CP violation in charm with the LHCb experiment

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on behalf of the LHCb collaboration

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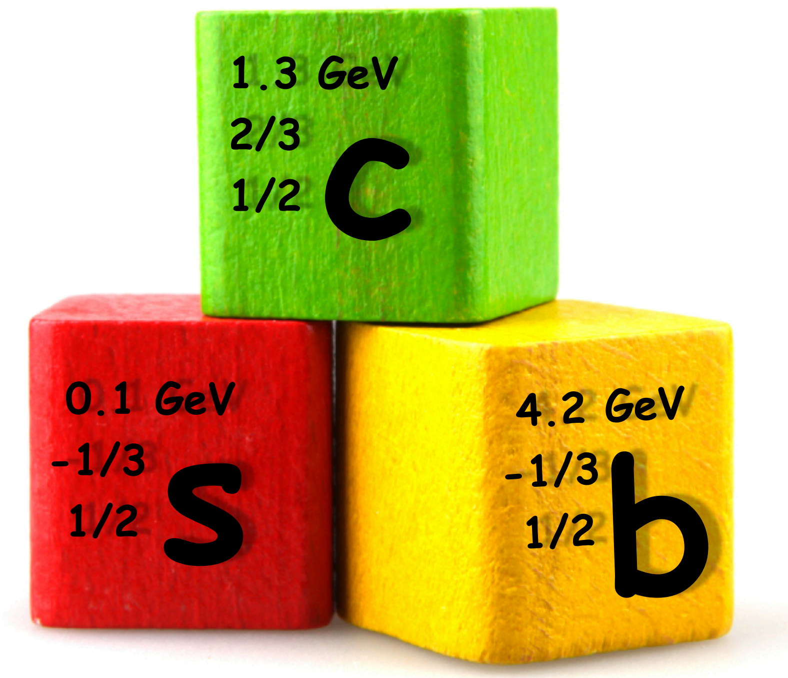
Why study charm physics?

- Searching for *CP* violation (**CPV**) in **charm** decay is a STRESS test to the Standard Model:
  - New Physics (**NP**) contributions could be hidden in the loops
  - **Up-type** quark: complementary to studies in **K** and **B** systems



- Small *CP* asymmetries expected **(0.01%÷0.1%)**
  - CKM/GIM suppression
  - Large uncertainties due to low-energy strong interaction effects [Phys.Lett. B222 (1989) 501]

- CPV in charm has been searched for since decades, In 2019, **observed** in the decay of D^0 *meson*!

- Why at ***LHCb***?

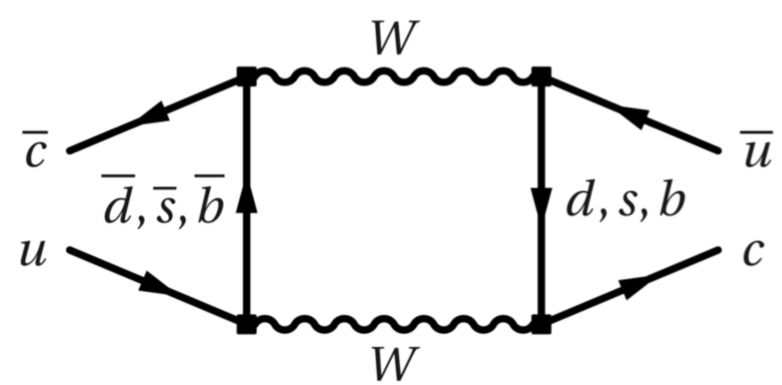
Huge **$c\bar{c}$** production cross-section:

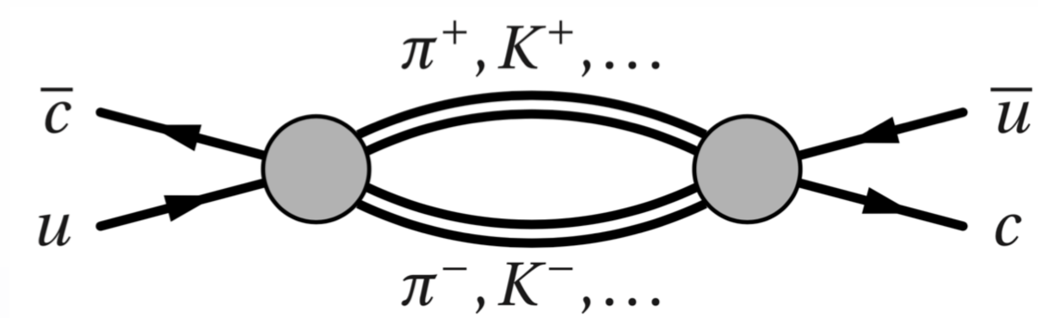
$$\sigma(pp \rightarrow c\bar{c}X)_{\sqrt{s}=13\,\text{TeV}} \cong 2.4\ \text{mb}$$

[JHEP 03 (2016) 159]

$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

Mixing of neutral *D* mesons





- *Mass* eigenstates are not the *flavour* eigenstates:

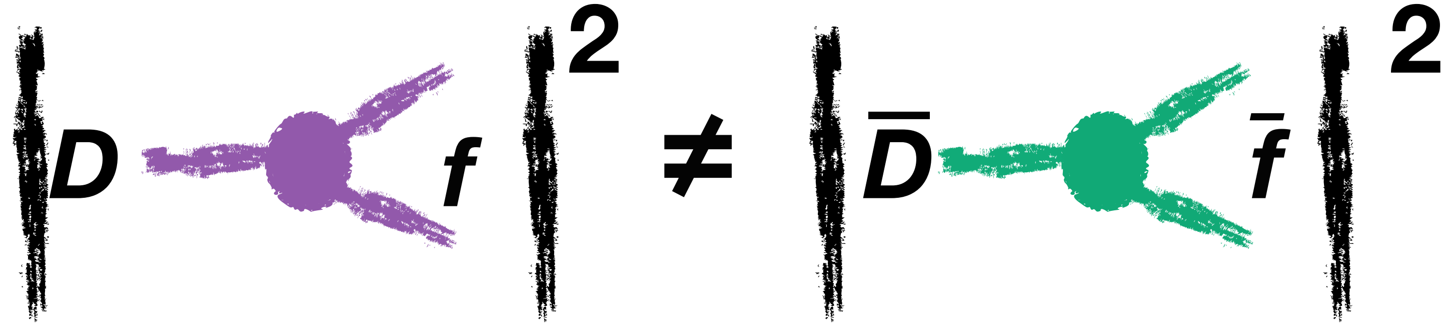
$$|D_{1,2}\rangle = p\,|D^0\rangle \pm q\,|\bar{D}^0\rangle$$

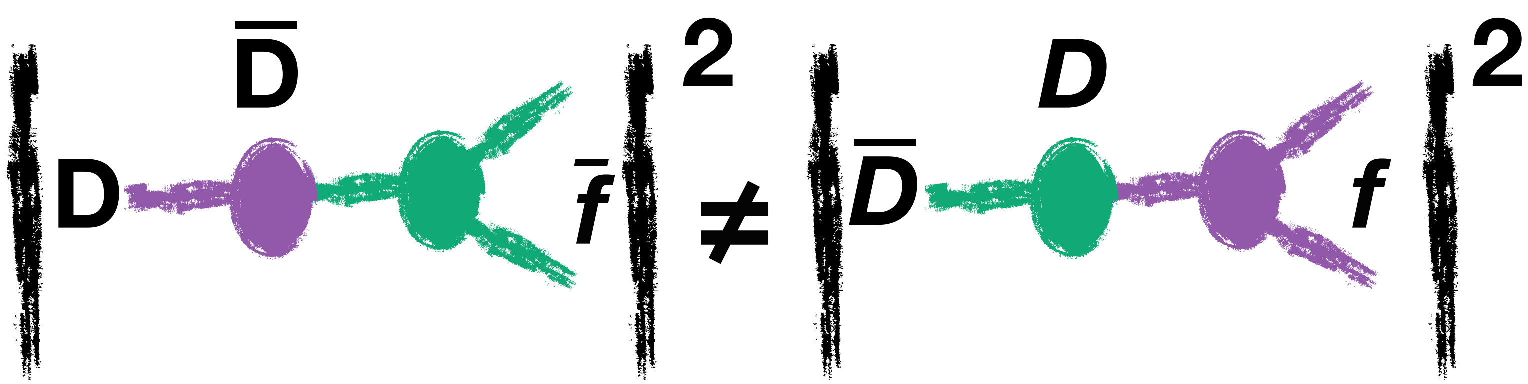
- This causes $\boldsymbol{D} \leftrightarrow \boldsymbol{\bar{D}}$ transitions described by $\begin{cases} x = \dfrac{m_1 - m_2}{\Gamma} \\ y = \dfrac{\Gamma_1 - \Gamma_2}{2\Gamma} \end{cases}$

- If *CP* is violated, two more observables: $\begin{cases} |q/p| \\ \phi = arg(q/p) \end{cases}$ or $\Delta x, \Delta y$

