Experimental Overview of Beauty at LHCb

– Mixing & CP Violation

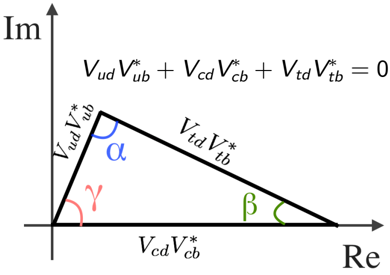
Peilian Li on behalf of the LHCb collaboration

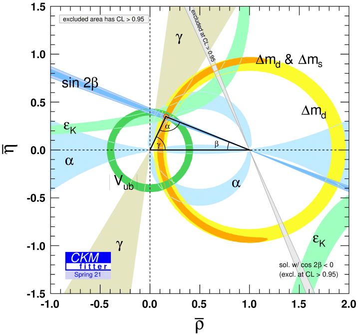
Implication Workshop 2022, 19-21 October

CKM matrix

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

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





Outline

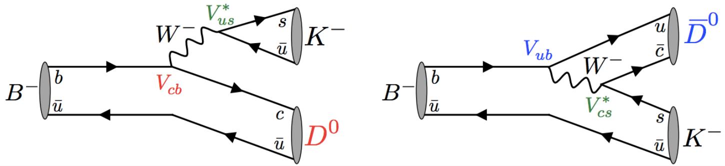
LHCb experiment is dedicated (but not limited) to beauty and charm physics
$\rightarrow$ an ideal lab for various CKM and CPV measurements — Guillaume's talk for charm

- γ measurements — JHEP12(2021)141
  - ◇ New γ measurement with $B^- \rightarrow D(hh'\pi^0)h^-$ — JHEP 07(2022)099
  - ◇ New γ measurement with $B^+ \rightarrow D(K^-\pi^+\pi^+\pi^-)h^+$ — arXiv:2209.03692
  - ◇ Latest γ combination New — LHCb-CONF-2022-003
- Direct CPV in B decays
  - ◇ Charmless three-body decays $B^+ \rightarrow hh'h'$ — arXiv:2206.07622
  - ◇ Charmless $B \rightarrow PV$ decays — arXiv:2206.02038
  - ◇ Charmless baryonic decay $B^0 \rightarrow p\bar{p}K^+\pi^-$ — arXiv:2205.08973
- τ_L measurement with $B_s^0 \rightarrow J/\psi\eta$ — arXiv:2206.03088
- Rare decays & Lepton flavor universality/violations & semi-leptonic measurements

see Christoph's, Suzanne's, Alexander and Blaise's talks

CP violating angle γ

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



CP violating angle γ

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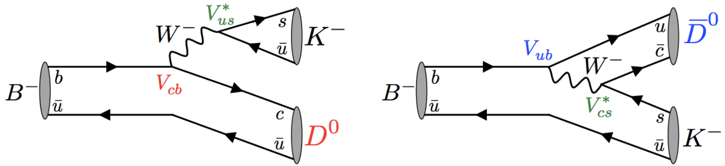


- Interference occurs when D^0 and $\bar{D}^0$ decay to the same final state f
  - ◇ GLW: CP eigenstates, e.g. $D \to KK$, $D \to \pi\pi$ PLB265(1991)172
  - ◇ ADS: CF or DCS decays, e.g. $D \to K\pi$ PRL78(1997)3257
  - ◇ BPGGSZ: self-conjugated 3-body final states, GLW/ADS analysis across the D decay phase space, e.g. $D \to K^0_S\pi\pi$ PRD68(2003)054018
- Time-dependent: e.g. $B^0_s \to D^-_s K^+$ & $B^0 \to \bar{D}^{\pm}\pi^{\mp}$ PLB562(2003)234, PLB253(1991)483
- Combination of all methods provides the best precision
  - ◇ Direct measurements from B decays: $\gamma = (66.2^{+3.3}_{-3.5})^\circ$ HFLAG
  - ◇ LHCb combination last year: $\gamma = (65.4^{+3.8}_{-4.2})^\circ$ JHEP12(2021)141
  - ◇ Indirectly inferred from other constraints: $\gamma_{\mathrm{CKMFitter}} = (65.5^{+1.1}_{-2.7})^\circ$

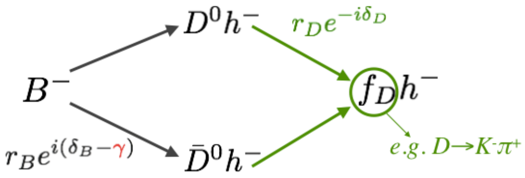
γ measurement

JHEP12(2021)141

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

$$r_B e^{i(\delta_B - \gamma)} \equiv \frac{A(B^- \to \bar{D}^0 h^-)}{A(B^- \to D^0 h^-)}, \; r_D e^{i\delta_D} \equiv \frac{A(D^0 \to f)}{\bar{D}^0 \to f}$$

