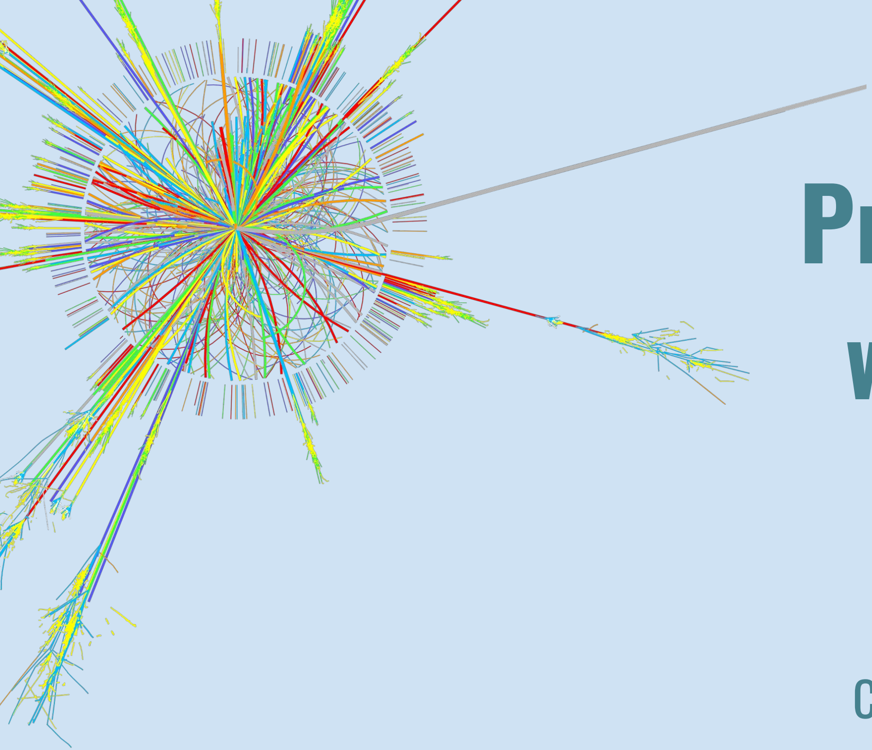


Prospects for PID at FCC with the IDEA detector

Andrea Coccaro

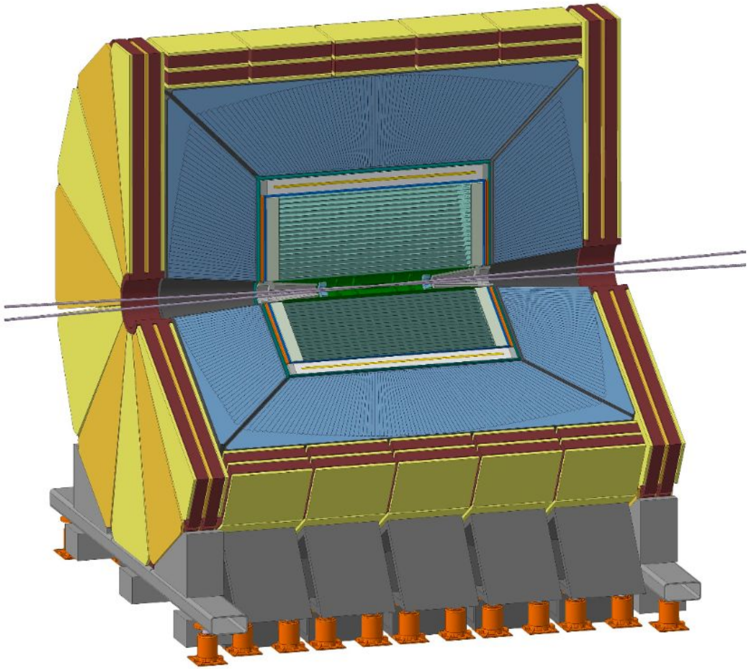
Corfu Workshop on Future Accelerators - May 2024

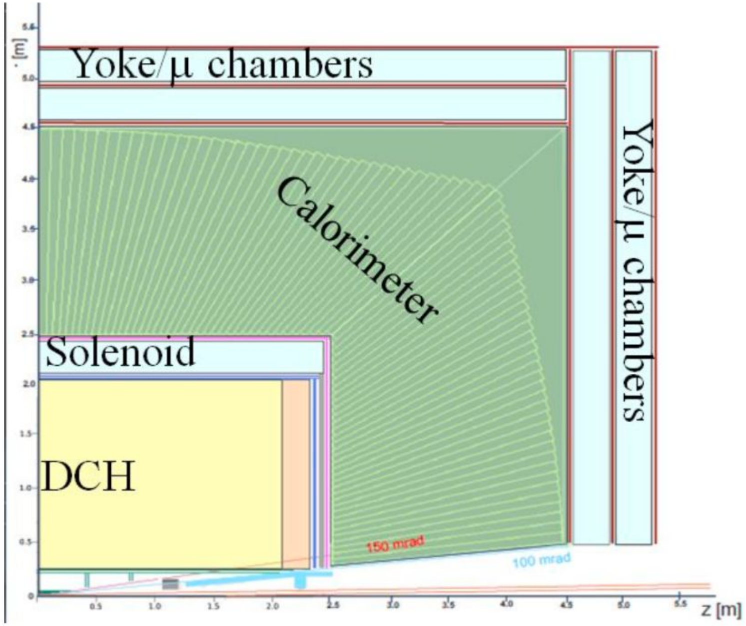
INFN GENOVA

Introduction

- The IDEA detector
- Inclusive PID studies with the IDEA detector
  - Using ee $\rightarrow$ Z $\rightarrow$ bb with exclusive D_sK and $D_s\pi$ decays
- Effect of PID in $B_s \rightarrow D_sK$ analysis, with $D_s \rightarrow \phi\pi$, $\phi \rightarrow KK$
  - Benchmark channel included in the FCC mid-term review
  - Based on studies by AC, Fabrizio Parodi and Emanuel Perez
- Effect of PID in a jet flavour-tagging algorithm
  - Using ee $\rightarrow$ ZH $\rightarrow$ qq/gg with q = (u,d), s, c, b
  - With emphasis on strange-jet tagging
  - Based on Eur. Phys. J. C 82 (2022) 7, 646 by F. Bedeschi, L. Gouskos, M. Selvaggi
- Impact of strange tagging on benchmark physics analyses
  - Measurement of V_{cs} using W decays – Phys. Lett. B 439 (1998) 209-224 by DELPHI
  - Measurement of H $\rightarrow$ ss – Phys. Rev. D 101 115005, arXiv:2203.07535
  - Background suppression in exclusive H $\rightarrow$ $\phi\gamma$ decays – JHEP 07 (2018) 127

Innovative Detector for Electron-positron Accelerator

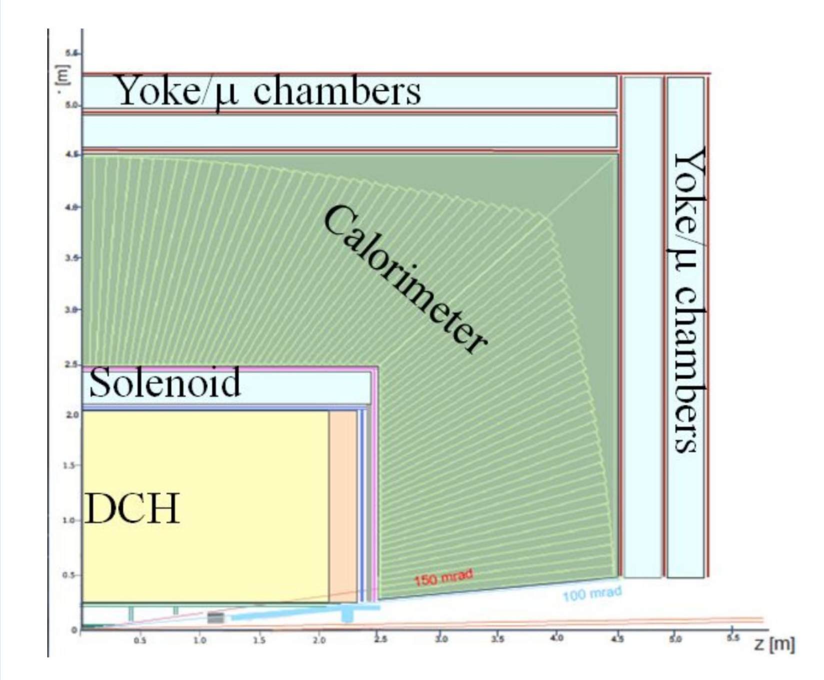




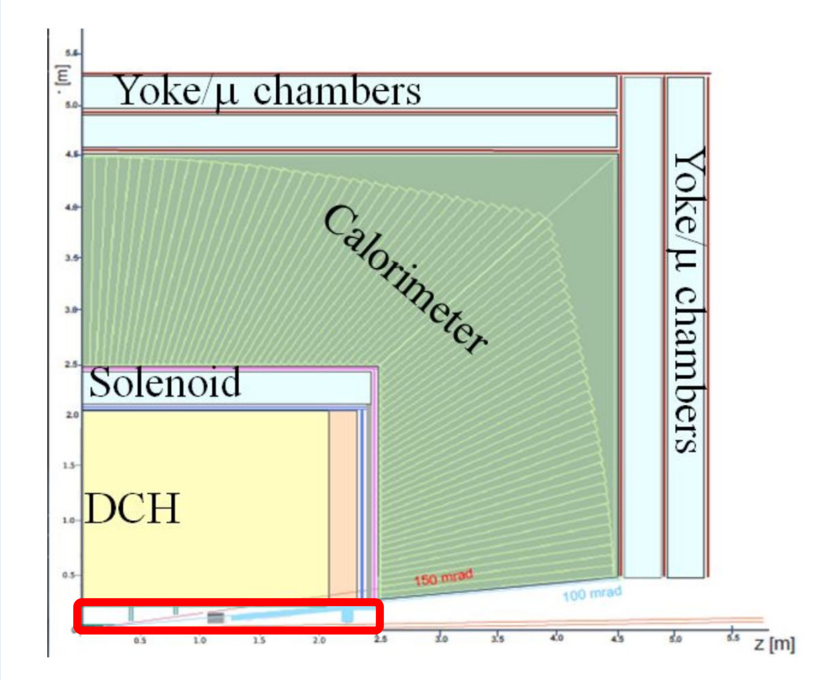
Ambitious detector for exploiting the physics potential of a future circular e^+e^- collider

