CP Violation and Mixing in Charm at LHCb

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On behalf of the
LHCb Collaboration

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Flavor Mixing in the Charm Sector

- Mass eigenstates ≠ flavor eigenstates
  $|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$

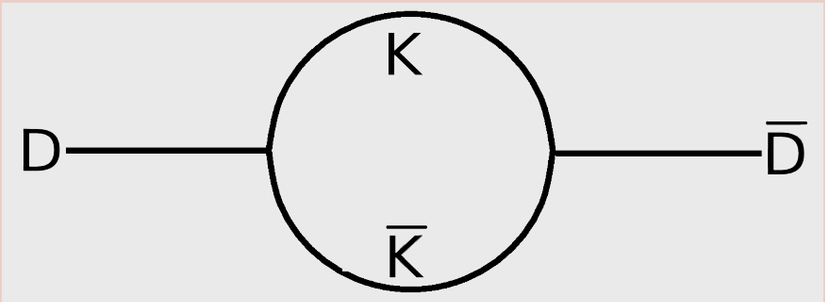
- Definitions: $m_{1,2}$ and $\Gamma_{1,2}$ are mass and width of $|D_{1,2}\rangle$ and $\Gamma_D=(\Gamma_1+\Gamma_2)/2$

- **Mixing parameters**

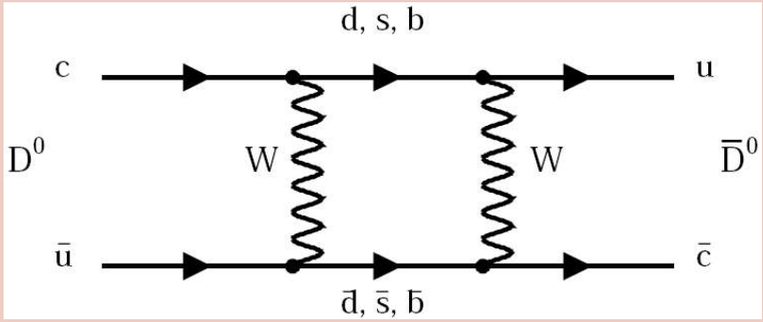
$$x = \frac{m_1 - m_2}{\Gamma_D}, \quad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma_D}$$

- Assuming CPT conservation, $|p|^2+|q|^2=1$
- Convention choice: D_1 is CP-even state, CP $|D^0\rangle = + |\overline{D}^0\rangle$

- Long-distance contributions, dominant but affected by large theory uncertainties



- short-distance contributions, GIM and CKM suppressed in SM



CP Violation in the Charm Sector

CPV in the decay $|A_f| \neq |\overline{A}_{\overline{f}}|$

- need at least amplitudes with different strong and weak phases. Some observables:

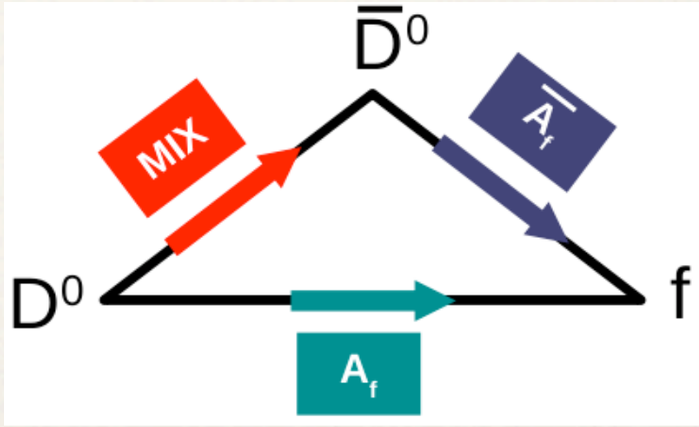
$$A_{CP}(f) = \frac{|A_f|^2 - |\overline{A}_{\overline{f}}|^2}{|A_f|^2 + |\overline{A}_{\overline{f}}|^2} \qquad A_D^f = \frac{|A_f/\overline{A}_f|^2 - |\overline{A}_{\overline{f}}/A_{\overline{f}}|^2}{|A_f/\overline{A}_f|^2 + |\overline{A}_{\overline{f}}/A_{\overline{f}}|^2}$$

CPV in mixing $R_M = \left|\frac{q}{p}\right| \neq 1$ or $A_M = \frac{R_M^2 - R_M^{-2}}{R_M^2 + R_M^{-2}}$

CPV in the interference $\phi_f \neq 0$

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f} = \left|\frac{q}{p}\frac{\overline{A}_f}{A_f}\right| \exp[i(\delta_f + \phi_f)]$$