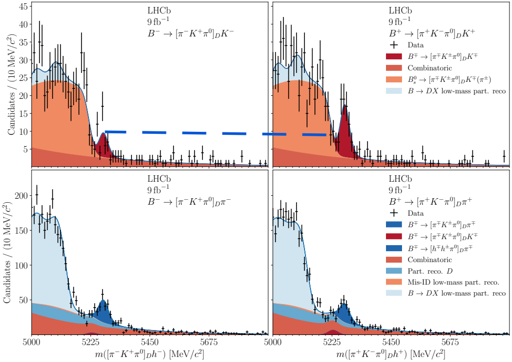
- → External inputs: r_D and δ_D are the magnitude ratio and strong-phase difference between $D^0 \to f$ and $\bar{D}^0 \to f$, for GLW modes, $r_D = 1$ and $\delta_D = 0$ or π
- → r_B, δ_B r_D and δ_D are specific to each B decay and subsequent D decay
- → CP-violating weak phase difference γ is shared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



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

JHEP07(2022)099

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



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

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

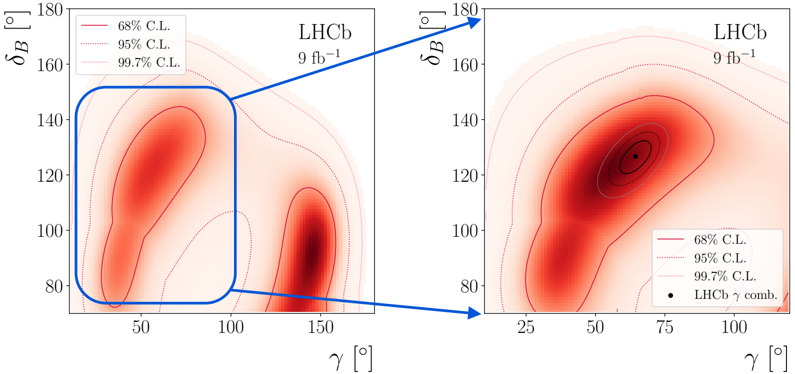
γ measurement with $B^{\pm} \to D(h^{\pm}h'^{\pm}\pi^0)h^{\pm}$

JHEP07(2022)099

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

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

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

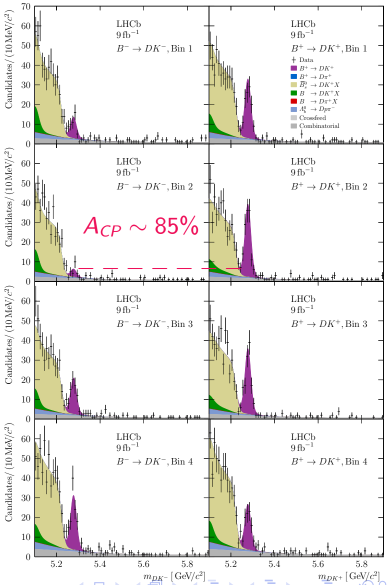


γ measurement with $B^{\pm} \to D(K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp})h^{\pm}$ arXiv:2209.03692

- Model independent determination of γ in four phase-space bins of D decay PLB802(2020)135188
- Hadronic D decay parameters $r_D^{K3\pi} e^{i\delta_D^{K3\pi}}$ vary across 4-body phase space Φ_4, averages provided by external measurements
- Dilution of the decay rate asymmetry $R_D^{K3\pi}$

$$R_D^{K3\pi} e^{i\delta_D^{K3\pi}} \propto \int A_{\bar{D}}(\Phi_4) A_D^*(\Phi_4) d\Phi_4$$

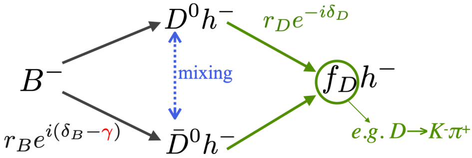
- $\gamma = (54.8^{+6.0}_{-5.8}(stat.)^{+0.6}_{-0.6}(syst.)^{+6.7}_{-4.3}(ext.))^{\circ}$, limited by external inputs (r_D, $\delta_D^{K3\pi}$) of hadronic D decay parameters
  one of the most precise determinations thus far using single D-decay mode



Simultaneous determination of γ + charm mixing

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

- $B^\pm \to DK^\pm$ with $D \to K\pi$ are sensitive to $\delta_D^{K\pi}$
- $\delta_D^{K\pi}$ and y_D are highly correlated, combination would improve precision on y_D
  $\frac{\Gamma(D^0 \to K^+\pi^-, t)}{\Gamma(D^0 \to K^-\pi^+, t} \propto (r_D^{K\pi})^2 + r_D^{K\pi}(x_D \sin \delta_D^{K\pi} - y_D \cos \delta_D^{K\pi}) \frac{t}{\tau}$
- Charm mixing parameters has significant effects on $B^\pm \to D\pi^\pm$



For $B^- \to DK^-$:
$r_B >> x_D, \; y_D$
For $B^- \to D\pi^-$:
$r_B \sim x_D, \; y_D$

