universität freiburg

Charm Physics at LHCb

FSP Jahrestreffen der deutschen LHCb-Gruppen

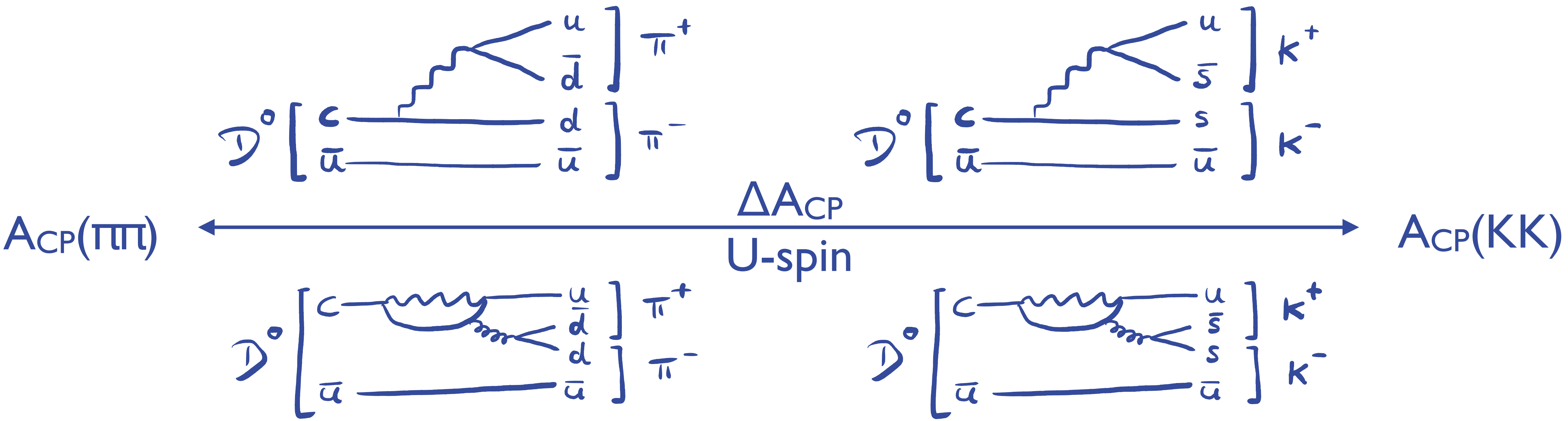
Prof. Dr. Marco Gersabeck

Bochum, 23-24 September 2024

Why do charm (CP violation) physics at LHCb?

- Because the field is only just getting started
  - CP violation discovered in two-body D^0 decays in 2019
  - Expect to see related effects in other decay modes
  - Time-dependent CP violation remains to be discovered
- Up-quark sector may yet hold some surprises
  - Excellent sensitivity to BSM contributions, but challenging SM calculations
- Because LHCb is the best place to do it
  - LHCb $c\bar{c}$ yield per fb^{-1} is a factor of 1600 greater than Belle II's yield per ab^{-1}
    - Even allowing for reconstruction efficiencies, Belle II will never reach our Run 1+2 yields in final states with charged particles only
  - Boost and detectors provide excellent decay-time resolution
- It's our responsibility to exploit these opportunities fully

$D^0 \to PP$



u
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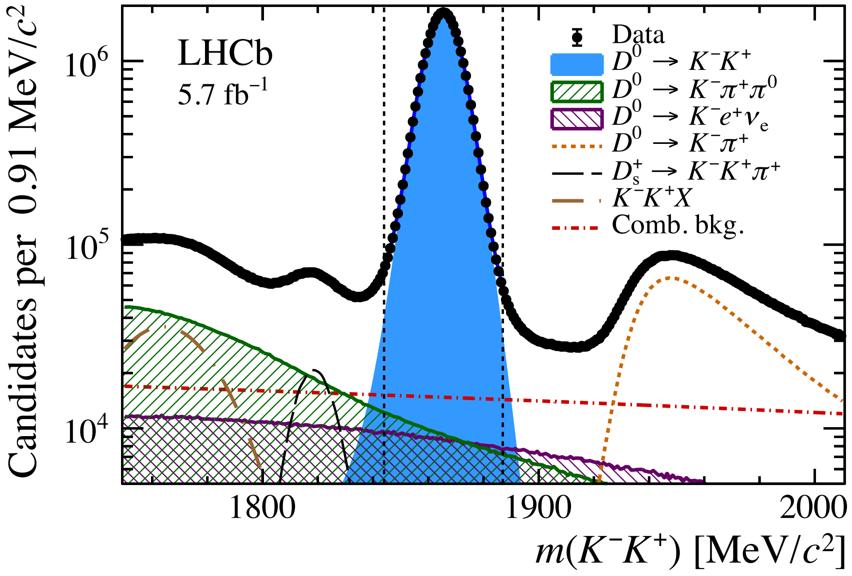
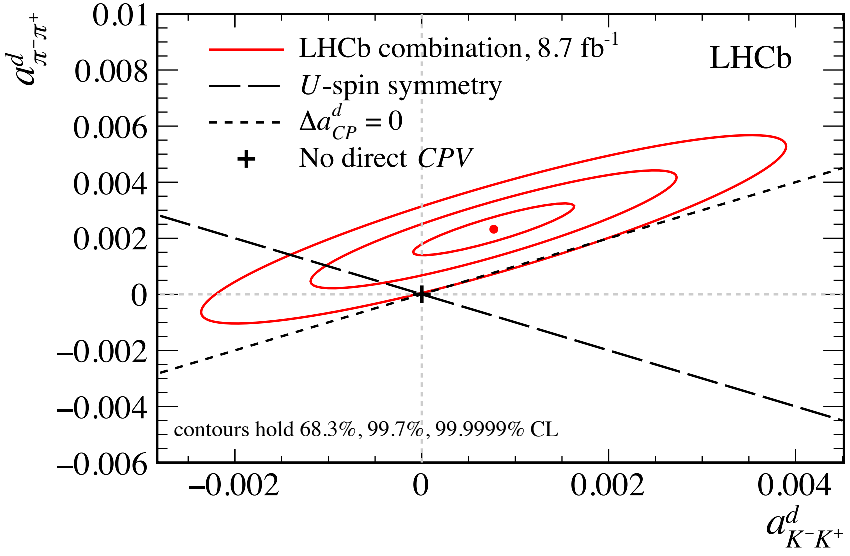
CP violation in decays

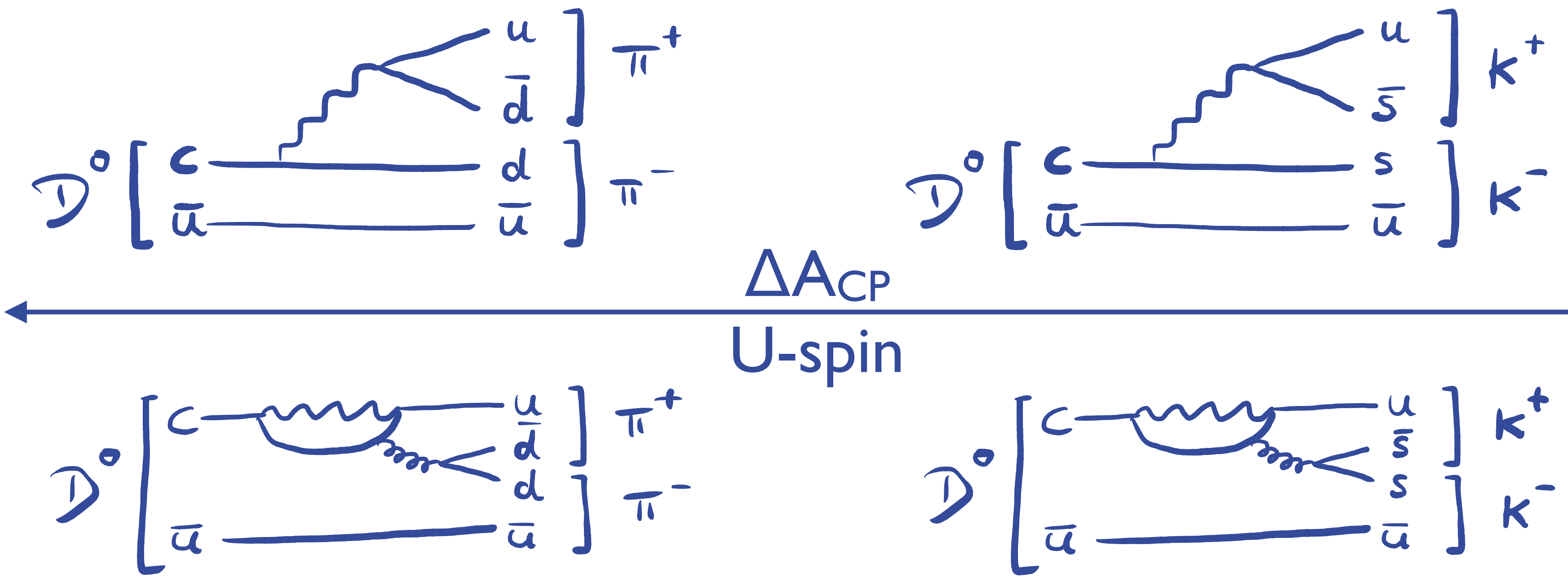
LHCb, PRL 131 (2023) 091802





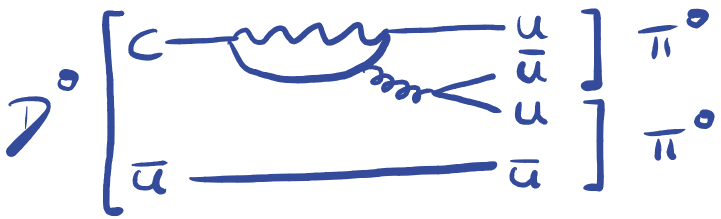
- 2019 discovery of CP violation in charm decays:
  $\Delta A_{CP} \equiv A_{CP}(KK) - A_{CP}(\pi\pi) = (-0.182 \pm 0.033)\%$ LHCb, PRL 122 (2019) 211803
  - Prompted investigation of individual decay modes
- Use control channels $D^0 \to K^-\pi^+$, $D^+ \to K^+\pi^+\pi^-$, $D^+ \to K_S\pi^+$ and $A_{CP}(K_S)$ to constrain production and detection asymmetries
- Result indicates ΔA_{CP} largely driven by $A_{CP}(\pi\pi)$
  - In tension with U-spin symmetry expectation

