Charm mixing and CP violation

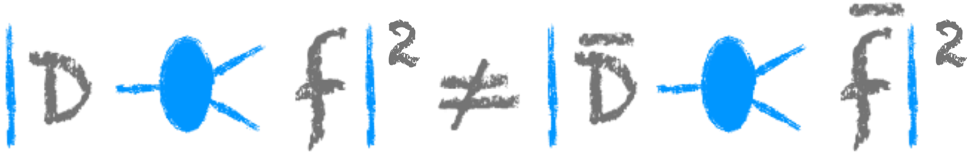
Fabio Ferrari on behalf of the LHCb collaboration, with results from the Belle collaboration

University of Bologna and INFN

FPCP 2019 – Victoria

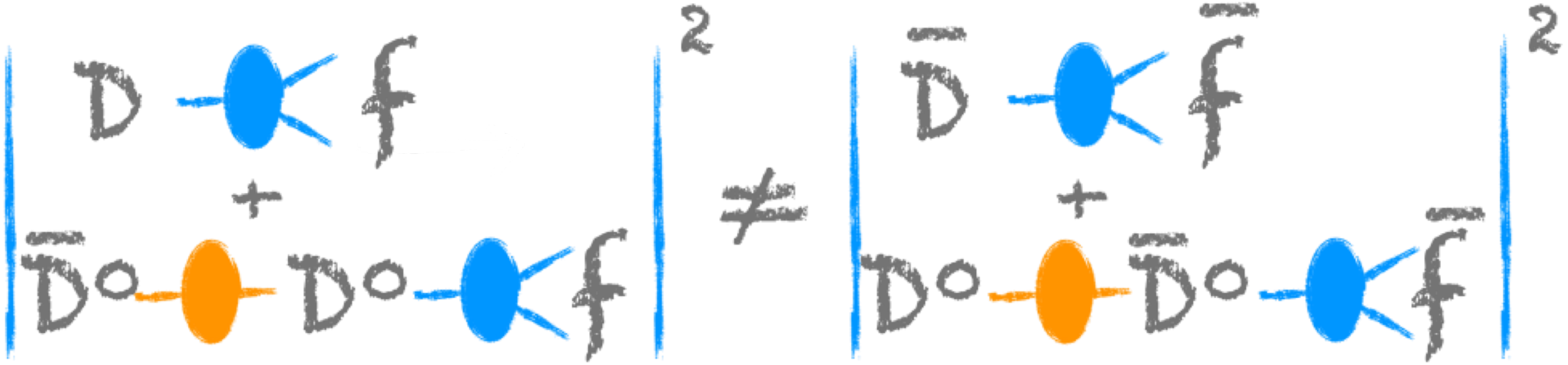
Setting the stage

CPV in decay (direct CPV)



CPV in mixing

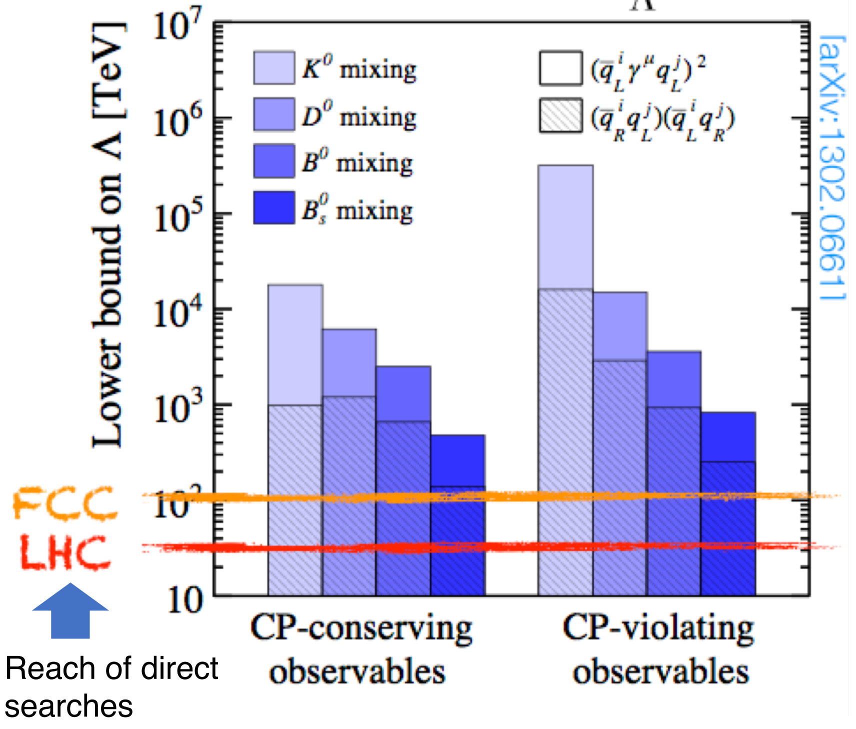
CPV in interference between mixing and decay



Why charm is charming?

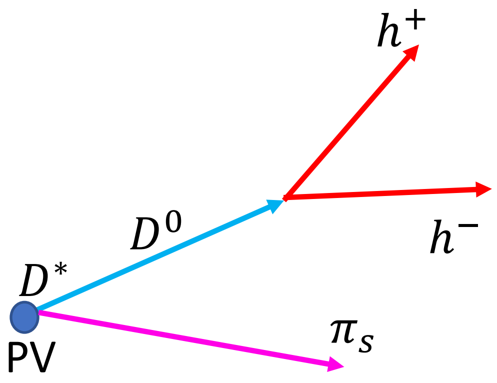
- Charm is the only up-type quark where we can look for flavor/CP violation
- Large production cross-section at LHC allows to perform very high precision measurements
- New Physics contributions could be hidden in the loops
- Assuming a generic NP scenario, much larger scales are accessible with respect to direct searches

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda^2}\mathcal{O}_{\Delta F=2}$$

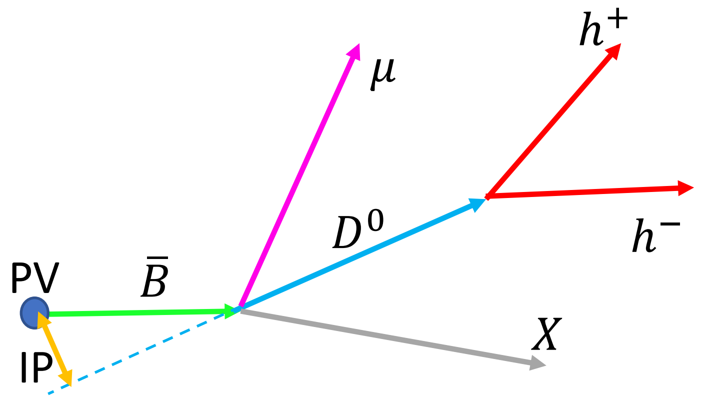


How to get the D flavor at production?

- The flavor of the D meson needs to be determined to perform mixing and CPV measurements
- Two possible tagging methods



Prompt tag – IP ~ 0



Semileptonic tag – IP > 0

- Prompt sample much bigger than semileptonic one, but semileptonic sample useful to extend the lifetime coverage

J. Instrum. 3 (2008) S08005

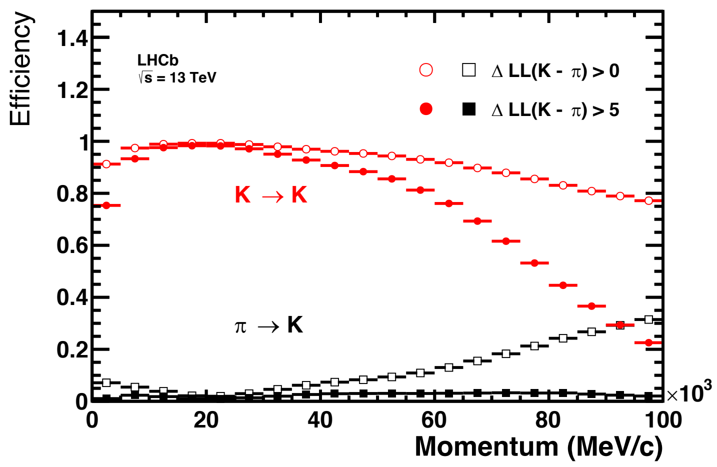
*Nucl.Phys. B871 (2013) 1-20
**J. High Energ. Phys. (2017) 74

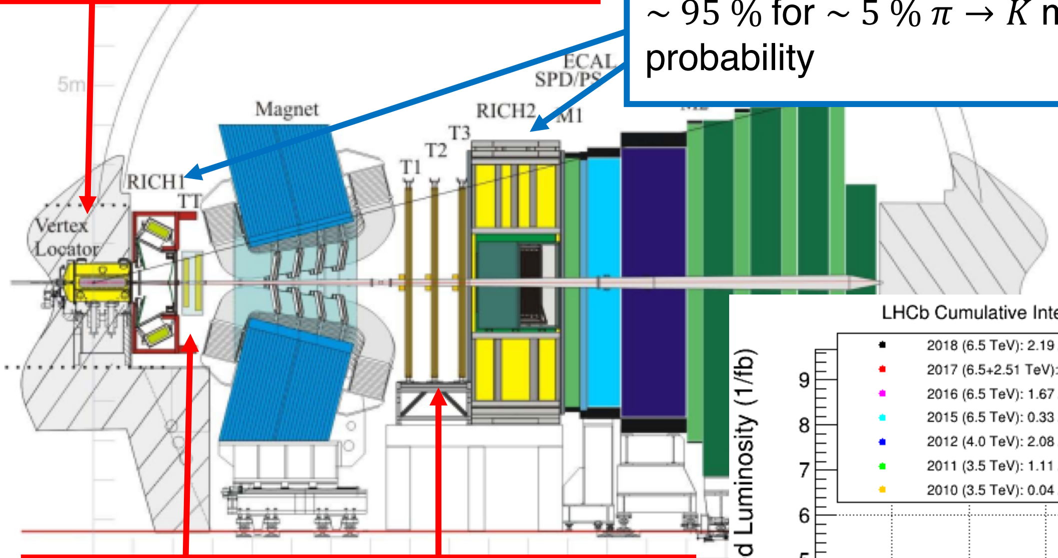
The LHCb detector

Single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$

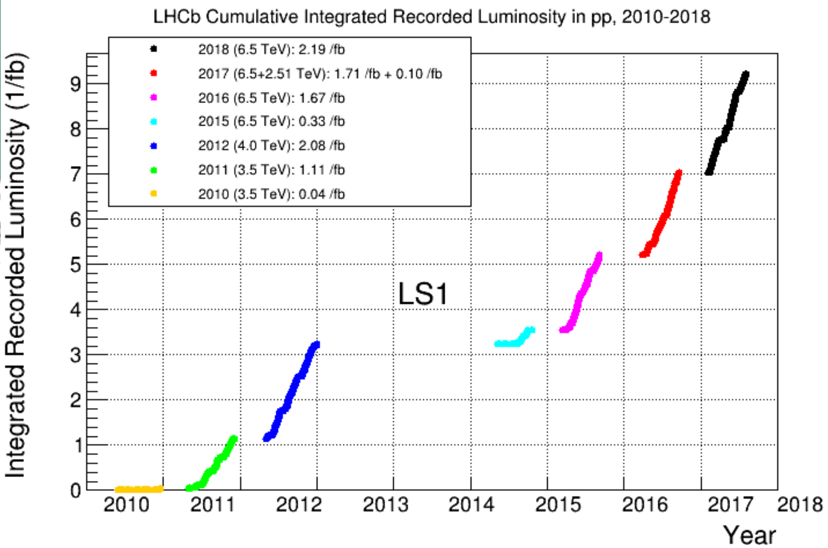
Silicon Vertex Locator (VELO)
$20\ \mu m$ impact parameter resolution, corresponding to $\sim 0.1\tau$ decay-time resolution for a 2-body charm decay

RICH 1 & 2
Provide discrimination between kaons, pions and protons between 5 and $150\ GeV/c$. Typical kaon ID $\sim 95\ \%$ for $\sim 5\ \%\ \pi \to K$ mis-ID probability





Tracking systems
$\Delta p/p = 0.4 - 0.6\%$ at $5 - 100\ GeV/c$, corresponding to $\sim 8\ MeV/c^2$ mass resolution for a 2-body charm decay



$$\sigma(pp \to c\bar{c}X) = 1419 \pm 134\ \mu b \ @ \sqrt{s} = 7\ TeV^*$$
$$\sigma(pp \to c\bar{c}X) = 2840 \pm 226\ \mu b \ @ \sqrt{s} = 13\ TeV^{**}$$

