CP violation and mixing in charm hadrons at LHCb

Giulia Tuci,
on behalf of the LHCb collaboration
giulia.tuci@cern.ch

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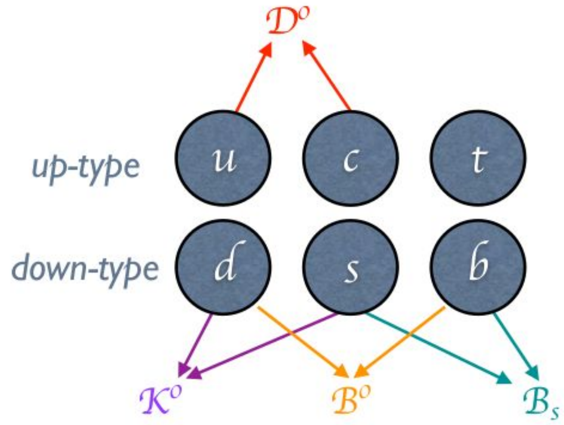
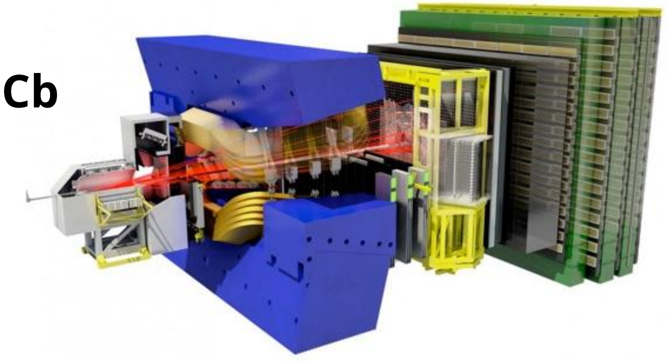
Istituto Nazionale di Fisica Nucleare

CPV in charm

- Charm transitions are a unique portal for obtaining a novel access to flavor dynamics
  - there might exist some New Physics coupling only to up-type quarks
  - expected CPV in charm $\lesssim 10^{-3} \rightarrow$ difficult to observe it experimentally

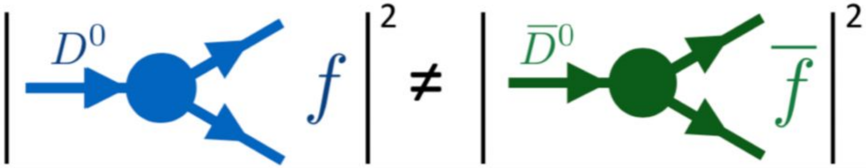


- **Finally CPV in charm has been observed!**
- Now it's the moment to start a systematic exploration of all the charm hadrons decay channels to do a quantitative study of CPV
- Large samples of charm hadrons decays needed → **LHCb**
  - ~ 1 billion D^0 decays to be analysed at LHCb
  - $\sigma(pp \rightarrow c\bar{c}X)$= (2940 ± 3 ± 180 ± 160)μb @ 13TeV for $p_T < 8$ GeV/c and $2 < \eta < 4.5$ JHEP03(2016)159



