Mixing and CP Violation in Charm at LHCb

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on behalf of the LHCb Collaboration

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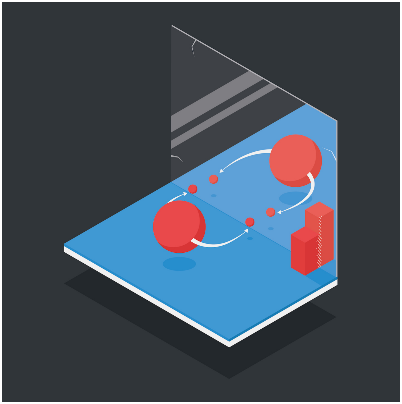
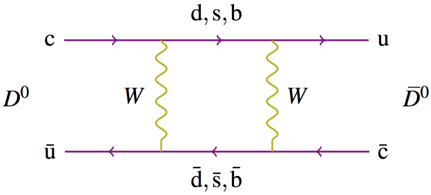
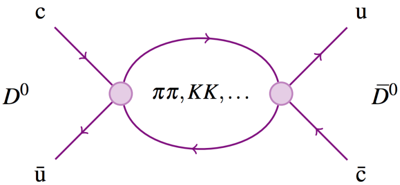
CP Violation

- CP violation discovered in charm in 2019 at LHCb
- CPV in charm is predicted to be small in the Standard Model ($\sim \mathbf{10^{-4} - 10^{-3}}$)
- Theoretical prediction has large uncertainties due to strong interactions
- CPV searches in charm complementary to those in kaons and B mesons



D^0 Mixing





Mass Eigenstates:

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

Mixing parameters:

$$x \equiv \frac{(m_1 - m_2)}{\Gamma} \qquad y \equiv \frac{(\Gamma_1 - \Gamma_2)}{2\Gamma}$$

Types of CP Violation

Direct CP Violation:

$$\Gamma(D^0 \to f) \neq \Gamma(\bar{D}^0 \to \bar{f})$$

$$|A_f| \neq |\bar{A}_{\bar{f}}|$$

CP Violation in Mixing:

$$\Gamma(D^0 \to \bar{D}^0) \neq \Gamma(\bar{D}^0 \to D^0)$$

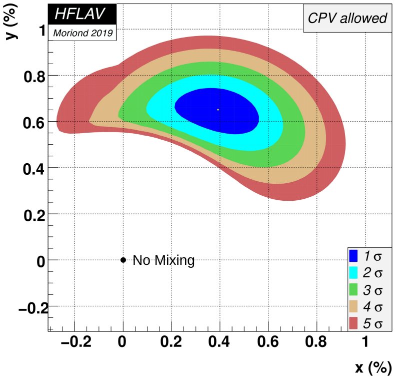
$$|q| \neq |p|$$

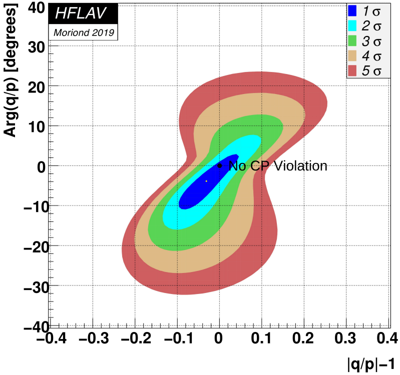
CP Violation in the interference between mixing and decay:

$$\Gamma(D^0 \to \bar{D}^0 \to f, t) \neq \Gamma(\bar{D}^0 \to D^0 \to f, t)$$

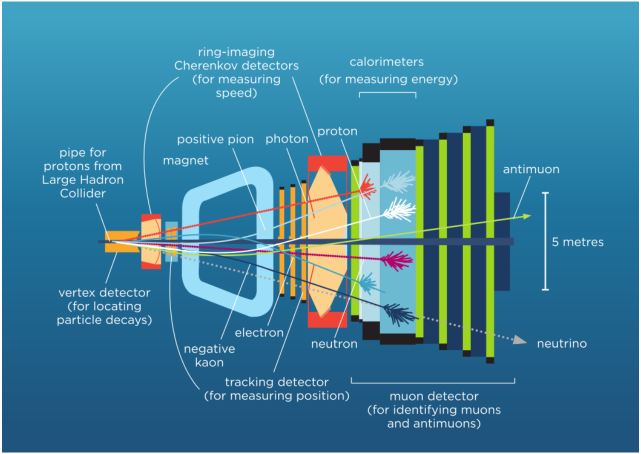
$$\phi = arg\left(\frac{q\bar{A}_f}{pA_f}\right) \neq 0$$

