CP violation in the decay of charmed hadrons at LHCb

Maurizio Martinelli
University of Milano Bicocca and INFN
On behalf of the LHCb Collaboration

ICHEP
Prague, 20.07.2024

Outline

CP Violation in Charm Decays

Recent LHCb Results

Summary

CP Violation in Charm Decays

CP Violation in Charm Hadrons Decays

Unique

- Only up-type quark decay in which new physics couplings can be probed

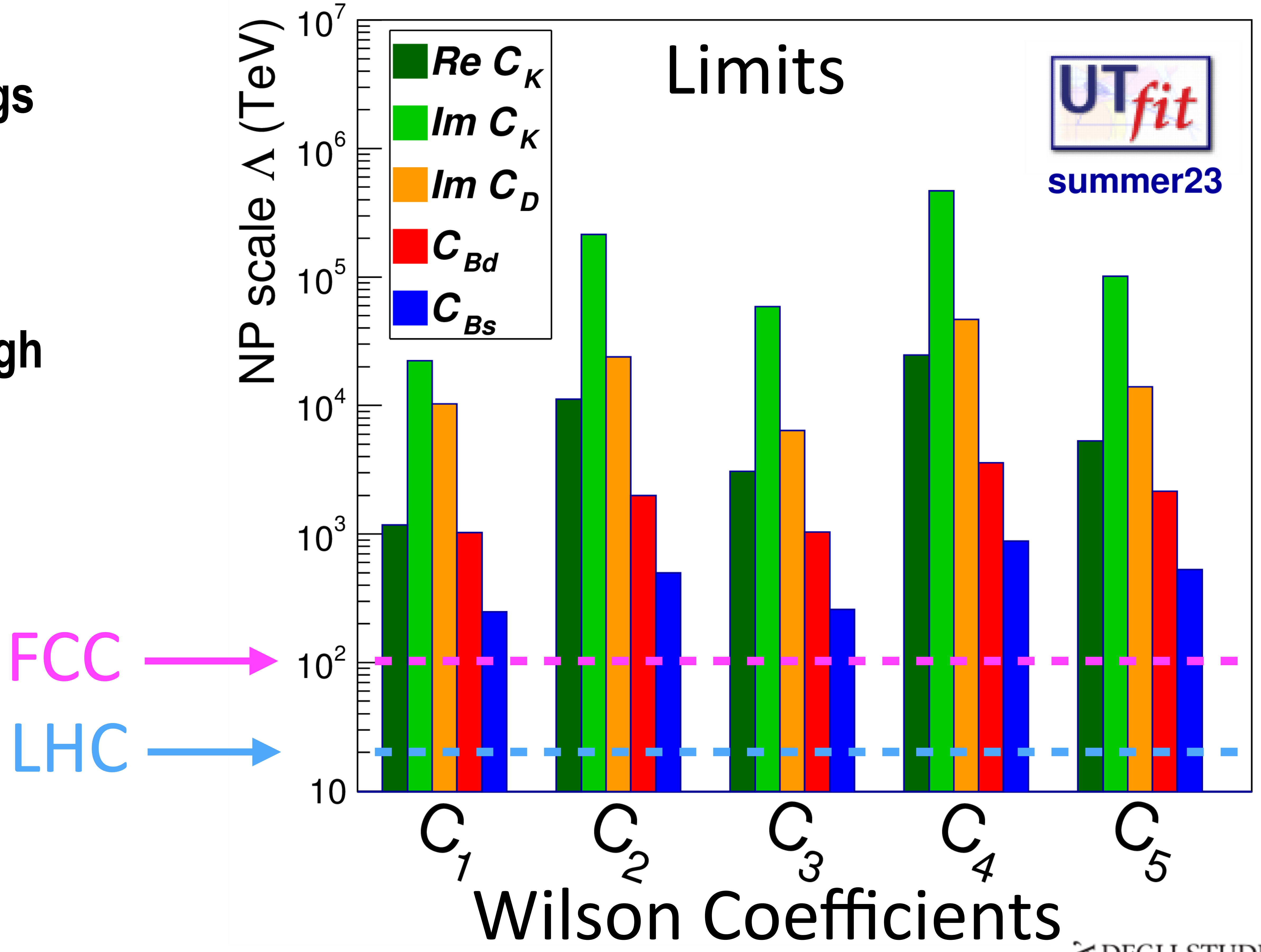
Discovery Tool

- Indirect CPV in Charm† decays could probe extremely high BSM scales and are highly suppressed in the SM
- Complementary to direct searches for BSM particles
- We have billions of decays ready to be studied at LHCb!

Challenging

- Predictions are difficult (not a precision probe)
- Interesting laboratory for non-perturbative QCD and (exotic) hadron dynamics

arXiv:2212:03894



†R. Ribatti's talk "Mixing and time-dependent CP violation in Charm decays at LHCb"

Status of CP Violation in Charm Decays

[(1)]PRL122(2019)2118032

History Being Made Now

- Observed for the first time direct CPV in $D^0 \rightarrow hh$ ($h=\pi,K$) decays in 2019[1]

