Mixing and Time-dependent CPV Searches in Charm at LHCb

Daniel Červenkov on behalf of the **LHCb** collaboration

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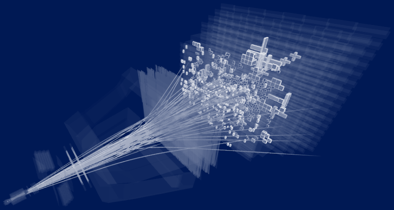

- Because of the severe GIM suppression, mixing is slow and CPV small (according to SM)
- m_c is (quite) close to the hadronic scale $\Lambda_{\text{QCD}} \rightarrow \Lambda_{\text{QCD}}/m_c$ perturbative expansion tricky
- Strong coupling $\alpha_s(m_c)$ is large $\rightarrow$ higher order contributions and/or non-perturbative effects can be significant

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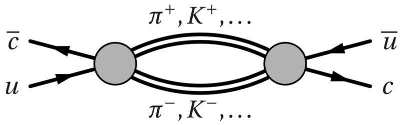
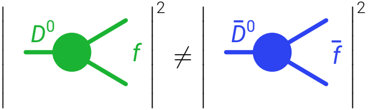
- Long distance contributions are important
- Precise theoretical predictions are difficult



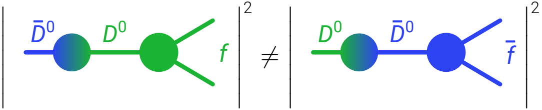
- Experimental input crucial to constrain charm dynamics
- Potential for measurable New Physics is great

CPV IN CHARM

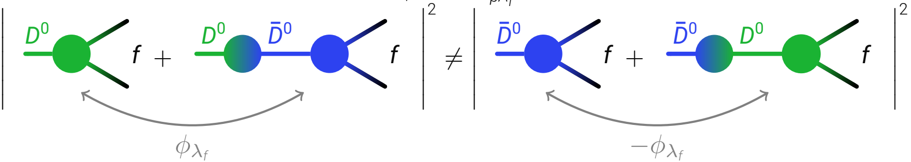
- The only up-type quark decays where CPV can be studied
- Complementary to K and B
- All three types of CPV are realized in charm
  - Decay ($|A_f|^2 \neq |\bar{A}_{\bar{f}}|^2$)



  - Pure mixing ($|q/p| \neq 1$)



  - Decay-mixing interference ($\phi_{\lambda_f} = \arg(\frac{q\bar{A}_f}{pA_f}) \neq 0$)



PARAMETERS

- Mixing comes from a mismatch between flavour and mass eigenstates

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

- Usually described by

$$x = \Delta m_D/\Gamma_D \quad \text{and} \quad y = \Delta\Gamma_D/2\Gamma_D$$

- In case of CPV $|q/p|$ and $\phi \approx \phi_{\lambda_f}$ or

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

Search for time-dependent CPV in $D^0 \to h^+h^-$ ($h \in \{K, \pi\}$)

PRD 104, 072010 (2021)

- Same channels as ΔA_{CP} discovery

$$A_{CP} = \frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)} = a_f^d + \underbrace{\Delta Y_f}_{\approx -A_\Gamma} \frac{t}{\tau_D} + \mathcal{O}(x^2, y^2, xy)$$

- SM prediction is very small $\sim 10^{-5}$ (Kagan & Silvestrini, 2020, Li & Umeeda, 2020)

- We don't observe A_{CP}

$$A_{\text{raw}} = \frac{N(D^0(t) \to f) - N(\bar{D}^0(t) \to f)}{N(D^0(t) \to f) + N(\bar{D}^0(t) \to f)} \approx a_f^d + \Delta Y_f \frac{t}{\tau_D} + \overbrace{A_{\text{prod}}(f, t) + A_{\text{det}}(f, t)}^{\text{Time-dep. nuisance parameters}}$$