Current World Averages





LHCb Detector



LHCb detector performance: Int. J. Mod. Phys. A 30 (2015) 1530022
The LHCb detector at the LHC: JINST 3 (2008) S08005

Observation of CP Violation in Charm Decays

arXiv:1903.08726

ΔA_{CP}: Time-integrated CP Asymmetry

CP asymmetry:

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}$$

where $f = K^-K^+$ and $f = \pi^-\pi^+$

Raw asymmetry:

$$A_{raw}(f) = \frac{N(D^0 \to f) - N(\bar{D}^0 \to f)}{N(D^0 \to f) + N(\bar{D}^0 \to f)}$$

where N is the number of reconstructed signal decays

$$A_{raw} = A_{CP}(f) + A_D(\pi_s^+) + A_P(D^{*+})$$

ΔA_{CP}

$$\boldsymbol{\Delta A_{CP} \equiv A_{CP}(D^0 \to K^- K^+) - A_{CP}(D^0 \to \pi^- \pi^+)}$$

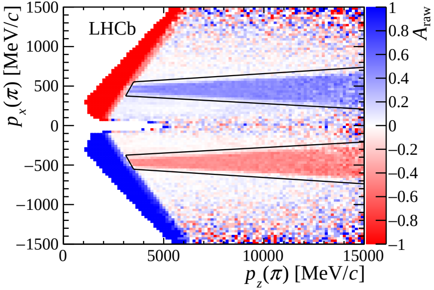
The initial flavour of the neutral D meson is tagged by the charge of the slow pion from $\boldsymbol{D^{*\pm} \to D^0 \pi^+}$decays or the muon from semi-leptonic B decays: $\boldsymbol{B \to D^0 \mu^- X}$.

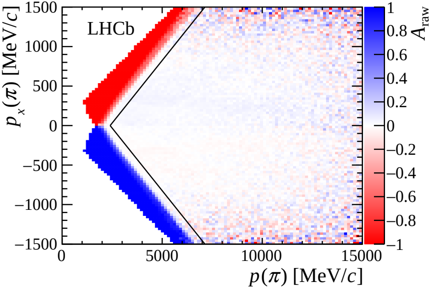
$$\boldsymbol{\Delta A_{CP} = \left[a_{CP}^{dir}(K^+ K^-) - a_{CP}^{dir}(\pi^+ \pi^-) \right] + \frac{\Delta \langle t \rangle}{\tau} a_{CP}^{ind}}$$

where $\Delta \langle t \rangle$ is the difference in proper time between $D^0 \to \pi^+ \pi^-$ and $D^0 \to K^+ K^-$

Fiducial Selection

- For some regions in phase space, the soft pion is kicked out of the detector acceptance by the magnetic field

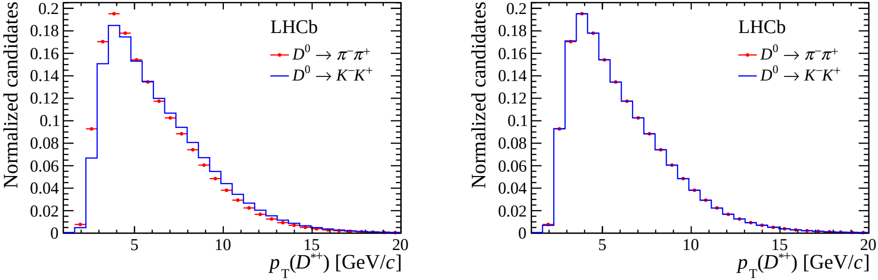




arXiv:1903.08726

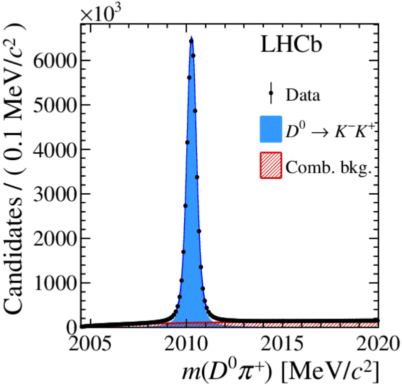
Kinematic Reweighting

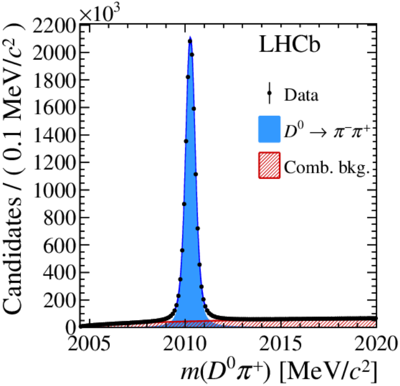
- The K^+K^- sample is corrected to match the $\pi^+\pi^-$ sample by a reweighting procedure



