Recent Results in Charm Physics at LHCb

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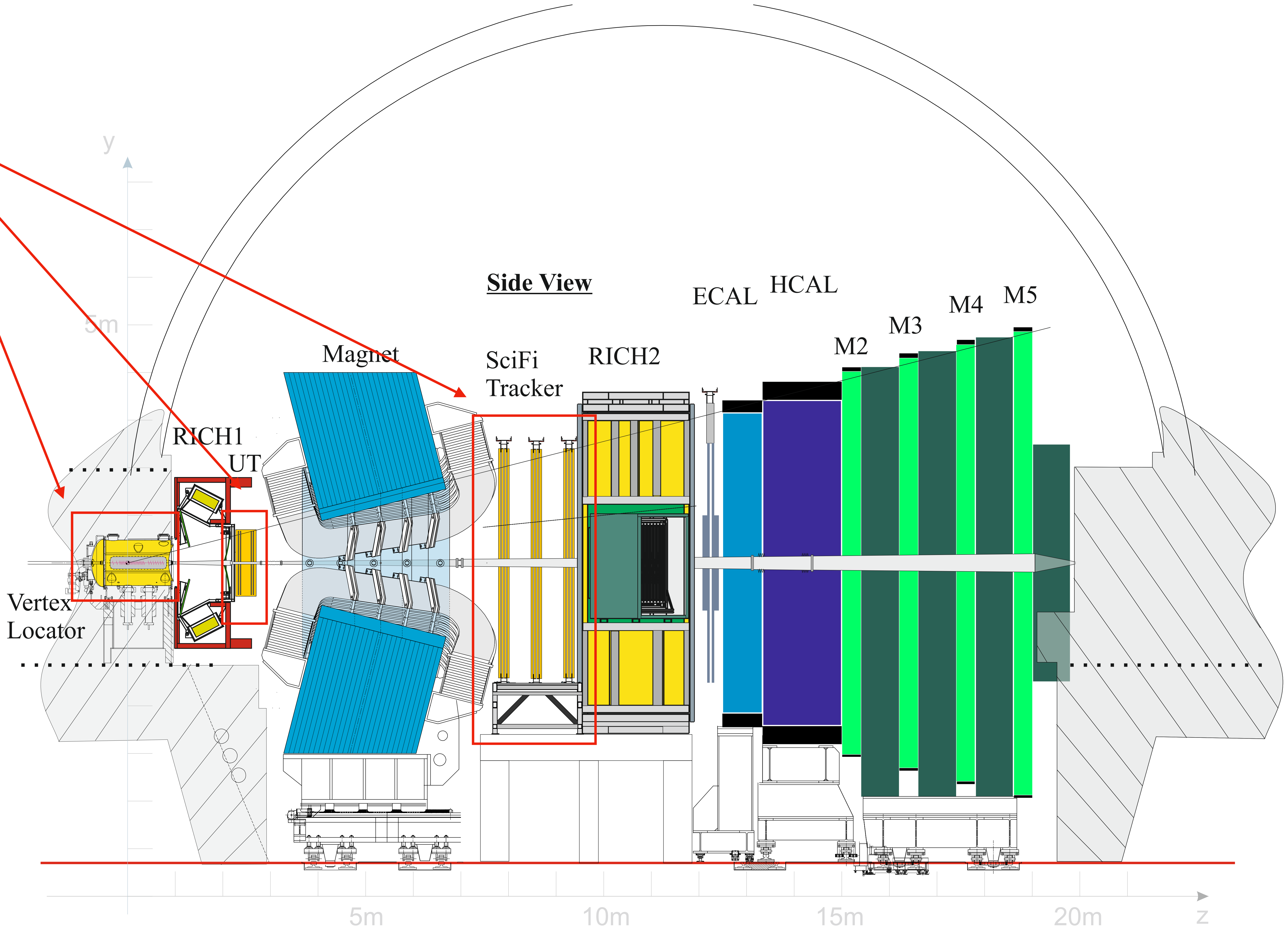
LHCb in Run 3

[JINST 19 (2024) P05065]

- In Run 3, pile-up increased of a factor ~5
- New trackers (UT not present in 2022, not active in 2023)
- Upgraded RICH optics, photodetectors and readout system
- Upgraded calorimeter and muon chamber electronics
- Removal of L0 hardware trigger, particularly important as it was one of the main source of systematic uncertainty for several analyses
- Full software trigger
  - GPU-based reconstruction
  - Readout of the full detector for each pp collision
- Centre-of-mass energy $\sqrt{s} = 13.6$ TeV



Measurements of charmed meson and antimeson production asymmetry at $\sqrt{s} = 13.6\ \text{TeV}$

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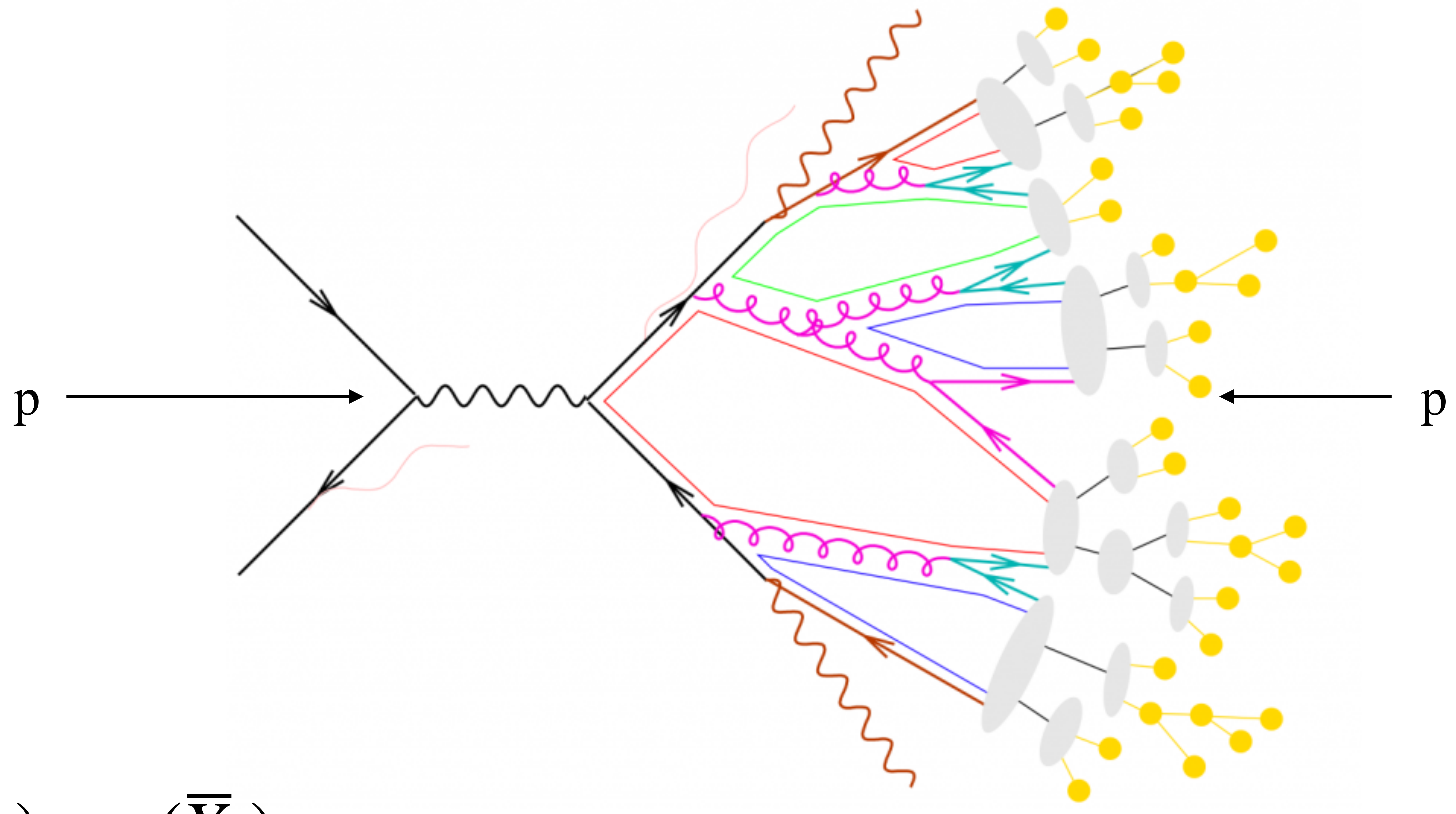
Charm production asymmetries

- In pp collisions $c - \bar{c}$ quark are produced in pairs
- But hadronisation into hadrons and anti-hadrons is not symmetrical due to proton valence quarks
- Various theoretical frameworks describe this process such as Lund string model, cluster-hadronisation mode, meson-cloud model and heavy-quark recombination.
- Simulation generators cannot predict precisely the hadronisation process. Charm production asymmetries can help constrain available models



$$A_P(X_c) = \frac{\sigma(X_c) - \sigma(\overline{X}_c)}{\sigma(X_c) + \sigma(\overline{X}_c)}$$