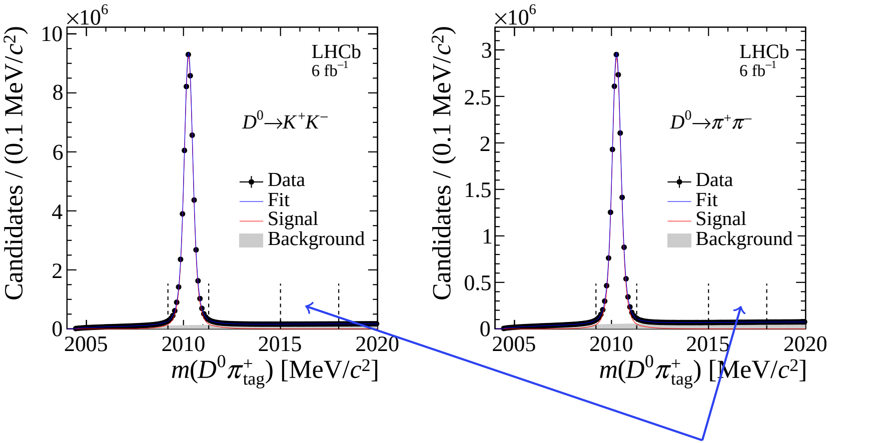
$$\Delta Y_f \approx \underbrace{x\phi_{\lambda_f}}_{\text{Decay-mix. interference}} - y \underbrace{\left(\left|\frac{q}{p}\right| - 1\right)}_{\text{Mixing}} + \underbrace{y a_f^d}_{\text{Decay } (\leq 10^{-5})} \approx -\Delta y$$

$\Delta Y_{K^+K^-}$ needed to measure CPV in decay from time-integrated $D^0 \to K^+K^-$

SEARCH FOR TIME-DEPENDENT CPV IN $D^0 \to h^+h^-$

PRD 104, 072010 (2021)

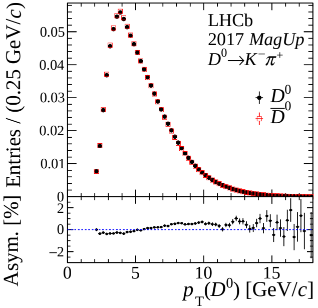
- D^0 from $D^{*+} \to D^0\pi^+_{\text{tag}}$
- At $\sqrt{s} = 13\,\text{TeV}$ with $\mathcal{L} = 5.7\,\text{fb}^{-1}$
- 58M $D^0 \to K^+K^-$, 18M $D^0 \to \pi^+\pi^-$, purity $\sim 95\%$

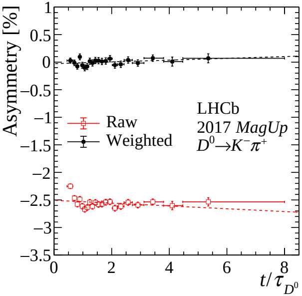


- Residual combinatorial background subtracted using sidebands

Search for time-dependent CPV in $D^0 \to h^+h^-$

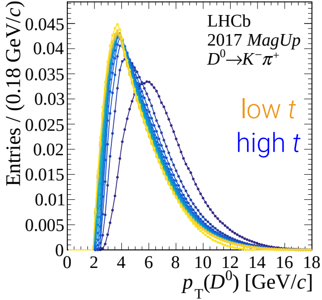
- Momentum-dependent detection asymmetries A_{det} based on magnet field polarity and charge of $\pi^{\pm}_{\mathrm{tag}}$
- $A_{\mathrm{det}} + A_{\mathrm{prod}} \longrightarrow D^0/\bar{D}^0$ momentum asym.
- Trigger correlates D^0 decay time with kinematics $\longrightarrow A_{\mathrm{det}}(t), A_{\mathrm{prod}}(t)$ become time-dependent
- Solution: equalize D^0 and $\bar{D}^0$ kinematics





← After reweighting $\Delta Y_{K^-\pi^+} \approx 0$ (control channel)