=

Unprecedented amount of charm decays collected during Run 1 and 2

Direct CPV

Observation of CP violation in charm decays

1956
Parity violation
T. D. Lee,
C. N. Yang and
C. S. Wu *et al.*

1963
Cabibbo Mixing
N. Cabibbo

1964
Strange particles:
***CP* violation in K meson decays**
J. W. Cronin,
V. L. Fitch *et al.*

1973
The CKM matrix
M. Kobayashi and
T. Maskawa

2001
Beauty particles:
***CP* violation in B^0 meson decays**
BaBar and Belle collaborations

2019
Charm particles:
***CP* violation in D^0 meson decays**
LHCb collaboration

TODAY

Observation of CP violation in charm decays

- New measurement performed with almost full Run 2 (5.9 fb^{-1}) data
- Both prompt and semileptonic sample used
- Observed raw asymmetry affected by instrumental and production effects

$$A_{h^+h^-} = A_{CP}(h^+h^-) + A_D + A_P$$

$\frac{N(D^0 \to h^+h^-) - N(\bar{D}^0 \to h^+h^-)}{N(D^0 \to h^+h^-) + N(\bar{D}^0 \to h^+h^-)}$

The asymmetry we want to measure

Detection asymmetry of tagging track (π or μ)

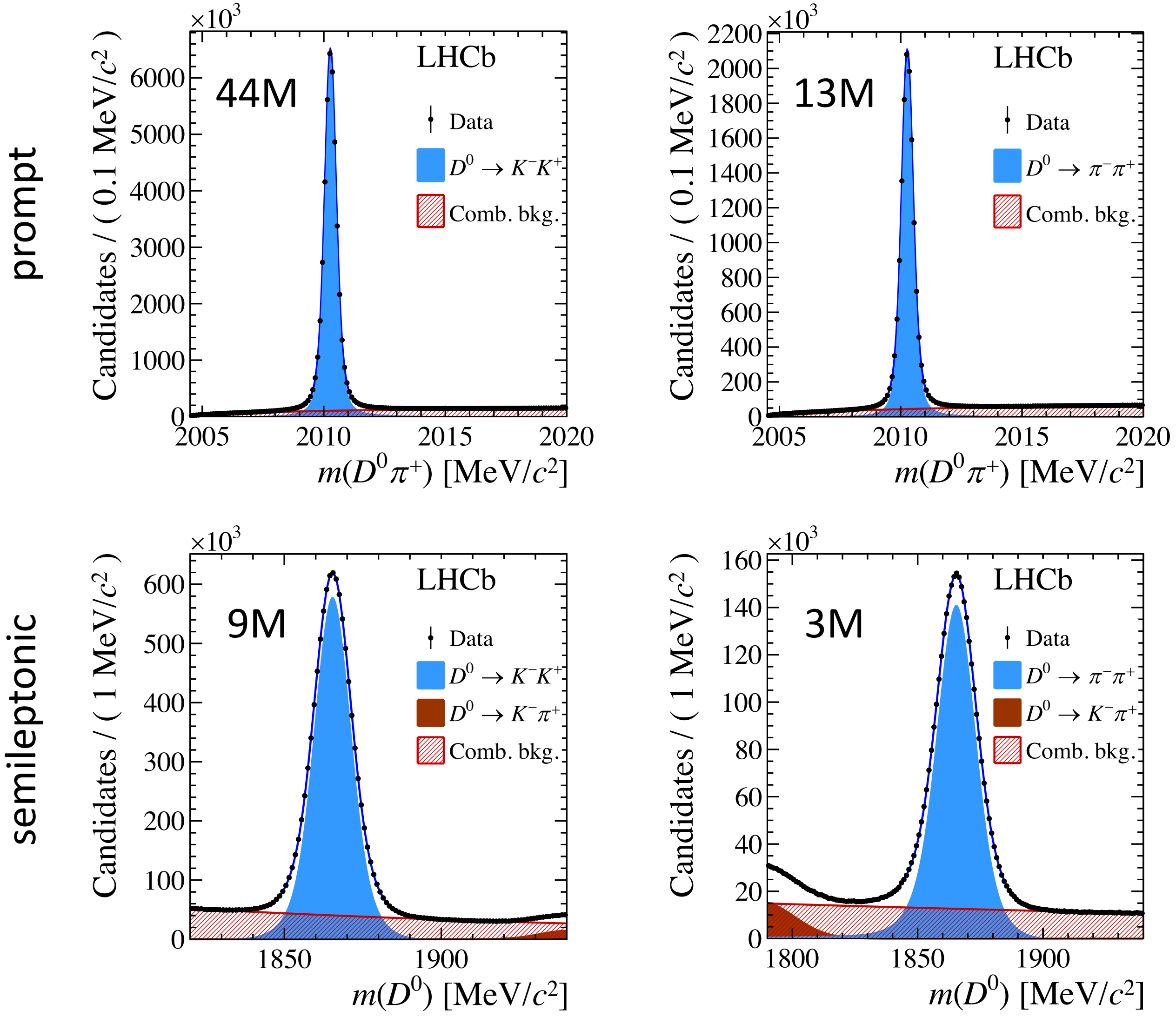
Production asymmetry of D^* or B

- Take difference of raw asymmetries to cancel unwanted effects, if the kinematics of D^*/B and π/μ for the two decay modes are equal

$$\Delta A_{CP} = A_{K^+K^-} - A_{\pi^+\pi^-} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

Observation of CP violation in charm decays

- Fits to the $m(D^0\pi^+)$ or $m(D^0)$ distributions to obtain the raw asymmetry
- $A_{h^+h^-}$ parameter of the fit shared between D^{*+} and D^{*-} (or D^0 and $\overline{D}^0$)
- Prompt: about **44 million** signal decays for K^-K^+ and **14 million** for $\pi^-\pi^+$
- Semileptonic: about **9 million** signal events for K^-K^+ and **3 million** for $\pi^-\pi^+$



Observation of CP violation in charm decays

- Evaluated several sources of systematic uncertainties

Source	π-tagged $[10^{-4}]$	μ-tagged $[10^{-4}]$
Fit model	0.6	2
Mistag	–	4
Weighting	0.2	1
Secondary decays	0.3	–
B^0 fraction	–	1
B reco. efficiency	–	2
Peaking background	0.5	–
Total	0.9	5

- **Prompt** dominated by:
  - **Fit model →** evaluated by fitting pseudoexperiments with alternative models
  - **Misreconstructed background** ($D^0 \to K^-\pi^+\pi^0$, $D^0 \to \pi^- l^+ \nu_l$) peaking in $m(D^0\pi)$ → estimated by measuring the yields and asymmetries of backgrounds on the $m(D^0)$ distributions
- **SL** dominated by **mistag** (wrong muon)
  - Evaluated on the $B \to D^0(\to K^-\pi^+)\mu X$ control sample

Observation of CP violation in charm decays

- Run 2 result

$$\Delta A_{CP}^{\pi-tag} = (-18.2 \pm 3.2 \pm 0.9)\times10^{-4}$$
$$\Delta A_{CP}^{\mu-tag} = (-9 \pm 8 \pm 5)\times10^{-4}$$

- Combination with LHCb Run 1 yields

$$\Delta A_{CP} = (-15.4 \pm 2.9)\times10^{-4}$$

CP violation observed at 5.3σ!

Observation of CP violation in charm decays

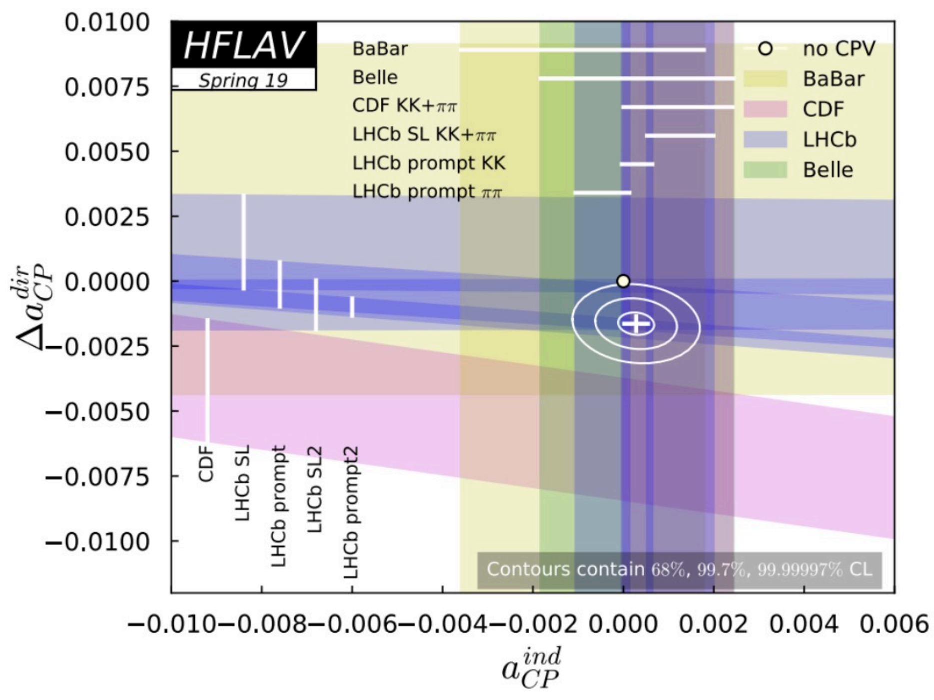
$$\Delta A_{CP} \simeq \Delta a_{CP}^{dir}\left(1+\frac{\langle\bar{t}\rangle}{\tau_{D^0}}y_{CP}\right)+\frac{\Delta\langle t\rangle}{\tau_{D^0}}a_{CP}^{ind}$$

Assumption:
a_{CP} in decay/mixing interference is universal

$\langle\bar{t}\rangle \equiv (\langle t\rangle_{KK}+\langle t\rangle_{\pi\pi})/2$
$\Delta\langle t\rangle \equiv \langle t\rangle_{KK}-\langle t\rangle_{\pi\pi}$

- $\langle\bar{t}\rangle/\tau_{D^0} = 1.71 \pm 0.10$ and $\Delta\langle t\rangle/\tau_{D^0} = 0.115 \pm 0.002$ from full dataset
- The LHCb averages for y_{CP} and $A_\Gamma \simeq -a_{CP}^{ind}$ are
  - $y_{CP} = (5.7 \pm 1.5)\times 10^{-3}$ [JHEP04(2012)129, PRL122(2019)011802]
  - $A_\Gamma \simeq -a_{CP}^{ind} = (-2.8 \pm 2.8)\times 10^{-4}$ [JHEP04(2015)043, PRL118(2017)261803]
- One obtains

$$\Delta a_{CP}^{dir} = (-15.6 \pm 2.9)\times 10^{-4}$$



Search for CPV in $D^+ \to K_S^0 K^+, D_s^+ \to K_S^0 \pi^+$ and $D^+ \to \phi\pi^+$

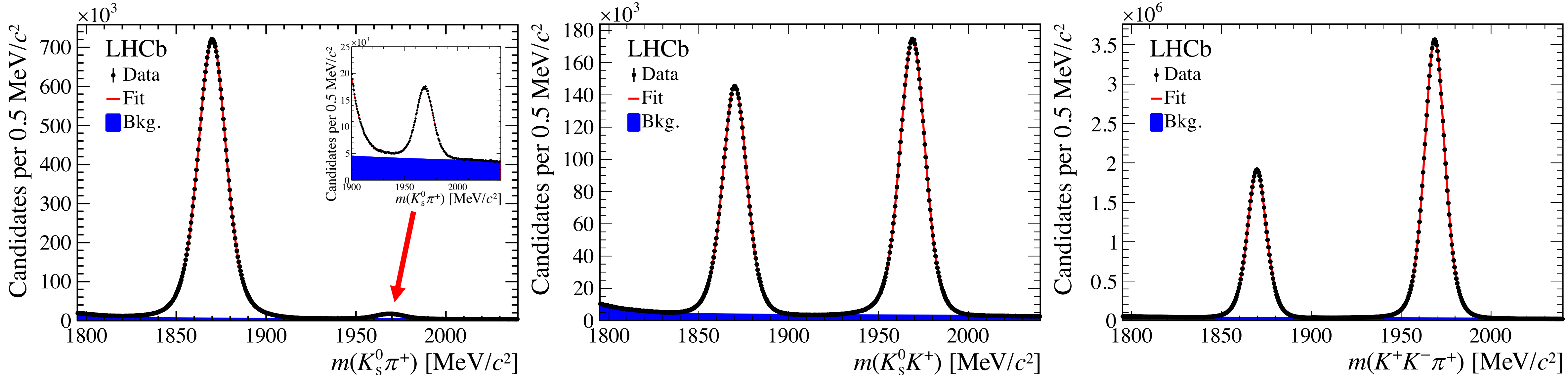
- CPV can arise in interference in tree- and loop-level diagrams in $c \to d\bar{d}u$ and $c \to s\bar{s}u$
- Measurement performed with 3.8 fb^{-1} collected at 13 TeV
- The CP asymmetries are obtained through a combination of the raw asymmetries of signal and control modes

$$
\begin{aligned}
\mathcal{A}_{CP}(D_s^+ \to K_S^0\pi^+) &\approx \boxed{A(D_s^+ \to K_S^0\pi^+) - A(D_s^+ \to \phi\pi^+),} \\
\mathcal{A}_{CP}(D^+ \to K_S^0 K^+) &\approx \boxed{\begin{aligned} &A(D^+ \to K_S^0 K^+) - A(D^+ \to K_S^0\pi^+) \\ &- A(D_s^+ \to K_S^0 K^+) + A(D_s^+ \to \phi\pi^+), \end{aligned}} \\
\mathcal{A}_{CP}(D^+ \to \phi\pi^+) &\approx \boxed{A(D^+ \to \phi\pi^+) - A(D^+ \to K_S^0\pi^+),}
\end{aligned}
$$

arXiv:1903.01150, submitted to PRL

Search for CPV in $D^+ \to K_S^0 K^+, D_s^+ \to K_S^0 \pi^+$ and $D^+ \to \phi\pi^+$