Not necessarily the final detector choice for the real experiment

The IDEA detector

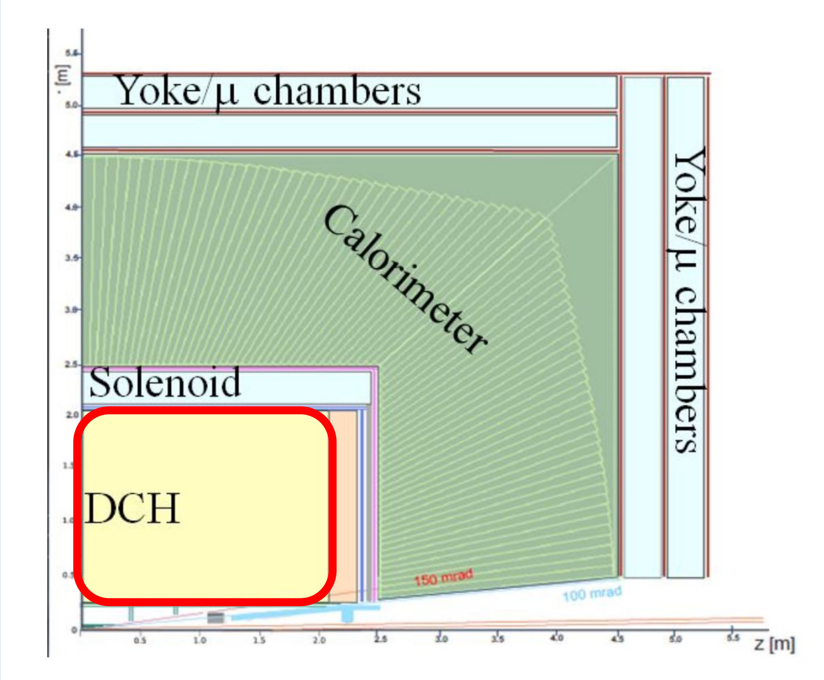


The IDEA detector



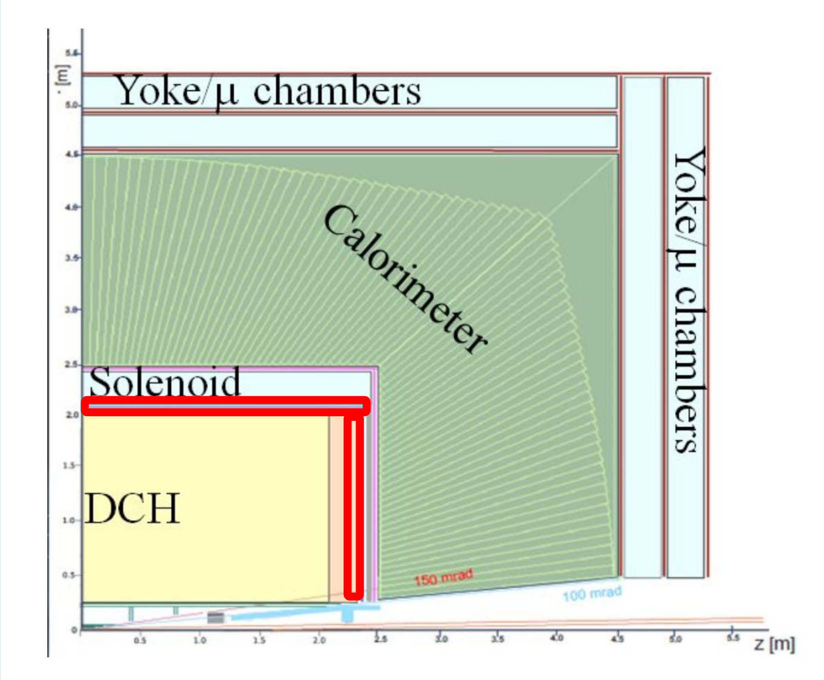
- 5-layer vertex detector with 20-μm active pixels with 3-μm space-point resolution and 2-μm of asymptotic track IP resolution

The IDEA detector



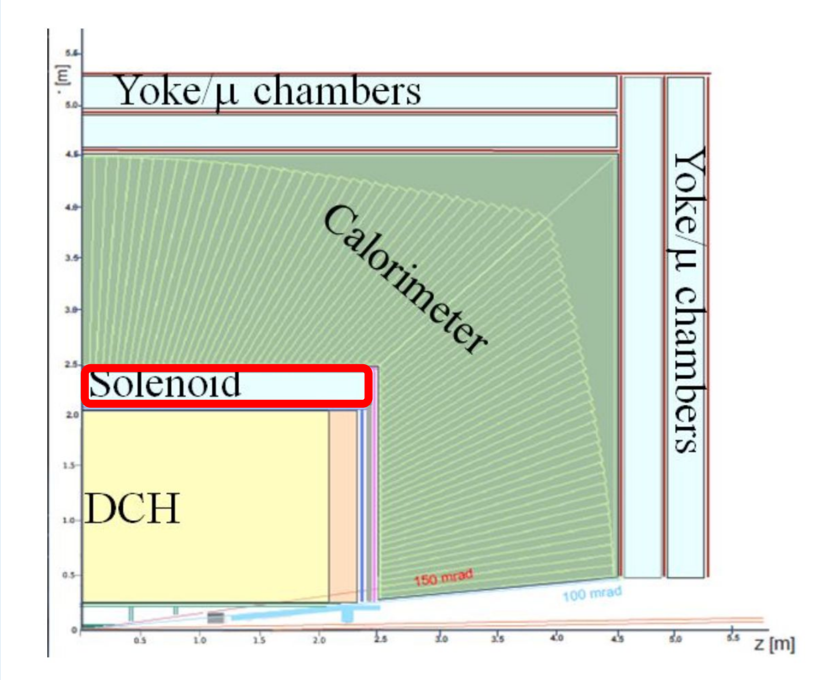
- 5-layer vertex detector with 20-μm active pixels with 3-μm space-point resolution and 2-μm of asymptotic track IP resolution
- 4-m long cylindrical drift chamber extending in radius up to 2 m. 1.6% X_0 for orthogonal tracks, ~100-μm of spatial resolution, 2% dE/dx resolution with cluster counting

The IDEA detector



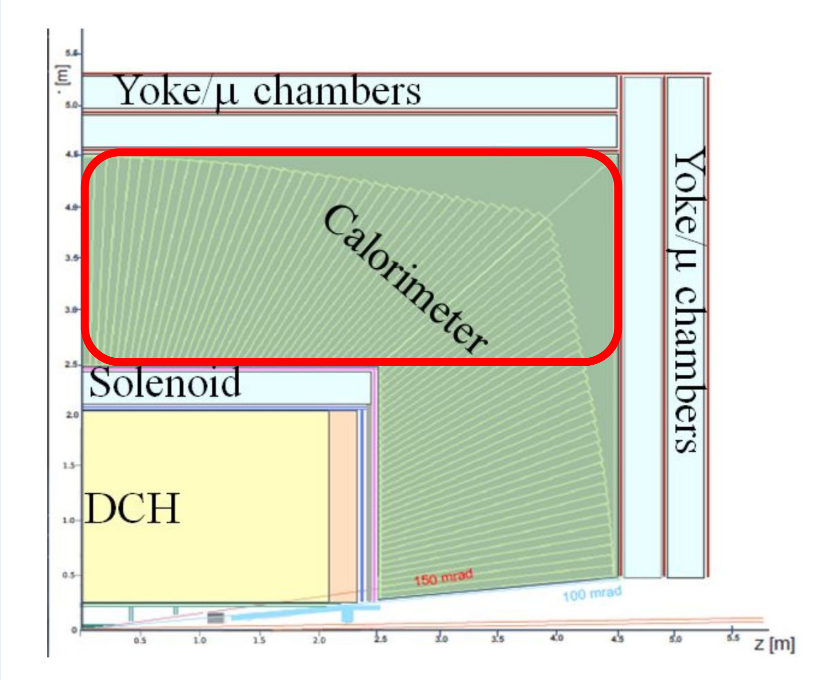
- 5-layer vertex detector with 20-μm active pixels with 3-μm space-point resolution and 2-μm of asymptotic track IP resolution
- 4-m long cylindrical drift chamber extending in radius up to 2 m. 1.6% X_0 for orthogonal tracks, ~100-μm of spatial resolution, 2% dE/dx resolution with cluster counting
- Double-layer of silicon micro-strips to improve momentum resolution and time-of-flight measurement

The IDEA detector



- 2-T solenoidal magnet. (A higher field would compromise the beam emittance and hence the delivered luminosity, in particular at low center-of-mass energy)

The IDEA detector

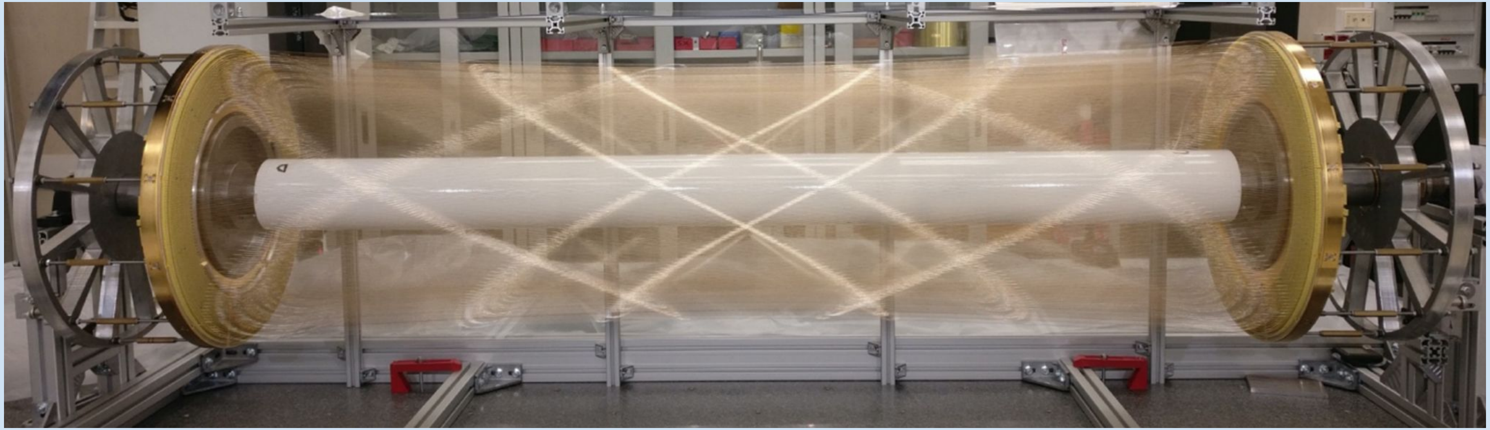


- 2-T solenoidal magnet. (A higher field would compromise the beam emittance and hence the delivered luminosity, in particular at low center-of-mass energy)
- Pre-shower and dual-readout calorimeter with a total depth of 2 m and ~8 pion interaction lengths.

Ongoing R&D for the various sub-detector technologies, in particular for

- Pixel technology, eventually curved and with timing
- Metal coating of carbon fiber filaments for wires
- Coupling of SiPM to fibers
- Various readout and dedicated electronics

Drift chamber



- Extremely transparent, with 112 layers of stereo wires
- Gas mixture of 90% He and 10% iC4H10
- Maximum drift time 350-400 ns with σ_{xy} ~100 μm and σ_Z < 1 mm
- Based on R&D and experience by KLOE and MEG-II detectors

PID at colliders

- The difference in interaction in the HEP detectors is primarily used for lepton and photon identification
- For unambiguously identifying hadrons, charge and mass need to be measured, the latter by simultaneous measurements of momentum and velocity
- Mass resolution determined primarily by the accuracy of the velocity measurement, being γ>>1

$$\left(\frac{\delta m}{m}\right)^2 = \left(\frac{\delta p}{p}\right)^2 + \left(\gamma^2 \frac{\delta \beta}{\beta}\right)^2$$

- Velocity inferred by
  - Measurement of the energy deposit by ionisation
  - Time-of-flight (TOF) measurement
  - Cherenkov radiation detection
  - Transition radiation detection
- Main application is classification of kaon vs pion candidates

PID studies with the IDEA detector

Possible options

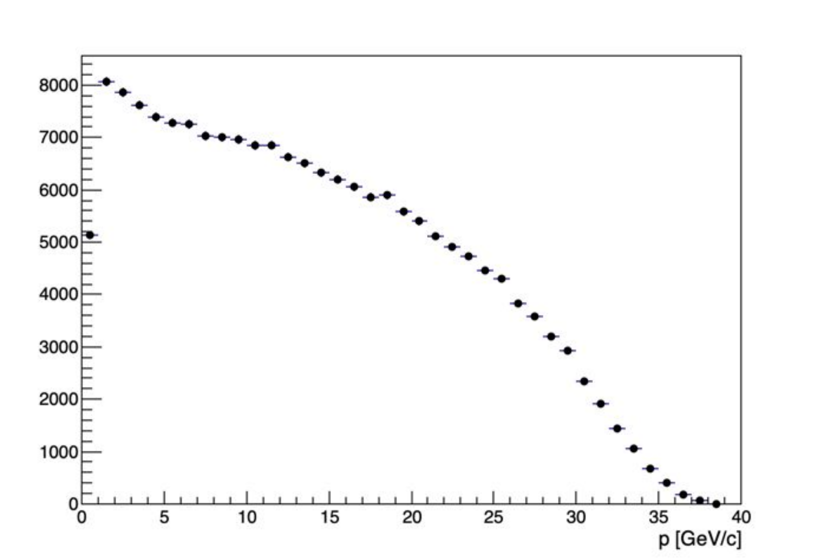
- Likelihood ratio (LR) on dN/dx
- LR on velocity / TOF
- Combined LR
- Also tested standard and x2 worse resolution in dN/dx and standard and improved TOF resolution