← Before reweighting $\Delta Y_{K^-\pi^+} \neq 0$

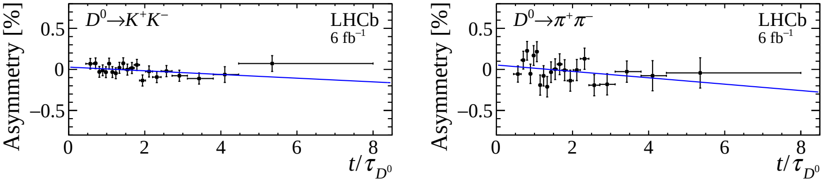


Search for time-dependent CPV in $D^0 \to h^+h^-$

PRD 104, 072010 (2021)

stat. ↓ syst. ↓

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



- $\Delta Y_{K^+K^-}$ and $\Delta Y_{\pi^+\pi^-}$ agree withing 0.5σ
- Compatible with no CPV within 2σ

Search for time-dependent CPV in $D^0 \to h^+h^-$

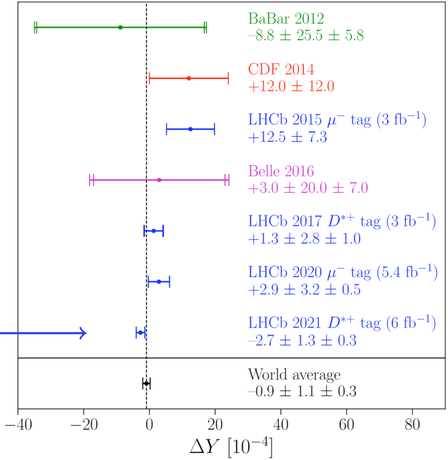
PRD 104, 072010 (2021)

Source	$\Delta Y_{K^+K^-}$ $[10^{-4}]$	$\Delta Y_{\pi^+\pi^-}$ $[10^{-4}]$
Subtraction of the $m(D^0\pi^+_{\text{tag}})$ background	0.2	0.3
Flavour-dependent shift of D^*-mass peak	0.1	0.1
D^{*+} from B-meson decays	0.1	0.1
$m(h^+h^-)$ background	0.1	0.1
Kinematic weighting	0.1	0.1
Total systematic uncertainty	0.3	0.4
Statistical uncertainty	1.5	2.8

- Combinatorial background subtraction

Search for time-dependent CPV in $D^0 \to h^+h^-$

This measurement

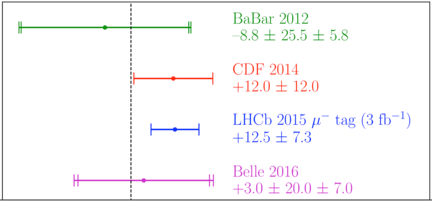


PRD 104, 072010 (2021)

- Previous world average $\Delta Y = (3.0 \pm 2.0 \pm 0.5) \times 10^{-4}$
- Precision improved by a factor of two
- Small systematic uncertainty $\longrightarrow$ great prospects for future LHCb measurements
  (σ approaching SM prediction $\mathcal{O}(10^{-5})$, LHCB-TDR-023-001)

SEARCH FOR TIME-DEPENDENT CPV IN $D^0 \to h^+h^-$

PRD 104, 072010 (2021)



This

Sample ($\mathcal{L}$)	Tag	Yield K^+K^-	$\sigma(A_\Gamma)$	Yield $\pi^+\pi^-$	$\sigma(A_\Gamma)$
Run 1–2 (9 fb^{-1})	Prompt	60M	0.013%	18M	0.024%
Run 1–3 (23 fb^{-1})	Prompt	310M	0.0056%	92M	0.0104 %
Run 1–4 (50 fb^{-1})	Prompt	793M	0.0035%	236M	0.0065 %
Run 1–5 (300 fb^{-1})	Prompt	5.3G	0.0014%	1.6G	0.0025 %