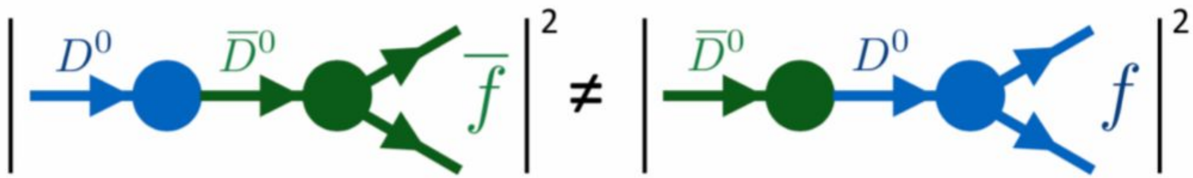
CPV in charm

5.3 σ observation by LHCb



CPV in decay

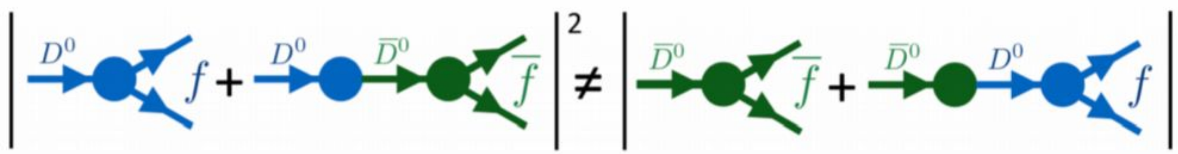
$|A_f| \neq |\bar{A}_{\bar{f}}|$



CPV in mixing

$|q/p| \neq 1$

Still no evidence of mixing-induced CPV



CPV in interference between decay and mixing

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

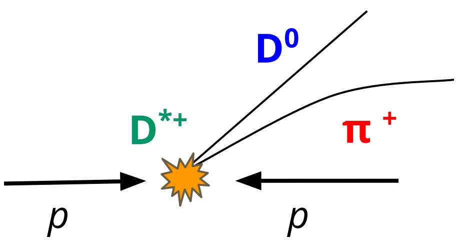
First observation of CP violation in charm

PRL122. 211803

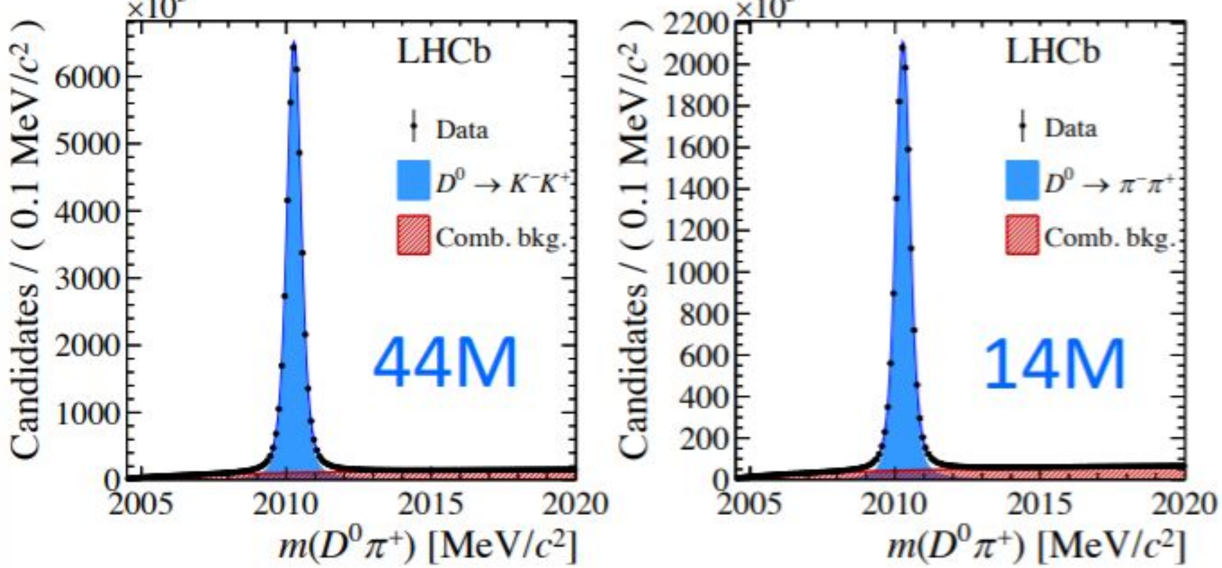
- Used $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays collected in Run2 ($6fb^{-1}$)

Prompt decays:

