LHCb Experiment at CERN
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Asymmetries in hadronic charm decays at LHCb

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On behalf of LHCb collaboration

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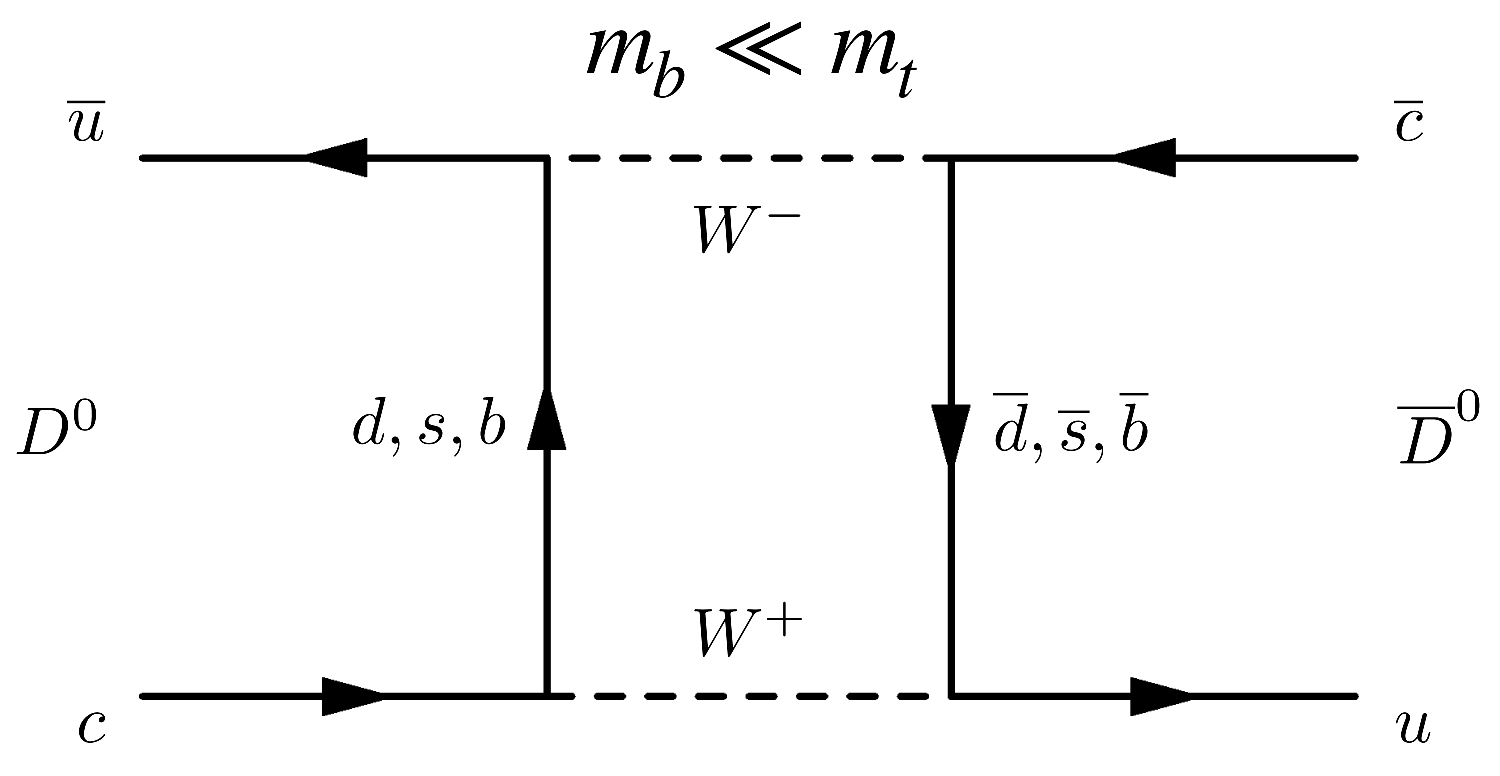
DFG Deutsche Forschungsgemeinschaft

Introduction

- The Charm sector offers a unique environment to search for New Physics and is the only way to study mixing and CPV with up-type quarks

Mixing

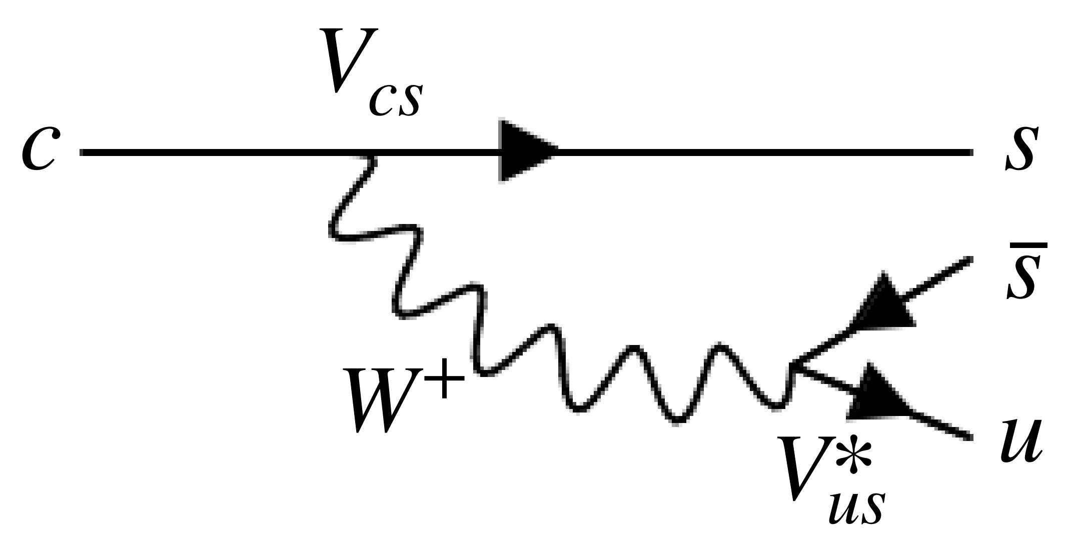


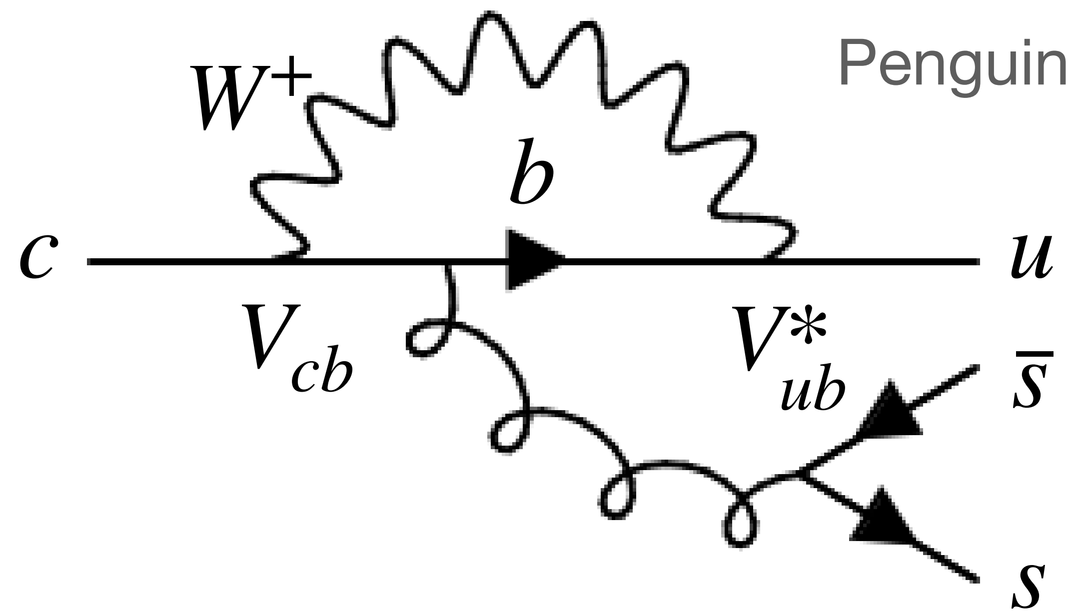
$$\Delta m_{D^0} \underset{\times 200}{\ll} \Delta m_{B^0} \underset{\times 35}{\ll} \Delta m_{B^0_s}$$

GIM suppression $\rightarrow \dfrac{m_s^2 - m_d^2}{m_W^2} = 0$ (U-spin limit)

CP violation

Originates from contributions from amplitudes with different strong and weak phases





Naive estimate $\rightarrow$ CPV $\propto \mathrm{Im}\left(\dfrac{V_{cb}V^*_{ub}}{V_{cs}V^*_{us}}\right) \approx -6 \times 10^{-4}$

