Direct CPV in D decays at LHCb

Jolanta Brodzicka [INP Krakow]
on behalf of LHCb

CKM2023 Santiago de Compostela

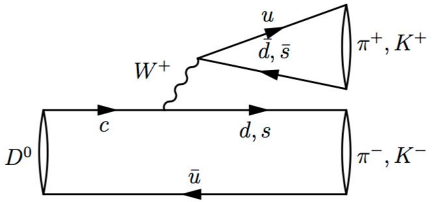
Outline

- Basics of direct CPV
- CP asymmetries in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$
- Search for CPV in $D_{(s)}^+ \to \eta^{(\prime)}\pi^+$ decays
- Search for CPV in $D_{(s)}^+ \to K^-K^+K^+$ with Miranda technique
- Examining $D^0 \to \pi^+\pi^-\pi^0$ and $D^0 \to K_S K \pi$ with Energy Test
- Summary

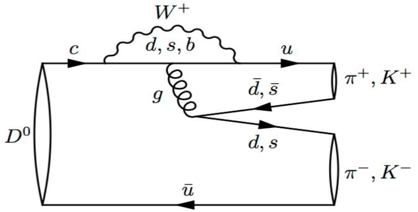
Basics of direct CPV

- Occurs in decays
- Results in asymmetries of decay widths (A_{CP}), amplitudes
- Requires two amplitudes with different weak and strong phases
- In charm decays realized through Tree + Penguin
- c⟶u Penguin is suppressed
  - b-loop is CKM suppressed
  - sd-loops are GIM suppressed, cancel in U-spin limit
- CPV in charm O(10^{-4}÷10^{-3}) within SM; depends on penguin size

Tree and Penguin contributions in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$



$$\mathcal{T} \simeq V_{ud}V_{cd}^*, V_{us}V_{cs}^*$$



$$\mathcal{P}_b \simeq \frac{m_b^2}{m_W^2} V_{ub}V_{cb}^*$$

$$\mathcal{P}_{sd} \simeq \frac{m_s^2 - m_d^2}{m_W^2}(V_{us}V_{cs}^* - V_{ud}V_{cd}^*)$$

Basics of direct CPV (II)

- Impact of phases on sensitivity to CPV
  - P-even asymmetry $$A_{CP} \equiv \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})} \simeq \left|\frac{\mathcal{P}}{\mathcal{T}}\right| \cos\Delta\phi_{weak} \boxed{\cos\Delta\phi_{strong}}$$
  - P-odd asymmetry e.g. triple-product or α-induced asymmetry [in $D_{(s)} \to 4h$, $\Lambda_c^+ \to \Lambda h^+$]

$$A_{CP}^{T-odd}, A_{CP}^{\alpha} \simeq \left|\frac{\mathcal{P}}{\mathcal{T}}\right| \cos\Delta\phi_{weak} \boxed{\sin\Delta\phi_{strong}}$$

- P-even and P-odd asymmetries are complementary
- Direct CPV is decay-dependent; penguin only in SCS decays
- Accessible through time-integrated measurements

What after the discovery?

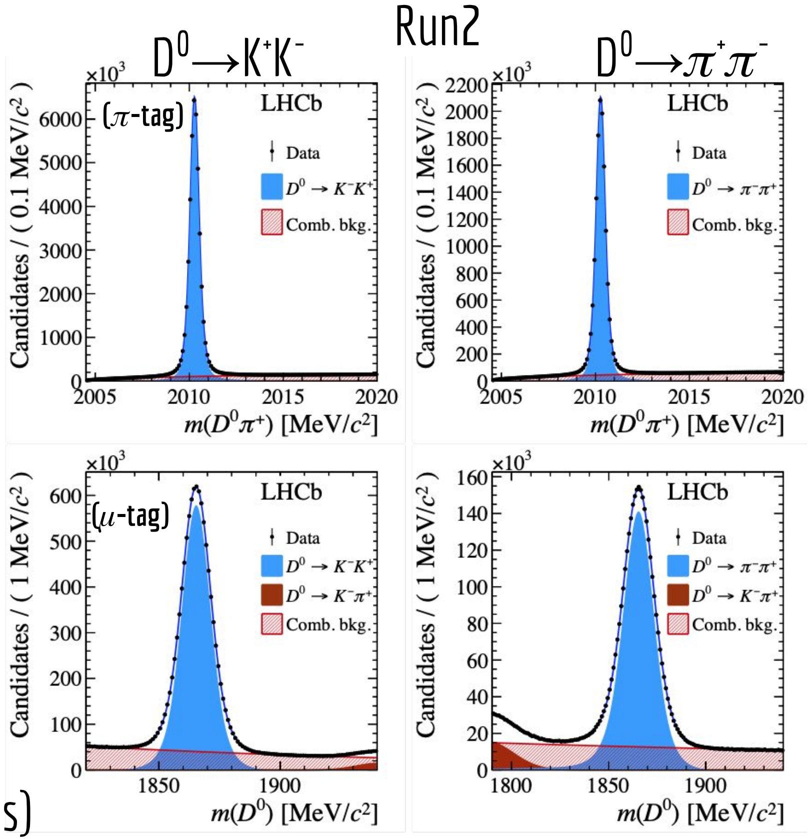
- Discovery of CPV in charm

$$\Delta A_{CP} \equiv A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$$

- LHCb Run1+Run2 data
- D^0 from $D^{*+} \to D^0\pi^+$ (π-tag) and B decays (μ-tag)

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4} \quad (5.3\sigma)$$

- The upper end of SM predictions. Is it SM or beyond?
- How about individual asymmetries within ΔA_{CP}?
- Other decays related to $D^0 \to h^+h^-$ (via $SU(3)_F$ or models)



From ΔA_{CP} to individual A_{CP}'s

- Measure $A_{CP}(D^0 \to K^+K^-)$ and disentangle $A_{CP}(D^0 \to \pi^+\pi^-)$ from ΔA_{CP}
- Run2 data, π-tagged sample: $D^0 \to K^+K^-$ from $D^{*+} \to D^0 \pi_{tag}^+$
- Measure raw asymmetry of signal yields

$$A_{raw}(D^0 \to K^+K^-) = \frac{N(D^0) - N(\bar{D}^0)}{N(D^0) + N(\bar{D}^0)}$$

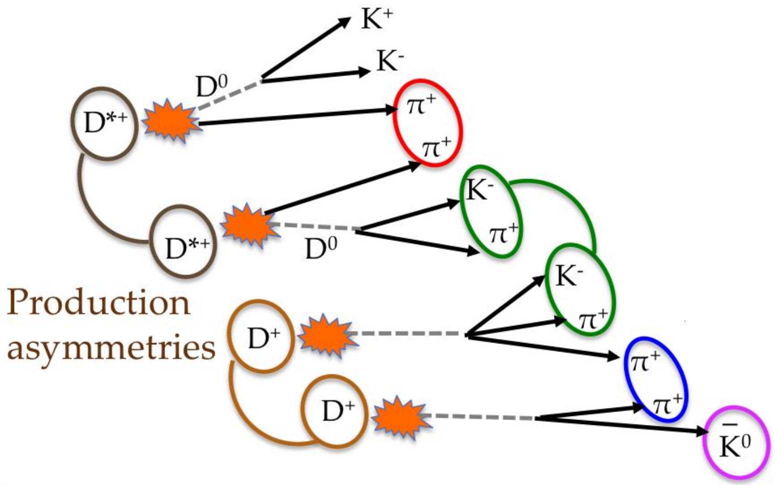
- Nuisance asymmetries of O(%) enter measured asymmetry [they cancel out in ΔA_{CP}]

$$A_{raw} \simeq A_{CP} + \boxed{A_{prod}(D^{*+})} + \boxed{A_{det}(\pi_{tag}^+)}$$

