
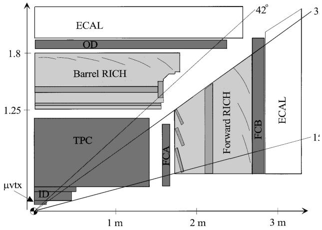


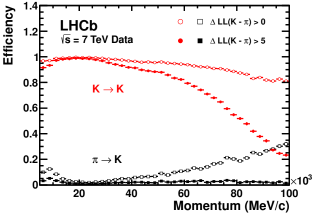
Figure 4: ARC: Array of RICH Cells

RICH detectors

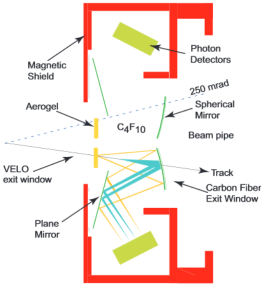
- Excellent hadron PID is crucial in flavour physics
- RICH detectors are very powerful for particle ID at high momentum
- At LHCb, π-K separation is excellent up to 100 GeV
- A 4π collider RICH layout was previously used at DELPHI and SLD
    - Challenging because of the space required



(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 $H \to s\bar{s}$

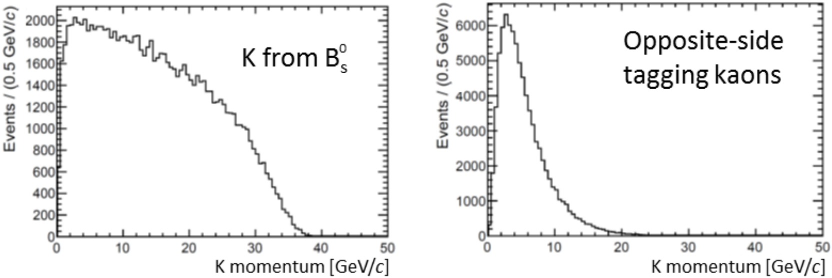


Figure 6: $B_s^0 \to D_s^{\pm} K^{\mp}$

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

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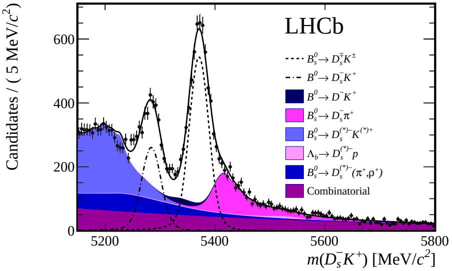


Figure 7: $B_s^0 \to D_s^{\pm} K^{\mp}$

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**ICH **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

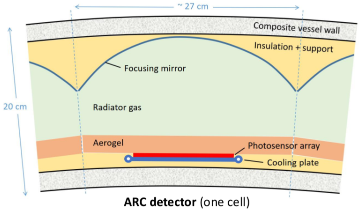


Figure 8: ARC has a cellular structure, similar to an insect's compound eyes

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

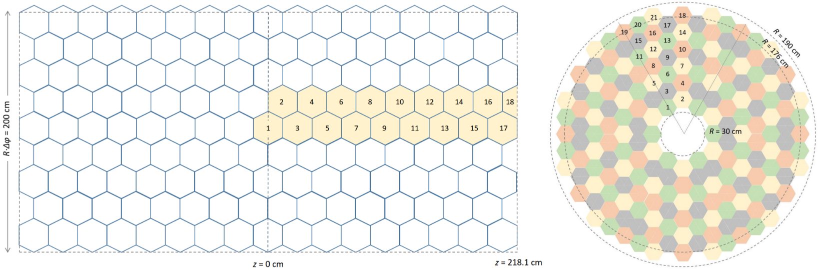
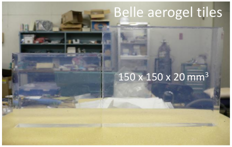


Figure 9: Barrel (left) and endcap (right) cells

- 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



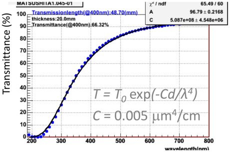


Figure 10: Belle aerogel tiles (left) and aerogel transmission function (right).

Photon hits

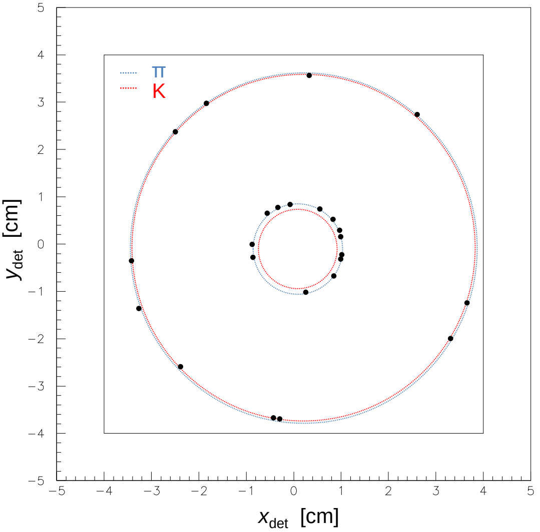


Figure 11: Photon hits on photodetector

Event display

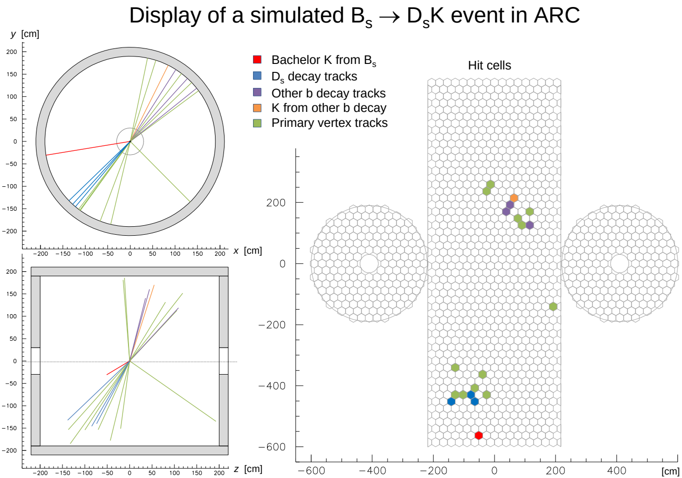


Figure 12: $B_s \to D_s K$ (no magnetic field yet)

