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Mixing and time-dependent CP violation in Charm decays at LHCb

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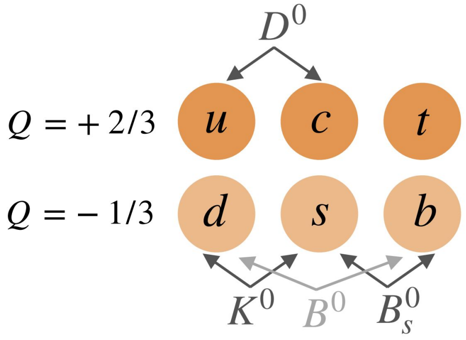
on behalf of the LHCb collaboration

What's charming in Charm physics?

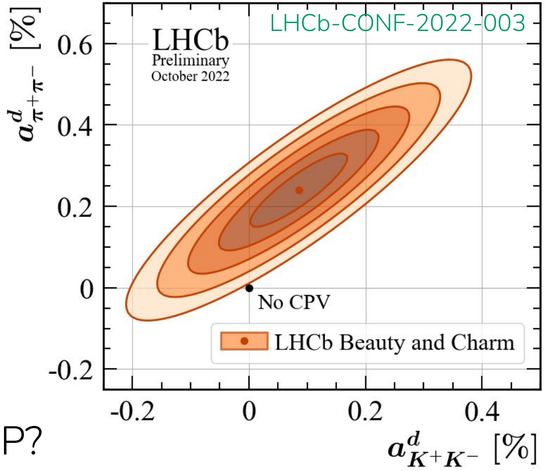


- Charmed neutral meson is the only one made of up-type quark.
  Mixing & *CPV* extremely suppressed in SM
  → powerful probe for new interactions at energy scales ≫ colliders

- In 2019 LHCb reported first observation of *CPV* in charm decay,

  $$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) \neq 0,$$ PRL122,211803

  followed in 2023 by first evidence of *CPV* in a single decay channel
  PRL131.091802



- Need further measurement to clarify theoretical interpretation, SM or NP?

Mixing and CPV in Charm

Grossman & al. 2009
Kagan & Sokoloff 2009
Kagan & Silvestrini 2021

- Flavoured neutral meson evolution effectively described by

$$i\frac{\partial}{\partial t}\begin{pmatrix} M^0(t) \\ \overline{M}^0(t) \end{pmatrix} = \left[\begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}\right]\begin{pmatrix} M^0(t) \\ \overline{M}^0(t) \end{pmatrix}$$

NP→off-shell transitions   on-shell transitions

- Oscillations are governed by two mixing parameters:

$$x_{12} \equiv \frac{2|M_{12}|}{\Gamma} \simeq \frac{\Delta m}{\Gamma}, \qquad y_{12} \equiv \frac{|\Gamma_{12}|}{\Gamma} \simeq \frac{\Delta\Gamma}{\Gamma}$$

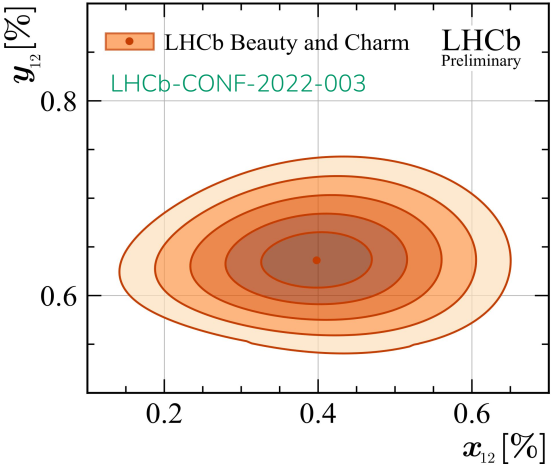
→Moving from first observation (2009) to precision measurements

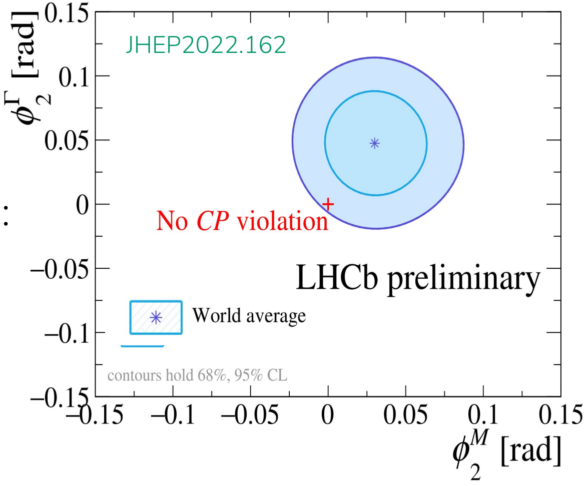
- *CPV* in mixing is regulated by absorptive and dispersive mixing phase:

$$\phi_2^M \sim \arg(M_{12}), \qquad \phi_2^\Gamma \sim \arg(\Gamma_{12})$$

→Still no evidence of *CPV* in mixing

current experimental precision ~20 mrad vs. SM prediction $O(2\text{ mrad})$





Recent LHCb measurements

- Measurement of mixing and *CPV* in $D^0 \to K^+\pi^-$ decay with Run 2 LHCb dataset   LHCb-PAPER-2024-008

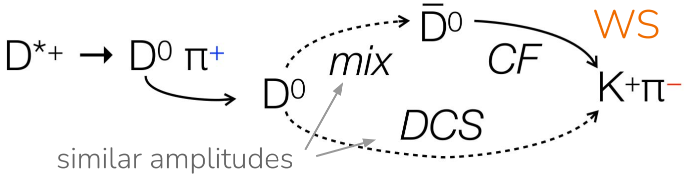
- Measurement of time-dependent CPV in $D^0 \to \pi^+\pi^-\pi^0$ decays with Run 1+2 LHCb dataset   arXiv:2405.06556

Mixing and CPV in $D^0 \to K^+\pi^-$

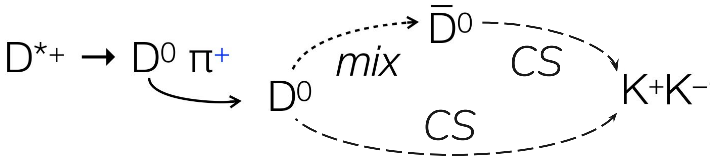
$D^0 \to K^+\pi^-$ WS decay channel

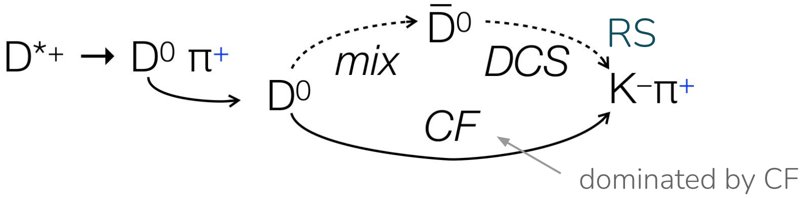
slow pions

- Neutral D meson flavour tagged exploiting strong decay $D^{*+} \to D^0\pi_s^+$ and $D^{*-} \to \overline{D}^0\pi_s^-$
- Final state of interest: Wrong sign (WS)



- Normalization channels: Right sign (RS) and *KK* ←used to cancel instrumental efficiency/asymmetry





- Measure the time dependence of the yield ratio $R^{\pm}_{K\pi}(t)$

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

Ratio decay-time dependency

t := D^0 decay time in unit of D^0 lifetime

$$\frac{\tilde{R}^+_{K\pi}(t)+\tilde{R}^-_{K\pi}(t)}{2} \approx R_{K\pi}\left(1+\frac{c_{K\pi}}{\sqrt{R_{K\pi}}}\,t+\frac{c'_{K\pi}}{R_{K\pi}}\,t^2\right),$$

$$\frac{\tilde{R}^+_{K\pi}(t)-\tilde{R}^-_{K\pi}(t)}{2} \approx R_{K\pi}\left(\tilde{A}_{K\pi}+\frac{\Delta\tilde{c}_{K\pi}}{\sqrt{R_{K\pi}}}\,t+\frac{\Delta\tilde{c}'_{K\pi}}{R_{K\pi}}\,t^2\right),$$

