


# CKM, CP violation and mixing results at LHCb

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*on behalf of the LHCb collaboration*

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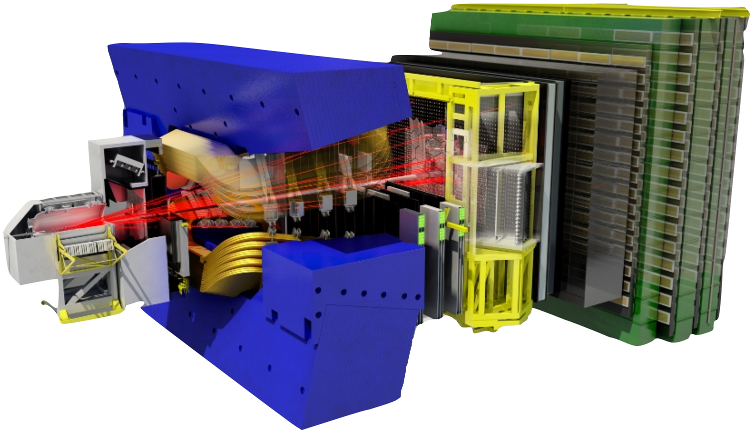


Charm physics:

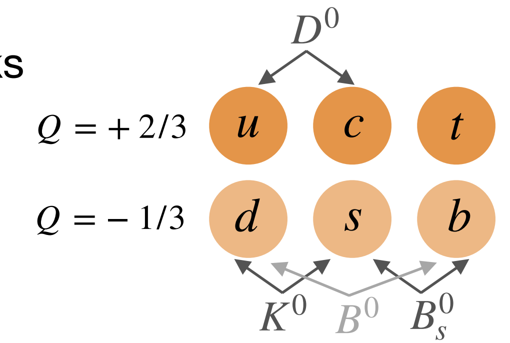
- $A_{CP}(D^0 \to K^0_S K^0_S)$
  PRD 104 (2021) L031102
- $A_{CP}(D^+_{(s)} \to h^+\pi^0, h^+\eta)$
  JHEP 06 (2021) 019
- time-dependent *CP* violation in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$
  arXiv:2105.09889
- mixing and time-dependent *CP* violation in $D^0 \to K^0_S\pi^+\pi^-$
  arXiv:2106.03744

Beauty physics:

- first $\gamma$+charm simultaneous combination
  LHCb-CONF-2021-001, LHCb-PAPER-2021-033 (in preparation)
- $\Delta m_s$ with $B^0_s \to D^-_s\pi^+$ decays
  arXiv:2104.04421
- amplitude analysis of $\Xi^-_b \to pK^-K^-$
  arXiv:2104.15074

# *CP* violation and mixing in charm

Charm neutral mesons are the only ones made up of up-type quarks
→ complementary sensitivity to BSM



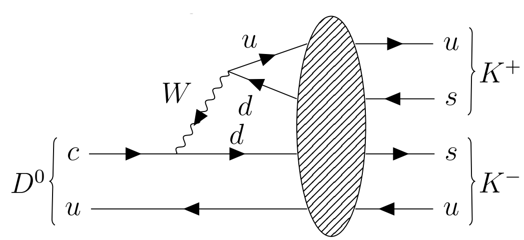

Mixing and CPV suppressed by

- **smallness of CKM elements involved:** $CPV \propto \mathrm{Im}\left(\frac{V_{cb}V^*_{bu}}{V_{cs}V^*_{su}}\right) \approx -6 \times 10^{-4}$
- **GIM mechanism** ($m_b/m_W \ll m_t/m_W$, $d$ and $s$ contributions cancel in *SU(3)*$_F$ limit)

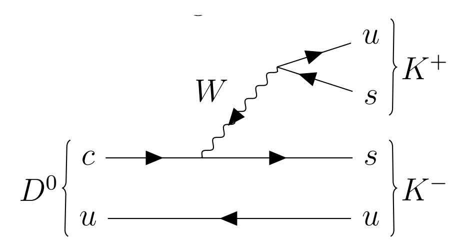
Need further measurements to confirm rescattering origin of first observation of CPV in the decay
($\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$
PRL 122 (2019) 211803)

e.g. Grossman & Schacht 2019

$$\begin{array}{cccc} & d & s & b \\ V_{\mathrm{CKM}} = & \left(\begin{array}{ccc} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda \; -iA\lambda^5\eta & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{array}\right) & \begin{array}{c} u \\ c \\ t \end{array} & + \mathcal{O}(\lambda^4) \end{array}$$




$\pi^+\pi^- \to K^+K^-$ rescattering



Kagan & Silvestrini 2021

# $CP$ violation and mixing in charm

Theoretical parametrisation of mixing:

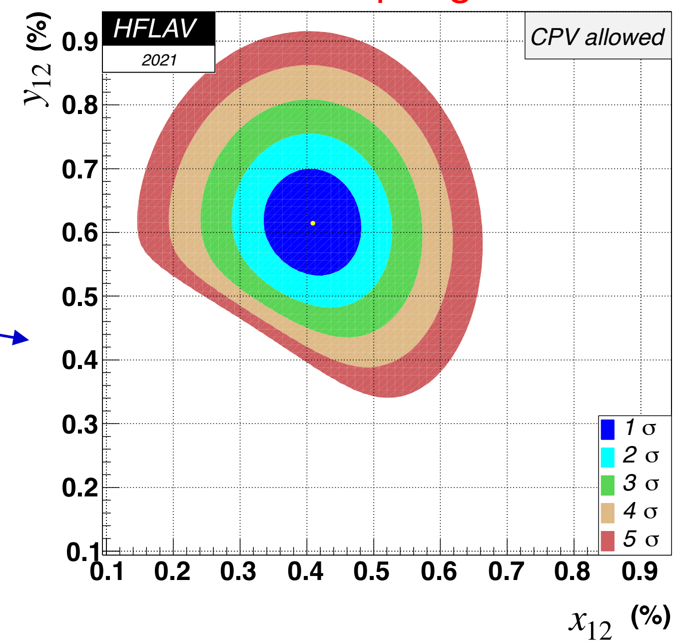
$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix}$$

*off-shell transitions. NP?* *on-shell transitions*

$$x_{12} \equiv \frac{2|M_{12}|}{\Gamma} \approx \frac{|\Delta m|}{\Gamma}$$
$$y_{12} \equiv \frac{|\Gamma_{12}|}{\Gamma} \approx \frac{|\Delta\Gamma|}{2\Gamma}$$

**mixing parameters**
(set the oscillation probability)

First observation that $x_{12} \neq 0$ this spring arXiv:2106.03744




$$\phi_2^M \equiv \arg\left(\frac{M_{12}}{M_{12}^{\Delta U=2}}\right)$$
$$\phi_2^\Gamma \equiv \arg\left(\frac{\Gamma_{12}}{\Gamma_{12}^{\Delta U=2}}\right)$$

**dispersive and absorptive mixing phases**
(responsible for CPV)

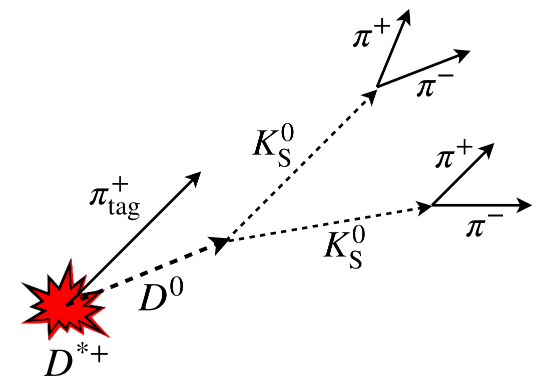
defined with respect to the dominant
$\Delta U = 2$ matrix elements (calculated in the SM)

No signs of CPV in the mixing so far

Independent test of the SM
wrt CPV in the decay
$\phi_2^M, \phi_2^\Gamma \approx 2\,\mathrm{mrad}$ in the SM
current precision is 20 and 30 mrad

Kagan & Silvestrini 2021
Grossman et al. (in preparation)
Li, Umeeda, Xu, Yu 2020

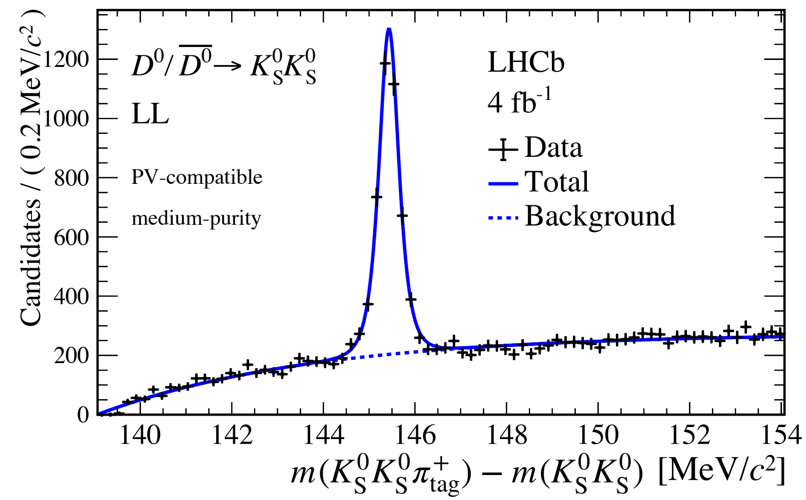
# *CP* violation in $D^0 \to K^0_S K^0_S$

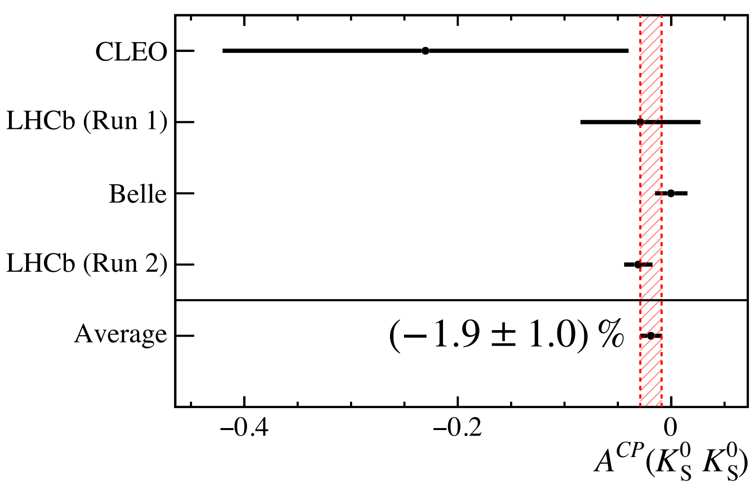



$A_{CP}(D^0 \to K^0_S K^0_S)$ can be larger than in other channels such as $D^0 \to K^+K^-$ (see backup):

- BR tends to zero in the $SU(3)_F$ limit
- *CP*-violating interference terms don't

- Run 2 data sample (2015–2018)
- Flavour tag from $D^{*+} \to D^0\pi^+_{\rm tag}$ decays
- use $K^0_S$ decayed both within or outside of the vertex detector
- **8k** candidates




$$A_{CP}(D^0 \to K^0_S K^0_S) = (-3.1 \pm 1.2({\rm stat}) \pm 0.4({\rm sys}) \pm 0.2)\ \%$$

compatible with zero within $2.4\,\sigma$

from control channel $A_{CP}(D^0 \to K^+K^-)$ PLB 767 (2017) 177

**World best measurement**

Previous was Belle $(0.0 \pm 1.5 \pm 0.2)$ % PRL 119 (2017) 171801

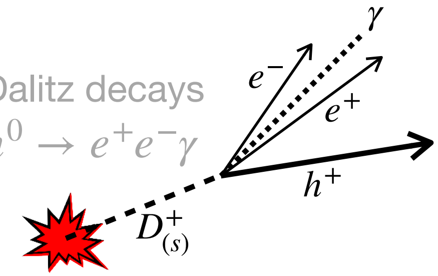
JHEP 06 (2021) 019

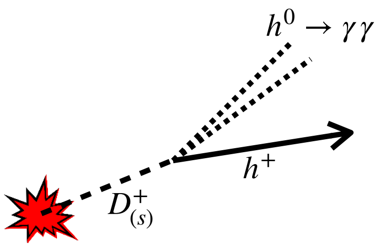
# *CP* violation in $D^+_{(s)} \to h^+h^0$ $\quad h^+ = \pi^+, K^+$ $\quad h^0 = \pi^0, \eta$

- Precision on $SU(3)_\mathrm{F}$ sum rules relating the relative size of $A_{CP}$ for different decay modes is often limited by decays with neutrals.
- $A_{CP}(D^+ \to \pi^+\pi^0) < 10^{-5}$ in the SM due to isospin selection rules

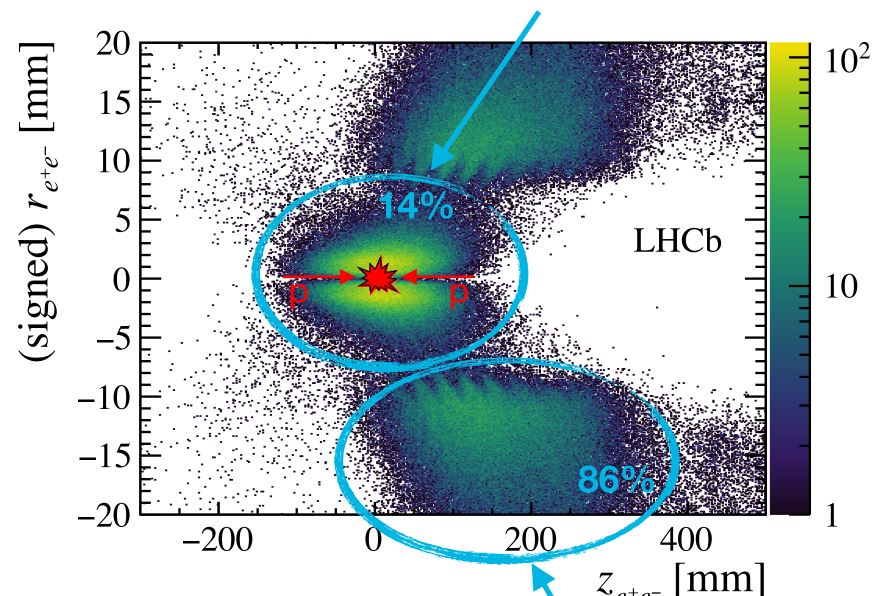
This is the first attempt to measure them at a hadron collider

Dalitz decays
$h^0 \to e^+e^-\gamma$



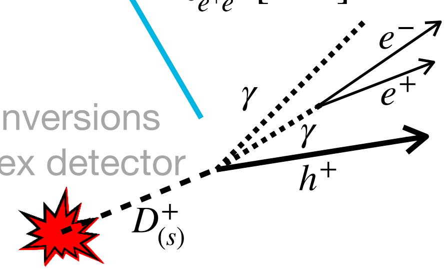

cannot reconstruct the $D^+_{(s)}$ decay vertex from a single displaced track
→ employ $e^+e^-\gamma$ final state for $h^0$




world best → $A_{CP}(D^+ \to \pi^+\pi^0) = (-1.3 \pm 0.9 \pm 0.6)\,\%$
world best → $A_{CP}(D^+ \to K^+\pi^0) = (-3.2 \pm 4.7 \pm 2.1)\,\%$
$A_{CP}(D_s^+ \to K^+\pi^0) = (-0.8 \pm 3.9 \pm 1.2)\,\%$

world best → $A_{CP}(D^+ \to \pi^+\eta) = (-0.2 \pm 0.8 \pm 0.4)\,\%$
$A_{CP}(D_s^+ \to \pi^+\eta) = (0.8 \pm 0.7 \pm 0.5)\,\%$
world best → $A_{CP}(D^+ \to K^+\eta) = (-6 \pm 10 \pm 4)\,\%$
$A_{CP}(D_s^+ \to K^+\eta) = (0.9 \pm 3.7 \pm 1.1)\,\%$

photon conversions in the vertex detector

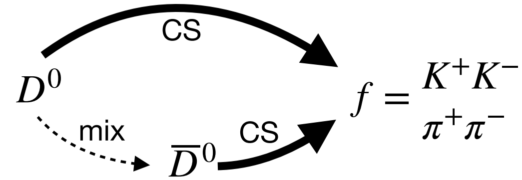


arXiv:2105.09889

# Time-dependent *CPV* in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$

$x_{12}, y_{12} \ll 1$

$$A_{CP}(f,t) \equiv \frac{\Gamma(D^0 \to f,t) - \Gamma(\bar{D}^0 \to f,t)}{\Gamma(D^0 \to f,t) + \Gamma(\bar{D}^0 \to f,t)} \approx a_f^d + \Delta Y_f \frac{t}{\tau_{D^0}}$$

