D⁰ oscillation and CP Violation in charm decays and at LHCb

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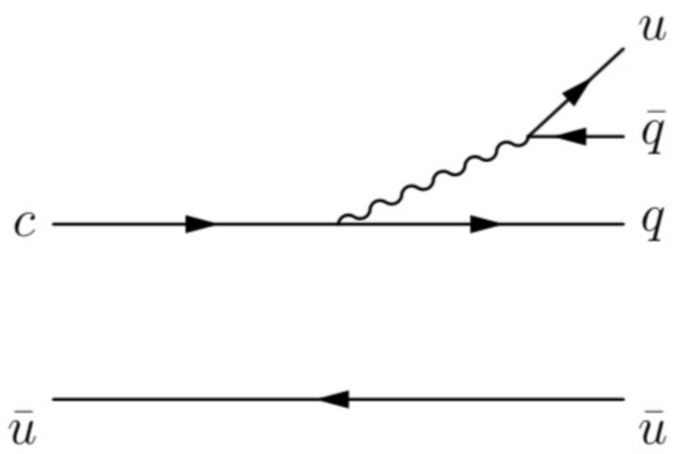
Outline

- Introduction
- D^0 oscillation and CP violation
- Impact of LHCb in the charm sector
  - CP violation in the decay
  - CP violation in D^0 mixing and in the interference between mixing and decay
  - New for today: Observation of the mass difference between neutral charm-meson eigenstates with the $D^0 \to K_s^0\pi^+\pi^-$ decay
- Impact of the new D^0 mixing results on the world averages
- Conclusions

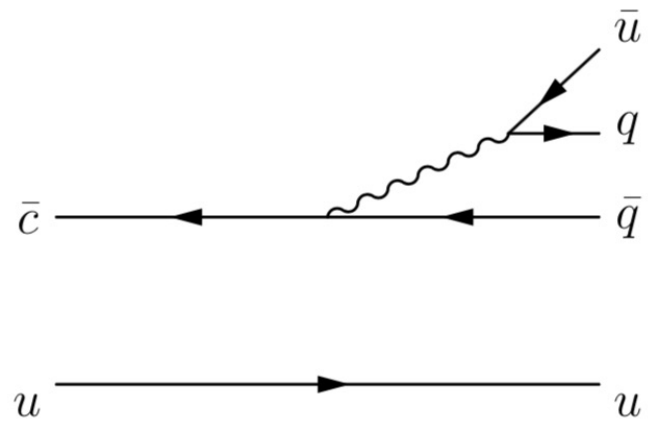
CP violation

CP violation



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

CP



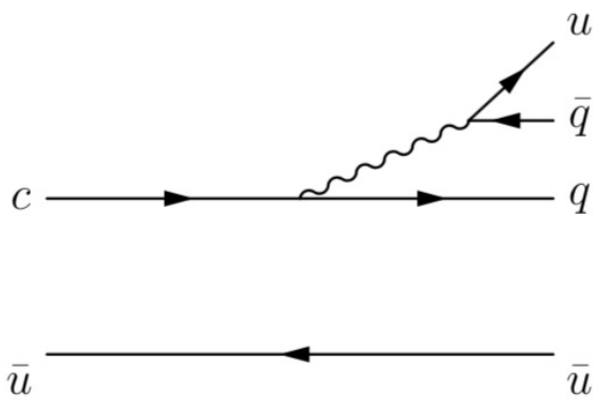
$$\bar{A} = \rho e^{i\delta} e^{-i\theta}$$

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)

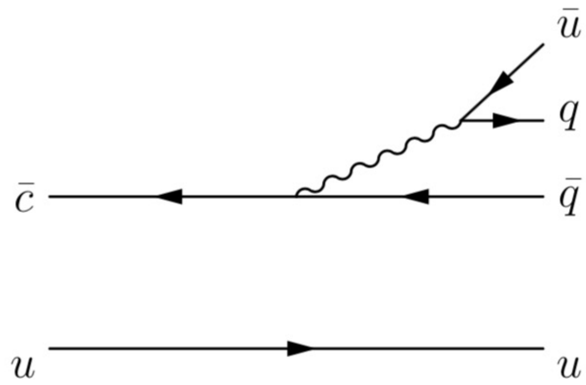
CP violation

Tree level



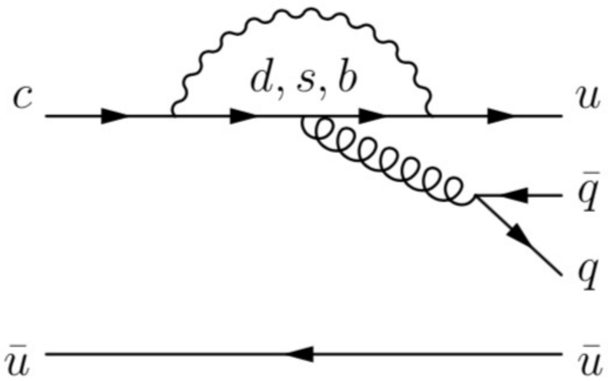
$A_1 = \rho_1 e^{i\delta_1} e^{i\theta_1}$

CP



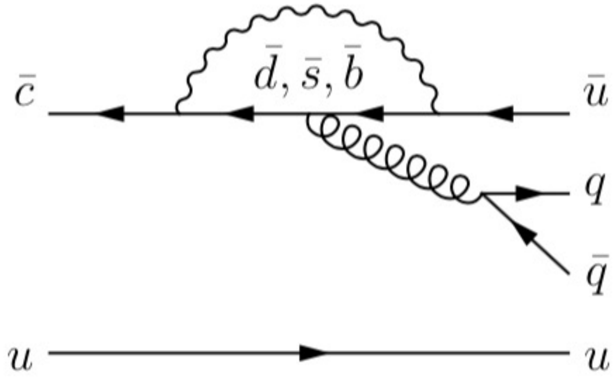
$\bar{A}_1 = \rho_1 e^{i\delta_1} e^{-i\theta_1}$