Very small SM predictions → High sensitivity to New Physics

Measuring asymmetries

- Measurement of time integrated CP asymmetries → $A_{CP}(X_c \to f) = \frac{\Gamma(X_c \to f) - \Gamma(\overline{X_c} \to \bar{f})}{\Gamma(X_c \to f) + \Gamma(\overline{X_c} \to \bar{f})}$
- Experimentally

$$A_{raw}(X_c \to f) = \frac{N(X_c \to f) - N(\overline{X_c} \to \bar{f})}{N(X_c \to f) + N(\overline{X_c} \to \bar{f})} \approx A_{CP} + A_D(f) + A_P(X_c)$$

A precise knowledge of nuisance asymmetries is required

Detection effects

$$A_D(f|p_T,\eta) = \frac{\varepsilon(f) - \varepsilon(\bar{f})}{\varepsilon(f) + \varepsilon(\bar{f})}$$

Production asymmetries

$$A_P(X_c|\sqrt{s},p_T,\eta) = \frac{\mathscr{P}(pp \to X_c) - \mathscr{P}(pp \to \overline{X_c})}{\mathscr{P}(pp \to X_c) + \mathscr{P}(pp \to \overline{X_c})}$$

- With neutral mesons, mixing plays a role → time dependence

Charm mesons slow mixing rate

$$A_{CP}(D^0 \to f, t) \approx a_{CP}^{\mathrm{dir}} + \frac{t}{\tau_{D^0}} \Delta Y_f$$

Asymmetry of the effective decay widths

Time independent direct CP violation

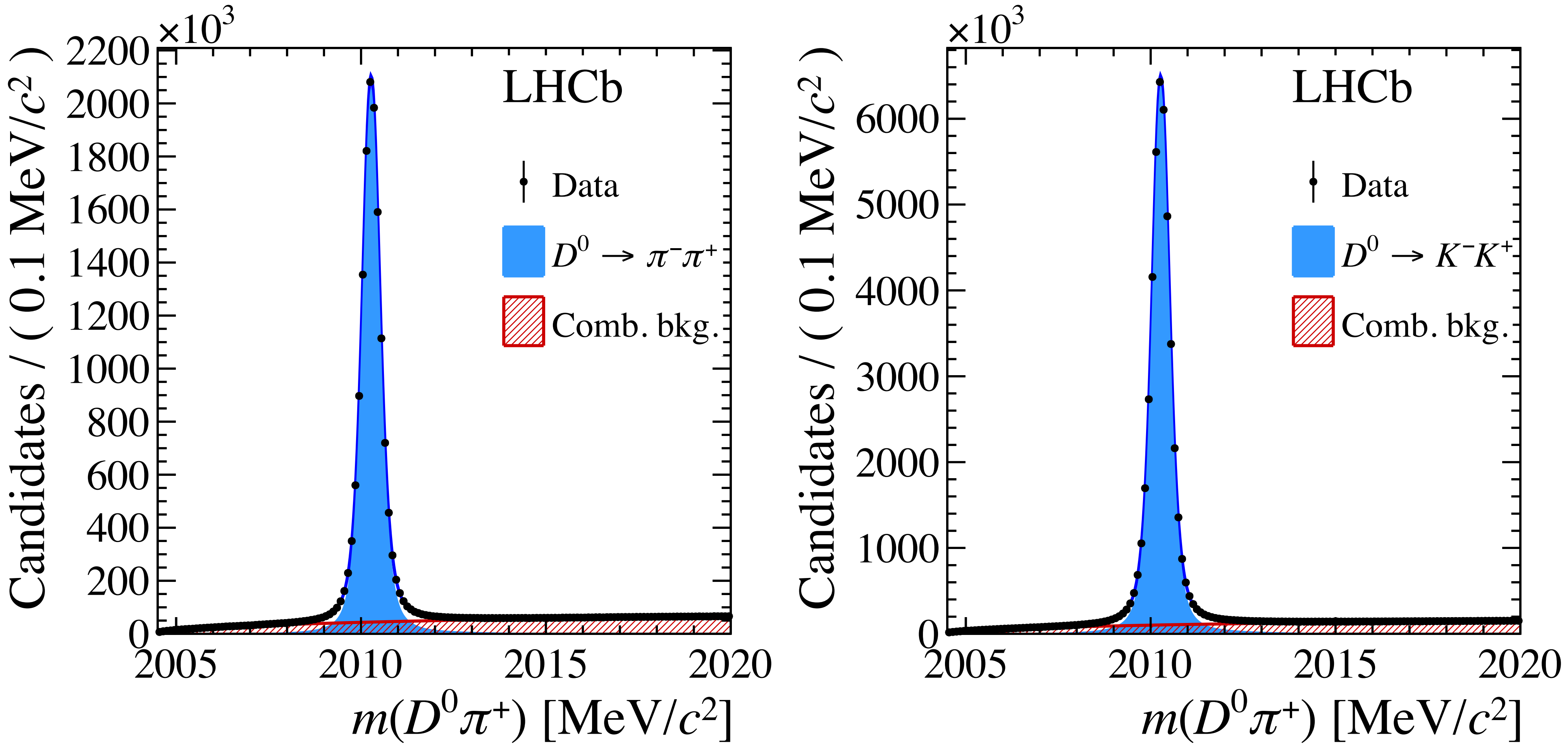
[Phys. Rev. Lett. 118, 261803]

Measurements highlights

- Discovery of CPV in Charm decays in 2019

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

Exploit nuisance asymmetries cancellation



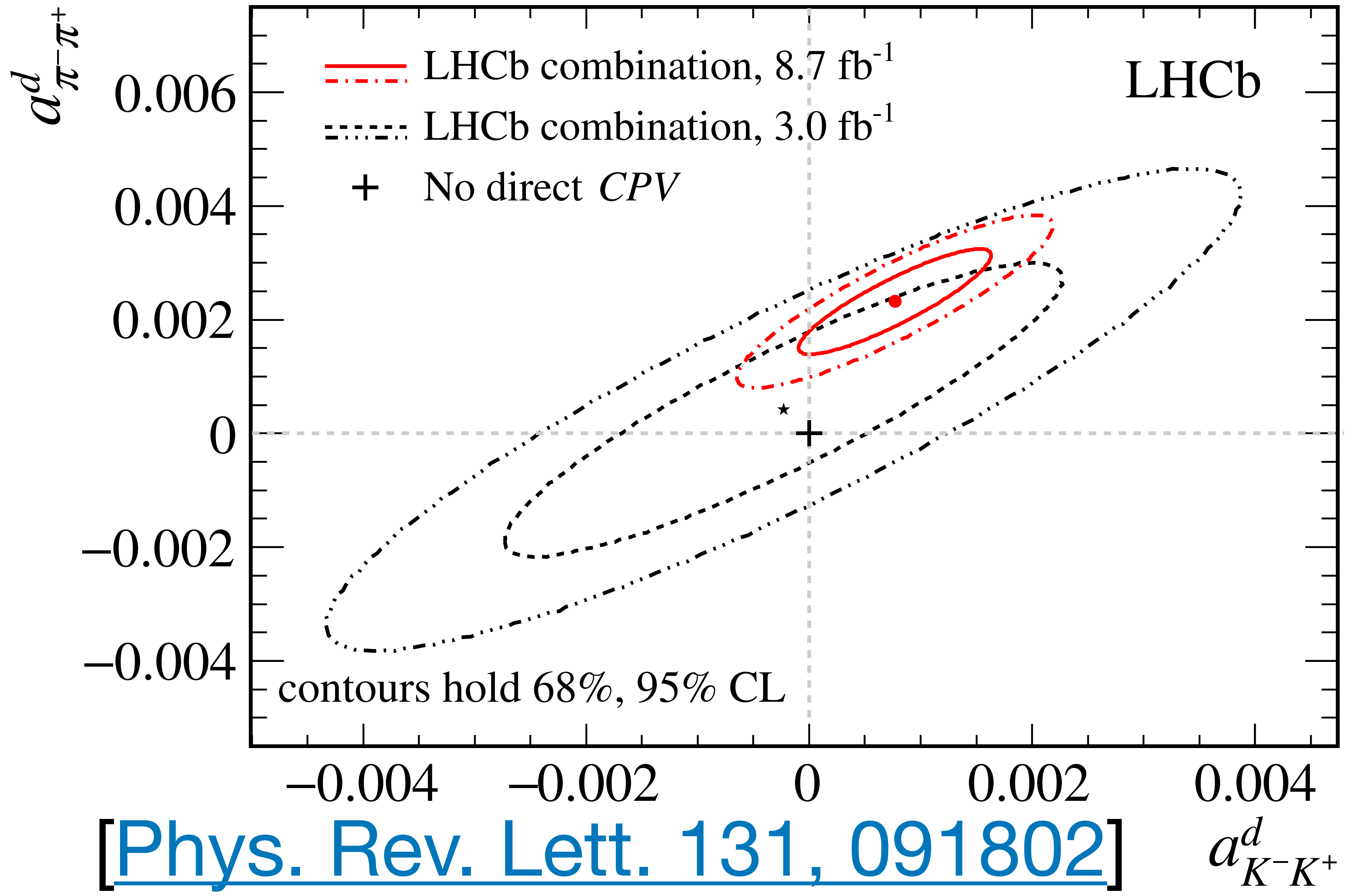
[Phys. Rev. Lett. 122, 211803]