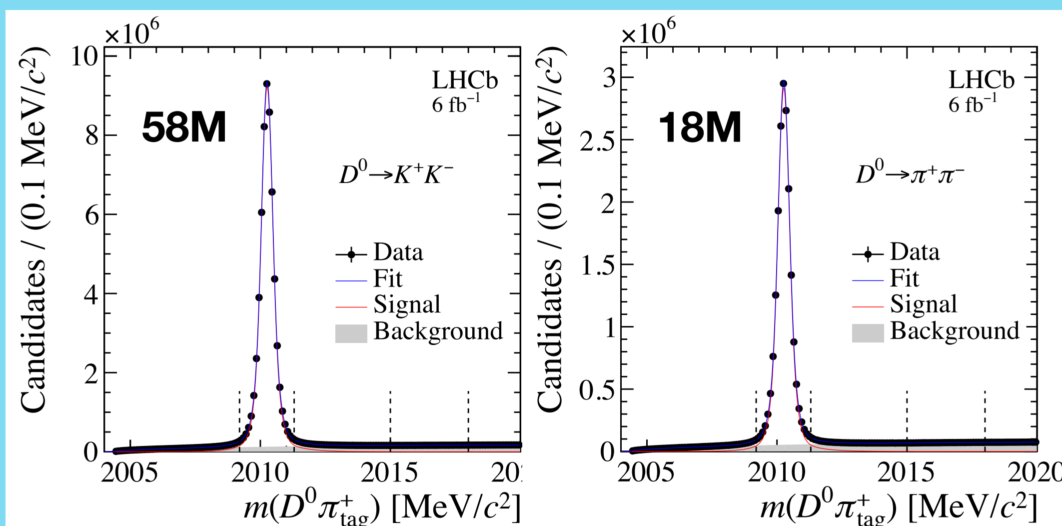



$$\Delta Y_f \approx -x_{12} \sin \phi_2^M$$

N.B. $\Delta Y \approx -A_\Gamma$

**Needed to measure *CPV* in the decay** from time-integrated $A_{CP}(K^+K^-)$:

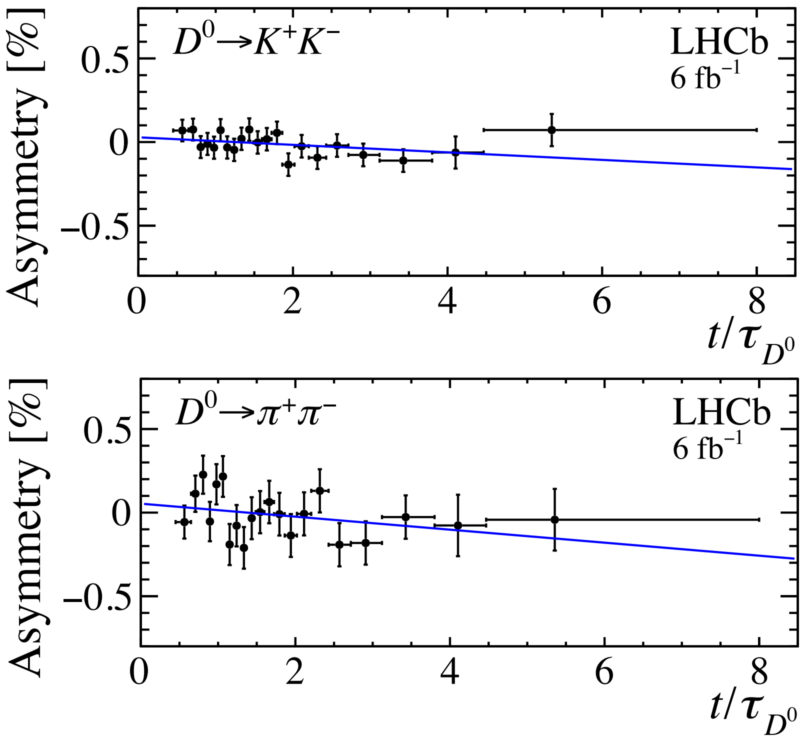
$$A_{CP}(K^+K^-) \approx a^d_{K^+K^-} + \Delta Y_{K^+K^-} \frac{\langle t \rangle_{K^+K^-}}{\tau_{D^0}}$$

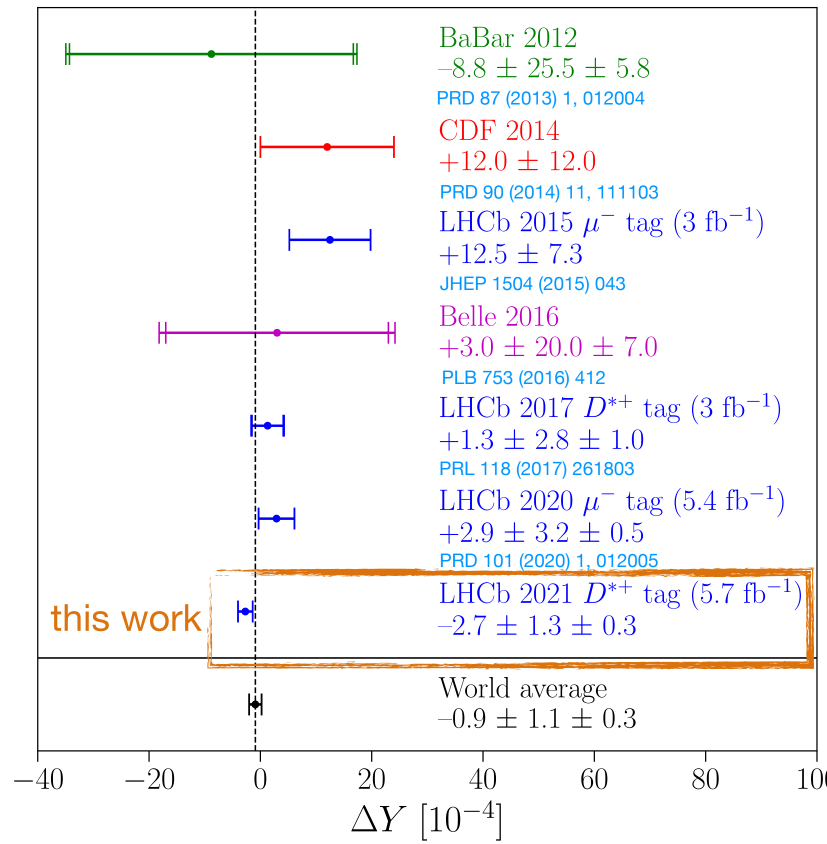



- 2015–2018 sample
- $D^{*+} \to D^0\pi^+_{\rm tag}$ flavour tagging
- instrumental asymmetries causing biases as large as 6x the exp. unc. are removed by equalising the kinematics of $D^0$ and $\overline{D}^0$ candidates
- asymmetry measured in 21 bins of decay time

**Method is validated on a sample of 518M $D^0 \to K^-\pi^+$ decays** → $\Delta Y_{K^-\pi^+} = (-0.4 \pm 0.5) \times 10^{-4}$ (known to be smaller than $0.2 \times 10^{-4}$)

# Time-dependent *CPV* in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$




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

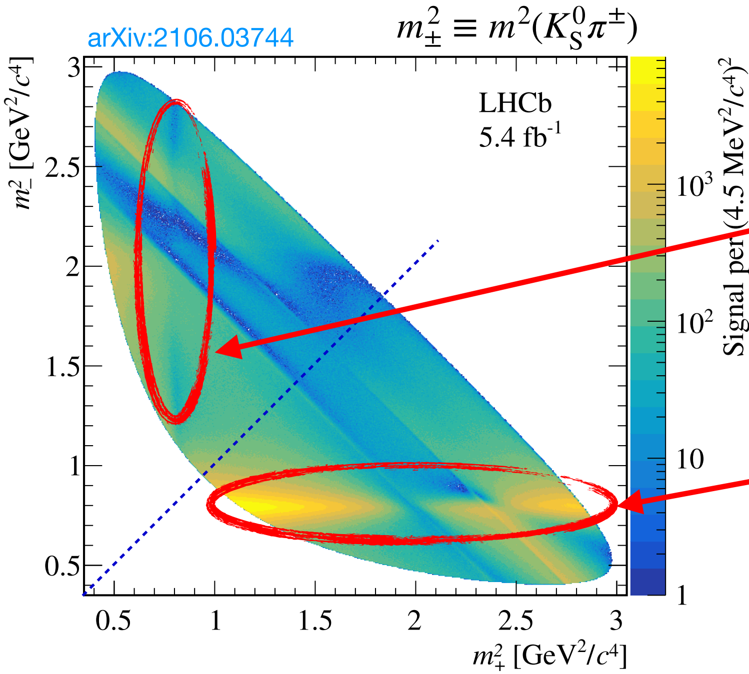
$$\Delta Y_{\pi^+\pi^-} = (-4.0 \pm 2.8 \pm 0.4) \times 10^{-4}$$

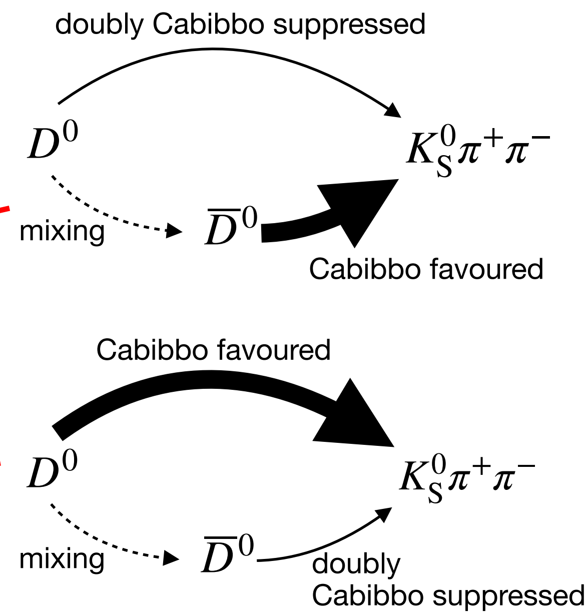
$1.3 \times 10^{-4}$ precision

Previous world average:

$\Delta Y = (3.0 \pm 2.0 \pm 0.5) \times 10^{-4}$

# Mixing and CPV with $D^0 \to K_S^0\pi^+\pi^-$




$m^2_+ < m^2_-$: mixed decays are more and more important as time passes.

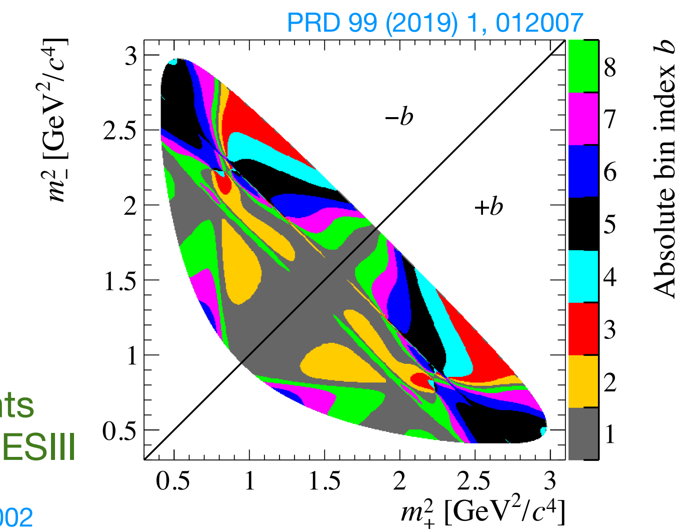
$m^2_+ > m^2_-$: dominated by unmixed CF **$D^0 \to K^*(892)^-\pi^+$** decays.

## ***Bin-flip method*** PRD 99 (2019) 1, 012007

Bin the Dalitz plane to keep strong-phase difference $\delta$ across the bisector approximately constant.

Measure ratio of yields in opposite bins across the bisector as a function of time:

- most acceptance effects and instrumental asymmetries cancel out in the ratio;
- ratios increase with $x_{12}\sin\delta$, $y_{12}\cos\delta$ external constraints from CLEO and BESIII PRD 82 (2010) 112006 PRD 101 (2020) 11, 112002
- **model-independent.**



arXiv:2106.03744

# Mixing and CPV with $D^0 \to K^0_S\pi^+\pi^-$

$X_b \equiv \langle e^{-i\delta}\rangle_b \equiv c_b - is_b$

$z_{CP} \equiv -(y_{CP} + i x_{CP})$

$\Delta z \equiv -(\Delta y + i\Delta x)$

$x_{CP} = +x_{12}\cos\phi_2^M$

$y_{CP} = +y_{12}\cos\phi_2^\Gamma$

$\Delta x = -y_{12}\sin\phi_2^\Gamma$

$\Delta y = +x_{12}\sin\phi_2^M$

$\Delta y = -\Delta Y$

Ratio of candidates in opposite bins across the Dalitz bisector:

$D^0/\overline{D}^0$ ratio at time zero

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

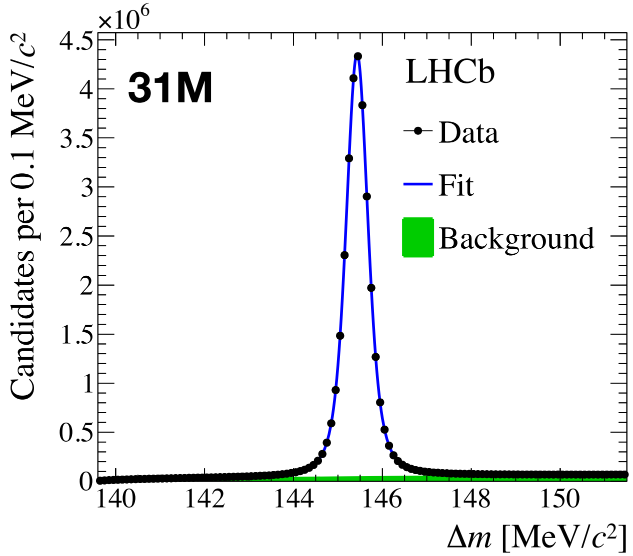
Dalitz bin

time bin

leading order:

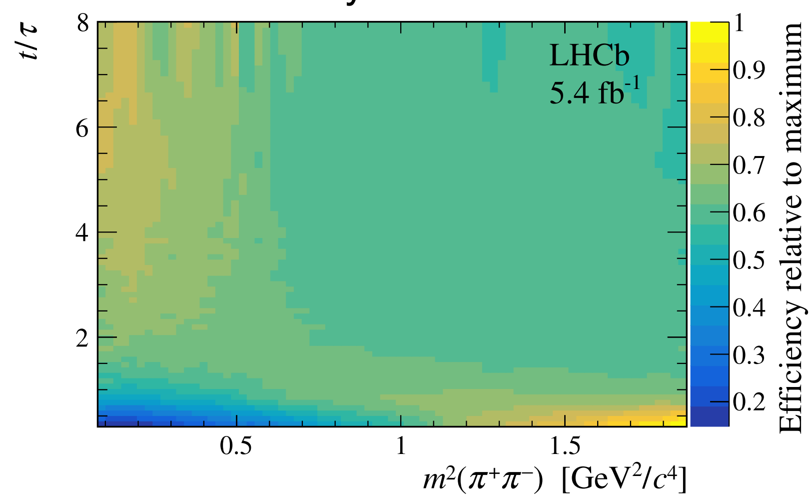
$$R^\pm_{bj} \approx r_b + \sqrt{r_b}\left[s_b(1 + r_b)(x_{CP} \pm \Delta x) - c_b(1 - r_b)(y_{CP} \pm \Delta y)\right]\langle t\rangle_j$$

