Measurement of $D^0 - \overline{D}^0$ mixing and CP violation in $D^0 \to K^+\pi^-$ decays

LHC seminar - March 26th 2024

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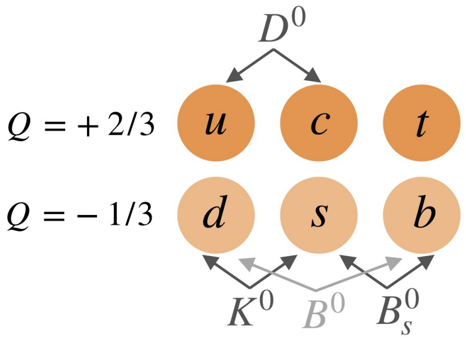
on behalf of the LHCb collaboration

What's charming in Charm physics?



- Charm is the only up-type quark that mixes and allows high precision *CP* violation (*CPV*) measurements

$$\begin{array}{c|ccc} & d & s & b \\ \hline u & 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ c & -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ t & A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{array}$$

- A single complex phase in CKM matrix is the only measured source of *CPV*
→ can't account for baryonic asymmetry observation

- In Charm, *CPV* and flavour changing neutral currents are extremely suppressed in SM
→ powerful probe for new interactions at energy scales ≫ colliders' energy

Flavour Changing Neutral Currents

- Weak interactions violate flavour conservation → flavoured neutral meson oscillate:

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

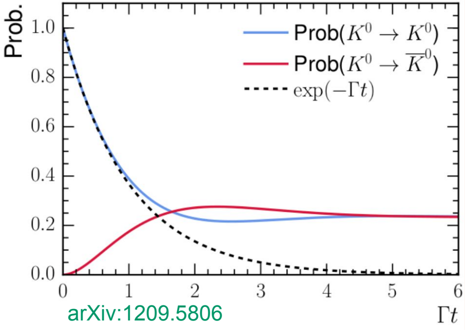
NP→off-shell transitions

on-shell transitions

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

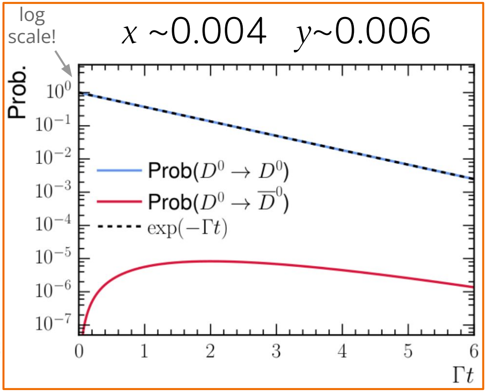
- Oscillations are governed by two mixing parameters $\boldsymbol{x_{12}} = 2|M_{12}|/\Gamma$ and $\boldsymbol{y_{12}} = 2|\Gamma_{12}|/\Gamma$

x ~-0.95 y~0.99

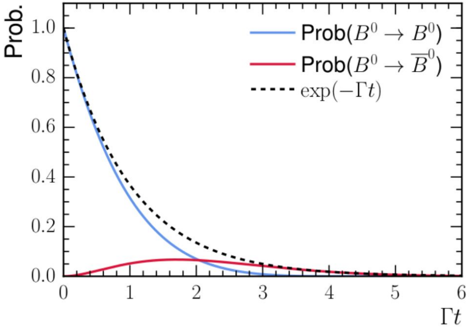


arXiv:1209.5806

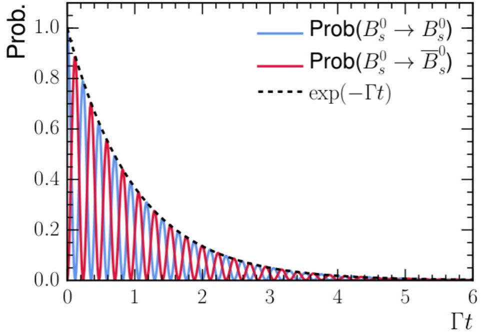
x ~0.004 y~0.006



x ~0.77 y~0.001



x ~27 y ~0.08

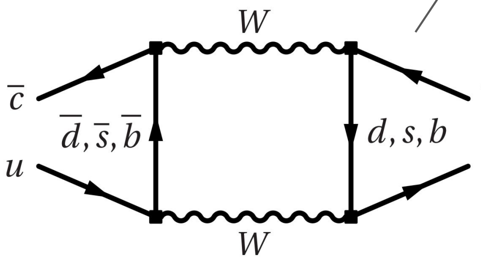


$D^0 - \overline{D}^0$ mixing SM predictions

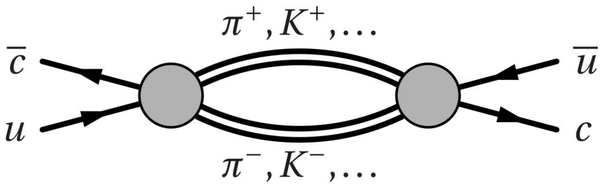
$$\begin{array}{c|ccc}
\lambda \sim 0.22 & d & s & b \\
\hline
u & 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\
c & -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\
t & A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1
\end{array}$$

- Mixing amplitudes governed by **two contributions**

- Short distance:
  → suppressed by CKM b couplings
  → suppressed by GIM cancellation broken by b quark



$\propto \left(\frac{m_{d,s,b}}{m_W}\right)^2$



- Long distance:
  → low-energy QCD through on-shell resonances
  → theoretical prediction of x and y very challenging

Experimental state of the art – Mixing

- First observation of mixing in charm dates back to 2009 in $D^0 \to K^+\pi^-$
- Today Charm global average largely dominated by LHCb results, which exploit the largest charm hadron dataset ever collected
- First observation of $x_{12} \neq 0$ in 2021 exploiting $D^0 \to K_S^0\pi^+\pi^-$ decay PRL127,111801
- Recent $D^0 \to h^+h^-$ measurement PRD105.092013 and charm+beauty combination leads to a 3% relative precision on y_{12}

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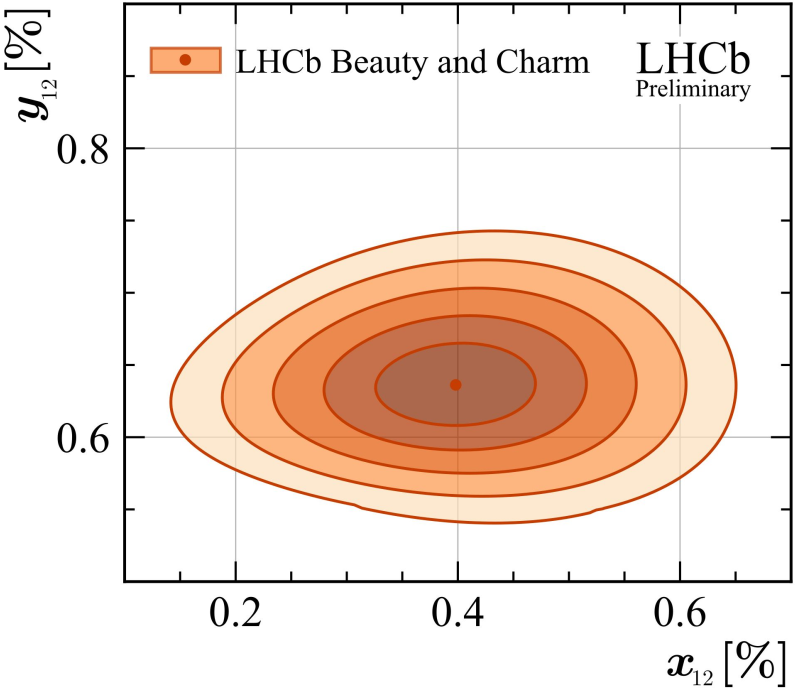
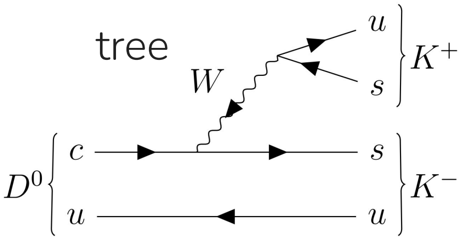


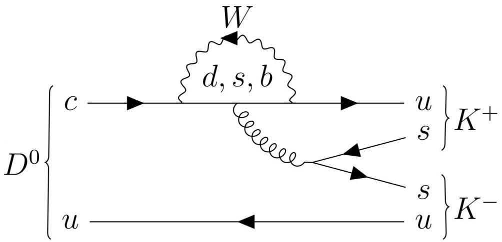
CP violation manifestations

- *CPV* in the decay 

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

tree





penguin

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

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

CP violation manifestations

- *CPV* in the decay

$$a_f^d = \frac{|\mathcal{A}(M \to f)|^2 - |\mathcal{A}(\overline{M} \to \bar{f})|^2}{|\mathcal{A}(M \to f)|^2 + |\mathcal{A}(\overline{M} \to \bar{f})|^2} \neq 0$$

Kagan & Silvestrini 2021

- *CPV* in the mixing

$$\arg\left(\frac{M_{12}}{\Gamma_{12}}\right) = \phi_2^M - \phi_2^\Gamma \neq 0$$

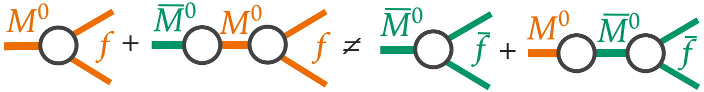
In Charm, SM predict ϕ_2^M, ϕ_2^Γ to be $O(2\ \mathrm{mrad})$

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

NP ?

- *CPV* in the interference

(of decay and mixing)



Experimental state of the art – CPV in the decay

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

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

PRL122,211803

- Followed in 2023 by evidence of *CPV* in $D^0 \to \pi^+\pi^-$ decay

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

PRL131.091802

- Theoretical interpretation is debated, is this NP or SM effect?