strong +weak phase

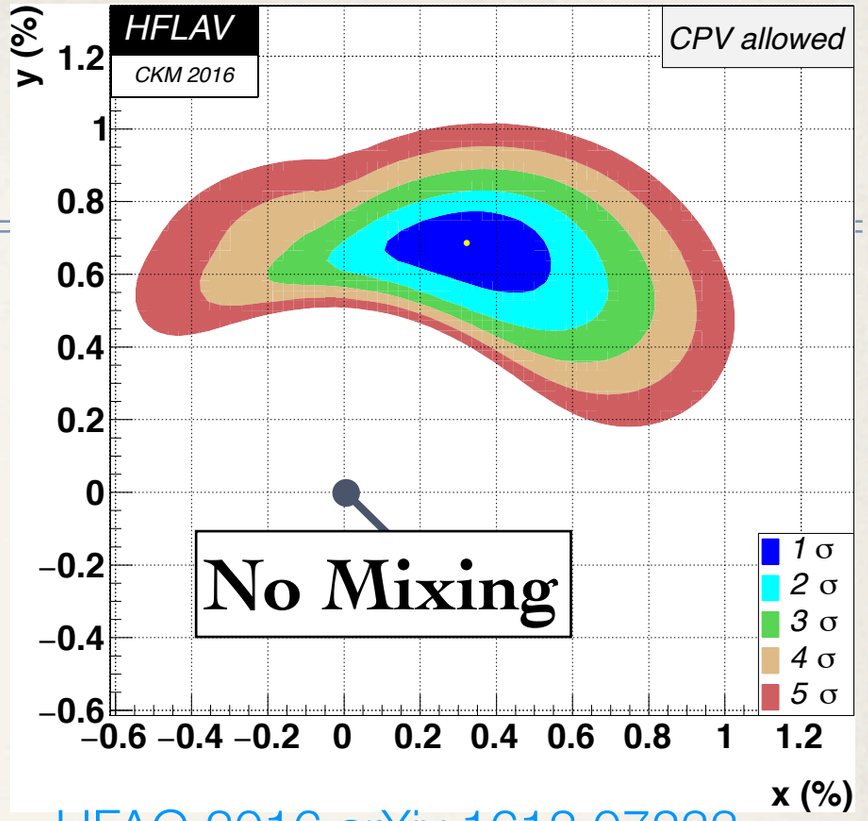


Experimental Status

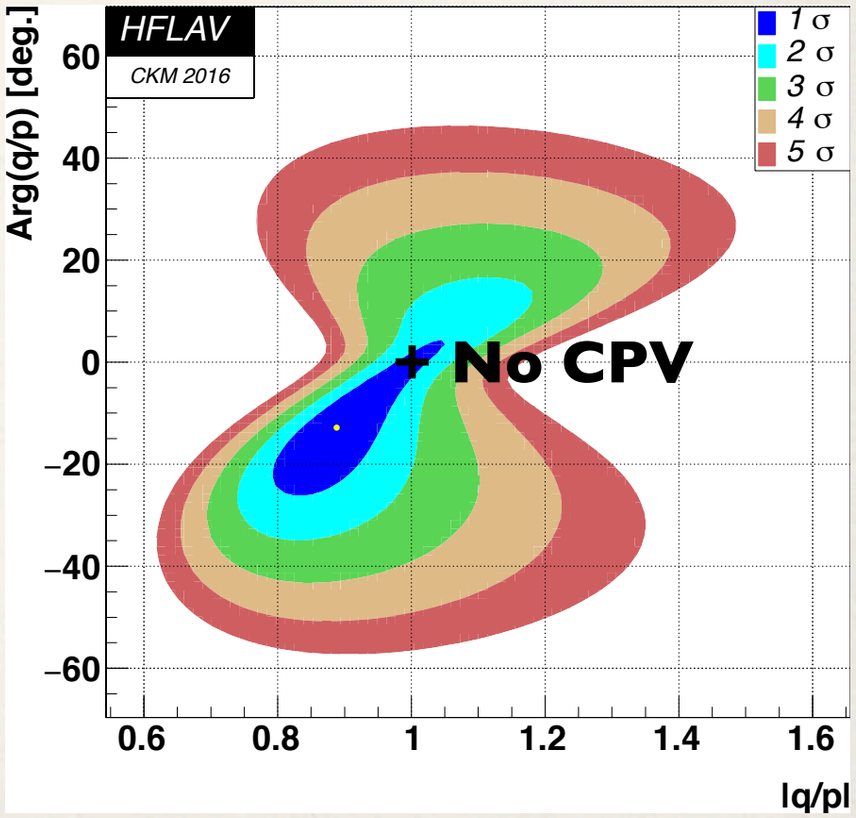
- **D^0 mixing experimentally well established**: very slow rate **x,y < 1%**; SM predictions affected by large uncertainties ~ $O(10^{-2}\text{-}10^{-7})$

- **CPV not yet observed in the charm sector**. SM expectations are of the order of 10^{-3} or less

- Experimental goals:
  - Improve precision (also for single asymmetries)
  - Measure single asymmetries in more decay channels



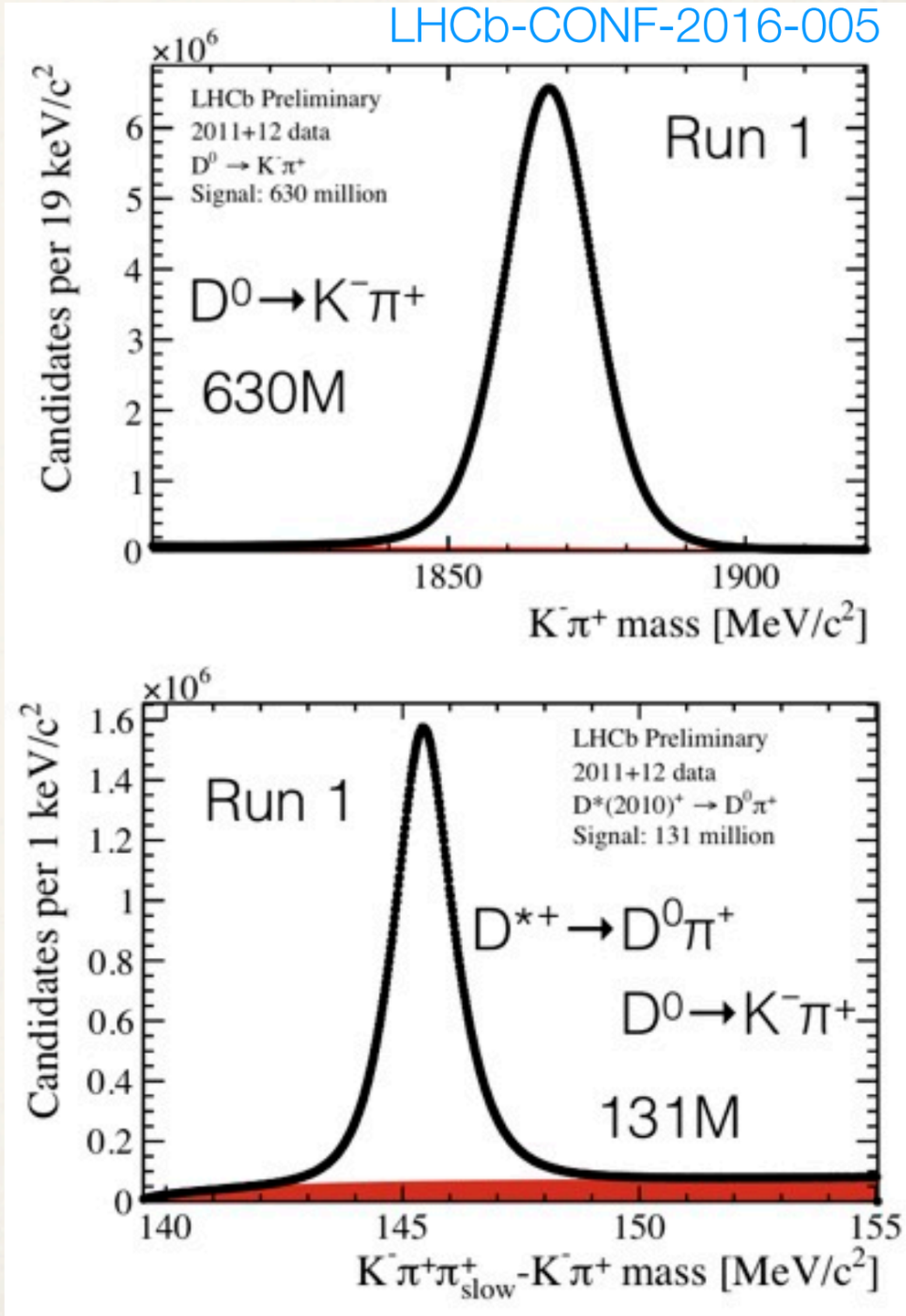
HFAG 2016 arXiv:1612.07233



Charm Physics at LHCb

- All c species produced in pp collisions with very large cross-section: ($pp \rightarrow c\bar{c}$)~11 mb at 13 TeV
- Produced **~5×10^{12} D^0 and ~2×10^{12} D^{*+} mesons in Run1 data** (3 fb^{-1}) at L = 4×10^{32} $cm^{-2}s^{-1}$, about factor of 30 larger than samples collected by past experiments
- **Run2 "effective" charm statistics** is already like Run1, due to increased cross-section and improved trigger