Goal of the analysis

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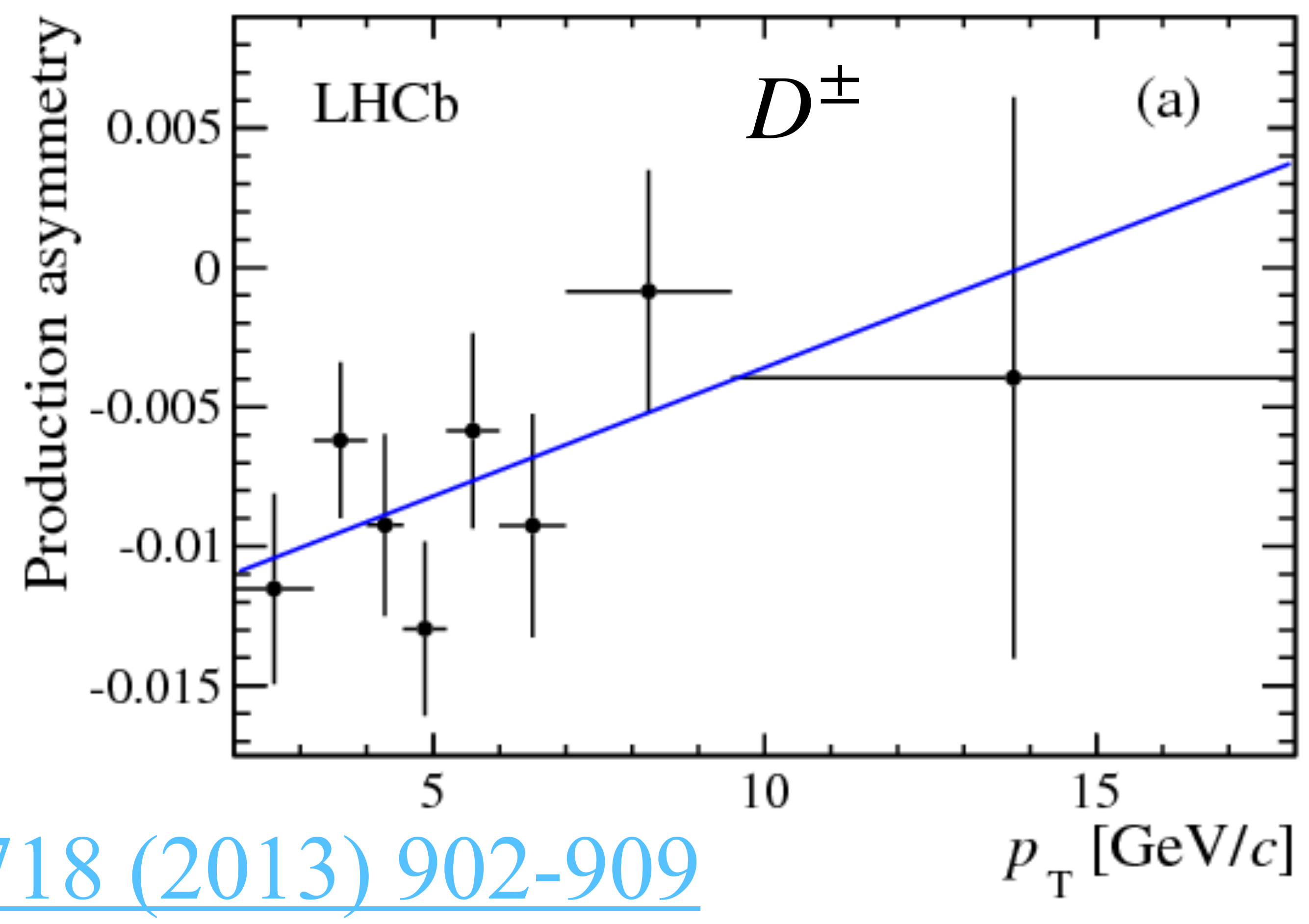
- Measure double differential production asymmetries for D^0, D^+ and D_s^+ as function of η, p_T
- Data collected in 2022 ($15\ \mathrm{pb}^{-1}$) and 2023 ($162\ \mathrm{pb}^{-1}$ for D^0 and $41\ \mathrm{pb}^{-1}$ for $D^+_{(s)}$) with upgraded LHCb detector
- Previous measurements:
  - Run 1 measurement of $D^\pm$ production asymmetry at $7\ \mathrm{TeV}$ [Phys. Lett. B 718 (2013) 902-909]

$$A_P(D^+) = (-0.96 \pm 0.26_{(stat)} \pm 0.18_{(syst)})\ \%$$

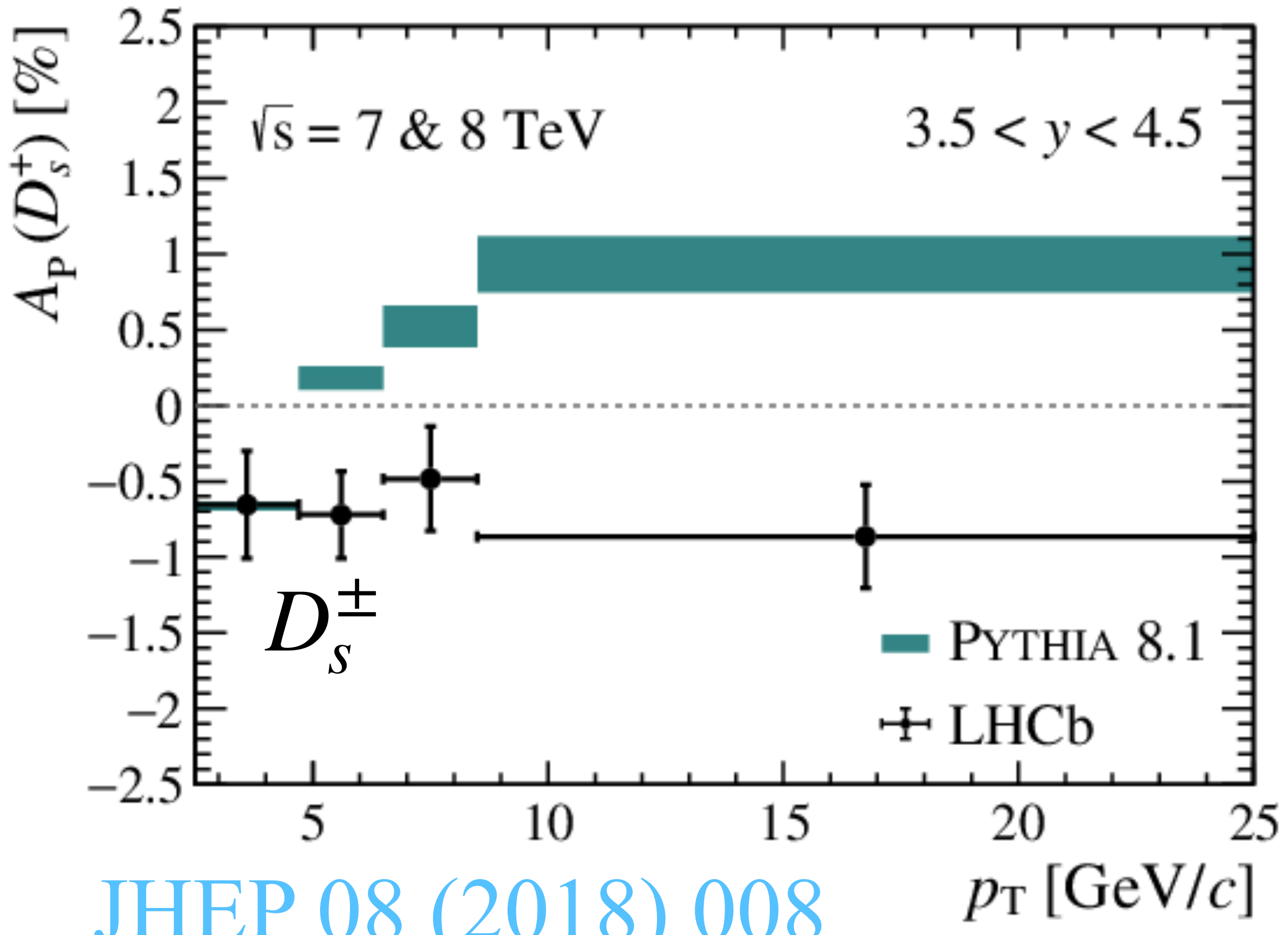
  - Run 1 measurement of the $D_s^\pm$ production asymmetry at $\sqrt{s} = 7$ and 8 TeV [JHEP 08 (2018) 008]

$$A_P(D_s^+) = (-0.52 \pm 0.13_{(stat)} \pm 0.10_{(syst)})\ \%$$

- Production asymmetry expected to depend on $\sqrt{s}, \eta, p_T$



Phys. Lett. B 718 (2013) 902-909



JHEP 08 (2018) 008

Strategy of the analysis

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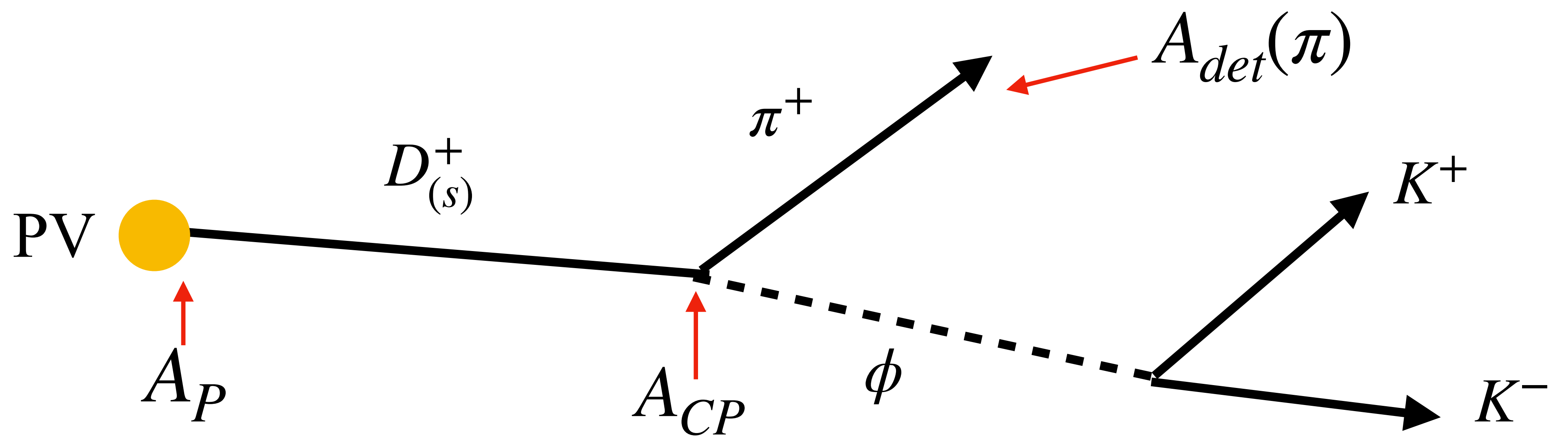
Raw asymmetries defined as $A_{raw} = \dfrac{N(X_c) - N(\overline{X}_c)}{N(X_c) + N(\overline{X}_c)}$ extracted from simultaneous fit to data

