Mixing and Indirect CPV charm measurements at LHCb

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Charm and New Physics

- In indirect searches for new physics, charm furnishes a unique probe of flavour physics in the up-quark sector
  - complementary to strange and bottom physics
- Indirect searches for NP with charm give complementary constraints to direct searches at the Energy Frontier
- Precision measurements in charm are necessary as inputs for B physics ($B \rightarrow DK$, $B \rightarrow D\pi$) and the measurement of the CKM angle γ
- Many "null-tests" available, one of them is the search for CP violation, which is expected to be small in SM (but not zero)
  - ... but SM predictions are difficult to be calculated

Phenomenology: D^0 Mixing and CP violation

D^0 mixing

The D^0 and $\bar{D}^0$ mesons are produced as flavor eigenstates
They propagate and decay according to

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

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Mixing occurs because D^0 and $\overline{D}^0$ are linear combinations of mass eigenstates

$$\begin{aligned} |D_1\rangle &= p|D^0\rangle + q|\overline{D}^0\rangle \\ |D_2\rangle &= p|D^0\rangle - q|\overline{D}^0\rangle \end{aligned}$$

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The mass eigenstates develop in time as follow

$$|D_{1,2}(t)\rangle = e_{1,2}(t)|D_{1,2}(0)\rangle$$

$$e_{1,2}(t) \equiv \exp\left[-i\left(M_{1,2} - \frac{i}{2}\Gamma_{1,2}\right)t\right]$$

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Two parameters characterize the D^0 and $\overline{D}^0$ mixing

$$x \equiv \frac{\Delta M}{\Gamma}, \quad \Delta M \equiv M_1 - M_2$$

$$y \equiv \frac{\Delta\Gamma}{2\Gamma}, \quad \Delta\Gamma \equiv \Gamma_1 - \Gamma_2$$

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If both x and y are different from zero, mixing occurs

$$|\langle \overline{D}^0|D^0(t)\rangle|^2 = \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-\Gamma t}\left[\cosh(y\Gamma t) - \cos(x\Gamma t)\right]$$

$$|\langle D^0|\overline{D}^0(t)\rangle|^2 = \frac{1}{2}\left|\frac{p}{q}\right|^2 e^{-\Gamma t}\left[\cosh(y\Gamma t) - \cos(x\Gamma t)\right]$$

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Mixing occurs because D^0 and

The mass eigenstate develop in time

Mixing is well established

Charm mixing parameters are small < 10^{-2}

Two parameters characterize the D^0 and $\overline{D}^0$ mixing

$$x \equiv \frac{\Delta M}{\Gamma}, \quad \Delta M \equiv M_1 - M_2$$

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$$|\langle \overline{D}^0 | D^0(t)\rangle|^2 = \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-\Gamma t}\left[\cosh(y\Gamma t) - \cos(x\Gamma t)\right]$$

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CP Violation in Charm

3 modes of observing CP violation

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in decay: amplitudes for a process and its conjugate differ

$$|D \to f|^2 \neq |\bar{D} \to \bar{f}|^2$$

direct CPV

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3 modes of observing CP violation

in decay: amplitudes for a process and its conjugate differ

direct CPV

in mixing: rates of $D^0 \to \overline{D}^0$ and $\overline{D}^0 \to D^0$ differ

in interference between mixing and decay diagrams

indirect CPV

CP Violation in Charm

3 modes of observing CP violation

in decay: amplitudes for a process and its conjugate differ

direct CPV

CP violation is not yet observed

in mixing: rates of $D^0 \rightarrow \bar{D}^0$ and $\bar{D}^0 \rightarrow D^0$ differ

in interference between mixing and decay diagrams

indirect CPV

Indirect CP violation:
LHCb results with $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays

PRL 118 (2017) 261803

A_Γ : a powerful observable to search for indirect CPV

- The time-dependent CP asymmetry for D^0 decaying into a CP eigenstate (i.e. KK or $\pi\pi$) is defined as

$$A_{CP}(t) \equiv \frac{\Gamma(D^0 \to f;t) - \Gamma(\bar{D}^0 \to f;t)}{\Gamma(D^0 \to f;t) + \Gamma(\bar{D}^0 \to f;t)} \qquad A_{CP}(t) \approx A_{CP}^{\mathrm{dir}} - A_\Gamma \frac{t}{\tau}$$

where $A_\Gamma \equiv \frac{\hat{\Gamma}_{D^0} - \hat{\Gamma}_{\bar{D}^0}}{\hat{\Gamma}_{D^0} + \hat{\Gamma}_{\bar{D}^0}}$ is the asymmetry of the effective D^0 lifetime

- A_Γ can be approximate in term of D^0 mixing parameters p, q and ϕ

$$A_\Gamma \approx \frac{1}{2}\left[\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y \cos\phi - \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x \sin\phi\right] \qquad \phi = \arg\left[\frac{q\bar{A}_f}{pA_f}\right]$$

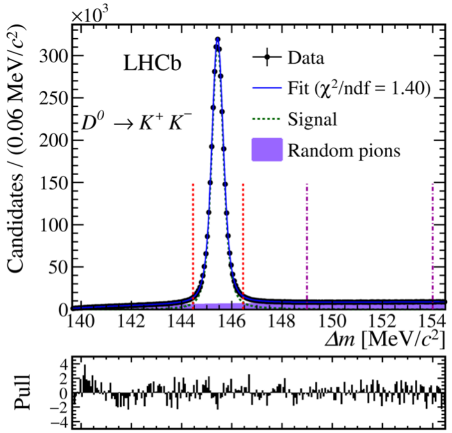
Recent LHCb A_Γ measurements

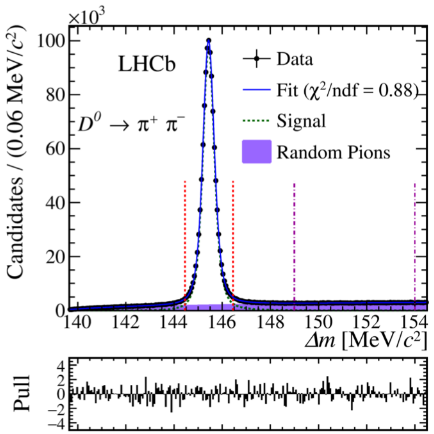
PRL 118 (2017) 261803

- Latest LHCb measurement using D^0 from $D^{*+} \rightarrow D^0\pi^+$
- Charge of the π used to define the flavour of D^0
- Two different approaches to measure A_Γ:
  - Binned fit versus decay time (lifetime efficiency cancel in the ratio)
  - Unbinned fit (description of lifetime reconstruction efficiency necessary)
- $D^0 \rightarrow K^-\pi^+$ used as control channel

Time-dependent binned analysis

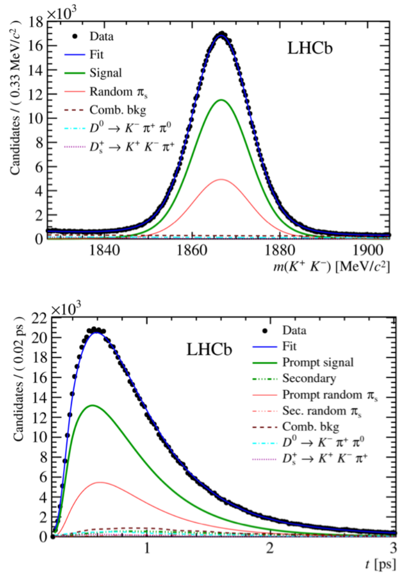
$N(KK) = 9.6 \times 10^6$ $N(\pi\pi) = 3.0 \times 10^6$