  - Production asymmetry: $\sigma(pp \to DX) < \sigma(pp \to \bar{D}X)$
  - Detection asymmetry: $\epsilon_{rec}(h^+) \neq \epsilon_{rec}(h^-)$ from different interactions with detector and detector asymmetries

Removing nuisance asymmetries

- Set of calibration CF decays of $D_{(s)}$ to overconstrain $A_{raw}(D^0 \to K^+K^-)$ and extract A_{CP}

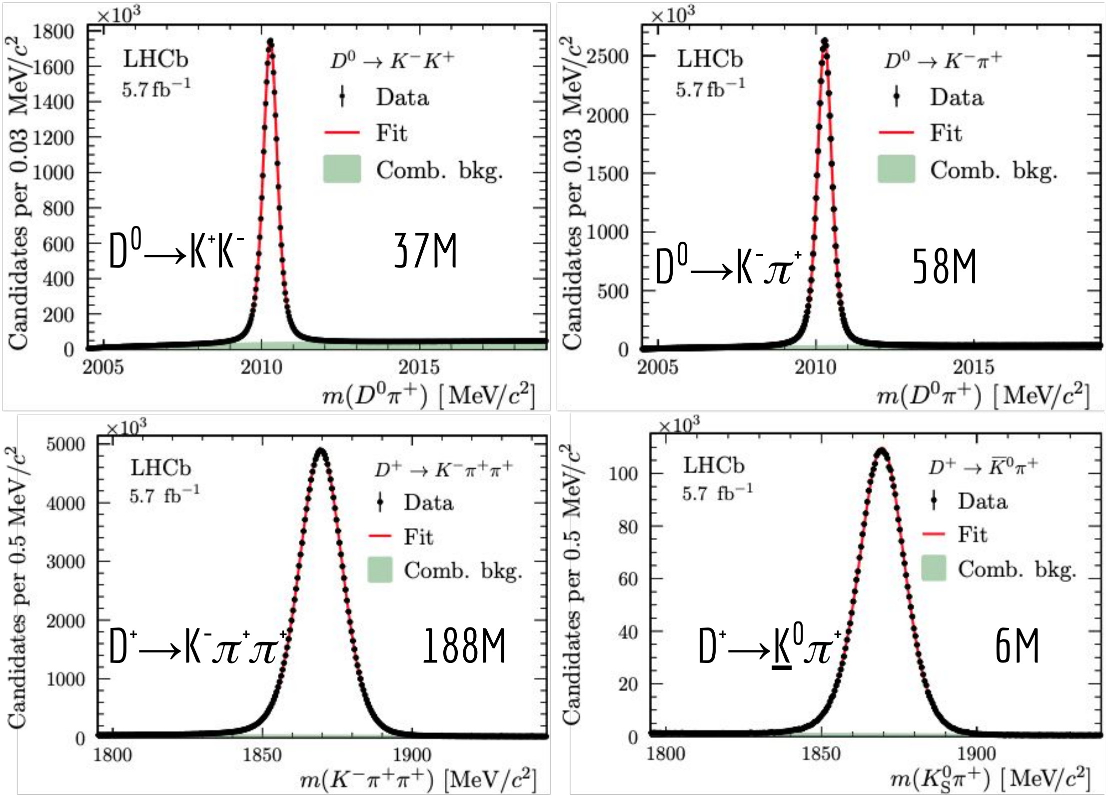


- A_{prod} and A_{det} depend on kinematics of underlying particles. Equalize kinematics of calibration and signal decays
- $A(\bar{K}^0)$ of $O(10^{-4})$, calculated from known interactions of K^0 and $\bar{K}^0$ with detector, and mixing/CPV in kaon system

- Two calibration methods to increase statistical sensitivity
  - with D^+ $\quad A_{CP}(K^+K^-) = A_{raw}(D^0 \to K^+K^-) - A_{raw}(D^0 \to K^-\pi^+) + A_{raw}(D^+ \to K^-\pi^+\pi^+) - A_{raw}(D^+ \to \bar{K}^0\pi^+) + A(\bar{K}^0)$
  - with D_s^+ $\quad A_{CP}(K^+K^-) = A_{raw}(D^0 \to K^+K^-) - A_{raw}(D^0 \to K^-\pi^+) + A_{raw}(D_s^+ \to \phi\pi^+) - A_{raw}(D_s^+ \to \bar{K}^0K^+) + A(\bar{K}^0)$

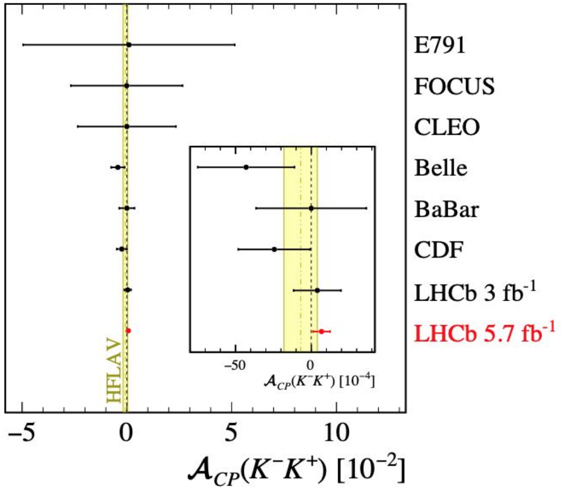
LHCb PRL 131, 091802 (2023)

Signal and calibration samples for D^+ method



LHCb PRL 131, 091802 (2023)

Individual direct CP asymmetries



- Combining two calibration methods gives

$$A_{CP}(D^0 \to K^+K^-) = (6.8 \pm 5.4 \pm 1.6) \times 10^{-4}$$

- A_{CP} is mostly from direct CPV with residual indirect CPV

$$A_{CP} \simeq a_{CP}^{dir} + \frac{\langle t \rangle}{\tau_D}\Delta Y \quad \Delta Y = -A_\Gamma(1 + y_{CP})$$

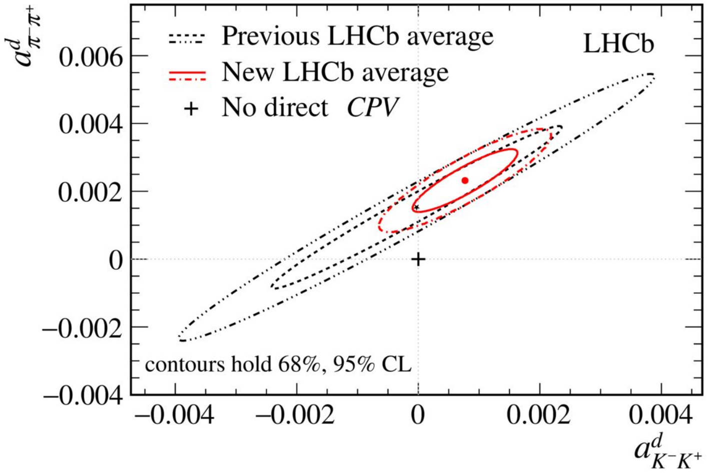
- Direct CP asymmetries extracted from $A_{CP}(D^0 \to K^+K^-)$ and ΔA_{CP}, and combined with Run1 results

$$a_{K^+K^-}^{dir} = (7.7 \pm 5.7) \times 10^{-4} \quad (1.4\sigma)$$
$$a_{\pi^+\pi^-}^{dir} = (23.2 \pm 6.1) \times 10^{-4} \quad (3.8\sigma)$$

First evidence!

