Observation of CP violation in charm decays with the LHCb experiment

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Outline

- Introduction
- *CP* violation (in charm)
- LHC as charm factory and the LHCb detector
- Recent LHCb results in the charm sector
  - Measurement of the mass difference between neutral charm-meson eigenstates with $D^0 \to K_S^0\pi^+\pi^-$ decay
  - Observation of *CP* violation in charm decays (ΔA_{CP} with $\mathrm{D}^0 \to \pi^-\pi^+$ and $\mathrm{D}^0 \to K^-K^+$)
- HFLAV update on CP violation searches
- Conclusions

Introduction

Why flavour physics?

- Some fundamental questions in flavour physics
  - Why three generations?
  - What's the origin of the mass hierarchy?
  - What's the origin of the coupling structure?
  - What's the origin of the baryon asymmetry of the universe?
- Discrepancies from the Standard Model could reveal the way to find the right answers

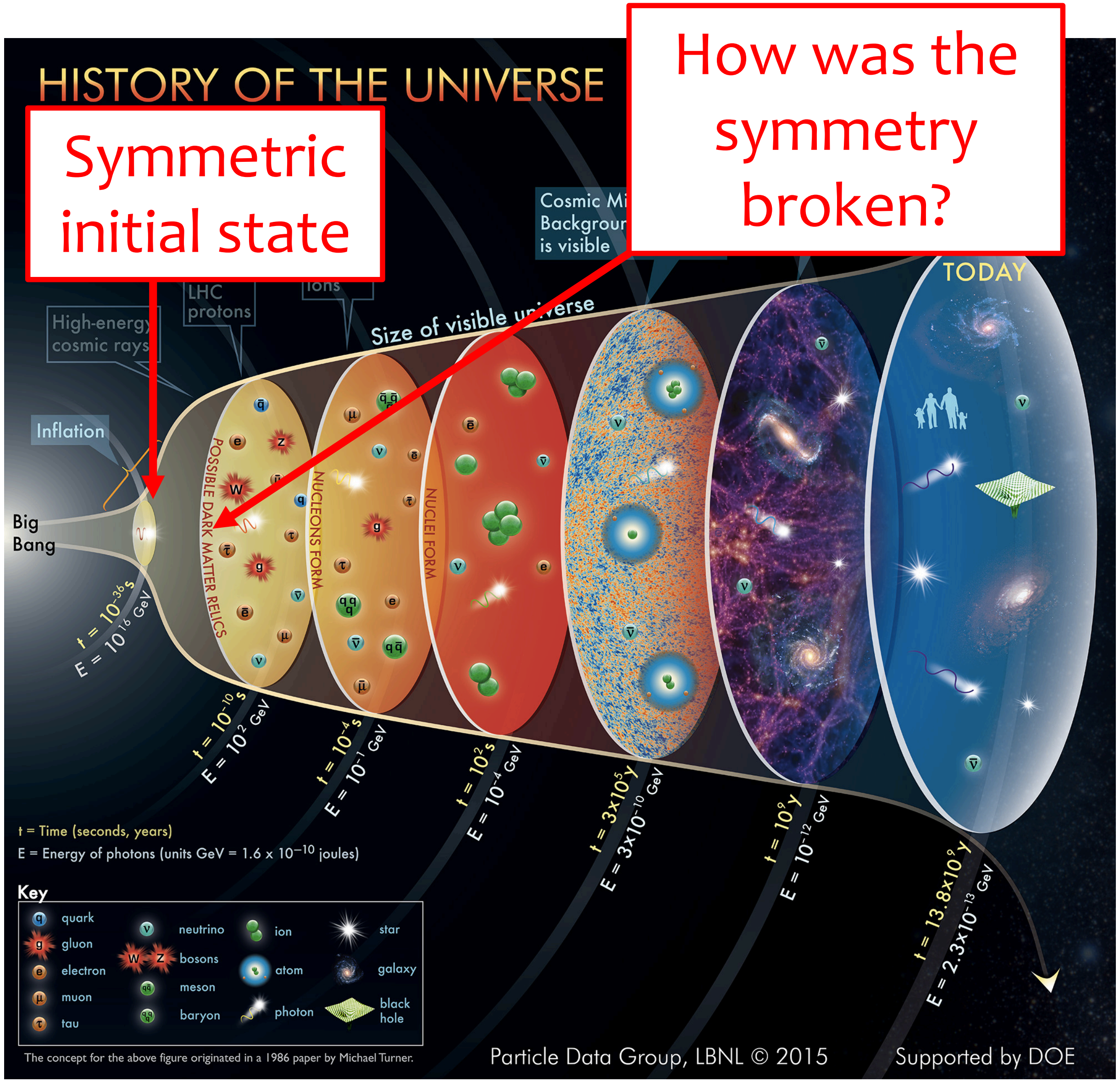
Ipse dixit

"If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods."

- Excerpt of Dirac's Nobel lecture in 1933
- At the time we were starting to wonder where had antimatter gone…

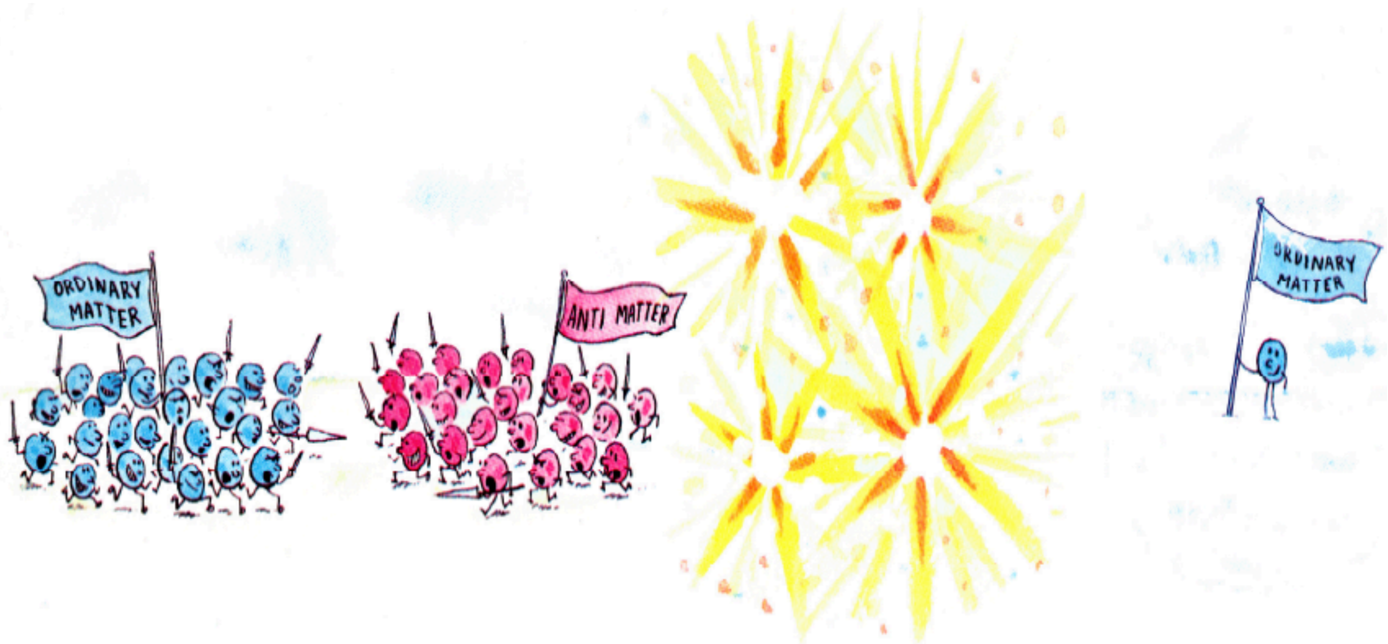
Matter-dominated Universe

- Nowadays we know that there's no evidence of primary antimatter on the scale of the observable universe
- What led to the disappearance of antimatter assuming an initial symmetric state?
- How big the asymmetry should have been?



Mainstream explanation

- Antimatter and matter particles annihilated massively in the early universe, but a tiny fraction of matter was left over: every 10 billion particles, a handful was not annihilated away



- The radiation produced by this gigantic initial annihilation is what we see today as the big bang afterglow: the cosmic microwave background

Sakharov conditions

- In 1967 Sakharov enumerated the three conditions which are necessary for the dynamical evolution of an initially symmetric to a matter-dominated universe

1. Baryon number should not be conserved
   - Otherwise there's no way to produce an excess of baryons
2. Charge (C) and Charge-Parity (CP) should not be conserved
   - Interactions which produce more baryons should not be counterbalanced by interactions which produce more anti-baryons
3. Interactions must be out of thermal equilibrium
   - Otherwise the baryonic asymmetry is diluted by inverse processes

- In a few words: the universe is asymmetric because the baryon number is not conserved in C- and CP-violating processes giving rise to more baryons than antibaryons in the expanding universe

Can we explain the asymmetry by known physics?

- Qualitatively: yes
  - The Standard model in principle contains all the necessary ingredients
- It is possible to derive the ratio of the number of baryons to that of photons in the universe

$$\eta = \frac{n_B}{n_\gamma} \sim \frac{(m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2)\,J}{M^{12}}$$

where $J \approx 3\times10^{-5}$ is the Jarlskog invariant quantifying the size of CP violation in the Standard Model and $M \approx 100$ GeV is the electroweak scale at which the baryon asymmetry freezes out

Can we explain the asymmetry by known physics?

- Quantitatively: no
- The previous equation gives $\eta \approx 10^{-19}$, whereas using Planck experimental data on cosmic microwave background one gets

$$\eta = (6.04 \pm 0.08) \times 10^{-10}$$

- This is off by 10 orders of magnitude!
- CP violation in the Standard Model is too small → strong indication that new sources of CP violation should exist in some beyond-the-SM physics

CP violation

The charge current Lagrangian

The spontaneous symmetry breaking introduce the CKM matrix in the charge current Lagrangian

Mass basis

$$\mathcal{L}_{kin}^{cc} = \frac{g}{\sqrt{2}} \bar{u}_{L,i} V_{u,L}^{\dagger} \gamma_{\mu} W^{-\mu} d_{L,i} V_{d,L}$$

$$\frac{g}{\sqrt{2}} \bar{d}_{L,i} V_{d,L}^{\dagger} \gamma_{\mu} W^{+\mu} u_{L,i} V_{u,L}$$

$$V_{u,L}^{\dagger} V_{d,L} =$$

$$V_{d,L}^{\dagger} V_{u,L} =$$

V_{CKM}

The CKM matrix

$$V \approx \begin{pmatrix} 1 & 0.2 & 0.004e^{-i65^\circ} \\ -0.2 & 1 & 0.04 \\ 0.009e^{-i22^\circ} & -0.04 & 1 \end{pmatrix}$$

$$V \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

The CKM matrix

very suggestive pattern

$$\lambda \approx 0.2 \qquad A \approx 0.8$$

$$\rho^2 + \eta^2 \approx 0.15 \qquad \eta/\rho \approx 2.3$$

$$V \approx \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

CP violation key dates

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

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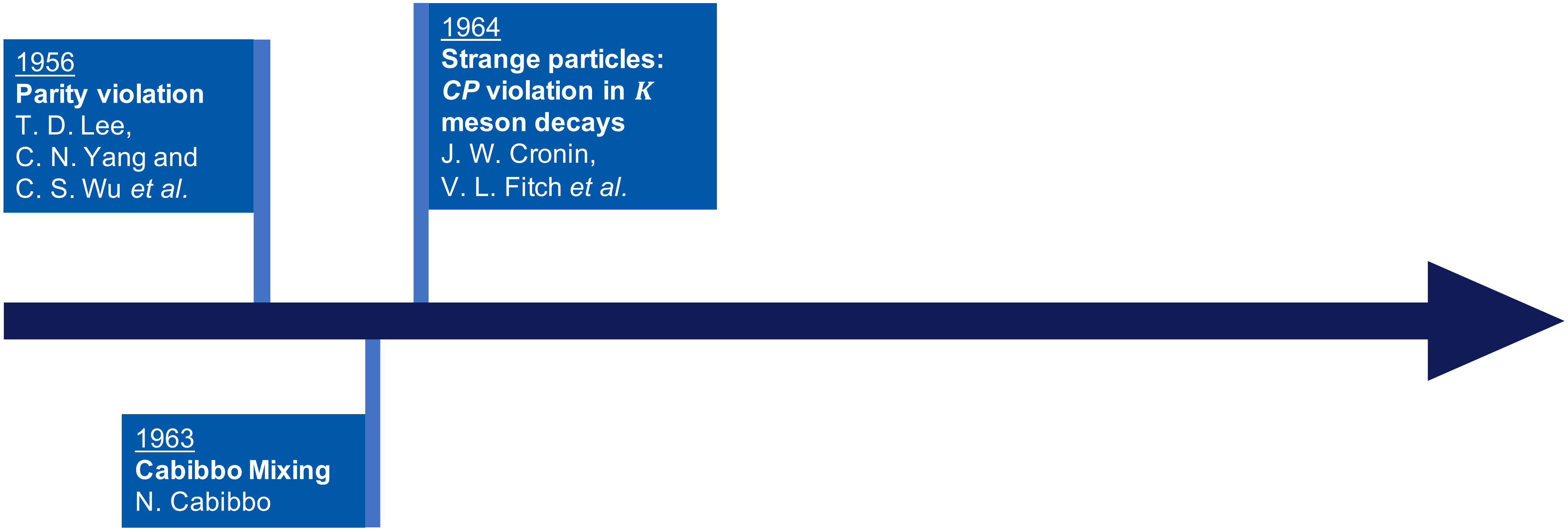
1963
Cabibbo Mixing
N. Cabibbo

CP violation key dates



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***CP* violation in K**
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J. W. Cronin,
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The CKM matrix
M. Kobayashi and
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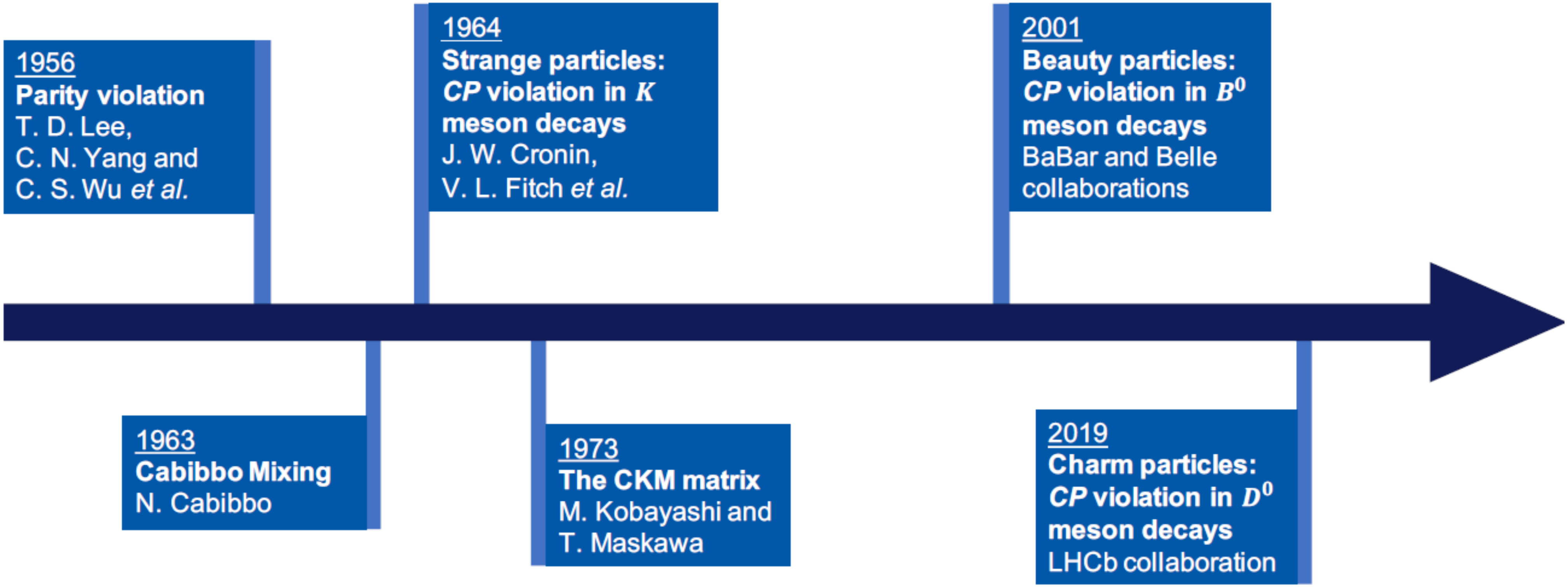
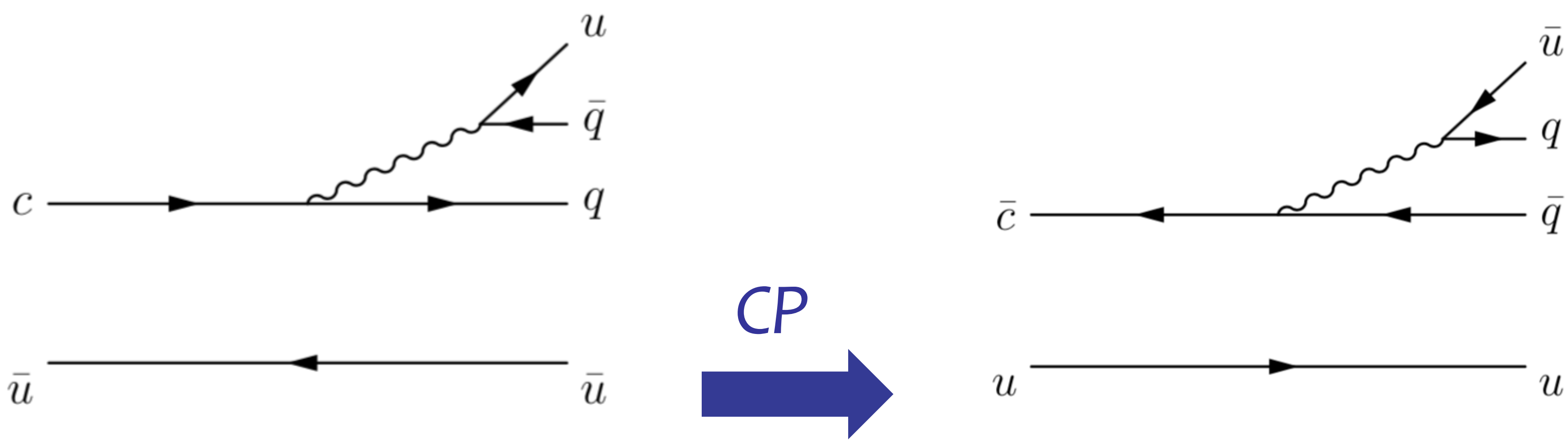
2001
Beauty particles:
***CP* violation in B^0**
meson decays
BaBar and Belle
collaborations

CP violation key dates



CP violation



$$A = \rho e^{i\delta} e^{i\theta}$$

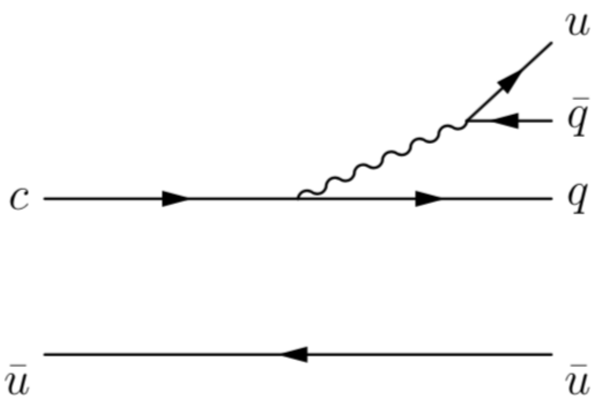
$$\bar{A} = \rho e^{i\delta} e^{-i\theta}$$

A *CP* transformation has the effect of :

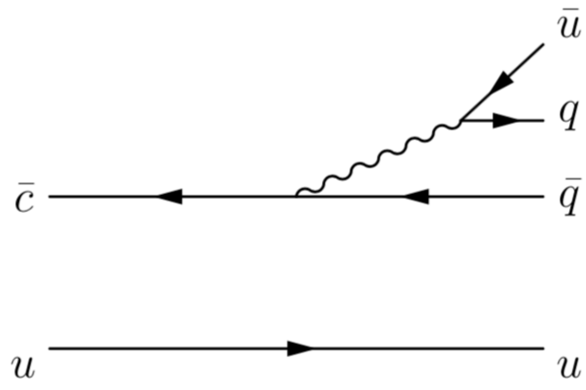
- changing the sign of the phase due to weak interactions (θ)
- leaving unchanged the phase due to strong interactions (δ)