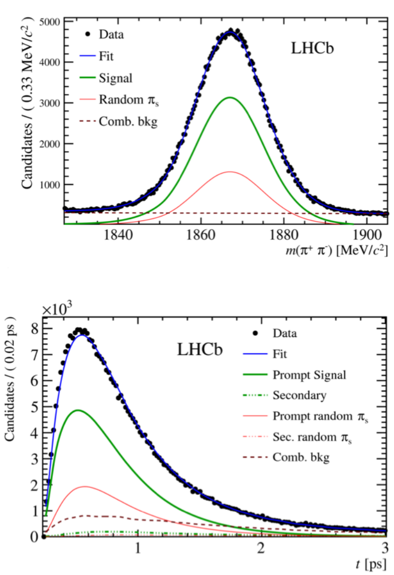




Time-dependent unbinned analysis

$N(KK) = 6.7 \times 10^6$ $N(\pi\pi) = 2.2 \times 10^6$





LHCb A_Γ results

PRL 118 (2017) 261803

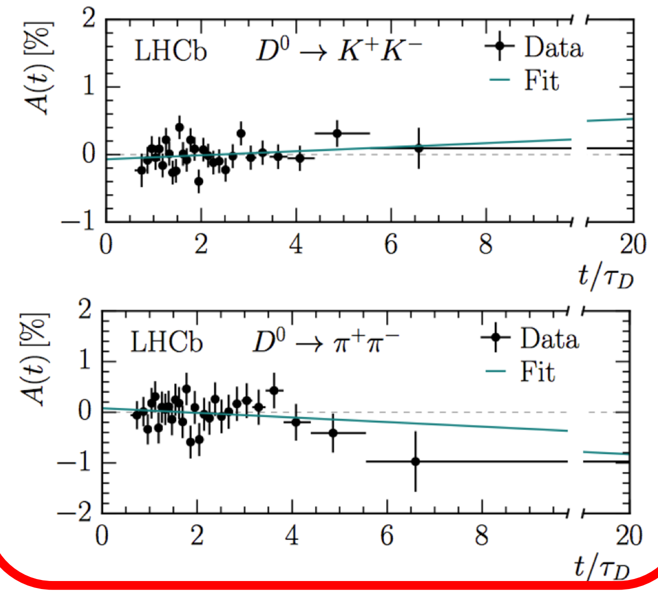
- Two methods consistent within 1σ (correlation included)
  - The most precise one is used as nominal result
- Consistent with no-CPV hypothesis
- Most precise measurements of CPV in charm system ever made
- Statistically limited

$$A_\Gamma(K^+K^-) = (-0.30 \pm 0.32 \pm 0.10) \times 10^{-3}$$

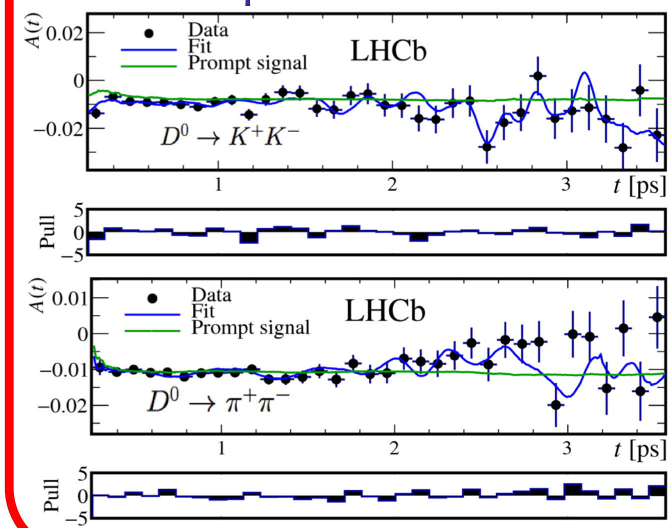
$$A_\Gamma(\pi^+\pi^-) = (0.46 \pm 0.58 \pm 0.12) \times 10^{-3}$$

$$A_\Gamma = (-0.13 \pm 0.28 \pm 0.10) \times 10^{-3}$$

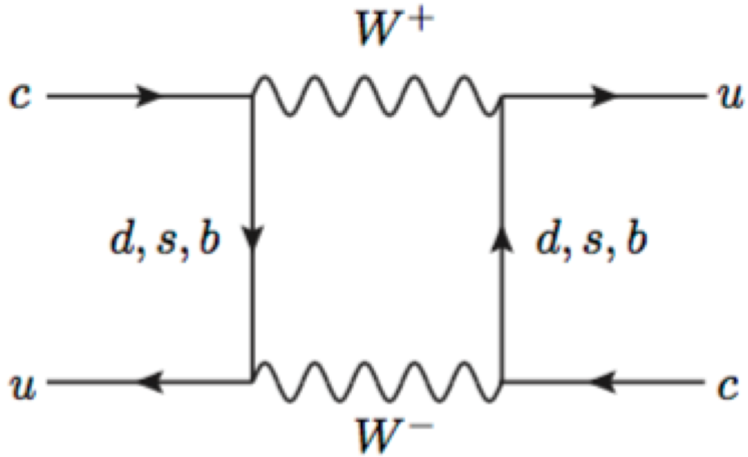
Time-dependent binned



Time-dependent unbinned



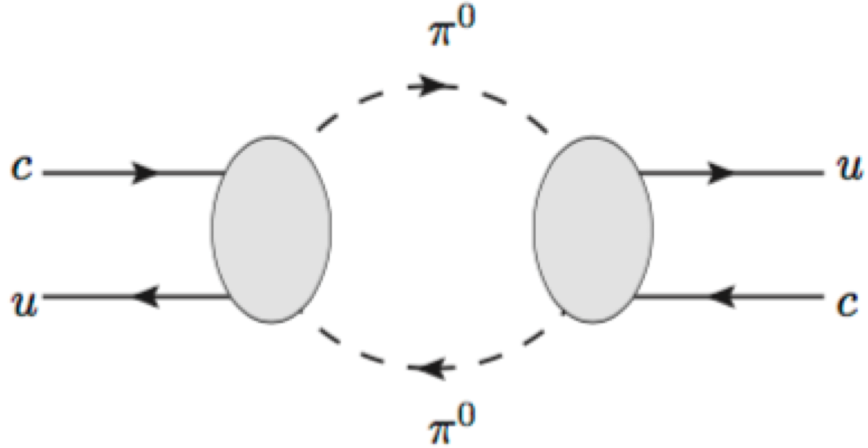
D^0 mixing



"Short distance"

Short distance contribution is CKM + GIM suppressed. NP might manifest in the loop

CKM suppression: b quark
GIM suppression: d,s quark



"Long distance"

Real particle in the loop

Long distance contribution is dominant but hard to predict

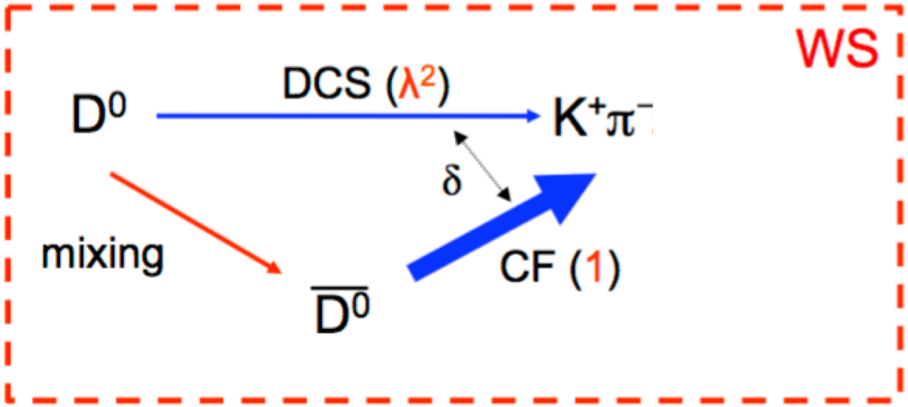
How the D^0 oscillation is observed (with $D^0 \to K^+\pi^-$ decay)

- The D^0 flavor at the production is tagged by $D^{*+} \to D^0\pi^+_s$
- Measure the time dependent ratio of Wrong-Sign $D^{*+} \to [K^+\pi^-]\,\pi^+_s$ and Right-Sign (RS) $D^{*+} \to [K^-\pi^+]\,\pi^+_s$

$$R(t) = \frac{N(D^0 \to K^+\pi^-)}{N(D^0 \to K^-\pi^+)}$$

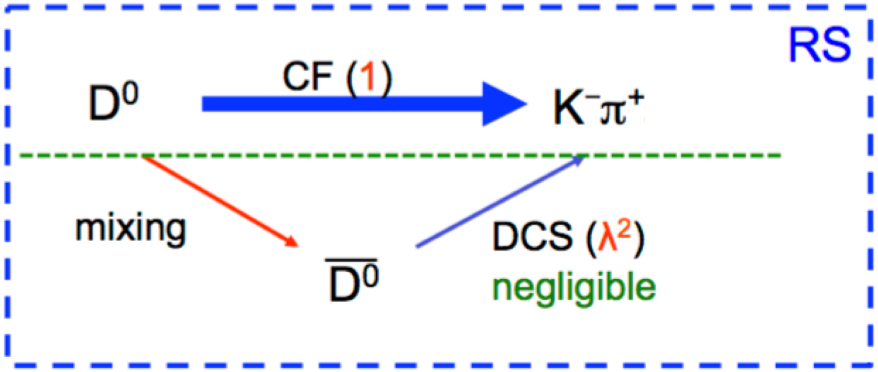
For WS two processes interfere:

- Mixing then Cabibbo-Favoured decay
- Doubly-Cabibbo-Suppressed decay



For RS only one process dominates:

- Cabibbo-Favoured decay



D^0 WS/RS as function time

Considering negligible CP violation and in the limit of x,y<<1, to second order in t/τ, the time-dependence of the phase-space integrated decay rate ratio R(t) is approximated by:

$$R(t) \approx R_D + \sqrt{R_D}\, y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} \left(\frac{t}{\tau}\right)^2$$

τ is the average D^0 lifetime

R_D is the ratio of suppressed-to- favored decay rates

$$x' \equiv x \cos\delta + y \sin\delta$$

$$y' \equiv y \cos\delta - x \sin\delta$$

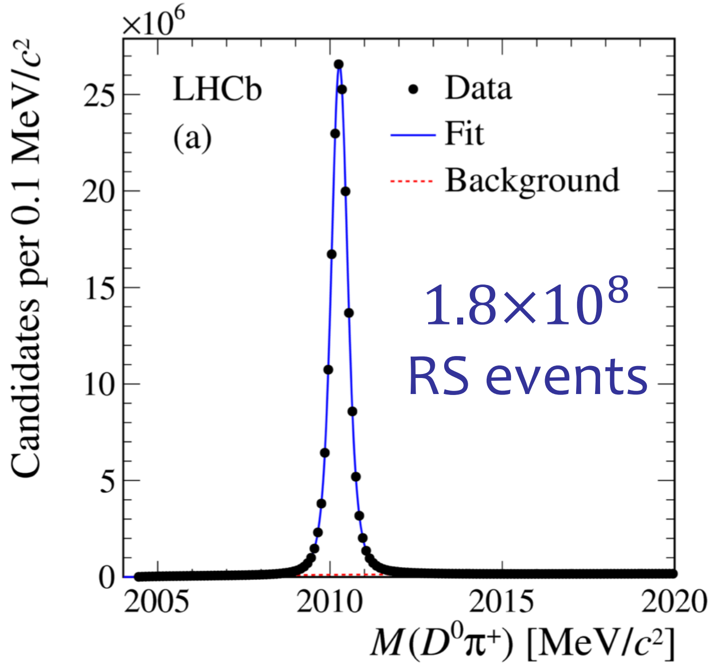
δ is the strong-phase difference between the suppressed and favored amplitudes

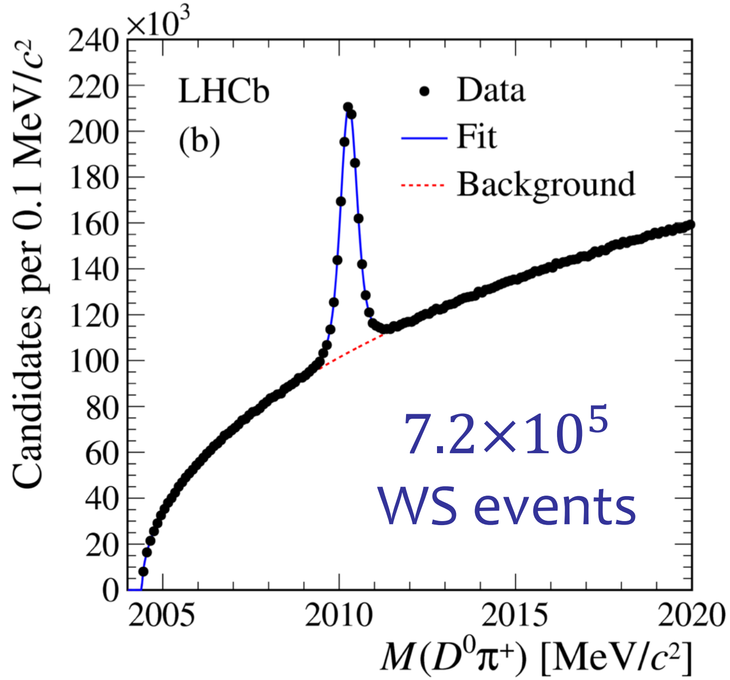
$$\mathcal{A}(D^0 \to K^+\pi^-)/\mathcal{A}(\overline{D}^0 \to K^+\pi^-) = -\sqrt{R_D} e^{-i\delta}$$

LHCb results with $D^0 \to K^+\pi^-$

PRD 97 (2018) 031101

- Use tagged (π) $D^0 \to K^+\pi^-$ decay from $D^{*+} \to D^0\pi^+$ decay
- Data sample of 5 fb^{-1} of integrated luminosity (2011-2016)
- Constrain $D^0\pi_s^+$ vertex to measured position of primary vertex ⇒ 0.3 MeV/c² invariant-mass resolution
- Fix WS signal shape parameters from RS fits in each decay time bin
- Run 2 signal yields (2015-2016) ~ 2 times larger than Run 1 (2011-2012)





Peaking background

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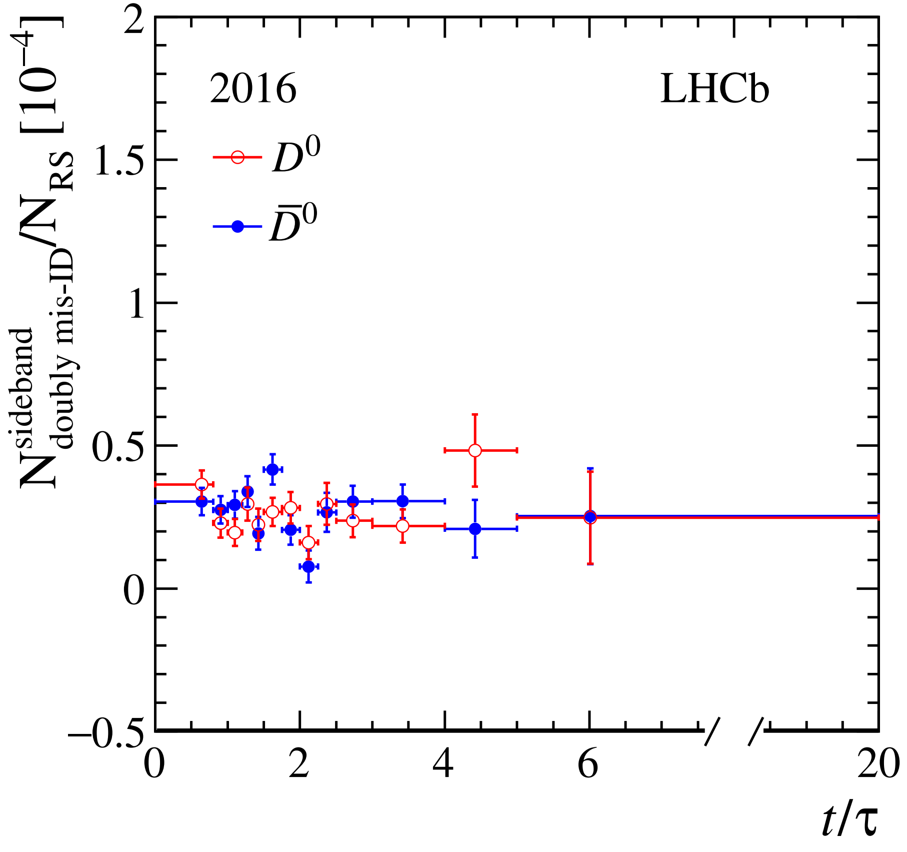
- The most dangerous background comes from doubly misidentified RS decays
  - Peaks in the $m(D^0\pi_s)$ spectrum
  - 0.5% of RS decays
- Suppression due to tight PID requirements
- Residual contribution estimated from RS doubly misID sideband
- time-dependence is included in the fit → no dependence observed



