CKM & CPV in Charm and Beauty at LHCb

Peilian Li on behalf of the LHCb collaboration

Les XXIV Rencontres de Physique de la Vallée d'Aoste

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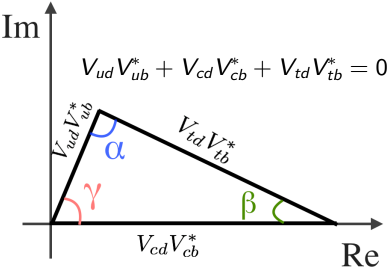
UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

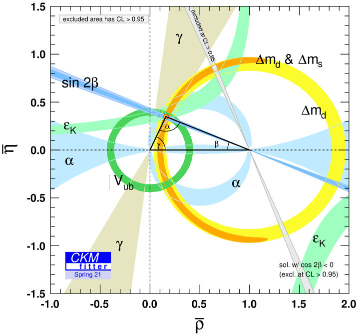
FSP LHCb Erforschung von Universum und Materie

CKM matrix

$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix} + \mathcal{O}(\lambda^4) \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

- Key test of the SM: Verify unitarity of CKM matrix
  - Magnitudes: branching fractions or mixing frequencies
  - Phases: CP violation measurements
- Sensitive to the physics beyond the SM





Outline

LHCb experiment is dedicated to beauty and charm physics
$\rightarrow$ an ideal lab for various CKM and CPV measurements

- CPV and mixing in charm decays:
  - ◇ Mass difference in $D^0 \rightarrow K_s^0 h^+ h^-$ PRL127(2021)111801
  - ◇ Measuring y_{CP} with $D^0 \rightarrow h^+ h^-$ arXiv:2202.09106
  - ◇ CPV with $D^0 \rightarrow h^+ h^- \mu^+ \mu^-$ see details in V. Lisovskyi's talk
- Latest combination γ and charm mixing parameters JHEP12(2021)141
  - ◇ New γ measurement with $B^- \rightarrow D(hh'\pi^0)h^-$ arXiv:2112.10617
- CPV in b baryons:
  - ◇ $\Lambda_b^0 \rightarrow DpK^-$ PRD104(2021)112008
  - ◇ $\Xi_b^- \rightarrow pK^+K^-$ PRD104(2021)052010

CPV and mixing in the D^0 system

- Neutral meson mixing:

$$|D_1>=p|D^0>+q|\bar{D}^0>,\ |D_2>=p|D^0>-q|\bar{D}^0>$$

with mixing parameters: $y=\frac{\Gamma_1-\Gamma_2}{2\Gamma}$, and $x=\frac{m_1-m_2}{\Gamma}$

$\rightarrow$ CP violation in mixing if $|\frac{q}{p}|\neq 1$

- Interference of mixing and decay in charm

$$\begin{tikzcd} D^0 \arrow[rr] \arrow[dr] & \phi_f & f \\ & \overline{D}^0 \arrow[ur] & \end{tikzcd} \neq \begin{tikzcd} \overline{D}^0 \arrow[rr] \arrow[dr] & -\phi_f & \bar{f} \\ & D^0 \arrow[ur] & \end{tikzcd}$$

$\rightarrow$ CP violation if weak phase $\phi_f=arg(\frac{q}{p}\frac{\bar{A}_f}{A_f})\neq 0$

- *CP* asymmetry: $y_{CP}\propto x sin\phi(|\frac{q}{p}|-|\frac{p}{q}|)+y cos\phi(|\frac{q}{p}|+|\frac{p}{q}|)$
  $\rightarrow$ Precise knowledge of x and y are important!

CPV and mixing in the D^0 system

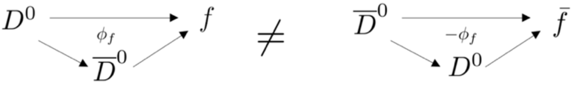
- Neutral meson mixing:

$$|D_1> = p|D^0> + q|\bar{D}^0>, \; |D_2> = p|D^0> - q|\bar{D}^0>$$

with mixing parameters: $y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$, and $x = \frac{m_1 - m_2}{\Gamma}$

$\rightarrow$ CP violation in mixing if $|\frac{q}{p}| \neq 1$

- Interference of mixing and decay in charm



$\rightarrow$ CP violation if weak phase $\phi_f = arg(\frac{q}{p}\frac{\bar{A}_f}{A_f}) \neq 0$

- *CP* asymmetry: $y_{CP} \propto x sin\phi(|\frac{q}{p}| - |\frac{p}{q}|) + y cos\phi(|\frac{q}{p}| + |\frac{p}{q}|)$
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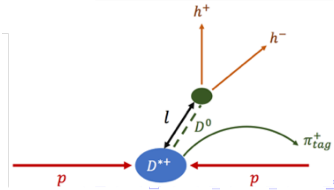
- Select $D^{*+} \rightarrow D^0\pi^+$ with $D^0 \rightarrow f$ to tag the production flavor of D^0



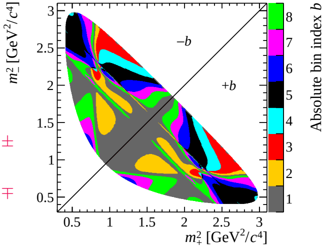
Bin-flip method with $D^0 \to K_S^0 h^+ h^-$