CERN-LHCC-2018-027

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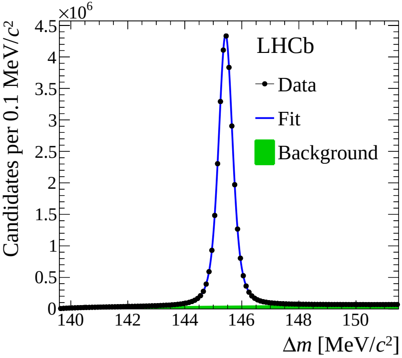
Mass difference between neutral D eigenstates

PRL 127, 111801 (2021)

- The Γ difference ($y \neq 0$) between neutral charm-meson eigenstates has been established in the past years (PRL 122, 011802 (2019), PRD 97, 031101 (2017), PLB 753 (2016), PRD 87, 012004 (2013))
- The mass difference ($x \neq 0$) has so far been elusive; the previous most precise measurement by LHCb reported $x_{CP} = (2.7 \pm 1.6) \times 10^{-3}$ (PRL 122, 231802 (2019))

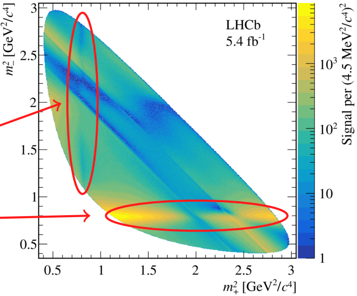
- $D^{*+} \to D^0 \pi^+_{\text{tag}}$
- $D^0 \to K^0_S \pi^+ \pi^-$
- $\mathcal{L} = 5.4\,\text{fb}^{-1}$
- 30.6M signal events
- Exploits multi-body final state; sensitive to mixing and CPV via time-dep. variations across phase-space



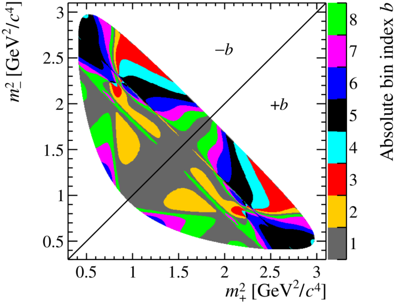
MASS DIFFERENCE BETWEEN NEUTRAL D EIGENSTATES

PRL 127, 111801 (2021)

- Rich resonant structure
- Many interfering amplitudes
  - $D^0 \xrightarrow{\text{DCS}} K^{*+}\pi^- \to K^0_S\pi^+\pi^-$
  - $D^0 \xrightarrow{\text{mix}} \bar{D}^0 \xrightarrow{\text{CF}} K^{*+}\pi^- \to K^0_S\pi^+\pi^-$
  - $D^0 \xrightarrow{\text{CF}} K^{*-}\pi^+ \to K^0_S\pi^+\pi^-$
  - $D^0 \xrightarrow{\text{CP}} K^0_S\rho^0 \to K^0_S\pi^+\pi^-$



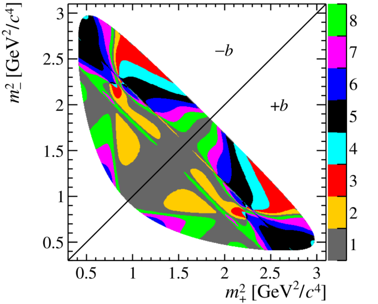
- Dalitz plot divided into $\pm$ bins; strong-phase difference is $\sim$ constant in each bin
- Strong-phases constrained using quantum-correlated D^0–$\bar{D}^0$ pairs (CLEO [PRD 82, 112006 (2010)] and BES-III [PRD 101, 112002 (2020)] inputs)



Mass difference between neutral D eigenstates

Bin-flip method

- Measure a time-dep. ratio for each $\pm$ bin; "bin-flip" (PRD 99, 012007 (2019))
- Slightly lower sensitivity than amplitude analysis
- Model-independent & most detector effects cancel