$D^0 \to PP$



$A_{CP}(\pi\pi)$ ⟵ ΔA_{CP} U-spin ⟶ $A_{CP}(KK)$

↕ Isospin



$$R \equiv \frac{|A_{\pi^+\pi^-}|^2 - |\overline{A}_{\pi^+\pi^-}|^2 + |A_{\pi^0\pi^0}|^2 - |\overline{A}_{\pi^0\pi^0}|^2 - \frac{2}{3}(|A_{\pi^+\pi^0}|^2 - |\overline{A}_{\pi^-\pi^0}|^2)}{|A_{\pi^+\pi^-}|^2 + |\overline{A}_{\pi^+\pi^-}|^2 + |A_{\pi^0\pi^0}|^2 + |\overline{A}_{\pi^0\pi^0}|^2 - \frac{2}{3}(|A_{\pi^+\pi^0}|^2 + |\overline{A}_{\pi^-\pi^0}|^2)}$$

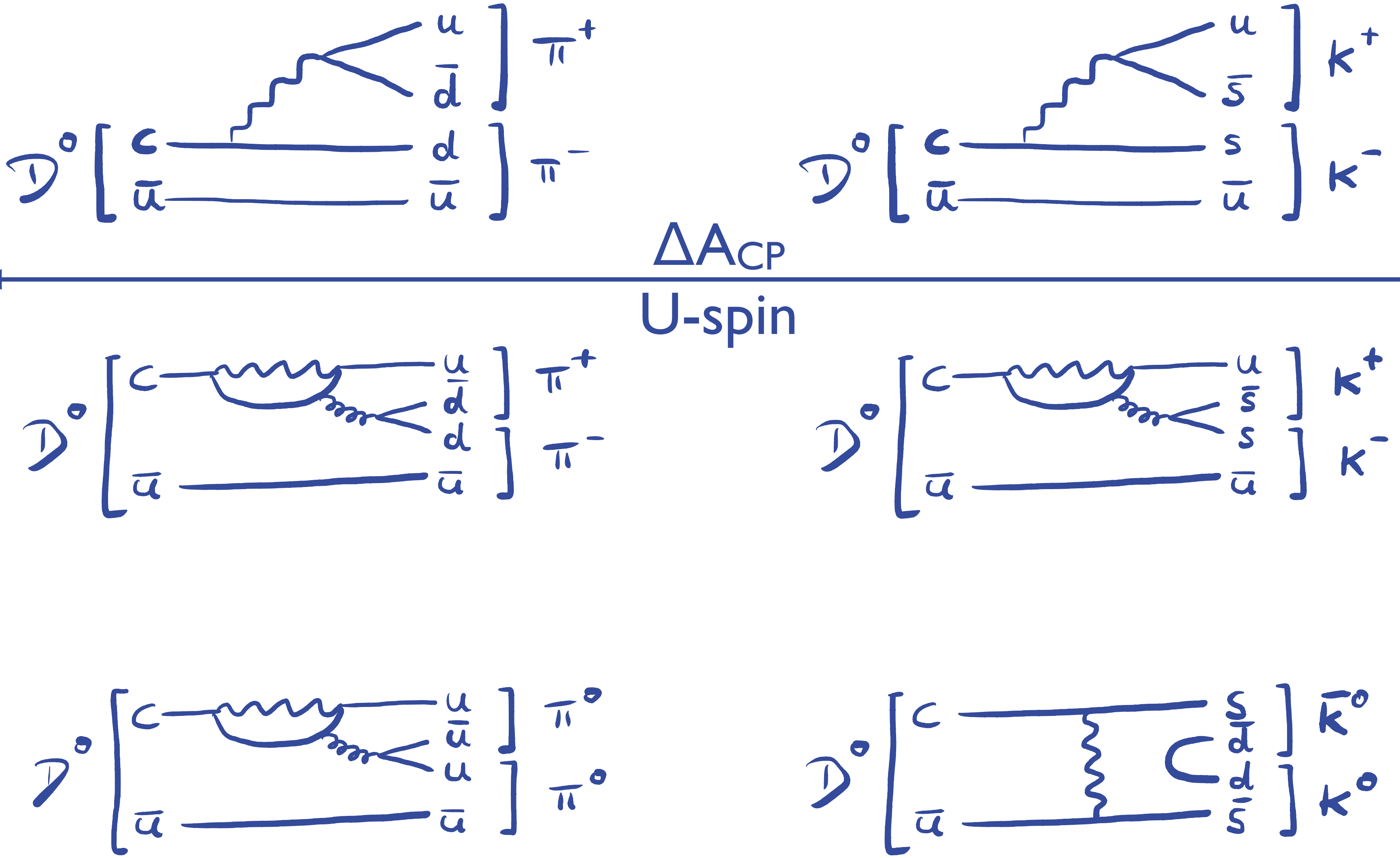
$$= \frac{A_{CP}(D^0 \to \pi^+\pi^-)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{+-}}(\frac{\mathcal{B}_{00}}{\tau_{D^0}} - \frac{2}{3}\frac{\mathcal{B}_{+0}}{\tau_{D^+}})} + \frac{A_{CP}(D^0 \to \pi^0\pi^0)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{00}}(\frac{\mathcal{B}_{+-}}{\tau_{D^0}} - \frac{2}{3}\frac{\mathcal{B}_{+0}}{\tau_{D^+}})} + \frac{A_{CP}(D^+ \to \pi^+\pi^0)}{1 - \frac{3}{2}\frac{\tau_{D^+}}{\mathcal{B}_{+0}}(\frac{\mathcal{B}_{00}}{\tau_{D^0}} + \frac{\mathcal{B}_{+-}}{\tau_{D^0}})}$$

$$R = (+0.86 \pm 3.09) \times 10^{-3}$$

Isospin sum rule: HFLAV 2023

$D^0 \to PP$

$A_{CP}(\pi\pi)$



$A_{CP}(KK)$

Isospin

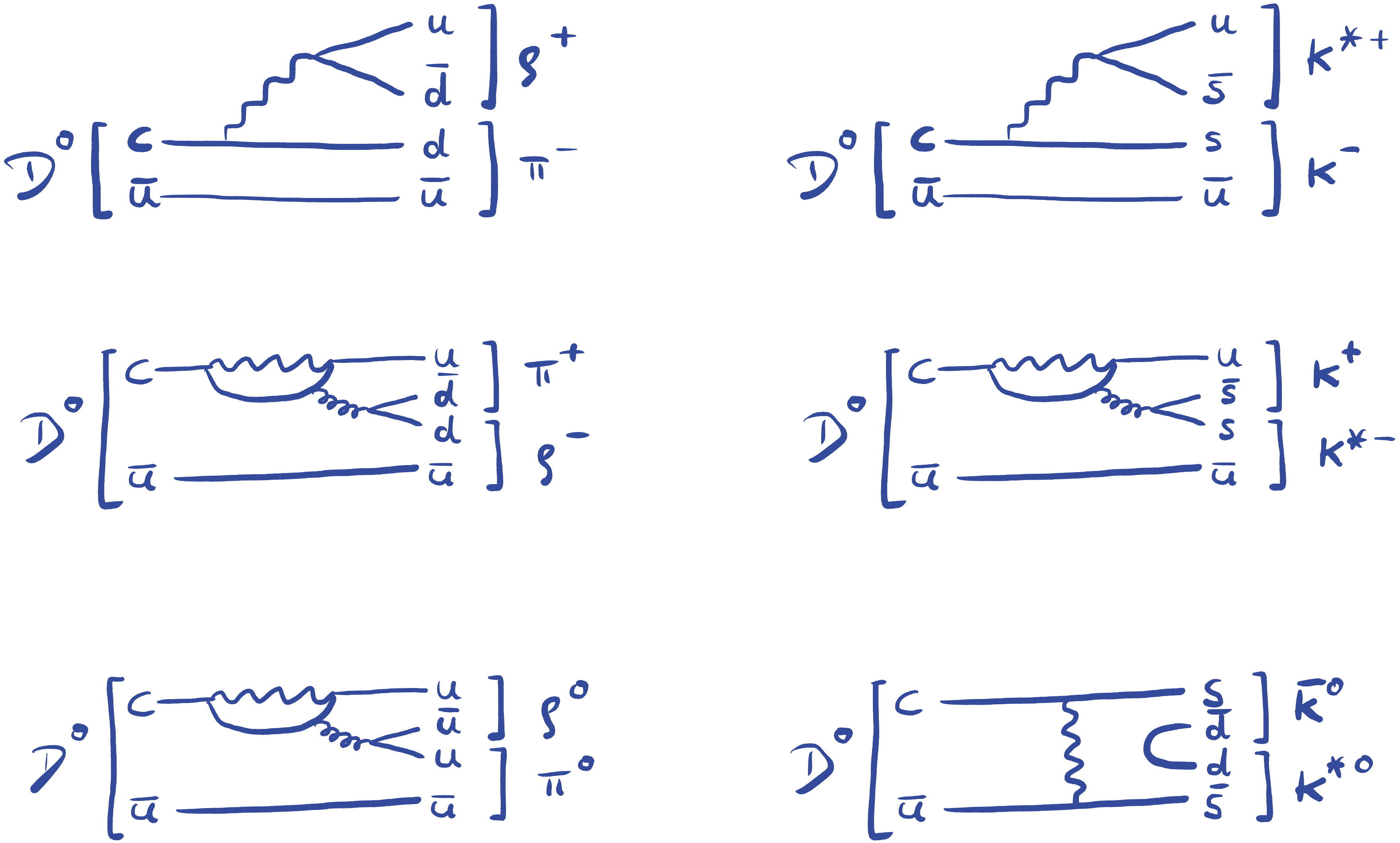
[Brod, Kagan Zupan (2011),](#)
[Hiller, Jung, Schacht (2013),](#)
[Nierste, Schacht (2015)](#)

Large ACP?