- $D^{*+} \to D^0\pi^+_{\mathrm{tag}}$ flavour tagging
- 2016–2018 sample (23× w.r.t. 2011–2012)




Data-driven corrections for:

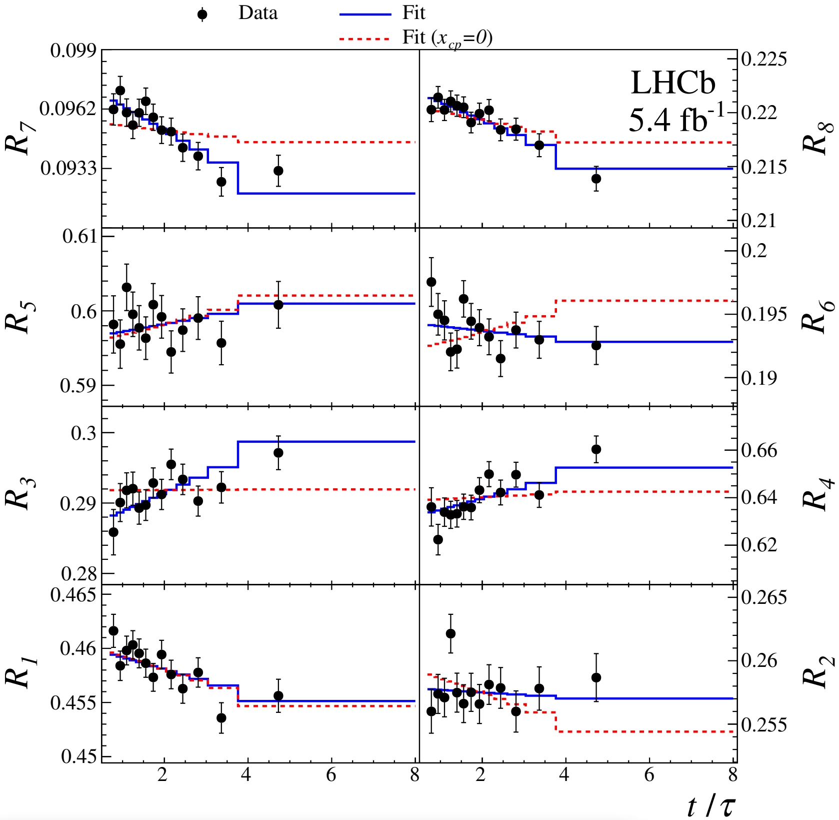
- detection asymmetry of $\pi^+\pi^-$ pair (from Cabibbo-favoured $D_s^+ \to \pi^+\pi^+\pi^-$ on and off the $\phi(1020)$ mass shell)
- variations of efficiency as a function of t and $m(\pi^+\pi^-)$



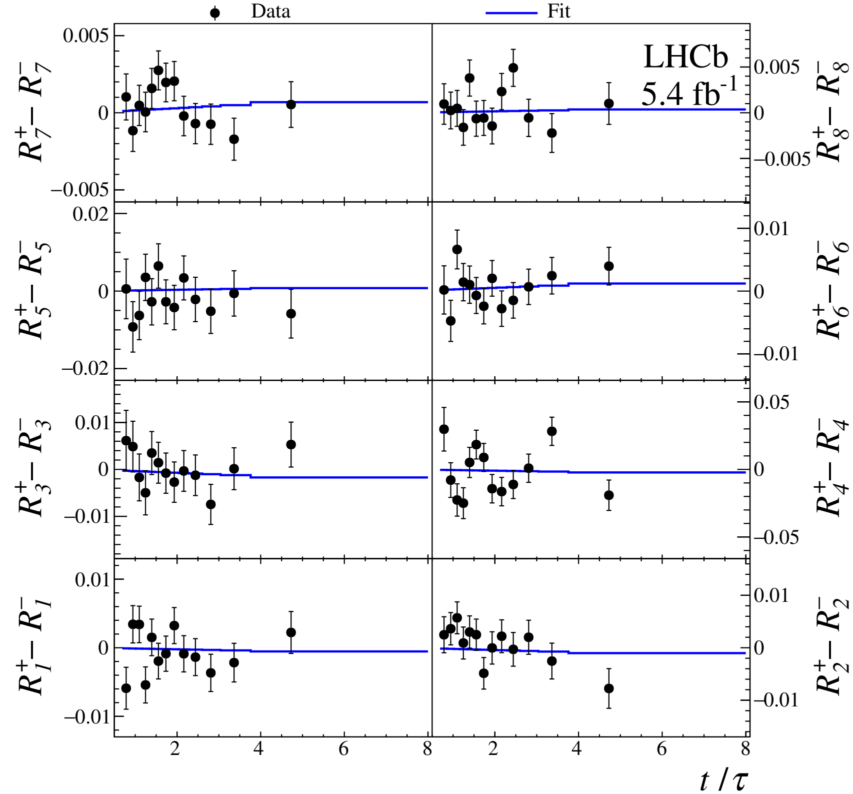
arXiv:2106.03744

# Mixing and CPV with $D^0 \to K^0_S \pi^+ \pi^-$

Deviations from constant values are due to mixing




Deviations from zero are due to CP violation




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

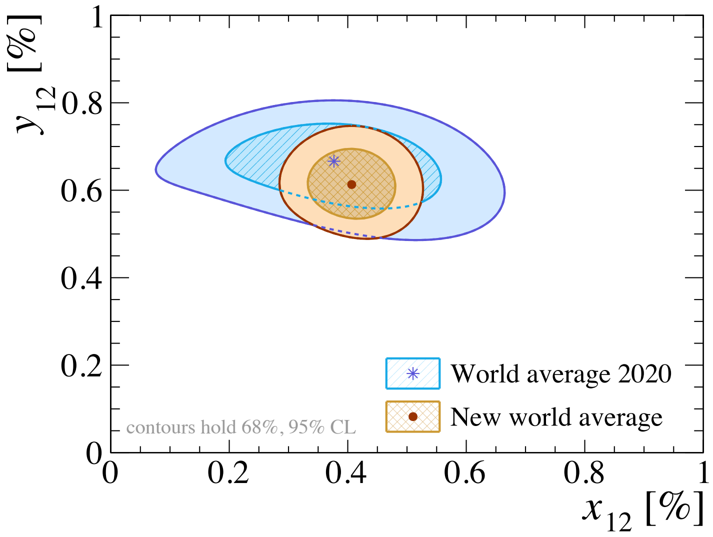
First observation of $x_{CP} \approx x_{12} \neq 0 \quad (7\sigma)$

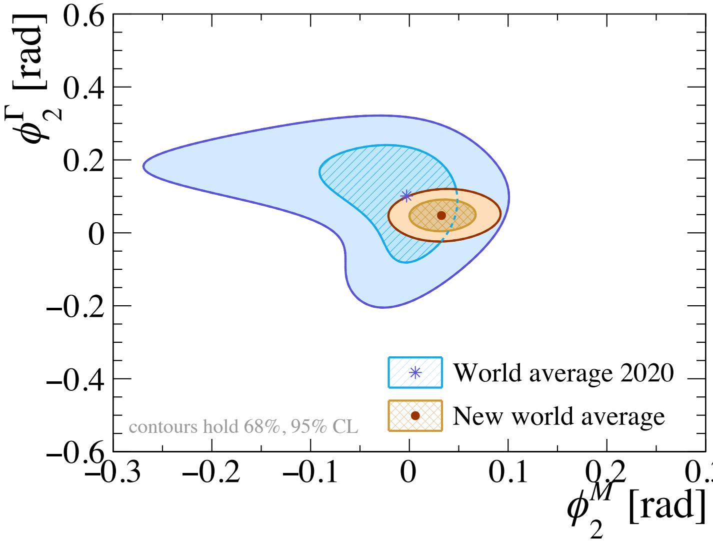
Largest systematics:

- trigger-induced efficiency variations
- wrong time measurement for secondary charm from B mesons

External inputs on strong phases → 40% of stat. unc. on $x_{12}$

# Impact on global fits




$x_{12} = (4.07 \pm 0.49) \times 10^{-3}$ ×2.5 improvement

$y_{12} = (6.13 \pm 0.53) \times 10^{-3}$ ×1.2 improvement

$\phi_2^M = (0.033 \pm 0.022)$ rad ×1.6 improvement

$\phi_2^\Gamma = (0.048 \pm 0.029)$ rad ×3 improvement

Improvements are mainly driven by $D^0 \to K_S^0 \pi^+ \pi^-$. $\Delta Y$ contributes to $\phi_2^M$

Both $\phi_2^M$ and $\phi_2^\Gamma$ are approximately equal to zero (rather than π):

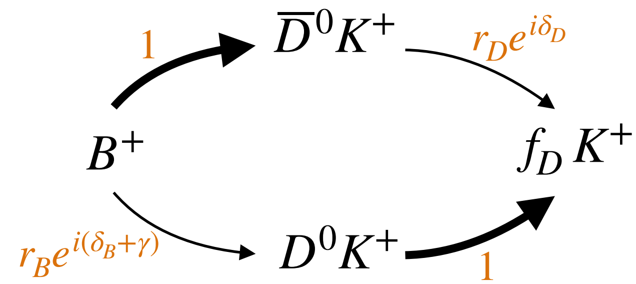
**the nearly CP-even $D$ eigenstate is shorter-lived and heavier**

# Simultaneous $\gamma$ + charm combination

Many new/updated $\gamma$ measurements since the last combination $\gamma = (74.0^{+5.0}_{-5.8})^\circ$.
LHCb-CONF-2018-002
Precision driven by golden modes $B^+ \to Dh^+$:

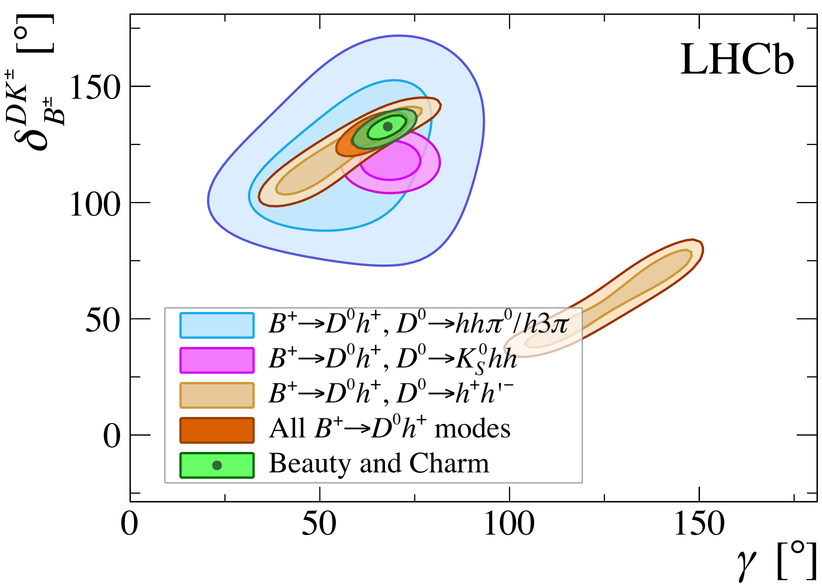
- BPGSSZ $D \to K^0_S\pi^+\pi^-$ JHEP 02 (2021) 169
- ADS/GLW $D \to h^+h'^-$ JHEP 04 (2021) 081

full list in backup




(2 body)

$$\Gamma(B^\pm \to \overset{(-)}{f}_D\, K^\pm) \propto |r_D e^{i\delta_D} + r_B e^{i(\delta_B \pm \gamma)}|^2$$
$$= r_D^2 + r_B^2 + r_D r_B \cos(\delta_B + \delta_D \pm \gamma)$$



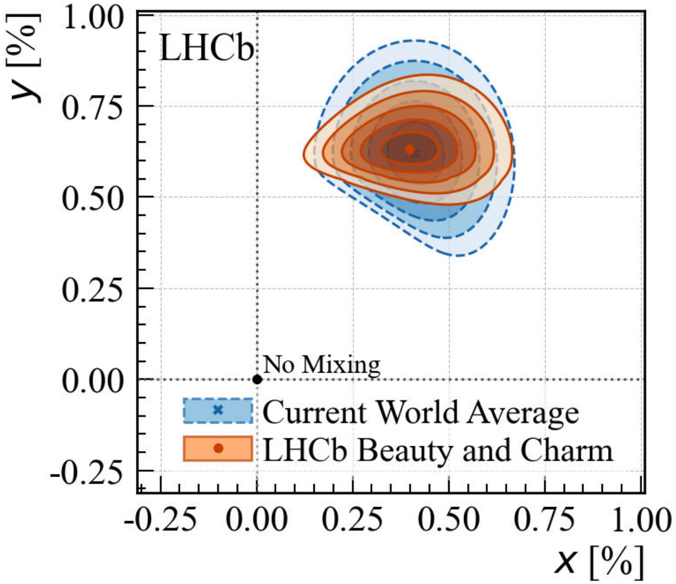

Small overlap of ADS $D \to K^+\pi^-$ with the contour of the total combination allows to **measure $\delta_D^{K\pi}$ with precision similar to combination of $\delta_B^{DK}$ (4°)**
**→ 2x better than charm-only fit**

Motivates a simultaneous fit to
γ + charm mixing and CPV

$$\gamma = \arg\left(-\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right)$$

LHCb-CONF-2021-001
LHCb-PAPER-2021-033 (in preparation)

# Simultaneous $\gamma$ + charm combination




$\delta_D^{K\pi}$ is highly correlated with $y_{12}$

- precision driven by measurement of $y' \equiv -y_{12}\cos\delta_D^{K\pi} + x_{12}\sin\delta_D^{K\pi}$ in $D^0 \to K^+\pi^-$ decays

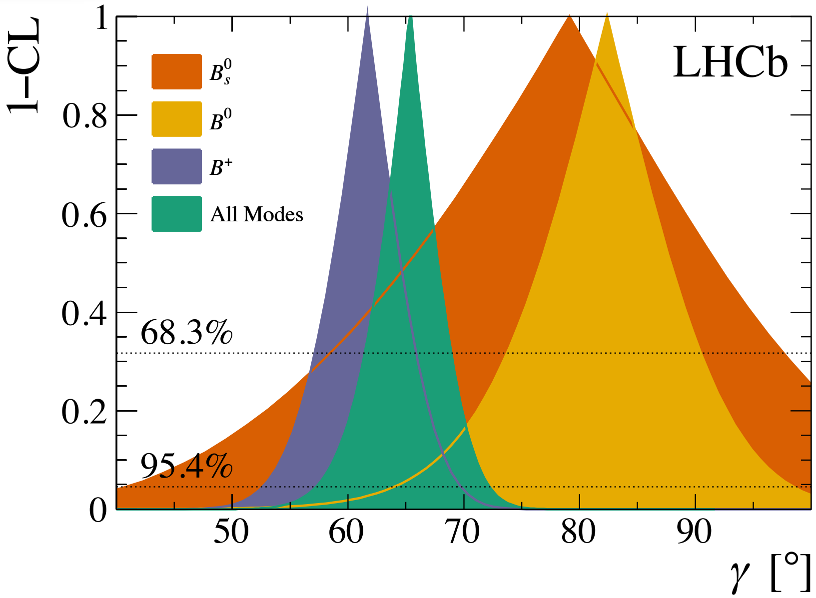
$$x_{12} = (4.00^{+0.52}_{-0.53}) \times 10^{-3}$$
$$y_{12} = (6.30^{+0.33}_{-0.30}) \times 10^{-3} \longleftarrow \text{1.8x improvement}$$
$$\delta_D^{K\pi} = (190.0^{+4.2}_{-4.1})^\circ \longleftarrow \text{2x improvement}$$

$$\gamma = (65.4^{+3.8}_{-4.2})^\circ$$

Compatible with indirect determinations

$\gamma = (65.7^{+0.9}_{-2.7})^\circ$ CKMfitter

$\gamma = (65.8 \pm 2.2)^\circ$ UTFit




frequentist approach
52 parameters
157 observables
fit probability: 67%

details (and new measurement of ADS $\Lambda_b^0 \to [K^+\pi^-]_D pK^-$) in backup