arXiv:1903.08726

Measurement of A_{raw}: π-tagged



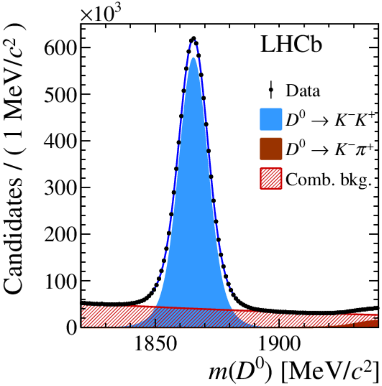


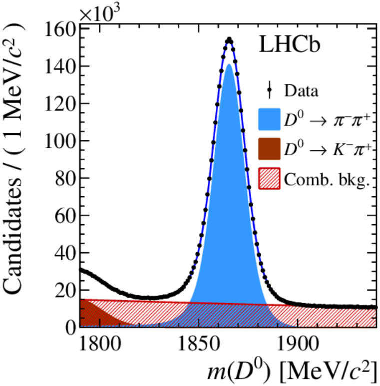
$D^0 \to K^+K^-$ yield: **44M**

$D^0 \to \pi^+\pi^-$ yield: **14M**

arXiv:1903.08726

Measurement of A_{raw}: μ-tagged





$D^0 \to K^+K^-$ yield: **9M**

$D^0 \to \pi^+\pi^-$ yield: **3M**

arXiv:1903.08726

ΔA_{CP}: Results

Run 2:

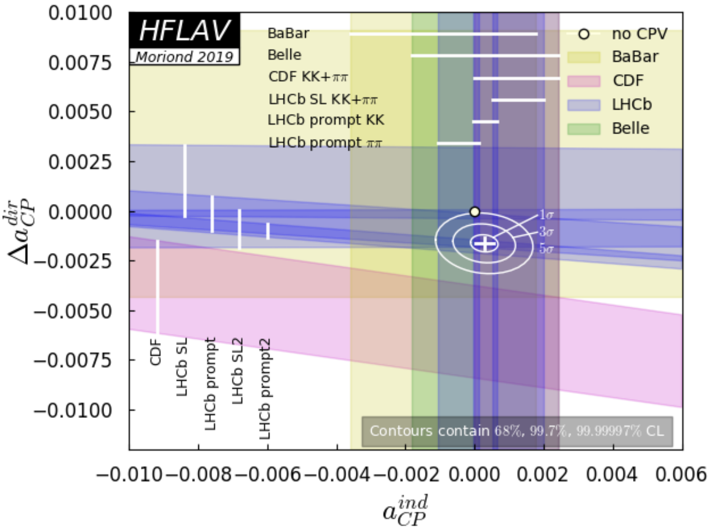
$$\Delta A_{CP}^{Prompt} = [-18.2 \pm 3.2(stat.) \pm 0.9(syst.)] \times 10^{-4}$$
$$\Delta A_{CP}^{SL} = [-9 \pm 8(stat.) \pm 5(syst.)] \times 10^{-4}$$

Combination with Run 1:

$$\boldsymbol{\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}}$$

CP violation observed in charm decays at $\mathbf{5.3\sigma}$

World Average



Search for CP violation in $D_s^+ \to K_s^0 \pi^+$, $D^+ \to K_s^0 K^+$ and $D^+ \to \phi\pi^+$ decays

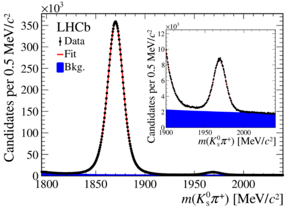
arXiv:1903.01150

Results:

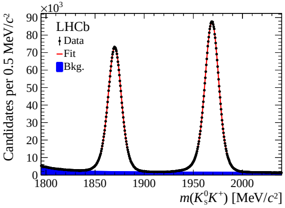
$$\mathcal{A}_{CP}(D_s^+ \to K_s^0 \pi^+) = (1.3 \pm 1.9 \pm 0.5) \times 10^{-3}$$

$$\mathcal{A}_{CP}(D^+ \to K_s^0 K^+) = (-0.09 \pm 0.65 \pm 0.48) \times 10^{-3}$$

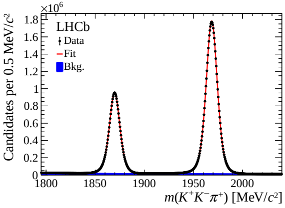
$$\mathcal{A}_{CP}(D^+ \to \phi\pi^+) = (0.05 \pm 0.42 \pm 0.29) \times 10^{-3}$$