Adding spin

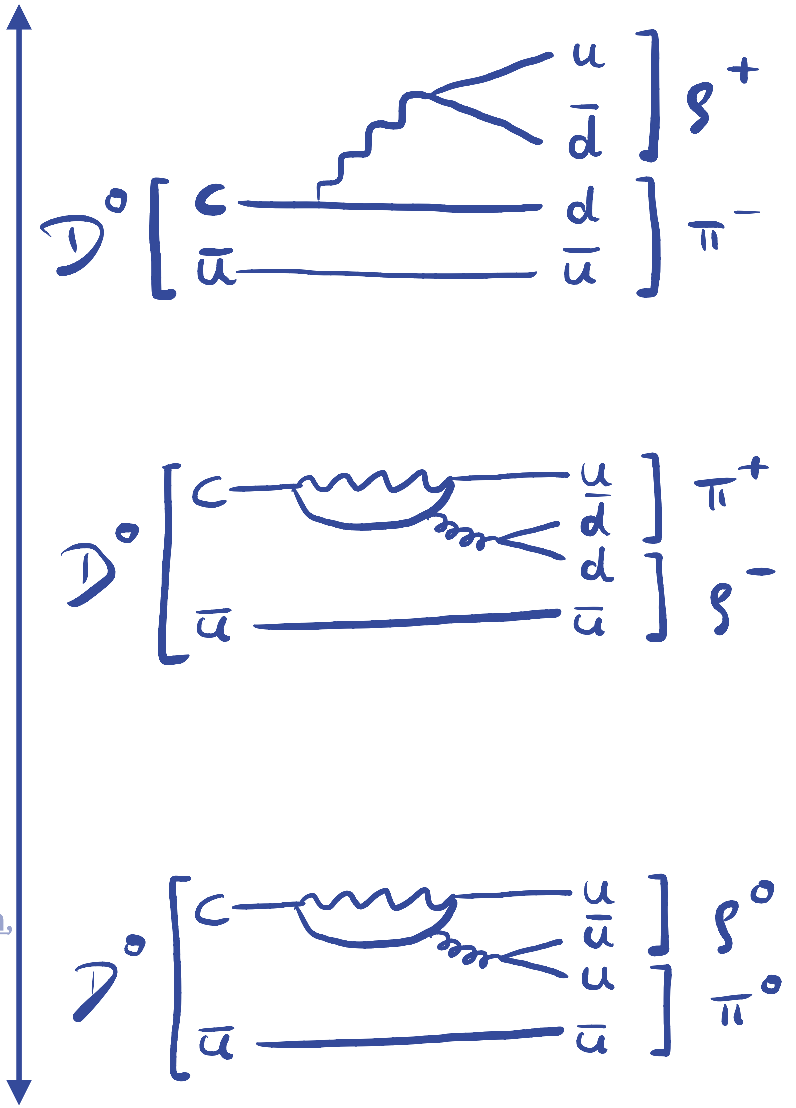
Keeping weak structure

$D^0 \to VP$



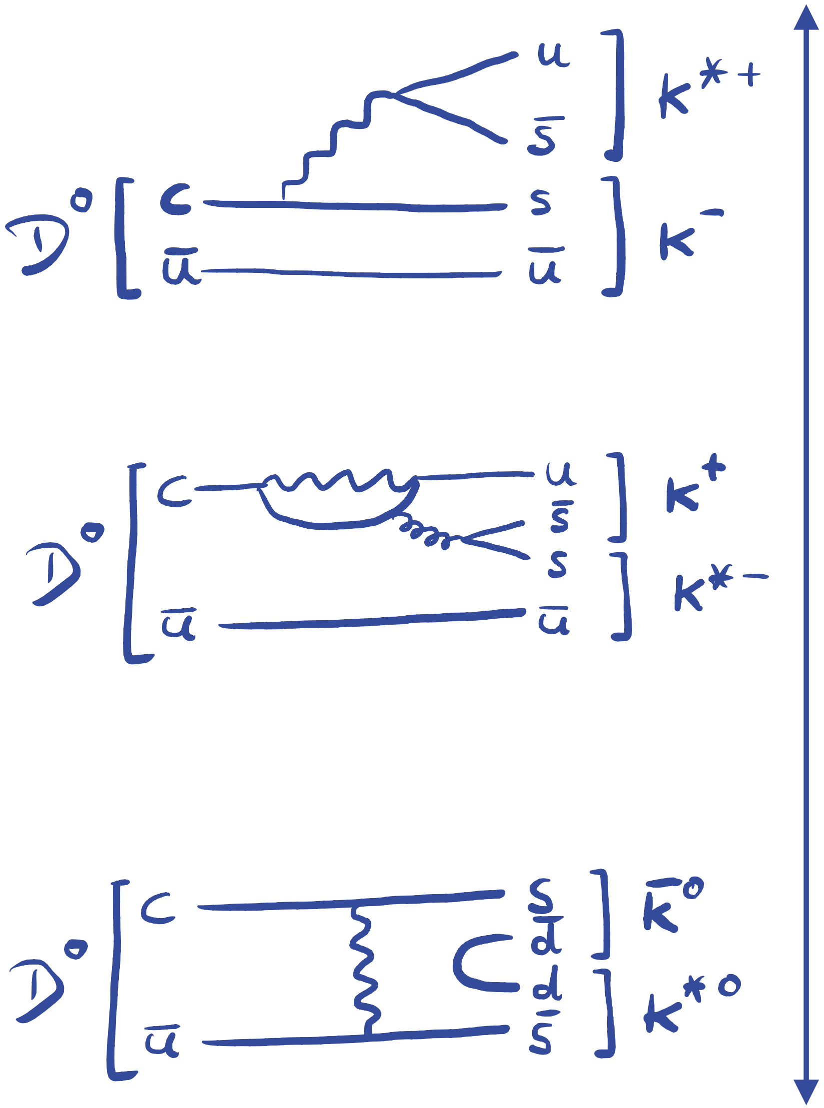
$D^0 \to VP$

Final state: $\pi^+\pi^-\pi^0$



Grossman, Kagan, Zupan (2012)

Sum rules



Final state: $K_SK^\pm\pi^\mp$

Nierste, Schacht (2017)

Also interesting

D^0 multibody

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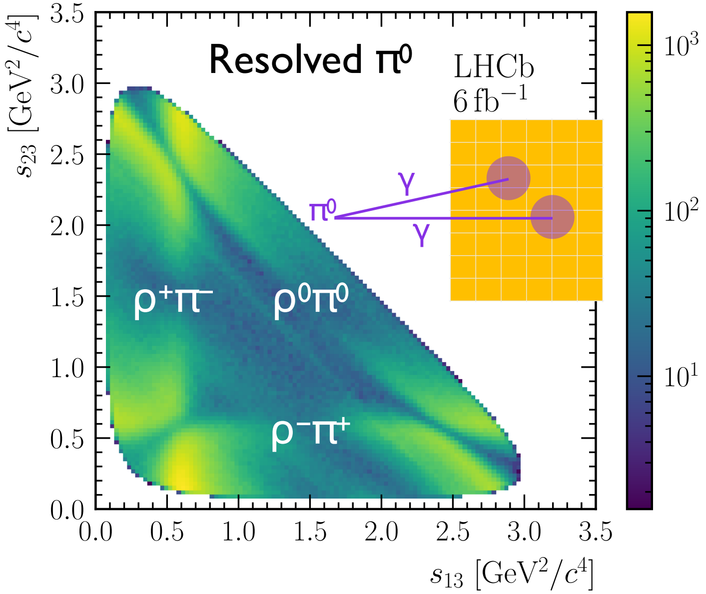
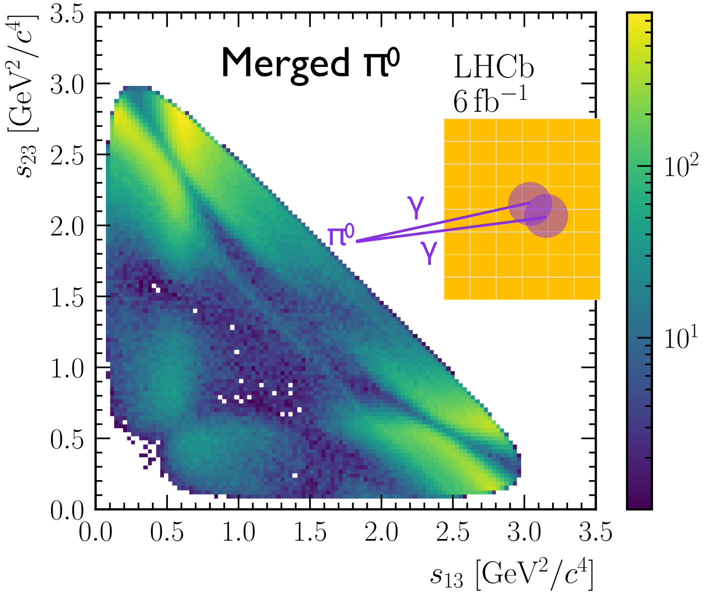
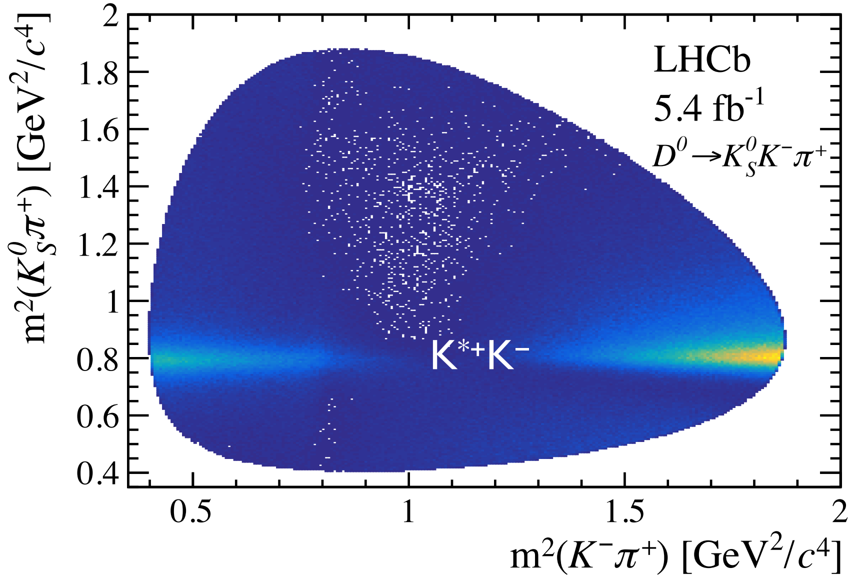
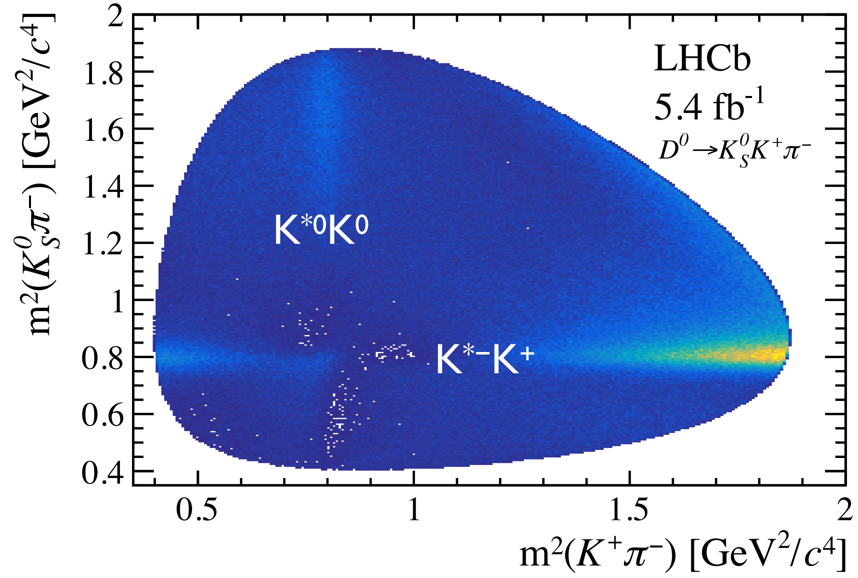
Multi-body intereference