- Simultaneous fits to extract the raw asymmetries for each decay mode
- Very high signal yields, ranging from ~ 600k for $D_s^+ \to K_S^0 \pi^+$ to 53M $D^+ \to \phi\pi^+$



arXiv:1903.01150, submitted to PRL

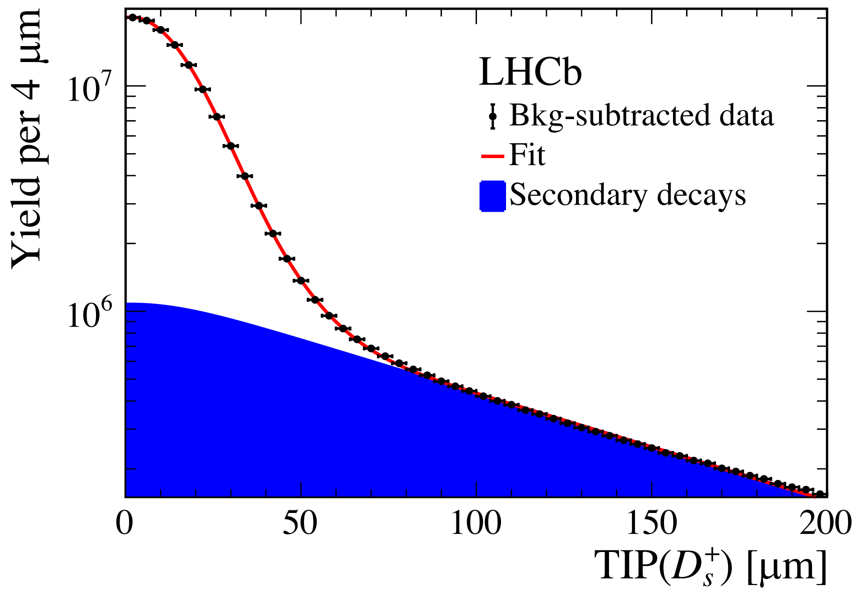
Search for CPV in $D^+ \to K_S^0 K^+, D_s^+ \to K_S^0 \pi^+$ and $D^+ \to \phi\pi^+$

- Main systematic uncertainties: fit model and contribution from secondary decays

Source	$\mathcal{A}_{CP}(D_s^+ \to K_S^0 \pi^+)$	$\mathcal{A}_{CP}(D^+ \to K_S^0 K^+)$	$\mathcal{A}_{CP}(D^+ \to \phi\pi^+)$
Fit model	0.39	0.44	0.24
Secondary decays	0.30	0.12	0.03
Kinematic differences	0.09	0.09	0.04
Neutral kaon asymmetry	0.05	0.05	0.04
Charged kaon asymmetry	0.08	0.09	0.15
Total	0.51	0.48	0.29

- Both uncertainties can be reduced collecting more data

TIP: impact parameter in the plane transverse to the beam



arXiv:1903.01150, submitted to PRL

Search for CPV in $D^+ \to K_S^0 K^+$, $D_s^+ \to K_S^0 \pi^+$ and $D^+ \to \phi\pi^+$

- Results

$$\mathcal{A}_{CP}(D_s^+ \to K_S^0 \pi^+) = (\ \ 1.3 \pm 1.9 \pm 0.5\ ) \times 10^{-3}$$
$$\mathcal{A}_{CP}(D^+ \to K_S^0 K^+) = (-0.09 \pm 0.65 \pm 0.48) \times 10^{-3}$$
$$\mathcal{A}_{CP}(D^+ \to \phi\pi^+) = (\ \ 0.05 \pm 0.42 \pm 0.29) \times 10^{-3}$$

- Best result on these asymmetries to date and second most precise measurement of CP asymmetries
- Combination with Run 1 measurement yields

$$\mathcal{A}_{CP}(D_s^+ \to K_S^0 \pi^+) = (\ \ 1.6 \pm 1.7 \pm 0.5\ ) \times 10^{-3}$$
$$\mathcal{A}_{CP}(D^+ \to K_S^0 K^+) = (-0.04 \pm 0.61 \pm 0.45) \times 10^{-3}$$
$$\mathcal{A}_{CP}(D^+ \to \phi\pi^+) = (\ \ 0.03 \pm 0.40 \pm 0.29) \times 10^{-3}$$

Search for CPV with kinematic asymmetries in the $D^0 \to K^+K^-\pi^+\pi^-$ decay

- Kinematic asymmetries probe the rich variety of interfering contributions in the decay
  - Sensitivity to non-SM CP-violating phases
- The CP-violating kinematic asymmetry is defined as $a_X^{CP} \equiv \frac{1}{2}(\mathcal{A}_X - \eta_X^{CP}\bar{\mathcal{A}}_{\bar{X}})$

  where X is the kinematic variable, η_X^{CP} is a CP eigenvalue and

$$\mathcal{A}_X \equiv \frac{\Gamma(X>0) - \Gamma(X<0)}{\Gamma(X>0) + \Gamma(X<0)}$$

  with Γ indicating the D^0 decay rate

Phys. Rev. D 99, 011104 (2019)

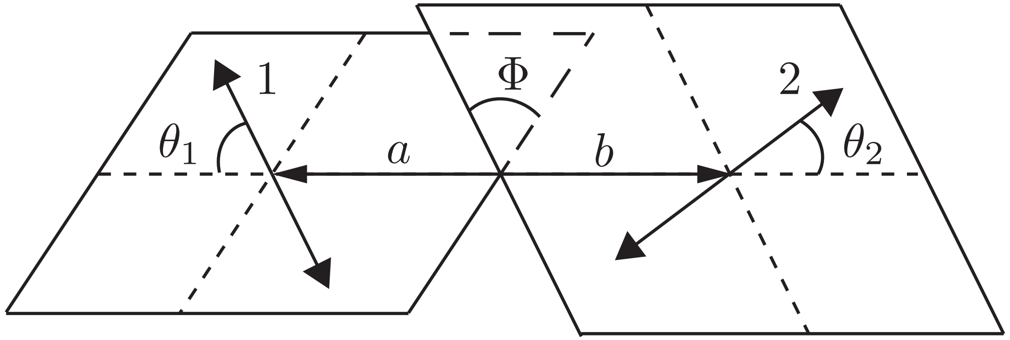
Search for CPV with kinematic asymmetries in the $D^0 \to K^+K^-\pi^+\pi^-$ decay

- Set of five kinematic variables

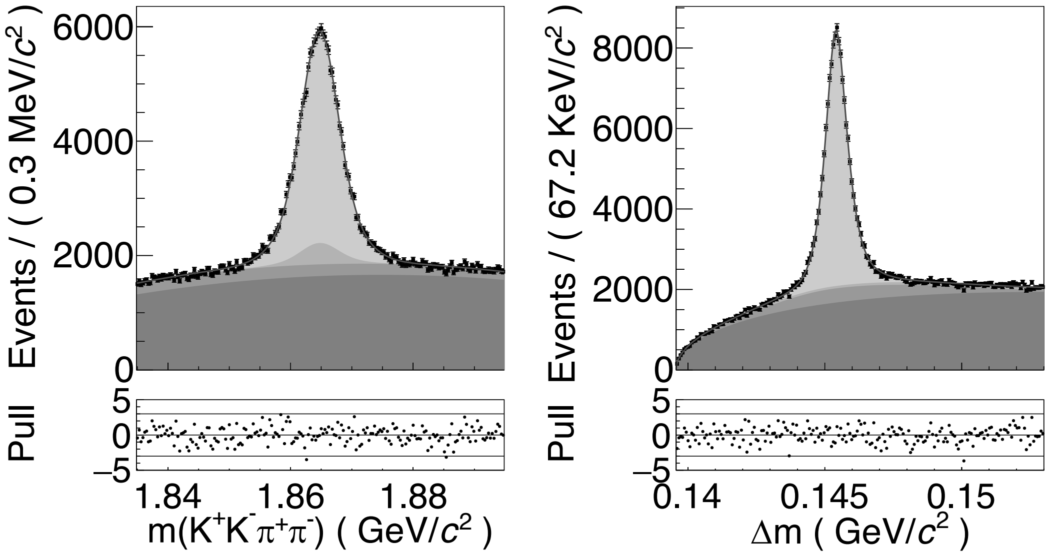
  $\cos\Phi$ $\quad\cos\theta_1\cos\theta_2\cos\Phi$

  $\sin\Phi$ $\quad\cos\theta_1\cos\theta_2\sin\Phi$

  $\sin 2\Phi$



- Use full dataset collected by Belle (978 fb^{-1})
- Tag the flavor of the D^0 at production using $D^{*+} \to D^0\pi_s^+$ decays
- Two-dimensional fits to $m(D^0)$ and Δm distributions



Phys. Rev. D 99, 011104 (2019)

Search for CPV with kinematic asymmetries in the $D^0 \to K^+K^-\pi^+\pi^-$ decay

- Results

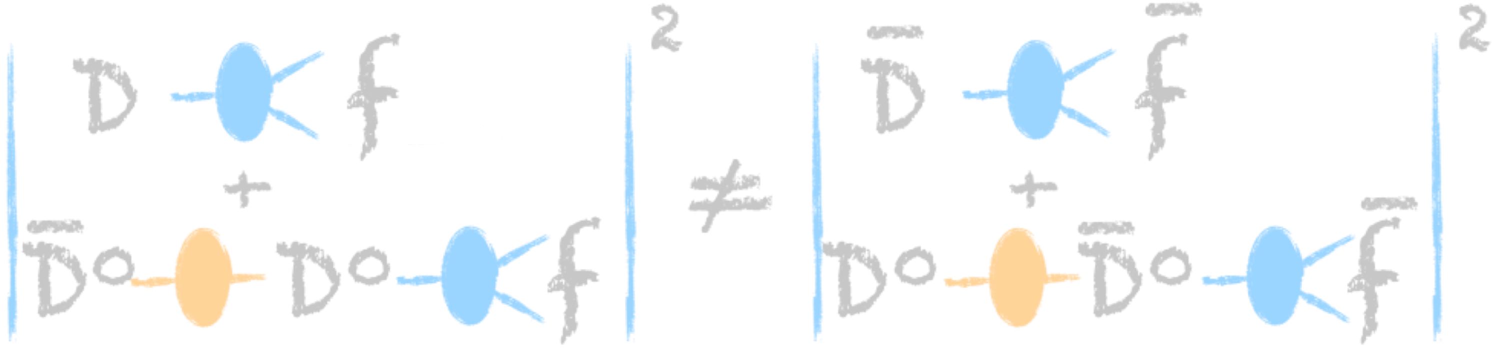
$$a^{CP}_{\cos\Phi} = (3.4 \pm 3.6 \pm 0.6) \times 10^{-3}$$
$$a^{CP}_{\sin\Phi} = (5.2 \pm 3.7 \pm 0.7) \times 10^{-3}$$
$$a^{CP}_{\sin 2\Phi} = (3.9 \pm 3.6 \pm 0.7) \times 10^{-3}$$
$$a^{CP}_{\cos\theta_1 \cos\theta_2 \cos\Phi} = (-0.2 \pm 3.6 \pm 0.7) \times 10^{-3}$$
$$a^{CP}_{\cos\theta_1 \cos\theta_2 \sin\Phi} = (0.2 \pm 3.7 \pm 0.7) \times 10^{-3}$$

- No CPV observed within current uncertainties
- Similar approach used by LHCb on Run 1 data using triple products of final-state particles*
    - Measure a_{CP}^{T-odd} that is the equivalent of $a^{CP}_{\sin\Phi}$ measured by Belle

$$a_{CP}^{T-odd} = (1.8 \pm 2.4 \pm 0.4)\times 10^{-3}$$

*JHEP 10 (2014) 005

Mixing and indirect CPV



Formalism

- Mass eigenstates (D_1 and D_2) are a superposition of the flavor ones (D^0 and $\bar{D}^0$)