CP violation

Tree level



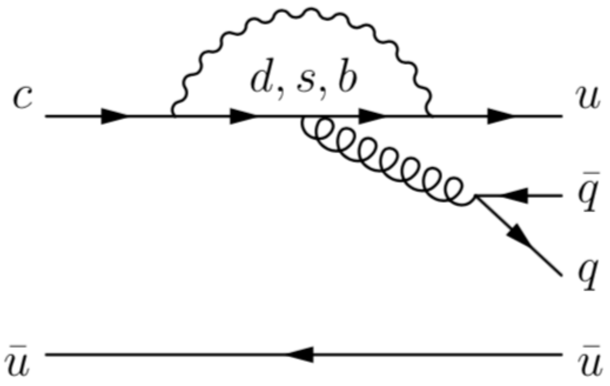
CP



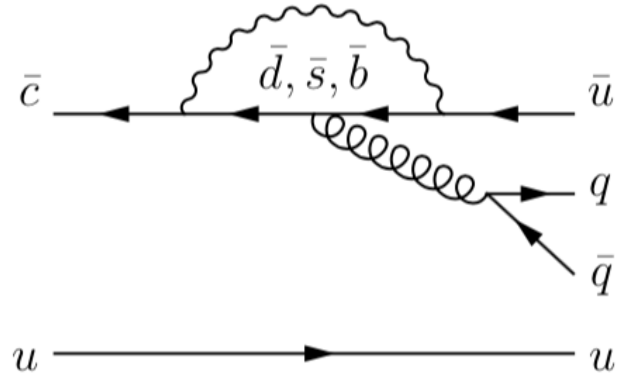
$A_1 = \rho_1 e^{i\delta_1} e^{i\theta_1}$

$\bar{A}_1 = \rho_1 e^{i\delta_1} e^{-i\theta_1}$

Loop level



CP



$A_2 = \rho_2 e^{i\delta_2} e^{i\theta_2}$

$\bar{A}_2 = \rho_2 e^{i\delta_2} e^{-i\theta_2}$

$$|\bar{A}_1 + \bar{A}_2|^2 - |A_1 + A_2|^2 = 4\rho_1\rho_2 \sin(\theta_1 - \theta_2)\sin(\delta_1 - \delta_2)$$

CP violation

$$|\bar{A}_1 + \bar{A}_2|^2 - |A_1 + A_2|^2 = 4\rho_1\rho_2 \sin(\theta_1 - \theta_2) \sin(\delta_1 - \delta_2)$$

It differs from zero if $\delta_1 \neq \delta_2$ and $\theta_1 \neq \theta_2$

To observe CP violation in the decay it is necessary to have two distinct paths with amplitudes of different phases

D^0 mixing

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

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

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

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

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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 either x or 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}

$x = (0.36^{+0.21}_{-0.16})\%$ $y = (0.67^{+0.06}_{-0.13})\%$ [HFLAV]

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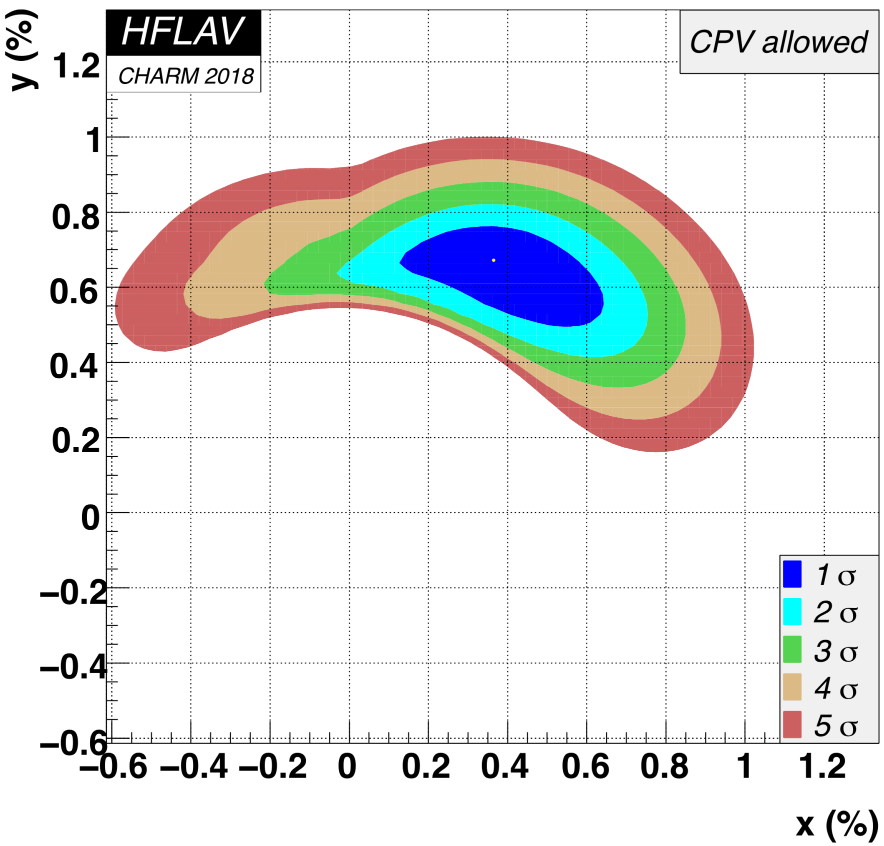
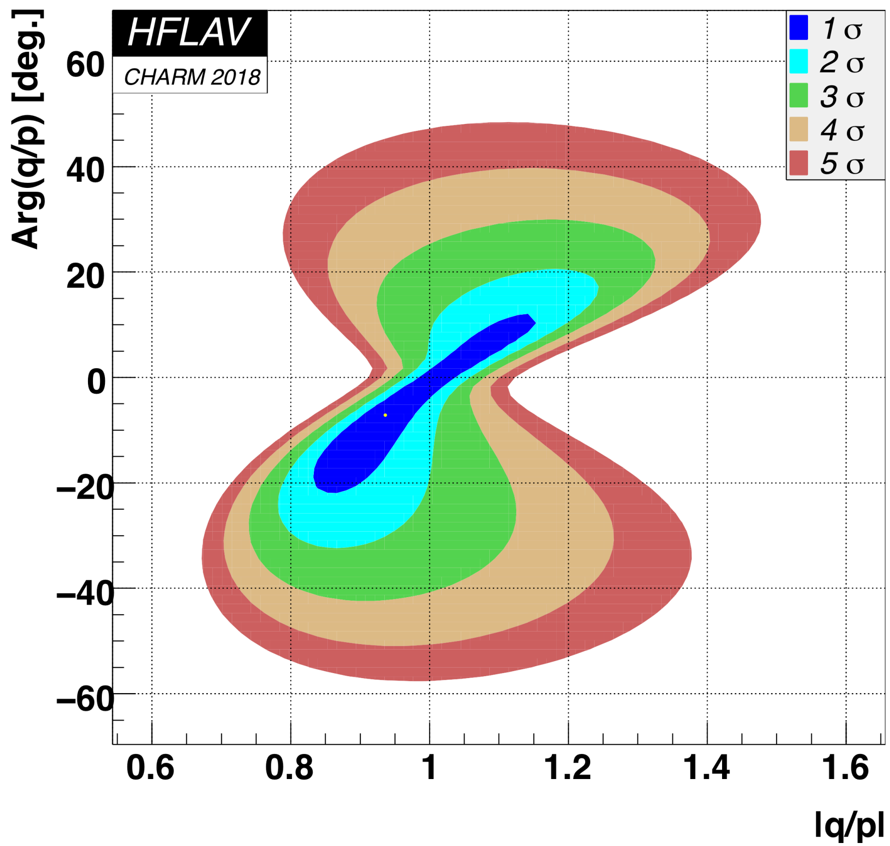
CP violation in D^0 mixing

If $|q/p| \neq 1$
CP violation occurs in D^0 mixing

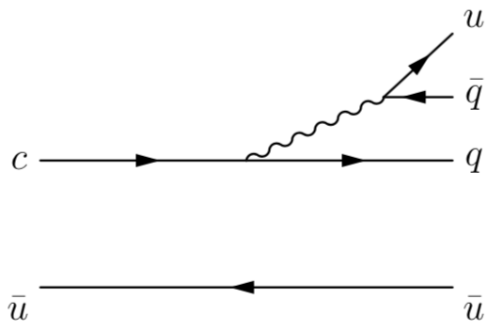
Current experimental status on D^0 mixing



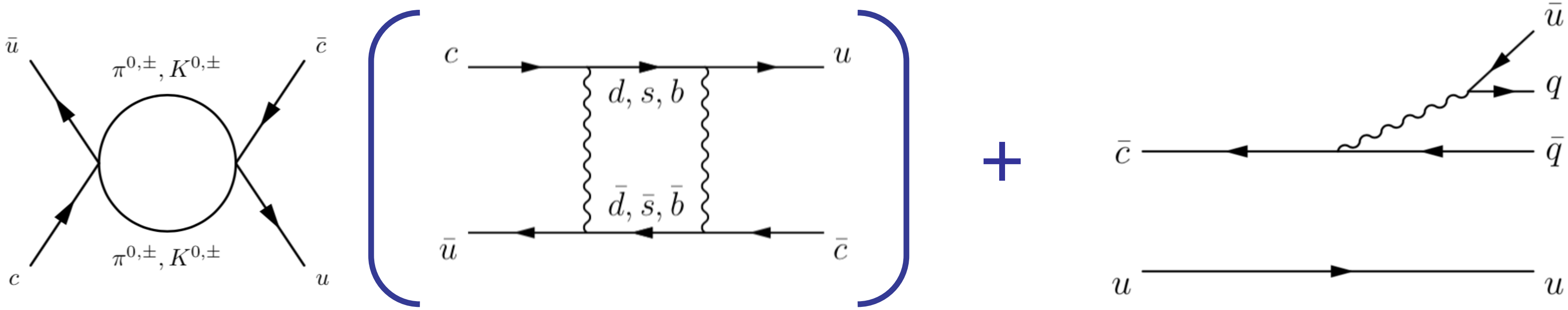


CP violation in the interference

Starting from a given D^0 or $\overline{D}^0$ meson there are two different quantum paths to get the same final state → interference!



OR



In case that $|D^0 \rightarrow \overline{D}^0 \rightarrow f|^2 \neq |\overline{D}^0 \rightarrow D^0 \rightarrow f|^2$, there is *CP* violation in the interference

Why charm is charming?

- *CP* violation in charm sector (was) not observed
- Only way to probe *CP* violation in up-type mesons
- Complementary to K and B mesons
- SM expectation lie in the range $10^{-3} - 10^{-4}$
- Intense theoretical activities since several years on this topic

(Not a complete) List of recent theoretical papers on charm physics

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., AR 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., arXiv:1902.05564 (2019)

Today results are on those observables

CP violation in the decay can be observed if the asymmetry

$$A_{CP}^{dir}(D^0 \to f) = \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2}$$

is different from zero

Direct *CP* violation

By defining:

$$z_{CP} \pm \Delta z = -(q/p)^{\pm 1}(y \pm ix)$$

$$x_{CP} = -\mathrm{Im}(z_{CP}), y_{CP} = -\mathrm{Re}(z_{CP})$$

$$\Delta x = -\mathrm{Im}(\Delta z), \Delta y = -\mathrm{Re}(\Delta z)$$

Phys. Rev. D 99 (2019) 012007

→

***CP* violation in mixing**

$$x_{CP} = x, y_{CP} = y$$

$$\Delta x = \Delta y = 0$$

if *CP* conserved

Δy is more often referred to as A_Γ

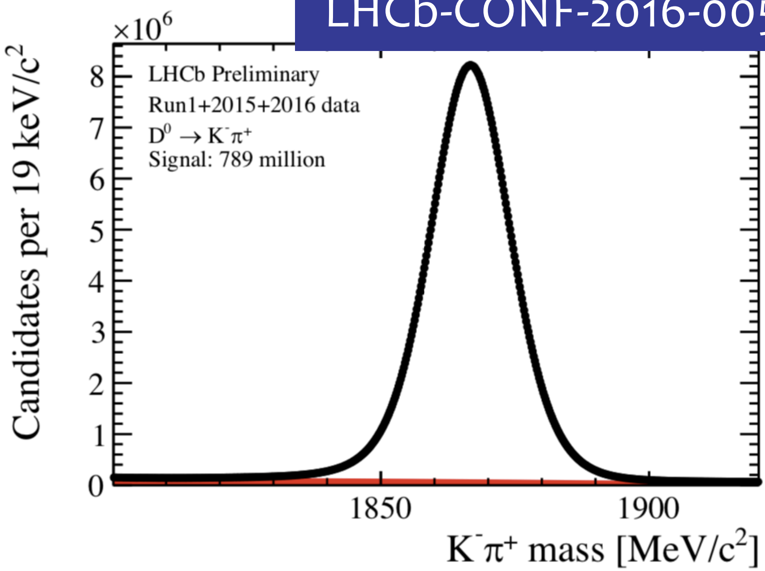
LHC: a charm factory

- At the LHC, the production cross-section of charm is ~ 20 times larger than the beauty one

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

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

LHCb-CONF-2016-005



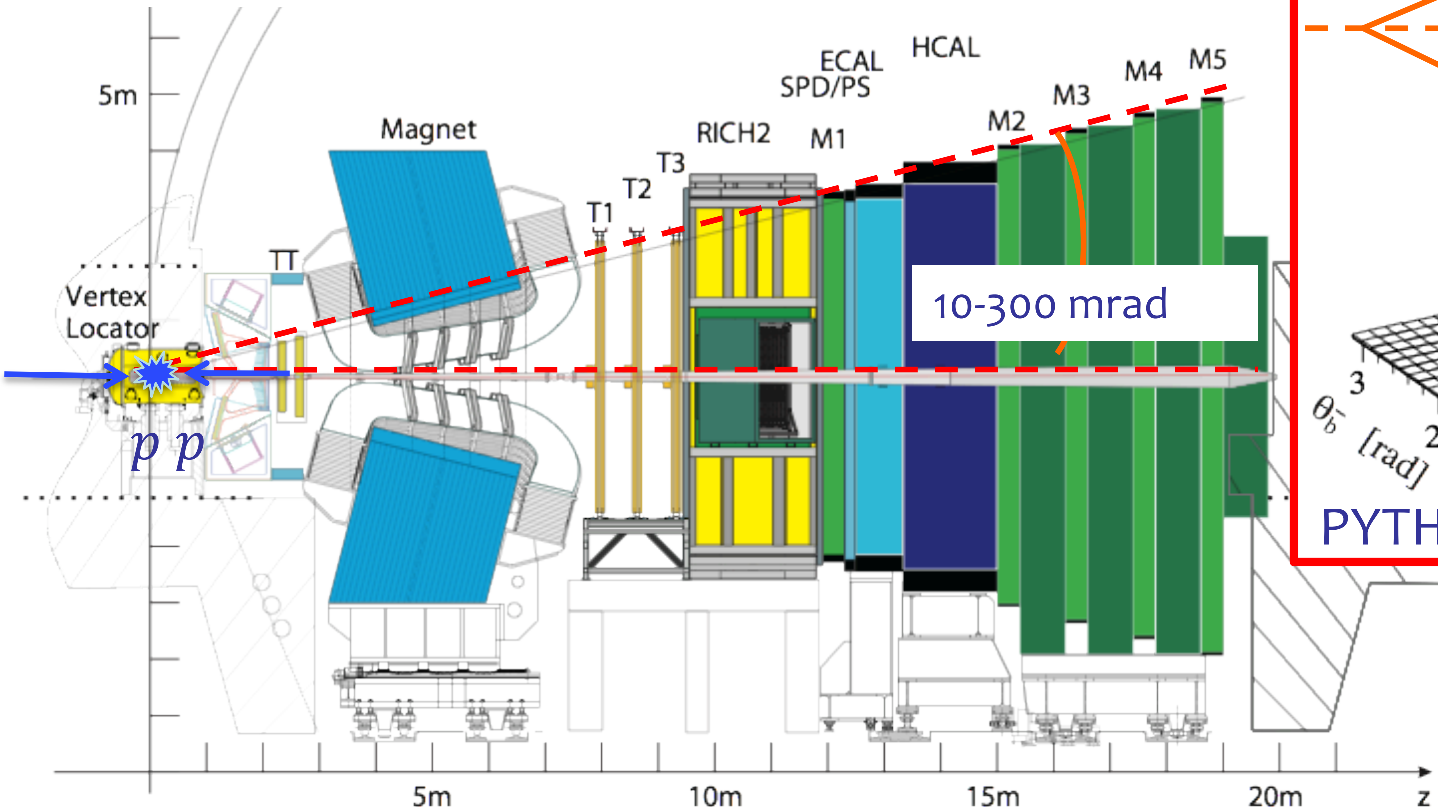
More than 1 billion of $D^0 \to K^-\pi^+$ events reconstructed with the full LHCb data sample

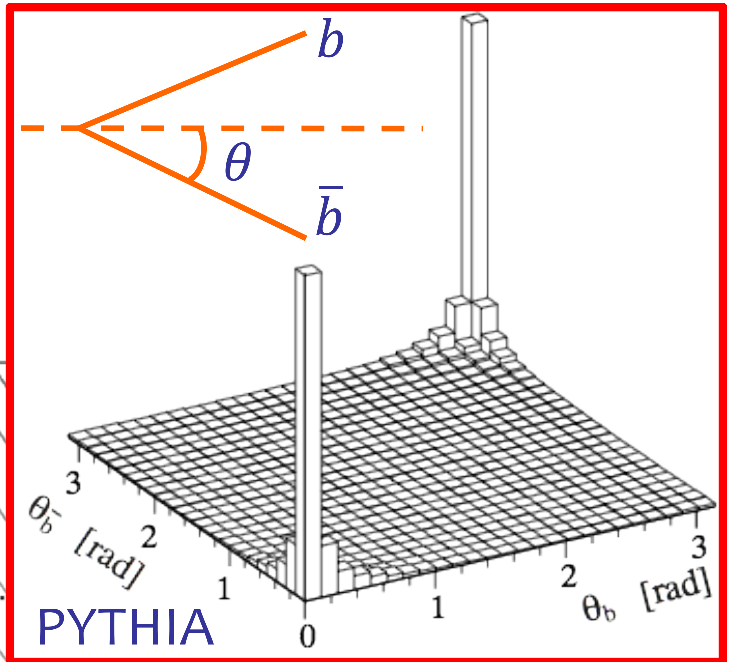
The LHCb detector

Int. J. Mod. Phys. A30 (2015) 07

FORWARD-PEAKED PRODUCTION

- LHCb designed as forward spectrometer (operating in collider mode) covering the pseudorapidity range $2 < \eta < 5$





The LHCb detector

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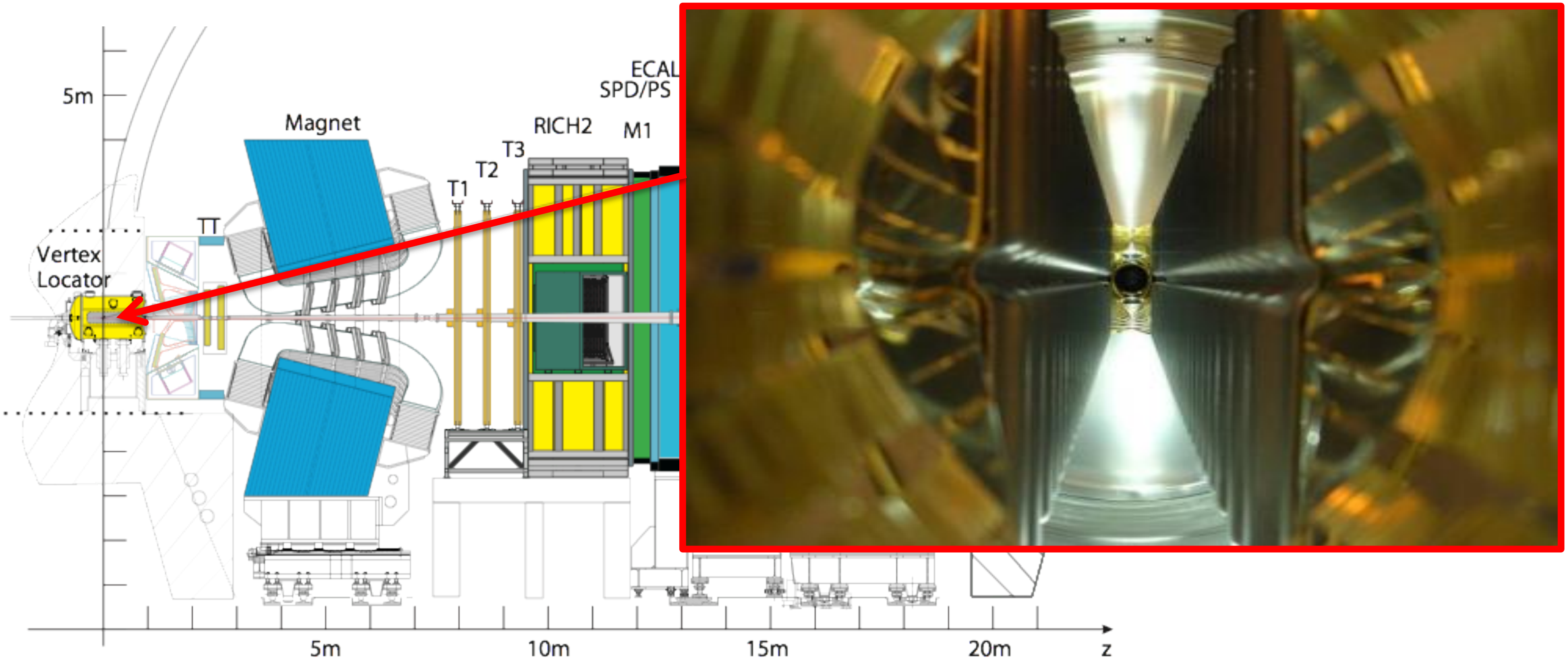
VELO PRECISION VERTEXING