- Combining ΔA^{CP} with results of $A_{CP}(K^+K^-)$

$$a^d_{K^-K^+} = (\ \ 7.7 \pm 5.7) \times 10^{-4}$$
$$a^d_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4}$$

U-spin symmetry violation (2.7σ)

First evidence of CPV in single decay mode (3.8σ)



[Phys. Rev. Lett. 131, 091802]

CPV in multi-body charm decays

[arXiv:2409.01414]

- Local CP asymmetry can be enhanced [Phys. Rev. Lett. 124, 031801]

$$A^{i,X}_{\text{raw}} = \frac{N^{i,X}_{+} - N^{i,X}_{-}}{N^{i,X}_{+} + N^{i,X}_{-}},$$ in bin i where $X = S, C$

⚠ A_D and A_P are also there

$D^{+} \to K^{+}K^{-}\pi^{+}$ signal channel (S)

Singly Cabibbo suppressed

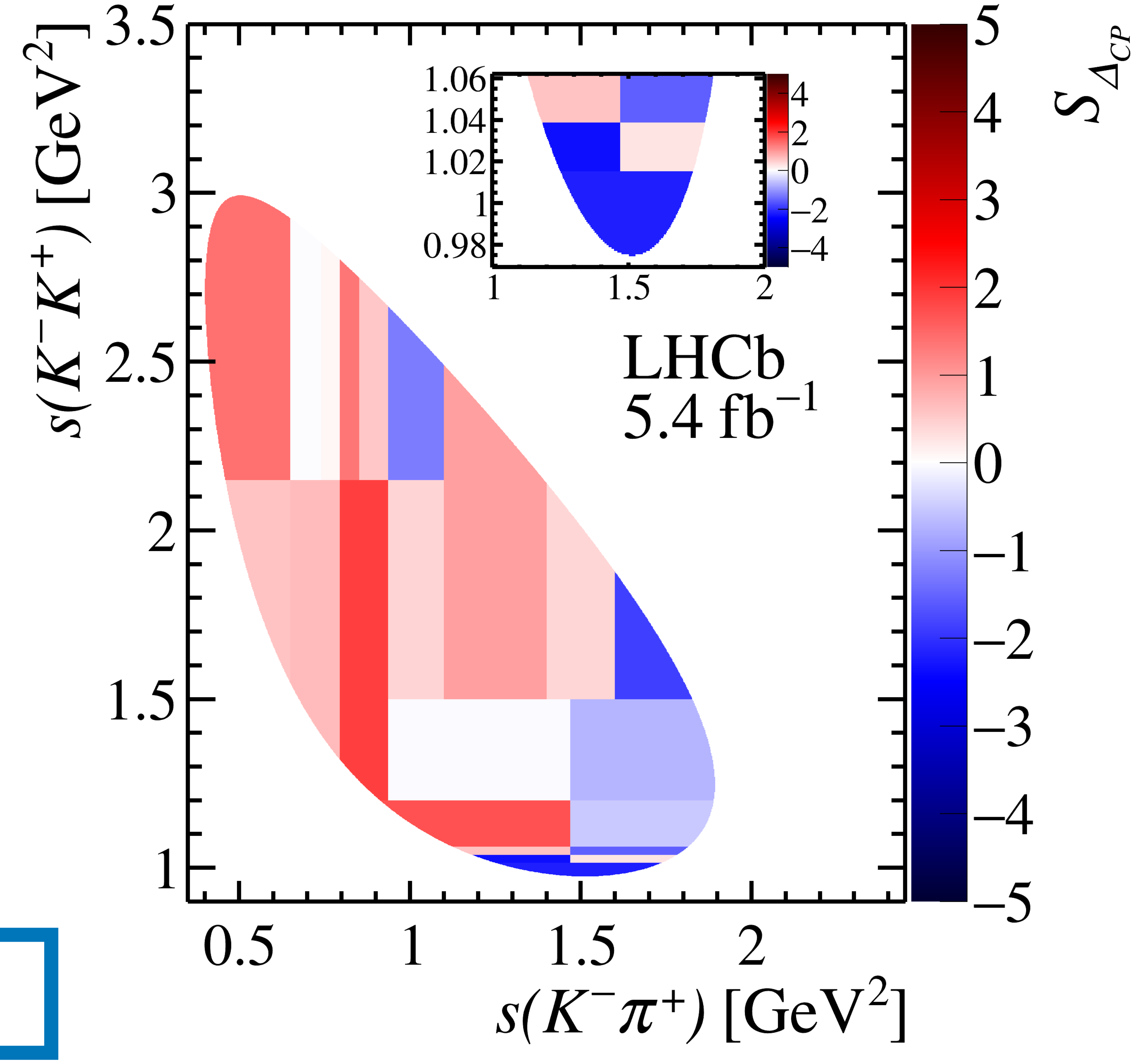
$D^{+}_{s} \to K^{+}K^{-}\pi^{+}$ control channel (C)

Cabibbo favoured → no CPV expected

$$\Delta A^{i}_{CP} = \overbrace{A^{i,S}_{\text{raw}} - A^{i,C}_{\text{raw}}}^{A_D \text{ cancellation}} - \underbrace{\Delta A^{\text{global}}_{\text{raw}}}_{\Delta A_P \text{ cancellation}}$$

- CP asymmetry significance tested in each bin

$$\mathcal{S}^{i}_{\Delta_{CP}} = \frac{\Delta A^{i}_{CP}}{\sigma_{\Delta A^{i}_{CP}}} \xrightarrow{\text{Test statistic assuming CP symmetry}} \chi^2(\mathcal{S}_{\Delta_{CP}}) = \sum_{i}^{N_{\text{bins}}} (\mathcal{S}^{i}_{\Delta_{CP}})^2$$



No evidence for global CPV → p-value for CP conservation $8.1\ \%$

CPV in multi-body charm decays

[arXiv:2409.01414]

- The $\overline{K}^*(892)^0$ and $\phi(1020)$ resonances are clearly visible in the Dalitz plot