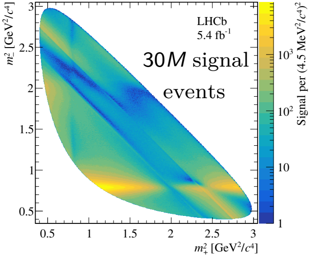
PRL127(2021)111801

- Bin-flip method: Dalitz-plot binning with minimal strong phase variations
  - ◇ Sensitivity to all mixing and CP violation parameters
  - ◇ Measure ratios of events in Dalitz-plot bins $-b$ & $+b$ for D^0 (R_b^+) and $\bar{D}^0$ (R_b^-)
    $\rightarrow$ Model-independent & most acceptance effects cancelled

$m^2_\pm(D^0) \equiv m^2_{K_S^0\pi^\pm}$

$m^2_\pm(\bar{D}^0) \equiv m^2_{K_S^0\pi^\mp}$





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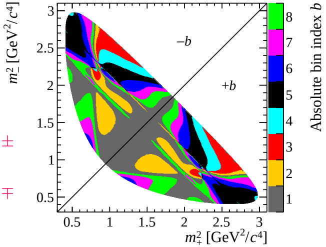
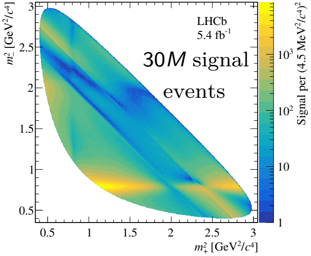




For Dalitz bin b and decay-time bin j, $r_b = R_{bj}$ at $t=0$, $X_b = e^{i\delta_D(b)}$, δ_D is the strong-phase difference

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

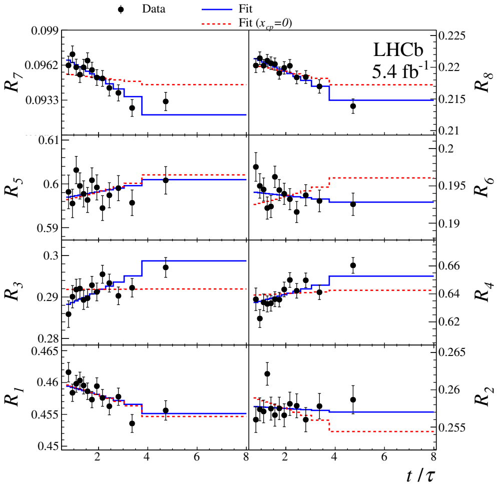
$z_{CP} \pm \Delta z \equiv -\left(\frac{q}{p}\right)^{\pm 1}(y + ix)$, $x_{CP} = Im(z_{CP})$, $y_{CP} = Re(z_{CP})$, $\Delta x = Im(\Delta z)$, $\Delta y = Re(\Delta z)$

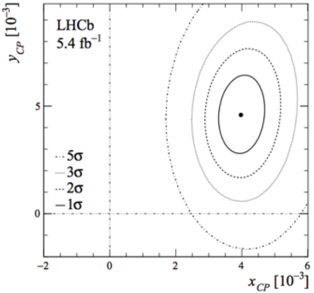
- Non zero of Δx and Δy $\to$ sign of CP violation

Mass difference in the D^0 system

PRL127(2021)111801

- Simultaneous fit with 8 bins of D^0 and $\bar{D}^0$ to determine x_{CP}, y_{CP}, Δx and Δy
- Effect of mixing clearly visible
  $\rightarrow x_{CP} = (3.97 \pm 0.36 \pm 0.29) \times 10^{-3}$, $y_{CP} = (4.59 \pm 1.20 \pm 0.85) \times 10^{-3}$

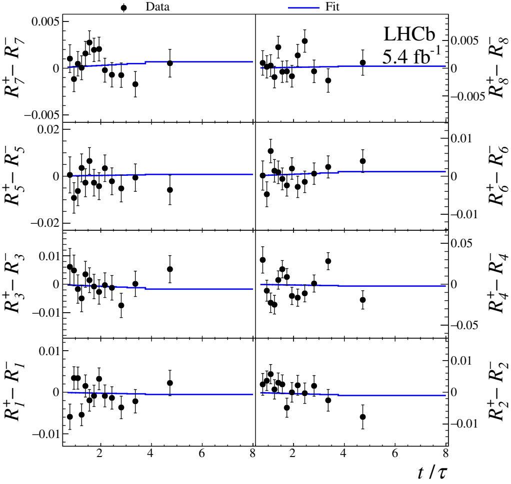




Mass difference in the D^0 system

PRL127(2021)111801

- CP violation: Look at differences of ratios for D^0 and $\bar{D}^0$
- Consistent with CP symmetry
  $\rightarrow \Delta x = (-0.27 \pm 0.18 \pm 0.01) \times 10^{-3}$, $\Delta y = (0.20 \pm 0.36 \pm 0.13) \times 10^{-3}$