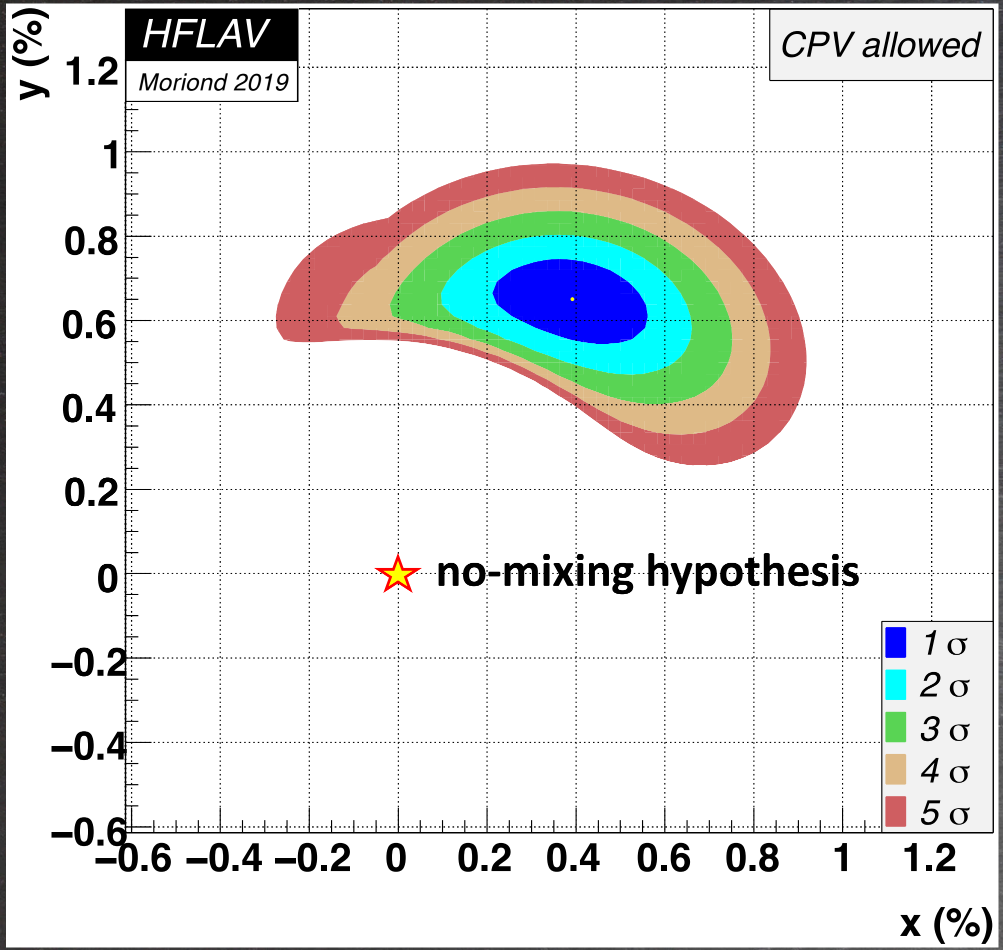
$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

$$\downarrow$$

$$x = (m_1 - m_2)/\Gamma$$

$$y = (\Gamma_1 - \Gamma_2)/2\Gamma$$

where m_1 (m_2) and Γ_1 (Γ_2) are the mass and width of the D_1 (D_2) mass eigenstates



No-mixing hypothesis excluded at > 11σ when all results are combined

LHCb-CONF-2019-001

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

- Complementary test of SM w.r.t. measurement of direct CPV
- SM expectations still ~ 1 order of magnitude below experimental precision → need to improve
- Measure time-dependent CP asymmetry of D^0 mesons to K^+K^- and $\pi^+\pi^-$ final states with ~ 2 fb^{-1} of Run 2

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

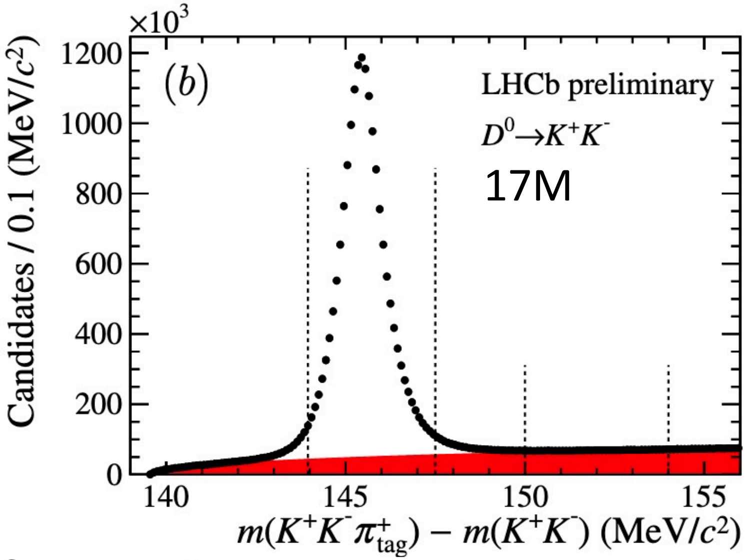
Since: $x, y \ll 1$

$$A_{CP}(f,t) \approx A_{CP}^{\mathrm{decay}}(f) - \boxed{A_\Gamma(f)}\frac{t}{\tau_{D^0}}$$

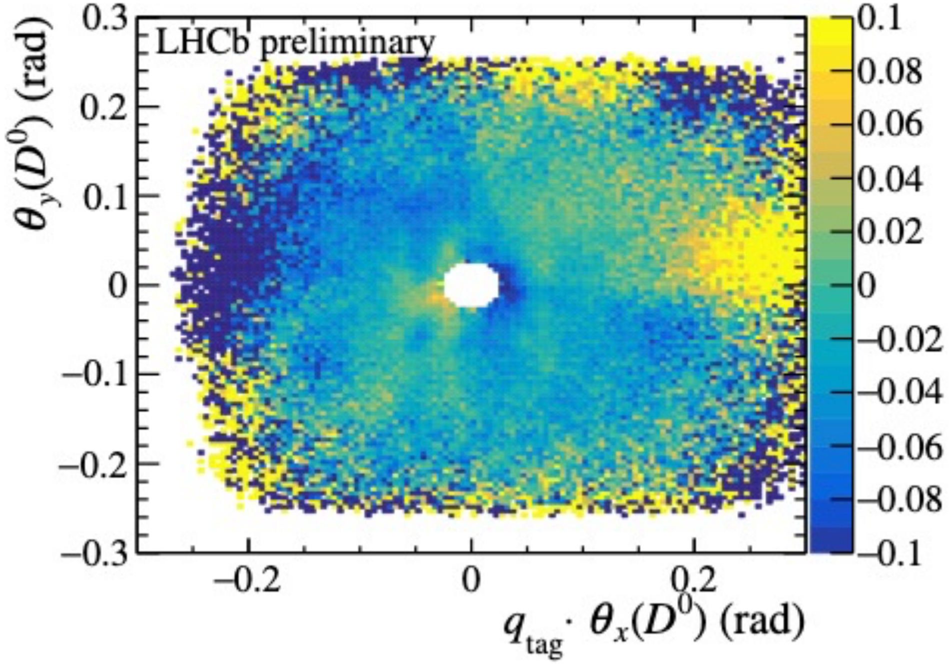
- Perform linear fit to the values of the CP asymmetry in bins of D^0 decay time to measure the slope parameter A_Γ

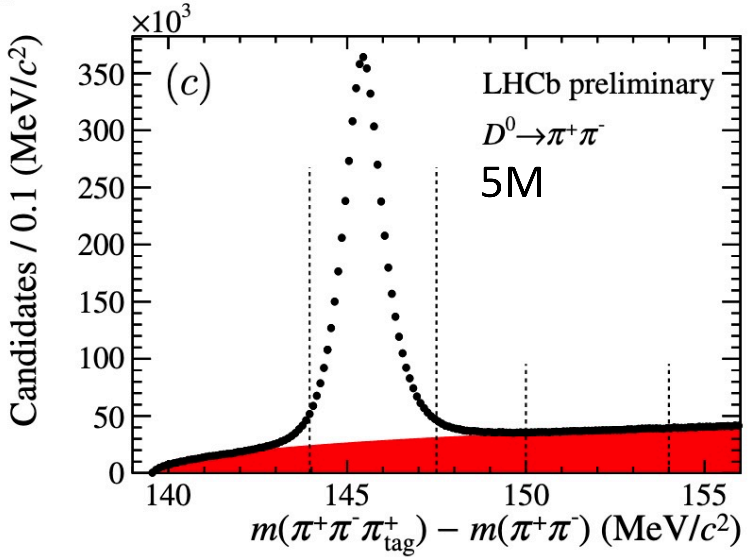
Search for time-dependent CPV in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays

- Parameter A_Γ determined from linear fit to time-dependent asymmetry in 21 bins of decay time
- Momentum-dependent charge asymmetries arise from the pion used to tag the D^0 flavor



- 3D weighting necessary to mitigate this effect





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

- Validate measurement on CF $D^0 \to K^-\pi^+$ decays $\to A_\Gamma$ expected to be well below experimental precision

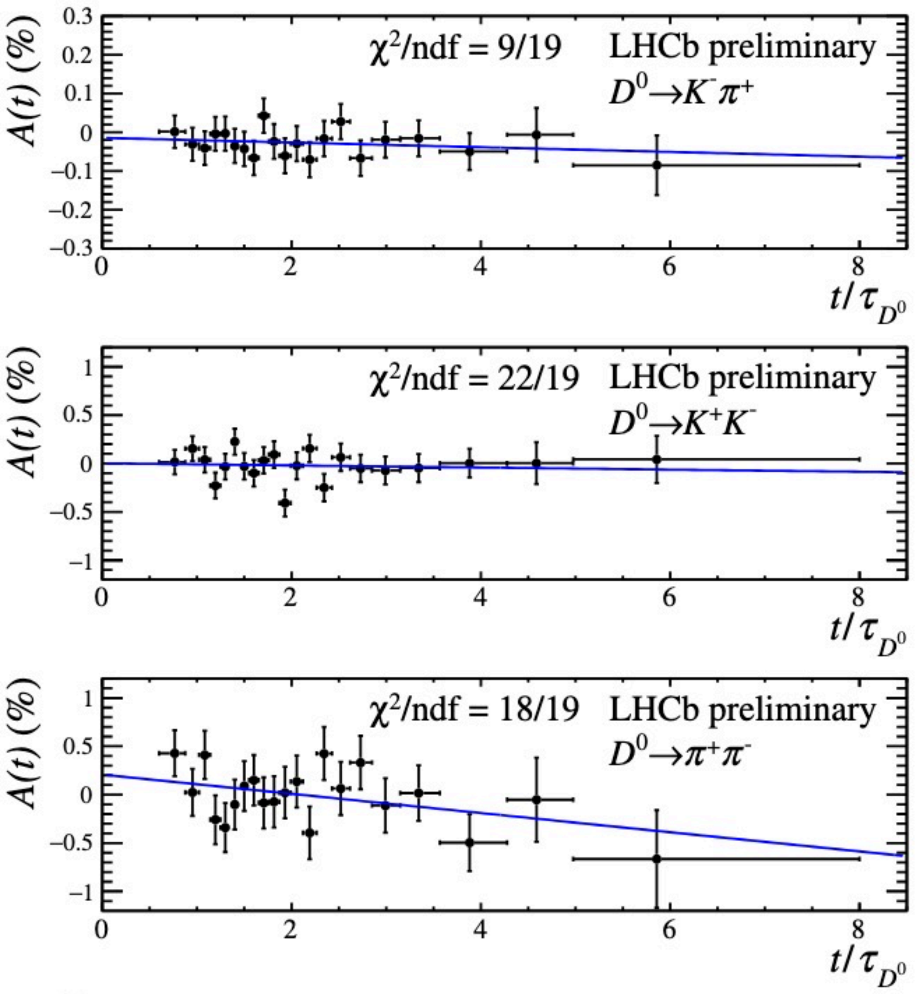
- Results

$$\begin{aligned} A_\Gamma(D^0 \to K^-\pi^+) &= (0.7 \pm 1.1) \times 10^{-4} \\ A_\Gamma(D^0 \to K^-K^+) &= (1.3 \pm 3.5 \pm 0.7) \times 10^{-4} \\ A_\Gamma(D^0 \to \pi^-\pi^+) &= (11.3 \pm 6.9 \pm 0.8) \times 10^{-4} \end{aligned}$$