LHCb-CONF-2016-005



CPV in $D^0 \to h^+h^-$ (1)

Run I ($3fb^{-1}$)

[PRL 118 (2017) 261803]

- Due to 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:

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

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

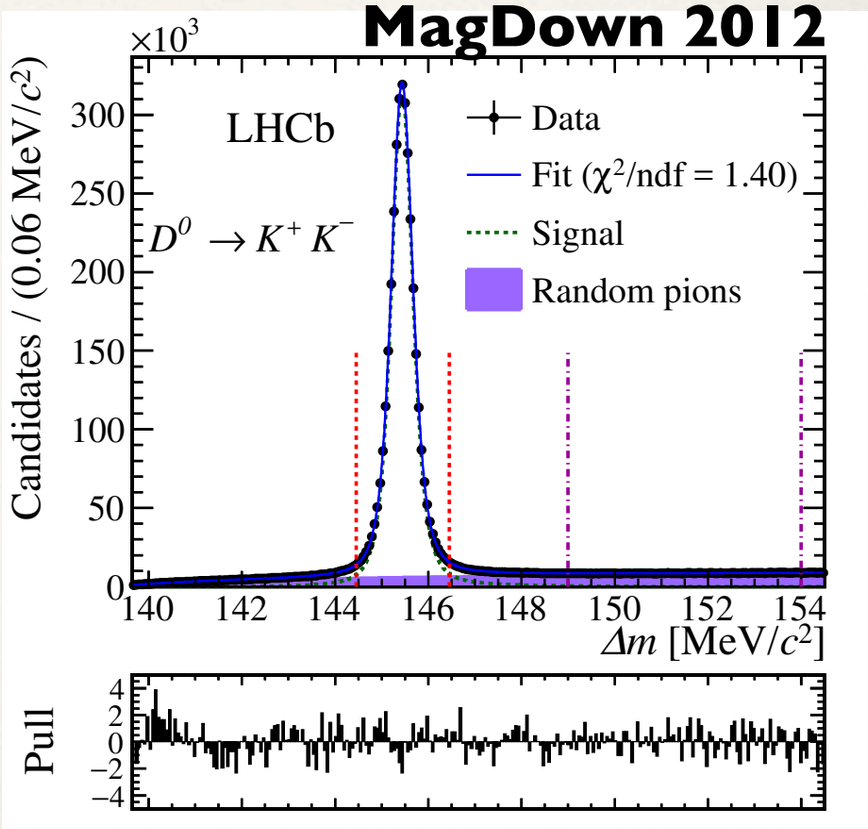
CPV in the mixing $|q/p| \neq 1$ — CPV in the interference $\varphi_f \neq 0,\pi$

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

defined as the asymmetry between effective lifetimes

- Neglecting subleading amplitudes, $A_{CP}^{\rm dir}$ vanishes and A_Γ is independent of the final state. If no CPV in mixing, $A_\Gamma = -x \sin(\phi) \to |A_\Gamma| < |x| < 5\times10^{-3}$
- **Goal is measure the time-dependent asymmetry**
- D^0 flavor inferred with strong $D^{*+} \to D^0\pi^+$ decay

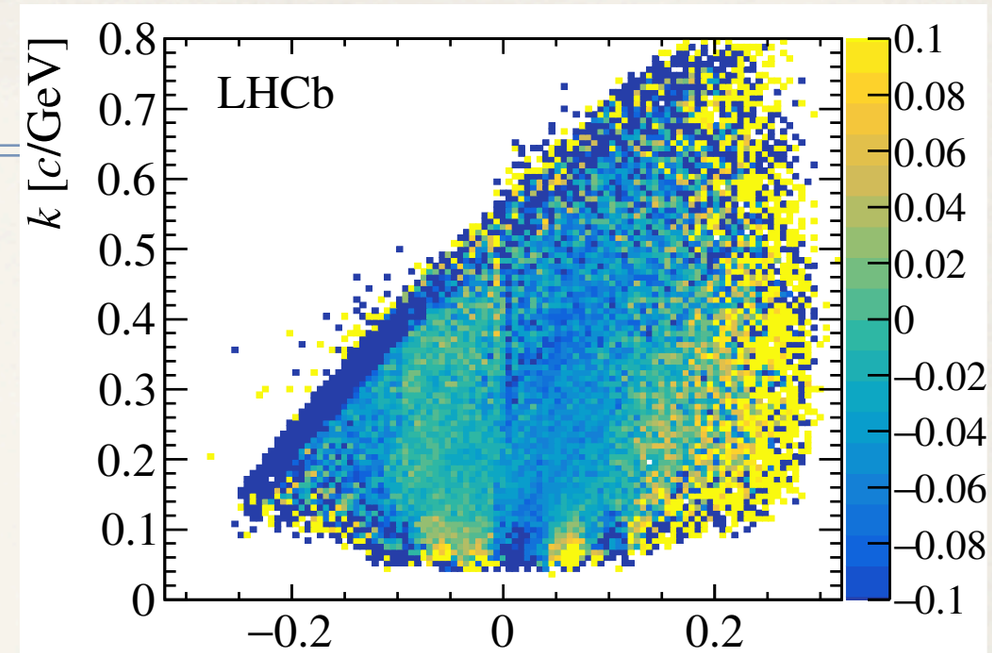
Subsample [10^6]	$D^0 \to K^-\pi^+$	$D^0 \to K^+K^-$	$D^0 \to \pi^+\pi^-$
2011 *MagUp*	10.7	1.2	0.4
2011 *MagDown*	15.5	1.7	0.5
2012 *MagUp*	30.0	3.3	1.0
2012 *MagDown*	31.3	3.4	1.1
Total	87.5	9.6	3.0