Loop level



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

CP



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

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

CP violation

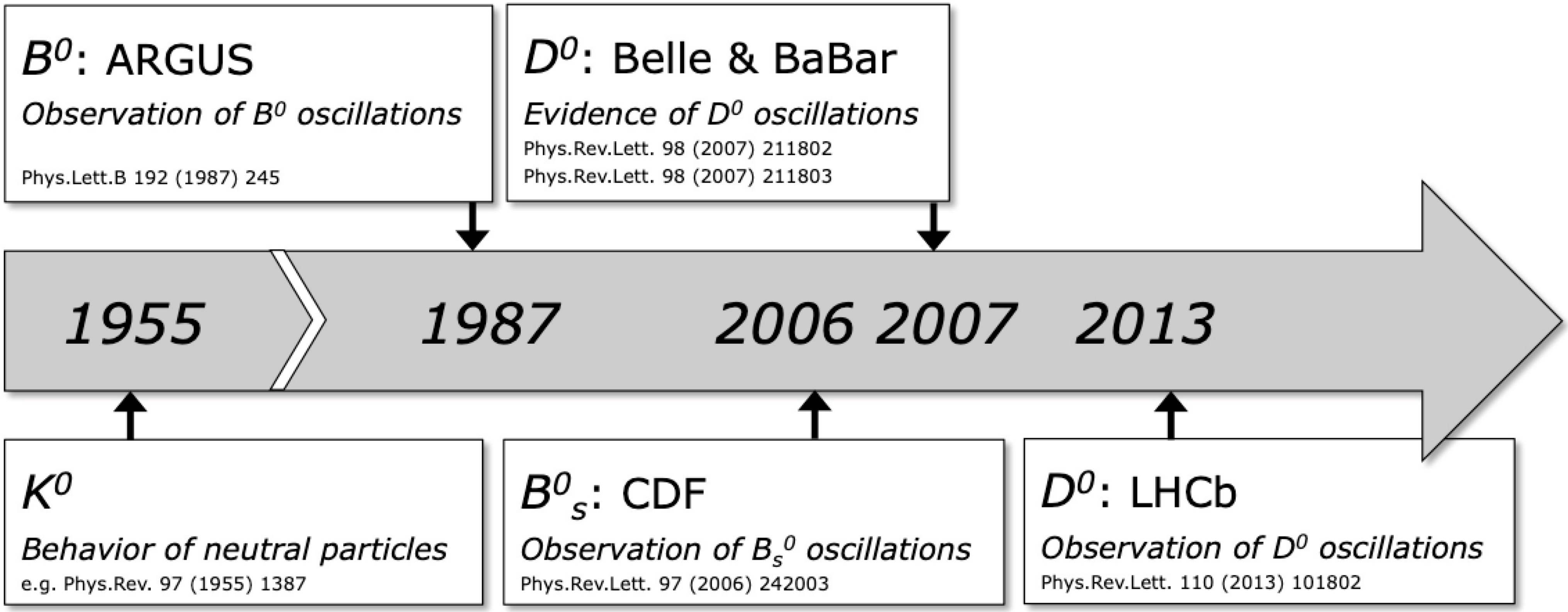
$$|\bar{A}_1 + \bar{A}_2|^2 - |A_1 + A_2|^2 = 4\rho_1\rho_2 \sin(\theta_1 - \theta_2) \sin(\delta_1 - \delta_2)$$

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 oscillation

D^0 oscillation and key dates



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

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

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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

$$\Delta M_D = m_2 - m_1 \qquad \Delta\Gamma_D = \Gamma_2 - \Gamma_1$$

$$x = \frac{\Delta M_D}{\Gamma_D}, \qquad y = \frac{\Delta\Gamma_D}{2\Gamma_D}$$

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$$\Delta M_D = m_2 - m_1 \qquad \Delta\Gamma_D = \Gamma_2 - \Gamma_1$$

$$x = \frac{\Delta M_D}{\Gamma_D}, \qquad y = \frac{\Delta\Gamma_D}{2\Gamma_D}$$

If either x or y are different from zero, mixing occurs

$$\begin{aligned} |\langle\bar{D}^0|D^0(t)\rangle|^2 &= \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-\Gamma t}\left[\cosh(y\Gamma t) - \cos(x\Gamma t)\right] \\ |\langle D^0|\bar{D}^0(t)\rangle|^2 &= \frac{1}{2}\left|\frac{p}{q}\right|^2 e^{-\Gamma t}\left[\cosh(y\Gamma t) - \cos(x\Gamma t)\right] \end{aligned}$$

CP violation in D^0 mixing

If $|q/p| \neq 1$

CP violation occurs in D^0 mixing

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

CP violation occurs in the interference between decay and D^0 mixing

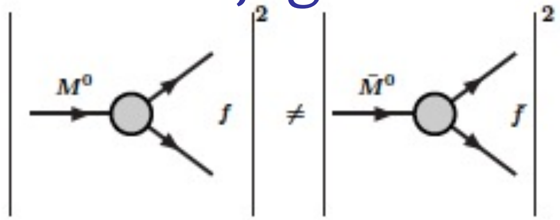
(*) definition ϕ is for common $D^0, \bar{D}^0$ final state where the final state dependent correction is neglected at the current level of experimental precision

Search for CP violation

The direct CPV

CPV in decay occurs when the absolute value of the decay rate $M \to f$ differs from the decay rate involving the CP-conjugate states