- Neglecting weak phases in the decay amplitude, A_Γ does not depend on final state and the results can be combined

$$A_\Gamma(K^+K^- + \pi^+\pi^-) = (3.4 \pm 3.1 \pm 0.6) \times 10^{-4}$$

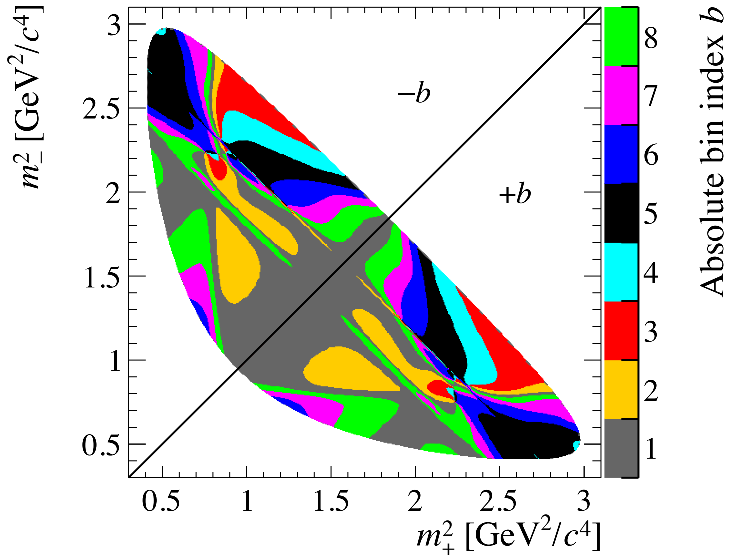
$$A_\Gamma(K^+K^- + \pi^+\pi^-,\ 2011\text{–}2016) = (0.9 \pm 2.1 \pm 0.7) \times 10^{-4}$$



arXiv:1903.03074, submitted to PRL

Measurement of the mass difference between neutral charm-meson eigenstates

- Use $D^0 \to K_S^0 \pi^+ \pi^-$ decays
  - Rich resonant structure
- Time-dependent Dalitz analysis performed with the model independent “bin-flip” approach [PRD99 (2019) 012007]
  - No need to have an accurate efficiency modelling
- Binning chosen to have about the same strong phase difference between D^0 and $\overline{D}^0$ amplitudes in each bin
- Run 1 data, both prompt and semileptonic (~2.3M events)



$$m_{\pm}^2 \equiv \begin{cases} m^2(K_S^0\pi^{\pm}) & \text{for } D^0 \to K_S^0\pi^+\pi^- \\ m^2(K_S^0\pi^{\mp}) & \text{for } \overline{D}^0 \to K_S^0\pi^+\pi^- \end{cases}$$

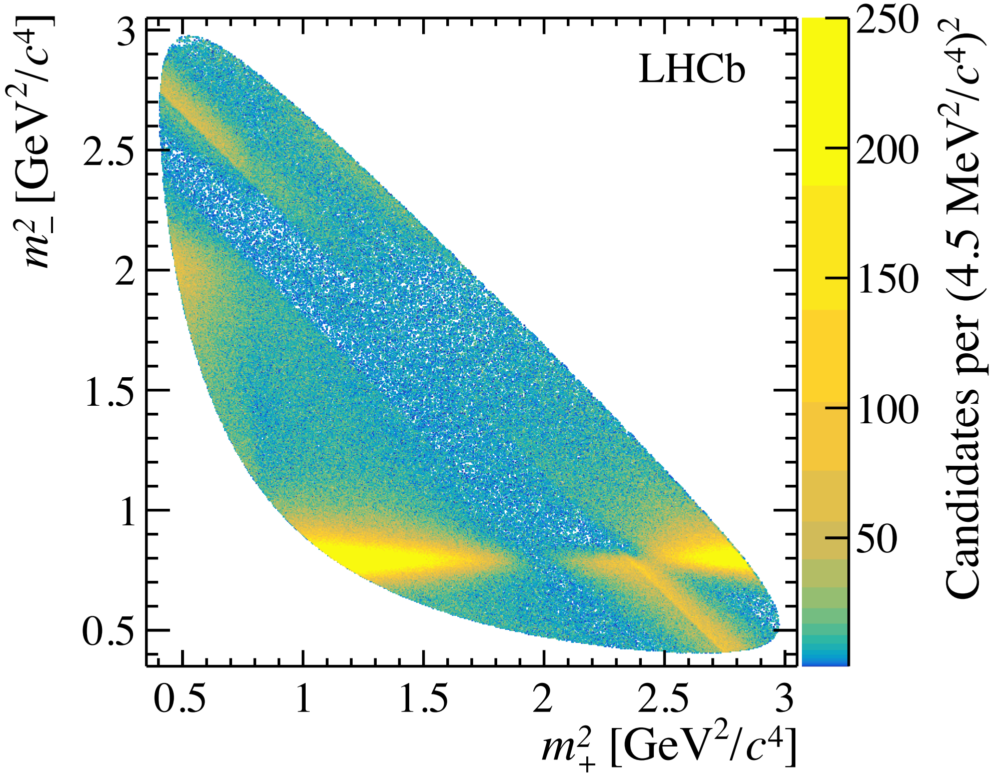
Measurement of the mass difference between neutral charm-meson eigenstates

- Observables: measure yield ratio (R), between b and –b bins, as a function of decay time. This is a function of

$$z_{CP} \pm \Delta z = -(q\backslash p)^{\pm 1}(y \pm ix)$$
$$x_{CP} = -Im(z_{CP}), y_{CP} = -Re(z_{CP})$$
$$\Delta x = -Im(\Delta z), \Delta y = -Re(\Delta z)$$

Δy often referred to as A_Γ

- Perform least-squares minimization that compares the decay-time evolution of signal yields in the Dalitz bins b and –b

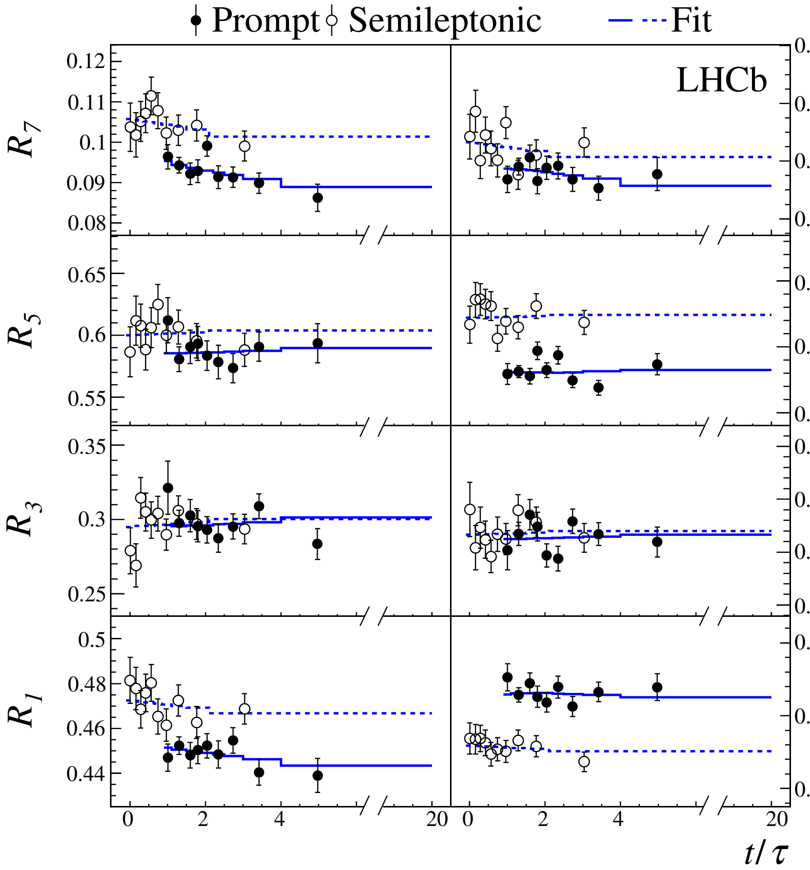


arXiv:1903.03074, submitted to PRL

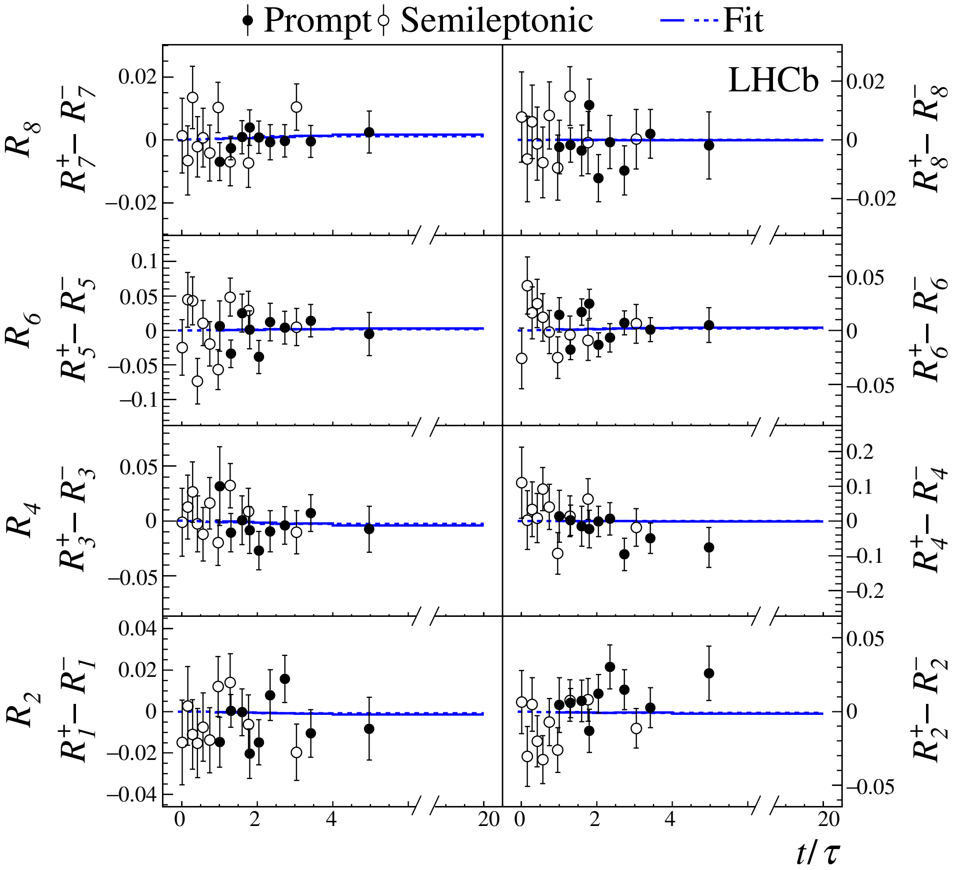
Measurement of the mass difference between neutral charm-meson eigenstates

- Allow for CPV in mixing

CP-averaged yield ratios



Difference of D^0 and $\overline{D}^0$ yield ratios

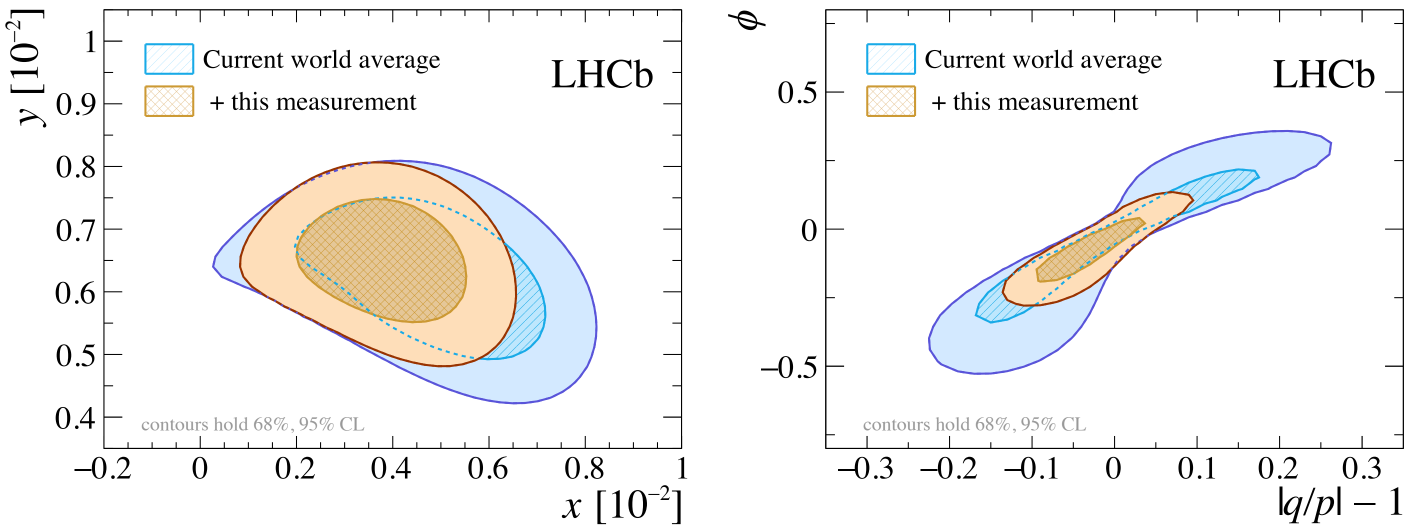


- Offset between prompt and semileptonic data due to efficiency variations across the Dalitz
- Slopes due to charm oscillations

Measurement of the mass difference between neutral charm-meson eigenstates

- Fit results compatible with CP symmetry hypothesis ($\Delta x = \Delta y = 0,\ x_{CP} = x, y_{CP} = y$)

