CPV measurements from LHCb

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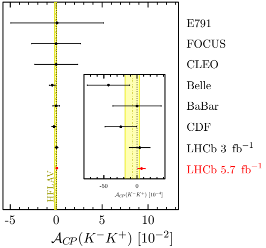
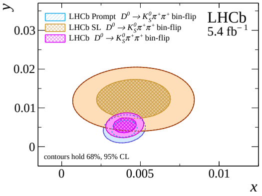
on behalf of the LHCb collaboration

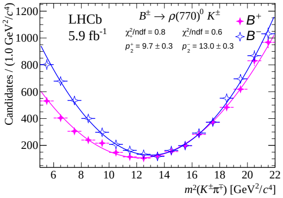
CIPANP - 30 Aug 2022

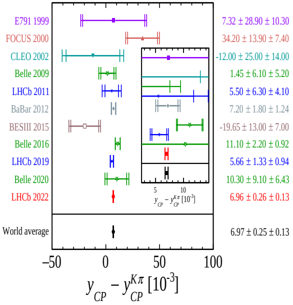
Overview

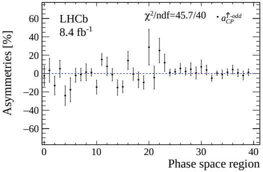
- Charm physics:
  - $D^0 \to K_S^0 \pi^+ \pi^-$ (Run 2)
    [arXiv:2208.0651]
  - $y_{CP} - y_{CP}^{K\pi}$ (Run 2)
    [Phys. Rev. D 105 (2022)]
  - $A_{CP}(D^0 \to K^+ K^-)$ (Run 2)
    [LHCB-PAPER-2022-024] in preparation
- Beauty physics:
  - CPV in $B^\pm \to h^\pm h^+ h^-$ (Run 2)
    [arXiv:2206.07622]
    [arXiv:2206.02038]
  - $\widehat{T}$-odd correlations in $B^0 \to p\bar{p}K^+\pi^-$ (Run 1+2)
    [arXiv:2205.08973]

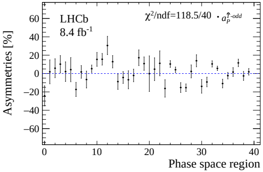


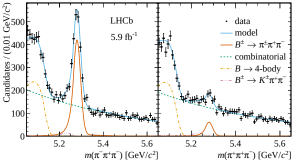




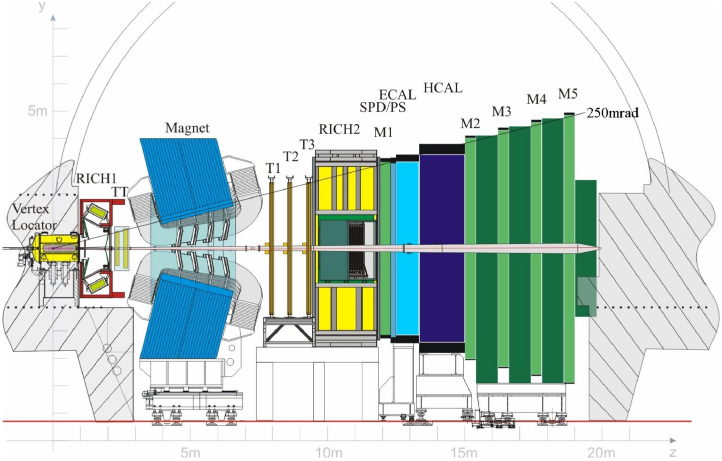








The LHCb detector



- Single-arm forward spectrometer
- Designed to study *b*- and *c*-hadron decays
- VErtex LOcator (VELO): IP resolution, secondary vertices reconstruction
- Ring Imaging CHerenkov (RICH): Particle IDentification (PID)
- Bending magnet, tracking stations, muon stations, calorimeters...
- Data collection:
  - Run 1: $\mathcal{L} = 3\,\text{fb}^{-1}$, $\sqrt{s} = $ 7-8 TeV
  - Run 2: $\mathcal{L} = 6\,\text{fb}^{-1}$, $\sqrt{s} = 13$ TeV

Measurement of charm-mixing parameters with $D^0 \to K_s^0 \pi^+ \pi^-$ decays

Measurement of charm-mixing parameters with $D^0 \to K_s^0\pi^+\pi^-$ decays

- Oscillations between D^0-$\overline{D}^0$ mesons can be described with two dimensionless parameters:

$$x = (m_1 - m_2)c^2/\Gamma$$
$$y = (\Gamma_1 - \Gamma_2)/2\Gamma$$

- If CP is violated due to mixing ($|q/p| \neq 1$), the following observables can be defined:

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

Notation:
mass eigenstates

$$|D_{1,2}\rangle = p\left|D^0\right\rangle \pm q\left|\overline{D}^0\right\rangle$$
$$|p|^2 + |q|^2 = 1$$
$$\Gamma = (\Gamma_1 + \Gamma_2)/2$$
$$\phi = \arg\left(\frac{q\overline{A}_f}{pA_f}\right)$$

- The self-conjugate decay $D^0 \to K_s^0\pi^+\pi^-$ provides access both to charm-mixing and CP-violating parameters.
- A LHCb analysis with prompt $D^{*\pm} \to D^0(\to K_s^0\pi^+\pi^-)\pi^\pm$ decays provided the first evidence of $x \neq 0$ ($m_1 \neq m_2$) [Phys. Rev. Lett. 127 (2021)]
- Complementary measurement using semileptonic decays $\overline{B} \to D^0(\to K_s^0\pi^+\pi^-)\mu^-\overline{\nu}_\mu X$ with the bin-flip method [arXiv:2208.0651]

- Bin-flip method: fit the ratio of signal yields in Dalitz bin $\pm b$ and decay-time bin j with this formula [Phys. Rev. D 99 (2019)]

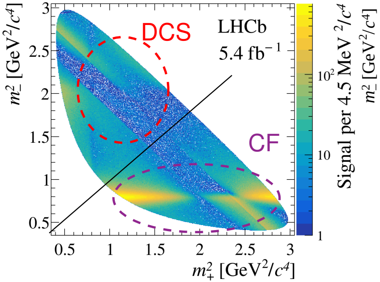
$$R_{bj}^{\pm} \approx \frac{r_b + \frac{1}{4} r_b \left\langle t^2 \right\rangle_j \mathrm{Re}(z_{CP}^2 - \Delta z^2) + \frac{1}{4} \left\langle t^2 \right\rangle_j |z_{CP} \pm \Delta z|^2 + \sqrt{r_b} \left\langle t \right\rangle_j \mathrm{Re}\left[X_B^* (z_{CP} \pm \Delta z)\right]}{1 + \frac{1}{4}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

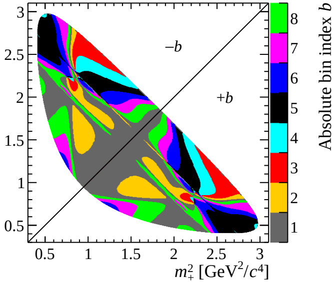
from which can be extracted

$$x_{CP} = -\mathrm{Im}(z_{CP}), \quad \Delta x = -\mathrm{Im}(\Delta z)$$
$$y_{CP} = -\mathrm{Re}(z_{CP}), \quad \Delta y = -\mathrm{Re}(\Delta z)$$

$\pm$: flavour of $D^0/\overline{D}^0$
r_b: ratio of yields in bin $-b$ and $+b$
$\langle t \rangle_j$: average decay-time in bin j
$z_{CP} \pm \Delta z = -(q/p)^{\pm 1}(y + ix)$

- Binning chosen to have constant strong phase difference between D^0 and $\overline{D}^0$ [Phys. Rev. D 82 (2010)]
- 10 equipopulated D^0 decay time bins
- Signal yields: 1.2×10^6





[arXiv:2208.0651]

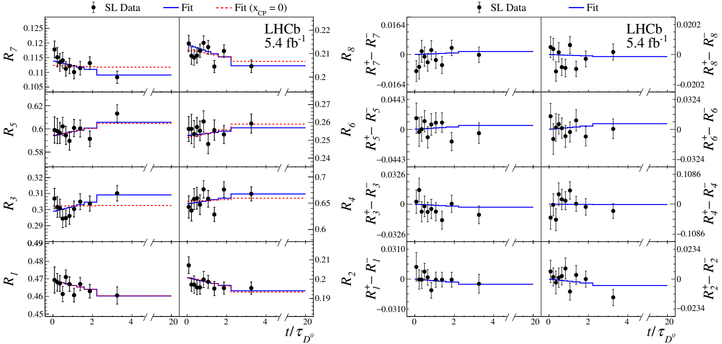
- Results are

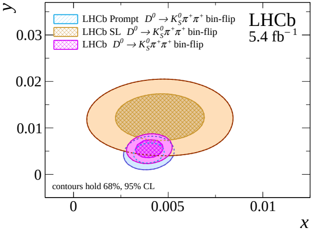
$$x_{CP} = (+\ 4.29 \pm 1.48 \pm 0.26) \times 10^{-3}$$
$$y_{CP} = (+12.61 \pm 3.12 \pm 0.83) \times 10^{-3}$$
$$\Delta x = (-\ 0.77 \pm 0.93 \pm 0.28) \times 10^{-3}$$
$$\Delta y = (+\ 3.01 \pm 1.92 \pm 0.26) \times 10^{-3}$$

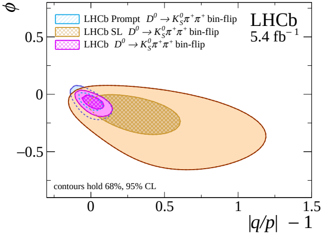
no evidence for *CP* violation

- Combination with prompt $D^{*\pm} \to D^0\pi^{\pm}$ analysis gives [Phys. Rev. Lett. 127 (2021)]

$$x_{CP} \approx x = (+4.0 \pm 0.4 \pm 0.2) \times 10^{-3} (8.1\sigma)$$
$$y_{CP} \approx y = (+5.5 \pm 1.2 \pm 0.6) \times 10^{-3}$$
$$\Delta x = (-0.3 \pm 0.2 \pm 0.0) \times 10^{-3}$$
$$\Delta y = (+0.3 \pm 0.3 \pm 0.1) \times 10^{-3}$$
$$|q/p| = 1.012^{+0.050}_{-0.048}$$
$$\phi = -0.061^{+0.037}_{-0.044}$$







Measurement of $y_{CP} - y_{CP}^{K\pi}$ using two-body D^0 decays

Measurement of $y_{CP} - y_{CP}^{K\pi}$ using two-body D^0 decays

Theory and strategy

- Due to mixing, Cabibbo Suppressed (CS) decays such as $D^0 \to K^+K^-$ or $D^0 \to \pi^+\pi^-$ proceed with effective decay widths $\widehat{\Gamma} \neq \Gamma$
- The ratio of $D^0 \to h^+h^-$ and $D^0 \to K^-\pi^+$ decay rates can deviate from 1:

$$y_{CP}^{hh} - \underbrace{y_{CP}^{K\pi}}_{\approx -0.04\%} \approx \frac{\widehat{\Gamma}(D^0 \to h^+h^-) + \widehat{\Gamma}(\overline{D}^0 \to h^+h^-)}{\widehat{\Gamma}(D^0 \to K^-\pi^+) + \widehat{\Gamma}(\overline{D}^0 \to K^+\pi^-)} - 1$$

  Measuring $y_{CP} - y_{CP}^{K\pi}$ allows to put tight constraints on the value of $y = (\Gamma_1 - \Gamma_2)/2\Gamma$
- At LHCb, a new measurement of $y_{CP} - y_{CP}^{K\pi}$ was performed with high-statistics prompt $D^{*\pm} \to D^0\pi^\pm$ decays [Phys. Rev. D 105 (2022)]
- Measure the ratio