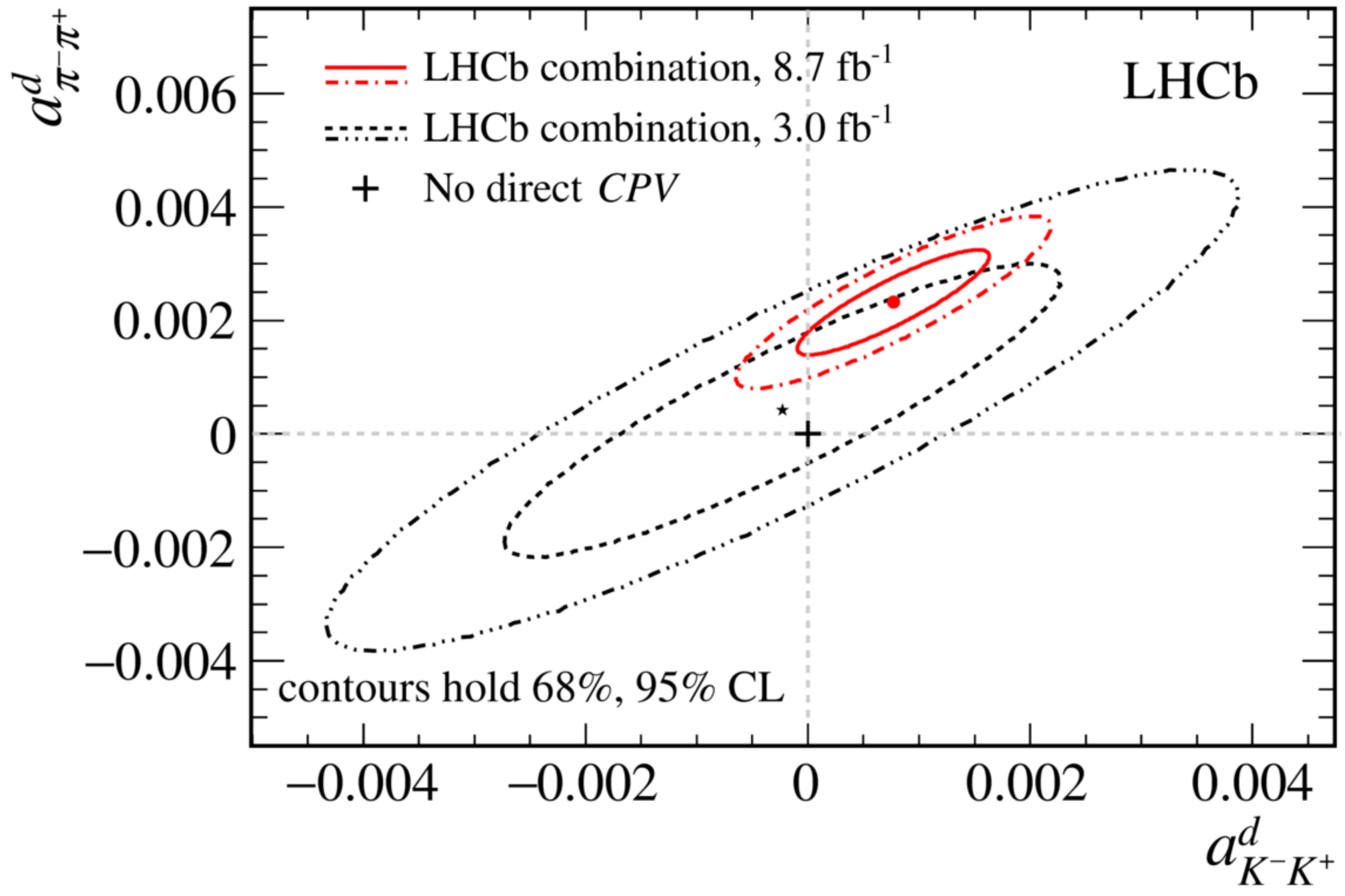
$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = \left(-15.4 \pm 2.9\right) \times 10^{-4}$$

- Later separated the measurement between $D^0 \rightarrow KK$ and $D^0 \rightarrow \pi\pi$ decays[2]

$$A_{CP}(K^+K^-) = \left(7.7 \pm 5.7\right) \times 10^{-4}$$

$$A_{CP}(\pi^+\pi^-) = \left(-23.2 \pm 6.1\right) \times 10^{-4}$$

[(2)]PRL131(2023)091802



Questions

- Standard Model or Beyond?
- Theoretical predictions challenged by strong interactions effects
- Strong breaking of U-spin symmetry?

Eur. Phys. J. Spec. Top. 233, 439–456 (2024) and references therein

Extending The Search

Decay Modes

- Any Cabibbo suppressed decay may exhibit CPV
- Cabibbo favored decays have CPV=0 also in BSM scenarios
- Doubly Cabibbo suppressed decay may have larger CPV in BSM scenarios

Dalitz Plot Analyses

- CPV observables arise from interference
  $$a_{CP} \propto \sin\left(\phi_1 - \phi_2\right) \sin\left(\delta_1 - \delta_2\right)$$
- In two-body decays $\delta_1 - \delta_2$ is given by the decay mode, and may not be the most sensitive for CPV
- Multi-body decays offer all values of this difference in the phase space
  Depending on the amplitude structure, there may be regions highly sensitive to CPV

Latest LHCb Results

CPV in $D^+ \to K^+K^-\pi^+$

NEW

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Motivation

- Cabibbo suppressed D^+ decay with largest BF
- Can use Cabibbo favored D_s^+ as control

Strategy

- Model independent χ^2 test

$$\chi^2(\mathcal{S}_{\Delta_{CP}}) = \sum_i^{N_{\text{bins}}} \left(\mathcal{S}^i_{\Delta_{CP}}\right)^2$$

i: phase space bin

$$\mathcal{S}^i_{\Delta_{CP}} = \frac{\Delta A^i_{CP}}{\sigma_{\Delta A^i_{CP}}}$$

- Local asymmetry for $D^+ \to K^{*0}K^+$ and $D^+ \to \phi\pi^+$

$$A_{CP|S} = \frac{1}{2}\left[\left(\Delta A_{\text{raw}}^{\text{top-left}} + \Delta A_{\text{raw}}^{\text{bottom-right}}\right) - \left(\Delta A_{\text{raw}}^{\text{top-right}} + \Delta A_{\text{raw}}^{\text{bottom-left}}\right)\right]$$

Raw asymmetries of signal and control samples

$$A_{\text{raw}}^{i,X} = \frac{N_+^{i,X} - N_-^{i,X}}{N_+^{i,X} + N_-^{i,X}}$$

$$\Delta A^i_{CP} = A_{\text{raw}}^{i,S} - A_{\text{raw}}^{i,C} - \Delta A_{\text{raw}}^{\text{global}}$$

$$\Delta A_{\text{raw}}^{\text{global}} = \frac{\sum_i^{N_{bins}} \frac{A_{raw}^{i,S} - A_{raw}^{i,C}}{\sigma^2_{A_{raw}^{i,S}} + \sigma^2_{A_{raw}^{i,C}}}}{\sum_i^{N_{bins}} \frac{1}{\sigma^2_{A_{raw}^{i,S}} + \sigma^2_{A_{raw}^{i,C}}}}$$

Global difference of asymmetries between signal and control samples

CPV in $D^+ \to K^+K^-\pi^+$ - Binning and Asymmetry

NEW

LHCb Run2 (5.4/fb)

