Charm CP violation and mixing at LHCb

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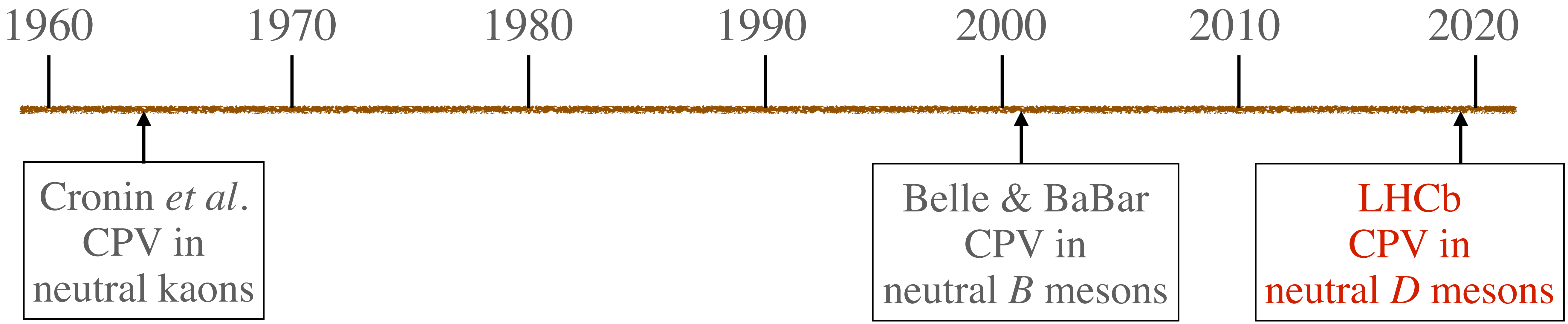
on behalf of the LHCb collaboration

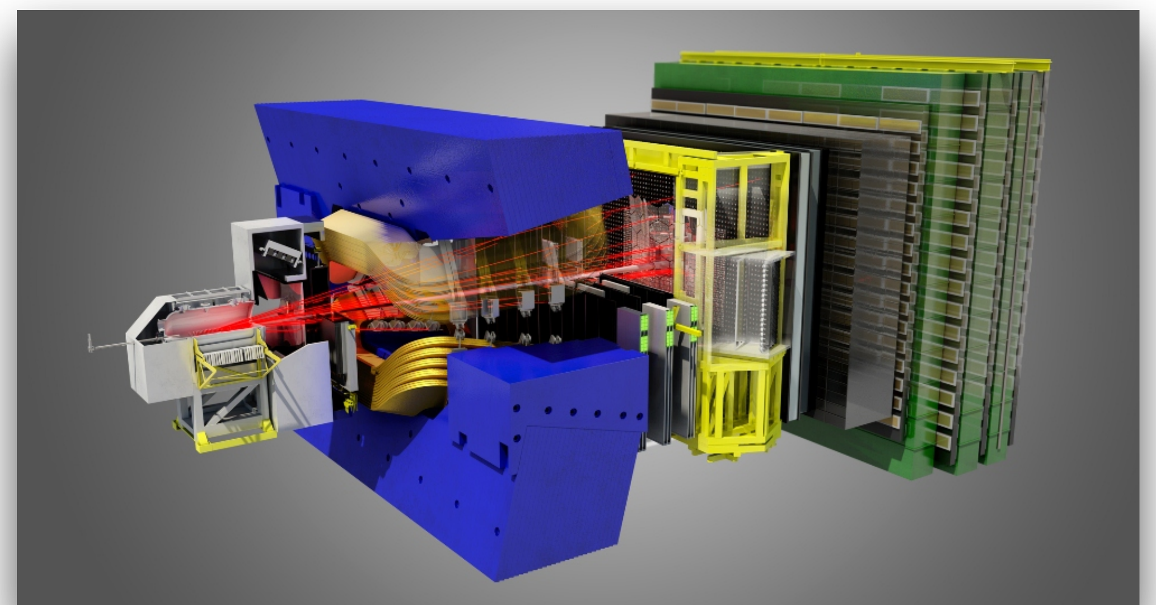
5th Colombian Meeting on High Energy Physics

First observation of CP violation in charm

PRL 122, 211803 (2019)

CP violation timeline





LHCb is a flavour factory:

$$\sigma(pp \to c\bar{c}X) = (2940 \pm 3 \pm 180 \pm 160)\ \mu\text{b}$$

for $p_T < 8$ GeV, $2 < \eta < 4.5$, $\sqrt{s} = 13$ TeV

JHEP 03 (2016) 159

$$\frac{\sigma_{c\bar{c}}}{\sigma_{\text{in}}} \sim \frac{1}{20} \ : \ \mathcal{O}(10^9) \text{ reconstructed } D \text{ decays}$$

JHEP 06 (2018) 100

Analysis combine Run 1 + Run 2 data sets $\longrightarrow \int \mathcal{L} \sim 9\ \text{fb}^{-1}$

The smallness of mixing and CPV in charm

Heavy mesons decays are described by effective Hamiltonians. For charm,

$$\mathcal{H}_{\rm eff} = \frac{G_F}{\sqrt{2}}\left(\lambda_d[C_1(\mu)Q_1^d + C_2(\mu)Q_2^d] + \lambda_s[C_1(\mu)Q_1^s + C_2(\mu)Q_2^s] + \lambda_b\sum_{i>2}C_i(\mu)Q_i\right)$$

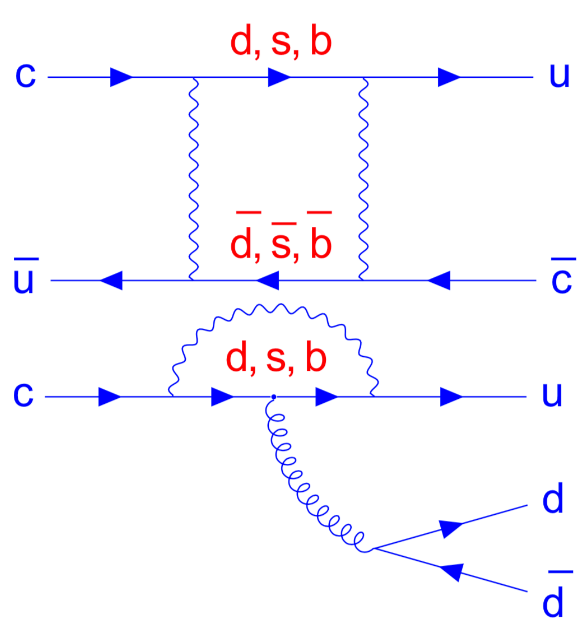
with $\lambda_q = V_{cq}V_{uq}^*$ and $\lambda_d = -0.21874 - i\,2.5\times10^{-5},\ \lambda_b = -1.5\times10^{-4} + i\,2.64\times10^{-5}$

$$\lambda_s = +0.21890 - i\,0.13\times10^{-5}$$

Assuming unitarity of CKM matrix: $\lambda_d + \lambda_s + \lambda_b = 0 \longrightarrow \lambda_d + \lambda_s \approx 0$

Mixing and CPV involves loops, which depend on the quantity $R_q \equiv \left(\frac{m_q}{M_W}\right)^2$

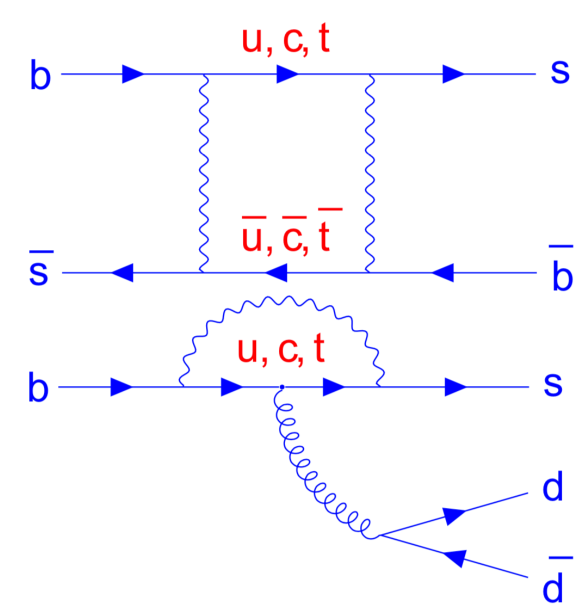
Wilkinson and Lenz, arXiv:2011.04443



$R_d \approx 0$

$R_s \approx 1.3\times10^{-6}$

$R_b \approx 2.8\times10^{-3}$



$R_u \approx 0$

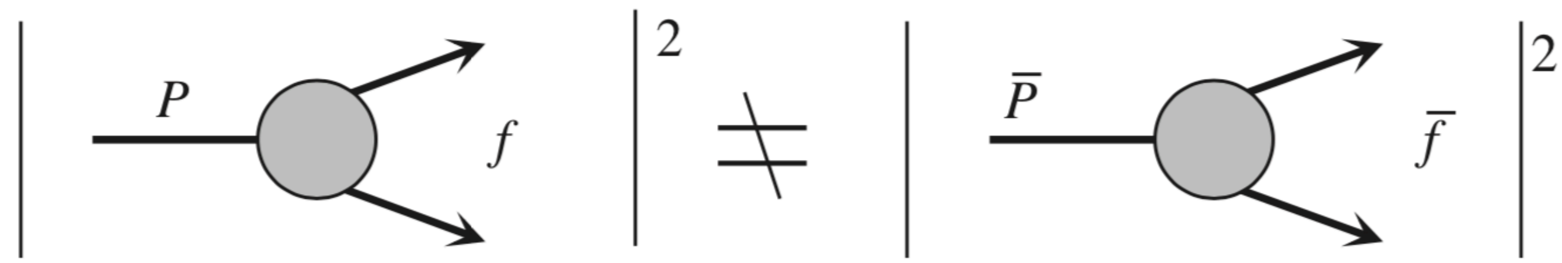
$R_c \approx 2.5\times10^{-4}$

$R_t \approx 4.5$

Severe GIM cancellation in the charm sector!

Direct CP violation

In this analysis:
$f = K^- K^+,\ \pi^- \pi^+$



Time-dependent CP asymmetry between states produced as a D^0 or $\overline{D}^0$

$$\mathcal{A}_{CP}(f;t) \equiv \frac{\Gamma(D^0(t) \to f) - \Gamma(\overline{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\overline{D}^0(t) \to f)}$$

The time-integrated asymmetry, to first order in $D^0 - \overline{D}^0$ mixing

$$\mathcal{A}_{CP}(f) \simeq a_{CP}^{\rm dir}(f) - A_{\Gamma}(f) \frac{\langle t(f) \rangle}{\tau(D^0)}$$

mean decay time

Assuming A_{Γ} to be independent of the final state

$$\Delta \mathcal{A}_{CP} \equiv \mathcal{A}_{CP}(K^+K^-) - \mathcal{A}_{CP}(\pi^+\pi^-)$$

$$\approx \Delta a_{CP}^{\rm dir} - A_{\Gamma} \frac{\Delta \langle t \rangle}{\tau(D^0)}$$

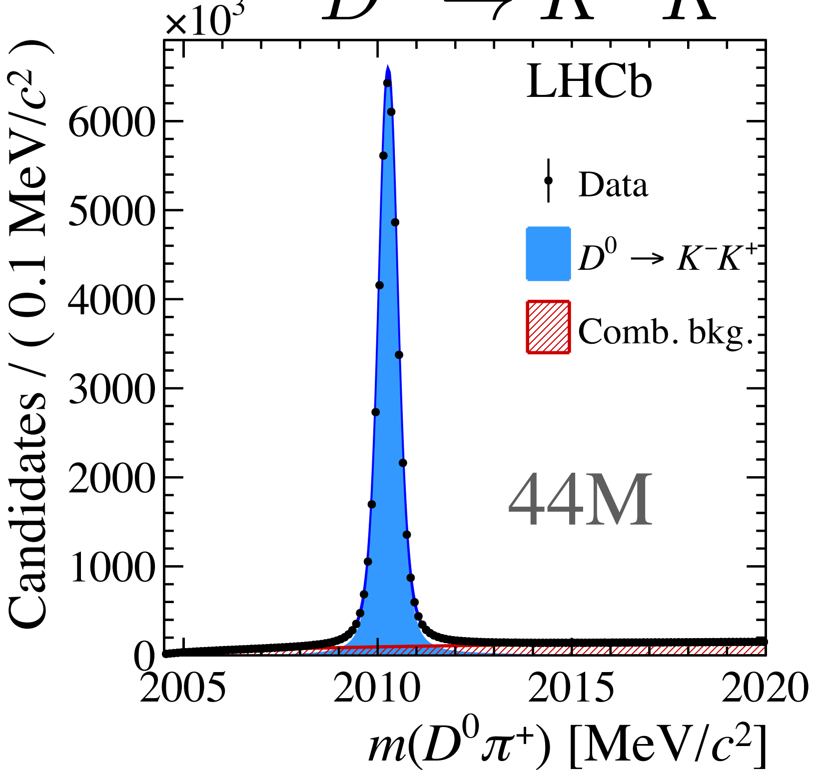
U-spin: CP asymmetries expected to have opposite signs