- 20 μm impact parameter resolution, corresponding to $\sim 0.1 \times \tau(D^0)$ decay-time resolution for a 2-body charm decay

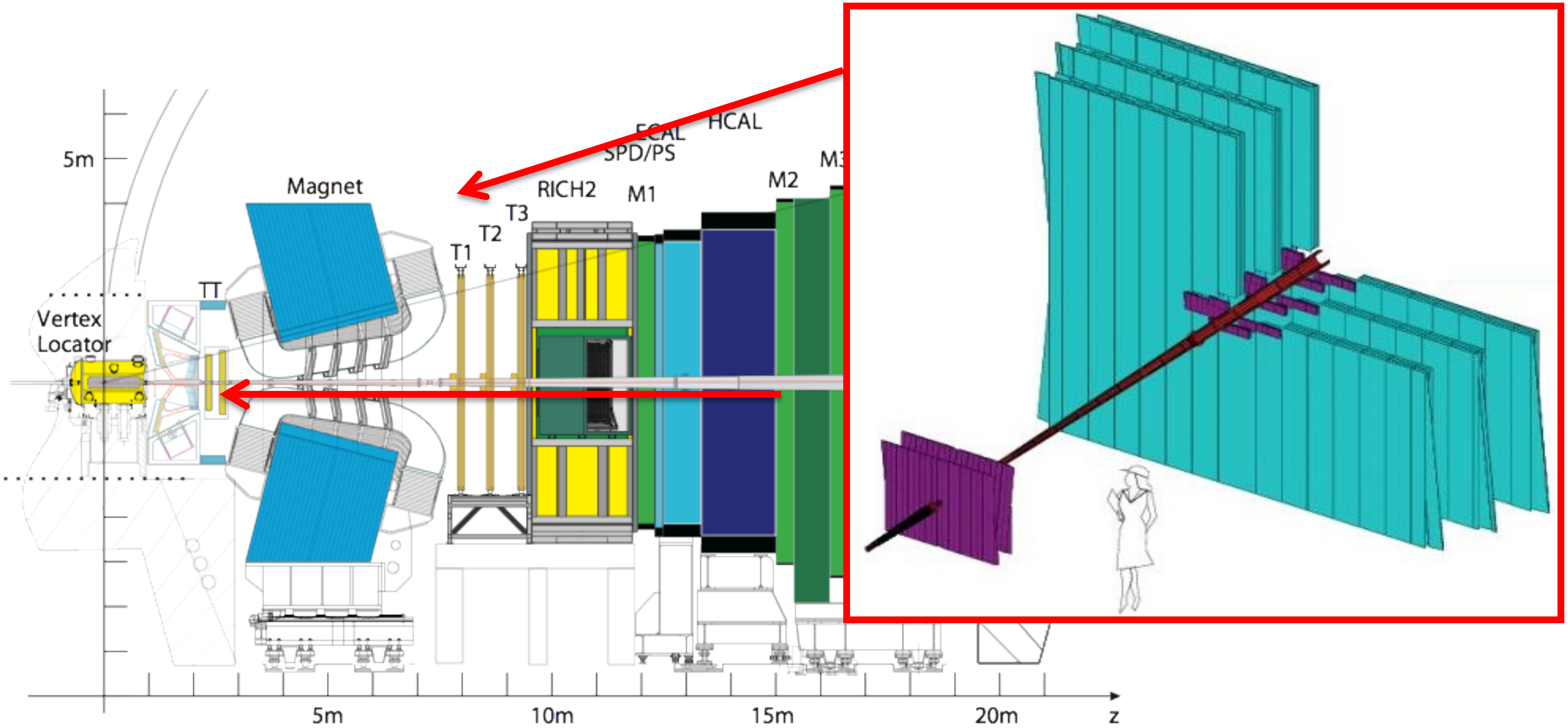


The LHCb detector

Int. J. Mod. Phys. A30 (2015) 07

TRACKING SYSTEM

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



The LHCb detector

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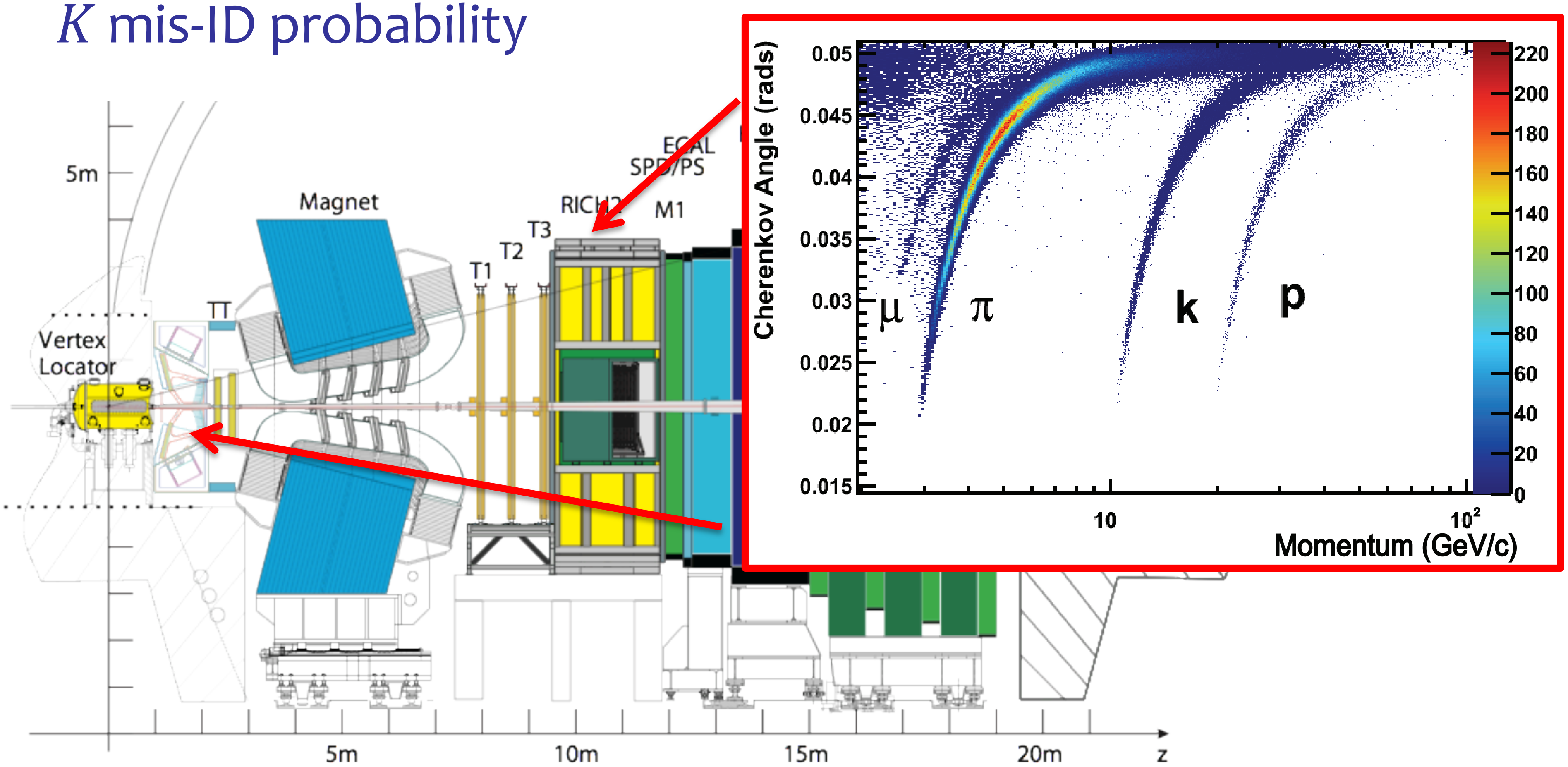
RICH DETECTORS

- Provide discrimination between kaons, pions and protons between 5 and 100 GeV/c. Typical kaon ID ~ 95 % for ~ 5 % $\pi \rightarrow K$ mis-ID probability



The LHCb detector

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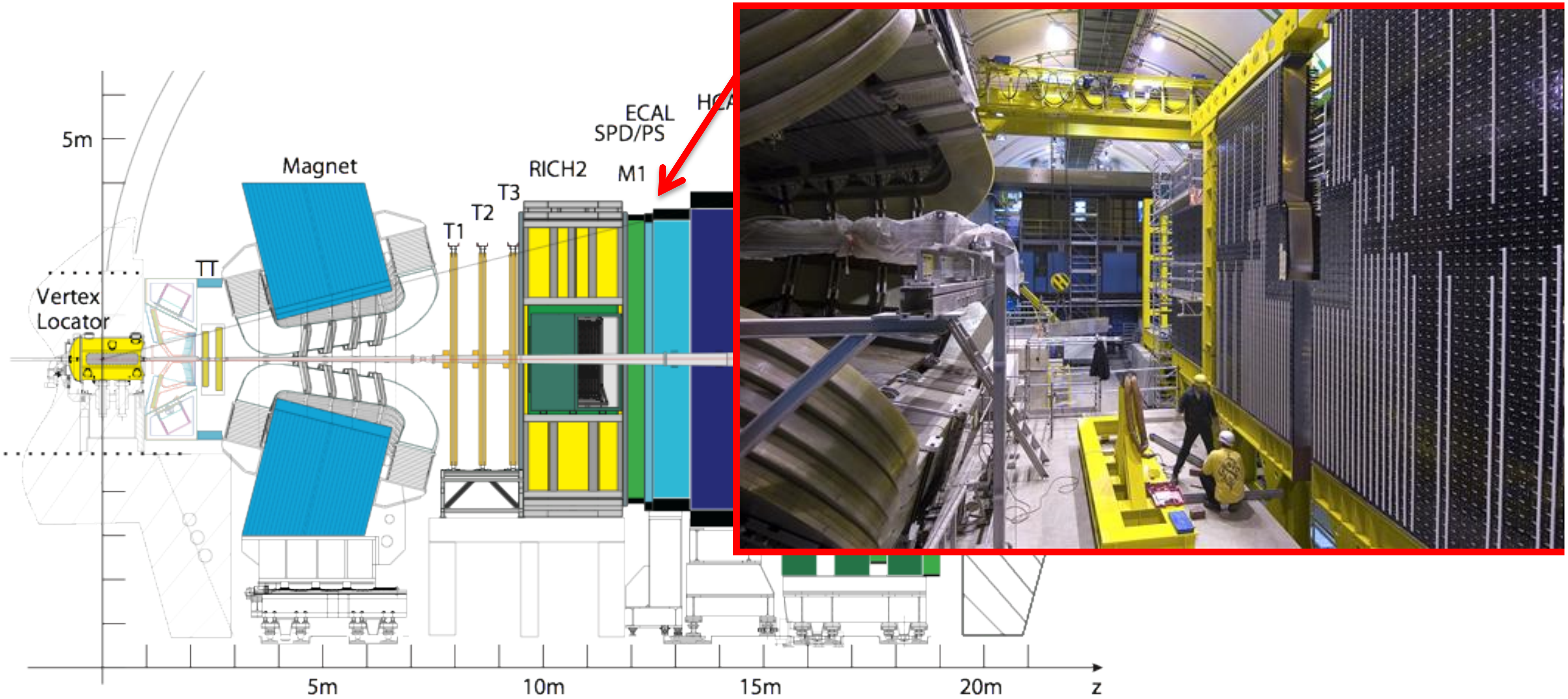
CALORIMETERS

- Preshower + SPD + electromagnetic + hadronic calorimeters
- Vital for hardware-level hadron triggering

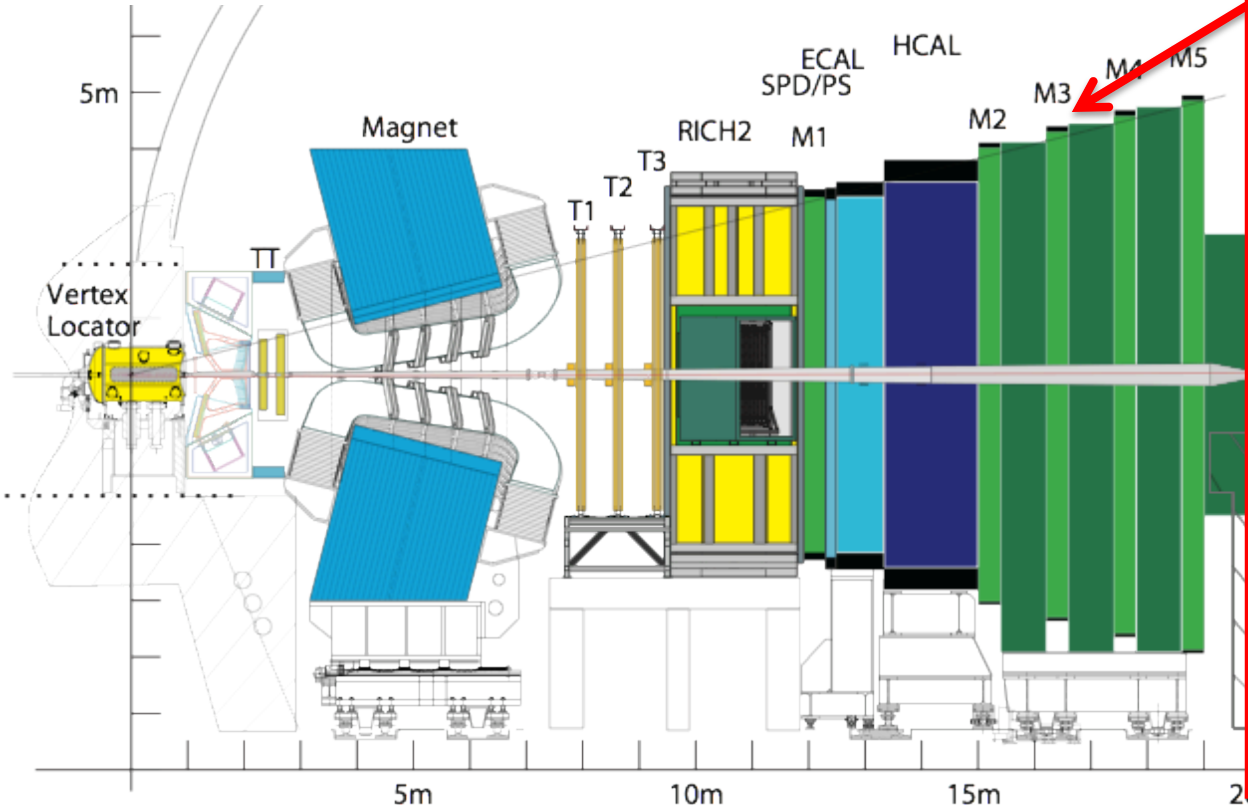


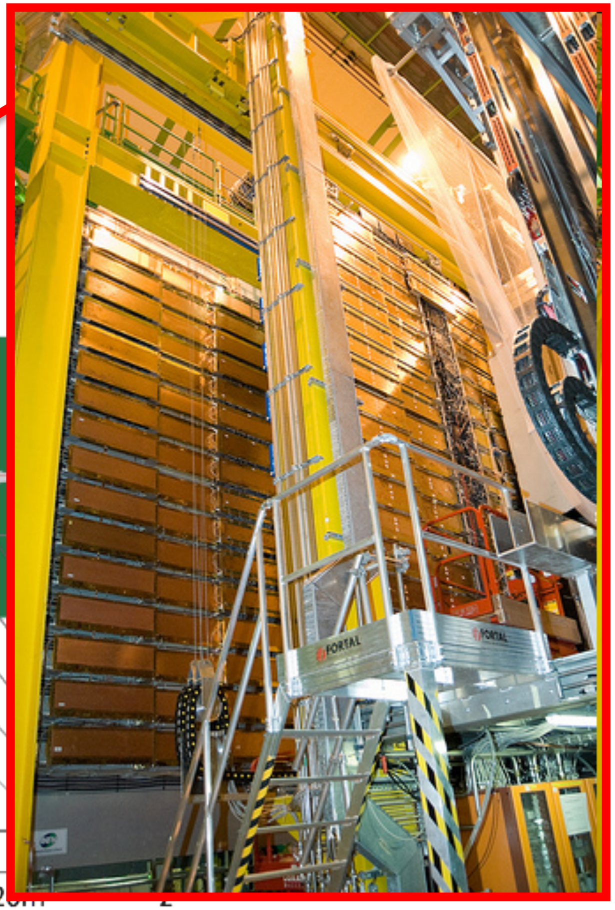
The LHCb detector

Int. J. Mod. Phys. A30 (2015) 07

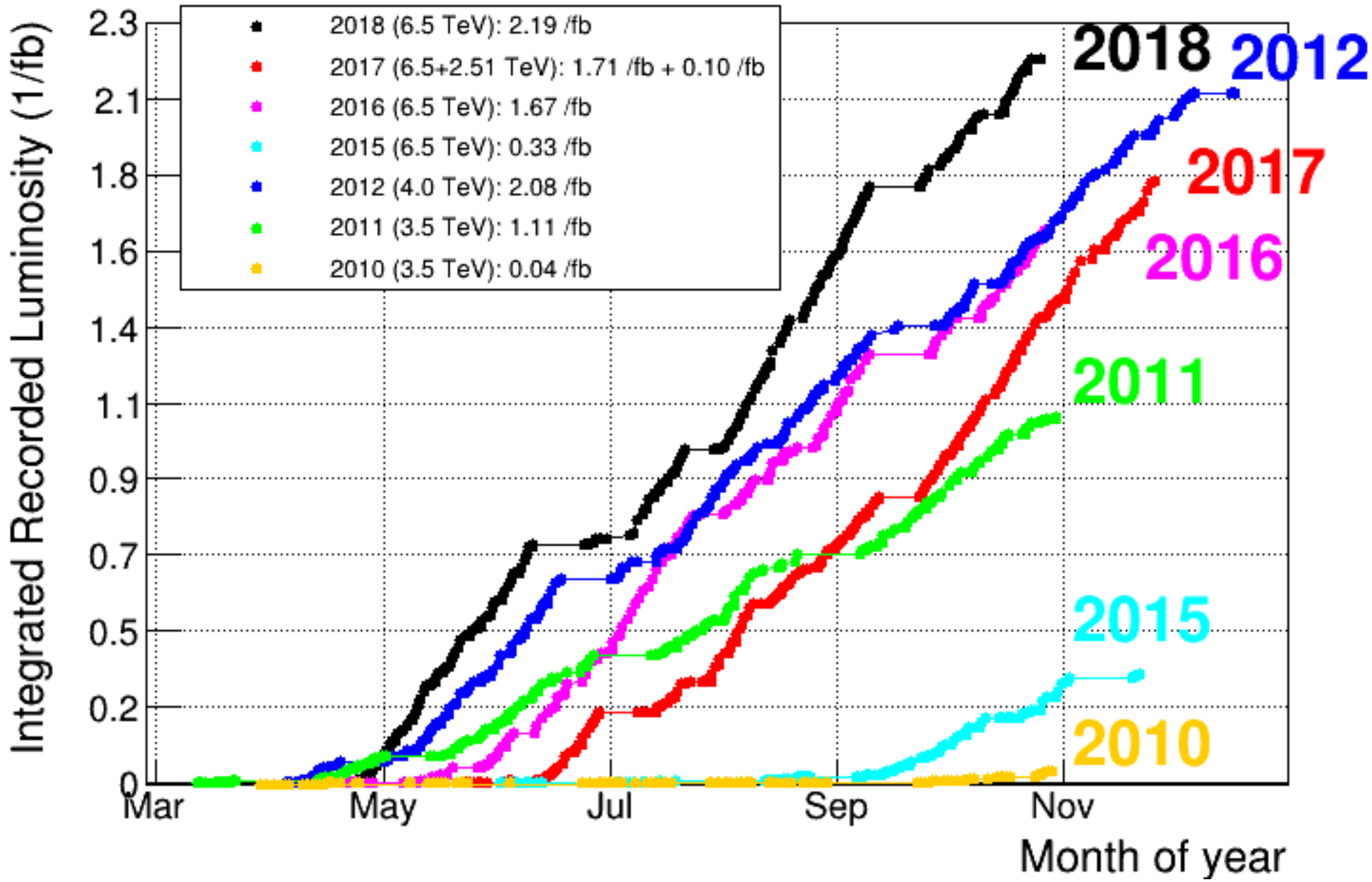
MUON STATIONS

- Five stations, used also in hardware trigger
- Excellent muon/pion separation (single hadron mis-ID rate 0.7% Phys. Lett. B699 (2011) 330)





Integrated recorded luminosity



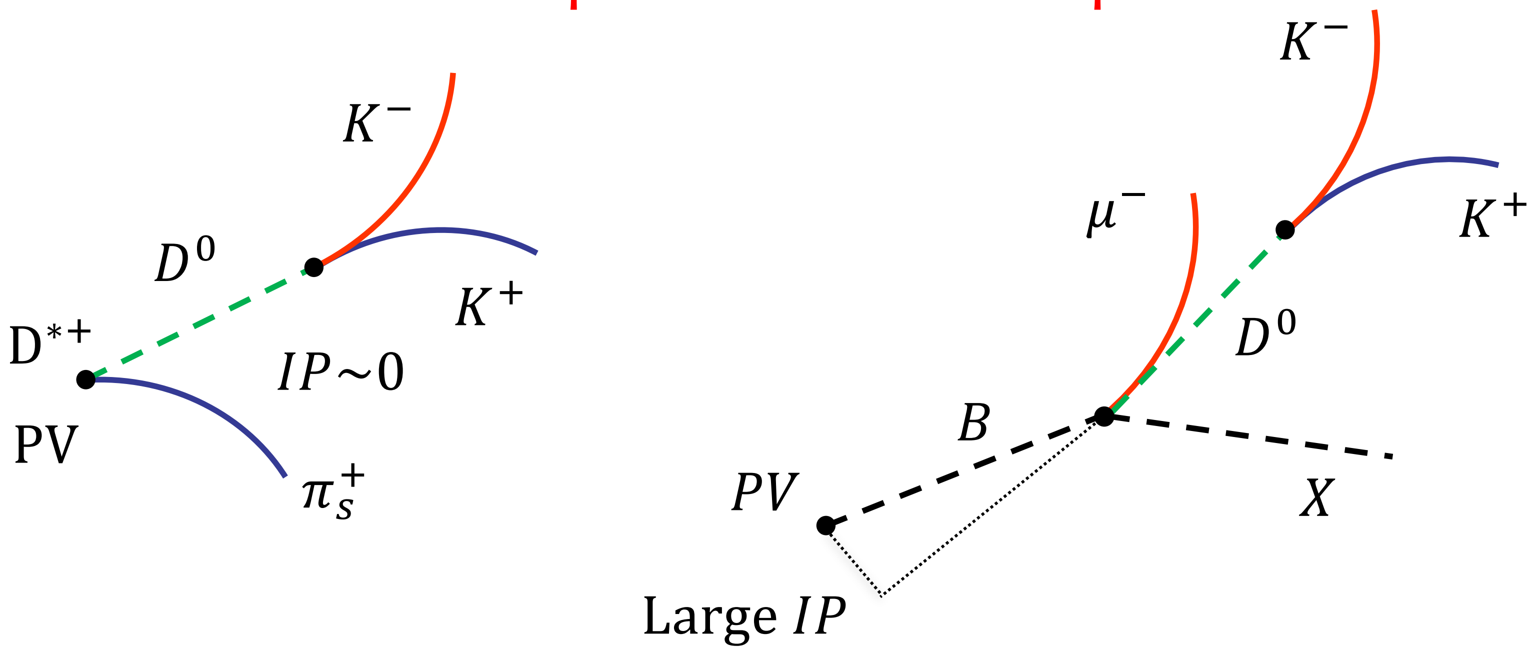
THANKS
LHC!!