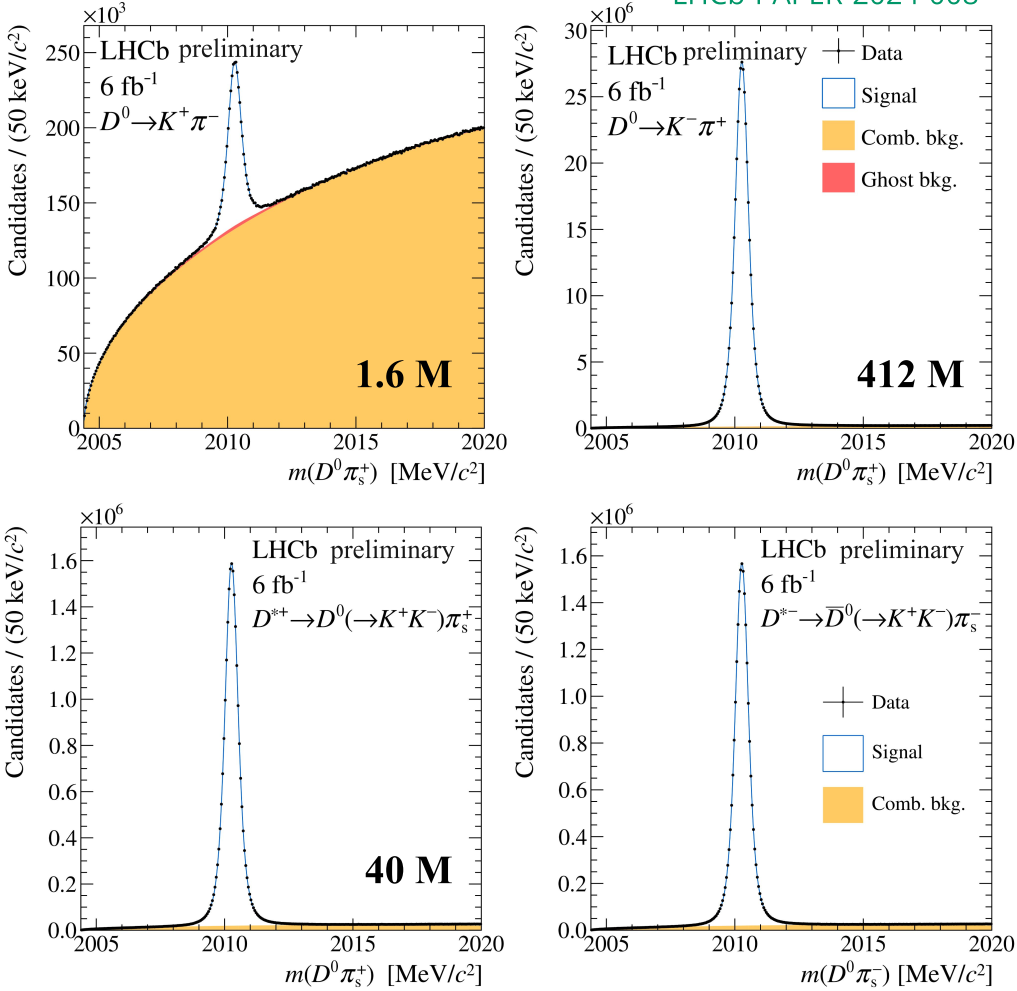
low sensitivity to quadratic term

- $R_{K\pi}$ is the DCS/CF ratio ~3.4 x 10^{-3}
- Mixing observables:
  - $c_{K\pi} \approx y_{12} + x_{12}\Delta_{K\pi}$
    - mostly sensitive to y_{12}
    - strong phase difference $\Delta_{K\pi}$ = -10°± 3°
      LHCb-CONF-2022-003, PRD86.112001, EPJC82.1009
  - $c'_{K\pi} \approx \frac{x_{12}^2 + y_{12}^2}{4}$
- *CPV* observables:
  - $\tilde{A}_{K\pi} \approx a^d_{\mathrm{DCS}} - 2a^d_{KK}$
    - SM predict $a^d_{DCS}=0$
    - only one amplitude in $D^0\to K\pi$
  - $\Delta\tilde{c}_{K\pi} \approx \phi_2^M\, x_{12}\left(1+2\sqrt{R_{K\pi}}\right) - \phi_2^\Gamma\, y_{12}\,\Delta_{K\pi}$
    - mostly sensitive to $\phi_2^M x_{12} \approx -\Delta Y$
  - $\Delta\tilde{c}'_{K\pi} \approx \left[\phi_2^M\left(1+4\sqrt{R_{K\pi}}\right) - \phi_2^\Gamma\right]\frac{x_{12}\,y_{12}}{2}$

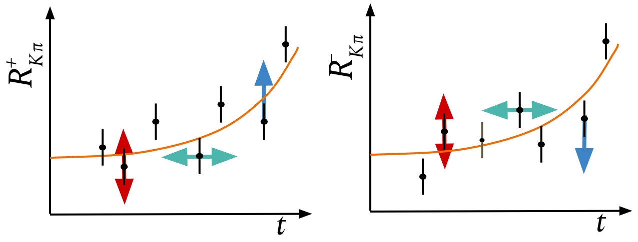
Dataset

- Dataset: Run 2, 6 fb^{-1} pp collision @ 13 TeV
- Sample divided depending on: D^0 final states, t and data-taking period
- Binned fit performed simultaneously to $D^0\pi^+$ invariant mass distributions of WS and RS to disentangle signal from main backgrounds
- Similar fit performed simultaneously to $D^0 \to K^+K^-$ samples from D^{*+} and D^{*-}

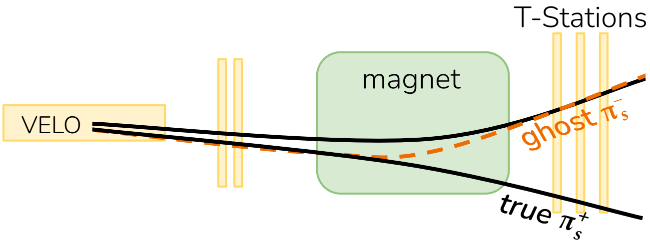
LHCb-PAPER-2024-008



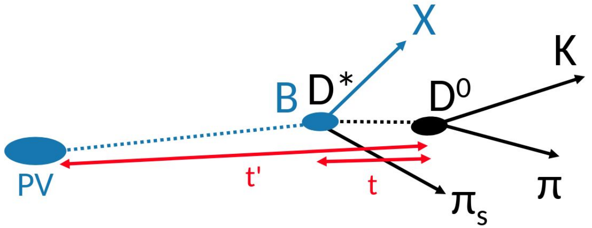
Experimental challenges



- Misassociation of correct VELO hits with wrong T-Stations hits turn RS π_s in **WS *ghosts* π_s that peak in D^* mass**
  → Pure ghost subsample used as proxy for bkg shape



- t biased towards higher values due to **secondary D^* from b-hadrons decays**
  → Reject bkg cutting on $\mathrm{IP}(D^0)$. Residual time biases determined via 2D template fit to t *vs.* $\mathrm{IP}(D^0)$



- $D^0 \to K^+K^-$ kinematics is equalized to $D^0 \to K^-\pi^+$ to exactly cancel **instrumental asymmetries**