CP violation

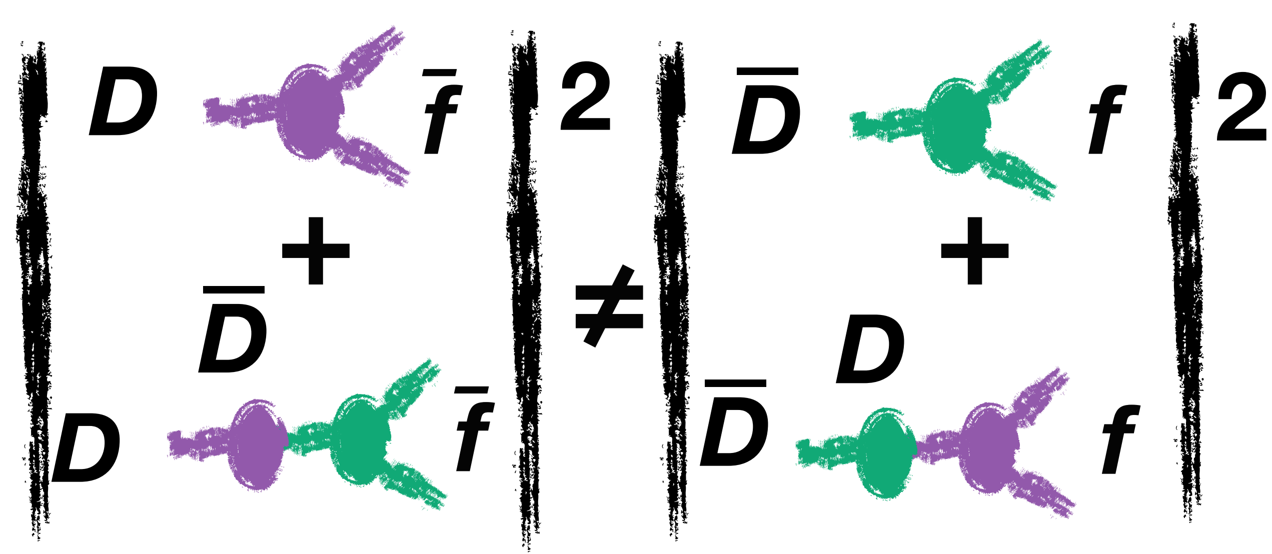
- CPV in the **decay**
  Occurs if $|A_f|^2 \neq |\bar{A}_{\bar{f}}|^2$
  (observed in 2019)





- CPV in **mixing**
  Occurs if $|q/p| \neq 1$

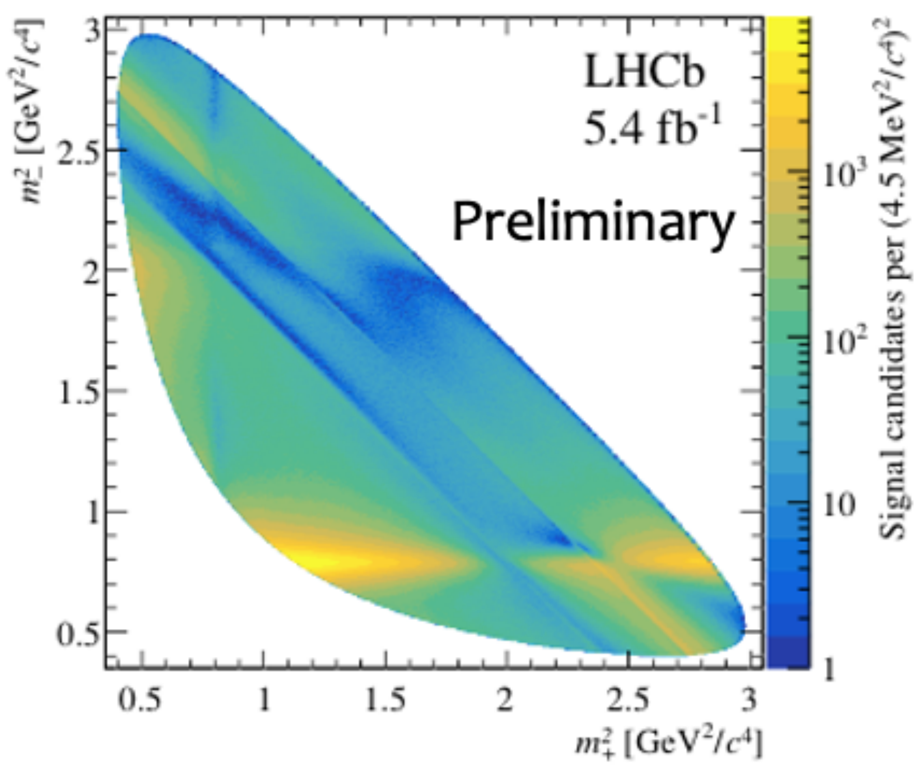
- Indirect CPV in **interference** between *mixing* and *decay*
  Occurs if $\phi_{\lambda_f} \equiv arg(q\bar{A}_{\bar{f}}/pA_f) \neq 0$



[arXiv:2106.03744]

Measurement of D^0 mixing parameters

- Using $D^0 \to K_S \pi^- \pi^+$ decays (rich resonance structure) which offer a *good sensitivity* to **mixing parameters**



[Phys. Rev. D 99, 012007]

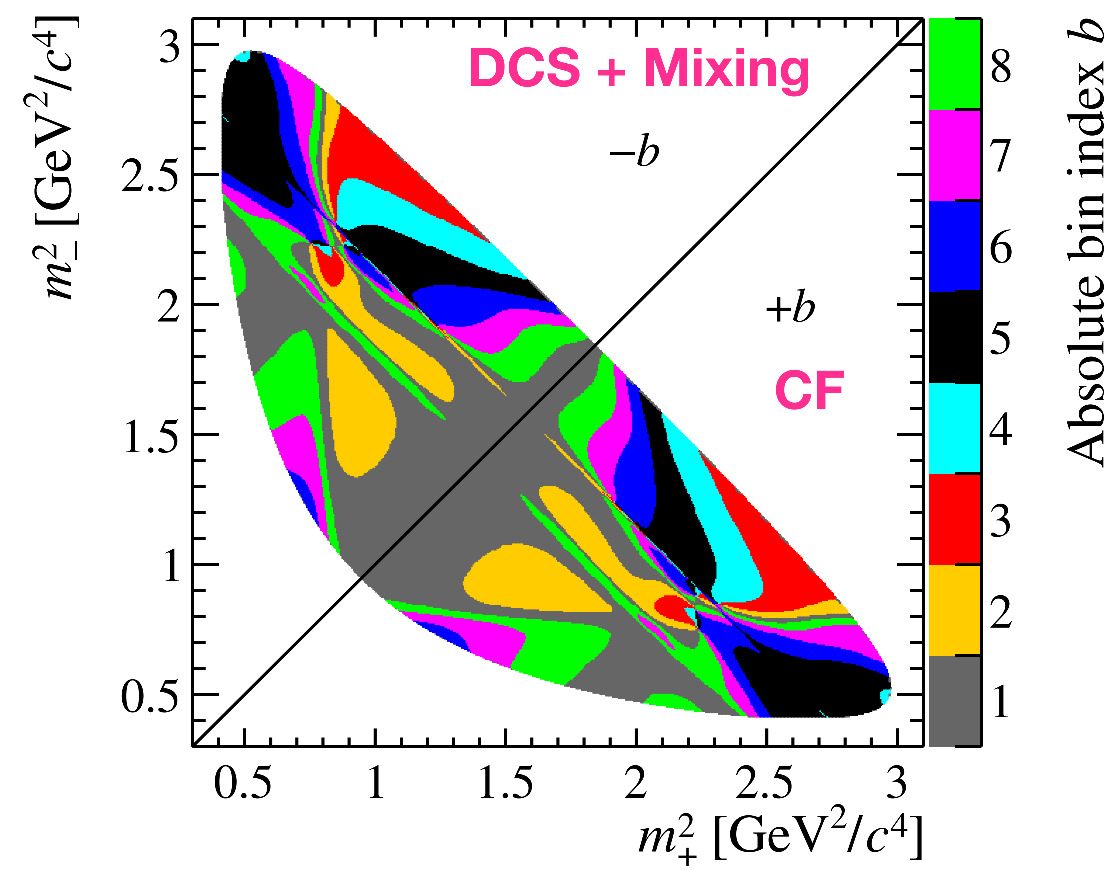
- Time-dependent Dalitz-plot analysis performed with the **Bin-Flip** approach
  → dynamics as input from external measurements
  → no accurate efficiency modeling
- $D^0 \to K_S \pi^- \pi^+$ decay receives contribution from Cabibbo-favoured and doubly-Cabibbo-suppressed decay amplitudes
- *CP* symmetry is conserved in the decay with good approximation
- Direct access to the **mixing phase** *independent* of the final state (**ϕ_2** for detail see [Kagan & Silvestrini 2020])

Analysis strategy

Complete formalism including CPV in backup

- Using prompt $D^{*+} \to D^0 \pi^+_{tag}$ decays collected during Run 2 (2015-2018, ~5.4 fb^{-1})
- Measure ratios of yields in *Dalitz* bins -***b*** and ***b*** in *decay-time* bins ***j***

$$R_{bj} = \frac{N_{-bj}}{N_{bj}}$$



- Assuming no *CP* violation:

$$R_{bj} \approx r_b - \sqrt{r_b}[(1 - r_b)c_b\, y - (1 + r_b)\, x]\langle t \rangle_j$$