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

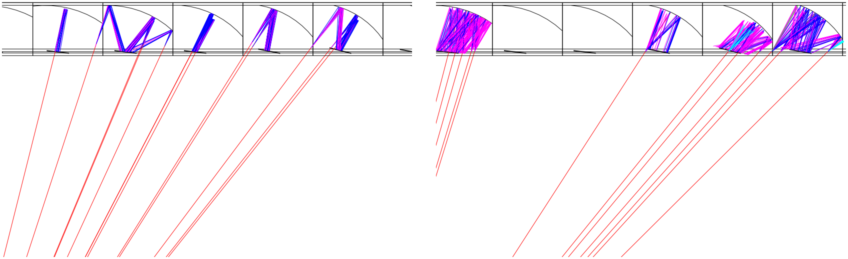


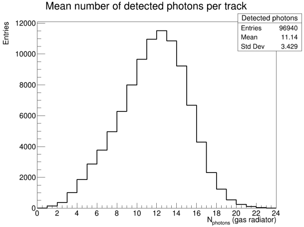
Figure 13: Tracking of photons from gas radiator (left) and aerogel radiator (right) through the ARC optics

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

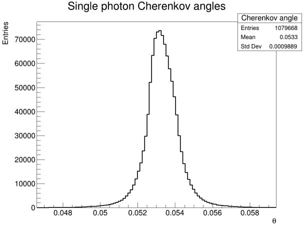
Technical details about minimisation

- Total Cherenkov angle uncertainty $\sigma(\vec{x})$ is not easy to calculate analytically
  - $\vec{x}$ are the 5 parameters we want to optimise
- Finite number of photons $\implies$ $\sigma(\vec{x})$ 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

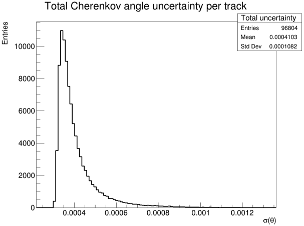
Cherenkov angle uncertainty for gas radiator



(a) Mean number of photons detected



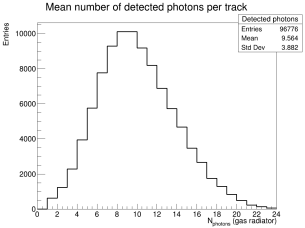
(b) Single photon uncertainty: 1.0 mrad



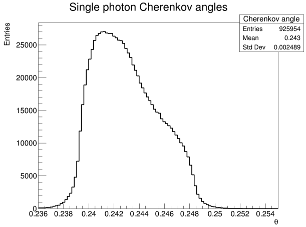
(c) Total uncertainty: 0.4 mrad

Figure 14: Gas radiator performance averaged over all barrel cells

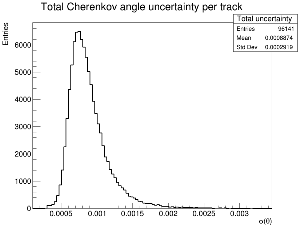
Cherenkov angle uncertainty for aerogel radiator



(a) Mean number of photons detected



(b) Single photon uncertainty: 2.5 mrad



(c) Total uncertainty: 0.9 mrad

Figure 15: Aerogel radiator performance averaged over all barrel cells

Performance of optimised ARC

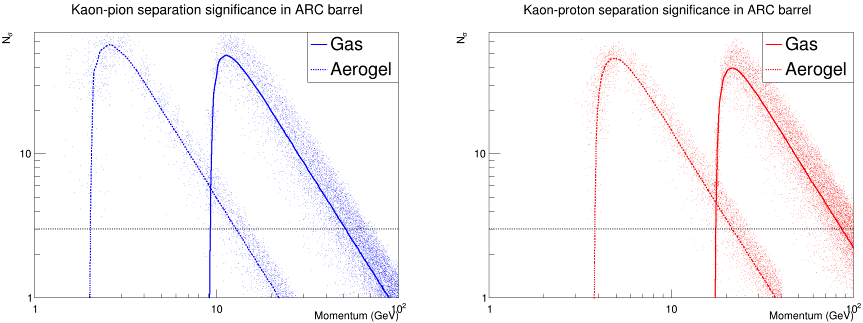


Figure 16: Separation significance per track for π-K (left) and p-K (right)

- Gas (aerogel) provides over 3σ pion-kaon separation in the range 10-50 GeV (2-10 GeV)
  - Effect of magnetic field not yet included in these studies
- Combined, the aerogel and gas ensure excellent PID performance over the whole range of interest to flavour physics

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
  - Our studies focus mainly on flavour physics at the Z-pole
- ARC will allow us to fully exploit the full range of flavour physics potential at future e^+e^- colliders
  - Will enhance the capabilities in Higgs, WW and top physics
- Next steps will include completing the optimisation, including magnetic field effects, and R&D on photodetectors

Thank you for listening!