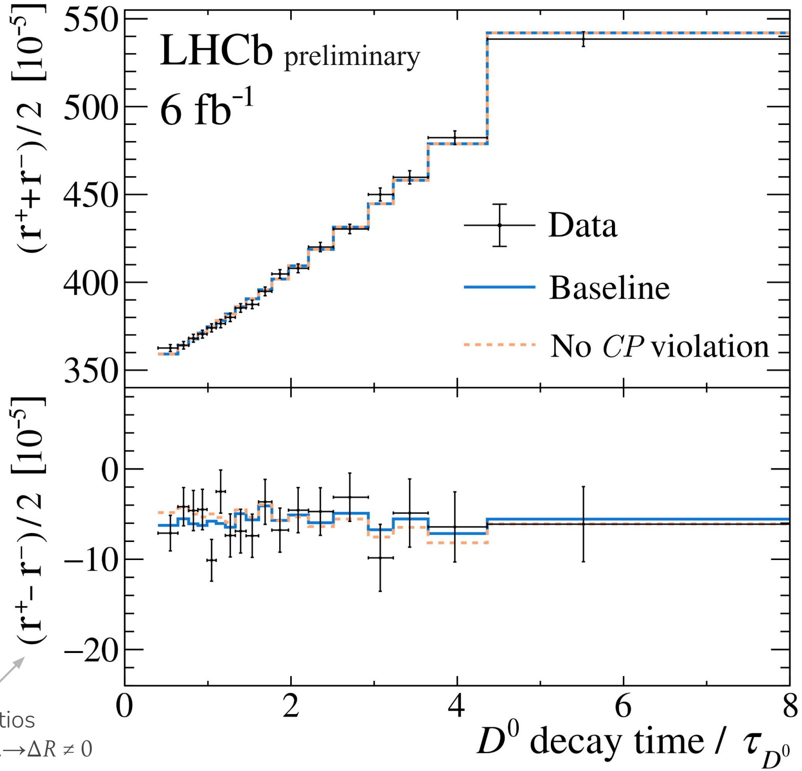
Mixing + CPV fit – Results

All parameters are statistically dominated
Uncertainty improved by 1.6x wrt PRD97,031101

Mixing observables
$c'_{K\pi} \neq 0$, 3.5σ evidence for a significant quadratic term

Parameters		Correlations (%)					
		$R_{K\pi}$	$c_{K\pi}$	$c'_{K\pi}$	$\tilde{A}_{K\pi}$	$\Delta\tilde{c}_{K\pi}$	$\Delta\tilde{c}'_{K\pi}$
$R_{K\pi}$	$(342.7 \pm 1.9) \times 10^{-5}$	100	−92.7	80.3	0.8	−0.7	0.0
$c_{K\pi}$	$(52.8 \pm 3.3) \times 10^{-4}$		100	−94.3	−1.4	1.3	−0.6
$c'_{K\pi}$	$(12.0 \pm 3.5) \times 10^{-6}$			100	0.7	−0.6	0.0
$\tilde{A}_{K\pi}$	$(-8.2 \pm 5.9) \times 10^{-3}$				100	−93.4	81.0
$\Delta\tilde{c}_{K\pi}$	$(3.2 \pm 3.6) \times 10^{-4}$					100	−94.3
$\Delta\tilde{c}'_{K\pi}$	$(-2.0 \pm 3.8) \times 10^{-6}$						100

CPV observables
No evidence of *CPV* neither in decay, mixing nor interference

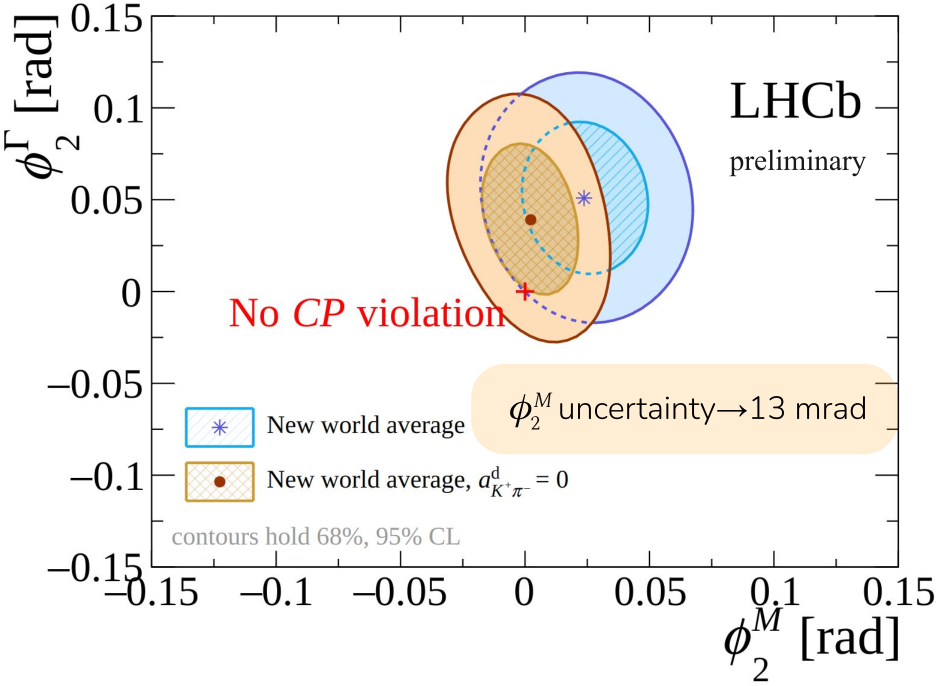


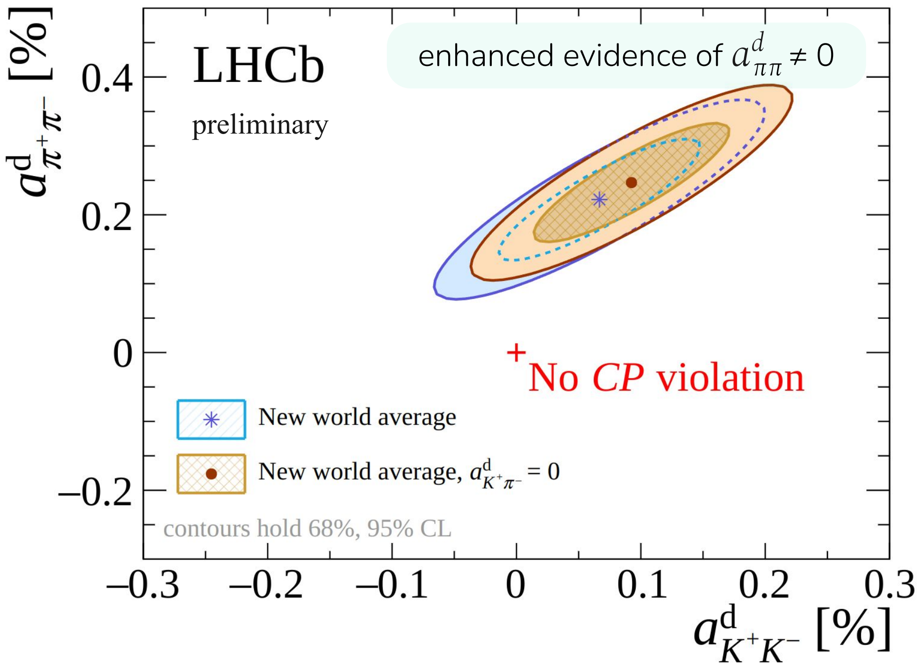
WS/RS ratios
detection asym.→$\Delta R \neq 0$

Impact on World Average – $a^d_{\mathrm{DCS}} = 0$

New charm+beauty LHCb fit
→ Aidan talk @ 17.30

- Assuming $a^d_{\mathrm{DCS}} = 0$ boosts ϕ_2^M sensitivity and allows to perform an independent measurement of a^d_{KK}





Time-dependent CPV in $D^0 \to \pi^+\pi^-\pi^0$

arXiv:2405.06556

Observable and dataset

- Time dependent CP asymmetry can be expanded as

$$A_{CP}^{f}(t) \equiv \frac{\Gamma\left(D^0(t) \to f\right) - \Gamma\left(\bar{D}^0(t) \to f\right)}{\Gamma\left(D^0(t) \to f\right) + \Gamma\left(\bar{D}^0(t) \to f\right)} \approx a_f^d + \Delta Y_f\, t$$

- In $D^0 \to \pi^+\pi^-\pi^0$ (self-conjugated multibody decay):