$D^{*+} \to D^0 \pi^+$

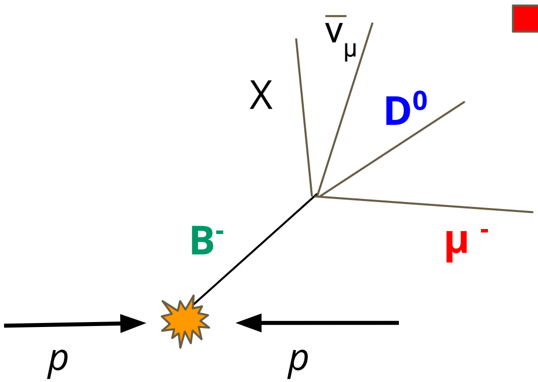


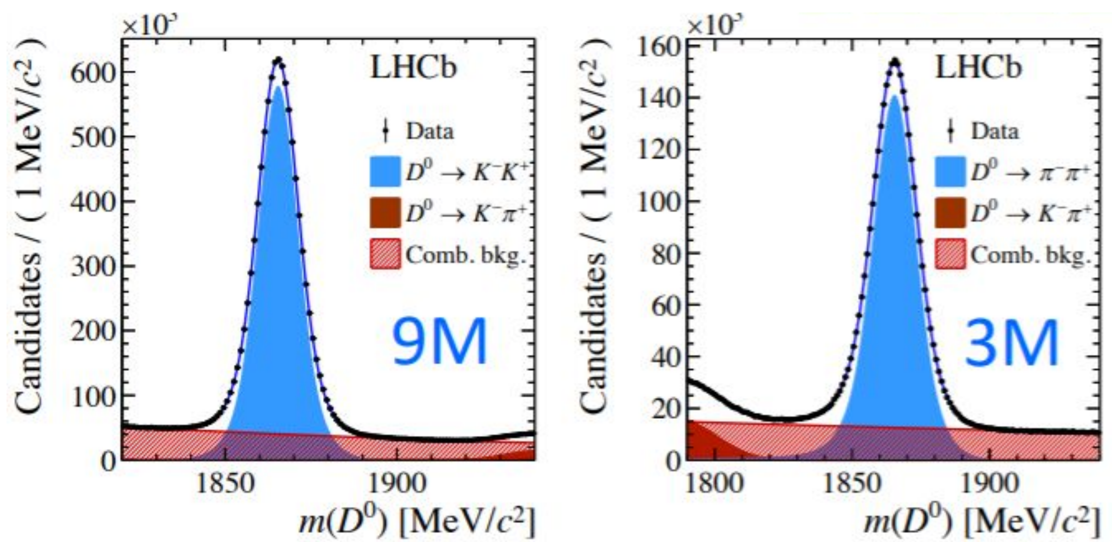
$D^0 \to K^+K^-$ $D^0 \to \pi^+\pi^-$



Semileptonic decays:

$B^- \to D^0\mu^- X$





ΔA^{CP} : measurement strategy

PRL122. 211803

$$\mathcal{A}^{CP}(f) = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}$$

- Quantity measured in LHCb

$$\mathcal{A}^{raw} \equiv \frac{N_{D^0} - N_{\bar{D}^0}}{N_{D^0} + N_{\bar{D}^0}}$$

Production asymmetry: initial state pp is not CP symmetric

$$\mathcal{A}^{raw} \approx \mathcal{A}^{CP} + \mathcal{A}^{prod} + \mathcal{A}^{det}$$

Asymmetric detector acceptance + material interaction different for particles/antiparticles

- If the kinematics of the two decays are equal

$$A_{raw}(KK) - A_{raw}(\pi\pi) = (A_{CP}(KK) + A_D(\text{tag}) + A_P) - (A_{CP}(\pi\pi) + A_D(\text{tag}) + A_P)$$

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

- Reweighting procedure applied to match kinematics of $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$

ΔA^{CP}: results

PRL122. 211803

- Run2 results:

$$\Delta A^{CP}(\text{prompt}) = (-18.2 \pm 3.2\ (\text{stat.}) \pm 0.9\ (\text{syst.})\ ) \times 10^{-4}$$

$$\Delta A^{CP}(\text{semileptonic}) = (-9 \pm 8\ (\text{stat.}) \pm 5\ (\text{syst.})\ ) \times 10^{-4}$$

- Run1 results: JHEP 07 (2014) 041 PRL 116 (2016) 191601

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

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

- Combining the two modes + Run1 measurement:

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

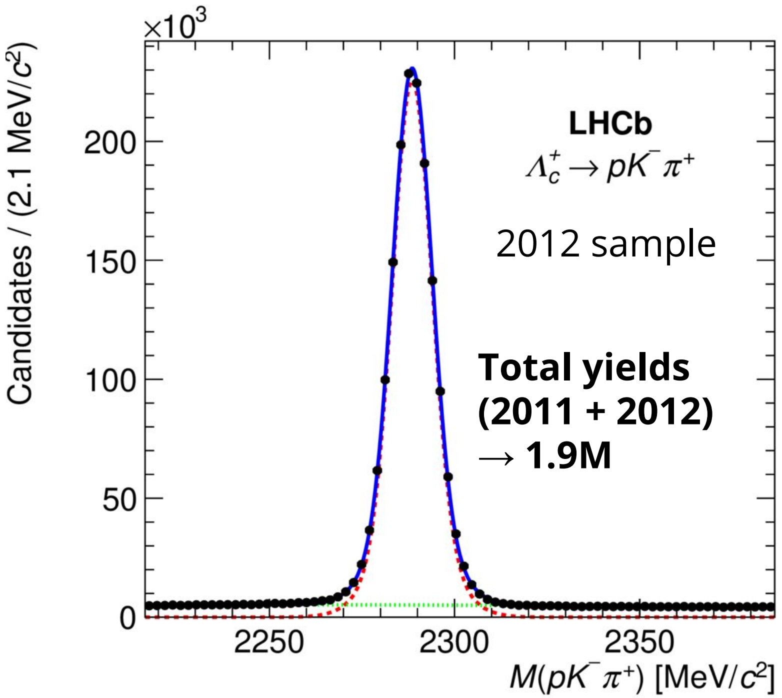
- **First observation of charm CPV at 5.3 σ!**