PLB 492 (2000) 297

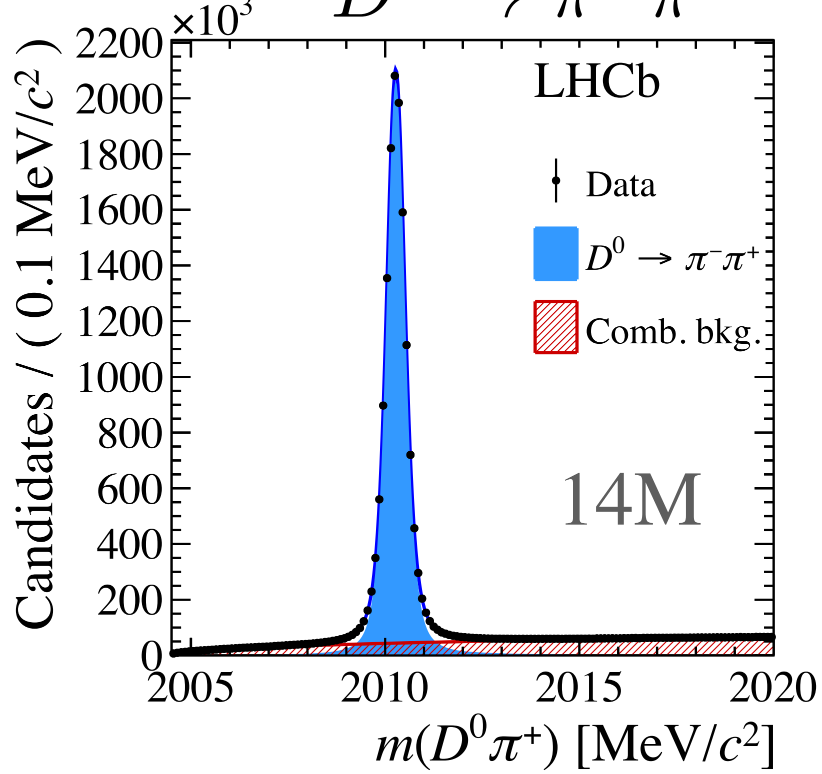
$$\Delta a_{CP}^{\rm dir} \equiv a_{CP}^{\rm dir}(K^+K^-) - a_{CP}^{\rm dir}(\pi^+\pi^-)$$

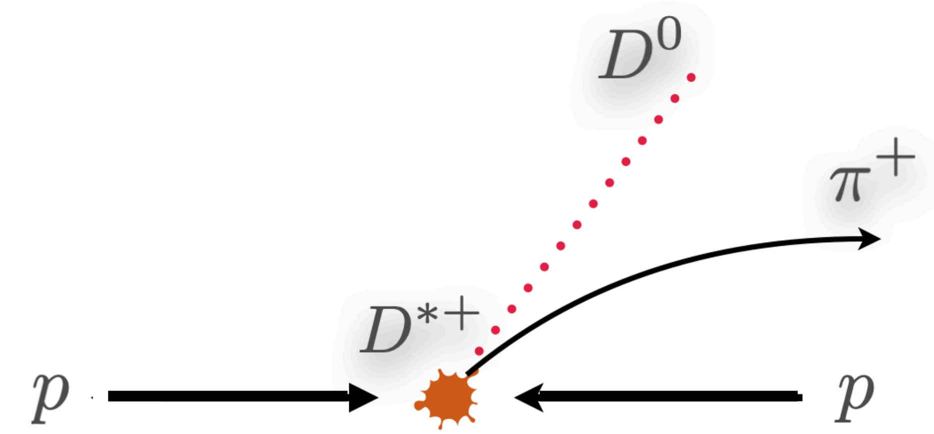
Two independent data sets (Run 2 data, 5.9 fb^{-1} @ 13 TeV)

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

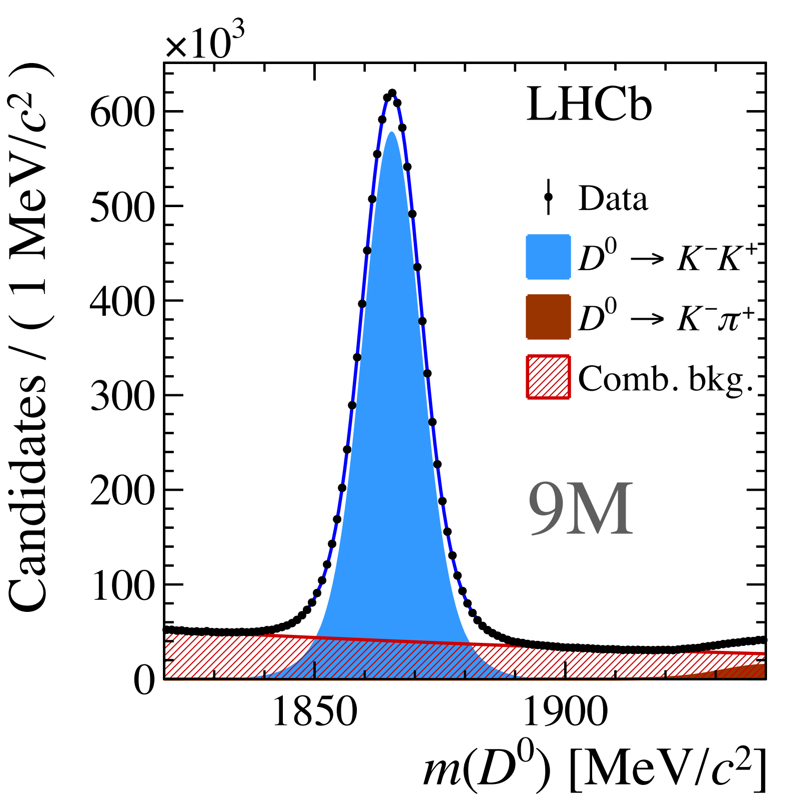


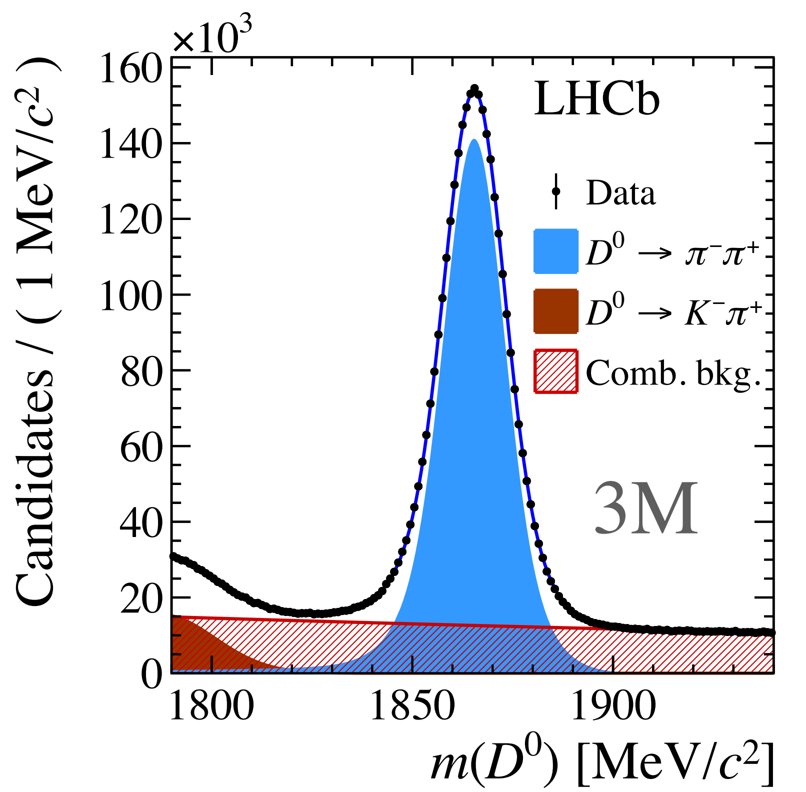
$D^0 \to \pi^-\pi^+$



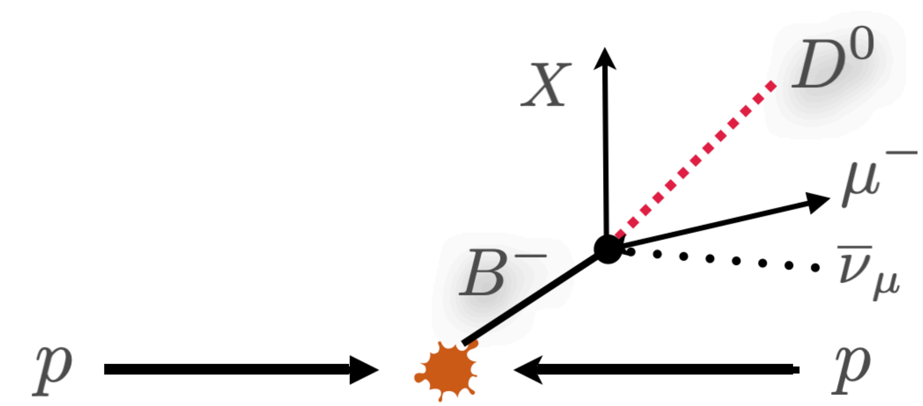


$D^{*+} \to D^0\pi^+$





$B^- \to D^0\mu^-\overline{\nu}_\mu X$



PRL **122**, 211803

The measured quantities are the charge asymmetries

$$A_{\rm raw}^{\pi-\rm tag}(f) \equiv \frac{N(D^{*+} \to D^0(f)\pi^+) - N(D^{*-} \to \overline{D}^0(f)\pi^-)}{N(D^{*+} \to D^0(f)\pi^+) + N(D^{*-} \to \overline{D}^0(f)\pi^-)}$$

$$A_{\rm raw}^{\mu-\rm tag}(f) \equiv \frac{N(\overline{B} \to D^0(f)\mu^- X) - N(B \to \overline{D}^0(f)\mu^+ X)}{N(\overline{B} \to D^0(f)\mu^- X) + N(B \to \overline{D}^0(f)\mu^+ X)}$$

Asymmetries in production and detection efficiencies are small:

$$A_{\rm raw}^{\pi-\rm tag}(f) \approx \mathcal{A}_{CP}(f) + A_D(\pi) + A_P(D^*)$$

$$A_{\rm raw}^{\mu-\rm tag}(f) \approx \mathcal{A}_{CP}(f) + A_D(\mu) + A_P(B)$$

Reweighting procedure matches kinematics of both final states and ensures cancellation of nuisance asymmetries

$$A_{\rm raw}(KK) - A_{\rm raw}(\pi\pi) = (\mathcal{A}_{CP}(KK) + A_D(\text{tag}) + \text{A}_\text{P}) - (\mathcal{A}_{CP}(\pi\pi) + A_D(\text{tag}) + \text{A}_\text{P})$$

$$A_{\rm raw}(KK) - A_{\rm raw}(\pi\pi) = \mathcal{A}_{CP}(KK) - \mathcal{A}_{CP}(\pi\pi)$$

Results

Systematic uncertainties (x 10^{-4})

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

$$\Delta\mathcal{A}_{CP}^{\pi-\text{tag}} = (-18.2 \pm 3.2 \pm 0.9) \times 10^{-4}$$

$$\Delta\mathcal{A}_{CP}^{\mu-\text{tag}} = (-9 \pm 8 \pm 5) \times 10^{-4}$$

Combining results from the two samples and from Run 1,

$$\Delta\mathcal{A}_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

First observation of CP violation in charm - 5.3σ

Results

This analysis:

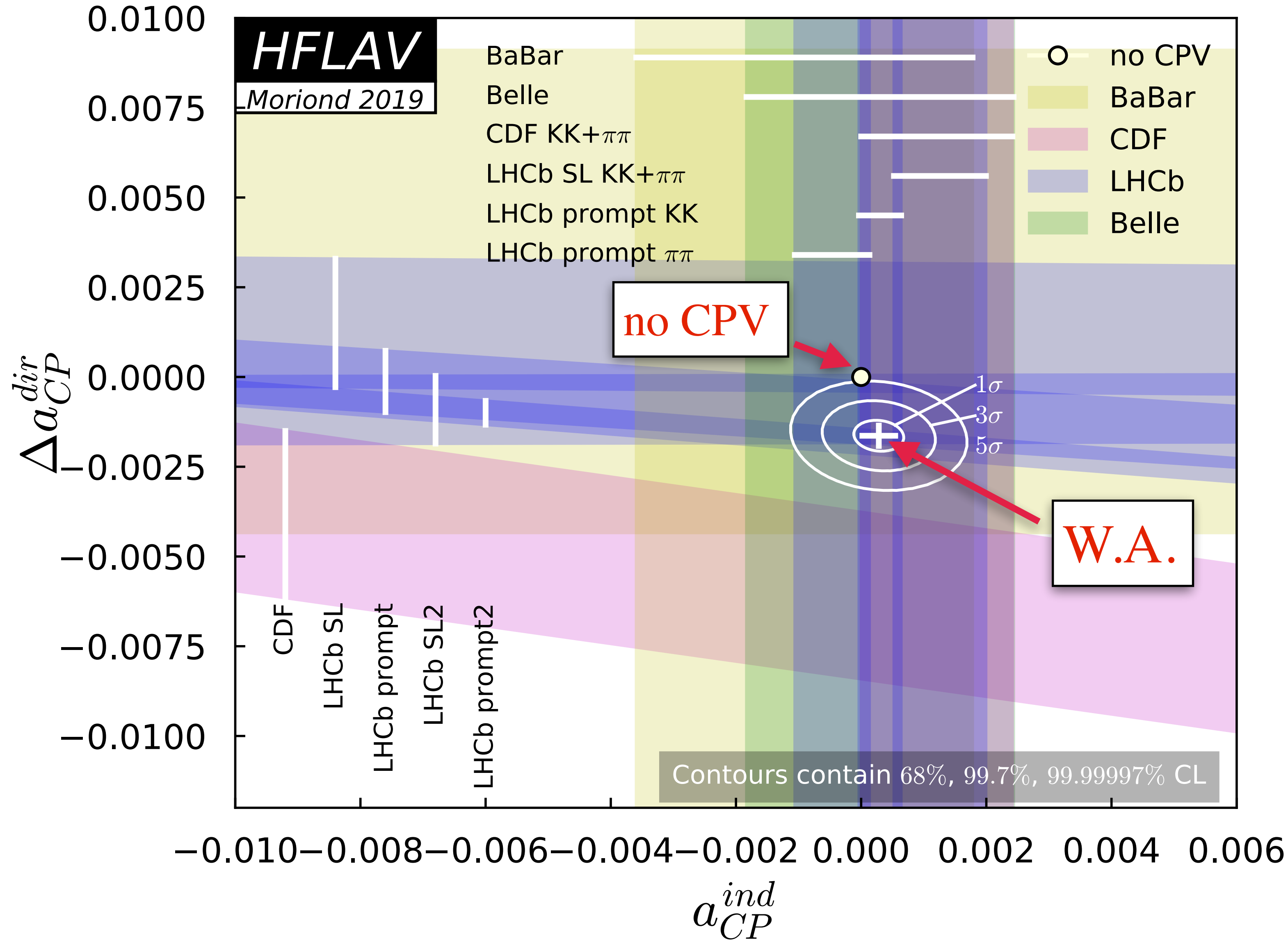
$$\frac{\Delta\langle t\rangle^{\pi-\mathrm{tag}}}{\tau(D^0)} = 0.135 \pm 0.002$$

$$\frac{\Delta\langle t\rangle^{\mu-\mathrm{tag}}}{\tau(D^0)} = 0.003 \pm 0.001$$

LHCb average:

$$A_\Gamma = (-2.8 \pm 2.8) \times 10^{-4}$$

JHEP 04 (2015) 043, PRL 118, 261803 (2017)



$$\Delta a_{CP}^{\mathrm{dir}} = (-15.7 \pm 2.9) \times 10^{-4}$$

SM predictions in the range $10^{-3} - 10^{-4}$

further measurements and theoretical improvements needed for a correct interpretation of CPV in charm.

CP violation search in

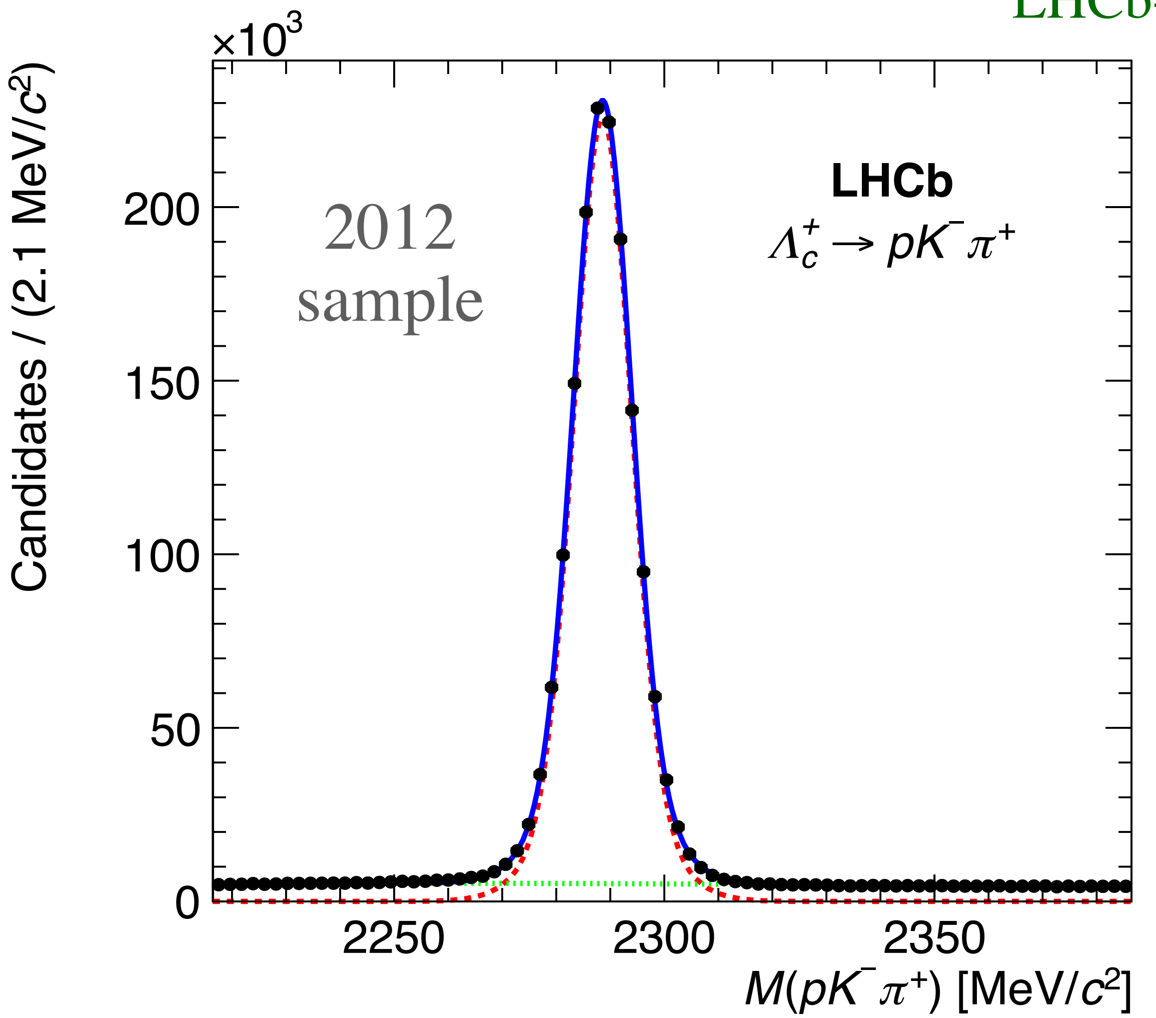
$$\Xi_c^+ \to pK^-\pi^+$$

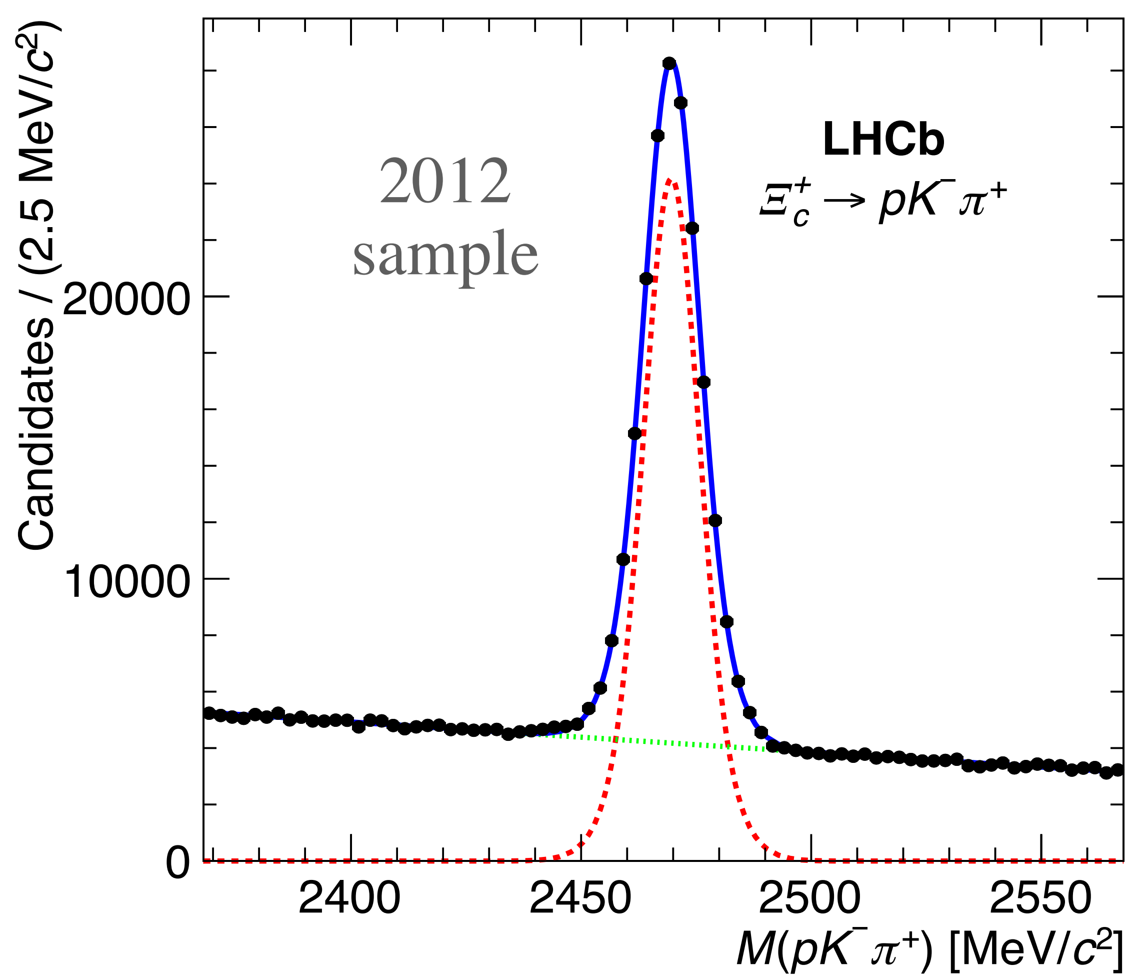
LHCb-PAPER-2019-026

arXiv:2006.03145

- Analysis based on Run 1 data (~3 fb^{-1} @ 7 and 8 TeV)
- Direct comparison between Ξ_c^- and Ξ_c^+ Dalitz plots (total yield ~ 190k) using two model-independent techniques
- Procedures tested on control channel $\Lambda_c^+ \to pK^-\pi^+$ (total yield ~ 1.9M) before applied to the signal

LHCb-PAPER-2019-026 (arXiv:2006.03145)





Binned method

- Dalitz plot divided into bins; for each bin compute the observable

$$\mathcal{S}^i_{CP} = \frac{n^i_+ - \alpha n^i_-}{\sqrt{\alpha(n^i_+ + n^i_-)}} \; , \quad \alpha = \frac{n^i_+}{n^i_-}$$: accounts for global asymmetries

- A p-value from $\chi^2 \equiv \sum(\mathcal{S}^i_{CP})^2$: test if Ξ^-_c and Ξ^+_c are statistically compatible

Unbinned method (kNN)

- Dalitz plot divided into regions around expected resonances. In each region compute the test statistic

$$T = \frac{1}{n_k(n_+ + n_-)} \sum_{i=1}^{n_+ + n_-} \sum_{k=1}^{n_k} I(i,k) \qquad (n_k = 50 \text{ in this analysis})$$

$I(i,k)$ = 1 if the i^{th} candidate and its k^{th} nearest neighbour have the same charge