Samples

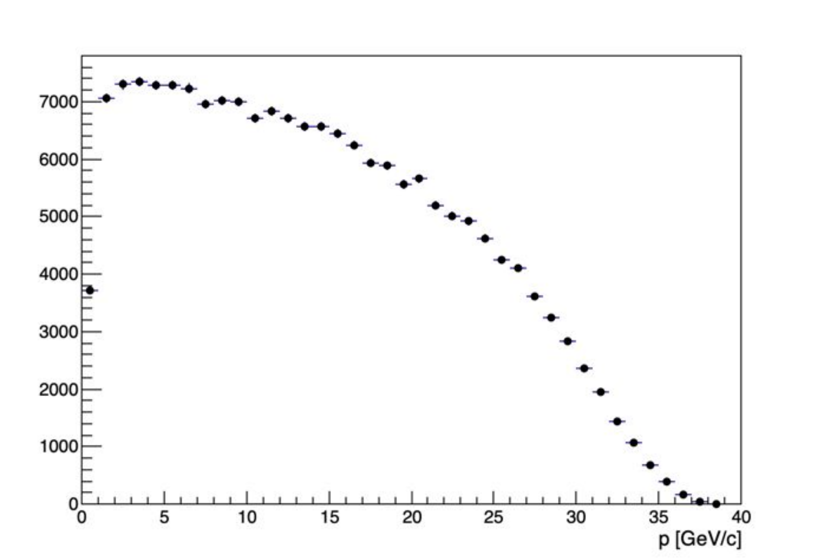
- ee$\rightarrow$ Z $\rightarrow$ bb with exclusive $D_s K$ and $D_s \pi$ decays
- MG_aMC@NLO plus P8 for modelling the decay, parton shower and hadronization processes
- Delphes with IDEA card

Inclusive PID studies with D_sK and $D_s\pi$

Pion



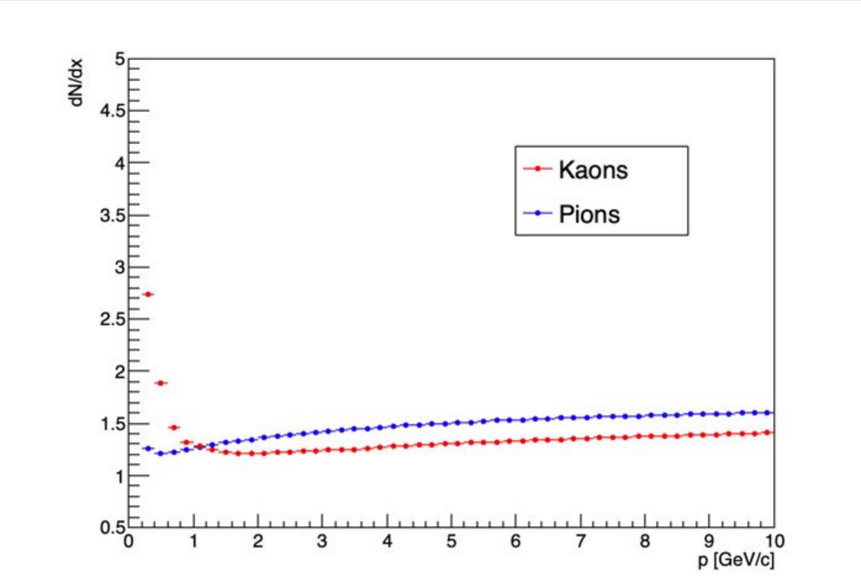
Kaon



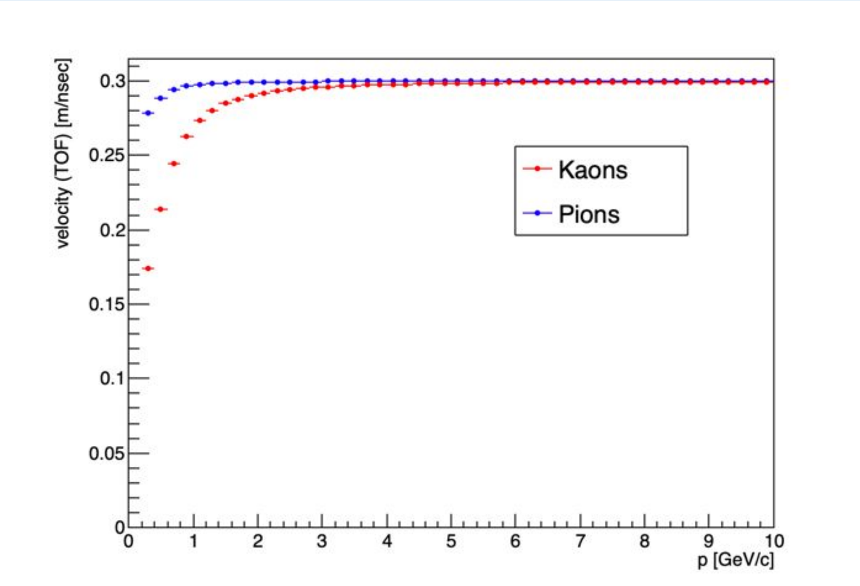
The bachelor kaon and bachelor pion are selected using the D_sK and $D_s\pi$ samples

Inclusive PID studies with D_sK and $D_s\pi$

dN/dx

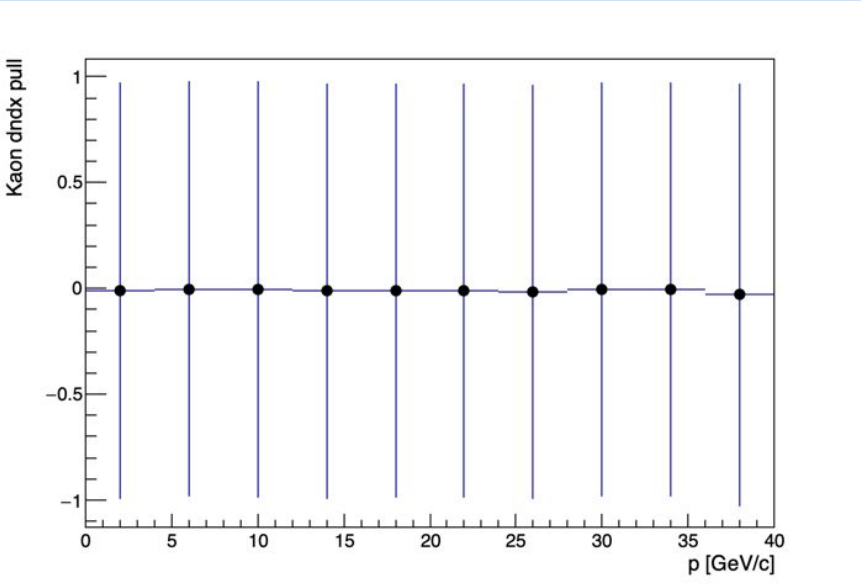


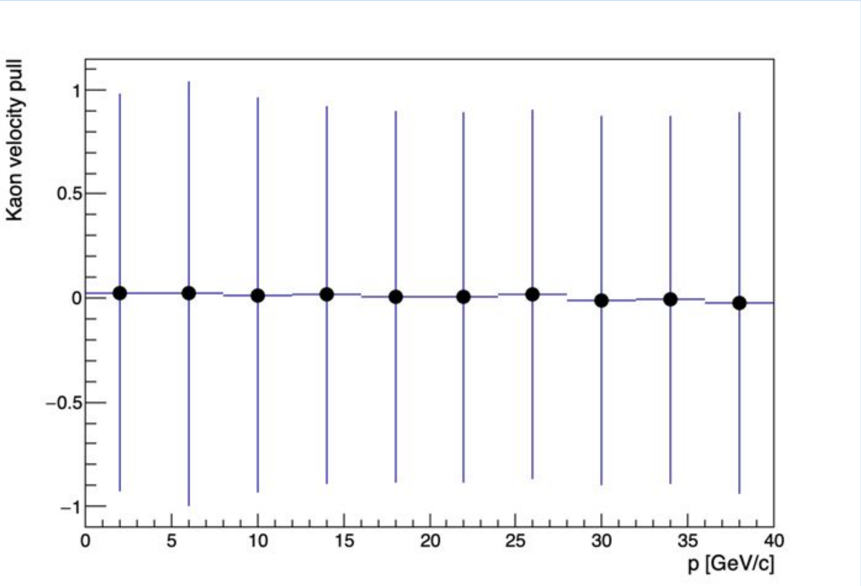
velocity



- dN/dx is being used instead of dE/dx to avoid tuning the truncated mean to suppress Landau tails
- Velocity is being used instead of TOF to have an observable independent of detector geometry