$$|A(M^0 \to f)| \neq |A(\bar{M}^0 \to \bar{f})|$$



CP violation in the decay can be observed if the asymmetry

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

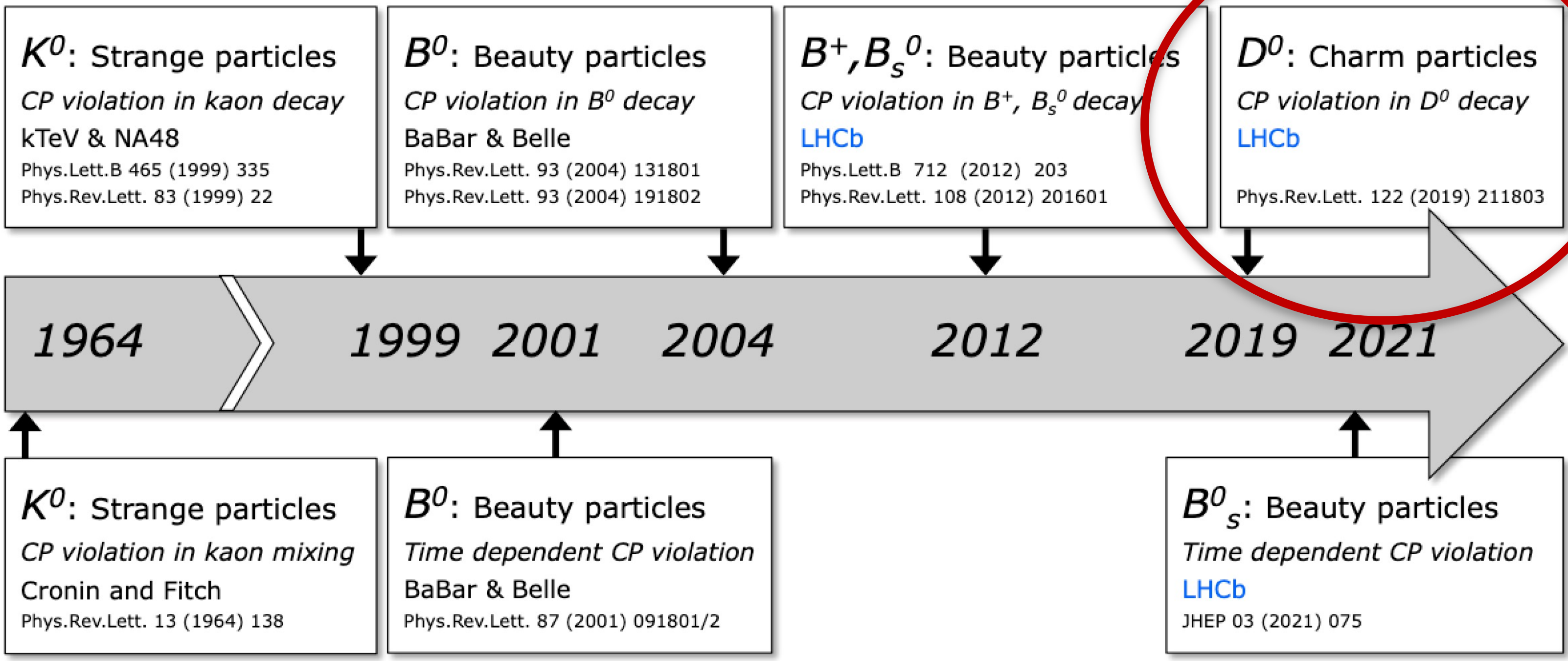
is different from zero

In the Standard Model direct CP violation is naively estimated to be

$$A_{CP}^{dir}(D^0 \to hh) \sim 10^{-3} - 10^{-4}$$

Non-perturbative QCD as well as New Physics effects can contribute to enhance CPV → but we already know that these effects can not be large

First observation of CP violation in charm decays [2019]

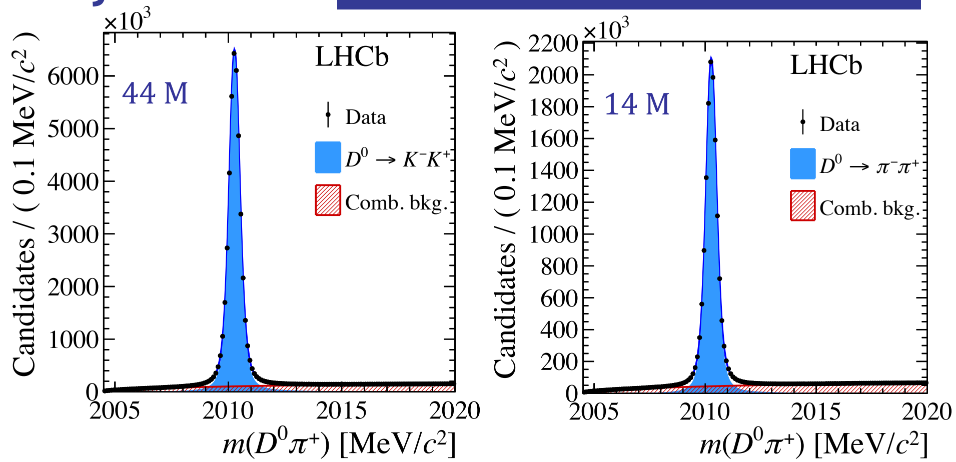


First observation of CPV in charm decays

LHCb-PAPER-2019-006

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

5.3 standard deviations from zero



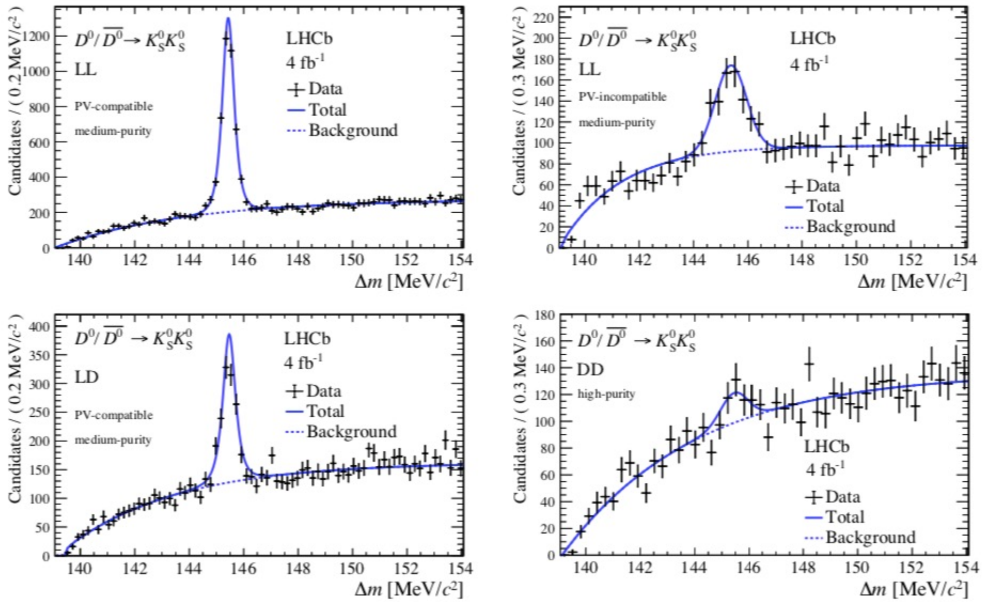
Recent LHCb results on direct CP violation

LHCb-PAPER-2020-047
PRD Lett.

see Lorenzo's talk @ CHARM 2020

LHCb-PAPER-2021-001
JHEP

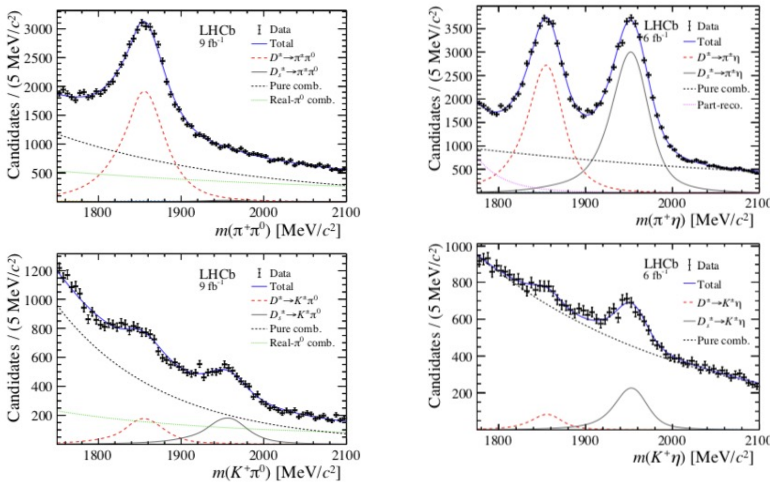
CPV in $D^0 \to K_S^0 K_S^0$ decay



$$\mathcal{A}^{CP}(D^0 \to K^0_S K^0_S) = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\%$$

compatible with no CP asymmetry at the level of 2.4 standard deviations.