Combination of LHCb measurements New LHCb-CONF-2022-003

- Using the Gammacombo package
  $\rightarrow$ a frequentist approach used with 173 observables to determine 52 parameters
- Last combination determines $\gamma = (65.4^{+3.8}_{-4.2})^\circ$ JHEP12(2021)141
- New/updated measurements included into the combination this year
  - ◇ Beauty - $B^\pm \rightarrow Dh^\pm$ with $D \rightarrow hh\pi^0$ & $D \rightarrow K\pi\pi\pi$ for improved γ
  - ◇ Charm - see details in Guillaume's talk
    - y_{CP} in $D^0 \rightarrow h^- h'^+$ PRD105(2022)092013
    - $x_{CP},\ y_{CP},\ \delta x,\ \delta y$ in $\bar{B} \rightarrow D^0(K^0_S\pi^+\pi^-)\mu^-\bar{\nu}_\mu X$ arXiv:2208.06512
    - $A_{CP}(KK)$ in $D^0 \rightarrow K^-K^+$ arXiv:2209.03179
  - ◇ External constraints:
    - CP-even fraction F^+ in $D^0 \rightarrow \pi^+\pi^+\pi^-\pi^-$ from BESIII arXiv:2208.10098
    - Strong phase difference $\delta_D^{K\pi}$ between $D^0 \rightarrow K^-\pi^+$ & $D^0 \rightarrow K^+\pi^-$ from CLEO

PRD86(2012)112001 arXiv:2208.09402

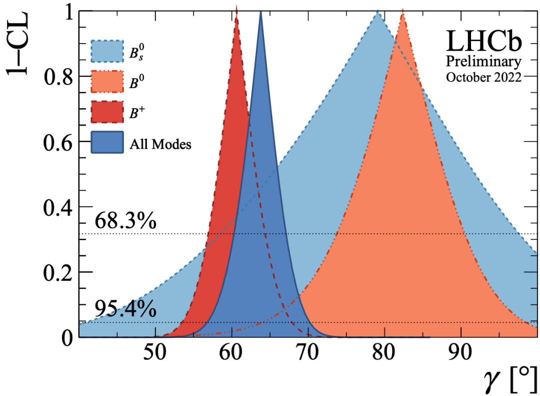
Combination of LHCb measurements

LHCb-CONF-2022-003

- $\gamma = (63.8^{+3.5}_{-3.7})^\circ$, $x_D = (0.398^{+0.050}_{-0.049})\%$, $y_D = (0.636^{+0.020}_{-0.019})\%$

  * Improvements about 10% on γ ($\sim$ 1 year data-taking), 6% on x_D and 38% on y_D

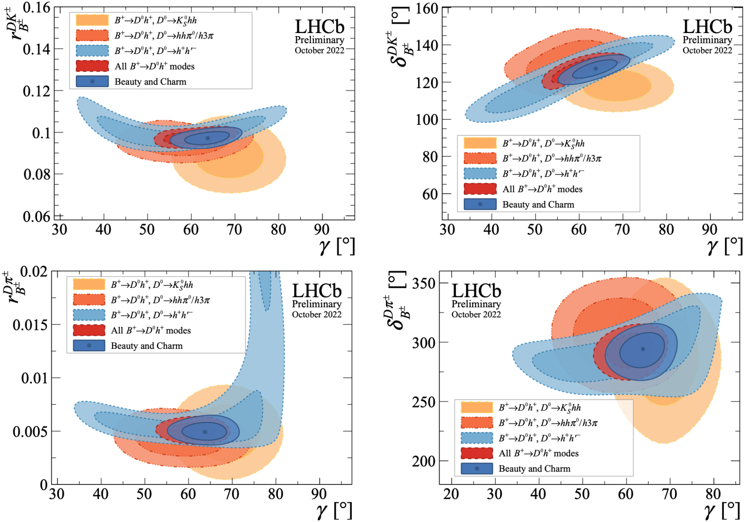
  - $\gamma_{\rm UTFit} = (65.8 \pm 2.2)^\circ$, $\gamma_{\rm CKMFitter} = (65.5^{+1.1}_{-2.7})^\circ$
- Tension between different B categories remains ($\sim 2\sigma$)



Combination of LHCb measurements

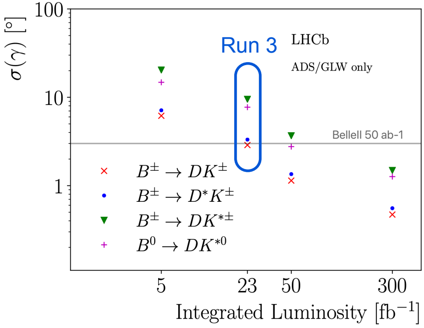
LHCb-CONF-2022-003

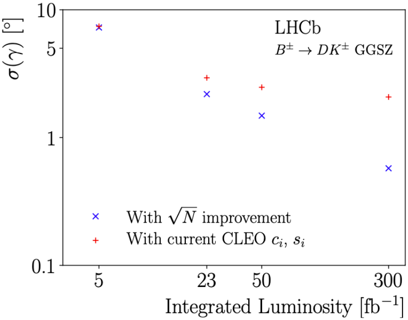
- Contributions of different decay modes agree with each other



Prospects for γ measurements

- Measurements with more decay modes and larger statistics from Upgrades
  $\rightarrow$ Be able to compete with Belle II 50 ab^{-1} with Upgrade I
- Essential to improve the precision of external parameters (c_i, s_i) from BESIII