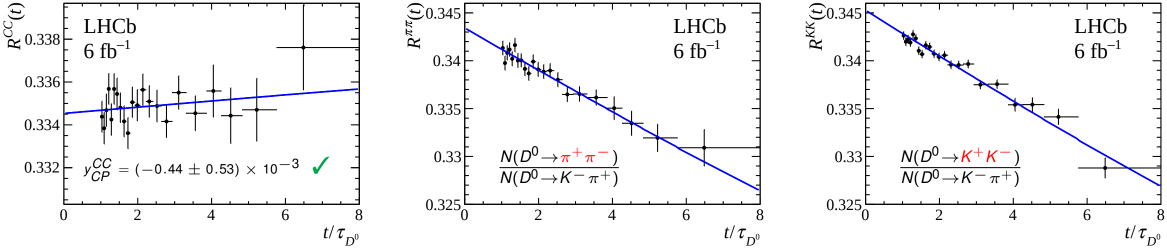
$$R^{hh}(t) = \frac{N(D^0 \to h^+h^-, t)}{N(D^0 \to K^-\pi^+, t)} \propto e^{-(y_{CP}^{hh} - y_{CP}^{K\pi})t/\tau_{D^0}} \frac{\varepsilon(hh, t)}{\varepsilon(K^-\pi^+, t)}$$

  and combine $y_{CP}^{KK} - y_{CP}^{K\pi}$ with $y_{CP}^{\pi\pi} - y_{CP}^{K\pi}$ to obtain $y_{CP} - y_{CP}^{K\pi}$

Measurement of $y_{CP} - y_{CP}^{K\pi}$ using two-body D^0 decays

[Phys. Rev. D 105 (2022)]

- The analysis is validated with $R^{CC}(t) = \dfrac{N(D^0 \to \pi^+\pi^-, t)}{N(D^0 \to K^+K^-, t)} \propto e^{y_{CP}^{CC} t/\tau_{D^0}} \dfrac{\varepsilon(\pi^+\pi^-, t)}{\varepsilon(K^+K^-, t)}$ (Should get $y_{CP}^{CC} = 0$)
- A new method of kinematic matching and reweighting was developed to equalize the time-dependent efficiencies of $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ decays



$$\left.\begin{aligned} y_{CP}^{\pi\pi} - y_{CP}^{K\pi} &= (6.57 \pm 0.53 \pm 0.16) \times 10^{-3} \\ y_{CP}^{KK} - y_{CP}^{K\pi} &= (7.08 \pm 0.30 \pm 0.14) \times 10^{-3} \end{aligned}\right\} \Longrightarrow y_{CP} - y_{CP}^{K\pi} = (6.96 \pm 0.26 \pm 0.13) \times 10^{-3}$$

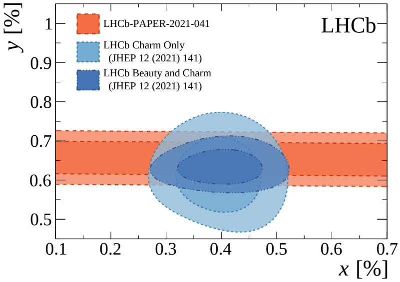
- To be compared with the world average value of $y = (6.15^{+0.56}_{-0.55}) \times 10^{-3}$ [HFLAV]

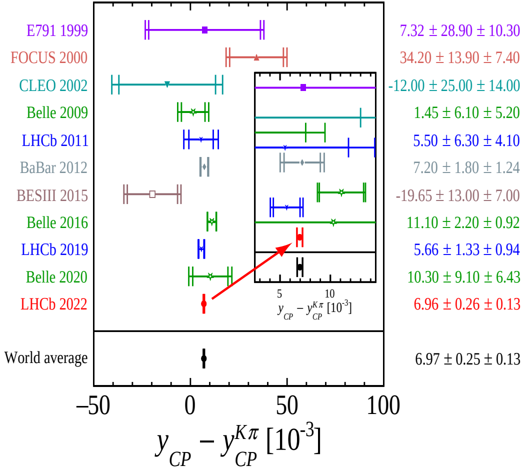
$$y_{CP} - y_{CP}^{K\pi} = (6.96 \pm 0.26 \pm 0.13) \times 10^{-3}$$

- The result is 4 times more precise than the previous world average
- LHCb charm measurements are combined to obtain updated constraints on y

$$y = (6.46^{+0.24}_{-0.25}) \times 10^{-3}$$

2 times more precise than previous estimate





CP asymmetry measurement with $D^0 \rightarrow K^+K^-$ decays

CP asymmetry measurement with $D^0 \to K^+K^-$ decays

- For final state f, $A_{CP}(f) \approx a_f^d + \frac{\langle t \rangle_f}{\tau_{D^0}} \Delta Y_f$, where [Phys. Rev. D 103 (2021)]

$$a_f^d = \frac{|A_f|^2 - |\overline{A}_f|^2}{|A_f|^2 + |\overline{A}_f|^2}, \qquad \Delta Y_f \approx \frac{\widehat{\Gamma}(\overline{D}^0 \to f) - \widehat{\Gamma}(D^0 \to f)}{2}$$

- Starting from the 2019 result (first observation of CPV in charm decays) [Phys. Rev. Lett. 122 (2019)]

$$\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-) = (-15.4 \pm 2.9) \times 10^{-4}$$
$$= a_{KK}^d - a_{\pi\pi}^d + \frac{\langle t \rangle_{KK} - \langle t \rangle_{\pi\pi}}{\tau_{D^0}} \Delta Y$$

and the Run 1 LHCb measurement: [Phys. Lett. B 767 (2017)]

$$A_{CP}(KK) = (4 \pm 12 \pm 10) \times 10^{-4}$$

- Provide an updated measurement of $A_{CP}(D^0 \to K^+K^-)$ with full Run 2 dataset ($\mathcal{L} = 5.7\,\text{fb}^{-1}$)
- Combination with ΔA_{CP} and time-dependent measurements gives access to a_{KK}^d and $a_{\pi\pi}^d$

[LHCB-PAPER-2022-024] in preparation

Talk by S. Maccolini at ICHEP 2022

CP asymmetry measurement with $D^0 \to K^+K^-$ decays

Analysis strategy

- Measure the raw asymmetry and subtract experimental asymmetries:

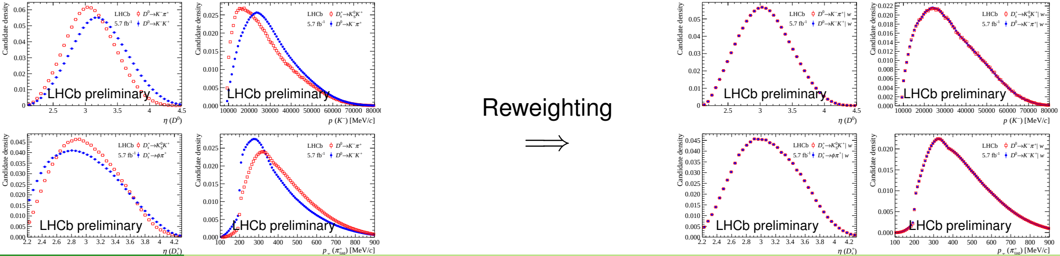
$$A(D^0 \to K^+K^-) = \frac{N(D^0 \to K^+K^-) - N(\overline{D}^0 \to K^+K^-)}{N(D^0 \to K^+K^-) + N(\overline{D}^0 \to K^+K^-)} = \underbrace{A_{CP}(D^0 \to K^+K^-)}_{target} + \underbrace{A_{prod}(D^0) + A_{det}(\pi^\pm_{soft})}_{nuisance}$$

- Exploit high-statistics $D^\pm$ and $D_s^\pm$ decays (negligible CPV) to correct nuisance asymmetries

$$\boldsymbol{C_{D+}}: \quad A_{CP}(D^0 \to K^-K^+) = +A(D^{*+} \to (D^0 \to K^-K^+)\,\pi^+_{soft}) - A(D^{*+} \to (D^0 \to K^-\pi^+)\,\pi^+_{soft}) + A(D^+ \to K^-\pi^+\pi^+) - \left[A(D^+ \to \overline{K}^0\,\pi^+) - A(\overline{K}^0)\right]$$

$$\boldsymbol{C_{Ds+}}: \quad A_{CP}(D^0 \to K^-K^+) = +A(D^{*+} \to (D^0 \to K^-K^+)\,\pi^+_{soft}) - A(D^{*+} \to (D^0 \to K^-\pi^+)\,\pi^+_{soft}) + A(D_s^+ \to \phi\pi^+) - \left[A(D_s^+ \to \overline{K}^0\,K^+) - A(\overline{K}^0)\right]$$

- Apply reweighting so that same-colored particles have identical kinematic distributions



CP asymmetry measurement with $D^0 \to K^+K^-$ decays

Results [LHCB-PAPER-2022-024] in preparation

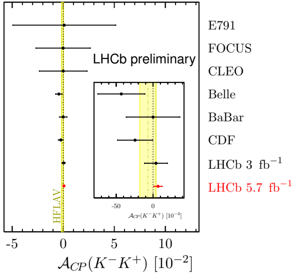
- Results for the two modes are:

$$C_{D^+}: \quad A_{CP}(KK) = (13.6 \pm 8.8 \pm 1.6) \times 10^{-4}$$
$$C_{D_s^+}: \quad A_{CP}(KK) = (\ 2.8 \pm 6.7 \pm 2.0) \times 10^{-4}$$

- With correlation $\rho = 0.06$, and their combination is

$$A_{CP}(KK) = (6.8 \pm 5.4 \pm 1.6) \times 10^{-4}$$

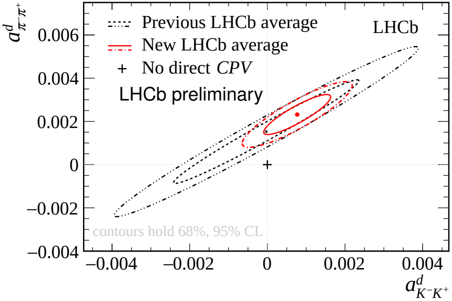
more than twice more precise than previous LHCb measurement



- Combining with ΔA_{CP}, Run 1 result, and time-dependent measurements yields:

$$a^d_{KK} = (\ 7.7 \pm 5.7) \times 10^{-4}$$
$$a^d_{\pi\pi} = (23.2 \pm 6.1) \times 10^{-4}$$

- Giving the first evidence of direct CP violation in $D^0 \to \pi^+\pi^-$ decays (3.8σ)



Combination sources [JHEP 07 (2014)] [Phys. Rev. Lett. 116 (2016)] [Phys. Lett. B 767 (2017)] [Phys. Rev. Lett. 122 (2019)] [Phys. Rev. D 104 (2021)]

Direct *CP* violation in $B^{\pm} \to h^{\pm}h^{+}h^{-}$ decays

- Study of phase-space integrated and localised CP asymmetries across the Dalitz plane of charmless thee-body $B^{\pm}$ decays [arXiv:2206.07622]
  - Already observed global and localised CP-violation across the Dalitz plane [Phys. Rev. D 90]
  - $\pi\pi \longleftrightarrow KK$ rescattering at play
  - Interference of S- and P-wave in $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ [Phys. Rev. D 101] [Phys. Rev. Lett. 124]
  - Test U-spin symmetry prediction that $\frac{\Delta\Gamma(B^{\pm}\to K^{\pm}\pi^{+}\pi^{-})}{\Delta\Gamma(B^{\pm}\to\pi^{\pm}K^{+}K^{-})} = \frac{\Delta\Gamma(B^{\pm}\to K^{\pm}K^{+}K^{-})}{\Delta\Gamma(B^{\pm}\to\pi^{\pm}\pi^{+}\pi^{-})} = -1$
- Measured quantity:

$$A_{CP} = \frac{A_{raw}^{corr} - A_P}{1 - A_{raw}^{corr} A_P}$$

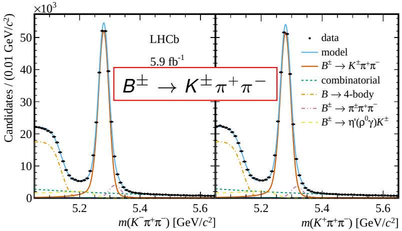
- $A_{raw}^{corr} = \frac{N_{B^-}/\varepsilon^- - N_{B^+}/\varepsilon^+}{N_{B^-}/\varepsilon^- + N_{B^+}/\varepsilon^+}$: efficiency-corrected $B^{\pm}$ signal yields ratio
- A_P: $B^{\pm}$ production asymmetry from control sample

$$A_P = A_{raw}^{corr}(B^{\pm} \to J/\psi K^{\pm}) - \underbrace{A_{CP}(B^{\pm} \to J/\psi K^{\pm})}_{0.0018\pm0.0030\ \text{[PDG]}} = -0.0070 \pm 0.0008^{+0.0007}_{-0.0008} \pm 0.0030$$