- The sum breaks U-spin limit at 2.7σ

$$a_{K^+K^-}^{dir} + a_{\pi^+\pi^-}^{dir} = (30.8 \pm 11.4) \times 10^{-4}$$

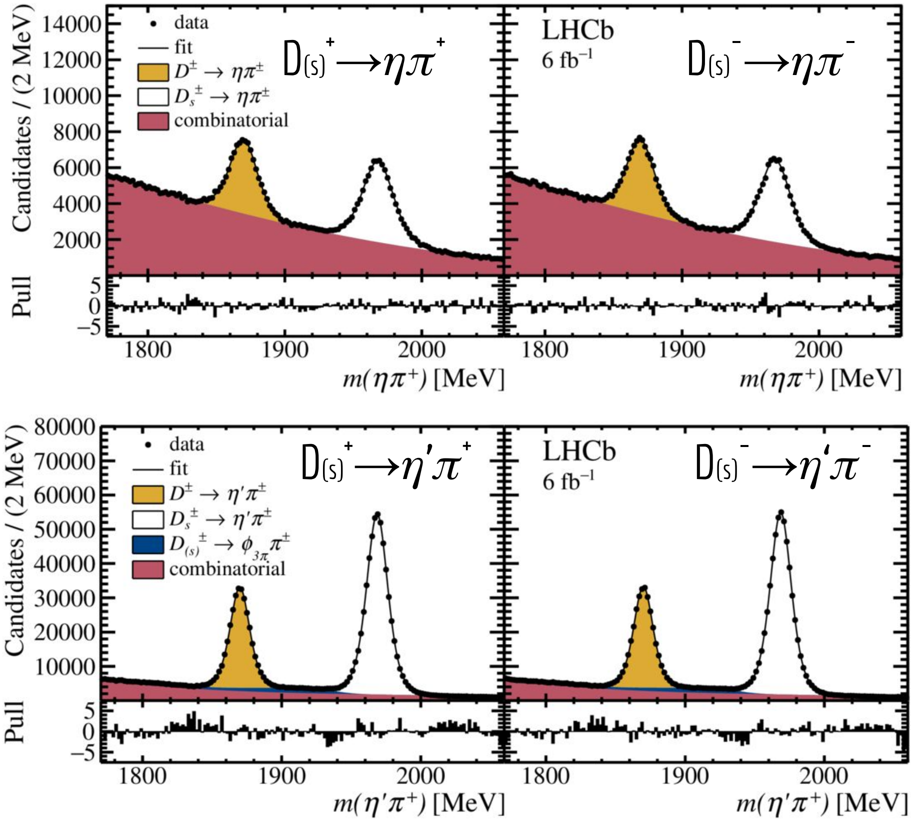


LHCb JHEP 04, 081 (2023)

Search for CPV in $D^+ \to \eta^{(\prime)}\pi^+$ and $D_s^+ \to \eta^{(\prime)}\pi^+$

- $D^+ \to \eta^{(\prime)}\pi^+$ are SCS decays (c⟶d<u>d</u>u, s<u>s</u>u), $D_s^+ \to \eta^{(\prime)}\pi^+$ are CF (c⟶s<u>d</u>u)
- Run2 data, with $\eta^{(\prime)} \to \pi^+\pi^-\gamma$
- $m(\eta^{(\prime)})$ constrained in $m(\eta^{(\prime)}\pi^+)$
- $D_{(s)}^+$ signals from fits to $m(\eta^{(\prime)}\pi^+)$
- x-check: $m(\eta^{(\prime)}\pi^+)$ fits in $m(\eta^{(\prime)})$ bins

- Total yields:
  0.1M of $D \to \eta\pi$, 0.6M of $D \to \eta'\pi$
  0.1M of $D_s \to \eta\pi$, 1.1M of $D_s \to \eta'\pi$



LHCb JHEP 04, 081 (2023)

Search for CPV in $D^+ \to \eta^{(\prime)}\pi^+$ and $D_s^+ \to \eta^{(\prime)}\pi^+$

- Nuisance asymmetries to account for

$$A_{raw}(D^+_{(s)} \to \eta^{(\prime)}\pi^+) \simeq A_{CP}(D^+_{(s)} \to \eta^{(\prime)}\pi^+) + A_{prod}(D^+_{(s)}) + A_{det}(\pi^+)$$

- Use $D_{(s)}^+ \to \phi\pi^+$ calibration channels, with $A_{CP}(D^+ \to \phi\pi^+) = (0.5 \pm 5.1) \times 10^{-4}$ and $A_{CP}(D_s^+ \to \phi\pi^+) = 0$

$$A_{CP}(D^+ \to \eta^{(\prime)}\pi^+) = A_{raw}(D^+ \to \eta^{(\prime)}\pi^+) - A_{raw}(D^+ \to \phi\pi^+) + A_{CP}(D^+ \to \phi\pi^+)$$

$$A_{CP}(D_s^+ \to \eta^{(\prime)}\pi^+) = A_{raw}(D_s^+ \to \eta^{(\prime)}\pi^+) - A_{raw}(D_s^+ \to \phi\pi^+) + \cancel{A_{CP}(D_s^+ \to \phi\pi^+)}$$

- Results consistent with CP symmetry

$$A_{CP}(D^+ \to \eta\pi^+) = (3.4 \pm 6.6 \pm 1.6 \pm 0.5) \times 10^{-3}$$
$$A_{CP}(D^+ \to \eta'\pi^+) = (4.9 \pm 1.8 \pm 0.6 \pm 0.5) \times 10^{-3}$$

$$A_{CP}(D_s^+ \to \eta\pi^+) = (3.2 \pm 5.1 \pm 1.2) \times 10^{-3}$$
$$A_{CP}(D_s^+ \to \eta'\pi^+) = (0.1 \pm 1.2 \pm 0.8) \times 10^{-3}$$

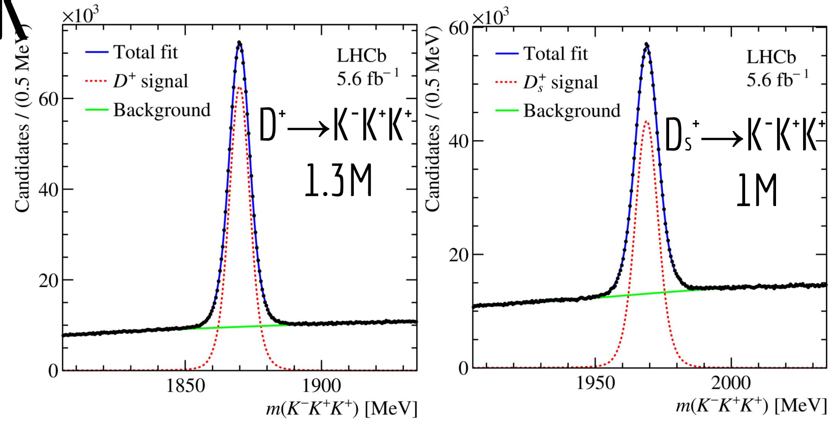
CPV in multibody $D_{(s)}$ decays

- Weak amplitudes as in two-body decays
- Similarities between $D^0 \to \pi^+\pi^-\pi^0$ and $D \to \pi\pi$, $D^0 \to K_S K^- \pi^+$ and $D \to KK$
- *Complications* arise from strong amplitudes
- But rich dynamics (resonances, rescattering, partial-waves) assure large strong-phase variation across decay phase-space ⇨ increase sensitivity to CPV