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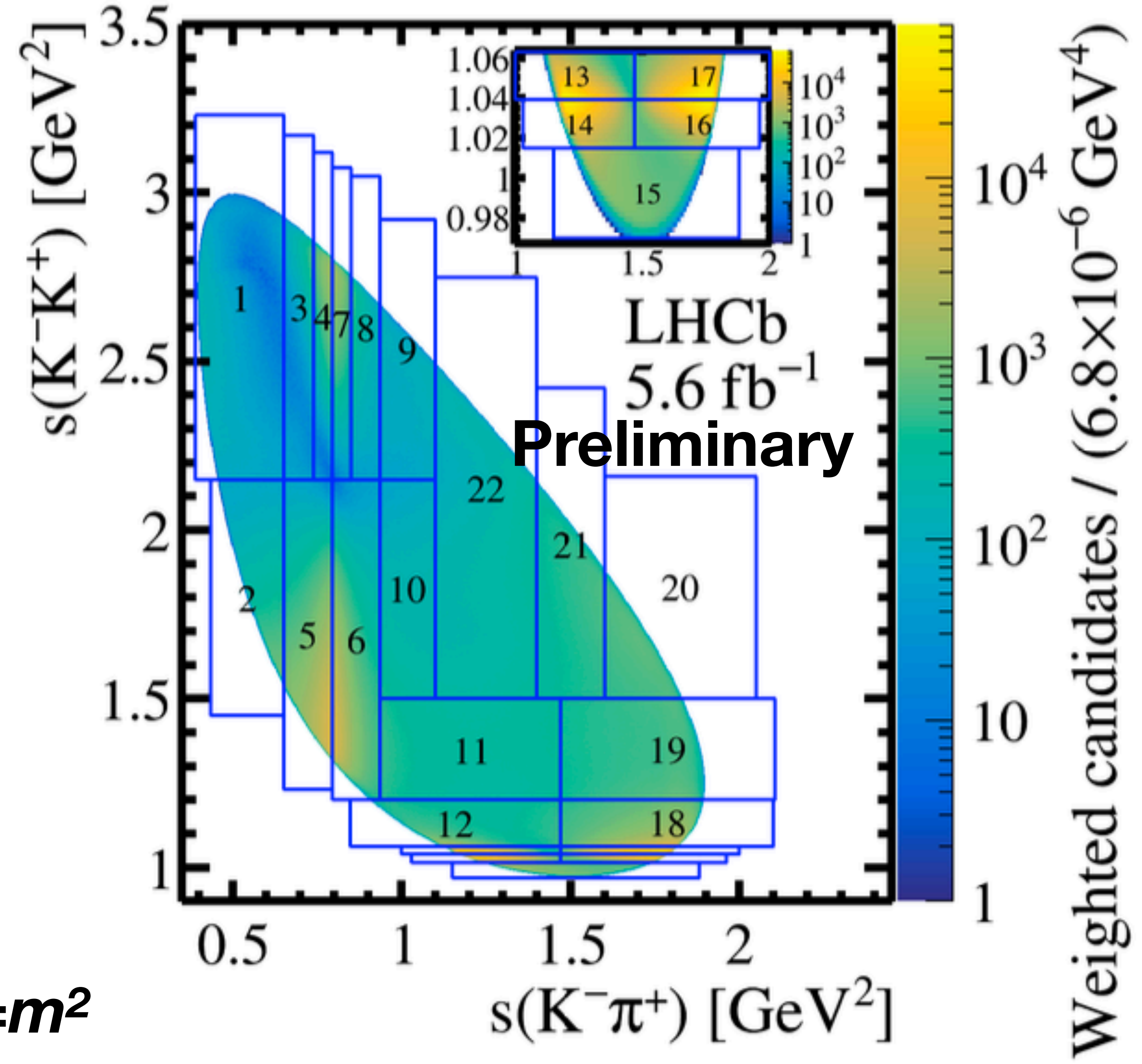
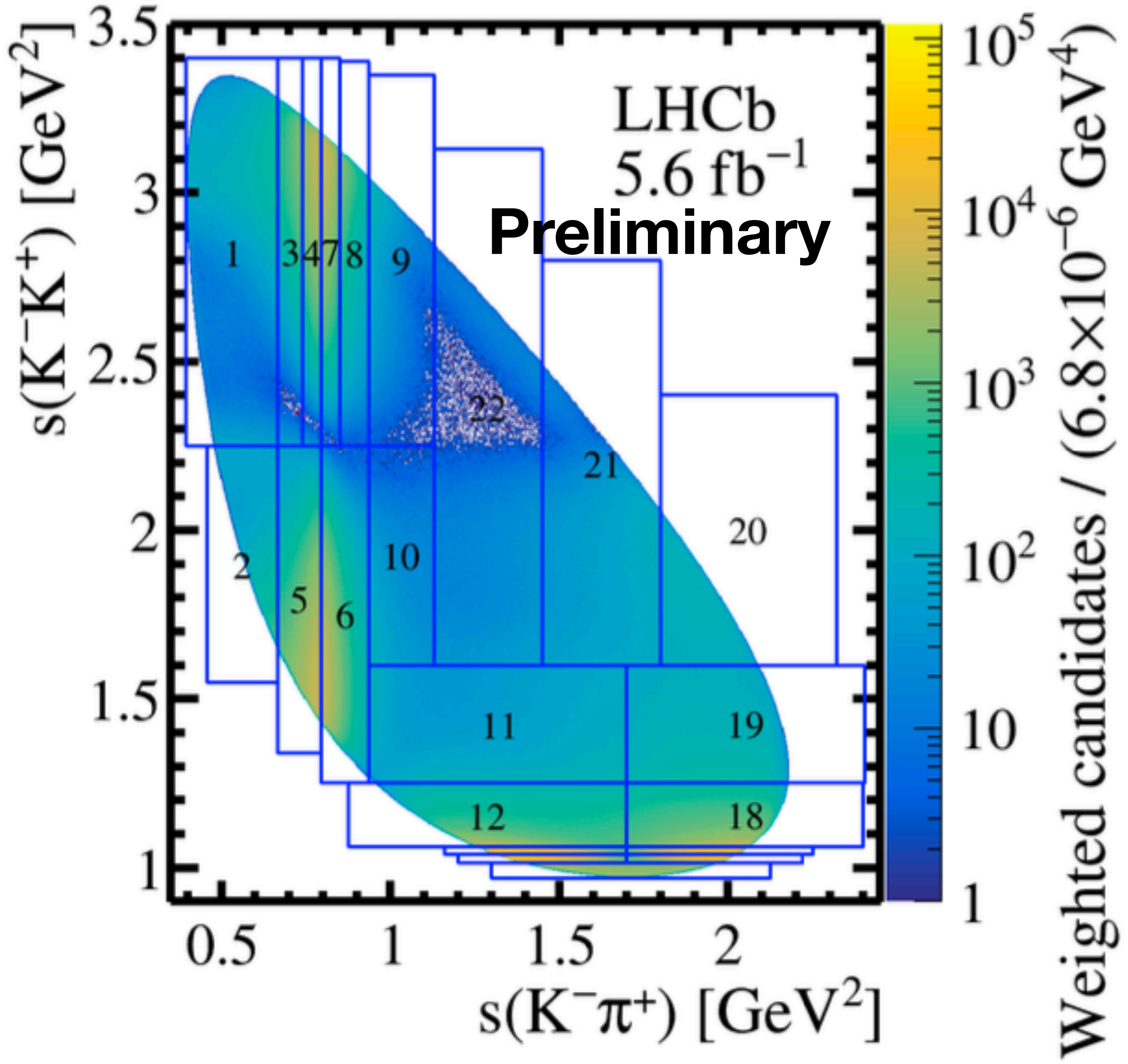