Inclusive PID studies with $D_s K$ and $D_s \pi$



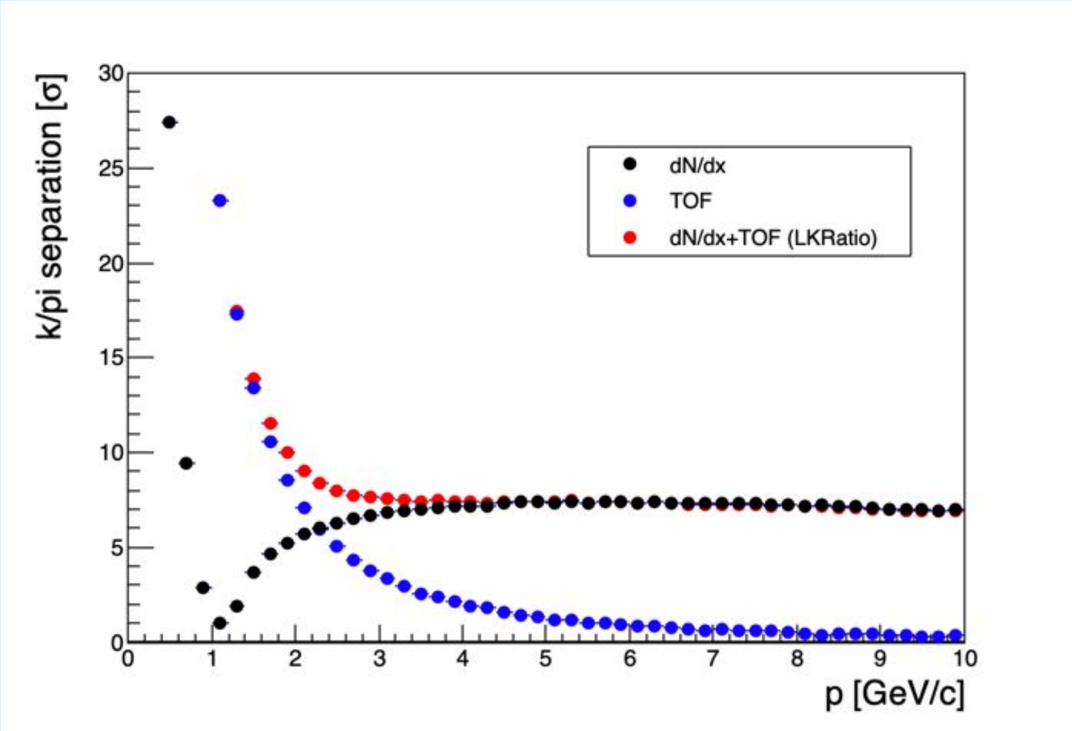


Pulls well under control for both variables

Inclusive PID studies with D_sK and $D_s\pi$

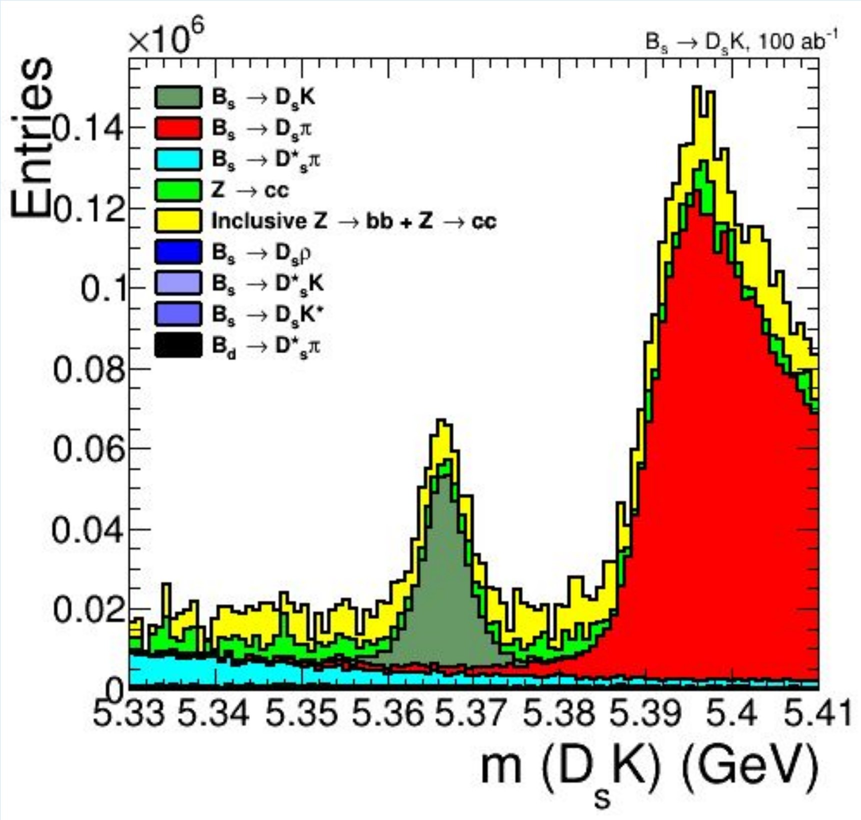
- K/π separation in dN/dx, velocity and combined approach
- The combined separation in terms of sigmas is obtained with

$$\text{Separation } [\sigma] = \sqrt{-2\ln(\text{LKRatio})}$$



$B_s \to D_s K$ analysis: mass spectrum without PID

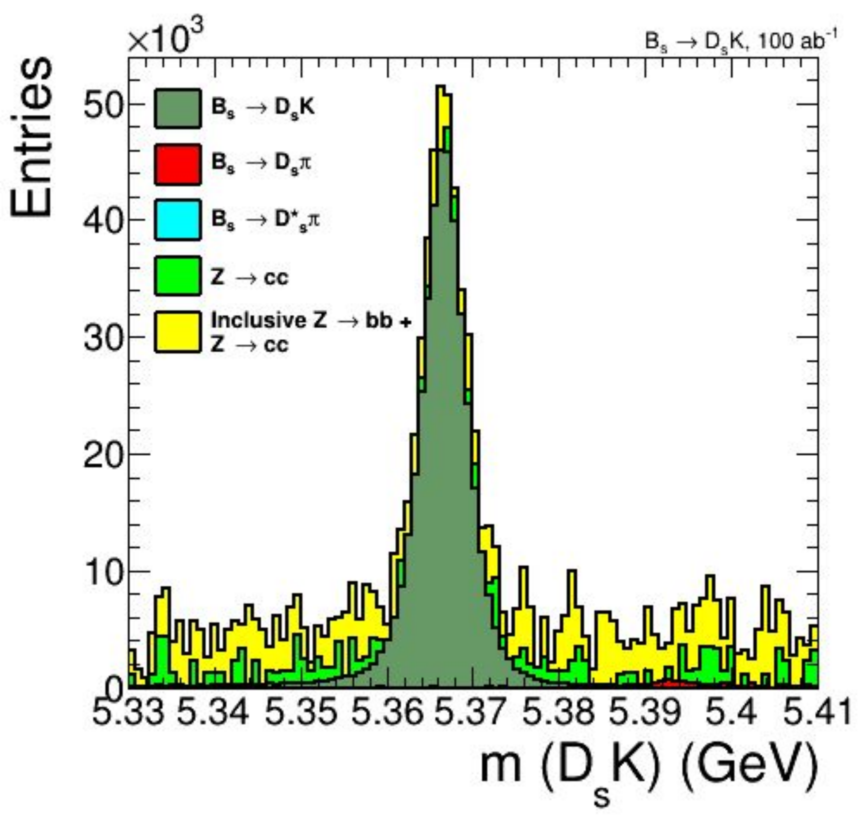
- Pre-selection based on Phi and D_s mass
- pT > 1.5 GeV for all tracks
- Vertex $\chi^2 < 5$
- cos(ϴ)_B_s - cos(ϴ)_bachelor < 0.5
- 5.33 GeV < m(B_s) < 5.41 GeV
- B/(S+B) defined in the region under the B_s peak



B/(S+B) = 48%

$B_s \to D_s K$ analysis: mass spectrum with dN/dx LR

- Pre-selection based on Phi and D_s mass
- pT > 1.5 GeV for all tracks
- Vertex χ^2 < 5
- cos(ϴ)_B_s - cos(ϴ)_bachelor < 0.5
- 5.33 GeV < m(B_s) < 5.41 GeV
- B/(S+B) defined in the region under the B_s peak



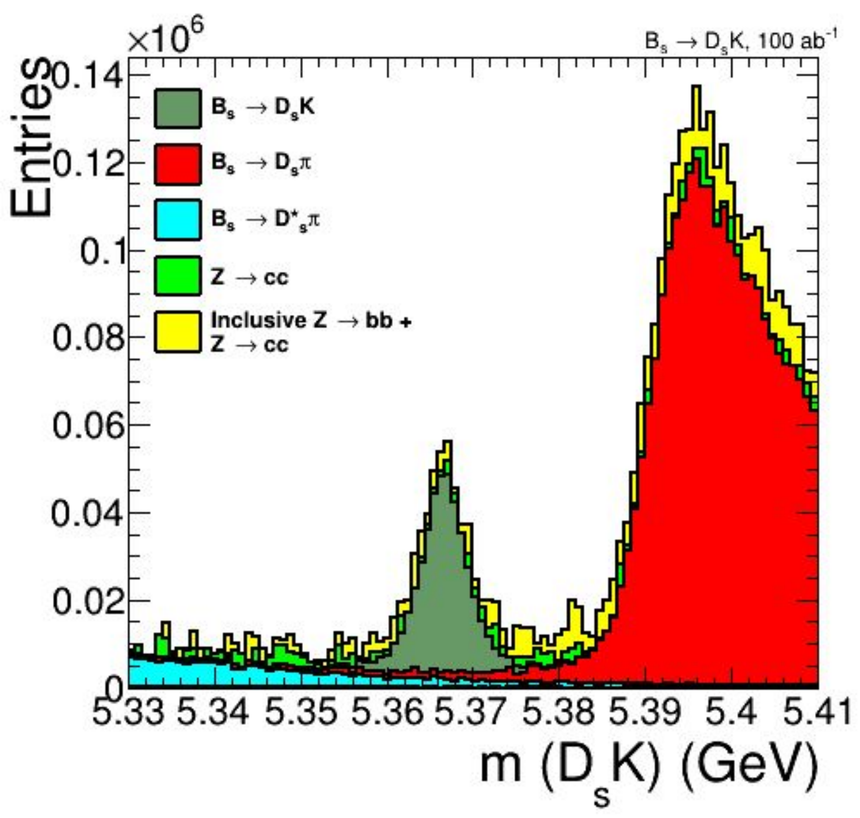
B/(S+B) = 19%

$D_s\pi$ efficiency = 0.27%

$B_s \to D_s K$ analysis: mass spectrum with velocity LR

- Pre-selection based on Phi and D_s mass
- pT > 1.5 GeV for all tracks
- Vertex $\chi^2 < 5$
- cos(Θ)_B_s - cos(Θ)_bachelor < 0.5
- 5.33 GeV < m(B_s) < 5.41 GeV
- B/(S+B) defined in the region under the B_s peak

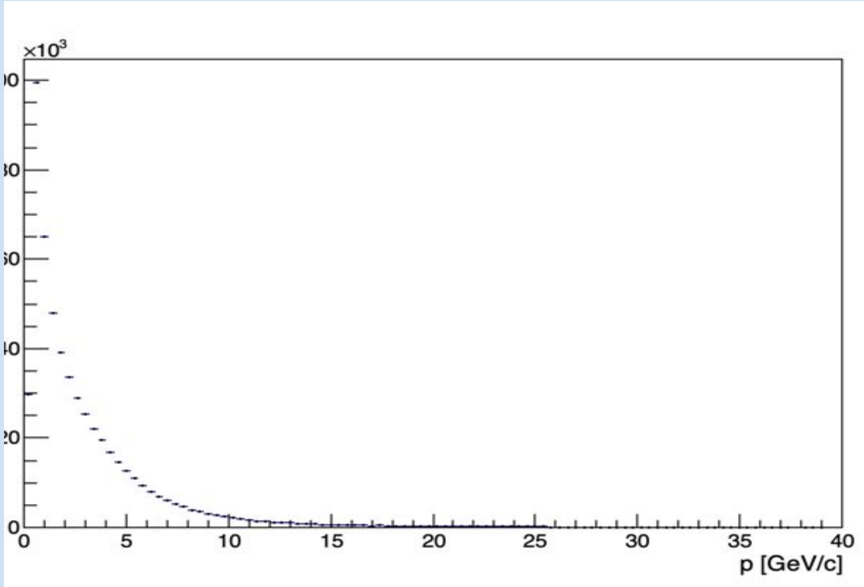
B/(S+B) = 33%



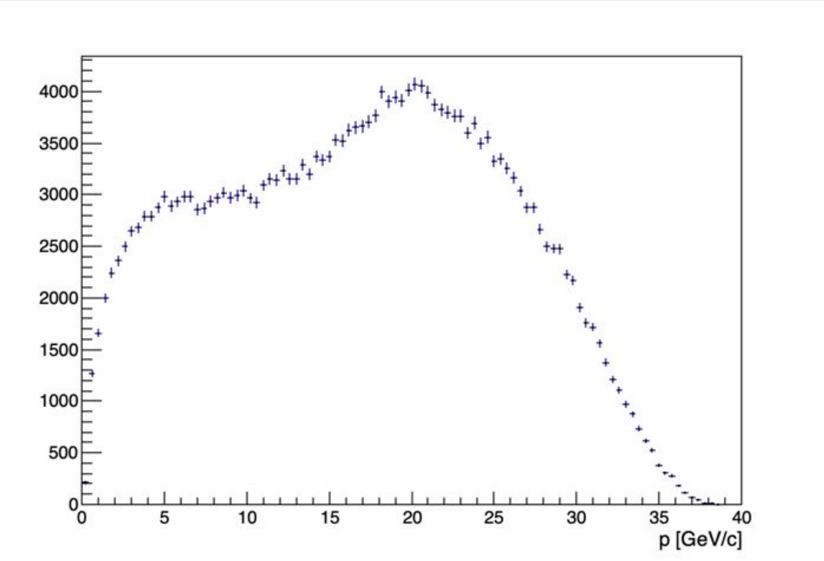
Focus on LR with velocity

- Likelihood ratio based on velocity has very low impact on signal but still reduces the inclusive Z⟶bb background by a factor of 2
- Directly related to the bachelor momentum spectrum in the two samples and the momentum-dependent PID performance with velocity

