CPV in Charmless B Meson Decays

on behalf of Belle, Belle II, and LHCb

17th International Conference on Heavy Quarks and Leptons
2025. 9. 16.

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Topics

Belle II

$B^0 \to \pi^0\pi^0$ — improved measurement, A_{CP} [arXiv:2412.14260, PRD111 L071102(2025)]

Belle

$B^0 \to \omega\omega$ — first observation, f_L, A_{CP} [arXiv:2401.04646, PRL133 081801(2024)]

LHCb

$B^0 \to \phi\phi$ — new upper limit [arXiv:2507.20945]

$B^+ \to \rho^0 K^{*+}$ — improved measurement, f_L, non-zero A_{CP} [arXiv:2508.13563]

$B \to (K_S K\pi)K$ — two-body decays with light-resonances [arXiv:2501.06483, PRD111, 092009(2025)]

$B^0_{(s)} \to K_S p\bar{p}$ — first observation for B_s [arXiv:2504.21269, JHEP07 (2025) 121]

$B^+ \to \bar{\Lambda} p\bar{p}p$ — first observation, A_{CP} [arXiv:2508.16259]

4 charmless B decay modes with A_{CP} measurements (other charmless B decay modes are also relevant to CPV)

Roles of charmless B Meson Decays

Rich sample for flavor physics

- Large number of interesting decay modes
- Interplays between $b \to s$ or $b \to d$ penguins and CKM-suppressed $b \to u$ tree
- Sensitivity to new physics in penguin amplitudes
- **CPV** from CKM complex phase in the SM, and from new physics if any
- Branching fractions in 10^{-5} to 10^{-8} range

Theory

- Individual branching fraction predictions are not so precise
- **Ratios / differences** (A_{CP}, ...) / **relations** (sum rules, ...) are more reliable
- Extraction of the CKM angle ϕ_2/α relies on the isospin analysis

Yet unresolved issues

- K-π puzzle — simplest modes, but *CPV* difference between $K^+\pi^-$ and $K^+\pi^0$ unexplained
- Polarization puzzle — large transverse polarization in $B \to (\rho/\omega/\phi)K^*$ modes unexplained

Two-body charmless B decays

Charmless two-body decays into PP, PV, VV (P:pseudoscaler V:vector)

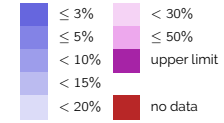
- PP modes are all measured except $\eta^{(\prime)}\eta^{(\prime)}$
- Upper limit only for many PV and VV modes [only one mode ($K^{*+}K_S$) not in PDG yet]

Decays into PS, VS are also heavily involved (S:scalar)

- Narrow scalars (e.g. $f_0(980)$) are easily distinguished
- Wide scalers (e.g. $f_0(500)$ overlap with vectors (e.g. $\rho(770)^0$)

Other combinations

- **Axial vectors**, tensors, Non-resonant 3- and 4-body decays, **baryonic** decays, …



Two-body charmless $B \to PP/PV/VV$ decay branching fraction errors (%) in PDG-live 2025

	π^+	π^0	K^+	K_S	η	η'
π^- or π^+	4	5	2	3	7	33
π^0		11	3	4	41	50
K^- or K^+			19	13	17	4
K_S				13	22	6
η					UL	UL
η'						UL

	ρ^+	ρ^0	K^{*+}	K^{*0}	ω	ϕ
π^- or π^+	10	14	5	8	7	47
π^0	12	25	13	18	UL	UL
K^- or K^+	13	14	UL	14	6	8
K_S	16	32	NA	UL	8	10
η	41	UL	8	6	43	UL
η'	23	UL	38	21	50	UL

	ρ^+	ρ^0	K^{*+}	K^{*0}	ω	ϕ
ρ^- or ρ^+	7	8	25	16	13	UL
ρ^0		16	16	33	UL	UL
K^{*-} or K^{*+}			UL	32	UL	20
$\overline{K}^{*0}$ or K^{*0}				29	25	5
ω					18	UL
ϕ						UL