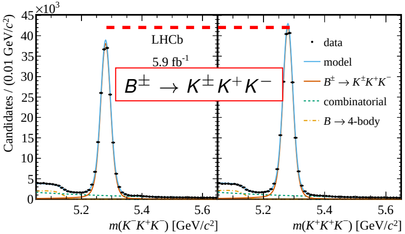
Decay mode	Total yield	A_{raw}	$R = <\epsilon^-> / <\epsilon^+>$
$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$	$499\,200 \pm 900$	0.006 ± 0.002	1.0038 ± 0.0027
$B^{\pm} \to K^{\pm}K^{+}K^{-}$	$365\,000 \pm 1000$	-0.052 ± 0.002	0.9846 ± 0.0024
$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$	$101\,000 \pm 500$	0.090 ± 0.004	1.0354 ± 0.0037
$B^{\pm} \to \pi^{\pm}K^{+}K^{-}$	$32\,470 \pm 300$	-0.132 ± 0.007	0.9777 ± 0.0032

Direct CP violation in $B^{\pm} \to h^{\pm}h^{+}h^{-}$ decays

Integrated CP asymmetries [arXiv:2206.07622]

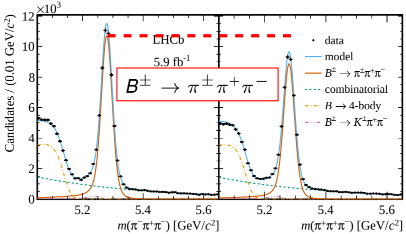


$$A_{CP}(B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}) = (+1.1 \pm 0.2 \pm 0.3 \pm 0.3_{J/\psi})\%$$



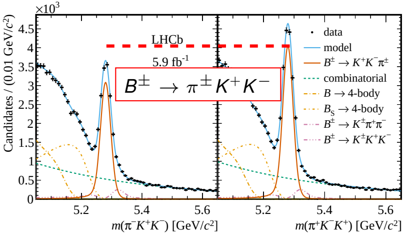
$$A_{CP}(B^{\pm} \to K^{\pm}K^{+}K^{-}) = (-3.7 \pm 0.2 \pm 0.2 \pm 0.3_{J/\psi})\% \ (8.5\sigma)$$

First observation!



$$A_{CP}(B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}) = (+8.0 \pm 0.4 \pm 0.3 \pm 0.3_{J/\psi})\% \ (14.1\sigma)$$

First observation!

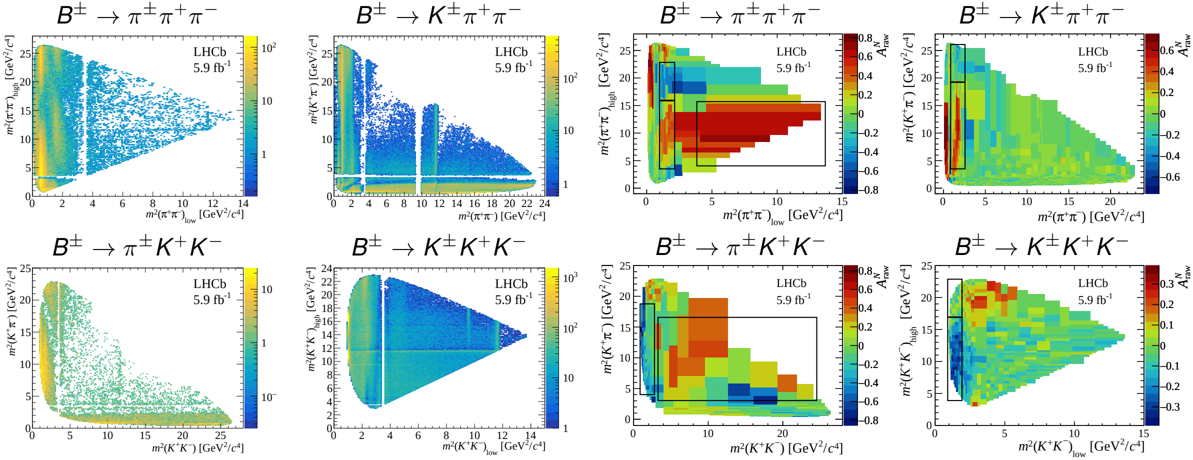


$$A_{CP}(B^{\pm} \to \pi^{\pm}K^{+}K^{-}) = (-11.4 \pm 0.7 \pm 0.3 \pm 0.3_{J/\psi})\% \ (13.6\sigma)$$

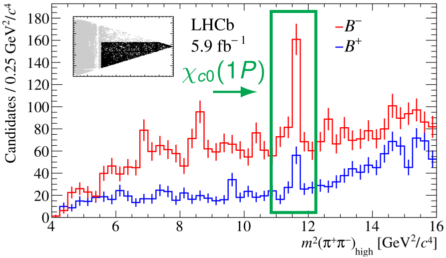
Direct *CP* violation in $B^\pm \to h^\pm h^+ h^-$ decays

Localised *CP* asymmetries

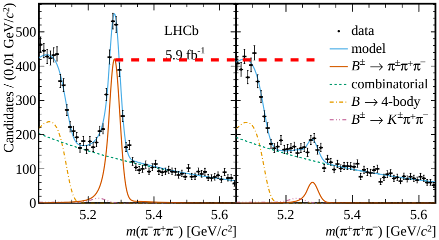
- Repeat the measurement in 9 regions of the Dalitz planes looking for local *CP* violation
- A rich landscape of large local asymmetries shows up



- Observed very high CP-violating effects in many regions
- Sizeable $\chi_{c0}(1P)$ contribution found in the $B^\pm \to \pi^\pm\pi^+\pi^-$ and $B^\pm \to \pi^\pm K^+ K^-$ spectra



$$A_{CP}(B^\pm \to \pi^\pm\pi^+\pi^-) = (74.5 \pm 2.7 \pm 1.8 \pm 0.3)\%$$



$B^\pm \to \pi^\pm\pi^+\pi^-$	N_{sig}	A_{raw}	A_{CP}
Region 1	$14\,330 \pm 150$	$+0.309 \pm 0.009$	$+0.303 \pm 0.009 \pm 0.004 \pm 0.003$
Region 2	$4\,850 \pm 130$	-0.287 ± 0.017	$-0.284 \pm 0.017 \pm 0.007 \pm 0.003$
Region 3	$2\,270 \pm 60$	$+0.747 \pm 0.027$	$+0.745 \pm 0.027 \pm 0.018 \pm 0.003$
$B^\pm \to K^\pm\pi^+\pi^-$			
Region 1	$41\,980 \pm 280$	$+0.201 \pm 0.005$	$+0.217 \pm 0.005 \pm 0.005 \pm 0.003$
Region 2	$27\,040 \pm 250$	-0.149 ± 0.007	$-0.145 \pm 0.007 \pm 0.006 \pm 0.003$
$B^\pm \to \pi^\pm K^+ K^-$			
Region 1	$11\,430 \pm 170$	-0.363 ± 0.010	$-0.358 \pm 0.010 \pm 0.014 \pm 0.003$
Region 2	$2\,600 \pm 120$	$+0.075 \pm 0.031$	$+0.097 \pm 0.031 \pm 0.005 \pm 0.003$
$B^\pm \to K^\pm K^+ K^-$			
Region 1	$76\,020 \pm 350$	-0.189 ± 0.004	$-0.178 \pm 0.004 \pm 0.004 \pm 0.003$
Region 2	$37\,440 \pm 320$	$+0.030 \pm 0.005$	$+0.043 \pm 0.005 \pm 0.004 \pm 0.003$

- Predictions of U-spin symmetry are tested and confirmed

$$\frac{\Delta\Gamma(B^\pm \to \pi^\pm K^+ K^-)}{\Delta\Gamma(B^\pm \to K^\pm\pi^+\pi^-)} = -0.92 \pm 0.18$$

$$\frac{\Delta\Gamma(B^\pm \to \pi^\pm\pi^+\pi^-)}{\Delta\Gamma(B^\pm \to K^\pm K^+ K^-)} = -1.06 \pm 0.08$$

Direct CP violation in $B^\pm \to h^\pm h^+ h^-$ decays

Amplitude analysis of $B \to PV$ decays

- Is also possible to study the resonant structure of $B^\pm \to V(\to h_1^- h_2^+) h_3^\pm$ decays with a model-independent approach [arXiv:2206.02038]
  - Vector resonances can interfere with other resonant components $\Longrightarrow$ estimate strong phases and penguin-diagram contributions
  - Investigate the role of long- and short-distance contributions in direct CP violation
- Resonances under investigation:
  - $B^\pm \to \rho(770)^0 K^\pm$
  - $B^\pm \to K^*(892)^0 \pi^\pm$
  - $B^\pm \to \phi(1020) K^\pm$
  - $B^\pm \to \rho(770)^0 \pi^\pm$
  - $B^\pm \to K^*(892)^0 K^\pm$

Notation:
$s_\parallel = m^2(h_1^+ h_2^\pm)$
$s_\perp = m^2(h_1^+ h_3^\pm)$
$\theta = \widehat{h_1^+ h_3^\pm}$

- For isolated and narrow resonances, the decay amplitude can be approximated as a quadratic polynomial:

$$|\mathcal{M}_\pm|^2 = \underbrace{p_0^\pm}_{\text{Scalar CPV}} + \underbrace{p_1^\pm \cos\theta(m_V^2, s_\perp)}_{\text{Scalar + Vector interf.}} + \underbrace{p_2^\pm \cos^2\theta(m_V^2, s_\perp)}_{\text{Vector CPV}}$$

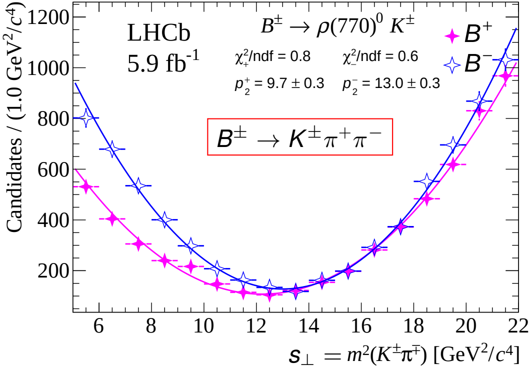
- Measuring $p_2^\pm$ with a polynomial fit, CPV can be tested with

$$A_{CP} = \frac{|\mathcal{M}_-|^2 - |\mathcal{M}_+|^2}{|\mathcal{M}_-|^2 + |\mathcal{M}_+|^2} = \frac{p_2^- - p_2^+}{p_2^- + p_2^+}$$

Direct CP violation in $B^\pm \to h^\pm h^+ h^-$ decays

$B^\pm \to \rho(770)^0 K^\pm$ polynomial fit

[arXiv:2206.02038]



$$A_{CP} = (15.0 \pm 1.9 \pm 1.1)\%, \quad (6.8\sigma)$$

- Candidates are selected with $s_\parallel = m^2(\pi^+\pi^-)$ within 150 MeV of the nominal $\rho(770)^0$ mass
- $\rho(770)^0 - \omega(782)$ mixing effects cannot be excluded with this method
- First observation of CP violation in $B^\pm \to \rho(770)^0 K^\pm$
- All other resonances give results compatible with CP symmetry conservation
- Some measurements are in slight tension with results from BaBar and Belle

[Phys. Rev. D 78 (2008)] [Phys. Rev. D 71 (2005)]

Decay channel	This work	Previous measurements
$B^\pm \to (\rho(770)^0 \to \pi^+\pi^-)\pi^\pm$	$-0.004 \pm 0.017 \pm 0.009$	$+0.007 \pm 0.011 \pm 0.016$ (LHCb [20,21])
$B^\pm \to (\rho(770)^0 \to \pi^+\pi^-)K^\pm$	$+0.150 \pm 0.019 \pm 0.011$	$+0.44 \pm 0.10 \pm 0.04$ (BaBar [42]) ← 2.9σ (stat only) $+0.30 \pm 0.11 \pm 0.02$ (Belle [22])
$B^\pm \to (K^*(892)^0 \to K^\pm\pi^\mp)\pi^\pm$	$-0.015 \pm 0.021 \pm 0.012$	$+0.032 \pm 0.052 \pm 0.011$ (BaBar [42]) $-0.149 \pm 0.064 \pm 0.020$ (Belle [22]) ← 2.6σ (stat only)
$B^\pm \to (K^*(892)^0 \to K^\pm\pi^\mp)K^\pm$	$+0.007 \pm 0.054 \pm 0.032$	$+0.123 \pm 0.087 \pm 0.045$ (LHCb [19])
$B^\pm \to (\phi(1020) \to K^+K^-)K^\pm$	$+0.004 \pm 0.010 \pm 0.007$	$+0.128 \pm 0.044 \pm 0.013$ (BaBar [26]) ← 2.8σ (stat only)

Search for CP violation using $\widehat{T}$-odd correlations in $B^0 \to p\bar{p}K^+\pi^-$ decays