CPV in $D^+_{(s)} \to h^+\pi^0$ $D^+_{(s)} \to h^+\eta$ decay



$$\begin{aligned}
\mathcal{A}_{CP}(D^+ \to \pi^+\pi^0) &= (-1.3 \pm 0.9 \pm 0.6)\%,\\
\mathcal{A}_{CP}(D^+ \to K^+\pi^0) &= (-3.2 \pm 4.7 \pm 2.1)\%,\\
\mathcal{A}_{CP}(D^+ \to \pi^+\eta) &= (-0.2 \pm 0.8 \pm 0.4)\%,\\
\mathcal{A}_{CP}(D^+ \to K^+\eta) &= (-6 \pm 10 \pm 4)\%,\\
\mathcal{A}_{CP}(D^+_s \to K^+\pi^0) &= (-0.8 \pm 3.9 \pm 1.2)\%,\\
\mathcal{A}_{CP}(D^+_s \to \pi^+\eta) &= (0.8 \pm 0.7 \pm 0.5)\%,\\
\mathcal{A}_{CP}(D^+_s \to K^+\eta) &= (0.9 \pm 3.7 \pm 1.1)\%,
\end{aligned}$$

Current experimental status on SCS

source HFLAV (May 2021)

Observable	Current precision $\times 10^4$	Experiments (ordered by precision)	Perspectives
$\Delta A_{CP}^{dir} = A_{CP}(KK) - A_{CP}(\pi\pi)$	-15.4 ± 2.9	LHCb, CDF, BaBar, Belle	Run1+Run2
$A_{CP}(D^0 \to K^- K^+)$	-9 ± 11	LHCb, CDF, Cleo, Focus, BaBar, Belle	update expected soon full Run1+Run2
$A_{CP}(D^0 \to \pi^- \pi^+)$	-1 ± 14	LHCb, CDF, Cleo, Focus, BaBar, Belle	update expected soon Run1+Run2
$A_{CP}(D^0 \to \pi^0 \pi^0)$	-3 ± 64	Cleo, Belle	
$A_{CP}(D^0 \to K_S^0 K_S^0)$	-150 ± 110	LHCb, Belle, Cleo	recently updated Run2
$A_{CP}(D^+ \to \pi^+ \pi^0)$	40 ± 80	LHCb, Belle, Cleo	recently updated Run2
$A_{CP}(D^+ \to K_S^0 K^+)$	1 ± 7	LHCb, Belle, BaBar	missing 30% of data Run2
$A_{CP}(D^+ \to \phi \pi^+)$	0.1 ± 5	LHCb, Belle, BaBar	missing 30% of data Run2
$A_{CP}(D_s^+ \to K_S^0 \pi^+)$	16 ± 18	LHCb, BaBar	missing 30% of data Run2
$A_{CP}(D_s^+ \to K^+ \pi^0)$	200 ± 300	LHCb, Belle, Cleo	recently updated

CP violation in oscillation and in the interference between D^0 decay and oscillation

Singly-Cabibbo-suppressed decays

PAPER-2020-045
[arXiv:2105.09889] PRD

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

[For details see Guillaume's talk @ CHAMR2020]

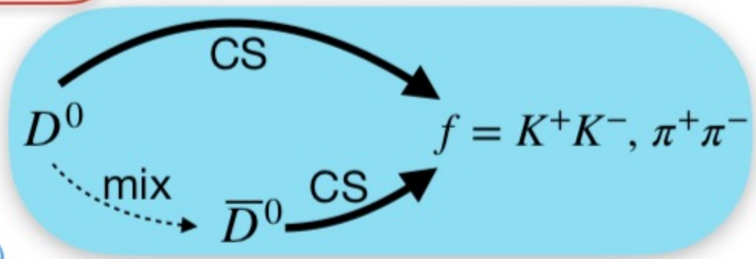
$$x_{12}, y_{12} \ll 1$$

$$A_{CP}(f,t) \equiv \frac{\Gamma(D^0 \to f,t) - \Gamma(\bar{D}^0 \to f,t)}{\Gamma(D^0 \to f,t) + \Gamma(\bar{D}^0 \to f,t)} \approx a_f^d + \Delta Y_f \frac{t}{\tau_{D^0}}$$

$$\Delta Y_f \approx -A_\Gamma$$

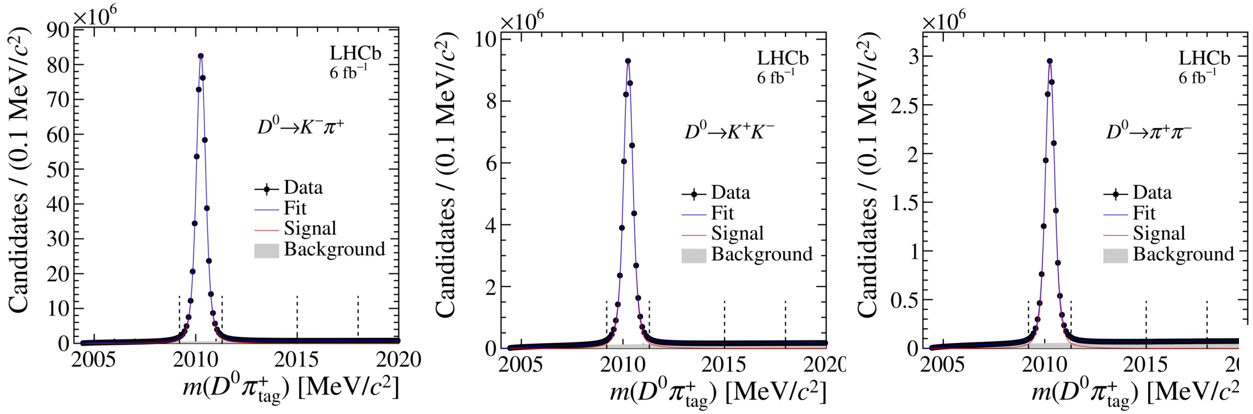
$$\Delta Y_f \approx -x_{12} \sin \phi_2^M$$

$$\phi_2^M \sim \arg(M_{12})$$



$\mathcal{O}(10^{-5} - 10^{-4})$ **in the SM**
current experimental precision: 2×10^{-4}

Kagan & Silvestrini 2020,
Grossman et al. (in preparation),
Li, Umeeda, Xu, Yu 2020



$$\Delta Y_{K^+K^-} = (-2.3 \pm 1.5 \pm 0.3) \times 10^{-4}$$
$$\Delta Y_{\pi^+\pi^-} = (-4.0 \pm 2.8 \pm 0.4) \times 10^{-4}$$

Neglecting final-state dependent contributions

$$\Delta Y = (-2.7 \pm 1.3 \pm 0.3) \times 10^{-4}$$

New for CHARM 2020

Observation of a nonzero mass difference between neutral charm-meson eigenstates

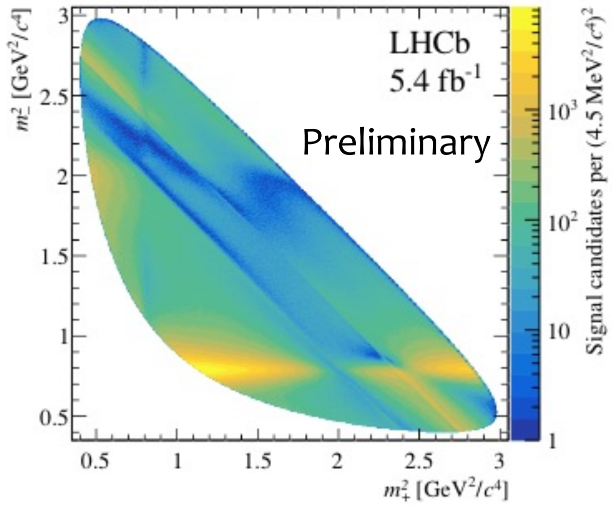
Run 2 [$5.4\ fb^{-1}$]