Belle II $B^0 \to \pi^0\pi^0$

Role of $B^0 \to \pi^0\pi^0$

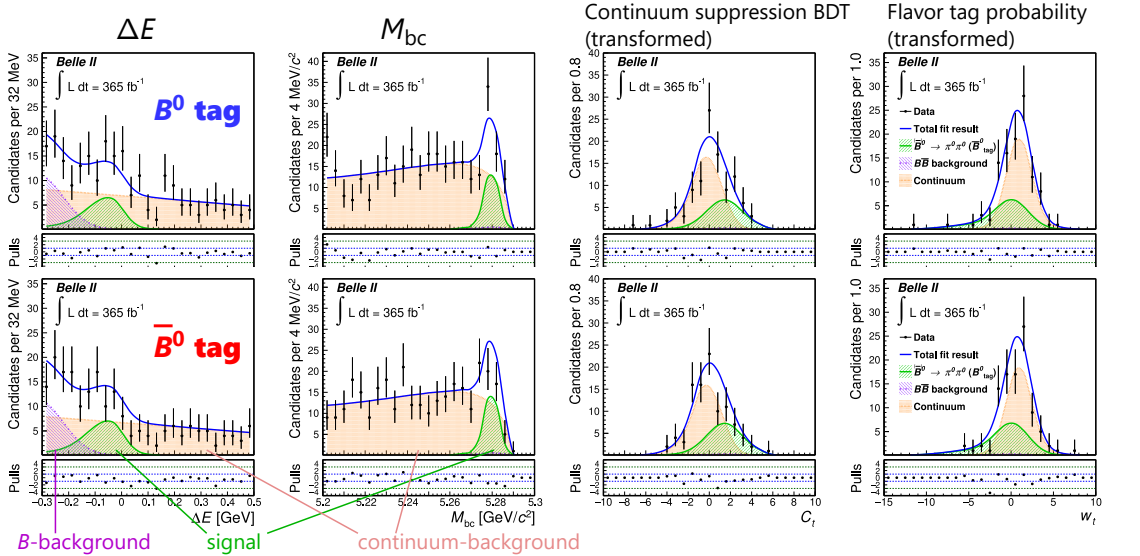
- Involves color-suppressed $b \to u$ tree and $b \to d$ penguin amplitudes
- Isospin analysis together with $B^0 \to \pi^+\pi^-$, $B^+ \to \pi^+\pi^0 \Rightarrow$ CKM UT angle ϕ_2
- Smallest $\mathcal{B}$ among $B \to \pi\pi$ (but larger than theory expectation)

Analysis

- Belle II Run 1 dataset (387M $B\bar{B}$)
- Photon only final state, large beam-induced background → new Photon-BDT
  (newly introduced to enhance the signal photon purity)
- Large background from $e^+e^- \to q\bar{q}$ → continuum-suppression-BDT
  ($B\bar{B}$: spherical ⇔ continuum: jet-like)
- Signal: peak in $M_{\rm bc} = \sqrt{(E^*_{\rm beam})^2 - |p^*_B|^2}$ and $\Delta E = E^*_B - E^*_{\rm beam}$
  (Only peaking background from $B \to (\pi\pi^0)\pi^0$ (including $\rho\pi^0$) and well separated in ΔE)
- Flavor from accompanying B → Belle II's new BDT-based flavor tag

[arXiv:2412.14260, PRD111 L071102(2025)]

Belle II $B^0 \to \pi^0\pi^0$ 4-d fit



[arXiv:2412.14260, PRD111 L071102(2025)]

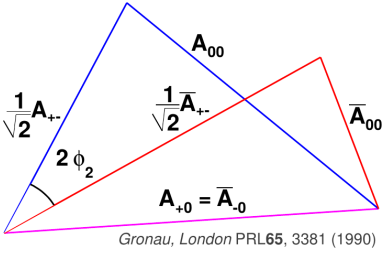
Belle II $B^0 \to \pi^0\pi^0$ and ϕ_2

Results (387M $B\bar{B}$)

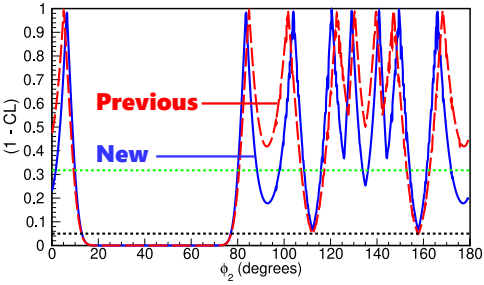
- $\mathcal{B} = (1.25 \pm 0.20 \pm 0.11) \times 10^{-6}$
  (best measurement)
- $A_{CP} = 0.03 \pm 0.30 \pm 0.04$
  (comparable with previous best)

