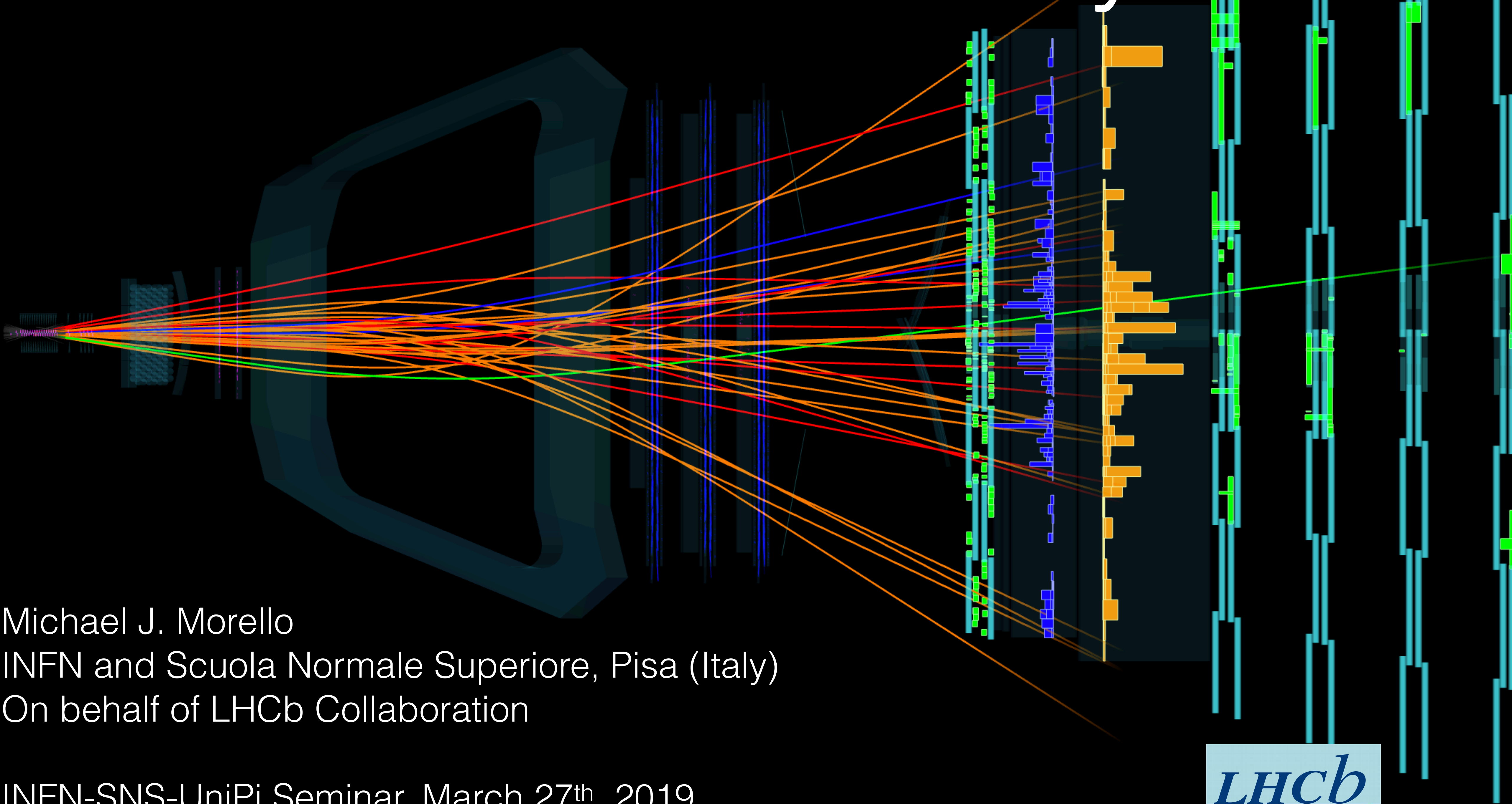
Observation of CP violation in charm decays



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On behalf of LHCb Collaboration

INFN-SNS-UniPi Seminar, March 27th, 2019

LHCb

CP Violation

- The non-invariance of the weak interactions with respect to the combined charge-conjugation (C) and parity (P) dates back to year 1964
  - discovered through the observation of $K_L \to \pi^+\pi^-$ decays, which exhibit a branching ratio at 10^{-3} level (the famous ε_K parameter),
  - it was the first manifestation of indirect CP violation.
- Ever since the understanding of CPV has become a crucial goal in HEP:
  - to study and test reliability and robustness of the SM,
  - to probe physics beyond the SM,
  - to shed light on cosmology issues. CPV present in the SM not sufficient to explain the observed baryonic asymmetry $O(10^{-10})$.

The CKM mechanism

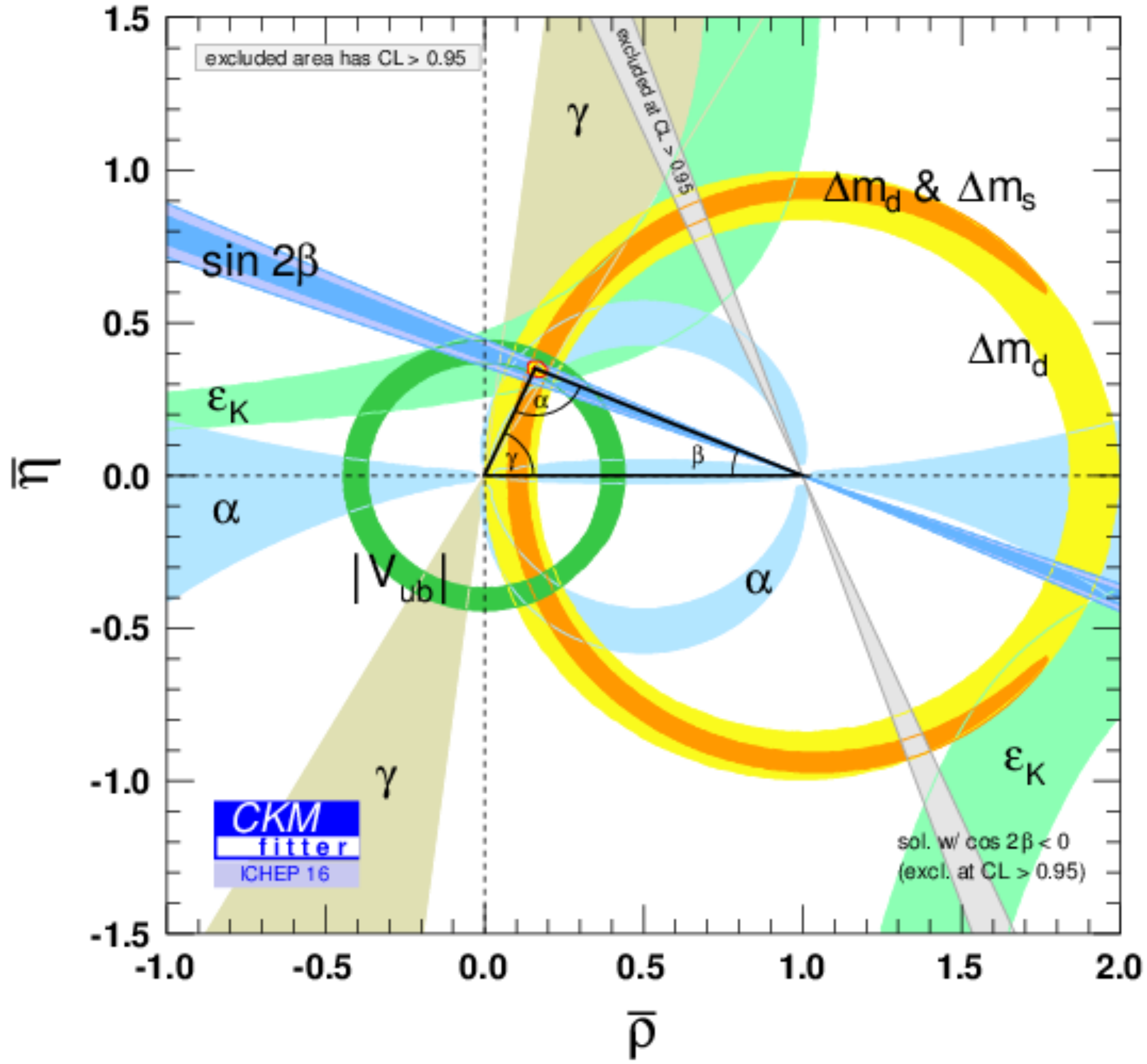
- CP-violating effects originate in the SM from the the charged-current interactions of quarks

$$\frac{-g}{\sqrt{2}}(\overline{u_L}, \overline{c_L}, \overline{t_L})\gamma^\mu W_\mu^+ V_{\rm CKM} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \text{h.c.}$$

- $V_{\rm CKM}$ matrix connects the electroweak states (d',s',b') of the down, strange and bottom quarks with their mass eigenstates (d,s,b) through an unitary transformation.

- This feature ensures the absence of flavour-changing neutral-current (FCNC) processes at the tree level in the SM, and is hence at the basis of the famous Glashow–Iliopoulos–Maiani (GIM) mechanism.

CPV accommodated in the SM through a single complex phase in the CKM matrix.



Why charm is charming?

- CPV not yet observed (until today) in charm and predicted to be “small” within SM.
  - SM expectations lie in the range of $10^{-3} - 10^{-4}$.
- Charm is the only up-type quark allowing full range of probes for mixing and CPV:
  - top quark decays too fast (no hadronization),
  - π^0-π^0 oscillations not possible (particle and antiparticle are identical).
- Complementarity to B and K mesons.

Charm transitions are a unique portal for obtaining a novel access to flavor dynamics with the experimental situation being a priori favorable (“low SM background”).

Charm Mixing

$$|D_{1,2}\rangle = q\,|D^0\rangle \pm q\,|\overline{D}^0\rangle \qquad x \equiv 2(m_2 - m_1)/(\Gamma_1 + \Gamma_2)$$

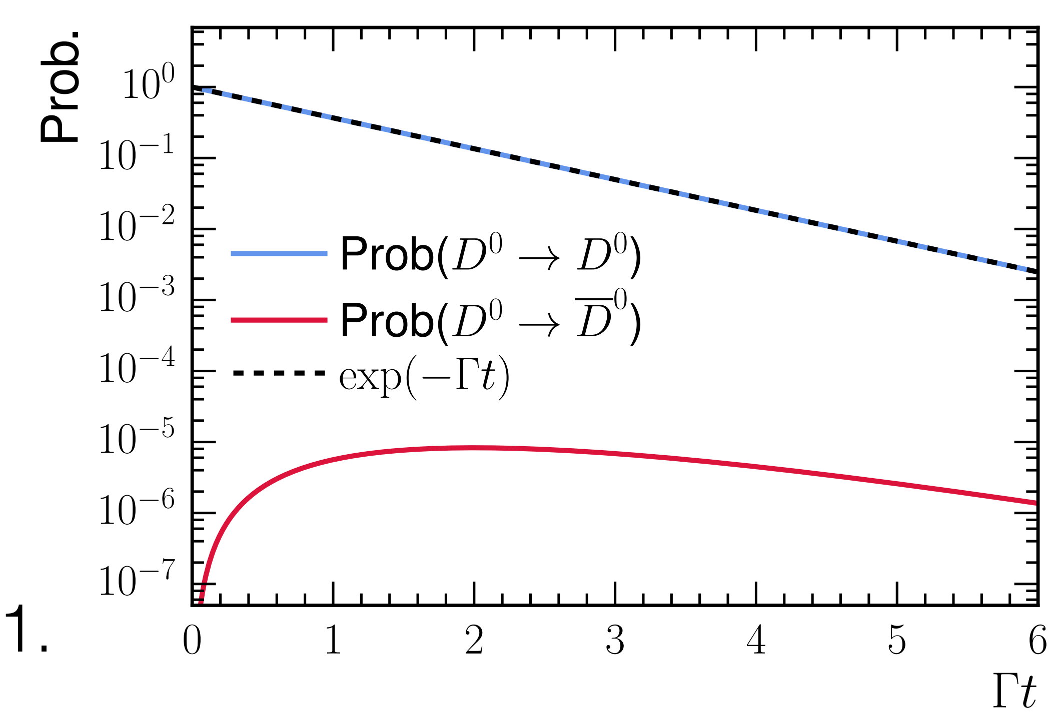
$$(|q|^2 + |p|^2 = 1, \phi = \arg\,(q/p)) \qquad y \equiv (\Gamma_2 - \Gamma_1)/(\Gamma_1 + \Gamma_2)$$

First hints from Babar/Belle in 2007. Very slow rate $x \leq 10^{-2}$ and $y \simeq 10^{-2}$.

$$\text{Prob}(D^0 \to \overline{D}^0; t) = |\langle D^0(t)|\overline{D}^0\rangle|^2 = \left|\frac{q}{p}\right|^2 \cdot |g_-(t)|^2$$

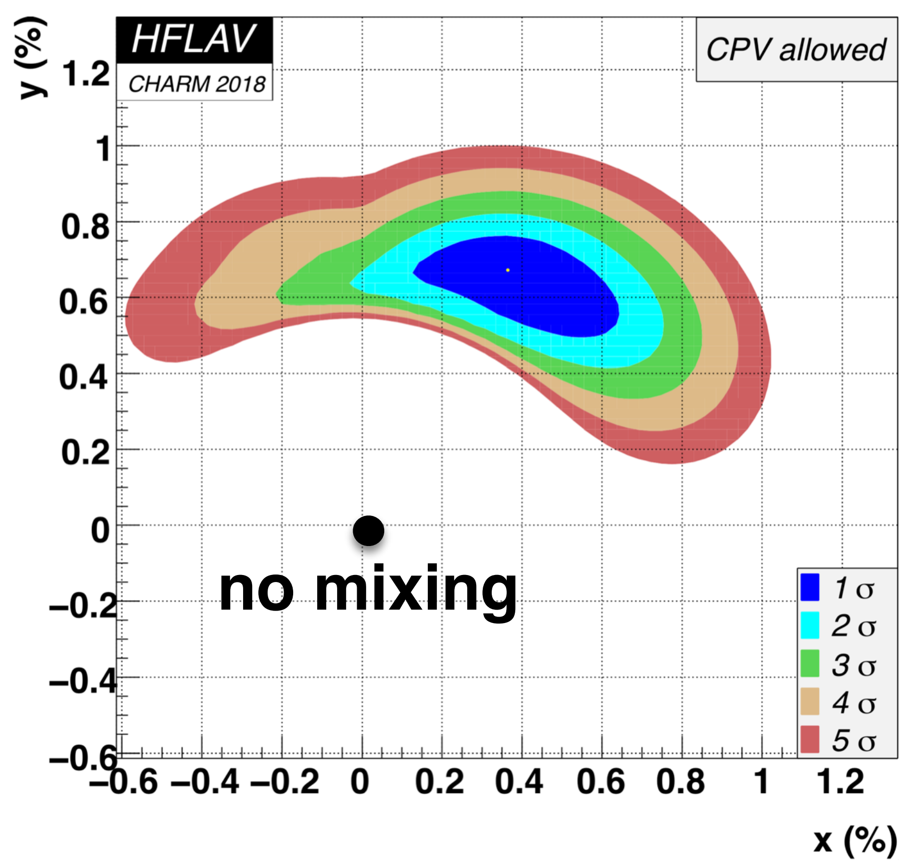
$$\text{Prob}(\overline{D}^0 \to D^0; t) = |\langle \overline{D}^0(t)|D^0\rangle|^2 = \left|\frac{p}{q}\right|^2 \cdot |g_-(t)|^2$$

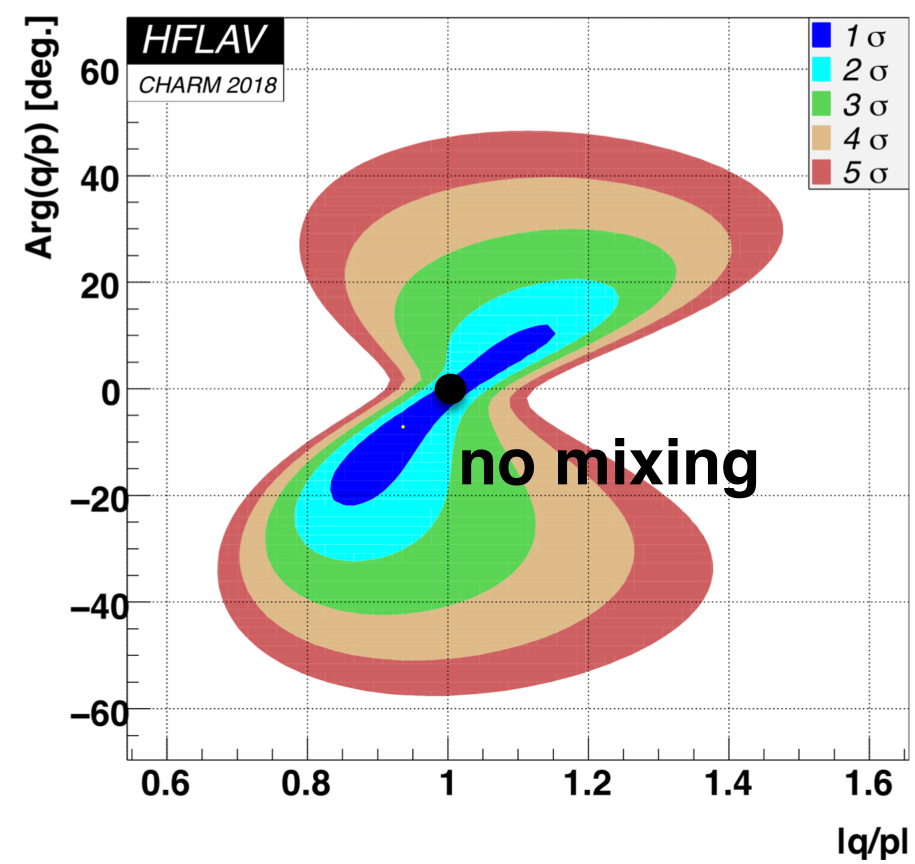
$$|g_\pm(t)|^2 = \frac{1}{2}e^{-\Gamma t}\left[\cosh\frac{\Delta\Gamma t}{2} \pm \cos\Delta M t\right].$$



CP violation in mixing
Prob(D^0 → anti-D^0) ≠ Prob(anti-D^0→D^0) if $|q/p| \neq 1$.