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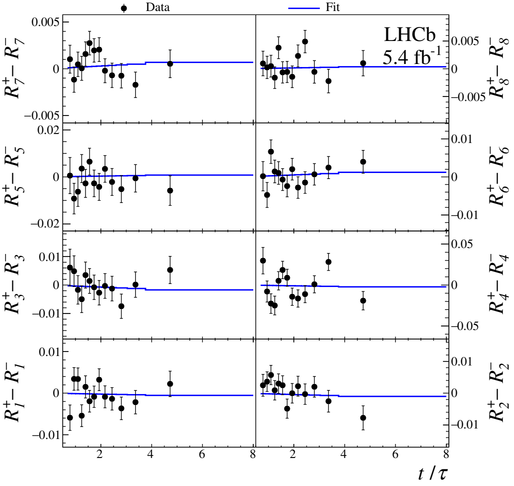

Convert to observables x, y, $|q/p|$, ϕ:
→ First observation of the non-zero mass difference in charm meson

Parameter	Value
$x\ [10^{-3}]$	$3.98\ ^{+0.56}_{-0.54}$
$y\ [10^{-3}]$	$4.6\ ^{+1.5}_{-1.4}$
$\lvert q/p \rvert$	0.996 ± 0.052
ϕ	$-0.056\ ^{+0.047}_{-0.051}$

Mixing parameter y_{CP} with $D^0 \to h^+h^-$

arXiv:2202.09106

- Measuring decay-time ratio of $D^0 \to f\,(h^+h^-)$ over $D^0 \to K^+\pi^-$
- Precise $y^f_{CP} - y^{K\pi}_{CP}$ adds constraint to $y = \frac{\Gamma_1-\Gamma_2}{2\Gamma}$

$$R^f(t) = \frac{N(D^0 \to f, t)}{N(D^0 \to K^-\pi^+, t)} \propto e^{-(y^f_{CP}-y^{K\pi}_{CP})t/\tau_{D^0}} \frac{\varepsilon(f, t)}{\varepsilon(K^-\pi^+, t)}$$

- $D^0 \to f$ kinematics are matched with $D^0 \to K^-\pi^+$ to ensure equal acceptance of kinematic phase space

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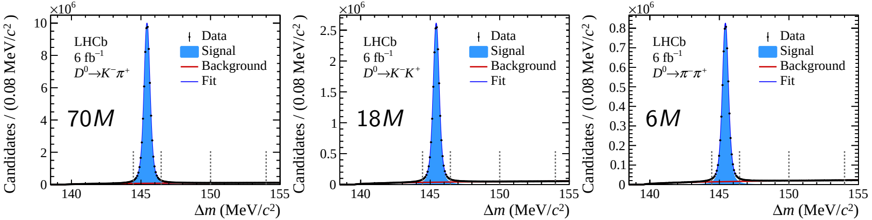
- $D^0 \to f$ kinematics are matched with $D^0 \to K^-\pi^+$ to ensure equal acceptance of kinematic phase space
- Fit to Δm: sum of three Gaussian + Johnson SU function for signal extraction

$$\Delta m = m(hh'\pi^+_{\rm tag}) - m(hh')$$



Mixing parameter y_{CP} with $D^0 \to h^+ h^-$

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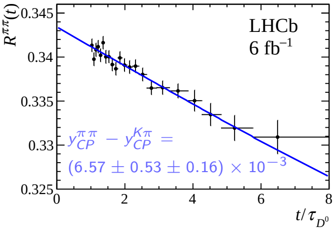
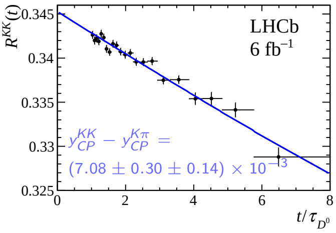
- Combined: $y_{CP} - y_{CP}^{K\pi} = (6.96 \pm 0.26 \pm 0.13) \times 10^{-3}$
  $\to$ improved precision by a factor of 4





- Previous world average:
  $y_{CP} - y_{CP}^{K\pi} = (7.16 \pm 0.93 \pm 0.60) \times 10^{-3}$

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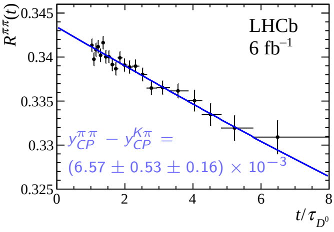
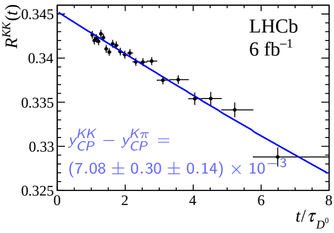
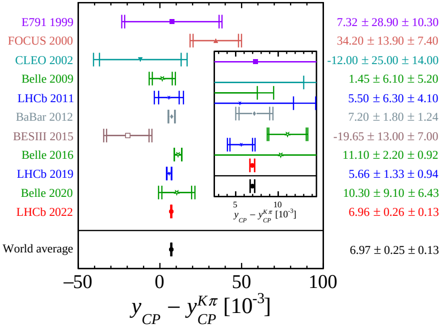