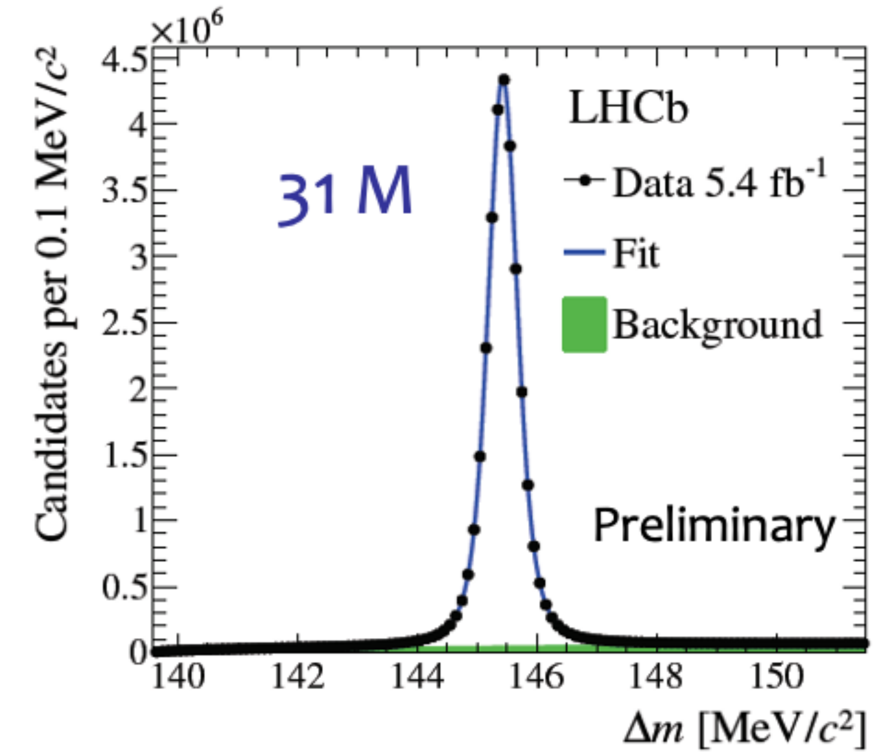
$x, y \to$ *mixing parameters*
$r_b \to$ value of the ratio for $t = 0$
$c_b, c_s \to$ *strong-phases*

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

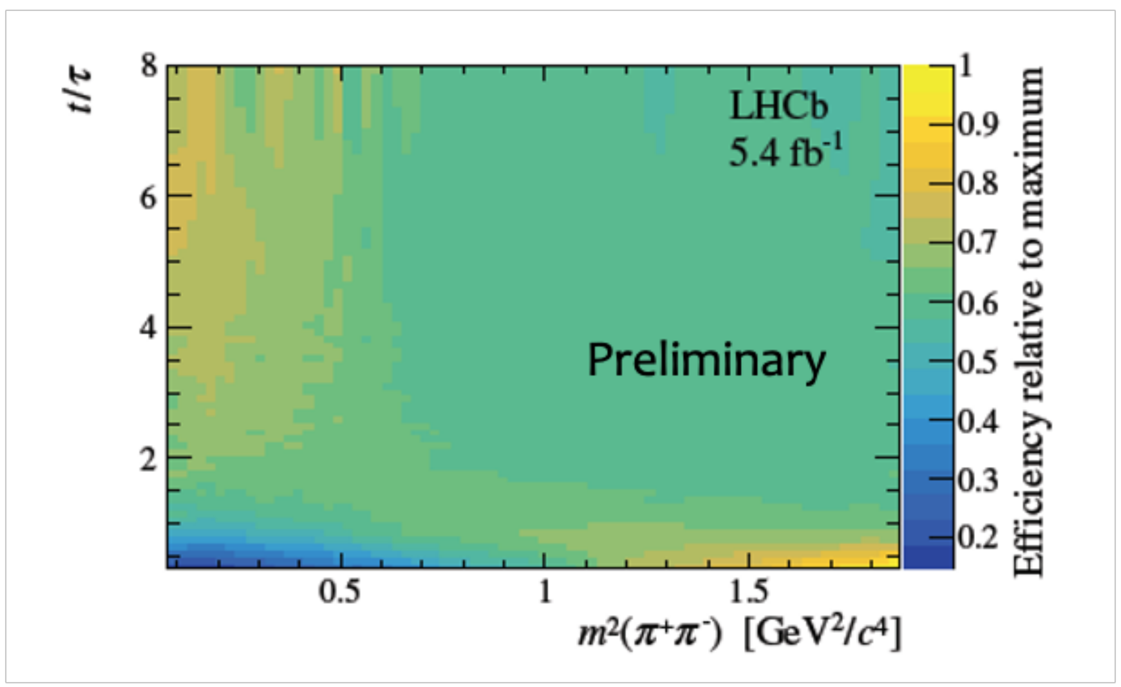
- Use binning which minimizes strong-phase variations: c_b, c_s from CLEO and BESIII [Phys. Rev. D 82, 112006, Phys. Rev. D 101, 112002]

Determination of $R_{bj}^{\pm}$

- 416 separate invariant mass fits to determine R_{bj} for D^0 and $\bar{D}^0$ candidates
- Yields are then corrected for two *effects* that do not cancel in the *ratio*:



Experimentally induced *correlations* between the phase-space and decay-time



→ Data driven approach to remove this correlation

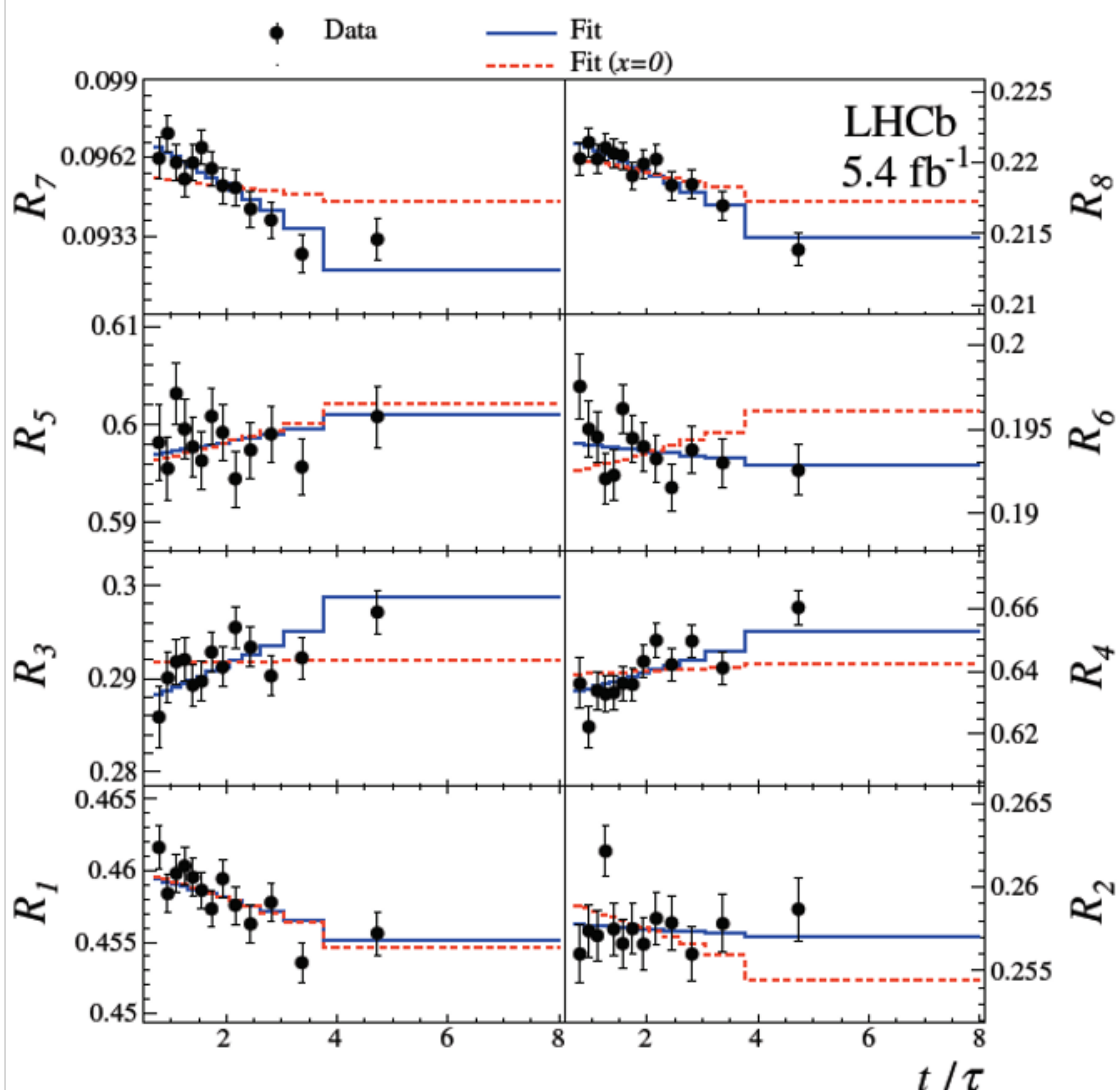
Charge-dependent efficiencies
→ Detection asymmetries $A_{det}(\pi^+\pi^-)$
measured by means of control samples