- The strong phase varies around resonances

[JHEP 06 (2013) 112] → Phase space integrated CPV may be canceled

- New observables

Bins around resonances

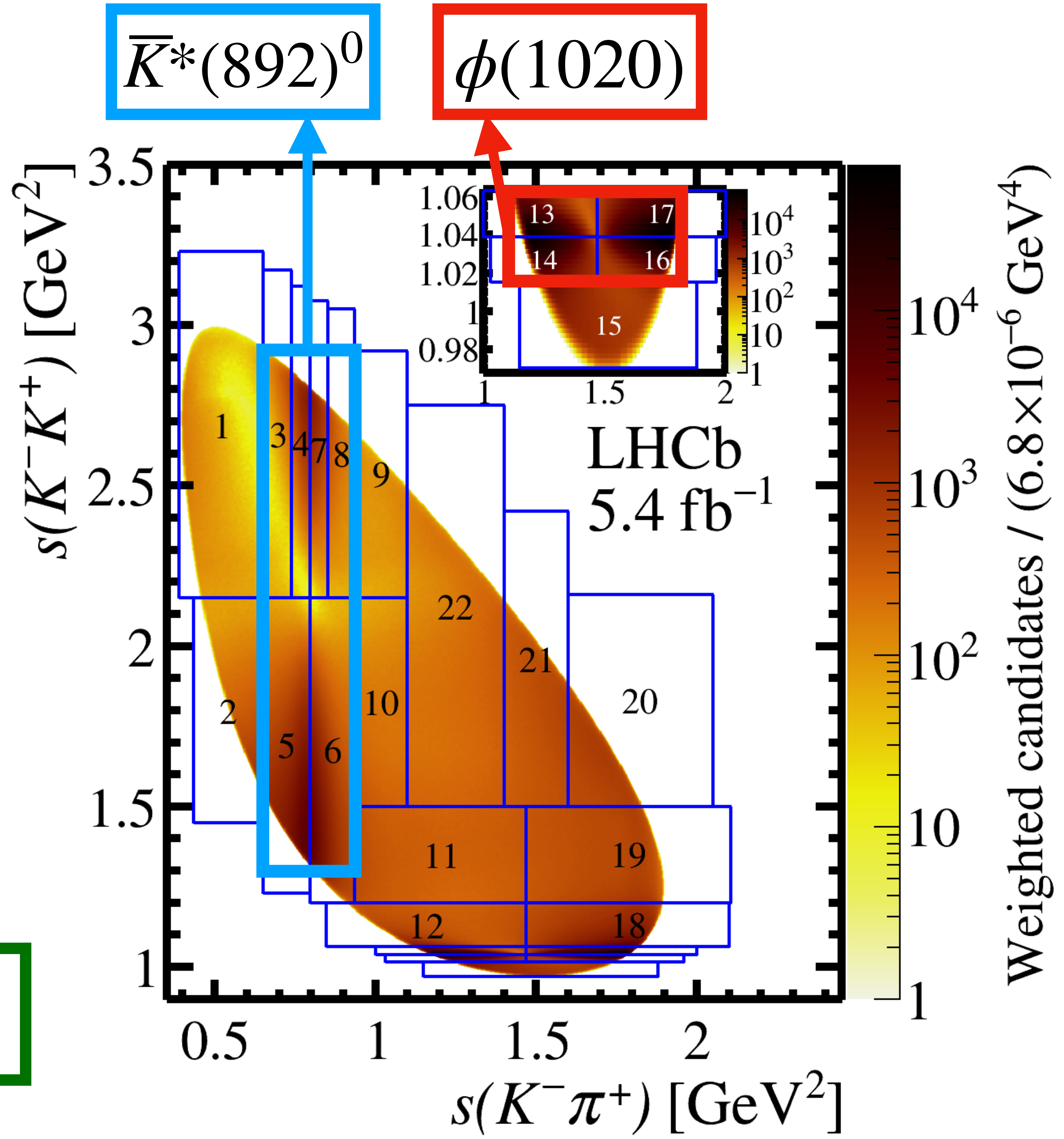
$$A_{CP|S} = \frac{1}{2}\left[\left(\Delta A^{\text{top-left}}_{\text{raw}} + \Delta A^{\text{bottom-right}}_{\text{raw}}\right) - \left(\Delta A^{\text{top-right}}_{\text{raw}} + \Delta A^{\text{bottom-left}}_{\text{raw}}\right)\right]$$

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

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

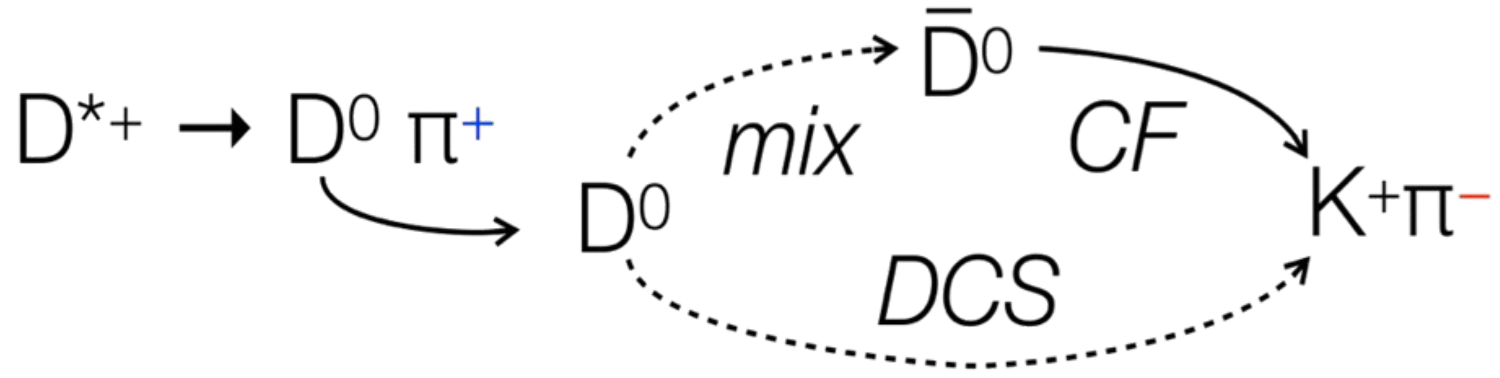
Sub-10^{-3} precision

No evidence for CPV around the resonances



Mixing and CPV in charm decays

- $D^0(t) \to K^+\pi^-$ is an ideal candidates to study oscillations



→ Meson produced in D^0 flavour eigenstate

- Doubly Cabibbo Suppressed (DCS) and mixing amplitudes are of the same order

Time evolution

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix}$$

Off-shell transitions

On-shell transitions

- Off-diagonal $\mathbf{M}$ elements are sensitive to new physics contributing in the mixing box

Mixing parameters

$$x_{12} = 2\frac{|M_{12}|}{\Gamma} \qquad y_{12} = \frac{|\Gamma_{12}|}{\Gamma}$$

Weak phases (CPV observables)

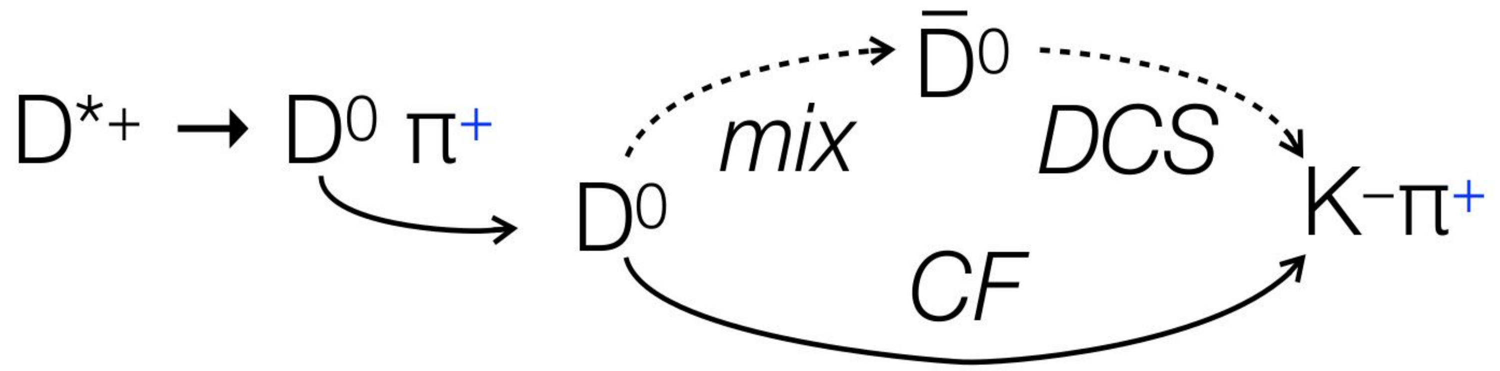
$$\phi_f^M \sim \arg(M_{12}) \qquad \phi_f^\Gamma \sim \arg(\Gamma_{12})$$

[Phys. Rev. D 103, 053008]

Mixing and CPV in charm decays

[arXiv:2407.18001]

- The ratio between $D^0 \to K^+\pi^-$ and $D^0 \to K^-\pi^+$ is sensitive to both mixing and CPV



$$R^+_{K\pi}(t) \equiv \frac{\Gamma(D^0(t) \to K^+\pi^-)}{\Gamma(\overline{D}^0(t) \to K^+\pi^-)} \qquad R^-_{K\pi}(t) \equiv \frac{\Gamma(\overline{D}^0(t) \to K^-\pi^+)}{\Gamma(D^0(t) \to K^-\pi^+)}$$