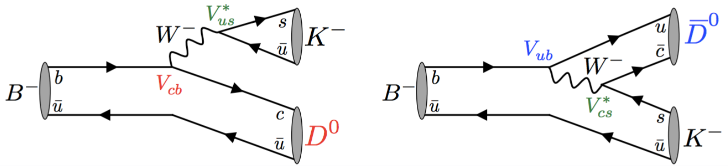


- Previous world average:
  $y_{CP} - y_{CP}^{K\pi} = (7.16 \pm 0.93 \pm 0.60) \times 10^{-3}$
- New: $(6.97 \pm 0.25 \pm 0.13) \times 10^{-3}$, dominated by LHCb's result



CP violating angle γ

- Relative weak phase γ in interference between $b \to c\bar{u}s$ and $b \to u\bar{c}s$ transitions
- $\gamma \equiv arg(-V_{ud}V^*_{ub}/V_{cd}V^*_{cb})$, measured with tree-level decays, theoretically simple



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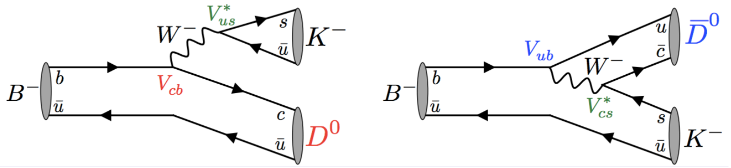

- Interference occurs when D^0 and $\bar{D}^0$ decay to the same final state f
  - ◇ GLW: CP eigenstates, e.g. $D \to KK$, $D \to \pi\pi$
  - ◇ ADS: CF or DCS decays, e.g. $D \to K\pi$
  - ◇ BPGGSZ: self-conjugated 3-body final states, GLW/ADS analysis across the D decay phase space, e.g. $D \to K_s^0\pi\pi$
  - ◇ Time-dependent: $B_s^0 \to D_s^- K^+$ & Dalitz: $B^0 \to \bar{D}^0 K^+ \pi^-$
- Combination of all methods provides the best precision
  - ◇ Direct measurements from B decays: $\gamma = (72.1^{+5.4}_{-5.7})^\circ$
  - ◇ Indirectly inferred from other constraints: $\gamma_{\mathrm{CKMFitter}} = (65.55^{+0.90}_{-2.65})^\circ$

γ measurement

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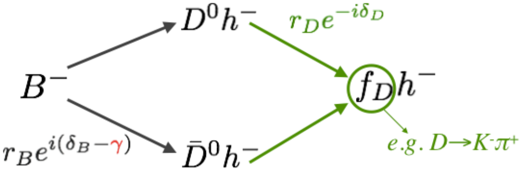
$$\Gamma(B^{\pm} \to Dh^{\pm}) \propto |r_D e^{-i\delta_D} + r_B e^{i(\delta_B \pm \gamma)}|^2 \Rightarrow r_D^2 + r_B^2 + 2 r_D r_B cos(\delta_B + \delta_D \pm \gamma)$$

- $\rightarrow$ External inputs: r_D and δ_D are the magnitude ratio and strong-phase difference between $D^0 \to f$ and $\bar{D}^0 \to f$, for GLW modes, $r_D = 1$ and $\delta_D = 0$
- $\rightarrow$ r_B, δ_B r_D and δ_D are specific to each B decay and subsequent D decay
- $\rightarrow$ CP-violating weak phase difference γ is shared by all such decays



γ combination + charm mixing

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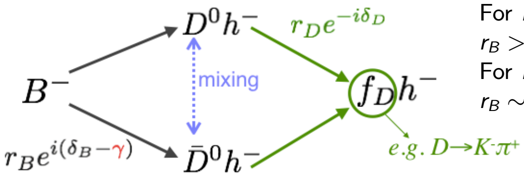
$$\Gamma(B^\pm \to Dh^\pm) \propto r_D^2 + r_B^2 + 2r_D r_B cos(\delta_B + \delta_D \pm \gamma) \\ - \alpha[(1 + r_B^2) r_D cos\delta_D - \alpha(1 + r_D^2) r_B cos(\delta_B \pm \gamma)]y \\ + \alpha[(1 - r_B^2) r_D sin\delta_D - \alpha(1 - r_D^2) r_B sin(\delta_B \pm \gamma)]x$$

- Larger B samples improve precisions of γ and δ_B
  $\rightarrow$ similar precision of strong phase difference $\delta_D^{K\pi}$ possible
- Charm mixing parameter y is limited by the current precision of $\delta_D^{K\pi}$
- Simultaneous combination of both beauty and charm measurements sensitive to γ and charm mixing parameters



For $B^- \to DK^-$:
$r_B >> x,\ y$
For $B^- \to D\pi^-$:
$r_B \sim x,\ y$

Combination of LHCb measurements

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- Using the Gammacombo package
  - $\rightarrow$ a frequentist approach used with 151 observables to determine 52 parameters
  - $\rightarrow$ 7 new/updated inputs from B-meson and 8 inputs from D-meson decays