LHCB-PAPER-2021-009
[soon on arXiv]

Measurement of D⁰ Mixing Parameters

Phys. Rev. D 99 (2019) 012007 [arXiv:1811.01032]

- $D^0 \to K_S^0 \pi^+ \pi^-$ has a rich resonance structure
- The analysis is performed by means of a quasi-model independent approach (bin-flip method)
  - avoids accurate modelling of the efficiency
- $D^0 \to K_S^0 \pi^+ \pi^-$ decay receive contribution from Cabibbo-favoured and doubly-Cabbibbo-suppressed decay amplitudes only
  - With good approximation CP symmetry is conserved in the decay
  - Direct access to the mixing phase independent of the final state (ϕ_2 for detail see Kagan & Silvestrini 2020)



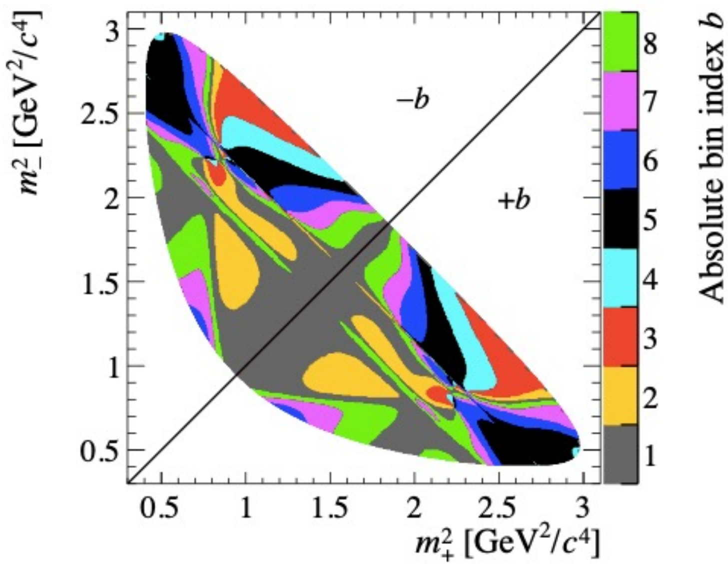
Analysis Strategy

LHCB-PAPER-2019-001
[soon on arXiv]

- Production flavour of D^0 and $\overline{D}^0$ identified by the reconstruction of $D^{*+} \to D^0\pi^+$ (apex → "±")

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

- 8 bins over the Dalitz plane chosen to have almost constant strong-phase differences (subscript → "b")
- Dalitz plane divided into two regions
  - $m_+ > m_-$ large contribution from CF decays $b = +1, \dots, +8$
  - $m_+ < m_-$ large contribution from DCS decays $b = -1, \dots, -8$
- Data further divided into 13 bins of decay-time (subscript → "j")
- A total of 416 disjoint data samples



The Formalism

Phys. Rev. D 99 (2019) 012007 [arXiv:1811.01032]

For each decay-time interval (j), the ratio of the number of decays in each negative Dalitz-plane bin (–b) to its positive counterpart (+b) is measured

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

r_b → value of the ratio for $t = 0$

$< t > (< t^2 >)$ → average (squared) decay time

$z = (-y + ix)$ with $z_{CP} \pm \Delta z \equiv \left(\frac{q}{p}\right)^{\pm 1} z$

X_b is the amplitude-weighted average strong phase as measured by CLEO and BESIII Collaboration [Phys. Rev. D82 (2010) 112006, Phys. Rev. D 101 (2020) 112002]

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

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

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

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

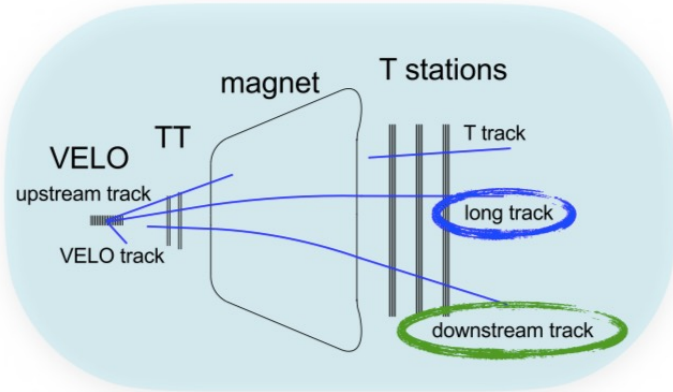
Useful parametrisation in terms of mixing parameters

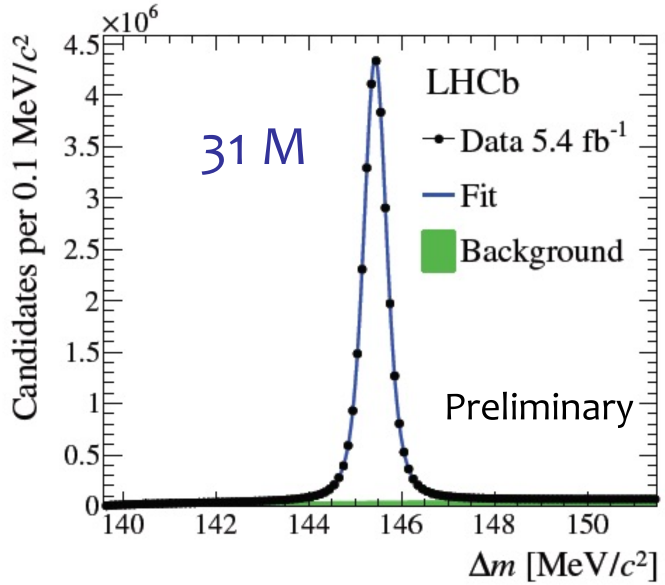
$$x_{CP}, y_{CP}, \Delta x, \Delta y \rightarrow x, y, \phi, \left|\frac{q}{p}\right|$$

The Signal Selection

LHCB-PAPER-2019-001
[soon on arXiv]

- $K_S^0 \rightarrow \pi^-\pi^+$ reconstructed as long and downstream
- Online event selection
  - L0-level (hardware) → based on calorimeter and muon detector information
  - High Level Trigger (software) → requirements on track and vertex quality, momenta and final-state charged-particle displacements from primary vertices, and particle identification
- Offline selection
  - Kinematical constrains the tracks to form vertices according to the decay topology
  - D mesons originating from b hadrons suppressed by requiring to point back to the interaction point