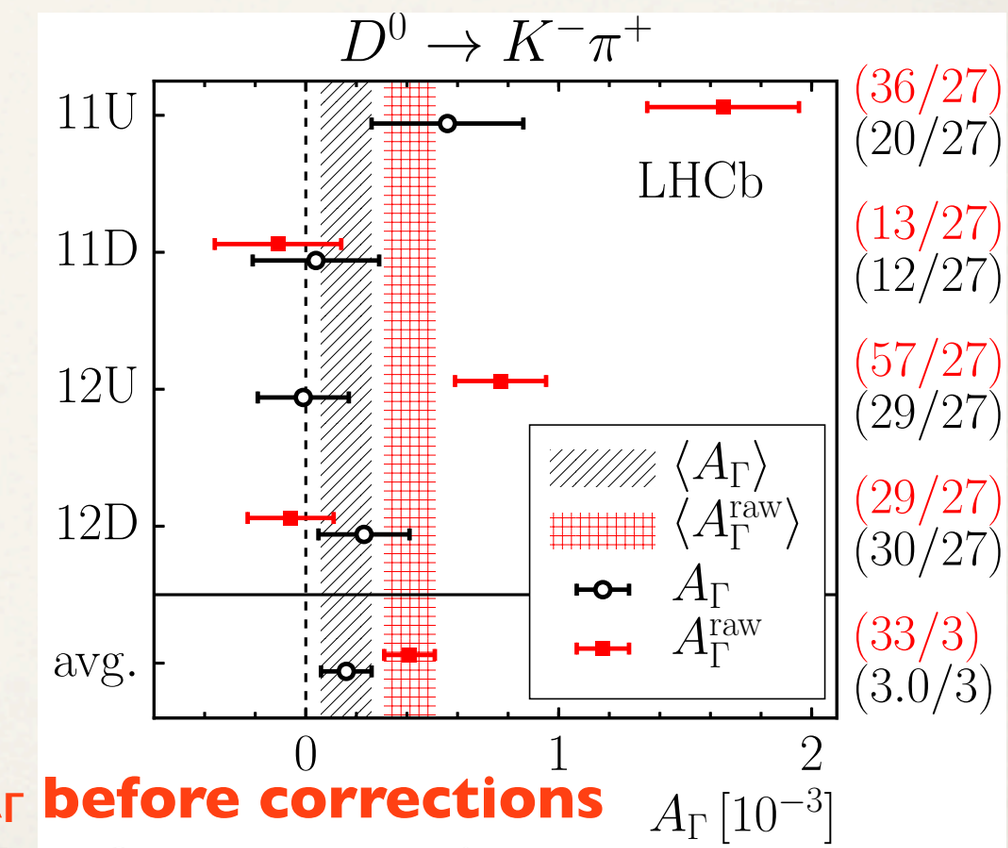
CPV in $D^0 \to h^+h^-$ (2)

[PRL 118 (2017) 261803]

- **D^0->Kπ mode used as high-statistics control sample** where expected CPV is below current sensitivity
- **D^0 reconstruction asymmetries** are corrected using D^0-$\overline{D}^0$ yield asymmetries in equally-populated bins of decay time
- Additional **soft-pion detection asymmetries** are corrected re-weighting the candidates using a 3D distribution (curvature in the bending plane, θ_x, θ_y)
- Main systematic: contribution from secondaries (D^0 from B decays)



Soft pions asymmetry



A_Γ before corrections

A_Γ after corrections

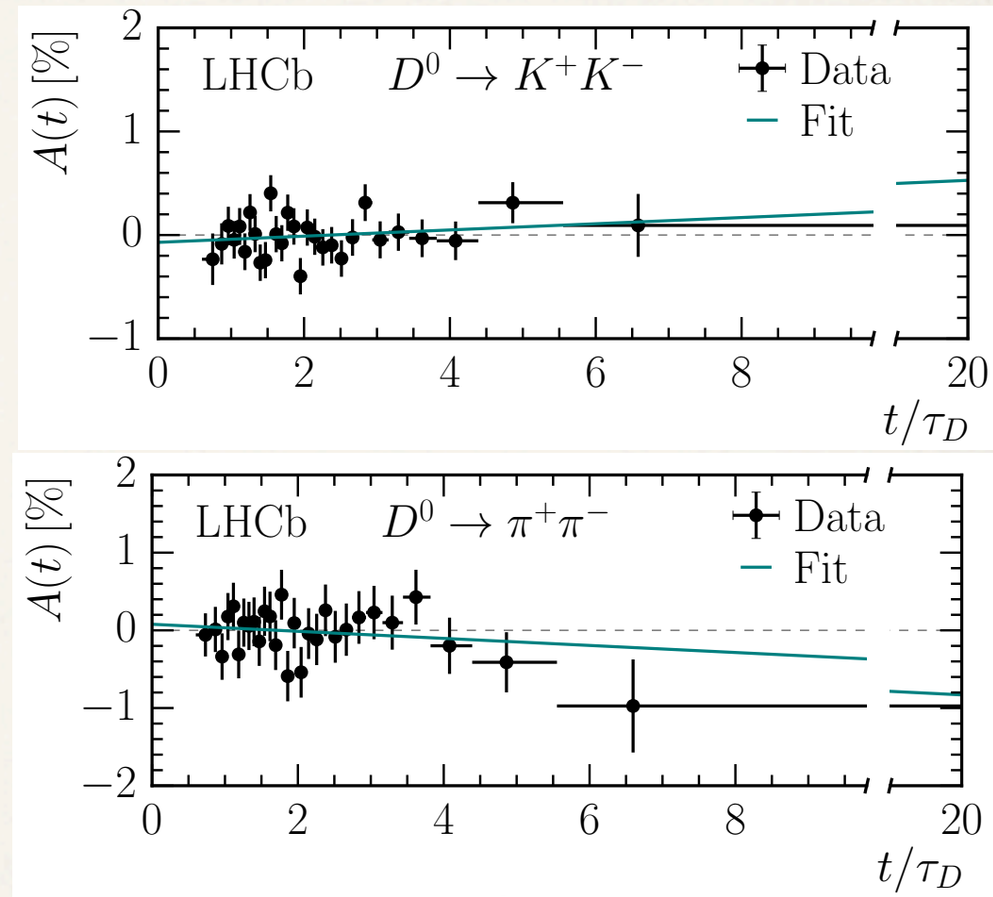
CPV in $D^0 \to h^+h^-$ (3)

Run I ($3fb^{-1}$)

[PRL 118 (2017) 261803]

- Precision approaches the level of **10^{-4}**. No evidence for CPV and **precision improved by x2** wrt previous best measurements