B decay	D decay	Ref.	Dataset	Status since Ref. [17]
$B^{\pm} \to Dh^{\pm}$	$D \to h^+h^-$	[20]	Run 1&2	**Updated**
$B^{\pm} \to Dh^{\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[21]	Run 1	As before
$B^{\pm} \to Dh^{\pm}$	$D \to h^+h^-\pi^0$	[22]	Run 1	As before
$B^{\pm} \to Dh^{\pm}$	$D \to K^0_S h^+h^-$	[19]	Run 1&2	**Updated**
$B^{\pm} \to Dh^{\pm}$	$D \to K^0_S K^{\pm}\pi^{\mp}$	[23]	Run 1&2	**Updated**
$B^{\pm} \to D^*h^{\pm}$	$D \to h^+h^-$	[20]	Run 1&2	**Updated**
$B^{\pm} \to DK^{*\pm}$	$D \to h^+h^-$	[24]	Run 1&2(*)	As before
$B^{\pm} \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[24]	Run 1&2(*)	As before
$B^{\pm} \to Dh^{\pm}\pi^+\pi^-$	$D \to h^+h^-$	[25]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to h^+h^-$	[26]	Run 1&2(*)	**Updated**
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[26]	Run 1&2(*)	**New**
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	[27]	Run 1	As before
$B^0 \to D^{\mp}\pi^{\pm}$	$D^+ \to K^-\pi^+\pi^+$	[28]	Run 1	As before
$B^0_s \to D_s^{\mp}K^{\pm}$	$D_s^+ \to h^+h^-\pi^+$	[29]	Run 1	As before
$B^0_s \to D_s^{\mp}K^{\pm}\pi^+\pi^-$	$D_s^+ \to h^+h^-\pi^+$	[30]	Run 1&2	**New**
D decay	Observable(s)	Ref.	Dataset	Status since Ref. [17]
$D^0 \to h^+h^-$	ΔA_{CP}	[31,32,33]	Run 1&2	**New**
$D^0 \to h^+h^-$	y_{CP}	[34]	Run 1	**New**
$D^0 \to h^+h^-$	ΔY	[35,36,37,38]	Run 1&2	**New**
$D^0 \to K^+\pi^-$ (Single Tag)	$R^{\pm}$, $(x'^{\pm})^2$, $y'^{\pm}$	[39]	Run 1	**New**
$D^0 \to K^+\pi^-$ (Double Tag)	$R^{\pm}$, $(x'^{\pm})^2$, $y'^{\pm}$	[40]	Run 1&2(*)	**New**
$D^0 \to K^{\pm}\pi^{\mp}\pi^+\pi^-$	$(x^2+y^2)/4$	[41]	Run 1	**New**
$D^0 \to K^0_S\pi^+\pi^-$	x, y	[42]	Run 1	**New**
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[43]	Run 1	**New**
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[44]	Run 2	**New**

Combination of LHCb measurements

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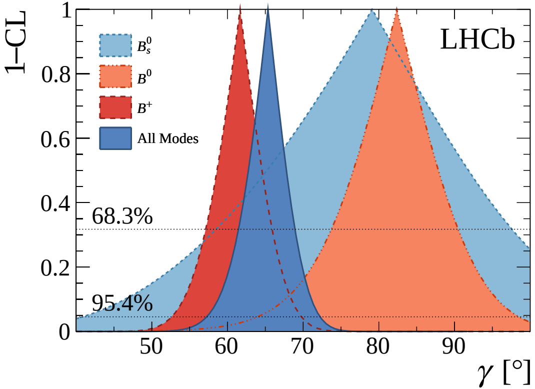
- Around two sigma tension between B^+ and B^0 results
- $\gamma = (65.4^{+3.8}_{-4.2})^\circ$, excellent agreement with indirect results:
  - UTFit: $\gamma = (65.8 \pm 2.2)^\circ$ - CKM fitter: $\gamma = (65.55^{+0.90}_{-2.65})^\circ$



* Does not include the latest $y_{CP} - y_{CP}^{K\pi}$ from arXiv:2202.09106

Combination of LHCb measurements

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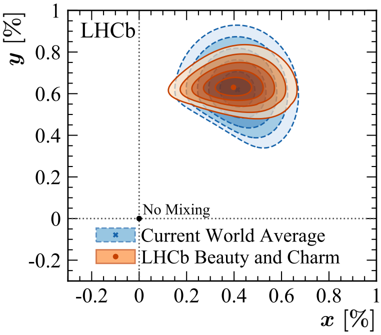
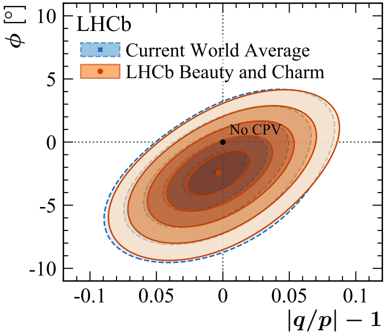
- $x \equiv \frac{M_1 - M_2}{\Gamma} = (0.400^{+0.052}_{-0.053})\%$
- $y \equiv \frac{\Gamma_1 - \Gamma_2}{2\Gamma} = (0.630^{+0.033}_{-0.030})\%$ $\rightarrow$ Factor of 2 more precise in y
- $|q/p| = 0.997 \pm 0.016$, $\phi \equiv arg(q/p) = (-2.4 \pm 1.2)^\circ$