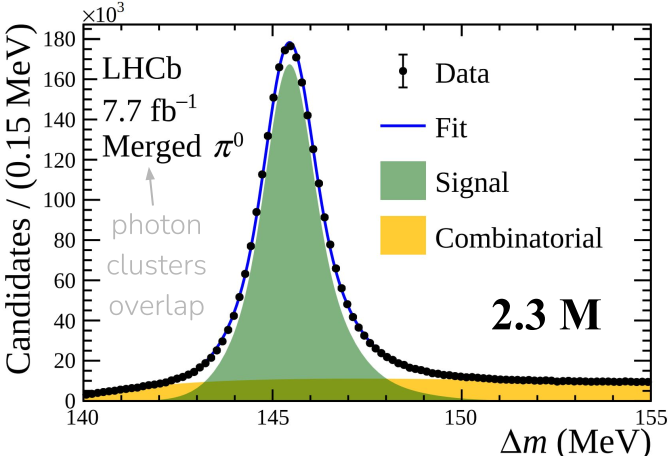
PRD91,094032 $$\Delta Y_f \approx \phi_2^M x_{12}\left(1 - 2F_f^+\right)$$ ← CP-even fraction

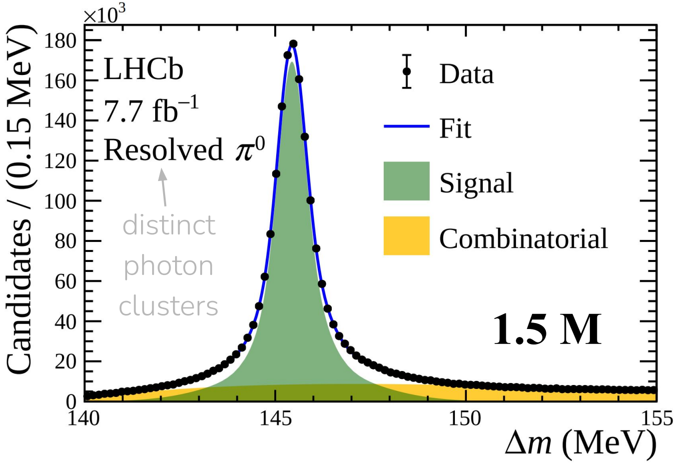
PLB747,9 $$F_{\pi\pi\pi^0}^{+} = 0.973 \pm 0.017$$ ~ entirely CP-even

- Dataset: 2012 + Run 2, 7.7 fb^{-1}, D^* tagged

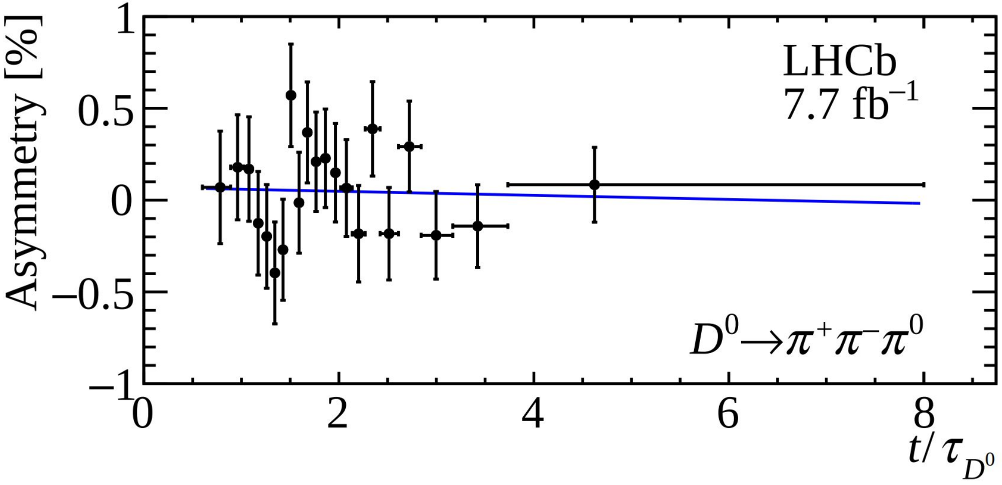
- Sample divided depending on t, data-taking period, magnet polarity and $\pi^0 \to \gamma\gamma$ decay category

- Trigger induced time-dependent asymmetries removed equalizing D^0, π_s kinematics among D^{*+} and D^{*-}





Final results



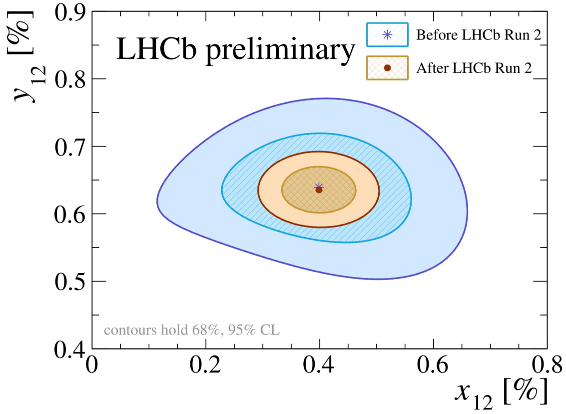
$$\Delta Y = (-1.3 \pm 6.3(\text{stat}) \pm 2.4(\text{syst})) \times 10^{-4}$$

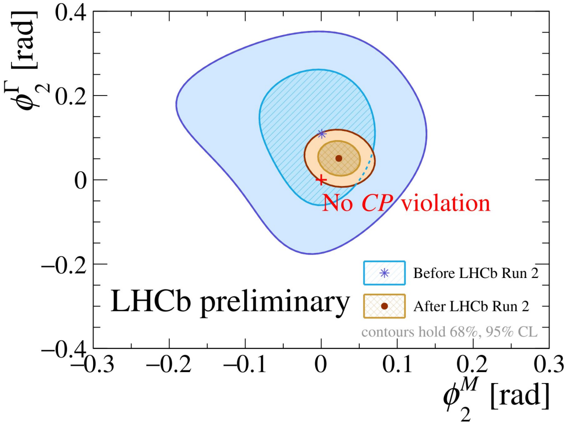
- Consistent with no CP violation and statistically limited
- First measurement of time-dependent *CPV* in a decay with π^0 @ hadron collider

Conclusions

LHCb-PAPER-2024-008

- **Main advancement in charm *CPV***
  - *CPV* mixing phase ϕ_2^M uncertainties down to 13 mrad
    $\longrightarrow$ compatible with zero, 6x SM prediction
  - new independent measurement of a^d_{KK}
    $\longrightarrow$ enhanced evidence of direct *CPV* in $D^0 \rightarrow \pi^+\pi^-$
- Very successful Run 2. Measurements still statistically dominated
- The way is paved for Run 3. Expected 2x efficiency / fb^{-1} for $D^0 \rightarrow hh'$
- **Still more to come from Run 1+2, stay tuned !**





Thank you!

Backup

Phenomenological vs Theoretical parametrization

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

Phenomenological

Theoretical

$$x = \Delta m / \Gamma \qquad x_{12} = 2|M_{12}| / \Gamma \qquad x_{12} \approx |x|$$

$$y = \Delta\Gamma / 2\Gamma \qquad y_{12} = |\Gamma_{12}| / \Gamma \qquad y_{12} \approx |y|$$

$$\left(\frac{q}{p}\right)^2 = \frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}$$

$$\phi_2 \equiv \arg\left[\frac{q}{p}\frac{(\lambda_s - \lambda_d)^2\,\Gamma_2}{4}\right]$$

$$\phi_2^\Gamma \equiv \arg\left[\frac{\Gamma_{12}}{\frac{1}{4}(\lambda_s - \lambda_d)^2\,\Gamma_2}\right]$$

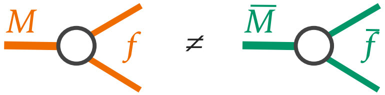
$$\phi_2^M \equiv \arg\left[\frac{M_{12}}{\frac{1}{4}(\lambda_s - \lambda_d)^2\,M_2}\right]$$

$$\left|\frac{q}{p}\right| - 1 \approx \frac{x_{12}y_{12}}{x_{12}^2 + y_{12}^2}\sin(\phi_2^M - \phi_2^\Gamma)$$