s=m²

$N_S(D^+)$= 135M



$N_S(D_s^+)$= 181M

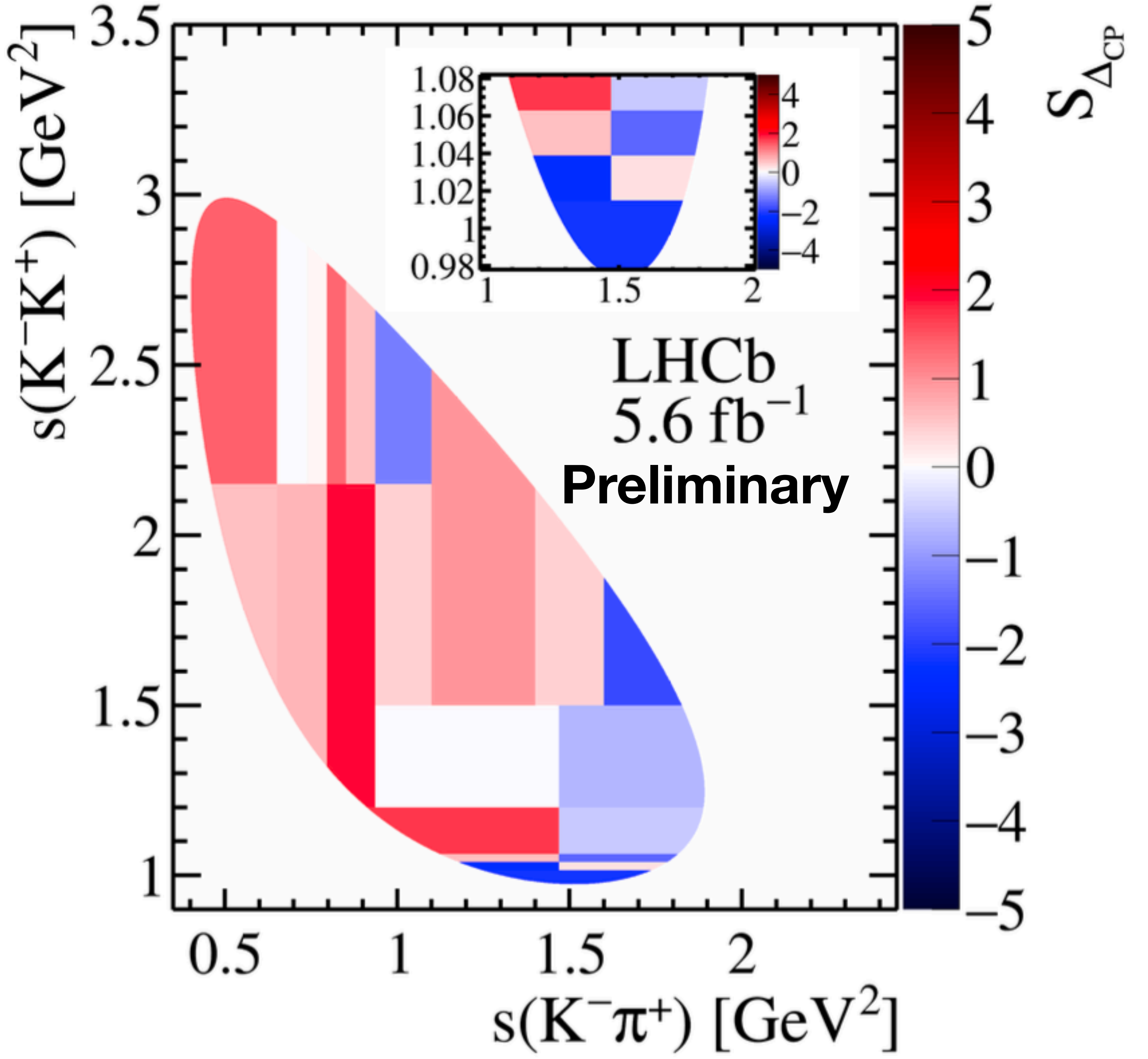


Figure 1: Dalitz plot for (left) $D^+ \to K^-K^+\pi^+$ and (right) $D_s^+ \to K^-K^+\pi^+$ decays in data with the binning scheme overlaid. The bins around the $\phi\pi^+$ region are shown in the inset.