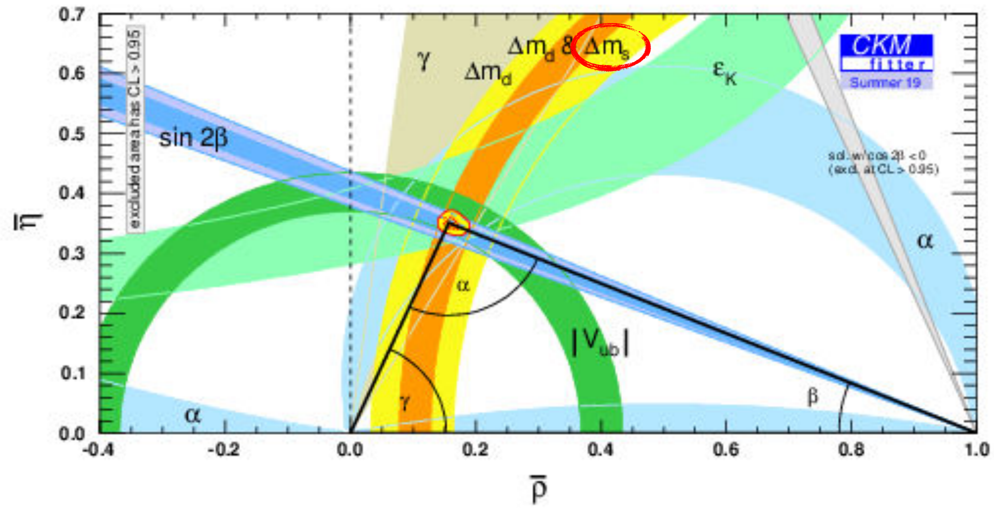
LHCb-CONF-2021-001
LHCb-PAPER-2021-033 (in preparation)

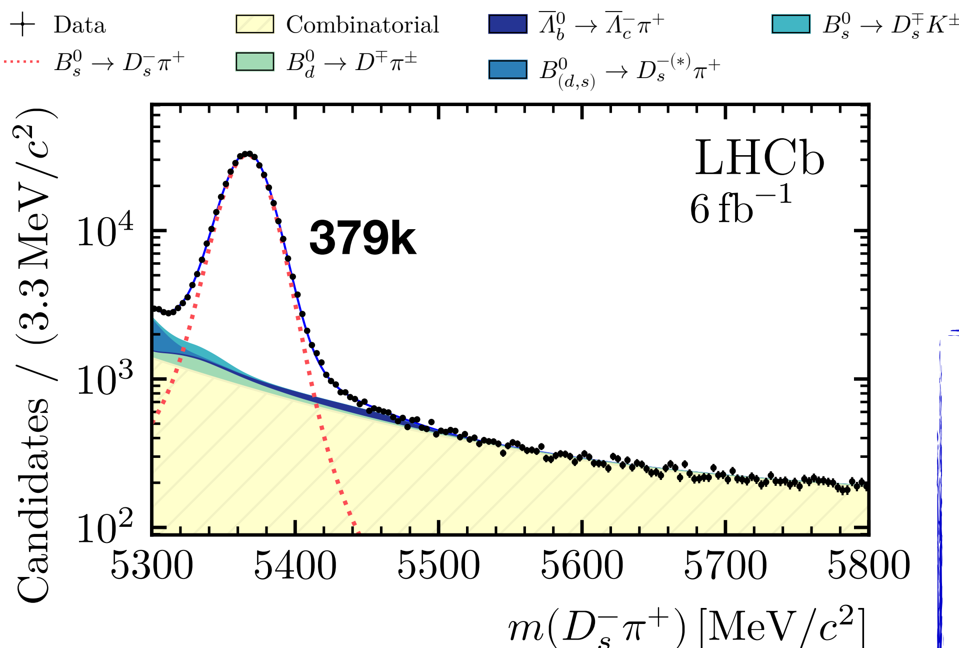
arXiv:2104.04421

# $\Delta m_s$ with $B_s^0 \to D_s^- \pi^+$ decays

- Constrain the CKM triangle (with $\Delta m_d$)
- reduce systematic uncertainty in CPV measurement of $\gamma - 2\beta_s$

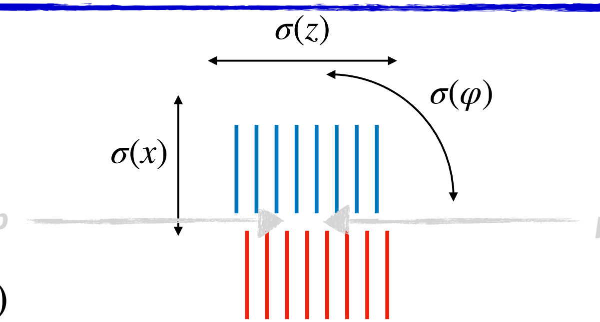
JHEP 03 (2018) 059




- Run 2 sample
- use both $D_s^- \to K^+ K^- \pi^-$ and $D_s^- \to \pi^+ \pi^- \pi^-$
- sWeights for time-dependent fit from 2D fit to $D_s^-$ and $B_s^0$ mass (~13% combinatorial, ~2% physical bkg.)

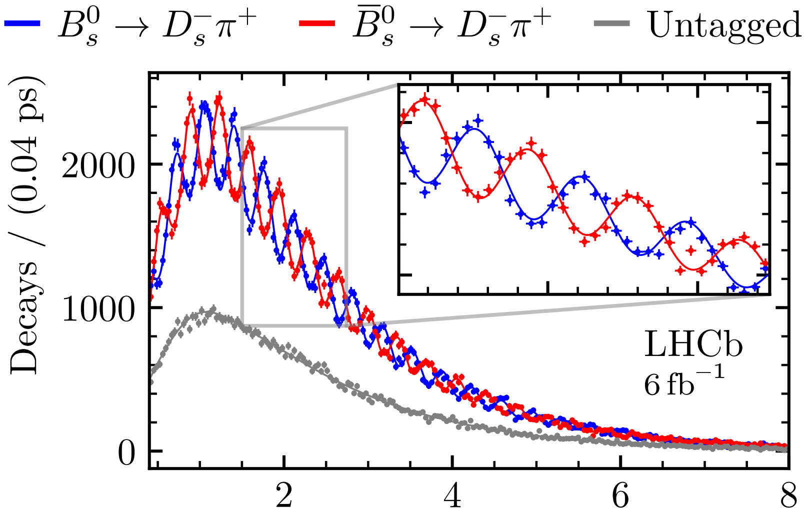
Control **vertex-detector alignment and length scale** at high precision to measure $t(B_s^0)$

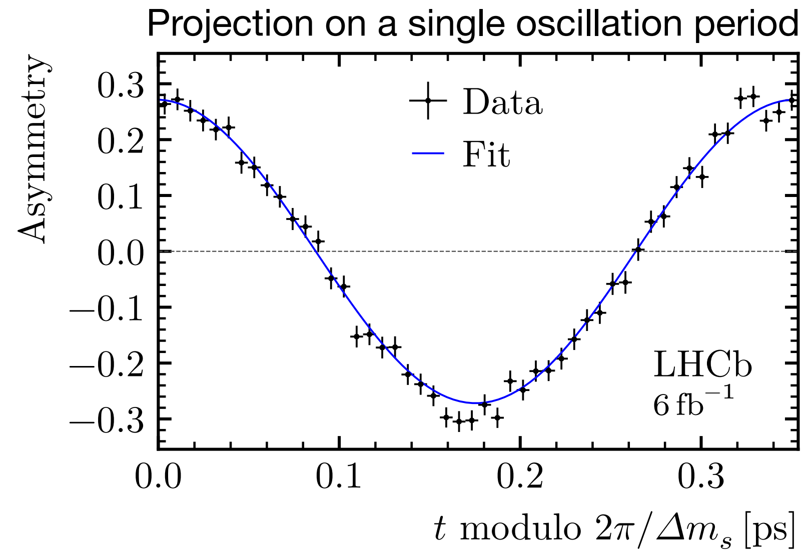



courtesy of Kevin Heinicke

arXiv:2104.04421

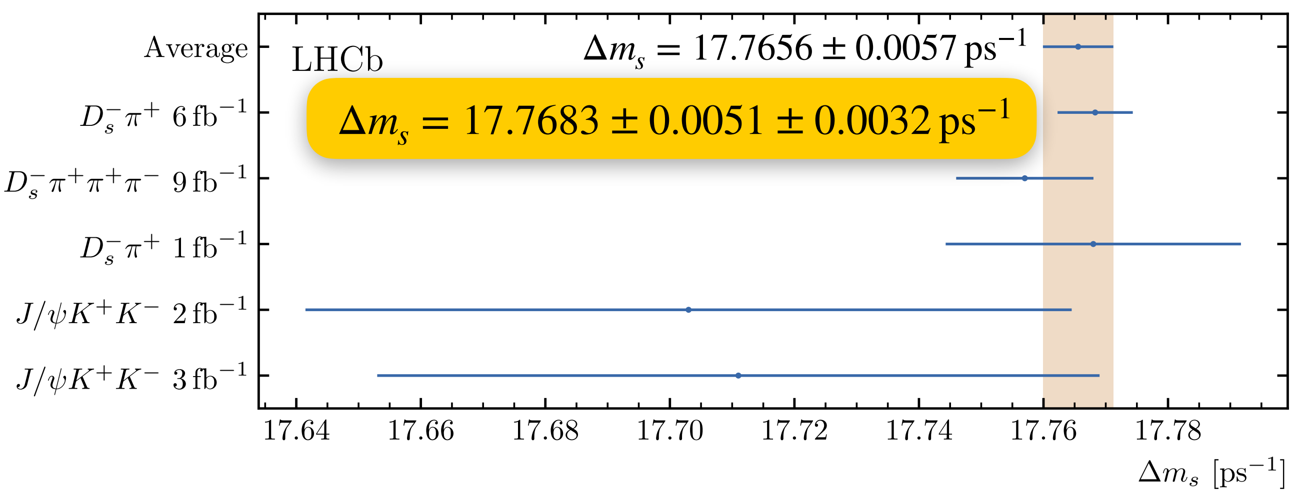
# $\Delta m_s$ with $B_s^0 \to D_s^- \pi^+$ decays




$$e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) \pm \cos(\Delta m_s t)\right]$$

+ flavour tagging, time acceptance and resolution

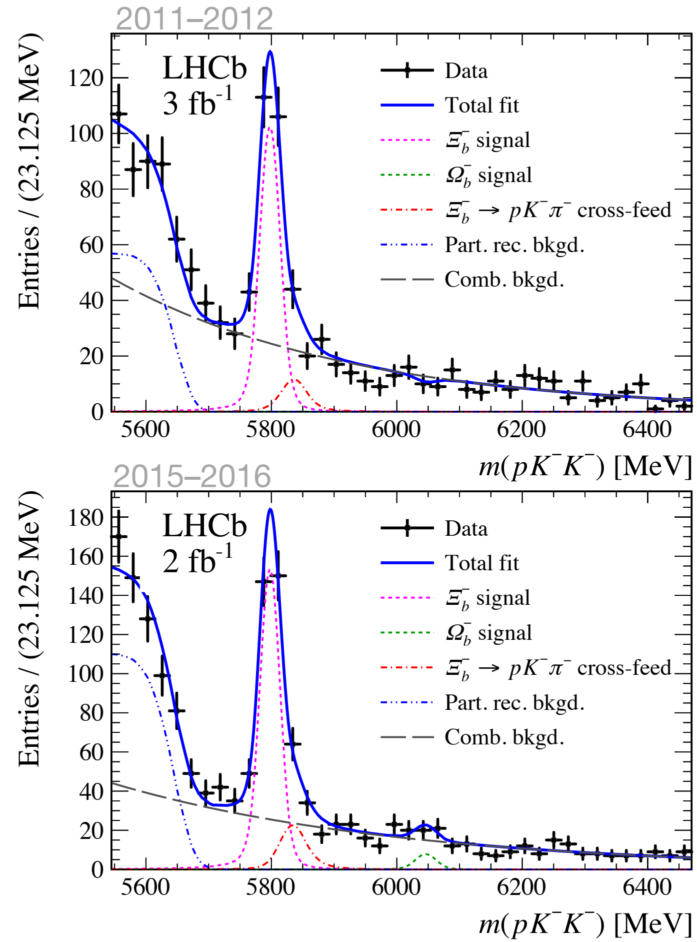



3 x 10-4 precision

arXiv:2104.15074

# Amplitude analysis of $\Xi_b^- \to pK^-K^-$

- 2011–2012 (5 fb$^{-1}$) + 2015–2016 (5 fb$^{-1}$) sample
- signal window $m(\Xi_b^-) \pm 40\,\mathrm{MeV}/c^2$
  - 193 + 297 candidates
  - 63% and 70% purity




Updated search for $\Omega_b^- \to pK^-K^-$

$$\mathcal{R} \equiv \frac{f_{\Omega_b^-}}{f_{\Xi_b^-}} \times \frac{\mathcal{B}(\Omega_b^- \to pK^-K^-)}{\mathcal{B}(\Xi_b^- \to pK^-K^-)} < 62\ (71) \times 10^{-3}$$

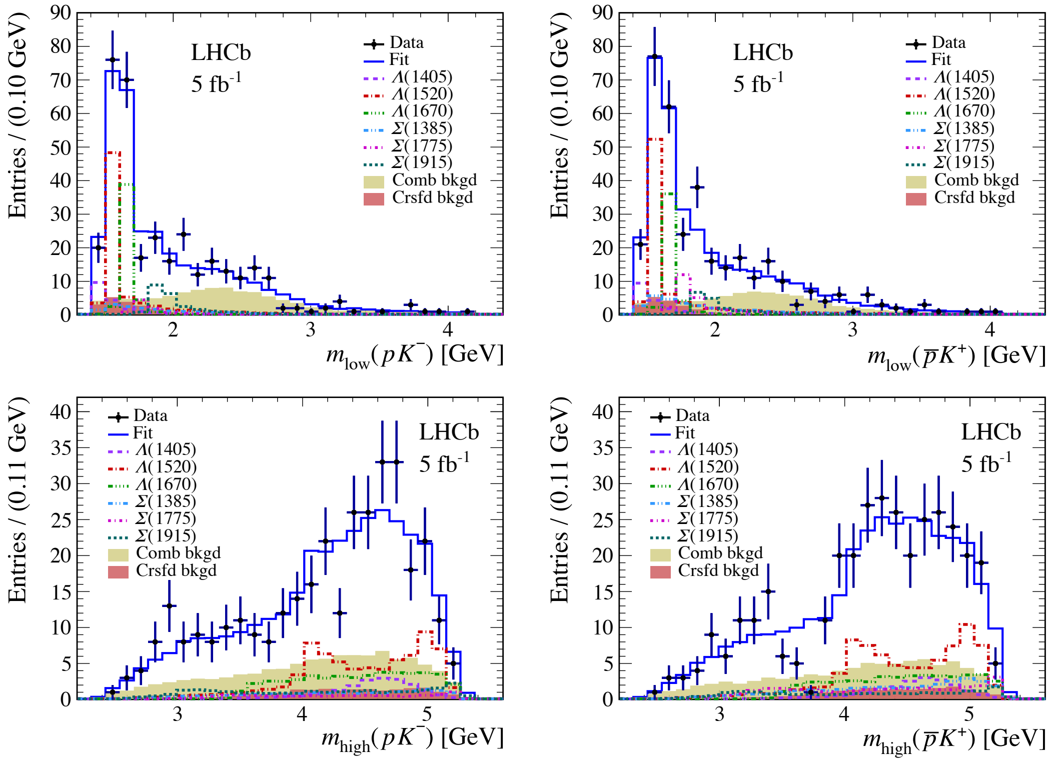
at 90(95)% CL

First amplitude analysis of this decay mode:

- assume unpolarised $\Xi_b^-$ → 2 d.o.f.
- Λ* and Σ* resonances modelled with a Breit-Wigner distribution, possible non-resonant components with exponential lineshape
- allows for CPV

arXiv:2104.15074

# Amplitude analysis of $\Xi_b^- \to pK^-K^-$




6 significant components identified

**Asymmetry of fit fractions compatible with no CPV**

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

$$\mathcal{B}\left(\Xi_b^- \to \Sigma(1385)K^-\right) = (0.26 \pm 0.11 \pm 0.17 \pm 0.10) \times 10^{-6}$$
$$\mathcal{B}\left(\Xi_b^- \to \Lambda(1405)K^-\right) = (0.19 \pm 0.06 \pm 0.07 \pm 0.07) \times 10^{-6}$$
$$\mathcal{B}\left(\Xi_b^- \to \Lambda(1520)K^-\right) = (0.76 \pm 0.09 \pm 0.08 \pm 0.30) \times 10^{-6}$$
$$\mathcal{B}\left(\Xi_b^- \to \Lambda(1670)K^-\right) = (0.45 \pm 0.07 \pm 0.13 \pm 0.18) \times 10^{-6}$$
$$\mathcal{B}\left(\Xi_b^- \to \Sigma(1775)K^-\right) = (0.22 \pm 0.08 \pm 0.09 \pm 0.09) \times 10^{-6}$$
$$\mathcal{B}\left(\Xi_b^- \to \Sigma(1915)K^-\right) = (0.26 \pm 0.09 \pm 0.21 \pm 0.10) \times 10^{-6}$$

**Quasi two-body branching ratios**

(BR x fit fraction)

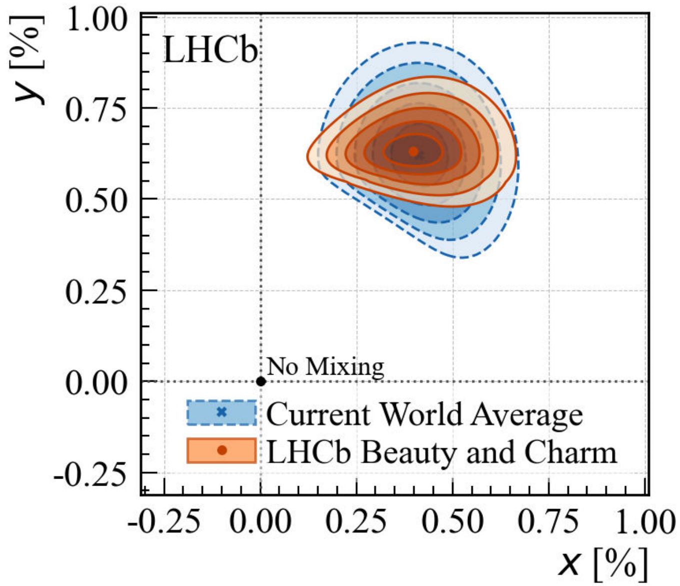
from $\mathcal{B}\left(\Xi_b^- \to pK^-K^-\right) = (2.3 \pm 0.9) \times 10^{-6}$

# Summary

Huge advances in charm

- world best measurements of $A_{CP}(D^0 \to K^0_S K^0_S)$ and $A_{CP}(D^+_{(s)} \to h^+\pi^0, h^+\eta)$
- first observation of nonzero mass difference of neutral charm-meson eigenstates in $D^0 \to K^0_S\pi^+\pi^-$
- CPV mixing phases $\phi_2^M$ and $\phi_2^\Gamma$ measured with precisions of 20 and 30 mrad
    - compatible with zero, precision one order of magnitude above SM predictions

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




New simultaneous combination of γ + charm provides $\gamma = (65.4^{+3.8}_{-4.2})^\circ$ and doubles the $y_{12}$ precision

2x improved precision on $\Delta m_s = 17.7656 \pm 0.0057\,\mathrm{ps}^{-1}$

First CPV amplitude analysis of a beauty-baryon decay $\Xi_b^- \to pK^-K^-$

Many other ongoing measurements with Run 2 data (e.g. $y_{CP}$ with $D^{*+}$ tag)

**Looking forward to Run 3!**

talk by Evelina Gersabeck


Thanks!

# Observation of $\Lambda_b^0 \to [K^+\pi^-]_D p K^-$

- Baryon analogue of the golden ADS mode Phys. Rev. D 63 (2001) 036005 $B^- \to [K^+\pi^-]_D K^-$ to measure the CKM angle γ
- two observables:

$$R = \frac{\mathcal{B}(\Lambda_b^0 \to [K^-\pi^+]_D p K^-)}{\mathcal{B}(\Lambda_b^0 \to [K^+\pi^-]_D p K^-)},$$

ratio of suppressed to favoured modes

$$A = \frac{\mathcal{B}(\Lambda_b^0 \to [K^+\pi^-]_D p K^-) - \mathcal{B}(\overline{\Lambda}_b^0 \to [K^-\pi^+]_D \overline{p} K^+)}{\mathcal{B}(\Lambda_b^0 \to [K^+\pi^-]_D p K^-) + \mathcal{B}(\overline{\Lambda}_b^0 \to [K^-\pi^+]_D \overline{p} K^+)}.$$

asymmetry of suppressed mode

$$R = 7.1 \pm 0.8\,(\text{stat.})^{+0.4}_{-0.3}\,(\text{syst.}),$$
$$A = 0.12 \pm 0.09\,(\text{stat.})^{+0.02}_{-0.03}\,(\text{syst.}),$$

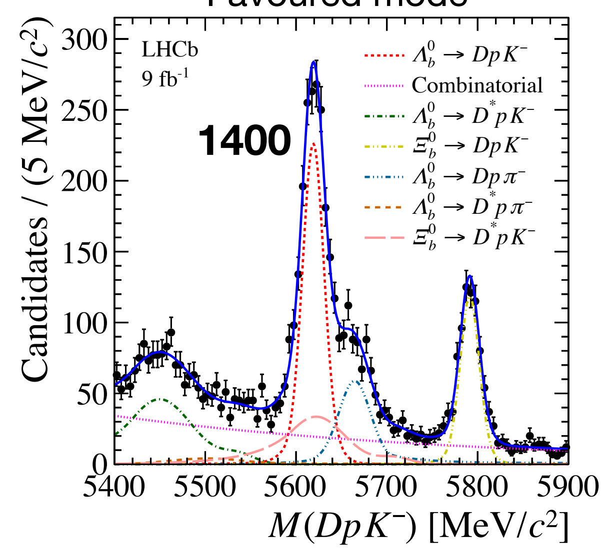
full Run 1+2 sample

Subsample $M^2(pK^-) < 5\,\text{GeV}^2/c^4$ with enhanced sensitivity expected due to Λ resonances:

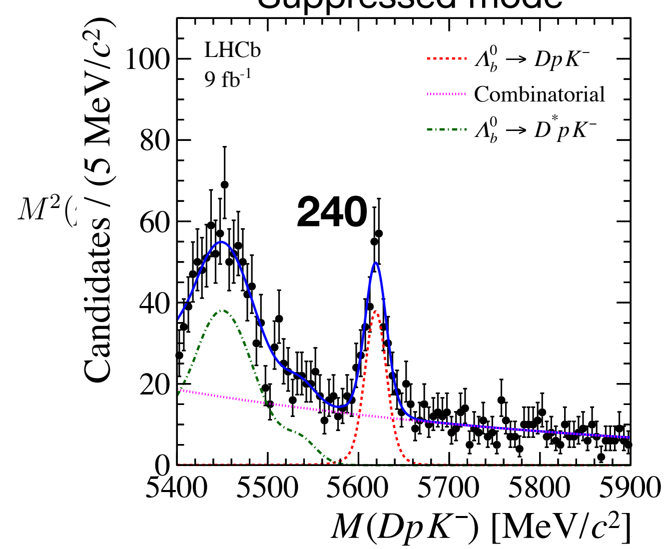
$$R = 8.6 \pm 1.5\,(\text{stat.})^{+0.4}_{-0.3}\,(\text{syst.}),$$
$$A = 0.01 \pm 0.16\,(\text{stat.})^{+0.03}_{-0.02}\,(\text{syst.}).$$

- This is the first observation of the suppressed decay
- asymmetry consistent with zero, not sensitive to γ angle yet → looking forward to Run 3

Favoured mode

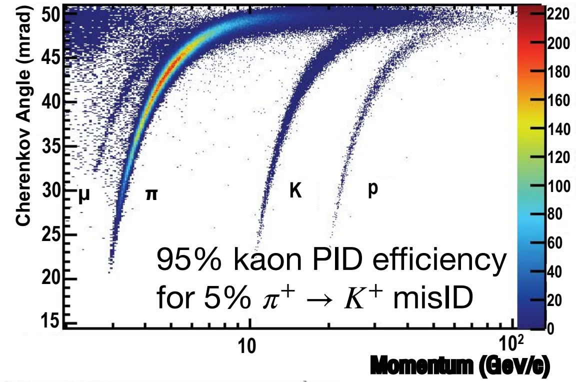


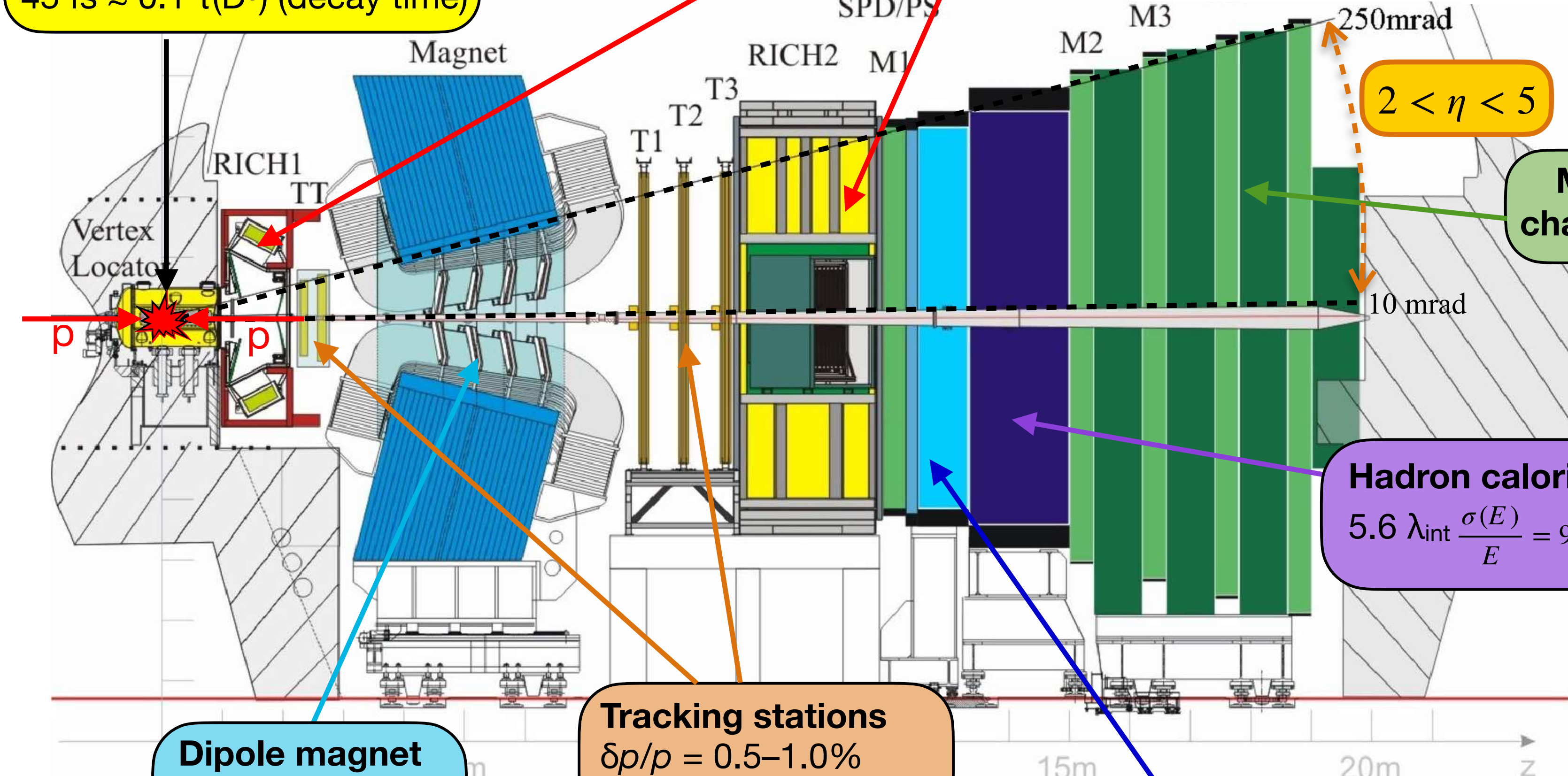

Suppressed mode




LHCb-PAPER-2021-027 (in preparation)

# LHCb experiment




**Vertex tracker**
15 + 29/$p_T$ μm (IP)
45 fs ≈ 0.1 τ($D^0$) (decay time)

**Cherenkov detectors**

$2 < \eta < 5$

**Muon chambers**

**Hadron calorimeter**
5.6 $\lambda_{int}$ $\frac{\sigma(E)}{E} = 9\% \oplus \frac{69\%}{\sqrt{E/GeV}}$

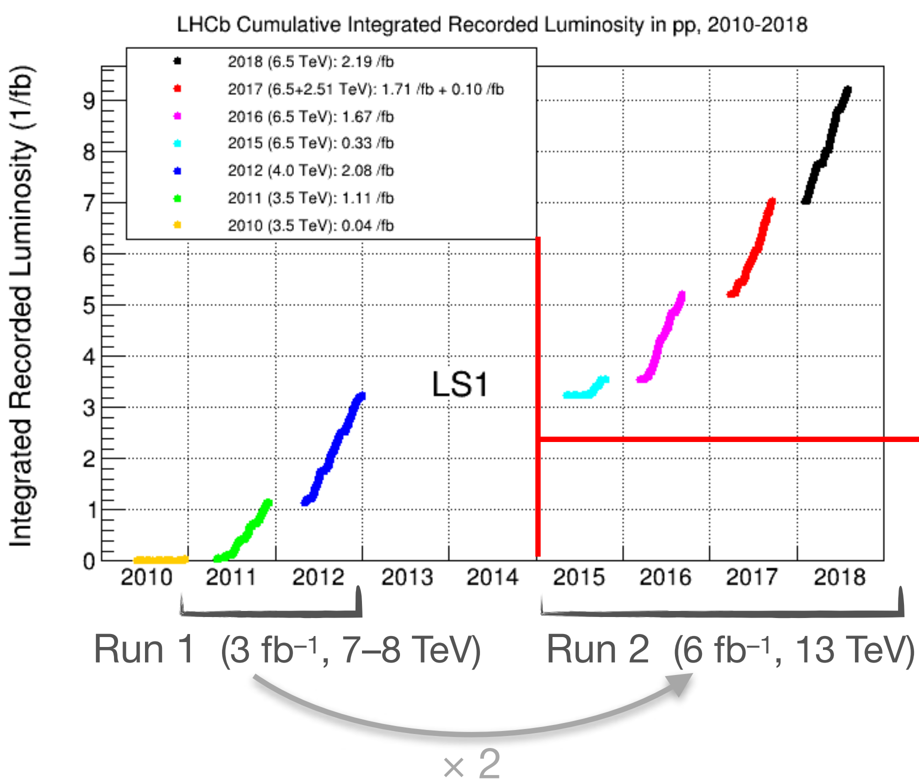
**Dipole magnet**
4 T·m (vertical)

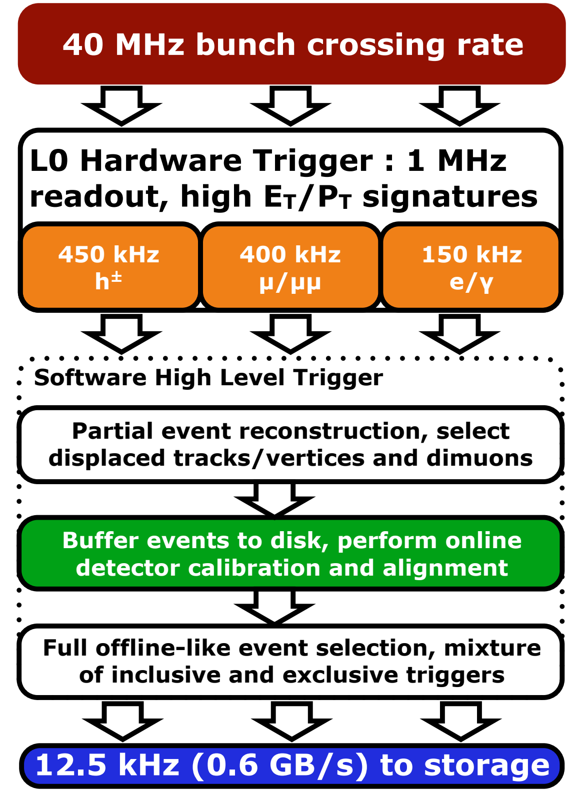
**Tracking stations**
$\delta p/p$ = 0.5–1.0%
for $p$ = 20–200 GeV/$c$

**Electromagnetic calorimeter**
25 $X_0$, 1.2 $\lambda_{int}$ $\frac{\sigma(E)}{E} = 1\% \oplus \frac{10\%}{\sqrt{E/GeV}}$

JINST 3 S08005 (2008)
Int. J. Mod. Phys. A 30 (2015) 7, 1530022

# Integrated luminosity




Comput. Phys. Commun. 208 (2016) 35

Yield has more than doubled between Run 1 and 2:

- × 1.7 increase in production cross-section;
- new “Turbo" data taking paradigm
  - only the signal candidates are recorded, rest of the event is discarded;
  - improved efficiency, higher rate recorded.