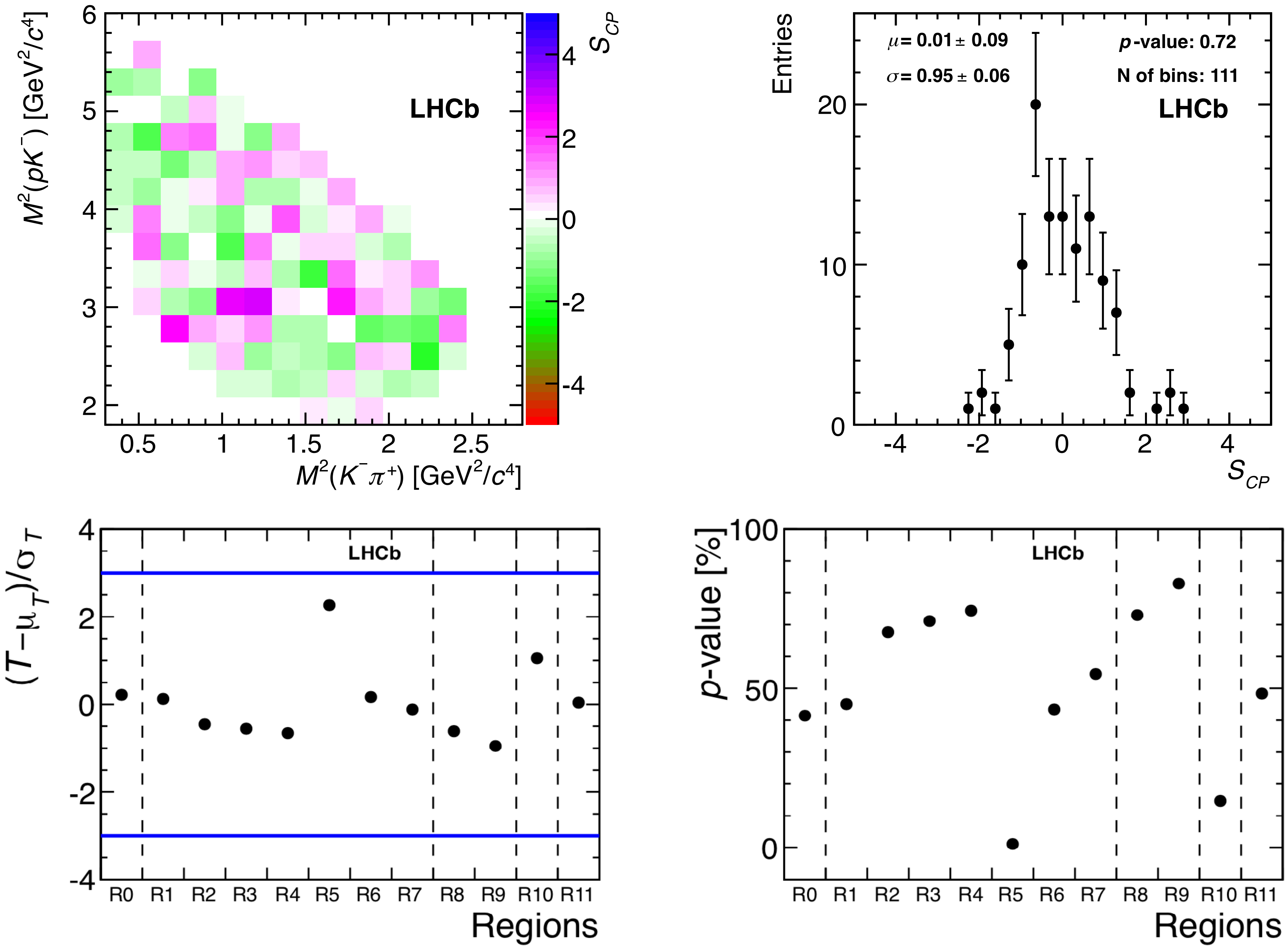
- For two statistically compatible samples, the distribution of T follows a normal distribution with known mean and width, (μ_T, σ_T)

- Compare T distribution with that for null CPV hypothesis

Results

CPV would be established with *p*-values < 3 x 10^{-7} (5σ)

LHCb-PAPER-2019-026 (arXiv:2006.03145)



large *p*-values

No evidence of CP violation

Measurement of the mass difference between neutral D mesons

PRL **122**, 231802 (2019)

Flavoured neutral-meson systems have both virtual and real transitions common to particle and antiparticle $\longrightarrow$ mixing

Mass eigenstates are linear combination of states with definite flavour $$|D_{1,2}\rangle \equiv p|D^0\rangle \pm q|\overline{D}^0\rangle$$

Mixing is governed by four parameters $$x \equiv \frac{m_1 - m_2}{\Gamma}, \quad y \equiv \frac{\Gamma_1 - \Gamma_2}{2\Gamma}, \quad \left|\frac{q}{p}\right|, \quad \phi_f \equiv \arg\left(\frac{q\overline{A}_f}{pA_f}\right)$$

The most sensitive mode for measuring mixing parameters is $D^0 \to K^0_S\pi^-\pi^+$

Direct CP violation is not expected in Cabibbo-favoured decays: $\phi_f \to \phi$

$$A_\Gamma = \underbrace{(|q/p| - |p/q|)}\, y\cos\phi - (|q/p| + |p/q|)\,\underbrace{x\sin\phi}$$

CPV in mixing: $|q/p| \neq 1$ CPV in interference: $\phi \neq 0$

A transformation of variables increases the sensitivity to q/p :

$$z \equiv -(y - ix)\,,\ (q/p)^{\pm}z \equiv z \pm \Delta z$$

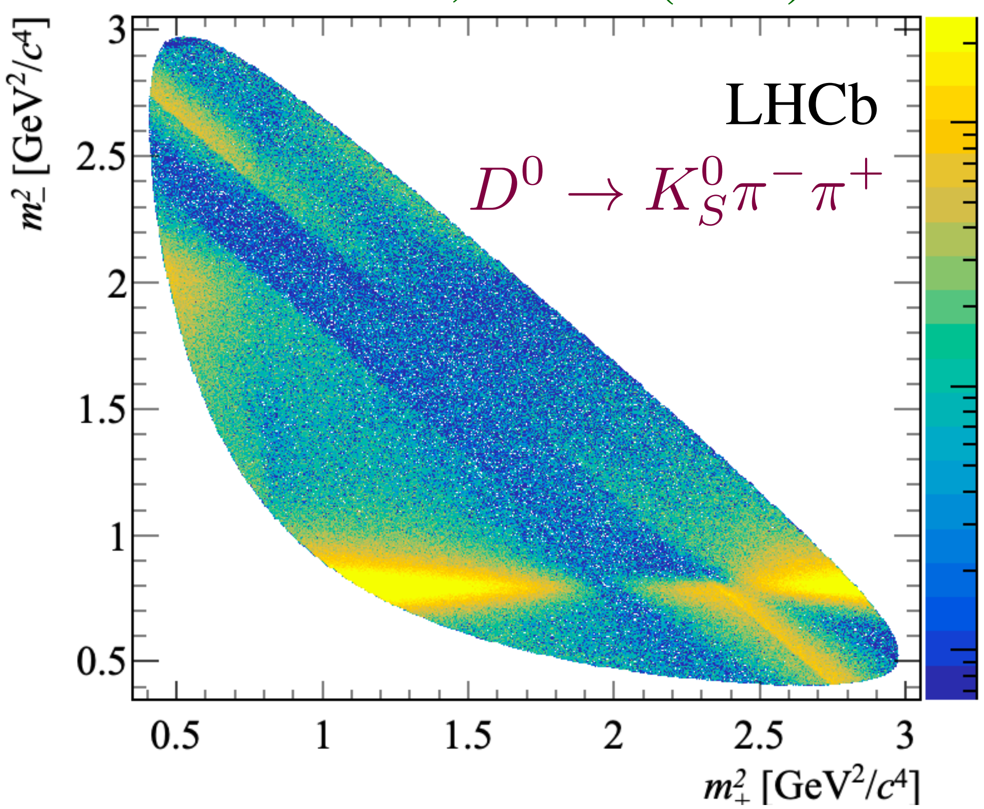
$$x,\ y,\ (q/p), \phi \longrightarrow x_{CP},\ y_{CP},\ \underbrace{\Delta x,\ \Delta y}$$

CP violating parameters

The bin-flip method

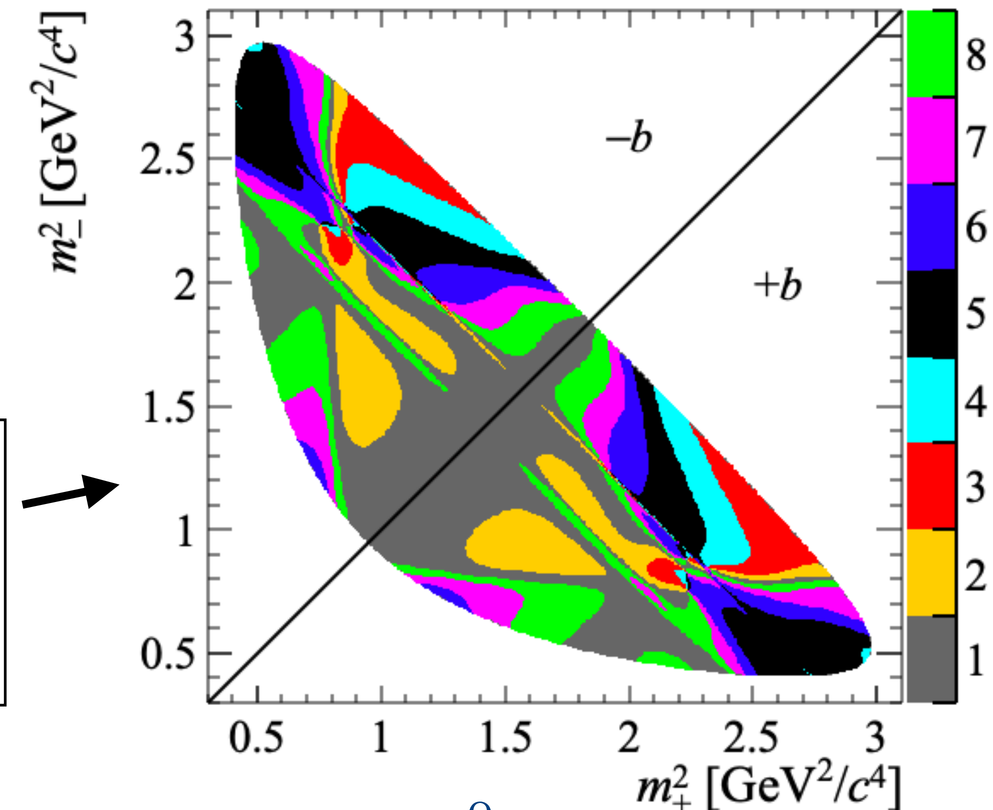
PRD **99**, 012007 (2019)

PRL **122**, 231802 (2019)



Similar Dalitz plot for $\overline{D}^0 \to K_S^0\pi^+\pi^-$ with $m_+ \to m_-$

16 bins symmetric about principal bisector $m_+^2 = m_-^2$



$$m_\pm^2 \equiv m^2(K_S^0\pi^\pm) \text{ for } D^0,\ m^2(K_S^0\pi^\mp) \text{ for } \overline{D}^0$$

- Dataset divided into bins of decay time; Dalitz plot divided into bins of nearly constant strong-phase difference between D^0 and $\overline{D}^0$ decay amplitudes
- In each decay time and Dalitz plot bin, fit the $D^0$and $\overline{D}^0$ invariant-mass distributions
- The mixing parameters are obtained from the ratios (details in backup slides)

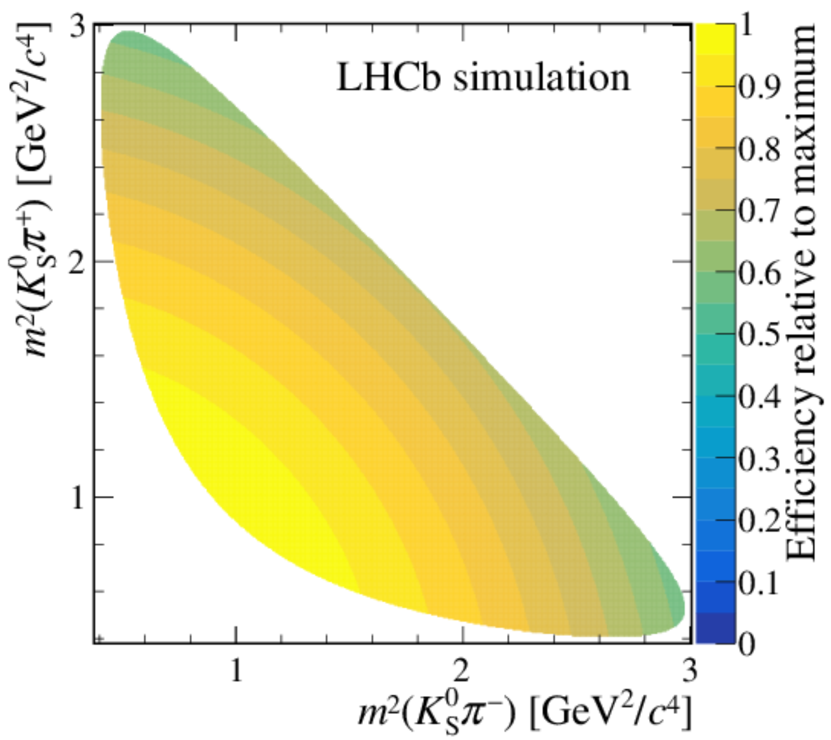
$$R_b(t_j) = \frac{N_{-b}(t_j)}{N_b(t_j)}, \quad \overline{R}_b(t_j) = \frac{\overline{N}_{-b}(t_j)}{\overline{N}_b(t_j)}$$