Z⟶bb

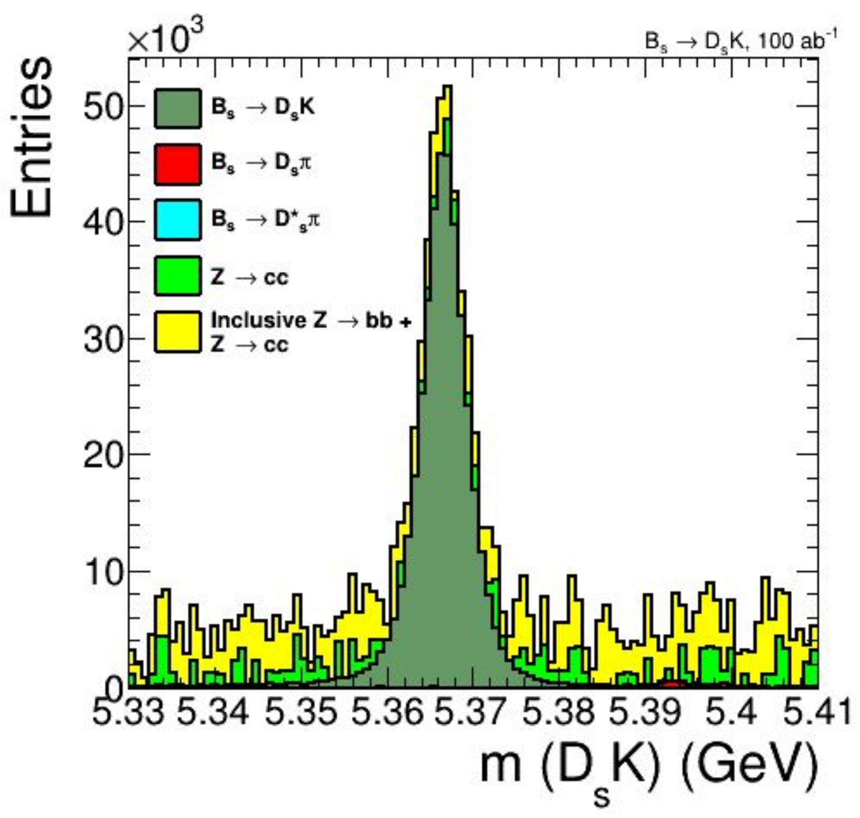


$D_s K + D_s \pi$



$B_s \rightarrow D_s K$ analysis: mass spectrum with combined likelihood

- Pre-selection based on Phi and D_s mass
- pT > 1.5 GeV for all tracks
- Vertex $\chi^2 < 5$
- cos(ϴ)_B_s - cos(ϴ)_bachelor < 0.5
- 5.33 GeV < m(B_s) < 5.41 GeV
- B/(S+B) defined in the region under the B_s peak



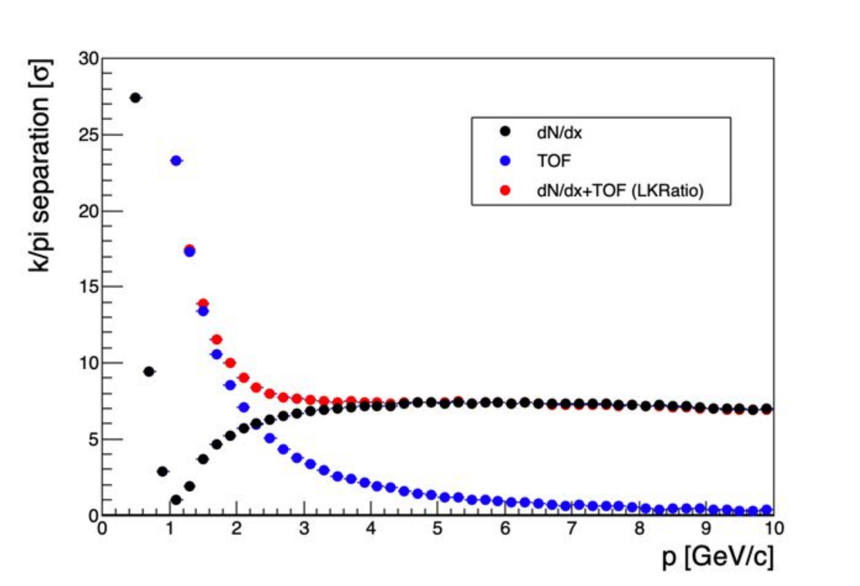
<u>B/(S+B) = 19%</u>

<u>$D_s\pi$ efficiency = 0.22%</u>

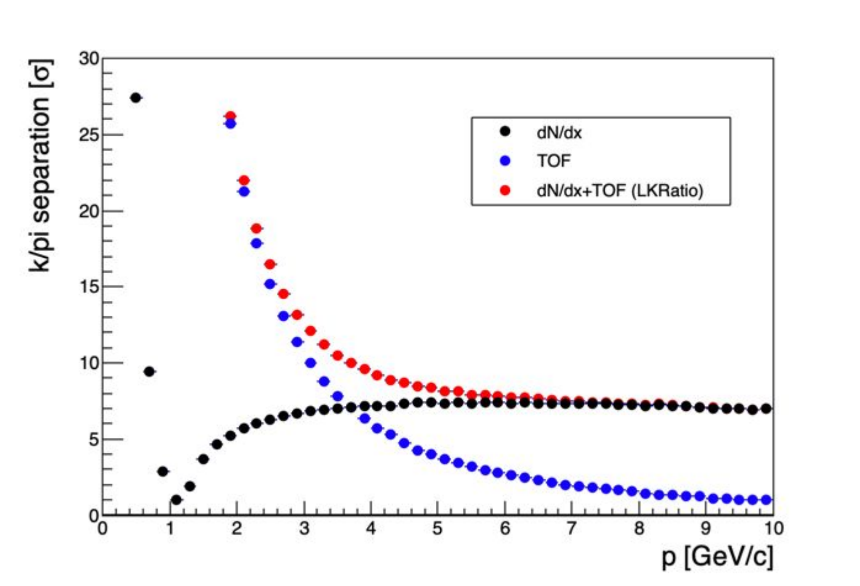
As proven in previous slide, the PID based on combined likelihood is only marginally improving over dN/dx because of the bachelor momentum

TOF resolution

Standard – 30 ps

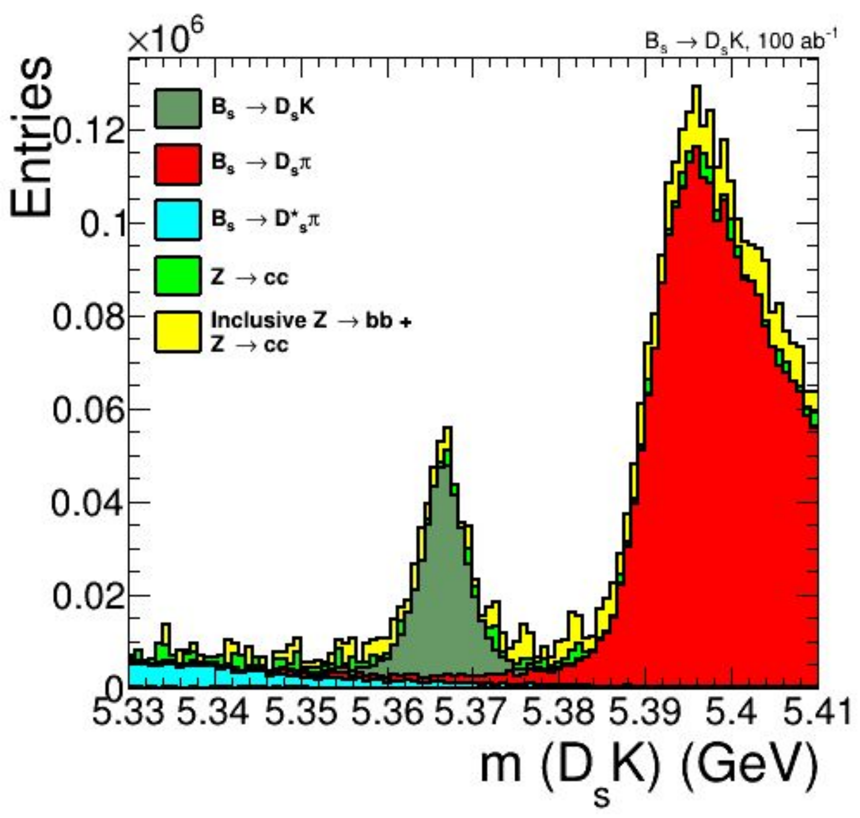


Improved – 10 ps



Away from nominal IDEA: 10 ps TOF resolution

- Pre-selection based on Phi and D_s mass
- pT > 1.5 GeV for all tracks
- Vertex $\chi^2 < 5$
- cos(ϴ)_B_s - cos(ϴ)_bachelor < 0.5
- 5.33 GeV < m(B_s) < 5.41 GeV
- B/(S+B) defined in the region under the B_s peak