- Expanding these ratios up to second order in x_{12} and y_{12}

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

Mixing observables

CP even

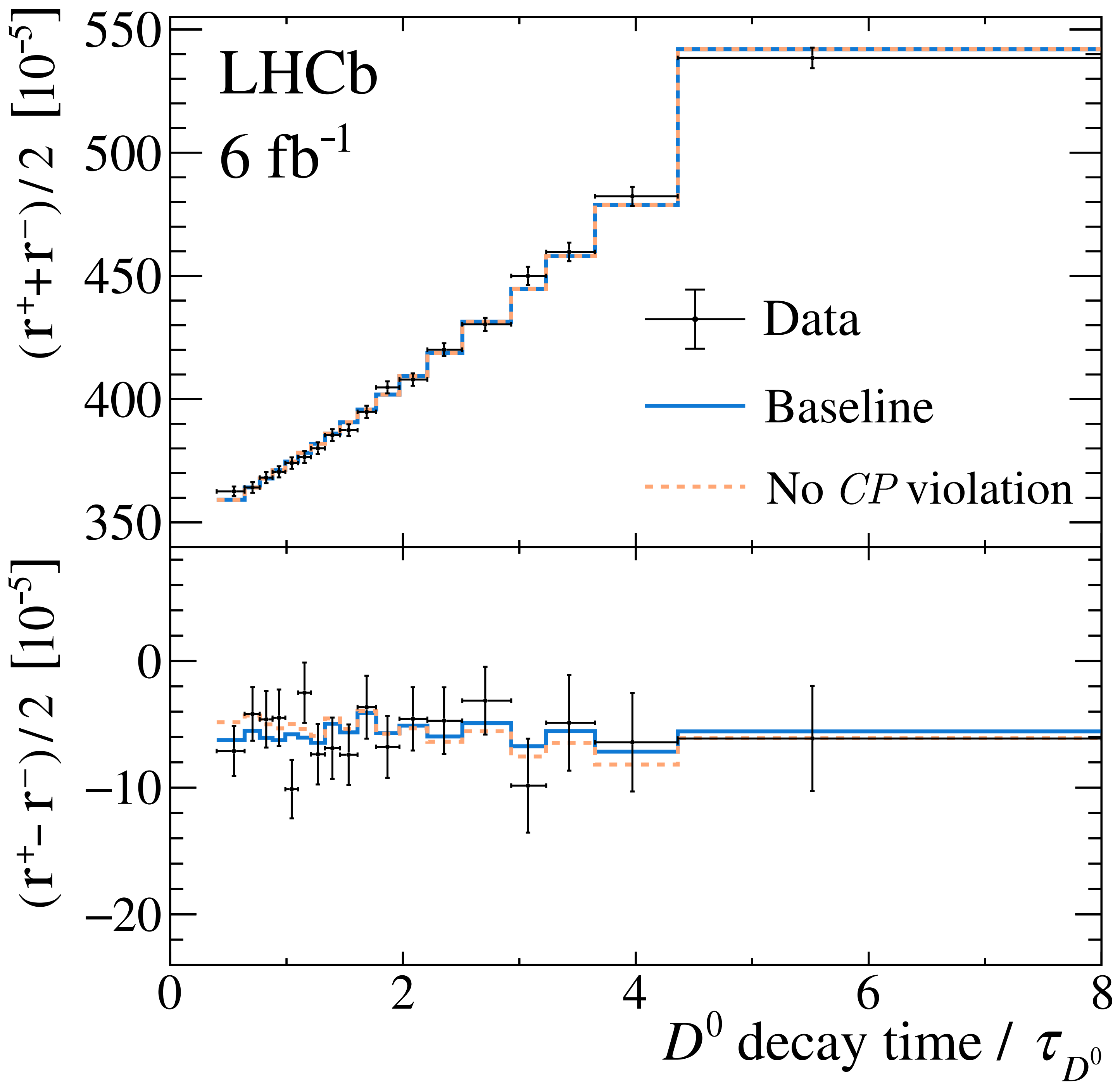
CP odd

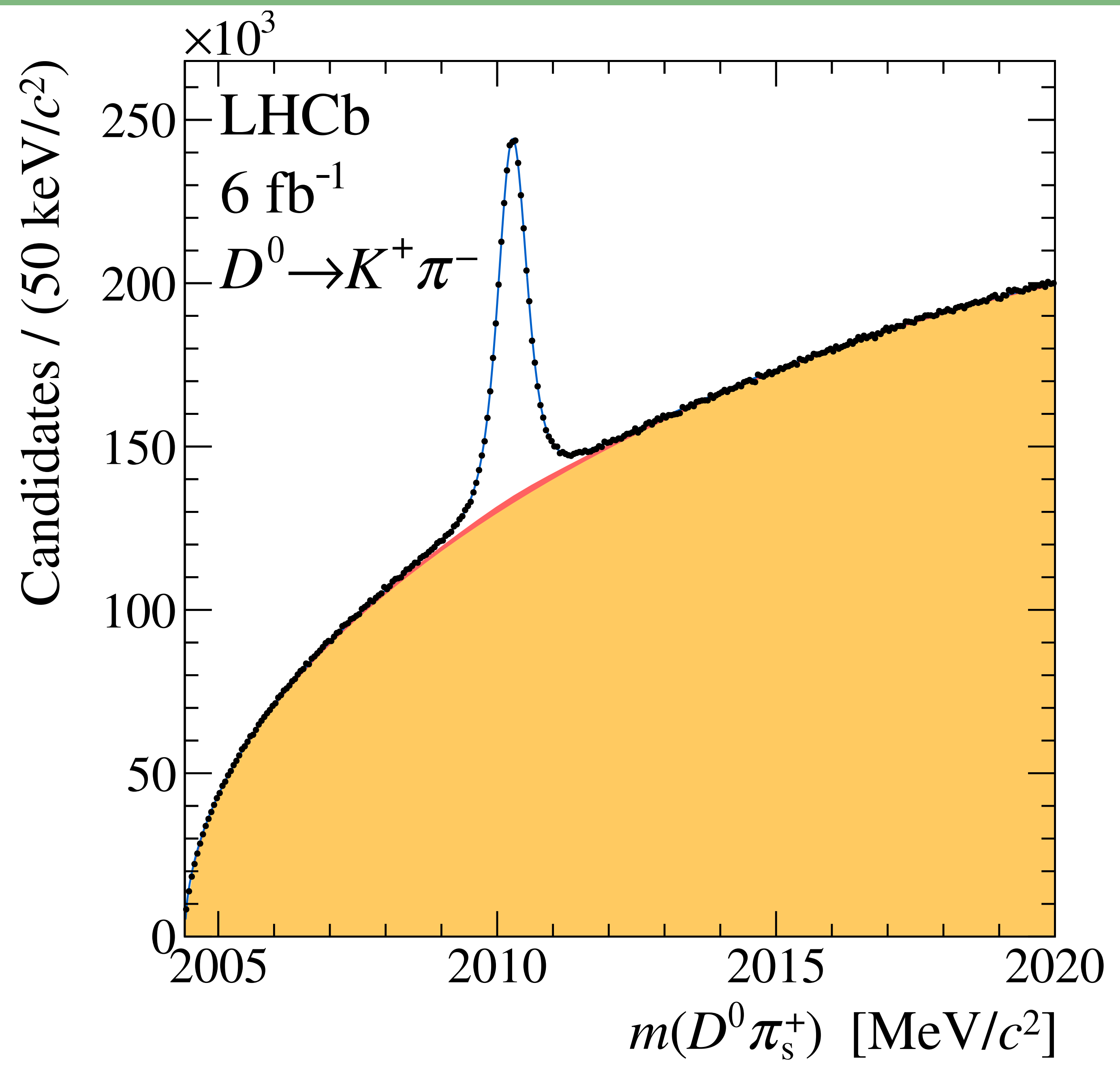
CPV observables

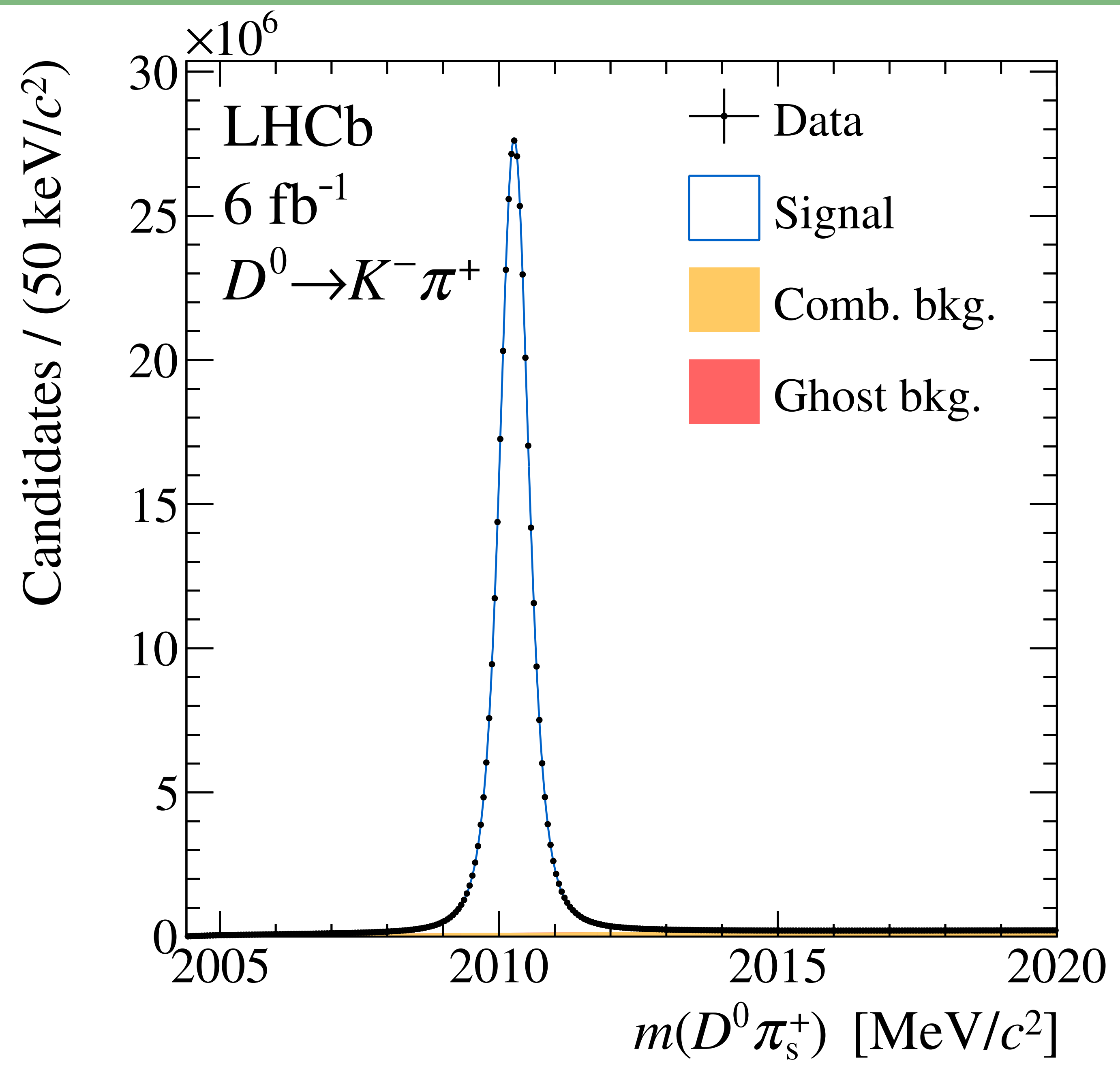
Mixing and CPV in charm decays

[arXiv:2407.18001]

- $R^{\pm}_{K\pi}(t)$ is fitted simultaneously for the two final states
- Direct determination of mixing and CPV parameters







Most precise results up to date

$R_{K\pi}$	$(343.1 \pm 2.0) \times 10^{-5}$
$c_{K\pi}$	$(51.4 \pm 3.5) \times 10^{-4}$
$c'_{K\pi}$	$(13.1 \pm 3.7) \times 10^{-6}$
$A_{K\pi}$	$(-7.1 \pm 6.0) \times 10^{-3}$
$\Delta c_{K\pi}$	$(3.0 \pm 3.6) \times 10^{-4}$
$\Delta c'_{K\pi}$	$(-1.9 \pm 3.8) \times 10^{-6}$

σ_{stat} decreased by $\times 1.6$

σ_{syst} decreased by $\times 2.0$

No evidence for CPV

Mixing in double-tagged decays