Production asymmetries extracted from $A_{raw}(X_c \to f) = (1 - f_{sec})A_P(X_c) + f_{sec}A_{sec}(X_c) + A_{CP}(X_c \to f) + A_{det}(f)$



$D^+_{(s)}$

- Decays of interest: $D^+_{(s)} \to \phi(1020)\pi^+$ with $\phi \to K^+K^-$
- $A_{det}(\pi)$ receives contributions from PID and reconstruction asymmetry
- $A_{PID}(\pi)$ extracted from $D^{*+}(2010) \to D^0\pi^+$ with $D^0 \to K^-\pi^+$ without PID requirements
- $A_{rec}(\pi)$ extracted with tag-and-probe method with $K^0_s \to \pi^+\pi^-$
- $A_{CP}(D^+ \to \phi\pi^+) = (0.05 \pm 0.42_{(stat)} \pm 0.29_{(syst)}) \times 10^{-3}$ from Run2

D^0

- Decay of interest: prompt $D^0 \to K^-\pi^+$
- $A_{det}(K\pi) = \quad A_{raw}(D^{*+} \to D^0(\to K^-\pi^+)\pi^+) +$
  $-A_{raw}(D^{*+} \to D^0(\to K^-K^+)\pi^+) +$
  $+A_{CP}(D^0 \to K^-K^+)$
- $A_{CP}(D^0 \to K^-K^+) = (6.8 \pm 5.4_{(stat)} \pm 1.6_{(syst)}) \times 10^{-4}$ from Run 2

After the selection of data, kinematic weights are applied to ensure asymmetries cancellation, and for each charmed meson and for each kinematic bin, asymmetries are extracted with simultaneous fits to both meson-anti meson invariant mass distributions

Results and Comparison with Monte Carlo generators

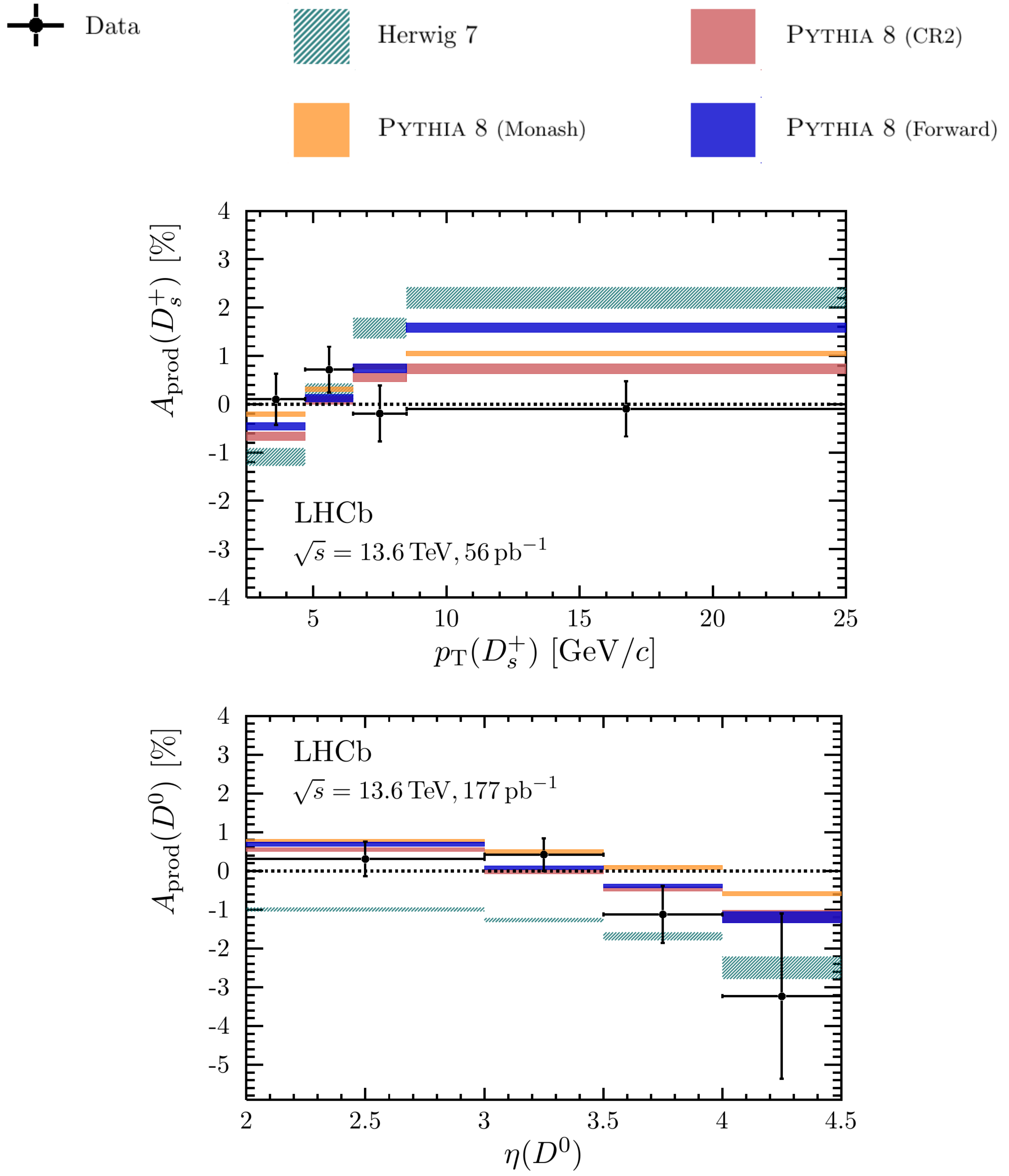
- No dependence of production asymmetry as functions of kinematics
- No evidence of production asymmetry for the phase-space integrated results:

$$A_P(D^0) = (0.07 \pm 0.26_{stat} \pm 0.10_{syst})\ \%$$

$$A_P(D^+) = (-0.33 \pm 0.29_{stat} \pm 0.14_{syst})\ \%$$

$$A_P(D_s^+) = (0.18 \pm 0.26_{stat} \pm 0.08_{syst})\ \%$$

- Integrated results compatible and with Run 1 results
- One dimensional projections show tensions in high and low p_T regions
- PYTHIA8 with color-reconnection tuning shows best agreement with experimental results
- These results have similar statistical uncertainty with respect to Run 1 but with a much lower integrated luminosity ($\sim 1/15$), thanks to the improved efficiency of the LHCb detector in Run 3
- This is the first measurement of LHCb with Run 3 data at a centre-of-mass energy of $\sqrt{s} = 13.6$ TeV



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2024 Data

Measurement of CP asymmetry in $D^0 \to K_S^0 K_S^0$ decays with the LHCb Upgrade I detector

[2510.14732] Submitted to JHEP

Motivation

[2510.14732] Submitted to JHEP

- Two body decay, analogous to $D^0 \to hh$, but tree diagram vanish in the SU(3) limit and only other possible diagram is penguin
- In the SM, possible enhancement of $A_{CP}(D^0 \to K^0_S K^0_S)$ up to $\mathcal{O}(1\%)$
- Complementary observable of $D^0 \to hh$ measurements
- Uncertainty on previous analysis with Run 2 data $A_{CP}(D^0 \to K^0_S K^0_S) = (-3.1 \pm 1.2_{(stat)} \pm 0.4_{(syst)} \pm 0.1_{(ext)})\ \%$ is statistically dominated [Phys. Rev. D 104, L031102]
- Recent measurement from Belle+Belle II in 2025 $A_{CP}(D^0 \to K^0_S K^0_S) = (1.3 \pm 2.0_{(stat)} \pm 0.2_{(syst)})\ \%$ [Phys. Rev. D 112, 012017]
- In Run 3, implementation of a dedicated trigger to reconstruct K^0_S, allowing to collect data at higher efficiency w.r.t. Run 2
- Low reliance on simulation allows this analysis to be the first analysis with 2024 data!