- Search for CP and P violation by studying triple-products asymmetries [arXiv:2205.08973]
- Baryonic multibody decay $\Longrightarrow$ interference between different amplitudes, expected large CP asymmetries [Phys. Rev. Lett. 98 (2007)] [Eur. Phys. J. C 80 (2020)]
- Found evidence for CPV in $B^+ \to p\bar{p}K^+$ decays [Phys. Rev. Lett. 113 (2014)]
- Define the $\widehat{T}$-odd triple-products:

$$C_{\widehat{T}} = \vec{p}_{K^+} \cdot (\vec{p}_{\pi^-} \times \vec{p}_p), \quad \overline{C}_{\widehat{T}} = \vec{p}_{K^-} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\bar{p}})$$

- The corresponding asymmetries are (N.B. $CP(C_{\widehat{T}}) = -\overline{C}_{\widehat{T}}, \quad N = N(B^0), \quad \overline{N} = N(\overline{B^0})$)

$$A_{\widehat{T}} = \frac{N(C_{\widehat{T}} > 0) - N(C_{\widehat{T}} < 0)}{N(C_{\widehat{T}} > 0) + N(C_{\widehat{T}} < 0)}, \quad \overline{A}_{\widehat{T}} = \frac{\overline{N}(-\overline{C}_{\widehat{T}} > 0) - \overline{N}(-\overline{C}_{\widehat{T}} < 0)}{\overline{N}(-\overline{C}_{\widehat{T}} > 0) + \overline{N}(-\overline{C}_{\widehat{T}} < 0)}$$

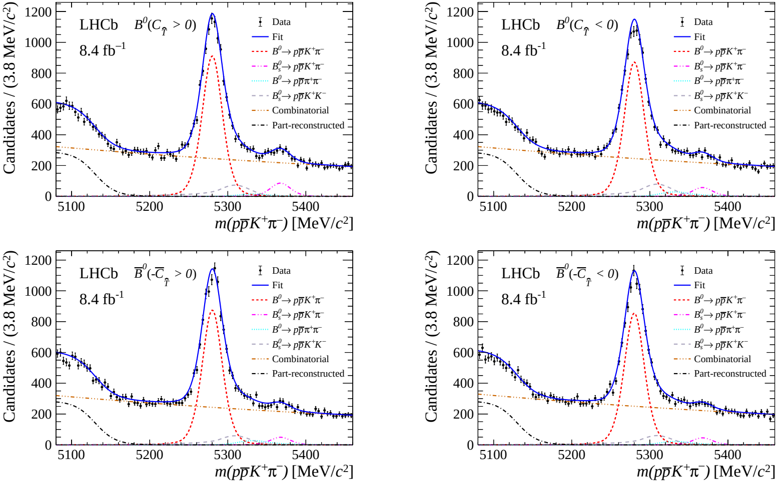
- The CP- and P-violating observables are then:

$$a_{CP}^{\widehat{T}\text{-odd}} = \frac{1}{2}(A_{\widehat{T}} - \overline{A}_{\widehat{T}}), \quad a_{P}^{\widehat{T}\text{-odd}} = \frac{1}{2}(A_{\widehat{T}} + \overline{A}_{\widehat{T}})$$

mostly insensitive to production and detection asymmetries $\Longrightarrow$ clean observables ✓

Search for CP violation using $\widehat{T}$-odd correlations in $B^0 \to p\bar{p}K^+\pi^-$ decays

Phase-space integrated results [arXiv:2205.08973]



- Signal yields: 70×10^3
- Results:

$$a_{CP}^{\widehat{T}\text{-odd}} = (0.51 \pm 0.85 \pm 0.08)\%$$

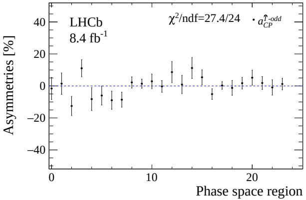
$$a_{P}^{\widehat{T}\text{-odd}} = (1.49 \pm 0.85 \pm 0.08)\%$$

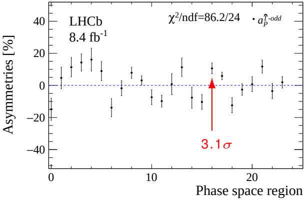
- Compatible with P and CP conservation
- Statistically limited

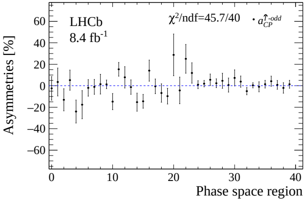
Search for CP violation using $\widehat{T}$-odd correlations in $B^0 \to p\bar{p}K^+\pi^-$ decays

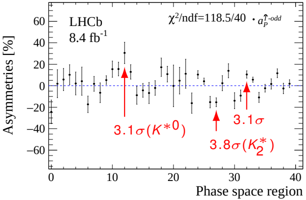
Phase-space regions results [arXiv:2205.08973]

- Perform the measurements also in regions of phase-space to improve sensitivity to resonances and interference effects
- Use two different binnings in $m(K^+\pi^-)$, $m(p\bar{p})$, $\cos\theta_{K\pi}$, $\cos\theta_{p\bar{p}}$, and ϕ, with 24 and 40 bins









- χ^2 compatibility test for P and CP conservation:

$a_{CP}^{\widehat{T}\text{-odd}}$	24 bins	40 bins
χ^2	$27.4/24$	$45.7/40$
p-value	0.28	0.24

consistent with CP conservation

$a_{P}^{\widehat{T}\text{-odd}}$	24 bins	40 bins
χ^2	$86.2/24$	$118.5/40$
p-value	6.1×10^{-9}	1.1×10^{-9}

consistent with P symmetry violation at 5.8σ

Summary

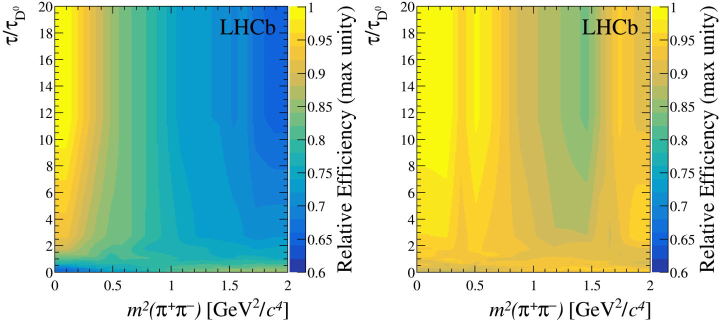
- Many new searches for *CP* violation in charm and beauty decays by LHCb were presented
- First evidence of CPV in $D^0 \to \pi^+\pi^-$ decays
- Observed CPV for the first time in several decays:
  - $B^\pm \to \pi^\pm\pi^+\pi^-$
  - $B^\pm \to K^\pm K^+ K^-$
  - $B^\pm \to \rho(770)^0 K^\pm$
- Precision on charm mixing observables is starting to reach below the per-mille level
  - Look deeply into the origin of *CP* violation in the charm sector
  - Search for New Physics phenomena mediated by massive virtual particles
- Some analyses are statistically limited $\Longrightarrow$ Run 3 will bring a lot more data to study
- Stay tuned for even more precise results!

Backup

Measurement of charm-mixing parameters with $D^0 \to K_s^0\pi^+\pi^-$ decays

Decorrelation

- Any correlation between Dalitz variables and decay-time must be suppressed
- Larger correlation given by online software selection of events
- Correct for it by evaluating online selection efficiency with simulation and applying inverse as weight to data



- Systematics much smaller than statistical uncertainties
- Estimated by running pseudo-experiments with the error source added to data and with a correction applied, and by taking the residual

Source	x_{CP} $[10^{-3}]$	y_{CP} $[10^{-3}]$	Δx $[10^{-3}]$	Δy $[10^{-3}]$
Reconstruction and selection	0.06	0.79	0.28	0.24
Detection asymmetry	0.06	0.03	0.01	0.09
Mass-fit model	0.03	0.09	0.01	0.01
Unrelated $D^0\mu$ combinations	0.24	0.22	0.01	0.05
Total systematic	0.26	0.83	0.28	0.26
Strong phase inputs	0.32	0.68	0.16	0.21
Statistical (w/o phase inputs)	1.45	3.04	0.92	1.91
Statistical	1.48	3.12	0.93	1.92

- External inputs on the strong phase differences in the 8 Dalitz bins are included into the statistical uncertainties

[Phys. Rev. D 82 (2010)] [Phys. Rev. D 101 (2020)]

Measurement of $y_{CP} - y_{CP}^{K\pi}$ using two-body D^0 decays

Why $y_{CP} - y_{CP}^{K\pi}$?

- In previous measurements of y_{CP} the decay width of D^0 mesons was approximated by

$$\Gamma \approx \frac{\hat{\Gamma}(D^0 \to K^-\pi^+) + \hat{\Gamma}(\overline{D^0} \to K^-\pi^+)}{2}$$

- Can be shown that $y_{CP}^{K\pi} = \frac{\hat{\Gamma}(D^0 \to K^-\pi^+) + \hat{\Gamma}(\overline{D^0} \to K^-\pi^+)}{2\Gamma} \approx \sqrt{R_D}(x_{12}\cos\phi_2^M \sin\Delta_{K\pi} - y_{12}\cos\phi_2^\Gamma \cos\Delta_{K\pi})$, with

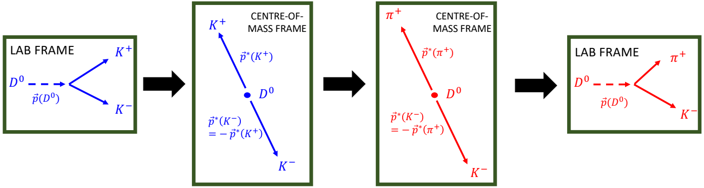
$$\sqrt{R_D} = \frac{\sqrt{\mathcal{B}(D^0 \to K^+\pi^-)}}{\sqrt{\mathcal{B}(D^0 \to K^-\pi^+)}} = (5.87 \pm 0.02) \times 10^{-2}$$

- And therefore,

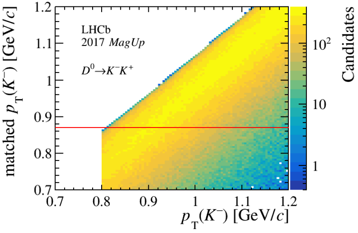
$$\frac{\hat{\Gamma}(D^0 \to f) + \hat{\Gamma}(\overline{D^0} \to f)}{\hat{\Gamma}(D^0 \to K^-\pi^+) + \hat{\Gamma}(\overline{D^0} \to K^-\pi^+)} \approx (1 + y_{CP})(1 - y_{CP}^{K\pi}) - 1$$
$$\approx y_{CP} - y_{CP}^{K\pi}$$

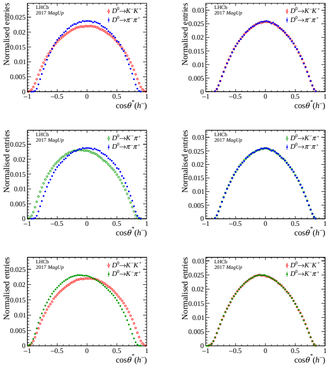
- According to predictions, $y_{CP}^{K\pi} \approx -3.5 \times 10^{-4}$ [JHEP 162 (2022)]

- Equalize the decay-time reconstruction efficiencies by transforming a $D^0 \to K^+K^-$ or $D^0 \to \pi^+\pi^-$ decays into a $D^0 \to K^-\pi^+$



- After matching, apply reweighting of p, p_T and η of the D^0 and the final-state particles
- By cutting on the matched variables you get equal efficiencies for $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$

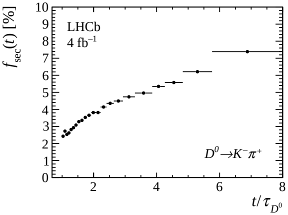


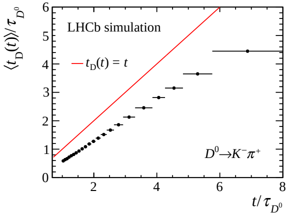


- Secondary D^{*+} mesons coming from B decays can survive the selection
- Account their contribution by modifying the fit function:

$$R^f(t) = (1 - f_{sec}(t))R^f_{prompt}(t) + f_{sec}(t)R^f_{sec}(t), \qquad R^f_{sec}(t) \propto e^{-(y^f_{CP} - y^{K\pi}_{CP})\langle t_D(t)\rangle/\tau_{D^0}}$$

with $f_{sec}(t)$ and $\langle t_D(t)\rangle$ obtained from simulation





	y_{CP}^{CC}	$y_{CP}^{KK} - y_{CP}^{K\pi}$	$y_{CP}^{KK} - y_{CP}^{K\pi}$
Raw	0.68 ± 0.47 (7.9)	7.48 ± 0.48 (5.5)	6.64 ± 0.27 (6.6)
Matching	-0.28 ± 0.52 (8.3)	6.80 ± 0.52 (2.9)	7.14 ± 0.29 (5.5)
Matching + Weighting	-0.43 ± 0.52 (9.0)	6.44 ± 0.52 (2.8)	6.94 ± 0.29 (5.9)
Matching + Weighting + Fit with secondaries	-0.44 ± 0.53 (9.0)	6.57 ± 0.53 (2.8)	7.08 ± 0.30 (5.9)