$D_s^+ \to K_s^0 \pi^+$

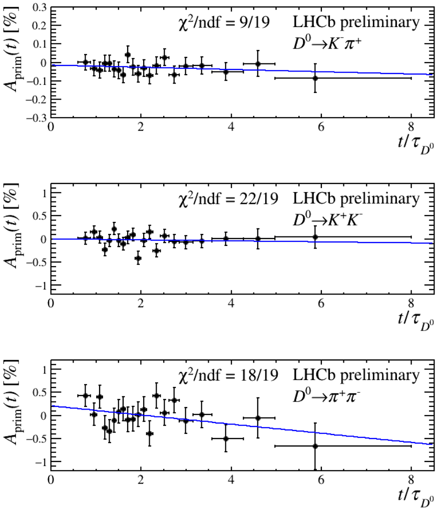


$D^+ \to K_s^0 K^+$



$D^+ \to \phi\pi^+$

Search for time-dependent CP violation in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays



$$A_{CP}(f) = A_{CP}^{decay}(f) - A_\Gamma(f)\frac{\langle t\rangle_f}{\tau_{D^0}}$$

$$\boldsymbol{A_\Gamma(K^+K^-) = (1.3 \pm 3.5 \pm 0.7) \times 10^{-4}}$$

$$\boldsymbol{A_\Gamma(\pi^+\pi^-) = (11.3 \pm 6.9 \pm 0.8) \times 10^{-4}}$$

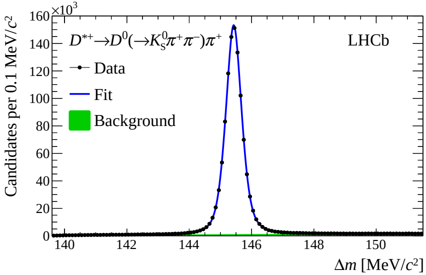
LHCb-CONF-2019-001

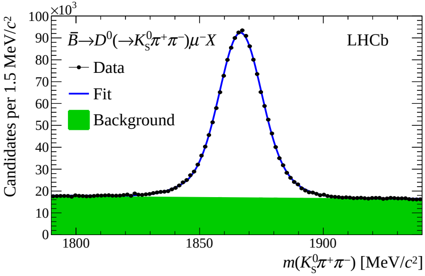
Measurement of the mass difference between neutral charm eigenstates

arXiv:1903.03074

Mixing in $D^0 \to K_s^0\pi^+\pi^-$

- $D^0 \to K_s^0\pi^+\pi^-$ has rich resonance structure
- Good sensitivity due to varying strong-phase differences
- Model-independent approach (bin-flip method) avoids modelling efficiency and dynamics of D^0 decay



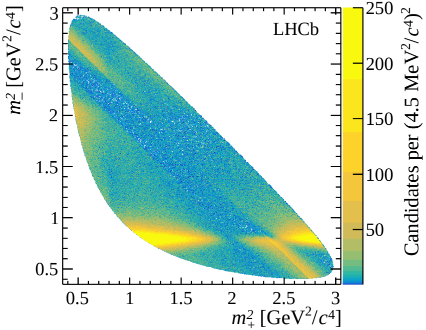


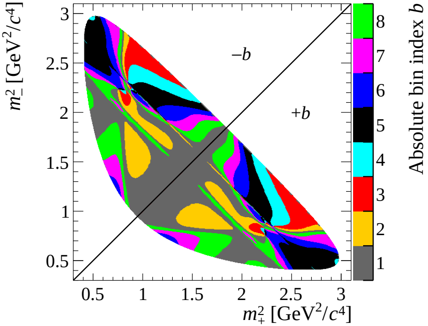
Prompt yield: **1.3M** Semi-leptonic yield: **1M**

Run 1 data: $\sim 3\text{fb}^{-1}$, arXiv:1903.03074

Bin-flip Method

- Data is binned in Dalitz coordinates where the binning scheme is chose to have approximately constant strong-phase differences
- Measure the yield ratio $R_{bj}^{\pm}$ between $-b$ and b in bins of decay time