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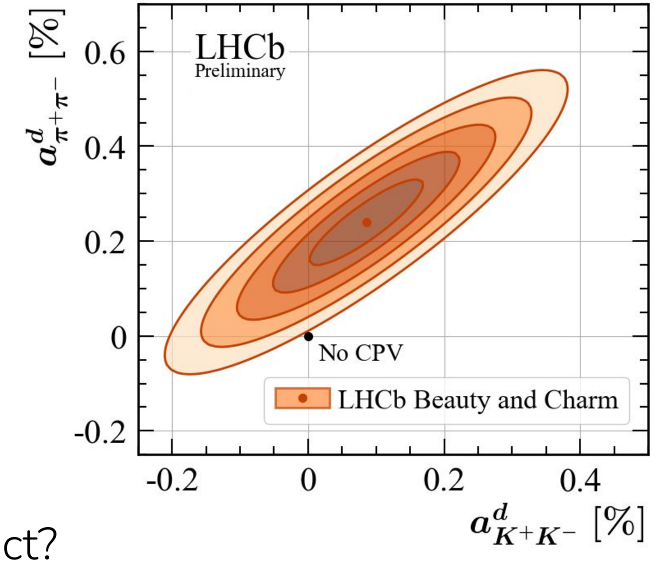
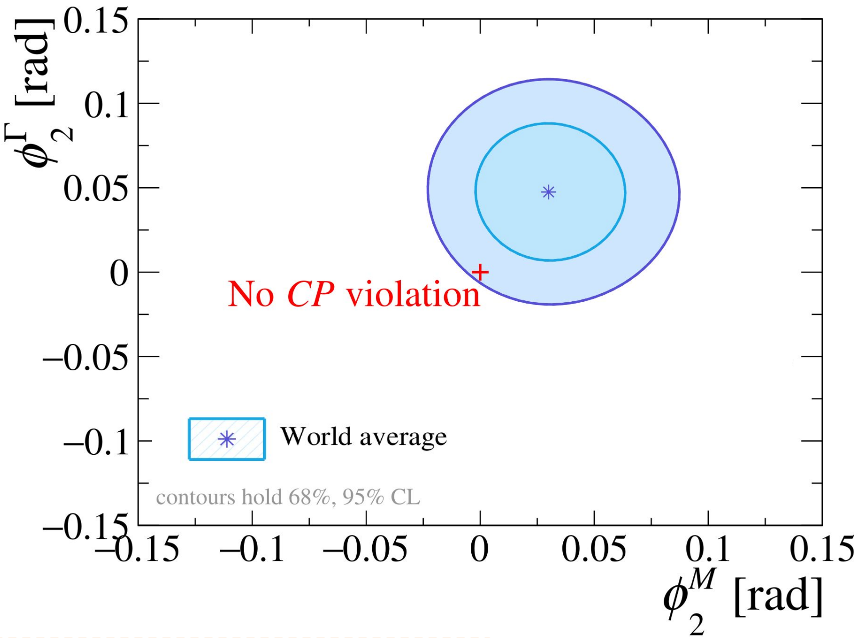


Experimental state of the art – Other CPV sources

- Crucial to search for other *CPV* manifestation in charm sector
- Still no evidence of *CPV* in mixing and interference
- $D^0 \to K^+\pi^-$ decay channel allows to simultaneously measure mixing and all types of *CPV*, with **excellent sensitivity to ϕ_2^M and y**

JHEP2022.162

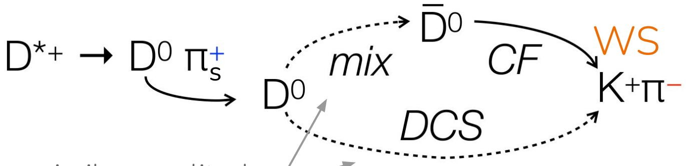


New world-best LHCb measurement of mixing and *CPV* in $D^0 \to K^+\pi^-$ is presented here for the first time

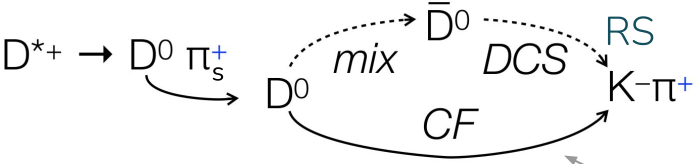
$D^0 \to K\pi$ WS/RS

slow pions

- Neutral D meson flavour tagged exploiting strong decay $D^{*+} \to D^0 \pi_s^+$ and $D^{*-} \to \overline{D}^0 \pi_s^-$
- Distinguish two processes: wrong sign (WS) and right sign (RS)



similar amplitudes



normalization ch.
dominated by CF

- Accounting for CPV we measure time dependence of WS/RS yield ratio $R^{\pm}_{K\pi}(t)$

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

- Since $x_{12}, y_{12} \ll 1$ the ratio can be expanded as:

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

$D^0 \to K\pi$ WS/RS

low sensitivity to quadratic term

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

- $R_{K\pi}$ is the DCS/CF ratio ~3.4 x 10^{-3}
- Mixing observables:
  - ○ $c_{K\pi} \approx y_{12}\cos\phi_2^{\Gamma}\cos\Delta_{K\pi} + x_{12}\cos\phi_2^{M}\sin\Delta_{K\pi}$
  - ○ $c'_{K\pi} \approx \frac{1}{4}\left(x_{12}^2 + y_{12}^2\right)$

small angle, large uncertainty

strong phase difference of DCS/CF

$\Delta_{K\pi}$ = -10° ± 3° measured by LHCb, CLEO, BESIII

LHCb-CONF-2022-003, PRD86.112001, EPJC82.1009

mostly sensitive to y_{12}

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

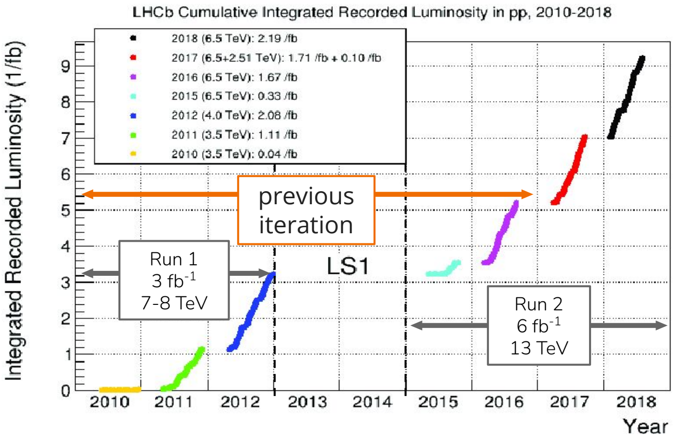
only one amplitude in $D^0 \to K\pi$

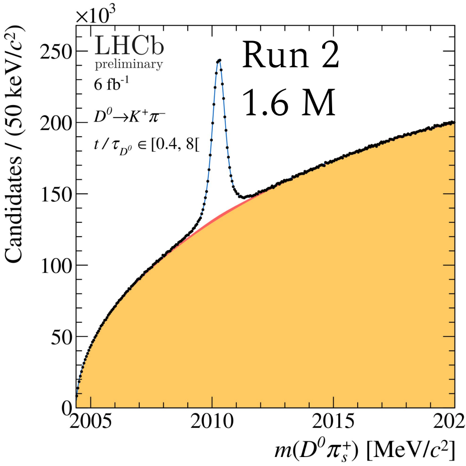
$\Rightarrow A_{K\pi} = 0$ null test of SM

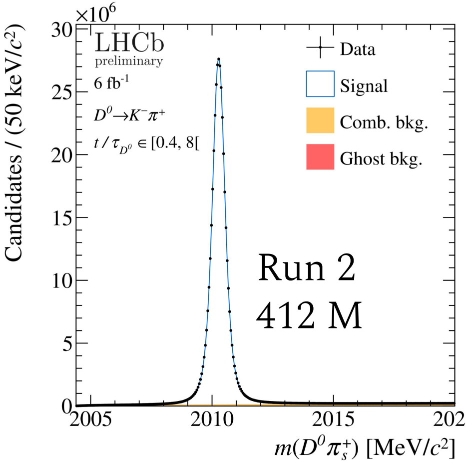
mostly sensitive to $x_{12}\phi_2^{M} \approx \Delta y \approx -\Delta Y$