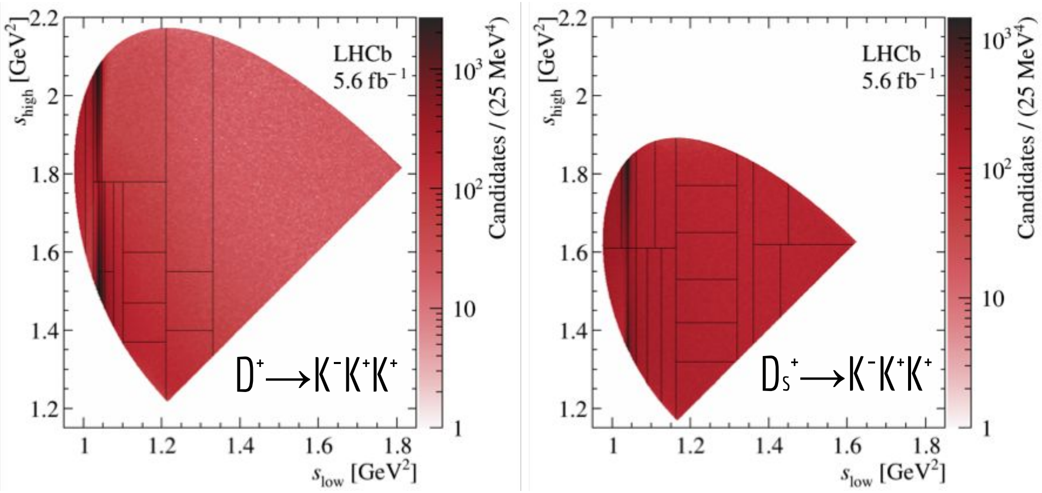
- Probe $D_{(s)}$ decay phase-space to search for local CPV
  - Model-dependent amplitude analysis: CP asymmetry per amplitude
  - Model-independent techniques: discovery tools checking consistency with CP symmetry

Search for CPV in $D_{(s)}^+ \to K^- K^+ K^+$

- $D^+ \to K^- K^+ K^+$ is DCS, while $D_s^+ \to K^- K^+ K^+$ is SCS
- S-wave dominated decays LHCb JHEP 04, 063 (2019)
- Run2 data, signal significance optimised with BDT
- Dalitz plots folded into higher vs. lower $m^2(K^+K^-)$



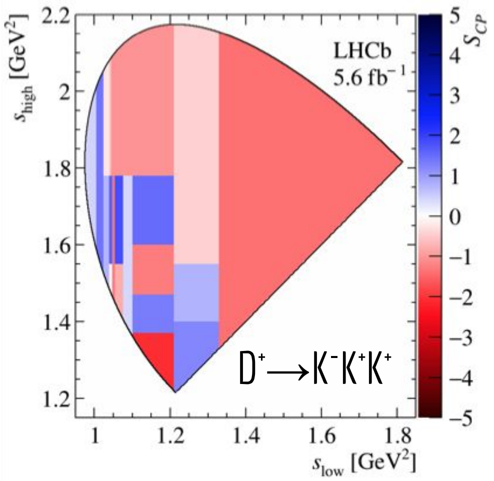
- ϕ state + broad S-wave
- 21 bins of similar statistics
- For CPV test, bckgd. subtracted with $m(K^- K^+ K^+)$ fits in Dalitz bins

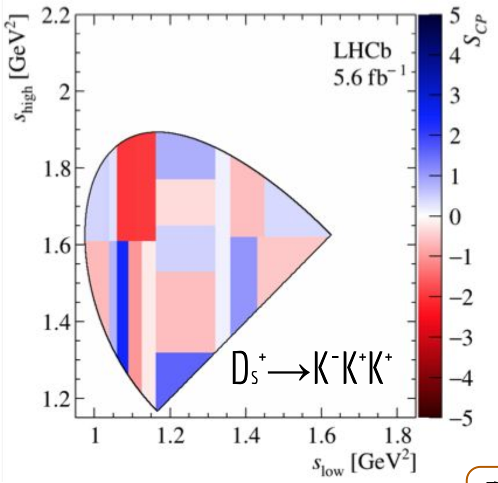


LHCb JHEP 07, 067 (2023)

Miranda Test for $D_{(s)}^+ \to K^-K^+K^+$ decays

- Local-CPV observable in i-th Dalitz bin $\mathcal{S}_{CP}^i = \frac{N^i(D_{(s)}^+) - \alpha N^i(D_{(s)}^-)}{\sqrt{\alpha(\delta^2_{N^i(D_{(s)}^+)} + \delta^2_{N^i(D_{(s)}^-)})}}$, with $\alpha = \frac{\sum_i N^i(D_{(s)}^+)}{\sum_i N^i(D_{(s)}^-)}$
- S_{CP} is significance of difference between $D_{(s)}^+$ and $D_{(s)}^-$ signals





- p-value=32% p-value=13%

- With no-CPV, S^i_{CP} follows standard normal distribution
- χ^2 test, $\chi^2 = \Sigma(S^i_{CP})^2$ ndf=nbins-1
- Give p-value for consistency with no-CPV hypothesis

Both consistent with CP symmetry

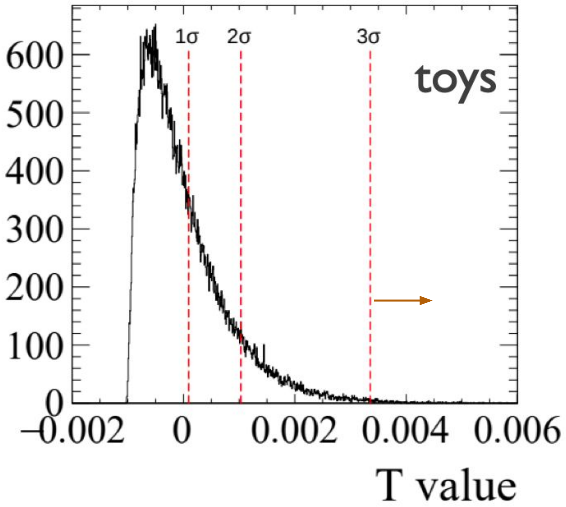
PRD 84, 054015 (2011)
J. Phys. G44, 085001 (2017)

Energy Test

- Unbinned method for statistical comparison of two distributions, e.g .D and D̄ phase space
- Test Statistics based on distance of event pairs (ij)

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

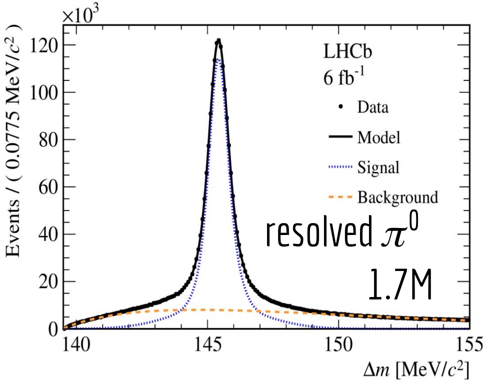
Average distance in D sample   in D̄ sample   between D and D̄