Experimental status on D^0 mixing





Parameter	No CPV	No direct CPV in DCS decays	CPV-allowed	CPV-allowed 95% CL Interval
x (%)	$0.50\,^{+0.13}_{-0.14}$	$0.46\,^{+0.12}_{-0.13}$	$0.36\,^{+0.21}_{-0.16}$	$[0.06, 0.70]$
y (%)	$0.63\,\pm 0.08$	$0.62\,\pm 0.07$	$0.67\,^{+0.06}_{-0.13}$	$[0.46, 0.79]$

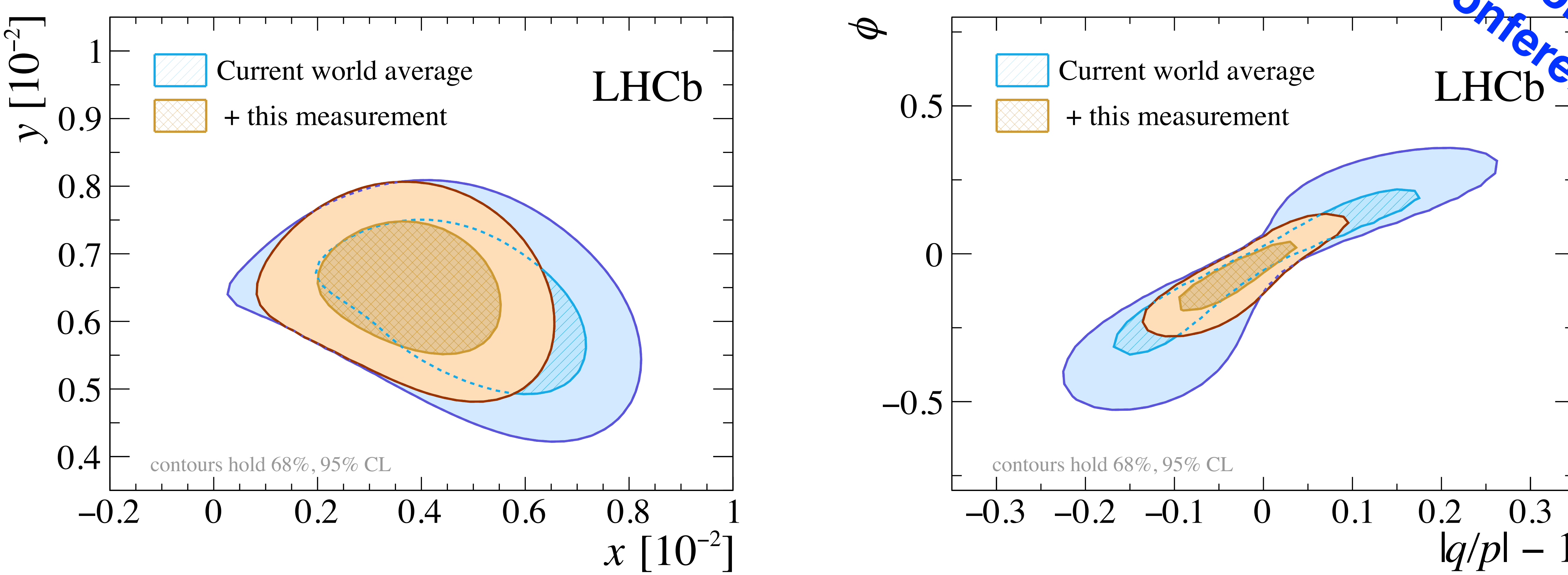
HFLAV 2018

Mixing well established. Charm mixing parameters are small < 10^{-2}

Measurement of the mass difference between neutral charm-meson eigenstates with $D^0 \rightarrow K^0_S \pi^+ \pi^-$ decay. (Run 1, $3fb^{-1}$)

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

New for Winter Conferences

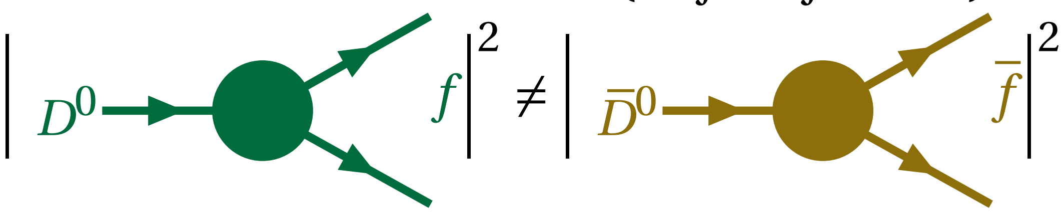


Most precise determination of x from a single experiment. Combination with current global knowledge provides $x > 0$ at more than 3σ level $\Longrightarrow$ **first evidence that the masses of the neutral charm meson eigenstates differ.**

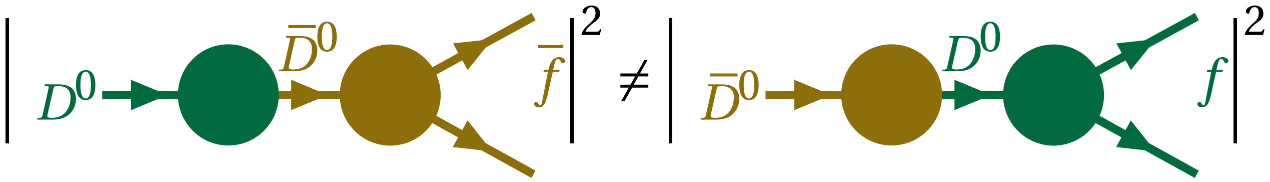
CPV observables

$$A_f = \langle f|\mathcal{H}|D^0\rangle$$
$$\bar{A}_{\bar{f}} = \langle \bar{f}|\mathcal{H}|\bar{D}^0\rangle$$

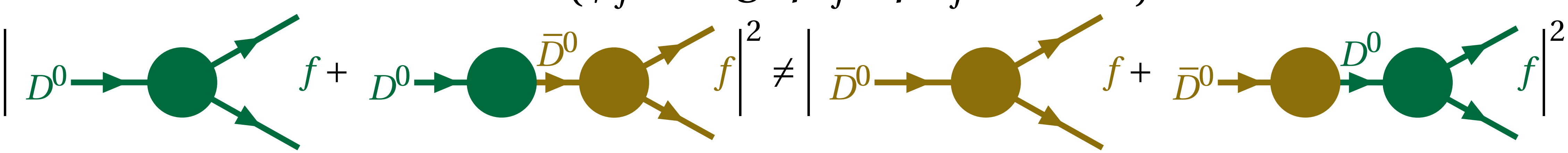
CPV in the decay $\left(|\bar{A}_f/A_f| \neq 1\right)$ → $R_f \equiv \left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| \neq 1$



CPV in the mixing $\left(|q/p| \neq 1\right)$ → $R_m \equiv \left|\frac{q}{p}\right| \neq 1$



CPV in the interference $\left(\phi_f = \arg(q\bar{A}_f/(pA_f)) \neq 0, \pi\right)$



CPV in the decay ("direct") is the topic of today's seminar

The intensity frontier

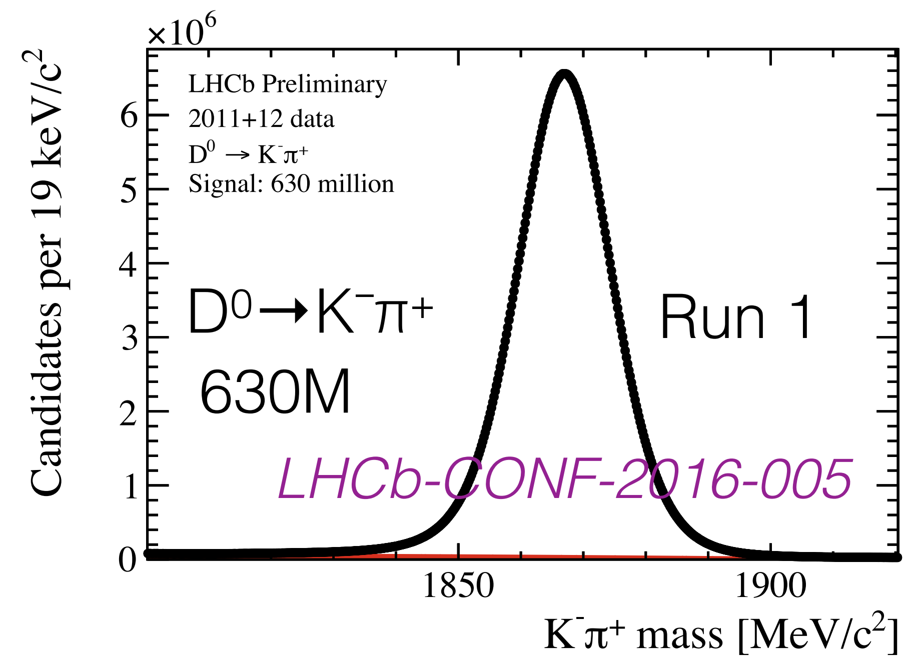
- Measuring CP-violating asymmetries below the level of 10^{-3} (10^{-4}) requires samples with $>10^6$ (10^8) charm decays.
  - note, with no background: $\sigma(A_{CP}) \approx 1/\mathrm{sqrt}(N)$
- Unprecedented huge and pure samples of charm decays are therefore needed for probing CPV and mixing.
- Slow mixing rate ask also for large samples enriched at higher lifetime values.

LHC: a charm factory

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

$$\sigma(pp \to c\bar{c}X) = 1419 \pm 134\ \mu b\ @\ \sqrt{s} = 7\,\mathrm{TeV}$$ [Nucl. Phys. B871 (2013) 1520]

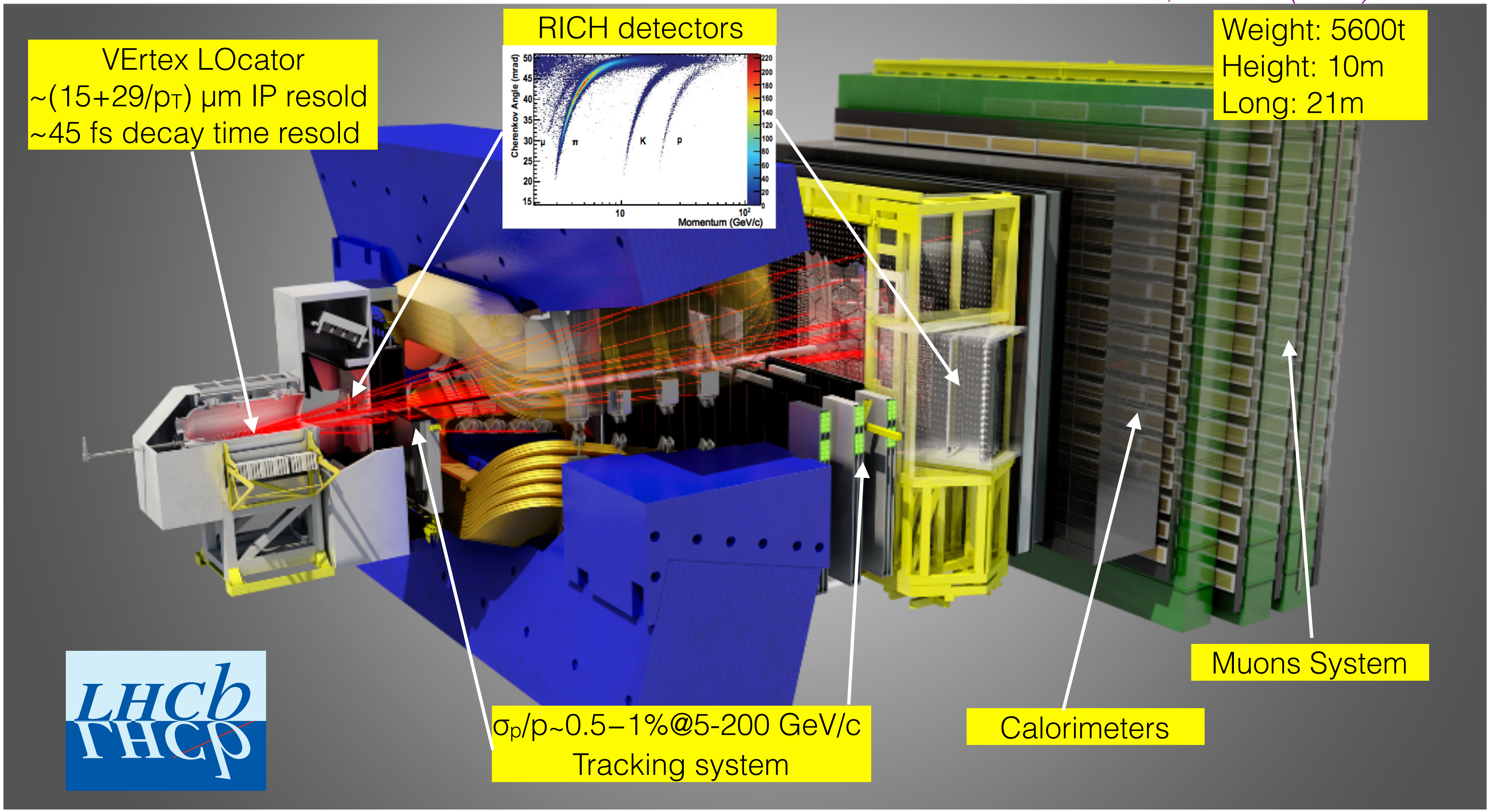
$$\sigma(pp \to c\bar{c}X) = 2840 \pm 226\ \mu b\ @\ \sqrt{s} = 13\,\mathrm{TeV}$$ [J. High Energ. Phys. (2017) 74]



Produced ~5×10^{12} D^0 (~10^{12} D^{*+}) mesons per year at L= 4×10^{32} $cm^{-2}s^{-1}$.
More than 1 billion of $D^0 \to K\pi$ decays in the full LHCb data sample.

The LHCb experiment

The LHC detector at LHC, JINST 3 (2008) S08005



Excellent trigger capabilities (Level-0 of custom electronics + HLT of commercial CPUs) to handle 11MHz of visible physics collisions. Events written on tape extremely fast at 5KHz, where typical event size is 60KBytes in Run 1 (2011-2012). In Run 2 (2015-2018) performances are even better (TURBO). [LHCb-PROC-2015-011].

Two-body $D^0 \to h^+h^-$ decays

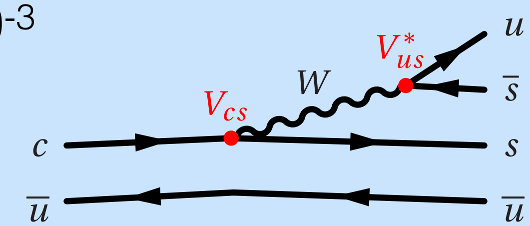
- $D^0 \to h^+h^-$ decays, where h=K,π, are experimentally clean channels allowing the study of the CP violation in the charm system.

- $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ Singly-Cabibbo-Suppressed decays. Final states are CP-eigenstates and allow a full probe of all types of CP-violation.

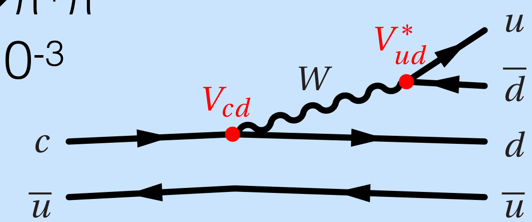
- $D^0 \to K^-\pi^+$ Cabibbo-Favored decays. They are flavour-specific and are used as a formidable control channel, being much more abundant than the SCS modes.

- $D^0 \to K^+\pi^-$ Doubly-Cabibbo-Suppressed decays. Essential to measure mixing parameters.

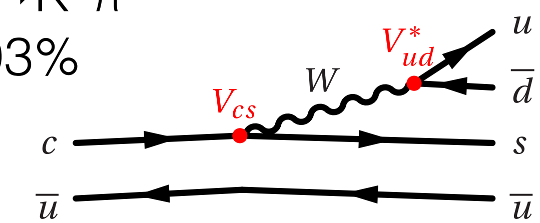
SCS: $D^0 \to K^+K^-$
BR≈4×10^{-3}



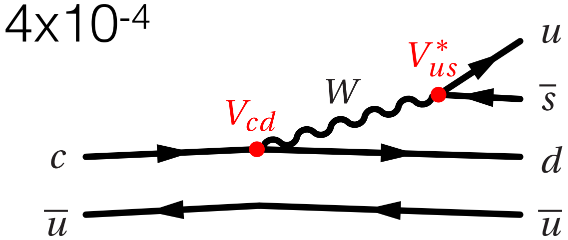
SCS: $D^0 \to \pi^+\pi^-$
BR≈1.4×10^{-3}



CF: $D^0 \to K^-\pi^+$
BR≈3.93%



DCS: $D^0 \to K^+\pi^-$
BR≈1.4×10^{-4}



Search for direct CP Violation with $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ decays with Run 2 data

(+ Run 1 combination)

Paper link: LHCb-PAPER-2019-006,arXiv:1903.08726
talk at Moriond EW (Federico Betti)
CERN Seminar (Angelo Carbone)

$A_{CP}(t)(D^0 \rightarrow h^+h^-)$ h=K,π

Because of the slow mixing rate of charm mesons (x,y~10^{-2}) the time-dependent asymmetry is approximated at first order as the sum of two terms:

$$A_{CP}(f;t) \approx A_{CP}^{\text{dir}}(f) + \frac{t}{\tau_D} A_{CP}^{\text{mix+int}}(f)$$

$$f = K^+K^- \text{ or } \pi^+\pi^-$$

$$A_{CP}^{\text{dir}}(f) \equiv A_{CP}(f, t=0) = \frac{|A_f|^2 - |\bar{A}_f|^2}{|A_f|^2 + |\bar{A}_f|^2} = \frac{1 - R_f^2}{1 + R_f^2}$$

$$A_{CP}^{\text{mix+int}}(f) = -\frac{2\eta_f^{CP} R_f^2}{(1+R_f^2)^2} \left[(R_m R_f - R_m^{-1} R_f^{-1}) y \cos\phi_f - (R_m R_f + R_m^{-1} R_f^{-1}) x \sin\phi_f\right]$$

The time-integrated asymmetry is the integral over the “experimental” observed distribution of proper decay time D(t):

$$A_{CP}(f) \approx A_{CP}^{\text{dir}}(f) + A_{CP}^{\text{mix+int}}(f) \int_0^\infty \frac{t}{\tau_D} D(t) dt = A_{CP}^{\text{dir}}(f) + \frac{\langle t \rangle}{\tau_D} A_{CP}^{\text{mix+int}}(f)$$

Direct CPV: $\Delta A_{CP}(D^0 \to h^+h^-)$

- Effects of "direct" CP violation can be isolated by taking the difference between the time-integrated CP asymmetries in the K^+K^- and $\pi^+\pi^-$ modes:

$$\Delta A_{CP} \equiv A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-) = \Delta A_{CP}^{\mathrm{dir}} \left(1 + \frac{\overline{\langle t \rangle}}{\tau_D} y_{CP}\right) + \frac{\Delta \langle t \rangle}{\tau} A_{CP}^{\mathrm{ind}} \quad (*)$$

- where a residual experiment-dependent contribution from "indirect" CP violation (<u>assumed to be universal above</u>) can be present, due to the fact that there may be a decay time dependent acceptance function that can be different for the K^+K^- and $\pi^+\pi^-$ channels.

- Experimentally very clean because of cancellation of instrumental and production asymmetries (well suited for LHCb).

(*) $A_{CP}^{\mathrm{mix+int}}(f) = A_{CP}^{\mathrm{dir}}(f) y_{CP} + A_{CP}^{\mathrm{mix+int}}(f; R_f = 1) = A_{CP}^{\mathrm{dir}}(f) y_{CP} + A_{CP}^{\mathrm{ind}}$

Experimental status (before March 21st)

HFLAV combination

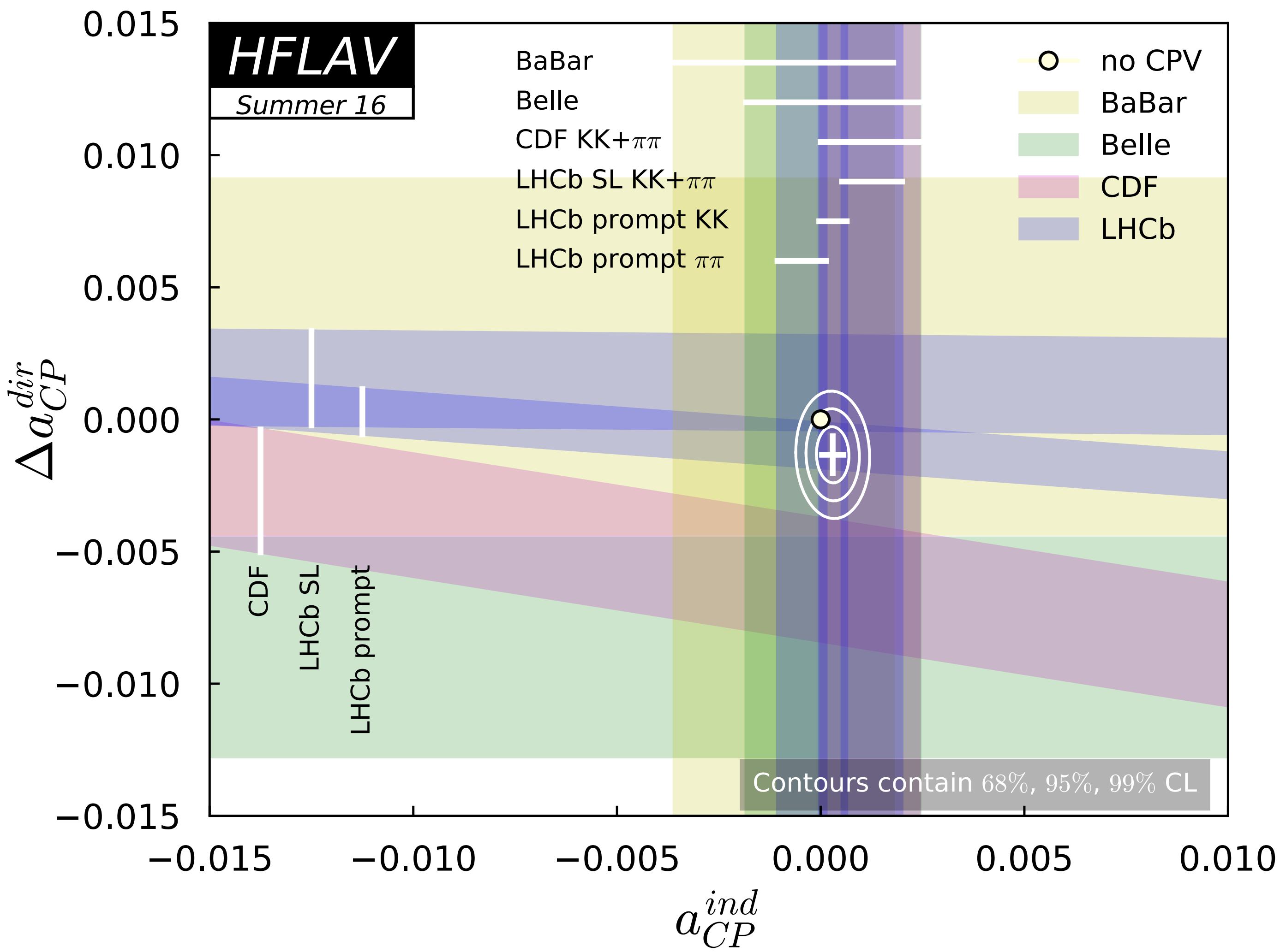
$a_{CP}^{\mathrm{ind}} = (0.030 \pm 0.026)\%$

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

Consistency with NO CPV hypothesis: 9.3%

World average already fully dominated by LHCb.