Phys. Rev. D99 (2019) 012007, arXiv:1811.01032l

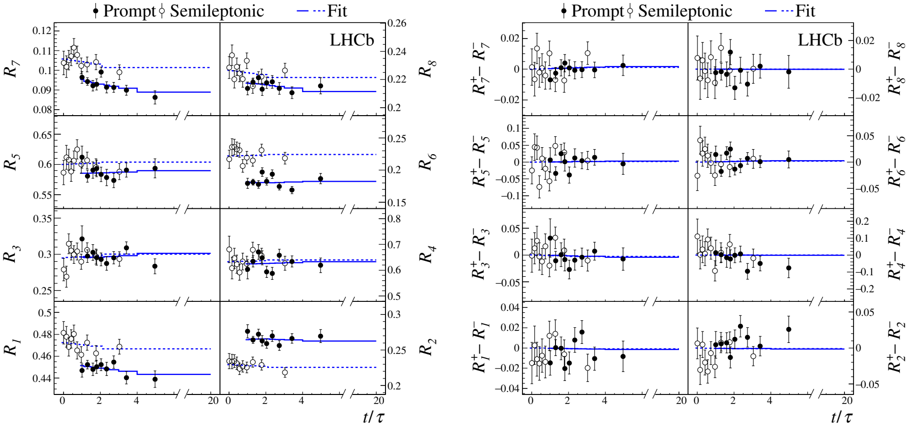
Bin-flip Method

For small mixing parameters and no CP Violation:

$$R_{bj}^{\pm} \approx \frac{r_b + \frac{1}{4} r_b \left\langle t^2 \right\rangle_j Re(z_{cp}^2 - \Delta z^2) + \frac{1}{4} \left\langle t^2 \right\rangle_j |z_{cp} \pm \Delta z|^2 + \sqrt{r_b} \left\langle t \right\rangle_j Re[X_b^*(z_{CP} \pm \Delta z)]}{1 + \frac{1}{4} \left\langle t^2 \right\rangle_j Re(z_{CP}^2 - \Delta z^2) + r_b \frac{1}{4} \left\langle t^2 \right\rangle_j |z_{CP} \pm \Delta z|^2 + \sqrt{r_b} \left\langle t \right\rangle_j Re[X_b(z_{CP} \pm \Delta z)]}$$

- $\langle t \rangle_j$: Average decay time of unmixed decays in bin j
- r_b: Ratio of signal yields in symmetric Dalitz bins $\pm b$ at $t = 0$
- X_b: Average strong phase difference in each bin
- z_{CP} and Δz: Obtained from a fit to $R_{bj}^{\pm}$ ratios in decay time

Fit Results



arXiv:1903.03074

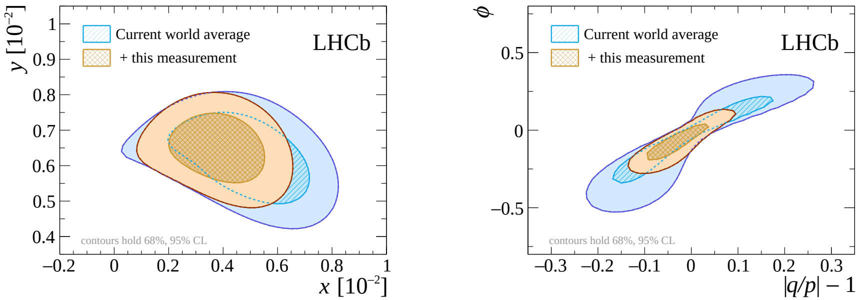
Results and impact on current world average

$$y_{CP} = [0.74 \pm 0.36(stat.) \pm 0.11(syst.)]\%$$

$$\Delta y = [-0.06 \pm 0.16(stat.) \pm 0.03(syst.)]\%$$

$$x_{CP} = [0.27 \pm 0.16(stat.) \pm 0.04(syst.)]\%$$

$$\Delta x = [-0.053 \pm 0.070(stat.) \pm 0.022(syst.)]\%$$



arXiv:1903.03074

Summary

- Measurements of CP violation is important for testing Standard Model predictions
- This is a promising area to look for new physics
- CP violation observed for the first time at LHCb with a significance of 5.3σ
- Several measurements still to be updated with the full Run 2 dataset

Backup Slides

Measurement of the charm-mixing parameter y_{CP}

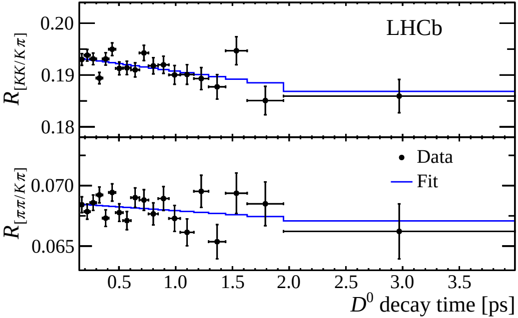
Phys. Rev. Lett. 122 (2019) 011802, arXiv:1810.06874

- Measurement of indirect CP Violation with $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$ and $D^0 \to K^-\pi^+$ decays with $\sim 3\text{fb}^{-1}$ data