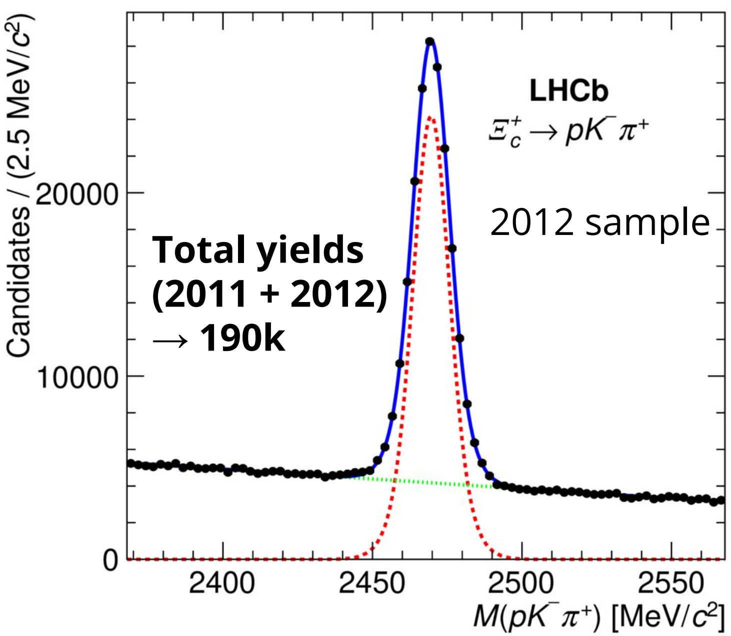
CPV in $\Xi_c^+ \rightarrow pK^-\pi^+$

LHCb-PAPER-2019-026

NEW

- Goal: perform searches for CPV in $\Xi^+_c \rightarrow pK^-\pi^+$ single-Cabibbo suppressed charm baryon (prompt) decays using Run 1 data (~3fb^{-1})
- 3-body hadronic decays: make use of the Dalitz plot to look for localized asymmetries
- $\Lambda_c^+ \rightarrow p K^-\pi^+$ Cabibbo favoured used as a control channel





CPV in $\Xi_c^+ \rightarrow pK^-\pi^+$: methodology

LHCb-PAPER-2019-026

NEW

- Search based on two techniques independent from the amplitude modeling in the Dalitz plot

Binned S_{CP} method

Search for localized asymmetries by a bin-by-bin comparison between baryons (n^+) and antibaryons (n^-)

$$S_{CP}^i = \frac{n_+^i - \alpha n_-^i}{\sqrt{\alpha(n_+^i + n_-^i)}}$$

$\alpha = n^+/n^-$ → takes into account global asymmetries

A $\chi^2/\text{ndf} \equiv \Sigma_i (S^i_{CP})^2 / (\text{nbins}-1)$ is calculated and a p-value for the null hypothesis is obtained → test if Ξ^+_c and Ξ^-_c distributions are statistically compatible

Unbinned kNN method

A test statistic for the null hypothesis is defined looking at the nearest neighbours (n_k) in a pooled sample of two data sets

$$T = \frac{1}{n_k(n_+ + n_-)} \sum_{i=1}^{n_+ + n_-} \sum_{k=1}^{n_k} I(i,k)$$

$I(i,k) = 1$ if the i^{th} event and its k^{th} nearest neighbour have the same charge, otherwise $I(i,k)=0$

If no CPV, T distributed as a Gaussian with well known mean and variance (μ_T, σ_T)