**Pioneered by charm triggers**

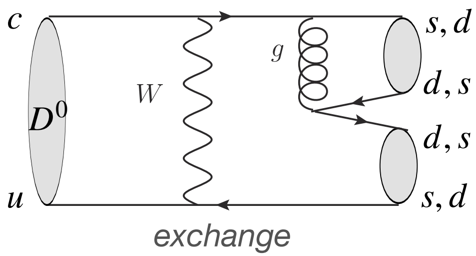
# Theory for $A_{CP}(D^0 \to K_S^0 K_S^0)$

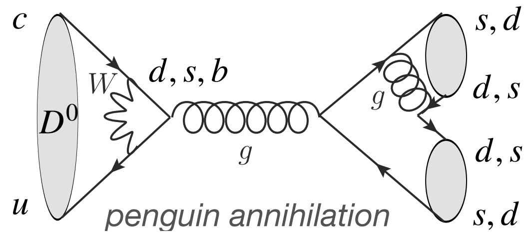
A confirmation channel for the observation?

Only exchange diagrams vanishing
in the $SU(3)_F$ limit contribute at tree level.

$$V_{\text{CKM}} = \begin{pmatrix} 1 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda \; -iA\lambda^5\eta & 1 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

CPV could be enhanced up to the percent level
Brod et al. 2011, Nierste & Schacht 2015
(though smaller are more likely, see e.g. Li et al. 2012, Buccella et al. 2019, Cheng & Chiang 2019)



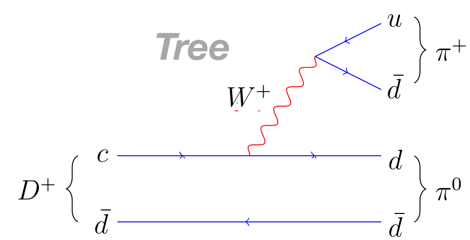

Figures from Cheng & Chiang 2012

# The missing piece for CPV in charm: decays with $\pi^0$

The absolute size of *CPV* is difficult to estimate, but $SU(3)_{\mathrm{F}}$-based sum rules predict the relative size among different decay modes

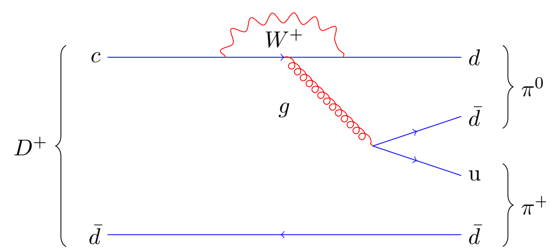
- e.g. $D^+ \to K^0_{\mathrm{S}} K^+$ vs. $D^+_s \to K^0_{\mathrm{S}} \pi^+$ vs. $D^+_s \to K^+ \pi^0$
- might be violated by NP.

**Tree**




$A_{CP}(D^+ \to \pi^+ \pi^0) < 10^{-5}$
in the SM due to isospin symmetry

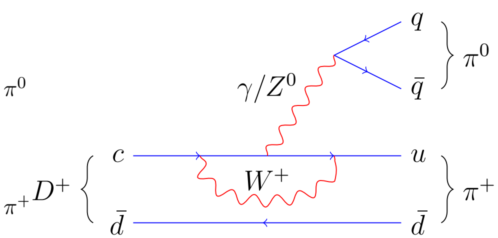
Buccella et al. 1993, Grossman et al. 2012




**Forbidden QCD loop**

$\Delta I = \frac{3}{2}$ transition prohibited for gluon

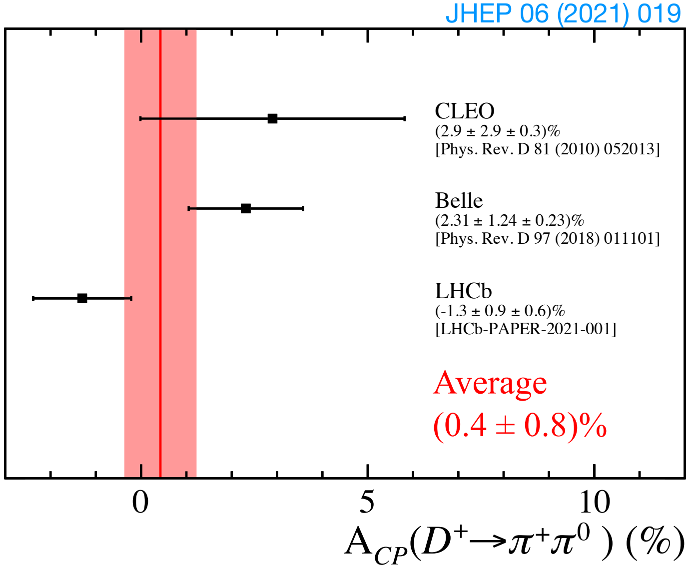
*…but not for NP*




**EW loop**

suppressed by $\alpha$

JHEP 06 (2021) 019




Figures courtesy of Tom Hadavizadeh

# $A_{CP}(D^{\pm}_{(s)} \to h^{\pm}h^{0})$: analysis strategy

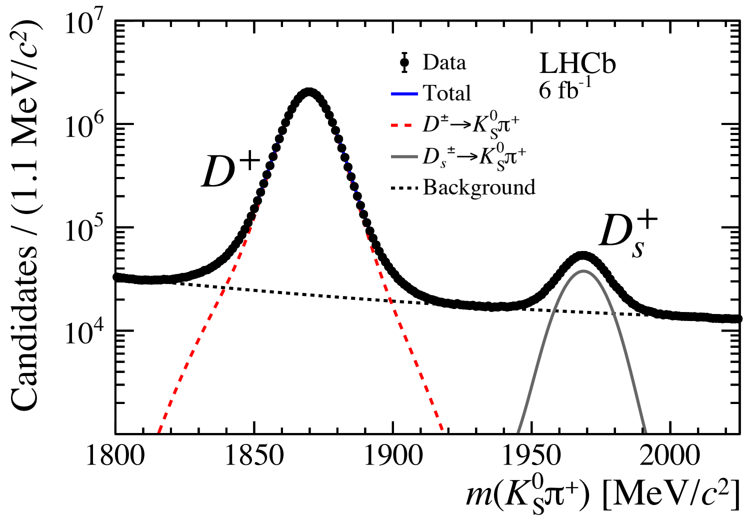
Run 1 + 2 data samples (dedicated triggers since 2015).

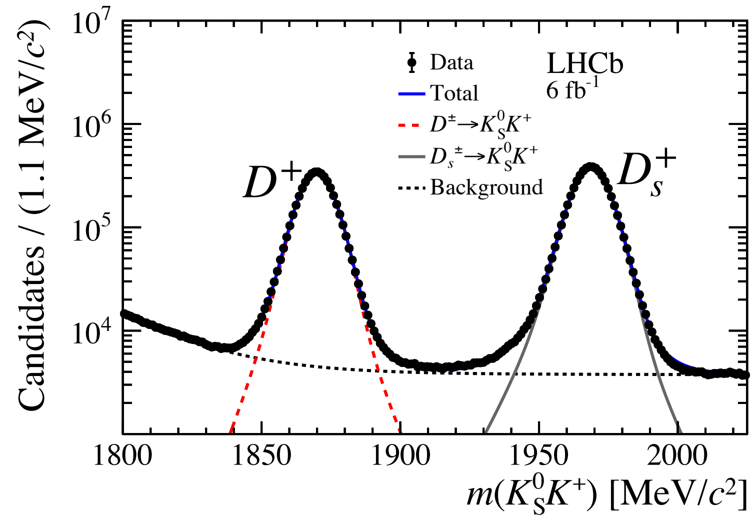
Nuisance asymmetries are removed by subtraction with $D^{+}_{(s)} \to h^{+}K^{0}_{S}$ decays;

- kinematically weighted to match the signal channels;
- asymmetry from $K^{0}_{S}$ regeneration and *CPV* is calculated and removed.

$D^{+}_{(s)} \to h^{+}K^{0}_{S}$

$D^{+}_{(s)} \to h^{+}h^{0}$




Asymmetries are measured from ML fits to the 2D distributions of the $D^{+}_{(s)}$ and $h^{0}$ mass;

- signal shapes based on simulation;
- account for correlations due to radiative tails.

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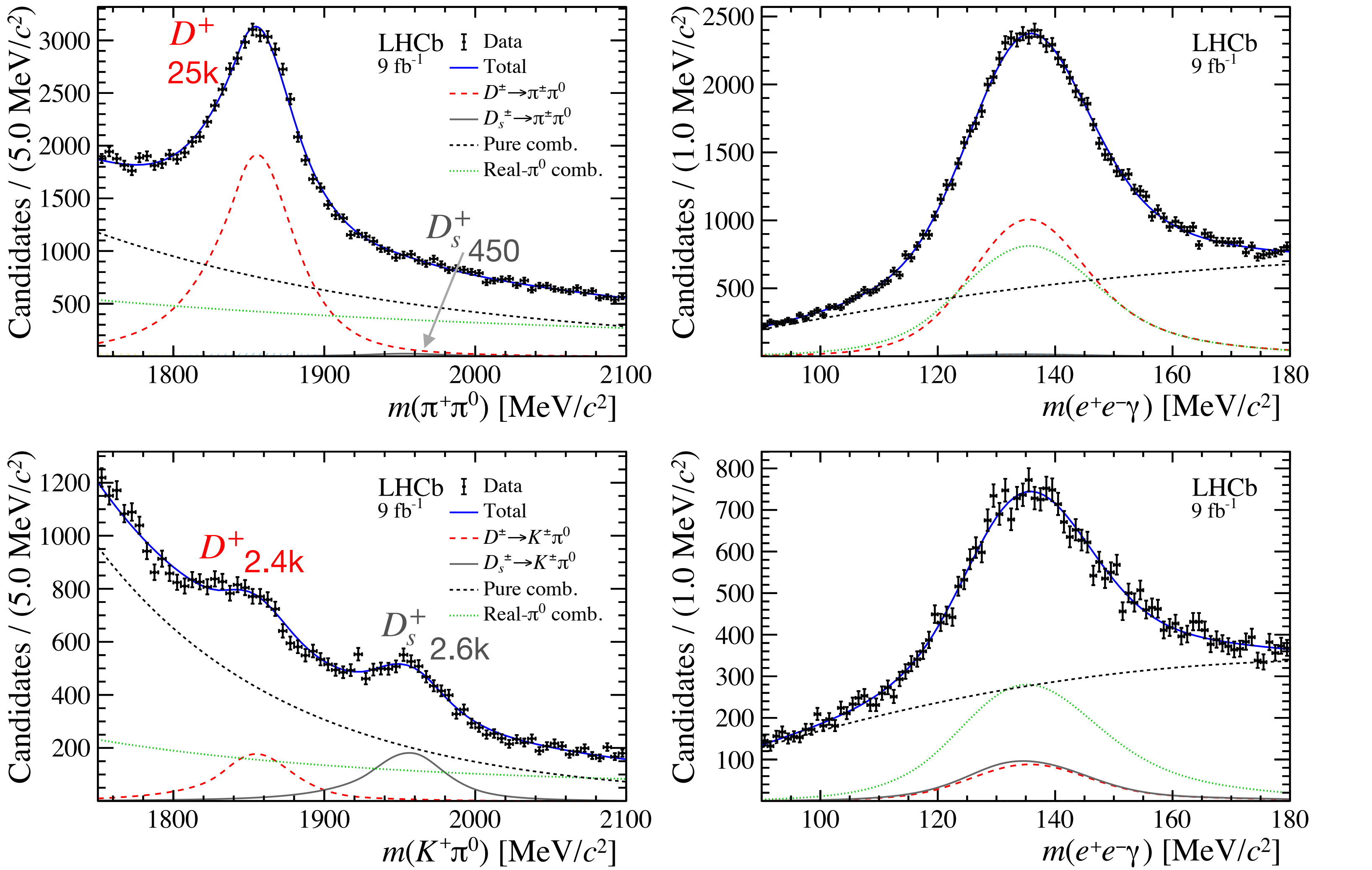
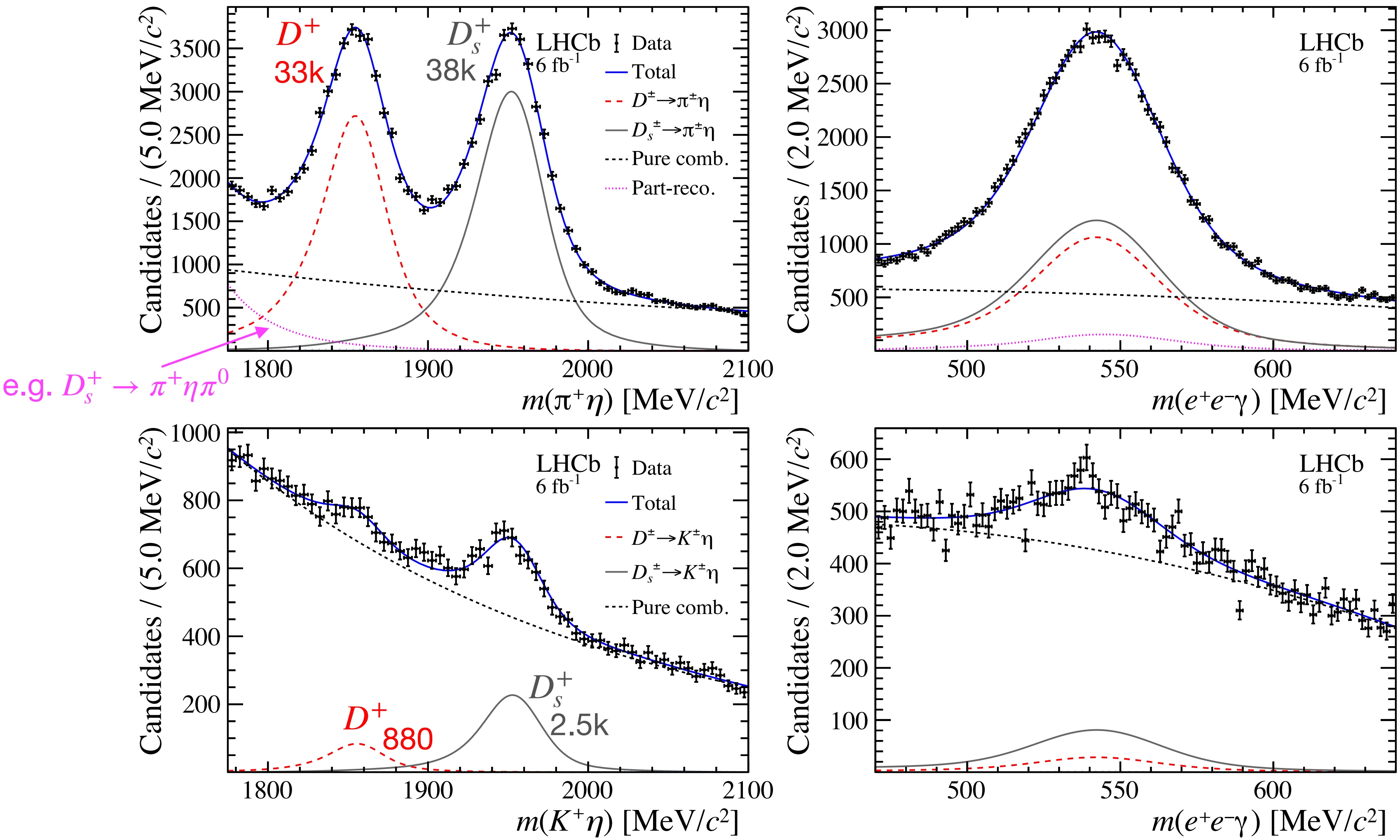
# Fits of $D^{\pm}_{(s)} \to h^{\pm}\pi^0$