- Three-body pseudo-scalar final-state phase space can be described with two variables
  - Dalitz plot
- Dalitz plots give access to interfering amplitudes with rapidly varying strong phases
  - Fertile ground for local CP asymmetries





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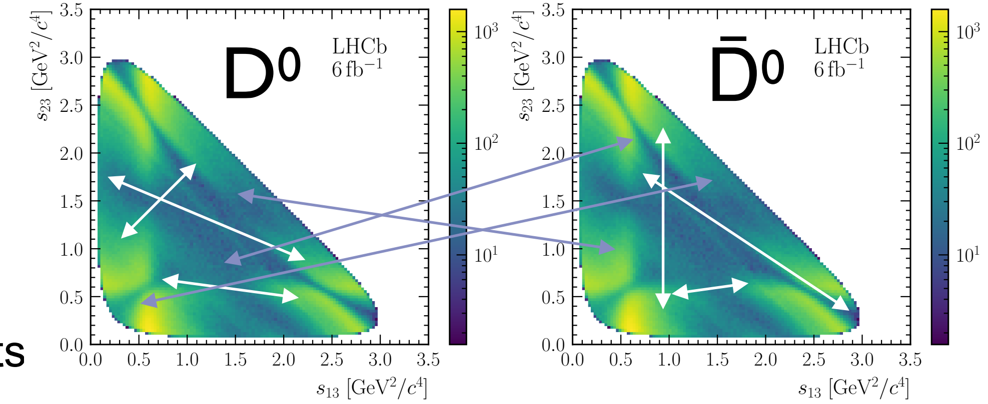
Energy test

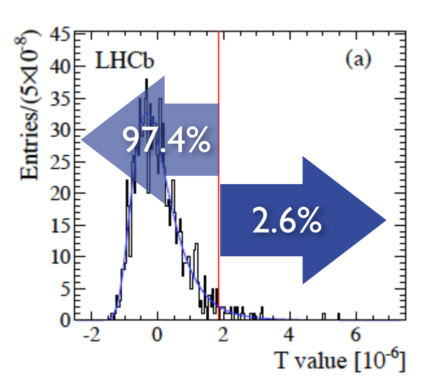


- Model-independent unbinned two-sample test to discover localised asymmetries
- Compares weighted distances in phase spaces among all pairs of events
  - Grouped in D0-D0, D̄0-D̄0, D0-D̄0
- Weighting function decreases with distance
  - Emphasising localised effects
- Weighted distances are averaged with opposite sign for D0-D̄0 cross term
  - Resulting statistic, T, approximately 0 if D0 & D̄0 from same underlying distribution
  - Asymmetry leads to T > 0
- T-value distribution for CP symmetry hypothesis from repeated random assignment of D0-D̄0 flavour tag
  - p-value obtained as fraction of distribution greater than measured T

$$d_{ij}^2 = [(\Delta s_{12})_{ij}^2 + (\Delta s_{13})_{ij}^2 + (\Delta s_{23})_{ij}^2]$$

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

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



Previous analysis:
p-value = 2.6%

Method: Aslan, Zech, 2004, Wiliams, 2011, Parkes et al. 2017, Barter, Burr, Parkes, 2018, Zech 2018

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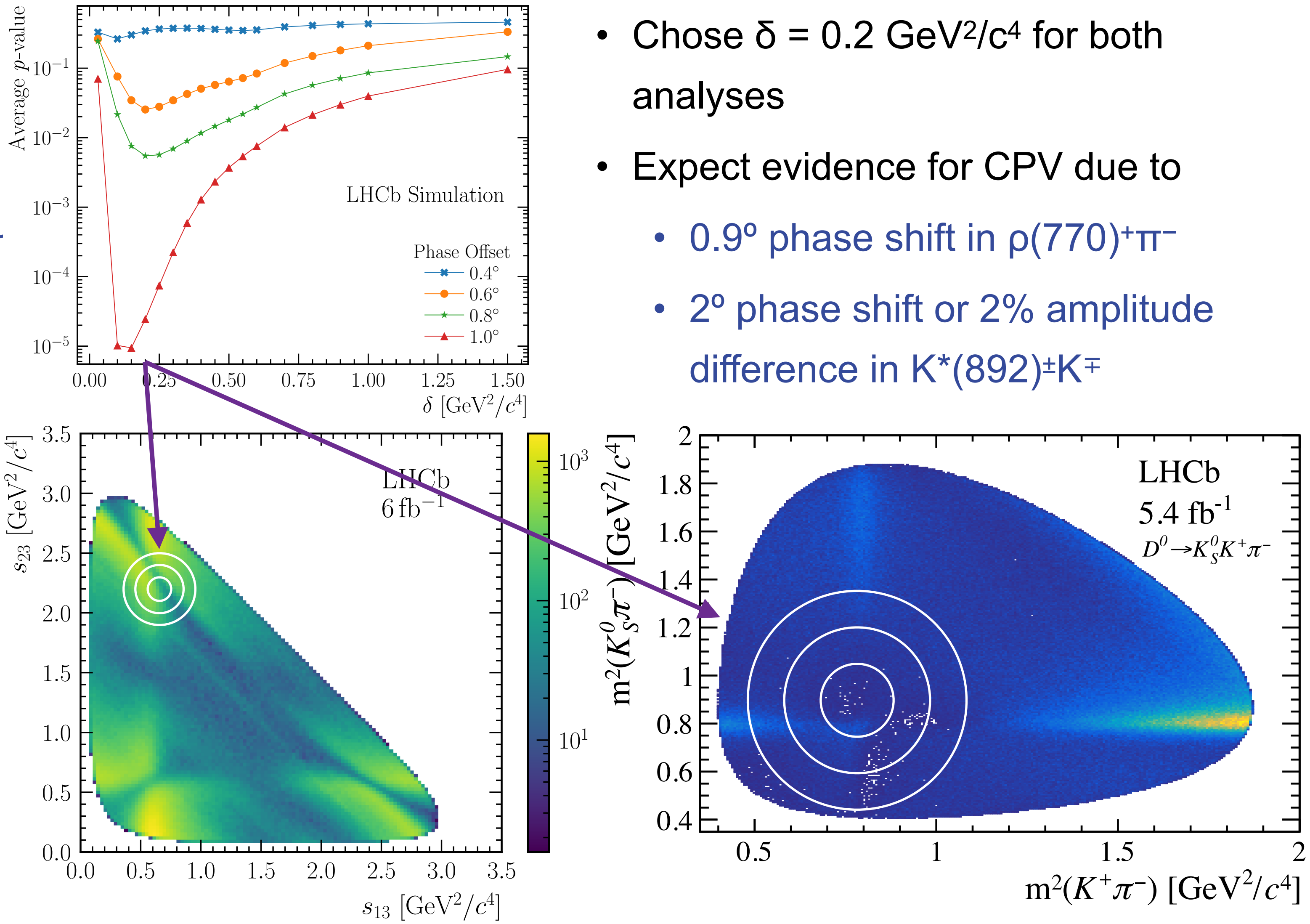
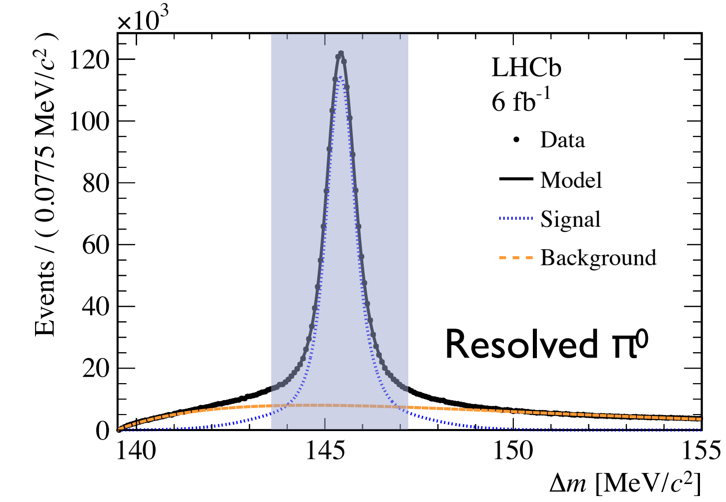
Sensitivity

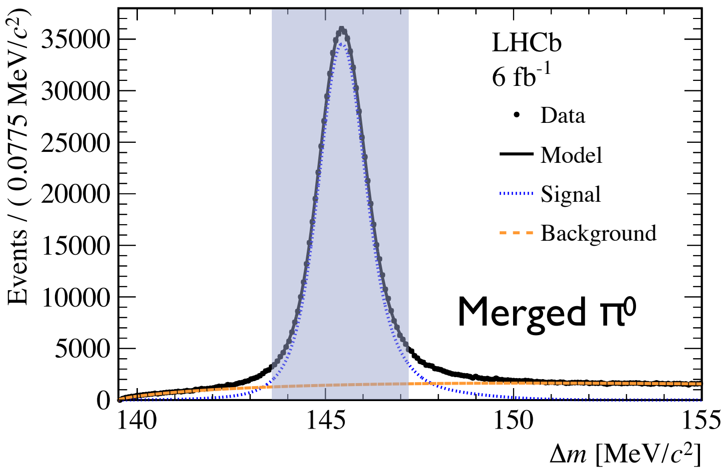
- Energy test is a discovery tool
  - Single result is a p-value for agreem
    symmetry hypothesis
    - Does not yield limits for specific
- Sensitivity tests can test effect of models
  - Can identify scenarios that should lead to observations
    - Non-observation can then use these as limits



- Chose δ = 0.2 GeV²/c⁴ for both analyses
- Expect evidence for CPV due to
  - 0.9° phase shift in $\rho(770)^{+}\pi^{-}$
  - 2° phase shift or 2% amplitude difference in $K^{*}(892)^{\pm}K^{\mp}$