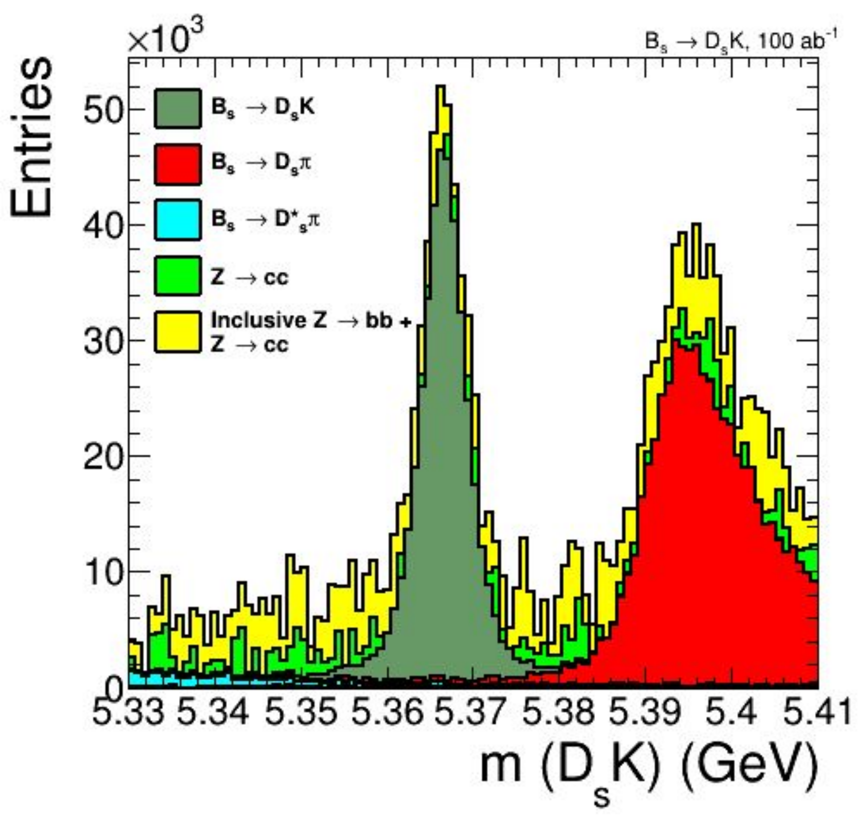


B/(S+B) = 29%

With 30 ps TOF resolution B/(S+B) = 33%

Away from nominal IDEA: x2 dN/dx worse resolution

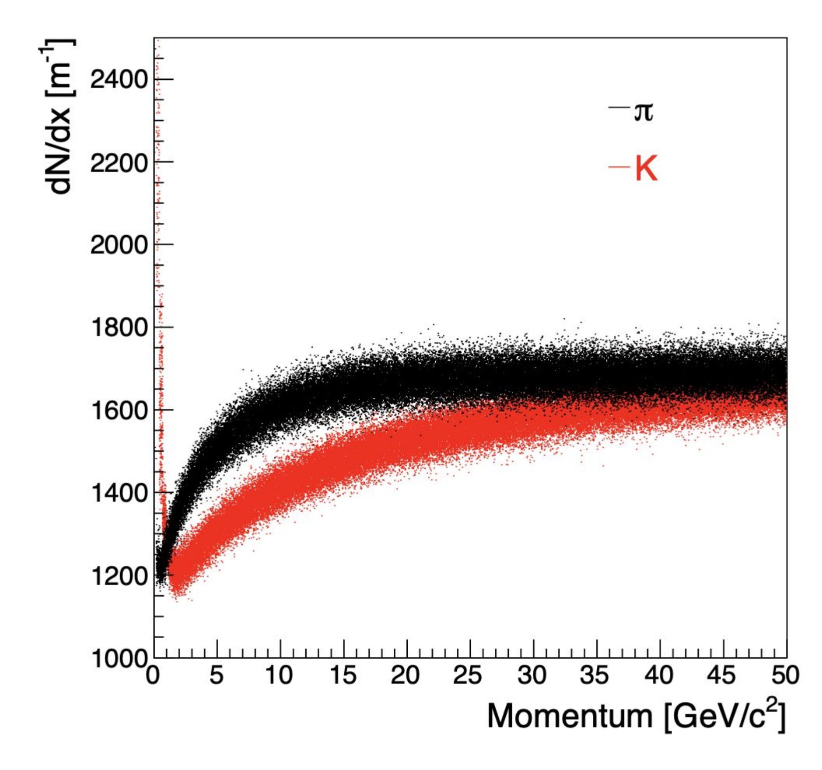
- Pre-selection based on Phi and D_s mass
- pT > 1.5 GeV for all tracks
- Vertex $\chi^2 < 5$
- cos(Θ)_B_s - cos(Θ)_bachelor < 0.5
- 5.33 GeV < m(B_s) < 5.41 GeV
- B/(S+B) defined in the region under the B_s peak

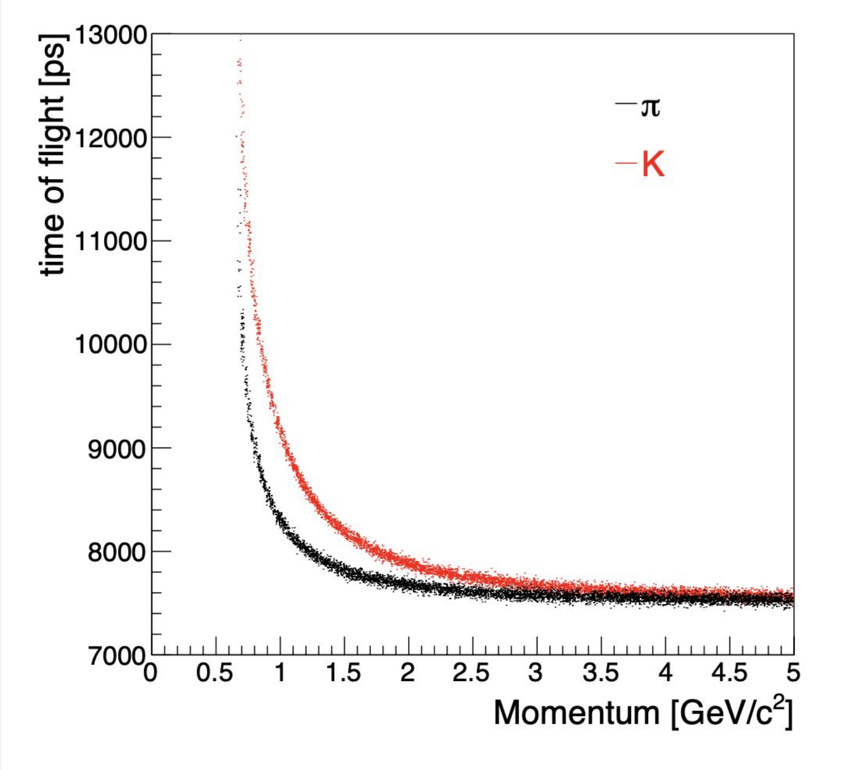


B/(S+B) = 24%

With baseline dN/dx resolution B/(S+B) = 19%

PID studies with ZH





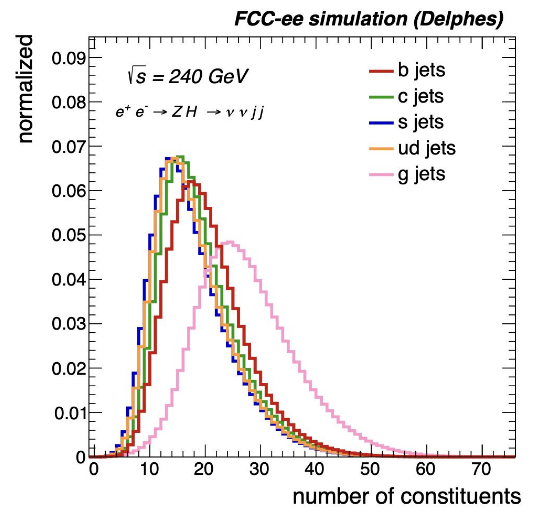
Charged pion and kaon tracks at θ = 90° in the IDEA drift chamber detector

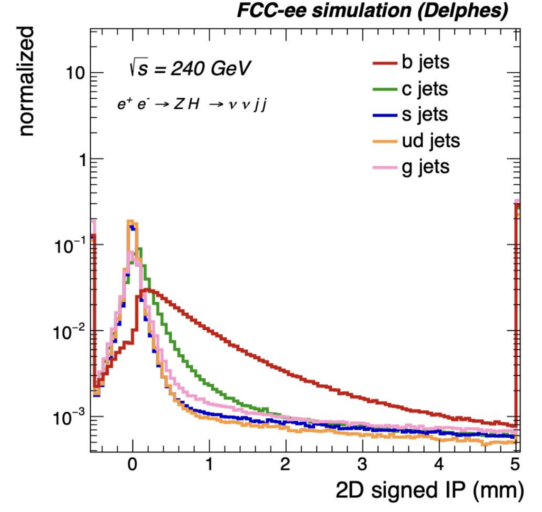
[Eur. Phys. J. C 82 (2022) 7, 646]

Jet flavour tagging with PID information

Variable	Description
Kinematics	
$E_{\text{const}}/E_{\text{jet}}$	energy of the jet constituent divided by the jet energy
θ_{rel}	polar angle of the constituent with respect to the jet momentum
ϕ_{rel}	azimuthal angle of the constituent with respect to the jet momentum
Displacement	
d_{xy}	transverse impact parameter of the track
d_z	longitudinal impact parameter of the track
$\text{SIP}_{2\text{D}}$	signed 2D impact parameter of the track
$\text{SIP}_{2\text{D}}/\sigma_{2\text{D}}$	signed 2D impact parameter significance of the track
$\text{SIP}_{3\text{D}}$	signed 3D impact parameter of the track
$\text{SIP}_{3\text{D}}/\sigma_{3\text{D}}$	signed 3D impact parameter significance of the track
$d_{3\text{D}}$	jet track distance at their point of closest approach
$d_{3\text{D}}/\sigma_{d_{3\text{D}}}$	jet track distance significance at their point of closest approach
C_{ij}	covariance matrix of the track parameters
Identification	
q	electric charge of the particle
$m_{\text{t.o.f.}}$	mass calculated from time-of-flight
dN/dx	number of primary ionisation clusters along track
`isMuon`	if the particle is identified as a muon
`isElectron`	if the particle is identified as an electron
`isPhoton`	if the particle is identified as a photon
`isChargedHadron`	if the particle is identified as a charged hadron
`isNeutralHadron`	if the particle is identified as a neutral hadron

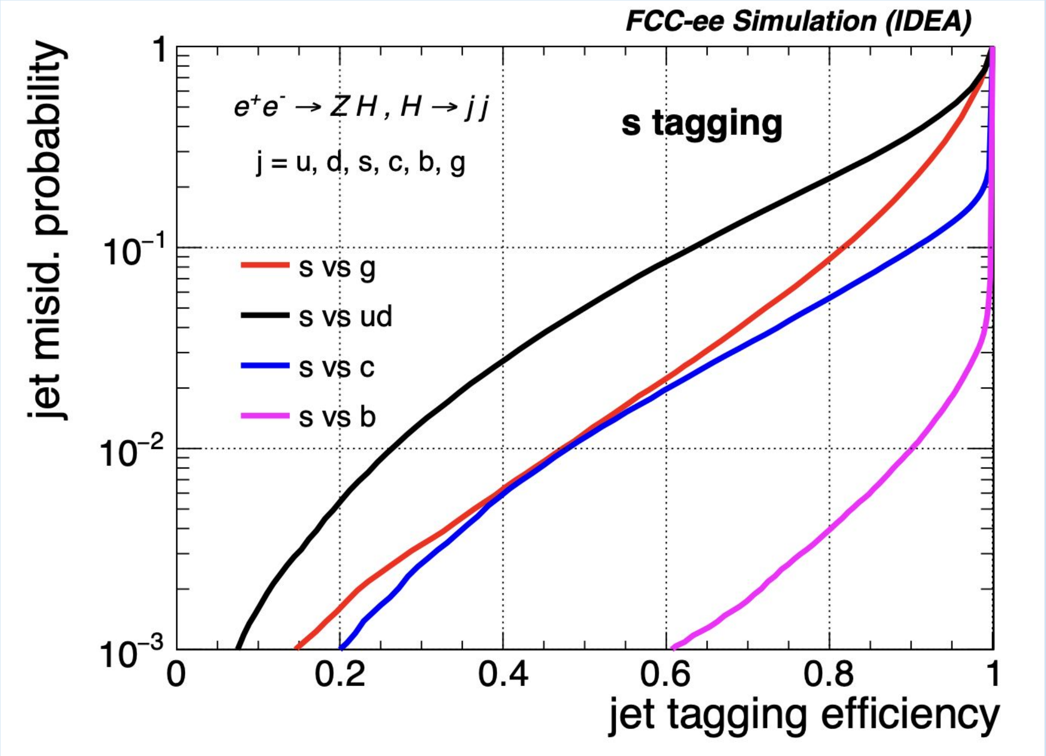
[Eur. Phys. J. C 82 (2022) 7, 646]





Jet flavour tagging with PID information

- Architecture based on GNN as in the ParticleNet tagging algorithm – Phys. Rev. D 101 056019
- Most effective discrimination against b-jets
- Mis-tag rate against ud and g substantially larger
- Rejection against g more effective due to higher particle multiplicities
- PID-related variables playing a crucial role for s-jet tagging