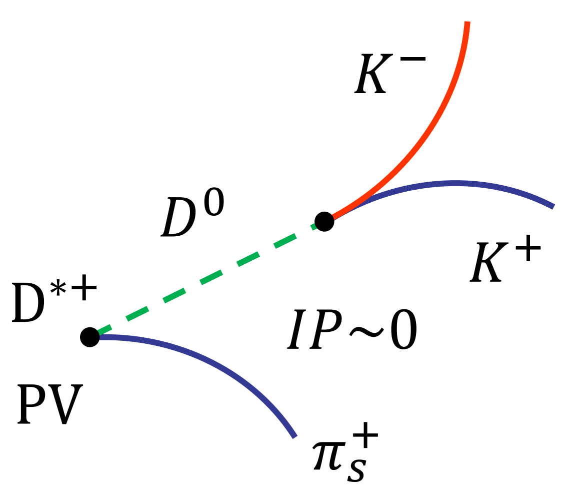
HFLAV 2016 arXiv:1612.07233 [hep-ex]
https://hflav.web.cern.ch



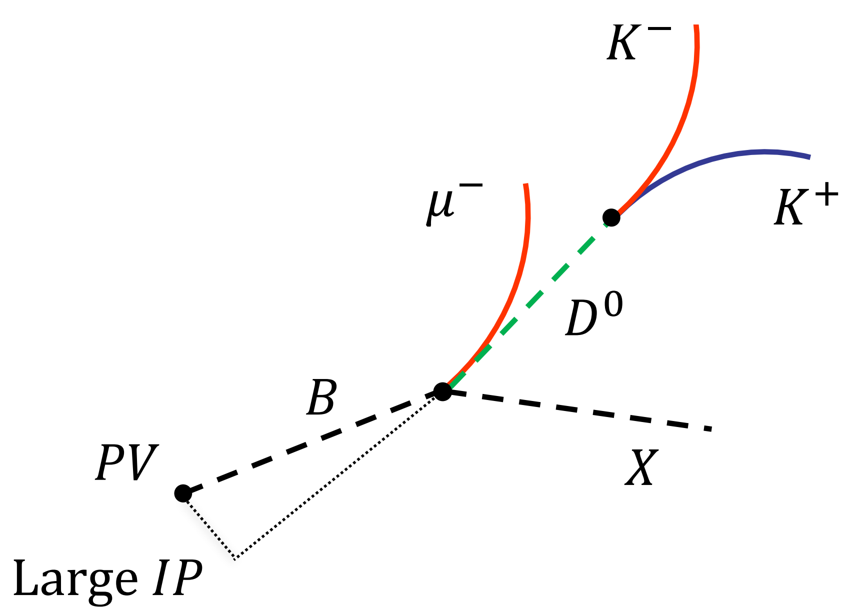
Flavour identification

K^+K^- and $\pi^+\pi^-$ are CP-eigenstates $\Longrightarrow$ D^0 flavour cannot be inferred from its decay products. Production mechanism is exploited.

D*-tagged (or π-tagged)



μ-tagged



Two independent samples used in the analysis presented today.

The raw CP asymmetry

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

$$A_{\rm raw}^{\pi-\rm tagged}(f) = \frac{N_{D^{*+}}(f) - N_{D^{*-}}(f)}{N_{D^{*+}}(f) + N_{D^{*-}}(f)} = A_{CP}(f) + \cancel{A_D(f)} + A_D(\pi_s^+) + A_P(D^{*+})$$

CP asymmetry

Any charge-dependent asymmetry in slow pion reconstruction

D^{*+} production asymmetry

where N is to the number of reconstructed candidates after background subtraction.

The raw CP asymmetry

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

$$A_{\mathrm{raw}}^{\mu-\mathrm{tagged}}(f) = \frac{N_{D^0}(f) - N_{\bar{D}^0}(f)}{N_{D^0}(f) + N_{\bar{D}^0}(f)} = A_{CP}(f) + \cancel{A_D(f)} + A_D(\mu^-) + A_{P,\mathrm{eff}}(B)$$

CP asymmetry

Any charge-dependent asymmetry in muon reconstruction

D effective production asymmetry (from B)

where N is to the number of reconstructed candidates after background subtraction.

ΔA_{CP} observable

- No detection asymmetry, by construction, for D^0 decay to K^+K^- and $\pi^+\pi^-$ CP eigenstates.
- The D^{*+} production asymmetry and slow pion detection asymmetry cancel out in the π-tagged sample.
- The D^0 effective production asymmetry (from B production asymmetry) and the muon detection asymmetry cancel out in the μ-tagged sample.
- For both samples one gets at very high level of precision:

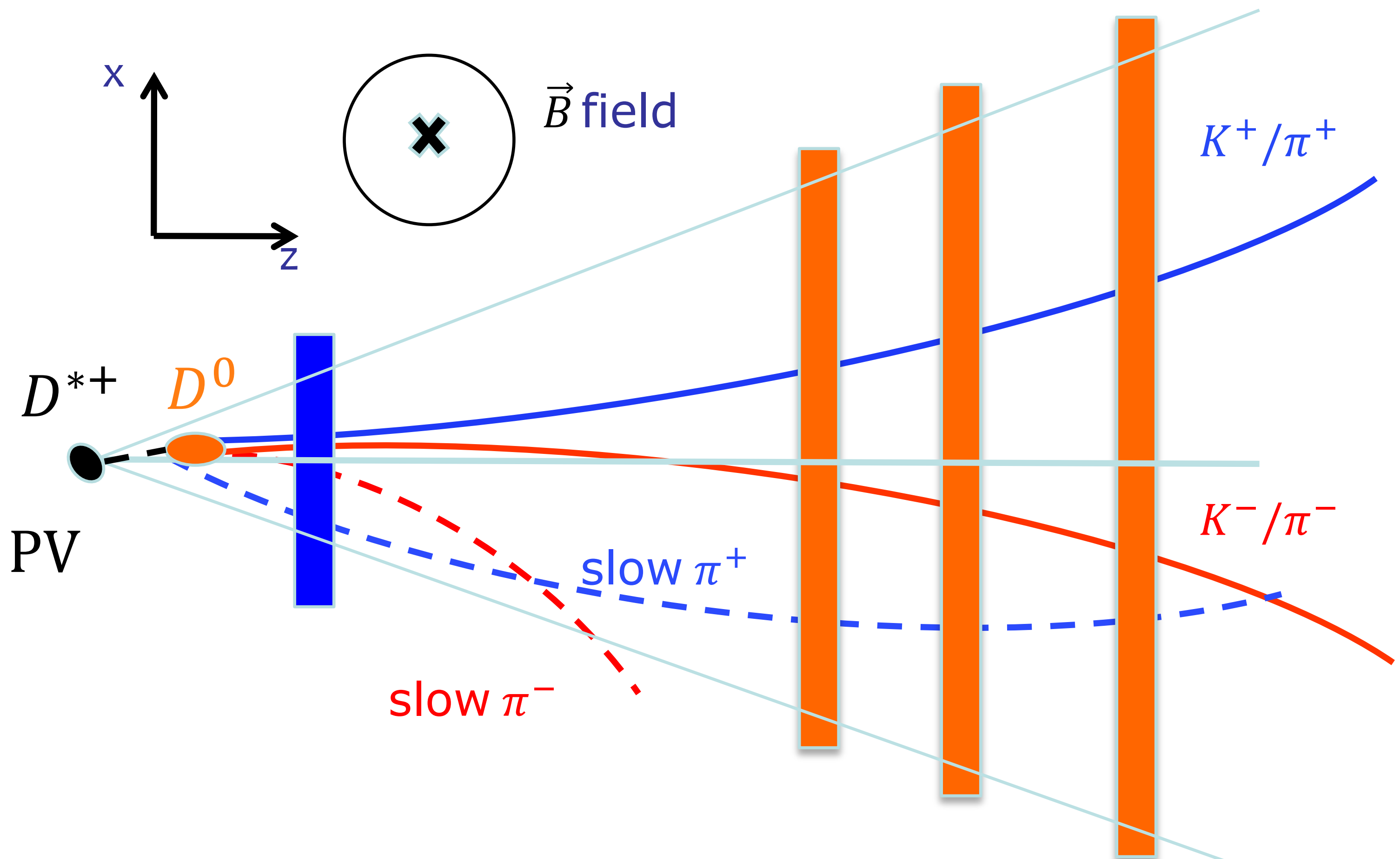
$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = A_{\mathrm{raw}}(K^+K^-) - A_{\mathrm{raw}}(\pi^+\pi^-)$$

Data sample selection

- Reconstruction performed online Turbo Stream *[Comput. Phys. Commun. 208 (2016) 35]*.
- Requirements placed on:
  - p_T of tracks and D^0 ;
  - IP of tracks and D^0.
  - quality and PID information of tracks;
  - D^0 vertex quality;
  - $m(D^0)$ for pion-tagged and $m(D^0\mu)$ for mu-tagged.
  - Additional requirements placed on for μ-tagged candidates:
    - Corrected mass: $m_{\text{corr}} \equiv \sqrt{m(D^0\mu)^2 + p_\perp(D^0\mu)^2} + p_\perp(D^0\mu)$
    - Candidates are further filtered with a MVA using as input the quality of the vertices, the D^0 flight distance, the IP and the p_T of the particles.

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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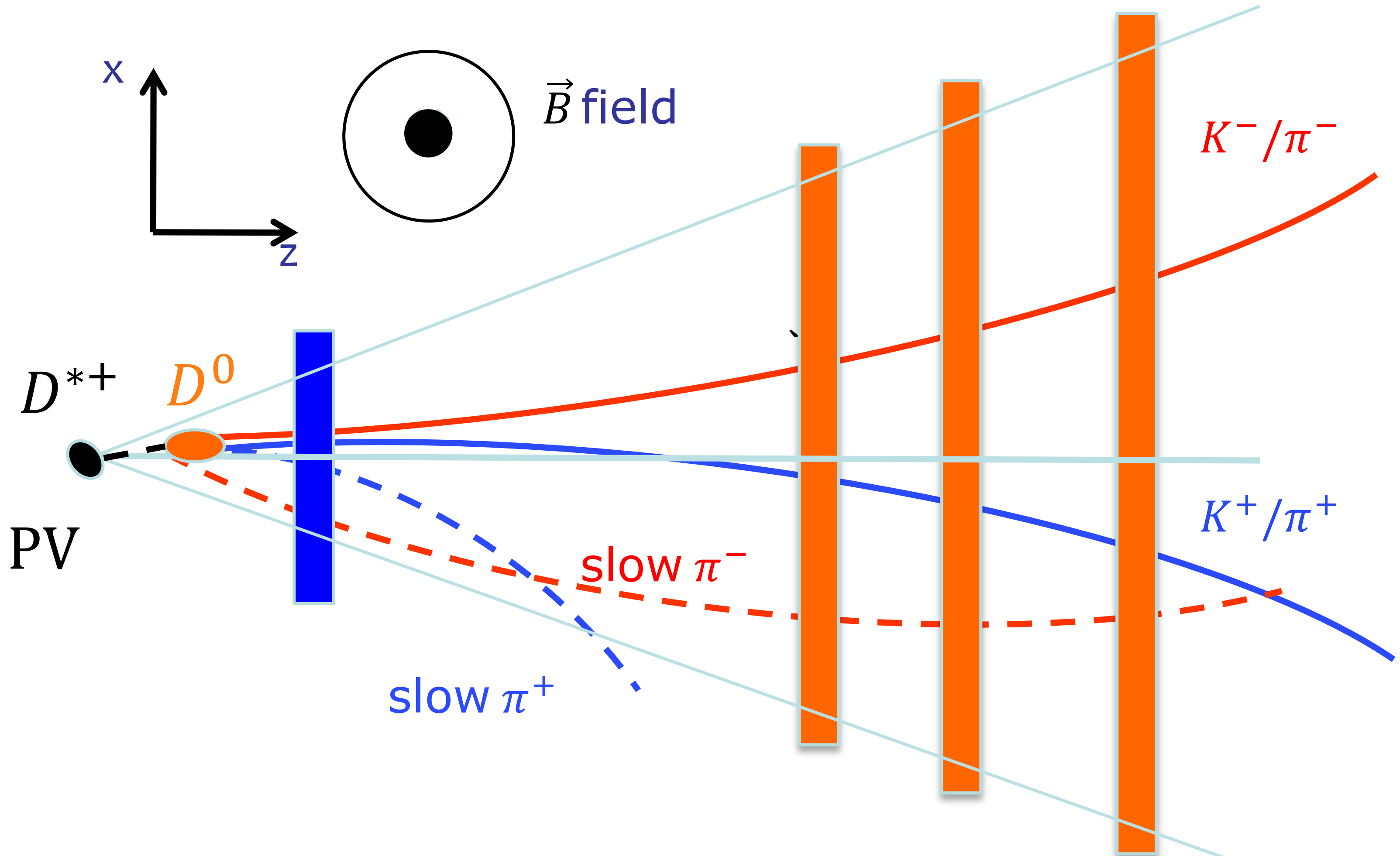
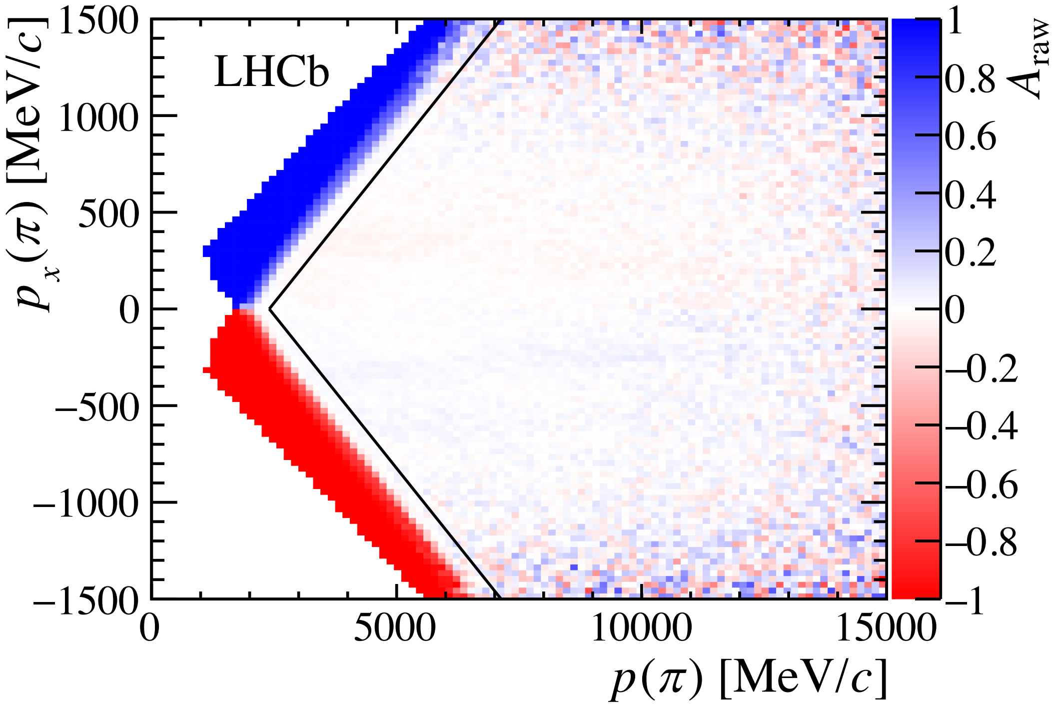
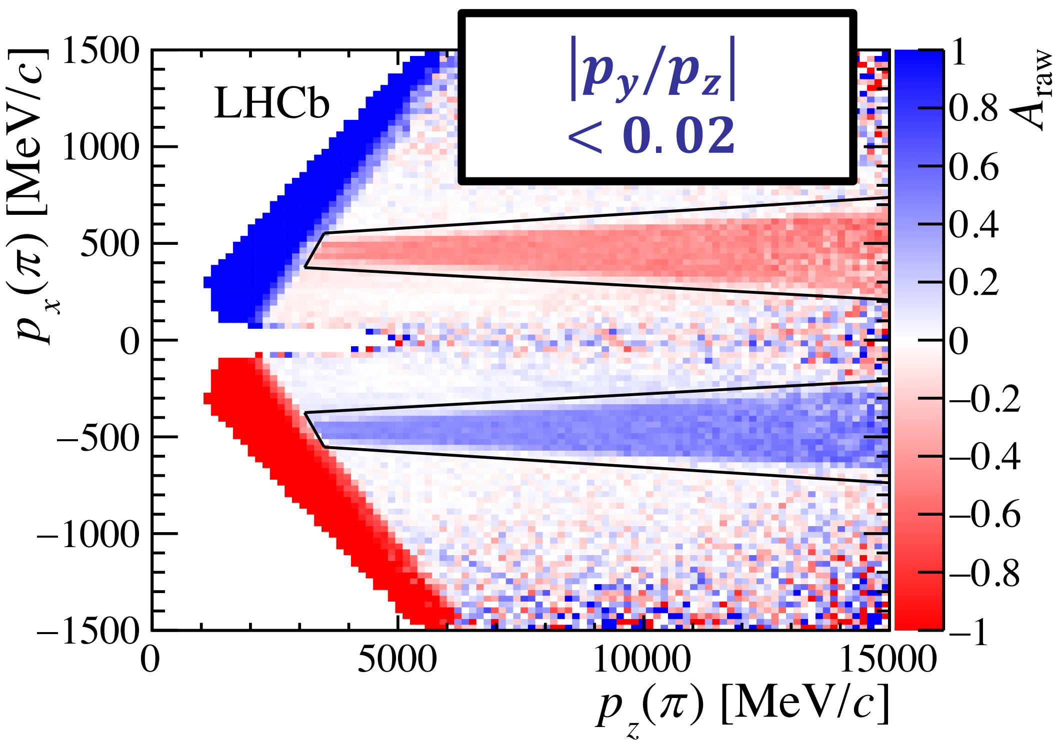


Fiducial selection

- There are regions of phase space where only D^{*+}, or only D^{*-}, is reconstructible.
    - large value of A_{raw} up to 100% in the edge regions;
    - independent of the D^0 decay modes but it breaks the assumption that the raw symmetries are small.

Magnetic filed





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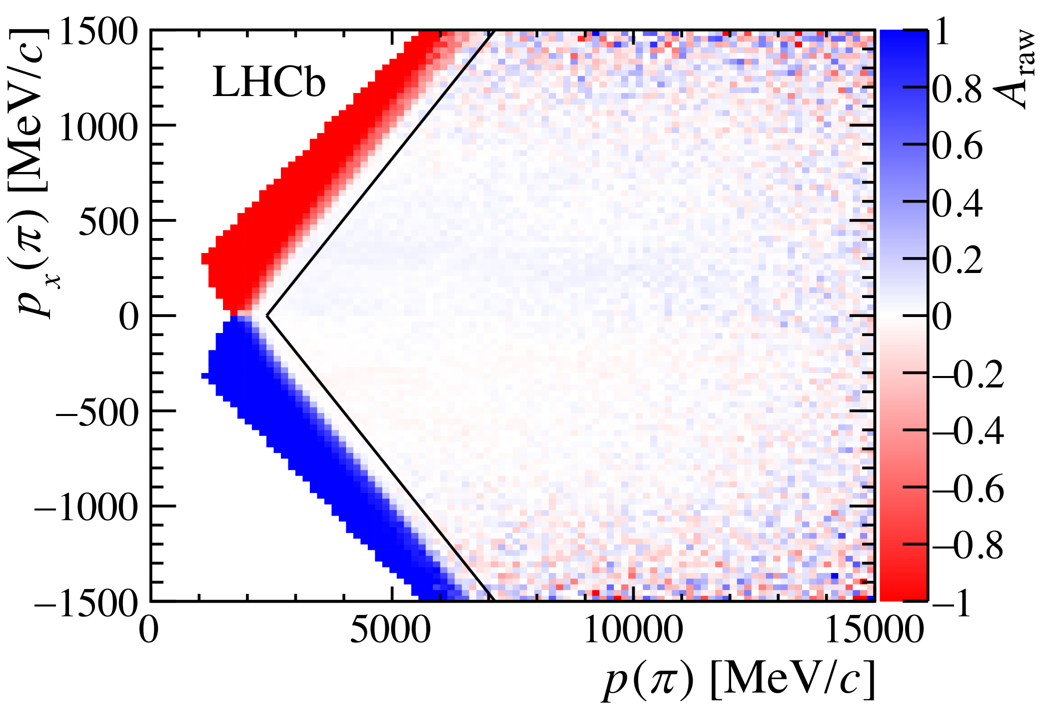
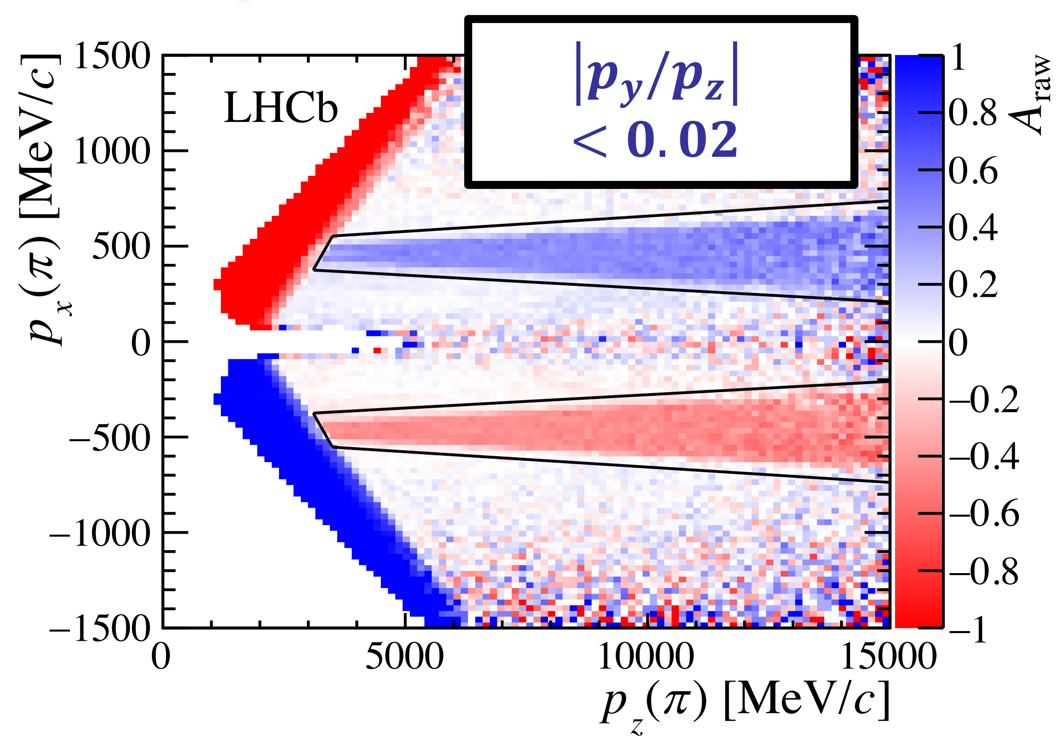
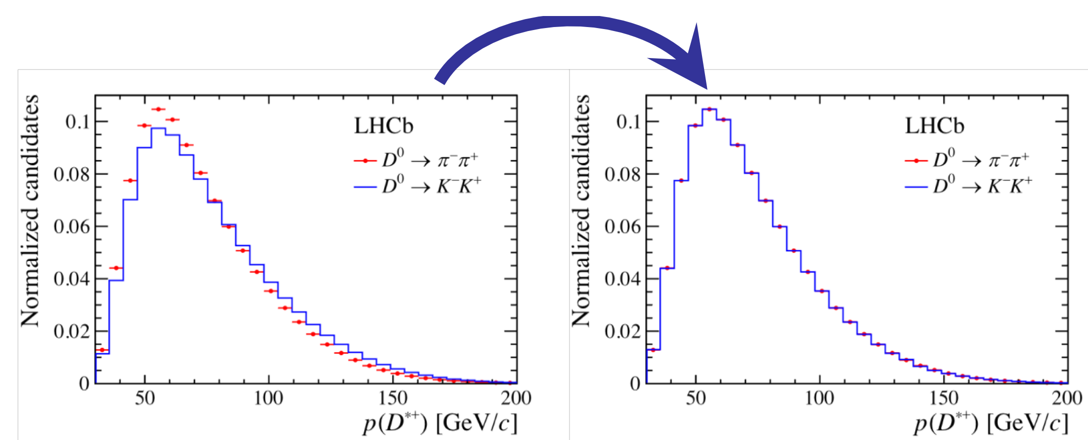