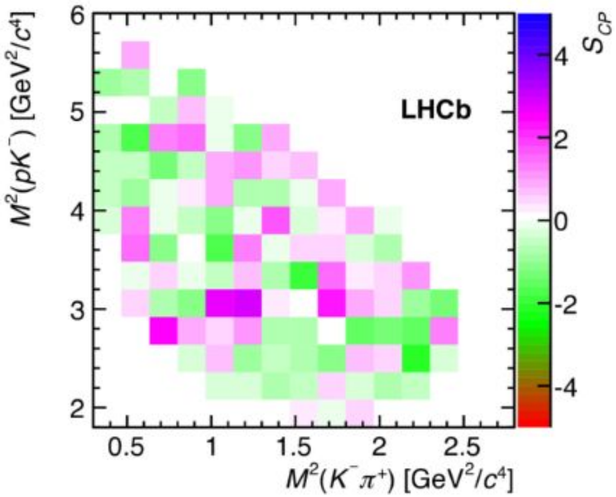
CPV in $\Xi_c^+ \to pK^-\pi^+$: results

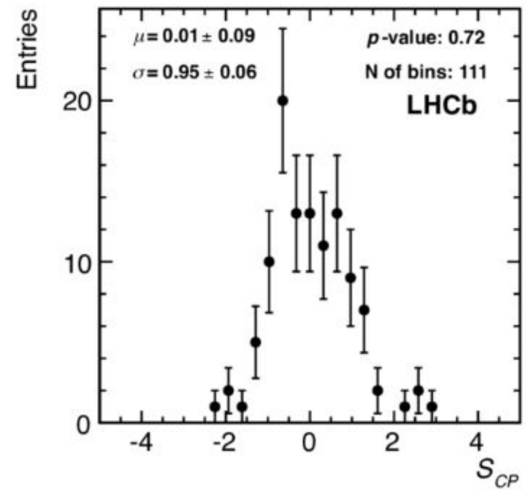
LHCb-PAPER-2019-026

NEW

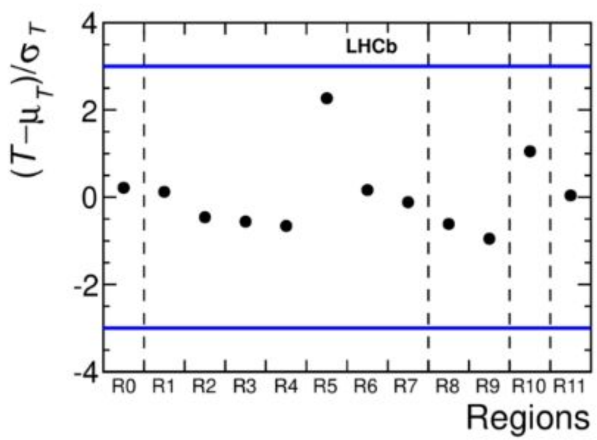
- No evidence of CPV found

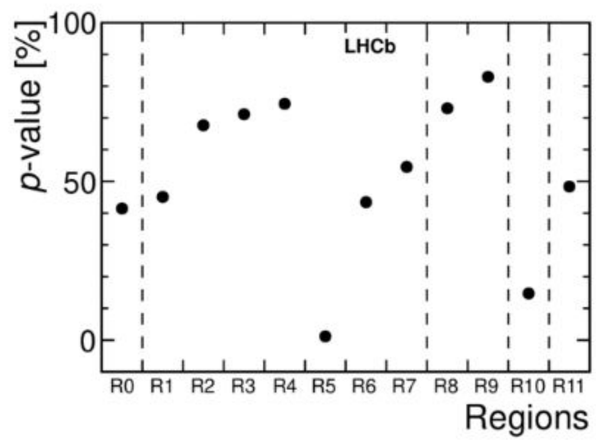
S_{CP} results





kNN results





Mixing and mixing-induced CPV

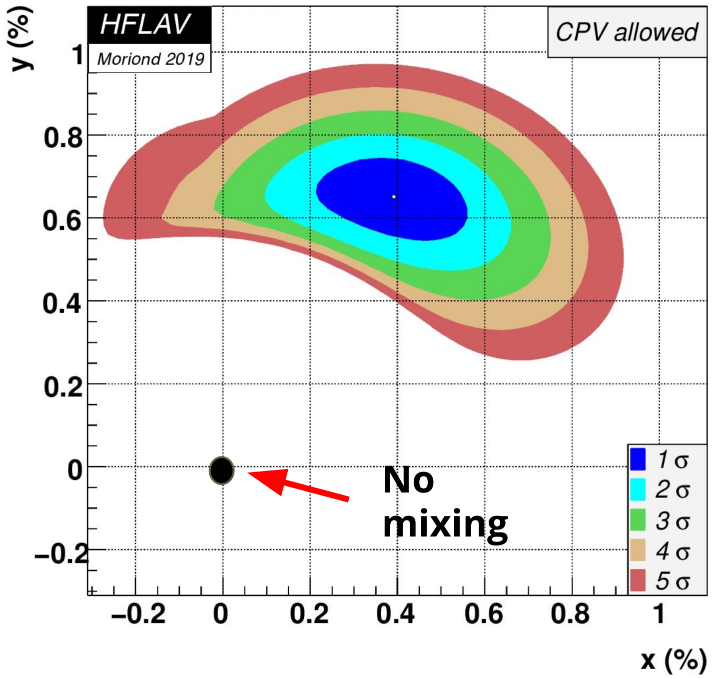
- Mass eigenstates linear combination of flavor eigenstates

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

$$x \equiv \Delta m/\Gamma$$
$$y \equiv \Delta\Gamma/2\Gamma$$

Experimental status

Mixing well established

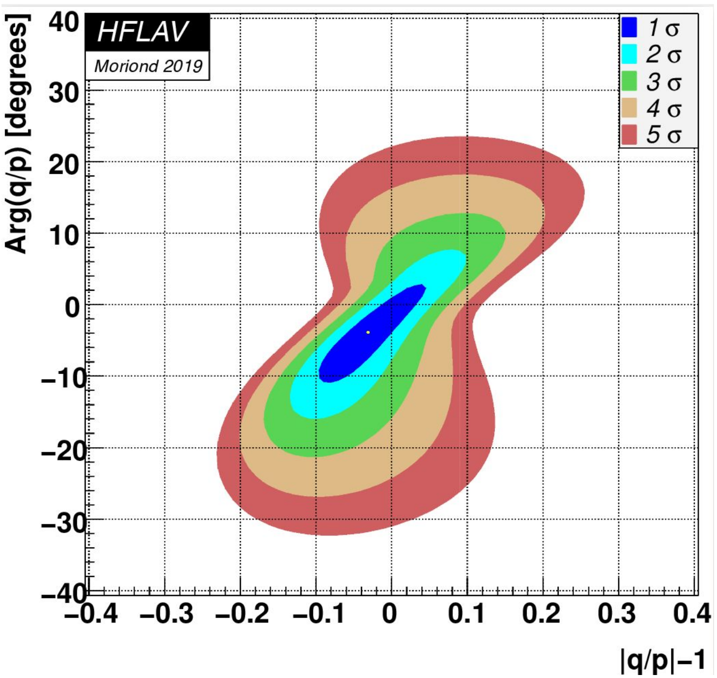