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



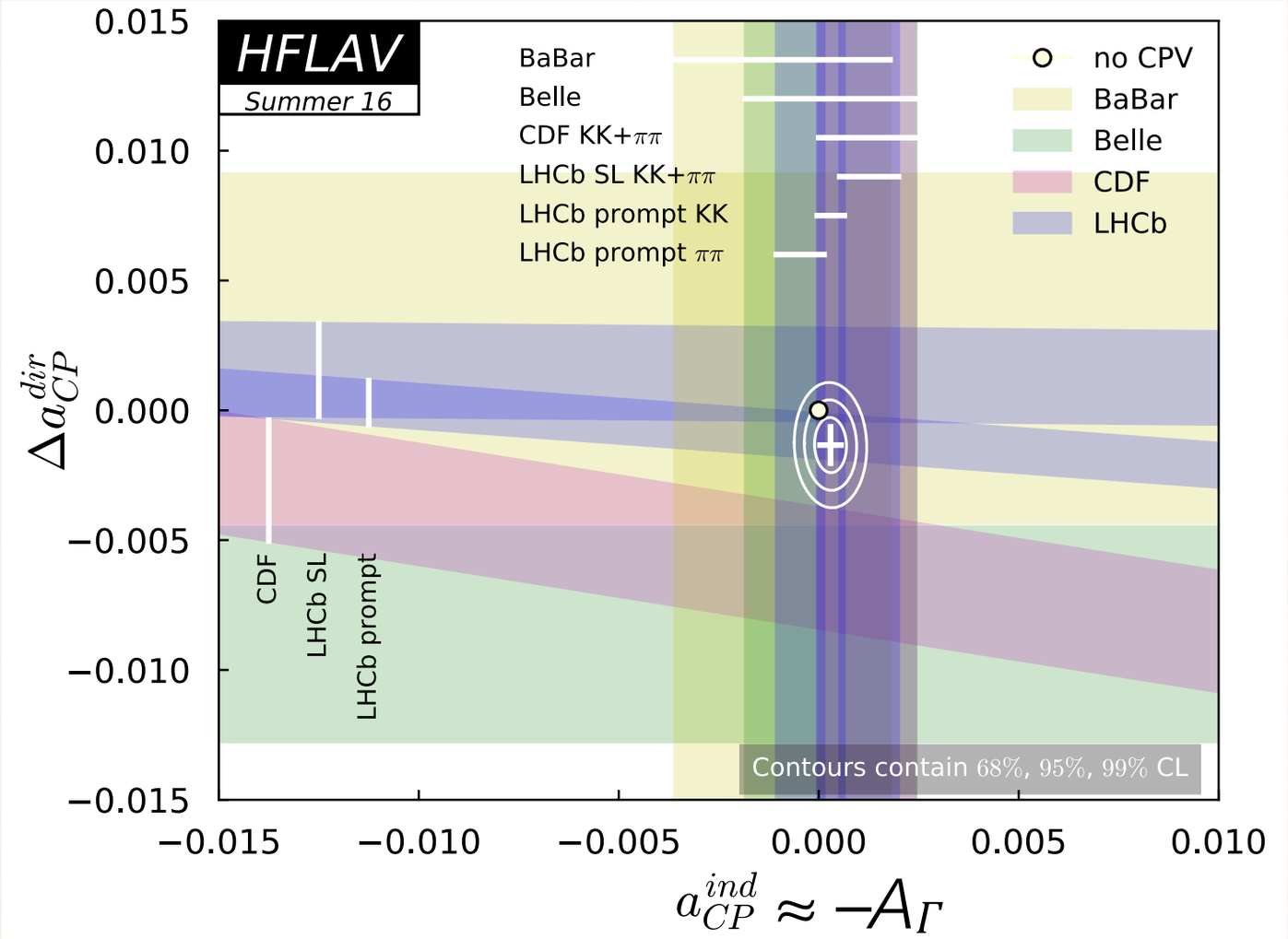
- Assuming only indirect CPV contributes to A_Γ, the two values can be combined

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

- Assuming universality of CPV and combining with result from muon-tagged sample [JHEP 1504 (2015) 043], we get the **world's most precise measurement to date** (still compatible with CP symmetry)

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

LHCb Impact on CPV in $D^0 \to h^+h^-$



- Results are consistent also with previous measurements
- LHCb values dominates the world average (same uncertainties if consider LHCb-only or average) and update with more data is coming

CPV in $D^+_{(s)} \to \eta'\pi^+$ (1)

Run I ($3fb^{-1}$)

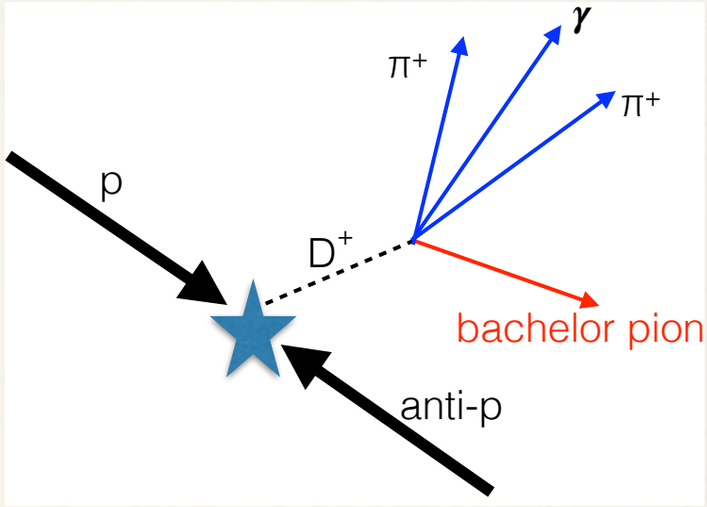
[PLB 771 (2017) 21]

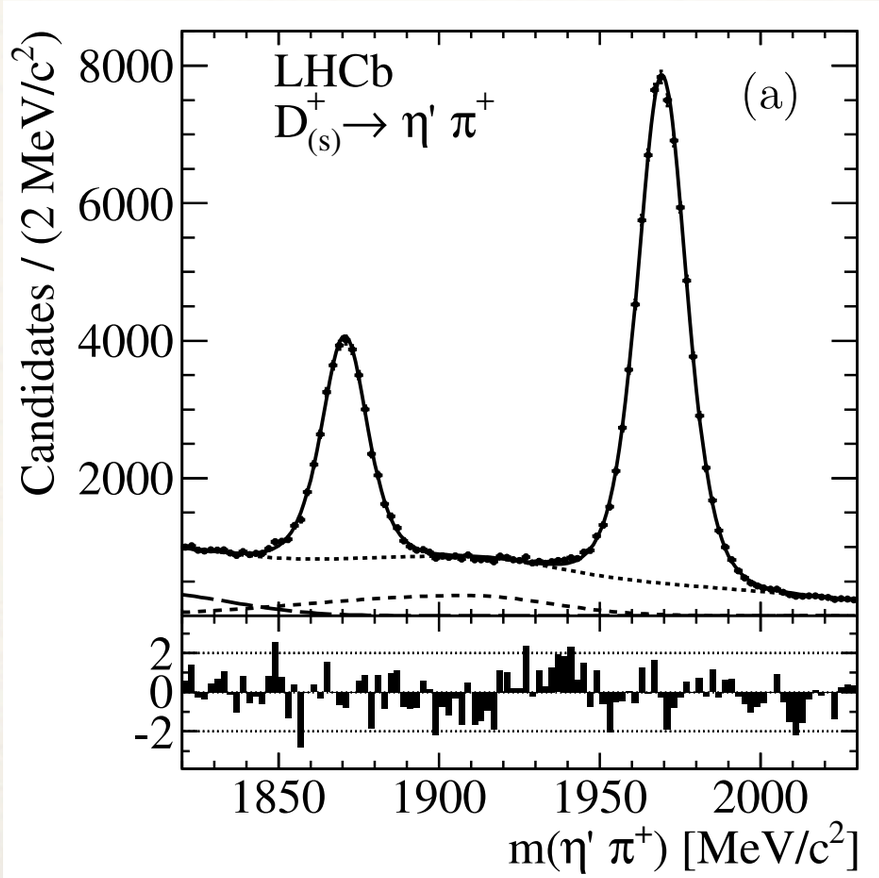
- Reconstruct $\eta' \to \pi^+\pi^-\gamma$
- Asymmetries measured relative to those of $D^+ \to K_s\,\pi^+$ and $D_s^+ \to \phi\pi^+$ decays to cancel production and detection asymmetries

$$\mathcal{A}_{CP}(D^\pm \to \eta'\pi^\pm) \approx \Delta\mathcal{A}_{CP}(D^\pm \to \eta'\pi^\pm) + \mathcal{A}_{CP}(D^\pm \to K^0_S\pi^\pm)$$

$$\mathcal{A}_{CP}(D_s^\pm \to \eta'\pi^\pm) \approx \Delta\mathcal{A}_{CP}(D_s^\pm \to \eta'\pi^\pm) + \mathcal{A}_{CP}(D_s^\pm \to \phi\pi^\pm)$$