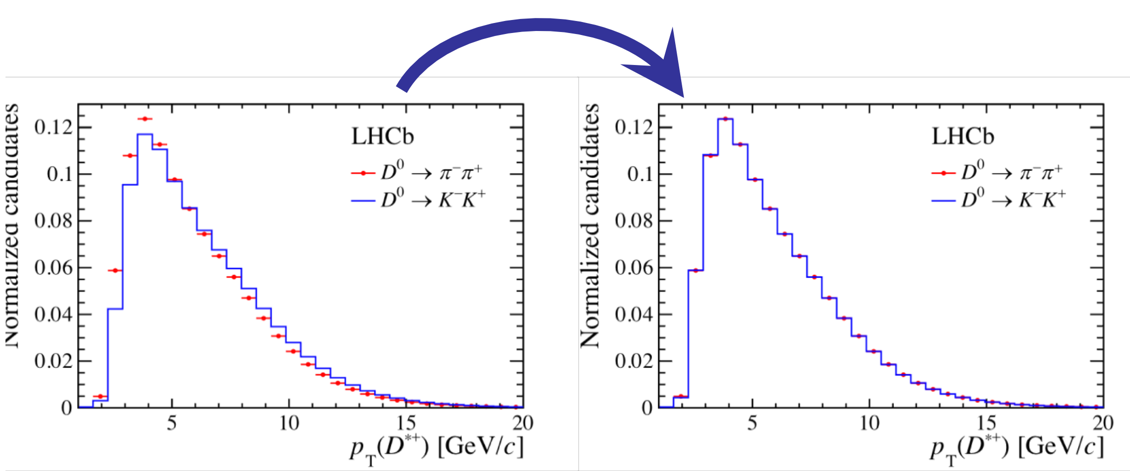


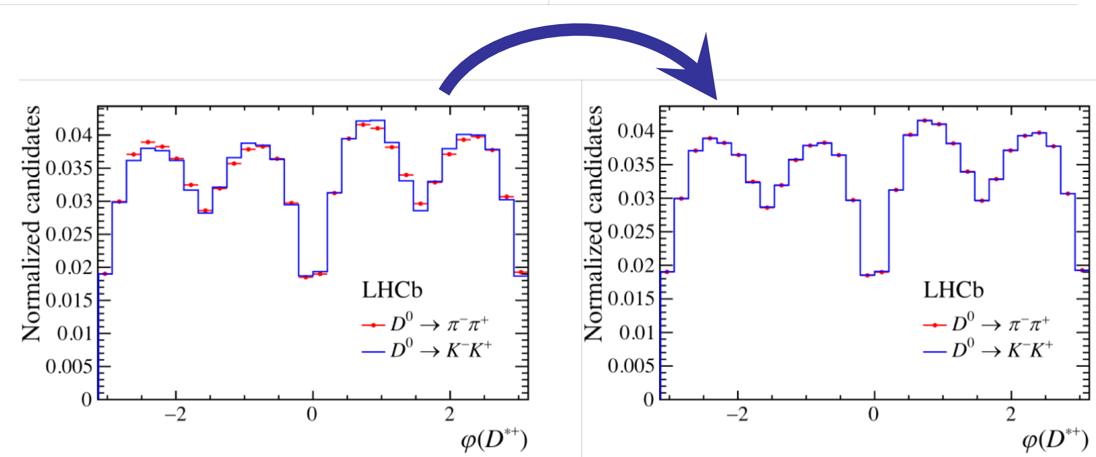
Kinematic weighing

- 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^0 candidates are different between KK and $\pi\pi$ modes.
  - a small correction to the K^+K^- sample is applied by means of a weighting procedure.



- π-tagged: $p_T(D^*)$, $p(D^*)$, $\phi(D^*)$.
- μ-tagged: $p_T(D^0)$, $p(D^0)$, $\phi(D^0)$.

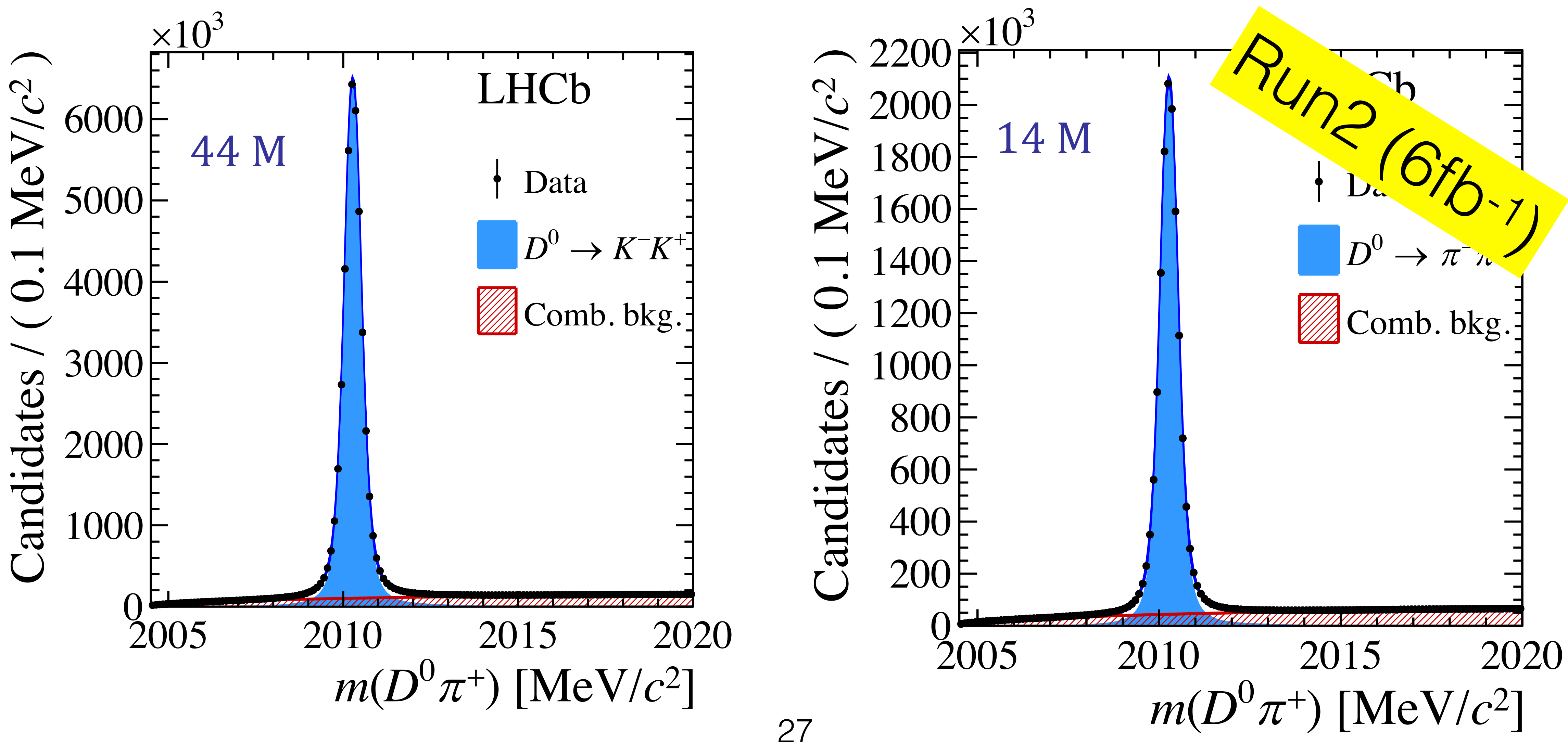




Very small effect on ΔA_{CP} below 10^{-4}.

A_{raw} measurement [π-tagged]

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



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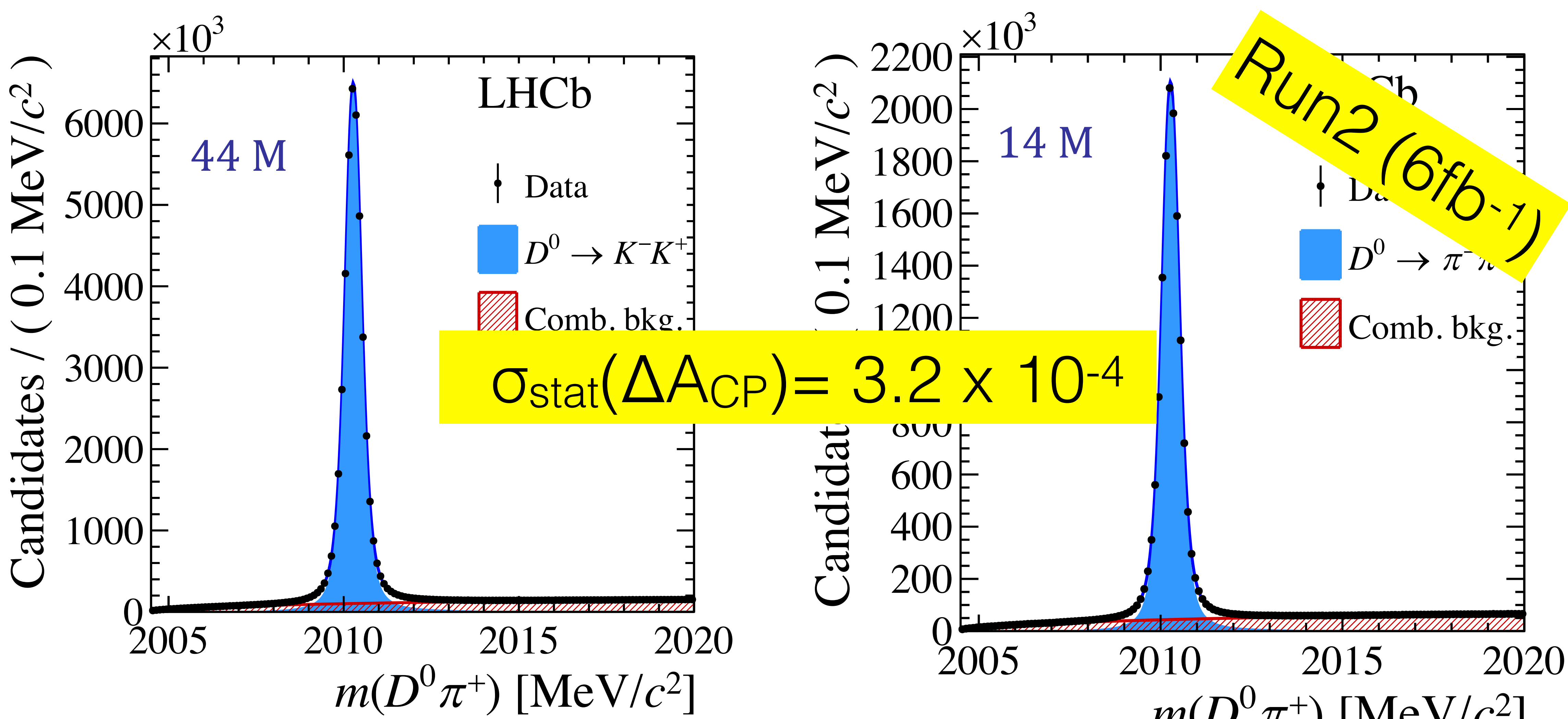
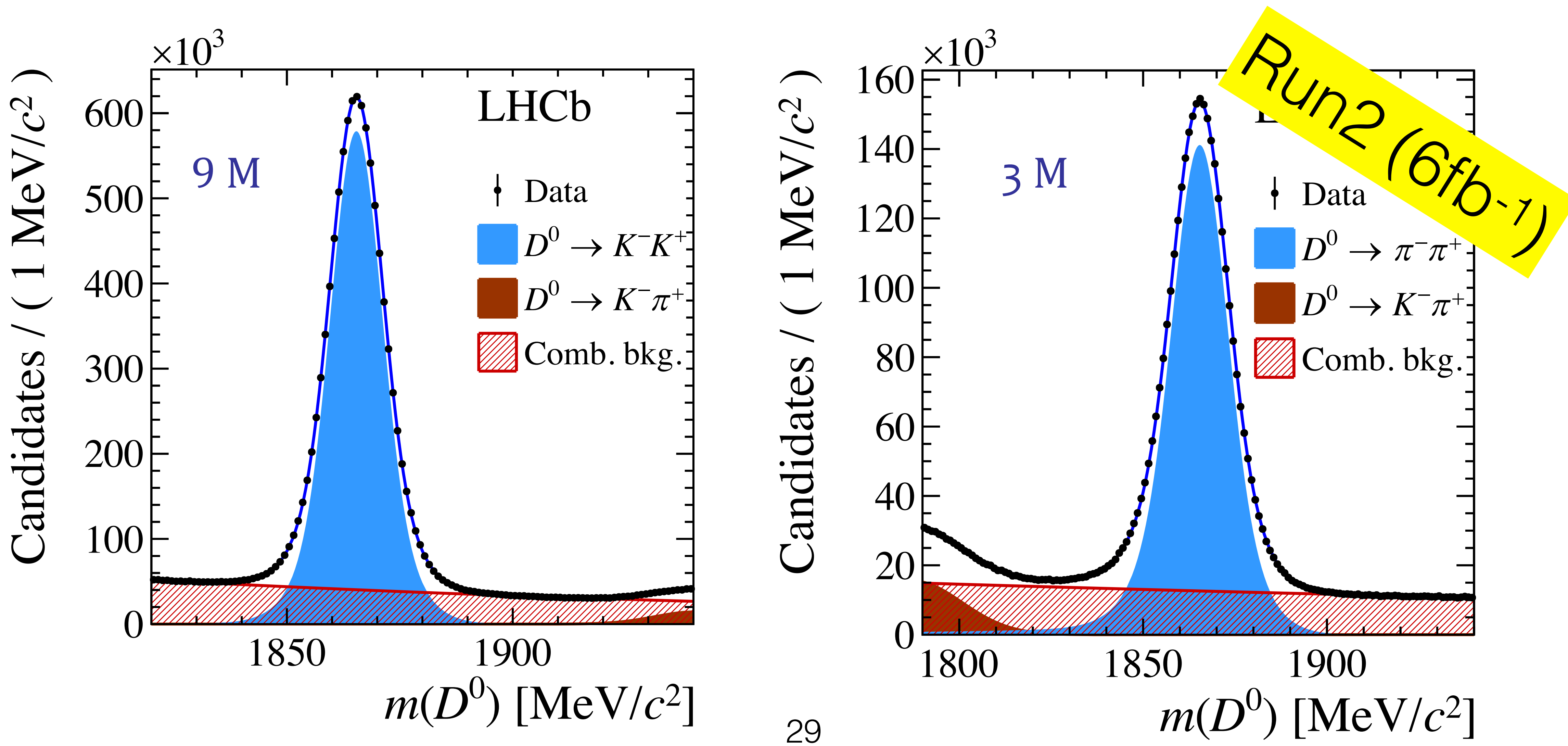


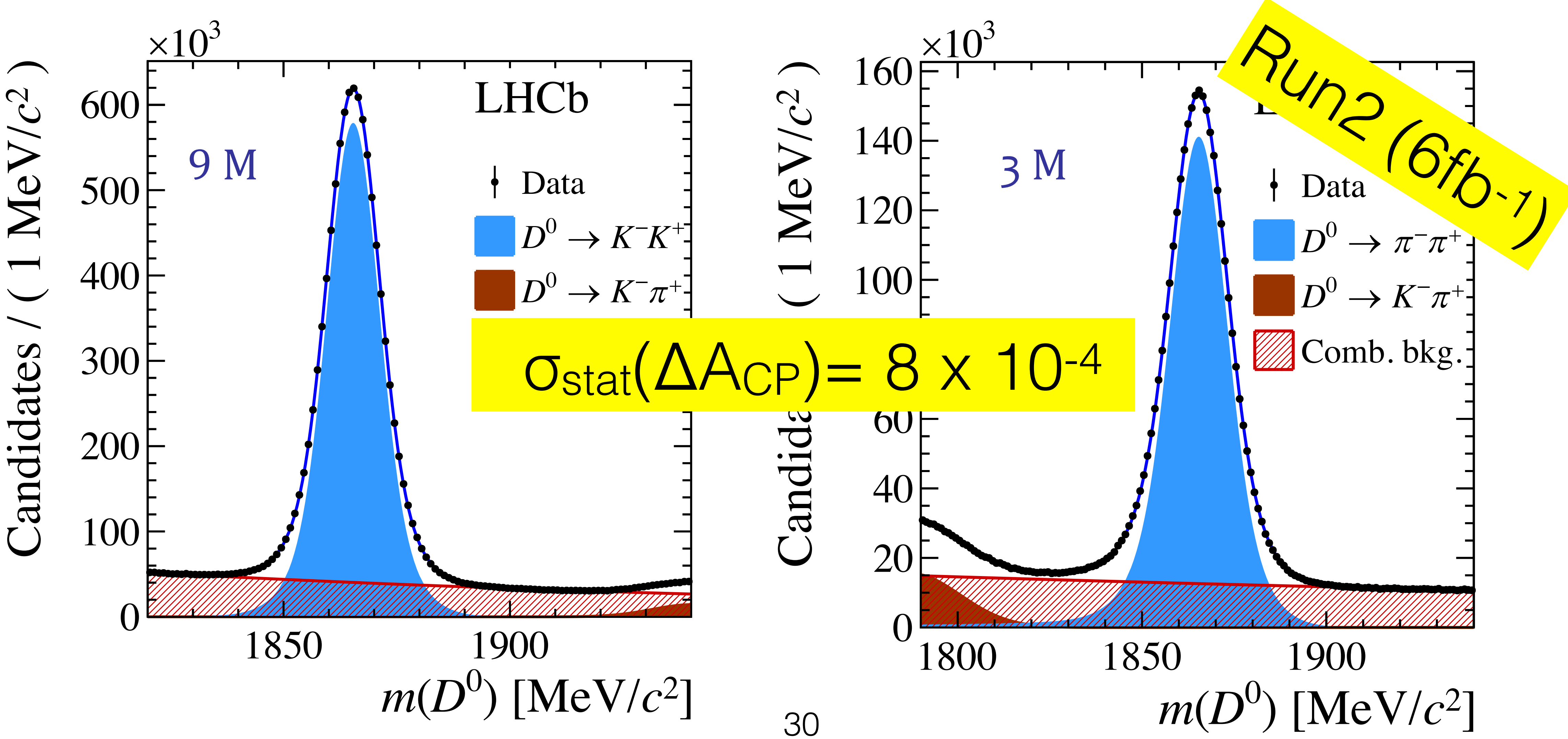
A_{raw} measurement [μ-tagged]

- Fit to m(D^0) mass distribution.
- A_{raw} measured from a simultaneous fit to D^0 and $\overline{D}^0$.



A_{raw} measurement [μ-tagged]

- Fit to $m(D^0)$ mass distribution.
- A_{raw} measured from a simultaneous fit to D^0 and $\overline{D}^0$.