Dataset

LHCb-PAPER-2024-008

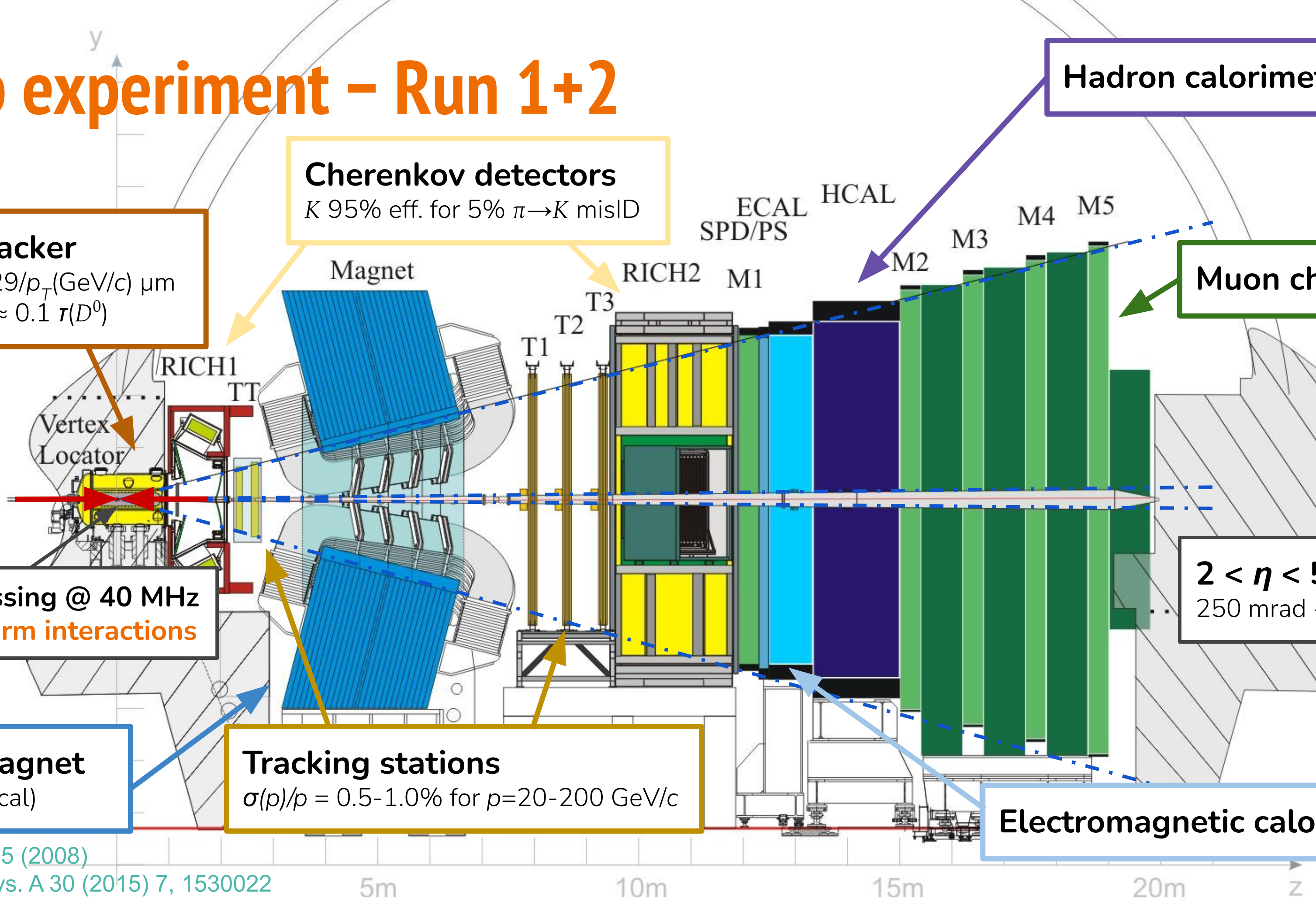






- This measurement is dominated by previous LHCb result
  → Run 1 + 2015/16: 0.7 M WS + 180 M RS PRD97,031101
- In 2017-2018 collected additional 1.1 M WS + 280 M RS
  → total yield more than doubled
- **The measurement presented here uses the full Run 2 sample**
  → 2015-2016 re-analysed with improved strategy
- Average with Run 1 results performed to return the LHCb Run 1+2 legacy results

LHCb experiment – Run 1+2



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

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

Hadron calorimeter

Muon chambers

bunch crossing @ 40 MHz
1 MHz charm interactions

$2 < \eta < 5$
250 mrad - 30 mrad

Dipole magnet
4 T·m (vertical)

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

Electromagnetic calorimeter

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

Online selection

- LHCb's excellent trigger capabilities reduce rate from 40 MHz bunch crossing to 12.5 kHz on tape

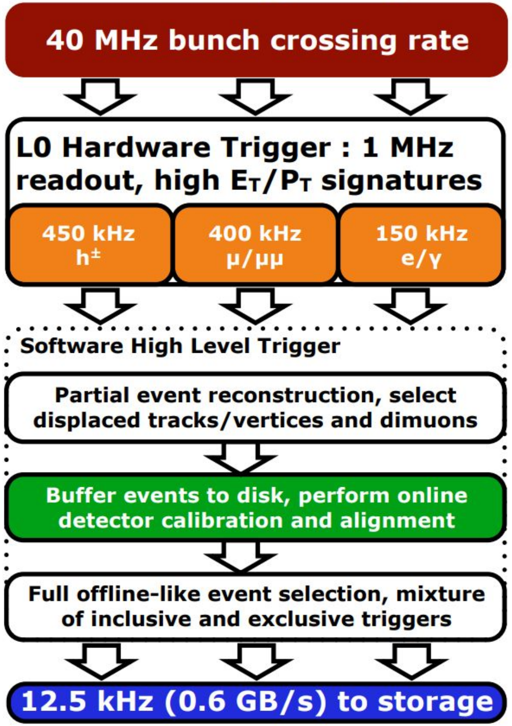
- Charm analysis pioneered "Turbo" data-taking paradigm

  → **only signal candidates recorded** →yield / fb^{-1} x2 wrt Run 1

  Comput.Phys.Commun. 208 (2016) 35-42

- Online selection designed to select signal with high purity while limited by a maximum bandwidth

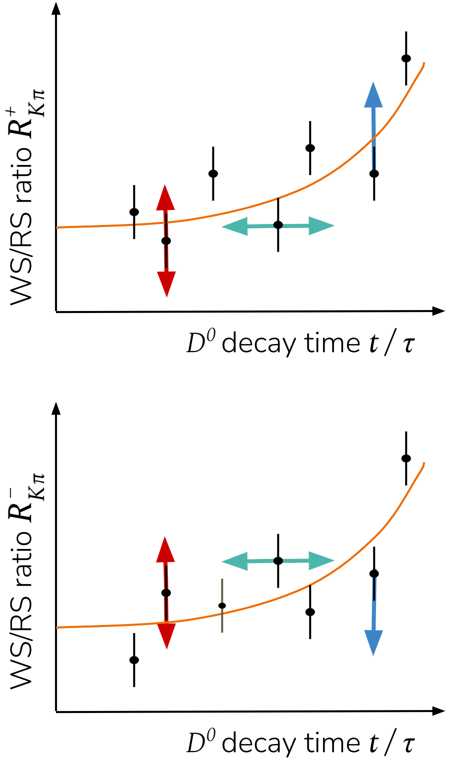
LHCb Run 2 trigger Diagram



Analysis workflow

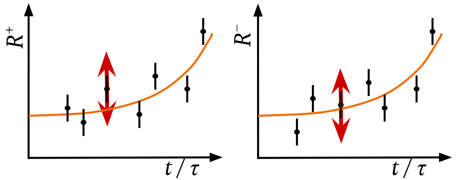
- General philosophy of offline selection design is targeting robustness
- Sample is divided between D^0 final state ($K^+\pi^-$, $K^-\pi^+$), 18 D^0 decay-time intervals and 3 data-taking period (2015-16, 2017 and 2018).

  In each subsample we determine:
  - average D^0 decay time, t
  - WS-to-RS ratio, R, fitting D^* mass to disentangle **signal** from **combinatorial** and **ghost** backgrounds
- And we correct them from the known systematic effects
  - bias to the ratio
  - bias to asymmetry
  - bias to D^0 decay-time
- Time dependence is fitted → extract mixing and *CPV* parameters

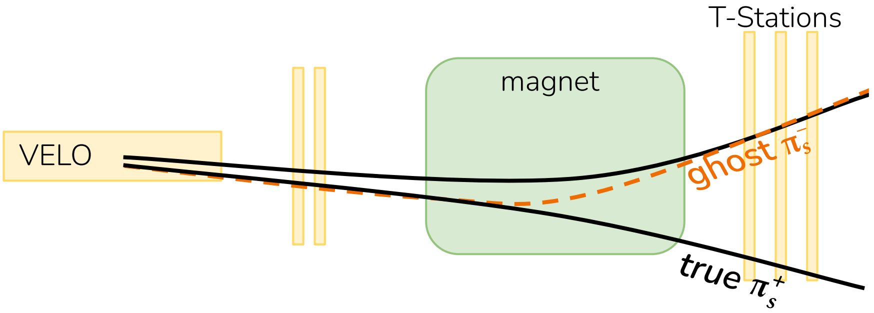


Systematic sources of biases

Ratio biases – Ghost background



- Our normalization channel, $D^0 \rightarrow K^- \pi^+$, is also one of the main source of background
  → much more abundant, if misidentified it can leak in our WS signal
- Ghost bkg result from misassociation of correctly-identified hits in VELO with hits in T-Stations from different particles



- Soft pion from RS decays seed the production of both RS and WS ghosts
  → **peak in D^* mass** because even if π_s momentum is random, direction is correct
- Percent level contamination but we aim at sub-percent precision

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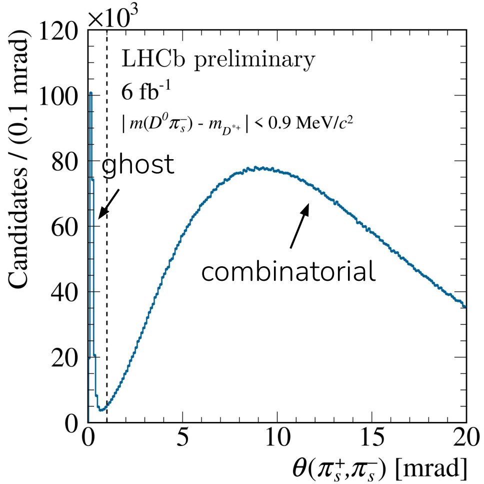
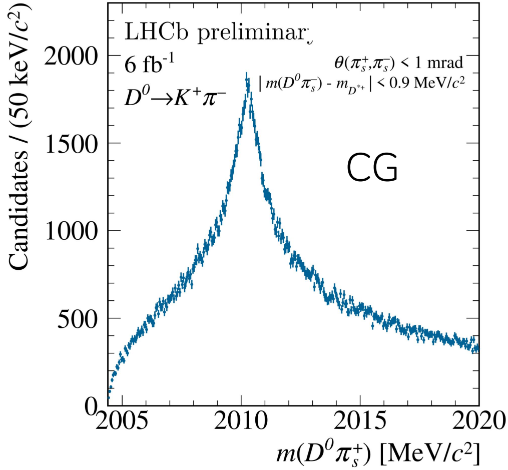
Ratio biases – Ghost background proxy

- 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 → **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