- Never measured before at hadron colliders due to challenging low-momentum photons
- Total yields: 63k $D^\pm$, 152k $D_{(s)}^\pm$





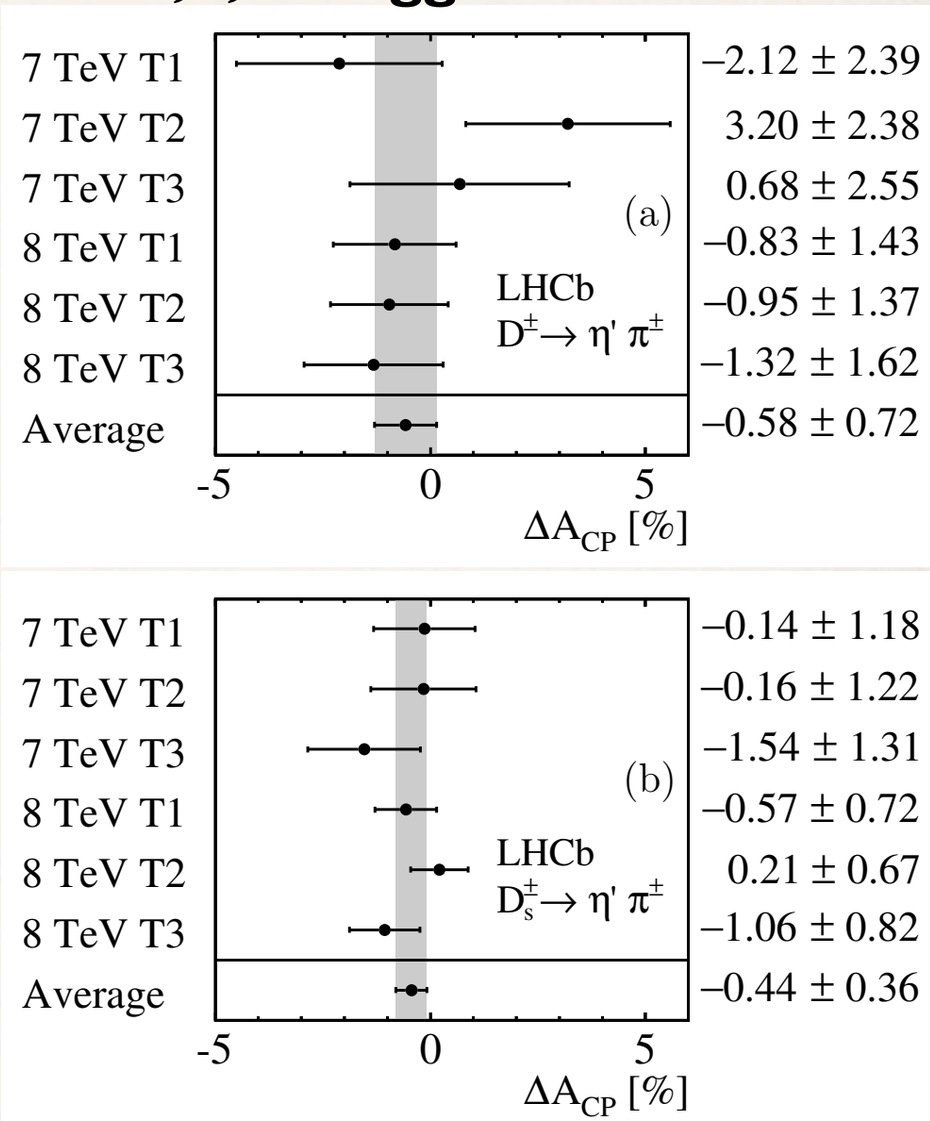
CPV in $D^+_{(s)} \to \eta'\pi^+$ (2)

Run1 ($3fb^{-1}$)

[PLB 771 (2017) 21]

- Invariant mass distribution fit in 12 mutually exclusive subsamples:
  - CM energy
  - Magnet polarity
  - Trigger selections
- Main systematic contribution from background model
- **Most precise measurements to date**

T1,2,3: trigger selections



$$\mathcal{A}_{CP}(D^\pm \to \eta'\pi^\pm) = (-0.61 \pm 0.72 \pm 0.53 \pm 0.12)\%,$$
$$\mathcal{A}_{CP}(D_s^\pm \to \eta'\pi^\pm) = (-0.82 \pm 0.36 \pm 0.22 \pm 0.27)\%,$$

Last contribution from subtracted ACP in calibration modes

CPV in $D^0 \to \pi^+ \pi^- \pi^+ \pi^-$ (1)

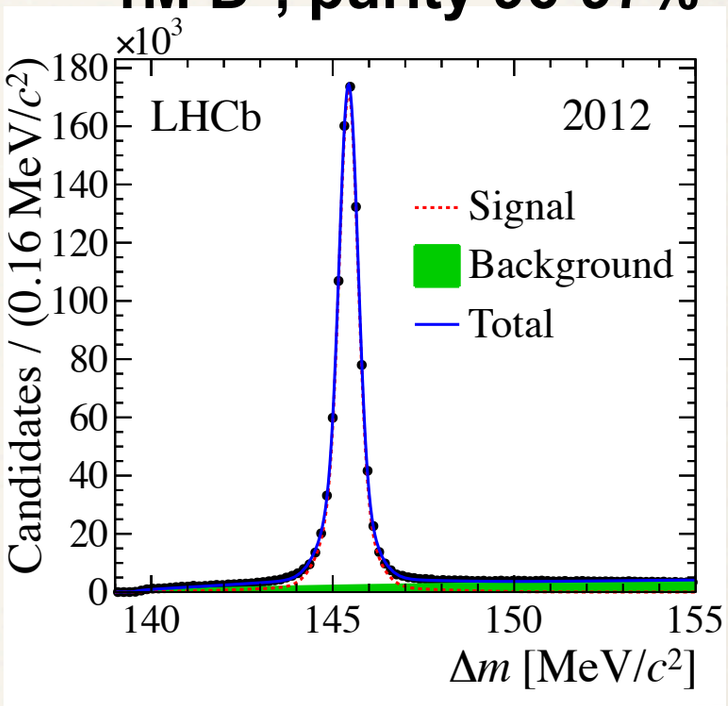
Run I ($3fb^{-1}$)

[PLB 769 (2017) 345]

- Test for CPV across the phase space (local CP asymmetries may be larger), sensitive to direct CPV