Systematic uncertainties [π-tagged]

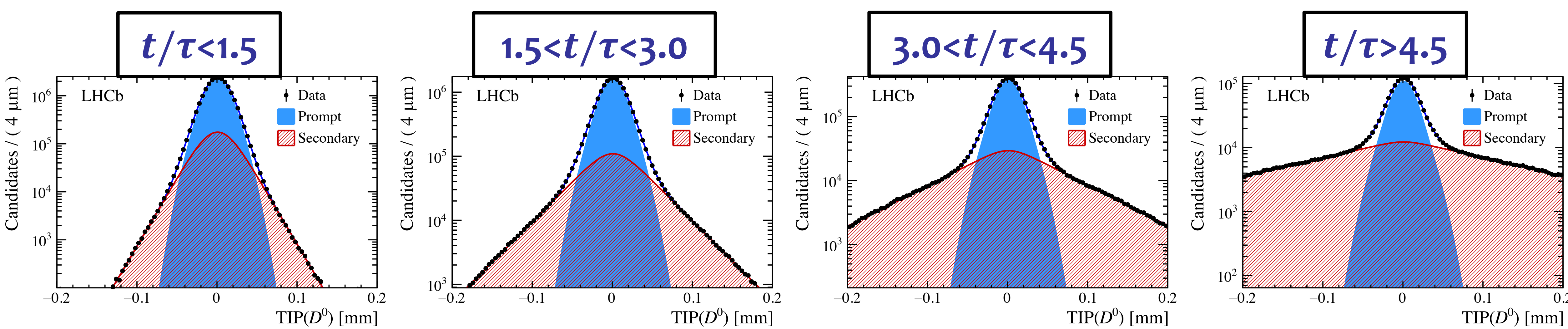
- **Fit model**: evaluated by fitting pseudo-experiments with alternative models $\Longrightarrow$ 0.6×10^{-4}.
- **Weighting procedure**: considered the statistical uncertainty of the weights $\Longrightarrow$ 0.2×10^{-4}.

Systematic uncertainties [π-tagged]

- **Secondaries decays**: determined the bias due to the residual contamination of D^{*+} decays from B $\Longrightarrow$ 0.3×10^{-4}.

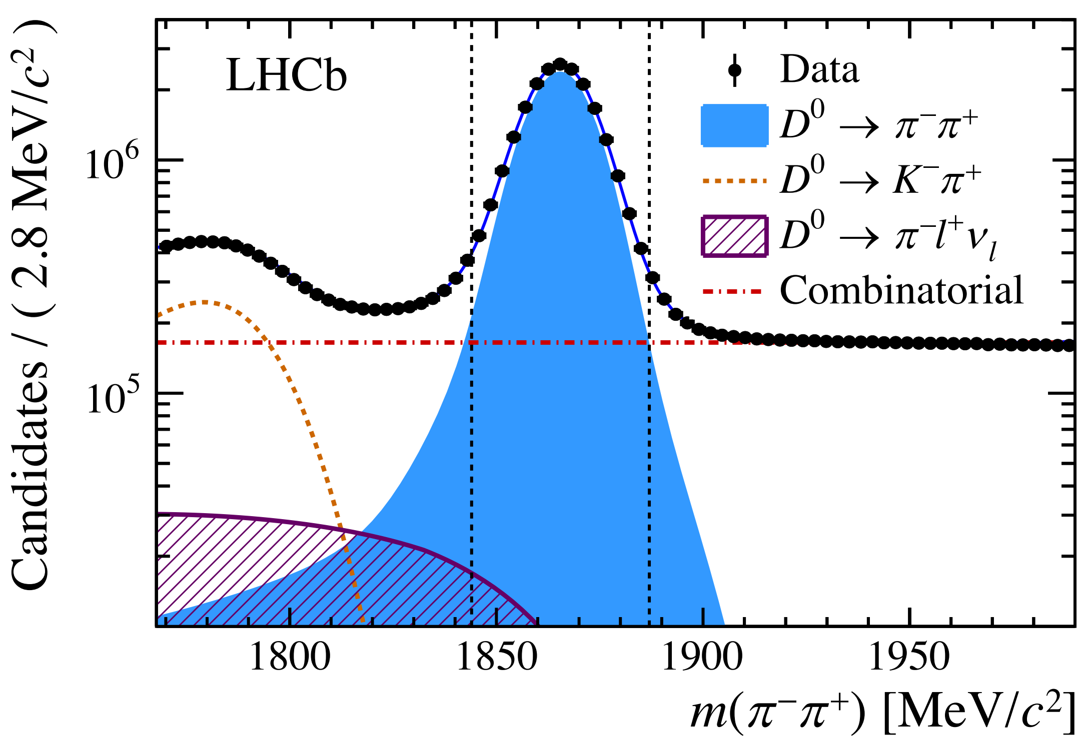
$$\Delta_{\text{sec}} = \frac{f_{\text{sec}}^{K^+K^-} - f_{\text{sec}}^{\pi^+\pi^-}}{2}\left[A_{\text{raw}}^{\text{sec}}(KK) + A_{\text{raw}}^{\text{sec}}(\pi\pi) - A_{\text{raw}}^{\text{prompt}}(KK) - A_{\text{raw}}^{\text{prompt}}(\pi\pi)\right]$$

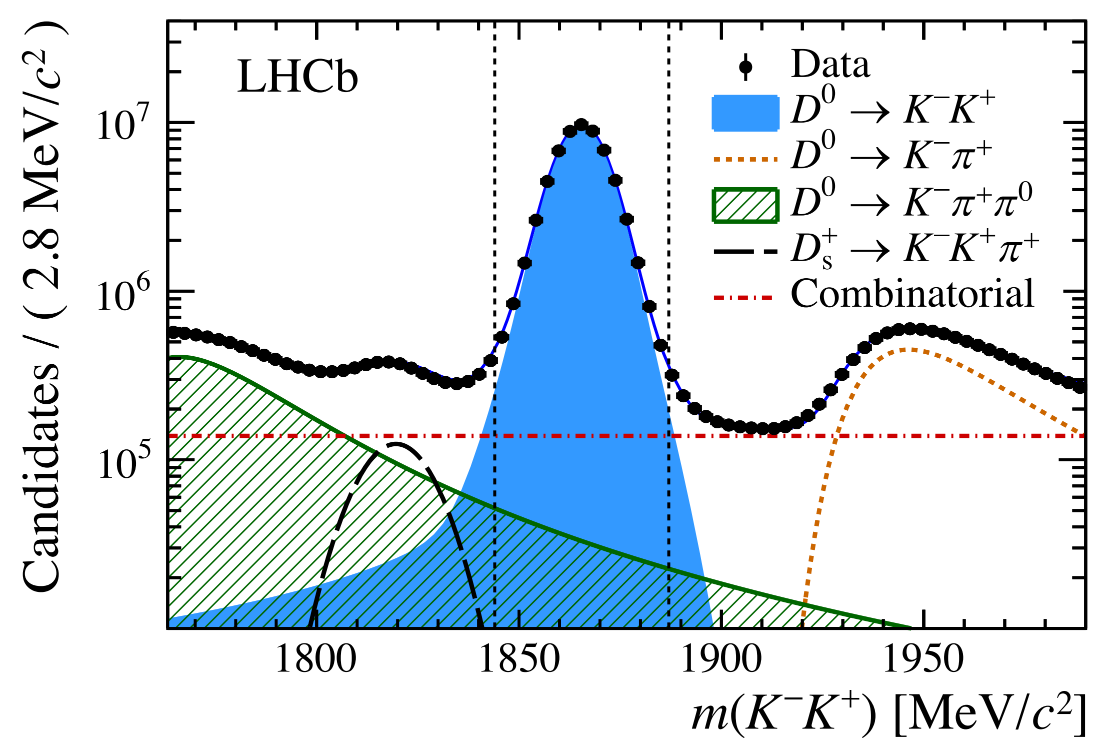
- Measure fraction of secondary D^{*+} by fitting the distribution of the D^0 IP in the plane transverse to the beam (TIP).
- Study performed in bins of proper decay time to have a better control on the resolution.



Systematic uncertainties [π-tagged]

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





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

Systematic uncertainties [μ-tagged]

- **Fit model:** evaluated by fitting pseudo-experiments with alternative models $\Longrightarrow$ 2×10^{-4}.
- **Mistag**: probability of mistag (wrong muon) evaluated on the $B\rightarrow D^0(\rightarrow K^-\pi^+)\mu^- X$ control sample $\Longrightarrow$ 4×10^{-4}.
- **Weighting procedure**: considered the statistical uncertainty of the weights $\Longrightarrow$ 10^{-4}.
- **B fraction:** fraction of reconstructed B^0 and B^+ decays can be slightly different between the K^-K^+ and $\pi^-\pi^+$ decay modes $\Longrightarrow$ 10^{-4}.
- **B reconstruction efficiency**: combination of a difference (between K^-K^+ and $\pi^-\pi^+$ modes) in the B reconstruction efficiency as function of decay time and the presence of B^0 oscillations $\Longrightarrow$ 2×10^{-4}.

Syst. uncertainties summary

Source	π-tagged	μ-tagged
Fit model	0.6	2
Mistag	–	4
Weighting	0.2	1
Secondary decays	0.3	–
B fractions	–	1
B reco. efficiency	–	2
Peaking background	0.5	–
Total	0.9	5
Stat.	3.2	8

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

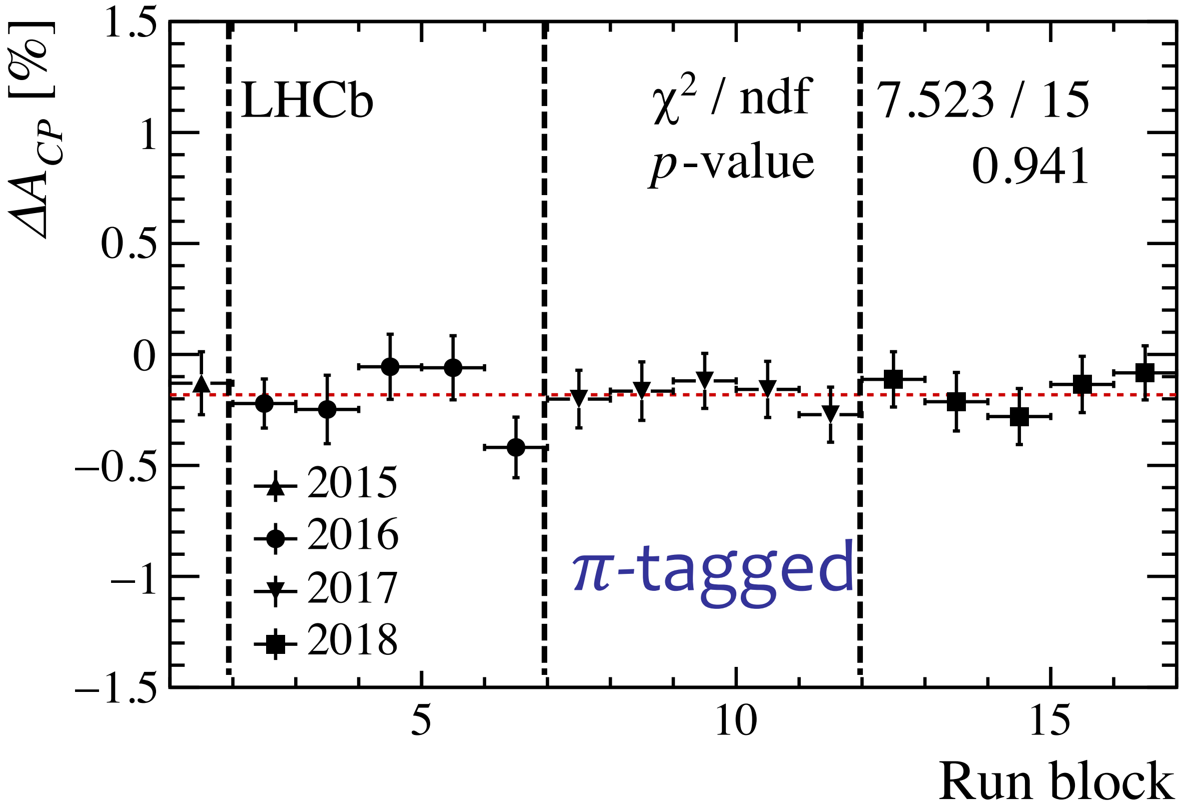
Robustness checks

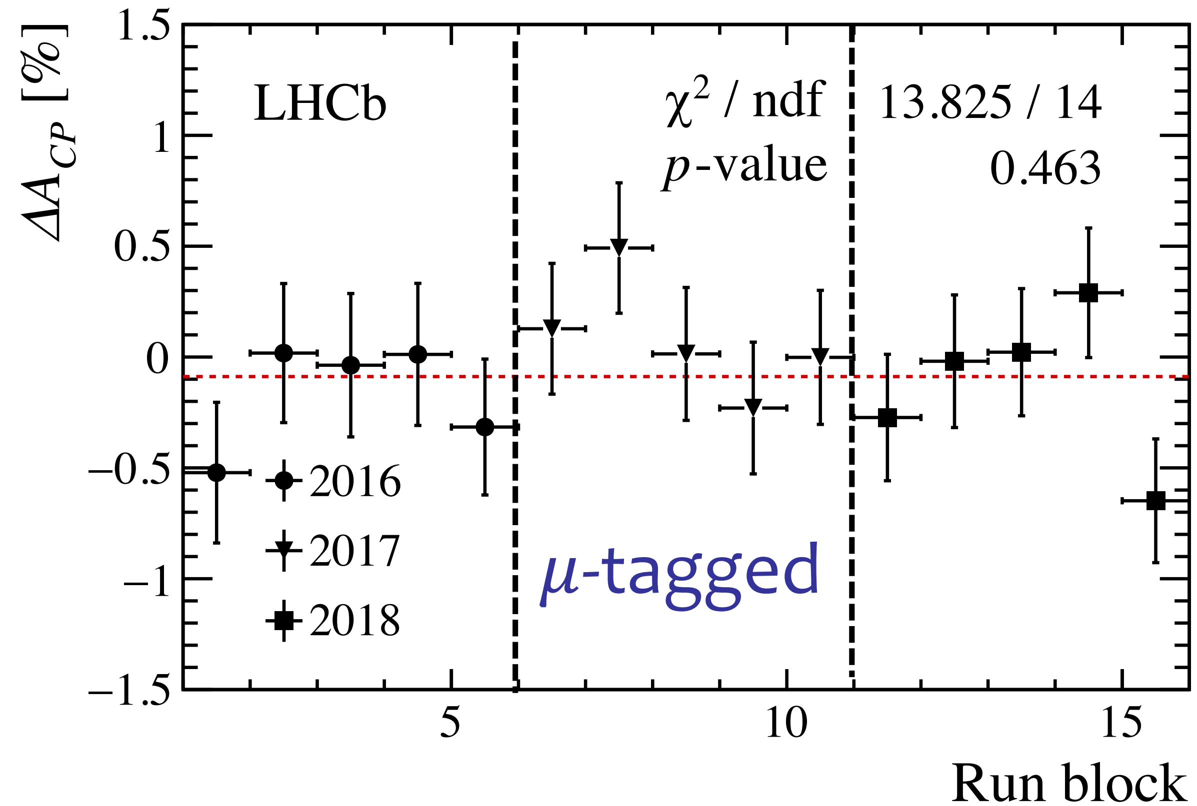
- Sample split according to year and magnet polarity $\Longrightarrow$ ΔA_{CP} consistent among the subsamples.
- Sample split according data taking period $\Longrightarrow$ ΔA_{CP} consistent among the subsamples.
- Analysis repeated with tighter PID and looser fiducial requirements $\Longrightarrow$ ΔA_{CP} compatible within statistical fluctuations.
- (Only π-tagged) measurement of ΔA_{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.
  - ΔA_{bkg} is expected to be compatible with zero.
  - $\Delta A_{bkg} = (-2 \pm 4) \times 10^{-4}$.

Additional robustness checks

ΔA_{CP} measured as a function of several variables

$\Longrightarrow$ data taking period



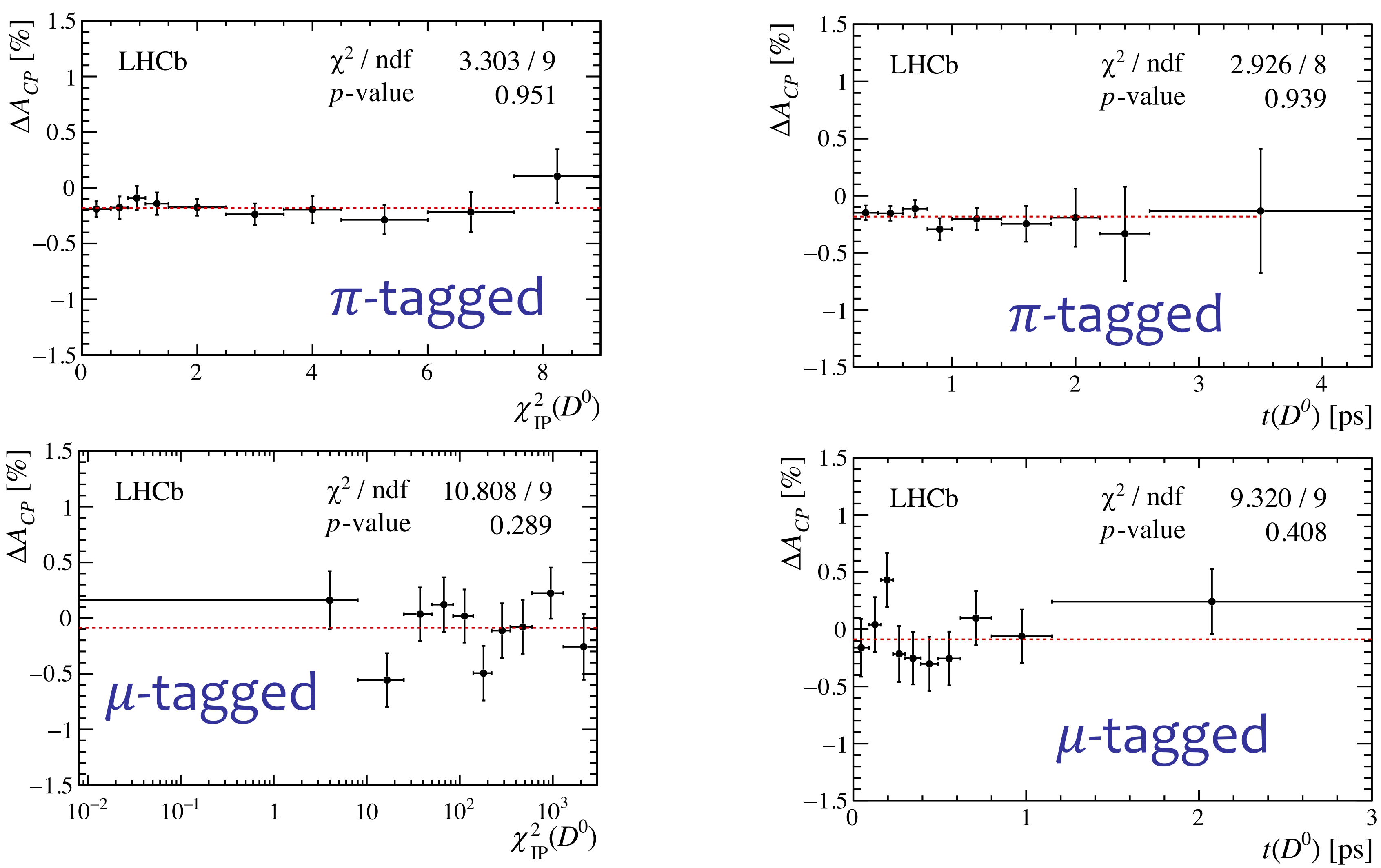


No evidence for unexpected dependences

Additional robustness checks

ΔA_{CP} measured as a function of several variables

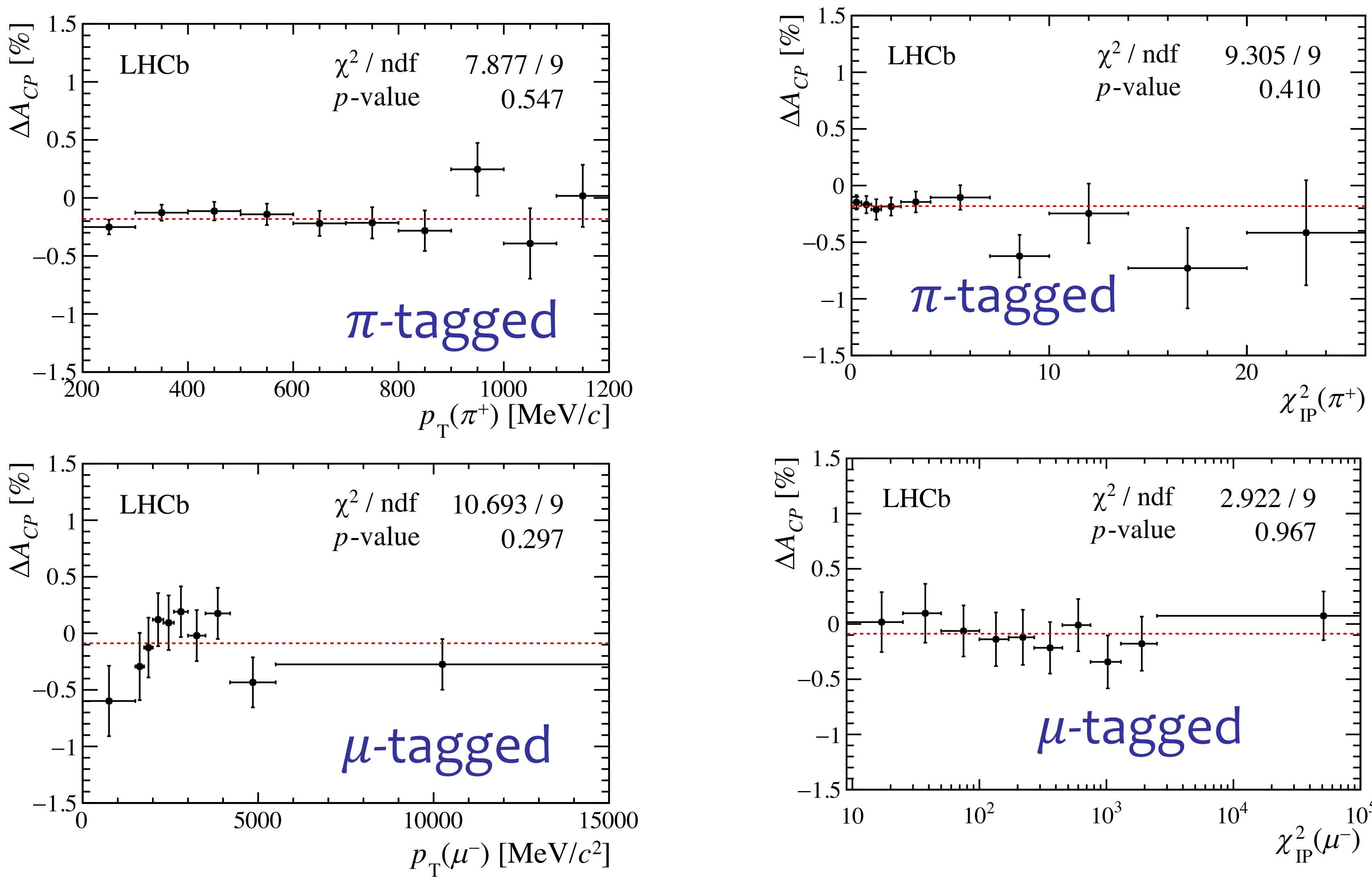
$\Longrightarrow$ D^0 impact parameter and proper decay time