Reminder:

Mixing-induced CPV
→ |q/p|≠1
and

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

No evidence for CP violation in mixing or interference



Mixing parameters using $D^0 \to K_S^0 \pi^+ \pi^-$ decays

PRL122.231802

- $D^0 \to K_S^0 \pi^+ \pi^-$ decays to measure charm mixing parameters

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

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

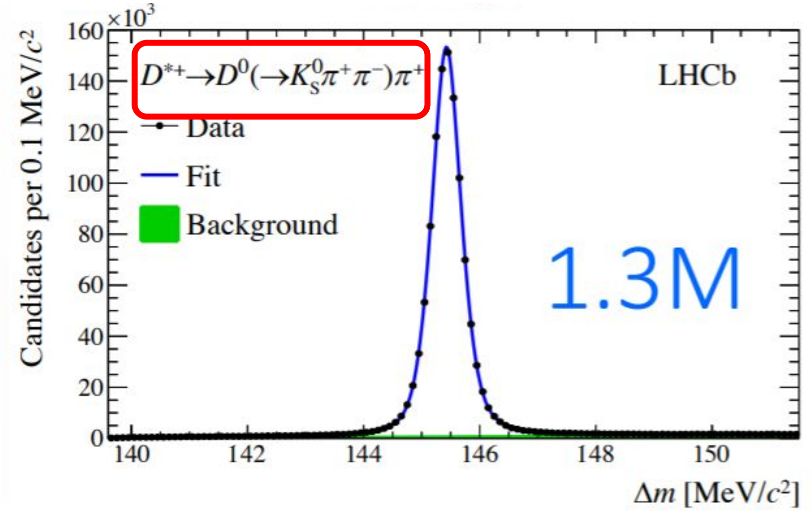
$$y_{CP} = \frac{1}{2}\left[y\cos\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) - x\sin\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\right]$$