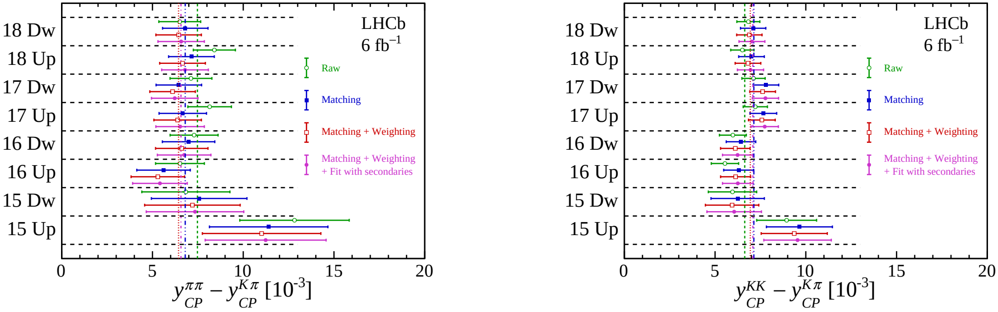
Measurement of $y_{CP} - y_{CP}^{K\pi}$ using two-body D^0 decays

Cross-checks and systematic uncertainties

- Systematic uncertainties under control

	$\sigma(y_{CP}^{\pi\pi} - y_{CP}^{K\pi})$ $[10^{-3}]$	$\sigma(y_{CP}^{KK} - y_{CP}^{K\pi})$ $[10^{-3}]$
Combinatorial background	0.12	0.07
Peaking background	0.02	0.11
Treatment of secondary decays	0.03	0.03
Kinematic weighting procedure	0.08	0.02
Input D^0 lifetime	0.03	0.03
Residual nuisance asymmetries	0.03	< 0.01
Fit bias	0.03	0.03
Total	0.16	0.14

- Repeated measurement separating by year and magnet polarity



CP asymmetry measurement with $D^0 \to K^+K^-$ decays

C_{D^+} and $C_{D_s^+}$ corrections

- C_{D^+} decays: $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D^+ \to \overline{K}^0\pi^+$
- $C_{D_s^+}$ decays: $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$, $D_s^+ \to \phi(\to K^-K^+)\pi^+$, $D_s^+ \to \overline{K}^0K^+$
- The corresponding asymmetries are

$$A(K^-\pi^+) \approx A_{prod}(D^{*+}) - A_{det}(K^+) + A_{det}(\pi^+) + A_{det}(\pi^+_{tag})$$
$$A(K^-\pi^+\pi^+) \approx A_{prod}(D^+) - A_{det}(K^+) + A_{det}(\pi^+_1) + A_{det}(\pi^+_2)$$
$$A(\overline{K}^0\pi^+) \approx A_{prod}(D^+) - A(K^0) + A_{det}(\pi^+)$$
$$A(\phi\pi^+) \approx A_{prod}(D_s^+) + A_{det}(\pi^+)$$
$$A(\overline{K}^0K^+) \approx A_{prod}(D_s^+) - A(K^0) + A_{det}(K^+)$$

- You can then combine them to obtain

$$C_{D^+} : A_{CP}(K^+K^-) = A(K^+K^-) - A(K^-\pi^+) + A(K^-\pi^+\pi^+) - A(\overline{K}^0\pi^+) - A(K^0)$$
$$C_{D_s^+} : A_{CP}(K^+K^-) = A(K^+K^-) - A(K^-\pi^+) + A(\phi\pi^+) - A(\overline{K}^0\pi^+) - A(K^0)$$

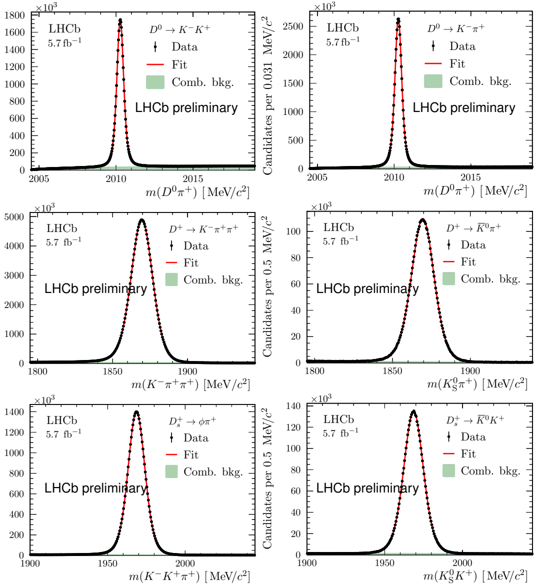
- $A(K^0) \implies$ CPV + mixing + different interaction of K^0-$\overline{K}^0$ with the detector material [Phys. Lett. B767 (2017)]

- Signal yields for all decay modes considered

Decay mode	Signal yield $[10^6]$		Reduction factor	
	CDP	CDS	CDP	CDS
$D^0 \to K^-K^+$	45	40	0.75	0.75
$D^0 \to K^-\pi^+$	60	55	0.35	0.75
$D^+ \to K^-\pi^+\pi^+$	192	–	0.25	–
$D_s^+ \to \phi\pi^+$	-	83	–	0.55
$D^+ \to \overline{K}^0\pi^+$	8	–	0.25	
$D_s^+ \to \overline{K}^0K^+$	–	6	–	0.40

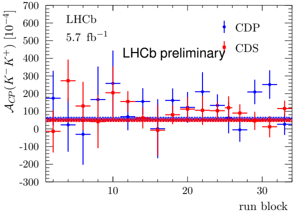
- Systematic uncertainties

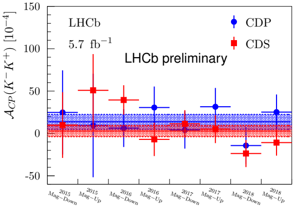
Source	CDP $[10^{-4}]$	CDS $[10^{-4}]$	Correlation
Secondary decays	0.6	0.3	–
Peaking backgrounds	0.3	0.4	0.74
Fit model	1.1	1.0	0.05
Kinematic weighting	0.8	0.4	–
Neutral kaon asymmetry	0.6	1.3	1.00
Charged kaon asymmetry	–	1.0	–
Total	1.6	2.0	0.28

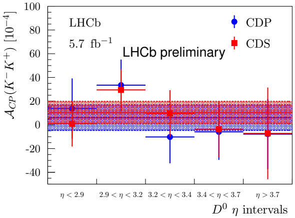


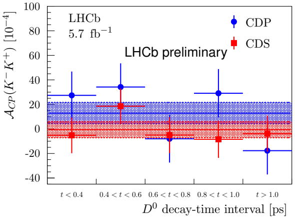
CP asymmetry measurement with $D^0 \to K^+K^-$ decays

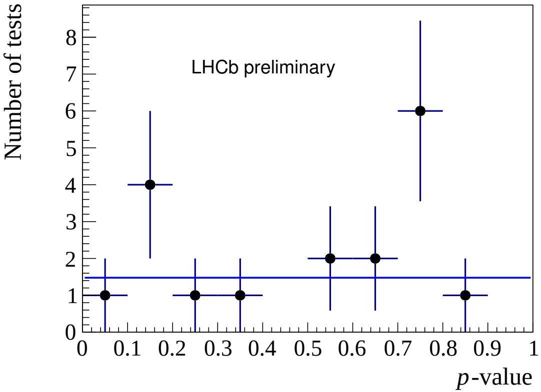
Consistency checks











Source of uncertainty	$K^{\pm}\pi^{+}\pi^{-}$	$K^{\pm}K^{+}K^{-}$	$\pi^{\pm}\pi^{+}\pi^{-}$	$\pi^{\pm}K^{+}K^{-}$
Signal model	0.0004	0.0007	0.0000	0.0001
Peaking background fraction	0.0005	0.0010	0.0002	0.0004
Peaking background asymmetry	0.0022	0.0001	0.0005	0.0007
Combinatorial model	0.0002	0.0005	0.0015	0.0025
Efficiency correction	0.0014	0.0016	0.0018	0.0019
Production asymmetry	0.0011	0.0011	0.0011	0.0011
Total	0.0029	0.0024	0.0027	0.0035

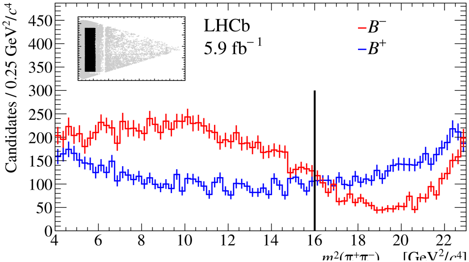
- Peak. back. fracs.: Vary the fractions within errors
- Peak. back. asymm.: Fixed to 0 in fits, free to float with value obtained in previous measurement within errors to estimate uncertainty
- Eff. corr.: Due to limited size of simulated sample used for evaluation

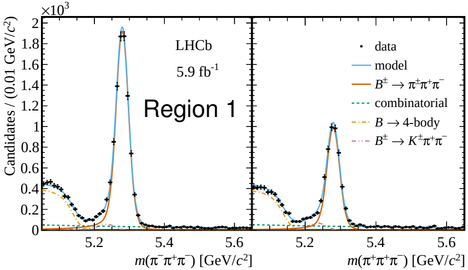
Direct *CP* violation in $B^\pm \to h^\pm h^+ h^-$ decays

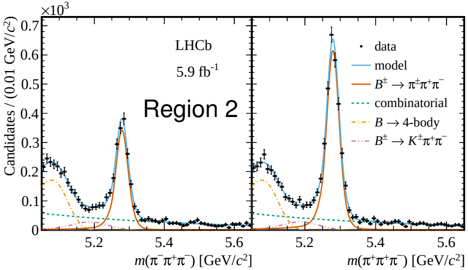
Localised *CP* asymmetries

- $B^\pm \to \pi^\pm \pi^+ \pi^-$ Dalitz plane regions 1&2

	$B^\pm \to \pi^\pm\pi^+\pi^-$		
Region 1	$1 < m^2(\pi^+\pi^-)_{\text{low}} < 2.25$	and	$3.5 < m^2(\pi^+\pi^-)_{\text{high}} < 16$
Region 2	$1 < m^2(\pi^+\pi^-)_{\text{low}} < 2.25$	and	$16 < m^2(\pi^+\pi^-)_{\text{high}} < 23$
Region 3	$4 < m^2(\pi^+\pi^-)_{\text{low}} < 15$	and	$4 < m^2(\pi^+\pi^-)_{\text{high}} < 16$
	$B^\pm \to K^\pm\pi^+\pi^-$		
Region 1	$1 < m^2(\pi^+\pi^-) < 2.25$	and	$3.5 < m^2(K^+\pi^-) < 19.5$
Region 2	$1 < m^2(\pi^+\pi^-) < 2.25$	and	$19.5 < m^2(K^+\pi^-) < 25.5$
	$B^\pm \to \pi^\pm K^+K^-$		
Region 1	$1 < m^2(K^+K^-) < 2.25$	and	$4 < m^2(K^+\pi^-) < 19$
Region 2	$4 < m^2(K^+K^-) < 25$	and	$3 < m^2(K^+\pi^-) < 16$
	$B^\pm \to K^\pm K^+K^-$		
Region 1	$1.1 < m^2(K^+K^-)_{\text{low}} < 2.25$	and	$4 < m^2(K^+K^-)_{\text{high}} < 17$
Region 2	$1.1 < m^2(K^+K^-)_{\text{low}} < 2.25$	and	$17 < m^2(K^+K^-)_{\text{high}} < 23$