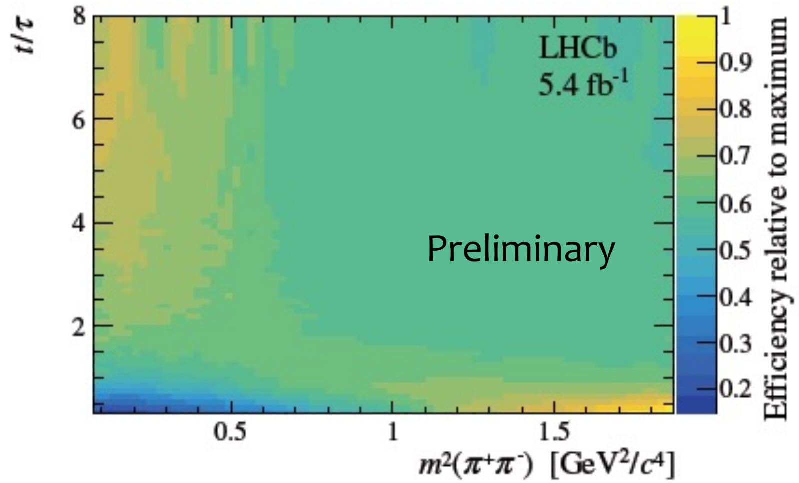


Determination of $R^{\pm}_{b,j}$

LHCB-PAPER-2019-001
[soon on arXiv]

- 416 separate invariant mass fits are performed for each set of Dalitz-plot, decay-time and D^0- $\overline{D}^0$ data samples
  - Fit model assumes same parameter for $\pm\, b$ data samples
  - Time-integrated fits used to fix some parameters in the fits
- Yields are then corrected for two effects that do not cancel in the ratio:
  - experimentally induced correlations between the phase space and decay time
  - charge-dependent efficiencies

Data driven approach to remove correlation between decay time and $m(\pi^+\pi^-)$



Detection efficiencies $A_{det}(\pi^-\pi^+)$ measured by means of control sample

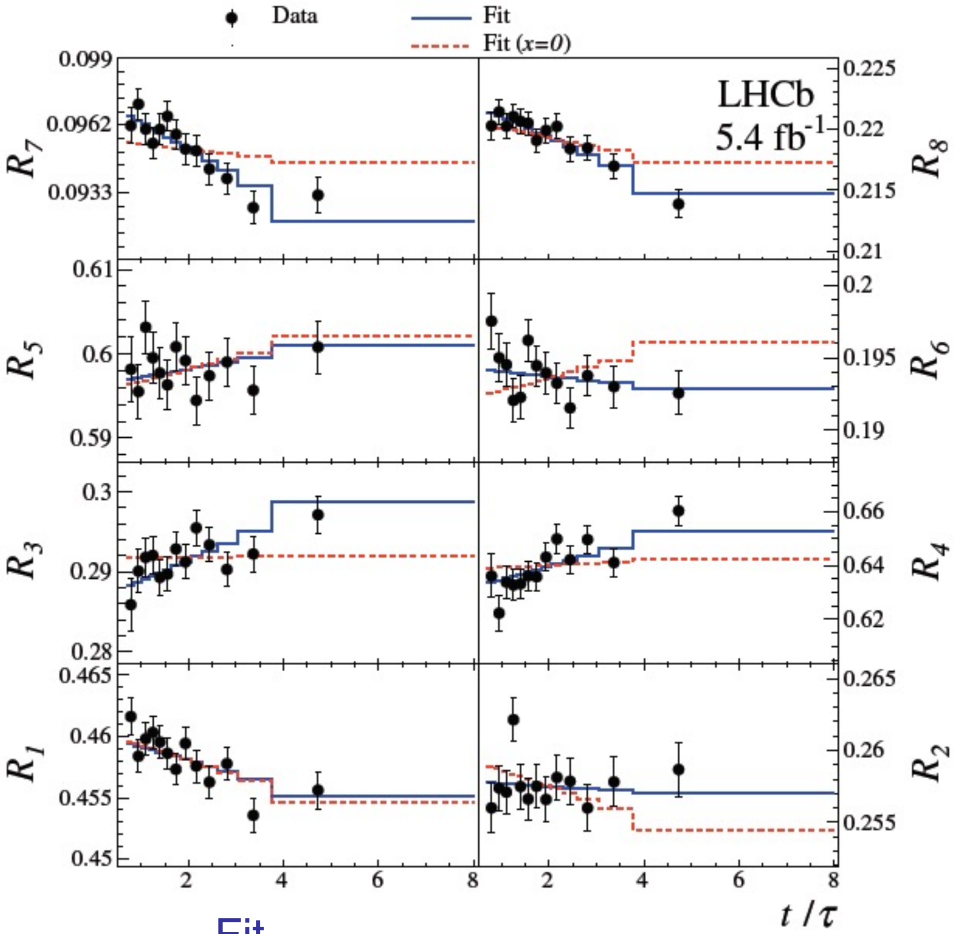
$$A_{\rm meas}(D_s^+ \to \pi^+\pi^+\pi^-) = A_{\rm det}(\pi^+\pi^-) + A_{\rm det}(\pi^+) + A_{\rm prod}(D_s^+) + A_{\rm trigger}(D_s^+)$$

$$A_{\rm meas}(D_s^+ \to \phi\pi^+) = A_{\rm det}(\pi^+) + A_{\rm prod}(D_s^+) + A_{\rm trigger}(D_s^+)$$