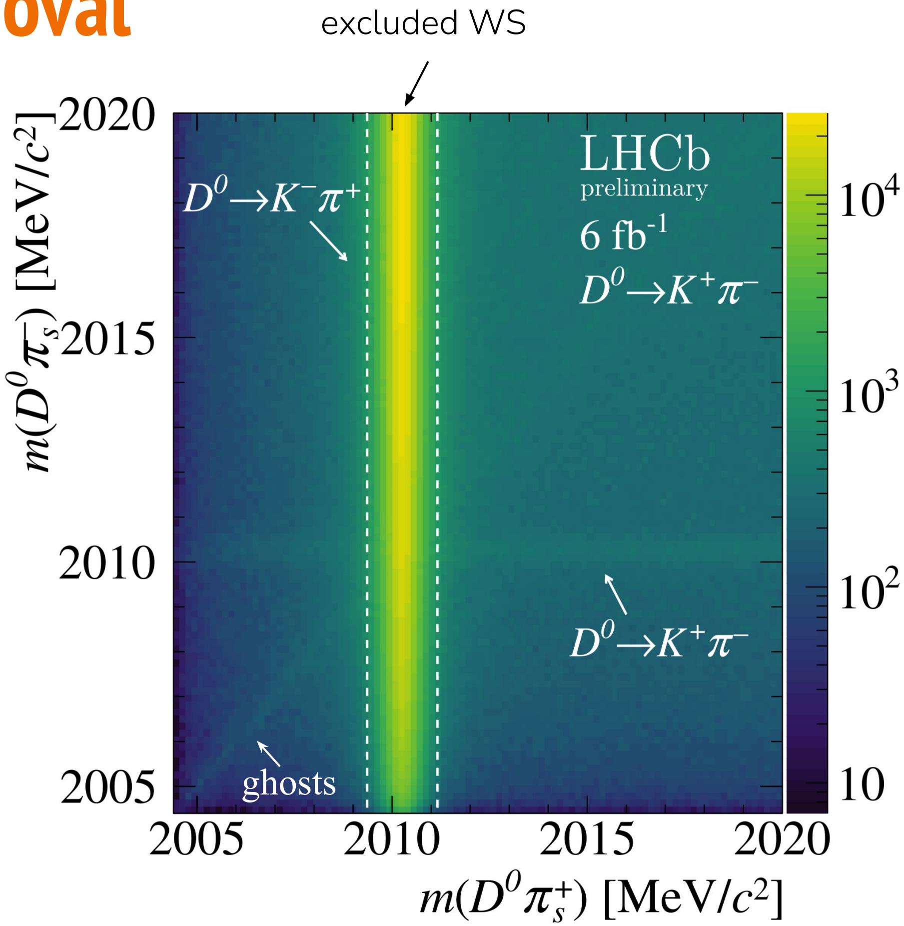




Ratio biases – common WS removal

- Removing these WS-RS multiple candidates, a small fraction of proper WS decays are removed, biasing the ratio

- Estimated and subtracted bias $\sim\sigma(R_{K\pi})/5$



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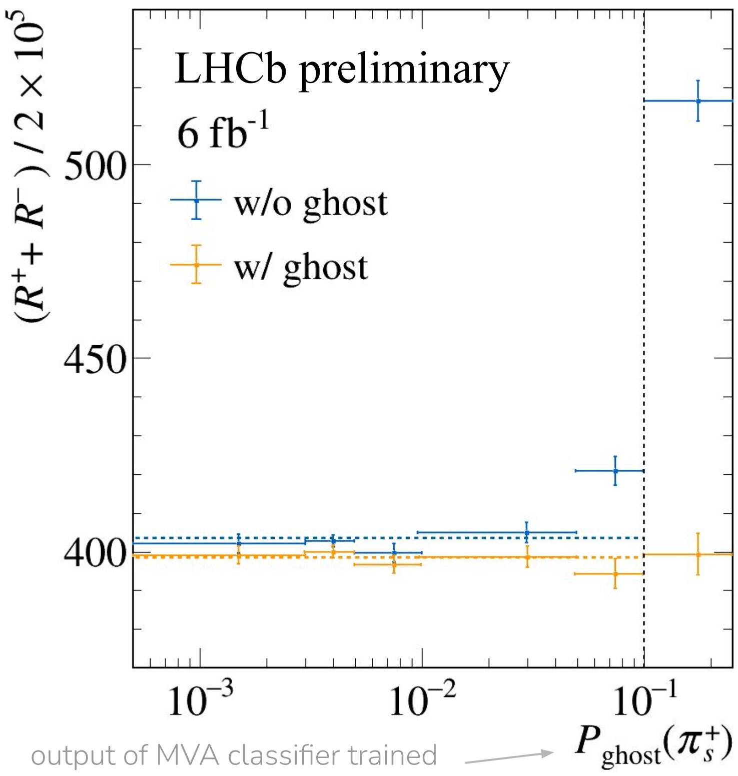
Ratio biases – Test of ghost bkg. subtraction

- 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%

excluded region



output of MVA classifier trained to distinguish fake tracks

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Ratio biases – Particles misidentification

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

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

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

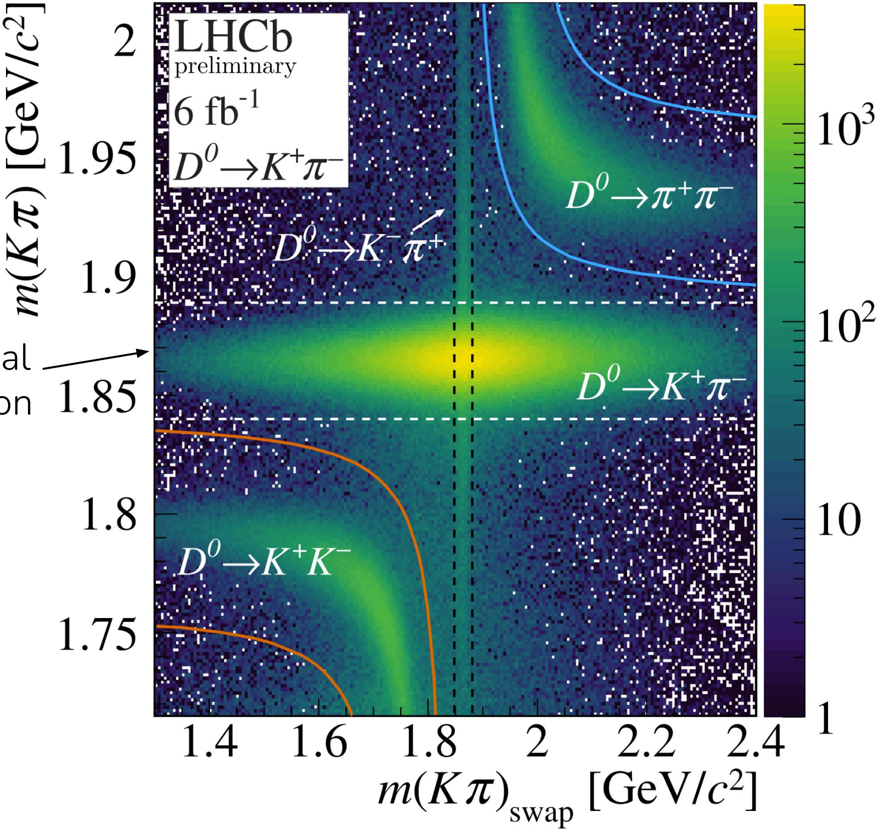
- Reduce by factor of 5 background from double mis-ID $D^0 \to K^-(\rightsquigarrow\pi^-)\,\pi^+(\rightsquigarrow K^+)$ (RS$\rightsquigarrow$WS)

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

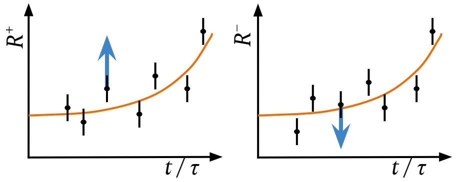
  Subtracted residual bias $\sim\sigma(R_{K\pi})/10$

excluded region
(15% signal loss)

signal
region



Asymmetry bias – Nuisance asymmetry



- Differences in reconstruction efficiency between WS and RS may mimic *CPV*

$$\widetilde{R'}^{\pm} = R'^{\pm}\frac{\int[1\pm A_P(D^*)]\epsilon(\pi_s^{\pm})\epsilon(K^{\pm}\pi^{\mp})\rho\, d\vec{p}_{D^0}\, d\vec{p}_{\pi_s}}{\int[1\mp A_P(D^*)]\epsilon(\pi_s^{\mp})\epsilon(K^{\pm}\pi^{\mp})\rho\, d\vec{p}_{D^0}\, d\vec{p}_{\pi_s}} \simeq R'^{\pm}\frac{1\pm[A_D(\pi_s)+A_P(D^*)]}{1\mp[A_D(\pi_s)+A_P(D^*)]}$$

- $A_D(\pi_s) + A_P(D^*)$ measured **exploiting a^d_{KK} LHCb analysis in $D^0 \to K^+K^-$** CS decays PRL131.091802

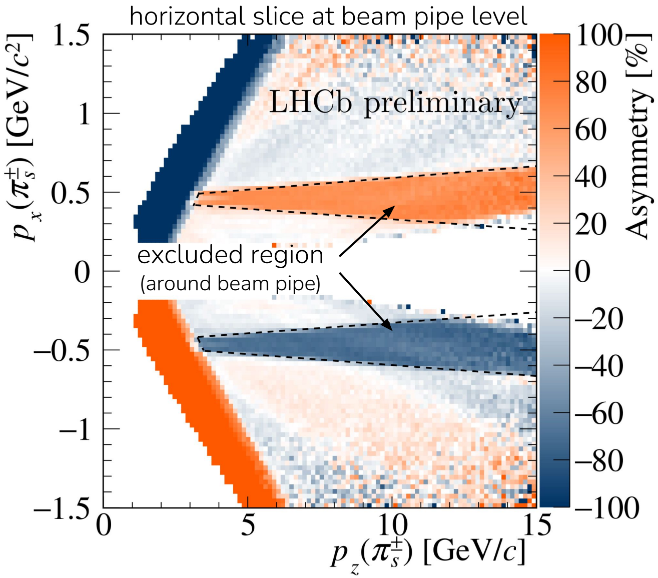
$$A_D(\pi_s) + A_P(D^*) = A^{raw}(KK) - a^d_{KK} - \Delta Y \langle t \rangle$$

direct
CP asymmetry
in $D^0 \to K^+K^-$

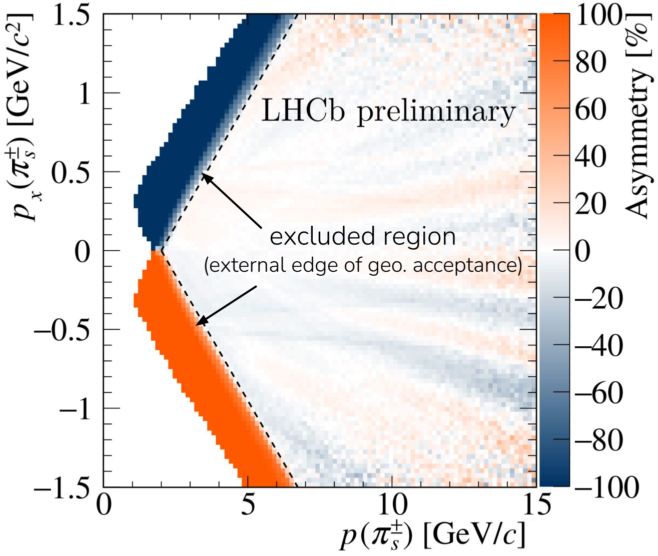
time dependent
CP asymmetry
in $D^0 \to K^+K^-$