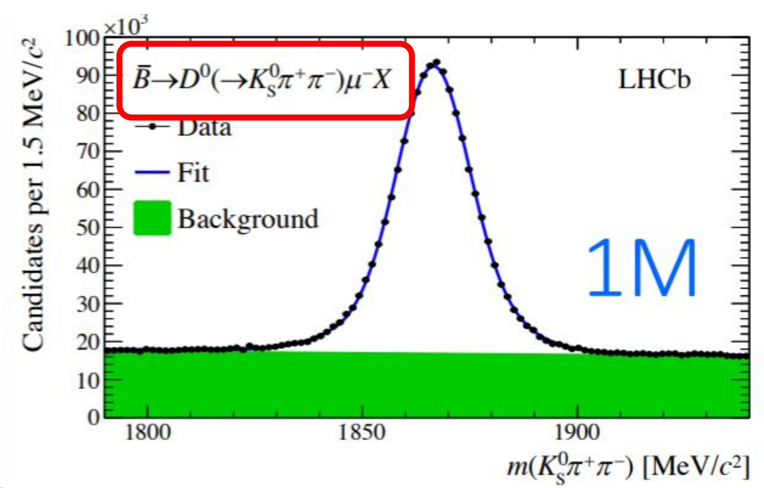
$$\Delta y = \frac{1}{2}\left[y\cos\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) - x\sin\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\right]$$

if no CPV →

$\phi = \arg\left(\frac{q\bar{A}_f}{pA_f}\right) = 0$ and $\left|\frac{q}{p}\right| = 1$

$$x_{CP} = x \qquad \Delta x = 0 \qquad y_{CP} = y \qquad \Delta y = 0$$



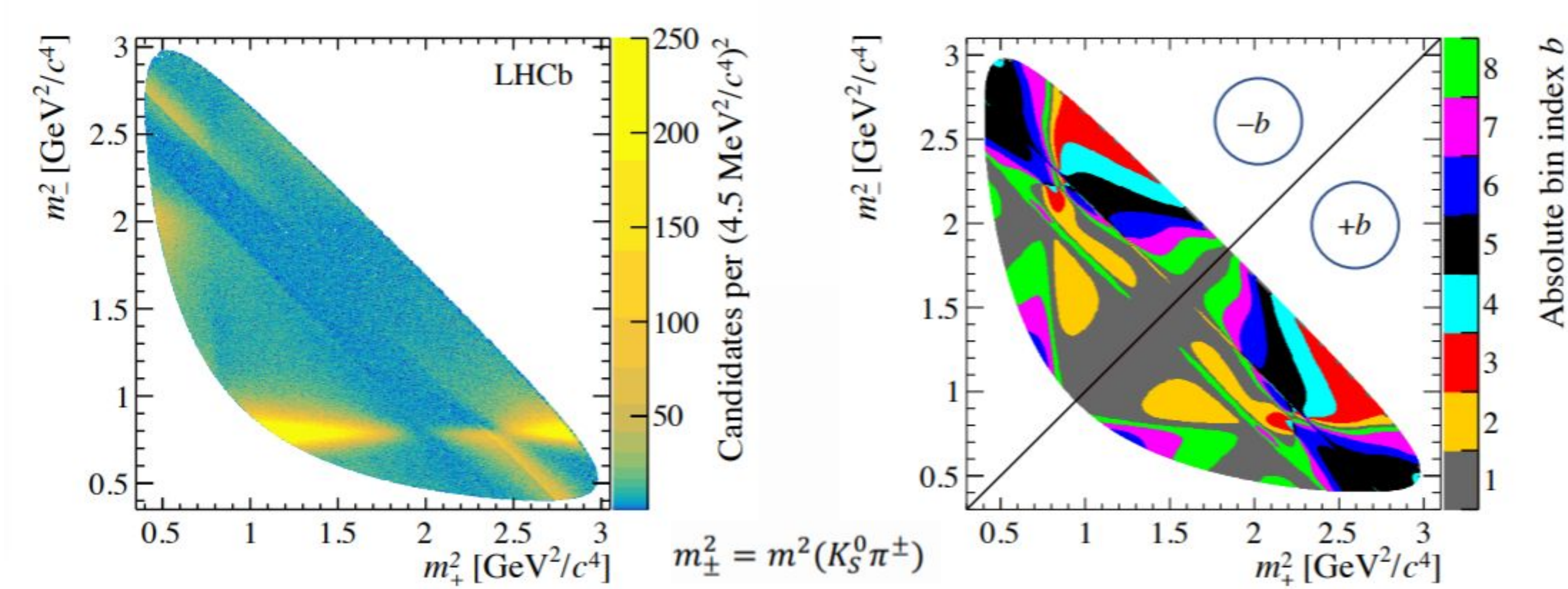


- Two production modes:
  - $D^{*+} \to D^0\pi^+$ (2012 sample, 2 fb^{-1})
  - $\overline{B} \to D^0 X \mu^-$ (2011+2012 samples, 3 fb^{-1})