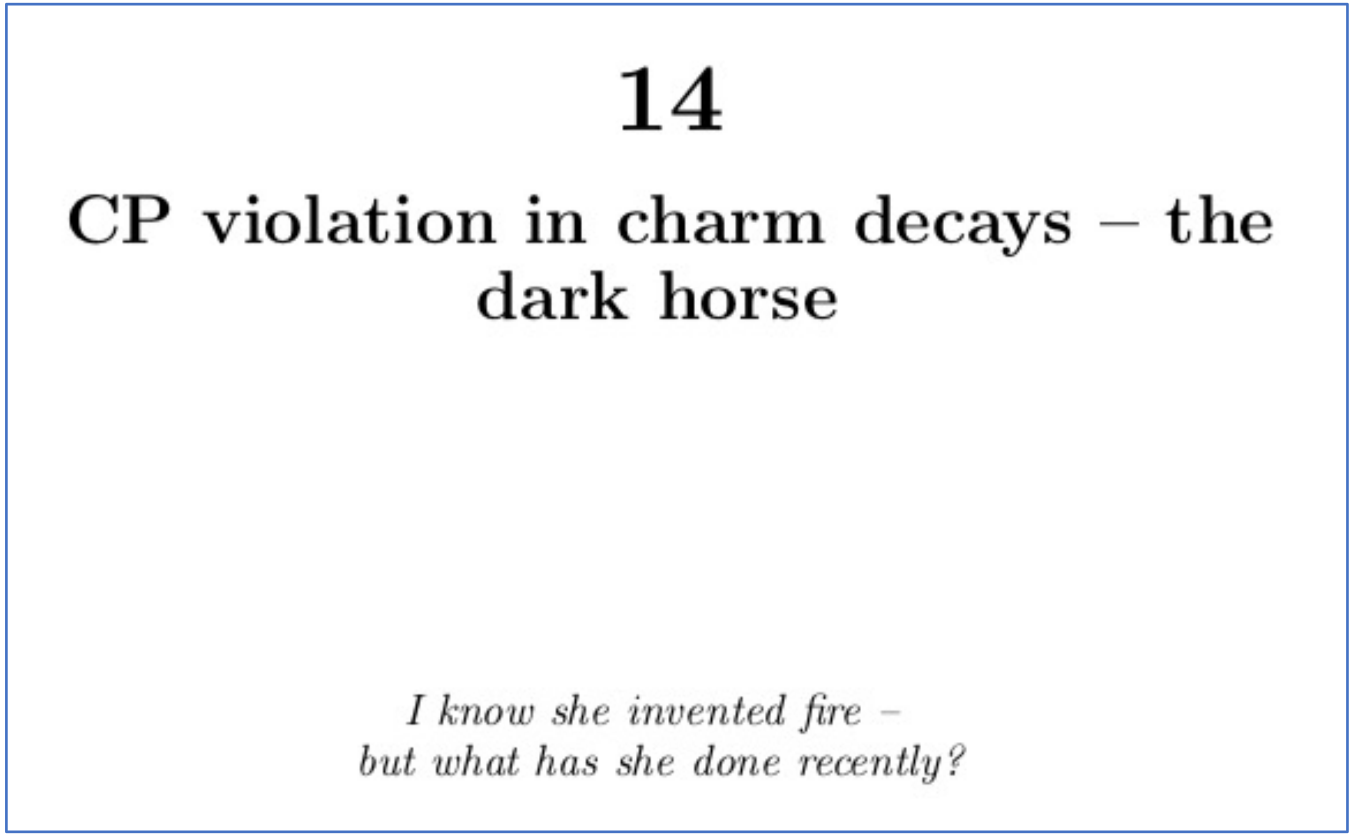
Parameter	Value $[10^{-3}]$
x_{CP}	$2.7 \pm 1.6 \pm 0.4$
y_{CP}	$7.4 \pm 3.6 \pm 1.1$
Δx	$-0.53 \pm 0.70 \pm 0.22$
Δy	$0.6 \pm 1.6 \pm 0.3$



- Most precise determination of x from single experiment!
- Combination with previous measurements → first evidence for $x > 0$.
  - Extremely important since sensitivity to ϕ relies on observables $\propto x\,sin(\phi)$

Conclusions

- Hope to have convinced you that charm physics is well alive and interesting
- Several recent and very important results
  - First observation of CP violation in charm decays
  - Most precise determination of x from single experiment and first evidence of $x > 0$
- Lots of analyses being updated to exploit the full LHCb dataset → exciting times ahead!
- Looking forward to first Belle II physics results, especially on final states with neutral particles



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CP violation in charm decays – the dark horse

I know she invented fire –
but what has she done recently?

I. I. Bigi and A. I. Sanda – CP violation – Cambridge University Press

Thanks for your attention!

Backup

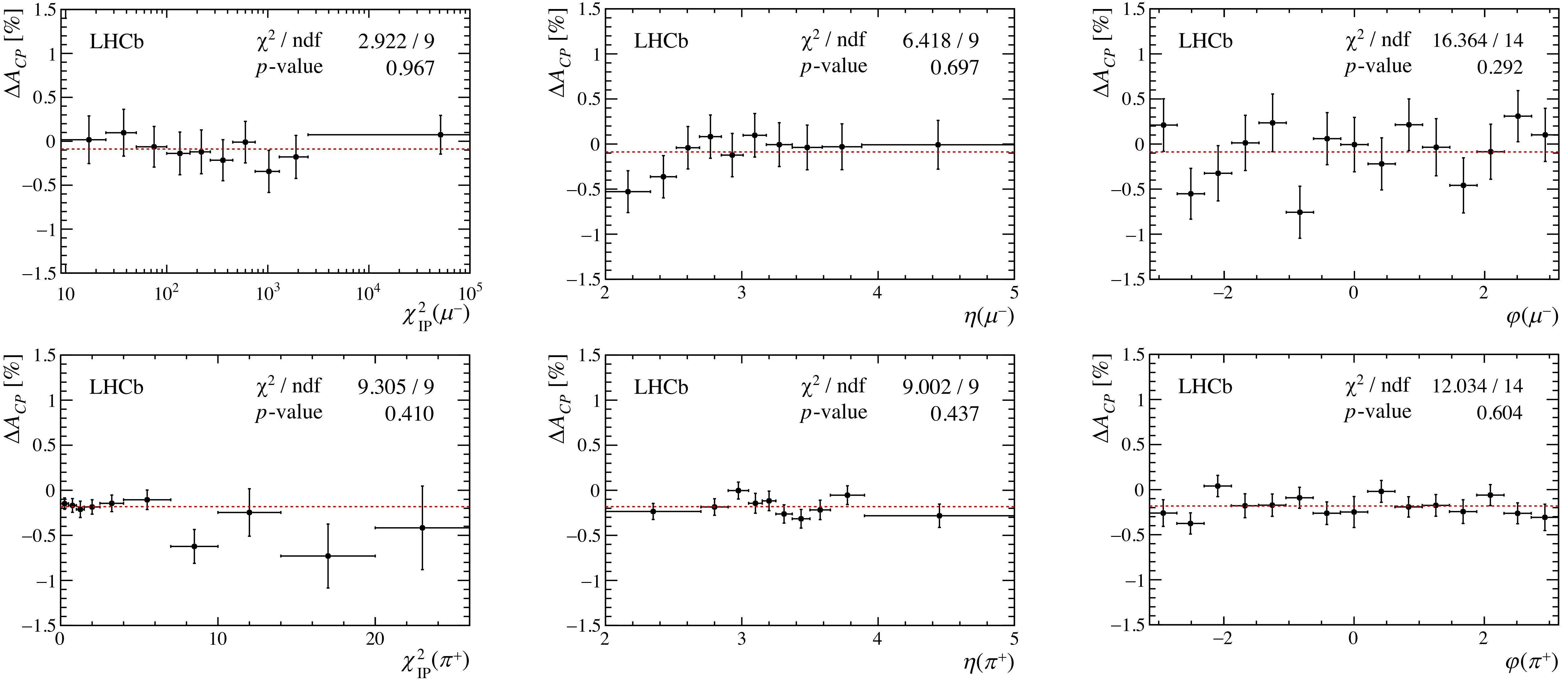
ΔA_{CP} future prospects

LHCB-PUB-2018-009

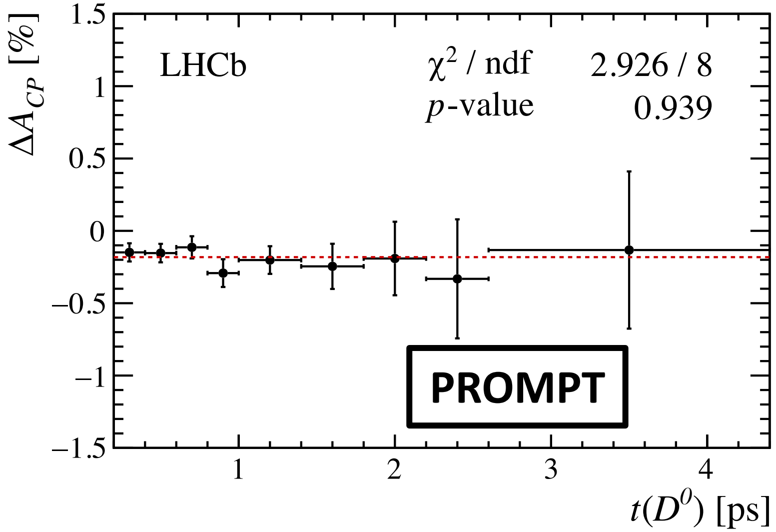
Sample ($\mathcal{L}$)	Tag	Yield $D^0 \to K^-K^+$	Yield $D^0 \to \pi^-\pi^+$	$\sigma(\Delta A_{CP})$ [%]	$\sigma(A_{CP}(hh))$ [%]
Run 1–2 (9 fb^{-1})	Prompt	52M	17M	0.03	0.07
Run 1–3 (23 fb^{-1})	Prompt	280M	94M	0.013	0.03
Run 1–4 (50 fb^{-1})	Prompt	1G	305M	0.01	0.03
Run 1–5 (300 fb^{-1})	Prompt	4.9G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

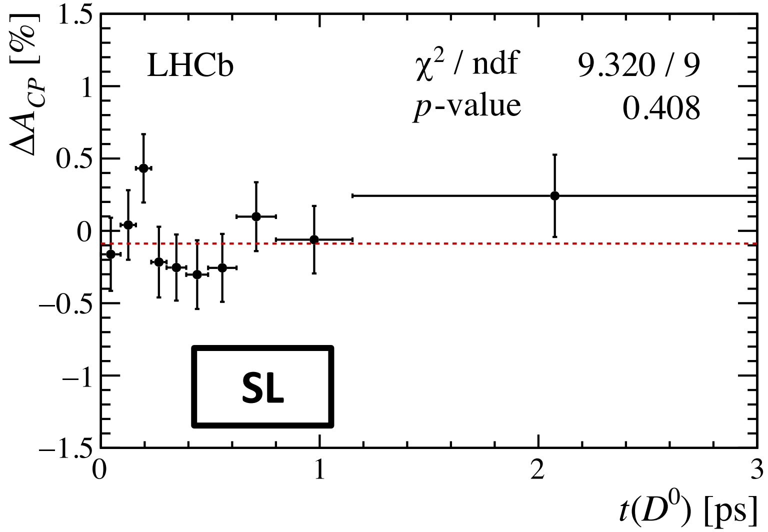
- With Upgrade-I $\sigma_{stat}(\Delta A_{CP})$ expected to be $\boldsymbol{\mathcal{O}(10^{-4})}$
- $\sigma_{stat}(\Delta A_{CP}) \sim \mathbf{3 \times 10^{-5}}$ including Run 5 (Upgrade-II)