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

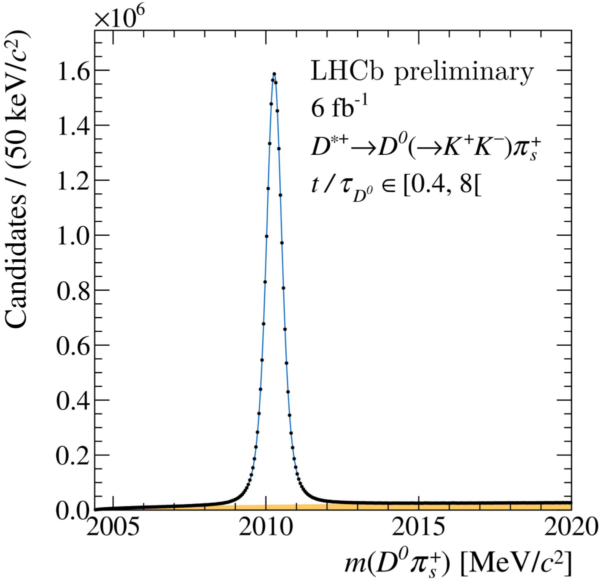

horizontal slice at beam pipe level

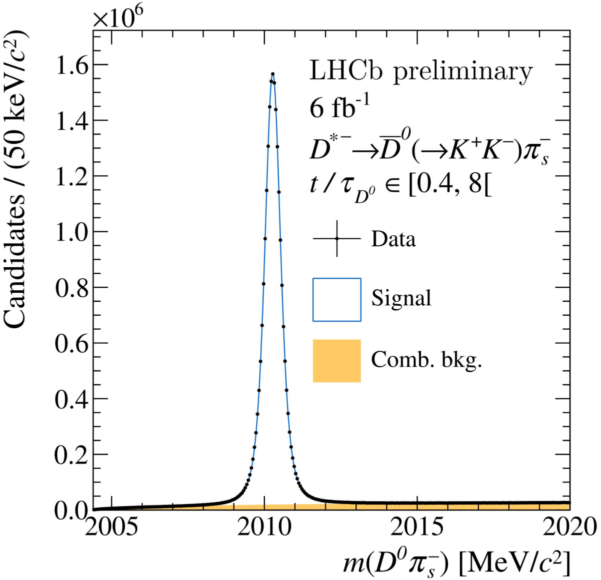
excluded region
(around beam pipe)

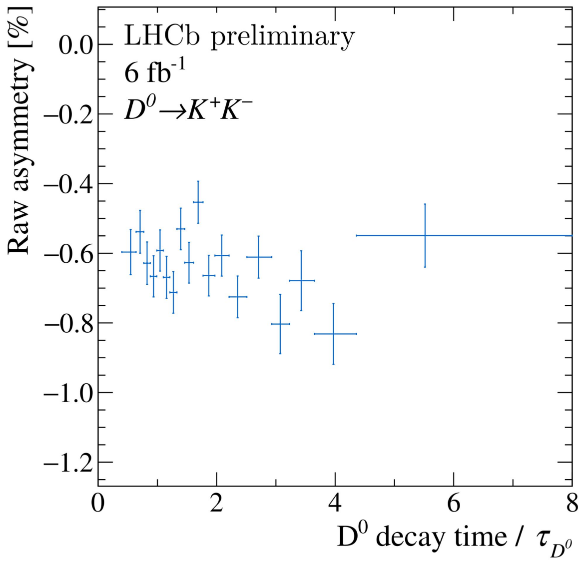

excluded region
(external edge of geo. acceptance)

Asymmetry bias – $A^{raw}(KK)$ measurement

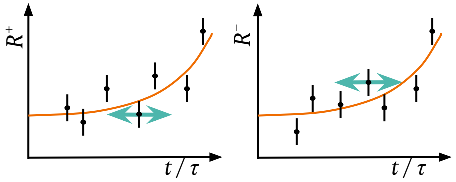
- $A_D(\pi_s)$ depends on kinematics → $D^0 \to K^+K^-$ kinematics is equalized to $D^0 \to K^-\pi^+$
- Then D^{*+} and D^{*-} samples are fitted simultaneously to extract the raw asymmetry



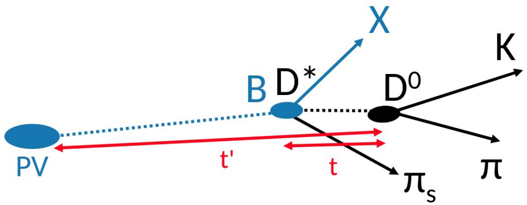




Decay-time biases – Sources



- Poor D^* vertex resolution (~1 cm) → D^* is constrained in the PV
- Due to this constraint, contamination from **secondary D^* from b-hadrons decays**
    - bias decay time towards higher values
    - feature a deformed D^* mass line-shape



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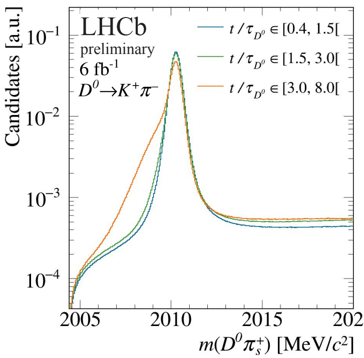


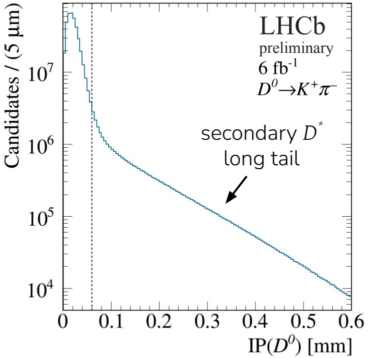
- Reject this background as much as possible requiring $\mathrm{IP}(D^0) < 60\,\mu\mathrm{m}$
- Total bias, in each decay-time bin *i*, is computed as the weighted sum

$$\delta t_i \equiv \langle\delta t\rangle_i^P (1 - f_i^S) + \langle\delta t\rangle_i^S f_i^S$$

secondary D^* fraction

bias in prompt D^*

bias in secondary D^*



Decay-time bias – Simulation tunings

- Time biases and f_i^S in each decay-time bin determined by a 2D template fit to $t(D^0)$ *vs.* $\mathrm{IP}(D^0)$
- Templates generated with LHCb simulation
  - Kinematics of simulated samples weighted to data
  - ~10 μm VELO misalignment, which degrades IP resolutions in data, identified and injected in simulation
  - PV and D^0 decay vertex (DV) resolutions tuned to reproduce the features observed in data → scale factors to PV and DV resolutions are applied and treated as nuisance parameters
  - The knowledge of the cocktail of b-hadron to D^* decay is partial. As an effective correction a small fraction of $B^0 \to D^{*+}X$ decays are added
    → $m(X)$ and relative fraction treated as nuisance parameters

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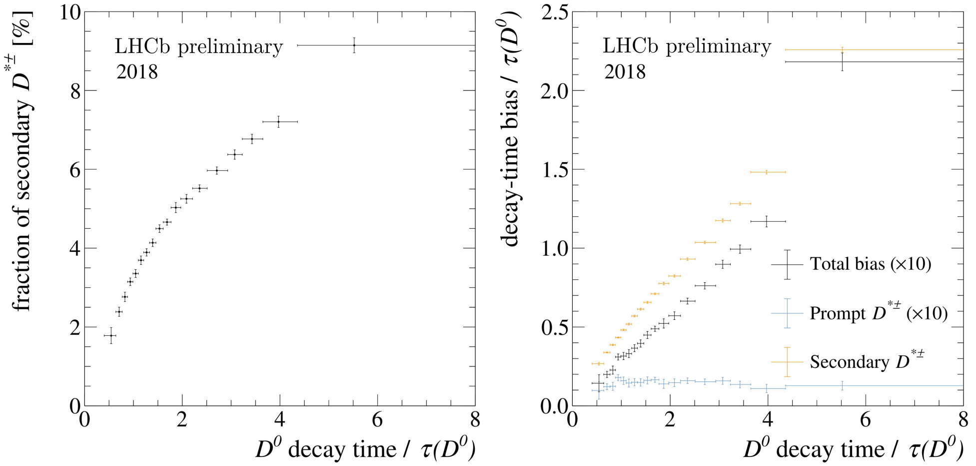
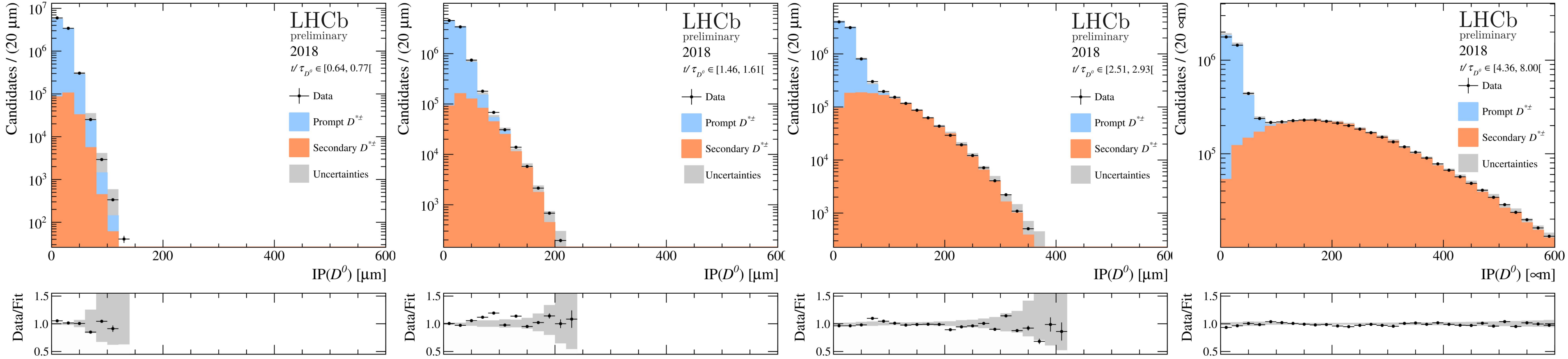
Decay-time bias – Results