Isospin analysis

- Calculate new $B^0 \to \pi^0\pi^0$ average
- $B^0 \to \pi^+\pi^-$ and $B^+ \to \pi^+\pi^0$ from PDG
- 10° reduction of 68% CL interval
- $B \to \pi\pi$ is now competitive with $B \to \rho\rho$ in ϕ_2 extraction



Gronau, London PRL65, 3381 (1990)



[arXiv:2401.04646, PRL133 081801(2024)]

Belle $B^0 \to \omega\omega$

Previous status

- One of the least measured charmless $B \to VV$ mode
- Previous mesurement: 4.4σ signal by BaBar
  $\mathcal{B} = (1.2 \pm 0.3\,^{+0.3}_{-0.2}) \times 10^{-6}$
- f_L and A_{CP} were not reported
- First time to report from Belle

Analysis

- Belle final dataset (772M $B\bar{B}$)
- Dominant background from continuum $e^+e^- \to q\bar{q}$
- Background: $\omega b_1(1235)^0(\to \omega\pi^0)$, $\omega K^{(*)0}$, $\omega\eta^{(\prime)}$, $\omega a_1(1260)^0$, non-resonant components
- Belle's flavor tag algorithm for A_{CP}
- 7-d fit: $M_{\rm bc}$, ΔE, continuum suppression variable, masses and helicity angles of two ωs

  (non-ω background is small, no amplitude analysis is performed)

Definitions

$B \to VV$ has three helicity amplitudes
H_0 (longitudinal), H_+, H_- (transverse)
$f_L = |H_0|^2/(|H_0|^2 + |H_+|^2 + |H_-|^2)$

Polarization puzzle

$B \to VV$ is expected to be dominated by longitudinal amplitude, but it turns out
$f_L \sim 0.5$ for $b \to s$ modes
($f_L \sim 1$ for $b \to u$ modes)

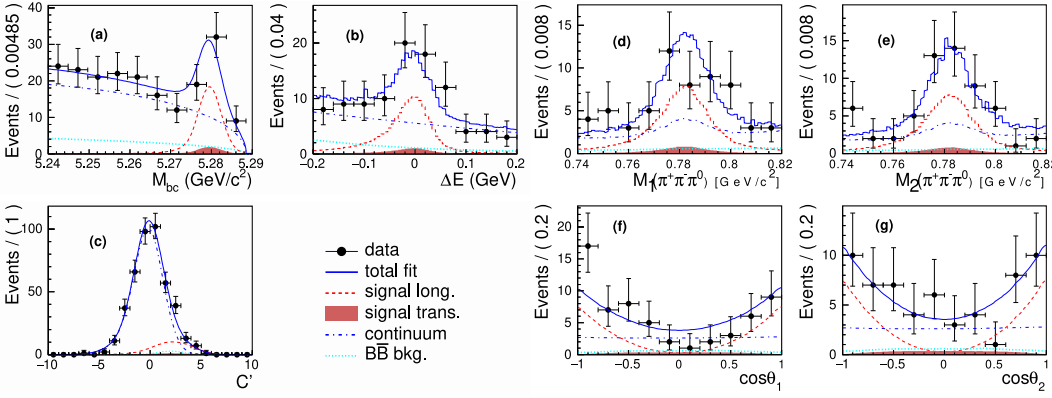
Belle $B^0 \to \omega\omega$ results

Results (Belle 772 M $B\bar{B}$)

$\mathcal{B} = (1.53 \pm 0.29 \pm 0.17) \times 10^{-6}$ (7.9σ first observation)

$f_L = 0.87 \pm 0.13 \pm 0.13$ (first measurement, consistent with $f_L \sim 1$)

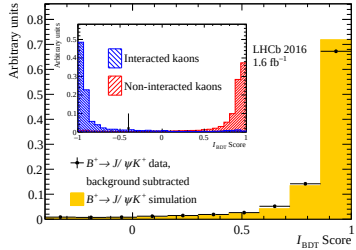
$A_{CP} = -0.44 \pm 0.43 \pm 0.11$ (first measurement)