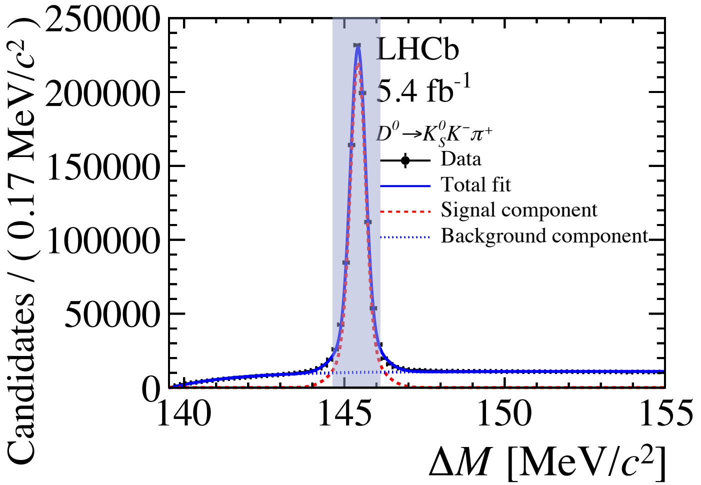
Data

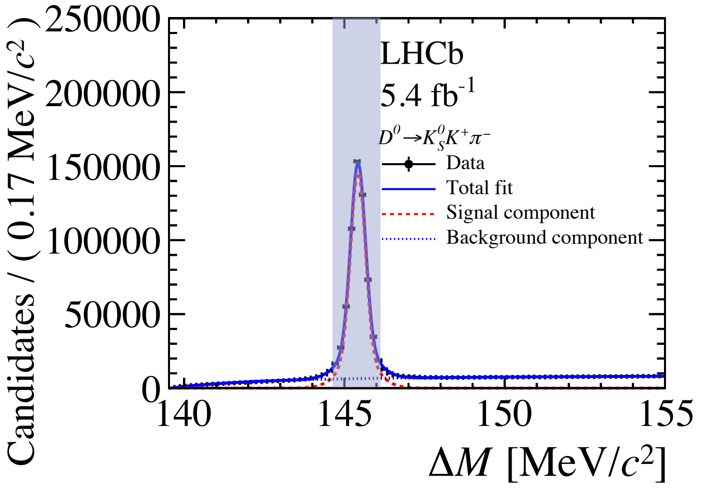




2.47M signal candidates (Run 1: 0.67M)

- All samples flavour-tagged by reconstructing $D^{*+} \to D^0\pi^+$ decays
- Purity above 90% (~80% for resolved π^0)
- All signal candidates in mass window passed to energy test
  - Resolved and merged π^0 samples are combined
  - Fit just indicative to assess background level

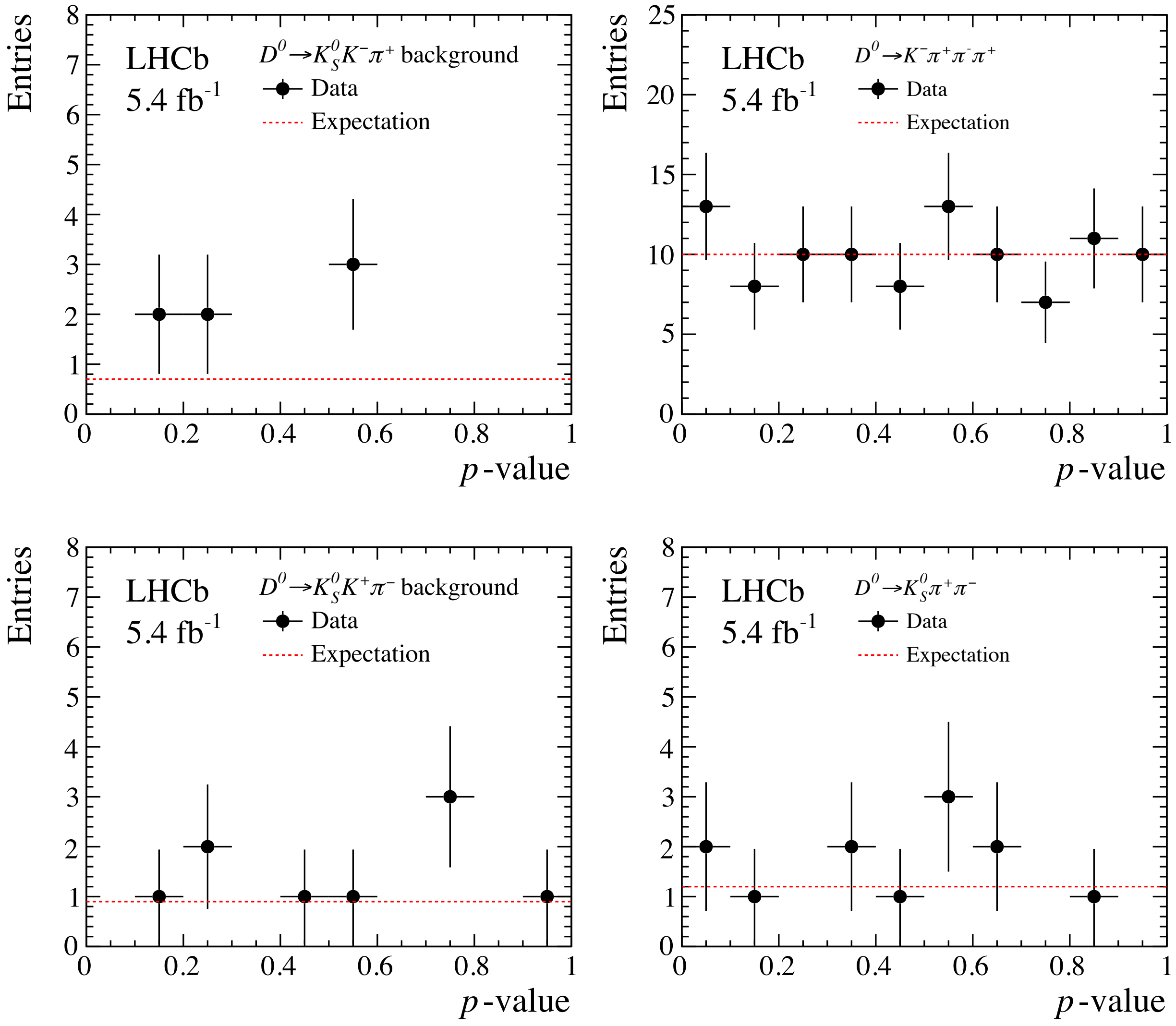




1.57M signal candidates in both final states

Nuisances

- All selected data analysed in energy test without efficiency correction or background subtraction
- Sources of asymmetry other than signal CP violation:
  - Background asymmetry (CP or other)
    - Symmetric background also affects (dilutes) sensitivity
  - Production or detection asymmetry
    - Needs to lead to localised effects in phase space
- Cross-checks
  - Measure control samples
    - Background dominated mass side bands
    - Control modes with related final states: $K^-\pi^+\pi^0$, $K_S\pi^+\pi^-$, $K^-\pi^+\pi^+\pi^-$
  - Pseudo-experiments with injected asymmetries
  - Sub-sample consistency checks (year, dipole polarity, trigger selection)



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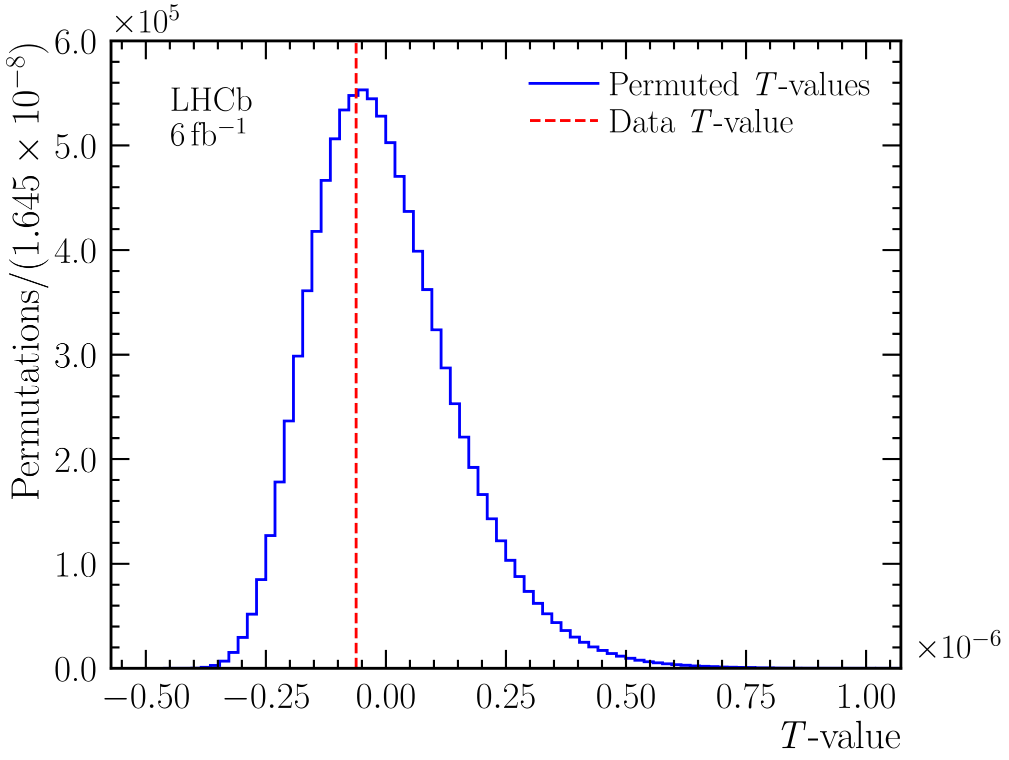
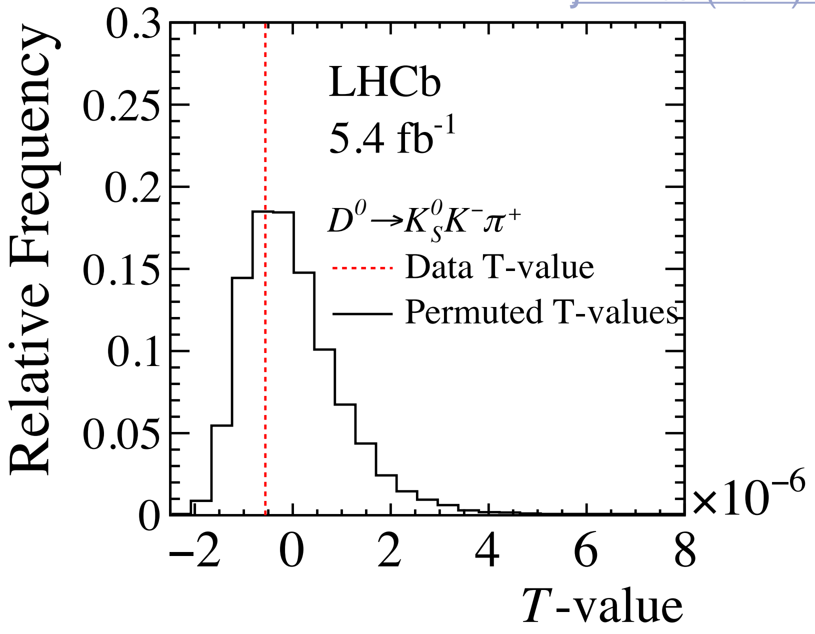
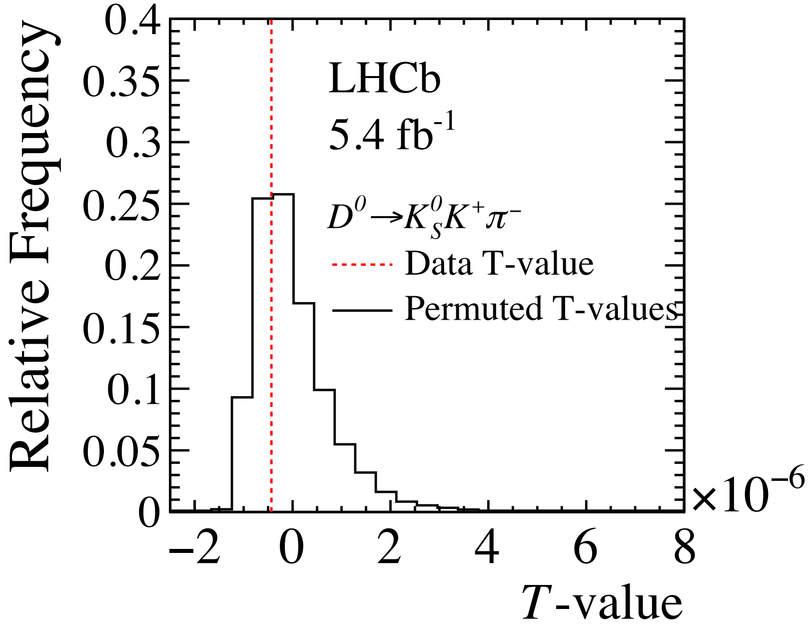
Results