Local Asymmetries

Binning scheme chosen to exploit resonant structures of $D^+ \to K^+K^-\pi^+$, sensitive to interference patterns and strong-phase variations

CPV in $D^+ \rightarrow K^+K^-\pi^+$ - Results

NEW

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Model-Independent Approach

- No localised CPV in the $D^+ \rightarrow K^+K^-\pi^+$ found

$$\chi^2/n_{dof} = 31.8/22 \longrightarrow P = 8.1\,\%$$

- Sensitivity limited by statistics

Preliminary

Local CPV

- Consistent with 0:

$$A_{CP|S}^{\phi\pi^+} = (0.95 \pm 0.43 \pm 0.26) \times 10^{-3}$$

$$A_{CP|S}^{K^{*0}K^+} = (-0.26 \pm 0.56 \pm 0.18) \times 10^{-3}$$

- Most precise measurement to date

Preliminary

Systematic Uncertainties

- Kinematic equalisation of D_s^+ to D^+ samples
- Fit model
- Meson lifetimes
- Trigger selection

Cross-Checks

- Consistency over D momentum
- Impact of detection and reconstruction asymmetry studied with simulations and calibration samples
- Impact of production asymmetry negligible
- Method validated with 10k pseudoexperiments

CPV in $D^0 \to K^0_S K^\pm \pi^\mp$

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Motivation

- Cabibbo suppressed decay dominated by
  $D^0 \to K^{*\mp} K^\pm$
  $D^0 \to K^0_S K^{*0}$
- Theoretical predictions of larger CPV in $D^0 \to K^0 \bar{K}^0$ wrt $D^0 \to K^+ K^-$[1]
- Control samples of Cabibbo favored decays
  $D^0 \to K^- \pi^+ \pi^- \pi^+$
  $D^0 \to K^0_S \pi^+ \pi^-$

Strategy - Energy Test

- Unbinned, model independent search for local CPV[2]

$$T \equiv \frac{1}{2n(n-1)} \sum_{i,j\neq i}^{n} \psi_{ij} + \frac{1}{2\bar{n}(\bar{n}-1)} \sum_{i,j\neq i}^{\bar{n}} \psi_{ij} - \frac{1}{n\bar{n}} \sum_{i,j}^{n,\bar{n}} \psi_{ij}$$

Euclidean distance between two candidates in the phsp

$$\psi_{ij} = e^{-d_{ij}^2/2\delta^2}$$

Distance scale probed

[1] Phys. Rev. Lett. 119 (2017) 251801
[2] Phys. Rev. D84 (2011) 054015

Energy Test Significance

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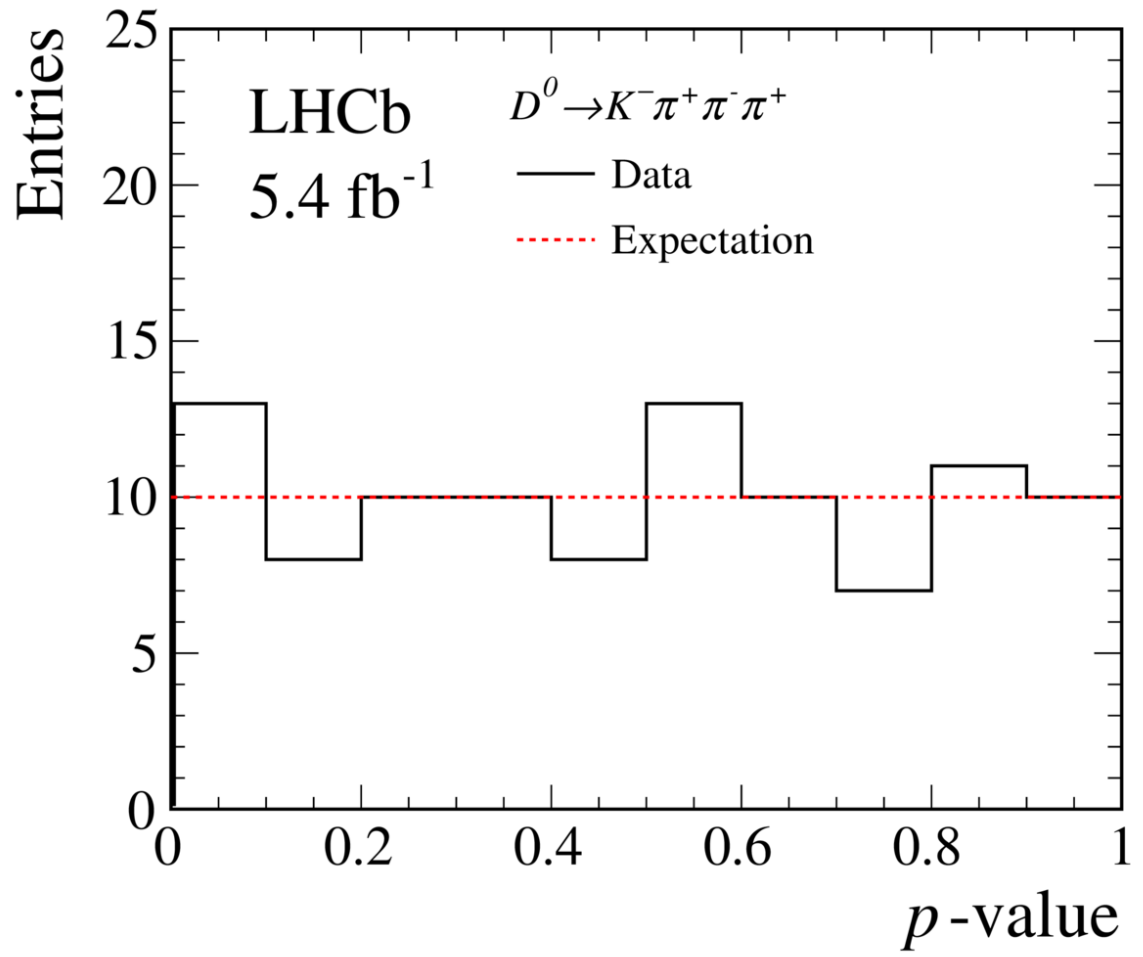
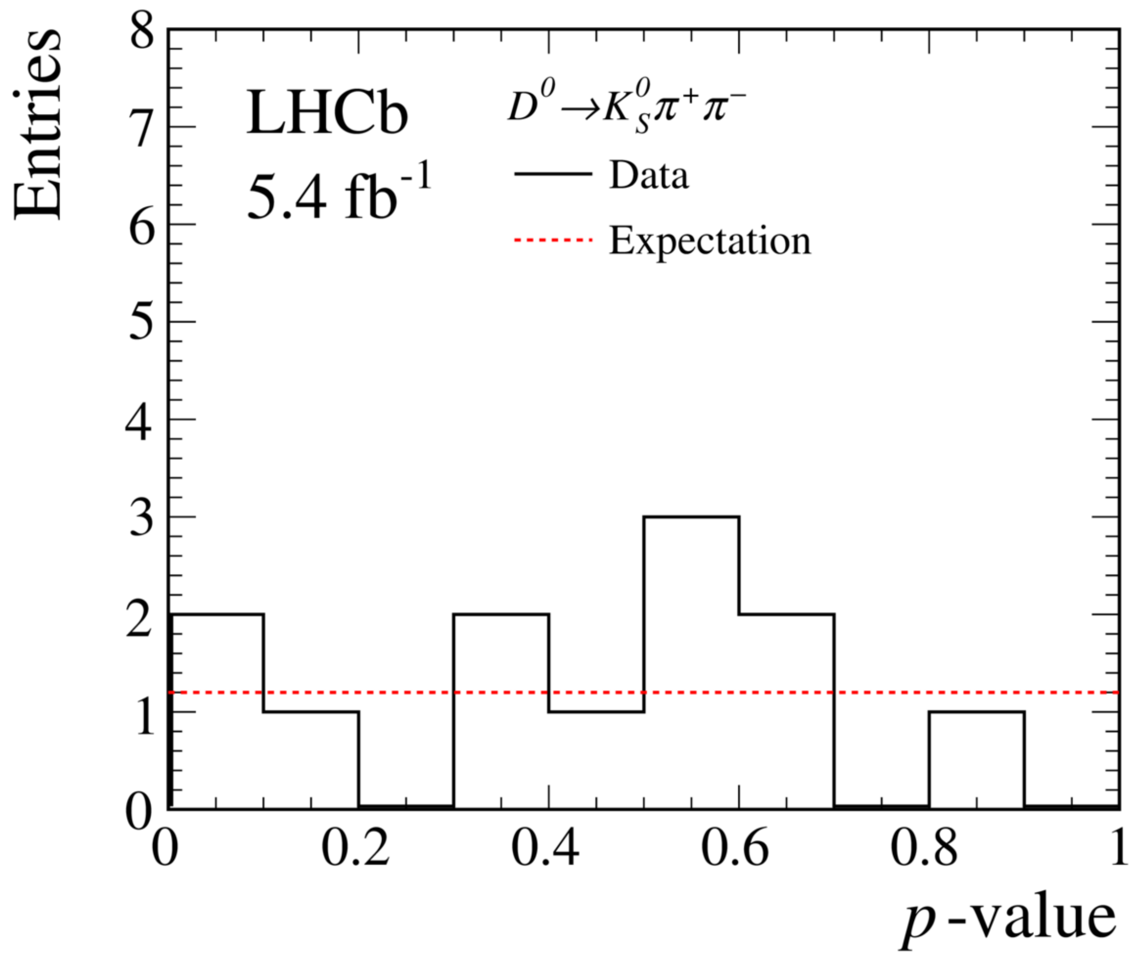
P-Value