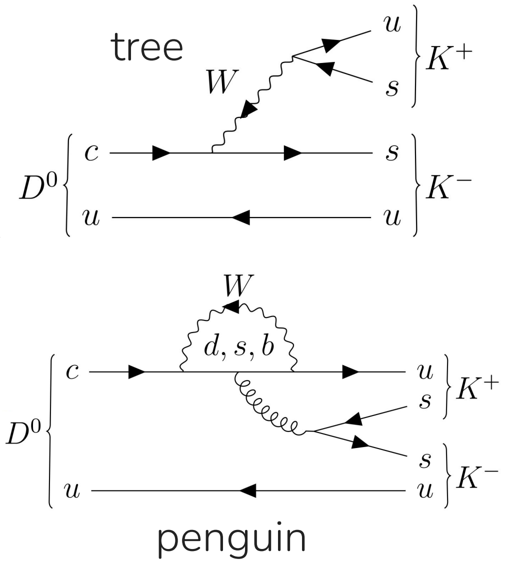
$$\phi_2 \approx -\frac{x_{12}^2}{x_{12}^2 + y_{12}^2}\phi_2^M - \frac{y_{12}^2}{x_{12}^2 + y_{12}^2}\phi_2^\Gamma$$

intrinsic CPV mixing phases, defined with respect to the dominant ΔU = 2 dispersive and absorptive mixing amplitudes
Kagan & Silvestrini 2021

CP violation manifestations

- *CPV* in the decay 

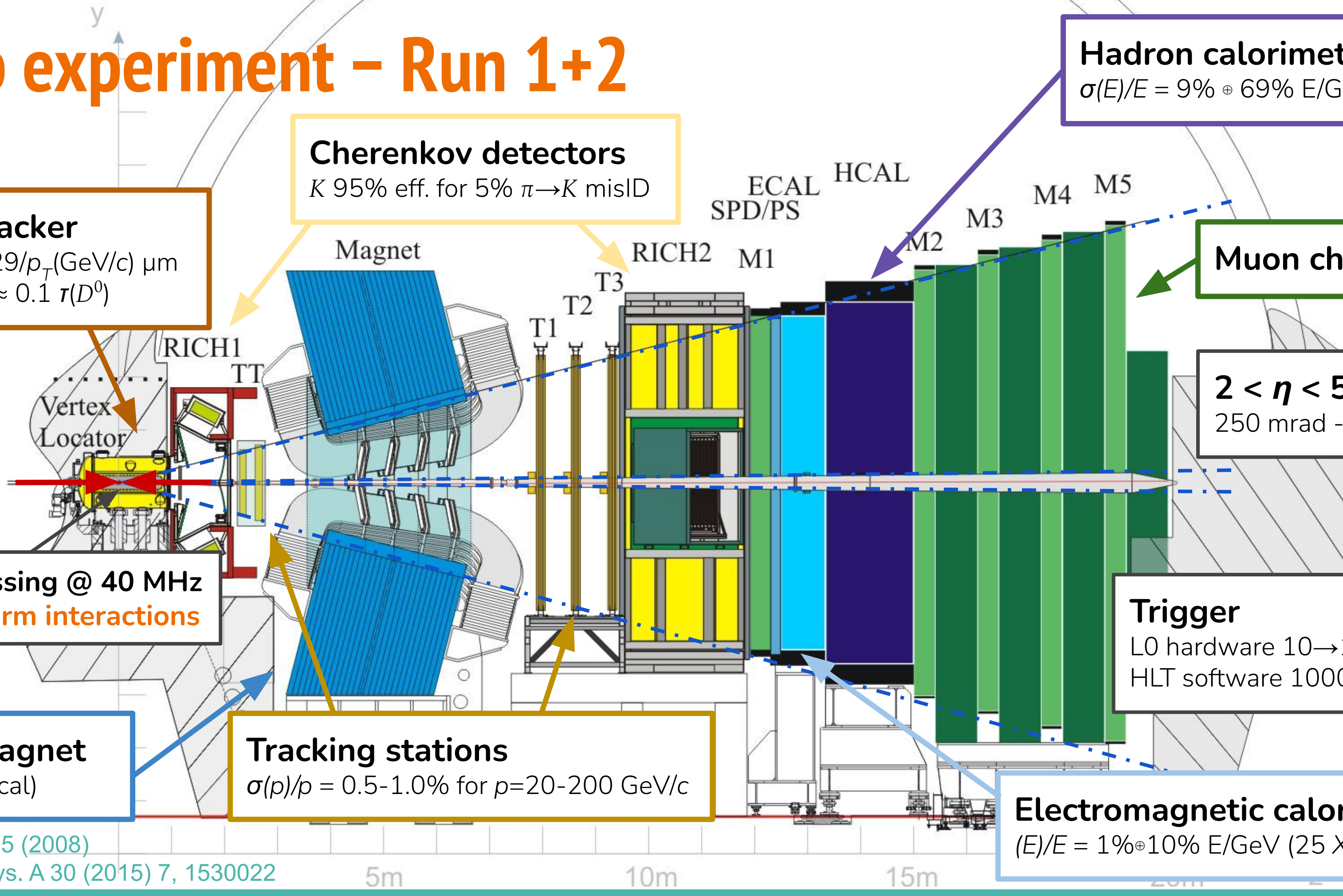
$$\mathcal{A}(M \to f) = |a_1|e^{i(\delta_1+\phi_1)} + |a_2|e^{i(\delta_2+\phi_2)}$$
$$\mathcal{A}(\overline{M} \to \overline{f}) = |a_1|e^{i(\delta_1-\phi_1)} + |a_2|e^{i(\delta_2-\phi_2)}$$



need for at least two interfering amplitudes with different weak ϕ and strong δ phases

$$a_f^d = \frac{|\mathcal{A}(M \to f)|^2 - |\mathcal{A}(\overline{M} \to \overline{f})|^2}{|\mathcal{A}(M \to f)|^2 + |\mathcal{A}(\overline{M} \to \overline{f})|^2} \propto \sin(\phi_2 - \phi_1)\sin(\delta_2 - \delta_1)$$

LHCb experiment – Run 1+2



Vertex tracker
σ(IP) = 15+29/p_T(GeV/c) μm
$\sigma(t)$ = 45 fs ≈ 0.1 $\tau(D^0)$

Cherenkov detectors
K 95% eff. for 5% $\pi \to K$ misID

Hadron calorimeter
$\sigma(E)/E$ = 9% ⊕ 69% E/GeV (5.6 λ_{int})

Muon chambers

2 < η < 5
250 mrad - 30 mrad

bunch crossing @ 40 MHz
1 MHz charm interactions

Trigger
L0 hardware 10→1 MHz
HLT software 1000→12 KHz

Dipole magnet
4 T·m (vertical)

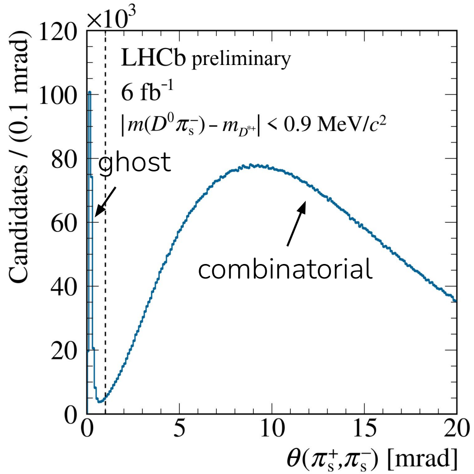
Tracking stations
$\sigma(p)/p$ = 0.5-1.0% for p=20-200 GeV/c

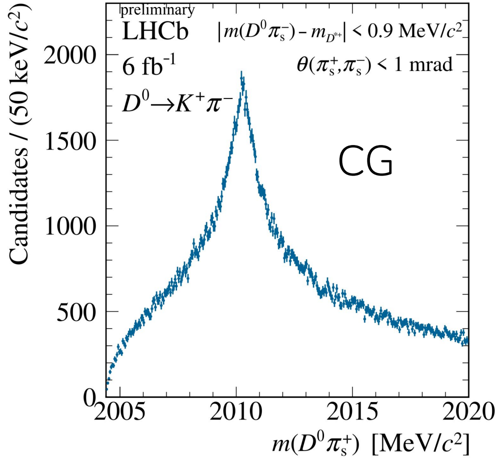
Electromagnetic calorimeter
$\sigma(E)/E$ = 1%⊕10% E/GeV (25 X^0, 1.2 λ_{int})