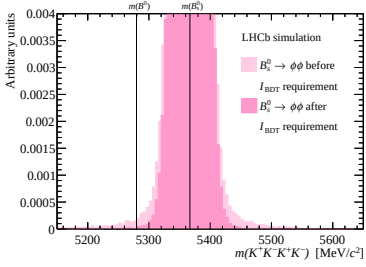


[arXiv:2507.20945]

LHCb $B^0 \to \phi\phi$

- Accessible only through annihilation / exchange amplitudes
- 4 charged-kaon final state
- Analysis strategy
  - Huge $B_s \to \phi\phi$ control sample ($b \to s$ penguin)
    also huge tail on top of $B^0 \to \phi\phi$
  - New kaon selection BDT → reduction of $B_s \to \phi\phi$ tail
    (by suppressing kaons interacted inside the detector)
  - Huge random ϕ from $D_s^+ \to \phi\pi^+$, $\phi\mu^+\nu_\mu$ and $\phi e^+\nu_e$,
    tagged/removed by gradient-BDT (~50% of D_s^+)
  - Still large untagged $D_s^+ \to \phi X$, → multilayer perceptron
    (99% background reduction while keeping 97.5% of signal)
  - Generic combinatorial background
    reduction using a gradient-BDT (XGBOOST)

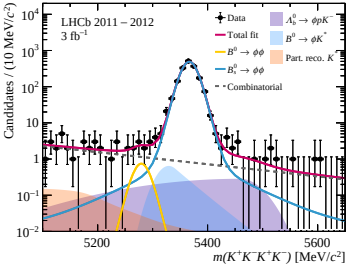


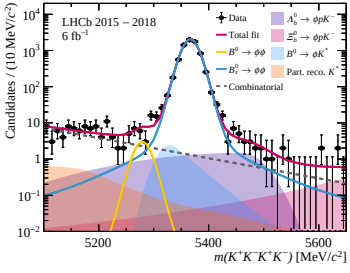


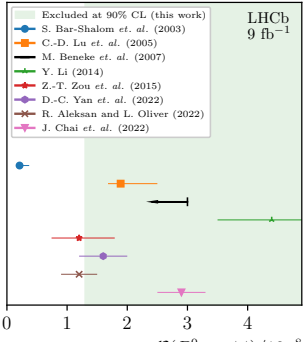
[arXiv:2507.20945]

LHCb $B^0 \to \phi\phi$

- Yield: 2.6 ± 1.5 (Run 1) + 10.5 ± 6.3 (Run 2) (1.9 σ excess)
- Largest systematic uncertainty: $B_s \to \phi\phi$ branching fraction (7.7%)
- Upper limit: $\mathcal{B}(B^0 \to \phi\phi) < 1.3 \times 10^{-8}$ (90% CL) or $< 1.4 \times 10^{-8}$ (95% CL)
- Already excluding many theory predictions,
  Signal would be seen with more LHCb data







[arXiv:2508.13563]

LHCb $B^+ \to \rho^0 K^{*+}$

Large branching fraction

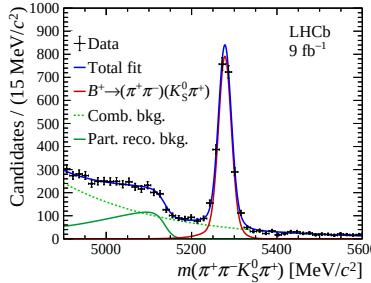
- $\mathcal{B}(B^+ \to \rho^0 K^{*+}) = (4.6 \pm 1.0 \pm 0.4) \times 10^{-6}$ by BaBar

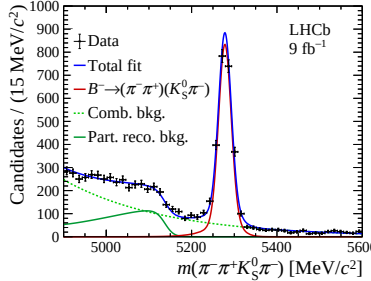
Huge signal of $B^+ \to (\pi^+\pi^-)(K_S\pi^+)$