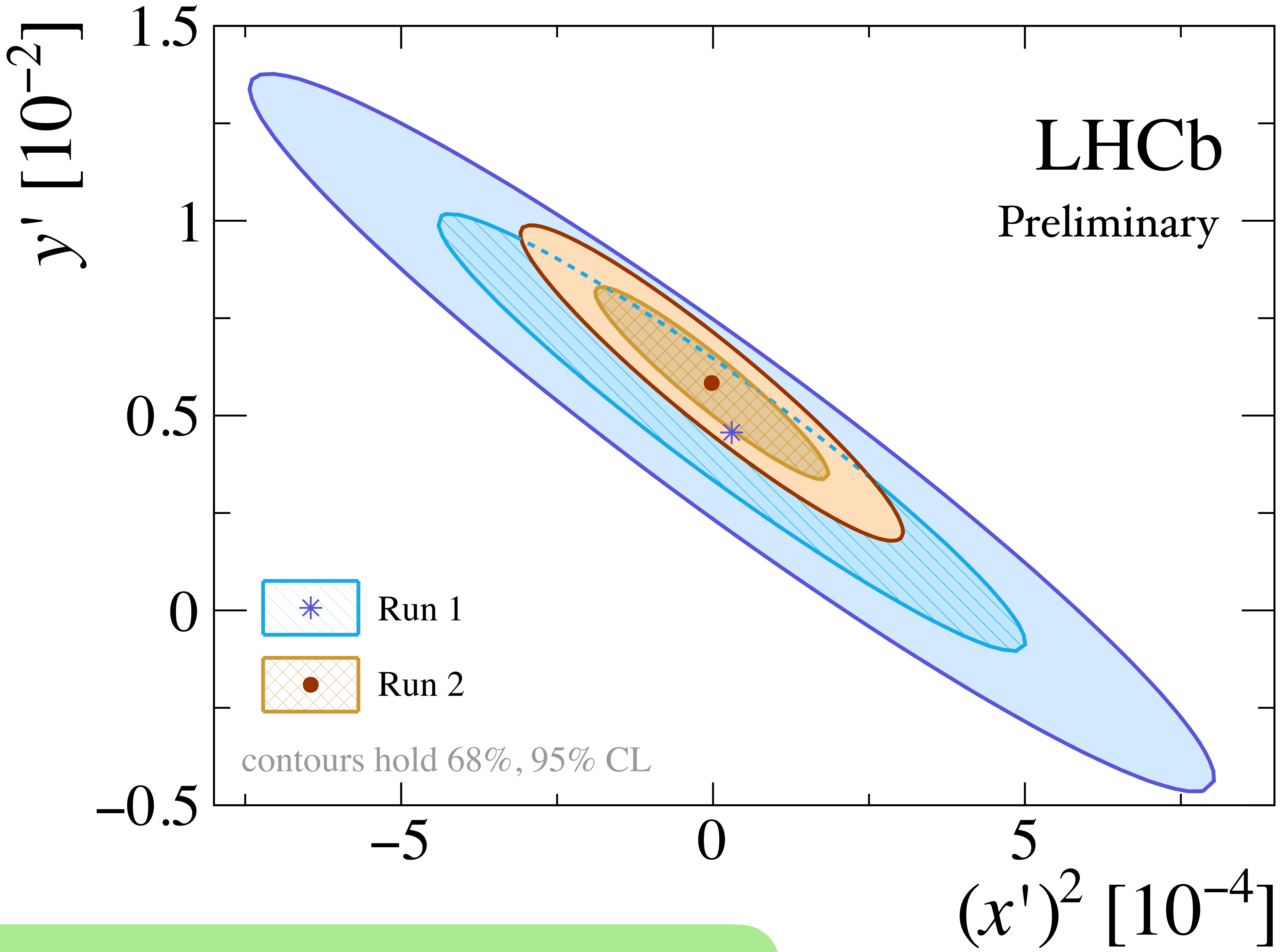
[LHCb-PAPER-2024-044]
(In preparation)

- Mixing and CPV parameters in double-tagged decays

$$\overline{B} \to D^*(2010)^+ \mu^- X$$
$$\hookrightarrow D^*(2010)^+ \to D^0 \pi^+$$

- Complementary to the prompt analysis
  - Higher low decay time sensitivity
  - Fewer statistics

Measuring ratio of $D^0 \to K^\mp \pi^\pm$ decays



Improvement on mixing parameters between $4.8 - 6.4\ \%$

Summary and outlook

- LHCb continues to be deeply involved in investigations on asymmetries in the Charm sector
- New **CPV in multi-body** decays and **mixing parameters** measurements released
- LHCb is still releasing cutting edge results with data from Run 2 (2015-2018)
- Measurements still **statistically limited** → New detector operating at higher luminosity and efficiency
- The 2024 data taking just ended recording $9.6\ \text{fb}^{-1}$ →

New high-precision measurements on the way!