Charmless three-body decays $B^+ \to hh'h'$ arXiv:2206.07622

- Direct *CP* violation manifested in decay rate asymmetry, where differences in both weak and strong phases of the contributing amplitudes are required
- Various *CP* asymmetries observed in three-body *B* decays due to:
  - ◇ interference between the *S*- and *P*-wave contributions in $B^\pm \to \pi^\pm\pi^+\pi^-$ PRL124(2020)031801
  - ◇ involving $K\bar{K} \leftrightarrow \pi\pi$ rescattering in $B^\pm \to \pi^\pm K^+ K^-$ PRL123(2019)231802
  - ◇ long-distance hadronic interactions in $B^\pm \to \pi^\pm\pi^+\pi^-$, $K^\pm K^+ K^-$, $\pi^\pm K^+ K^-$ and $K^\pm\pi^+\pi^-$ PRD90(2014)112004, Prog.Part. Nucl. Phys. 114(2020)103808
- *CP* asymmetry studied in $B^\pm \to \pi^\pm\pi^+\pi^-$, $K^\pm K^+ K^-$, $\pi^\pm K^+ K^-$ and $K^\pm\pi^+\pi^-$ for both integrated and binned phase-space using Run 2 data (5.9 fb^{-1})

* Acceptance-corrected raw asymmetry is:

$$A^{acc}_{\rm raw} \equiv \frac{N^{acc}_{B^-} - N^{acc}_{B^+}}{N^{acc}_{B^-} + N^{acc}_{B^+}} \quad \to \quad A_{CP} = \frac{A^{acc}_{\rm raw} - A_P}{1 - A^{acc}_{\rm raw} A_P}$$

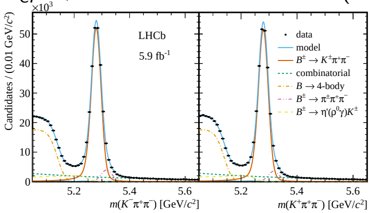
A_P is the production asymmetry and obtained from control mode $B^\pm \to J/\psi K^\pm$

Direct CP violation in $B^+ \to hh'h'$

arXiv:2206.07622

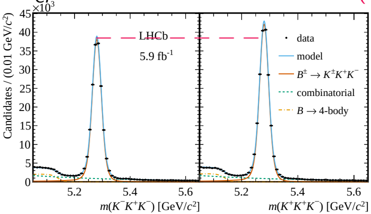
$B^\pm \to K^\pm\pi^+\pi^-$: 499200±900

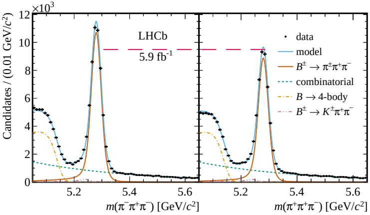
A_{CP}=+0.011±0.002±0.003±0.003 (2.4σ)



$B^\pm \to K^\pm K^+K^-$: 365000±1000

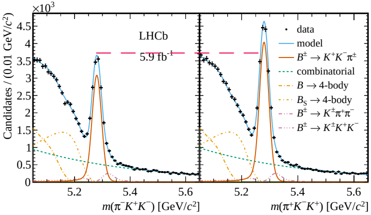
A_{CP}=−0.037±0.002±0.002±0.003 (8.5σ)





$B^\pm \to \pi^\pm\pi^+\pi^-$: 101000±500

A_{CP}=+0.080±0.004±0.003±0.003 (14.1σ)



$B^\pm \to \pi^\pm K^+K^-$: 32470±300

A_{CP}=−0.114±0.007±0.003±0.003 (13.6σ)

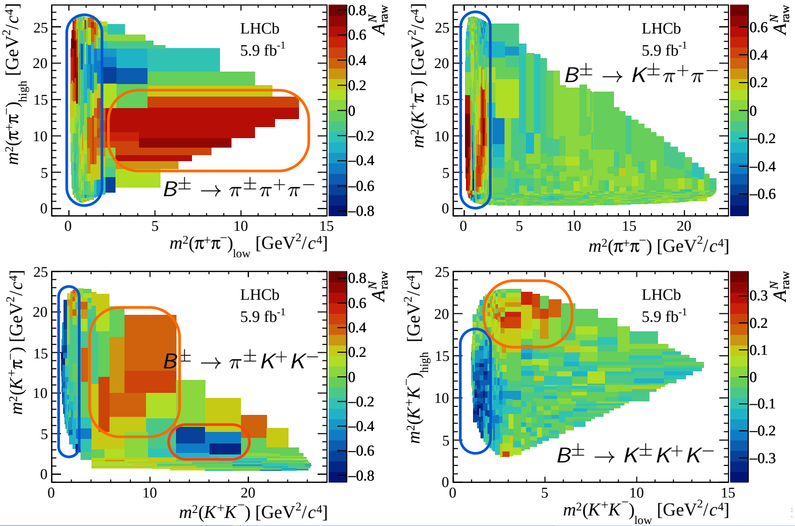
* Uncertainties in order are statistical, systematic and from control mode $B^\pm \to J/\psi K^\pm$