The full LHCb data set is about 9 fb^{-1}

D^0 production exploits in the analysis presented today

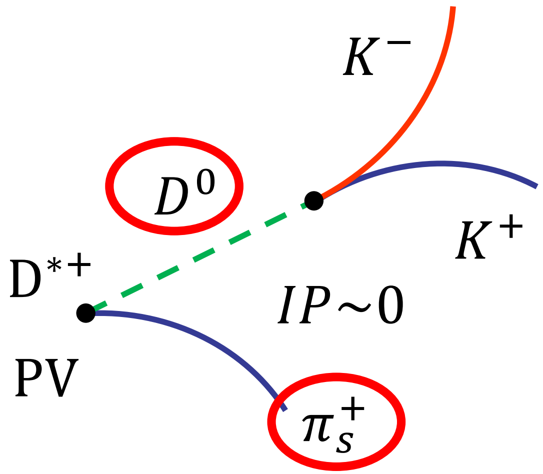
Two mechanisms of D^0 production

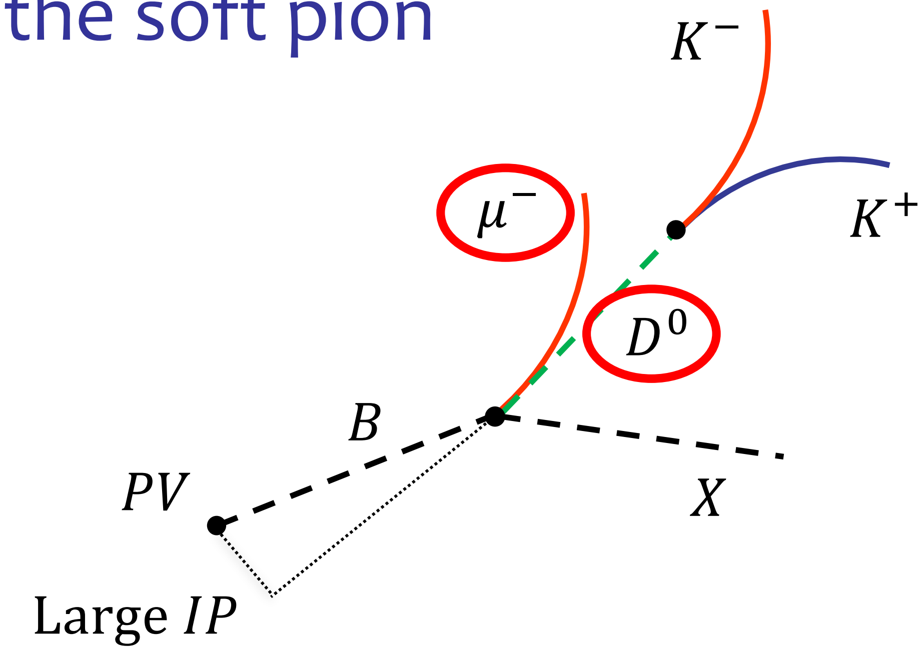
Independent data sample



D^0 production exploits in the analysis presented today

Experimentally we can tag D^0 flavour at production by means of the charge of the muon and the soft pion





New for winter conferences

Measurement of the mass difference between neutral charm-meson eigenstates with $D^0 \to K_s^0\pi^+\pi^-$ decay

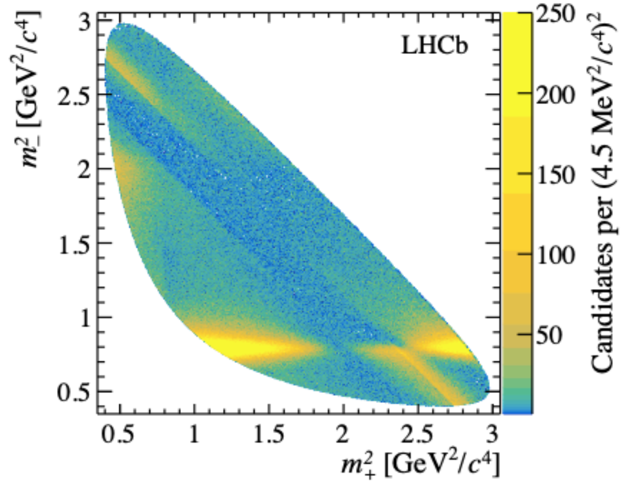
Run 1 [$3\ fb^{-1}$]

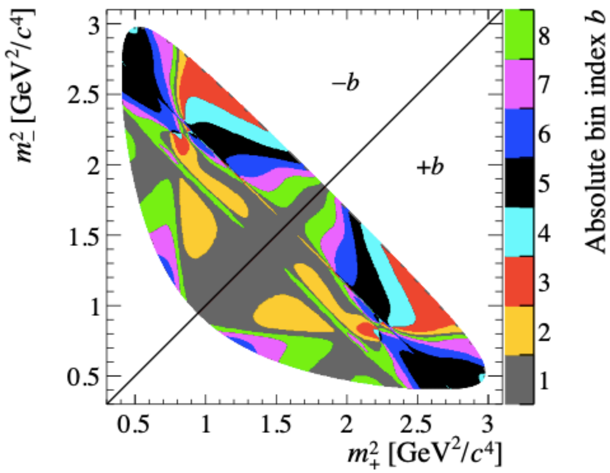
LHCB-PAPER-2019-001
Phys. Rev. Lett. 122 (2019) 231802

Measurement of x_{CP} and Δx

LHCB-PAPER-2019-001 [arXiv:1903.03074]

- $D^0 \to K_S^0 \pi^+ \pi^-$ has a rich resonance substructure
- The analysis is performed by means of a model independent approach (bin-flip method) Phys. Rev. D 99 (2019) 012007 [arXiv:1811.01032]
  - avoids accurate modelling of the efficiency
- Binning scheme chosen to have almost constant strong-phase differences
- Measure yield ratio $R_{bj}^{\pm}$ between $-b$ and b in bins (j) of decay time
- D^0 flavour identified with the charge of π and μ
- $R_{bj}^{\pm}$ is function of x_{CP}, y_{CP}, Δx and Δy





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

Search for *CP* Violation in Mixing

LHCB-PAPER-2019-001
[arXiv:1903.03074]

Results

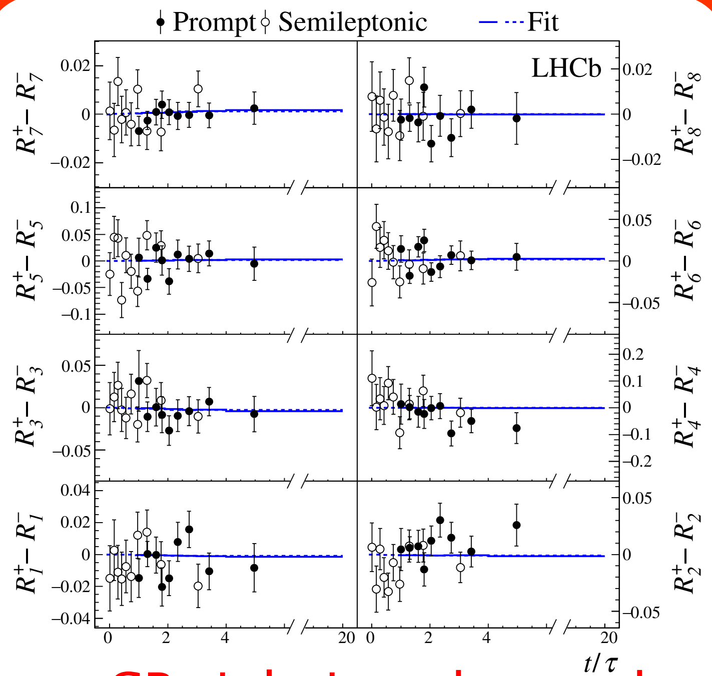
$$y_{CP} = [0.74 \pm 0.36\,(stat) \pm 0.11\,(syst)]\%$$

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

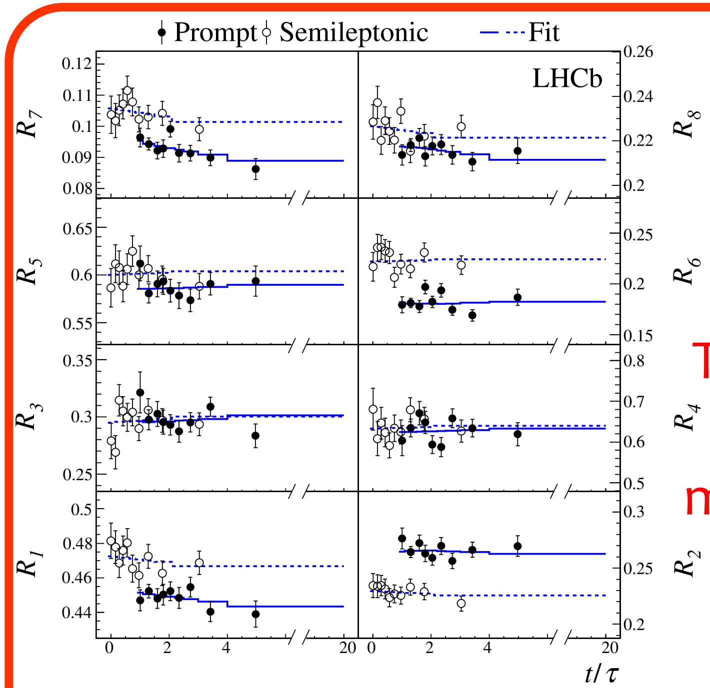
$$x_{CP} = [0.27 \pm 0.16\,(stat) \pm 0.04\,(syst)]\%$$

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

Most precise determination of x from a single experiment



no CP violation observed

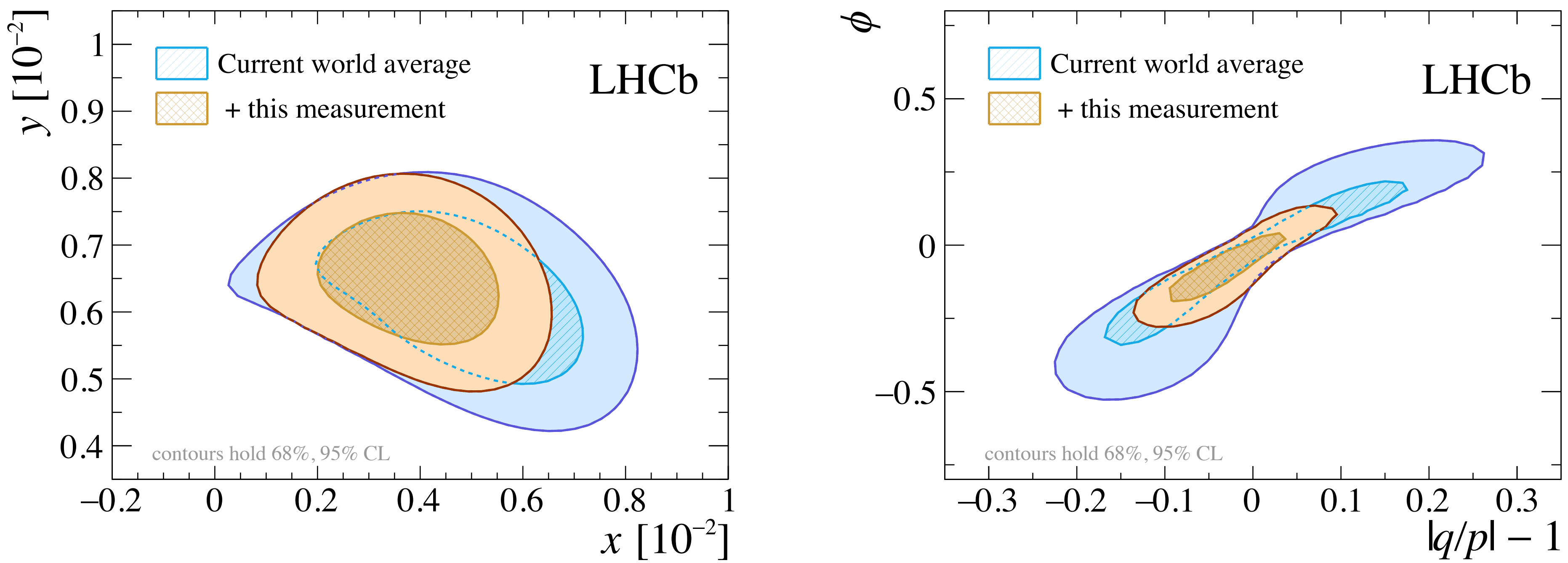


Combination with current global knowledge gives $x > 0$ at more than 3σ

This bring to the first evidence that the masses of the neutral charm-meson eigenstates differ

Search for *CP* Violation in Mixing

LHCB-PAPER-2019-001
[arXiv:1903.03074]



Impact on the current world average

Presented for the first time at CERN-Seminar and Moriond QCD the 21st of March

LHCb-PAPER-2019-006

Phys. Rev. Lett. 122, 211803 (2019)

Search for Direct *CP* Violation with $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ decays

Run 2 $[6.0\ \mathrm{fb}^{-1}]$

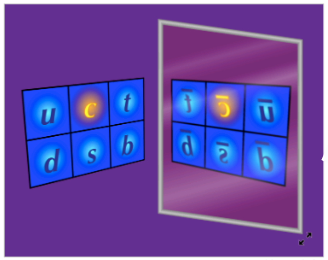
+ Run 1 combination

Viewpoint: Charm Reflects Poorly on Anticharm

Hiroaki Aihara, Department of Physics, University of Tokyo, Tokyo, Japan

May 29, 2019 • *Physics* 12, 52

A study of particles containing charm quarks has uncovered a violation of so-called *CP* symmetry, which could help in understanding why matter dominates antimatter in the Universe.



APS/Alan Stonebraker

Time-integrated CP asymmetry

CP asymmetry is defined as

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

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

The flavour of the initial state (D^0 or $\overline{D}^0$) is tagged by the charge of the slow pion from $D^{*\pm} \to D^0\pi^+$ or muon from $B \to D^0(\to f)\mu^- X$

The raw asymmetry for tagged D^0 decays to a final state f is given by

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

where N refers to the number of reconstructed events of decay after background subtraction

ΔA_{CP} π-tagged

What we measure is the physical asymmetry plus asymmetries due both to production and detector effects

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

CP asymmetry

Any charge-dependent asymmetry in slow pion reconstruction

$D^{*\pm}$ production asymmetry

- No detection asymmetry for D^0 decays to K^-K^+ or $\pi^-\pi^+$
- … if we take the raw asymmetry difference

$$\Delta A_{CP} \equiv A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$$

- the D^{*+} production and the slow pion detection asymmetries will cancel

ΔA_{CP} μ-tagged

What we measure is the physical asymmetry plus asymmetries due both to production and detector effects

$$A_{\rm raw}(f) = A_{CP}(f) + A_{D}(f) + A_{\rm D}(\mu^{-}) + A_{\rm P,eff}(D^0)$$

CP asymmetry

Any charge-dependent asymmetry in muon reconstruction

D^0 effective production asymmetry

- No detection asymmetry for D⁰ decays to K^-K^+ or $\pi^-\pi^+$
- … if we take the raw asymmetry difference

$$\Delta A_{CP} \equiv A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$$

- the D^0 effective production and the muon detection asymmetries will cancel

Current experimental status

HFLAV
[https://hflav.web.cern.ch]

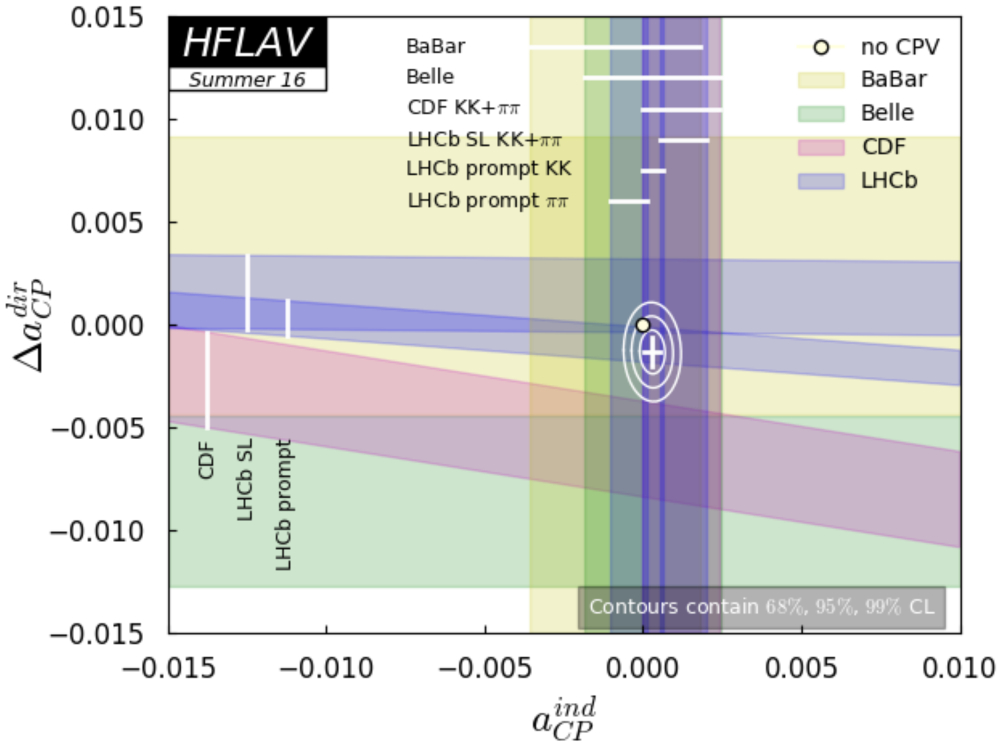
- Both CPV in decay (dir) and in the interference between mixing/decay (ind) can contribute
- assumed universality in mixing/decay interference

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

Relative difference of average proper time between $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$