Backup

The LHCb detector during LHC run 2

[JINST 3 S08005]

LHCb is a forward spectrometer → Optimal for charm physics in pp $\left(\sqrt{s} \sim \text{TeV}\right)$ collisions

$\sigma(pp \to c\bar{c}X) \approx 20 \times \sigma(pp \to b\bar{b}X)$

Data Flow

↓

Hardware trigger - L0
Selects high $E,\ p_T$ signatures

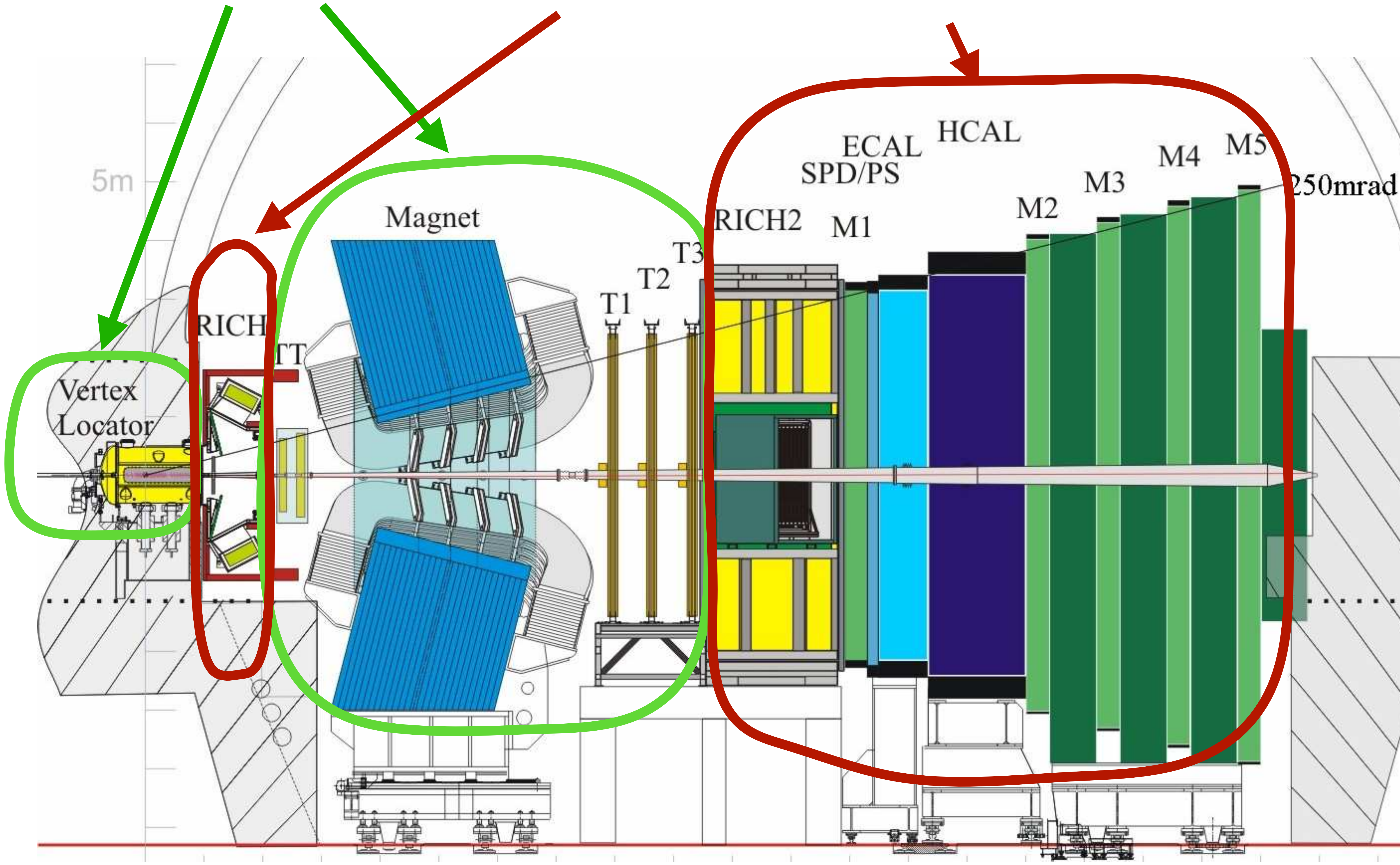
↓

First software level - HLT1
Partial event reconstruction, displaced tracks/vertices selection

↓ Online alignment and calibration

Second software level - HLT2
Full event reconstruction

Tracking stations **Particle identification systems**



Additional materia for multi-body CPV

- To ensure production asymmetry cancellation, and assuming A_P does not depend on the Dalitz plot region region it is measured in, $\Delta A_{\text{raw}}^{\text{global}}$ is defined

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

- In the absence of CPV $\Delta A_{\text{raw}}^{\text{global}}$ corresponds to the production asymmetries difference

Mixing and CPV in charm decays

[arXiv:2407.18001]

- Combining this result with previous results from LHCb [Phys. Rev. D 97, 031101]
- Significant sensitivity to the quadratic term of the time dependant expansion ($c'_{K\pi}$)

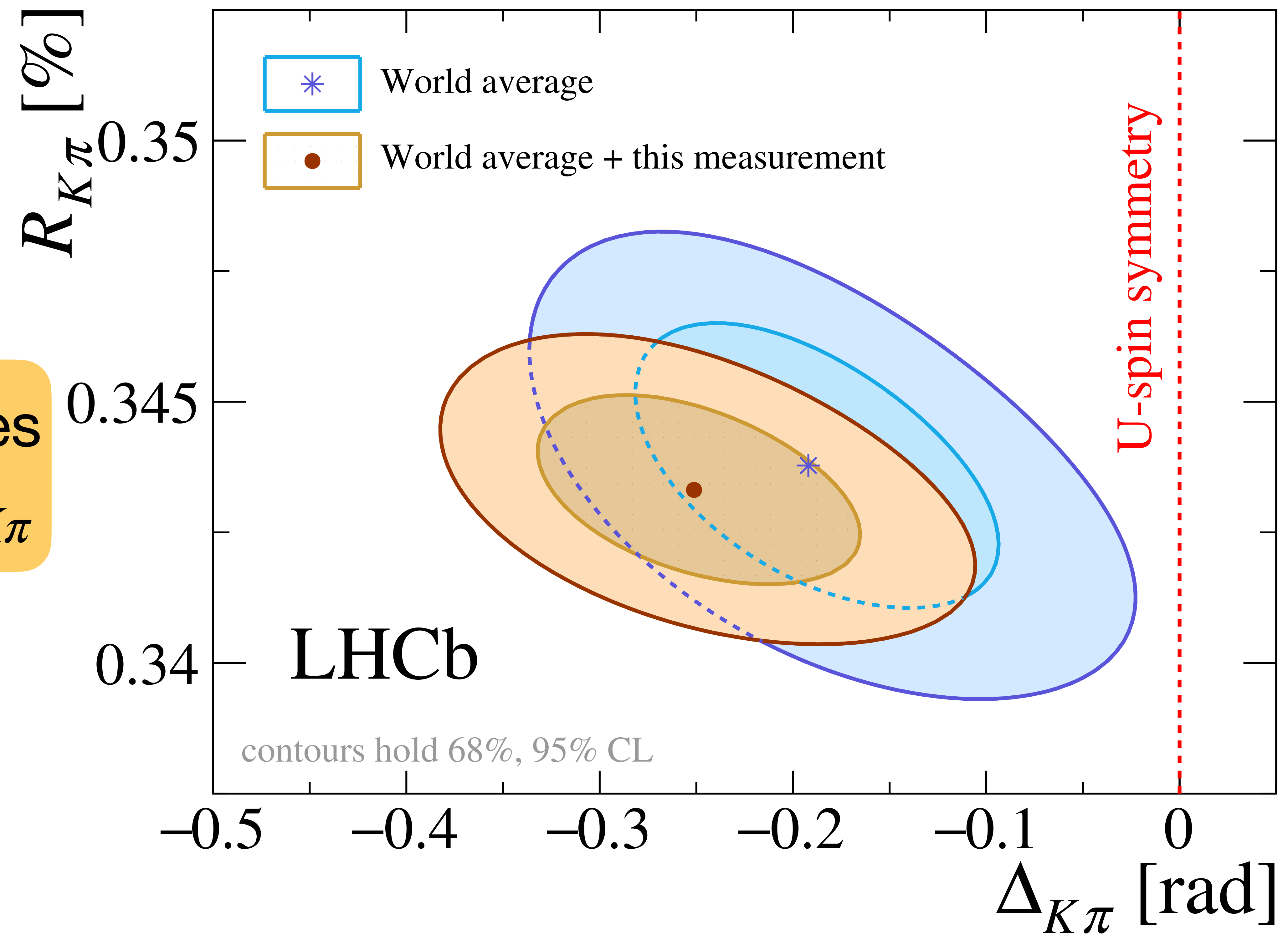
$R_{K\pi}$	$(342.7 \pm 1.9) \times 10^{-5}$
$c_{K\pi}$	$(52.8 \pm 3.3) \times 10^{-4}$
$c'_{K\pi}$	$(12.0 \pm 3.5) \times 10^{-6}$
$A_{K\pi}$	$(-6.6 \pm 5.7) \times 10^{-3}$
$\Delta c_{K\pi}$	$(2.0 \pm 3.4) \times 10^{-4}$
$\Delta c'_{K\pi}$	$(-0.7 \pm 3.6) \times 10^{-6}$