No evidence for unexpected dependences

Additional robustness checks

ΔA_{CP} measured as a function of several variables
⟹ π/μ impact parameter and transverse momentum



No evidence for unexpected dependences

Results with Run2 [6fb^{-1}]

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

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

π-tagged result differs from zero at 5.5 standard deviation
compatible with previous LHCb results and world average

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

π-tagged Run 1 (3 fb^{-1})

JHEP 07 041 (2014)

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

μ-tagged Run 1 (3 fb^{-1})

Phys. Rev. Lett. 116 (2016)

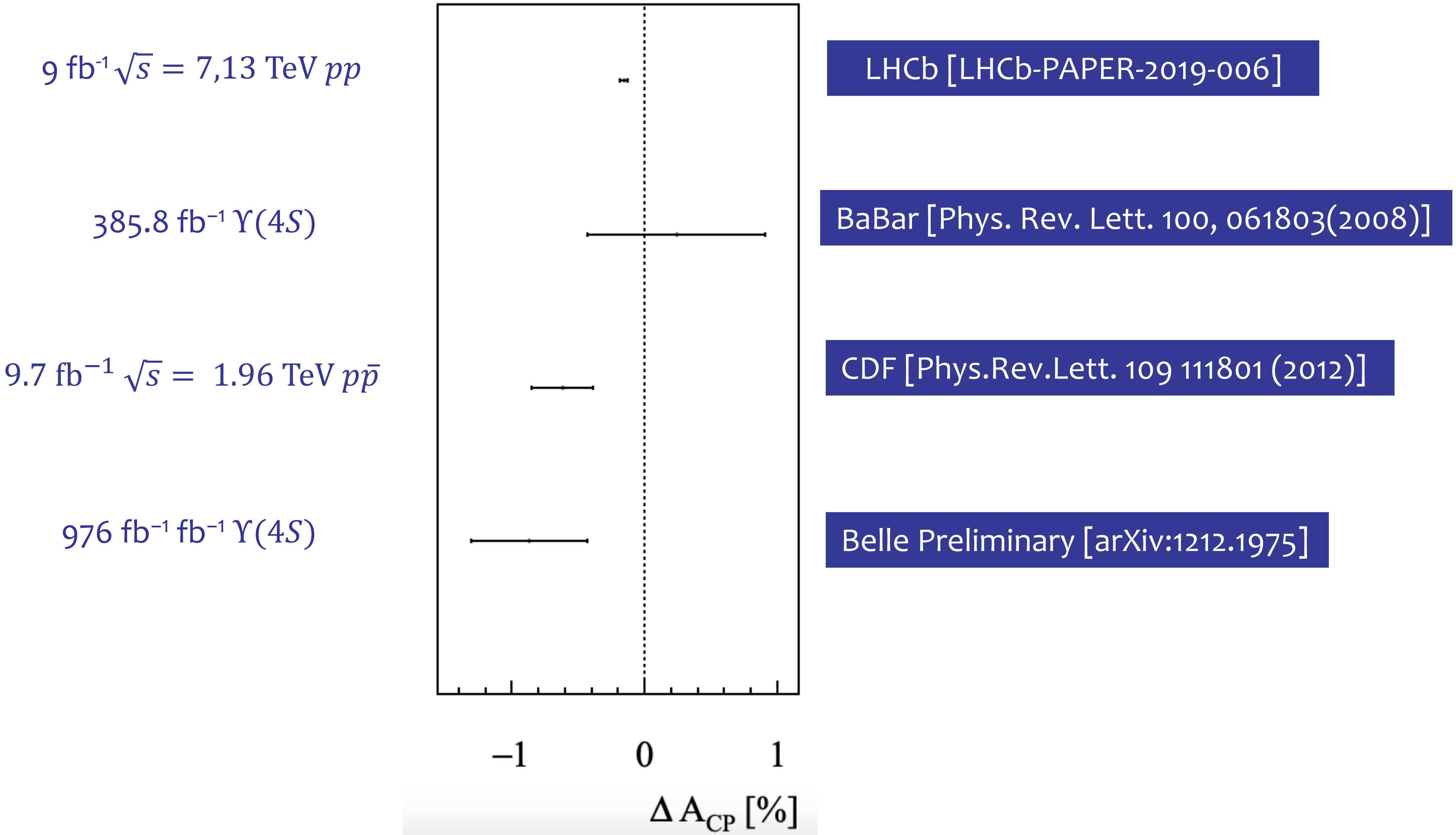
Results with full LHCb sample [9fb^{-1}]

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

5.3 standard deviation from zero

first observation of CP violation in the decay of charm hadrons

ΔA_{CP} experimental status today



Result interpretation

$$\Delta A_{CP} \simeq \Delta A_{CP}^{\mathrm{dir}} \left(1 + \frac{\overline{\langle t \rangle}}{\tau_D} y_{CP}\right) + \frac{\Delta \langle t \rangle}{\tau} A_{CP}^{\mathrm{ind}}$$

$$\overline{\langle t \rangle} = \frac{\langle t \rangle_{KK} + \langle t \rangle_{\pi\pi}}{2} \qquad \Delta \langle t \rangle = \langle t \rangle_{KK} - \langle t \rangle_{\pi\pi}$$

where $\langle t \rangle_f$ is the averaged reconstructed decay time of the $D^0 \to f$ decay

Assuming universal contribution from mixing/decay interference (A_{CP}^{ind}) in KK and $\pi\pi$

Result interpretation

For the full LHCb data set (9 fb^{-1}):

$\Delta\langle t\rangle/\tau(D^0) = 0.115 \pm 0.002$

$\overline{\langle t\rangle}/\tau(D^0) = 1.71 \pm 0.10$

Using the LHCb averages:

$y_{CP} = (5.7 \pm 1.5)\times 10^{-3}$

$A_\Gamma = (-2.8 \pm 2.8)\times 10^{-4} \simeq -a_{CP}^{\text{ind}}$

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

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

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

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

HFLAV update

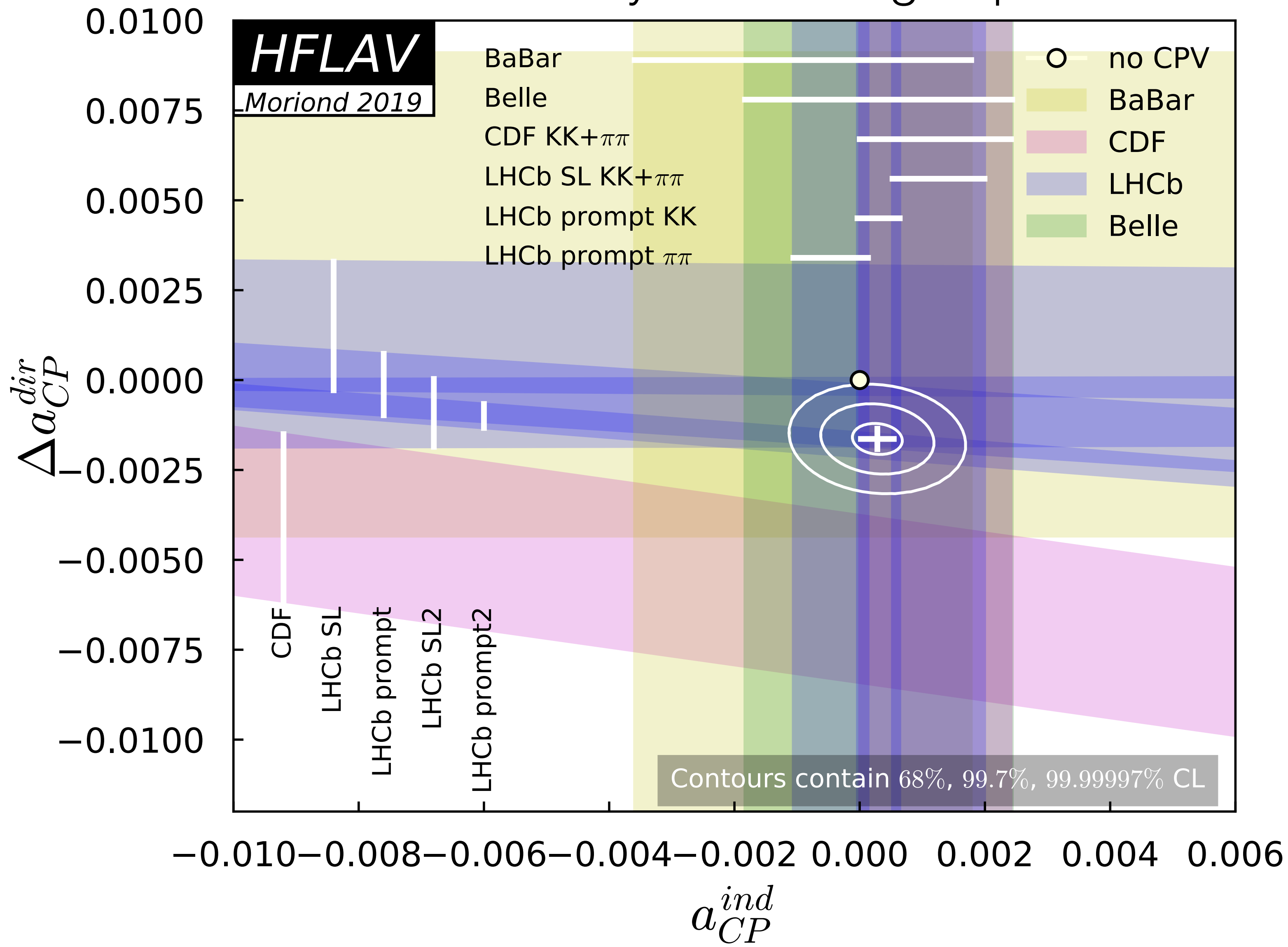
HFLAV combination

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

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

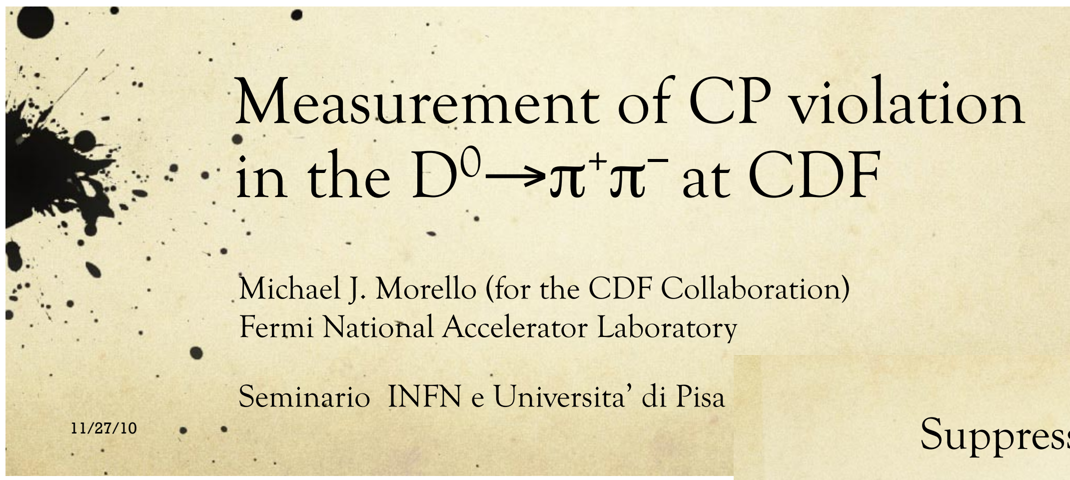
Consistency with NO CPV hypothesis: $5{\times}10^{-8}$

Courtesy of HFLAV group

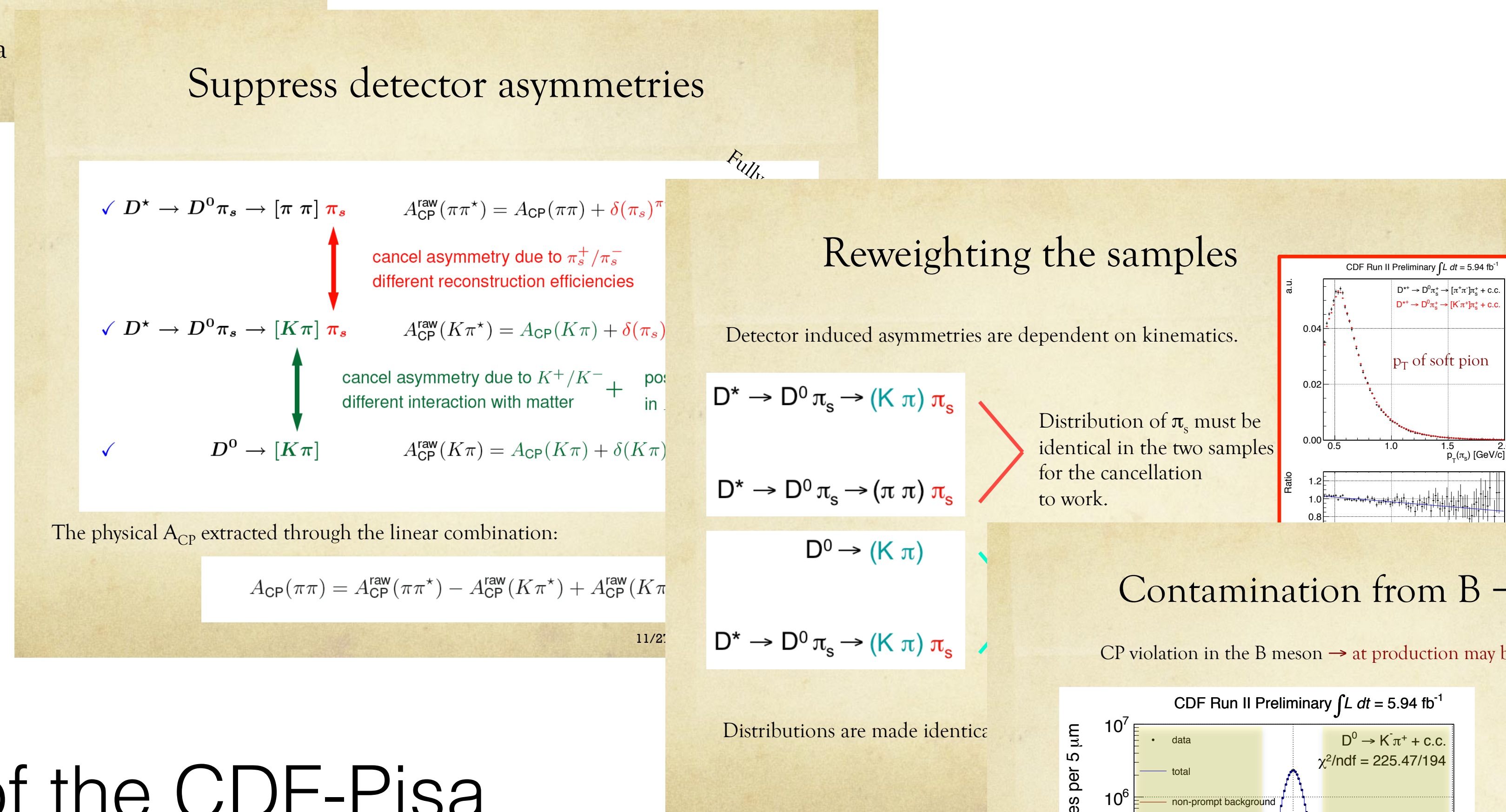


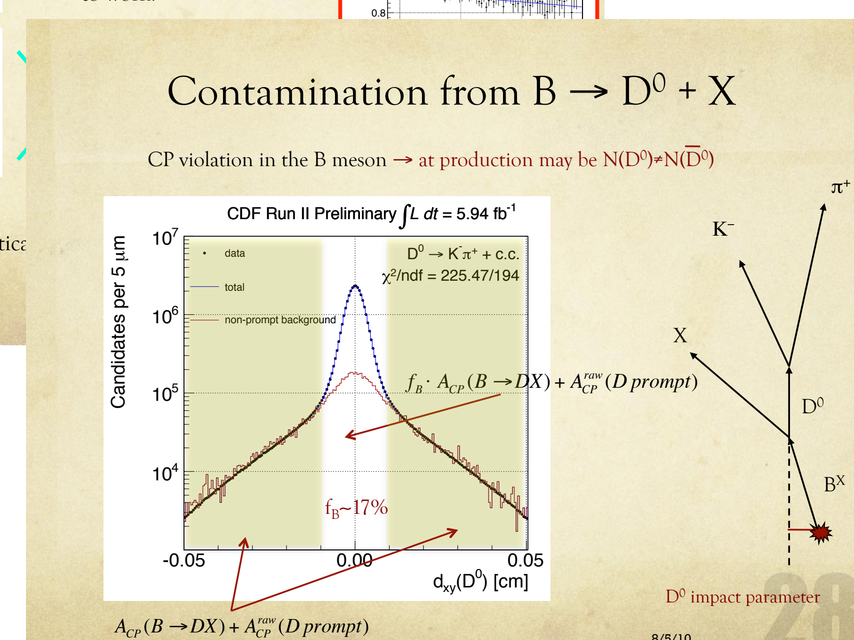
World average dominated by the LHCb

A very long path



INFN Seminar (Pisa) - Nov 2010





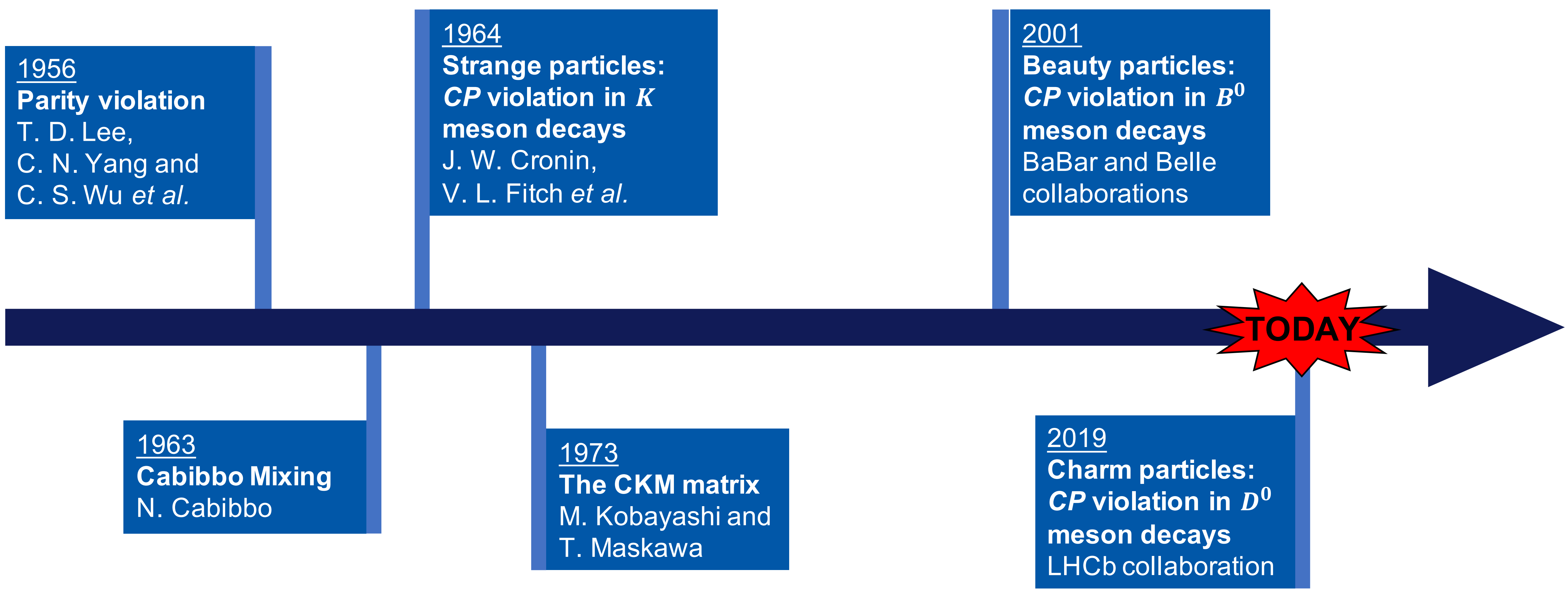
In 2010 members of the CDF-Pisa (now members of LHCb-Pisa) group pioneered the charm physics at hadron collisions *[Phys. Rev. D 85, 012009 (2012)]*