Methodology of the analysis

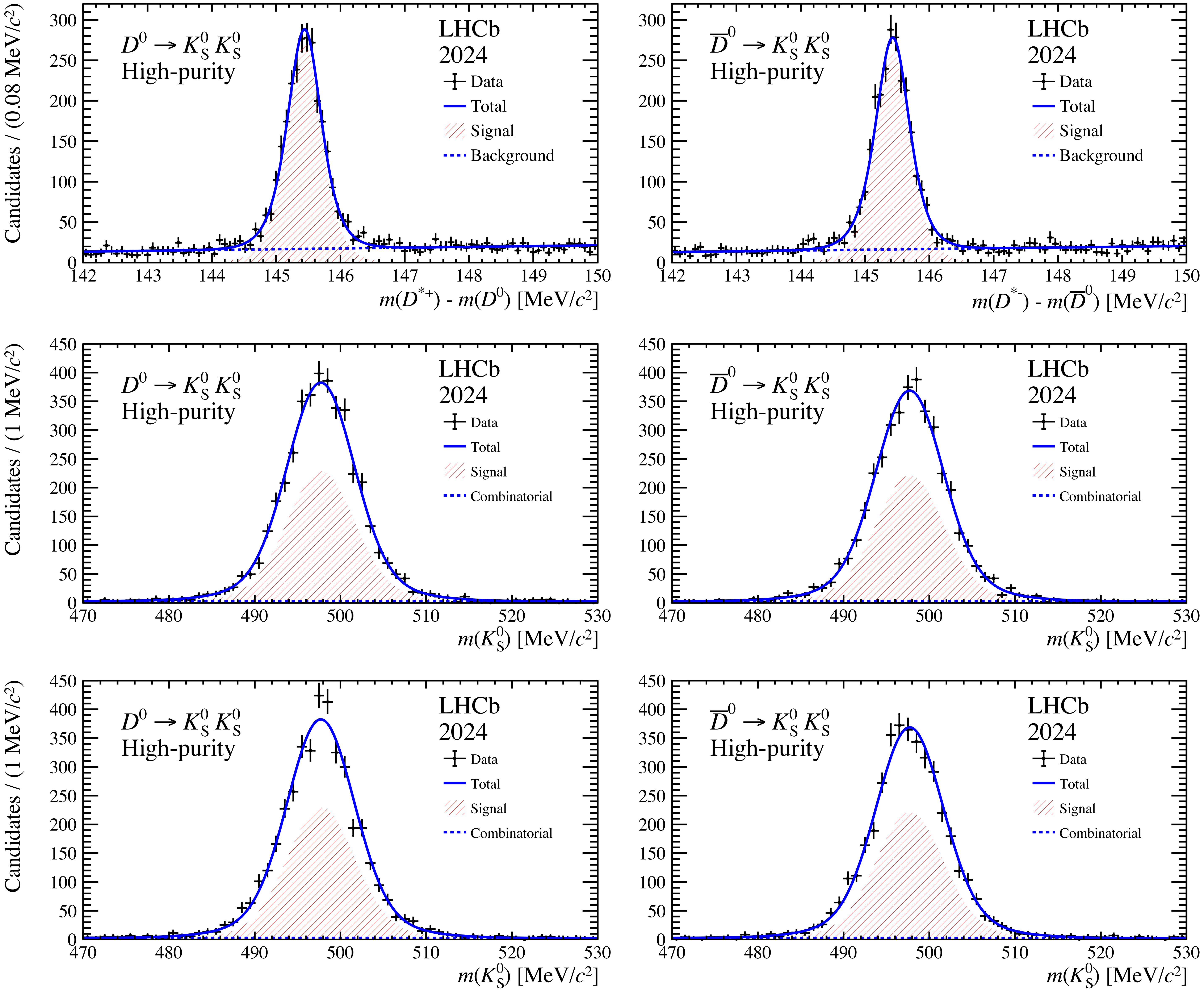
[2510.14732] Submitted to JHEP

- Tag of D^0 flavour with $D^{*+}(2010) \to D^0(\to K_S^0 K_S^0)\pi^+$
- Data collected at LHCb with a centre-of-mass energy of $\sqrt{s} = 13.6$ TeV during 2024 with integrated luminosity of $\mathscr{L} = 6.2\ \mathrm{fb}^{-1}$
- Data is divided into sub-sample accounting for different data taking conditions during 2024
- For now only analysing K_S^0 that decays in the VELO, but will be revisited with the full Run 3 analysis
- To account for nuisance asymmetry the $D^0 \to K_S^0 \pi^+\pi^-$ decay is used as a calibration sample
  - Same final state as signal channel but due to the main contribution of $D^0 \to K^{*-}(\to K_S^0\pi^-)\pi^+$, a weighting of the kinematics of the pions is necessary, and it is carried out with a kNN
  - Different from Run 2, where it was used $D^0 \to K^+K^-$
- Presence of b-produced D^{*+} is accounted for by allowing the same fraction present also in the calibration channel
- Event-wise weighting with an independent kNN to eliminate spurious asymmetries
- Three dimensional fit to $\Delta m = m(D^{*+}) - m(D^0)$ and the two $m(K_S^0)$

Results

- Fit results averaged over all sub-samples:
  $A_{CP}(D^0 \to K_S^0 K_S^0) = (1.86 \pm 1.04_{(stat)} \pm 0.41_{(syst)})\ \%$
- Compatible with the hypothesis of no CP violation
- Most precise measurement up to date
- Significant improvement in the statistical precision thanks to the newly upgraded detector and the dedicated trigger
- Combining this result with previous LHCb results gives
  $A_{CP}(D^0 \to K_S^0 K_S^0) = (-0.37 \pm 0.78_{(stat)} \pm 0.29_{(syst)})\ \%$
- First result with 2024 data!

[2510.14732] Submitted to JHEP



Preliminary!

2024 Data

ΔA_{CP} from $D^0 \to h^+h^-$ decays with 2024 data

Analysis Strategy

- ΔA_{CP} is the observable which allowed to observe CP violation in 2019 [PRL 122, 211803]

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4} \text{ (combination Run1-Run2)}$$

- Current measurement is statistically dominated → new datasets from LHCb Upgrade I
- Goal of the analysis: measure ΔA_{CP} with $D^0 \to KK$ and $D^0 \to \pi\pi$ decays with 2024 data
- D^0 are produced from prompt $D^{*\pm} \to D^0 \pi_s^\pm$
- Strategy analogous as with Run 2 measurement

$$\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi) =$$
$$= A_{raw}(KK) - A_{raw}(\pi\pi) - A_D^{KK}(\pi_s) + A_D^{\pi\pi}(\pi_s) - A_P^{KK}(D^*) + A_P^{\pi\pi}(D^*)$$

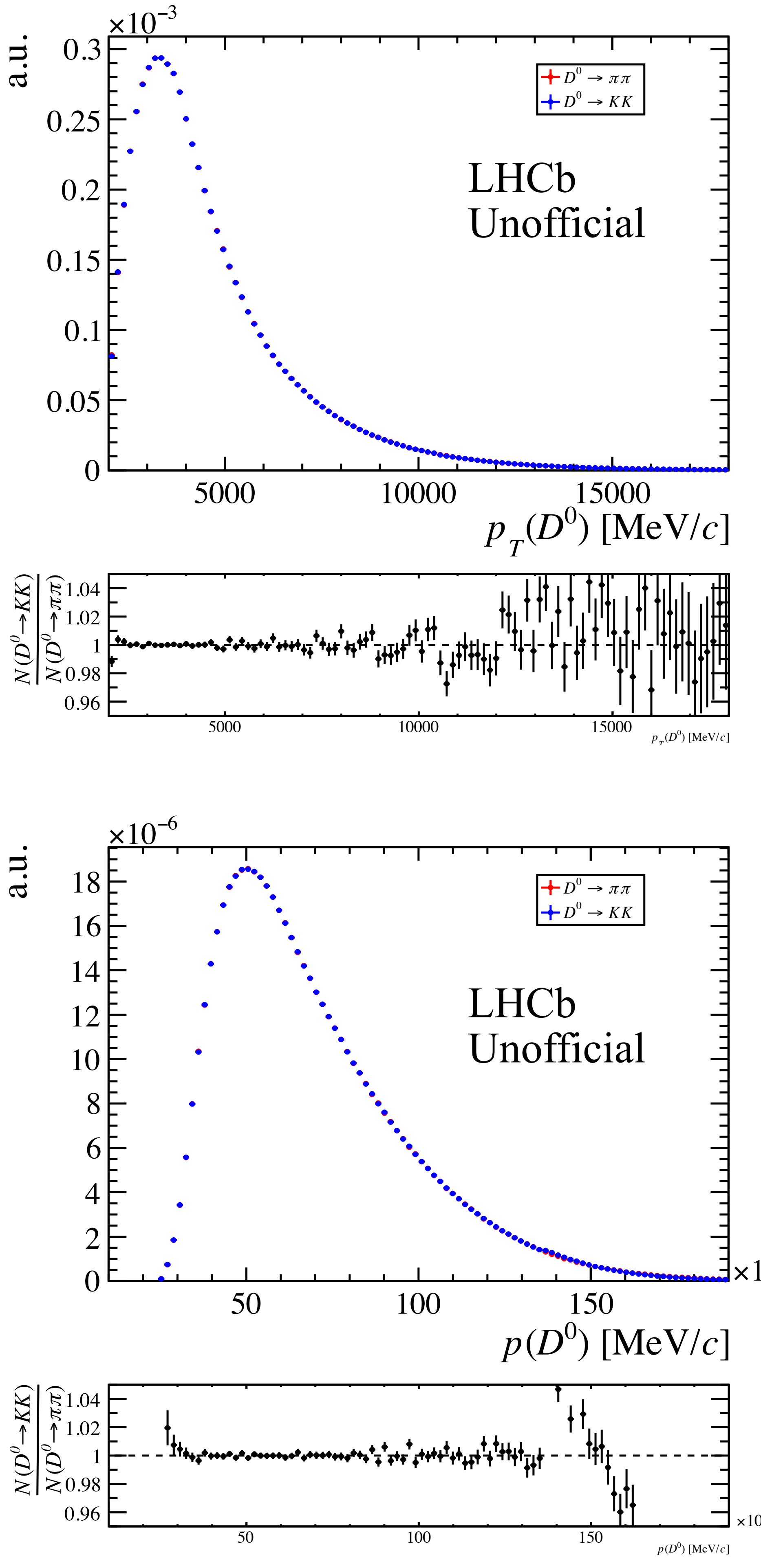
- To ensure the cancellation of nuisance asymmetries, kinematic weights are applied to the $D^0 \to KK$ decay
- After weighting then
- $$\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi) = A_{raw}^w(KK) - A_{raw}(\pi\pi)$$
- Aim to use the 2024 dataset of 6.2 fb^{-1} divided in different sub-samples to account for different data-taking conditions