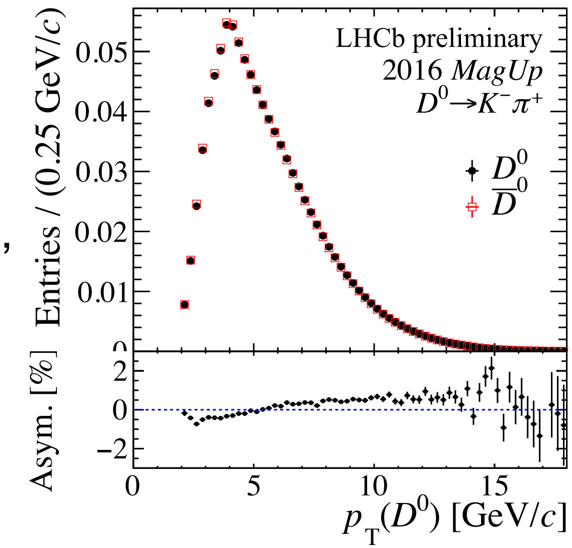
JHEP 06 (2021) 019

# Fits of $D^{\pm}_{(s)} \to h^{\pm}\eta$

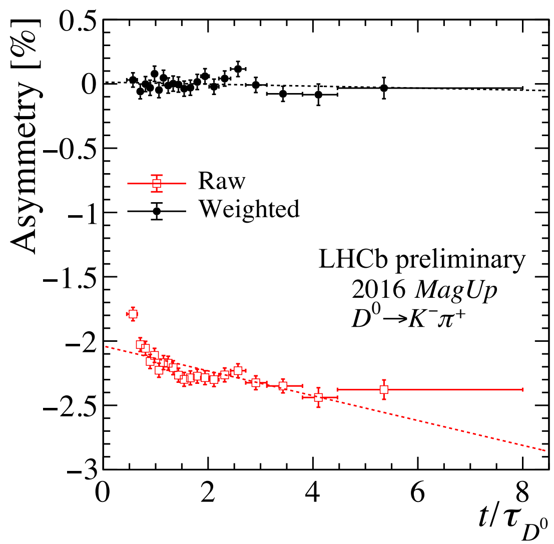


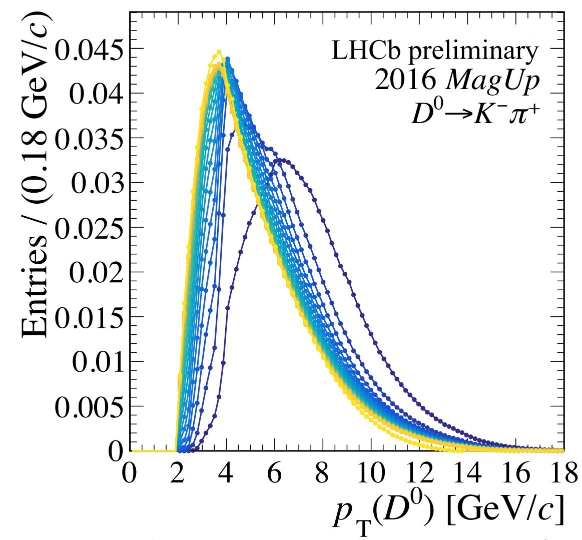
# Time-dependent detection asymmetry

- Large momentum-dependent detection asymmetries (mainly from the dipole magnet).
- Owing to the selection requirements (e.g. on $D^0$ flight distance), they reflect into time-dependent asymmetries.




Removed by equalising the distributions of the vector momentum of $\pi^+_{\text{tag}}$ and $\pi^-_{\text{tag}}$ candidates, and of $D^0$ and $\bar{D}^0$ candidates (binned procedure).

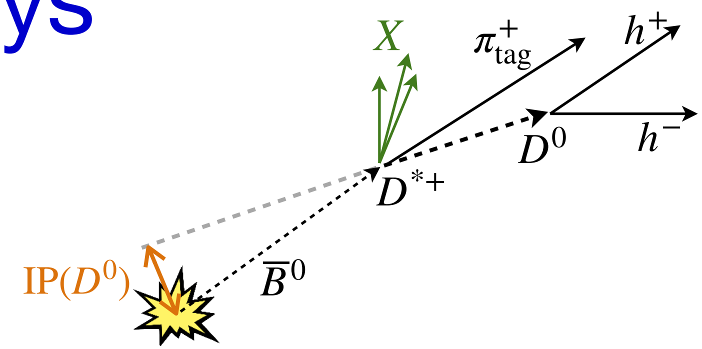



high decay times
low decay times

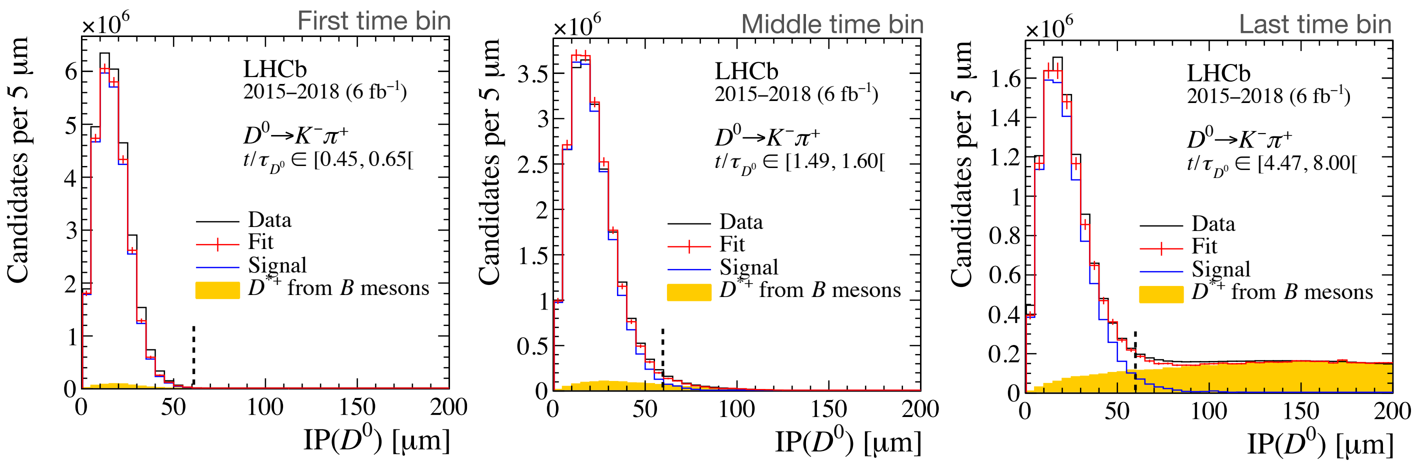
# Asymmetry from B decays

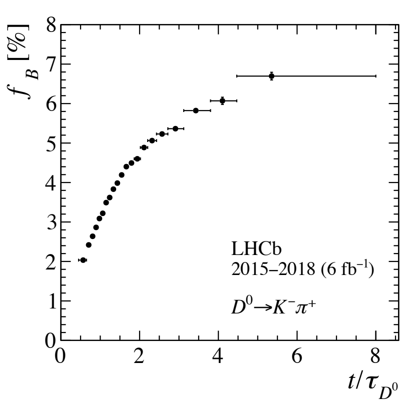
Suppressed by requiring $\mathrm{IP}(D^0) < 60\,\mu\mathrm{m}$




$$A(t) = A_{\mathrm{sig}}(t) + f_B(t)[A_B(t) - A_{\mathrm{sig}}(t)]$$

Fraction is measured with template fit to the 2D distribution of $\mathrm{IP}(D^0)$ *vs.* time.




Asymmetry difference, $(2.2 \pm 0.4) \times 10^{-3}$, measured from data at large IP.

**Total size of subtracted bias:** $0.26 \times 10^{-4}$

# Simultaneous $\gamma$ + charm combination – inputs and results

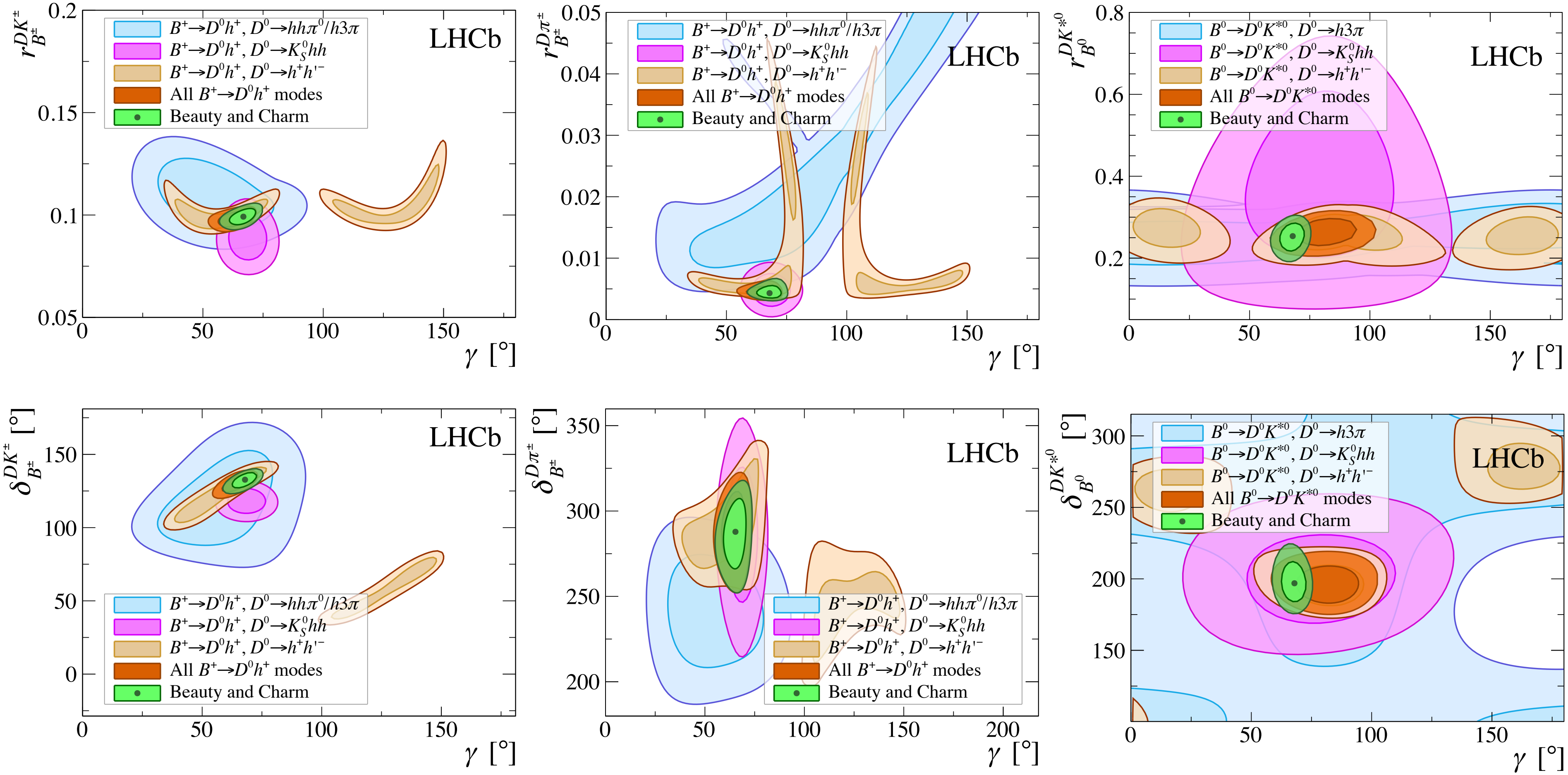
LHCb-CONF-2021-001
LHCb-PAPER-2021-033 (in preparation)

| $B$ decay | $D$ decay | Ref. | Dataset | Status since Ref. [25] |
|---|---|---|---|---|
| $B^\pm \to Dh^\pm$ | $D \to h^+h^-$ | [27] | Run 1&2 | **Updated** |
| $B^\pm \to Dh^\pm$ | $D \to h^+\pi^-\pi^+\pi^-$ | [28] | Run 1 | As before |
| $B^\pm \to Dh^\pm$ | $D \to h^+h^-\pi^0$ | [29] | Run 1 | As before |
| $B^\pm \to Dh^\pm$ | $D \to K_S^0 h^+h^-$ | [26] | Run 1&2 | **Updated** |
| $B^\pm \to Dh^\pm$ | $D \to K_S^0 K^\pm\pi^\mp$ | [30] | Run 1&2 | **Updated** |
| $B^\pm \to D^*h^\pm$ | $D \to h^+h^-$ | [27] | Run 1&2 | **Updated** |
| $B^\pm \to DK^{*\pm}$ | $D \to h^+h^-$ | [31] | Run 1&2(*) | As before |
| $B^\pm \to DK^{*\pm}$ | $D \to h^+\pi^-\pi^+\pi^-$ | [31] | Run 1&2(*) | As before |
| $B^\pm \to Dh^\pm\pi^+\pi^-$ | $D \to h^+h^-$ | [32] | Run 1 | As before |
| $B^0 \to DK^{*0}$ | $D \to K^+\pi^-$ | [33] | Run 1&2(*) | **Updated** |
| $B^0 \to DK^{*0}$ | $D \to h^+\pi^-\pi^+\pi^-$ | [33] | Run 1&2(*) | **New** |
| $B^0 \to DK^+\pi^-$ | $D \to h^+h^-$ | [34] | Run 1 | **Superseded** |
| $B^0 \to DK^{*0}$ | $D \to K_S^0\pi^+\pi^-$ | [35] | Run 1 | As before |
| $B^0 \to D^\mp\pi^\pm$ | $D^+ \to K^-\pi^+\pi^+$ | [36] | Run 1 | As before |
| $B_s^0 \to D_s^\mp K^\pm$ | $D_s^+ \to h^+h^-\pi^+$ | [37] | Run 1 | As before |
| $B_s^0 \to D_s^\mp K^\pm\pi^+\pi^-$ | $D_s^+ \to h^+h^-\pi^+$ | [38] | Run 1&2 | **New** |
| – | $D^0 \to h^+h^-$ | [39–41] | Run 1&2 | **New** |
| – | $D^0 \to h^+h^-$ | [42] | Run 1 | **New** |
| – | $D^0 \to h^+h^-$ | [43–46] | Run 1&2 | **New** |
| – | $D^0 \to K^+\pi^-$ | [47] | Run 1 | **New** |
| – | $D^0 \to K^+\pi^-$ | [48] | Run 1&2(*) | **New** |
| – | $D^0 \to K^\pm\pi^\mp\pi^+\pi^-$ | [49] | Run 1 | **New** |
| – | $D^0 \to K_S^0\pi^+\pi^-$ | [50, 51] | Run 1&2 | **New** |
| – | $D^0 \to K_S^0\pi^+\pi^-$ | [52] | Run 1 | **New** |