Conclusions

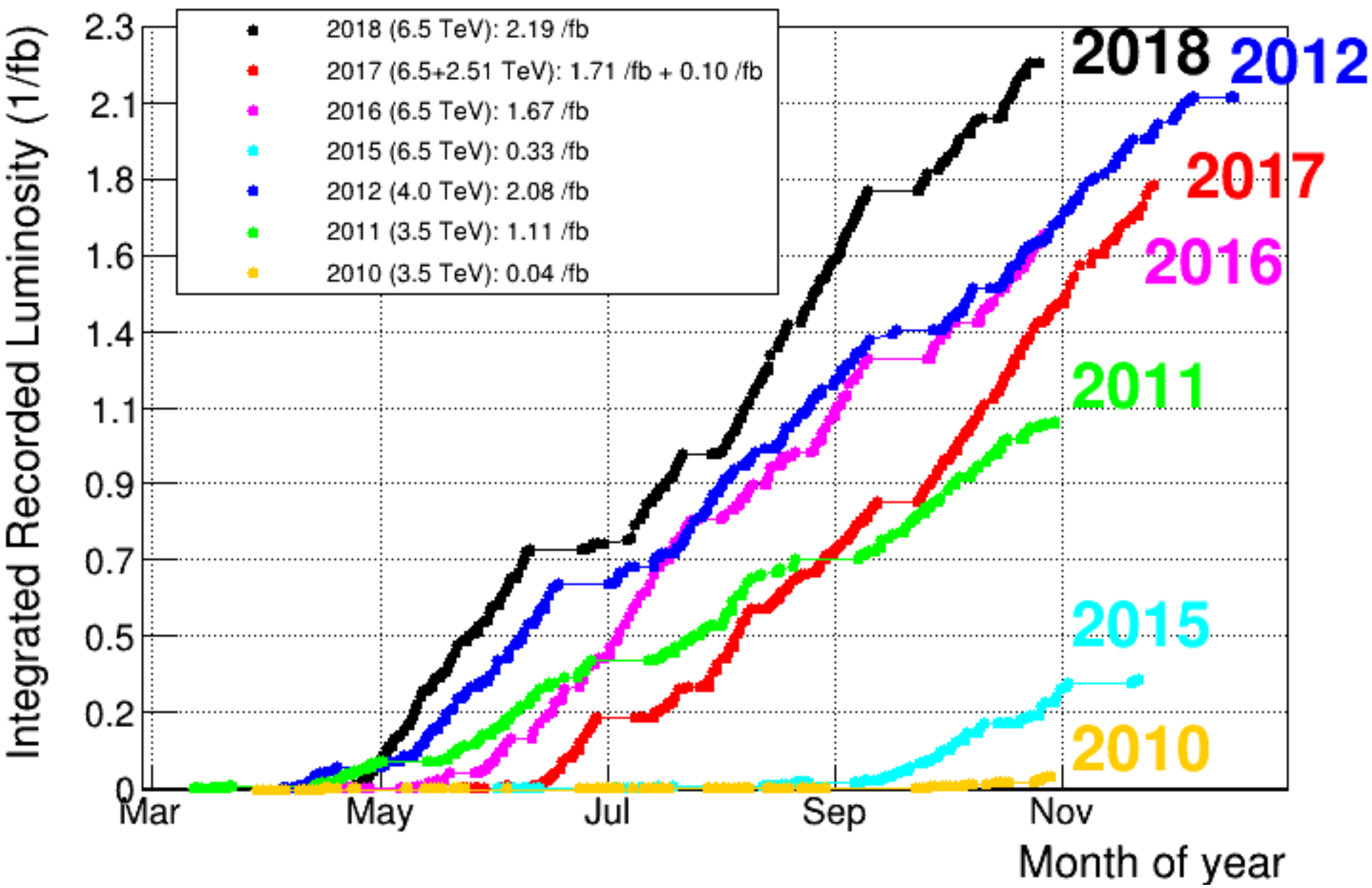
- **First observation of CP violation in charm decays with a significance of 5.3 standard deviations.**
- Result consistent with, although at the upper end of, SM expectations, which lie in the range [10^{-3} – 10^{-4}].
- Present theoretical predictions have large uncertainties due to low-energy strong-interaction effects which are difficult to compute. No strong statement can be made from this single result today.
- However, it opens up a new chapter of measurements in other decay modes and of further refinements of theoretical calculations, to provide soon a definitive answer about its standard or non-standard nature.

Backup

CP violation key dates

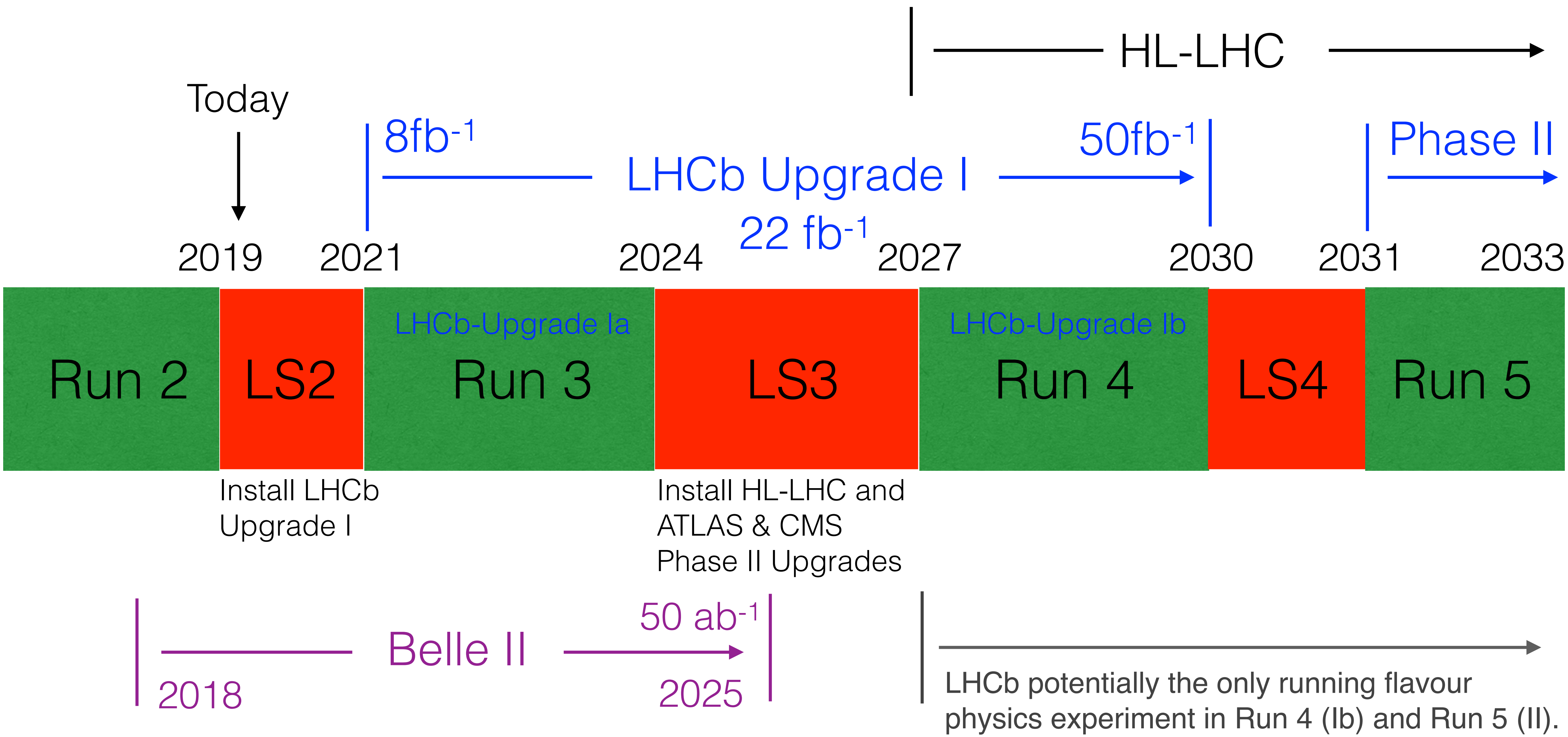


Integrated recorded luminosity



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

LHCb timeline in the next decades

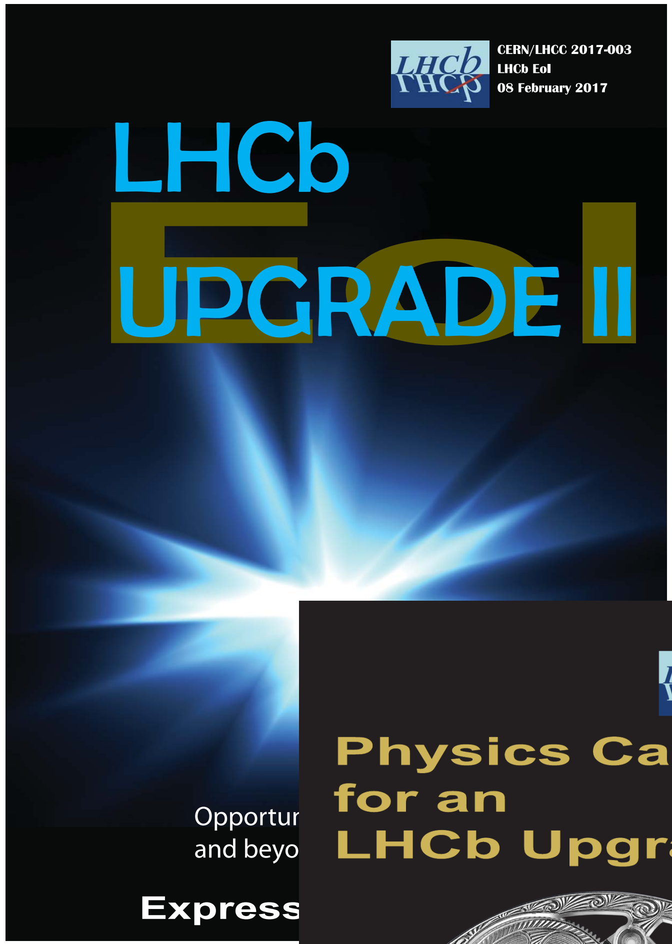


The LHCb Upgrade I will enable to integrate about 22 fb^{-1} by end of Run 3 and 50 fb^{-1} by end of Run 4.

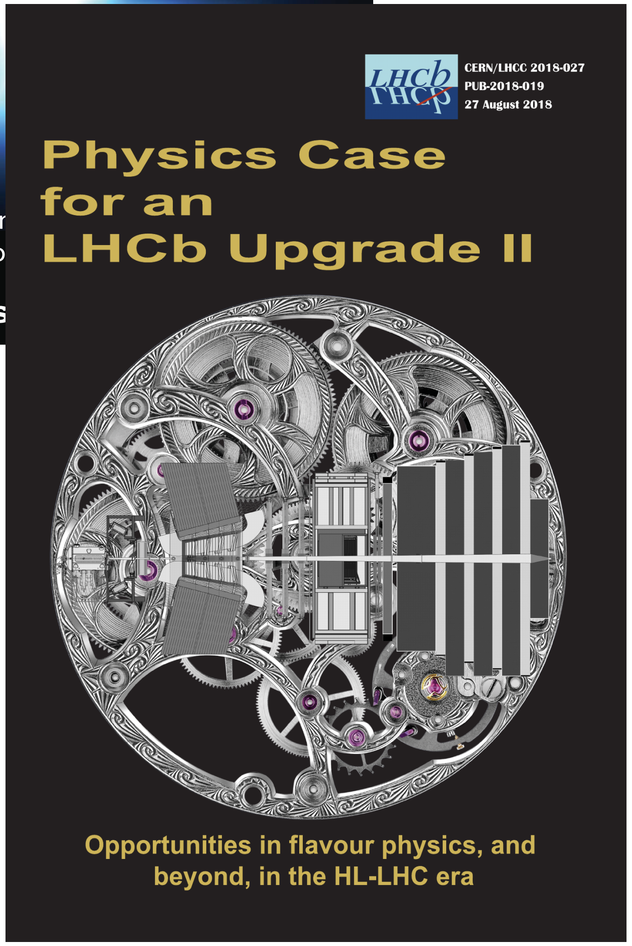
Intensity frontier

- LHCb Upgrade Ia in Run-3 (2021-2023)
  - L_{inst}= 2 x 10^{33} cm^{-2} s^{-1}.
- LHCb Upgrade Ib Run-4 (2026-2029)
  - Integrate 50 fb^{-1} by the end of Run 4.
  - Profit from LS3 for a "consolidation".
- LHCb Upgrade II in Run 5 (2031-2033) and beyond.
  - New experiment to be installed in LS4 to integrate > 300 fb^{-1}.

LHC Run	2010–12 1	2015–18 2	2021–23 3	2026–29 4	2031-33 5
$E_{\rm cm}$ (TeV)	$7-8$	13	14	14	14
LHC $L_{\rm peak}$ ($\rm cm^{-2}\,s^{-1}$)	$7.7\cdot10^{33}$	$1.7\cdot10^{34}$	$2\cdot10^{34}$	$7\cdot10^{34}$	$7\cdot10^{34}$
LHCb $L_{\rm peak}$ ($\rm cm^{-2}\,s^{-1}$)	$2-4\cdot10^{32}$	$2-4\cdot10^{32}$	$2\cdot10^{33}$	$2\cdot10^{33}$	$>10^{34}$



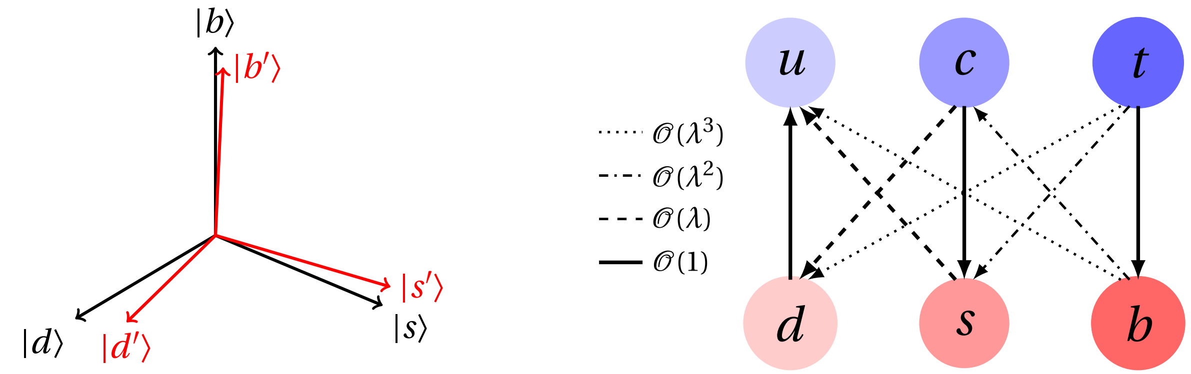
CERN-LHCC-2017-003



CERN-LHCC-2018-027

CKM Matrix

$$\boldsymbol{V}_{\text{CKM}} \equiv \boldsymbol{V}_{uL}\boldsymbol{V}_{dL}^{\dagger} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$



(a) Quark mass eigenstates interactions representation.

(b) Mass and interaction eigenstates decay scheme.

$$\boldsymbol{V}_{\text{CKM}} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

$$\lambda = s_{12}, \quad A\lambda^2 = s_{23}, \quad A\lambda^3(\rho - i\eta) = s_{13}\mathrm{e}^{-i\delta}$$

$$\lambda = |V_{us}| \approx 0.22$$

$$\boldsymbol{V}_{\text{CKM}} = \begin{bmatrix} 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda + \frac{1}{2}\lambda^5 A^2(1 - 2(\rho + i\eta)) & 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4(1 + 4A^2) & A\lambda^2 \\ A\lambda^3[1 - (\rho + i\eta)] + \frac{1}{2}\lambda^5 A(\rho + i\eta) & -A\lambda^2 + \frac{1}{2}\lambda^4 A(1 - 2(\rho + i\eta)) & 1 - \frac{1}{2}\lambda^4 A^2 \end{bmatrix} + \mathcal{O}(\lambda^6)$$

Mixing phenomenology

meson system	$\Delta M/\Gamma$	$\Delta\Gamma/(2\Gamma)$
K^0–$\overline{K}^0$	−0.95	0.99
D^0–$\overline{D}^0$	0.005	0.006
B^0–$\overline{B}^0$	0.77	−0.001
B_s^0–$\overline{B}_s^0$	26.7	0.06

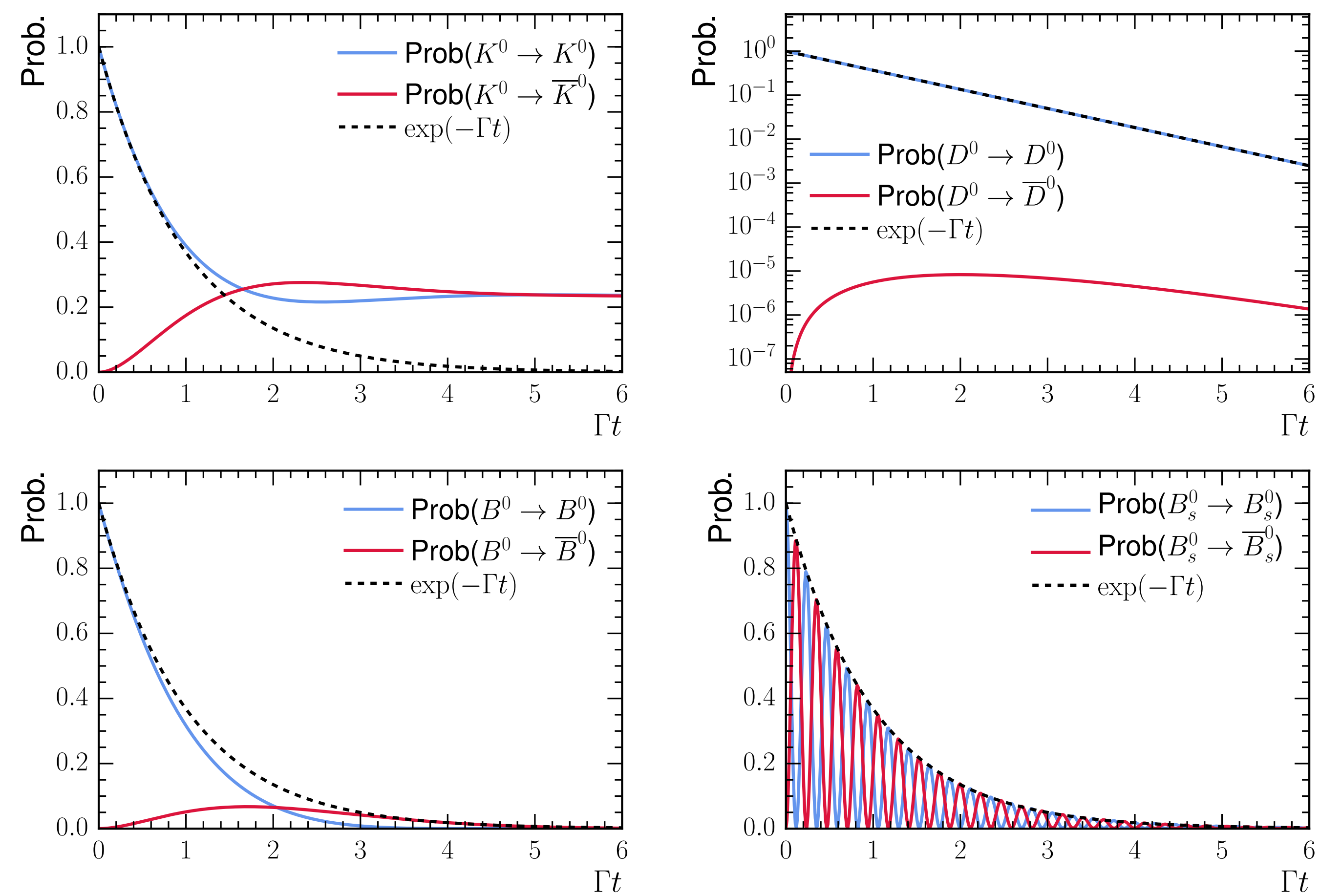


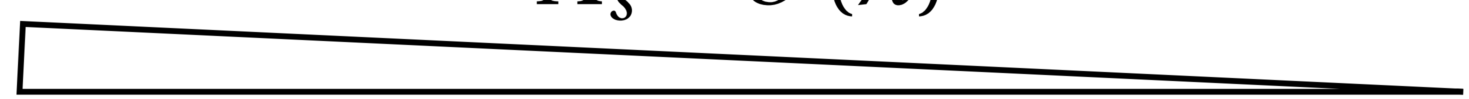
Figure 1.6 – Flavour-changing and flavour-unchanging PDFs for the four neutral meson systems (from left to right and from top to bottom): K^0–$\overline{K}^0$, D^0–$\overline{D}^0$ (note the logarithmic scale), B^0–$\overline{B}^0$, B_s^0–$\overline{B}_s^0$. The single exponential function, black-dashed line, it is also drawn.