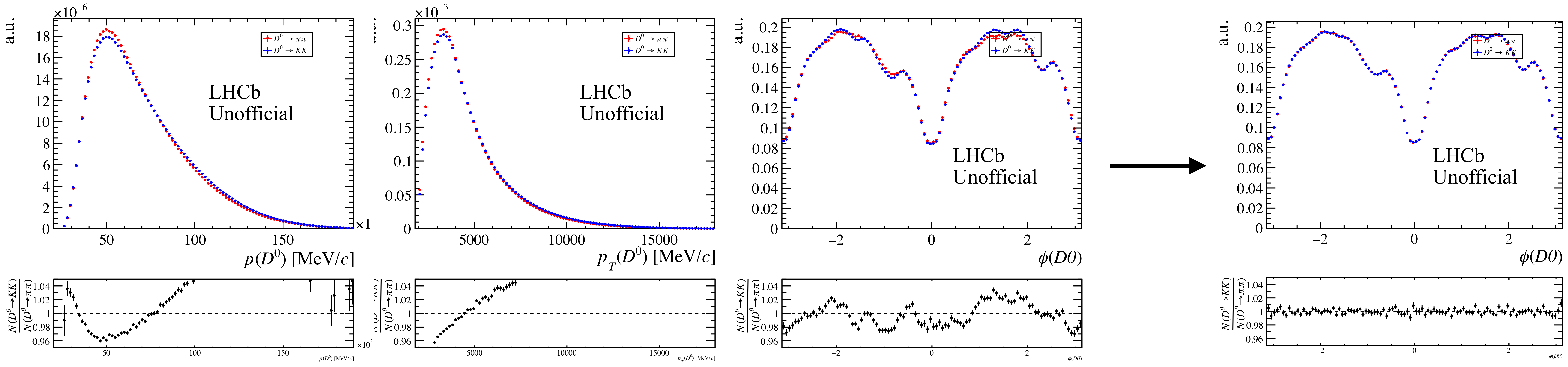
Weighting

A sub-sample has been shown as an example

- Weighting of $D^0 \to KK$ channel to $D^0 \to \pi\pi$ one
- Current strategy consist of 3D histograms with 40x40x40 bins
  - Bin edges are computed with quantiles of each 1D histogram
  - Ratio of histograms are employed to compute the weights
  - Current implementation based on the hep_ml modified python package
  - Each block is weighted independently starting from s-weighted distribution
- Variables of the weighting $P(D^0)$, $P_T(D^0)$ and $\phi(D^0)$
  - After the weighting, also D^{*+}, π_s variables are checked to ensure proper asymmetry cancellation

Range of ratios KK/pipi [95 % ,105%]





Fit Model

- Fit on $m(D^0\pi) \equiv \left(m_{D^0}^2 + m_\pi^2 + 2\sqrt{m_{D^0}^2 + |\vec{p}_{D^0}|^2} \cdot \sqrt{m_\pi^2 + |\vec{p}_\pi|^2} - 2\vec{p}_{D^0} \cdot \vec{p}_\pi\right)^{\frac{1}{2}}$
- For $D^0 \to K^+K^-$: 3 Gaussian functions and 1 Johnson function
- For $D^0 \to \pi^+\pi^-$: 2 Gaussian function and 1 Johnson function
- Tail parameters of the Johnson function are constrained from simulation