Background from ghost pions

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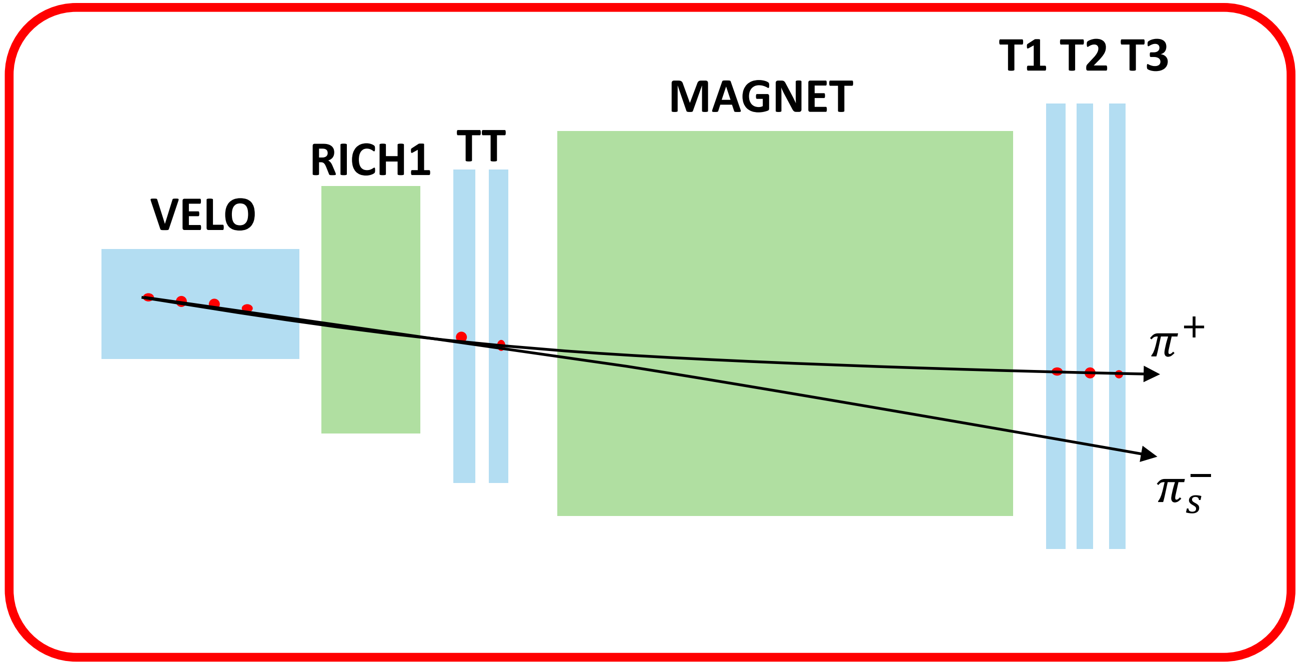
- Source: pions built from correctly identified clusters in VELO and TT, associated with clusters from a different particle in the T stations
- Potentially dangerous
  - Peaks in $m(D^0\pi_s)$ due to very similar opening angle w.r.t. correct pion $\Rightarrow$ wrong counting of signal events
  - π_s charge wrong 50% of the time $\Rightarrow$ RS confused for a WS



Background from ghost pions

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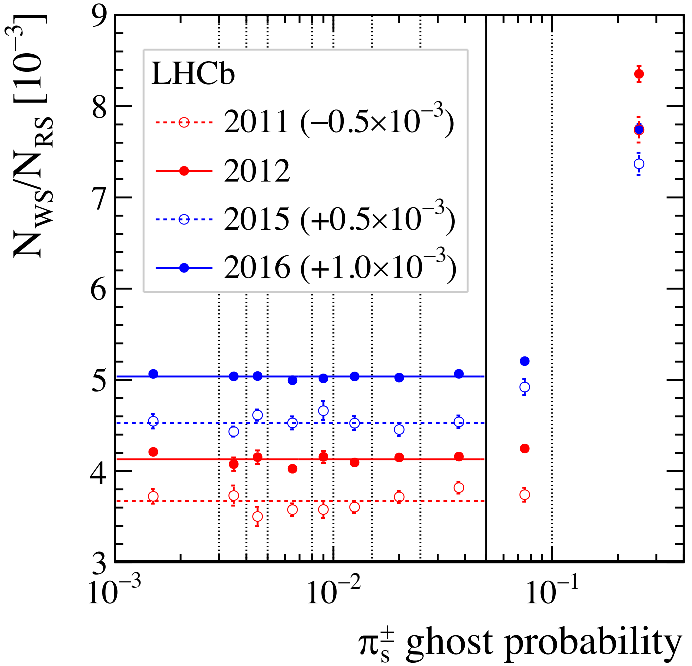
- Use a track-based classifier to reject this background
  - Combination of the track number of hits in the various sub-detectors and track quality variables
- Study the N_{WS}/N_{RS} ratio as a function of the requirement on the classifier output
- Choose loosest requirement (0.05) that preserve flatness of N_{WS}/N_{RS} ratio



Secondary D^0 decays

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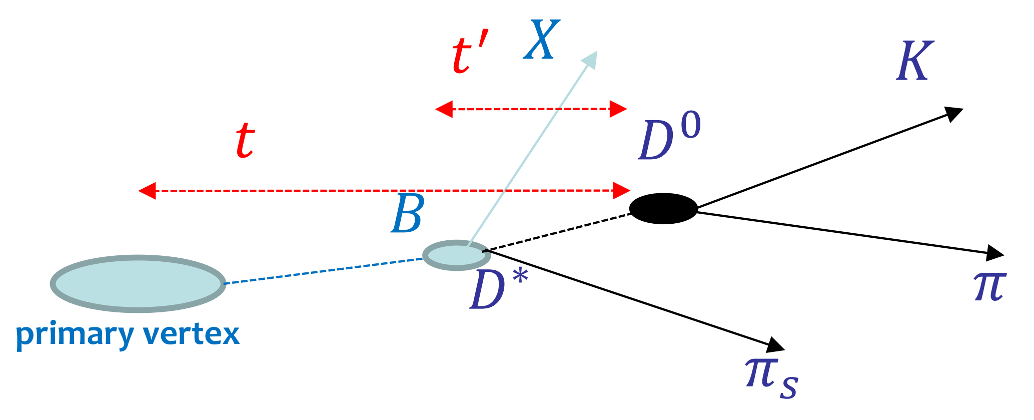
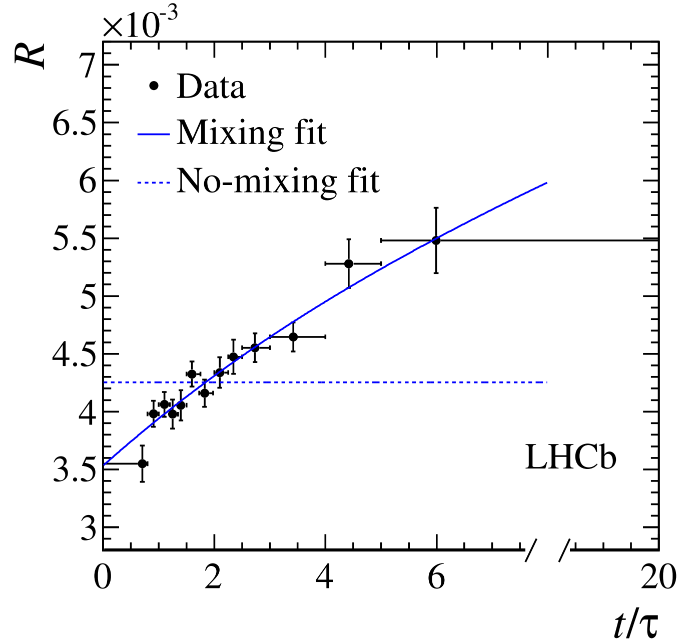
- D^0 decaying from a B meson have a larger and wrong decay time
- They bias the time dependence of the WS-to-RS ratio
  - Secondary D^0 decays tend to populate bins at higher decay time