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

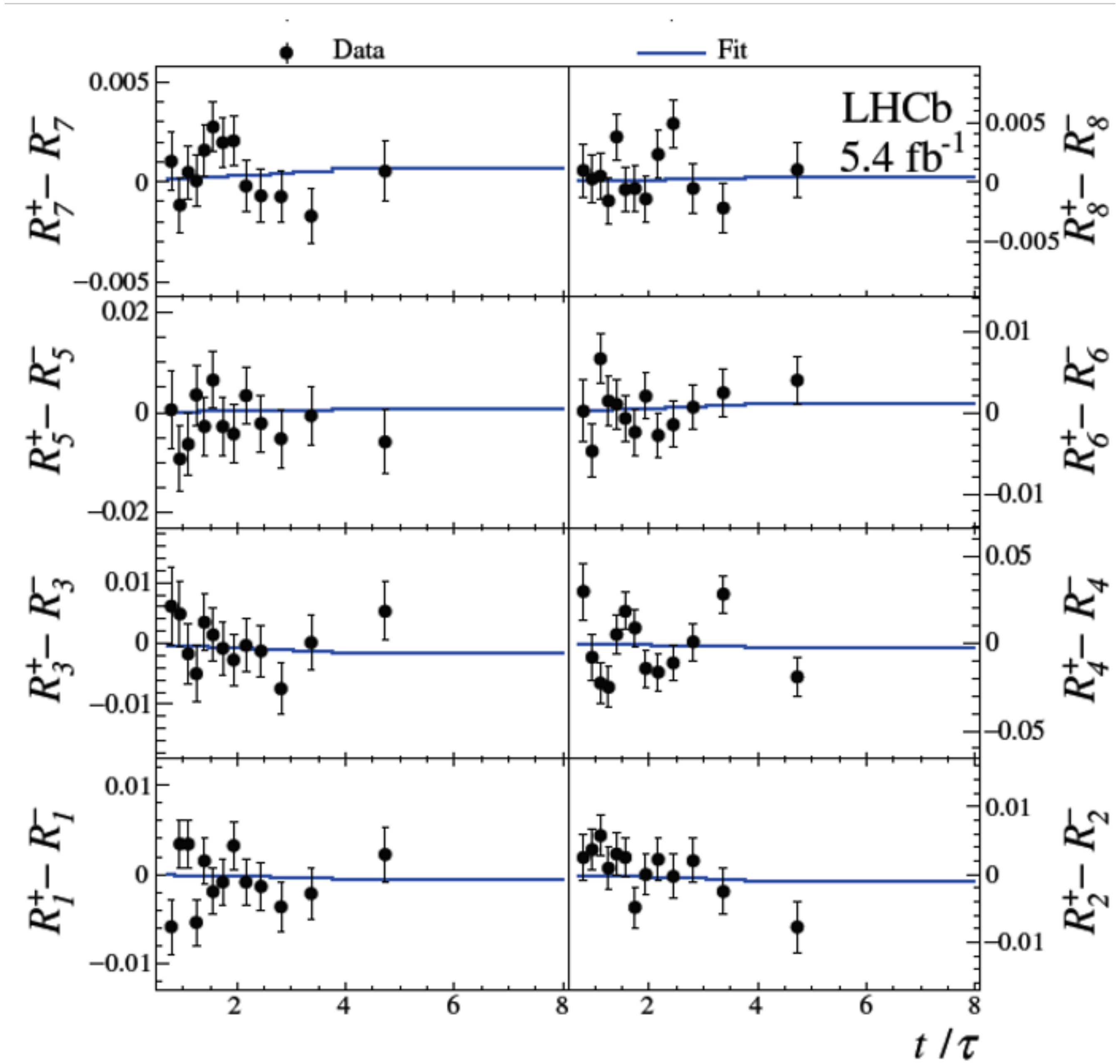
$$A_{meas}(D_s^+ \to \phi\pi^+) = A_{det}(\pi^+) + A_{prod}(D_s^+) + A_{trigger}(D_s^+)$$

Fit results

The deviations from constant values are due to mixing



The deviations from constant values are due to CPV



Results

- After a meticulous validation and evaluation of *systematic uncertainties* based on the emulation of nuisance effects (more details in backup), the mixing parameters are measured to be

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

→

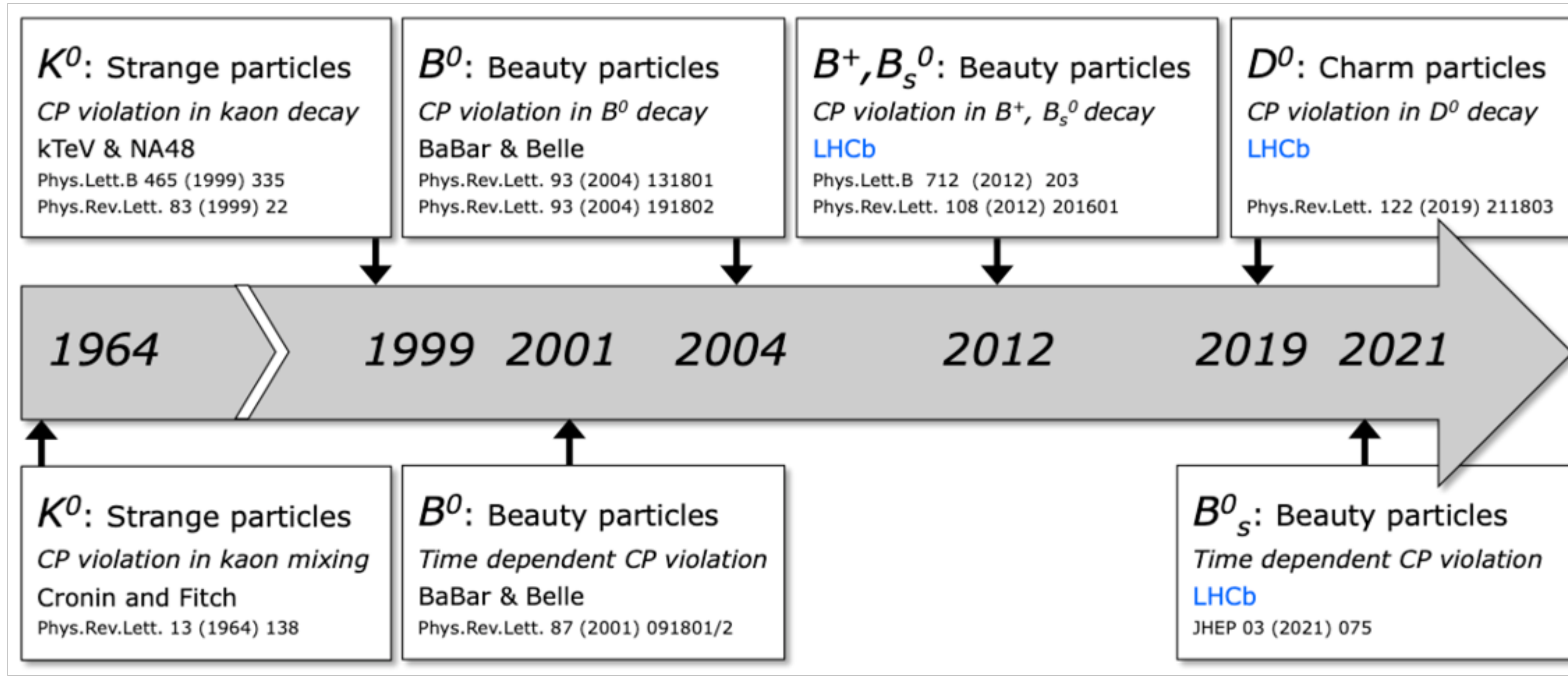
Parameter	Value	95.5% CL interval
$x\ [10^{-3}]$	$3.98\,^{+0.56}_{-0.54}$	$[2.9, 5.0]$
$y\ [10^{-3}]$	$4.6\,^{+1.5}_{-1.4}$	$[2.0, 7.5]$
$\lvert q/p \rvert$	0.996 ± 0.052	$[\ \ 0.890, 1.110]$
ϕ	$-0.056\,^{+0.047}_{-0.051}$	$[-0.172, 0.040]$

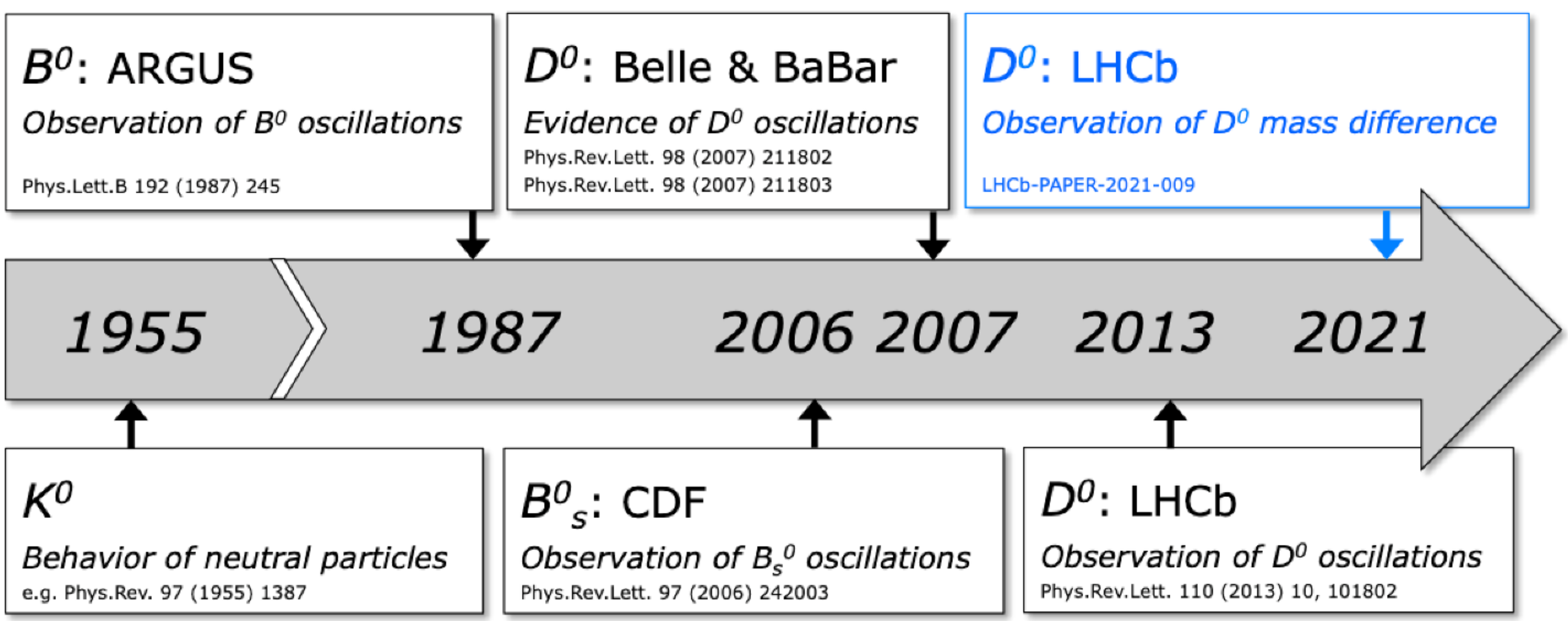
- **First observation** (at the level of 7 std. dev.) of the *mass difference between D^0 eigenstates*!!