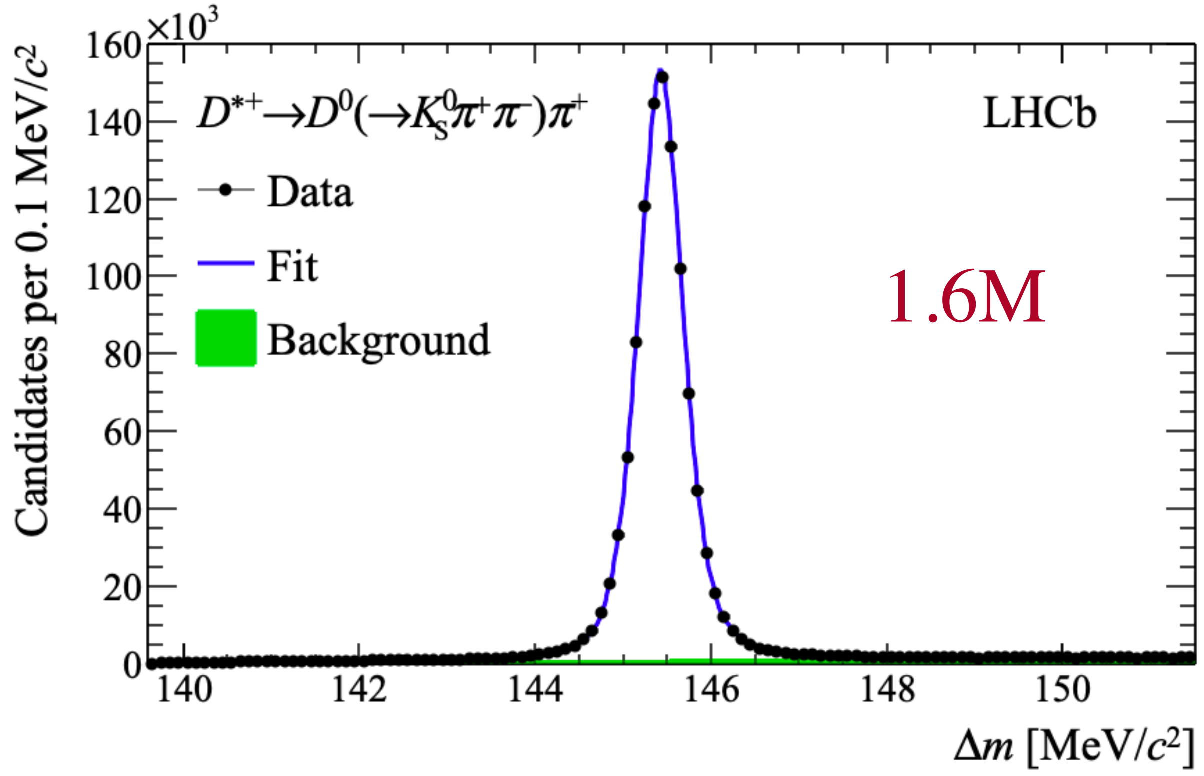
- Analysis based on Run 1 dataset (Run 2 results to appear soon)

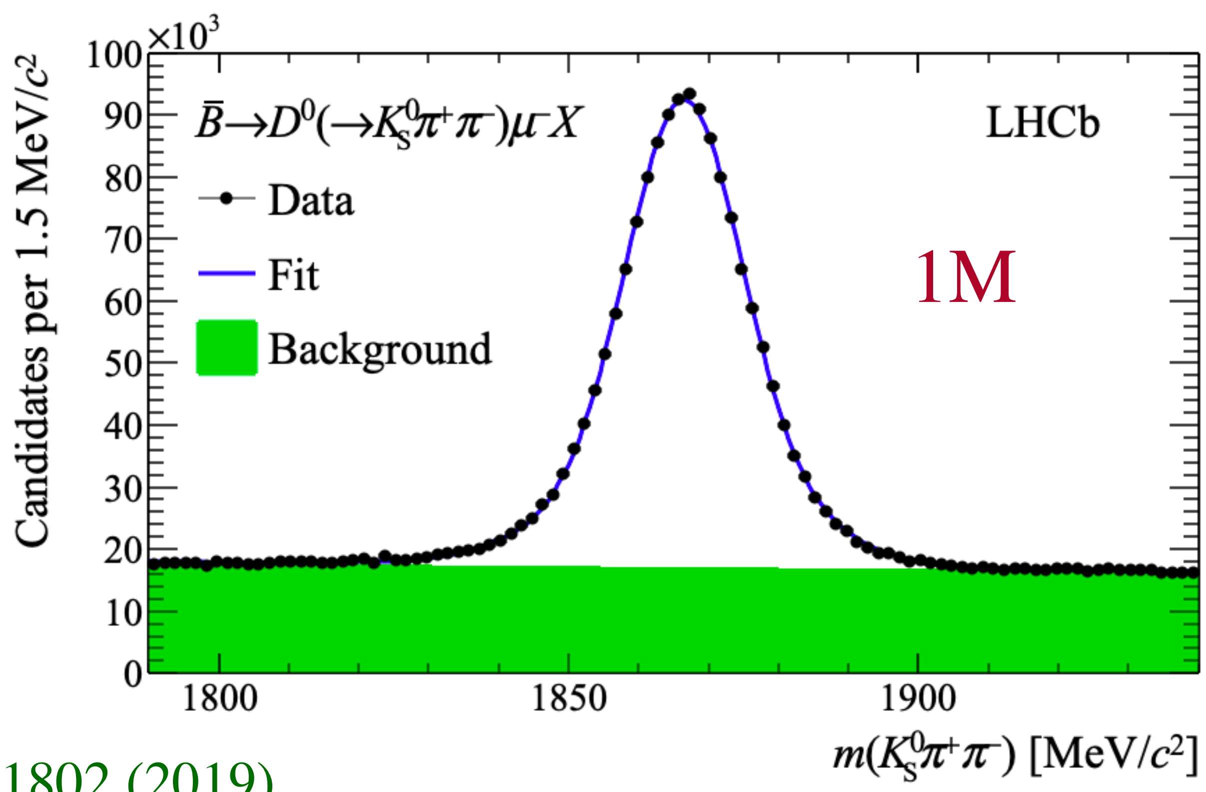
- Two independent samples:
  $D^{*+} \to D^0(\to K_S^0\pi^-\pi^+)\pi^+$ (2 fb-1)
  $\overline{B} \to D^0(\to K_S^0\pi^-\pi^+)\mu^- X$ (3 fb-1)

- Strong-phase differences are external input from CLEO PRD **82**, 112006 (2010)

- Symmetric efficiency variation across the Dalitz plot for both samples







PRL **122**, 231802 (2019)

Results

PRL **122**, 231802 (2019)

The measured quantities are:

$$x_{CP} = -\mathrm{Im}(z_{CP}) = \frac{1}{2}\left[x\cos\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) + y\sin\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\right]$$

$$\Delta x = -\mathrm{Im}(\Delta z) = \frac{1}{2}\left[x\cos\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) + y\sin\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\right]$$

$$y_{CP} = -\mathrm{Re}(z_{CP}) = \frac{1}{2}\left[y\cos\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) - x\sin\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\right]$$

$$\Delta y = A_\Gamma = -\mathrm{Re}(\Delta z) = \frac{1}{2}\left[y\cos\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) - x\sin\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\right]$$

Systematic uncertainties dominated by CLEO input, D^0 from B decays (prompt), and unrelated μD^0 combinations (semileptonic)

Values $[10^{-3}]$

$x_{CP} = 2.7 \pm 1.7 \pm 0.4$	$\Delta x = -0.53 \pm 0.70 \pm 0.22$
$y_{CP} = 7.4 \pm 3.6 \pm 1.1$	$\Delta y = 0.6 \pm 1.6 \pm 0.3$

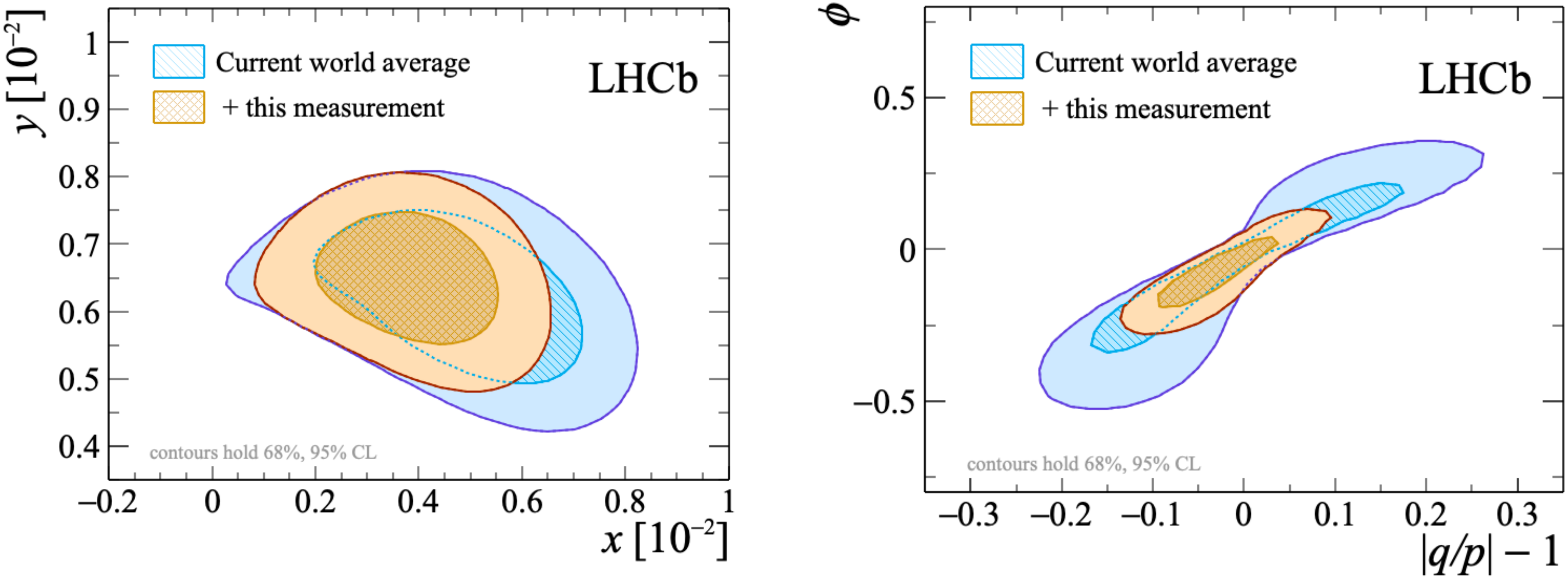
No evidence for indirect CPV

Results

A likelihood is formed to yield the usual mixing parameters:

$$x = (0.27^{+0.17}_{-0.15}) \times 10^{-2} \qquad |q/p| = 1.05^{+0.22}_{-0.17}$$

$$y = (0.74 \pm 0.37) \times 10^{-2} \qquad \phi = -0.09^{+0.11}_{-0.16}\ \text{rad}$$



PRL **122**, 231802 (2019)

HFLAV average:

$$x = (0.37 \pm 0.12) \times 10^{-2} \longrightarrow x = 0 \quad \text{excluded by } 2.96\sigma$$

https://hflav-eos.web.cern.ch/hflav-eos/charm/ICHEP20/results_mix_cpv.html

Time-dependent CP asymmetries in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$

PRD 101, 012005 (2020)

Mixing-induced CP violation has not been observed in charm yet

The time evolution of an initially pure beam of $D^0(\overline{D}^0)$ decaying to a final state f

$$\Gamma(D^0(t) \to f) = e^{-\Gamma t}|A_f|^2\,[1 - |q/p|(y\cos\phi_f - x\sin\phi_f)\Gamma t]$$

$$\Gamma(\overline{D}^0(t) \to f) = e^{-\Gamma t}|\overline{A}_f|^2\,[1 - |p/q|(y\cos\phi_f + x\sin\phi_f)\Gamma t]$$

for $xt,\ yt \lesssim \Gamma^{-1}$ and with the usual definitions $x \equiv \dfrac{\Delta m}{\Gamma}, \quad y \equiv \dfrac{\Delta\Gamma}{2\Gamma}$

The effective rates, due to the smallness of x and y

$$\hat{\Gamma}(D^0 \to f) = \Gamma[1 + |q/p|(y\cos\phi_f - x\sin\phi_f)]$$

$$\hat{\Gamma}(\overline{D}^0 \to f) = \Gamma[1 + |p/q|(y\cos\phi_f + x\sin\phi_f)]$$

The asymmetry between effective decay rates is sensitive to indirect CP violation

$$A_\Gamma(f) \equiv \frac{\hat{\Gamma}(D^0 \to f) - \hat{\Gamma}(\overline{D}^0 \to f)}{\hat{\Gamma}(D^0 \to f) + \hat{\Gamma}(\overline{D}^0 \to f)} \approx x\phi_f + y(|q/p| - 1) - \underbrace{y a_{CP}^{\text{dir}}(f)}_{\mathcal{O}(10^{-5})}$$