PRL 110, 101802 (2013)



Secondary D^0 decays

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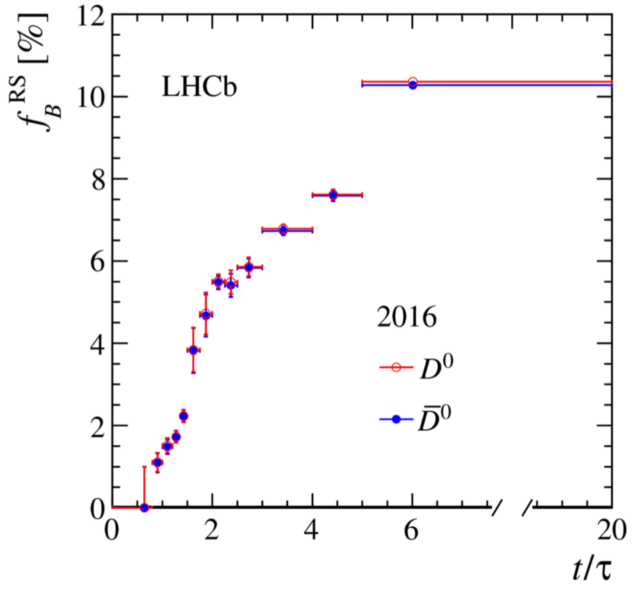
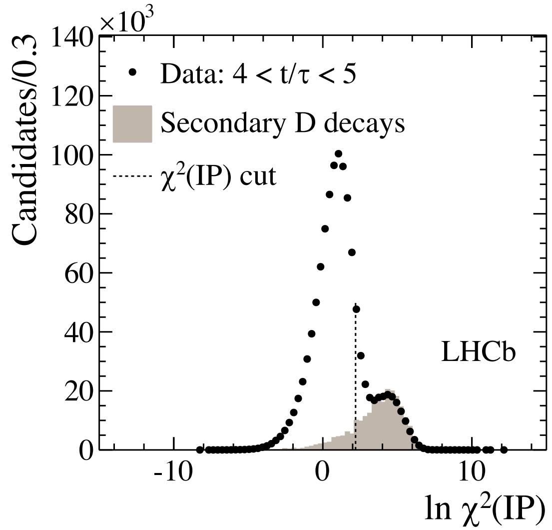
- B mesons flight about $c\tau \simeq 450\ \mu m$ before decaying $\Rightarrow D^0$ has nonzero impact parameter
- Require D^0 to point to the primary vertex is very effective in rejecting these candidates, but still 3-10% (depending on the lifetime) of them pass the requirement
- Fraction of secondary D^0 surviving the requirement on impact parameter estimated as a function of the decay time



PRL 111, 251801 (2013)



$K\pi$ detection asymmetry

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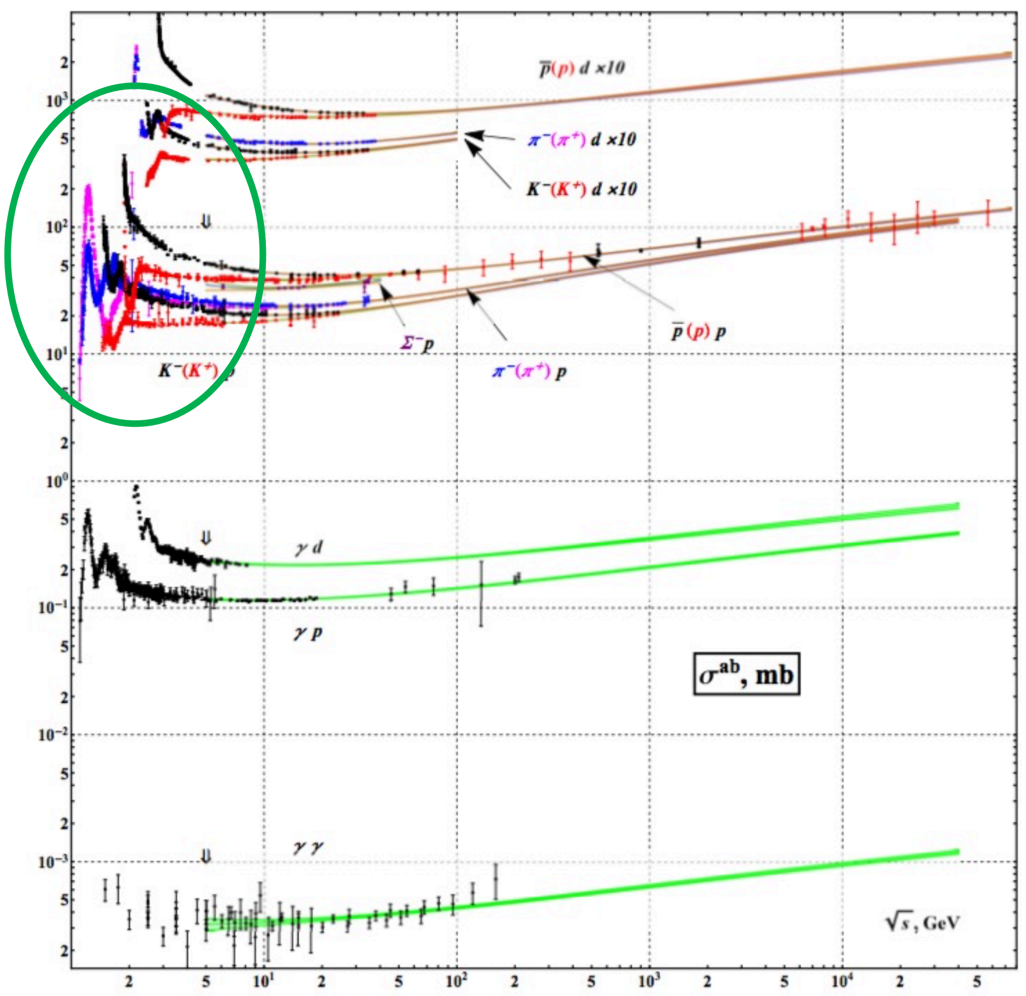
- Detection asymmetry in WS/RS ratio:
$$\frac{N^{\pm}_{WS}(t)}{N^{\pm}_{RS}(t)} = R^{\pm}\frac{\varepsilon(K^{\pm}\pi^{\mp})}{\varepsilon(K^{\mp}\pi^{\pm})}$$
- Charge-conjugated particles have different probabilities to interact with the material LHCb is made of
    - this results in a detection asymmetry
- Effect relevant for particles momenta lower than 100 GeV/c

Chin. Phys. C, 40, 100001 (2016)



$K\pi$ detection asymmetry

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- Use CF $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to \overline{K}^0\,\pi^+$ decays
  - CPV in these decays is expected to be negligible
- Measure raw asymmetries with fits to the invariant-mass spectra in bins of kaon momentum

$$A_{raw}^{K\pi\pi} = A_{CP}^{K\pi\pi} + A_D^{\pi trig} + A_P^D + A_D^{K\pi}$$
$$A_{raw}^{\overline{K}^0\pi} = A_{CP}^{\overline{K}^0\pi} + A_D^{\pi trig} + A_P^D + A_D^{\overline{K}^0}$$
$$A_{raw}^{K\pi\pi} - A_{raw}^{\overline{K}^0\pi} = A_D^{K\pi} - A_D^{\overline{K}^0}$$

Obtained from previous LHCb measurement [JHEP 07 (2014) 041]

- Need to reweight D^+ and π_{trig} kinematics to ensure a perfect cancellation
- $A_D^{K\pi} \sim 1\%$