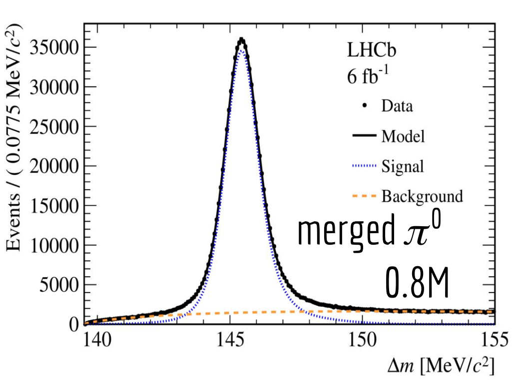


- Distance function $\psi(d_{ij}) = \exp(-d_{ij}^2/2\delta)$
- Distance in Dalitz space $d_{ij}^2 = (\Delta s_{12})_{ij}^2 + (\Delta s_{13})_{ij}^2 + (\Delta s_{23})_{ij}^2$
- Compare measured T_0 value with T-distribution for CP-symmetrized sample (permutations)
- p-value= n(T>T_0)/n for no-CPV hypotheis

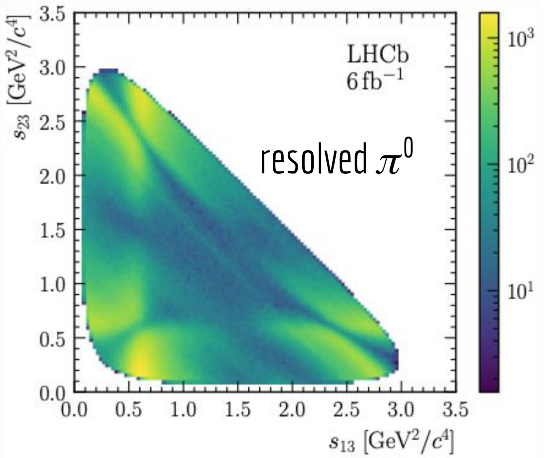
Search for CPV in $D^0 \to \pi^+\pi^-\pi^0$

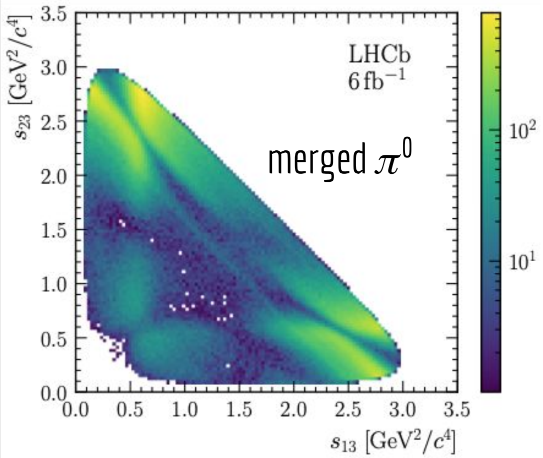
- SCS decays
- p-value≃2% in Run1 PLB 740, 158 (2015)
- Run2 data, D^0 from $D^{*+} \to D^0 \pi_{tag}^+$
- Resolved and merged $\pi^0 \to \gamma\gamma$
- BDT selection for resolved sample





- $\rho^\pm, \rho^0$ dominate Dalitz space
- Efficiency drop for low-p_T π^0 in merged sample

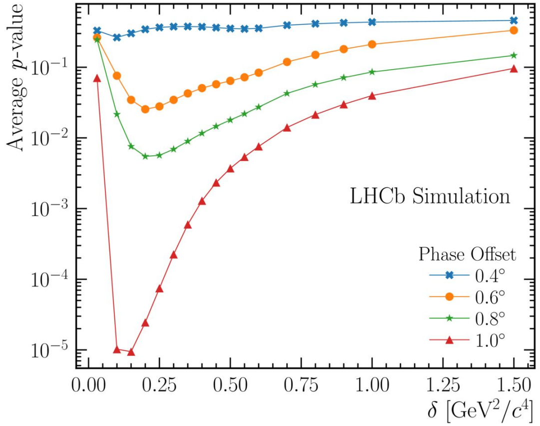




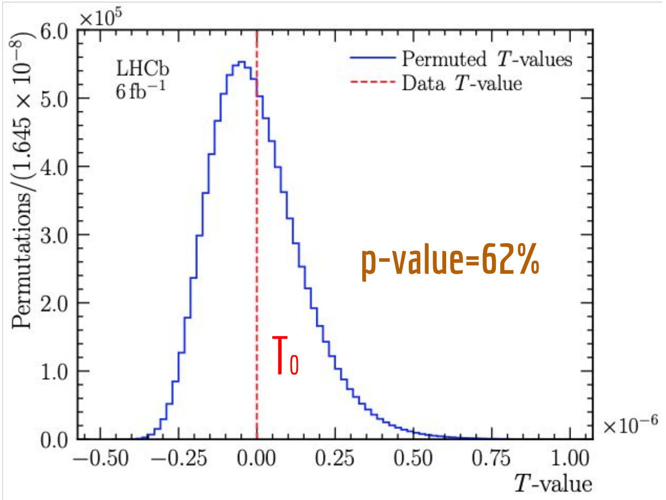
Energy Test for $D^0 \to \pi^+ \pi^- \pi^0$

- For combined merged and resolved samples
- Optimisation of δ metric parameter with *realistic* toys

  CPV induced via phase offset between $D^0 \to \rho^- \pi^+$ and $\bar{D}^0 \to \rho^+ \pi^-$