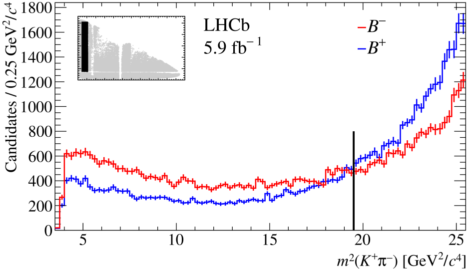


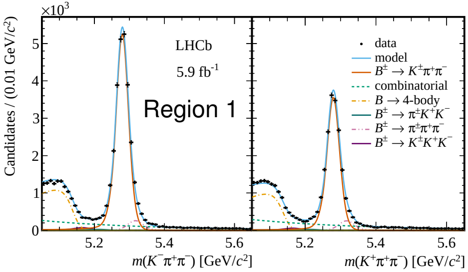
Direct *CP* violation in $B^\pm \to h^\pm h^+ h^-$ decays

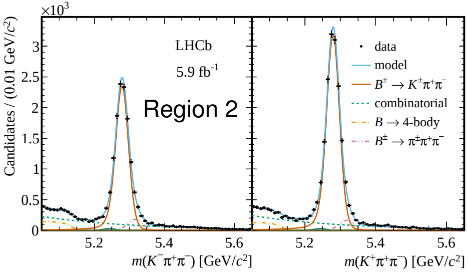
Localised *CP* asymmetries

- $B^\pm \to K^\pm \pi^+ \pi^-$ Dalitz plane regions 1&2

	$B^\pm \to \pi^\pm\pi^+\pi^-$		
Region 1	$1 < m^2(\pi^+\pi^-)_{\rm low} < 2.25$	and	$3.5 < m^2(\pi^+\pi^-)_{\rm high} < 16$
Region 2	$1 < m^2(\pi^+\pi^-)_{\rm low} < 2.25$	and	$16 < m^2(\pi^+\pi^-)_{\rm high} < 23$
Region 3	$4 < m^2(\pi^+\pi^-)_{\rm low} < 15$	and	$4 < m^2(\pi^+\pi^-)_{\rm high} < 16$
	$B^\pm \to K^\pm\pi^+\pi^-$		
Region 1	$1 < m^2(\pi^+\pi^-) < 2.25$	and	$3.5 < m^2(K^+\pi^-) < 19.5$
Region 2	$1 < m^2(\pi^+\pi^-) < 2.25$	and	$19.5 < m^2(K^+\pi^-) < 25.5$
	$B^\pm \to \pi^\pm K^+K^-$		
Region 1	$1 < m^2(K^+K^-) < 2.25$	and	$4 < m^2(K^+\pi^-) < 19$
Region 2	$4 < m^2(K^+K^-) < 25$	and	$3 < m^2(K^+\pi^-) < 16$
	$B^\pm \to K^\pm K^+K^-$		
Region 1	$1.1 < m^2(K^+K^-)_{\rm low} < 2.25$	and	$4 < m^2(K^+K^-)_{\rm high} < 17$
Region 2	$1.1 < m^2(K^+K^-)_{\rm low} < 2.25$	and	$17 < m^2(K^+K^-)_{\rm high} < 23$





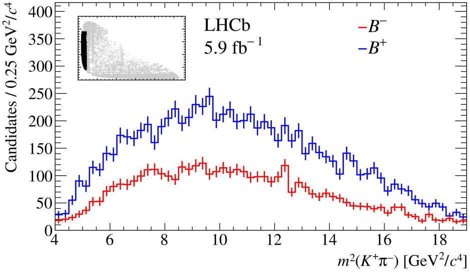


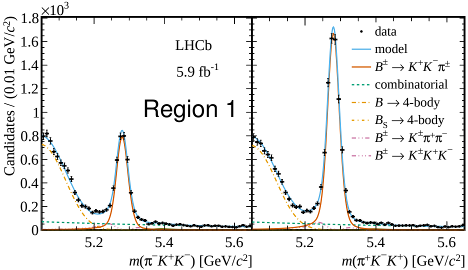
Direct CP violation in $B^{\pm} \to h^{\pm} h^{+} h^{-}$ decays

Localised CP asymmetries

- $B^{\pm} \to \pi^{\pm} K^{+} K^{-}$ Dalitz plane region 1

		$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$	
Region 1	$1 < m^2(\pi^+\pi^-)_{\text{low}} < 2.25$	and	$3.5 < m^2(\pi^+\pi^-)_{\text{high}} < 16$
Region 2	$1 < m^2(\pi^+\pi^-)_{\text{low}} < 2.25$	and	$16 < m^2(\pi^+\pi^-)_{\text{high}} < 23$
Region 3	$4 < m^2(\pi^+\pi^-)_{\text{low}} < 15$	and	$4 < m^2(\pi^+\pi^-)_{\text{high}} < 16$
		$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$	
Region 1	$1 < m^2(\pi^+\pi^-) < 2.25$	and	$3.5 < m^2(K^+\pi^-) < 19.5$
Region 2	$1 < m^2(\pi^+\pi^-) < 2.25$	and	$19.5 < m^2(K^+\pi^-) < 25.5$
		$B^{\pm} \to \pi^{\pm}K^{+}K^{-}$	
Region 1	$1 < m^2(K^+K^-) < 2.25$	and	$4 < m^2(K^+\pi^-) < 19$
Region 2	$4 < m^2(K^+K^-) < 25$	and	$3 < m^2(K^+\pi^-) < 16$
		$B^{\pm} \to K^{\pm}K^{+}K^{-}$	
Region 1	$1.1 < m^2(K^+K^-)_{\text{low}} < 2.25$	and	$4 < m^2(K^+K^-)_{\text{high}} < 17$
Region 2	$1.1 < m^2(K^+K^-)_{\text{low}} < 2.25$	and	$17 < m^2(K^+K^-)_{\text{high}} < 23$



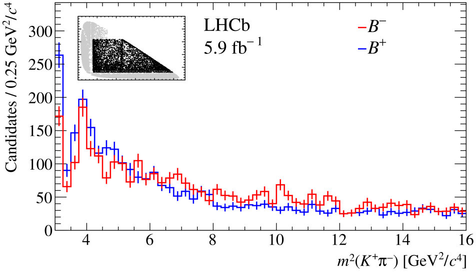


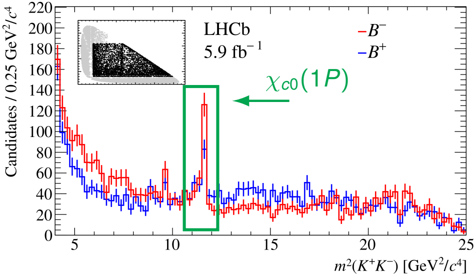
Direct CP violation in $B^{\pm} \to h^{\pm}h^{+}h^{-}$ decays

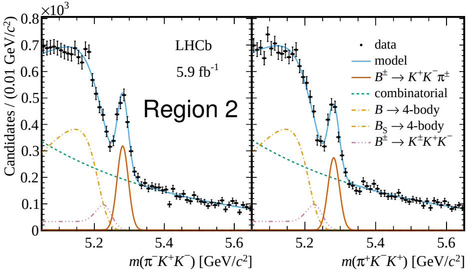
Localised CP asymmetries

- $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ Dalitz plane region 2

		$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$	
Region 1	$1 < m^2(\pi^+\pi^-)_{\rm low} < 2.25$	and	$3.5 < m^2(\pi^+\pi^-)_{\rm high} < 16$
Region 2	$1 < m^2(\pi^+\pi^-)_{\rm low} < 2.25$	and	$16 < m^2(\pi^+\pi^-)_{\rm high} < 23$
Region 3	$4 < m^2(\pi^+\pi^-)_{\rm low} < 15$	and	$4 < m^2(\pi^+\pi^-)_{\rm high} < 16$
		$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$	
Region 1	$1 < m^2(\pi^+\pi^-) < 2.25$	and	$3.5 < m^2(K^+\pi^-) < 19.5$
Region 2	$1 < m^2(\pi^+\pi^-) < 2.25$	and	$19.5 < m^2(K^+\pi^-) < 25.5$
		$B^{\pm} \to \pi^{\pm}K^{+}K^{-}$	
Region 1	$1 < m^2(K^+K^-) < 2.25$	and	$4 < m^2(K^+\pi^-) < 19$
Region 2	$4 < m^2(K^+K^-) < 25$	and	$3 < m^2(K^+\pi^-) < 16$
		$B^{\pm} \to K^{\pm}K^{+}K^{-}$	
Region 1	$1.1 < m^2(K^+K^-)_{\rm low} < 2.25$	and	$4 < m^2(K^+K^-)_{\rm high} < 17$
Region 2	$1.1 < m^2(K^+K^-)_{\rm low} < 2.25$	and	$17 < m^2(K^+K^-)_{\rm high} < 23$





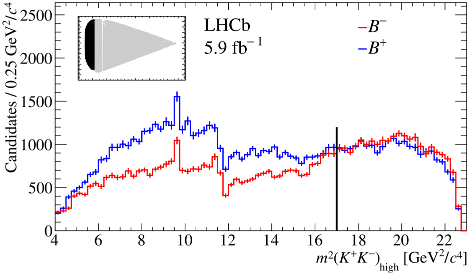


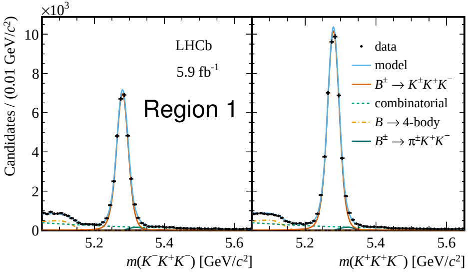
Direct *CP* violation in $B^{\pm} \to h^{\pm}h^{+}h^{-}$ decays

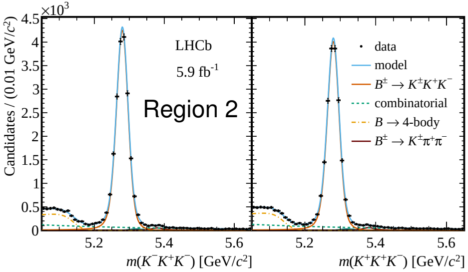
Localised *CP* asymmetries

- $B^{\pm} \to K^{\pm}K^{+}K^{-}$ Dalitz plane regions 1&2

		$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$	
Region 1	$1 < m^2(\pi^+\pi^-)_{\rm low} < 2.25$	and	$3.5 < m^2(\pi^+\pi^-)_{\rm high} < 16$
Region 2	$1 < m^2(\pi^+\pi^-)_{\rm low} < 2.25$	and	$16 < m^2(\pi^+\pi^-)_{\rm high} < 23$
Region 3	$4 < m^2(\pi^+\pi^-)_{\rm low} < 15$	and	$4 < m^2(\pi^+\pi^-)_{\rm high} < 16$
		$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$	
Region 1	$1 < m^2(\pi^+\pi^-) < 2.25$	and	$3.5 < m^2(K^+\pi^-) < 19.5$
Region 2	$1 < m^2(\pi^+\pi^-) < 2.25$	and	$19.5 < m^2(K^+\pi^-) < 25.5$
		$B^{\pm} \to \pi^{\pm}K^{+}K^{-}$	
Region 1	$1 < m^2(K^+K^-) < 2.25$	and	$4 < m^2(K^+\pi^-) < 19$
Region 2	$4 < m^2(K^+K^-) < 25$	and	$3 < m^2(K^+\pi^-) < 16$
		$B^{\pm} \to K^{\pm}K^{+}K^{-}$	
Region 1	$1.1 < m^2(K^+K^-)_{\rm low} < 2.25$	and	$4 < m^2(K^+K^-)_{\rm high} < 17$
Region 2	$1.1 < m^2(K^+K^-)_{\rm low} < 2.25$	and	$17 < m^2(K^+K^-)_{\rm high} < 23$