The measured quantity is the time-dependent charge asymmetry

$$A_{\rm raw}(D^0 \to f;t) = \frac{N(\overline{B} \to D^0(f)\mu^- X) - N(B \to \overline{D}^0(f)\mu^+ X)}{N(\overline{B} \to D^0(f)\mu^- X) + N(B \to \overline{D}^0(f)\mu^+ X)}$$

$$A_{\rm raw}(D^0 \to f;t) \approx \mathcal{A}_{CP}(D^0 \to f;t) + A_{\rm det} + A_{\rm P}$$

time independent

The time-dependent CP asymmetry:

$$\mathcal{A}_{CP}(D^0 \to f;t) = \frac{\Gamma(D^0(t) \to f) - \Gamma(\overline{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\overline{D}^0(t) \to f)} \approx a_{CP}^{\rm dir} - A_\Gamma(f)\frac{t}{\tau}$$

The time-dependent charge asymmetry is computed for 20 bins of decay time and fitted to a linear function

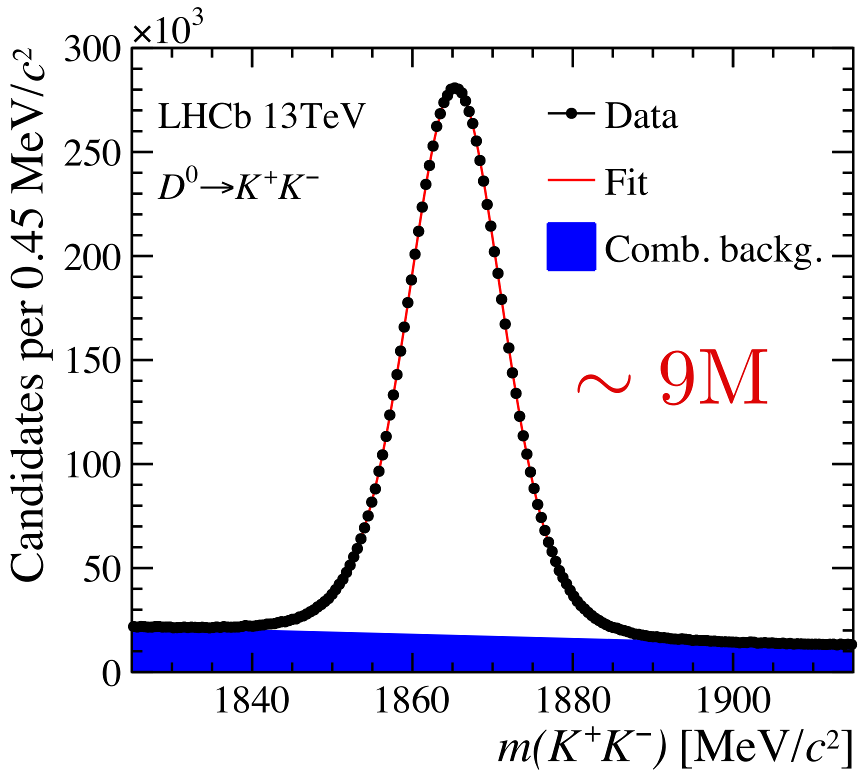
$$A_{\rm raw}(t) = A_{\rm raw}(0) + A_\Gamma \frac{\langle t \rangle_i}{\tau}$$

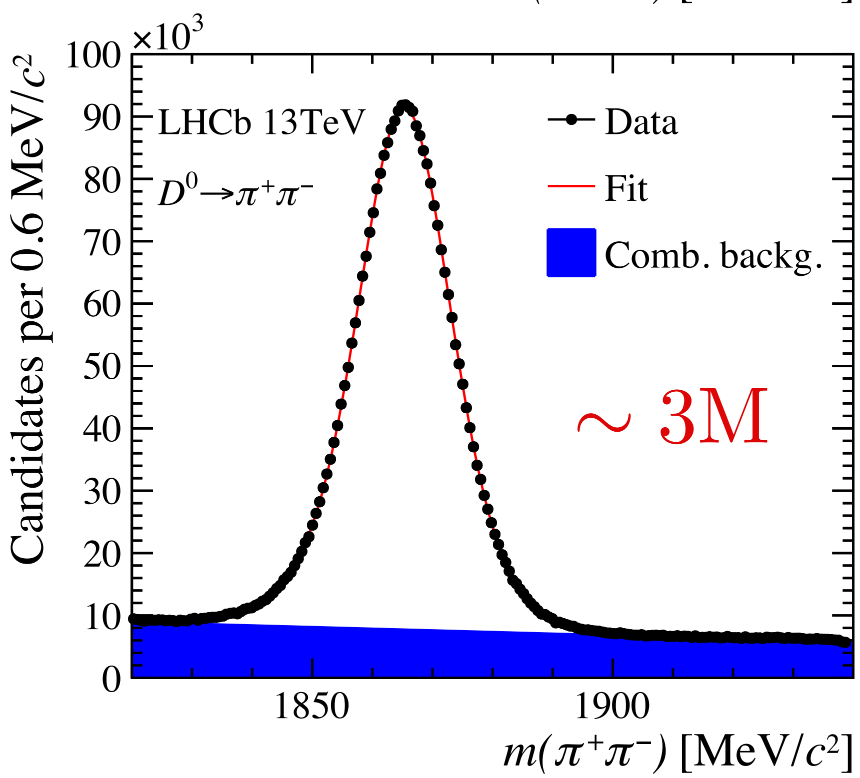
Neglecting CPV in decay: $\phi_f = \arg\left(\frac{q\overline{A}_f}{pA_f}\right) \approx \arg\left(\frac{q}{p}\right) = \phi \;\to\; A_\Gamma(KK) = A_\Gamma(\pi\pi)$

Analysis based on Run 2 data (5.4 fb^{-1} @13 TeV)

$\overline{B} \to D^0 \mu^- X, \quad D^0 \to K^+ K^- / \pi^+ \pi^-$

PRD 101, 012005 (2020)