CPV in the charm sector

Amplitudes in charm meson decays and mixing are described, to an excellent approximation, by the physics of the two first generations only.

$$\Lambda_s \sim \mathcal{O}(\lambda)$$

$$\Lambda_b \sim \mathcal{O}(\lambda^5)$$



$$\Lambda_d \sim \mathcal{O}(\lambda)$$

"charm unitary triangle"

$$\Lambda_q = V_{cq}^* V_{uq} \; (q \in d, s, b)$$

$$\Lambda_d = -\lambda + \frac{\lambda^3}{2} + \frac{\lambda^5}{8}(1+4A^2) - \lambda^5 A^2(\rho + i\eta) + \mathcal{O}(\lambda^7),$$

$$\Lambda_s = \lambda - \frac{\lambda^3}{2} - \frac{\lambda^5}{8}(1+4A^2) + \mathcal{O}(\lambda^7),$$

$$\Lambda_b = \lambda^5 A^2(\rho - i\eta) + \mathcal{O}(\lambda^{11}),$$

SM expectations are of the order of $(V_{ub}V^*_{cb}/V_{us}V^*_{cs}) \sim 10^{-3}$ (or less).

CPV, until today, has always eluded experimental searches in the last decades.

CPV observables

Experimentally three manifestation of CP-violation, enclosed in the following variable:

$$\lambda_f = \frac{q\overline{A}_f}{pA_f} = -\eta_{CP} R_m R_f e^{i\phi_f} \quad \text{where} \quad R_m = \left|\frac{q}{p}\right|, \quad R_f = \left|\frac{\overline{A}_f}{A_f}\right|, \quad \phi_f = \arg\left(\frac{q\overline{A}_f}{pA_f}\right).$$

Direct CPV

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

$$A_{CP}(f) = A_{CP}^{\text{dir}} = \frac{|A_f|^2 - |\overline{A}_f|^2}{|A_f|^2 + |\overline{A}_f|^2} = \frac{1-R_f^2}{1+R_f^2}.$$

It occurs if:

$$R_f = \left|\frac{\overline{A}_f}{A_f}\right| \neq 1.$$

CPV in mixing

Prob(D0->antiD0)≠Prob(antiD0->D0)

$$\left|\frac{q}{p}\right|^2 = \frac{|M_{12}^* - i\Gamma_{12}^*/2|}{|M_{12} - i\Gamma_{12}/2|},$$

It occurs if:

$$R_m = \left|\frac{q}{p}\right| \neq 1,$$

CPV in the interference

$$D^0 \to f \;\neq\; D^0 \to \overline{D}^0 \to f$$

It occurs if:

$$\arg(\lambda_f) + \arg(\lambda_{\overline{f}}) \neq 0$$

For f CP eigenstate it simplifies :

$$\Im(\lambda_f) \neq 0,$$

equivalent to $\phi_f \neq \{0, \pi\}$

CPV in the decay: $R_f \equiv \left| \frac{\bar{A}_{\bar{f}}}{A_f} \right| \neq 1$

$$A_{CP} \equiv \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})} = \frac{1 - R_f^2}{1 + R_f^2}$$

$$\begin{aligned} A_f &= |a_1| e^{i(\delta_1 + \phi_1)} + |a_2| e^{i(\delta_2 + \phi_2)} \\ \bar{A}_{\bar{f}} &= |a_1| e^{i(\delta_1 - \phi_1)} + |a_2| e^{i(\delta_2 - \phi_2)} \end{aligned}$$

CP

δ_1, δ_2 strong phases

ϕ_1, ϕ_2 weak phases

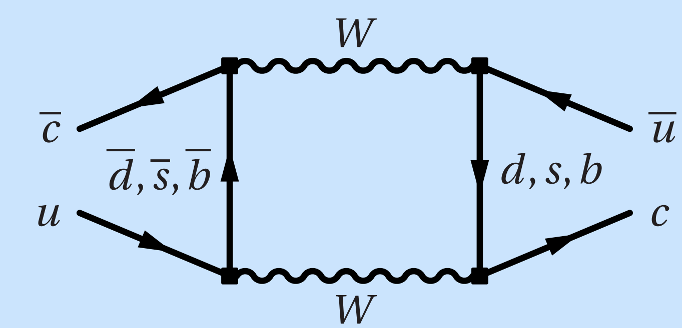
$$A_{CP} = \frac{2|a_1 a_2| \sin(\delta_2 - \delta_1) \sin(\phi_2 - \phi_1)}{|a_1|^2 + |a_2|^2 + 2|a_1 a_2| \cos(\delta_2 - \delta_1) \cos(\phi_2 - \phi_1)}$$

Necessary interference of at least two amplitudes (tree + penguin topologies) contributing simultaneously to the process, with different strong and weak phases.

SM predictions

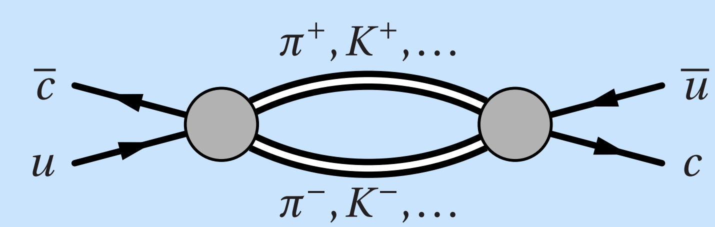
- Affected by "large uncertainties" due to the difficulties in the computation of the long-distance contributions:
  - non perturbative calculation (approximations holding in the B and K cases do not apply for charm)
  - the available computational power is not yet enough for lattice QCD.
- Inclusive approaches (i.e. Heavy Quark Effective Field Theory) rely on expansions in powers of $O(1/m_c)$, which are of limited validity because the intermediate value of the charm quark mass.
- Exclusive approaches rely on explicitly accounting for all possible intermediate states, which may be modeled or fitted directly to experimental data.
  - However, the D meson is not light enough to have few final states, and in absence of sufficiently precise measurements of amplitudes and strong phases of many decays, several assumptions are made limiting the predictions.

Short distance



intermediate state massive off-shell W
mainly contributing to $\Delta m = 2M_{12}$
strongly suppressed
x,y predicted to be ~10^{-6} (very far from %)

Long distance



intermediate state on–shell light quarks
can travel from interaction point
mainly contributing to $\Delta\Gamma = 2\Gamma_{12}$
precise calculations are difficult

Time-dependent CPV in $D^0 \rightarrow h^+h^-$

Because of the slow mixing rate of charm mesons ($x,y \sim 10^{-2}$) the time-dependent asymmetry is approximated at first order as the sum of two terms:

$$A_{CP}(h^+h^-;t) \approx A_{CP}^{\text{dir}}(h^+h^-) + \frac{t}{\tau} A_{CP}^{\text{ind}}(h^+h^-)$$

$$A_{CP}^{\text{ind}}(h^+h^-) = \frac{\eta_{CP}}{2}\left[y\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right| \right)\cos\varphi - x\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right| \right)\sin\varphi \right],$$

CPV in the mixing $|q/p| \neq 1$ CPV in the interference $\varphi_f \neq 0,\pi$

$$A_\Gamma \approx -A_{\text{CP}}^{\text{ind}}$$

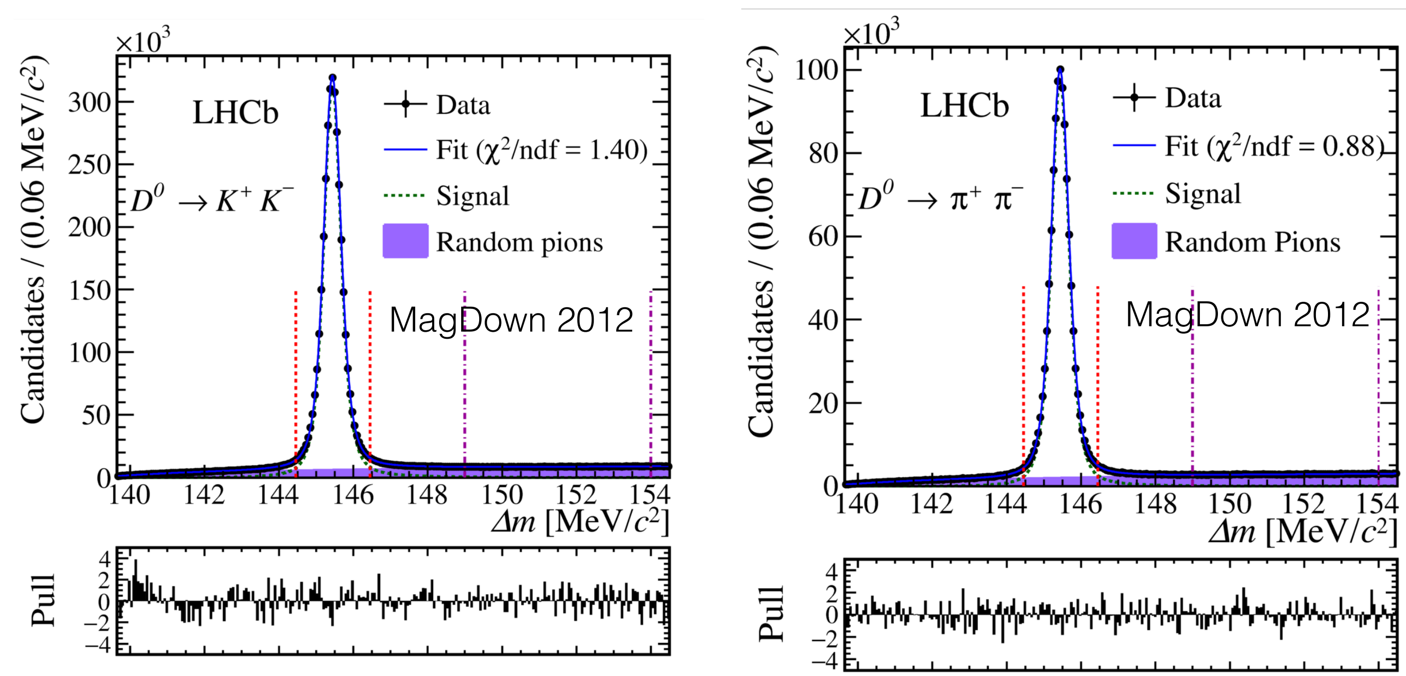
defined as the asymmetry between D^0 and antiD^0 effective lifetimes

Neglecting subleading amplitudes A_Γ is independent of the final state f. Furthermore, in the absence of CP violation in mixing, it can be found that $A_\Gamma = -x \sin\varphi \longrightarrow |A_\Gamma| \leq |x| < 5\times10^{-3}$.

Full Run 1 data sample (3fb-1).
D^0 flavor inferred with strong $D^{*+} \rightarrow D^0\pi^+$ decay.

Subsample [10^6]	$D^0 \rightarrow K^-\pi^+$	$D^0 \rightarrow K^+K^-$	$D^0 \rightarrow \pi^+\pi^-$
2011 *MagUp*	10.7	1.2	0.4
2011 *MagDown*	15.5	1.7	0.5
2012 *MagUp*	30.0	3.3	1.0
2012 *MagDown*	31.3	3.4	1.1
Total	87.5	9.6	3.0

arXiv:1702.06490 [hep-ex].



Time-dependent CPV in $D^0 \rightarrow h^+h^-$

$$A_\Gamma(K^+K^-) = (-0.30 \pm 0.32 \pm 0.10) \times 10^{-3}$$
$$A_\Gamma(\pi^+\pi^-) = (0.46 \pm 0.58 \pm 0.12) \times 10^{-3}$$

Precision approaches the level of 10^{-4}. No evidence for CP violation and improve on the precision of the previous best measurements by nearly a factor of 2.

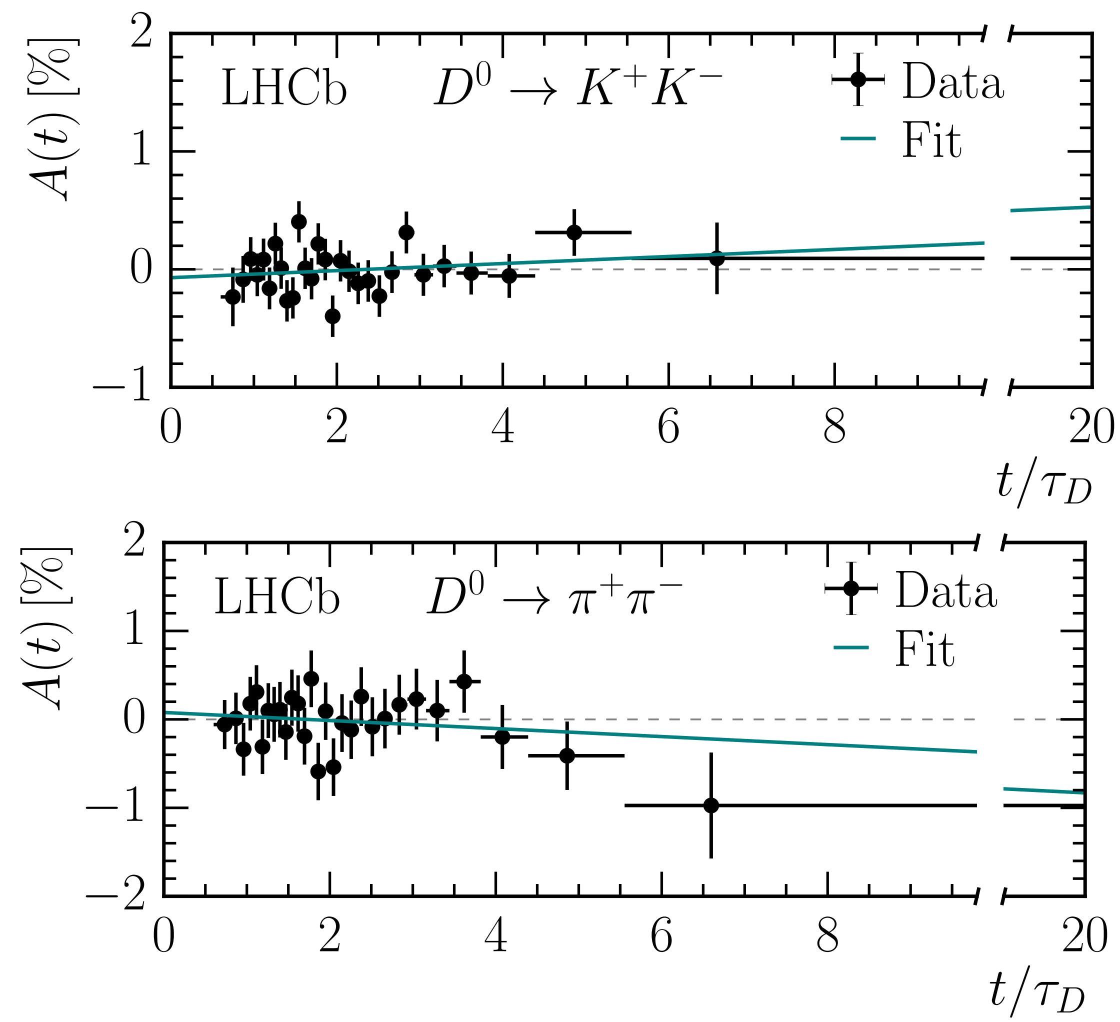
Assuming that only indirect CP violation contributes to A_Γ, the two values, can be averaged to yield a single value:

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

Consistent with the result obtained by LHCb in a muon-tagged sample [*JHEP 1504 (2015) 043*], which is statistically independent. The two results are therefore combined to yield an overall LHCb Run 1 value:

$$A_\Gamma = (-0.29 \pm 0.28) \times 10^{-3}$$

arXiv:1702.06490 [hep-ex]



Most precise measurement of CPV in the charm sector.

Time-integrated $A_{CP}(D^0 \rightarrow K^+K^-)$

Full Run 1 data sample (3fb-1).
D^0 flavor inferred with strong $D^{*+} \rightarrow D^0\pi^+$ decay chain.
CPV in calibration channels assumed negligible

$$
\begin{aligned}
A_{CP}(D^0 \to K^-K^+) &\\
= A_{\mathrm{raw}}(D^0 \to K^-K^+) &- A_{\mathrm{raw}}(D^0 \to K^-\pi^+)\\
+ A_{\mathrm{raw}}(D^+ \to K^-\pi^+\pi^+) &- A_{\mathrm{raw}}(D^+ \to \overline{K}^0\pi^+)\\
+ A_D(\overline{K}^0). &
\end{aligned}
$$

$$A_{CP}(K^-K^+) = (0.14 \pm 0.15\,(\mathrm{stat}) \pm 0.10\,(\mathrm{syst}))\%$$

A combination with other LHCb measurements yields

$$A_{CP}(K^-K^+) = (0.04 \pm 0.12\,(\mathrm{stat}) \pm 0.10\,(\mathrm{syst}))\%$$
$$A_{CP}(\pi^-\pi^+) = (0.07 \pm 0.14\,(\mathrm{stat}) \pm 0.11\,(\mathrm{syst}))\%$$

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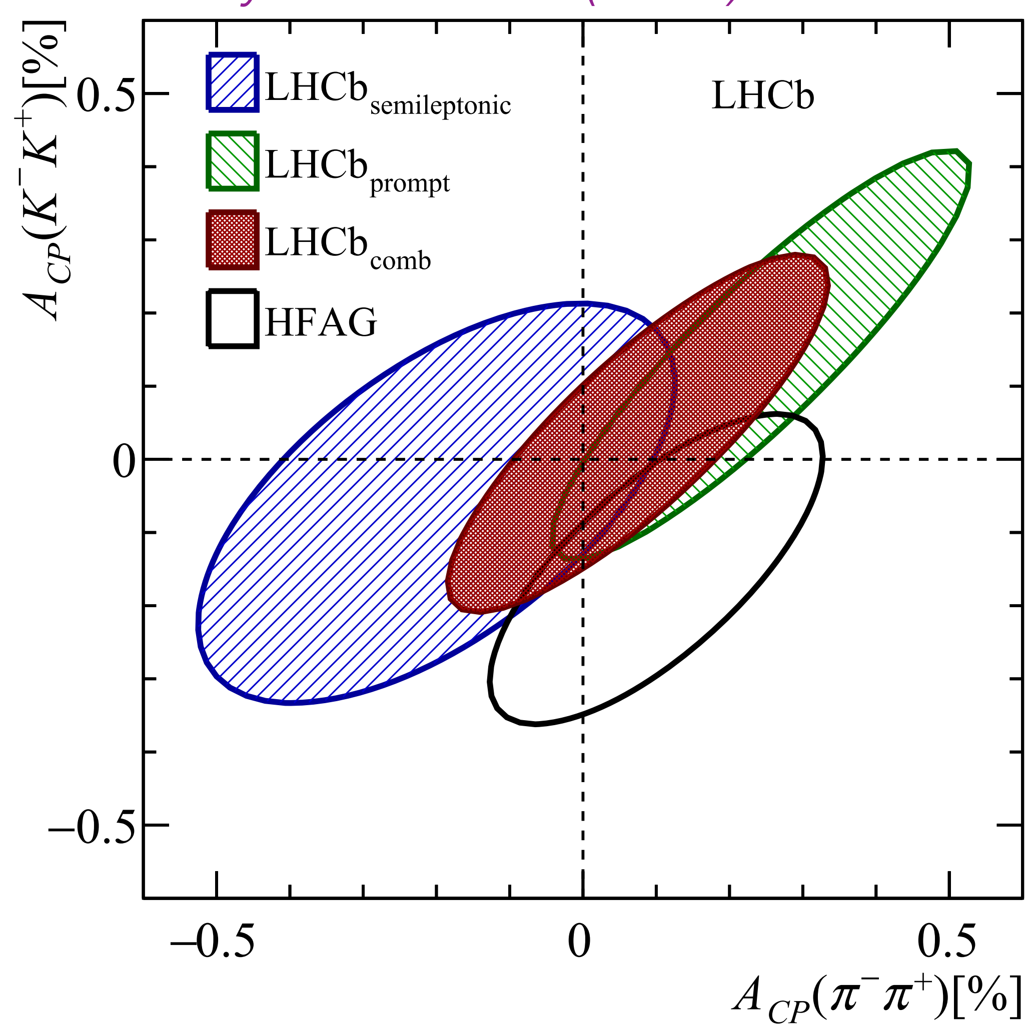

Most precise measurements from a single experiment. No evidence of CP asymmetry.