- *CP* symmetry is conserved, but limits on mixing-induced CP violation significantly improved!

LHCb milestones

In *CP* violation …



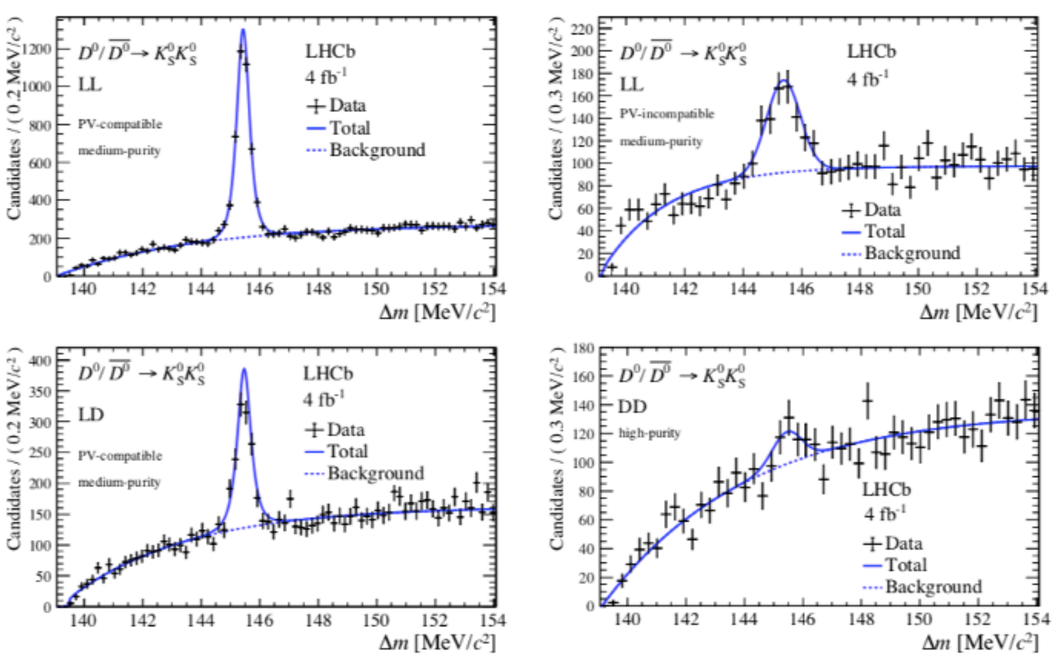


… and mixing

Recent LHCb results in charm physics

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

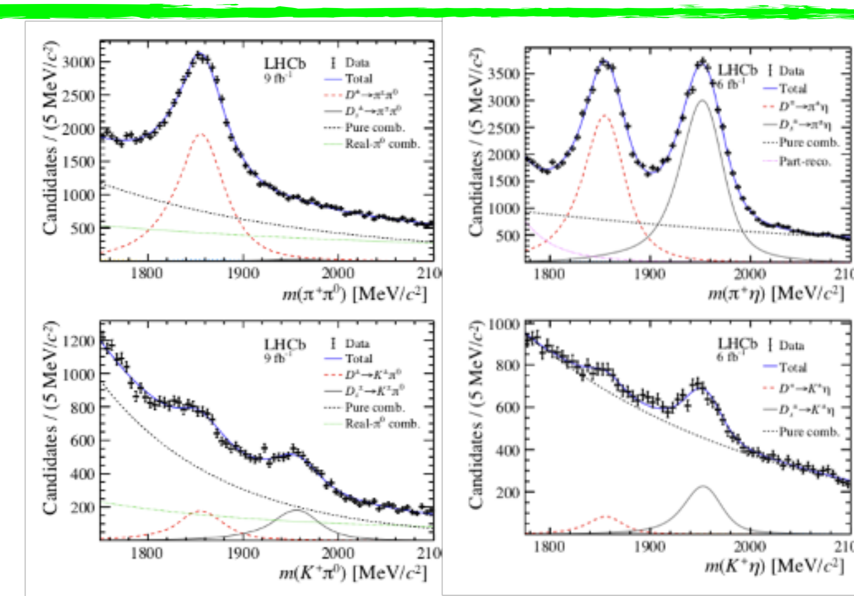
[arXiv:2105.01565]



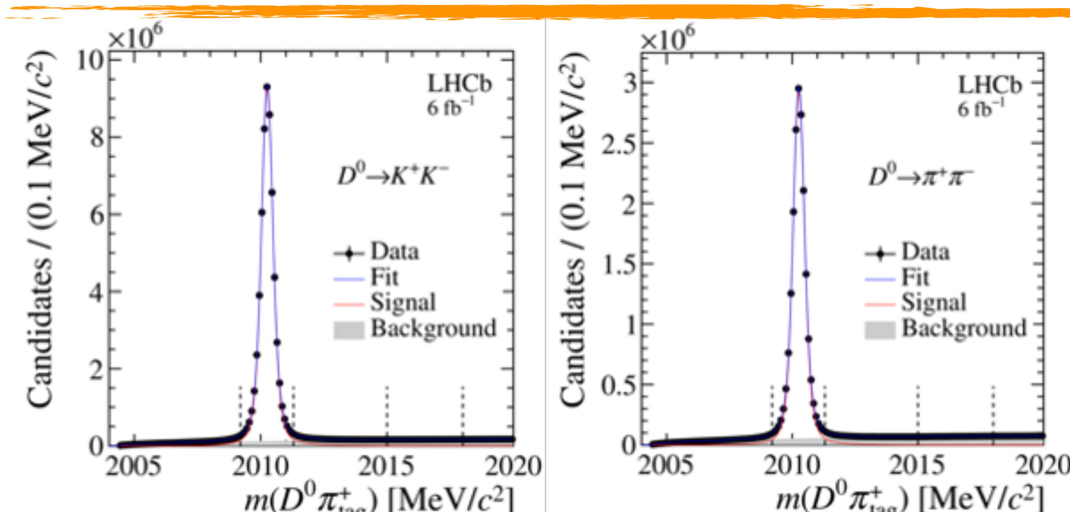
$$\mathcal{A}^{CP}(D^0 \to K^0_S K^0_S) = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\%$$

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

[arXiv:2103.11058]



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



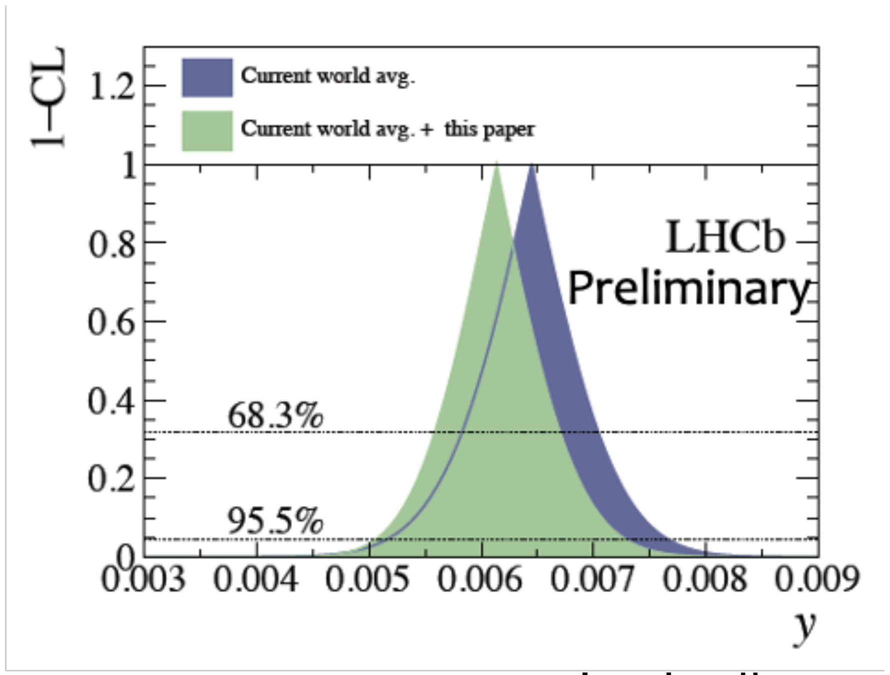
Time-dependent CPV in $D^0 \to h^-h^+$ decays