- Secondary production vertex for B meson decays
- $m_{\pi^+\pi^-} \in [0.3, 1.1]$ GeV, $m_{K_S\pi^+} \in [0.75, 1.2]$ GeV
- Veto $\Lambda \to p\pi^-$ and charm meson decay combinations
- BDT to suppress combinatorials
- $2208 \pm 53(B^+)$ / $2333 \pm 55(B^-)$ events from Run 1+2
- 6.3% background fraction

Multiple quasi-two-body modes

- $(\pi^+\pi^-)$ includes $\rho(770)$, ω, $f_0(500)$, $f_0(980)$, $f_0(1370)$
- $(K_S\pi^+)$ includes $K^*(892)$ and LASS-model scalars
- $(\pi^+\pi^-\pi^+)K_S$ component with $a_1(1260)$ and $a_1(1640)$



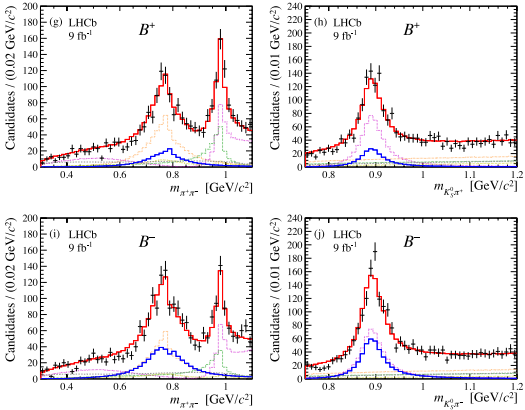


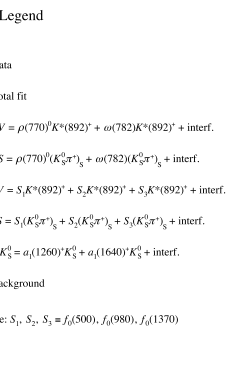
[arXiv:2508.13563]

LHCb $B^+ \to \rho^0 K^{*+}$

5-d unbinned full-amplitude fit

- $m_{\pi^+\pi^-}$, $m_{K_S\pi^\pm}$, $\cos\theta_{\pi^+\pi^-}$, $\cos\theta_{K_S\pi^\pm}$, ϕ
  to completely describe the kinematics





Results for $B^+ \to \rho^0 K^{*+}$

- $f_L = 0.720 \pm 0.028 \pm 0.009$
  (consistent with BaBar's $0.78 \pm 0.12 \pm 0.03$)
- $A_{CP} = 0.507 \pm 0.062 \pm 0.017$ (**> 9σ**)
  (consistent with BaBar's $0.31 \pm 0.13 \pm 0.03$)

(results for helicity amplitudes)
$A_{CP}(A_0) = 0.664 \pm 0.083 \pm 0.025$
$A_{CP}(A_\parallel) = -0.063 \pm 0.137 \pm 0.024$
$A_{CP}(A_\perp) = 0.284 \pm 0.140 \pm 0.022$

(results for phase differences [rad])
$\Delta_{CP}(A_0) = 0.720 \pm 0.177 \pm 0.048$
$\Delta_{CP}(A_\parallel) = 0.477 \pm 0.187 \pm 0.040$
$\Delta_{CP}(A_\perp) = 0.412 \pm 0.180 \pm 0.048$

Longitudinal amplitude is the main source of CPV

(triple product asymmetry results in backup slides)

[arXiv:2501.06483, PRD111, 092009(2025)]

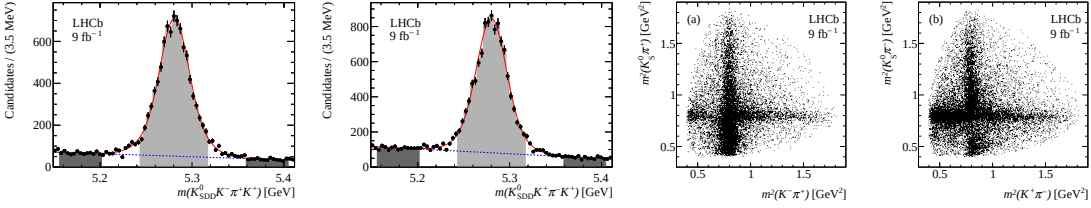
LHCb $B^+ \to (K_S K\pi) K^+$

Charmless B meson decays as a laboratory of light resonances (R^0)