- Measurement for data



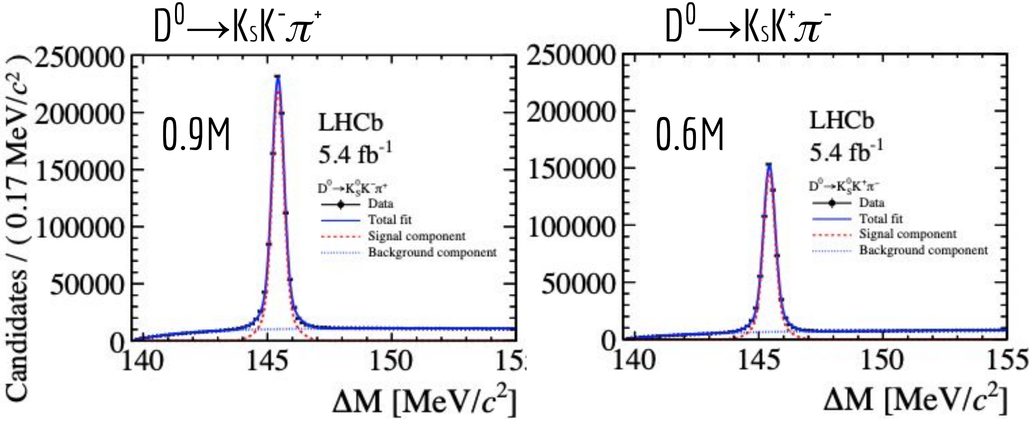
- Data consistent with CP symmetry

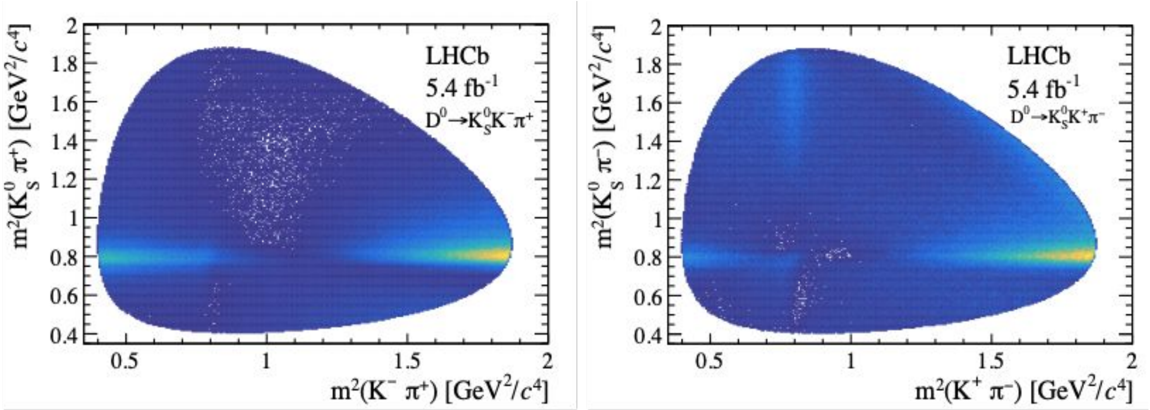
- Method validated with $D^0 \to K^- \pi^+ \pi^0$, toys with detection asymmetries, Δm sidebands

LHCb-PAPER-2023-019

Search for CPV in $D^0 \to K_S K^- \pi^+$ and $D^0 \to K_S K^+ \pi^-$ PRELIMINARY

- SCS decays
- Model-dependent search in Run1
  PRD 93, 052018 (2016)
- Run2 data, D^0 from $D^{*+} \to D^0 \pi_{tag}^+$
- $K_S \to \pi^+ \pi^-$ inside or outside VELO



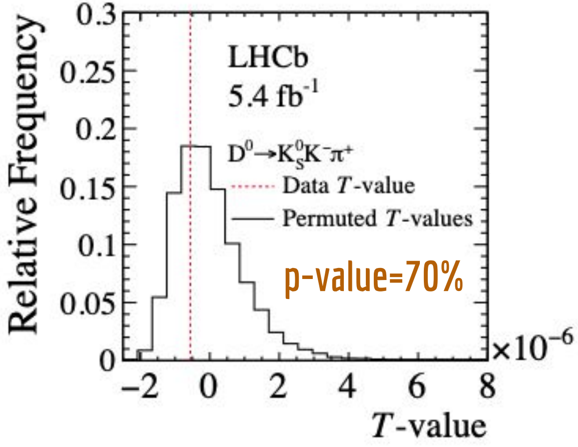


PRELIMINARY

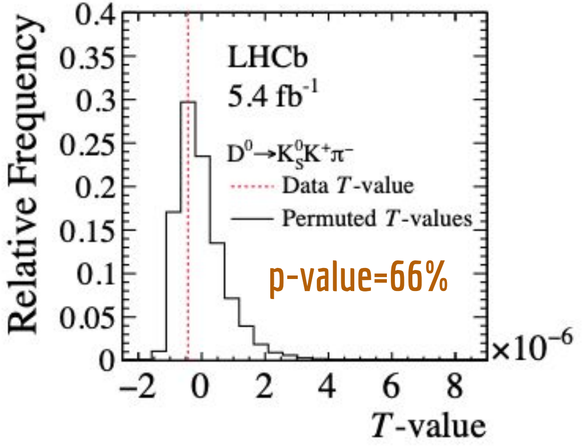
Energy Test for $D^0 \to K_S K^- \pi^+$ and $D^0 \to K_S K^+ \pi^-$

- Optimal metric parameter $\delta \simeq 0.2$ GeV^2
- Sensitivity to CPV scenarios with phase offset≃2° or amplitude difference≃2% between D^0 and $\bar{D}^0$ in $\bar{D}^0 \to K^{*\pm} K^{\mp}$
- Data consistent with no-CPV

$D^0 \to K_S K^- \pi^+$



$D^0 \to K_S K^+ \pi^-$



- Method validated with $D^0 \to K^- \pi^+ \pi^- \pi^+$ and $D^0 \to K_S \pi^+ \pi^-$ decays, and Δm sidebands

Summary

- Large charm samples at LHCb give a unique opportunity for CP violation searches
- Milestone: CPV discovery through ΔA_{CP} in 2019
- First evidence in individual channel, $D^0 \to \pi^+\pi^-$

$$a^{dir}_{\pi^+\pi^-} = (23.2 \pm 6.1) \times 10^{-4} \quad (3.8\sigma)$$

- Recent searches in other two-body channels, $D^0 \to K^+K^-$ and $D_s^+ \to \eta^{(\prime)}\pi^+$
- Testing multibody decays for local CPV

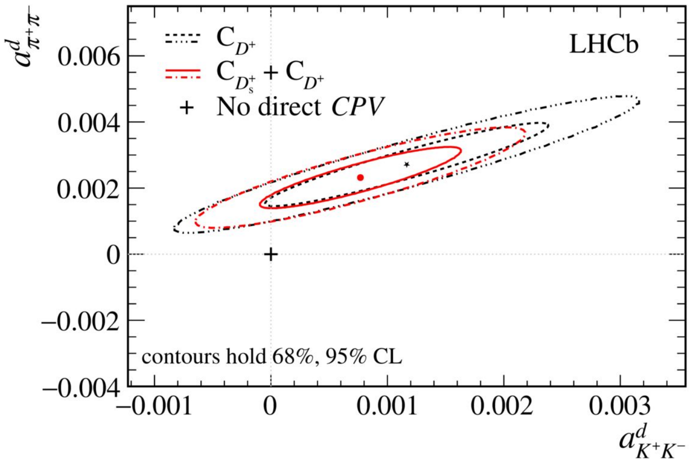
  $D_{(s)}^+ \to K^-K^+K^+$, $D^0 \to \pi^+\pi^-\pi^0$ and $D^0 \to K_S K^\pm \pi^\mp$ All consistent with CP symmetry
- More to come with Run2 data

Backup slides

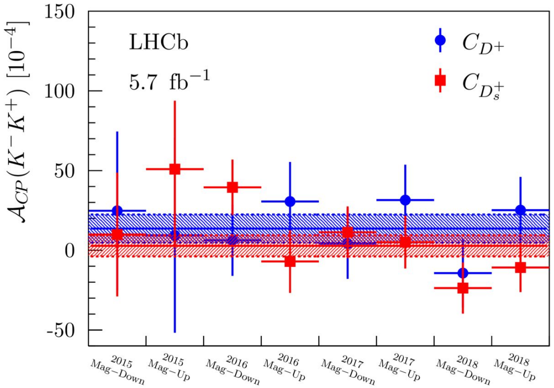
Cross-checks in $A_{CP}(D^0 \to K^+K^-)$