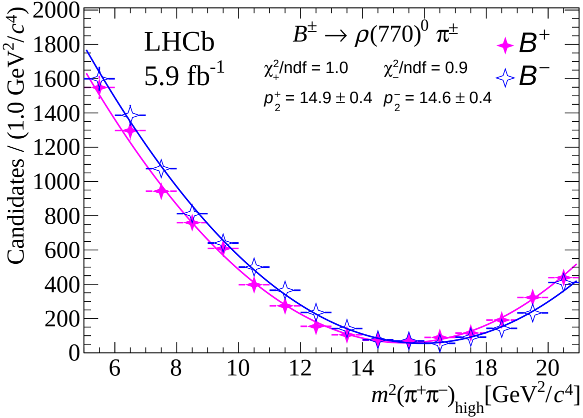




- Dalitz regions results

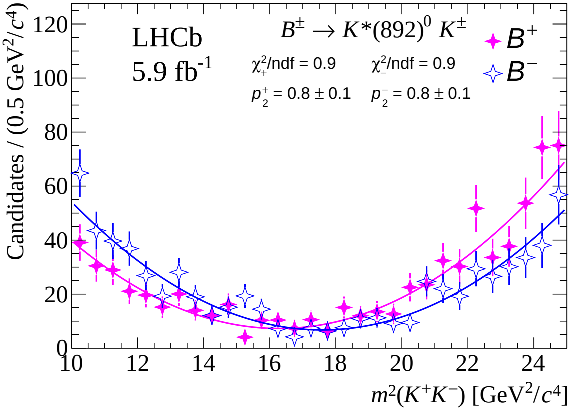
$B^\pm \to \pi^\pm\pi^+\pi^-$	N_{sig}	A_{raw}	A_{CP}	
Region 1	$14\,330 \pm 150$	$+0.309 \pm 0.009$	$+0.303 \pm 0.009 \pm 0.004 \pm 0.003$	29.4σ
Region 2	$4\,850 \pm 130$	-0.287 ± 0.017	$-0.284 \pm 0.017 \pm 0.007 \pm 0.003$	15.2σ
Region 3	$2\,270 \pm 60$	$+0.747 \pm 0.027$	$+0.745 \pm 0.027 \pm 0.018 \pm 0.003$	22.9σ
$B^\pm \to K^\pm\pi^+\pi^-$				
Region 1	$41\,980 \pm 280$	$+0.201 \pm 0.005$	$+0.217 \pm 0.005 \pm 0.005 \pm 0.003$	28.3σ
Region 2	$27\,040 \pm 250$	-0.149 ± 0.007	$-0.145 \pm 0.007 \pm 0.006 \pm 0.003$	15.0σ
$B^\pm \to \pi^\pm K^+ K^-$				
Region 1	$11\,430 \pm 170$	-0.363 ± 0.010	$-0.358 \pm 0.010 \pm 0.014 \pm 0.003$	20.5σ
Region 2	$2\,600 \pm 120$	$+0.075 \pm 0.031$	$+0.097 \pm 0.031 \pm 0.005 \pm 0.003$	3.1σ
$B^\pm \to K^\pm K^+ K^-$				
Region 1	$76\,020 \pm 350$	-0.189 ± 0.004	$-0.178 \pm 0.004 \pm 0.004 \pm 0.003$	27.8σ
Region 2	$37\,440 \pm 320$	$+0.030 \pm 0.005$	$+0.043 \pm 0.005 \pm 0.004 \pm 0.003$	6.1σ

- $B^{\pm} \to \rho(770)^0\pi^{\pm}$ polynomial fit



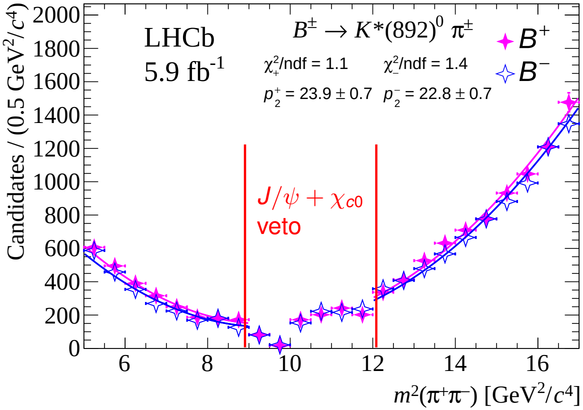
$$A_{CP}(\rho(770)^0\pi^{\pm}) = (-0.4 \pm 1.7 \pm 0.9)\%$$

- $B^\pm \to K^*(892)^0 K^\pm$ polynomial fit



$$A_{CP}(K^*(892)^0 K^\pm) = (+0.7 \pm 5.4 \pm 3.2)\%$$

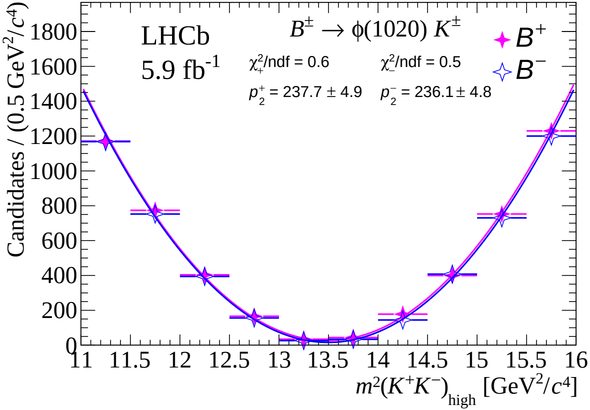
- $B^{\pm} \to K^{*}(892)^{0}\pi^{\pm}$ polynomial fit



;

$$A_{CP}(K^{*}(892)^{0}\pi^{\pm}) = (-1.5 \pm 2.1 \pm 1.2)\%$$

- $B^\pm \to \phi(1020)K^\pm$ polynomial fit



$$A_{CP}(\phi(1020)K^\pm) = (+0.4 \pm 1.0 \pm 0.7)\%$$

Search for CP violation using $\widehat{T}$-odd correlations in $B^0 \to p\bar{p}K^+\pi^-$ decays

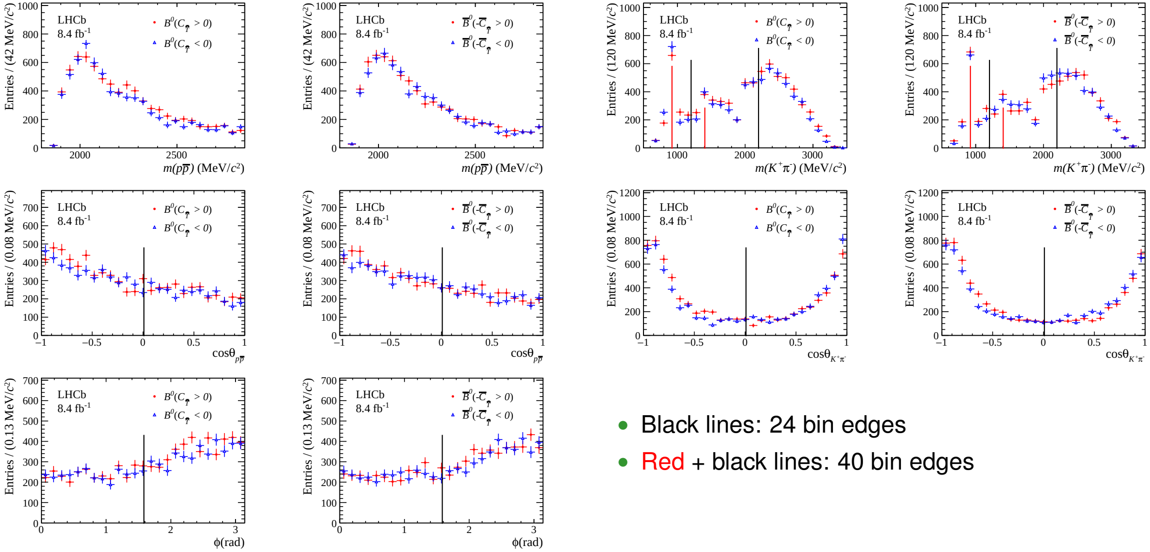
Phase-space regions definition

Region	$m_{p\bar{p}}(\mathrm{MeV}/c^2)$	$m_{K^+\pi^-}(\mathrm{MeV}/c^2)$	$\cos\theta_{p\bar{p}}$	$\cos\theta_{K^+\pi^-}$	ϕ
0	$(1800, 2850)$	$(500, 1200)$	$(-1, 0)$	$(-1, 0)$	$(0, \pi/2)$
1	$(1800, 2850)$	$(500, 1200)$	$(-1, 0)$	$(-1, 0)$	$(\pi/2, \pi)$
2	$(1800, 2850)$	$(500, 1200)$	$(-1, 0)$	$(0, 1)$	$(0, \pi/2)$
3	$(1800, 2850)$	$(500, 1200)$	$(-1, 0)$	$(0, 1)$	$(\pi/2, \pi)$
4	$(1800, 2850)$	$(500, 1200)$	$(0, 1)$	$(-1, 0)$	$(0, \pi/2)$
5	$(1800, 2850)$	$(500, 1200)$	$(0, 1)$	$(-1, 0)$	$(\pi/2, \pi)$
6	$(1800, 2850)$	$(500, 1200)$	$(0, 1)$	$(0, 1)$	$(0, \pi/2)$
7	$(1800, 2850)$	$(500, 1200)$	$(0, 1)$	$(0, 1)$	$(\pi/2, \pi)$
8	$(1800, 2850)$	$(1200, 2200)$	$(-1, 0)$	$(-1, 0)$	$(0, \pi/2)$
9	$(1800, 2850)$	$(1200, 2200)$	$(-1, 0)$	$(-1, 0)$	$(\pi/2, \pi)$
10	$(1800, 2850)$	$(1200, 2200)$	$(-1, 0)$	$(0, 1)$	$(0, \pi/2)$
11	$(1800, 2850)$	$(1200, 2200)$	$(-1, 0)$	$(0, 1)$	$(\pi/2, \pi)$
12	$(1800, 2850)$	$(1200, 2200)$	$(0, 1)$	$(-1, 0)$	$(0, \pi/2)$
13	$(1800, 2850)$	$(1200, 2200)$	$(0, 1)$	$(-1, 0)$	$(\pi/2, \pi)$
14	$(1800, 2850)$	$(1200, 2200)$	$(0, 1)$	$(0, 1)$	$(0, \pi/2)$
15	$(1800, 2850)$	$(1200, 2200)$	$(0, 1)$	$(0, 1)$	$(\pi/2, \pi)$
16	$(1800, 2850)$	$(2200, 3600)$	$(-1, 0)$	$(-1, 0)$	$(0, \pi/2)$
17	$(1800, 2850)$	$(2200, 3600)$	$(-1, 0)$	$(-1, 0)$	$(\pi/2, \pi)$
18	$(1800, 2850)$	$(2200, 3600)$	$(-1, 0)$	$(0, 1)$	$(0, \pi/2)$
19	$(1800, 2850)$	$(2200, 3600)$	$(-1, 0)$	$(0, 1)$	$(\pi/2, \pi)$
20	$(1800, 2850)$	$(2200, 3600)$	$(0, 1)$	$(-1, 0)$	$(0, \pi/2)$
21	$(1800, 2850)$	$(2200, 3600)$	$(0, 1)$	$(-1, 0)$	$(\pi/2, \pi)$
22	$(1800, 2850)$	$(2200, 3600)$	$(0, 1)$	$(0, 1)$	$(0, \pi/2)$
23	$(1800, 2850)$	$(2200, 3600)$	$(0, 1)$	$(0, 1)$	$(\pi/2, \pi)$