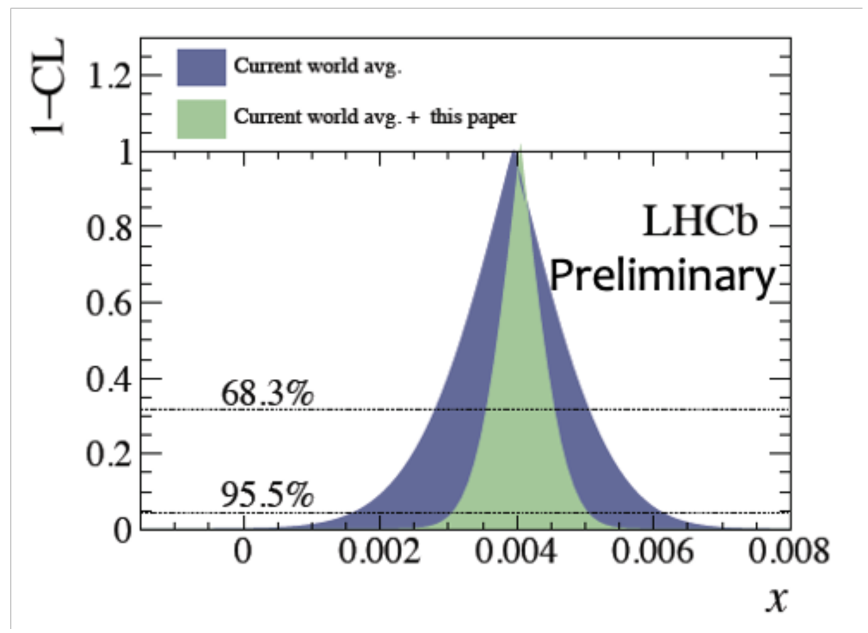
[arXiv:2105.09889]

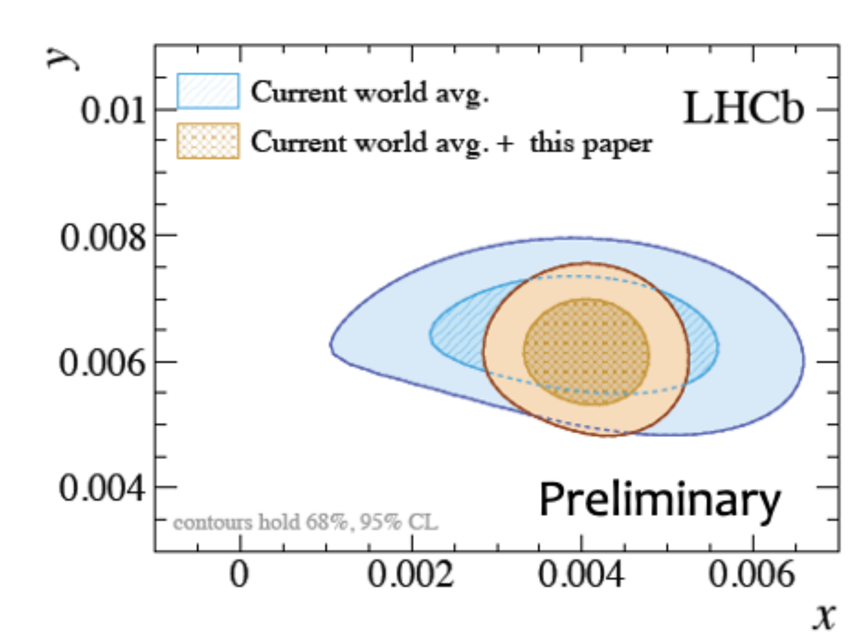
$$\Delta Y = (-2.7 \pm 1.3 \pm 0.3) \times 10^{-4}$$

LHCb impact on world averages

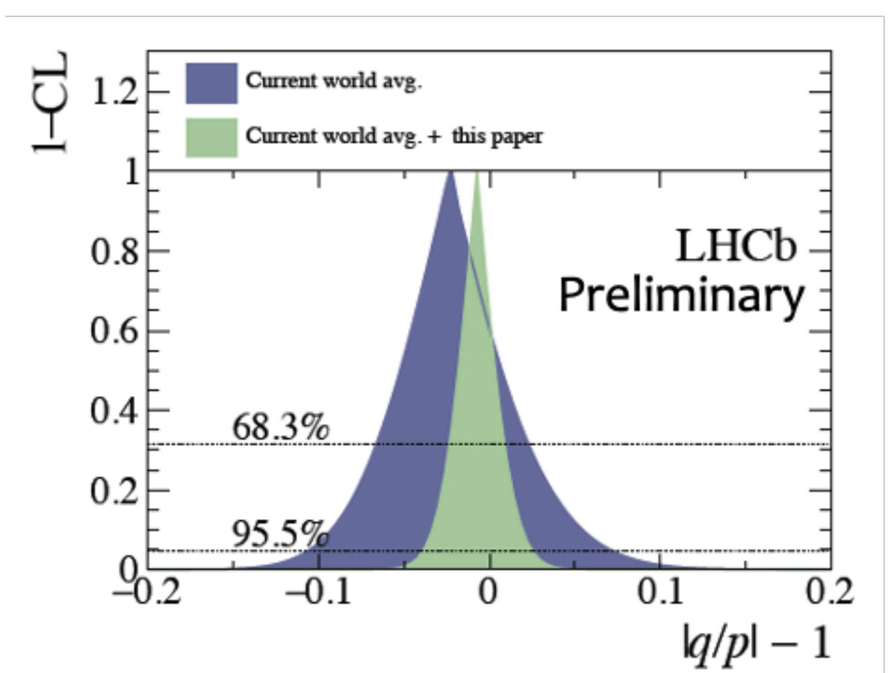
- The combination procedure follows closely HFLAV methods