- Distribution of H_0 built by sampling the dataset and randomly assigning the D^0 flavor to the candidate
- Fraction of samples with larger T value than the one from data gives the P-value

Cross-Checks

- Energy Test run on control samples by randomly splitting to a size comparable to the signal dataset
- Flat distribution of P-values found
- Similarly the effect of instrumental asymmetries can be checked





CPV in $D^0 \to K^0_S K^\pm \pi^\mp$ - Results

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Backgrounds

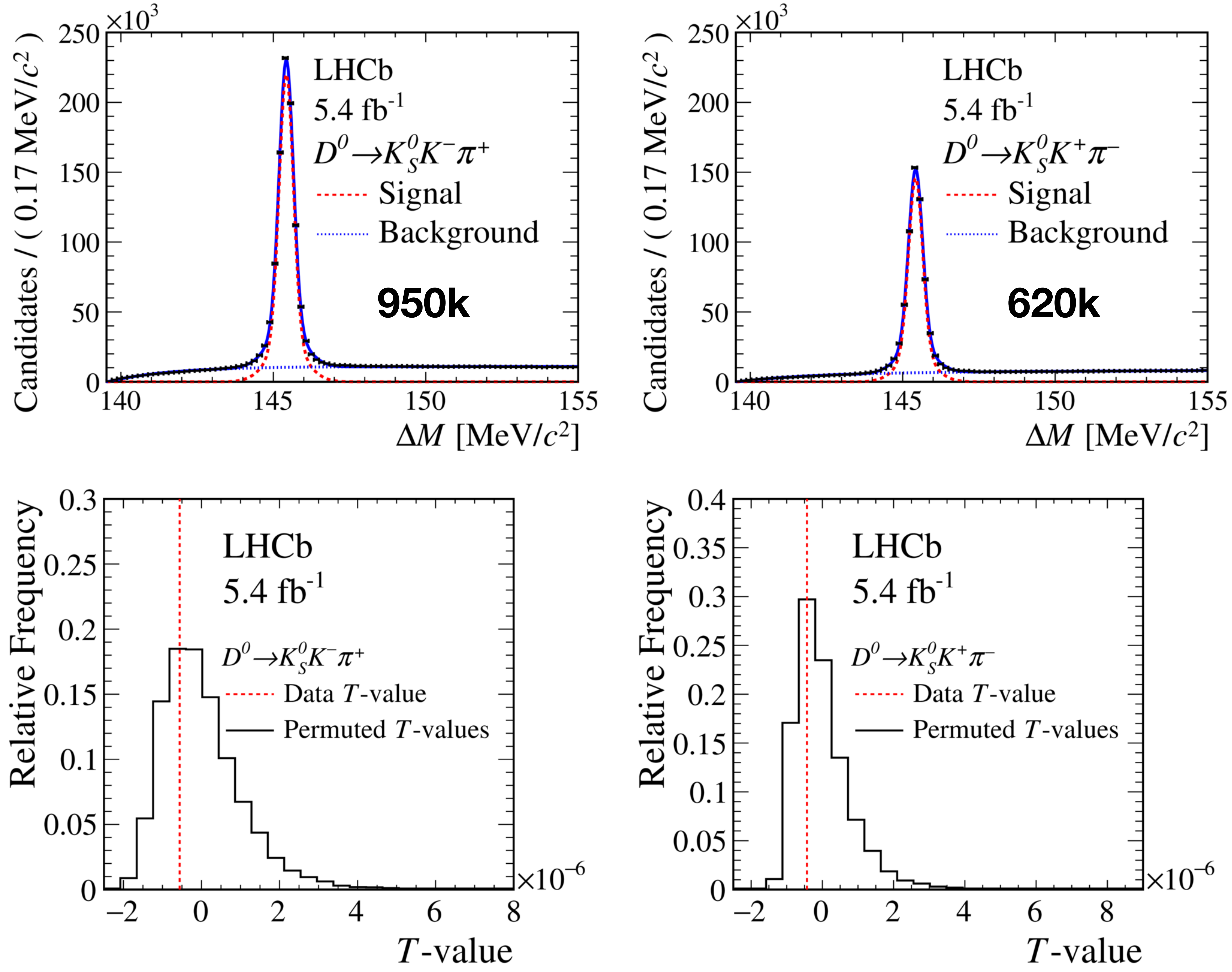
- **Combinatorial**
  Background-enhanced samples return flat P-values distributions
- **Physical**
  Simulated $D^0 \to K^0_S \pi^+ \pi^- \pi^0$, $D^0 \to K^0_S \pi^+ \pi^-$, and $D^0 \to K^0_S K^+ K^-$
  Found that when selected could not mimic CPV