Localized asymmetries in $B^+ \to hh'h'$

arXiv:2206.07622

- Rich pattern of large and localized asymmetry from interference between the resonant contributions, and possible $\pi\pi \leftrightarrow K\bar{K}$ rescattering

$$A^i_{\rm raw} = \frac{N^i_{B^-} - N^i_{B^+}}{N^i_{B^-} + N^i_{B^+}}$$

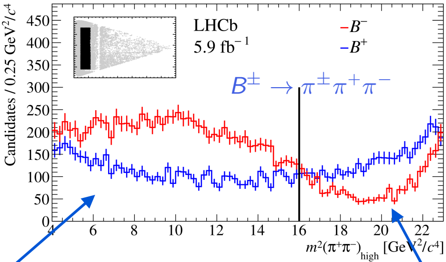


Localized asymmetries in $B^+ \to h h' h'$

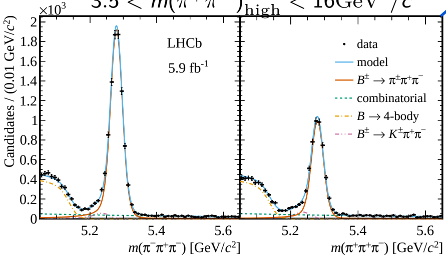
arXiv:2206.07622

- $\pi\pi \leftrightarrow K\bar{K}$ rescattering region ($1 < m^2(hh) < 2.25\ \mathrm{GeV}^2/c^4$)
- *CP* asymmetry presents positively and negatively in left and right region of $m^2(\pi^+\pi^-)_{\mathrm{high}}$ projection
- Similar A_{CP} sign change observed in $B^\pm \to K^\pm\pi^+\pi^-$ and $B^\pm \to K^\pm K^+ K^-$

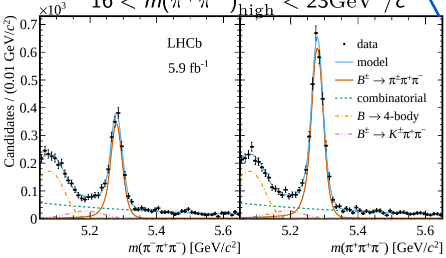
Background subtracted signal candidates in $1 < m(\pi^+\pi^-)^2_{\mathrm{low}} < 2.25\ \mathrm{GeV}^2/c^4$



$3.5 < m(\pi^+\pi^-)^2_{\mathrm{high}} < 16\mathrm{GeV}^2/c^4$



$16 < m(\pi^+\pi^-)^2_{\mathrm{high}} < 23\mathrm{GeV}^2/c^4$

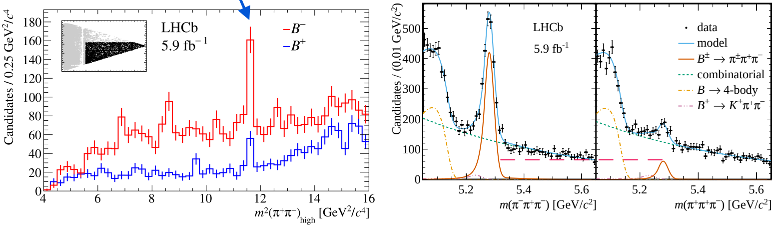


Localized asymmetries with charmonium

arXiv:2206.07622

- A large asymmetry $A_{CP} = (74.5 \pm 2.7 \pm 1.8)\%$ in $m(\pi^+\pi^-)_{\rm low} \in (4, 15)\rm GeV^2/c^4$ region, including $\chi_{c0}(1P)$ resonance contribution from $B^\pm \to \pi^\pm\pi^+\pi^-$ decays

$4 < m(\pi^+\pi^-)_{\rm low} < 15\rm GeV^2/c^4$



- Direct A_{CP} for charmnomium χ_{c0} is expected to be small, any other contributions for such large CP asymmetry?
  - ◇ Interference with non-resonant contributions? PRL74(1995)4984
  - ◇ Hadronic charm-loop and S-wave $D\bar{D} - \pi\pi$ rescattering? PLB806(2020)135490

Charmless $B \to PV$ decays

arXiv:2206.02038

- Huge theoretical interest in $B \to PV$ decays but few measurements in the literature
- Large phase space available & dominance of scalar and vector resonances below/around 1 GeV/^{2} & clear signatures
- For isolated vector resonances, $A_{CP} \propto$ square modulus of amplitude difference

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

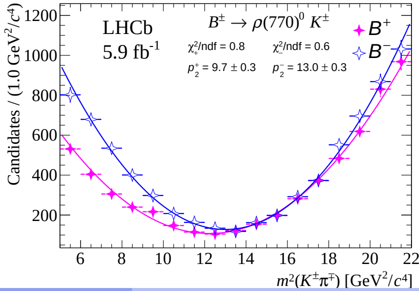
* model independent analysis of quasi two-body decays of $B^+ \to R(h_1^- h_2^+)h_3^+$:
$s_{||} = m^2(h_1^- h_2^+),\ s_\perp = m^2(h_1^- h_3^+)$

$p_2^\pm$ obtained from a simple quadratic fit:

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

- A large CP asymmetry found in $B^\pm \to \rho(770)^0(\pi^+\pi^-)K^\pm$ decays
  $A_{CP} = (15.0 \pm 1.9_{\text{stat}} \pm 1.1_{\text{syst}} \pm 0.3_{J/\psi K})\%$
  $(6.8\ \sigma)$

No isolation of $\rho(770)^0$ contribution from the influence of $\omega(782)$ resonance



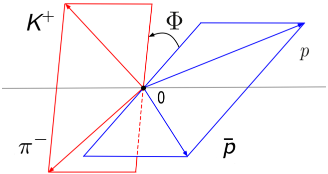
Charmless baryonic decay $B^0 \to p\bar{p}K^+\pi^-$

arXiv:2205.08973

- Baryonic multibody decay: interference between different amplitudes, expected large CP asymmetries PRL98(2006)011801
- Decay governed mainly by $b \to u\bar{u}s$ and $b \to s\bar{u}u$ below $m_{p\bar{p}} < 2.85\ \mathrm{GeV}/c^2$, weak-phase difference $\arg(V_{ub}V_{us}^*/V_{tb}V_{ts}^*)$ is approximately equal to CKM angle γ