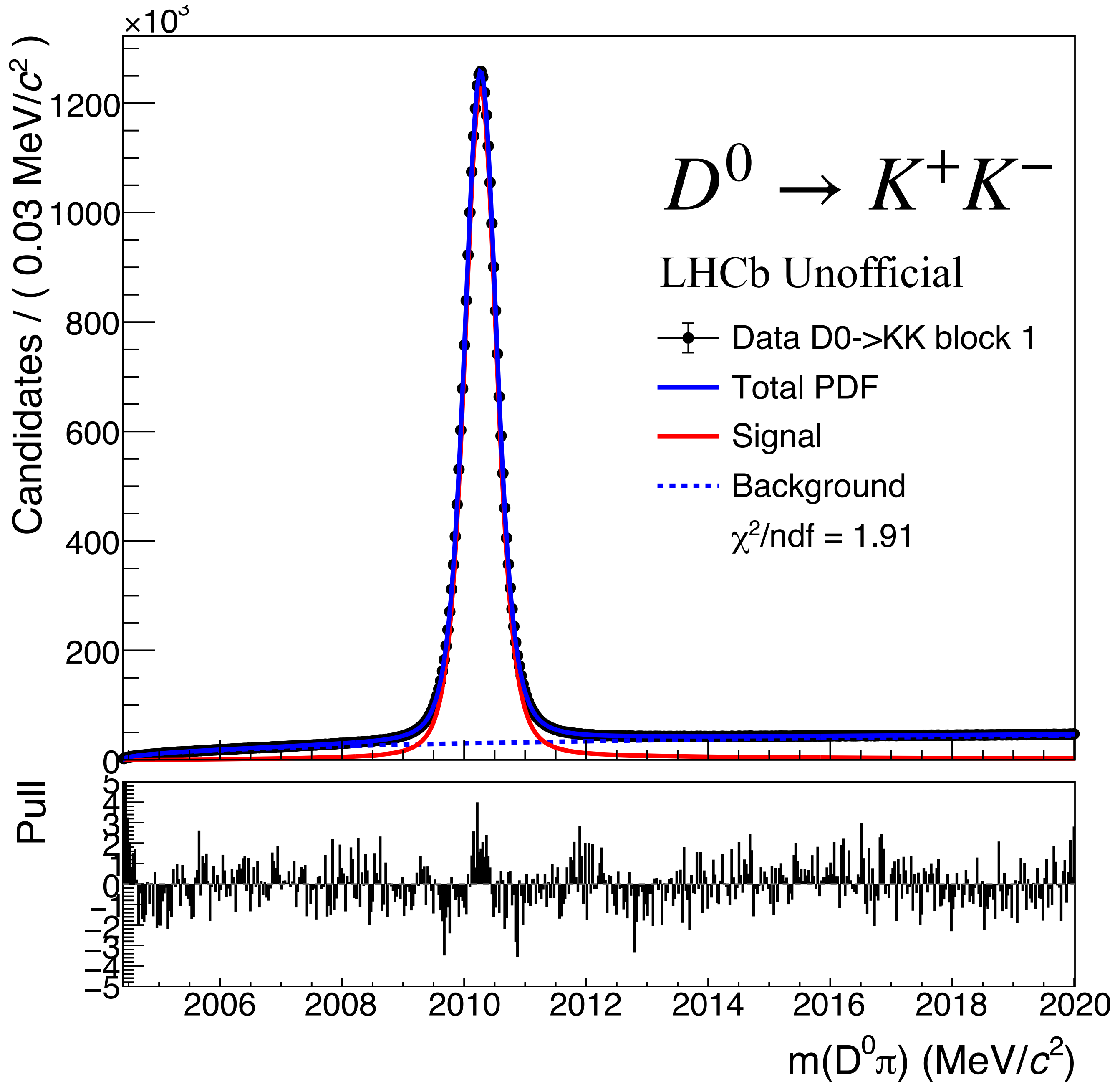
Johnson function

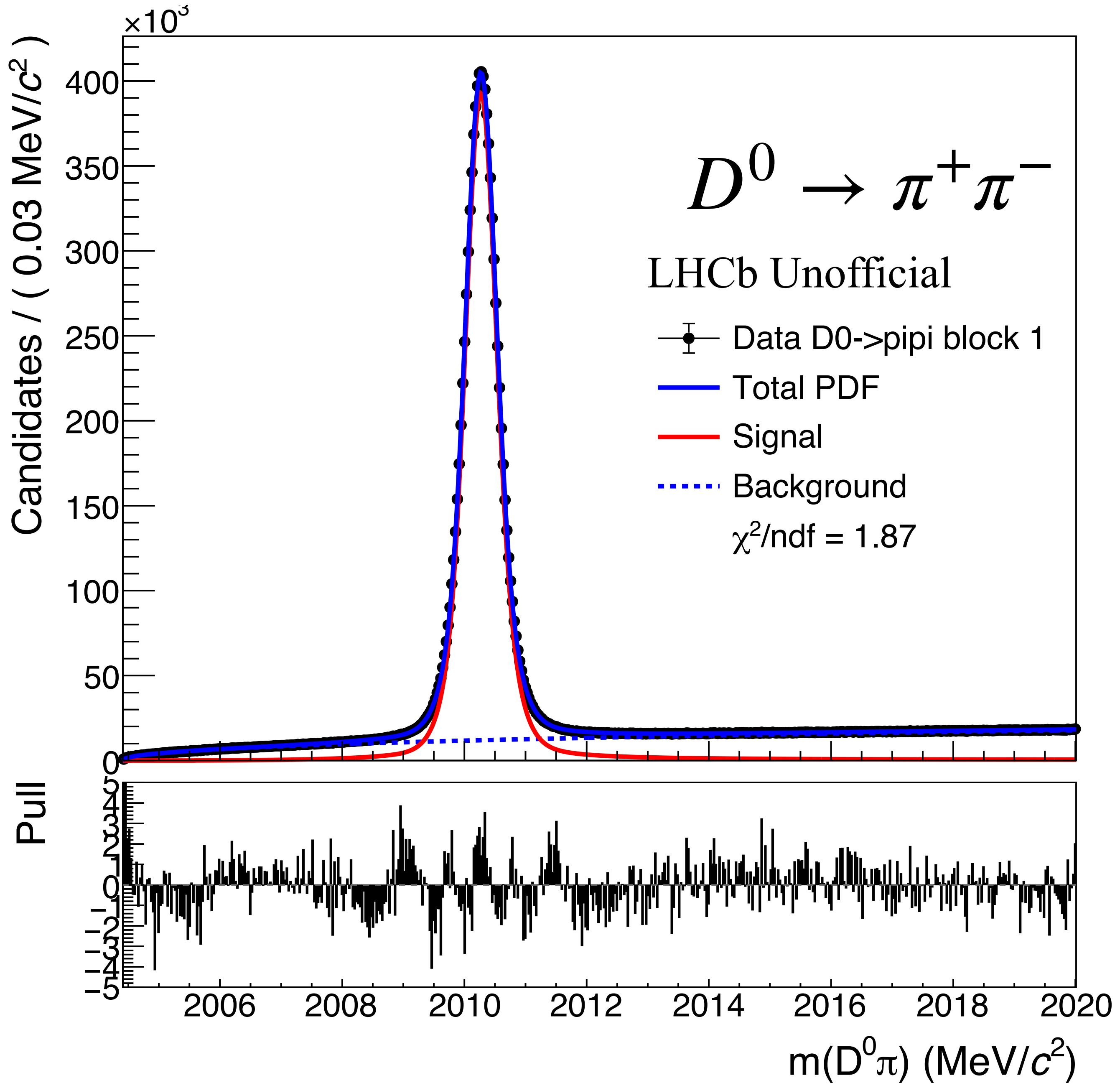
$$\mathcal{J}(m;\mu_J,\sigma_J,\delta_J,\gamma_J) = \frac{e^{-\frac{1}{2}\left[\gamma_J+\delta_J \sinh^{-1}\left(\frac{m-\mu_J}{\sigma_J}\right)\right]^2}}{\sqrt{1+\left(\frac{m-\mu_J}{\sigma_J}\right)^2}}$$

- Combining each sub-sample gives an uncertainty of

$$\delta_{stat}(\Delta A_{CP}) = 1.67 \times 10^{-4}$$

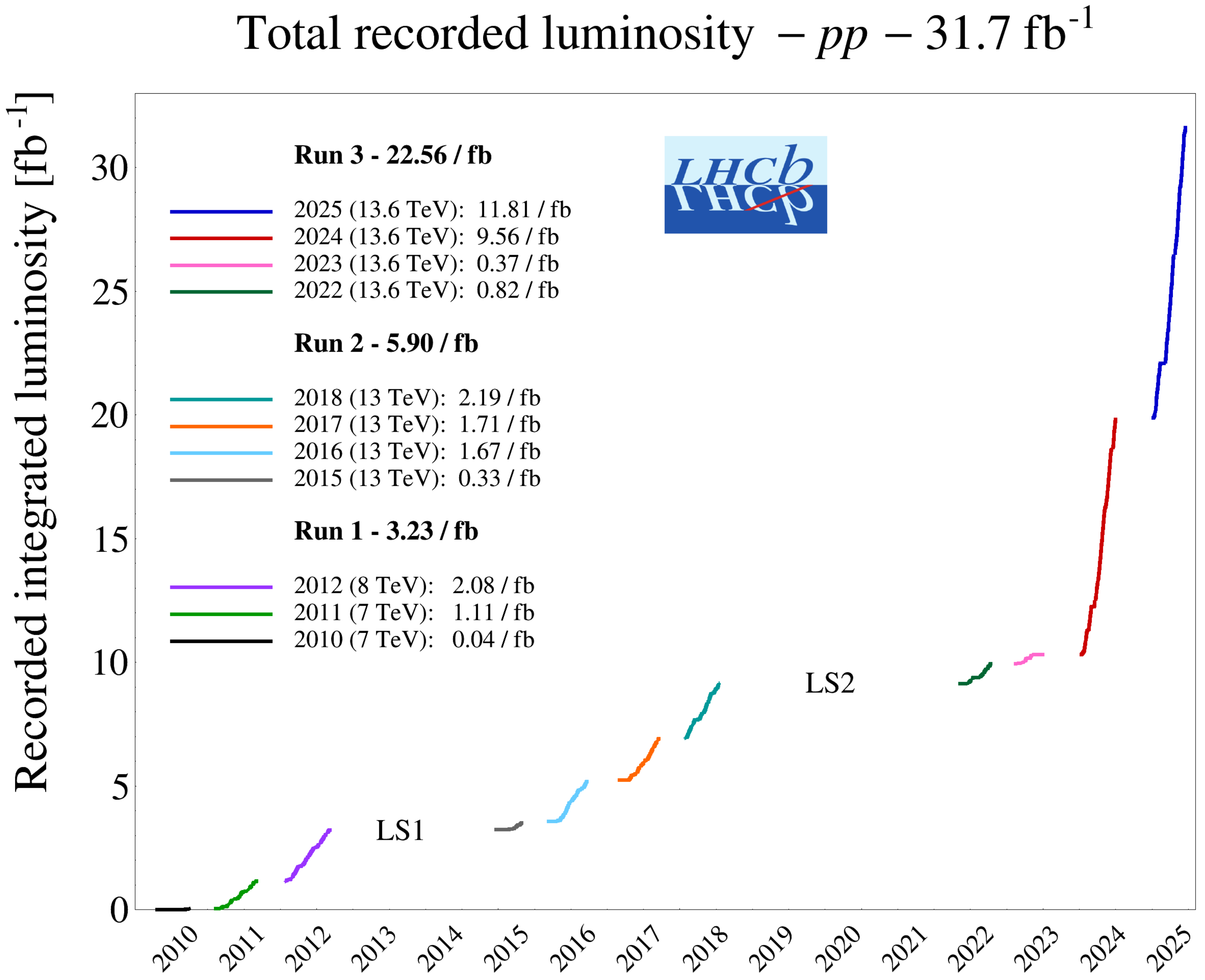
- Similar luminosity w.r.t. to Run 2 but a statistical error reduced by a factor 2
- Great ongoing effort to finalize the analysis so stay tuned





Conclusions

- Charm physics at LHCb is greatly benefitting from Upgrade I
- First analyses with Run 3 data are starting to be published
- In Run 3 LHCb has already collected 22.56 fb^{-1} (almost a factor 3 w.r.t. Run1+2) with 2026 still to go
- The improved trigger procedure allows to collect data at an higher instantaneous luminosity and with greater efficiency
- The Upgrade I will allow to reach unprecedented precisions in established observable while also explore new possible observables that were previously inaccessible due to the limited data sample