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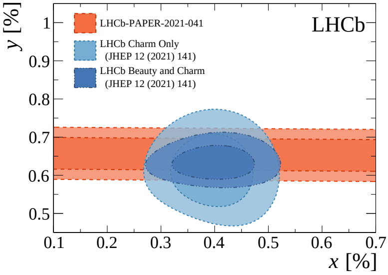
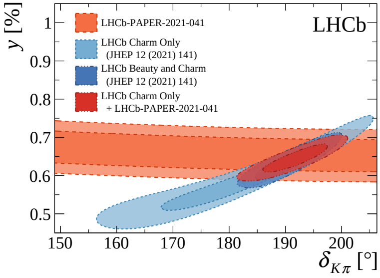
LHCb combination for charm only

arXiv:2202.09106

LHCb Charm only global fits taking latest $y_{CP} - y_{CP}^{K\pi}$ into account:

- Mixing parameter $y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma} = (6.46^{+0.24}_{-0.25}) \times 10^{-3}$
  $\rightarrow$ Further improvement (1.4x) w.r.t the previous combination
- Strong phase difference between CF and DCS $D^0 \rightarrow K\pi$: $\delta_D^{K\pi} = (192.1^{+3.7}_{-4.0})^\circ$
  $\rightarrow$ 3σ deviation from 180°, evidence for U-spin symmetry breaking



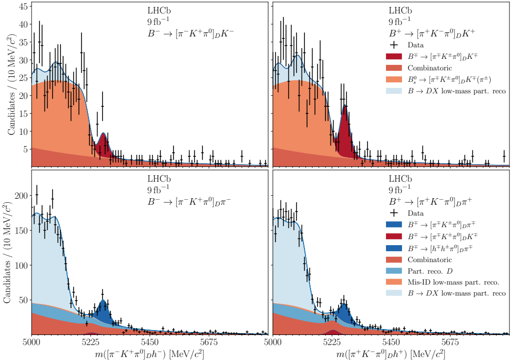


- Further improvement with simultaneous fit of γ

γ measurement with $B^{\pm} \to D(\to h^{\pm} h'^{\pm} \pi^0) h^{\pm}$

arXiv:2112.10617

- quasi-ADS modes $B^- \to D(\pi^{\mp} K^{\pm} \pi^0) h^-$:
  $\to$ r_D as magnitude ratio of the favored and suppressed D decay
- quasi-GLW modes $B^- \to D(\pi^- \pi^+ \pi^0) h^-$ and $B^- \to D(K^- K^+ \pi^0) h^-$:
  $\to$ admixtures of CP-even and CP-odd states
- Sensitivity to γ varies over the phase space, dilution factor κ_D from quantum-correlated $D\bar{D}$ pairs produced at $\psi(3770)$



- Simultaneous mass fit to 8 modes (16 subsamples) together

Mode	Yield
$B^{\pm} \to [K^{\pm} K^{\mp} \pi^0]_D \pi^{\pm}$	4026 ± 77
$B^{\pm} \to [\pi^{\pm} \pi^{\mp} \pi^0]_D \pi^{\pm}$	14180 ± 140
$B^{\pm} \to [K^{\pm} \pi^{\mp} \pi^0]_D \pi^{\pm}$	140696 ± 589
$B^{\pm} \to [\pi^{\pm} K^{\mp} \pi^0]_D \pi^{\pm}$	293 ± 27
$B^{\pm} \to [K^{\pm} K^{\mp} \pi^0]_D K^{\pm}$	401 ± 29
$B^{\pm} \to [\pi^{\pm} \pi^{\mp} \pi^0]_D K^{\pm}$	1189 ± 51
$B^{\pm} \to [K^{\pm} \pi^{\mp} \pi^0]_D K^{\pm}$	12265 ± 158
$B^{\pm} \to [\pi^{\pm} K^{\mp} \pi^0]_D K^{\pm}$	155 ± 19

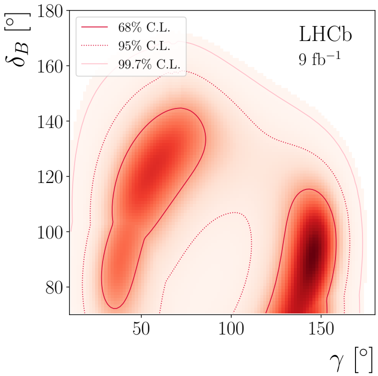
γ measurement with $B^{\pm} \to D(\to h^{\pm}h'^{\pm}\pi^0)h^{\pm}$

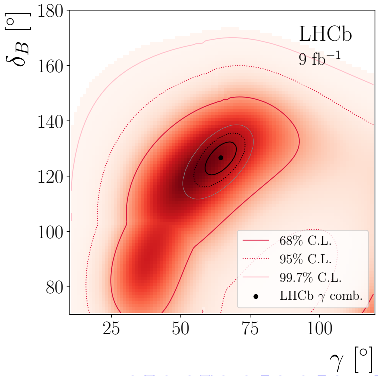
arXiv:2112.10617

- Suppressed $B^- \to D(\pi^- K^+ \pi^0)K^-$ decay is observed for the first time with a significance of 7.8 σ
- Eleven CP observables ($A_h^{hh'\pi^0}$, $R_h^{\pm}$) are measured with world-best precision

$$A_{K/\pi}^{hh\pi^0} = \frac{\Gamma(B^- \to D(hh\pi^0)K^-/\pi^-) - \Gamma(B^+ \to D(hh\pi^0)K^+/\pi^+)}{\Gamma(B^- \to D(hh\pi^0)K^-/\pi^-) + \Gamma(B^+ \to D(hh\pi^0)K^+/\pi^+)}$$