* Define the $\hat{T}-$odd triple-products using three-momenta of final states:

$$C_{\hat{T}} = \vec{p}_{K^+} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{p})$$
$$\bar{C}_{\hat{T}} = \vec{p}_{K^-} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\bar{p}})$$
$$CP(C_{\hat{T}}) = -\bar{C}_{\hat{T}}$$



- $\hat{T}-$odd asymmetry: $A_{\hat{T}} = \frac{N(C_{\hat{T}}>0)-N(C_{\hat{T}}<0)}{N(C_{\hat{T}}>0)+N(C_{\hat{T}}<0)}$, $\bar{A}_{\hat{T}} = \frac{\bar{N}(-\bar{C}_{\hat{T}}>0)-\bar{N}(-\bar{C}_{\hat{T}}<0)}{\bar{N}(-\bar{C}_{\hat{T}}>0)+\bar{N}(-\bar{C}_{\hat{T}}<0)}$
- CP and P violating observables:

$$a_{CP}^{\hat{T}-\mathrm{odd}} = \frac{1}{2}(A_{\hat{T}} - \bar{A}_{\hat{T}}),\ a_{P}^{\hat{T}-\mathrm{odd}} = \frac{1}{2}(A_{\hat{T}} + \bar{A}_{\hat{T}})$$

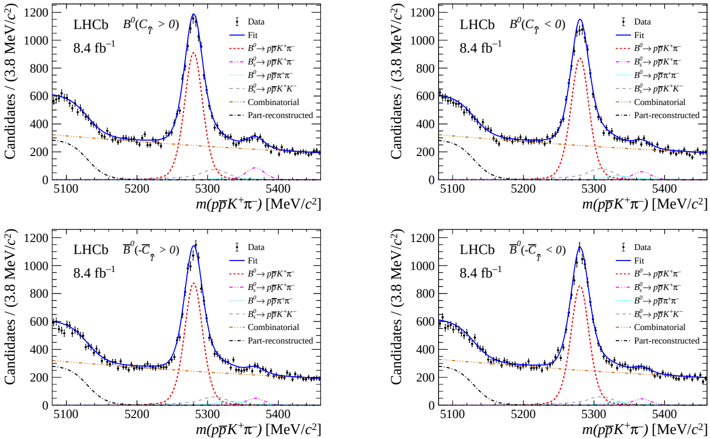
→ Clean observables: mostly insensitive to production and detection asymmetries

→ Sensitive to interference of P-even and P-odd amplitudes & different sensitivity to strong phases

Charmless baryonic decay $B^0 \to p\bar{p}K^+\pi^-$

arXiv:2205.08973

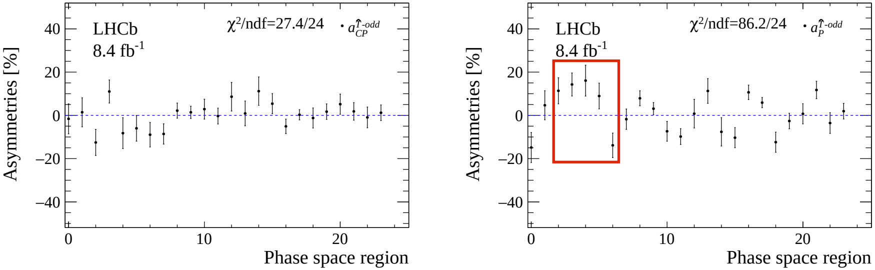
- Signal yields: 70×10^3
- $a_{CP}^{\widehat{T}-\mathrm{odd}} = (0.51 \pm 0.85_{\mathrm{stat}} \pm 0.08_{\mathrm{syst}})\%$, $a_{P}^{\widehat{T}-\mathrm{odd}} = (1.49 \pm 0.85_{\mathrm{stat}} \pm 0.08_{\mathrm{syst}})\%$
  Compatible with *CP* and *P* conservation



Charmless baryonic decay $B^0 \to p\bar{p}K^+\pi^-$

arXiv:2205.08973

- Asymmetries in regions of phase-space with enhanced sensitivity to resonances and interference effects

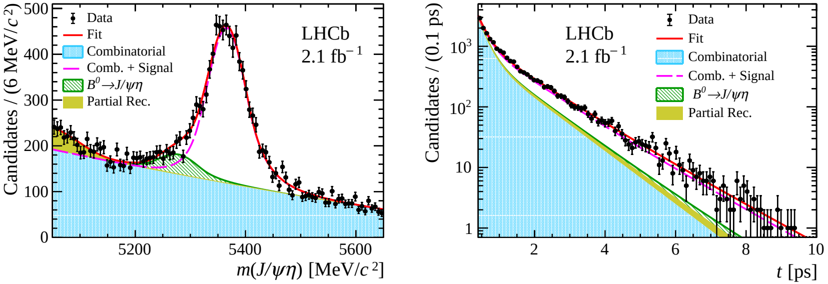


- P symmetry violation with 5.8 σ, significant in the region of low $p\bar{p}$ mass and near the $K^*(892)^0$ resonance
  - $\rightarrow$ Full amplitude analysis needed to associate the P violation with any underlying resonance
- CP conserved within 1σ, theoretical prediction up to 20% level not excluded