No CPV Found

- **P-values**

$$D^0 \to K^0_S K^- \pi^+ : 70\,\%$$

$$D^0 \to K^0_S K^+ \pi^- : 66\,\%$$



LHCb Run2 (5.4/fb)

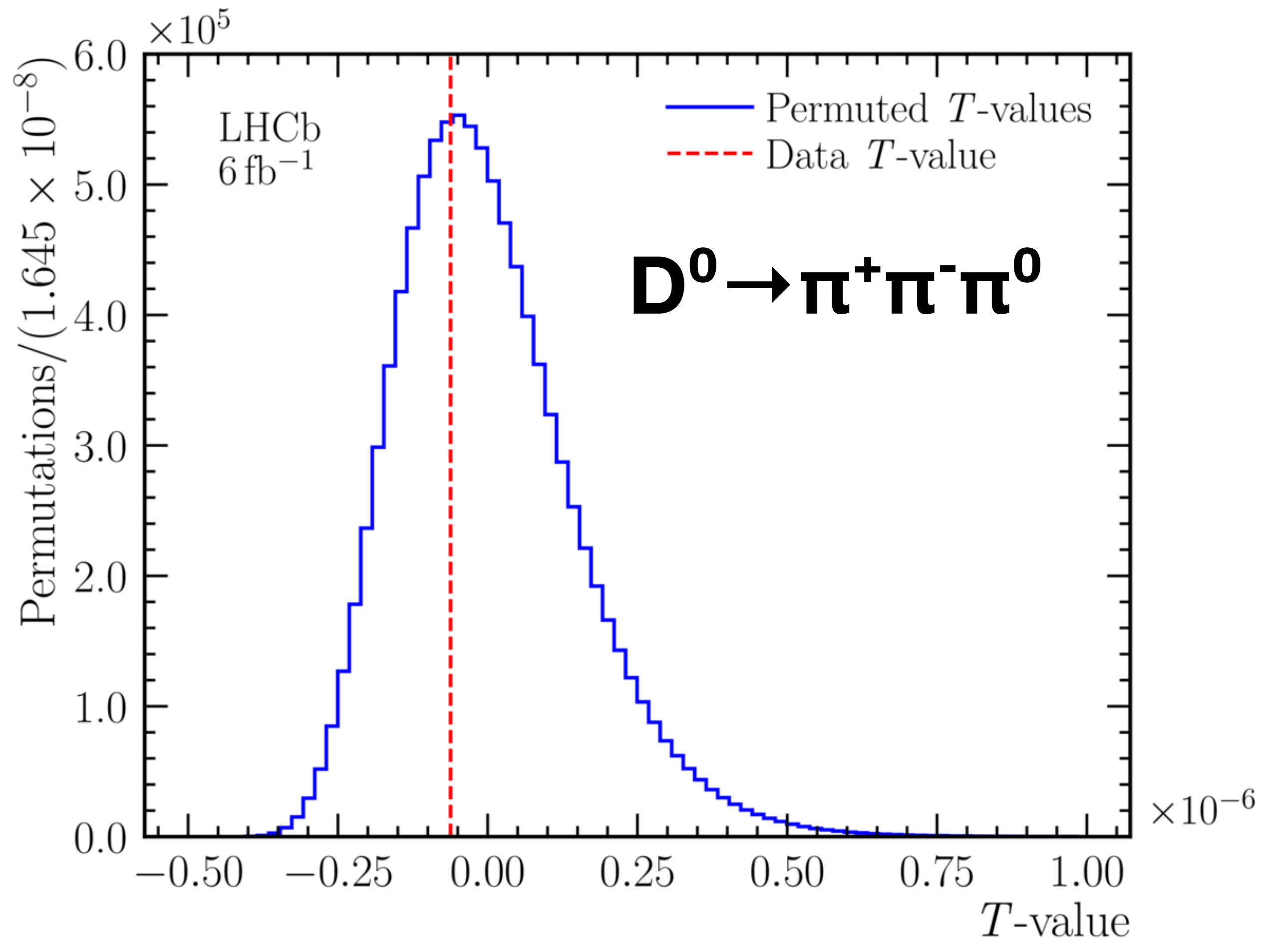
Honorable Mentions

Unbinned

- **Energy test on $D^0 \to \pi^+\pi^-\pi^0$**
  Run2 6/fb data - 2.5M D^0 decays
  P = 62%

Binned

- **Miranda technique on $D_{(s)}^+ \to K^+K^-K^+$**
  Run2 5.6/fb data - 1M D_s^+ and 1.3M D^+ decays
  $P(D^+)$ = 31.6%
  $P(D_s^+)$ = 13.3%