Consistency checks

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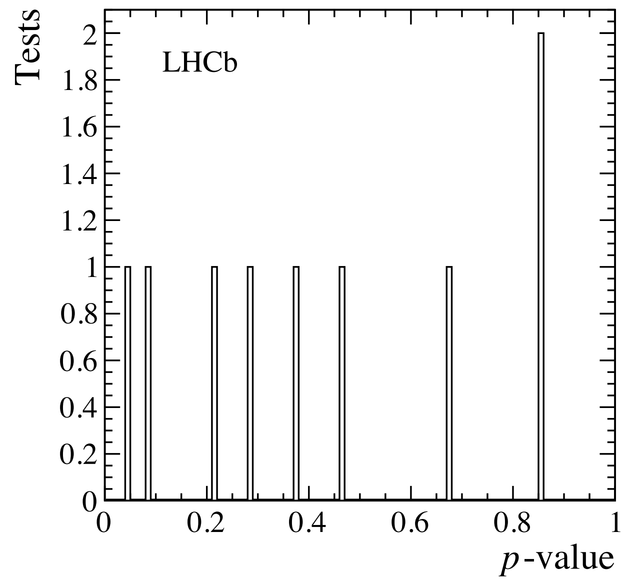
- The observed WS-to-RS yield ratio is measured again dividing the sample in statistically independent sub-samples, according to
  - Data-taking year
  - Magnetic field orientation
  - Number of primary vertices in the event
  - Candidate multiplicity per event
  - Trigger category
  - D^0 momentum
  - D^0 χ^2_{IP} with respect to the primary vertex
  - Probability of reconstructing a ghost pion



- P-values of CP parameters distributed uniformly in the $4\% - 85\%$ range

Systematic uncertainties

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- Several sources of systematic uncertainties have been evaluated
  - Instrumental asymmetries ($K\pi$ detection asymmetry)
  - Contribution due to peaking background
  - Contribution from secondary decays
  - Background due to ghost soft pions
- Systematic uncertainty is roughly half of the statistical one

Table 2: Summary of systematic uncertainties.

No CP violation			
Source	R_D $[10^{-3}]$	y' $[10^{-3}]$	x'^2 $[10^{-3}]$
Instrumental asymm.	< 0.001	< 0.01	< 0.001
Peaking background	± 0.003	± 0.04	± 0.002
Secondary D decays	± 0.010	± 0.21	± 0.011
Ghost soft pions	± 0.008	± 0.15	± 0.008
Total syst. uncertainty	± 0.014	± 0.27	± 0.014
Statistical uncertainty	± 0.028	± 0.45	± 0.023

Result on search for CP violation in mixing

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Fit efficiency-corrected data to extract ($x'^{\pm}$, $y'^{\pm}$, $R_D^{\pm}$) under three hypotheses:

- No CPV
- No direct CPV ($R_D^+ = R_D^-$)
- All CPV allowed

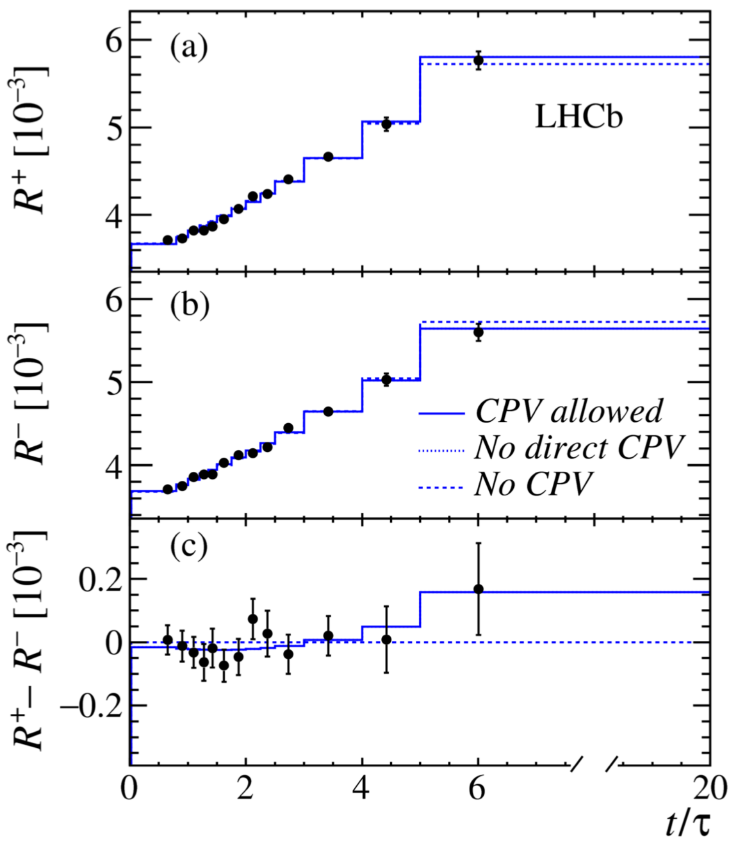
No *CP* violation	
Parameter	Value
R_D	$3.454 \pm 0.028 \pm 0.014$
y'	$5.28 \pm 0.45 \pm 0.27$
x'^2	$0.039 \pm 0.023 \pm 0.014$

Allowing for CP violation, the WS rates $R_-(t)$ and $R_+(t)$ of initially produced D^0 and $\overline{D}^0$ mesons are functions of independent sets of mixing parameters

$$(R_D^{\pm}, x'^{2\pm}, y'^{\pm})$$

Direct and indirect *CP* violation	
Parameter	Value
R_D^+	$3.454 \pm 0.040 \pm 0.020$
y'^+	$5.01 \pm 0.64 \pm 0.38$
$(x'^+)^2$	$0.061 \pm 0.032 \pm 0.019$
R_D^-	$3.454 \pm 0.040 \pm 0.020$
y'^-	$5.54 \pm 0.64 \pm 0.38$
$(x'^-)^2$	$0.016 \pm 0.033 \pm 0.020$

No direct *CP* violation	
Parameter	Value
R_D	$3.454 \pm 0.028 \pm 0.014$
y'^+	$5.01 \pm 0.48 \pm 0.29$
$(x'^+)^2$	$0.061 \pm 0.026 \pm 0.016$
y'^-	$5.54 \pm 0.48 \pm 0.29$
$(x'^-)^2$	$0.016 \pm 0.026 \pm 0.016$



Direct CP

$$A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-} = (-0.1 \pm 8.1(stat) \pm 4.2(syst)\,)\times 10^{-3}$$