In BaBar and Belle this quantity is zero

$\Delta A_{CP}^{\rm dir}$



HFLAV combination

$a_{CP}^{\rm ind} = (0.030 \pm 0.026)\%$

$\Delta A_{CP}^{\rm dir} = (-0.134 \pm 0.070)\%$

Consistency with NO CPV hypothesis: 9.3%

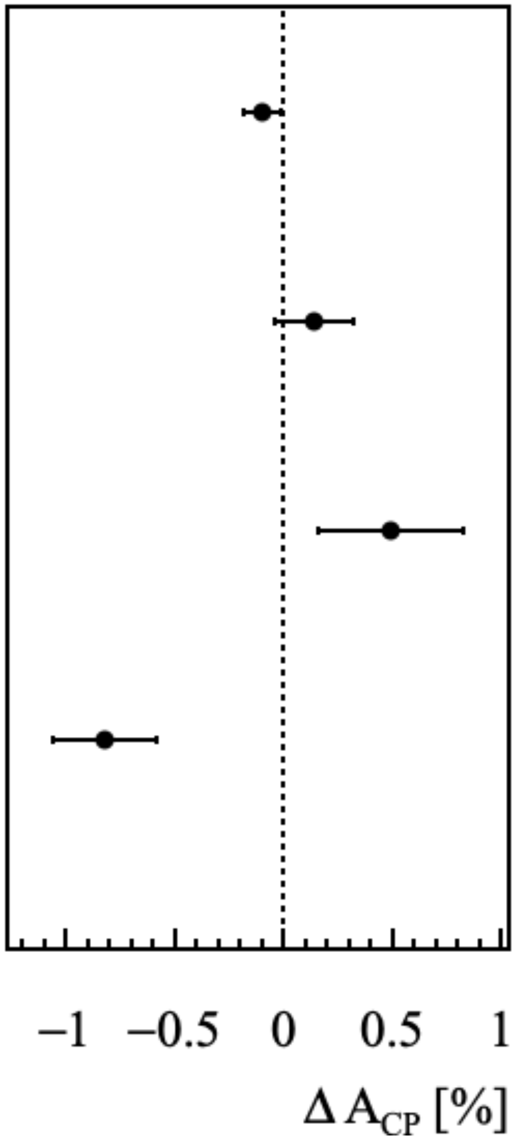
LHCb ΔA_{CP} history [2012-2016]

π-tagged (3 fb^{-1}) — Phys. Rev. Lett. 116 (2016)

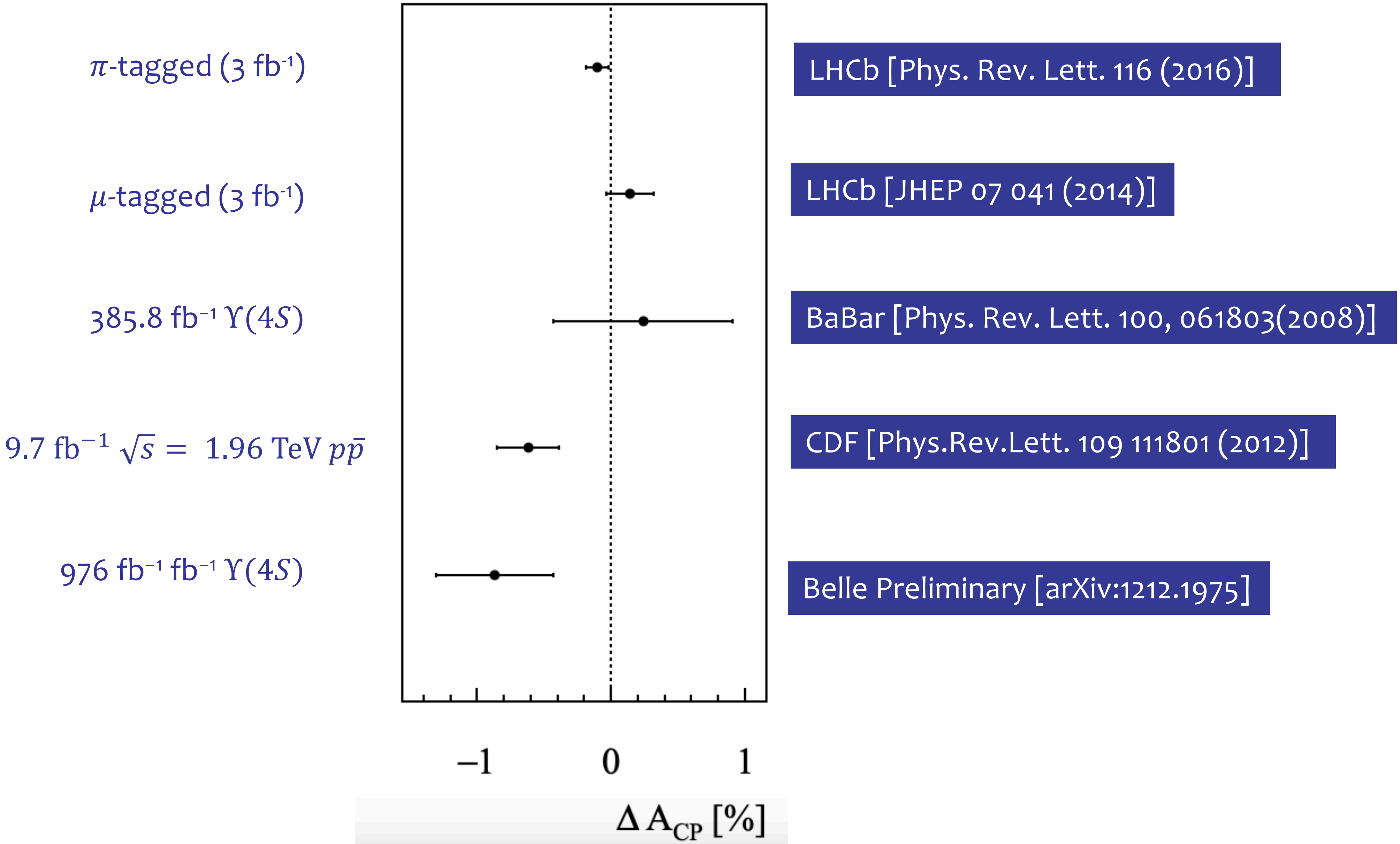
μ-tagged (3 fb^{-1}) — JHEP 07 041 (2014)

μ-tagged (1 fb^{-1}) — Phys. Lett. B723 33 (2013)

π-tagged (0.62 fb^{-1}) — Phys. Rev. Lett. 108 (2012)



ΔA_{CP} experimental status (before this result)

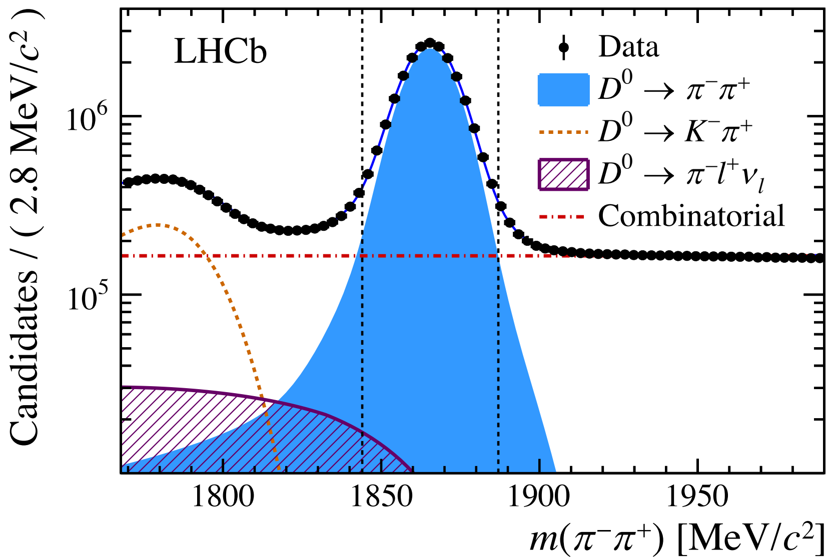


Data sample selection

LHCb-PAPER-2019-006

- Reconstruction performed online
  - Turbo stream

  Comput. Phys. Commun. 208 (2016) 35
- Requirements placed on:
  - Quality and PID information of tracks
  - p_{T} of tracks and D^0
  - D^0 vertex quality
  - IP of D^0



for π-tagged
$\mathrm{m(D^0)} \in [1844{,}1887]\ \mathrm{MeV}/c^2$

Data sample selection

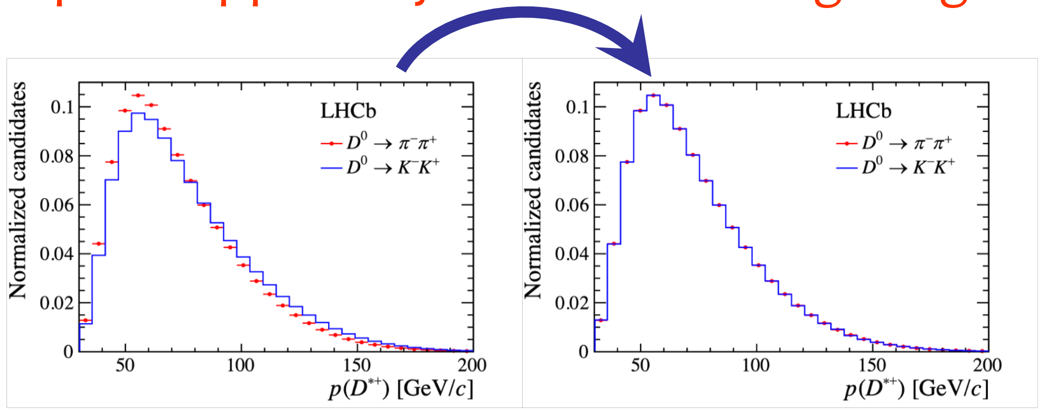
LHCb-PAPER-2019-006

- Additional requirements placed on for μ-tagged candidates:
  - $m_{corr} = \sqrt{m(D^0\mu) + p_T'(D^0\mu)} + p_T'(D^0\mu)$
  - $m(D^0)$ for prompt and $m(D^0\mu)$ for
- μ-tagged candidates are further filtered with a MVA using as input the quality of the vertices, the D^0 flight distance, the IP and p_{T} of the particles

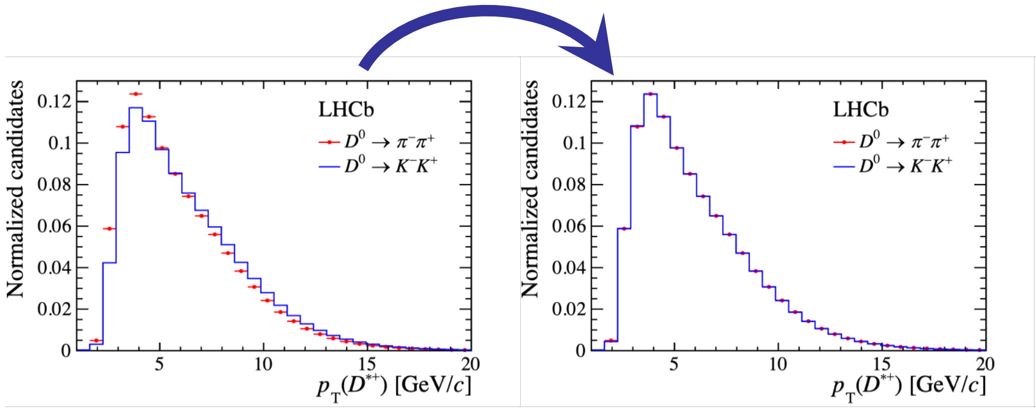
Kinematic weighting

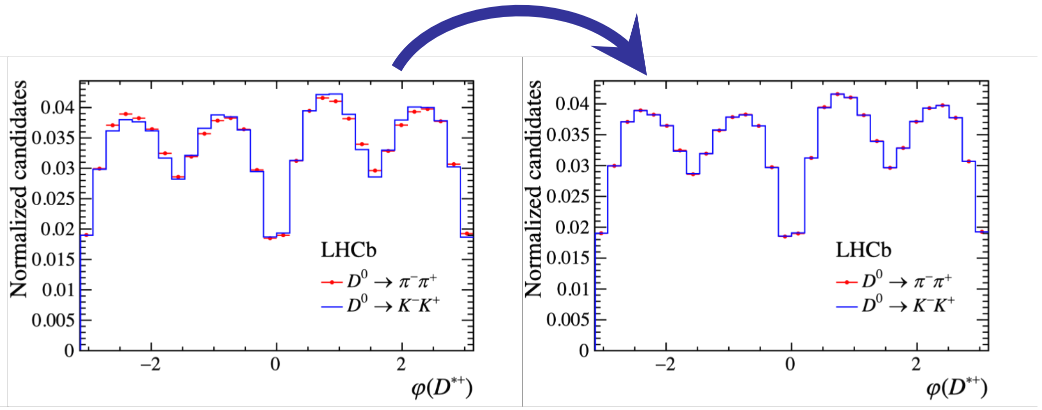
LHCb-PAPER-2019-006

- Detection and production asymmetries are expected to depend on the kinematics of the reconstructed particles
  - the cancellation of nuisance asymmetries may be incomplete if the kinematic distributions of reconstructed $D^{*\pm}$ or B candidates
  - a small correction to the K^-K^+ sample is applied by means of a weighting procedure.
- π-tagged: $p_T(D^*), p(D^*), \phi(D^*)$



Very small effect on ΔA_{CP} below 10^{-4}





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LHCb-PAPER-2019-006

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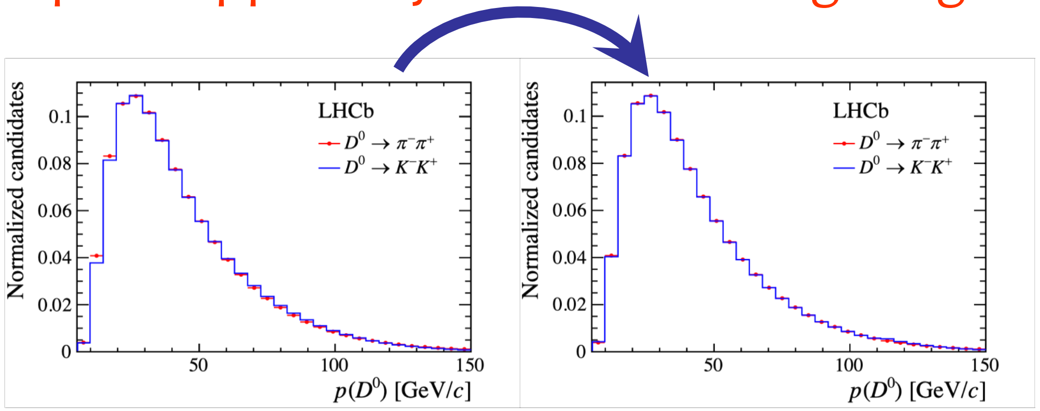
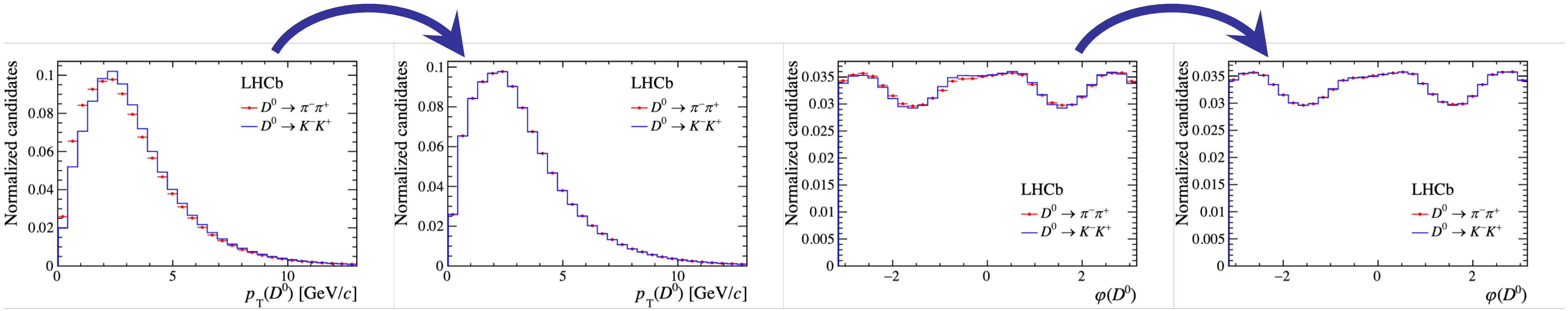
  - the cancellation of nuisance asymmetries may be incomplete if the kinematic distributions of reconstructed $D^{*\pm}$ or B candidates
  - a small correction to the K^-K^+ sample is applied by means of a weighting procedure.
- μ-tagged : $p_T(D^0)$, $p(D^0)$, $\phi(D^0)$



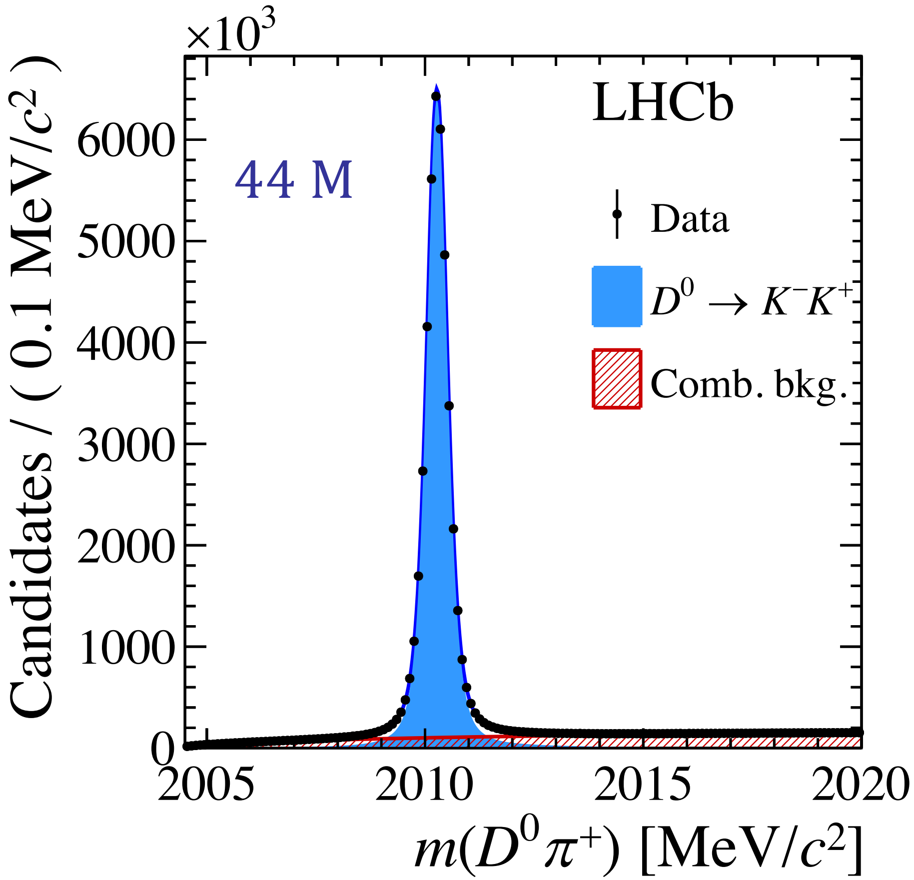
Very small effect on ΔA_{CP} below 10^{-4}

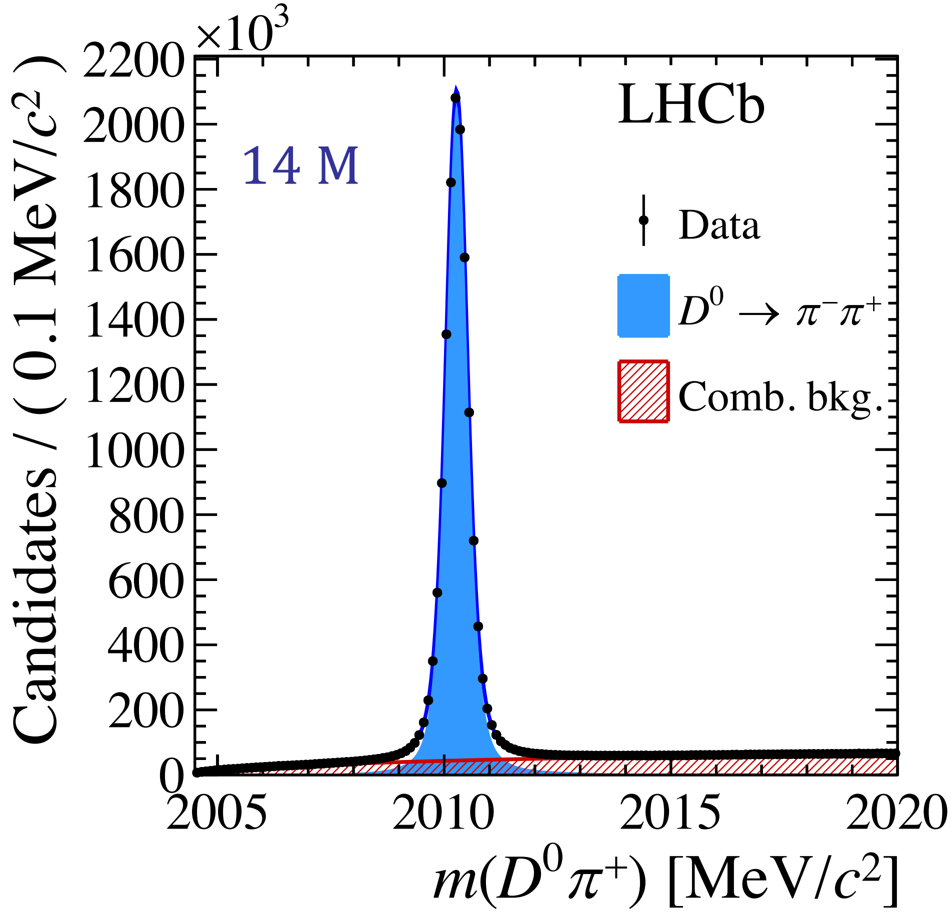


A_{raw} measurements [π-tagged]