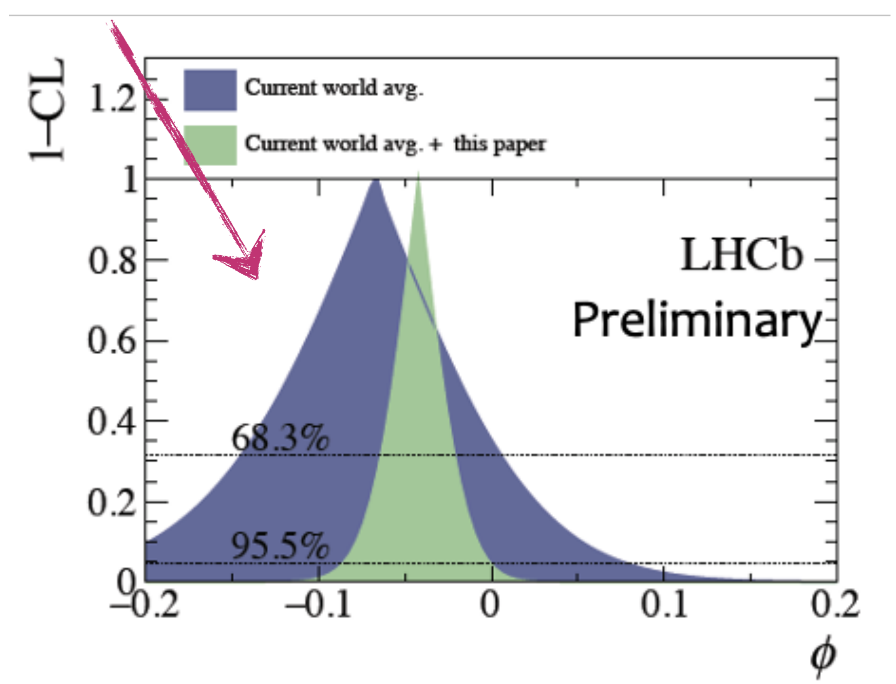


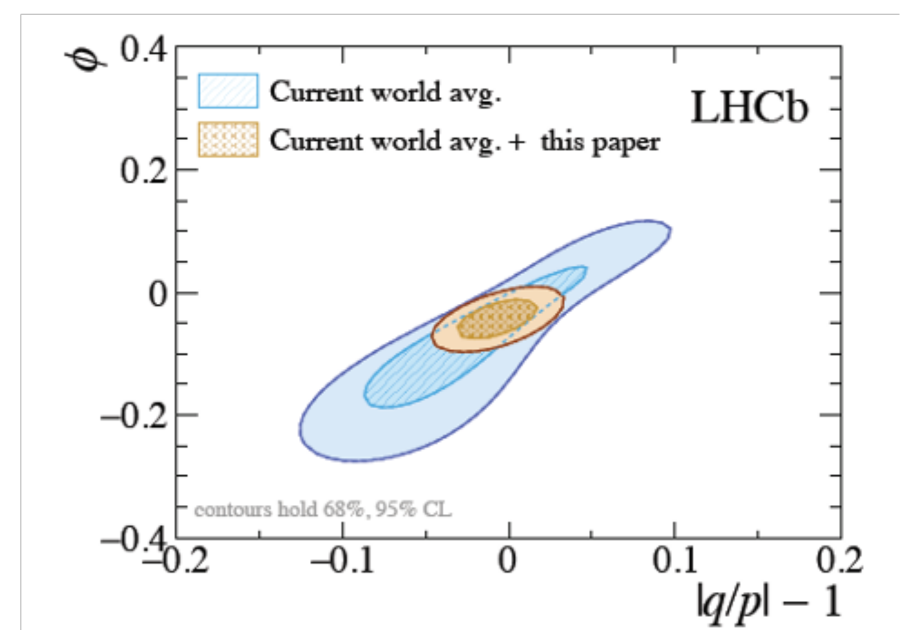




Including ΔY Run 2 measurement







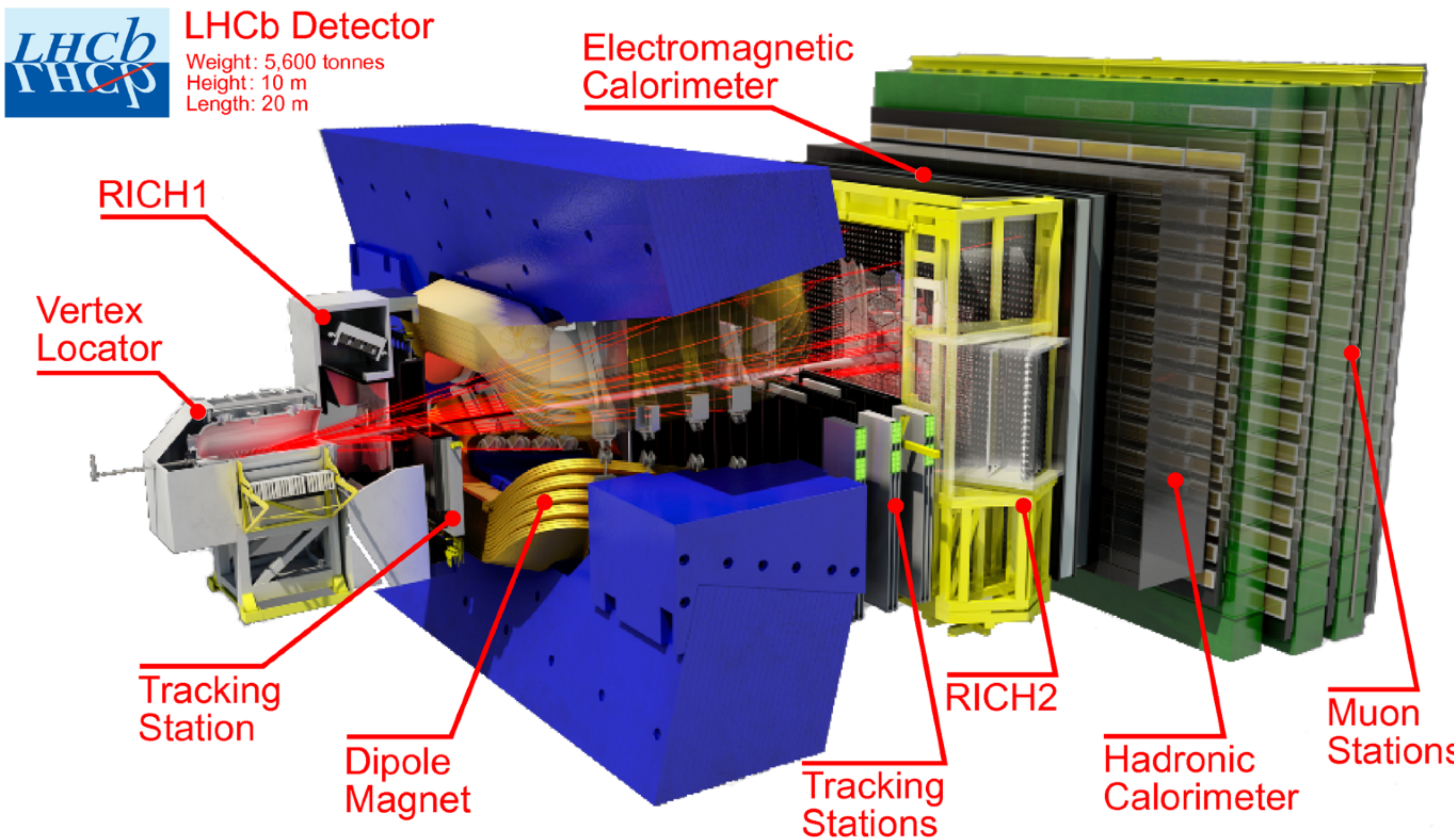
Conclusions

- The LHCb Collaboration observed 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
- LHCb is dominating the world scenario and many other measurements are in progress.
- The upcoming *LHCb-upgrade* will start a new era of *very high precision* measurements in the search for *time-dependent* and *independent* CPV


Thanks!

The LHCb detector at the Large Hadron Collider (CERN)

[J. Instrum. 3, S08005 (2008)]



$$\sigma(\,pp \rightarrow b\bar{b}\,X\,)_{\sqrt{s}\,=\,13\,\mathrm{TeV}} \sim 144\ \mu\mathrm{b}$$

[PRL118,052002 (2017)]

$$\sigma(\,pp \rightarrow c\bar{c}\,X\,)_{\sqrt{s}\,=\,13\,\mathrm{TeV}} \sim 2.4\ \mathrm{mb}$$

[JHEP 03 (2016) 159]

- **LHCb** is a forward spectrometer ($2 < \eta < 5$) designed for ***B*** physics
- **Momentum resolution**: 0.4% at 5 GeV and 0.6% at 100 GeV.
- **VELO** performances: Impact parameter resolution of 13-20 μm at high p_T
  90% correct forward/ backward decay assignment
- **Muon ID** efficiency: 97% with 1-3% $\mu \rightarrow \pi$ mis-identification.

$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

Mixing of neutral *D* mesons

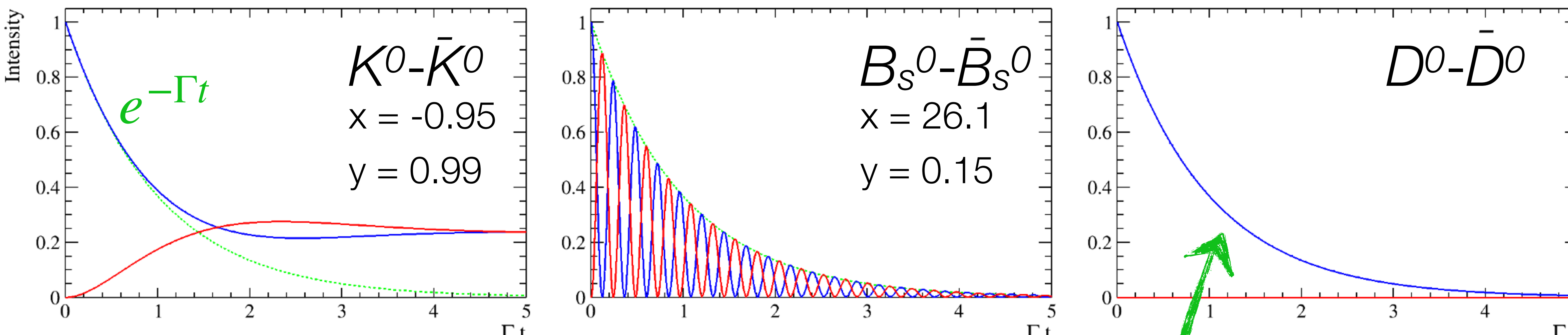
- *Mass* eigenstates are <u>not</u> the *flavor* eigenstates:

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

- This causes $\boldsymbol{D \leftrightarrow \bar{D}}$ transitions described by

$$x = \frac{m_1 - m_2}{\Gamma}$$

$$y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

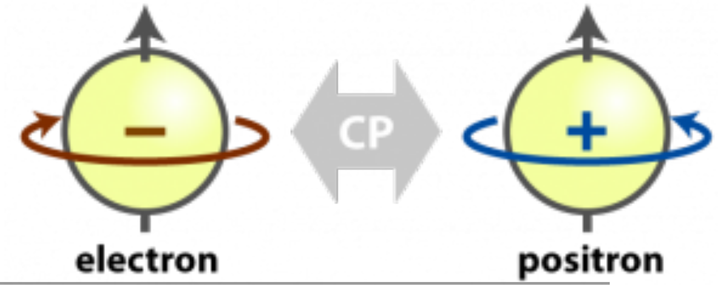


$$|\langle P^0(0)|P^0(t)\rangle|^2 \propto e^{-\Gamma t}[\cosh(y\Gamma t) + \cos(x\Gamma t)]$$

$$|\langle P^0(0)|\bar{P}^0(t)\rangle|^2 \propto e^{-\Gamma t}[\cosh(y\Gamma t) - \cos(x\Gamma t)]$$

Tiny mixing in charm!

CP violation

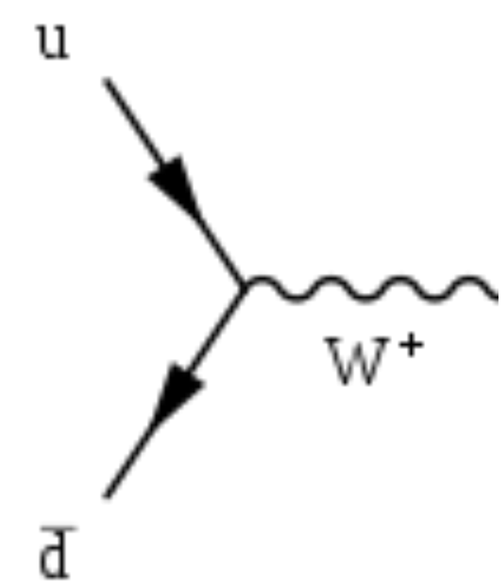


- ***CP*** is the combination of the charge conjugation *C* and parity transformation *P*

- If there is a difference between the ways nature treats ***matter*** and ***antimatter*** then *CP* is violated

- Within the Standard Model (SM), *CP* is naturally violated in weak *charged-current* interactions of *quarks* because of the complex phase in the **CKM matrix**

$$-\mathcal{L}_{W^\pm} = \frac{g}{\sqrt{2}} \begin{pmatrix} \overline{u} & \overline{c} & \overline{t} \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \gamma^\mu W_\mu^+ + h.c.$$