- p-values for agreement with CP symmetry
  - $D^0 \to \pi^+\pi^-\pi^0$: 62%
  - $D^0 \to K_S K^- \pi^+$: 70%
  - $D^0 \to K_S K^+ \pi^-$: 66%







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

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

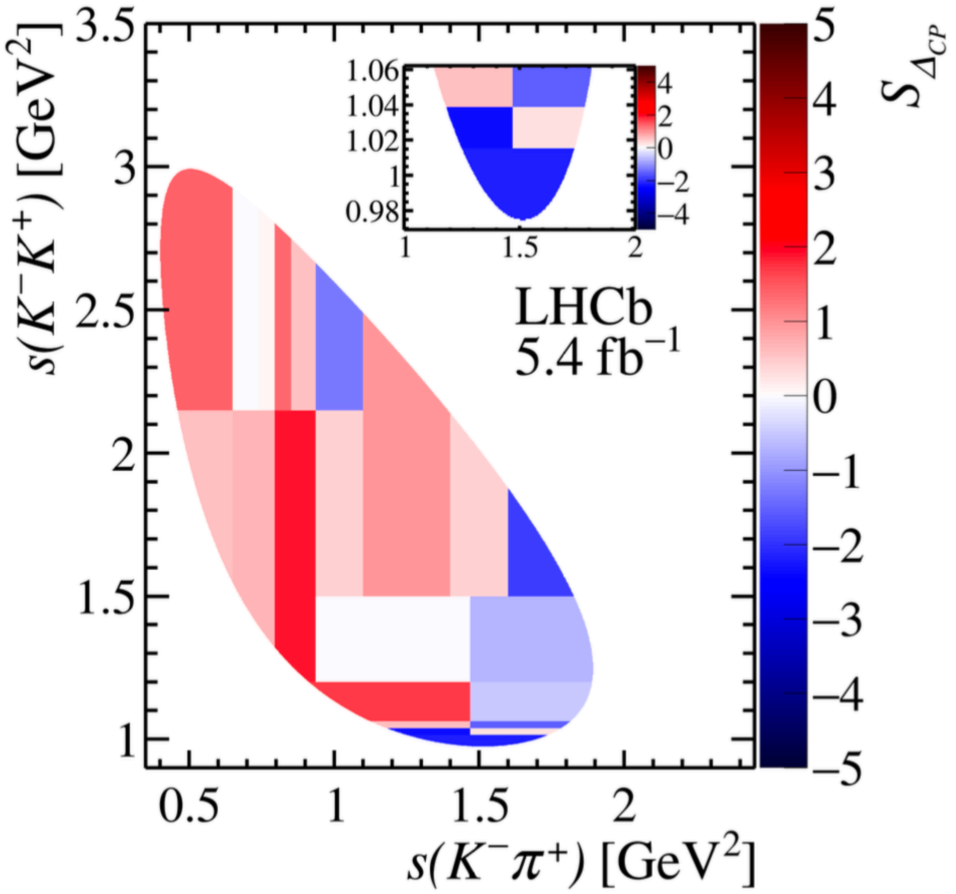
- Search for local CP violation in D^+ decays (S) with D_s^+ decays (C) used to control production and detection asymmetries

$$\mathcal{S}^i_{\Delta_{CP}} = \frac{\Delta A^i_{CP}}{\sigma_{\Delta A^i_{CP}}} \qquad \Delta A^i_{CP} = A^{i,S}_{\text{raw}} - A^{i,C}_{\text{raw}} - \Delta A^{\text{global}}_{\text{raw}}$$

- In addition, compute “diagonal” asymmetry to test effects linked to resonances

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

$$A^{\phi\pi^+}_{CP|S} = (0.95 \pm 0.43 \pm 0.26) \times 10^{-3},$$
$$A^{\bar{K}^{*0}K^+}_{CP|S} = (-0.26 \pm 0.56 \pm 0.18) \times 10^{-3}$$



Decay-time dependent CPV

Wrong-sign Kπ decays

- Fit time-dependent wrong-sign (WS) to right-sign (RS) yield ratios to parabolic function split by D^0 charge

$$R^{\pm}_{K\pi}(t) \approx R_{K\pi}(1 \pm A_{K\pi}) + \sqrt{R_{K\pi}(1 \pm A_{K\pi})}(c_{K\pi} \pm \Delta c_{K\pi})\, t + (c'_{K\pi} \pm \Delta c'_{K\pi})\, t^2$$

- Observables linked to mixing and CP-violating parameters, but obscured by strong-phase difference Δ_f

$$R_{K\pi} \equiv \frac{1}{2}\left(\left|\frac{A_{\bar f}}{\bar A_{\bar f}}\right|^2 + \left|\frac{\bar A_f}{A_f}\right|^2\right),$$

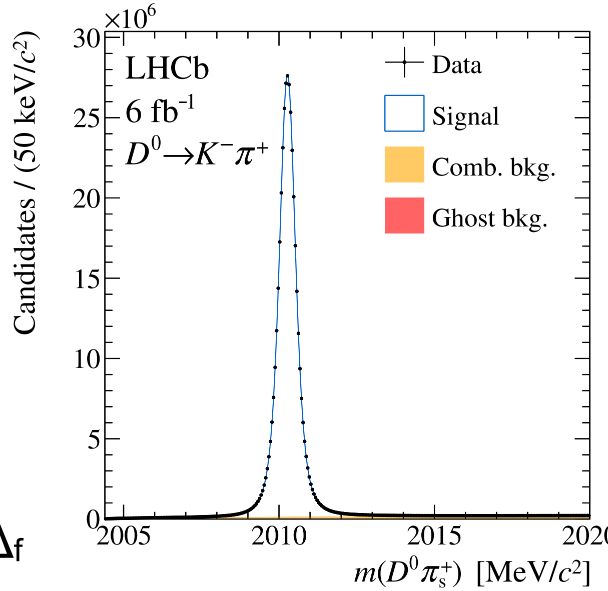
$$A_{K\pi} \equiv \frac{\left|A_{\bar f}/\bar A_{\bar f}\right|^2 - \left|\bar A_f/A_f\right|^2}{\left|A_{\bar f}/\bar A_{\bar f}\right|^2 + \left|\bar A_f/A_f\right|^2} \approx a^d_{\mathrm{DCS}},$$

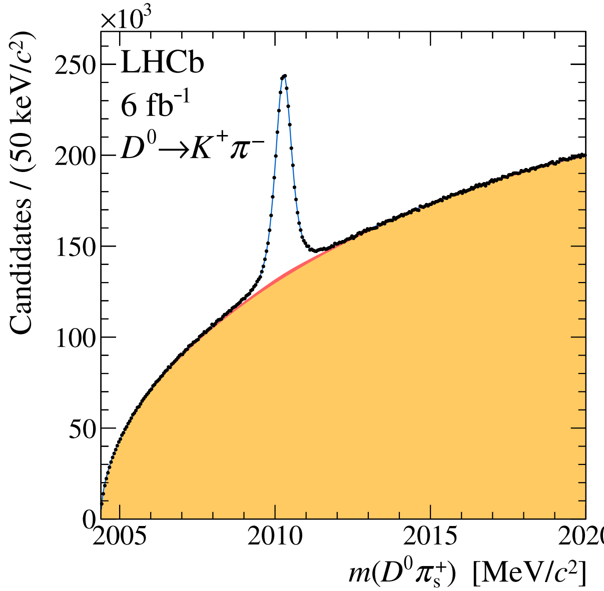
$$c_{K\pi} \approx y_{12}\cos\phi^\Gamma_f \cos\Delta_f + x_{12}\cos\phi^M_f \sin\Delta_f,$$

$$\Delta c_{K\pi} \approx x_{12}\sin\phi^M_f \cos\Delta_f - y_{12}\sin\phi^\Gamma_f \sin\Delta_f,$$

$$c'_{K\pi} \approx \frac{1}{4}\left(x^2_{12} + y^2_{12}\right),$$

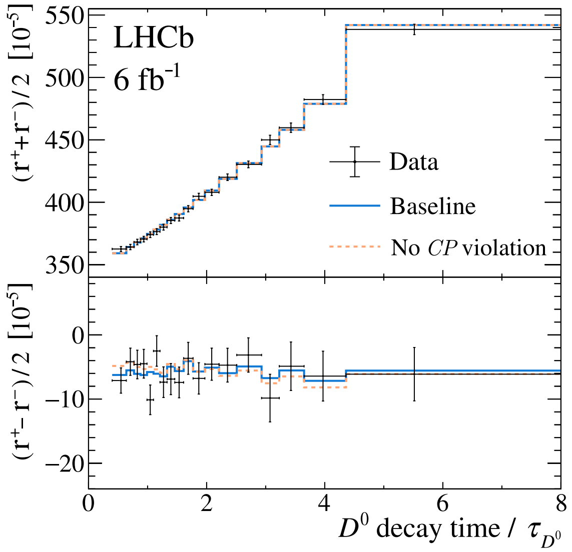
$$\Delta c'_{K\pi} \approx \frac{1}{2} x_{12} y_{12} \sin(\phi^M_f - \phi^\Gamma_f).$$