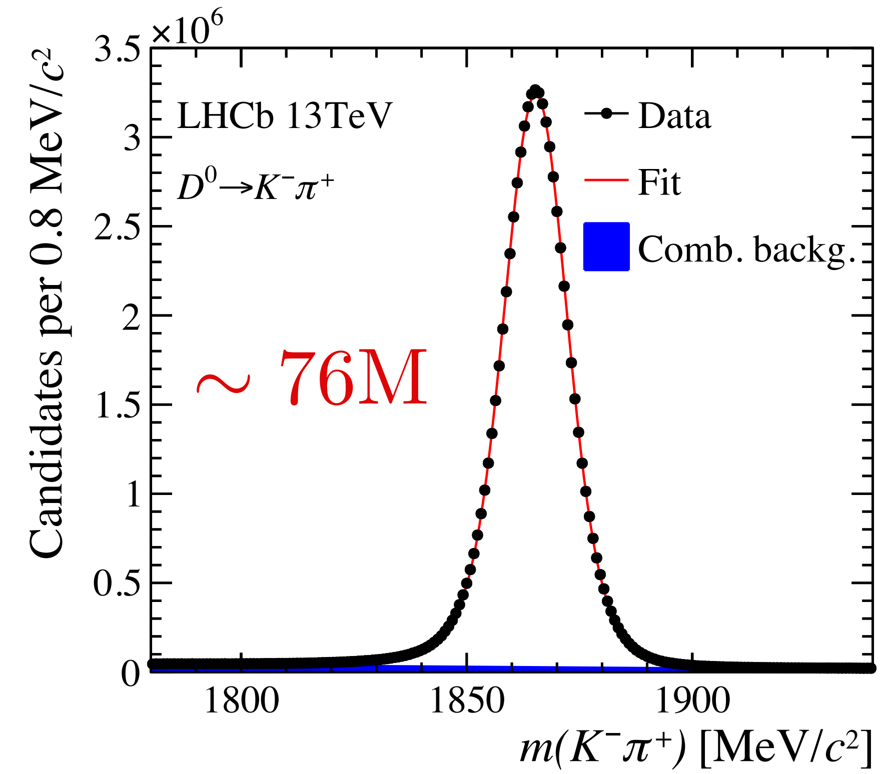


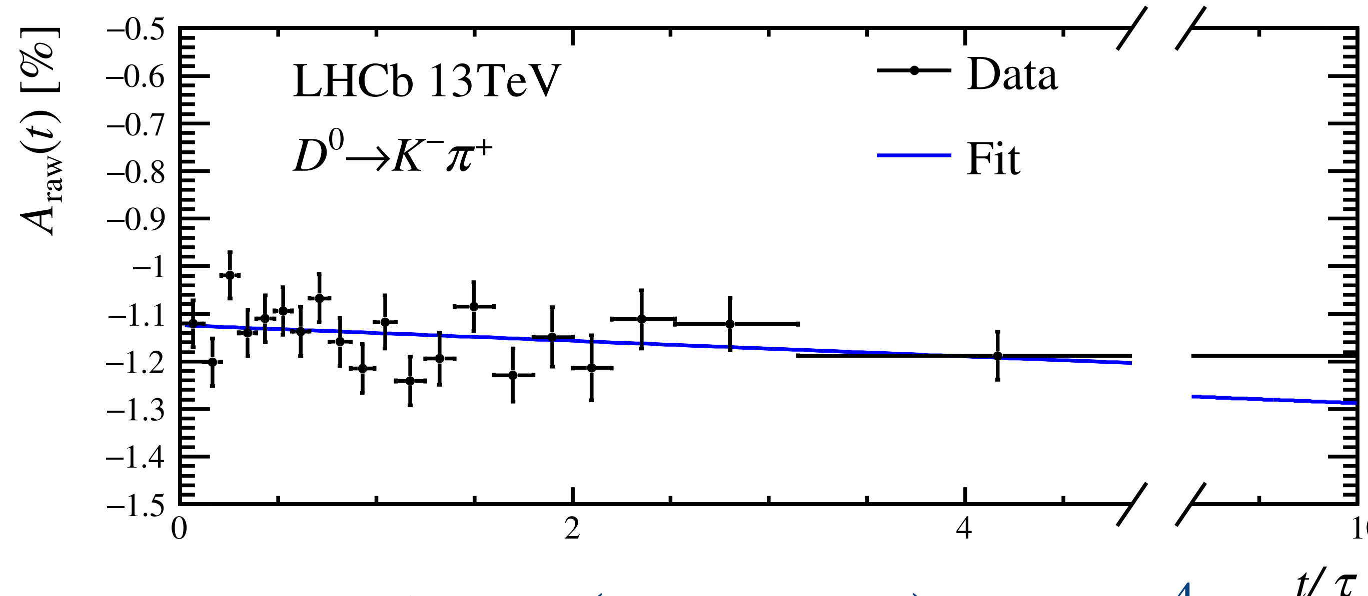


$\overline{B} \to D^0 \mu^- X, \quad D^0 \to K^- \pi^+$

$D^0 \to K^- \pi^+$ control channel

Expected $A_\Gamma = 0$

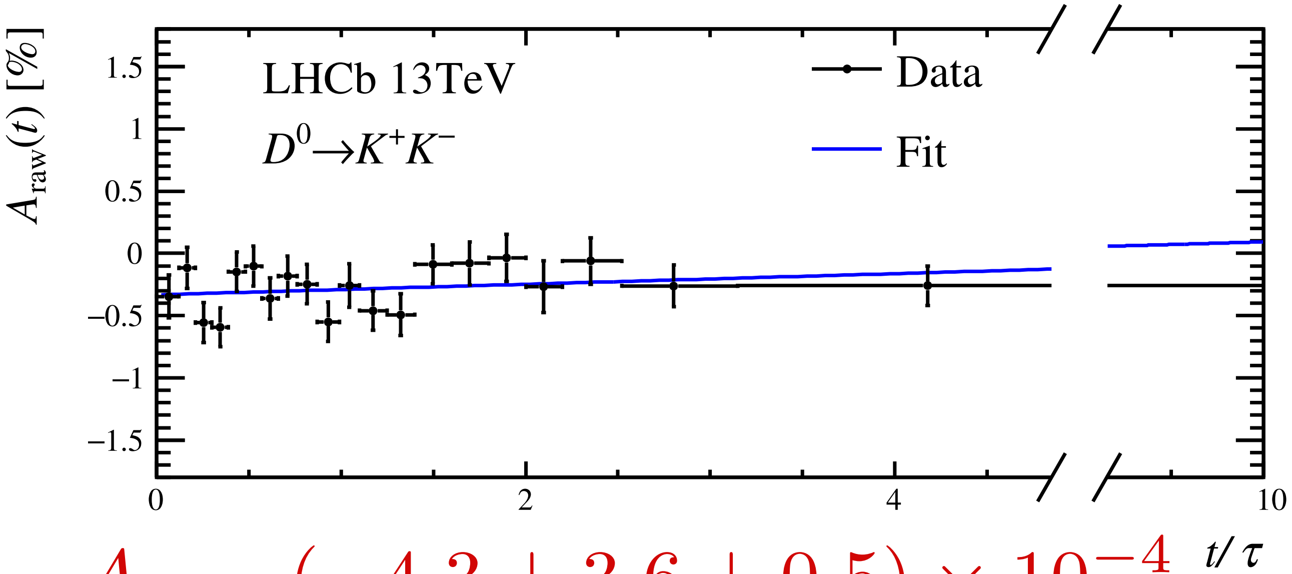




$$A_\Gamma = (1.6 \pm 1.2) \times 10^{-4}$$

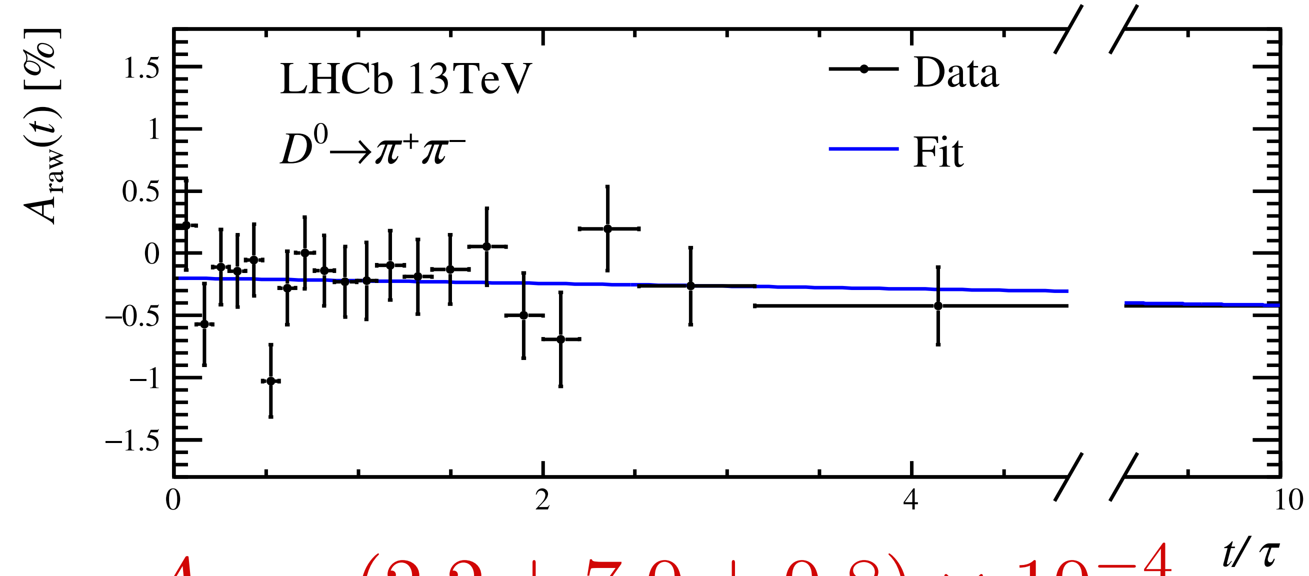
Results

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



$A_\Gamma = (-4.3 \pm 3.6 \pm 0.5) \times 10^{-4}$

$D^0 \to \pi^+\pi^-$



$A_\Gamma = (2.2 \pm 7.0 \pm 0.8) \times 10^{-4}$

PRD 101, 012005 (2020)

Dominant systematic uncertainties

Source of uncertainty	$A_\Gamma(K^+K^-)$ $[10^{-4}]$	$A_\Gamma(\pi^+\pi^-)$ $[10^{-4}]$
Decay-time resolution and acceptance	0.3	0.4
Mistag probability	0.3	0.6
Mass-fit model	0.3	0.3
Total	0.5	0.8

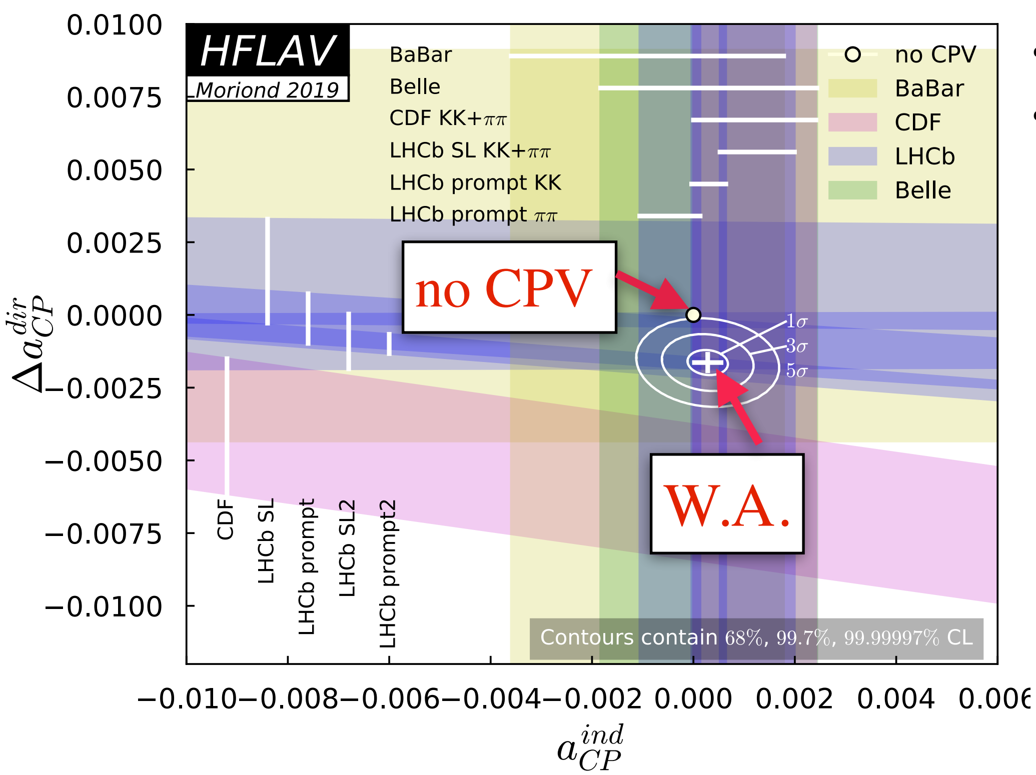
$\sigma_t \sim 127$ fs (decay-time resolution and acceptance)

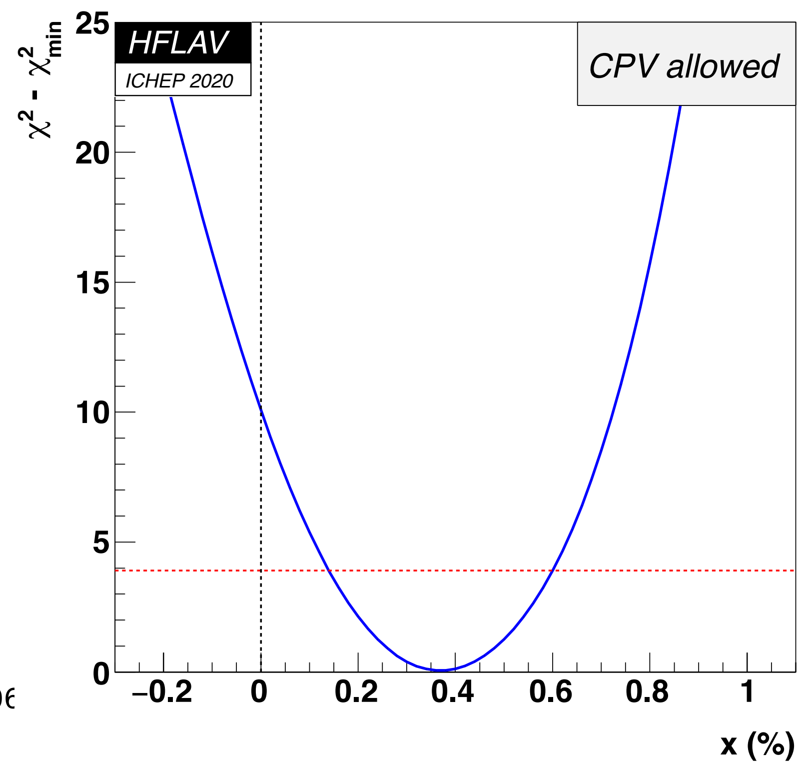
Combining with Run1 results and assuming A_Γ to be universal

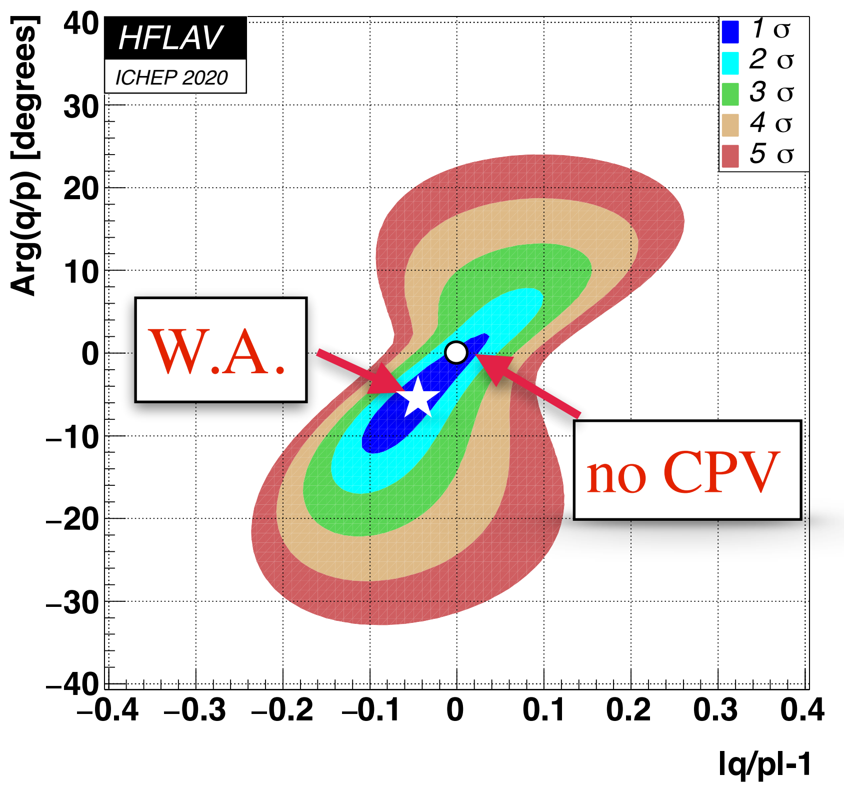
$$A_\Gamma = (-2.9 \pm 2.0 \pm 0.6) \times 10^{-4}$$

No indication of indirect CPV

Summary and prospects







First observation of direct CPV in charm

$x = 0$ excluded by $2.96\ \sigma$

No evidence for indirect CPV

https://hflav-eos.web.cern.ch/hflav-eos/charm/ICHEP20/results_mix_cpv.html

- Ongoing searches for CPV in D^+ and charm baryons
- New results with full Run1+Run2 data to appear soon
- Warming up for Run 3, already looking forward to Upgrade II

Backup slides

The decay amplitude for $D^0 \to K_S^0 \pi^+ \pi^-$ (similar expression for $\overline{D}^0 \to K_S^0 \pi^+ \pi^-$)

$$A_f(m_+^2, m_-^2) = a_f(m_+^2, m_-^2) e^{i\delta(m_+^2, m_-^2)}$$

Defining $g_\pm(t) = \theta(t) e^{-imt} e^{-t/2} \, {}^{\cosh}_{\sinh}(zt/2)$, the decay rate at decay time t:

$$\left|T_f(m_+^2, m_-^2; t)\right|^2 = \left|A_f(m_+^2, m_-^2)\, g_+(t) + \bar{A}_f(m_-^2, m_+^2)\, \frac{q}{p}\, g_-(t)\right|^2$$

With $F_b \equiv \int_b dm_+^2 dm_-^2 \left|A_f(m_+^2, m_-^2)\right|^2$ and

$$X_b \equiv \frac{1}{\sqrt{F_b \overline{F}_{-b}}} \int_b dm_+^2 dm_-^2 \, A_f^\star(m_+^2, m_-^2) \bar{A}_f(m_-^2, m_+^2)$$

the yield in bin b is

$$N_b(t) = \int_b dm_+^2 dm_-^2 \left|T_f(m_+^2, m_-^2; t)\right|^2$$

$$= F_b \left|g_+(t)\right|^2 + \left|\frac{q}{p}\right|^2 \overline{F}_{-b} \left|g_-(t)\right|^2 + 2\sqrt{\overline{F}_{-b} F_b}\, \mathrm{Re}\left[\frac{q}{p} X_b\, g_+^\star(t) g_-(t)\right]$$

PRD **99,** 012007 (2019)

Information regarding the strong phase difference taken from CLEO

$$c_b \equiv \frac{1}{\sqrt{F_b F_{-b}}} \int_b dm_+^2 dm_-^2 \, \left|A_f(m_+^2, m_-^2)\right| \left|A_f(m_-^2, m_+^2)\right| \cos[\Delta\delta(m_+^2, m_-^2)]$$

$$s_b \equiv \frac{1}{\sqrt{F_b F_{-b}}} \int_b dm_+^2 dm_-^2 \, \left|A_f(m_+^2, m_-^2)\right| \left|A_f(m_-^2, m_+^2)\right| \sin[\Delta\delta(m_+^2, m_-^2)]$$

PRD **82,** 112006 (2010)