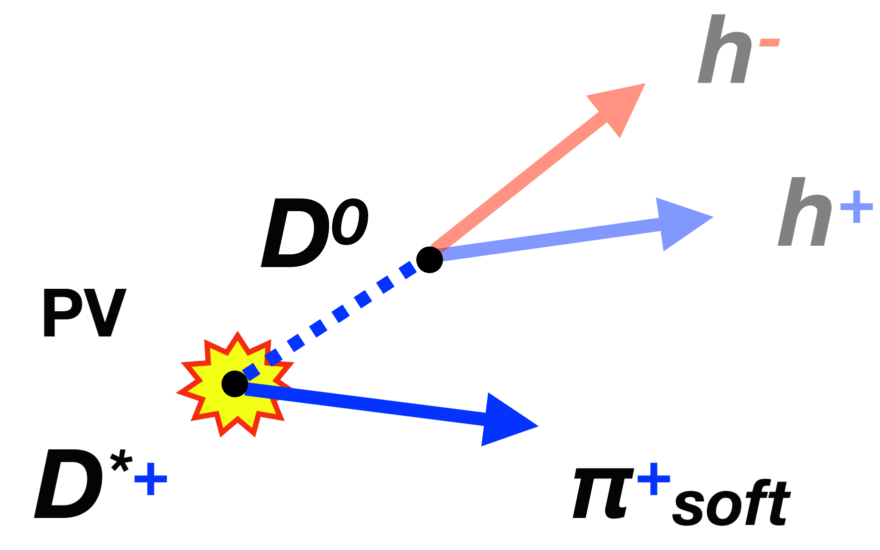


The D^0 or $\bar{D}^0$ tagging

- **Prompt**: coming form primary vertex

$$D^{*\pm} \to \overset{(-)}{D}{}^0 \pi^{\pm}_{soft}$$

  - D^0 points to PV (small IP)
  - Decay time acceptance
  - High yields

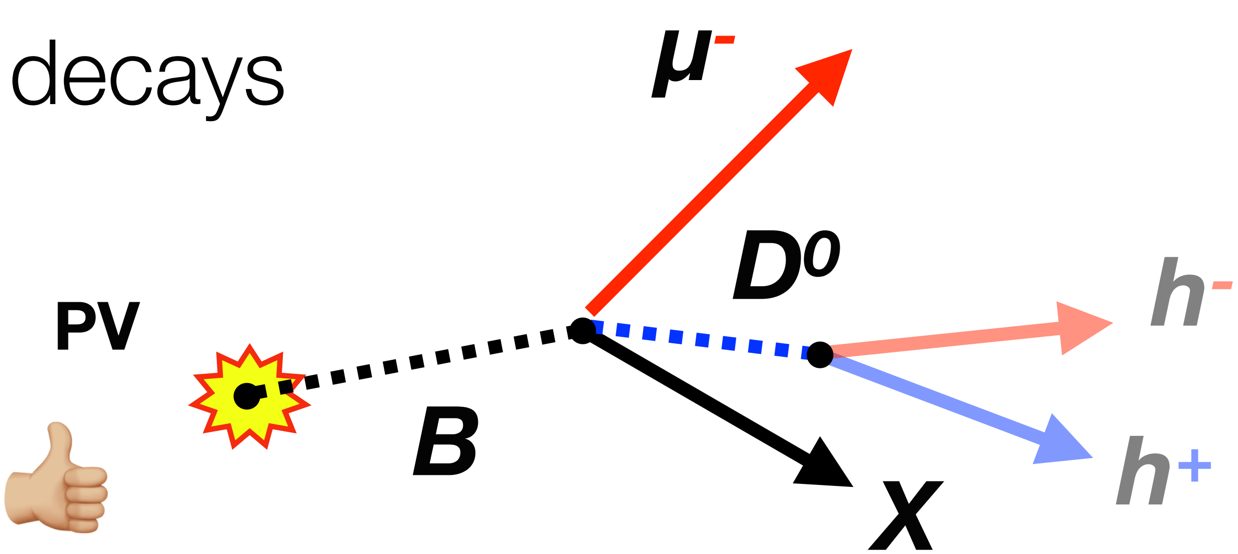


π-tagged

- **Semi-leptonic**: coming from B decays

$$B \to \overset{(-)}{D}{}^0 \mu^{\mp} X$$

  - D^0 does not point to PV
  - Access to all D^0 decay times
  - Lower yields

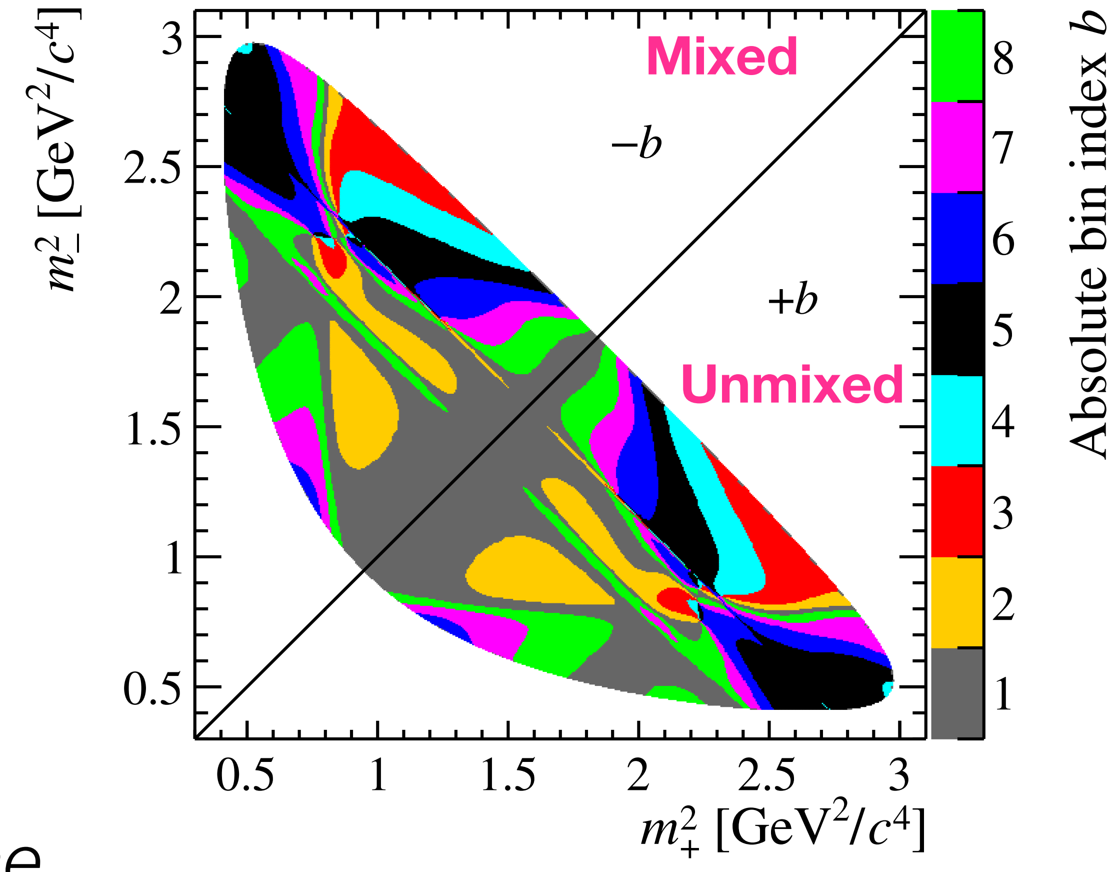


μ-tagged

Analysis strategy

- Production flavour of D^0 and $\bar{D}^0$ identified by the reconstruction of $D^{*+} \to D^0\pi^+_{tag}$ *(apex* → **"±"**)
- 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 > 0)
  $m_+ < m_-$ larger contribution from DCS decays (b < 0)
- Data further divided into 13 bins of *decay-time* (subscript → **"j"**)
- A total of 416 disjoint data samples

Binning from CLEO: [Phys. Rev. D 82, 112006]



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

[arXiv:2106.03744]

The formalism

- For each *decay-time* interval (j), the **ratio** $R_{bj}^{\pm}$ of the number of decays in each *negative* Dalitz-plane bin (–*b*) to its *positive* counterpart (+*b*) is measured

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

- r_b → value of the ratio for $t = 0$
  $\langle t \rangle$ ($\langle t^2 \rangle$) → average (squared) decay-time
  $X_b^{(*)}$ → the amplitude-weighted average *strong-phase* as measured by CLEO and BESIII [Phys. Rev. D 82, 112006, Phys. Rev. D 101, 112002]
  $z_{CP} \pm \Delta z \equiv (q/p)^{\pm 1} z$ with $z = (-y + ix)$

Useful parametrization in terms of mixing parameters:
$x_{CP}, y_{CP}, \Delta x, \Delta y$ → $x, y, \phi, |q/p|$

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

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

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

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

[arXiv:2106.03744]

Systematic uncertainties

- Systematic uncertainties are assessed from ensembles of *pseudo-experiments* generated with different systematic effects. The *impact* on measured parameters is then evaluated.
- Reconstruction and selection effects (decay-time and $m_{\pm}$ corr., det. efficiency) and contamination from secondary decays: mainly affect x_{CP} and y_{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

- Neglecting *time-dependent* detection *asymmetries*: mainly affects Δy
- Mis-modelling in the signal yield fits: mainly affect x_{CP}
- Approximation of constant *strong-phase* in each Dalitz bin: mainly affects y_{CP}
- *Consistency checks*: analysis repeated in subsets of the data selected based on magnet polarity, trigger, K_S category, data-taking period and D^{*+} meson kinematics

Future prospects

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

Sample ($\mathcal{L}$)	Tag	$\sigma(A_\Gamma)$	$\sigma(A_\Gamma)$
Run 1–2 (9 fb^{-1})	Prompt	0.013%	0.024%
Run 1–3 (23 fb^{-1})	Prompt	0.0056%	0.0104 %
Run 1–4 (50 fb^{-1})	Prompt	0.0035%	0.0065 %
Run 1–5 (300 fb^{-1})	Prompt	0.0014%	0.0025 %