PRL 127, 111801 (2021)

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

- b — Dalitz bin, j — time bin
- r_b ratio at $t = 0$
- $X_b = c_b - is_b$
- $z_{CP} = -y_{CP} - ix_{CP}, \Delta z = -\Delta y - i\Delta x$

At leading order

$$R_{bj}^{\pm} \approx r_b + \sqrt{r_b}\,\left[(1 + r_b)(x_{CP} \pm \Delta x)c_b - (1 - r_b)(y_{CP} \pm \Delta y)s_b\right]\langle t\rangle_j$$

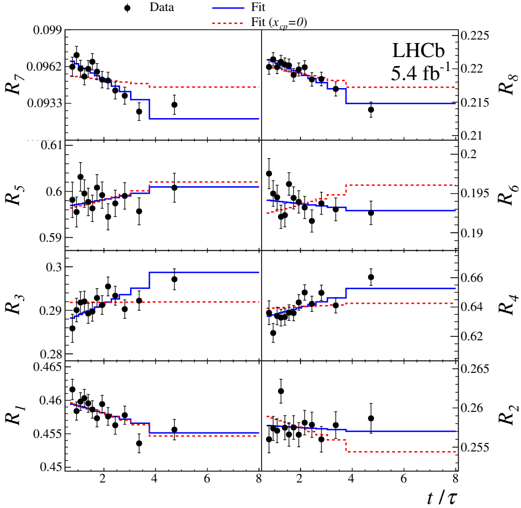
Mass difference between neutral D eigenstates

PRL 127, 111801 (2021)

- Ratios of $\pm$ bins
- Deviations from constant values due to mixing
- Red lines are fit projections where $x_{CP} \equiv 0 \longrightarrow y_{CP}$ alone can't reproduce observation

$$x_{CP} = (3.97 \pm 0.46 \pm 0.29) \times 10^{-3}$$
$$y_{CP} = (4.59 \pm 1.20 \pm 0.85) \times 10^{-3}$$

- First measurement of non-zero x ($> 7\sigma$)

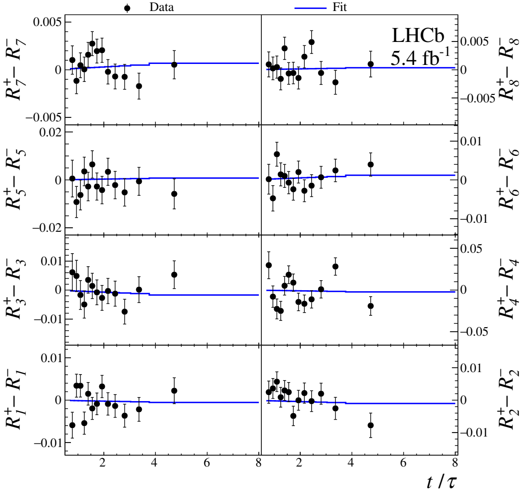


PRL 127, 111801 (2021)

- Difference of ratios for D^0 and $\bar{D}^0$
- No CPV observed (slope)

$\Delta x = (0.27 \pm 0.18 \pm 0.01) \times 10^{-3}$
$\Delta y = (0.20 \pm 0.36 \pm 0.13) \times 10^{-3}$

- Limits on Δx significantly improved



Uncertainties

PRL 127, 111801 (2021)

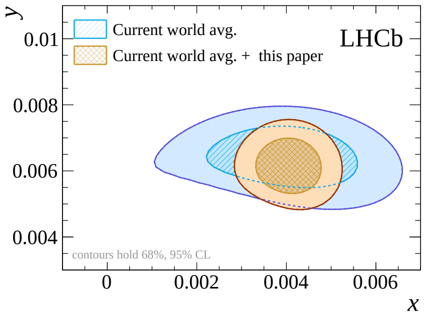
Source	x_{CP}	y_{CP}	Δx	Δy
Reconstruction and selection	0.199	0.757	0.009	0.044
Secondary charm decays	0.208	0.154	0.001	0.002
Detection asymmetry	0.000	0.001	0.004	0.102
Mass-fit model	0.045	0.361	0.003	0.009
Total systematic uncertainty	0.291	0.852	0.010	0.110