Thank you for your attention

BACKUP

$A_{rec}(\pi)$ from tag-and-probe method

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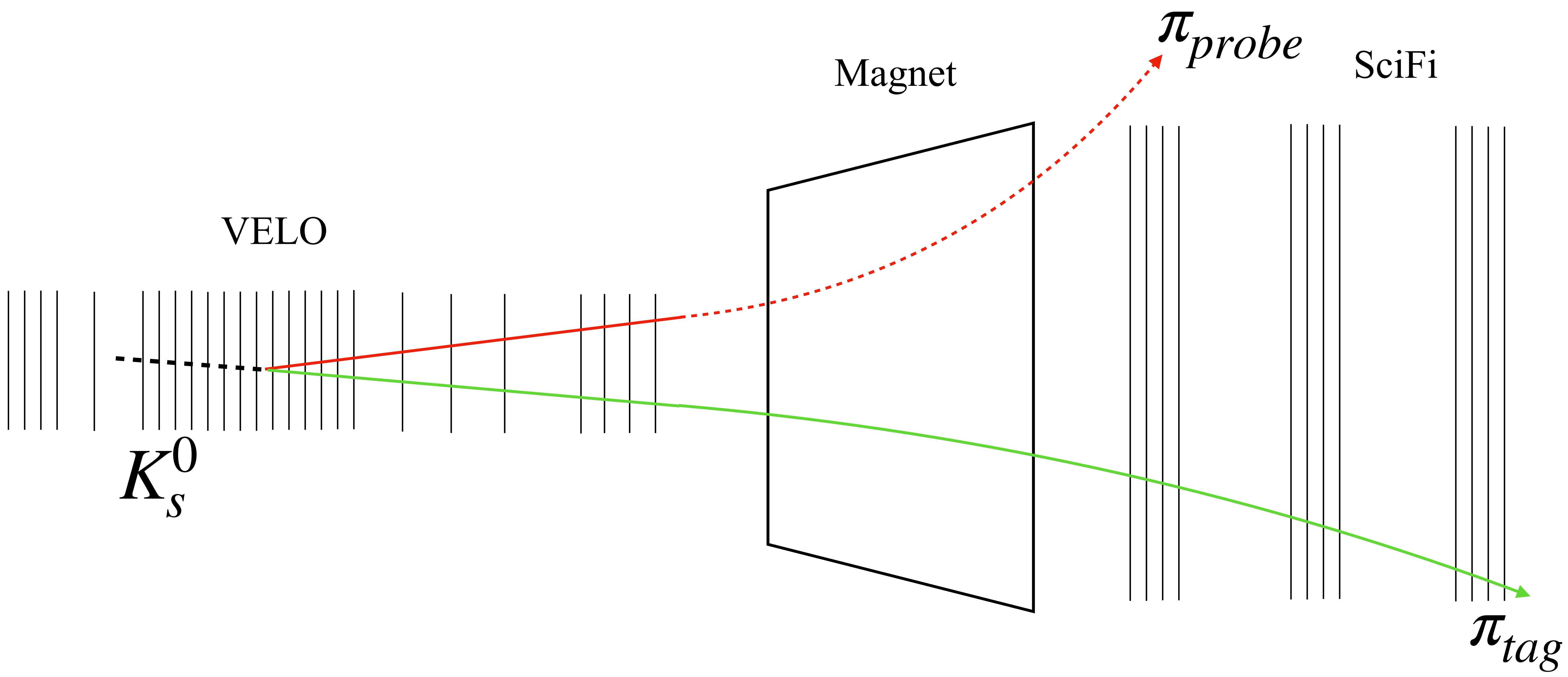
- Reconstruction of $K^0_S \to \pi\pi$ with a long (tag) track and with a VELO (probe) track
- The probe track is then compared with other long tracks to count matched tracks and unmatched tracks
- $A_{rec}(\pi)$ is then extracted from

$$A_{rec} = \frac{\epsilon_{rec}(\pi^+) - \epsilon_{rec}(\pi^-)}{\epsilon_{rec}(\pi^+) + \epsilon_{rec}(\pi^-)} \quad \text{with } \epsilon(\pi) = \frac{N_{match}}{N_{match} - N_{unmatch}}$$

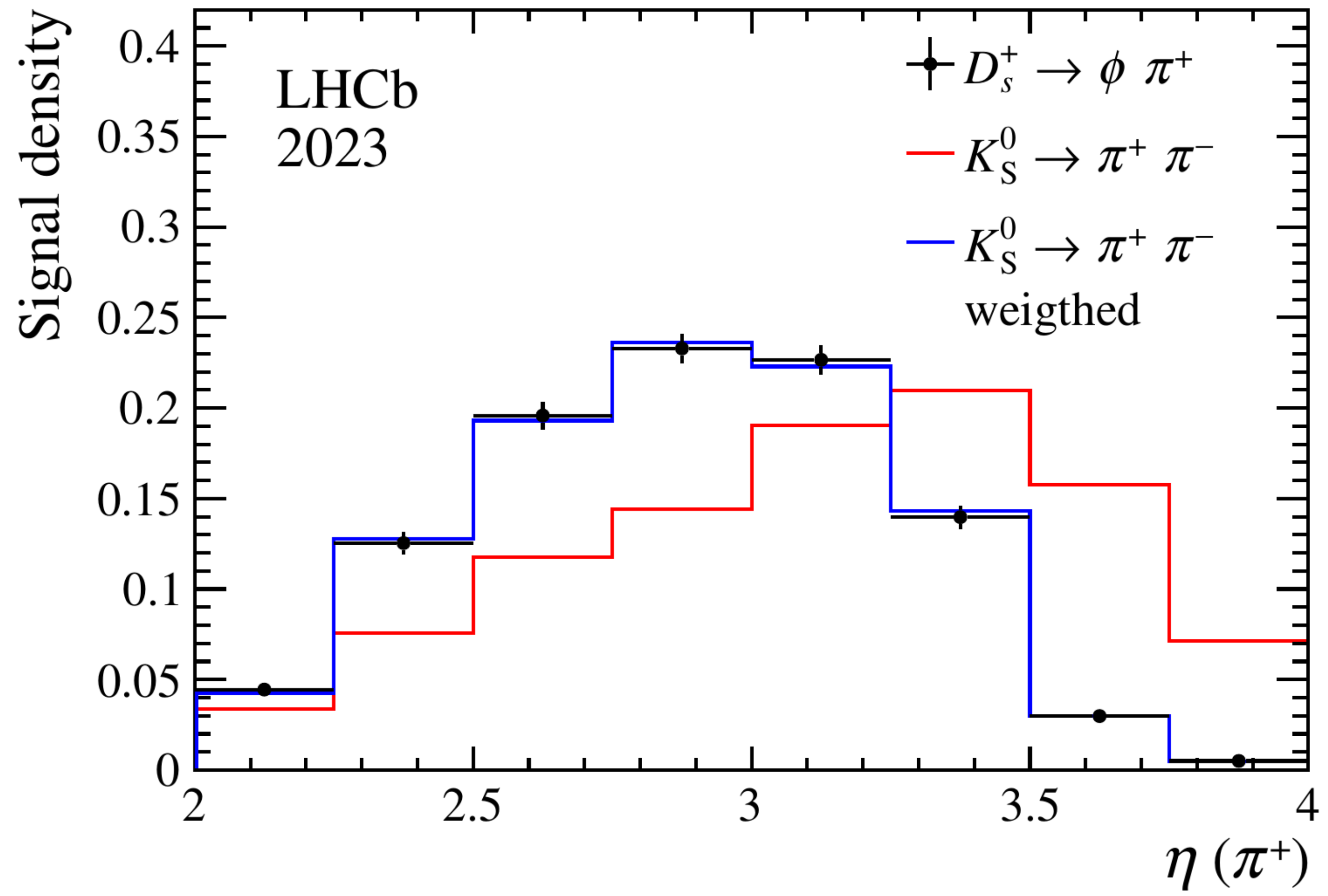


Weighting and asymmetry estimation

[JHEP 09 (2025) 157]

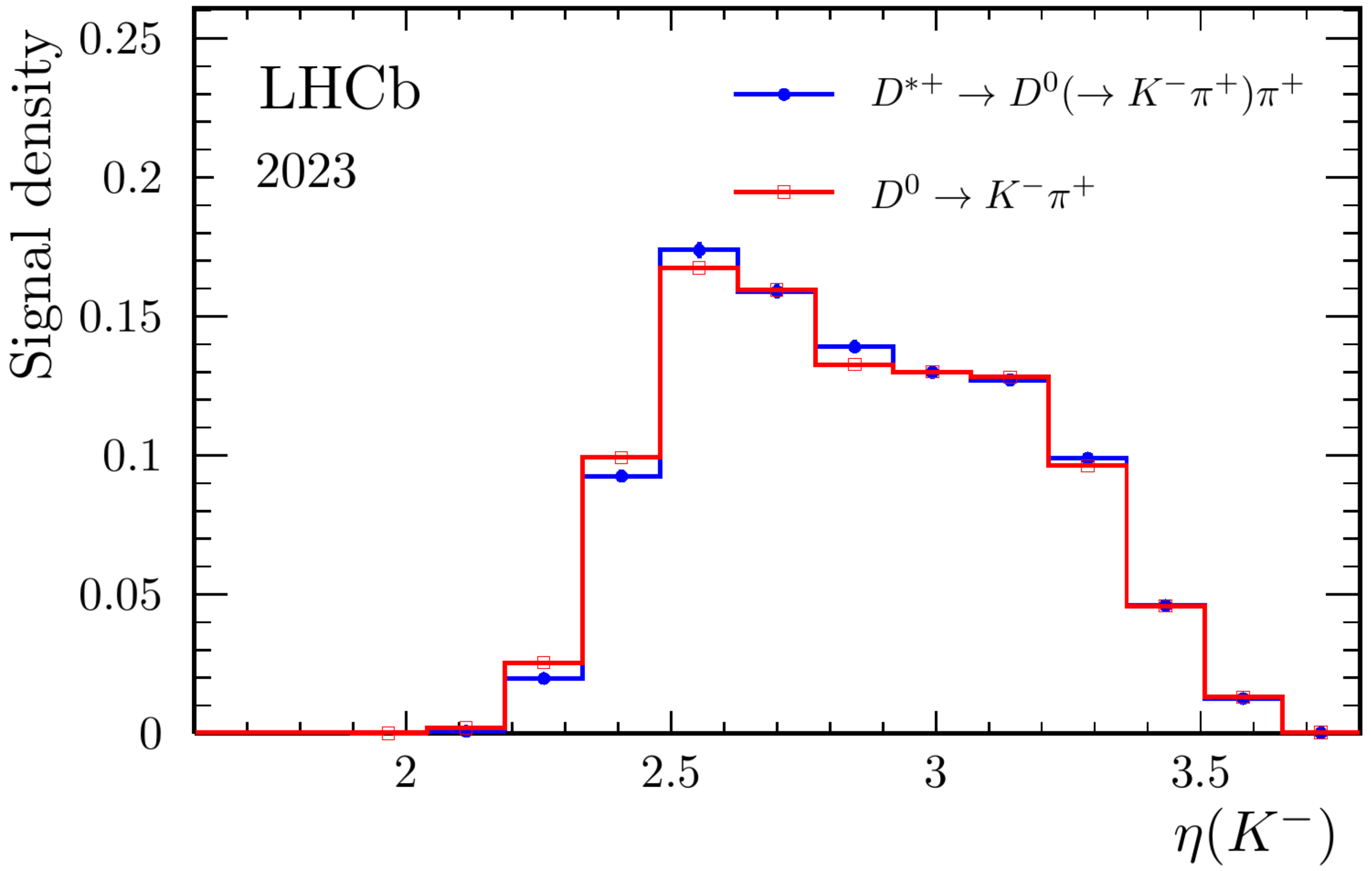
- $A_{rec}(\pi)$ depends on the kinematic of the pion
- Kinematic weights are applied to the signal candidates from $K_s^0 \to \pi\pi$ sample
- The strategy is repeated for each kinematic region of the charmed meson and for A_{PID}