- **Energy test method:** J. Stat. Comp. Sim. 75 (2005) 109 NIM A537 (2005) 626
  - Statistical test of two subsamples based on distance in phase space between pairs of particles
  - Distance **d** is a function of squared invariant masses
  - Used here to check compatibility of data with CP symmetry

1M D^0, purity 96-97%



- **P-even**: subsamples split using D flavor
- **P-odd**: subsamples split using D flavor and triple products of final-state particle momenta

$$C = \vec{p}_{\pi^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$$
$$\bar{C} = \vec{p}_{\pi^-} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+})$$

CPV in $D^0 \to \pi^+ \pi^- \pi^+ \pi^-$ (2)

Run I (3fb^{-1})

[PLB 769 (2017) 345]

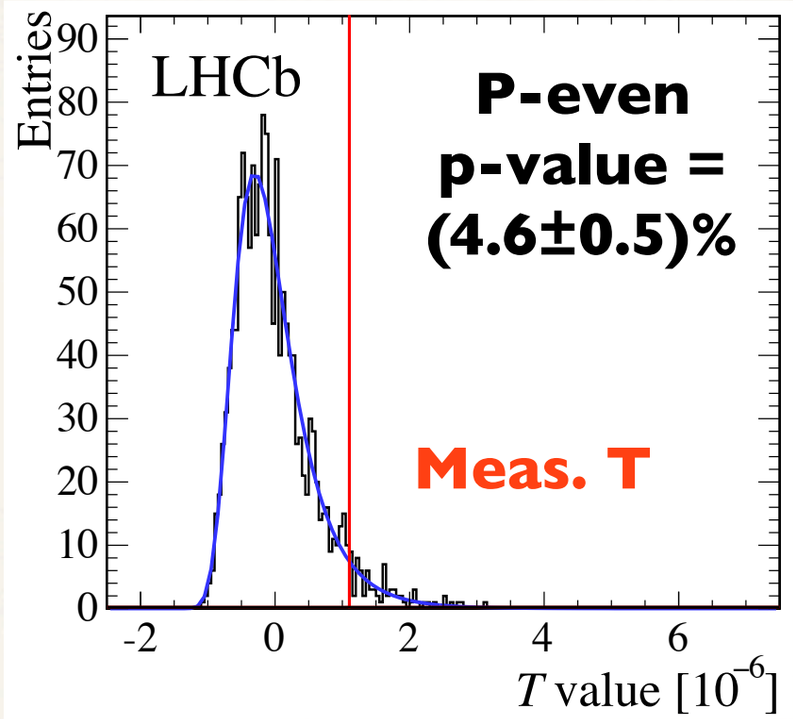
- Statistical test on samples n and n̄

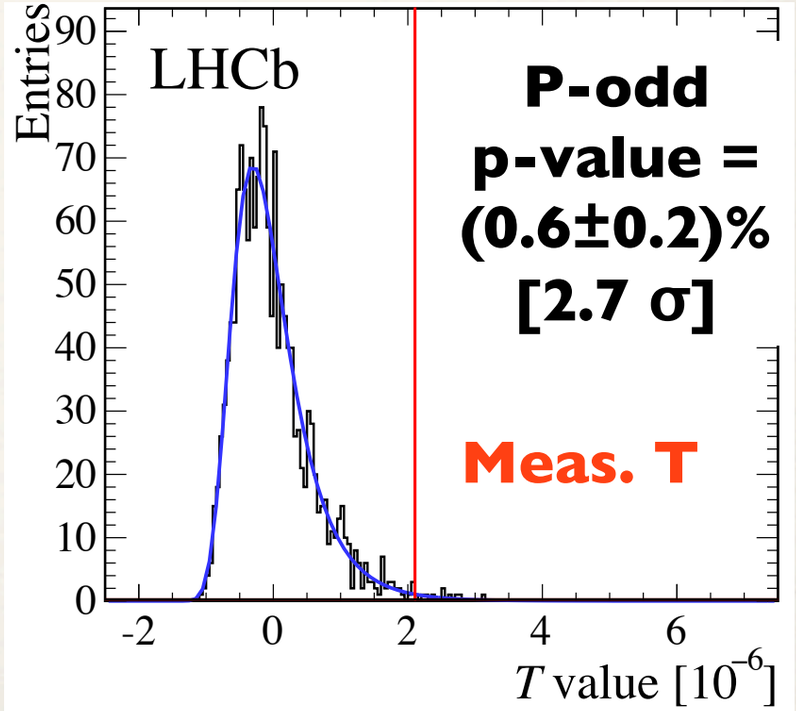
$$T = \sum_{i,j>i}^{n} \frac{\psi_{ij}}{n(n-1)} + \sum_{i,j>i}^{\overline{n}} \frac{\psi_{ij}}{\overline{n}(\overline{n}-1)} - \sum_{i,j}^{n,\overline{n}} \frac{\psi_{ij}}{n\overline{n}}$$

Relevant term Depends on both samples

$\psi(d_{ij}) = e^{-d_{ij}^2/2\delta^2}$, δ tunable parameter

- Compared with T distribution of no CPV case (candidates assigned randomly to each subsample)
- Compute using dedicated GPU implementation (see talk by H. Schreiner on Computing session, Thu morning)
- Possible systematic effects (background and detection asymmetries) were found below the current level of sensitivity
- **P-odd test marginally consistent with no CPV**





Conclusions

- Precision measurements of mixing and CP violation are a fundamental tool to **test the SM at energy scales and couplings unaccessible at the energy frontier**

- Thanks to LHC being also a charm-factory, **LHCb is collecting the largest ever charm samples (~10^9)**