LHCb-PAPER-2019-006

- Fit $m(D^0\pi)$ distribution
- A_{raw} measured from a simultaneous fit between D^{*+} and D^{*-}





A_{raw} measurements [μ-tagged]

LHCb-PAPER-2019-006

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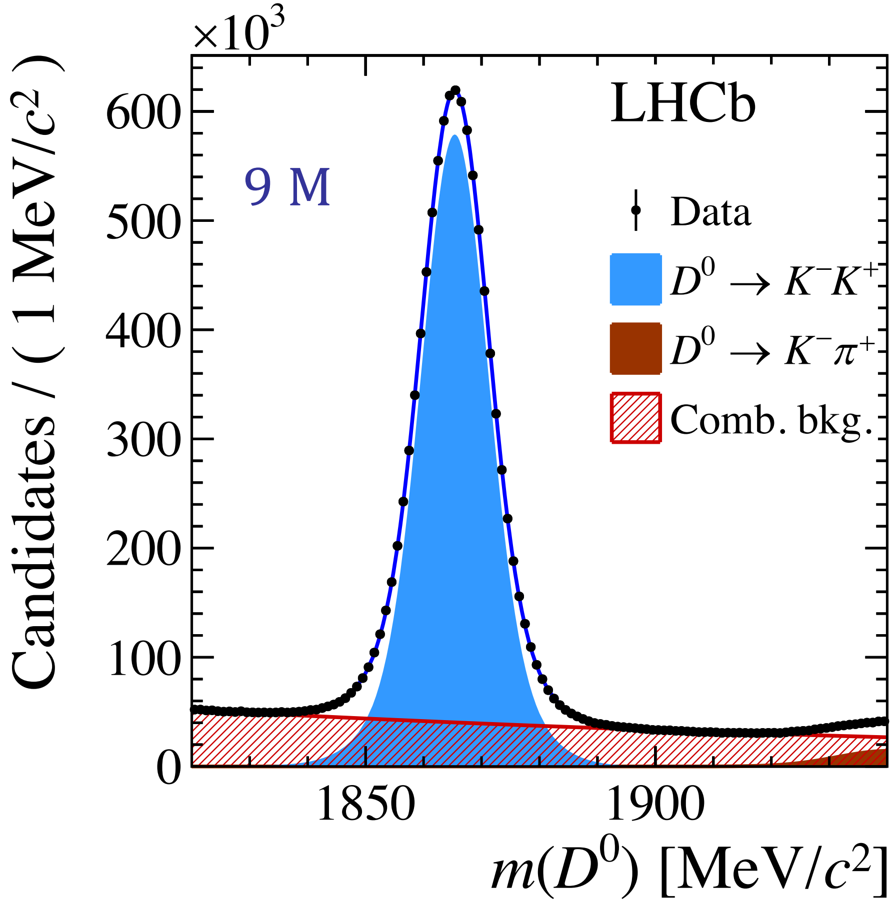
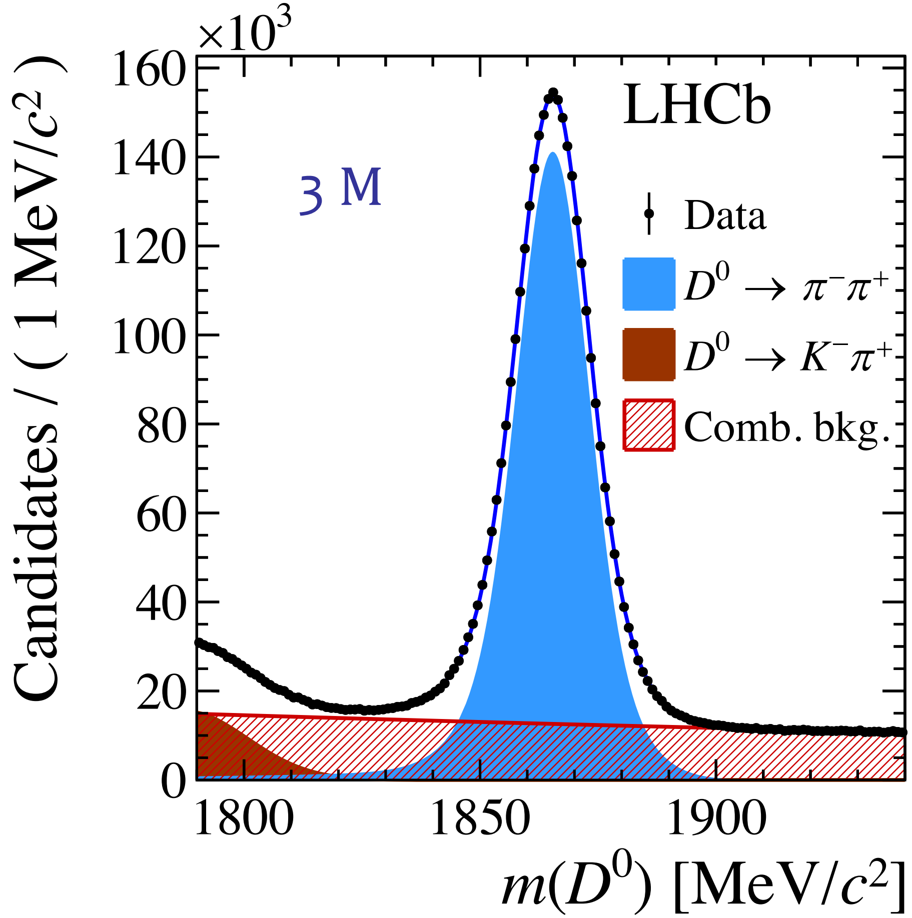




Systematic uncertainties [π-tagged]

LHCb-PAPER-2019-006

- Fit model: evaluated by fitting pseudoexperiments with alternative models → $0.6{\times}10^{-4}$

Systematic uncertainties [π-tagged]

LHCb-PAPER-2019-006

- Fit model: evaluated by fitting pseudoexperiments with alternative models → 0.6×10^{-4}
- Weighting procedure: considered the statistical knowledge of the weights → 0.2×10^{-4}

Systematic uncertainties [π-tagged]

LHCb-PAPER-2019-006

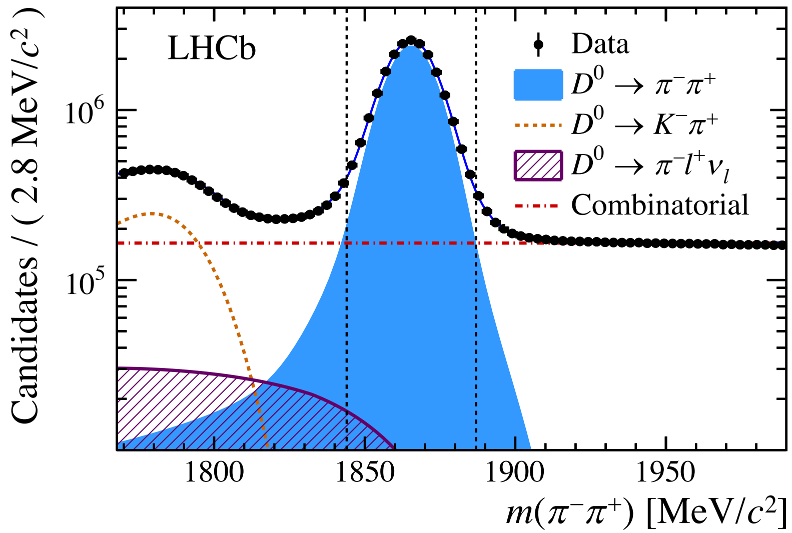
- Fit model: evaluated by fitting pseudoexperiments with alternative models → 0.6×10^{-4}
- Weighting procedure: considered the statistical knowledge of the weights → 0.2×10^{-4}
- Secondaries decays: evaluated the presence of D^0 decaying from B → 0.3×10^{-4}

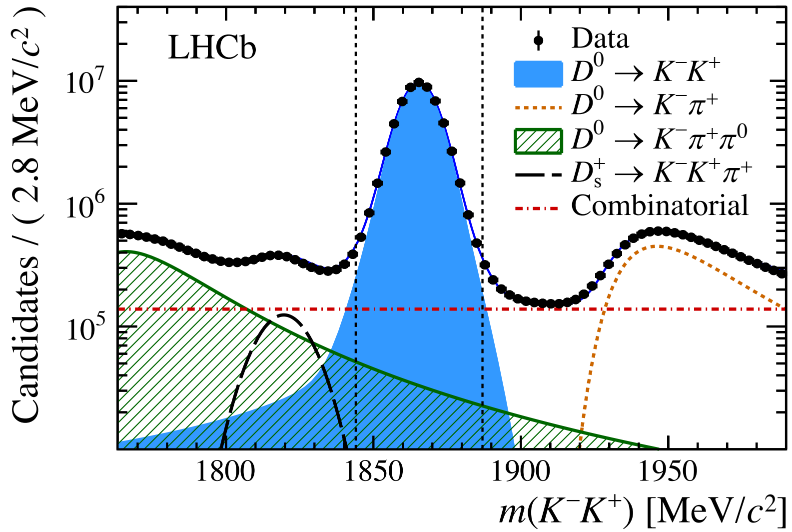
Systematic uncertainties [π-tagged]

- Misreconstructed background: e.g. $D^0 \to K^-\pi^+\pi^0$, $D^0 \to \pi^- l^+ \nu_l$ peaking in $m(D^0\pi)$ estimated by measuring the yields and asymmetries of backgrounds on the $m(D^0)$ distributions → 0.5×10^{-4}

LHCb-PAPER-2019-006

yields and raw asymmetries of peaking background measured and extrapolated to the signal region [1844,1887] MeV/c^2





Systematic uncertainties [μ-tagged]

LHCb-PAPER-2019-006

- Fit model: evaluated by fitting pseudoexperiments with alternative models → 2×10^{-4}
- μ-tagged dominated by mistag (wrong muon) evaluated on the $B \to D^0(\to K^-\pi^+)\mu^- X$ control sample → 4×10^{-4}

Systematic uncertainties [μ-tagged]

LHCb-PAPER-2019-006

- Fit model: evaluated by fitting pseudoexperiments with alternative models → 2×10^{-4}
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- Weighting procedure: considered the statistical knowledge of the weights → 10^{-4}

Systematic uncertainties [μ-tagged]

LHCb-PAPER-2019-006

- Fit model: evaluated by fitting pseudoexperiments with alternative models → 2×10^{-4}
- μ-tagged dominated by mistag (wrong muon) evaluated on the $B \to D^0(\to K^-\pi^+)\mu^- X$ control sample → 4×10^{-4}
- Weighting procedure: considered the statistical knowledge of the weights → 10^{-4}
- B^0 fraction: reconstructed B^0 and B^+ decays can be slightly different between the K^-K^+ and $\pi^-\pi^+$ decay modes → 10^{-4}

Systematic uncertainties [μ-tagged]

LHCb-PAPER-2019-006

- Fit model: evaluated by fitting pseudoexperiments with alternative models → $2{\times}10^{-4}$
- μ-tagged dominated by mistag (wrong muon) evaluated on the $B \to D^0(\to K^-\pi^+)\mu^- X$ control sample → $4{\times}10^{-4}$
- Weighting procedure: considered the statistical knowledge of the weights → 10^{-4}
- B^0 fraction: reconstructed B^0 and B^+ decays can be slightly different between the K^-K^+ and $\pi^-\pi^+$ decay modes → 10^{-4}
- B^0 reconstruction efficiency: difference (K^-K^+ and $\pi^-\pi^+$ modes) B^0 in reconstruction efficiency as function of decay time and B^0 oscillation → $2\ {\times}10^{-4}$

Systematic uncertainties summary

LHCb-PAPER-2019-006

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

π-tagged systematic uncertainty below 10^{-4}!

Robustness checks

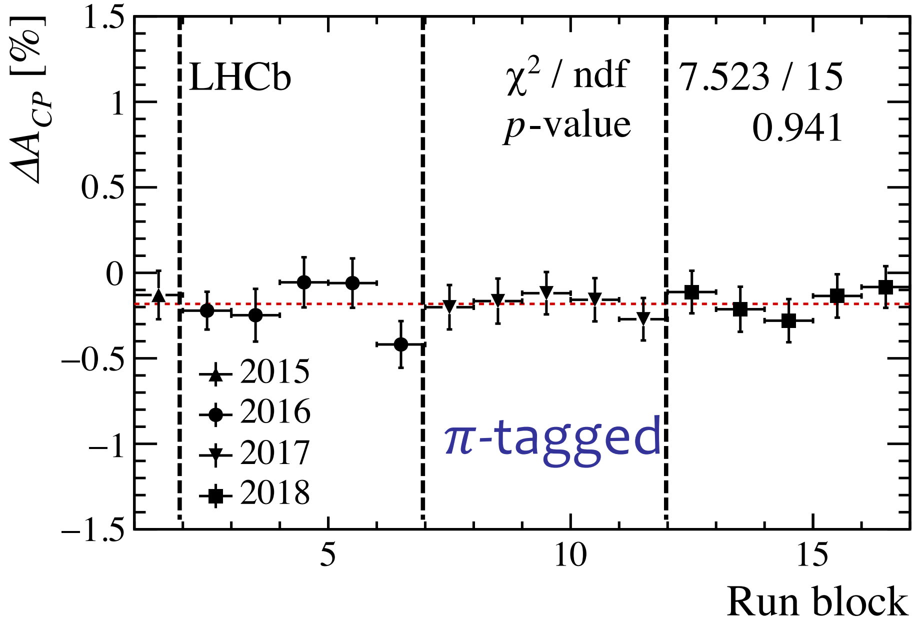
LHCb-PAPER-2019-006

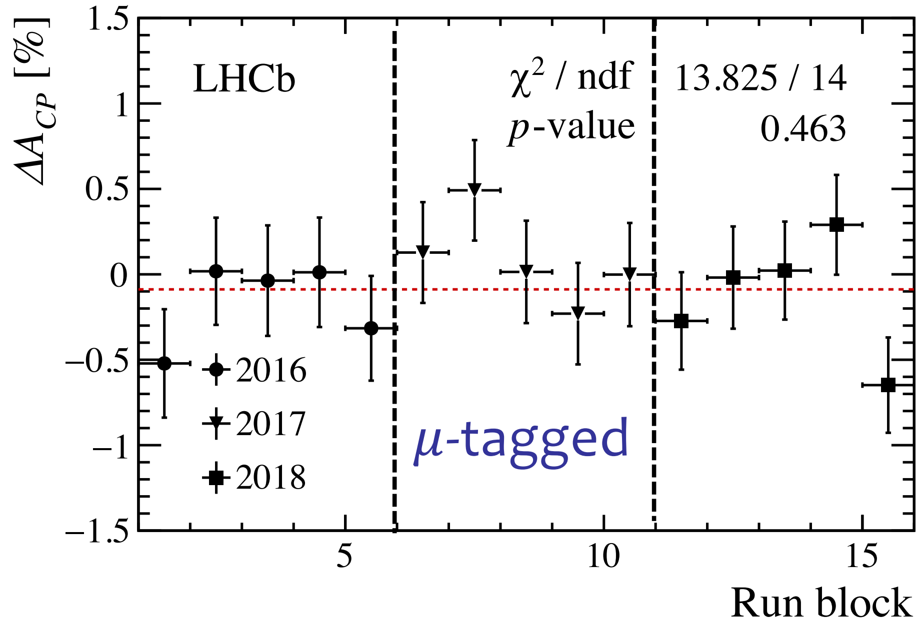
- Sample split according to year and magnet polarity → ΔA_{CP} consistent among the subsamples
- Sample split according data taking period→ ΔA_{CP} consistent among the subsamples
- Analysis repeated with tighter PID and looser fiducial requirements → ΔA_{CP} compatible with statistical fluctuations
- (Only π-tagged) measurement of $\Delta A_{\rm bkg}$ (the difference between the background raw asymmetries of K^-K^+ and $\pi^-\pi^+$ modes
  - the prompt background is mainly composed of genuine D^0 and unrelated pions originating from PV
  - $\Delta A_{\rm bkg}$ is expected to be compatible with zero
  - $\Delta A_{\rm bkg} = (-2 \pm 4)\times 10^{-4}$

Additional robustness checks

LHCb-PAPER-2019-006

Measured value of ΔA_{CP} is studied as a function of several variables
→ data taking period



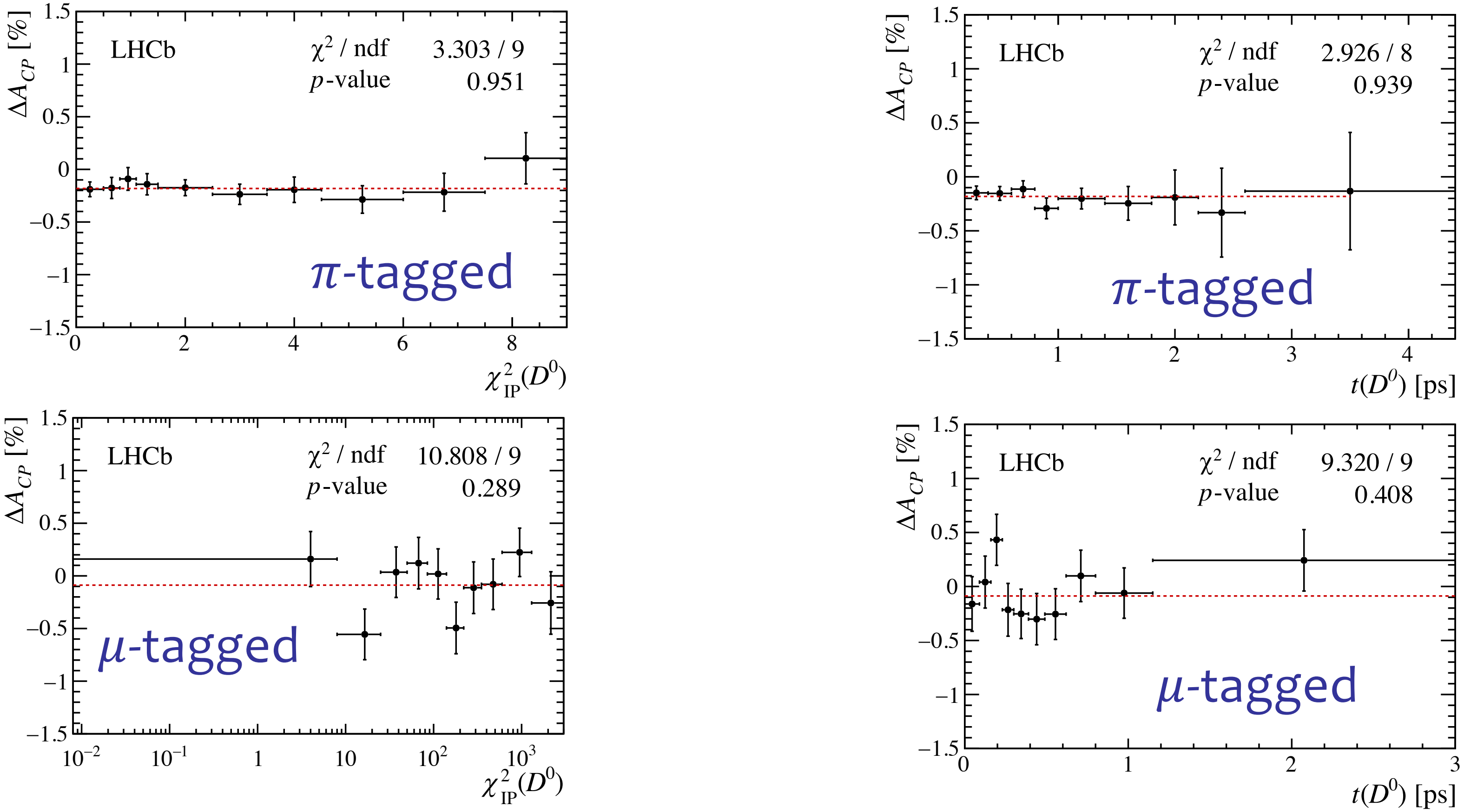


No evidence for unexpected dependences

Additional robustness checks

LHCb-PAPER-2019-006

- Measured value of ΔA_{CP} is studied as a function of several variables → D^0 impact parameter and decay time