$D_{(s)}^{+}$



- To extract $A_{det}(K\pi)$ all other asymmetries must cancel out
- Due to limited size of the control sample, kinematic weights are applied to the $D^0 \to K\pi$ sample

D^0



After the weighting, for each charmed meson and for each kinematic bin, asymmetries are extracted with simultaneous fits to both meson-anti meson invariant mass distributions

Secondary contributions estimate

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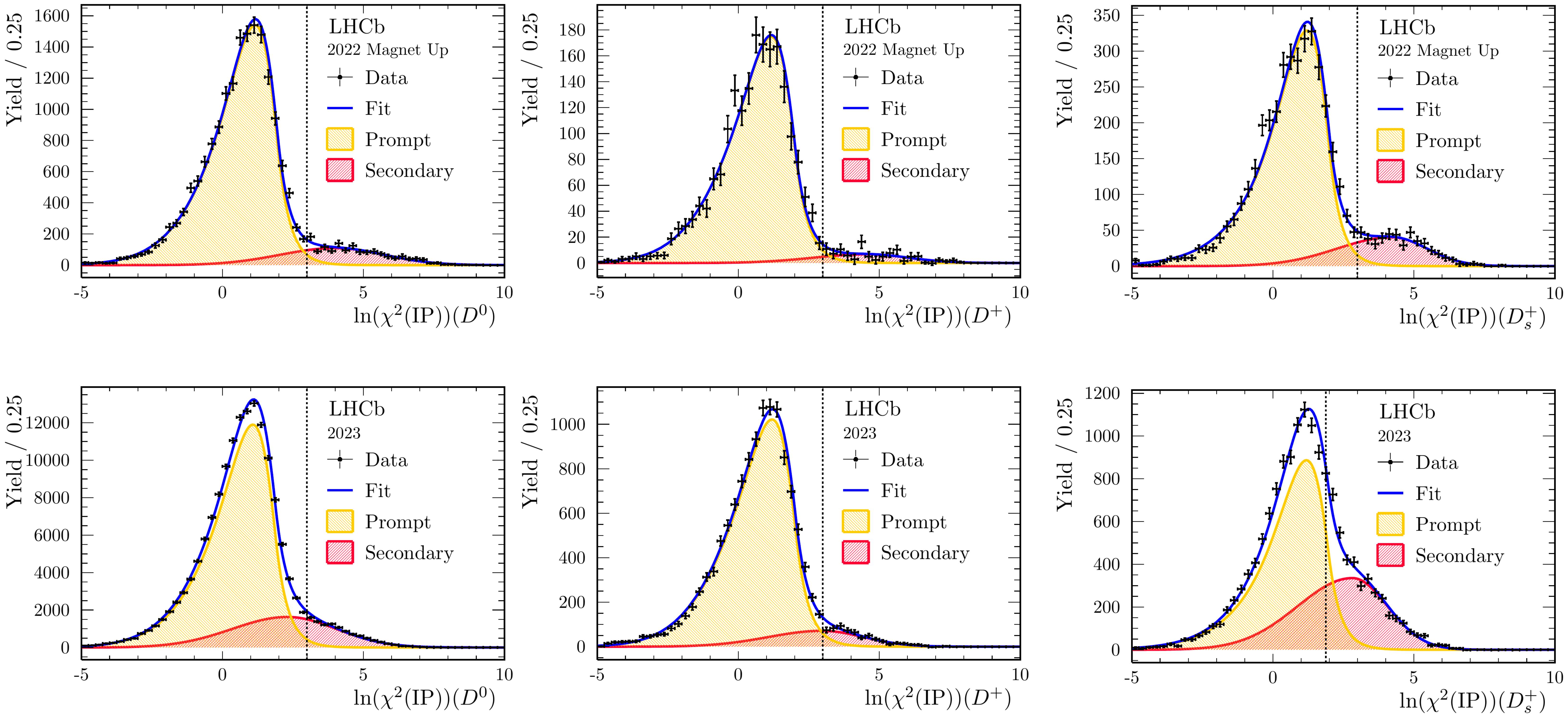
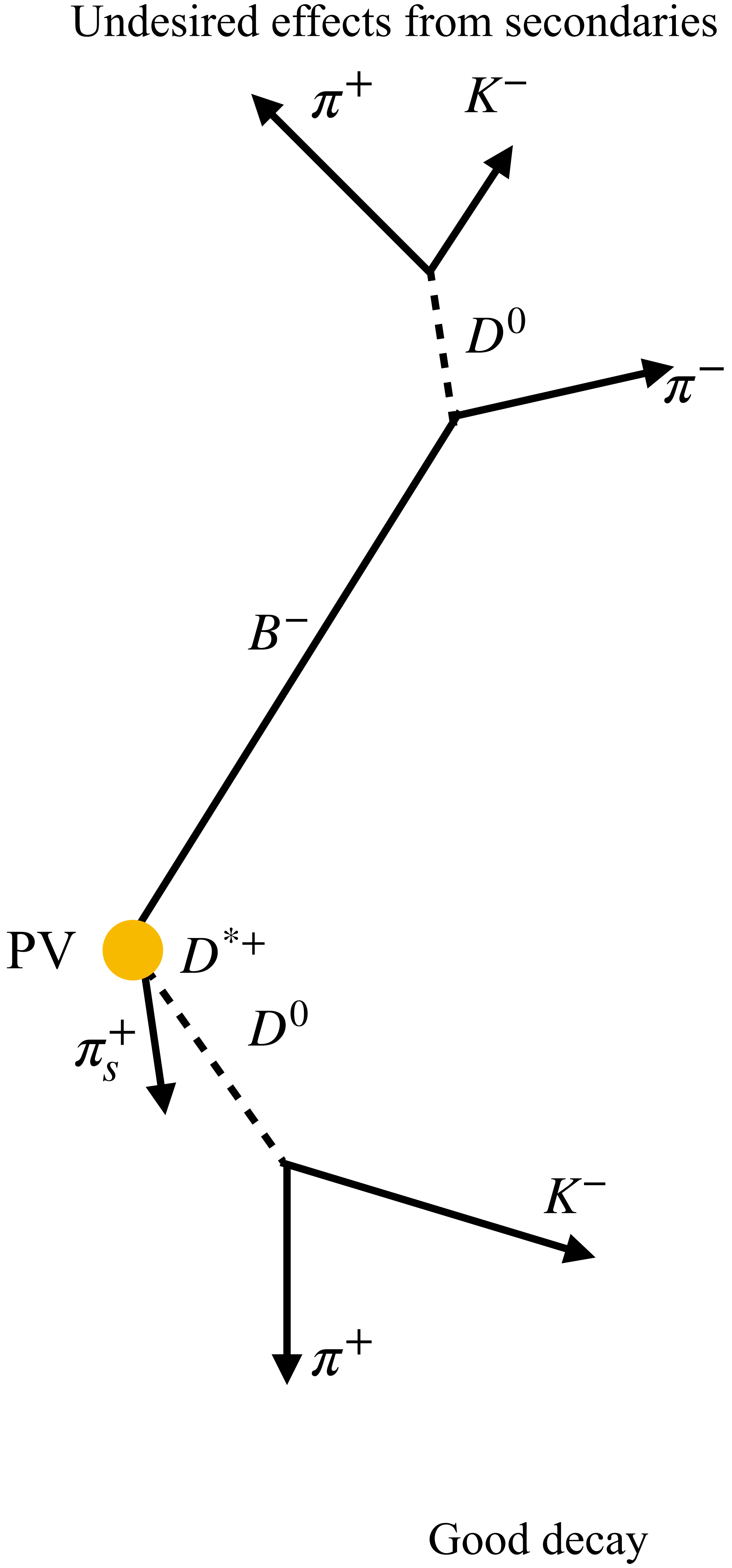
- Correction for b-produced charm mesons: $\Delta A_{sec} = f_{sec}(A_P(X_c) - A_{sec}(X_c))$
- To extract f_{sec}, A_{sec} unbinned maximum likelihood fit to $\ln(\chi^2_{IP})$





- All ΔA_{sec} are compatible with zero within 3 standard deviations

Results

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- No dependence of production asymmetry as functions of kinematics
- Integrated results over the kinematic regions compatible with symmetry:

$$A_P(D^0) = (0.07 \pm 0.26_{stat} \pm 0.10_{syst})\ \%$$

$$A_P(D^+) = (-0.33 \pm 0.29_{stat} \pm 0.14_{syst})\ \%$$

$$A_P(D_s^+) = (0.18 \pm 0.26_{stat} \pm 0.08_{syst})\ \%$$