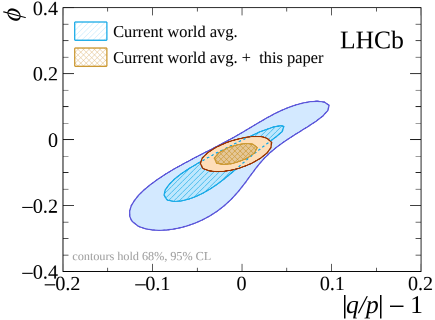
Strong phase inputs	0.23	0.66	0.02	0.04
Detection asymmetry inputs	0.00	0.00	0.04	0.08
Statistical (w/o inputs)	0.40	1.00	0.18	0.35
Total statistical uncertainty	0.46	1.20	0.18	0.36

- Trigger-induced efficiency correlations
- Possible bias due to charm from $B \to D$
- Inputs from CLEO and BES III; new strong-phase measurements from BES III of great interest for Run 3 measurement
- Especially Δx and Δy statistically dominated $\longrightarrow$ future improvement

PRL 127, 111801 (2021)

- WA significantly improved for both mixing and CPV





Mass difference between neutral D eigenstates

PRL 127, 111801 (2021)

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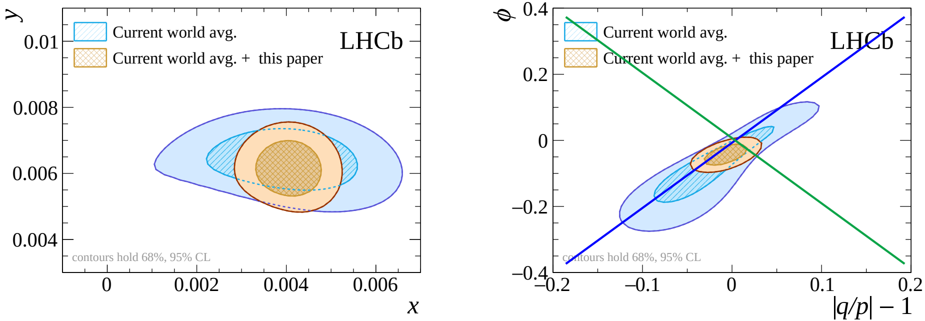
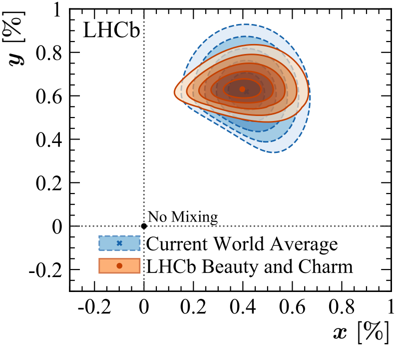
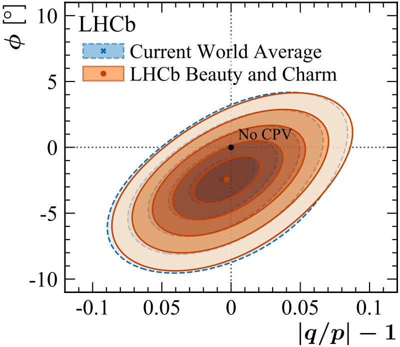


- Very complementary with the $D^0 \to h^+h^-$ analysis
- Δx improvement shrinks uncertainty on diagonal
- Δy improvement shrinks uncertainty on diagonal

LHCb Beauty + Charm Combination

- "Simultaneous determination of CKM angle γ and charm mixing parameters" (arXiv:2110.02350)
- Provides the most precise determination of γ from a single experiment; $\gamma = (65.4^{+3.8}_{-4.2})^{\circ}$; see talks by Anna, Arnau, and Fidan
- Improves the precision on *y* by a **factor of two** w.r.t. the current WA!
- $y = (0.630^{+0.033}_{-0.030})\%$