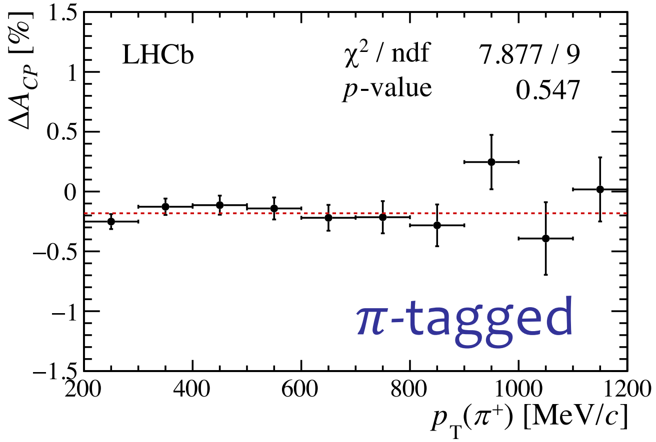


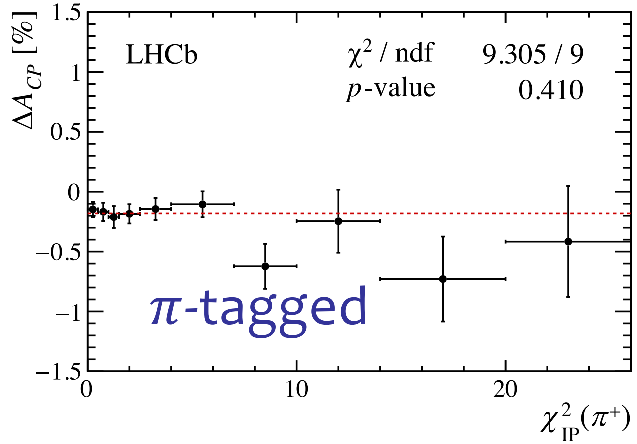
No evidence for unexpected dependences

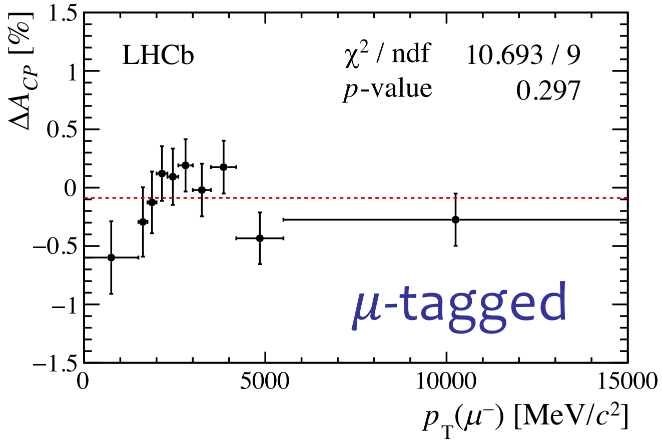
Additional robustness checks

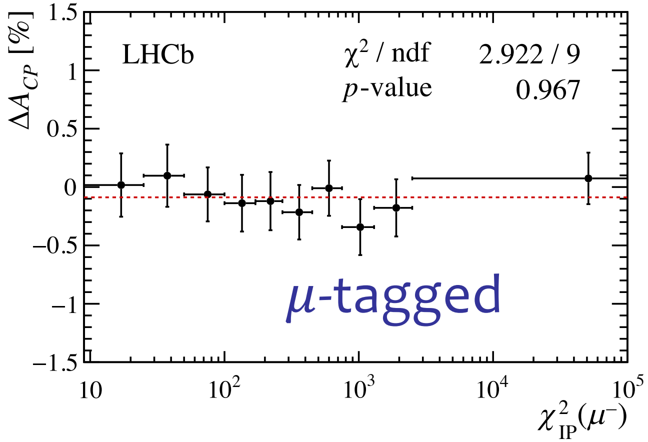
LHCb-PAPER-2019-006

- Measured value of ΔA_{CP} is studied as a function of several variables → π/μ impact parameter and transverse momentum









No evidence for unexpected dependences

Results with Run-2 [6 fb^{-1}]

LHCb-PAPER-2019-006

$$\Delta A_{CP}^{\pi-\text{tagged}} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4}$$
$$\Delta A_{CP}^{\mu-\text{tagged}} = [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4}$$

Compatible with previous LHCb results and the WA

$$\Delta A_{CP} = (+14 \pm 16(\text{stat}) \pm 8\ (\text{syst}))\times 10^{-4}$$

μ-tagged Run 1 (3 fb^{-1})

Phys. Rev. Lett. 116 (2016)

$$\Delta A_{CP} = (-10 \pm\ 8\ (\text{stat}) \pm 3\ (\text{syst}))\times 10^{-4}$$

π-tagged Run 1 (3 fb^{-1})

JHEP 07 041 (2014)

Results with full LHCb data sample [9 fb^{-1}]

LHCb-PAPER-2019-006

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

5.3 standard deviations from zero

This is the first observation of *CP* violation in the decay of charm hadrons

Interpretation

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

$$\Delta\langle t\rangle = \langle t\rangle_{KK} - \langle t\rangle_{\pi\pi}$$

$\langle t\rangle_f$ is the reconstructed decay time of a given decay

assuming universal contribution from mixing/decay interference in KK and $\pi\pi$

Interpretation

LHCb-PAPER-2019-006

For the full LHCb data set (9 fb^{-1}):
$\Delta\langle t\rangle/\tau(D^0) = 0.115 \pm 0.002$

Using the LHCb averages:
$y_{CP} = (5.7 \pm 1.5)\times 10^{-3}$
$A_\Gamma = (-2.8 \pm 2.8)\times 10^{-4}$

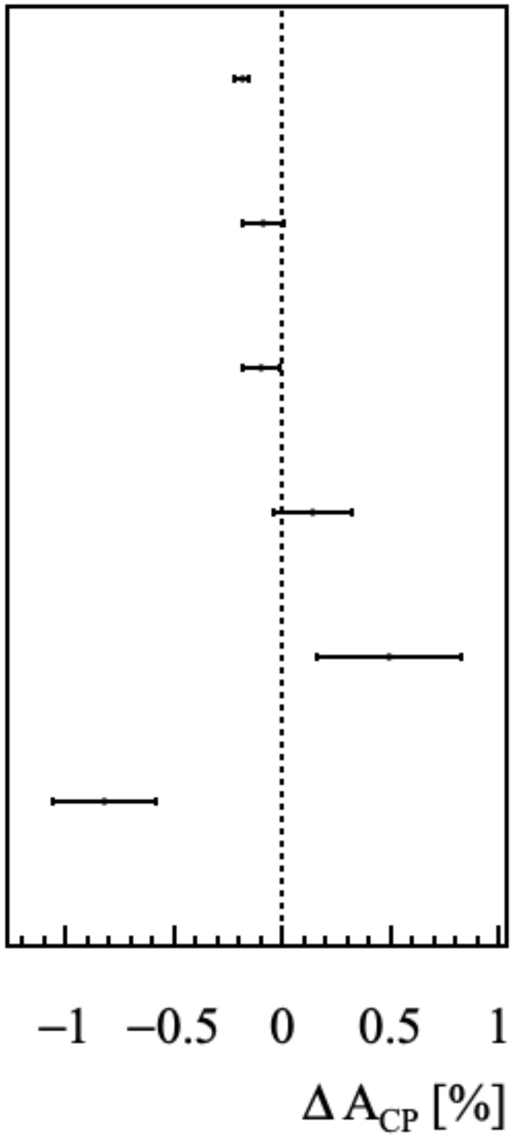
JHEP 04 (2012) 129
Phys. Rev. Lett. 122 (2019) 011802

JHEP 04 (2015) 043
Phys. Rev. Lett. 118 (2017) 261803,

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

ΔA_{CP} mostly sensitive to direct *CP* violation

ΔA_{CP} history in LHCb [2012-2019]



π-tagged (6 fb^{-1})	LHCb-PAPER-2019-006
μ-tagged (6 fb^{-1})	LHCb-PAPER-2019-006
π-tagged (3 fb^{-1})	Phys. Rev. Lett. 116 (2016)
μ-tagged (3 fb^{-1})	JHEP 07 041 (2014)
μ-tagged (1 fb^{-1})	Phys. Lett. B723 33 (2013)
π-tagged (0.62 fb^{-1})	Phys. Rev. Lett. 108 (2012)

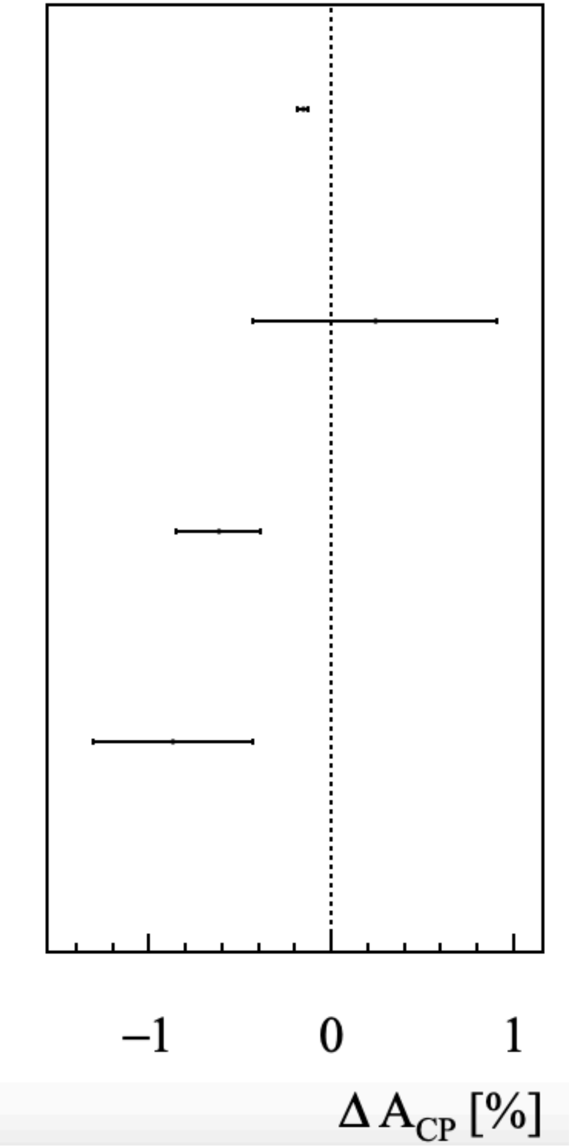
ΔA_{CP} experimental status (today)

9 fb⁻¹ $\sqrt{s} = 7{,}13$ TeV pp — LHCb [LHCb-PAPER-2019-006]

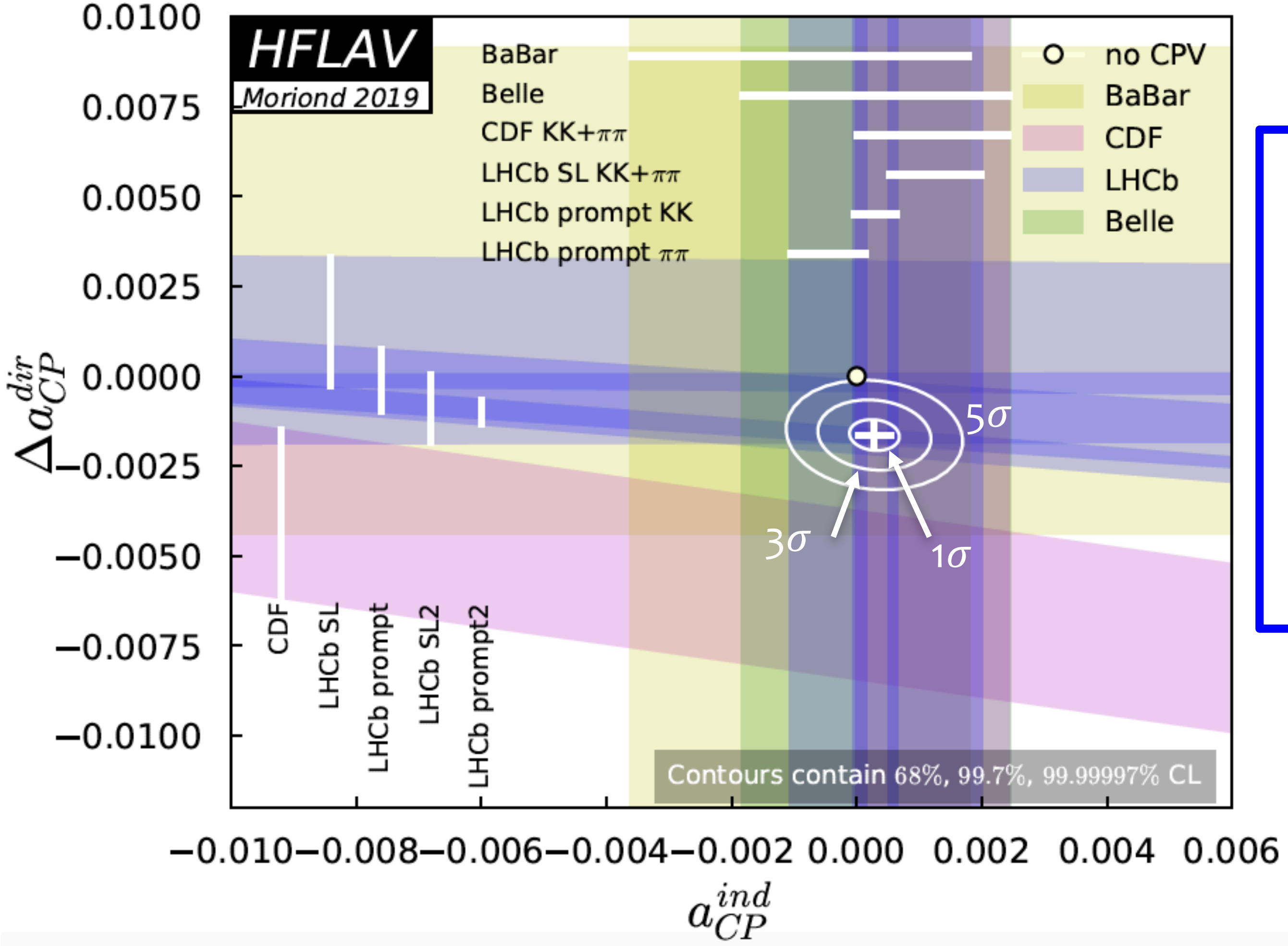
385.8 fb⁻¹ $\Upsilon(4S)$ — BaBar [Phys. Rev. Lett. 100, 061803(2008)]

9.7 fb^{-1} $\sqrt{s} = 1.96$ TeV $p\bar{p}$ — CDF [Phys.Rev.Lett. 109 111801 (2012)]

976 fb⁻¹ fb⁻¹ $\Upsilon(4S)$ — Belle Preliminary [arXiv:1212.1975]



HFLAV update



HFLAV combination

$a_{CP}^{\text{ind}} = (0.028 \pm 0.026)\%$

$\Delta a_{CP}^{\text{dir}} = (-0.164 \pm 0.028)\%$

Consistency with NO CPV hypothesis: $5{\times}10^{-8}$

World average dominated by LHCb results

provided by the courtesy of M. Gersabeck

Conclusions

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Several other searches for *CP* violation in charm are carried out with different decay modes and new updates with full data set will be available soon → Stay tuned!

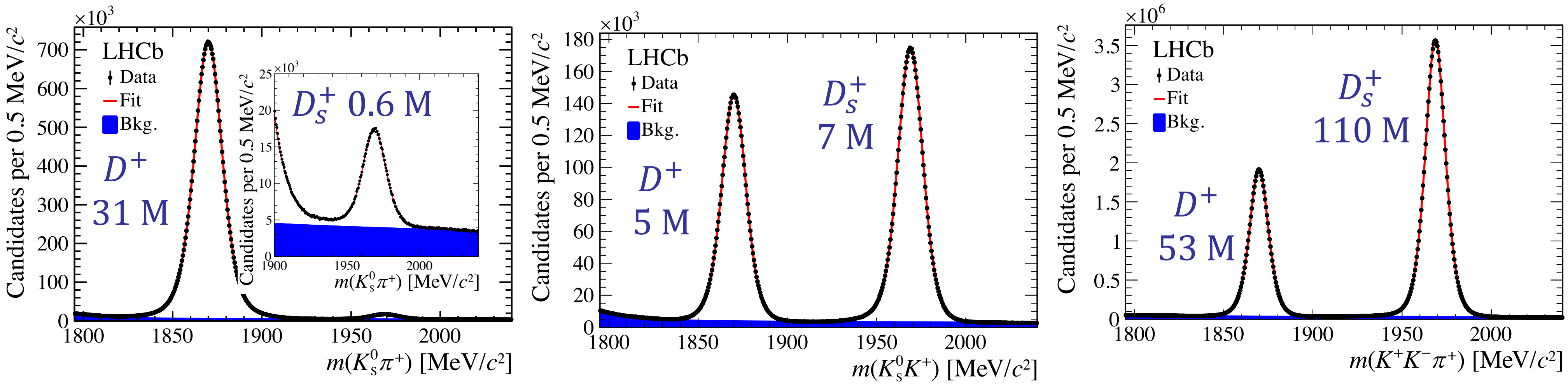
Backup

Search for Direct *CP* Violation

Run 2
($3.8\ fb^{-1}$)

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

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



No *CP* violation observed

Measurement of the mass difference between neutral charm-meson eigenstates with $D^0 \to K_s^0 \pi^+ \pi^-$ decay

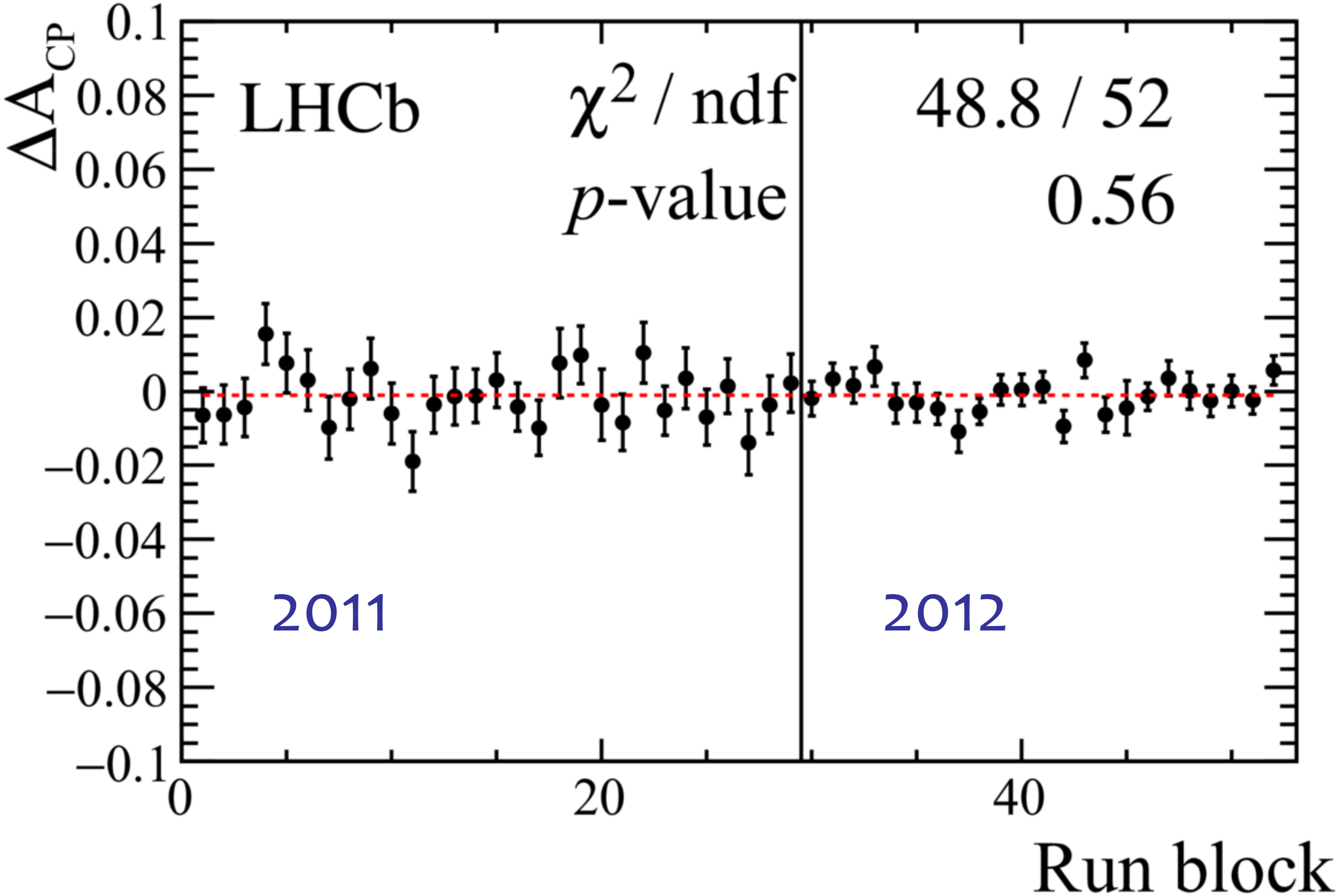
LHCB-PAPER-2019-001
[arXiv:1903.03074]

Table 5: Updated global combinations of charm-mixing measurements.