Two-dimensional confidence regions in the y' and x'^2

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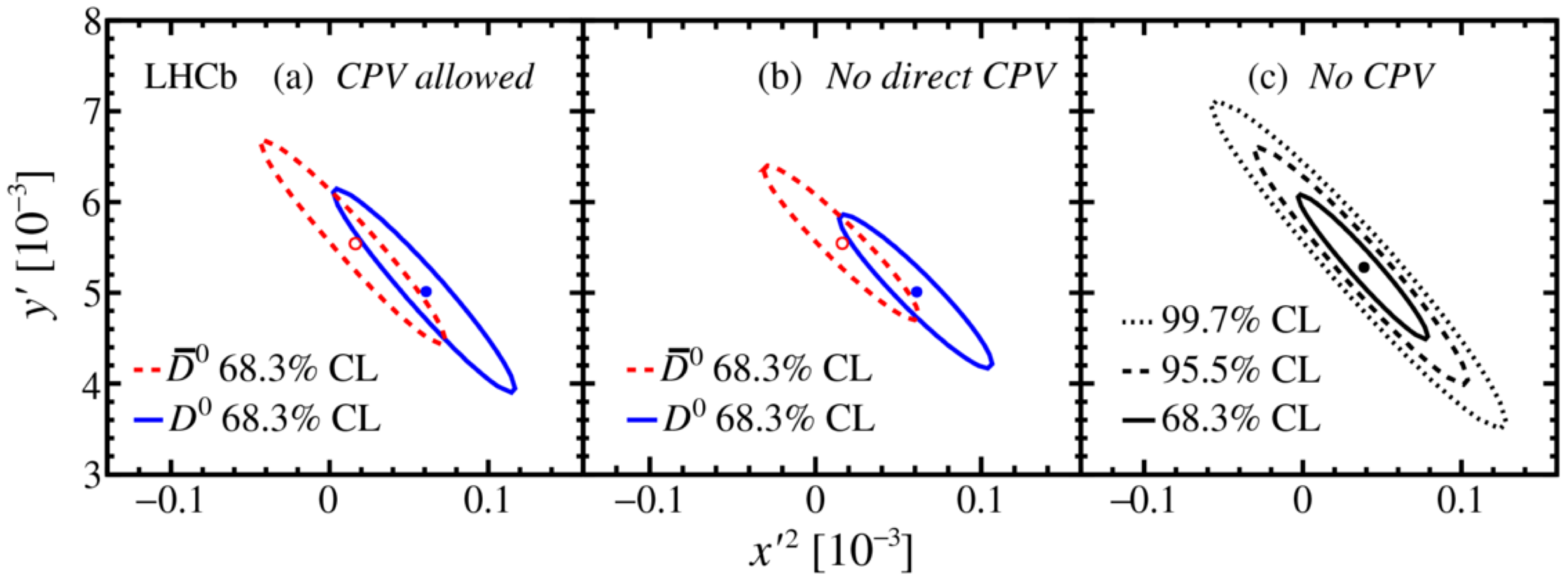
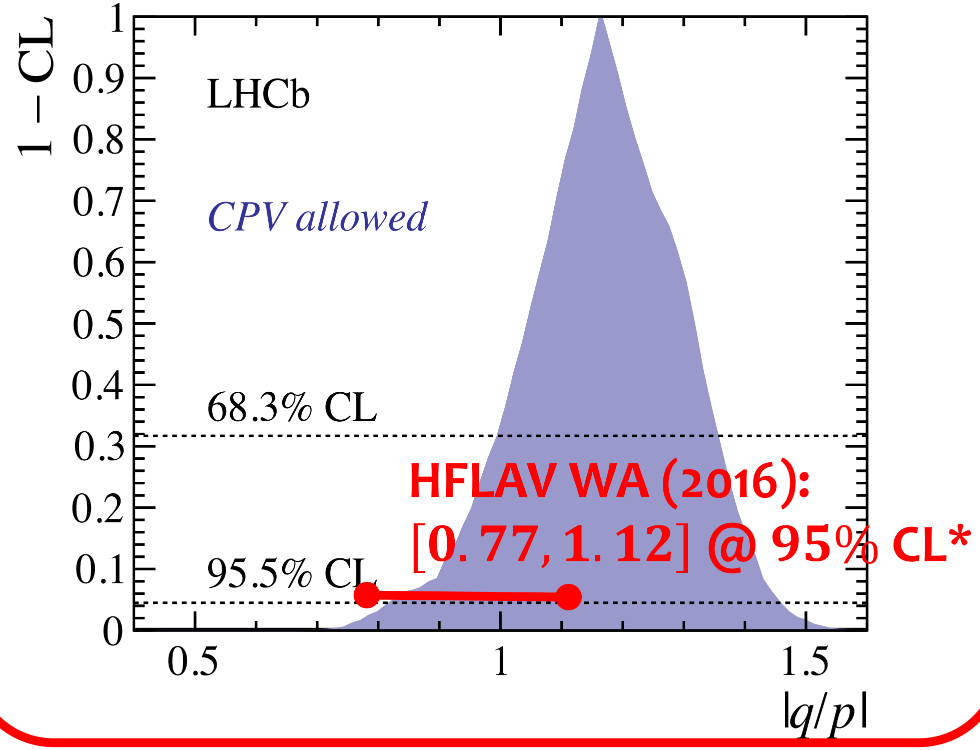


- Bounds on $|q/p|$ can be calculated from x' and y'

$$x'^{\pm} = |q/p|^{\pm 1} \times (x' \cos\phi \pm y' \sin\phi)$$
$$y'^{\pm} = |q/p|^{\pm 1} \times (y' \cos\phi \mp x' \sin\phi)$$

Results

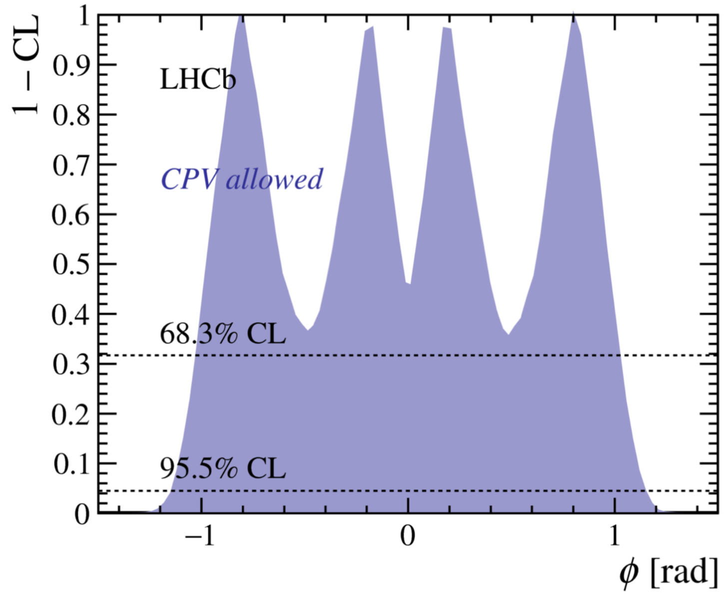
PRD 97 (2018) 031101

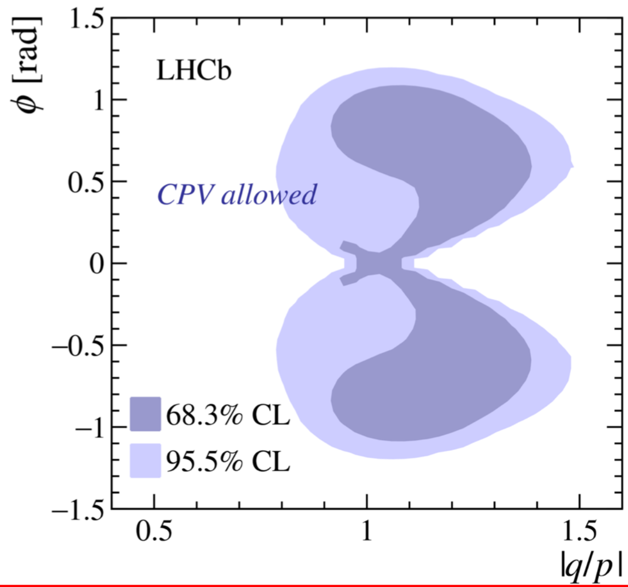


$1.00 < |q/p| < 1.35$ @ 68.3% C.L.

$0.82 < |q/p| < 1.45$ @ 95.5% C.L.

*this includes also LHCb Run 1 results, obtained with a subset of the sample used in this analysis





Comparison with previous results

- Assuming CP conservation

	R_D (10^{-3})	y' (10^{-3})	x'^2 (10^{-3})
CDF[1]	3.51 ± 0.35	4.3 ± 4.3	0.08 ± 0.18
Belle[2]	3.53 ± 0.13	4.6 ± 3.4	0.09 ± 0.22
BaBar[3]	3.03 ± 0.19	9.7 ± 5.4	-0.22 ± 0.37
LHCb Run 1+2[4]	3.454 ± 0.031	5.28 ± 0.52	0.039 ± 0.027