JINST 3 S08005 (2008)
Int. J. Mod. Phys. A 30 (2015) 7, 1530022

Ratio biases – Ghost background proxy

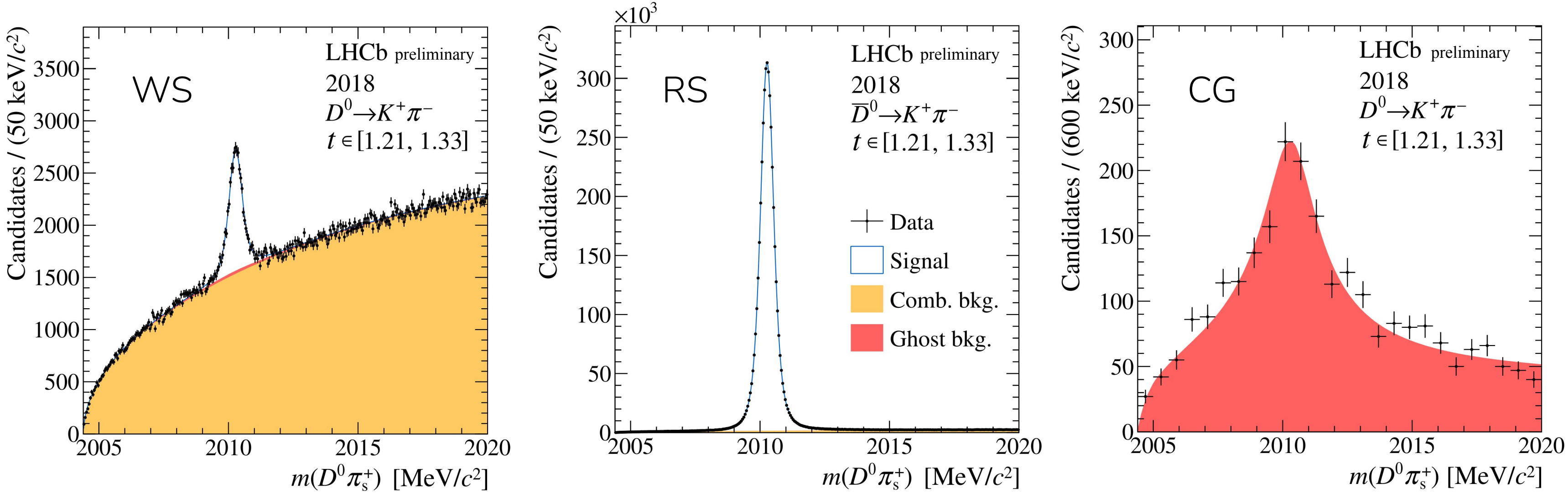
- A fraction of D^0 candidates is used to reconstruct both WS D^{*+} and RS D^{*-}
- RS D^* within 3σ from D^* peak, are most likely genuine $\rightarrow$ common WS are are either ghost or combinatorial bkg and discarded to improve signal-to-noise ratio
- In this sample, ghost and combinatorial component can be disentangled looking at angle between π_s^+ and π_s^-
- This pure subsample of common ghost (CG) is used as a proxy for residual ghost bkg





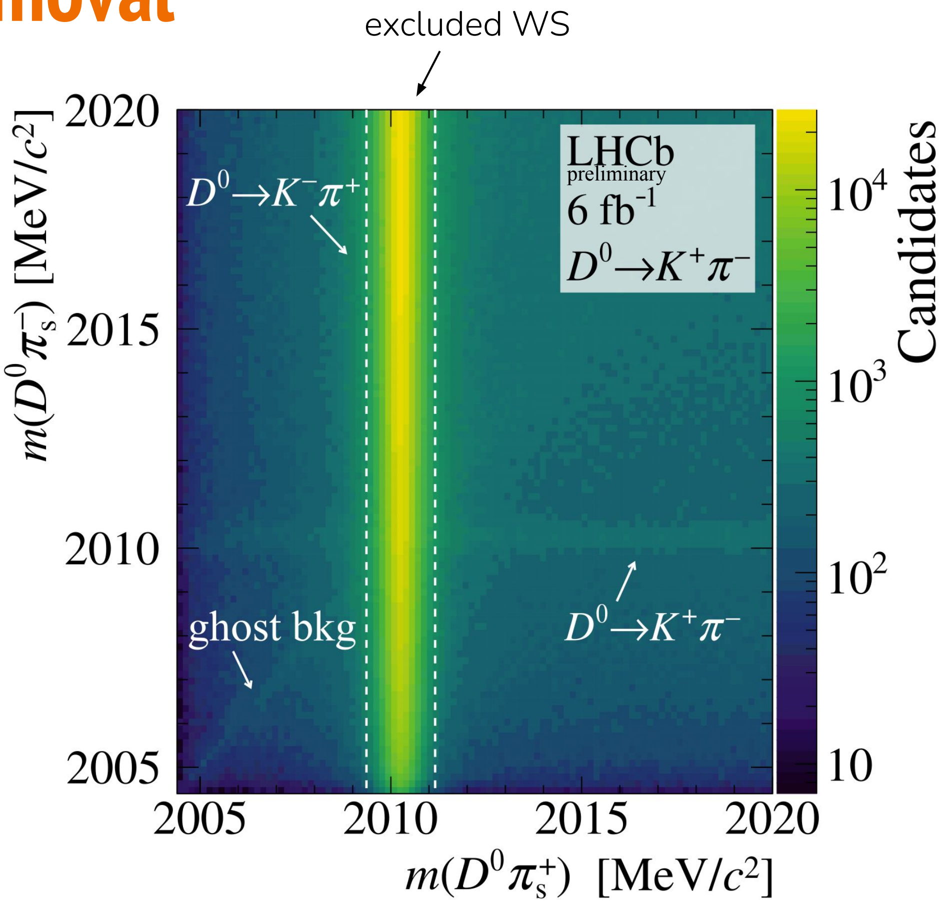
WS/RS Ratio determination – D^* mass fit

- Constraining D^* in the PV improve mass resolution by a factor of 2
- A χ^2 binned fit is performed **simultaneously to D^* mass distributions of WS, RS and CG**
- Each subsample independently fitted (decay-time interval, data-taking period, and D^0 final state)
- Signal and Ghost bkg pdf are shared



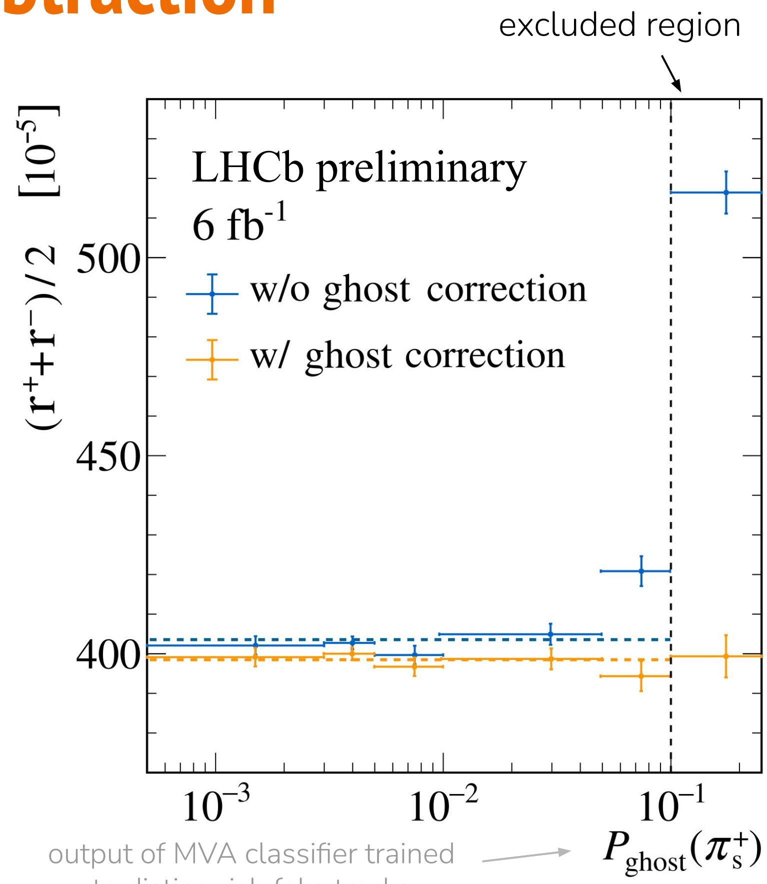
Ratio biases – common WS removal

- Removing these WS-RS multiple candidates, **a small fraction of proper WS decays are removed, biasing the ratio**
- Estimated and subtracted bias $\sim\sigma(R_{K\pi})/5$