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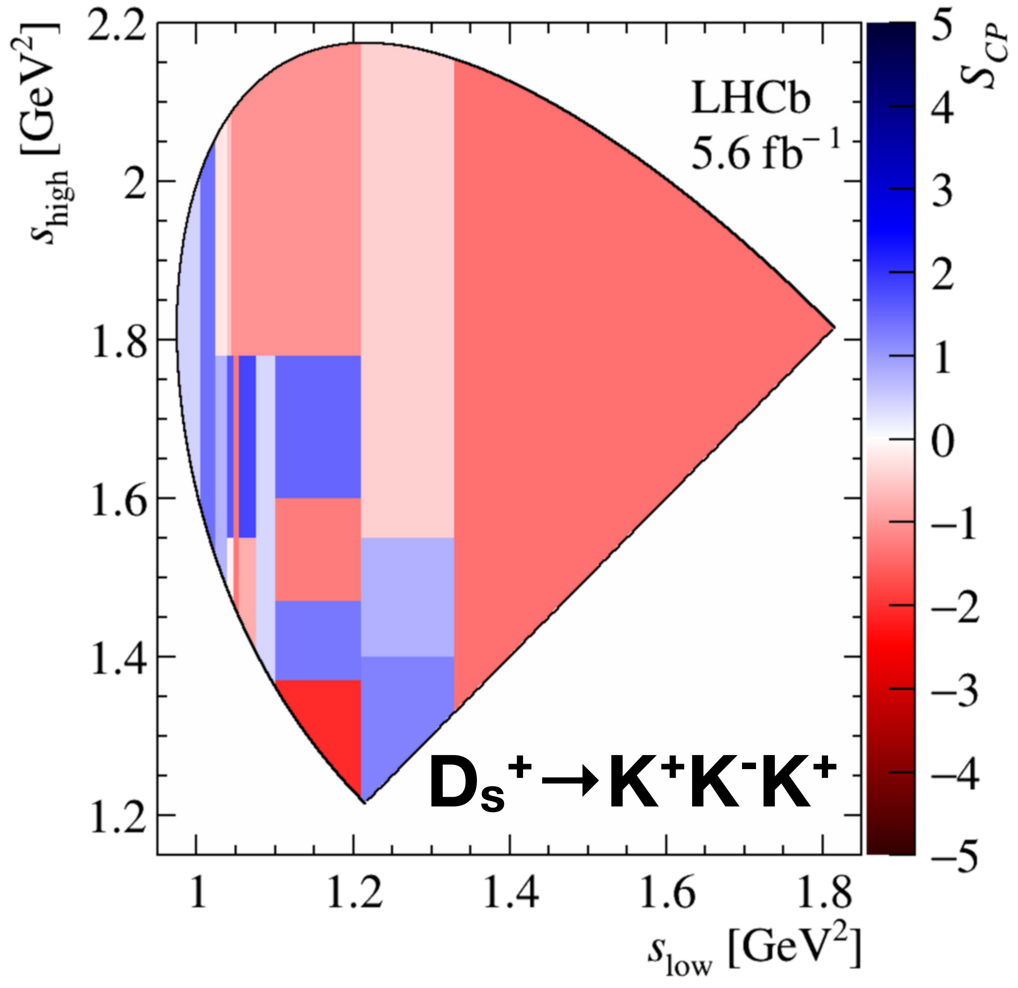

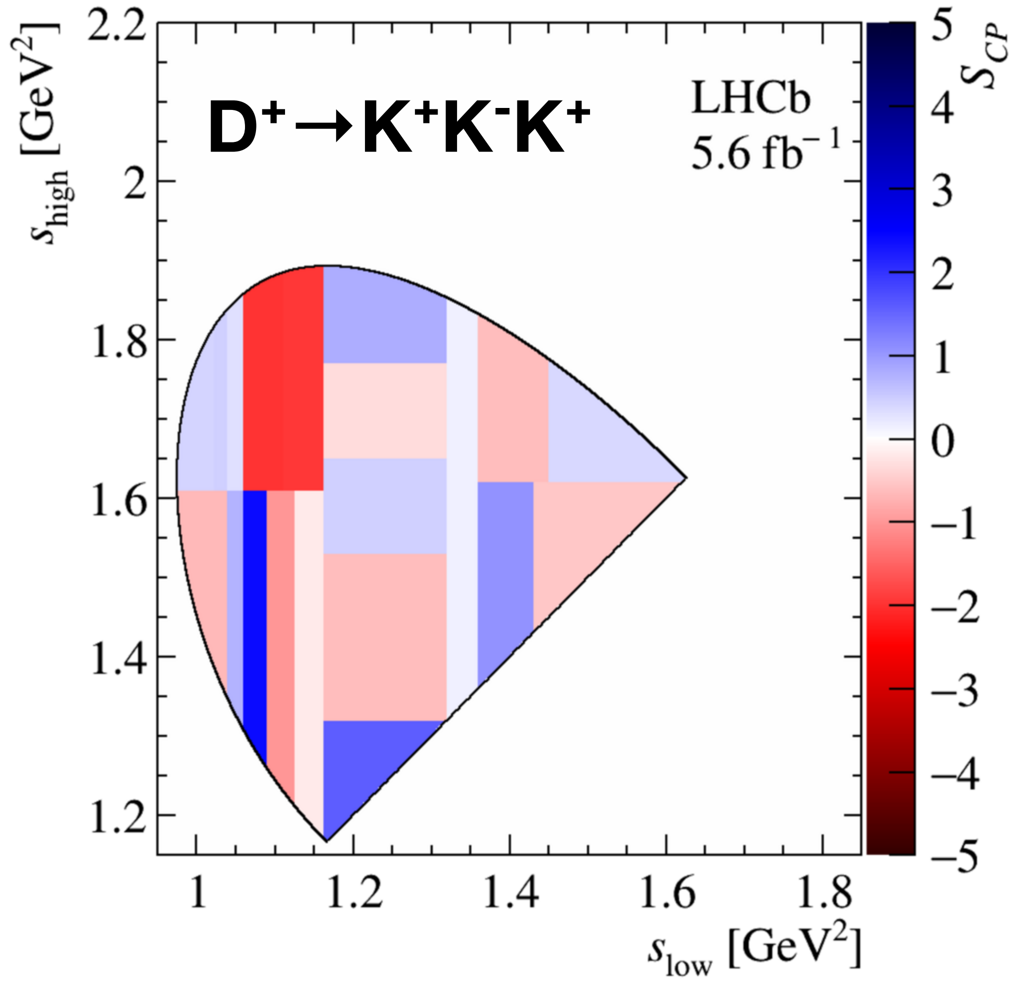

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Summary

Conclusions

CPV in Charm Still a Developing Field

- Observed in two-body decays
- Observing it in other decay channels would clarify the picture
- In recent years, significant effort has been dedicated to studying multi-body decays, aided by a comprehensive understanding of the LHCb detector

Run3 Data

- LHCb upgraded to record (among others) even larger charm datasets
- The precision on the two-body CPV will become even smaller
- The chances of observing it in other decay channels will increase; otherwise, we will impose stronger limits on CP violation in those channels
- A fully software-based trigger will simplify the analysis of the efficiency of multi-body decays