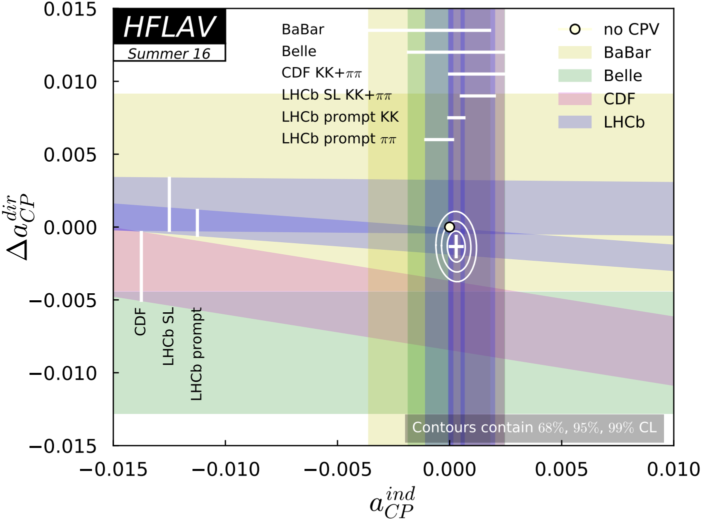
y_{CP} result:

$$y_{CP} = (0.57 \pm 0.13(stat.) \pm 0.09(syst.))\%$$

$$y_{CP} = \frac{\Gamma_{CP+}}{\Gamma} - 1$$



ΔA_{CP}: World Average



ΔA_{CP}: Selection

Selection

- D^0 decay vertex
- Quality and PID information of tracks
- p_T of tracks and D^0
- Angle between D^0 momentum and flight direction
- χ^2_{IP}: the difference between the χ^2 of the PV with and without the considered particle
- m_{corr} and $m(D^0\mu)$ for SL and $m(D^0)$ for Prompt
- SL sample further filtered with MVA

ΔA_{CP}: Semi-leptonic sample BDT input variables

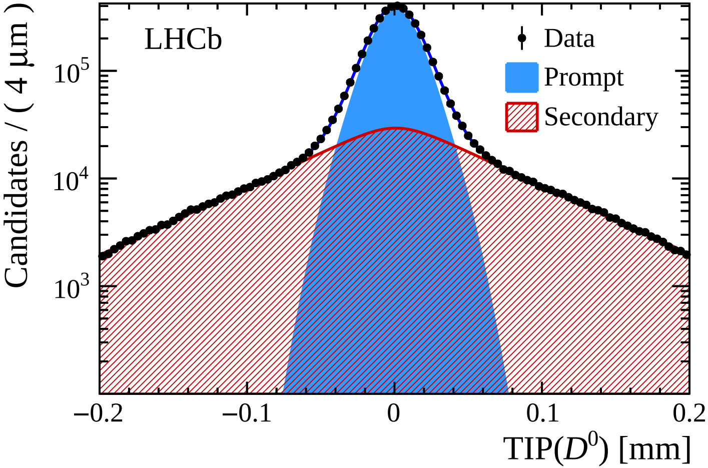
BDT Input Variables:

- Fit quality of D^0 and B decay vertices
- D^0 flight distance
- D^0 impact parameter: the minimum distance of its trajectory to the nearest primary vertex
- p_T of D^0 decay products
- Significance of the distance between the D^0 and B decay vertices
- Invariant mass $m(D^0\mu)$
- Corrected mass of B meson m_{corr}

ΔA_{CP}: Systematic Uncertainties

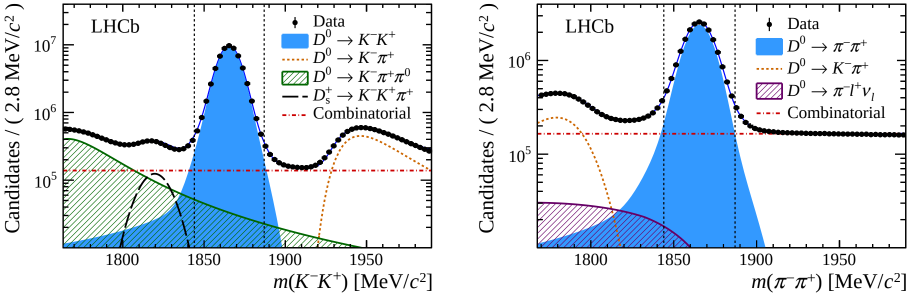
Source	π-tagged	μ-tagged
Fit model	0.6	2
Mistag	–	4
Weighting	0.2	1
Secondary decays	0.3	–
B fractions	–	1
B reco. efficiency	–	2
Peaking background	0.5	–
Total	0.9	5