- Final results in 2018 data-taking period





WS/RS measurements & results

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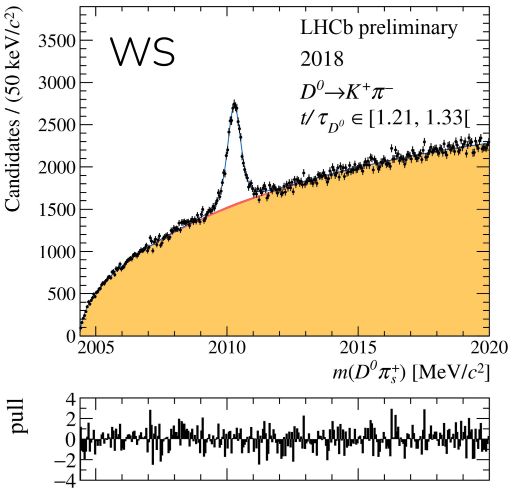
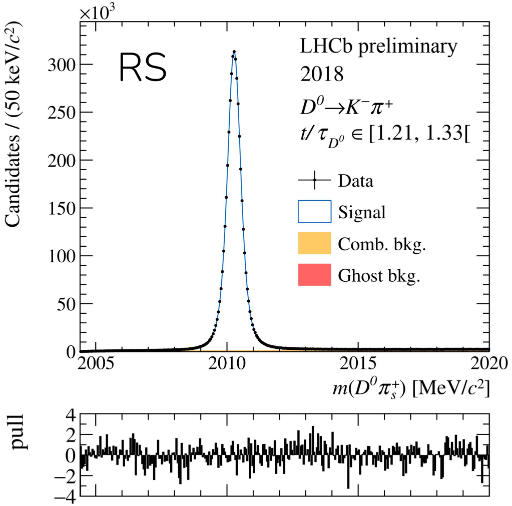
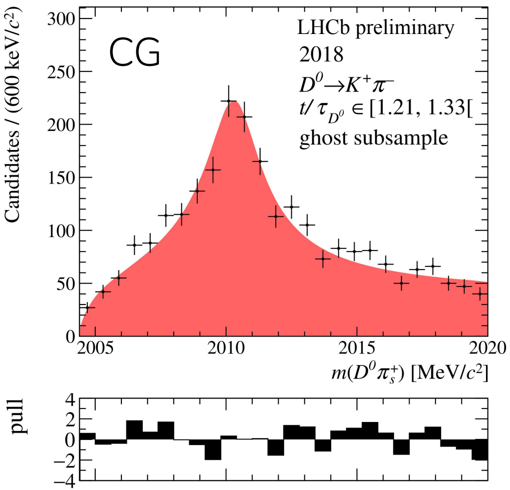
WS/RS Ratio determination – D^* mass fit

- 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







Mixing + CPV fit – Model

- Minimize a χ^2 that incorporates all systematic biases:

sum over 108 bins
18 decay-time t
x 3 data period y
x 2 final state f(±)

$$\chi^2 = \sum_{t,y,f} \left(\frac{r^f_{ty} - R^f_{ty}}{\epsilon \cdot \sigma(r^f_{ty})} \right)^2 + \chi^2_{\text{nuis}}$$

mass model

measurement
of nuisance
parameters

6 parameters of interest: $R_{K\pi}$, mixing & CPV parameters.

removed
common WS

$$R^\pm_{ty} \equiv \left[R_{K\pi}(1 \pm A_{K\pi}) + \sqrt{R_{K\pi}(1 \pm A_{K\pi})}\,(c_{K\pi} \pm \Delta c_{K\pi})\,\langle T\rangle^\pm_{ty} + (c'_{K\pi} \pm \Delta c'_{K\pi})\,\langle T^2\rangle^\pm_{ty}\right] \times \left(1 \pm 2A_{ty} - C\right) + D$$

doubly
mis-ID

$$\langle T\rangle^\pm_{ty} \equiv \left(\langle t\rangle^\pm_{ty} - \langle \delta T\rangle_{ty}\right) \cdot S$$

$$A_{ty} \equiv A^{\text{raw}}_{ty}(KK) - a^d_{KK} - \Delta Y \cdot \langle T\rangle_{ty}$$

decay-time bias

$m(D^0)/\tau(D^0)$
ext. input

raw KK
asymmetry

direct KK
CP asymmetry *ext. input*

time dep. KK
CP asymmetry *ext. input*

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Mixing + CPV fit – Results

Mixing observables

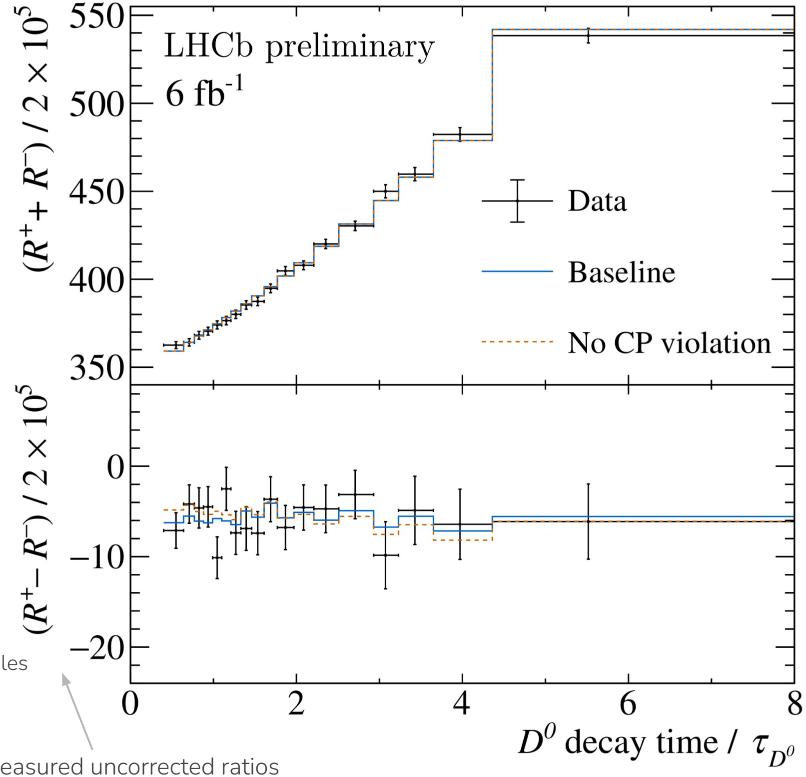
$c'_{K\pi} \neq 0$ (3.5σ) evidence for a significant quadratic term

Parameters		Correlations (%)					
		$R_{K\pi}$	$c_{K\pi}$	$c'_{K\pi}$	$A_{K\pi}$	$\Delta c_{K\pi}$	$\Delta c'_{K\pi}$
$R_{K\pi}$	$(343.1 \pm 2.0) \times 10^{-5}$	100.0	−92.4	80.0	0.9	−0.8	0.1
$c_{K\pi}$	$(51.4 \pm 3.5) \times 10^{-4}$		100.0	−94.1	−1.4	1.4	−0.7
$c'_{K\pi}$	$(13.1 \pm 3.7) \times 10^{-6}$			100.0	0.7	−0.7	0.1
$A_{K\pi}$	$(-7.1 \pm 6.0) \times 10^{-3}$				100.0	−91.5	79.4
$\Delta c_{K\pi}$	$(3.0 \pm 3.6) \times 10^{-4}$					100.0	−94.1
$\Delta c'_{K\pi}$	$(-1.9 \pm 3.8) \times 10^{-6}$						100.0

CPV observables

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

mixing and *CPV* observables largely uncorrelated



measured uncorrected ratios
detection asym. → $\Delta R \neq 0$

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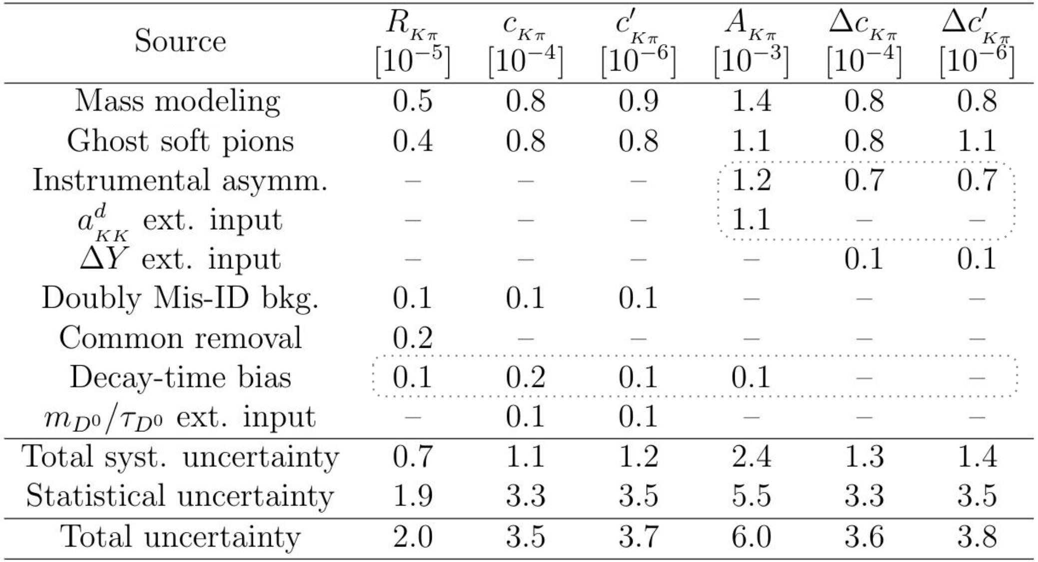
Mixing + CPV fit – Systematic uncertainties