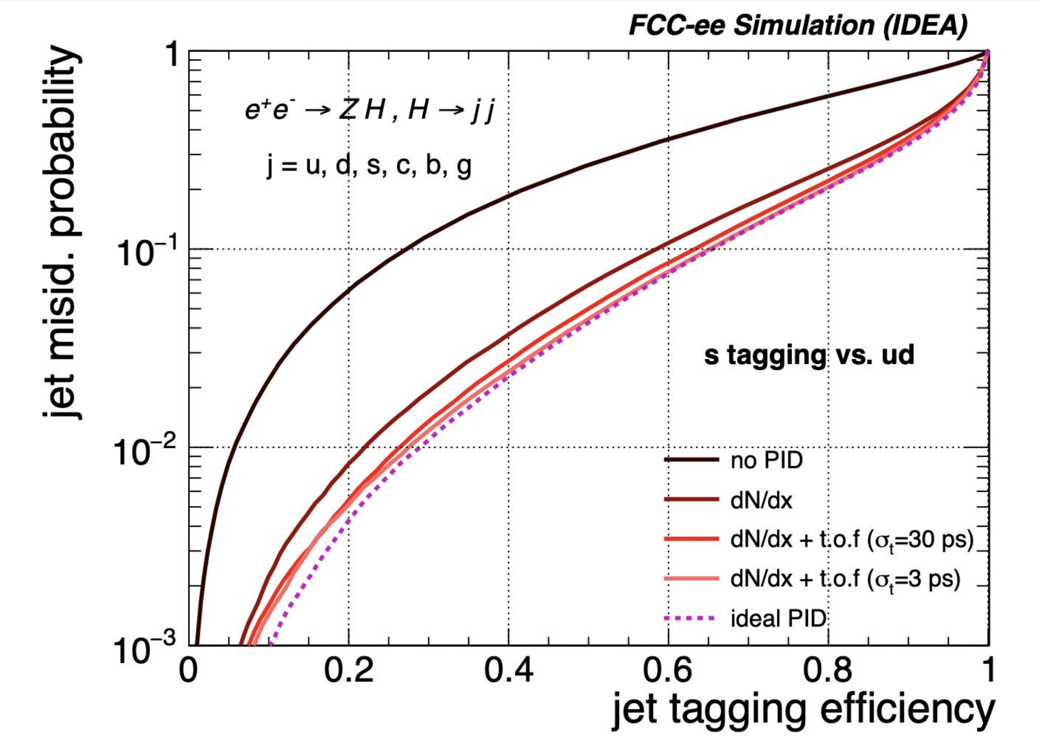


[Eur. Phys. J. C 82 (2022) 7, 646]

Jet flavour tagging with PID information

- PID yields one order of magnitude of reduced mis-tag rate
- PID with a 3 ps resolution yields some additional improvement, close to the ideal PID case obtained by using MC truth information

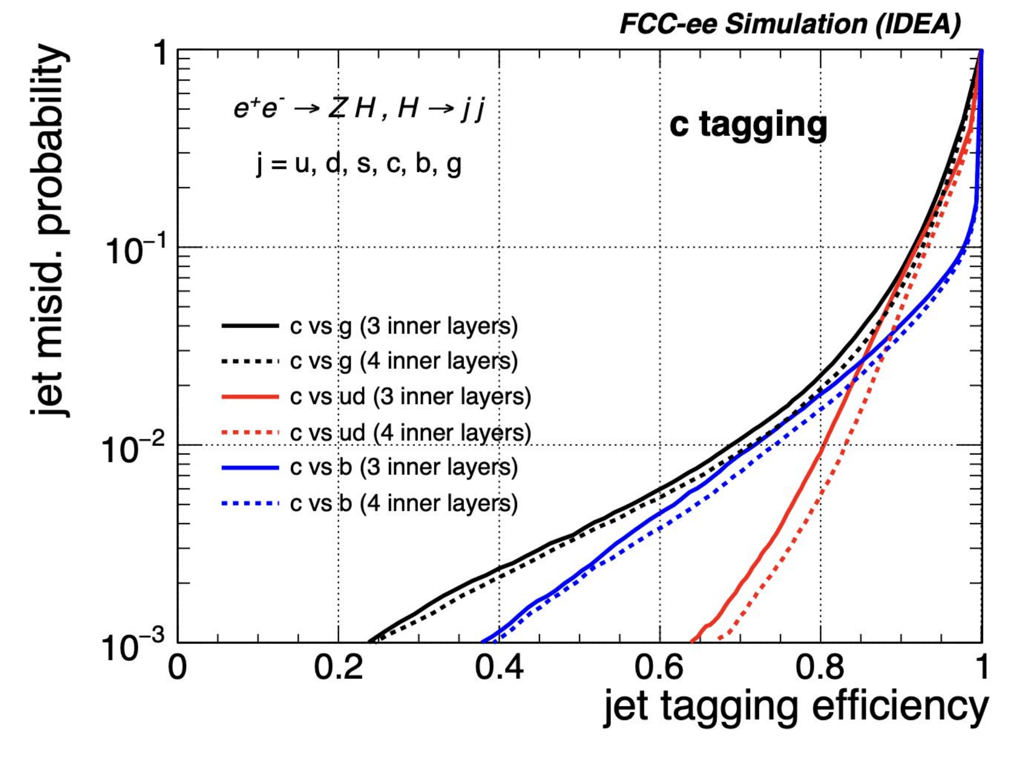
Great example of detector design choice on observable of interests for physics analyses



[Eur. Phys. J. C 82 (2022) 7, 646]

Jet flavour tagging with PID information

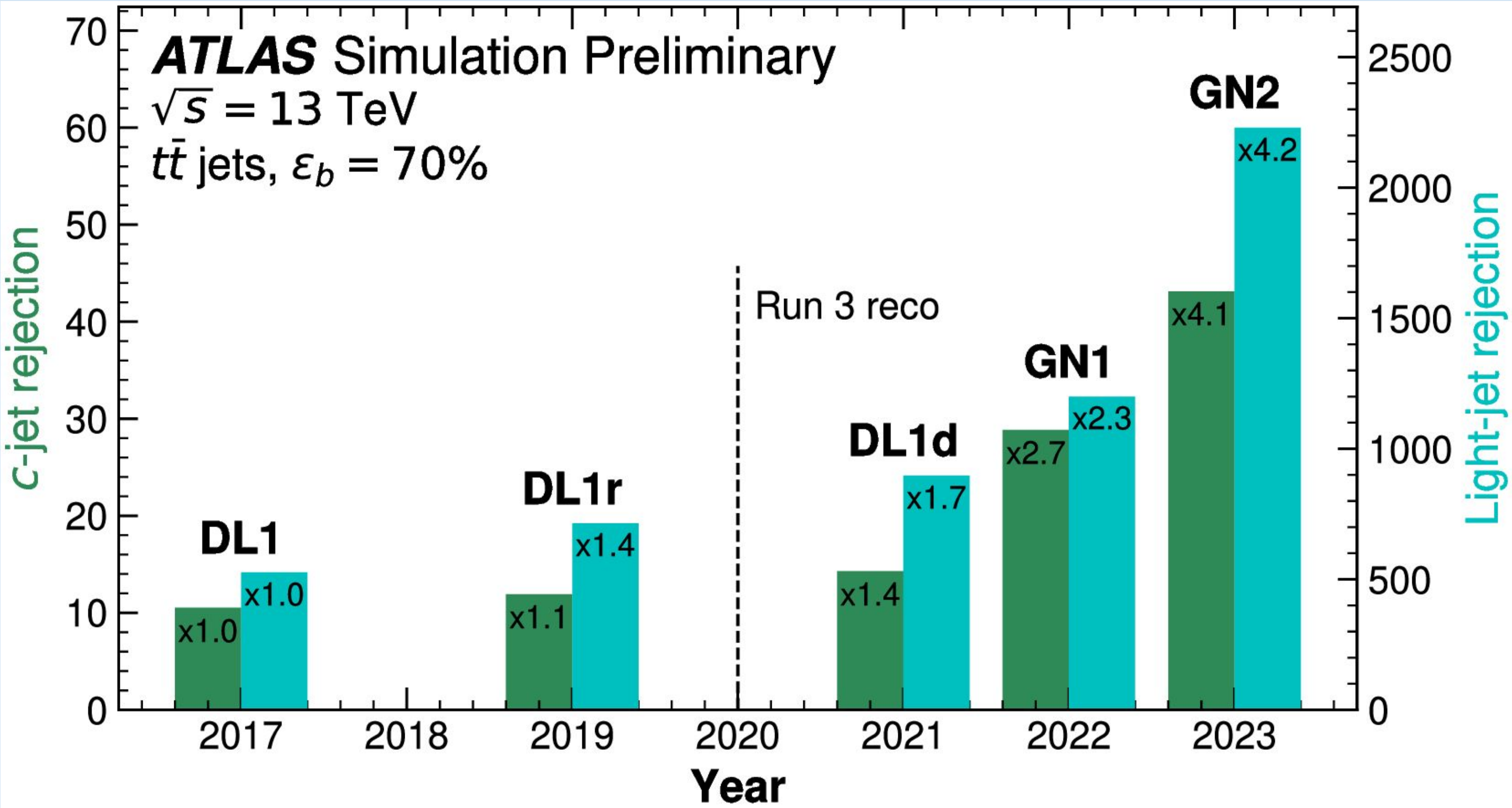
- Impact on flavour tagging by introducing an additional fourth layer at 1 cm from the interaction point



Great example of detector design choice on observable of interests for physics analyses

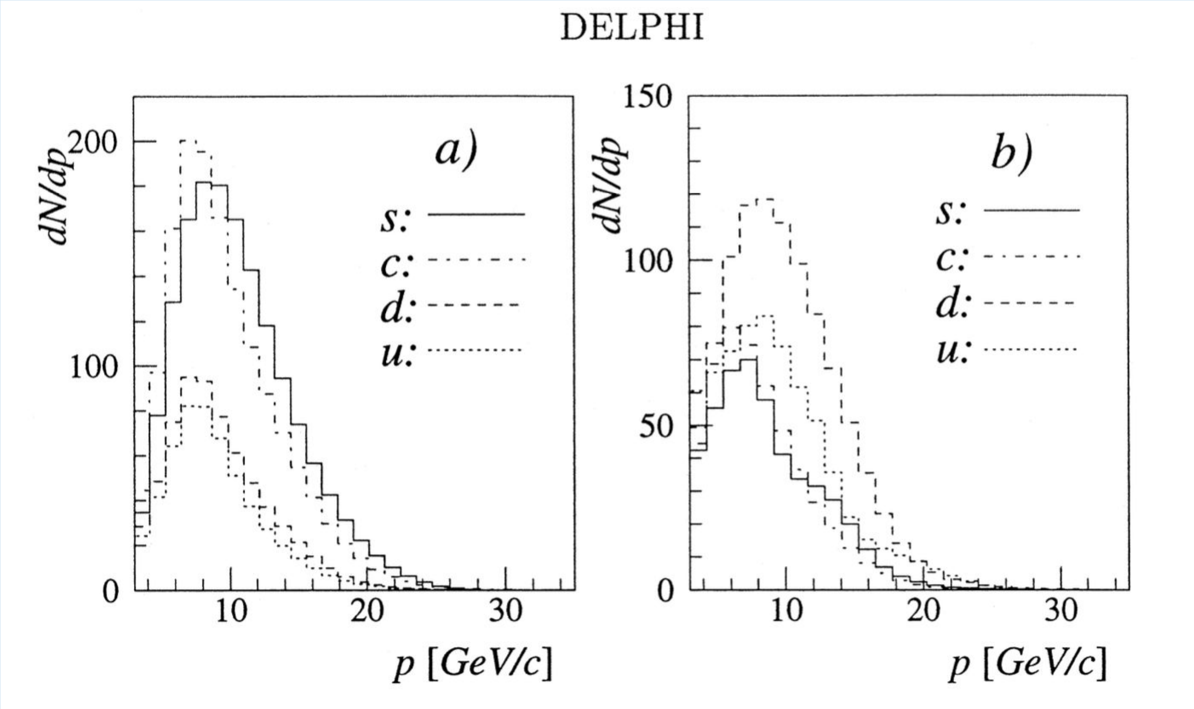
[Eur. Phys. J. C 82 (2022) 7, 646]

Interlude on jet flavour classification



[ATLAS-FTAG-2023-01]