ΔA_{CP}: Secondary charm decays in π-tagged sample



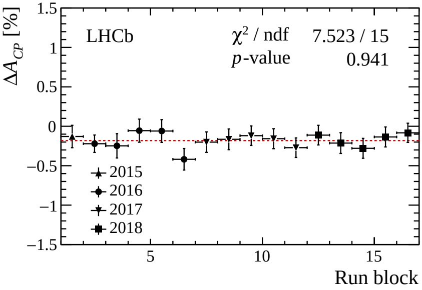
ΔA_{CP}: Peaking backgrounds

- Background components peaking in $m(D^0\pi)$ is estimated by measuring the yields of backgrounds in $m(D^0)$ distribution

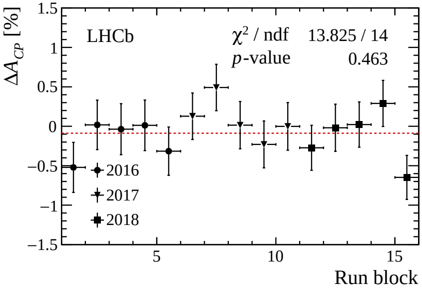


ΔA_{CP}: Crosschecks

- Measured value of ΔA_{CP} is studied as a function of several variables: data-taking period, D^0 impact parameter and decay time, π and μ impact parameter and transverse momentum