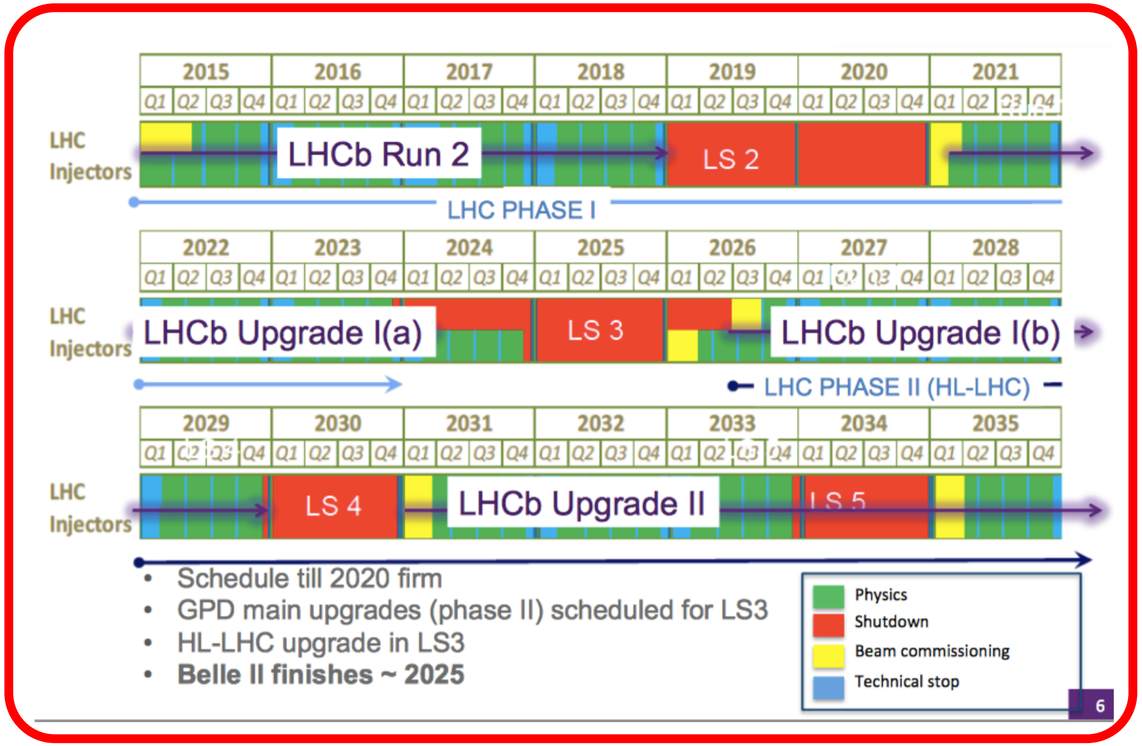
- LHCb completely dominating the scene

[1]CDF: PRL 111 (2013) 231802
[2]Belle: PRL 112 (2014) 111801
[3]BaBar: PRL 98 (2007) 211802
[4]LHCb: PRD 97 (2018) 031101

Prospects

LHCb and the future

- Run-2 → 9 fb^{-1}
- After Run 2, raise instantaneous luminosity from $4 \times 10^{32}\ cm^{-2}s^{-1}$ → $2 \times 10^{33}\ cm^{-2}s^{-1}$
- Run-3 – Run-4 → 50 fb^{-1}
- Run-5+ → 300 fb^{-1}
  - assuming an LHCb Upgrade II (funded) to raise the instantaneous luminosity to $2 \times 10^{34}\ cm^{-2}s^{-1}$



- Upgrade I and II → replace L0 hardware trigger (1 MHz output) with a software trigger (40 MHz output)
- Charm physics will reach the (extreme) high precision era
  - Lot of measurements limited by statistical uncertainties

Prospects for mixing and CPV in $D^0 \to K^+\pi^-$

LHCb unofficial

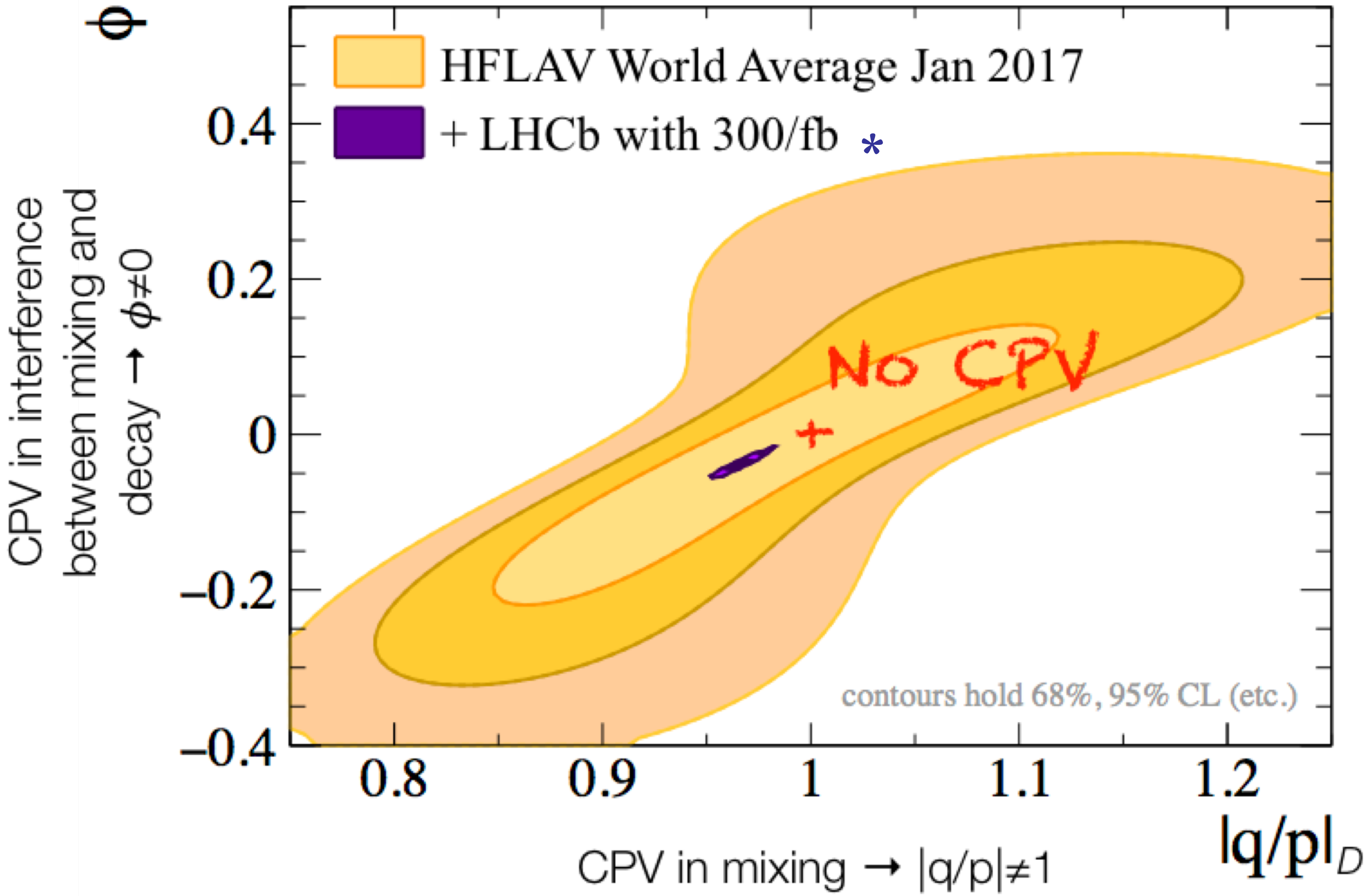
Table 6.1: Extrapolated signal yields, and statistical precision on the mixing and CP-violation parameters, from the analysis of promptly-produced WS $D^{*+} \to D^0(\to K^+\pi^-)\pi^+$ decays. Signal yields of promptly-produced RS $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ decays are typically 245 times larger.

Sample ($\mathcal{L}$)	Yield ($\times 10^6$)	$\sigma(x'^2)$	$\sigma(y')$	$\sigma(A_D)$	$\sigma(\lvert q/p\rvert)$	$\sigma(\phi)$
Run 1-2 ($9\,\text{fb}^{-1}$)	1.8	1.5×10^{-5}	2.9×10^{-4}	0.51%	0.12	10°
Run 1-4 ($50\,\text{fb}^{-1}$)	25	3.9×10^{-6}	7.6×10^{-5}	0.14%	0.03	4°
Run 1-6 ($300\,\text{fb}^{-1}$)	170	1.5×10^{-6}	2.9×10^{-5}	0.05%	0.01	1°

- Systematic uncertainty assessed using control samples
  - Scale with luminosity
- Run 1/2 PID and tracking performance sufficient to control most dangerous backgrounds
  - Should be at same level/improve in Upgrade I

At the end of Run 5...

[CERN-LHCC-2017-003]



* Several analysis contribute to the plot: WS $D^0 \to K^+\pi^-$, A_Γ, mixing in $D^0 \to K_S^0\pi^+\pi^-$

Conclusions

- Charm mixing and indirect CP violation are very promising probes for indirect searches of physics beyond the SM
  - especially if contributions affect mostly the up sector
- A_Γ and $D^0 - \overline{D}^0$ mixing have reached an unprecedented precision
  - $A_\Gamma \rightarrow 3\times10^{-4}$
  - $y' \rightarrow 5\times10^{-4}$ $x'^2 \rightarrow 3\times10^{-5}$
- With coming data LHCb will reach the precision to observe CP violation as expected by SM
- In the coming years, LHCb will be a leading player in searching for indirect CP violation with charm decays