Impact of strange tagging on physics analyses – V_{cs}



Momentum distribution of highest-momentum particle in s, c, d u-jets when particles are charged kaons, on the left, or charged pions, on the right

[Phys. Lett. B 439 (1998) 209-224]

Impact of strange tagging on physics analyses – V_{cs}

With ~100 W bosons collected, two measurements based on hadronic branching ratios and tagging the jet flavour with also PID from RICH counters of $|V_{cs}|$ were performed by DELPHI

$$BR(W \to \text{hadrons}) = 0.660^{+0.036}_{-0.037}(\text{stat}) \pm 0.009(\text{syst})$$

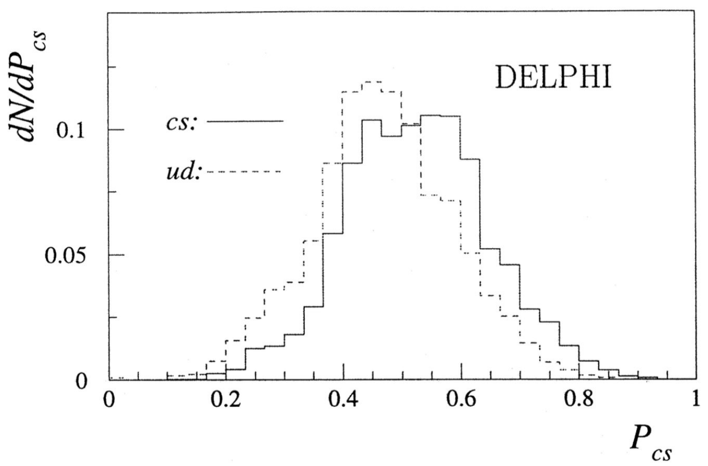
$$|V_{cs}| = 0.90 \pm 0.17(\text{stat}) \pm 0.04(\text{syst})$$

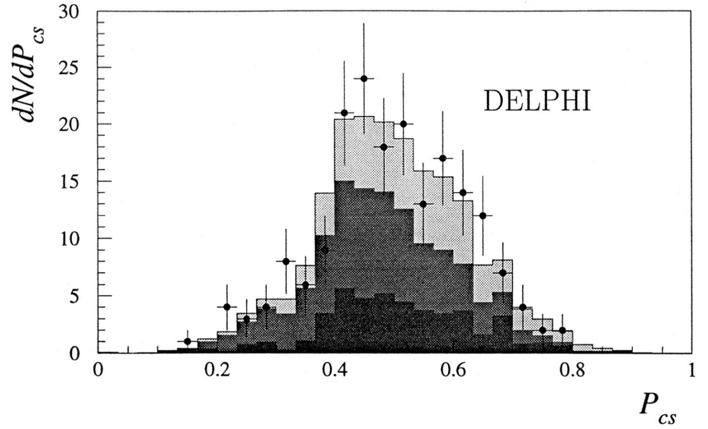
$$r^{(cs)} = \frac{\Gamma(W^+ \to c\bar{s})}{\Gamma(W^+ \to \text{hadrons})} = 0.46^{+0.18}_{-0.14}(\text{stat}) \pm 0.07(\text{syst})$$

$$|V_{cs}| = 0.94^{+0.32}_{-0.26}(\text{stat}) \pm 0.13(\text{syst})$$

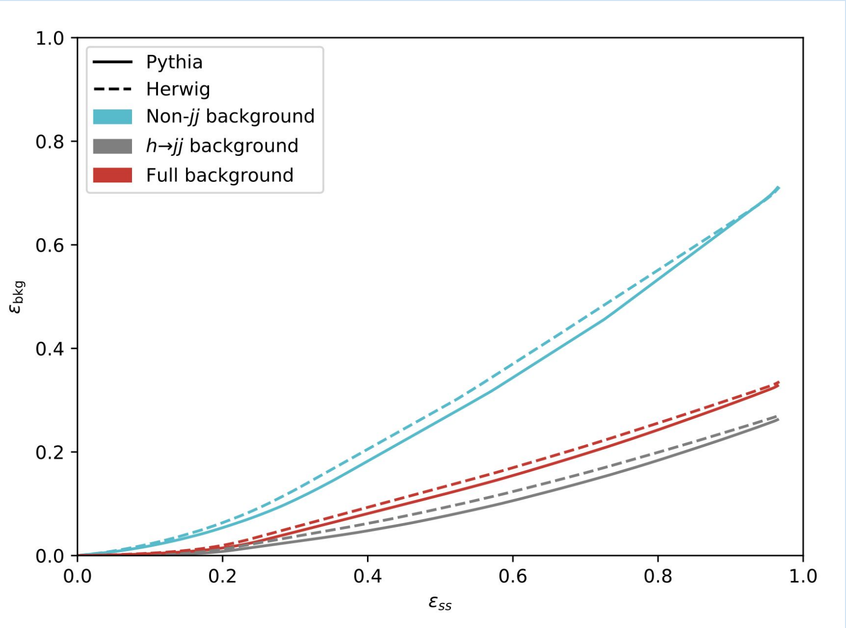
The former measurement comes with more assumptions, the latter could be substantially improved with larger-statistics tagger calibration at the Z pole

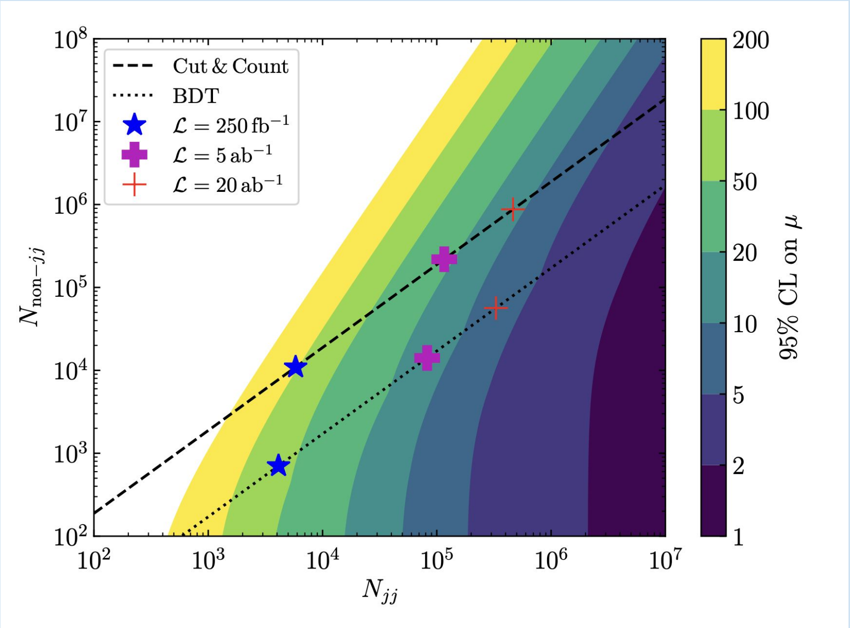
[Phys. Lett. B 439 (1998) 209-224]





Impact of strange tagging on physics analyses – H → ss



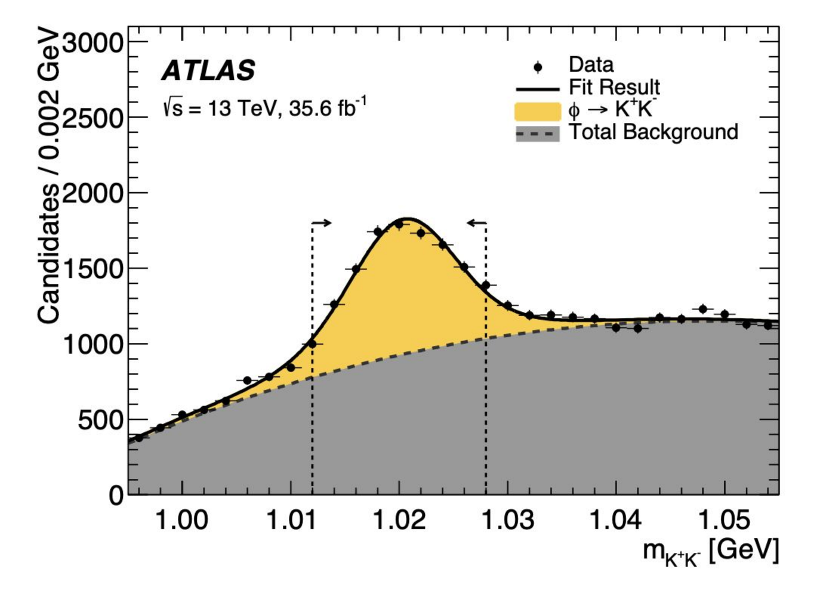


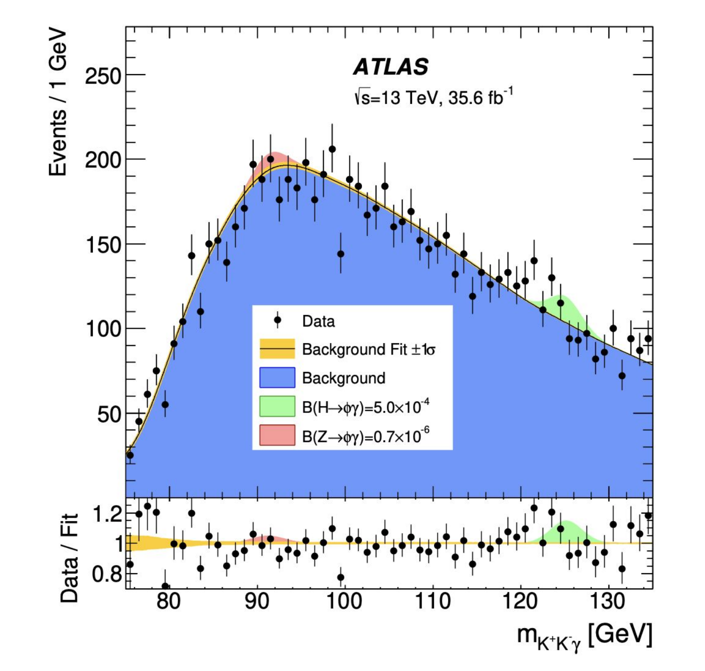
$$J_F = \frac{\sum_H \mathbf{p}_H \cdot \hat{\mathbf{s}}\, R_H}{\sum_H \mathbf{p}_H \cdot \hat{\mathbf{s}}}$$

Colour contours represent the best limit on signal strength μ for the process H → ss after applying a strange-jet tagger based on a jet-flavour variable plus PID from the simulated IDEA drift chamber

[Phys. Rev. D 101 115005]

Impact of strange tagging on physics analyses – H → ϕγ





BRs as predicted by the SM

$$\mathcal{B}(H \to \phi\gamma) = (2.31 \pm 0.11) \times 10^{-6}$$
$$\mathcal{B}(H \to \rho\gamma) = (1.68 \pm 0.08) \times 10^{-5}$$

Measurement by ATLAS

$$\mathcal{B}(H \to \phi\gamma) < 5.0 \times 10^{-4}$$
$$\mathcal{B}(H \to \rho\gamma) < 10.4 \times 10^{-4}$$

[JHEP 07 (2018) 127]

Conclusions and Outlook

IDEA detector is in Delphes with PID-related variables. Allows studies on performance, expected physics reach, and back to detector layout optimisation and technology choices.

Some literature on the topic exist and something new has been included in the FCC mid-term report. Much more is obviously possible and welcome.

Full potential of strange-flavour tagging at a future circular lepton collider to be studied. In addition, ML architectures for jet flavour classification still evolving.

More methods to be developed and studied such as

- Estimate of systematic uncertainties to strange-flavour tagging
- Reconstruction of in-flight decays
- Holistic tagging including beauty, charm, tau and strange, with impact from gluon spitting
- Complementarity of PID techniques for charged hadron identification