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



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

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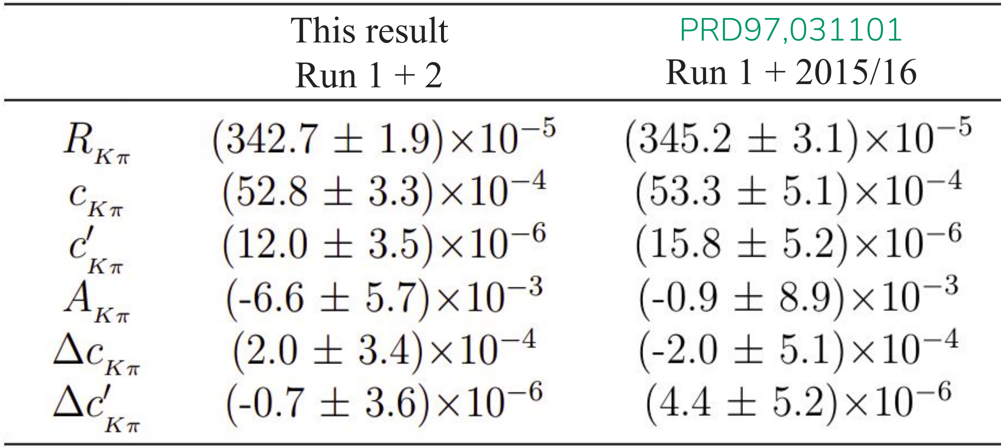
Mixing + CPV fit – LHCb Run 1+2 Legacy result

- Simultaneous minimization of Run 2 χ^2 and Run 1 χ^2 from PRD97,031101 [LHCb internal note]



	This result Run 1 + 2	PRD97,031101 Run 1 + 2015/16
$R_{K\pi}$	$(342.7 \pm 1.9)\times10^{-5}$	$(345.2 \pm 3.1)\times10^{-5}$
$c_{K\pi}$	$(52.8 \pm 3.3)\times10^{-4}$	$(53.3 \pm 5.1)\times10^{-4}$
$c'_{K\pi}$	$(12.0 \pm 3.5)\times10^{-6}$	$(15.8 \pm 5.2)\times10^{-6}$
$A_{K\pi}$	$(-6.6 \pm 5.7)\times10^{-3}$	$(-0.9 \pm 8.9)\times10^{-3}$
$\Delta c_{K\pi}$	$(2.0 \pm 3.4)\times10^{-4}$	$(-2.0 \pm 5.1)\times10^{-4}$
$\Delta c'_{K\pi}$	$(-0.7 \pm 3.6)\times10^{-6}$	$(4.4 \pm 5.2)\times10^{-6}$

Results are compatible

Total uncertainty improved by 1.6x

Impact on World average – CP violation

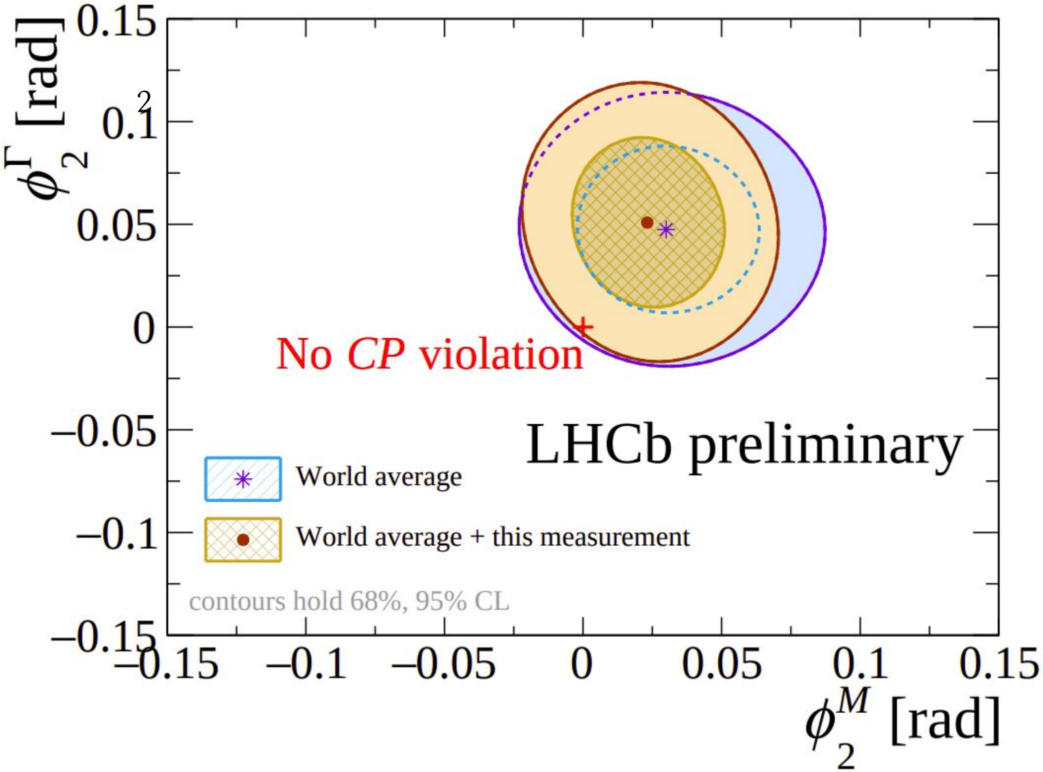
- Global fit performed à la HFLAV

JHEP2022.162

20% improvement on ϕ_2^M

$$\Delta c_{K\pi} \approx x_{12} \sin \phi_2^M \cos \Delta_{K\pi} - y_{12} \sin \phi_2^\Gamma \sin \Delta_{K\pi}$$

→ $\Delta_{K\pi}$ small, mostly sensitive to dispersive *CPV*



Impact on World average – Mixing

- $c_{K\pi} \approx y_{12} \cos\Delta_{K\pi} + x_{12} \sin\Delta_{K\pi}$

  → sensitivity to y_{12} is limited by independent $\Delta_{K\pi}$ measurements

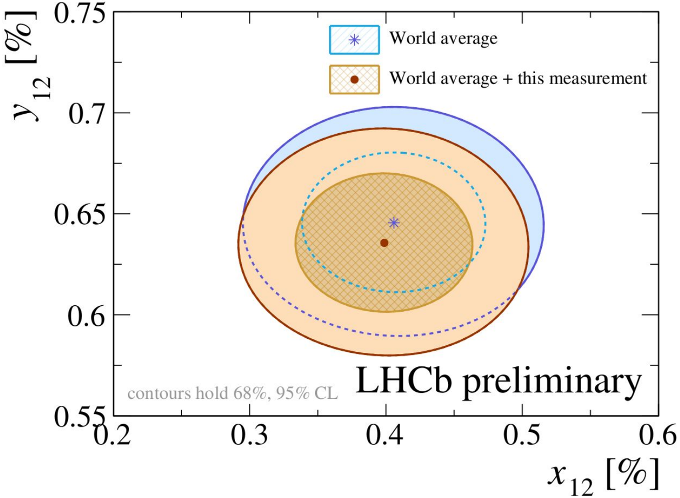
- Conversely, combining $c_{K\pi}$ with LHCb measurements

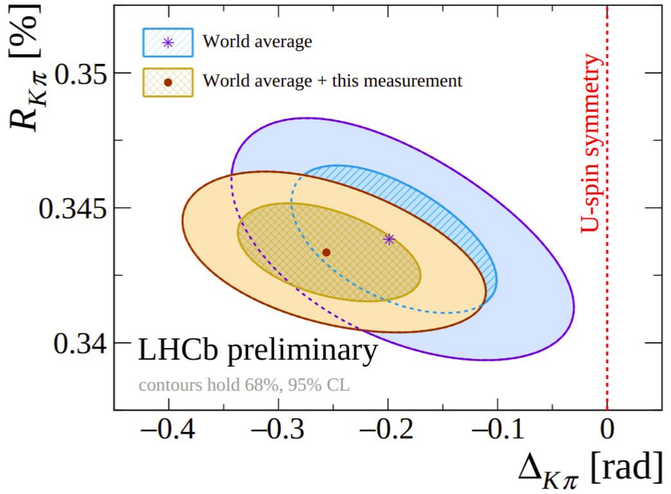
  $\rightarrow\ y_{CP} \approx y_{12}$ PRD105.092013 $\rightarrow\ x_{CP} \approx x_{12}$ PRL127.111801

  allows for a precise determination of $\Delta_{K\pi}$

- Further improvements expected from future charm + beauty LHCb combination

expected 4σ evidence of U-spin symmetry breaking





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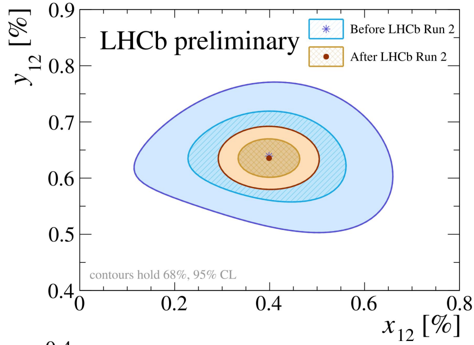
Conclusions