- Many unresolved spectroscopy issues in the mass range around 1.4 GeV
- $(K_S K\pi)$ could be 0^{-+} states (η), 1^{++} states (f_1), 1^{+-} states (h_1), and 2^{-+} states (η_2)
- $(K_S K\pi)$ could be $(K_S K^+\pi^-)$ or $(K_S K^-\pi^+)$ — these are naively identical, but interference makes intermediate states look different
- Intermediate states of $(K_S K\pi)$ include $K^*\overline{K}$ (S-wave and D-wave), $a_0\pi$, and phase space

Data sample

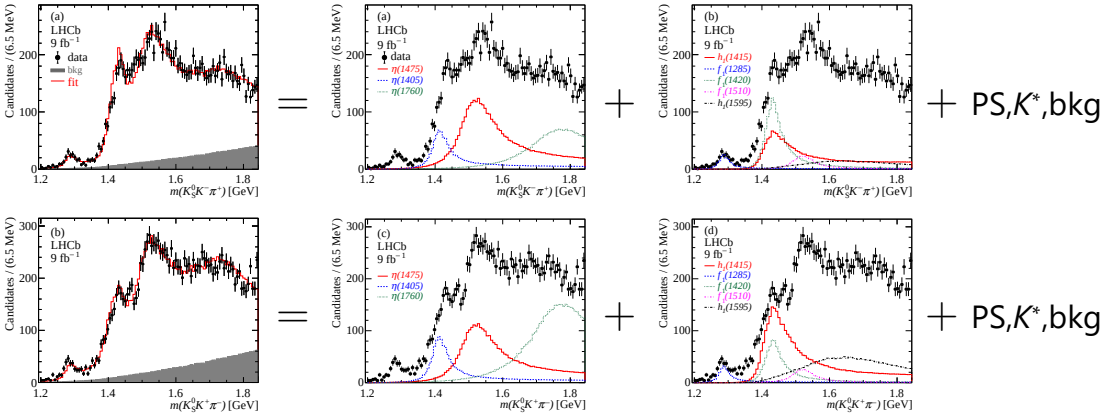
- Run 1+2 data, >10 k events, >80% purity for both combinations



[arXiv:2501.06483, PRD111, 092009(2025)]

LHCb $B^+ \to (K_S K\pi)K^+$

- Dominated by $\mathbf{0^{-+}}$ $(\eta(\ldots))$, $\mathbf{1^{++}}$ $(\boldsymbol{f_1}(\ldots))$, and $\mathbf{1^{-+}}$ $(\boldsymbol{h_1}(\ldots))$ amplitudes
- Branching fractions for two-body $B^+ \to R^0 K^+$ are reported (1.5×10^{-6} to 2.2×10^{-5}, table in backup)
- New information on light mesons in the low-mass region



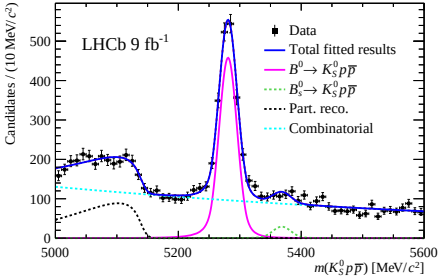
[arXiv:2504.21269, JHEP07 (2025) 121]

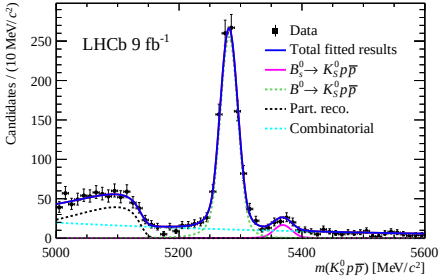
LHCb $B^0 \to K_S p\bar{p}$ and $B_s^0 \to K_S p\bar{p}$

- $\Lambda_c^+ \to K^0 p$, $\eta_c, J/\psi, \psi(2S) \to p\bar{p}$ are vetoed
- normalization channel: $B^0 \to K^0\pi^+\pi^-$
- Separate optimization for B^0 and B_s^0 on BDT requirement
- **Results (Run 1+2 data)**
  - $\mathcal{B}(B^0 \to K^0 p\bar{p}) = (2.82 \pm 0.08_{\text{stat}} \pm 0.12_{\text{sys}} \pm 0.10_{\text{norm}}) \times 10^{-6}$, much more precise than world average
  - $\mathcal{B}(B_s^0 \to K^0 p\bar{p}) = (9.14 \pm 1.69_{\text{stat}} \pm 0.90_{\text{sys}} \pm 0.33_{\text{norm}} \pm 0.20_{f_s/f_d}) \times 10^{-7}$, 5.6σ, first observation