- $\gamma = (56^{+24}_{-19})^{\circ}$, $\delta_B = (122^{+19}_{-23})^{\circ}$, $r_B = (9.3^{+1.0}_{-0.9}) \times 10^{-2}$





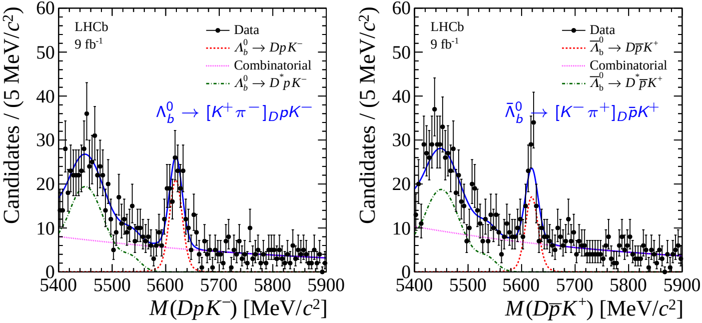
CPV search with $\Lambda_b^0 \to DpK^-$

PRD104(2021)112008

- Few studies of b-baryon decays to final states involving single open-charm meson exist, promising for measurements of CP violation
- First observation of $\Lambda_b^0 \to DpK^-$ with $D \to K^+\pi^-$

$$A_{CP} = \frac{\mathcal{B}(\Lambda_b^0 \to [K^+\pi^-]_D pK^-) - \mathcal{B}(\bar{\Lambda}_b^0 \to [K^-\pi^+]_D \bar{p}K^+)}{\mathcal{B}(\Lambda_b^0 \to [K^+\pi^-]_D pK^-) + \mathcal{B}(\bar{\Lambda}_b^0 \to [K^-\pi^+]_D \bar{p}K^+)}$$

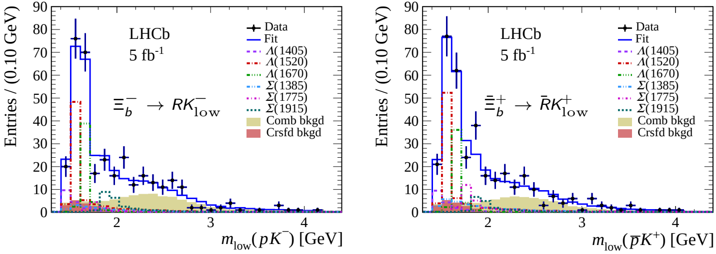
$\to A_{CP} = 0.12 \pm 0.09^{+0.02}_{-0.03}$, $R = \frac{\mathcal{B}(\Lambda_b^0 \to [K^+\pi^-]_D pK^-)}{\mathcal{B}(\Lambda_b^0 \to [K^-\pi^+]_D pK^-)} = 7.1 \pm 0.8^{+0.4}_{-0.3}$



CPV search with $\Xi_b^- \to pK^-K^-$

PRD104(2021)052010

- Large CP violation effects observed in three-body charmless B meson decays, $B \to hhh^{(\prime)}$ $(h = K, \pi)$
- No breaking of CP symmetry observed in any b-baryon yet
- First amplitude analysis of $\Xi_b^- \to pK^-K^-$ to measure A_{CP} of various resonances



Component	A^{CP} (10^{-2})
$\Sigma(1385)$	-27 ± 34 (stat) ± 73 (syst)
$\Lambda(1405)$	-1 ± 24 (stat) ± 32 (syst)
$\Lambda(1520)$	-5 ± 9 (stat) ± 8 (syst)
$\Lambda(1670)$	3 ± 14 (stat) ± 10 (syst)
$\Sigma(1775)$	-47 ± 26 (stat) ± 14 (syst)
$\Sigma(1915)$	11 ± 26 (stat) ± 22 (syst)

All are consistent with CP symmetry

Summary

- Numerous LHCb measurements dominate the world average for CKM angle and mixing parameters
  - ◇ First observation of mass difference in D^0 meson
  - ◇ First simultaneous combination of γ and charm mixing parameters
  - ◇ Most precise $B_s^0 - \bar{B}_s^0$ oscillation parameter Δm_s Nat.Phys.18(2022)1-5
  - ◇ Various CPV search in both charm and beauty decays
- A lot of more measurements are in good progress
- Run 3 is approaching! Exciting to see further improvement soon!

Stay tuned!

Thanks for your attention!