$D^0 \to K_S^0\pi^+\pi^-$: bin-flip method

PRL122.231802

- Bin-flip method → model-independent approach which avoids the need for a fit of the decay amplitudes PRD99.012007
  - Data is binned in Dalitz coordinates where the binning scheme is chosen to have approximately constant strong-phase differences
- A simultaneous fit of the yield ratio between +b and -b in bins of decay time gives access to the CP parameters



$D^0 \longrightarrow K_S^0\pi^+\pi^-$: results

PRL122.231802

- The measured values are:

$$x_{CP} = (2.7 \pm 1.6 \pm 0.4) \times 10^{-3} \qquad \Delta x = (-0.53 \pm 0.70 \pm 0.22) \times 10^{-3}$$

$$y_{CP} = (7.4 \pm 3.6 \pm 1.1) \times 10^{-3} \qquad \Delta y = (0.6 \pm 1.6 \pm 0.3) \times 10^{-3}$$

- We can therefore derive the mixing parameters:

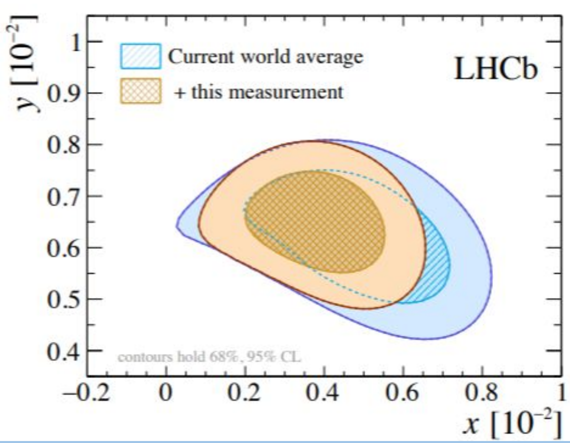
$$x = 0.27^{+0.17}_{-0.15} \times 10^{-2} \qquad |q/p| = 1.05^{+0.22}_{-0.17}$$

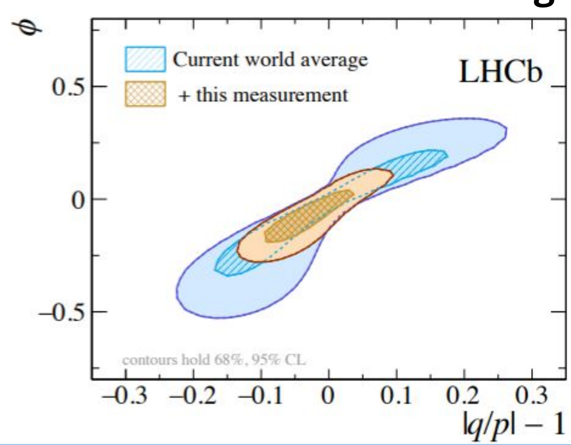
$$y = (0.74 \pm 0.37) \times 10^{-2} \qquad \phi = -0.09^{+0.11}_{-0.16}$$

- Combining with the world average value

$$x = 3.9^{+1.1}_{-1.2} \times 10^{-3}$$

Evidence of a positive mass difference between the neutral charm meson eigenstates





Conclusion

- **Direct CPV observed for the first time by LHCb**
- Now exploring different decay channels to better clarify the physics picture
- **New results on Run2 data are coming!**
- New data will arrive in 2021/2022 with an almost completely new detector and trigger system
  - Instantaneous luminosity will increase by a factor of 5 (2×10^{33} $cm^{-2}s^{-1}$)
  - Removal of the hardware trigger → bigger trigger efficiency for some channels
- Current results limited by statistics
  - **We expect significant gains in precision, and sensitivity to CPV effects, in LHCb Run 3**
  - **Stay tuned!**

Backup slides

The LHCb experiment