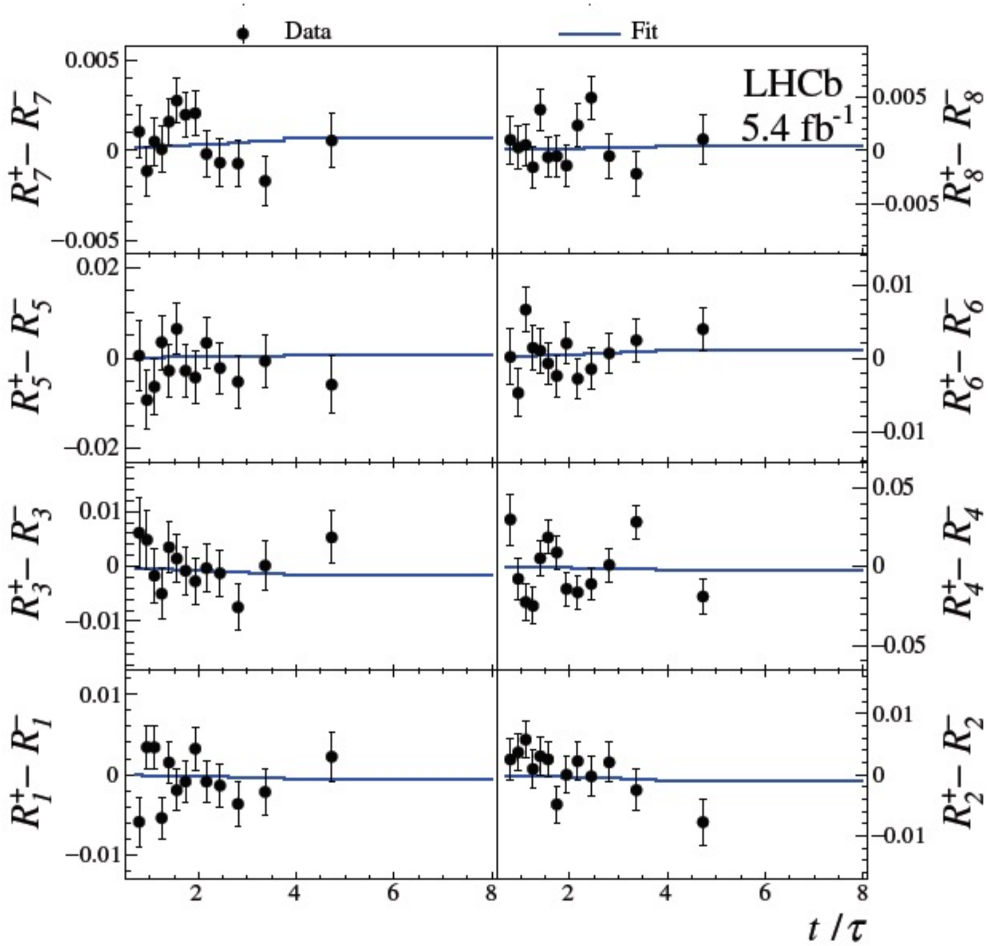
Results

LHCB-PAPER-2019-001
[soon on arXiv]

The deviations from constant values are due to mixing



The deviations from constant values are due to CPV



Fit
Fit (x=0)

Systematic uncertainties

LHCB-PAPER-2019-001
[soon on arXiv]

- Systematic uncertainties are assessed from ensembles of pseudoexperiments generated with different systematic effects
- The impact on measured parameters is then evaluated
- Reconstruction and selection (mainly affect x_{CP} and y_{CP})
  - Neglecting decay time and $m_{\pm}$ resolutions and efficiencies (mainly effect x_{CP} and y_{CP})
  - Correction to remove the correlation between decay time and $m_{\pm}$
- Approximation of constant strong phase in each Dalitz bin (mainly affect y_{CP})
- Neglecting time-dependent detection asymmetries (mainly affect Δy)
- Mis-modelling in the signal yield fits (mainly affect x_{CP})

Source	x_{CP}	y_{CP}	Δx	Δy
Reconstruction and selection	0.199	0.757	0.009	0.044
Secondary charm decays	0.208	0.154	0.001	0.002
Detection asymmetry	0.000	0.001	0.004	0.102
Mass-fit model	0.045	0.361	0.003	0.009
Total Systematic Uncertainty	0.291	0.852	0.010	0.110

Strong phase inputs	0.23	0.66	0.02	0.04
Det. asymm. inputs	0.00	0.00	0.04	0.08
Statistical (w/o inputs)	0.40	1.00	0.18	0.35
Statistical	0.46	1.20	0.18	0.36

Consistency check: analysis repeated in subsets of the data selected based on

- magnet polarity
- trigger and K_s^0 category
- data-taking period
- D^{*+} meson kinematics

Results

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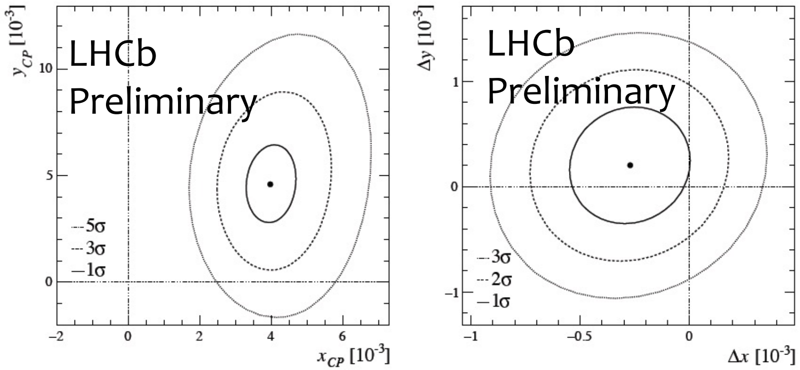
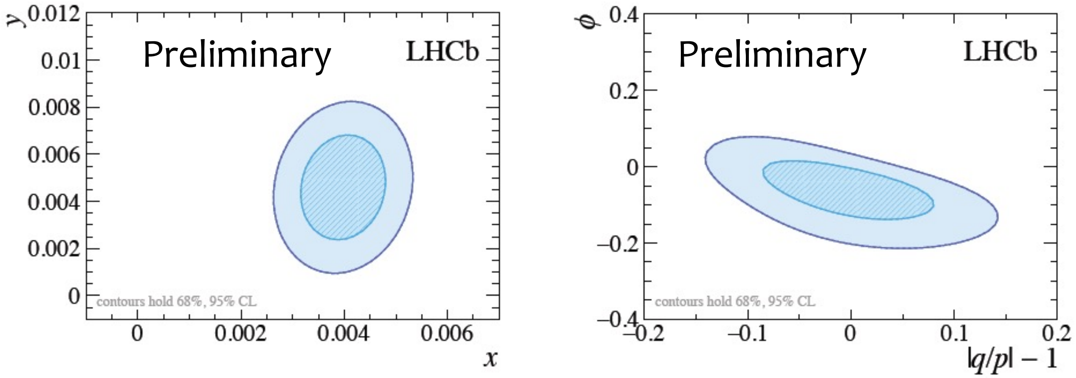
$$x_{CP} = (\ \ 3.97 \pm 0.46 \pm 0.29) \times 10^{-3}$$
$$y_{CP} = (\ \ 4.59 \pm 1.20 \pm 0.85) \times 10^{-3}$$
$$\Delta x = (-0.27 \pm 0.18 \pm 0.01) \times 10^{-3}$$
$$\Delta y = (\ \ 0.20 \pm 0.36 \pm 0.13) \times 10^{-3}$$

Parameter	Value	95.5% CL interval
$x\ [10^{-3}]$	$3.98\,^{+0.56}_{-0.54}$	$[2.9, 5.0]$
$y\ [10^{-3}]$	$4.6\,^{+1.5}_{-1.4}$	$[2.0, 7.5]$
$\lvert q/p\rvert$	0.996 ± 0.052	$[\ \ 0.890, 1.110]$
ϕ	$-0.056\,^{+0.047}_{-0.051}$	$[-0.172, 0.040]$





First observation at the level of 7 standard deviations of the mass difference between D^0 mass eigenstates

limits on mixing-induced CP violation significantly improved

Yet another milestone by LHCb!