Ratio biases – Test of ghost bkg. subtraction

- Test capability to correctly remove ghost bkg.
- Fit WS-to-RS ratio in 6 bin of $P_{\text{ghost}}(\pi_s^+)$ with and without ghost component
- When ghosts are neglected clear bias appears
- Adding ghost component removes any dependence
- The subtracted bias on $R_{K\pi}$ from ghost bkg. is ~1%



output of MVA classifier trained to distinguish fake tracks

Ratio biases – Particles misidentification

- Remove background from single mis-ID
  $D^0 \to K^+(\rightsquigarrow \pi^+)\, K^-$ and $D^0 \to \pi^+(\rightsquigarrow K^+)\, \pi^-$

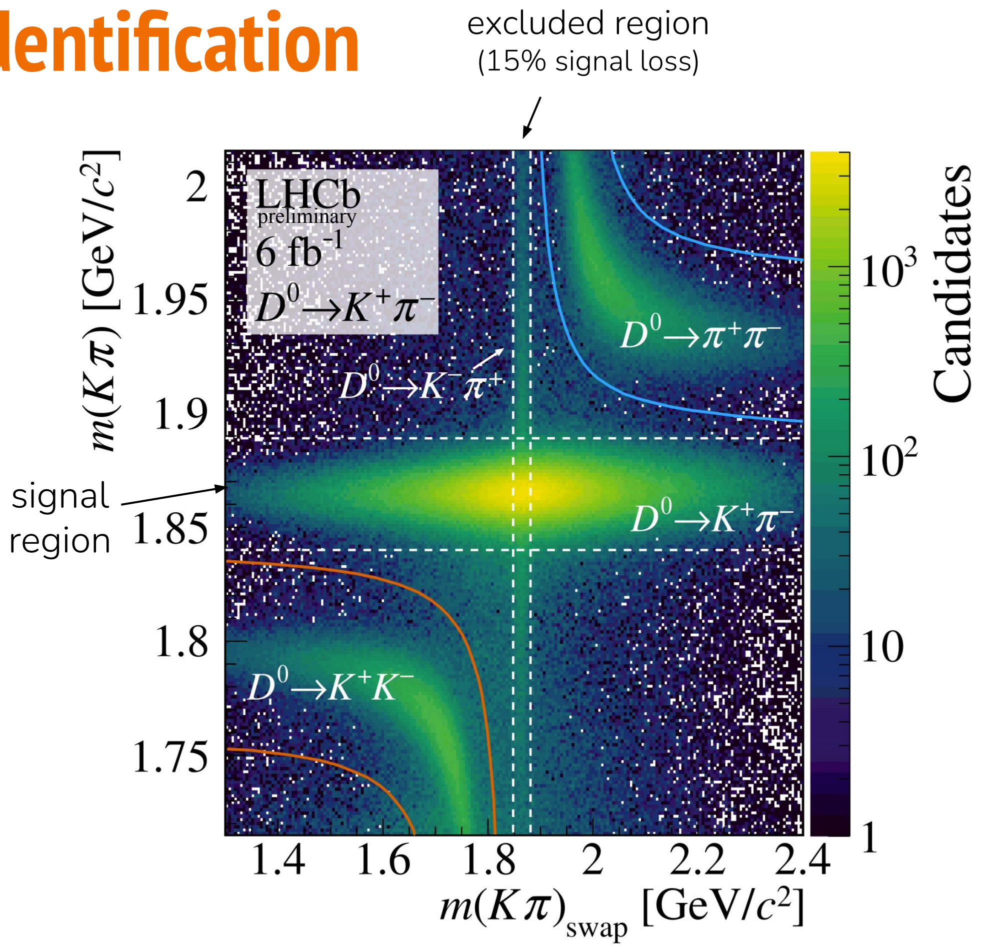
  $|m(K\pi) - m(D^0)_{\rm PDG}| < 24$ MeV (3σ)

- Misreconstructed multibody charm decays found to be negligible in previous studies

- Reduce by factor of 5 background from double mis-ID $D^0 \to K^-(\rightsquigarrow \pi^-)\, \pi^+(\rightsquigarrow K^+)$ (RS⇝WS)

  $|m(K\pi)_{\rm swap} - m(D^0)_{\rm PDG}| > 16$ MeV (1.5σ)

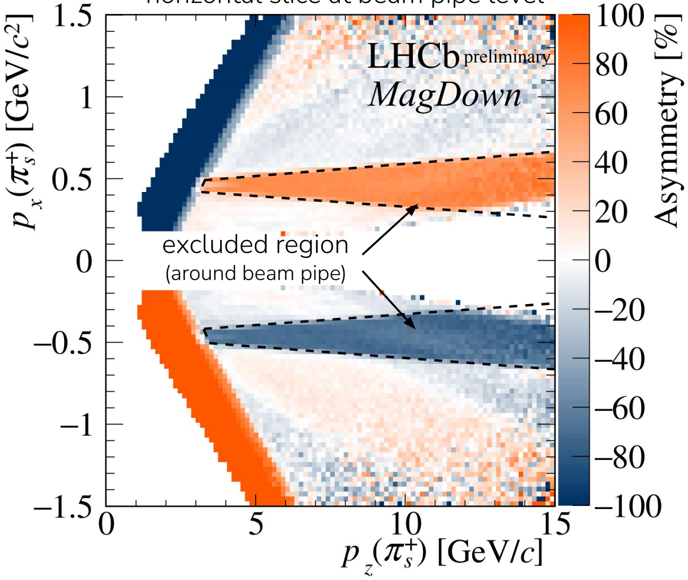
  Subtracted residual bias $\sim \sigma(R_{K\pi})/10$

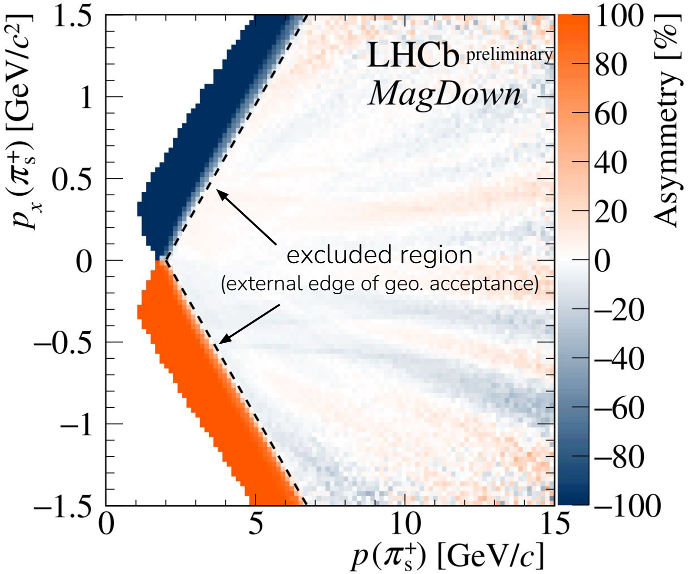


Asymmetry bias – Nuisance asymmetry correction

- When $A_D(\pi_s)$ is not small, correction terms appear in equations in previous slide
- Very high asymmetry regions are conservatively removed (15% signal loss)
  → collateral benefit: remove 40% of residual ghost contamination