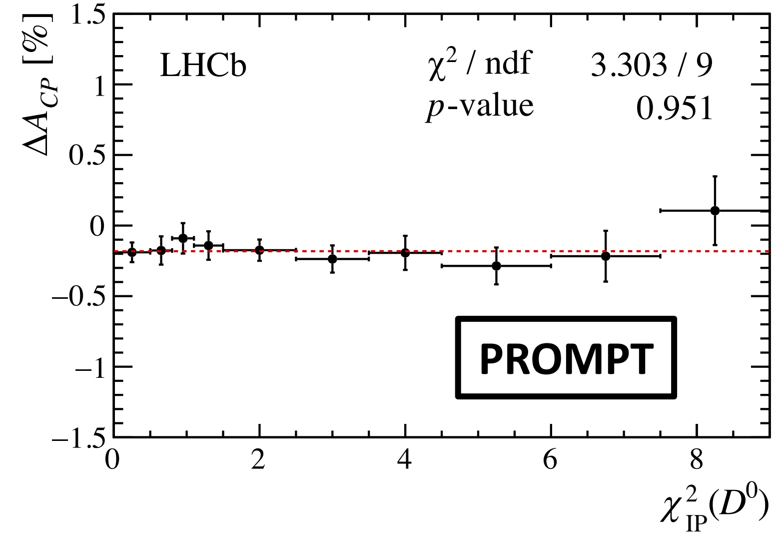
ΔA_{CP} - stability checks

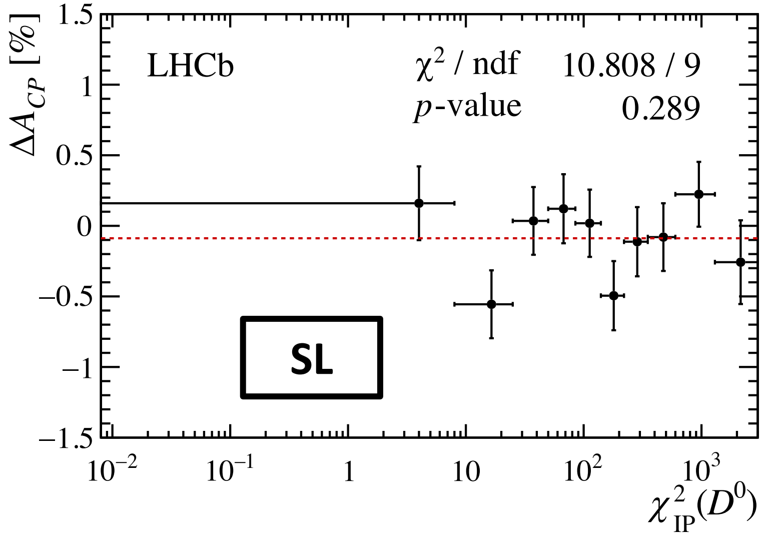


ΔA_{CP} - stability checks

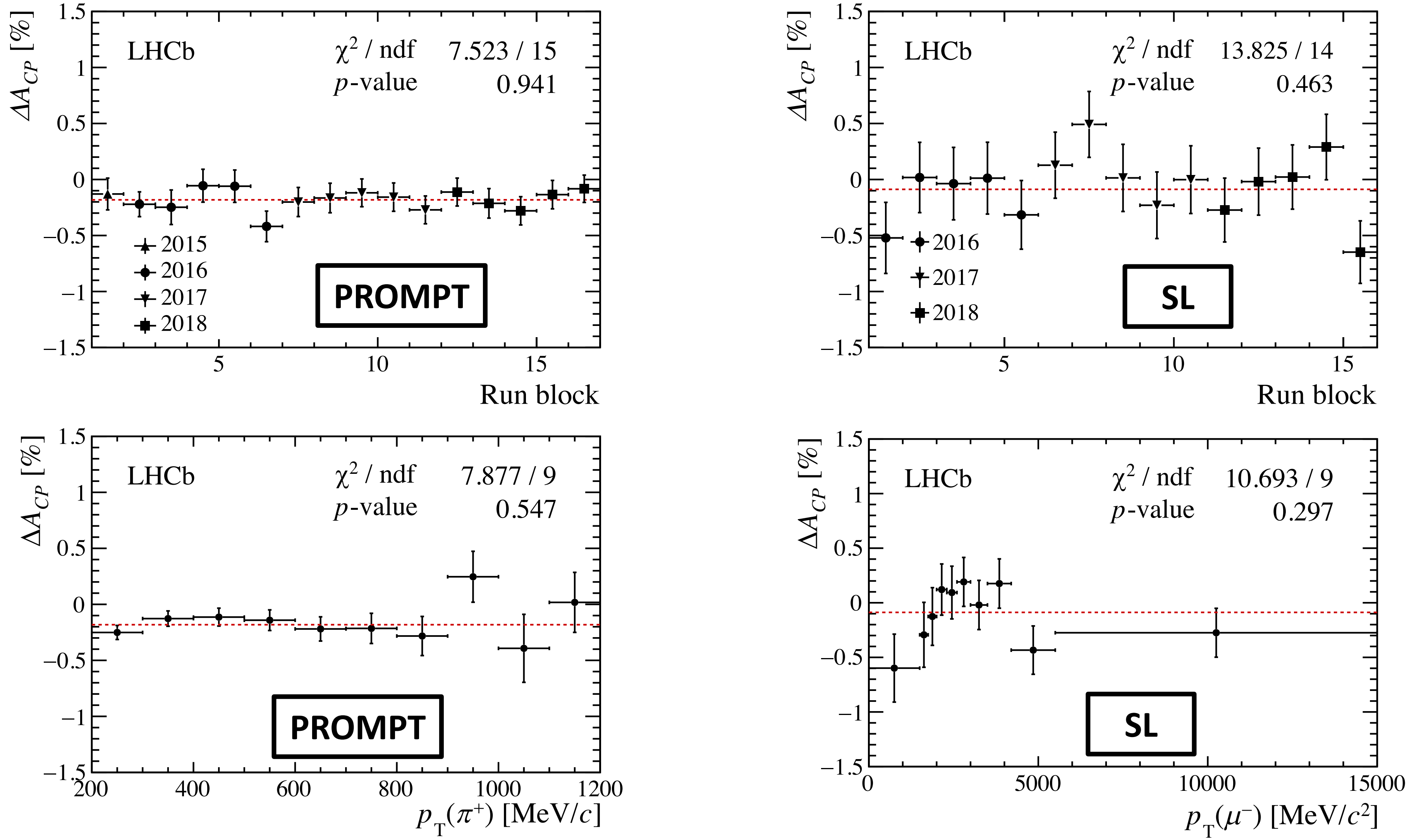








ΔA_{CP} - stability checks

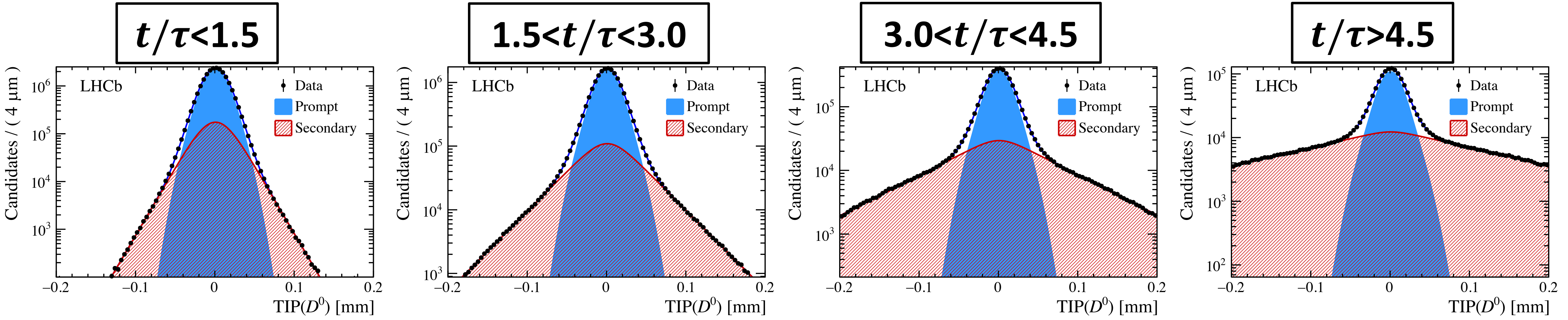


ΔA_{CP} - secondaries (prompt)

$$\Delta_{\rm sec} = \frac{f_{\rm sec}^{K^+K^-} - f_{\rm sec}^{\pi^+\pi^-}}{2}\left[A_{\rm raw}^{\rm sec}(KK) + A_{\rm raw}^{\rm sec}(\pi\pi) - A_{\rm raw}^{\rm prompt}(KK) - A_{\rm raw}^{\rm prompt}(\pi\pi)\right]$$

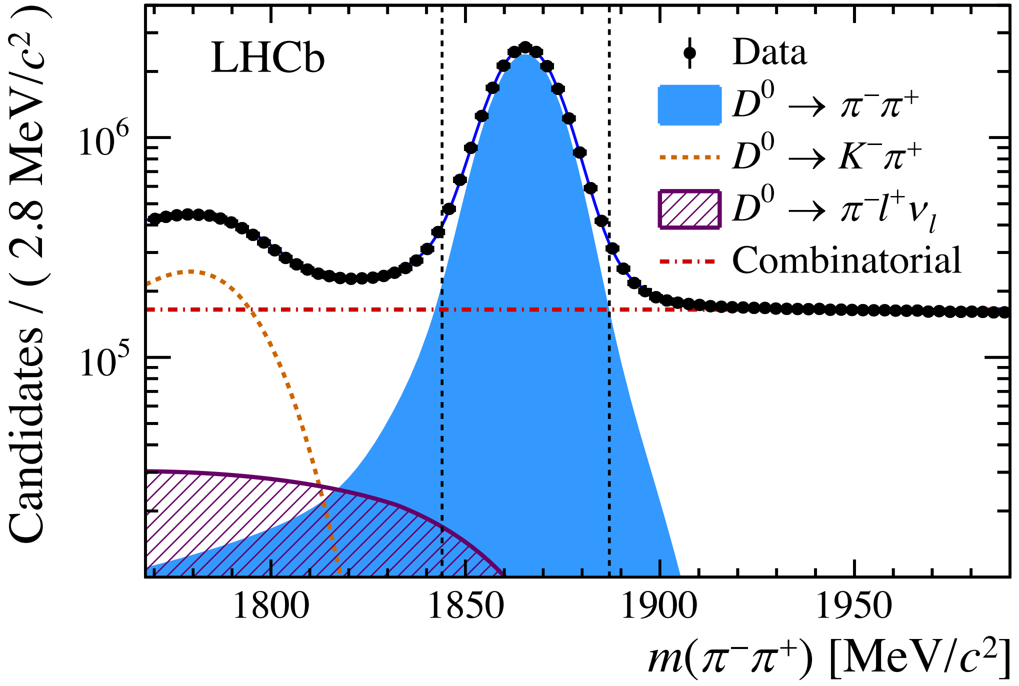
- Measure fraction of **secondary** D^0 by fitting the distribution of the D^0 IP in the plane transverse to the beam (**TIP**)
- Study performed in **bins of $t/\tau(D^0)$** to have a better control on the resolution

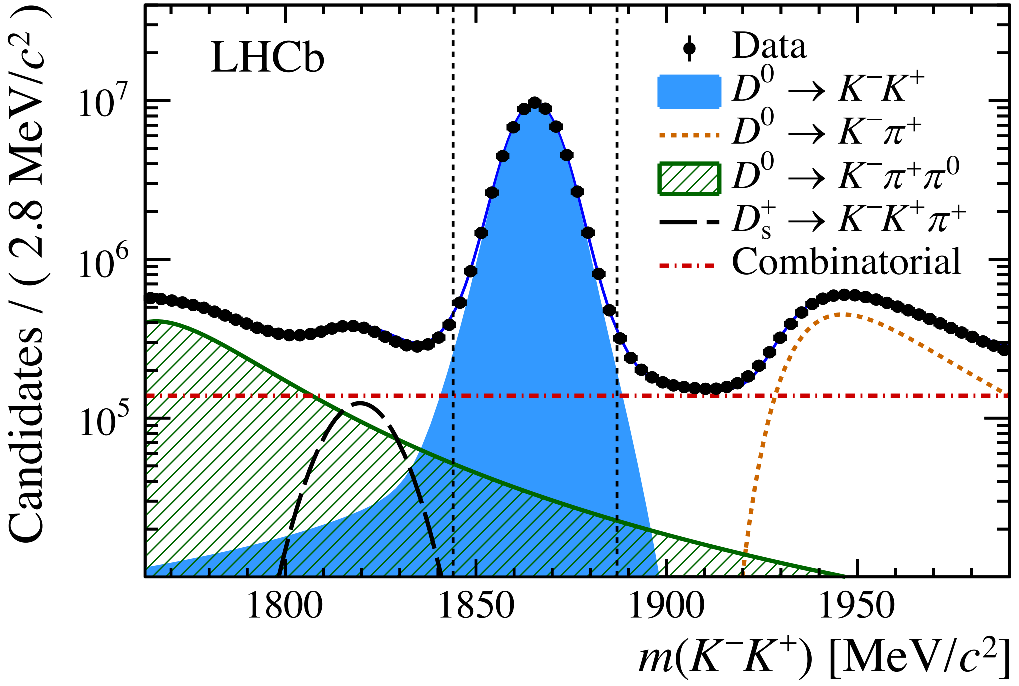
$$\mathrm{TIP} = \frac{\hat{n}_z \wedge \vec{p}}{|\hat{n}_z \wedge \vec{p}|} \cdot (\vec{x}_{\rm DV} - \vec{x}_{\rm PV})$$



ΔA_{CP} - peaking background (prompt)

The yields and raw asymmetries of $D^0 \to K^-\pi^+\pi^0$ ($D^0 \to \pi^- l^+ \nu_l$) are measured by fits to $m(K^-K^+)$ ($m(\pi^-\pi^+)$) and extrapolated to the signal region $[1844,1887]$ MeV$/c^2$





ΔA_{CP} – Difference in B^0 fraction (SL)