Region	$m_{p\bar{p}}(\mathrm{MeV}/c^2)$	$m_{K^+\pi^-}(\mathrm{MeV}/c^2)$	$\cos\theta_{p\bar{p}}$	$\cos\theta_{K^+\pi^-}$	ϕ
0	$(1800, 2850)$	$(500, 892)$	$(-1, 0)$	$(-1, 0)$	$(0, \pi/2)$
1	$(1800, 2850)$	$(500, 892)$	$(-1, 0)$	$(-1, 0)$	$(\pi/2, \pi)$
2	$(1800, 2850)$	$(500, 892)$	$(-1, 0)$	$(0, 1)$	$(0, \pi/2)$
3	$(1800, 2850)$	$(500, 892)$	$(-1, 0)$	$(0, 1)$	$(\pi/2, \pi)$
4	$(1800, 2850)$	$(500, 892)$	$(0, 1)$	$(-1, 0)$	$(0, \pi/2)$
5	$(1800, 2850)$	$(500, 892)$	$(0, 1)$	$(-1, 0)$	$(\pi/2, \pi)$
6	$(1800, 2850)$	$(500, 892)$	$(0, 1)$	$(0, 1)$	$(0, \pi/2)$
7	$(1800, 2850)$	$(500, 892)$	$(0, 1)$	$(0, 1)$	$(\pi/2, \pi)$
8	$(1800, 2850)$	$(892, 1200)$	$(-1, 0)$	$(-1, 0)$	$(0, \pi/2)$
9	$(1800, 2850)$	$(892, 1200)$	$(-1, 0)$	$(-1, 0)$	$(\pi/2, \pi)$
10	$(1800, 2850)$	$(892, 1200)$	$(-1, 0)$	$(0, 1)$	$(0, \pi/2)$
11	$(1800, 2850)$	$(892, 1200)$	$(-1, 0)$	$(0, 1)$	$(\pi/2, \pi)$
12	$(1800, 2850)$	$(892, 1200)$	$(0, 1)$	$(-1, 0)$	$(0, \pi/2)$
13	$(1800, 2850)$	$(892, 1200)$	$(0, 1)$	$(-1, 0)$	$(\pi/2, \pi)$
14	$(1800, 2850)$	$(892, 1200)$	$(0, 1)$	$(0, 1)$	$(0, \pi/2)$
15	$(1800, 2850)$	$(892, 1200)$	$(0, 1)$	$(0, 1)$	$(\pi/2, \pi)$
16	$(1800, 2850)$	$(1200, 1430)$	$(-1, 0)$	$(-1, 0)$	$(0, \pi/2)$
17	$(1800, 2850)$	$(1200, 1430)$	$(-1, 0)$	$(-1, 0)$	$(\pi/2, \pi)$
18	$(1800, 2850)$	$(1200, 1430)$	$(-1, 0)$	$(0, 1)$	$(0, \pi/2)$
19	$(1800, 2850)$	$(1200, 1430)$	$(-1, 0)$	$(0, 1)$	$(\pi/2, \pi)$
20	$(1800, 2850)$	$(1200, 1430)$	$(0, 1)$	$(-1, 0)$	$(0, \pi/2)$
21	$(1800, 2850)$	$(1200, 1430)$	$(0, 1)$	$(-1, 0)$	$(\pi/2, \pi)$
22	$(1800, 2850)$	$(1200, 1430)$	$(0, 1)$	$(0, 1)$	$(0, \pi/2)$
23	$(1800, 2850)$	$(1200, 1430)$	$(0, 1)$	$(0, 1)$	$(\pi/2, \pi)$
24	$(1800, 2850)$	$(1430, 2200)$	$(-1, 0)$	$(-1, 0)$	$(0, \pi/2)$
25	$(1800, 2850)$	$(1430, 2200)$	$(-1, 0)$	$(-1, 0)$	$(\pi/2, \pi)$
26	$(1800, 2850)$	$(1430, 2200)$	$(-1, 0)$	$(0, 1)$	$(0, \pi/2)$
27	$(1800, 2850)$	$(1430, 2200)$	$(-1, 0)$	$(0, 1)$	$(\pi/2, \pi)$
28	$(1800, 2850)$	$(1430, 2200)$	$(0, 1)$	$(-1, 0)$	$(0, \pi/2)$
29	$(1800, 2850)$	$(1430, 2200)$	$(0, 1)$	$(-1, 0)$	$(\pi/2, \pi)$
30	$(1800, 2850)$	$(1430, 2200)$	$(0, 1)$	$(0, 1)$	$(0, \pi/2)$
31	$(1800, 2850)$	$(1430, 2200)$	$(0, 1)$	$(0, 1)$	$(\pi/2, \pi)$
32	$(1800, 2850)$	$(2200, 3600)$	$(-1, 0)$	$(-1, 0)$	$(0, \pi/2)$
33	$(1800, 2850)$	$(2200, 3600)$	$(-1, 0)$	$(-1, 0)$	$(\pi/2, \pi)$
34	$(1800, 2850)$	$(2200, 3600)$	$(-1, 0)$	$(0, 1)$	$(0, \pi/2)$
35	$(1800, 2850)$	$(2200, 3600)$	$(-1, 0)$	$(0, 1)$	$(\pi/2, \pi)$
36	$(1800, 2850)$	$(2200, 3600)$	$(0, 1)$	$(-1, 0)$	$(0, \pi/2)$
37	$(1800, 2850)$	$(2200, 3600)$	$(0, 1)$	$(-1, 0)$	$(\pi/2, \pi)$
38	$(1800, 2850)$	$(2200, 3600)$	$(0, 1)$	$(0, 1)$	$(0, \pi/2)$
39	$(1800, 2850)$	$(2200, 3600)$	$(0, 1)$	$(0, 1)$	$(\pi/2, \pi)$

Search for CP violation using $\widehat{T}$-odd correlations in $B^0 \to p\bar{p}K^+\pi^-$ decays

Kinematic distributions for binnings



- Black lines: 24 bin edges
- Red + black lines: 40 bin edges

Search for CP violation using $\hat{T}$-odd correlations in $B^0 \to p\bar{p}K^+\pi^-$ decays

Phase-space regions results

Region	$A_{\hat{T}}(\%)$	$\bar{A}_{\hat{T}}(\%)$	$a_{CP}^{\hat{T}\text{-odd}}(\%)$	$a_{P}^{\hat{T}\text{-odd}}(\%)$	
0	-16.5 ± 10.1	-13.2 ± 9.5	-1.6 ± 7.0	-14.9 ± 7.0	
1	6.1 ± 9.2	3.2 ± 9.8	1.4 ± 6.7	4.7 ± 6.7	
2	-1.2 ± 7.0	23.9 ± 10.0	-12.5 ± 6.0	11.4 ± 6.0	
3	25.3 ± 7.2	3.2 ± 7.8	11.0 ± 5.3	14.3 ± 5.3	
4	7.8 ± 11.1	24.3 ± 9.0	-8.2 ± 7.1	16.1 ± 7.1	
5	2.9 ± 8.3	14.9 ± 8.6	-6.0 ± 6.0	8.9 ± 5.9	
6	-22.8 ± 7.4	-4.9 ± 8.6	-8.9 ± 5.7	-13.9 ± 5.7	
7	-10.4 ± 6.8	6.8 ± 6.6	-8.6 ± 4.7	-1.8 ± 4.7	
8	10.1 ± 5.0	5.7 ± 4.9	2.2 ± 3.5	7.9 ± 3.5	
9	4.5 ± 4.0	1.7 ± 4.0	1.4 ± 2.8	3.1 ± 2.8	
10	-4.5 ± 6.5	-10.2 ± 6.5	2.9 ± 4.6	-7.4 ± 4.6	
11	-10.1 ± 5.2	-9.5 ± 5.2	-0.3 ± 3.7	-9.8 ± 3.7	
12	9.4 ± 9.2	-7.8 ± 9.5	8.6 ± 6.6	0.8 ± 6.6	
13	12.2 ± 8.2	10.4 ± 8.0	0.9 ± 5.7	11.3 ± 5.7	
14	3.6 ± 9.8	-18.8 ± 8.7	11.2 ± 6.6	-7.6 ± 6.6	
15	-4.9 ± 6.0	-15.7 ± 7.1	5.4 ± 4.7	-10.3 ± 4.7	
16	5.5 ± 4.8	15.7 ± 4.7	-5.1 ± 3.4	10.6 ± 3.4	← 3.1σ
17	6.2 ± 3.4	5.6 ± 3.3	0.3 ± 2.4	5.9 ± 2.4	
18	-13.6 ± 6.7	-11.2 ± 6.4	-1.2 ± 4.6	-12.4 ± 4.6	
19	-0.9 ± 5.1	-4.3 ± 5.1	1.7 ± 3.6	-2.6 ± 3.6	
20	5.9 ± 6.2	-4.4 ± 6.9	5.2 ± 4.7	0.7 ± 4.7	
21	13.6 ± 5.6	9.9 ± 5.8	1.8 ± 4.0	11.7 ± 4.0	
22	-4.5 ± 6.9	-2.6 ± 6.6	-0.9 ± 4.8	-3.5 ± 4.8	
23	3.1 ± 5.0	0.7 ± 5.2	1.2 ± 3.6	1.9 ± 3.6	

Region	$A_{\hat{T}}(\%)$	$\bar{A}_{\hat{T}}(\%)$	$a_{CP}^{\hat{T}\text{-odd}}(\%)$	$a_{P}^{\hat{T}\text{-odd}}(\%)$	
0	-26.7 ± 17.8	-21.9 ± 12.9	-2.4 ± 11.0	-24.3 ± 11.0	
1	5.4 ± 15.8	-1.6 ± 20.7	3.5 ± 13.0	1.9 ± 13.0	
2	-7.3 ± 11.1	18.9 ± 17.4	-13.1 ± 10.3	5.8 ± 10.3	
3	15.4 ± 12.8	5.0 ± 13.7	5.2 ± 9.4	10.2 ± 9.4	
4	-21.9 ± 13.9	26.1 ± 16.3	-24.0 ± 10.7	2.1 ± 10.7	
5	-13.4 ± 13.9	21.9 ± 22.3	-17.6 ± 13.1	4.2 ± 13.1	
6	-19.3 ± 10.4	-15.3 ± 11.4	-2.0 ± 7.7	-17.3 ± 7.7	
7	0.7 ± 10.9	2.8 ± 8.4	-1.1 ± 6.9	1.8 ± 6.9	
8	-5.1 ± 12.8	-8.0 ± 13.2	1.5 ± 9.2	-6.5 ± 9.2	
9	6.6 ± 5.8	4.0 ± 5.6	1.3 ± 4.0	5.3 ± 4.0	
10	0.7 ± 9.0	30.2 ± 12.2	-14.8 ± 7.6	15.4 ± 7.6	
11	30.9 ± 8.7	0.2 ± 9.4	15.3 ± 6.4	15.6 ± 6.4	
12	38.4 ± 16.8	22.7 ± 10.7	7.9 ± 10.0	30.58 ± 9.96	← 3.1σ (K^{*0})
13	11.6 ± 10.2	14.2 ± 8.8	-1.3 ± 6.7	12.9 ± 6.7	
14	-24.1 ± 10.5	6.4 ± 13.2	-15.3 ± 8.4	-8.8 ± 8.4	
15	-18.8 ± 8.6	10.2 ± 9.5	-14.5 ± 6.4	-4.3 ± 6.4	
16	7.3 ± 11.9	-20.9 ± 15.6	14.1 ± 9.8	-6.8 ± 9.8	
17	-2.6 ± 10.4	-1.5 ± 9.0	-0.5 ± 6.9	-2.1 ± 6.9	
18	10.5 ± 11.7	24.0 ± 12.6	-6.8 ± 8.6	17.2 ± 8.6	
19	1.1 ± 10.9	20.5 ± 9.8	-9.7 ± 7.3	10.8 ± 7.3	
20	28.6 ± 32.0	-28.9 ± 21.9	28.7 ± 19.4	-0.1 ± 19.4	
21	0.4 ± 19.3	9.1 ± 15.6	-4.4 ± 12.4	4.7 ± 12.4	
22	36.2 ± 19.0	-13.9 ± 19.2	25.1 ± 13.4	11.1 ± 13.6	
23	-4.3 ± 12.5	-28.1 ± 14.3	11.9 ± 9.5	-16.2 ± 9.5	
24	11.4 ± 5.4	9.4 ± 5.1	1.0 ± 3.7	10.4 ± 3.7	
25	6.1 ± 4.2	2.2 ± 4.3	1.9 ± 3.0	4.2 ± 3.0	
26	-9.7 ± 7.6	-20.8 ± 7.6	5.6 ± 5.4	-15.3 ± 5.4	
27	-13.1 ± 5.9	-17.7 ± 5.8	2.3 ± 4.1	-15.4 ± 4.1	← 3.75σ (K_2^*)
28	7.0 ± 9.5	-2.2 ± 10.5	4.6 ± 7.1	2.4 ± 7.1	
29	14.6 ± 8.9	13.3 ± 9.6	0.6 ± 6.5	13.9 ± 6.5	
30	-6.6 ± 11.4	-21.2 ± 9.7	7.3 ± 7.5	-13.9 ± 7.5	
31	-5.3 ± 6.7	-13.0 ± 8.0	3.8 ± 5.2	-9.2 ± 5.2	
32	5.5 ± 4.8	15.5 ± 4.8	-5.0 ± 3.4	10.5 ± 3.4	← 3.1σ
33	6.1 ± 3.4	5.3 ± 3.4	0.4 ± 2.4	5.7 ± 2.4	
34	-11.9 ± 6.7	-9.9 ± 6.5	-1.0 ± 4.7	-10.9 ± 4.7	
35	-0.9 ± 5.1	-3.8 ± 5.0	1.4 ± 3.6	-2.3 ± 3.6	
36	5.9 ± 6.3	-2.6 ± 7.1	4.2 ± 4.8	1.6 ± 4.8	
37	12.4 ± 5.7	10.8 ± 5.9	0.8 ± 4.1	11.6 ± 4.1	
38	-4.6 ± 7.1	-0.5 ± 6.8	-2.0 ± 4.9	-2.5 ± 4.9	
39	3.3 ± 5.0	0.5 ± 5.3	1.4 ± 3.6	1.9 ± 3.6	