PRL98(2007)011801

Effective lifetime measurement with $B_s^0 \to J/\psi\eta$ arXiv:2206.03088

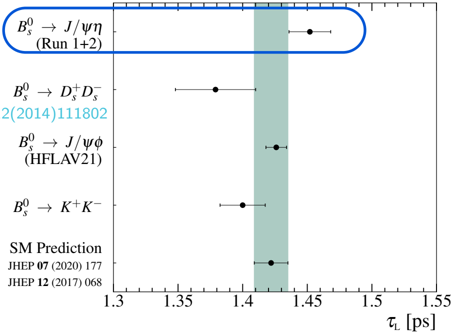
- *CP* violation in B_s^0-$\bar{B}_s^0$ mixing is small, to a high precision the mass eigenstates are also *CP* eigenstates
  $\to$ Effective lifetime in *CP*-even mode $B_s^0 \to J/\psi(\mu\mu)\eta(\gamma\gamma)$ determines $\tau_L = 1/\Gamma_L$
- Improving the precision enables stringent tests of consistency between direct $\Delta\Gamma_s$ measurements, *e.g.* $B_s^0 \to J/\psi\phi$ and those inferred from effective lifetimes
- 2D maximum-likelihood fit to mass & decay time from Run 2 (5.7 fb^{-1} in total)
- $\tau_L = (1.445 \pm 0.016(\text{stat}) \pm 0.008(\text{syst}))$ ps



plots for data from 2018 as illustration

Effective lifetime measurement with $B_s^0 \to J/\psi\eta$ arXiv:2206.03088

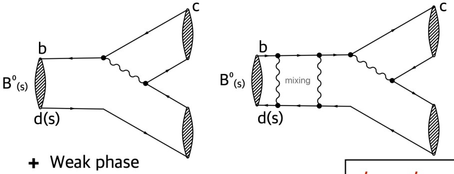
- Combined with Run 1 result: τ_L =(1.452±0.014±0.007±0.002)ps PLB762(2016)484
  $\to$ Good agreement with other measurements and SM prediction



- Further improvements both by considering other *CP*-even B_s^0 decays, *e.g.* $B_s^0 \to J/\psi\eta'$, $B_s^0 \to D_s^+ D_s^-$ and using larger coming datasets

Mixing-induced *CP* violation

- Mixing-induced *CP* violating phase $\beta_{d/s}$ measured from the interference between the decays and $B^0_{d/s} - \bar{B}^0_{d/s}$ oscillation



$\phi_{d/s} \approx -2\sin\beta_{d/s}$

ignore penguin contribuions

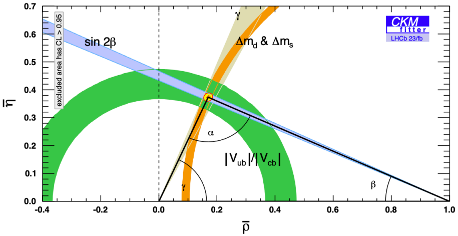
$\phi_{d/s} = \phi_{mix} - 2\phi_{dec}$

- Many observables $\Delta m_{d/s}$, $\Delta\Gamma_{d/s}$, $\beta_{d/s}$
- Flagship measurements of $\beta_{d/s}$ with $B^0 \to J/\psi K^0_S$ and $B^0_s \to J/\psi\phi$ are well progressed with full Run 2 data
- LHCb will keep leading contributions in various CPV & mixing measurements

CKM tests	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
γ, with $B^0_s \to D^+_s K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K^0_S$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B^0_s \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B^0_s \to D^+_s D^-_s$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B^0_s \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
$a^s_{\rm sl}$	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–

Summary

- Numerous LHCb measurements dominate the world average for CKM angles and mixing parameters
  - ◇ Simultaneous determination of γ and charm mixing parameters updated with 5 new inputs with improvement about 10% (38%) for γ (y_D)
  - ◇ Large CP asymmetries from different contributions observed in $B \to hh'h'$
  - ◇ Charmless baryonic decay $B^0 \to p\bar{p}K^+\pi^-$ consistent with CP conservation
  - ◇ Latest τ_L measurement with $B_s^0 \to J/\phi\eta$ consistent with SM prediction
- A lot of more measurements are in good progress using Run 1+2 data
- Run 3 is in commissioning! Exciting to see further improvements soon!



Stay tuned!

Thanks for your attention!