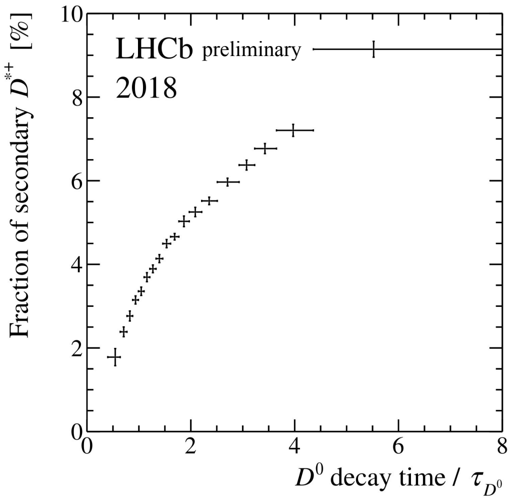
horizontal slice at beam pipe level

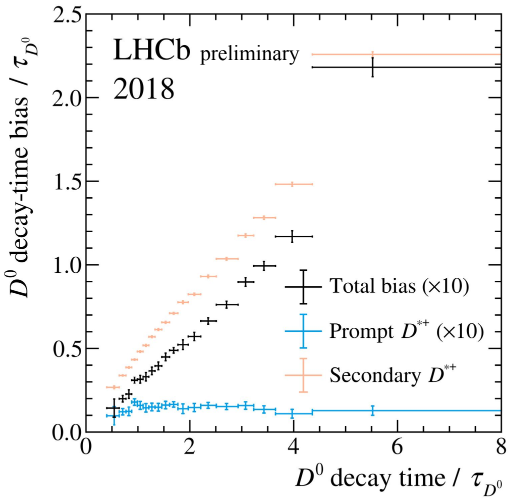


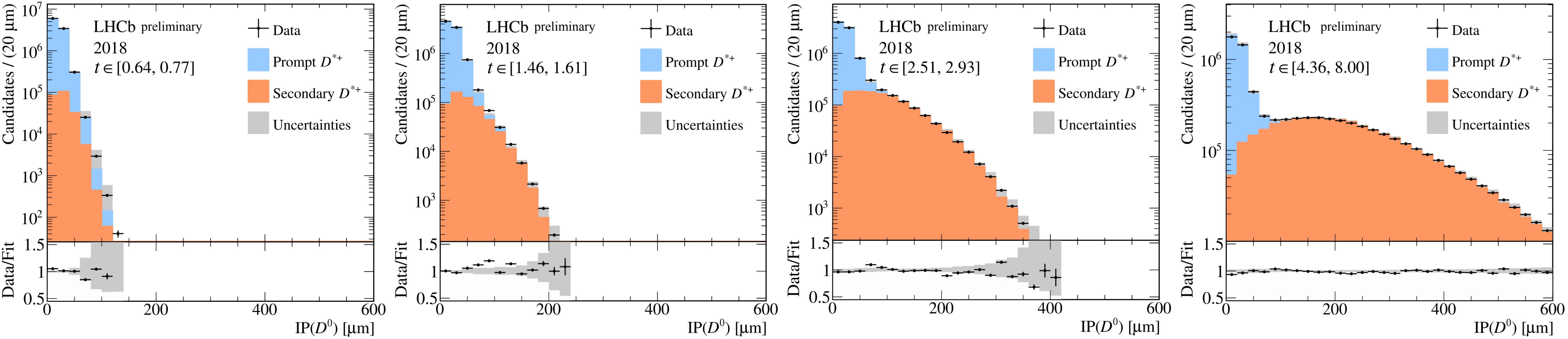


Decay-time bias – Results

- Final results in 2018 data-taking period







Alternative observable/parametrization

- Alternative observable/parameterization already presented at previous LHC seminar:

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

$$R^{\pm}_{K\pi}(t) = R_{K\pi}(1 \pm A_{K\pi}) + \sqrt{R_{K\pi}(1 \pm A_{K\pi})}\,(c_{K\pi} \pm \Delta c_{K\pi})\, t/\tau_{D^0} + (c'_{K\pi} \pm \Delta c'_{K\pi})\,(t/\tau_{D^0})^2$$

  - $R_{K\pi}$ and mixing observables are unchanged
  - *CPV* observables transform to:
    - $A_{K\pi}$ is the *CP* asymmetry in DCS
    - $\Delta c_{K\pi} \approx x_{12} \sin\phi_2^M \cos\Delta_{K\pi} - y_{12}\sin\phi_2^\Gamma \sin\Delta_{K\pi}$
    - $\Delta c'_{K\pi} \approx \frac{1}{2} x_{12} y_{12} \sin\left(\phi_2^M - \phi_2^\Gamma\right)$

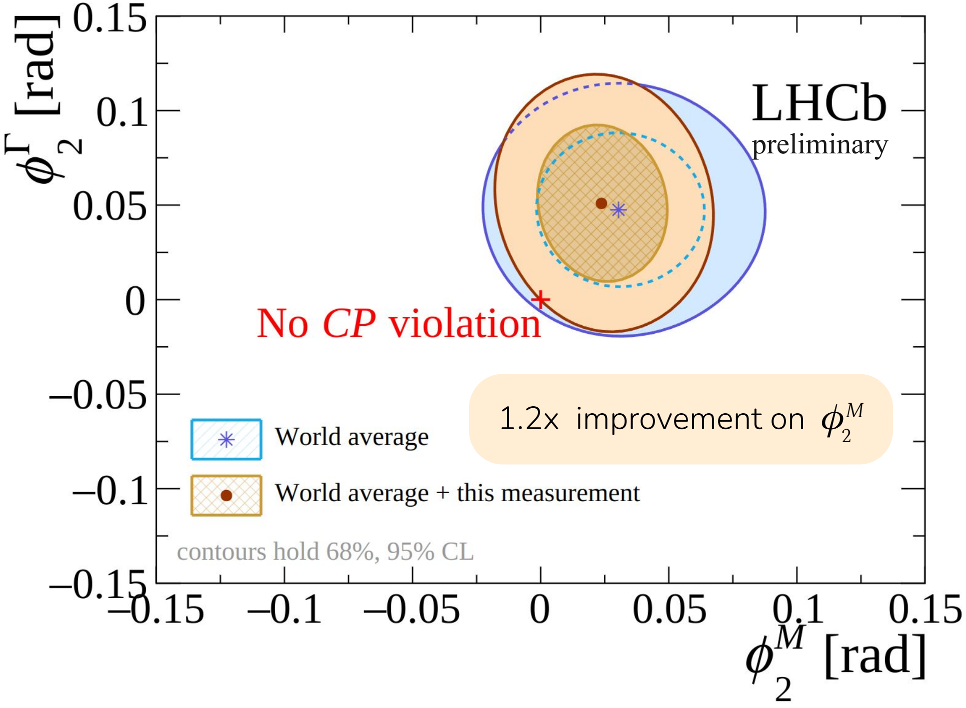
Mixing + CPV fit – Systematic uncertainties

- Main systematic sources are D^{*+} mass fit model and ghost bkg pdf
- Instrumental asymmetry are relevant only for *CPV* observables → statistically dominated
- Dominant systematic in previous iteration (decay-time bias) reduced by one order of magnitude
- Total systematic uncertainty improved by a factor of 2 PRD97,031101
- a^d_{KK} and ΔY external inputs are absorbed in the new observable definition

Source	$R_{K\pi}$ $[10^{-5}]$	$c_{K\pi}$ $[10^{-4}]$	$c'_{K\pi}$ $[10^{-6}]$	$A_{K\pi}$ $[10^{-3}]$	$\Delta c_{K\pi}$ $[10^{-4}]$	$\Delta c'_{K\pi}$ $[10^{-6}]$
Mass modeling	0.5	0.8	0.9	1.4	0.8	0.8
Ghost soft pions	0.4	0.8	0.8	1.1	0.8	1.1
Instrumental asymm.	–	–	–	1.2	0.7	0.7
a^d_{KK} ext. input	–	–	–	1.1	–	–
ΔY ext. input	–	–	–	–	0.1	0.1
Doubly Mis-ID bkg.	0.1	0.1	0.1	–	–	–
Common removal	0.2	–	–	–	–	–
Decay-time bias	0.1	0.2	0.1	0.1	–	–
m_{D^0}/τ_{D^0} ext. input	–	0.1	0.1	–	–	–
Total syst. uncertainty	0.7	1.1	1.2	2.4	1.3	1.4
Statistical uncertainty	1.9	3.3	3.5	5.5	3.3	3.5
Total uncertainty	2.0	3.5	3.7	6.0	3.6	3.8

Impact on World average

- Global fit performed à la HFLAV JHEP2022.162



4σ evidence of U-spin symmetry breaking