| Quantity | Value | 68.3% CL | | 95.4% CL | |
|---|---|---|---|---|---|
| | | Uncertainty | Interval | Uncertainty | Interval |
| $\gamma\,[^\circ]$ | 65.4 | $^{+3.8}_{-4.2}$ | $[61.2, 69.2]$ | $^{+7.5}_{-8.7}$ | $[56.7, 72.9]$ |
| $r_{B^\pm}^{DK^\pm}$ | 0.0984 | $^{+0.0027}_{-0.0026}$ | $[0.0958, 0.1011]$ | $^{+0.0056}_{-0.0052}$ | $[0.0932, 0.1040]$ |
| $\delta_{B^\pm}^{DK^\pm}\,[^\circ]$ | 127.6 | $^{+4.0}_{-4.2}$ | $[123.4, 131.6]$ | $^{+7.8}_{-9.2}$ | $[118.4, 135.4]$ |
| $r_{B^\pm}^{D\pi^\pm}$ | 0.00480 | $^{+0.00070}_{-0.00056}$ | $[0.00424, 0.00550]$ | $^{+0.0017}_{-0.0011}$ | $[0.0037, 0.0065]$ |
| $\delta_{B^\pm}^{D\pi^\pm}\,[^\circ]$ | 288 | $^{+14}_{-15}$ | $[273, 302]$ | $^{+26}_{-31}$ | $[257, 314]$ |
| $r_{B^\pm}^{D^*K^\pm}$ | 0.099 | $^{+0.016}_{-0.019}$ | $[0.080, 0.115]$ | $^{+0.030}_{-0.038}$ | $[0.061, 0.129]$ |
| $\delta_{B^\pm}^{D^*K^\pm}\,[^\circ]$ | 310 | $^{+12}_{-23}$ | $[287, 322]$ | $^{+20}_{-71}$ | $[239, 330]$ |
| $r_{B^\pm}^{D^*\pi^\pm}$ | 0.0095 | $^{+0.0085}_{-0.0061}$ | $[0.0034, 0.0180]$ | $^{+0.017}_{-0.0089}$ | $[0.0006, 0.026]$ |
| $\delta_{B^\pm}^{D^*\pi^\pm}\,[^\circ]$ | 139 | $^{+22}_{-86}$ | $[53, 161]$ | $^{+32}_{-129}$ | $[10, 171]$ |
| $r_{B^\pm}^{DK^{*\pm}}$ | 0.106 | $^{+0.017}_{-0.019}$ | $[0.087, 0.123]$ | $^{+0.031}_{-0.040}$ | $[0.066, 0.137]$ |
| $\delta_{B^\pm}^{DK^{*\pm}}\,[^\circ]$ | 35 | $^{+20}_{-15}$ | $[20, 55]$ | $^{+57}_{-28}$ | $[7, 92]$ |
| $r_{B^0}^{DK^{*0}}$ | 0.250 | $^{+0.023}_{-0.024}$ | $[0.226, 0.273]$ | $^{+0.044}_{-0.052}$ | $[0.198, 0.294]$ |
| $\delta_{B^0}^{DK^{*0}}\,[^\circ]$ | 197 | $^{+10}_{-9.3}$ | $[187.7, 207]$ | $^{+24}_{-18}$ | $[179, 221]$ |
| $r_{B_s^0}^{D_s^\mp K^\pm}$ | 0.310 | $^{+0.098}_{-0.092}$ | $[0.218, 0.408]$ | $^{+0.20}_{-0.21}$ | $[0.10, 0.51]$ |
| $\delta_{B_s^0}^{D_s^\mp K^\pm}\,[^\circ]$ | 356 | $^{+19}_{-18}$ | $[338, 375]$ | $^{+39}_{-39}$ | $[317, 395]$ |
| $r_{B_s^0}^{D_s^\mp K^\pm\pi^+\pi^-}$ | 0.460 | $^{+0.081}_{-0.084}$ | $[0.376, 0.541]$ | $^{+0.16}_{-0.17}$ | $[0.29, 0.62]$ |
| $\delta_{B_s^0}^{D_s^\mp K^\pm\pi^+\pi^-}\,[^\circ]$ | 345 | $^{+13}_{-12}$ | $[333, 358]$ | $^{+26}_{-25}$ | $[320, 371]$ |
| $r_{B^0}^{D^\mp\pi^\pm}$ | 0.030 | $^{+0.014}_{-0.012}$ | $[0.018, 0.044]$ | $^{+0.036}_{-0.028}$ | $[0.002, 0.066]$ |
| $\delta_{B^0}^{D^\mp\pi^\pm}\,[^\circ]$ | 30 | $^{+26}_{-37}$ | $[-7, 56]$ | $^{+45}_{-81}$ | $[-51, 75]$ |
| $r_{B^\pm}^{DK^\pm\pi^+\pi^-}$ | 0.079 | $^{+0.028}_{-0.034}$ | $[0.045, 0.107]$ | $^{+0.050}_{-0.079}$ | $[0.000, 0.129]^*$ |
| $r_{B^\pm}^{D\pi^\pm\pi^+\pi^-}$ | 0.067 | $^{+0.025}_{-0.029}$ | $[0.038, 0.092]$ | $^{+0.040}_{-0.067}$ | $[0.000, 0.107]^*$ |
| $x\,[\%]$ | 0.400 | $^{+0.052}_{-0.053}$ | $[0.347, 0.452]$ | $^{+0.10}_{-0.11}$ | $[0.29, 0.50]$ |
| $y\,[\%]$ | 0.630 | $^{+0.033}_{-0.030}$ | $[0.600, 0.663]$ | $^{+0.069}_{-0.058}$ | $[0.572, 0.699]$ |
| $r_D^{K\pi}$ | 0.05867 | $^{+0.00015}_{-0.00015}$ | $[0.05852, 0.05882]$ | $^{+0.00031}_{-0.00030}$ | $[0.05837, 0.05898]$ |
| $\delta_D^{K\pi}\,[^\circ]$ | 190.0 | $^{+4.2}_{-4.1}$ | $[185.9, 194.2]$ | $^{+8.6}_{-8.3}$ | $[181.7, 198.6]$ |
| $\lvert q/p\rvert$ | 0.997 | $^{+0.016}_{-0.016}$ | $[0.981, 1.013]$ | $^{+0.033}_{-0.033}$ | $[0.964, 1.030]$ |
| $\phi\,[^\circ]$ | $-2.4$ | $\pm1.2$ | $[-3.6, -1.2]$ | $\pm2.5$ | $[-4.9, 0.1]$ |

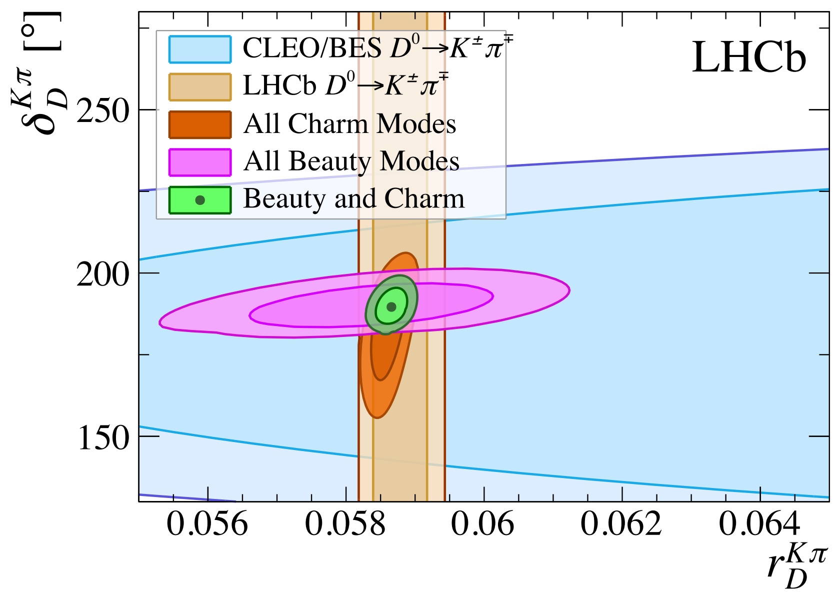
# Simultaneous $\gamma$ + charm combination results

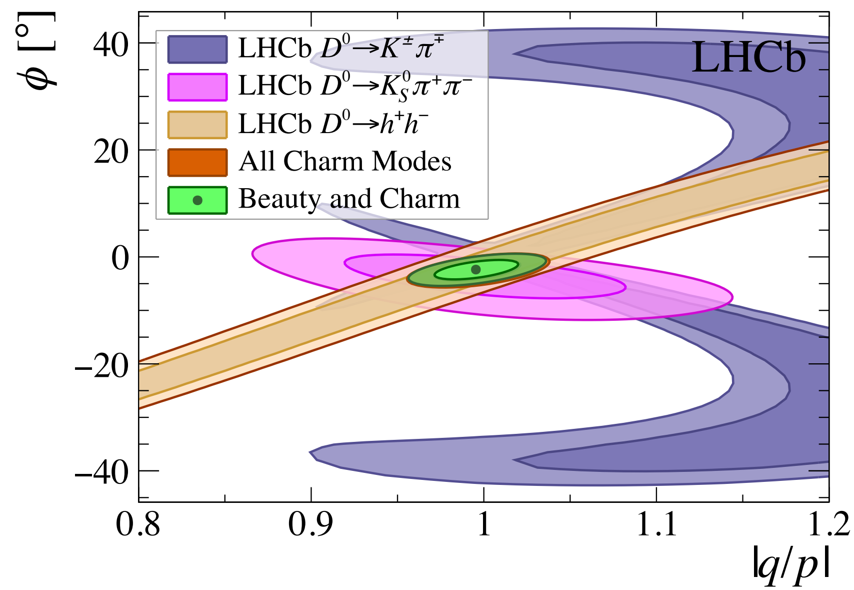
LHCb-CONF-2021-001
LHCb-PAPER-2021-033 (in preparation)



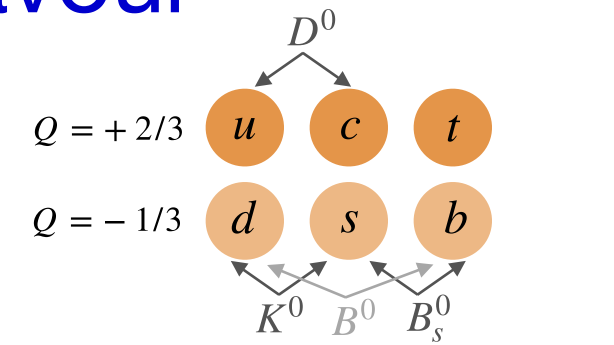
# Simultaneous $\gamma$ + charm combination – impact on charm

LHCb-CONF-2021-001
LHCb-PAPER-2021-033 (in preparation)



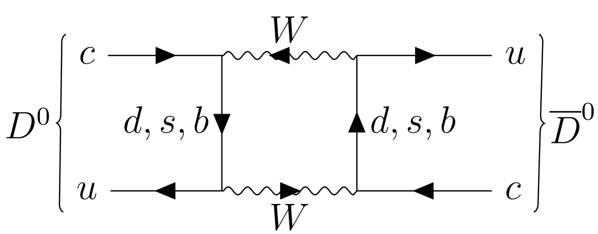
# Charm: the dark horse of flavour




**Charm is the only up-type quark which mixes and allows high-precision *CPV* measurements**

**FCNC are <u>extremely</u> suppressed**

GIM mechanism broken by the beauty-quark mass (instead of top)




$$\propto \left(\frac{m_{d,s,b}}{m_W}\right)^2$$

*mixing – short distance*

$$\begin{array}{c} \\ V_{\text{CKM}} = \end{array} \begin{array}{ccc} d & s & b \\ \end{array}$$

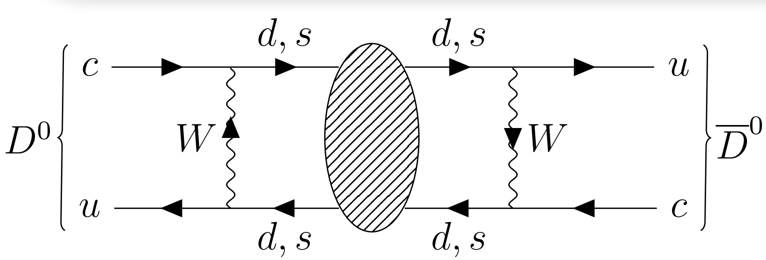
$$V_{\text{CKM}} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \begin{array}{c} \text{u} \\ \text{c} \\ \text{t} \end{array} + \mathcal{O}(\lambda^4)$$

$\lambda = \sin\theta_C \approx 0.23$

CKM suppression of **b**-quark contribution

The third generation of quarks nearly decouples from the first two, while the contributions from **d**, **s** quarks cancel out in the limit of $U$-spin symmetry ($m_s = m_d$)

Experimentally $x_{12} \approx 0.4\,\%$ , $y_{12} \approx 0.6\,\%$




*mixing – long distance*

Main contributions come from low-energy QCD interactions through on-shell resonances.

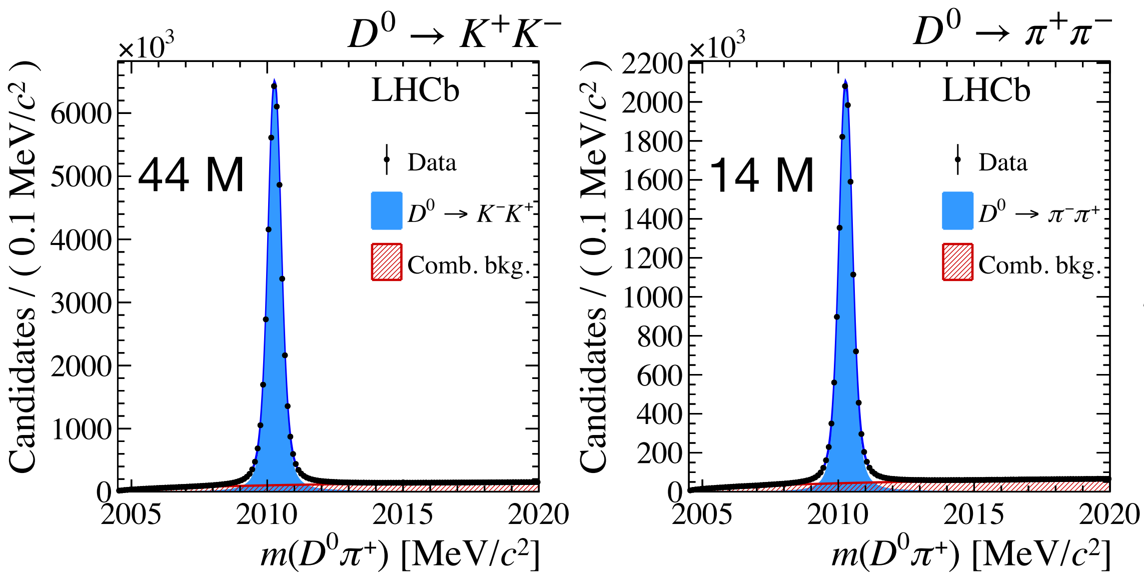
Theory predictions are challenging.

# The first observation

PRL 122 (2019) 211803

$$\Delta A_{CP} = A_{\rm raw}(K^+K^-) - A_{\rm raw}(\pi^+\pi^-)$$
$$\approx a^d_{K^+K^-} - a^d_{\pi^+\pi^-} = (-1.54 \pm 0.29) \times 10^{-3} \quad (5.3\sigma)$$

- Nuisance asymmetries cancel out in the difference;
- dynamical asymmetries add up ($a^d_{K^+K^-} \approx -a^d_{\pi^+\pi^-}$ in the $U$-spin limit).




6 fb$^{-1}$
2015–2018

- Observed value is at the upper end of the SM predictions, **challenges first-principles QCD calculations** Grossman et al. 2007, Li et. al 2012, Cheng & Chiang 2012, Khodjamirian & Petrov 2017
- Prompted intense theoretical study: **O(1–10) enhancement of QCD rescattering or NP**? Chala et al. 2019, Grossman & Schacht 2019, Buccella et al. 2019, Cheng & Chiang 2019, Soni 2019, Dery & Nir 2019, Li et al. 2019, Wang et al. 2020, Bause et al. 2020, Dery et al. 2020, Cheng & Chiang 2021