SUMMARY

- LHCb collected the largest sample of charm decays; leading to **new world-best measurements**
  - Time-integrated CP asymmetries (including **channels with neutrals**; see Andrea Contu's talk)
  - Time-dependent CP asymmetries and mixing parameters (including **first observation of a mass difference** between neutral *D* mass eigenstates)

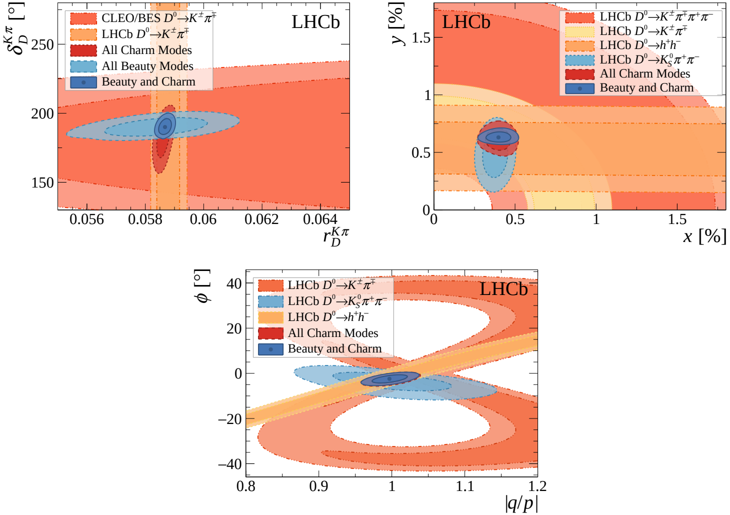
- More interesting Run 2 analyses in the pipeline
  - y_{CP} from $D^0 \to h^+h^-$
  - x, y from semi-leptonic $D^0 \to K_S\pi\pi$
  - Time-dep amplitude analysis of $D^0 \to K_S\pi\pi$
  - Update WS/RS(t) measurement of $D^0 \to K\pi$ with full Run2 sample
- Other approaches under investigation
  - Four-body final states
  - ...
- Precision of the measurements is mostly limited by statistics $\rightarrow$ **improvement expected**
- Run 3 (starting next year) - higher luminosity, upgraded trigger and detector

$\downarrow$

Stay tuned!

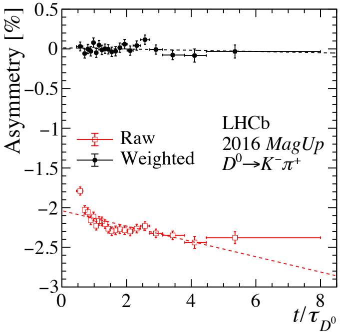
THANK YOU!

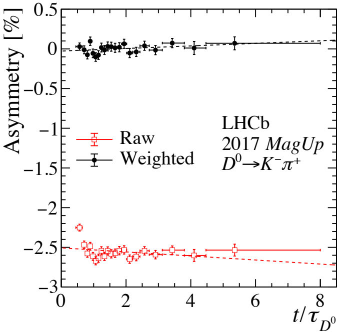
SIMULTANEOUS γ AND CHARM



- Improvement on y driven almost entirely by $\delta_D^{K\pi}$ from beauty
- Correlation of $\delta_D^{K\pi}$ and $\delta_{B^\pm}^{DK^\pm}$ is -57% $\longrightarrow$ $B^\pm \to DK^\pm$ dominates

$\Delta Y_{K\pi}$ VALIDATION





- $\Delta Y_{K\pi} = (0.4 \pm 0.5\,(\text{stat}) \pm 0.2\,(\text{syst})) \times 10^{-4}$
- From global fit: $|\Delta Y_{K\pi}| < 0.3 \times 10^{-4}$ at 90% CL