γ measurement

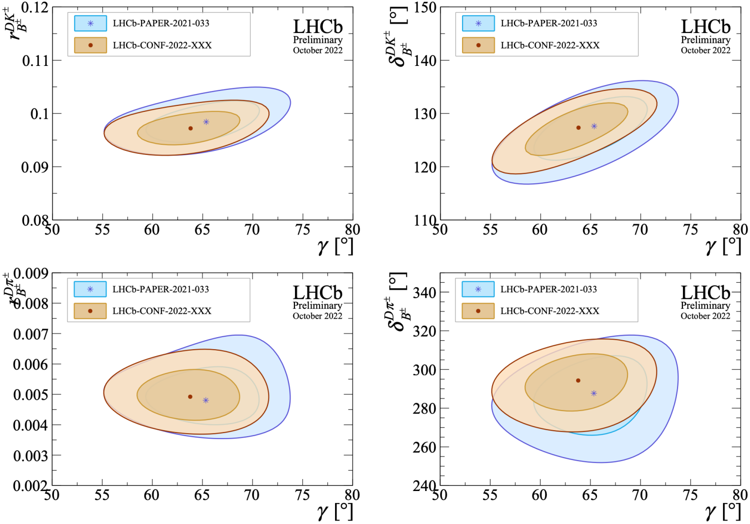
$$
\begin{aligned}
\Gamma(B^\pm \to Dh^\pm) \propto\ & r_D^2 + r_B^2 + 2\kappa_D\kappa_B r_D r_B \cos(\delta_B + \delta_D \pm \gamma) \\
& - \alpha[(1 + r_B^2)\kappa_D r_D \cos\delta_D - \alpha(1 + r_D^2)\kappa_B r_B \cos(\delta_B \pm \gamma)]y \\
& + \alpha[(1 - r_B^2)\kappa_D r_D \sin\delta_D - \alpha(1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

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

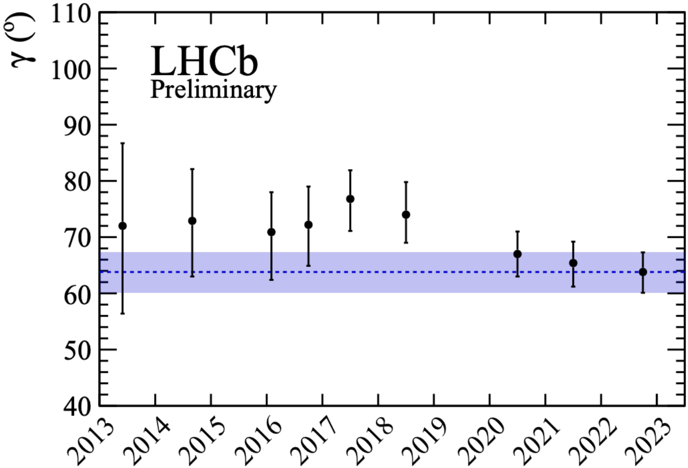
Combination of LHCb measurements

LHCb-CONF-2022-003

- Improvement compared to last combination



History of γ measurements at LHCb



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

arXiv:2112.10617

- Eleven observables with world-best precision

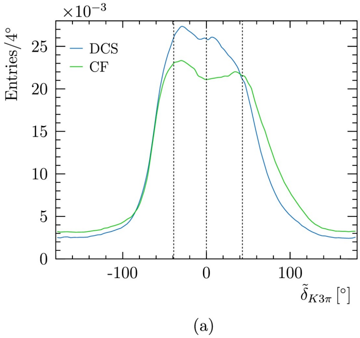
$$R^{\mp}_{ADS(h)} = \frac{\Gamma(B^{\mp}\to D(\pi^{\mp}K^{\pm}\pi^0)h^{\mp})}{\Gamma(B^{\mp}\to D(K^{\mp}\pi^{\pm}\pi^0))h^{\mp}},\quad R^{hh\pi^0}_{K/\pi} = \frac{\Gamma(B^-\to D(hh\pi^0)K^-/\pi^-)}{\Gamma(B^-\to D(K^-\pi^+\pi^0))K^-/\pi^-)}$$

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

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

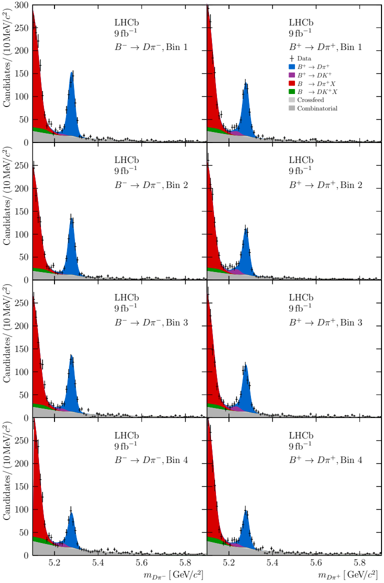
Binning in phase-space for $B^{\pm} \to D(K\pi\pi\pi)K^{\pm}$ PLB802(2020)135188

∗ Dividing the phase space with one-dimensional binning in the normalized strong-phase difference



γ measurement with $B^\pm \to D(K^\mp\pi^\pm\pi^\pm\pi^\mp)h^\pm$

arXiv:2209.03692



Direct CP violation in $B^+ \to hh'h'$

arXiv:2206.07622

	$B^\pm \to \pi^\pm\pi^+\pi^-$		
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	$17 < m^2(K^+K^-)_{\text{high}} < 23$

$B^\pm \to \pi^\pm\pi^+\pi^-$	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	$37\,440 \pm 320$	$+0.030 \pm 0.005$	$+0.043 \pm 0.005 \pm 0.004 \pm 0.003$

Direct CP violation in $B^+ \to hh'h'$

arXiv:2206.07622

- Large asymmetry in other three channels as well in $\pi\pi - K\bar{K}$ rescattering region
- Similar A_{CP} sign change for $B^\pm \to K^\pm\pi^+\pi^-$ and $B^\pm \to K^\pm K^+ K^-$
- $\chi_{c0}(1P)$ contributions seen also in $B^\pm \to K^\pm K^+ K^-$ and $B^\pm \to \pi^\pm K^+ K^-$