Large enough data for time-dependent CPV study

$m_{p\bar{p}}$ information is not provided while $B \to K^{(*)} p\bar{p}$ modes have $p\bar{p}$ threshold enhancement



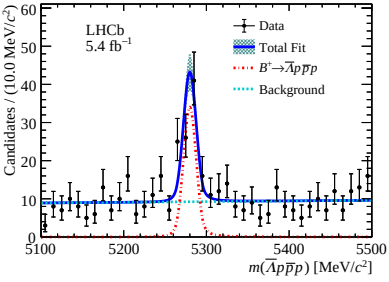


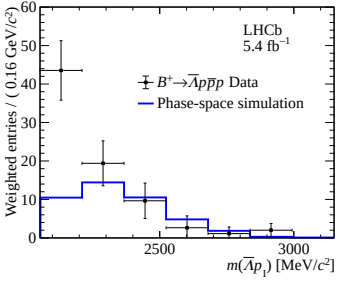
[arXiv:2508.16259]

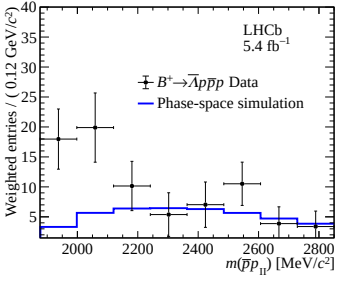
LHCb $B^+ \to \bar{\Lambda} p \bar{p} p$

Results (LHCb 5.4 fb^{-1})

- normalization channel: $B^+ \to J/\psi(\to \Lambda p K^-) K^+$
- $\mathcal{B} = (2.08 \pm 0.34_{\text{stat}} \pm 0.12_{\text{sys}} \pm 0.26_{\text{norm}}) \times 10^{-7}$, $>5\sigma$, first observation
- $A_{CP} = (5.4 \pm 15.6 \pm 2.4)\%$
  (no non-zero A_{CP} yet in any baryonic charmless B decays)
- Threshold enhancements both in $\bar{\Lambda} p$ and $\bar{p} p$
  (like ppK and $pp\pi$, and in contrast to $B^0 \to p\bar{p}p\bar{p}$ which shows no enhancement)







Summary

New$(>5\sigma)$**:** $B^0 \to \omega\omega$**,** $A_{CP}(B^+ \to \rho^0 K^{*+})$**,** $B \to R^0(\to K_S K\pi)K$**,** $B_s \to K_S p\bar{p}$**,** $B^+ \to \bar{\Lambda} p\bar{p}p$
Update: $B^0 \to \pi^0\pi^0$**,** $UL(B^0 \to \phi\phi)$**,** $f_L(B^+ \to \rho^0 K^{*+})$**,** $B^0 \to K_S p\bar{p}$

Non-zero CP asymmetry is a common phenomenon in charmless B decays

- Whenever branching fraction is measured, A_{CP} can be usually measured
- CP final states are subject to time-dependent CPV measurement
- New non-zero A_{CP} is now added for $B^+ \to \rho^+ K^{*0}$

Spectroscopy techniques are more and more relevant in charmless B decays

- Amplitude analysis of quasi-two-body decays into multi-body final states
- $B \to VV$ modes are now reliably disentangled from $B \to SV$, $B \to SS$, …

Many unknowns yet to tackle

- Polarization puzzle, threshold enhancement in baryonic decays, $K\pi$ puzzle, …
- Charmless decays with charged particle final states are extensively explored by LHCb
- Charmless decays with neutral particle final states are Belle II's expertise, still data-limited

More results are expected from Belle II and LHCb, and charmless *B* decay is a very active topic!

Thanks!