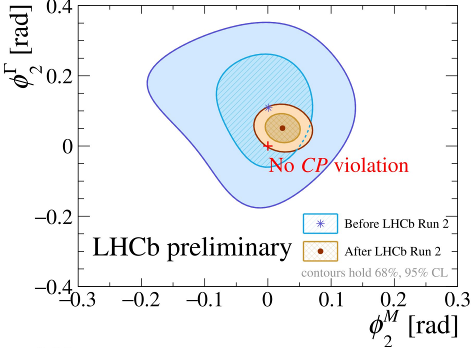
- **Presented for the first time the LHCb full Run 2 measurement of mixing and *CPV* parameters in prompt $D^0 \to K^+\pi^-$** and legacy Run 1+2 LHCb combination
  → total uncertainties improved by 1.6x
  → strong systematics reduction makes the measurement statistically dominated
  → it was one of the last missing Run 1+2 measurement in Charm mixing & CPV

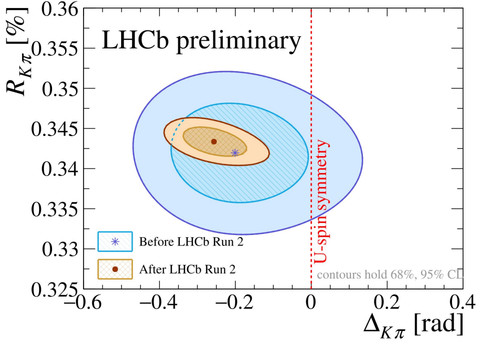
- **Future charm+beauty LHCb fit will be significatively impacted**

- The way is paved for Run 3 and beyond
  LHCb plans to collect $D^0 \to hh'$ decays with doubled efficiency/fb^{-1} wrt Run 2
  Uncertainties expected to halve by the end of Run 3

- **Still more to come from Run 1+2, stay tuned!**







Thank you for your attention!

Backup

Phenomenological vs Theoretical parametrization

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

Phenomenological

Theoretical

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

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

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

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

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

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

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

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

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

Bias on $A^{\mathrm{raw}}(KK)$ determination

- Both Eq. (1) and (2) (slide 21) assume that $A_D(\pi_s)$ is small, however if fiducial cuts are not applied, regions with high detection asymmetry are present

$$A(D^*\pi_s) \equiv A_D(\pi_s) + A_P(D^*)$$

- Removing this assumption, Eq. (1) becomes:

$$\tilde{R}_i^{\pm} \simeq R_i^{\pm} \cdot \left(1 \pm 2\int^{t_i} A(D^*\pi_s)\omega\, dt d\vec{p} + 2\int^{t_i} \underline{A(K\pi)A(D^*\pi_s)\omega\, dt d\vec{p}}\right)$$

- While Eq. (2) becomes:

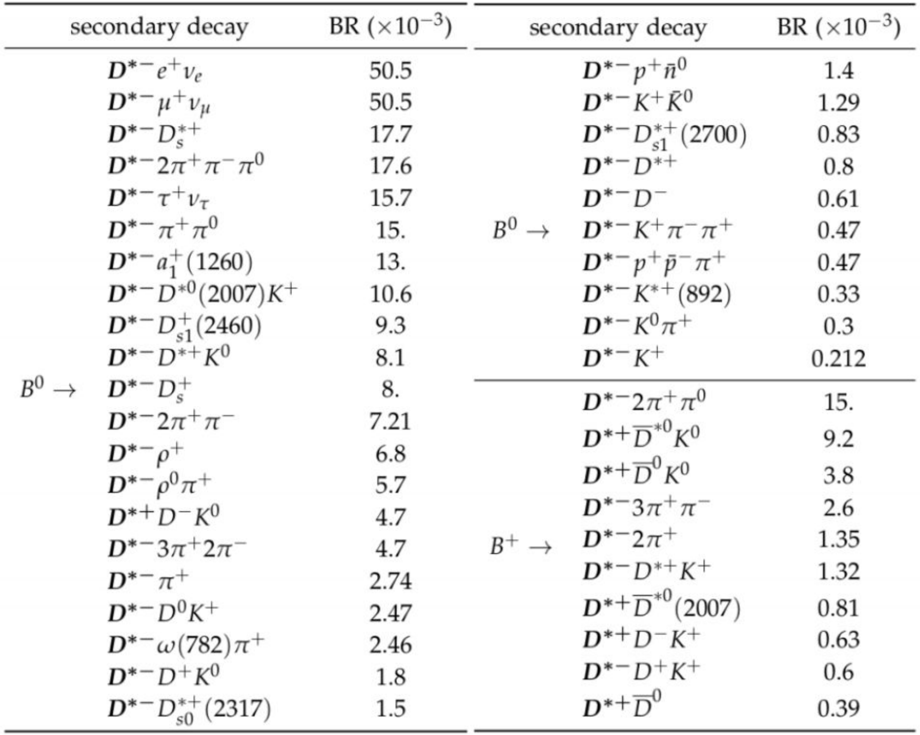
$$A_{\mathrm{raw}}^{\mathrm{rwgt},i}(KK) - A_{CP}^{KK,i} \simeq \int^{t_i} A(D^*\pi_s)\omega'(t)\, dt\, d\vec{p} - \int^{t_i} \underline{A^2(D^*\pi_s)\left[A(K\pi) + A_{CP}^{KK}\right]\omega'(t)\, dt\, d\vec{p}}$$

- Correcting R_{CP} and A_D, neglecting these two additional terms, could produce a bias O(stat. unc.)

$$\overline{R}_{CP} \simeq R_{CP}\left(1 + 2\int A(K\pi)A(D^*\pi_s)\,\omega\, dt\, d\vec{p}\right)$$

$$\overline{A}_D \simeq A_D + 2\int A^2(D^*\pi_s)\left[A(K\pi) + A_{CP}^{KK}\right]\omega\, dt\, d\vec{p}$$

Inclusive secondary D^* cocktail



	secondary decay	BR ($\times 10^{-3}$)
$B^0 \to$	$\boldsymbol{D}^{*-} e^+ \nu_e$	50.5
	$\boldsymbol{D}^{*-} \mu^+ \nu_\mu$	50.5
	$\boldsymbol{D}^{*-} D_s^{*+}$	17.7
	$\boldsymbol{D}^{*-} 2\pi^+ \pi^- \pi^0$	17.6
	$\boldsymbol{D}^{*-} \tau^+ \nu_\tau$	15.7
	$\boldsymbol{D}^{*-} \pi^+ \pi^0$	15.
	$\boldsymbol{D}^{*-} a_1^+(1260)$	13.
	$\boldsymbol{D}^{*-} D^{*0}(2007) K^+$	10.6
	$\boldsymbol{D}^{*-} D_{s1}^+(2460)$	9.3
	$\boldsymbol{D}^{*-} D^{*+} K^0$	8.1
	$\boldsymbol{D}^{*-} D_s^+$	8.
	$\boldsymbol{D}^{*-} 2\pi^+ \pi^-$	7.21
	$\boldsymbol{D}^{*-} \rho^+$	6.8
	$\boldsymbol{D}^{*-} \rho^0 \pi^+$	5.7
	$\boldsymbol{D}^{*+} D^- K^0$	4.7
	$\boldsymbol{D}^{*-} 3\pi^+ 2\pi^-$	4.7
	$\boldsymbol{D}^{*-} \pi^+$	2.74
	$\boldsymbol{D}^{*-} D^0 K^+$	2.47
	$\boldsymbol{D}^{*-} \omega(782) \pi^+$	2.46
	$\boldsymbol{D}^{*-} D^+ K^0$	1.8
	$\boldsymbol{D}^{*-} D_{s0}^{*+}(2317)$	1.5
$B^0 \to$	$\boldsymbol{D}^{*-} p^+ \bar{n}^0$	1.4
	$\boldsymbol{D}^{*-} K^+ \bar{K}^0$	1.29
	$\boldsymbol{D}^{*-} D_{s1}^{*+}(2700)$	0.83
	$\boldsymbol{D}^{*-} D^{*+}$	0.8
	$\boldsymbol{D}^{*-} D^-$	0.61
	$\boldsymbol{D}^{*-} K^+ \pi^- \pi^+$	0.47
	$\boldsymbol{D}^{*-} p^+ \bar{p}^- \pi^+$	0.47
	$\boldsymbol{D}^{*-} K^{*+}(892)$	0.33
	$\boldsymbol{D}^{*-} K^0 \pi^+$	0.3
	$\boldsymbol{D}^{*-} K^+$	0.212
$B^+ \to$	$\boldsymbol{D}^{*-} 2\pi^+ \pi^0$	15.
	$\boldsymbol{D}^{*+} \overline{D}^{*0} K^0$	9.2
	$\boldsymbol{D}^{*+} \overline{D}^0 K^0$	3.8
	$\boldsymbol{D}^{*-} 3\pi^+ \pi^-$	2.6
	$\boldsymbol{D}^{*-} 2\pi^+$	1.35
	$\boldsymbol{D}^{*-} D^{*+} K^+$	1.32
	$\boldsymbol{D}^{*+} \overline{D}^{*0}(2007)$	0.81
	$\boldsymbol{D}^{*+} D^- K^+$	0.63
	$\boldsymbol{D}^{*-} D^+ K^+$	0.6
	$\boldsymbol{D}^{*+} \overline{D}^0$	0.39

Decay-time bias – Template fit

- Systematic uncertainties on PV and DV res. scale, $m(X)$ and f_X are treated with the template profile likelihood approach:
    - templates produced with PV and DV resolution independently scaled by a factor of -10%, 1, +10%, $m(X)$ is chosen between 0.5, 1.5, 2.5 GeV/c^2 and f_X between 0%, 3%, 6%
    - templates corresponding to intermediate values obtained through linear interpolation
- Uncertainties on simulation statistics treated with Beeston-Barlow prescription:
    - each template bin became a nuisance parameter constrained (in the likelihood) with its statistical uncertainty
- The parameters of interest are the normalizations of prompt and secondary templates

Impact on World average – Superweak approximation

- Superweak approximation PRL13.562 assumes that the only CPV source is interaction with BSM particles with mass much higher than D^0

  → only parameter responsible for CPV would be ϕ_2^M

- In the fit, this limit is implemented by fixing $A_{K\pi} = 0$ and $\phi_2^\Gamma = 0$

  → under this assumption, precision on ϕ_2^M improves by 20% reaching 13 mrad precision