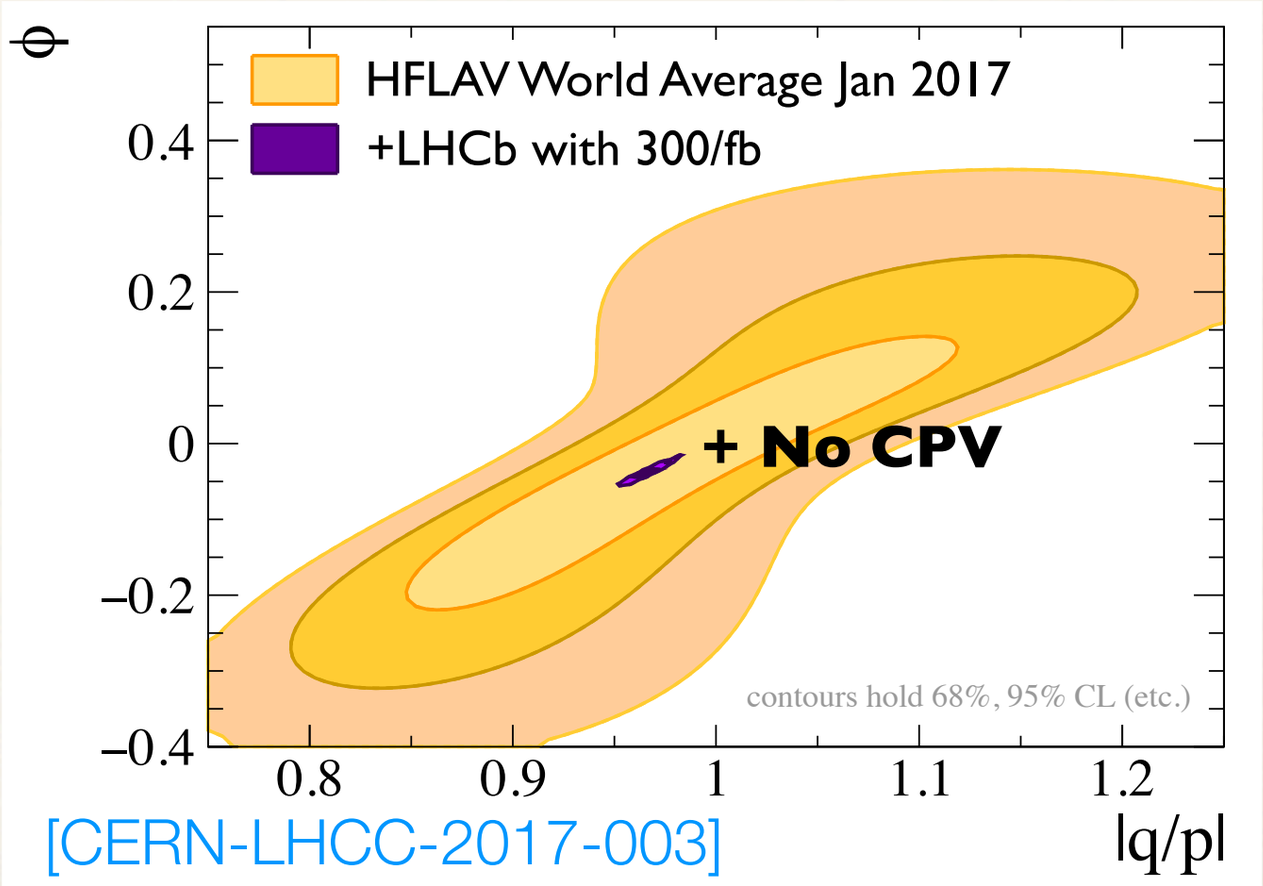
- Latest Run1 results presented here already exceed those from the B-factories and the Tevatron, achieving (at least in the golden modes) a **statistical precision below 10^{-3}**, and **systematics already close to 10^{-4}**

- All the results are **consistent with CP symmetry** and mostly limited by statistics

LHCb Upgrade and Beyond

- **Analyses update using Run2 data is ongoing**: "effective" charm statistics is already like Run1, due to increased cross-section and improved trigger. **Many efforts towards relaxing the selection w/o increasing the systematic contributions**

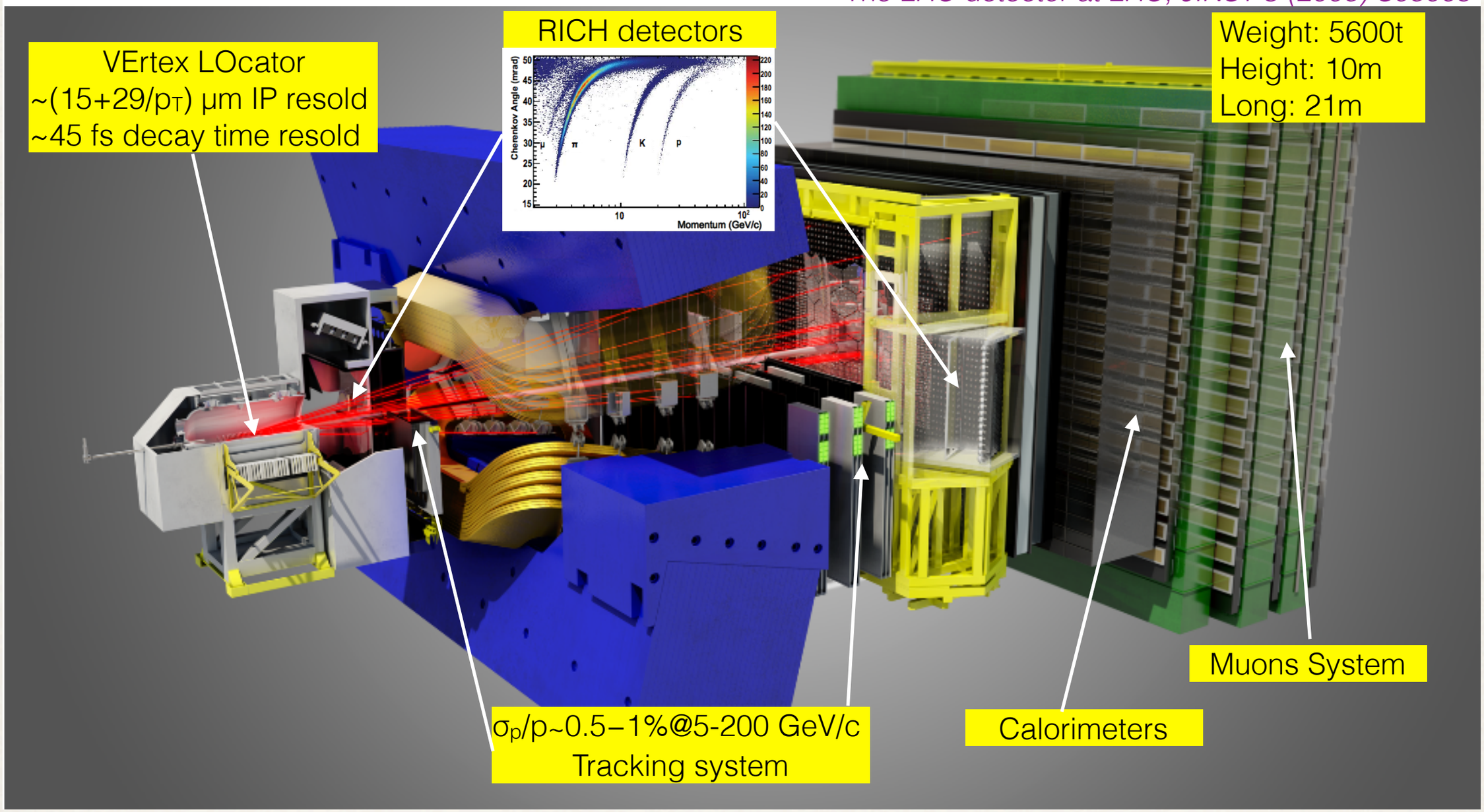
- **LHCb Upgrade (Run3-4, 50 fb-1) is around the corner** and Phase 2 upgrade is under discussion (Run5-..., 300 fb-1)



[CERN-LHCC-2017-003]

The LHCb Detector

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 2.5KHz, where typical event size is 60-100KBytes in Run 1 (2011-2012). In Run 2 (2015-2016) performances are even better. [LHCb-PROC-2015-011]