Backup

[arXiv:2508.13563]

LHCb $B^+ \to \rho^0 K^{*+}$ triple product asymmetries

- Interference between CP-odd and -even amplitudes ($A_\perp \Leftrightarrow A_0$, $A_\perp \Leftrightarrow A_\parallel$)
  → Triple product asymmetry (TPA)
- **Definitions**

$$\mathcal{A}^{(1)}_{\text{true,fake}} \equiv -\frac{2\sqrt{2}}{\pi}\frac{\mathfrak{Im}(A_\perp A_0^* \mp \overline{A}_\perp \overline{A}_0^*)}{\sum_\lambda(|A_\lambda|^2 + |\overline{A}_\lambda|^2)}$$

$$\mathcal{A}^{(2)}_{\text{true,fake}} \equiv -\frac{2\sqrt{2}}{\pi}\frac{\mathfrak{Im}(A_\perp A_\parallel^* \mp \overline{A}_\perp \overline{A}_\parallel^*)}{\sum_\lambda(|A_\lambda|^2 + |\overline{A}_\lambda|^2)}$$

- True TPA due to CP-violating weak phase
  Fake TPA due to CP-conserving strong phase

Results

$$\mathcal{A}^{(1)}_{\text{true}} = -0.105 \pm 0.024 \pm 0.006\ (\sim 4\sigma)$$
$$\mathcal{A}^{(1)}_{\text{fake}} = -0.157 \pm 0.024 \pm 0.008\ (\sim 6\sigma)$$
$$\mathcal{A}^{(2)}_{\text{true}} = 0.007 \pm 0.019 \pm 0.003$$
$$\mathcal{A}^{(2)}_{\text{fake}} = 0.008 \pm 0.018 \pm 0.004$$

[arXiv:2501.06483, PRD111, 092009(2025)]

LHCb $B^+ \to R^0 K^+$ branching fractions

Contribution	$\mathcal{B}(B^+ \to R^0 K^+) \times 10^{-5}$
$B^+ \to \eta(1475)K^+ \to (K^*\overline{K})K^+$	$1.45 \pm 0.11 \pm 0.12 \pm 0.09$
$B^+ \to \eta(1475)K^+ \to (a_0(980)\pi)K^+$	$0.22 \pm 0.04 \pm 0.03 \pm 0.01$
$B^+ \to \eta(1475)K^+ \to (K^0K\pi)K^+$	$1.51 \pm 0.16 \pm 0.24 \pm 0.09$
$B^+ \to \eta(1760)K^+ \to (K^*\overline{K})K^+$	$0.34 \pm 0.04 \pm 0.04 \pm 0.02$
$B^+ \to \eta(1760)K^+ \to (a_0(980)\pi)K^+$	$0.26 \pm 0.04 \pm 0.02 \pm 0.02$
$B^+ \to \eta(1760)K^+ \to (K^0K\pi)K^+$	$2.21 \pm 0.20 \pm 0.33 \pm 0.13$
$B^+ \to \eta(1405)K^+ \to (K^*\overline{K})K^+$	$0.38 \pm 0.05 \pm 0.09 \pm 0.02$
$B^+ \to \eta(1405)K^+ \to (K^0K\pi)K^+$	$0.80 \pm 0.05 \pm 0.09 \pm 0.05$
$B^+ \to f_1(1285)K^+ \to (a_0(980)\pi)K^+$	$0.28 \pm 0.02 \pm 0.02 \pm 0.02$
$B^+ \to f_1(1420)K^+ \to (K^*\overline{K})K^+$	$1.14 \pm 0.06 \pm 0.19 \pm 0.07$
$B^+ \to f_1(1510)K^+ \to (K^*\overline{K})K^+$	$0.38 \pm 0.03 \pm 0.15 \pm 0.02$
$B^+ \to h_1(1415)K^+ \to (K^*\overline{K})K^+$	$2.22 \pm 0.10 \pm 0.23 \pm 0.10$
$B^+ \to h_1(1595)K^+ \to (K^*\overline{K})K^+$	$1.04 \pm 0.10 \pm 0.12 \pm 0.06$
$B^+ \to \eta_2(1645)K^+ \to (K^*\overline{K})K^+$	$0.15 \pm 0.02 \pm 0.02 \pm 0.01$

(inverse-variance-averages of $B^+ \to (K^0K^-\pi^+)K^+$ and $B^+ \to (\overline{K}^0K^+\pi^-)K^+$)