For $|z|t \ll 1$,

$$|g_+(t)|^2 \approx e^{-t} + \frac{1}{4} e^{-t} t^2 \, \mathrm{Re}\left(z^2\right) + \mathcal{O}(z^4),$$

$$|g_-(t)|^2 \approx \frac{1}{4} e^{-t} t^2 |z|^2 + \mathcal{O}(z^4), \quad \text{and}$$

$$g_+^\star(t) g_-(t) \approx \frac{1}{2} e^{-t} \, t \, z + \mathcal{O}(z^3).$$

Neglecting terms of $\mathcal{O}(z^3)$, the integration over decay time bin *j* yields

$$\int_j dt \, |g_+(t)|^2 \approx n_j \left[1 + \frac{1}{4} \langle t^2 \rangle_j \, \mathrm{Re}\left(z^2\right)\right], \quad \int_j dt \, |g_-(t)|^2 \approx n_j \frac{1}{4} \langle t^2 \rangle_j \, |z|^2,$$

$$\int_j dt \, g_+^\star(t) g_-(t) \approx n_j \frac{1}{2} \langle t \rangle_j \, z,$$

The yield at Dalitz plot bin b and decay-time bin j is

$$N_{bj} = \int_j dt N_b(t)$$
$$\approx F_b \left[1 + \frac{1}{4}\langle t^2\rangle_j \ \mathrm{Re}\left(z^2\right)\right] + \frac{1}{4}\langle t^2\rangle_j \ |z|^2 \left|\frac{q}{p}\right|^2 F_{-b} + \langle t\rangle_j \sqrt{F_{-b}F_b}\,\mathrm{Re}\left(\frac{q}{p}X_b z\right)$$

The ratio between yields of bins b and -b is ($r_b = F_{-b} / F_b$)

$$R_{bj} = \frac{N_{-bj}}{N_{bj}} \approx \frac{r_b\left[1 + \frac{1}{4}\langle t^2\rangle_j \ \mathrm{Re}\left(z^2\right)\right] + \frac{1}{4}\langle t^2\rangle_j \ |z|^2 \left|\frac{q}{p}\right|^2 + \langle t\rangle_j \sqrt{r_b}\,\mathrm{Re}\left(X_b^\star \frac{q}{p}\, z\right)}{1 + \frac{1}{4}\langle t^2\rangle_j \ \mathrm{Re}\left(z^2\right) + \frac{1}{4}\langle t^2\rangle_j \ |z|^2 r_b \left|\frac{q}{p}\right|^2 + \langle t\rangle_j \sqrt{r_b}\,\mathrm{Re}\left(X_b \frac{q}{p}\, z\right)}$$

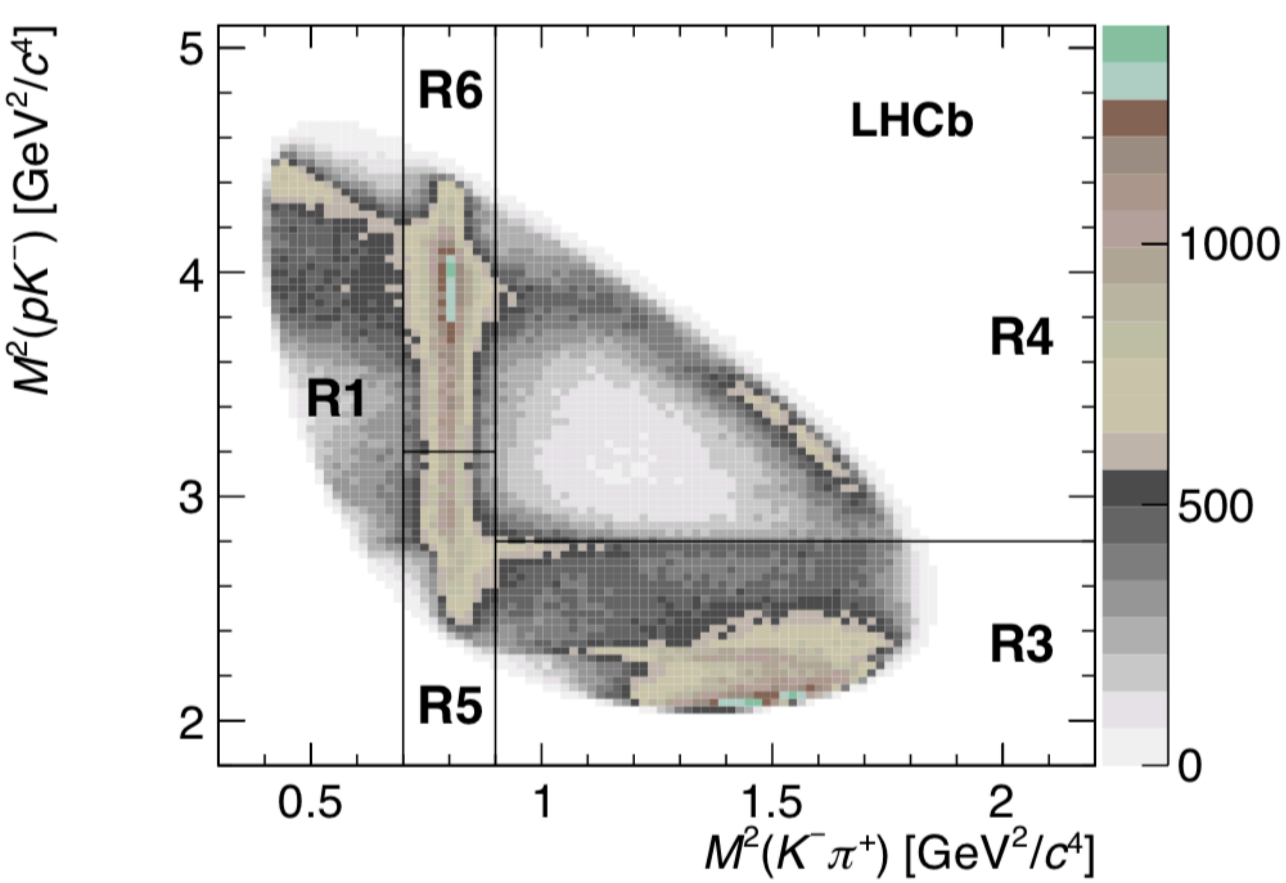
With the definition $z_{CP} \pm \Delta Z \equiv (q/p)^{\pm} z$, the ratio between yields becomes

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

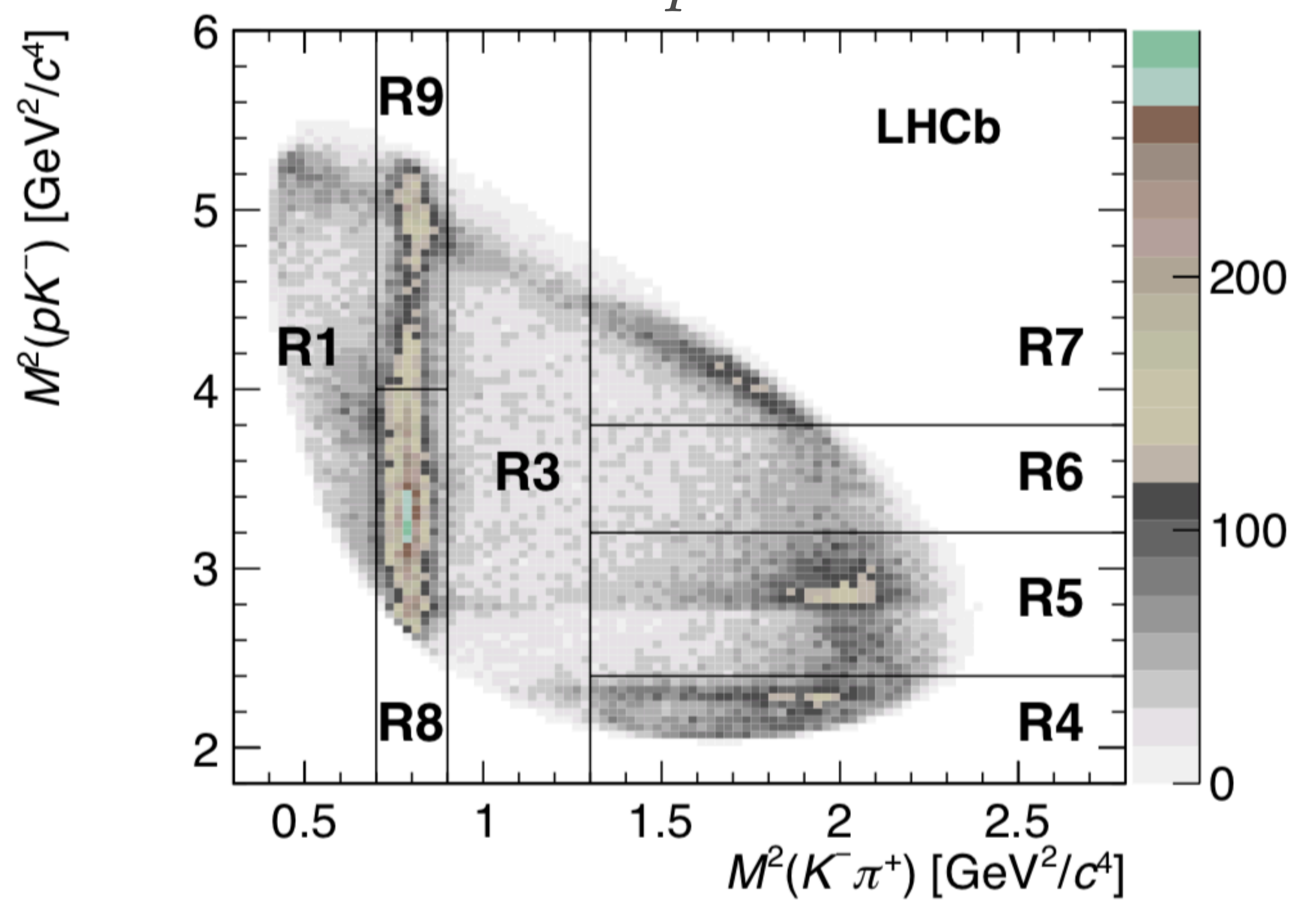
CPV search in $\Xi \to pK^-\pi^+$

Definition of the Dalitz plot regions

$\Lambda_c \to pK^-\pi^+$



$\Xi \to pK^-\pi^+$



In case of CP symmetry, the test statistic T follows a normal distribution with

$$\mu_T = \frac{n_+(n_+ - 1) + n_-(n_- - 1)}{n(n-1)} \quad \text{and} \quad \sigma_T^2 = \frac{1}{nn_k}\left(\frac{n_+n_-}{n^2} + 4\frac{n_+^2 n_-^2}{n^4}\right)$$

Table 6.4: Extrapolated signal yields, and statistical precision on indirect CP violation from A_Γ.

Sample ($\mathcal{L}$)	Tag	Yield K^+K^-	$\sigma(A_\Gamma)$	Yield $\pi^+\pi^-$	$\sigma(A_\Gamma)$
Run 1–2 (9 fb^{-1})	Prompt	60M	0.013%	18M	0.024%
Run 1–3 (23 fb^{-1})	Prompt	310M	0.0056%	92M	0.0104 %
Run 1–4 (50 fb^{-1})	Prompt	793M	0.0035%	236M	0.0065 %
Run 1–5 (300 fb^{-1})	Prompt	5.3G	0.0014%	1.6G	0.0025 %

Table 6.5: Extrapolated signal yields and statistical precision on direct CP violation observables for the promptly produced samples.

Sample ($\mathcal{L}$)	Tag	Yield $D^0 \to K^-K^+$	Yield $D^0 \to \pi^-\pi^+$	$\sigma(\Delta A_{CP})$ [%]	$\sigma(A_{CP}(hh))$ [%]
Run 1–2 (9 fb^{-1})	Prompt	52M	17M	0.03	0.07
Run 1–3 (23 fb^{-1})	Prompt	280M	94M	0.013	0.03
Run 1–4 (50 fb^{-1})	Prompt	1G	305M	0.01	0.03
Run 1–5 (300 fb^{-1})	Prompt	4.9G	1.6G	0.003	0.007

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Table 6.3: Extrapolated signal yields, and statistical precision on the mixing and *CP* violation parameters, for the analysis of the decay $D^0 \to K^0_S \pi^+\pi^-$. Candidates tagged by semileptonic B decay (SL) and those from prompt charm meson production are shown separately.

Sample (lumi $\mathcal{L}$)	Tag	Yield	$\sigma(x)$	$\sigma(y)$	$\sigma(\lvert q/p\rvert)$	$\sigma(\phi)$
Run 1–2 (9 fb^{-1})	SL	10M	0.07%	0.05%	0.07	4.6°
	Prompt	36M	0.05%	0.05%	0.04	1.8°
Run 1–3 (23 fb^{-1})	SL	33M	0.036%	0.030%	0.036	2.5°
	Prompt	200M	0.020%	0.020%	0.017	0.77°
Run 1–4 (50 fb^{-1})	SL	78M	0.024%	0.019%	0.024	1.7°
	Prompt	520M	0.012%	0.013%	0.011	0.48°
Run 1–5 (300 fb^{-1})	SL	490M	0.009%	0.008%	0.009	0.69°
	Prompt	3500M	0.005%	0.005%	0.004	0.18°

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