γ measurement

$$
\begin{aligned}
\Gamma(B^{\pm} \to Dh^{\pm}) \propto\ & r_D^2 + r_B^2 + 2\kappa_D\kappa_B r_D r_B cos(\delta_B + \delta_D \pm \gamma) \\
& - \alpha[(1 + r_B^2)\kappa_D r_D cos\delta_D - \alpha(1 + r_D^2)\kappa_B r_B cos(\delta_B \pm \gamma)]y \\
& + \alpha[(1 - r_B^2)\kappa_D r_D sin\delta_D - \alpha(1 - r_D^2)\kappa_B r_B sin(\delta_B \pm \gamma)]x
\end{aligned}
$$

- x and y are charm mixing parameters
- r_D and δ_D is the ratio of magnitudes and strong phase difference of DCS and CF D decay amplitudes
- For quasi-GLW modes, $r_D = 1$, $\delta_D = 0$ and $\kappa_D = 2F_+^f - 1$
- κ_D and κ_B are unity for two-body and account for a dilution of the interference term due to strong phase variation

LHCb combination with beauty and charm measurements

- Auxiliary parameters from other experiment

Decay	Parameters	Source	Ref.	Status since Ref. [17]
$B^\pm \to DK^{*\pm}$	$\kappa_{B^\pm}^{DK^{*\pm}}$	LHCb	[24]	As before
$B^0 \to DK^{*0}$	$\kappa_{B^0}^{DK^{*0}}$	LHCb	[45]	As before
$B^0 \to D^\mp\pi^\pm$	β	HFLAV	[11]	**Updated**
$B_s^0 \to D_s^\mp K^\pm\ (\pi\pi)$	ϕ_s	HFLAV	[11]	**Updated**
$D \to h^+h^-\pi^0$	$F_{\pi\pi\pi^0}^+$, $F_{K\pi\pi^0}^+$	CLEO-c	[46]	As before
$D \to \pi^+\pi^-\pi^+\pi^-$	$F_{4\pi}^+$	CLEO-c	[46]	As before
$D \to K^+\pi^-\pi^0$	$r_D^{K\pi\pi^0}$, $\delta_D^{K\pi\pi^0}$, $\kappa_D^{K\pi\pi^0}$	CLEO-c+LHCb+BESIII	[47,48,49]	**Updated**
$D \to K^\pm\pi^\mp\pi^+\pi^-$	$r_D^{K3\pi}$, $\delta_D^{K3\pi}$, $\kappa_D^{K3\pi}$	CLEO-c+LHCb+BESIII	[41,47,48,49]	**Updated**
$D \to K_S^0K^\pm\pi^\mp$	$r_D^{K_S^0K\pi}$, $\delta_D^{K_S^0K\pi}$, $\kappa_D^{K_S^0K\pi}$	CLEO	[50]	As before
$D \to K_S^0K^\pm\pi^\mp$	$r_D^{K_S^0K\pi}$	LHCb	[51]	As before

- Assumptions: negligible effect at the current precision
  - ◇ Neutral kaon mixing
  - ◇ *CP* violation in *D*-meson decays
  - ◇ Strong phases in $D \to K_s^0 h^+ h^-$ decays
  - ◇ Correlations of systematic uncertainties between input measurements

γ measurement with $B^\pm \to D(\to h^\pm h'^\pm \pi^0) h^\pm$

arXiv:2112.10617

- Eleven observables with world-best precision

$$R^{\mp}_{ADS(h)} = \frac{\Gamma(B^\mp \to D(\pi^\mp K^\pm \pi^0) h^\mp)}{\Gamma(B^\mp \to D(K^\mp \pi^\pm \pi^0)) h^\mp}, \quad R^{hh\pi^0}_{K/\pi} = \frac{\Gamma(B^- \to D(hh\pi^0) K^-/\pi^-)}{\Gamma(B^- \to D(K^-\pi^+\pi^0)) K^-/\pi^-)}$$

$$A^{hh\pi^0}_{K/\pi} = \frac{\Gamma(B^- \to D(hh\pi^0)K^-/\pi^-) - \Gamma(B^+ \to D(hh\pi^0)K^+/\pi^+)}{\Gamma(B^- \to D(hh\pi^0)K^-/\pi^-) + \Gamma(B^+ \to D(hh\pi^0)K^+/\pi^+)}$$

$$\begin{aligned}
R^{KK\pi^0} &= 1.021 \pm 0.079 \pm 0.005\\
R^{\pi\pi\pi^0} &= 0.902 \pm 0.041 \pm 0.004\\
A^{K\pi\pi^0}_K &= -0.024 \pm 0.013 \pm 0.002\\
A^{KK\pi^0}_K &= 0.067 \pm 0.073 \pm 0.003\\
A^{\pi\pi\pi^0}_K &= 0.109 \pm 0.043 \pm 0.003\\
A^{KK\pi^0}_\pi &= -0.001 \pm 0.019 \pm 0.002\\
A^{\pi\pi\pi^0}_\pi &= 0.001 \pm 0.010 \pm 0.002\\
R^+_K &= 0.0179 \pm 0.0024 \pm 0.0003\\
R^-_K &= 0.0085 \pm 0.0020 \pm 0.0004\\
R^+_\pi &= 0.00188 \pm 0.00027 \pm 0.00005\\
R^-_\pi &= 0.00227 \pm 0.00028 \pm 0.00004.
\end{aligned}$$