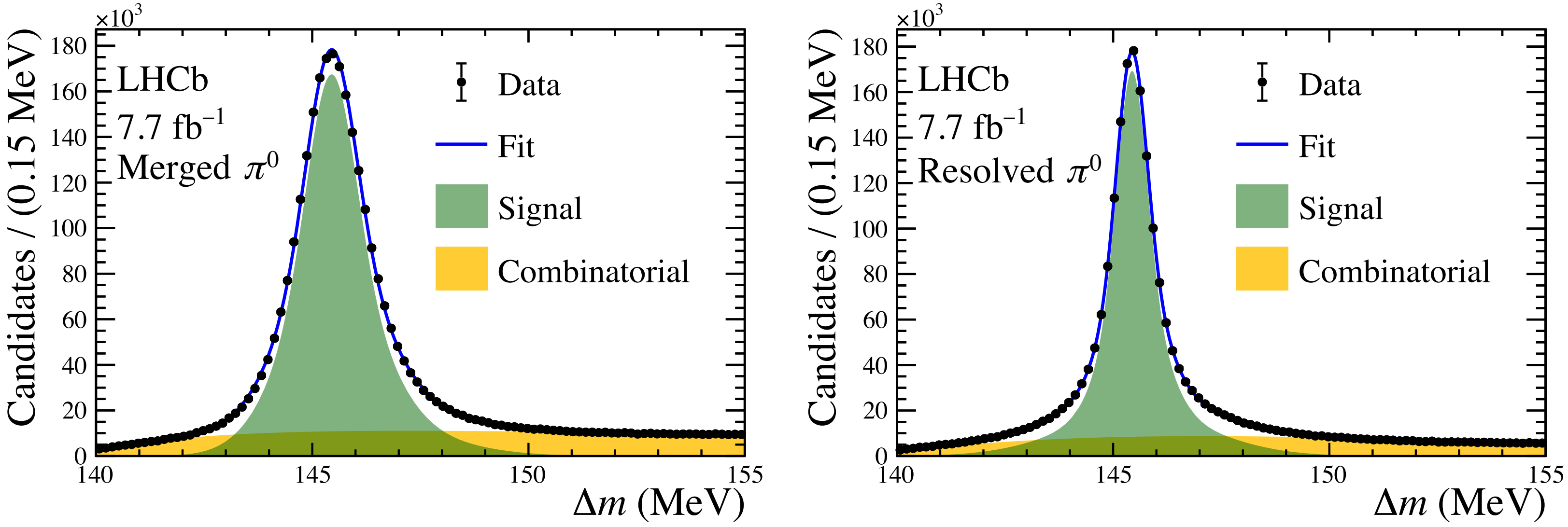
Results:
$R_{K\pi} = (343.1 \pm 2.0) \times 10^{-5}$
$c_{K\pi} = (51.4 \pm 3.5) \times 10^{-4}$
$c'_{K\pi} = (13 \pm 4) \times 10^{-6}$

$D^0 \to K^+K^-$ used to control D^{*+} production and π_s detection asymmetries



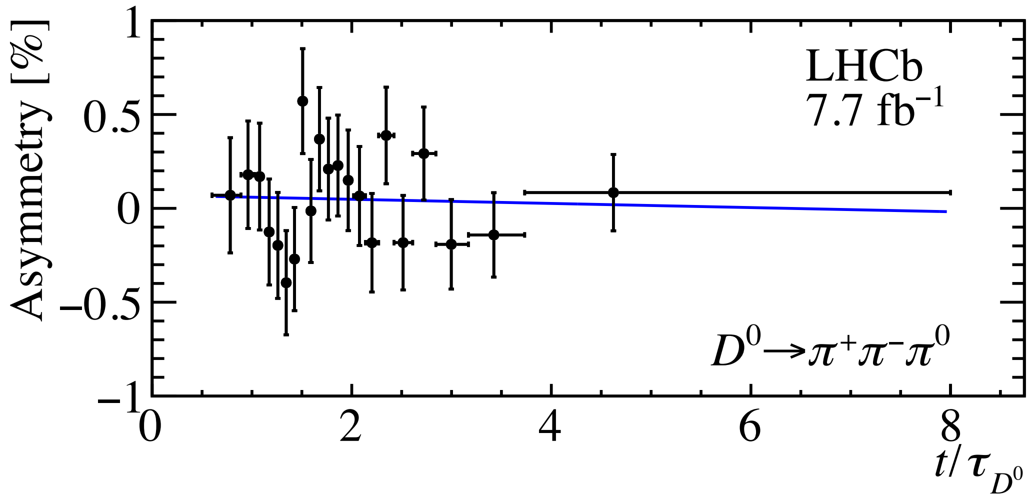
No significant asymmetry found

$D^0 \to \pi^+\pi^-\pi^0$ time-dependent

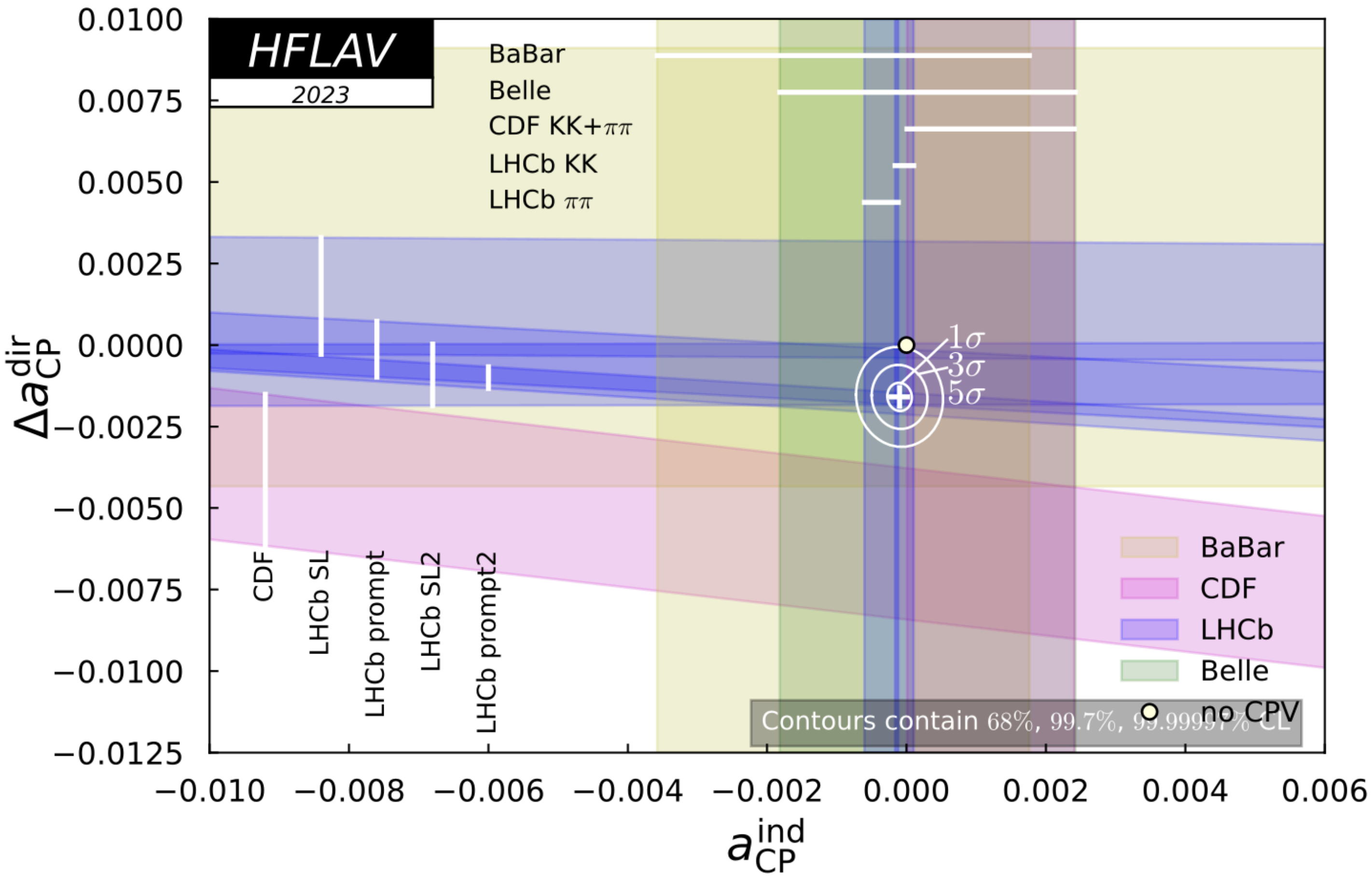


- Measure time dependent decay-time asymmetry for D^0-$\overline{D}^0$ decays
- For CP-eigenstate final states measure observable that is expected to be universal in SM
- Result: $\Delta Y = (-1.3 \pm 6.3 \pm 2.4) \times 10^{-4}$
- Compare to previous results:
  - $\Delta Y(K^+K^-) = (-0.3 \pm 1.3 \pm 0.3) \times 10^{-4}$
  - $\Delta Y(K^+K^-) = (-3.6 \pm 2.4 \pm 0.4) \times 10^{-4}$