Constrain the values of x_{12}, y_{12} and $\Delta_{K\pi}$

Strong null test of SM
↓
Consistent with CP symmetry

y_{12} precisely known, significant improvement in $\Delta_{K\pi}$ determination

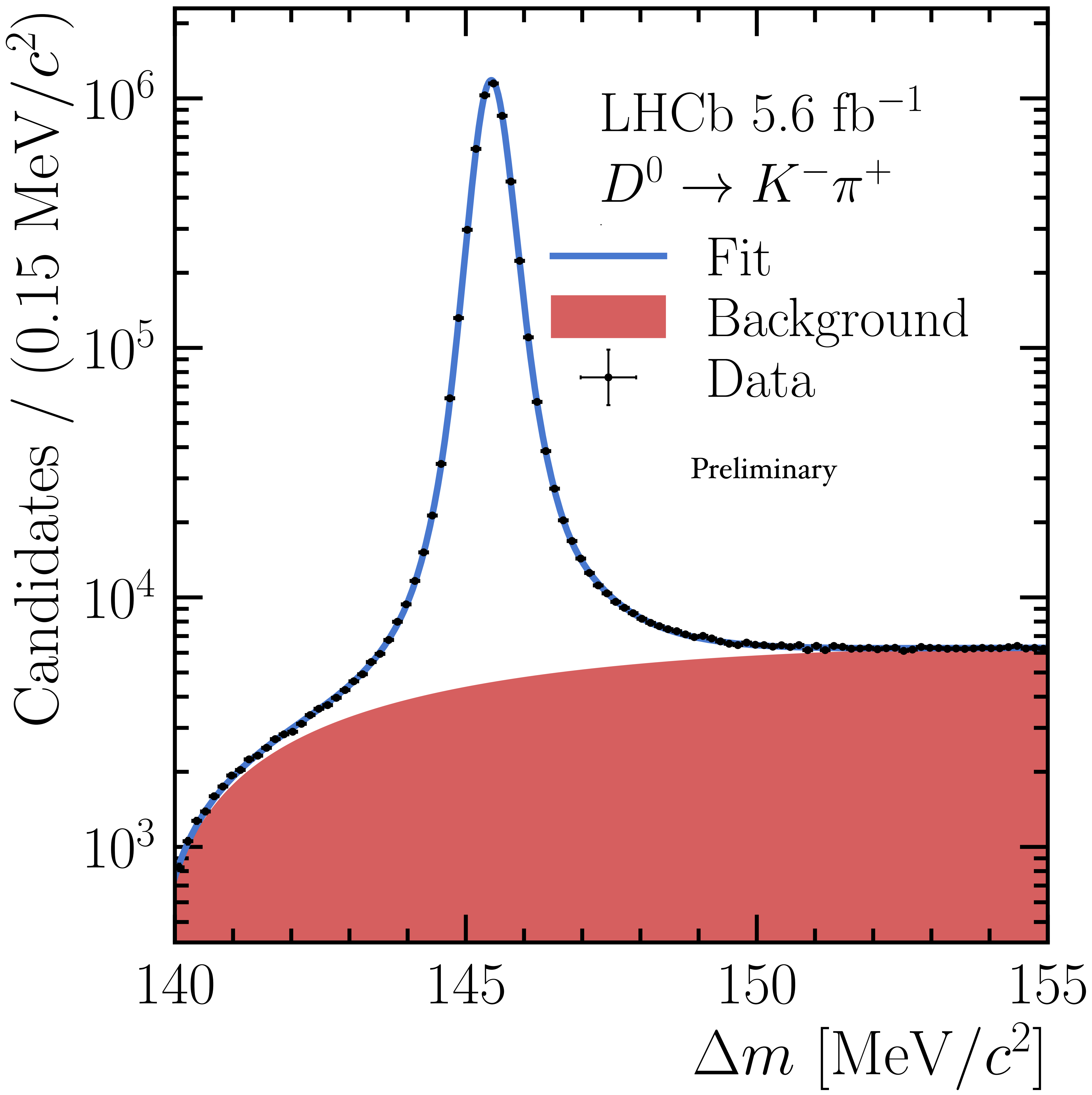
[Phys. Rev. D 105, 092013]

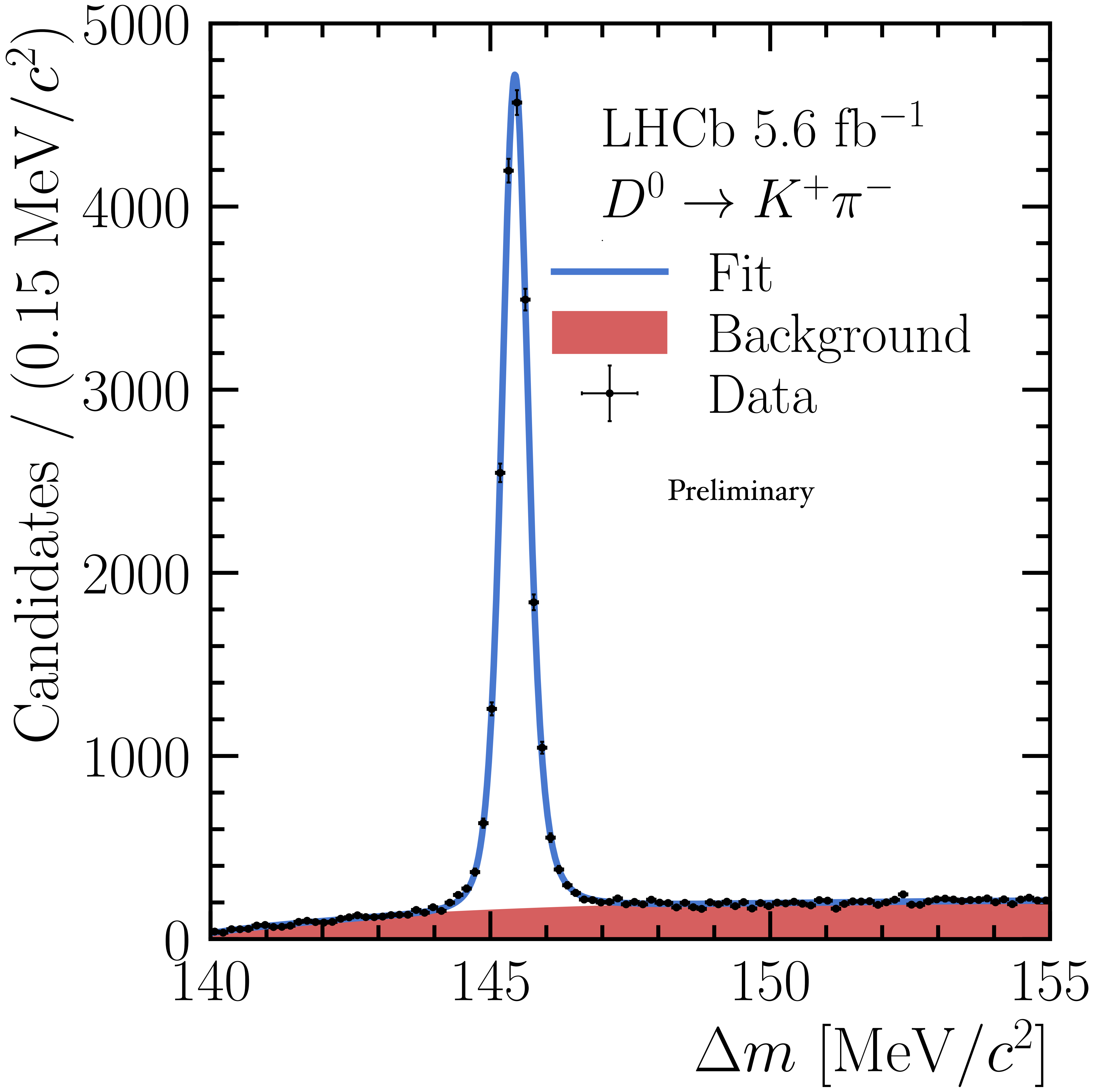


Significant departure from $SU(3)_F$ symmetry

[Phys. Rev. D 103, 053008]

Mass plots double-tagged analysis





Alternative mixing parametrisation

$$\bar{R}^{\pm}(t) \approx R_D(1 \pm A_D) + \sqrt{R_D(1 \pm A_D)}(c_{K\pi} \pm \Delta c_{K\pi}) \left(\frac{t}{\tau_{D^0}}\right) + (c'_{K\pi} \pm \Delta c'_{K\pi}) \left(\frac{t}{\tau_{D^0}}\right)^2$$

$$\begin{aligned}
R_D &= \frac{R_D^+ + R_D^-}{2}, \\
c_{K\pi} &= \frac{y'^+ + y'^-}{2}, \\
c'_{K\pi} &= \frac{1}{2}\left[\frac{(x'^+)^2 + (y'^+)^2}{4} + \frac{(x'^-)^2 + (y'^-)^2}{4}\right], \\
A_D &= \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-}, \\
\Delta c_{K\pi} &= \frac{y'^+ - y'^-}{2}, \\
\Delta c'_{K\pi} &= \frac{1}{2}\left[\frac{(x'^+)^2 + (y'^+)^2}{4} - \frac{(x'^-)^2 + (y'^-)^2}{4}\right].
\end{aligned}$$