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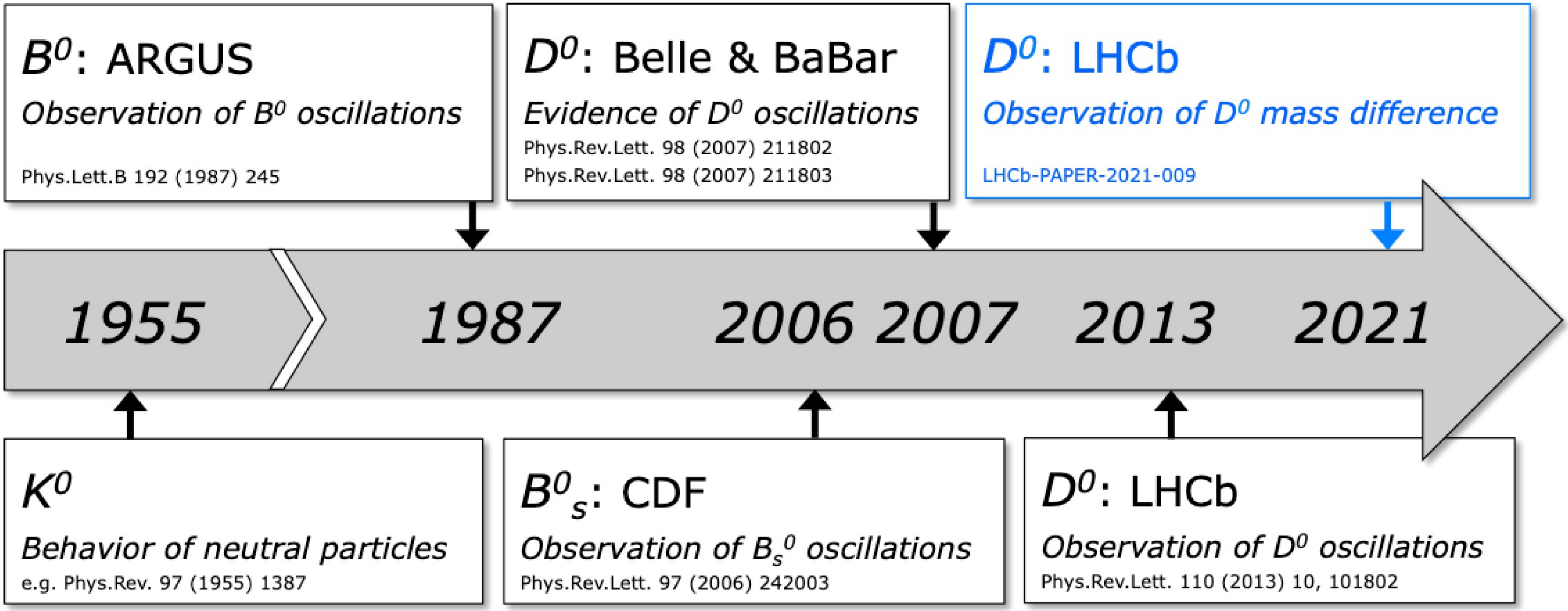

LHCb impact on world averages

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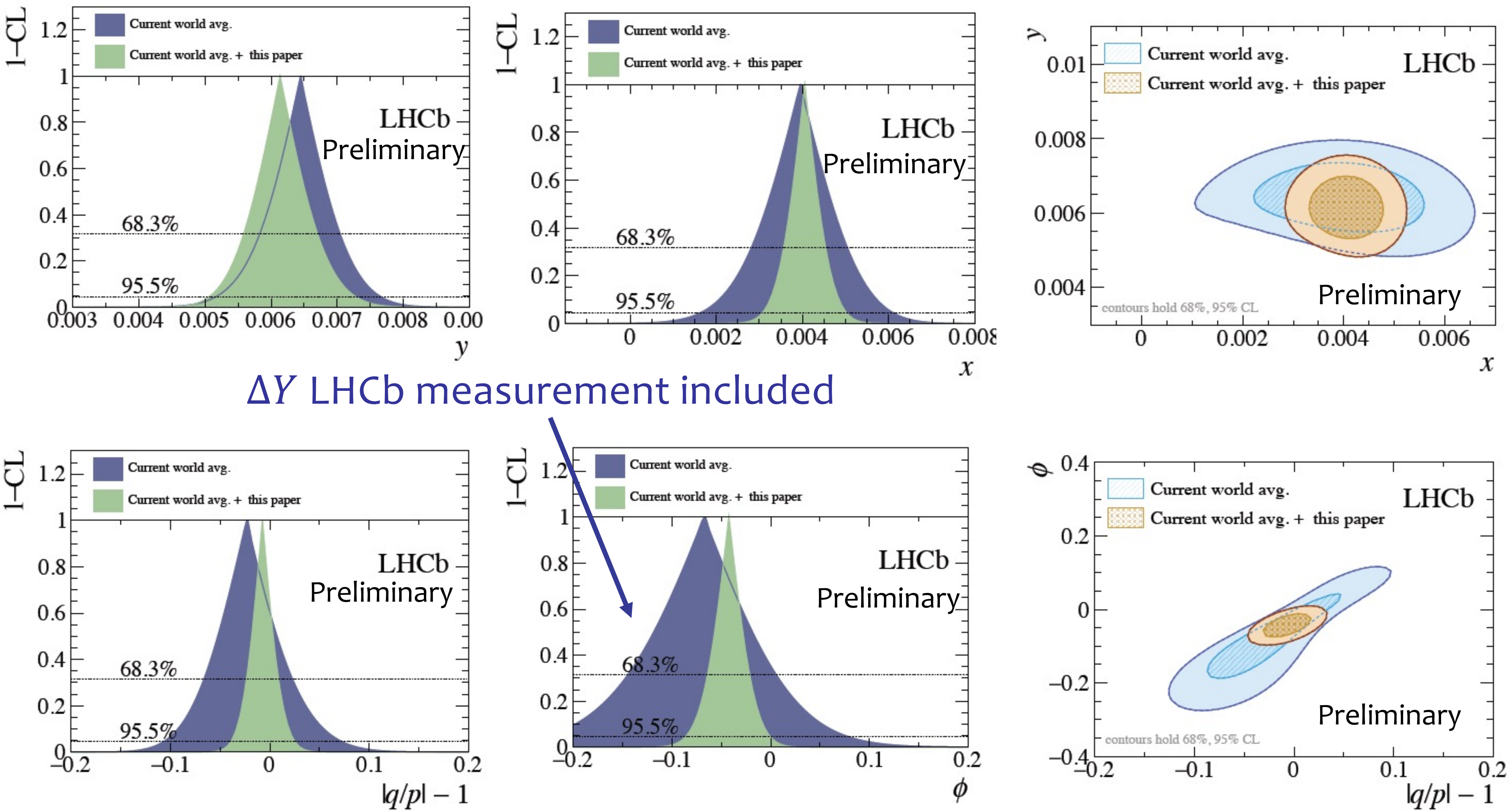
The combination procedure follows closely HFLAV methods



Conclusions

The LHCb Collaboration observes for the first time a difference between D^0 mass eigenstates with a significance of about 7 standard deviations

No mixing-induced CP violation was observed, but limits have been significatively improved

Search for CPV in pure mixing and interference of decay amplitudes with and without mixing remains an important tool for constraining New Physics

The upcoming LHCb-upgrade precision era will have an exciting time in store for us