Parameter	Value	Allowed interval 68.3% CL	95.5% CL	99.7% CL
x [10^{-2}]	0.38 ± 0.12	[0.26 , 0.50]	[0.14, 0.61]	[0.02, 0.71]
y [10^{-2}]	$0.655\,^{+0.062}_{-0.067}$	[0.588, 0.717]	[0.52, 0.78]	[0.44, 0.84]
$\lvert q/p \rvert$	$0.967\,^{+0.050}_{-0.045}$	[0.922, 1.017]	[0.88, 1.07]	[0.84, 1.13]
ϕ	$-0.070\,^{+0.079}_{-0.081}$	[−0.151, 0.009]	[−0.24, 0.09]	[−0.33, 0.19]

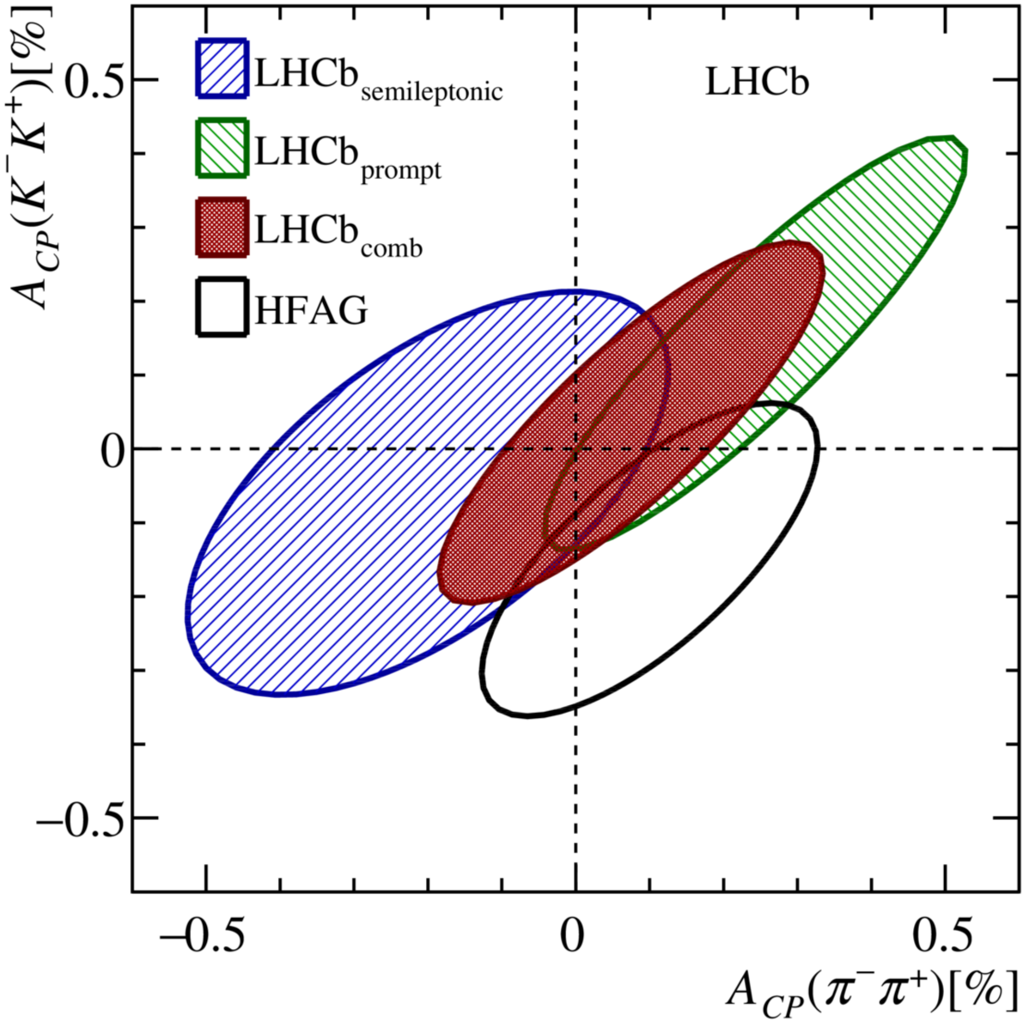
ΔA_{CP} vs data taking period Run 1

Phys. Rev. Lett. 116 (2016) 191601



$A_{CP}(KK)$ and $A_{CP}(\pi\pi)$

Phys. Lett. B767 (2017) 177



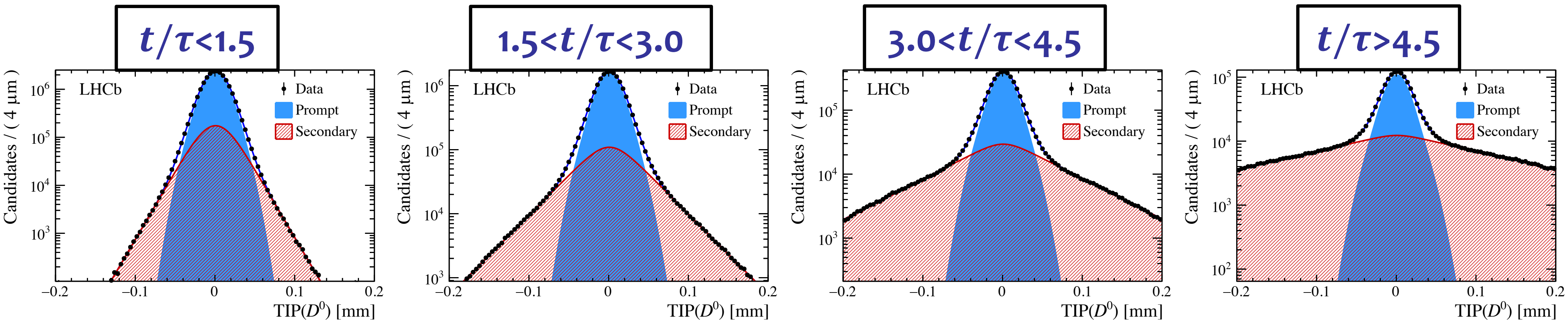
Systematic uncertainties [π-tagged]

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

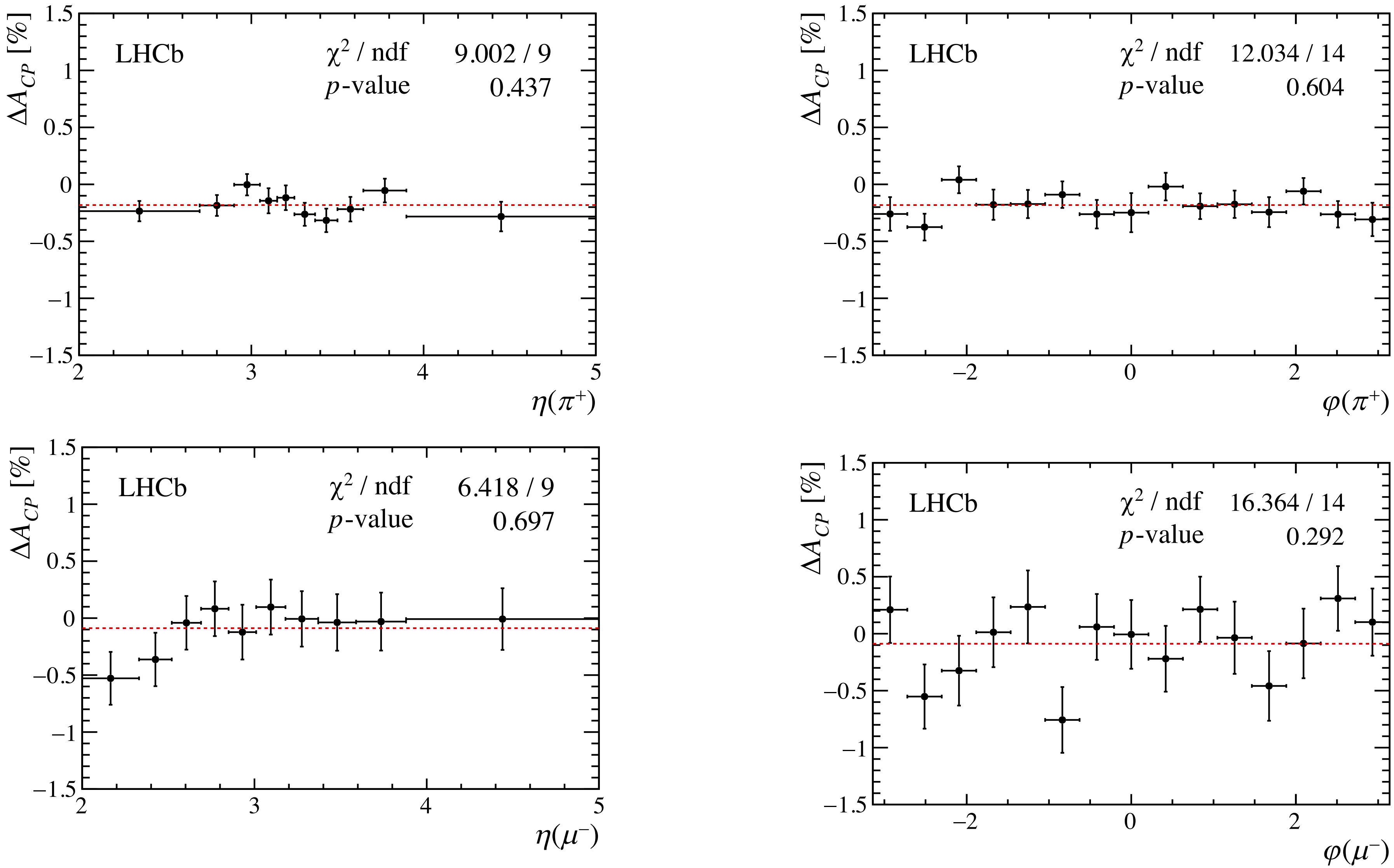
- Measure fraction of secondary D^0 by fitting the distribution of the D^0 IP in the plane transverse to the beam (TIP)

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

- Study performed in bins of $t/\tau(D^0)$ to have a better control on the resolution



Further cross-checks



ΔA_{CP} – Fit model systematic

- Choose 6 alternative fit models
- 1000 toys for each subsample → generate with baseline → fit with baseline and alternative → calculate $\Delta A_{CP,alt} - \Delta A_{CP,nom}$
- Sum in quadrature mean and σ of $\Delta A_{CP,alt} - \Delta A_{CP,nom}$ distribution for each model
- As a conservative choice, take the maximum as systematic uncertainty

→ 0.6×10^{-4} for π-tagged

→ 2×10^{-4} for μ-tagged

ΔA_{CP} – Weighting systematic

- Uncertainty on weighting function due to limited statistics
- Gaussian extraction of alternative weight event by event → fit to get $\Delta A_{CP,alt}$
- Perform 300 tests
- Uncertainty is the sum in quadrature of mean and σ of $\Delta A_{CP,alt} - \Delta A_{CP,nom}$

→ 0.2×10^{-4} for π-tagged

→ 10^{-4} for μ-tagged

ΔA_{CP} – Difference in B^0 fraction (μ-tagged)

- Effective D^0 production asymmetry in μ-tagged B decays:

$$A_{\mathrm{P,eff}}(D^0) = A_{\mathrm{P}}(B^+) + f(B^0)[A_{\mathrm{P}}(B^0) \cdot D - A_{\mathrm{P}}(B^+)]$$

- In Run 1 analysis: difference in $f(B^0)$ is $(0.34 \pm 0.18)\%$ between KK and $\pi\pi$ due to difference in B^0 and B^+ reconstruction efficiencies
- $A_P(B^0)$ and $A_P(B^+)$ 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 10^{-4} as systematic uncertainty

ΔA_{CP} – Difference in τ acceptance (μ-tagged)

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

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

- Syst uncertainty taken unchanged from Run 1 analysis
➔ estimated to be maximum 2×10^{-4}

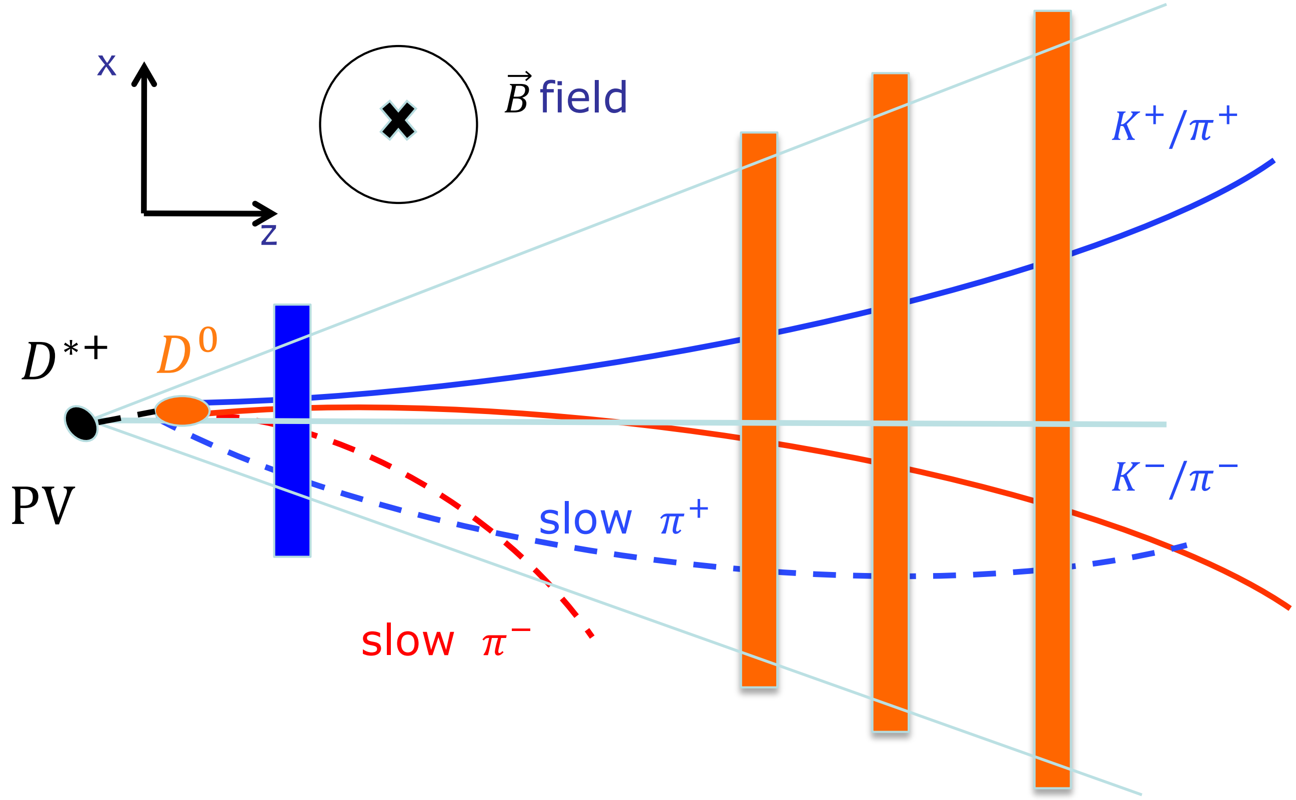
Mistag rate (μ-tagged)

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

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

Fiducial Selection

- For some regions of phase space, the soft pion of a specific charge is kicked out from the detector acceptance by the magnetic field
- This breaks the assumption that the raw asymmetries are small



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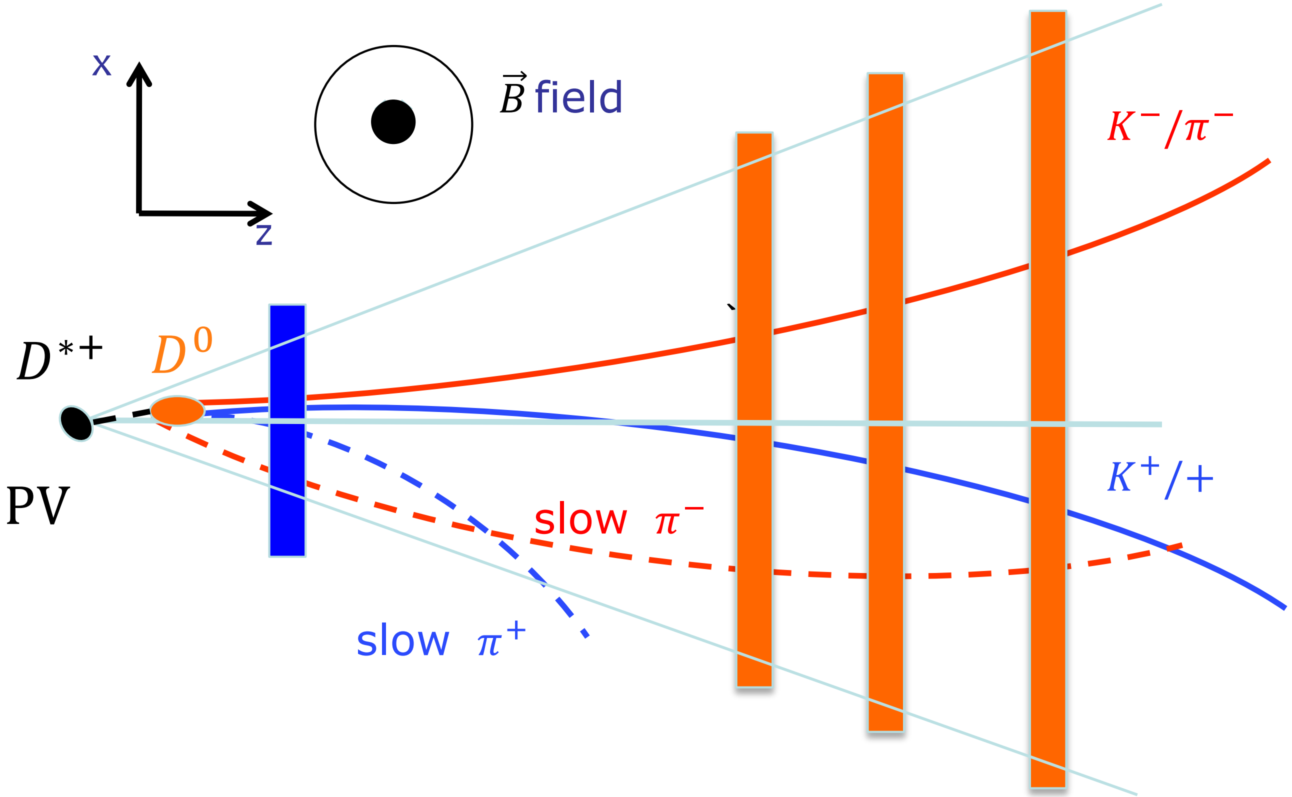
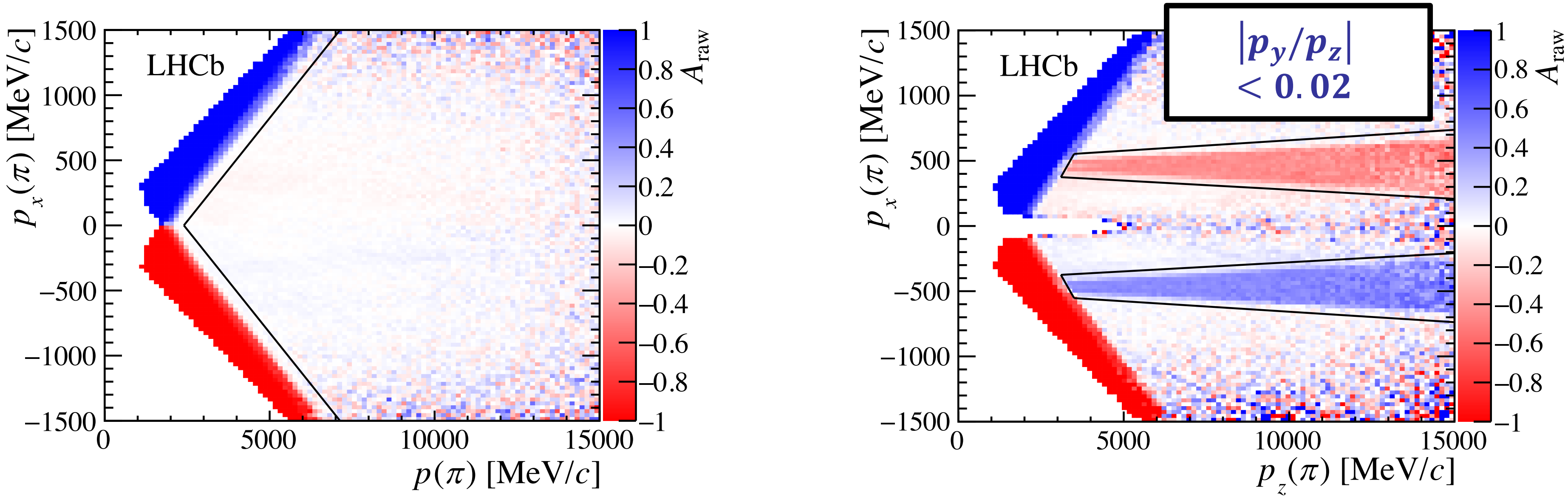


Fiducial Selection

LHCb-PAPER-2019-006

- There are regions of phase space where only D^{*+} or only D^{*-} is kinematically possible.
  - this causes large value of $A_{\rm raw}$ up to 100% in the edge regions where only D^{*+} or D^{*-} is reconstructed
  - this asymmetry is independent of the D⁰ decay modes but it breaks the assumption that the raw asymmetries are small

Magnetic field ⬆



Fiducial Selection

LHCb-PAPER-2019-006

- There are regions of phase space where only D^{*+} or only D^{*-} is kinematically possible.
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  - this asymmetry is independent of the D⁰ decay modes but it breaks the assumption that the raw asymmetries are small

Magnetic field ⬇