- Effective D^0 production asymmetry in SL B decays:
$$\boldsymbol{A}_{\mathbf{P,eff}}\left(\boldsymbol{D}^{\mathbf{0}}\right) = A_{\mathrm{P}}(B^+) + f(B^0)[A_{\mathrm{P}}(B^0) \cdot D - A_{\mathrm{P}}(B^+)]$$
- In Run 1 analysis: **difference in $\boldsymbol{f}\left(\boldsymbol{B}^{\mathbf{0}}\right)$** is $(0.34 \pm 0.18)\%$ between KK and $\pi\pi$ due to difference in B^0 and B^+ reconstruction **efficiencies**
- $\boldsymbol{A}_{\boldsymbol{P}}\left(\boldsymbol{B}^{\mathbf{0}}\right)$ **and** $\boldsymbol{A}_{\boldsymbol{P}}(\boldsymbol{B}^+)$ measured by LHCb (PLB 774 (2017) 139)
- Conservative assumption → $f(B^0)$ difference is **1%**
  ➔ difference in $A_{\mathrm{P,eff}}(D^0)$ is $(-0.0001 \pm 0.0058)\%$
  ➔ take $\mathbf{1 \times 10^{-4}}$ as syst uncertainty

ΔA_{CP} – Difference in τ acceptance (SL)

- Effective D^0 production asymmetry in SL B decays:
$$\boldsymbol{A_{P,eff}(D^0)} = A_P(B^+) + f(B^0)[A_P(B^0) \cdot D - A_P(B^+)]$$
- That depends also on $D = 1 - 2\mathcal{P}_{osc}$, so also on **lifetime acceptance** (slightly different between KK and $\pi\pi$)

$$\mathcal{P}_{\text{osc}} = \frac{\Gamma_d}{2}\int_{t_0}^{\infty} e^{-\Gamma_d t}(1-\cos(\Delta m_d t))\mathrm{t}$$

- Syst uncertainty taken **unchanged** from Run1 analysis ➔ estimated to be maximum $\boldsymbol{2\times10^{-4}}$

ΔA_{CP} – Mistag rate (SL)

$$\delta_\omega = \Delta A_{CP} - \Delta A_{\text{raw}} = 2\omega_{KK} A_{CP}(K^-K^+) - 2\omega_{\pi\pi}[A_{CP}(K^-K^+) - \Delta A_{CP}] \\ + 2A_{P,\text{eff}}(D^0)(\omega_{KK} - \omega_{\pi\pi}) + \Delta\omega_{KK} - \Delta\omega_{\pi\pi},$$

- Measure mistag on $\boldsymbol{D^0} \rightarrow \boldsymbol{K\pi}$ sample
- Take into account also **mixed** $D^0 \rightarrow K\pi$
- Use $A_{CP}(KK)$ and ΔA_{CP} from Run 1 SL
- Assume $\boldsymbol{A_{\mathrm{P,eff}}(D^0)} = 3\%$
- Systematic uncertainty is $\boldsymbol{4{\times}10^{-4}}$

*non-exhaustive list

ΔA_{CP} – some theoretical reference*

Golden et. al., PLB 222 (1989) 501

Buccella et al., PRD 51 (1995) 3478

Bianco et al., Riv. Nuovo Cim . 26N7 (2003) 1

Grossman et al, PRD 75 (2007) 036008

Artuso et al., Ann . Rev. Nucl. Part. Sci. 58 (2008) 249

Khodjamirian et al., PLB 774 (2017) 235

Pirtskhalava et al. , PLB 712 (2012) 81

Cheng et al., PRD 85 (2012) 034036

Feldmann et al., JHEP 06 (2012) 007

Li et al., PRD 86 (2012) 036012

Franco et al., JHEP 05 (2012) 140

Brod et al., JHEP 10 (2012) 161

Atwood et al., PTEP 2013 (2013) 093B05

Hiller et al., PRD 87 (2013) 014024

Grossman et al., JHEP 04 (2013) 067

Müller et al., PRL 115 (2015) 251802

Buccella et al., (2019) arXiv:1902.05564

- Result compatible with SM predictions that range from 10^{-3} to 10^{-4}
- However contributions from NP cannot be excluded at the moment

A_{CP} in $D_s^+ \to K_S^0\pi^+$, $D^+ \to K_S^0 K^+$, $D^+ \to \phi\pi^+$

- To cancel **production** and **detection** asymmetries, **control samples** are used: $D_s^+ \to K_S^0 K^+$, $D^+ \to K_S^0\pi^+$, $D_s^+ \to \phi\pi^+$
- *CP* asymmetries are obtained from the raw asymmetries differences:

$$A_{CP}(D_s^+ \to K_S^0\pi^+) = [A(D_s^+ \to K_S^0\pi^+) - A_D(K^0)] - A(D_s^+ \to \phi\pi^+)$$

$$\begin{aligned}A_{CP}(D^+ \to K_S^0 K^+) = {} & [A(D^+ \to K_S^0 K^+) - A_D(\bar{K}^0)] - [A(D^+ \to K_S^0\pi^+) - A_D(\bar{K}^0)] \\ & - [A(D_s^+ \to K_S^0 K^+) - A_D(\bar{K}^0)] + A(D_s^+ \to \phi\pi^+)\end{aligned}$$

$$A_{CP}(D^+ \to \phi\pi^+) = A(D^+ \to \phi\pi^+) - [A(D^+ \to K_S^0\pi^+) - A_D(\bar{K}^0)]$$

- Kinematics of $D_{(s)}^+$, π^+ and K^+ are weighted
- $\boldsymbol{A_{\mathrm{D}}(K^0)}$ is estimated by using simulation (JHEP 1407 (2014) 041)

Search for CPV with kinematic asymmetries – systematic uncertainties

Effect	$a_{\cos\Phi}^{CP}$	$a_{\sin\Phi}^{CP}$	$a_{\sin 2\Phi}^{CP}$	$a_{\cos\theta_1 \cos\theta_2 \cos\Phi}^{CP}$	$a_{\cos\theta_1 \cos\theta_2 \sin\Phi}^{CP}$
Signal model PDF	0.1	0.3	0.1	0.2	0.0
Partial-D^* model PDF	0.1	0.1	0.2	0.2	0.0
Combinatorial model PDF	0.1	0.1	0.3	0.0	0.3
Detector bias	0.6	0.6	0.6	0.6	0.6
Likelihood fit bias	0.1	0.1	0.1	0.1	0.1
Total	0.6	0.7	0.7	0.7	0.7

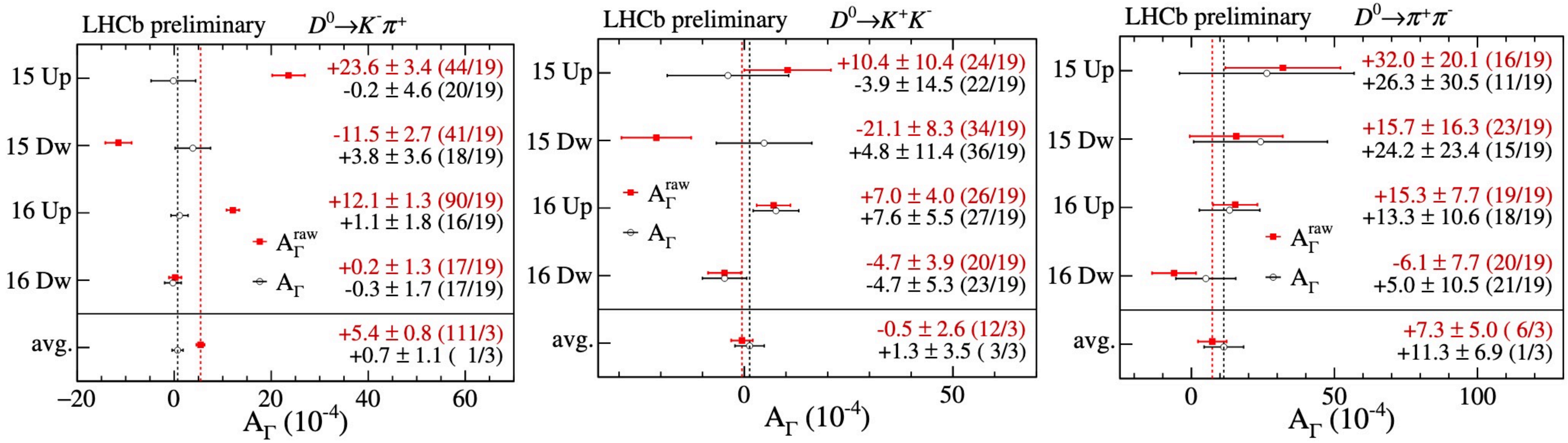
- Repeat measurement with CF $D^0 \rightarrow K^-\pi^+\pi^-\pi^+$ decays (CP asymmetries expected to be much smaller than experimental precision) → assign the statistical uncertainty as systematic uncertainty for this measurement

Measurement of A_Γ - systematic uncertainties

Source	$A_\Gamma(D^0 \to K^+K^-)$	$A_\Gamma(D^0 \to \pi^+\pi^-)$
Secondary decays	0.4	0.4
Δm background	0.3	0.5
$m(h^+h^-)$ background	0.3	0.2
Kinematic weighing	0.3	0.3
Sum in quadrature	0.7	0.8

Measurement of A_Γ - raw vs corrected asymmetries

Numerical values and chi2/ndof reported on the right of each plot



- Solid red squares: raw A_Γ value before any correction
- Empty black points: asymmetries measured after 3D weighting and subtracting secondaries contribution

Measurement of the charm mixing parameter y_{CP}

- Use $D^0 \to K^+K^-(\pi^+\pi^-)$ and $D^0 \to K^-\pi^+$ decays from semileptonic B decays
- Dataset: 3 fb^{-1} collected during Run 1
- Because of $D^0 - \overline{D}^0$ mixing, effective decay width (Γ_{CP+}) of decays to CP-even final states such as h^+h^-, with $h = K, \pi$, differs from the average width Γ
- The average width can be measured in decays with equal mixture of CP-even and CP-odd states, such as $K^-\pi^+$
- One can define

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

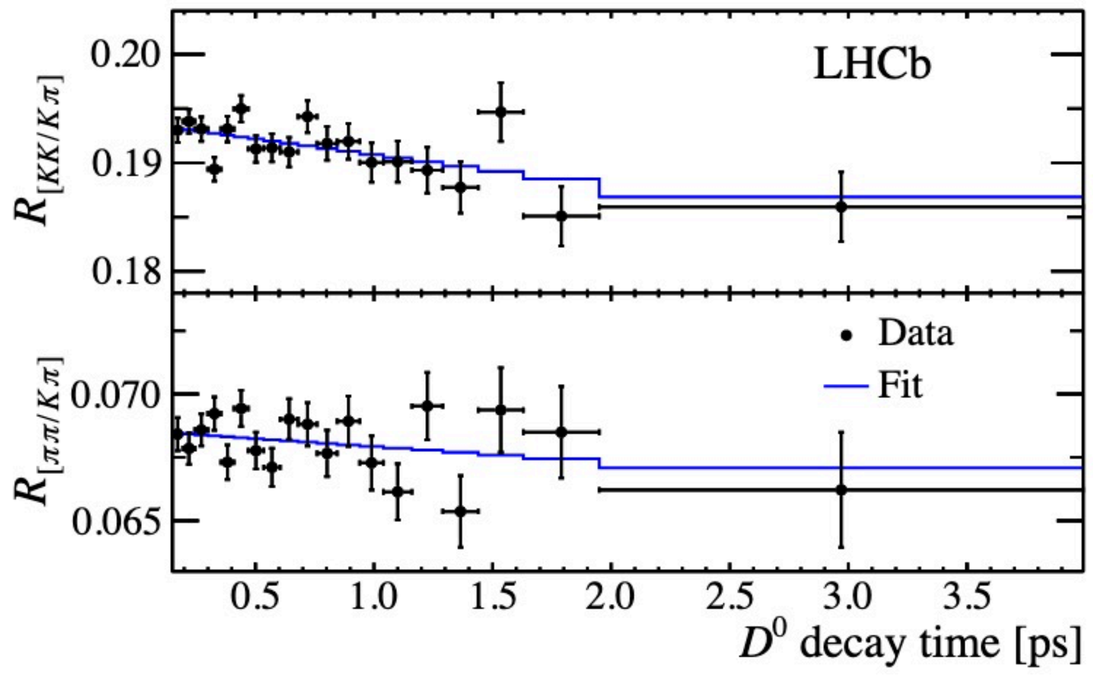
where $y_{CP} = y$, if CP is conserved or

$$2y_{CP} \simeq (|q/p| + |p/q|)y\cos\phi - (|q/p| - |p/q|)x\sin\phi$$

if CP is violated

Measurement of the charm mixing parameter y_{CP}

- Measure $\Delta\Gamma \equiv \Gamma - \Gamma_{CP+}$ from ratio of K^+K^- (or $\pi^+\pi^-$) and $K^-\pi^+$ signal yields as a function of decay time
- Obtain y_{CP} using Γ from external inputs as $y_{CP} = \Delta\Gamma/\Gamma$
- Combination of K^+K^- and $\pi^+\pi^-$ measurements yields



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

- Consistent with, and as precise as the current WA: $\boxed{(0.84 \pm 0.16)\%}$
- Also consistent with known value of y: $\boxed{(0.62 \pm 0.07)\%}$ ➡ No CPV in mixing