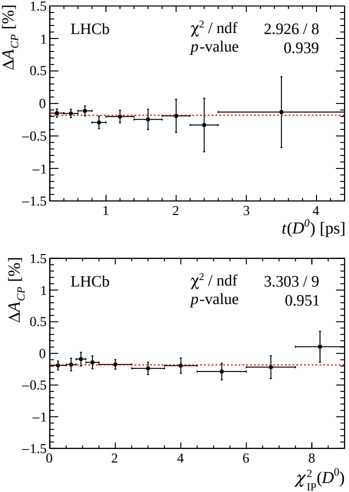


Prompt sample

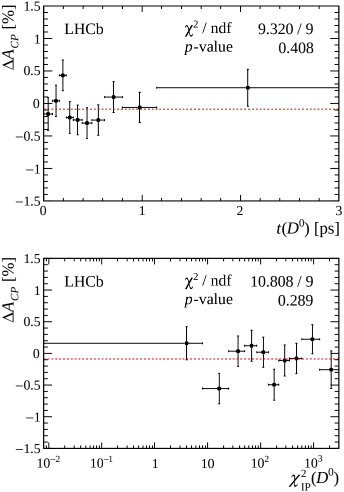


Semi-leptonic sample

Crosschecks: D^0 impact parameter and decay time

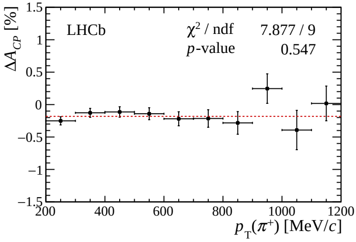


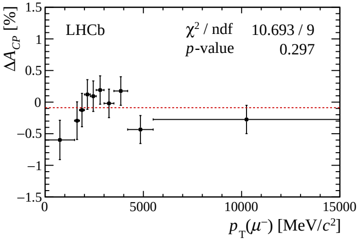
Prompt sample

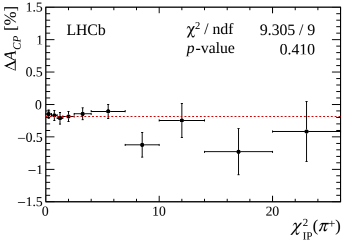


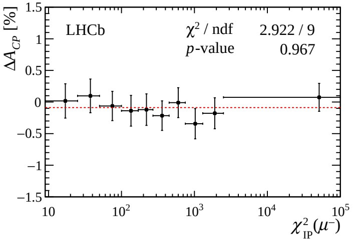
Semi-leptonic sample

Crosschecks: π and μ impact parameter and transverse momentum



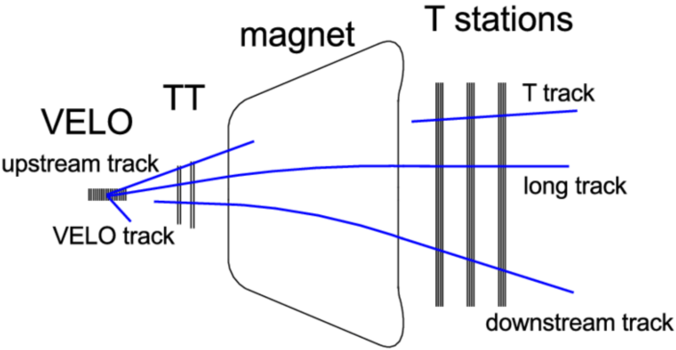




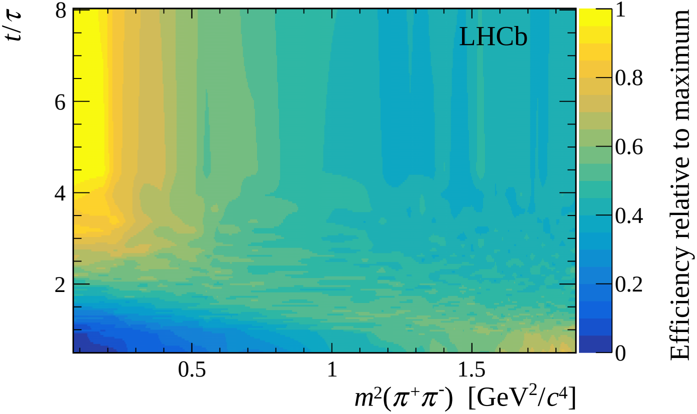


Data samples

For Prompt and Semi-leptonic samples, data is split into **LL** and **DD** K_s^0 type



Phase Space Efficiency



Smoothed efficiency distribution: $K_s^0(DD)$ Prompt candidates

Results: Mixing and CP Violation parameters

Mixing parameters:

$$x_{CP} \equiv -\mathrm{Im}(z_{CP}) \qquad y_{CP} \equiv -\mathrm{Re}(z_{CP})$$
$$\Delta x \equiv -\mathrm{Im}(\Delta z) \qquad \Delta y \equiv -\mathrm{Re}(\Delta z)$$

and in the limit of CP symmetry $x_{CP} = x$, $y_{CP} = y$ and $\Delta x = \Delta y = 0$

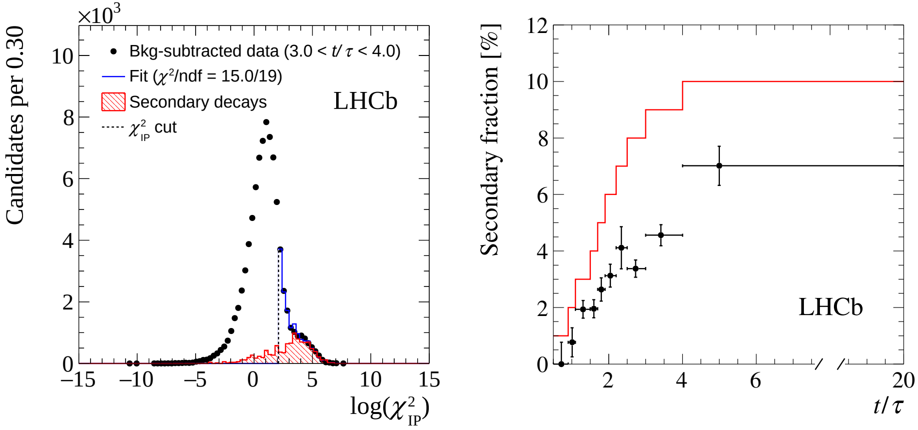
Parameter	Value	95.5% CL interval
x $[10^{-2}]$	$0.27\,^{+0.17}_{-0.15}$	$[-0.05, 0.60]$
y $[10^{-2}]$	0.74 ± 0.37	$[\ \ 0.00, 1.50]$
$\lvert q/p \rvert$	$1.05\,^{+0.22}_{-0.17}$	$[\ \ 0.55, 2.15]$
ϕ	$-0.09\,^{+0.11}_{-0.16}$	$[-0.73, 0.29]$

Fit results and correlations

Parameter	Value $[10^{-3}]$	Stat. correlations			Syst. correlations		
		y_{CP}	Δx	Δy	y_{CP}	Δx	Δy
x_{CP}	$2.7 \pm 1.6 \pm 0.4$	-0.17	0.04	-0.02	0.15	0.01	-0.02
y_{CP}	$7.4 \pm 3.6 \pm 1.1$		-0.03	0.01		-0.05	-0.03
Δx	$-0.53 \pm 0.70 \pm 0.22$			-0.13			0.14
Δy	$0.6 \pm 1.6 \pm 0.3$						

Fit results. The first contribution to the uncertainty is statistical, the second systematic.

Systematic uncertainties: Secondary contamination



(Left) Fit to distribution of $D^0 \log(\chi^2_{IP})$ for Prompt candidates. (Right) Fraction of secondary D^* decays as a function of decay time.