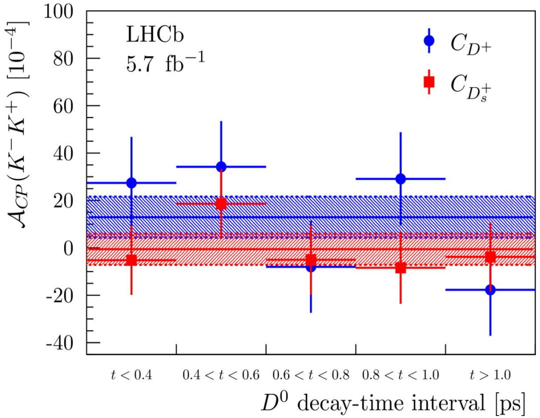
- A_{CP} from two methods, correlations: 0.05 (stat), 0.28 (syst)

$$C_{D^+}: \ \mathcal{A}_{CP}(K^-K^+) = [13.6 \pm 8.8\,(\text{stat}) \pm 1.6\,(\text{syst})] \times 10^{-4},$$
$$C_{D_s^+}: \ \mathcal{A}_{CP}(K^-K^+) = [\ 2.8 \pm 6.7\,(\text{stat}) \pm 2.0\,(\text{syst})] \times 10^{-4},$$



- Stability against various conditions

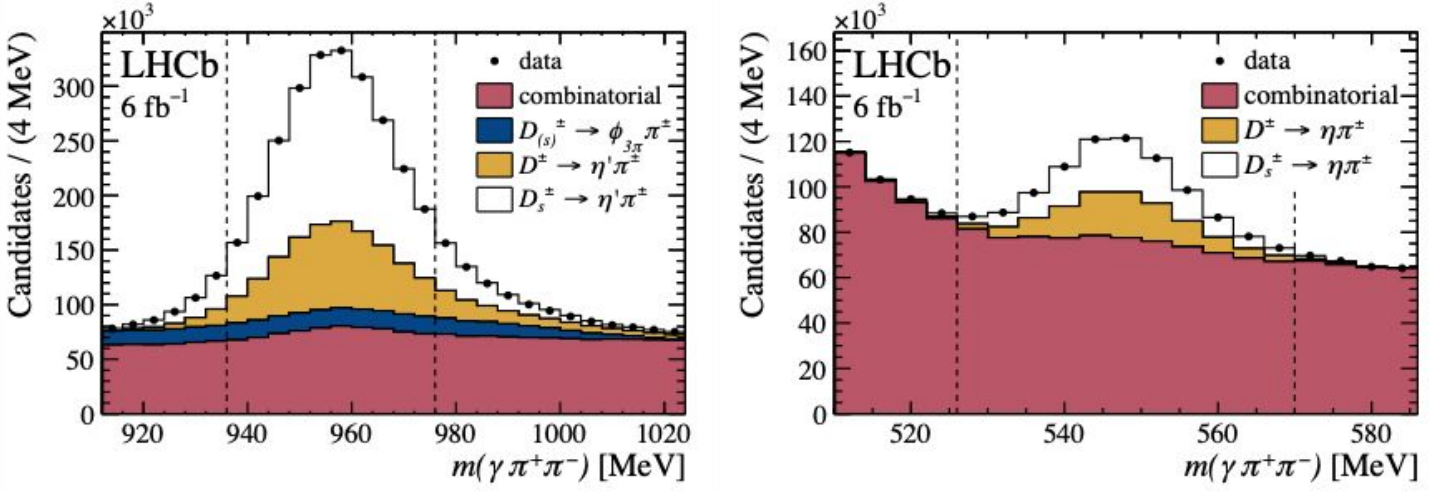




LHCb JHEP 04, 081 (2023)

Search for CPV in $D_{(s)}^+ \to \eta\pi^+$ and $D_{(s)}^+ \to \eta'\pi^+$

- Fits to $m(\eta^{(\prime)}\pi^+)$ in $m(\eta^{(\prime)})$ bins to check for non-$\eta^{(\prime)}$ background



- $D_{(s)}^+$ signal contains correctly reconstructed $\eta^{(\prime)}$ signal
- Small background from random combinations of correct $\eta^{(\prime)}$

LHCb JHEP 04, 081 (2023)

Search for CPV in $D_{(s)}^+ \to \eta\pi^+$ and $D_{(s)}^+ \to \eta'\pi^+$

Table 1: Systematic uncertainties associated to values of $\mathcal{A}^{\rm raw}$ (%).

Source	$D_s^+ \to \eta'\pi^+$	$D^+ \to \eta'\pi^+$	$D_s^+ \to \eta\pi^+$	$D^+ \to \eta\pi^+$
Fit model, signal	0.04	0.04	0.10	0.16
Fit bias	0.01	0.01	0.01	0.02
Secondary decays	0.06	0.03	0.06	0.03
$\mathcal{A}^{\rm KK}$	0.01	0.02	0.01	0.02
Fit model, control	0.03	0.00	0.03	0.00
Weighting	0.01	0.01	0.02	0.00
Total	0.08	0.06	0.12	0.16

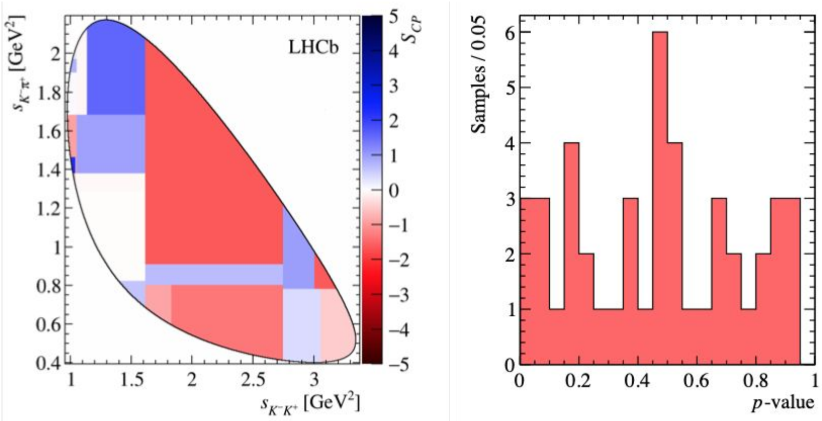
- 1% correlation btw A_{CP} of $D_{(s)}^+$ channels due to using shared control mode $D_{(s)}^+ \to \phi\pi^+$
- Combination with Run1 PLB 771, 21 (2017) and Run2 results for $D_{(s)}^+ \to \eta\pi^+$ with $\eta \to e^+ e^- \gamma$ JHEP 06, 019 (2021)

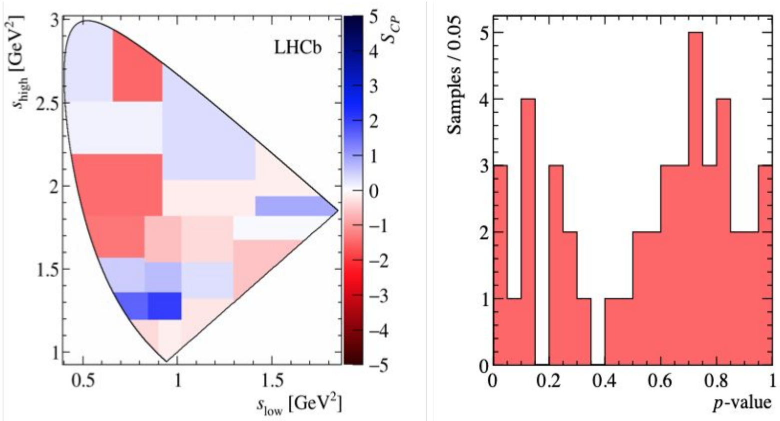
$$\mathcal{A}^{CP}(D^+ \to \eta\pi^+) = (0.34 \pm 0.66 \pm 0.16 \pm 0.05)\%,$$
$$\mathcal{A}^{CP}(D_s^+ \to \eta\pi^+) = (0.32 \pm 0.51 \pm 0.12)\%,$$
$$\mathcal{A}^{CP}(D^+ \to \eta'\pi^+) = (0.49 \pm 0.18 \pm 0.06 \pm 0.05)\%,$$
$$\mathcal{A}^{CP}(D_s^+ \to \eta'\pi^+) = (0.01 \pm 0.12 \pm 0.08)\%,$$