  Phys.Rev.Lett. 118 (2017) 261803

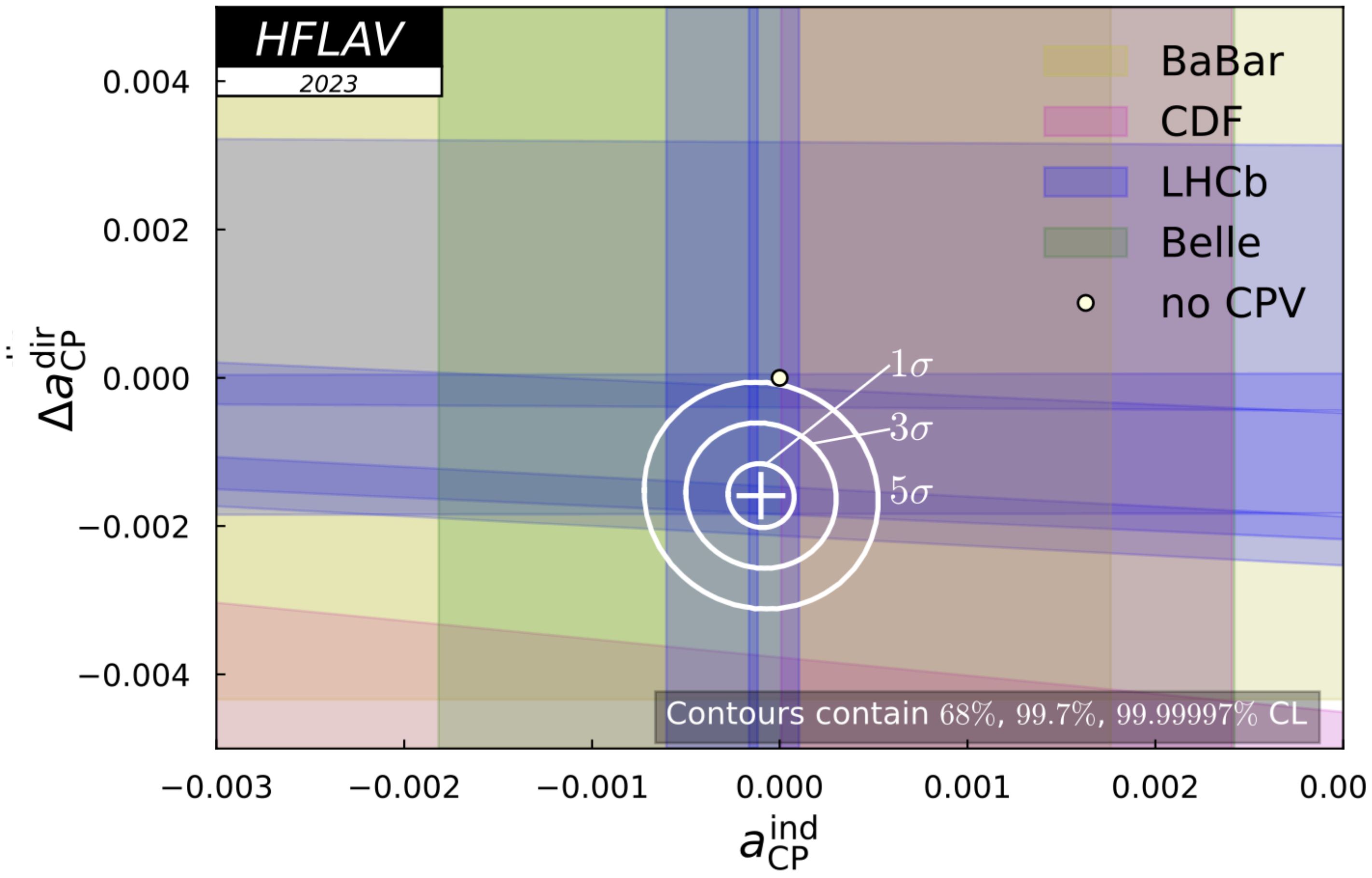


HFLAV



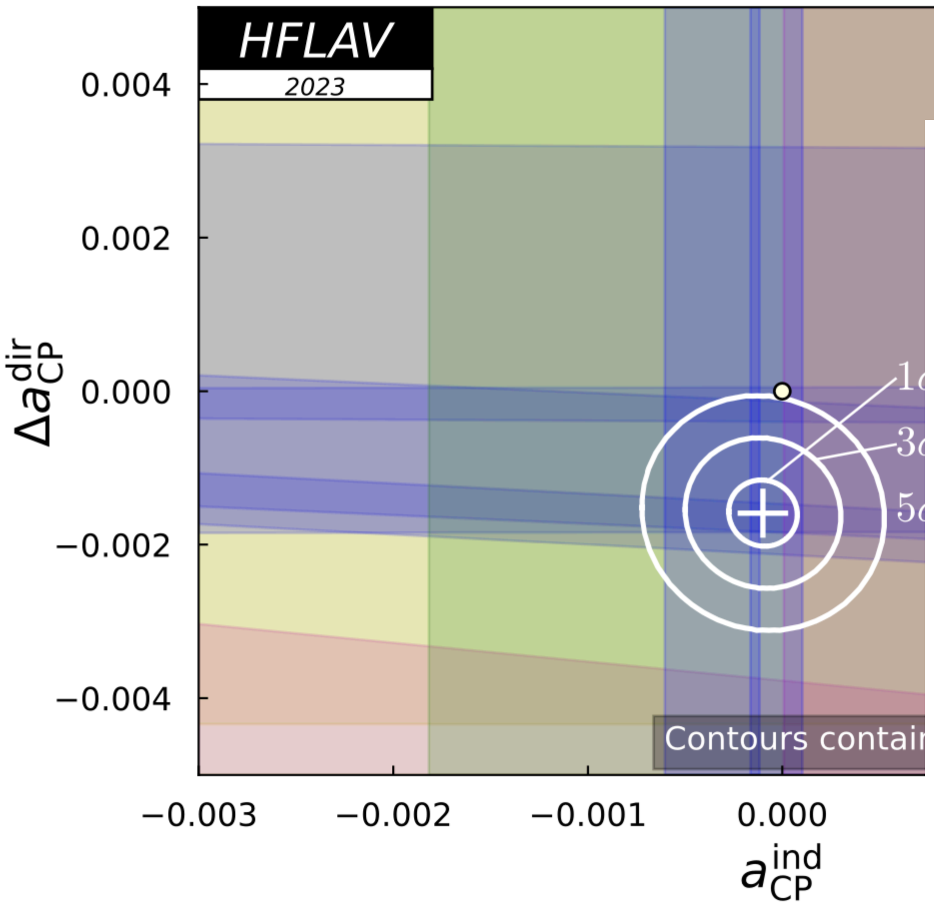
Assumes KK-ππ universality

HFLAV

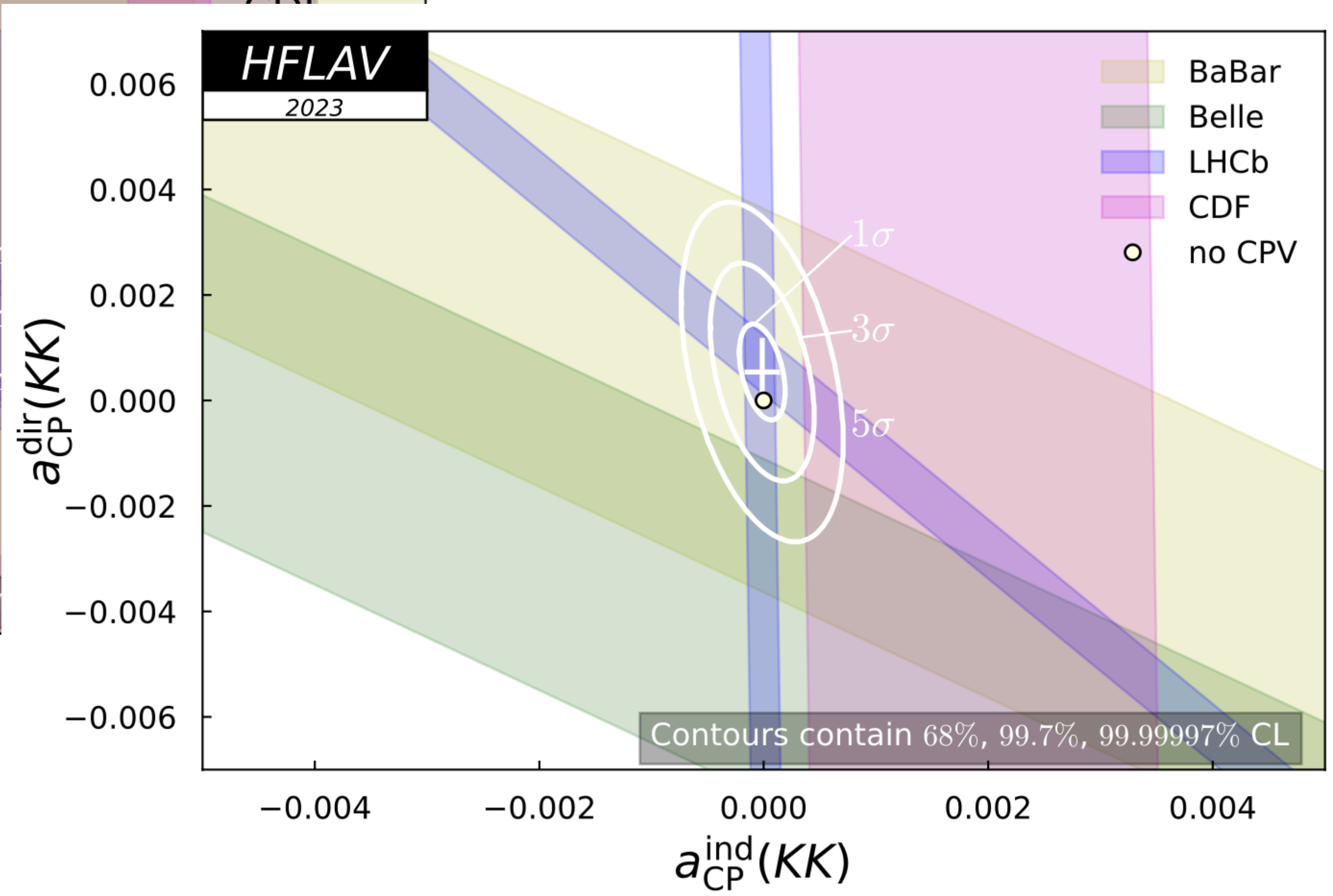


Assumes KK-ππ universality

HFLAV



KK only



Conclusions

- Unique opportunities for charm physics at LHCb
- CP violation discovery opened up searches for complementary signals
  - Searches in
    - Complementary two-body decays
    - Phase space of multibody decays
    - Time-dependent two-body decays
    - Time-dependent CP-eigenstate decays
  - None found yet
  - More to come
    - Time-dependent multi-body decays
      - Other than $D^0 \to K_S \pi^+ \pi^-$
- Plenty of potential going forward
  - Will benefit hugely from Upgrade II

CERN-LHCC-2021-012