LHCb JHEP 07, 067 (2023)

Search for CPV in $D_{(s)}^+ \to K^- K^+ K^+$ decays

- Sensitivity to (local) nuisance asymmetries tested with CF decays, with various binning schemes
- $D_s^+ \to K^- K^+ \pi^+$ $D^+ \to K^- \pi^+ \pi^+$



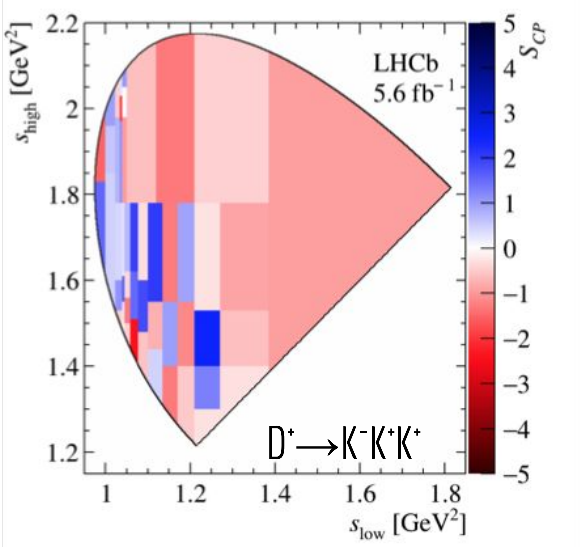


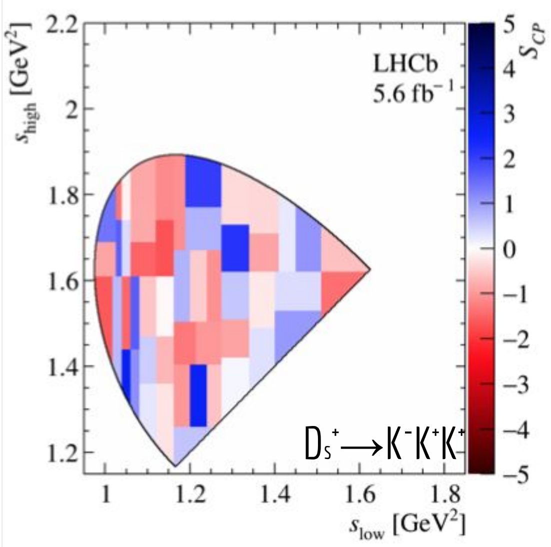
- p-value distributions for CF samples split into subsamples of signal-like statistics

LHCb JHEP 07, 067 (2023)

Miranda Test for $D_{(s)}^+ \longrightarrow K^-K^+K^+$ decays

- Alternative binning schemes [50 bins]

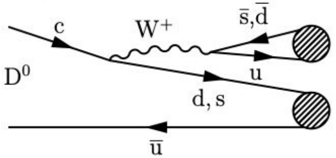




- p-value= 8% p-value=10%

Quark diagrams for $D^0 \to K_S K^- \pi^+$ and $D^0 \to K_S K^+ \pi^-$

- $D^0 \to K_S K^- \pi^+$ favoured over $D^0 \to K_S K^+ \pi^-$ (BF ratio~0.65) [*]
- External W-emission, SCS

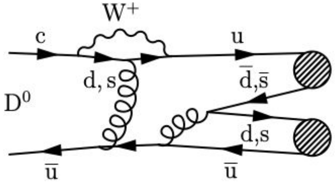


$K^{*+} \to K_S \pi^+$, $a^+ \to K_S K^+$

$K^{*-} \to K_S \pi^-$, $a^- \to K_S K^-$

[*] $BR(D^0 \to K^*(892)^+ K^-) > BR(D^0 \to K^*(892)^- K^+)$, as respectively K^{*+} and K^+ couple to W^+

- Penguin diagram

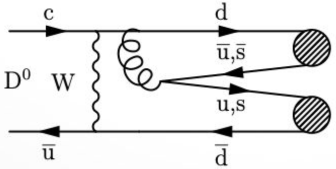


$K^{*+} \to K_S \pi^+$, $a^+ \to K_S K^+$

$K^{*-} \to K_S \pi^-$, $a^- \to K_S K^-$

- W-exchange, SCS & colour suppressed

the only way to get $K^{*0}\underline{K}^0$ and $K^0\underline{K}^{*0}$; they contribute with opposite signs

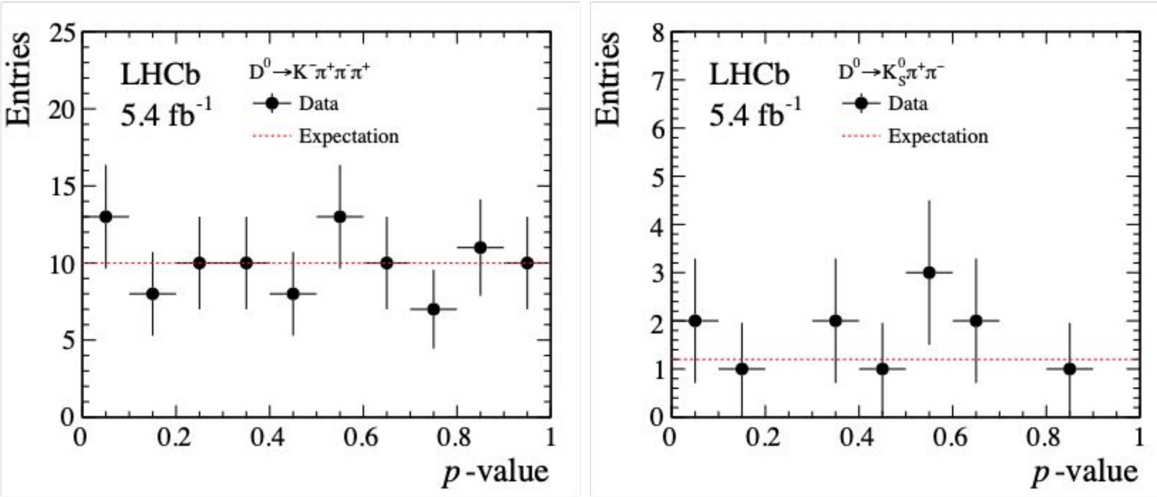


$K^{*0} \to K^+ \pi^-$, $a^- \to K_S K^-$

$\underline{K}^{*0} \to K^- \pi^+$, $a^+ \to K_S K^+$

Energy Test for $D^0 \to K_S K^- \pi^+$ and $D^0 \to K_S K^+ \pi^-$

- Method validation with CF-dominated decays, $D^0 \to K^- \pi^+ \pi^- \pi^+$ and $D^0 \to K_S \pi^+ \pi^-$



- No sensitivity to detection asymmetries of $K\pi$ system or K_S related asymetries