Study of charmless $B \to VV$ decays at LHCb

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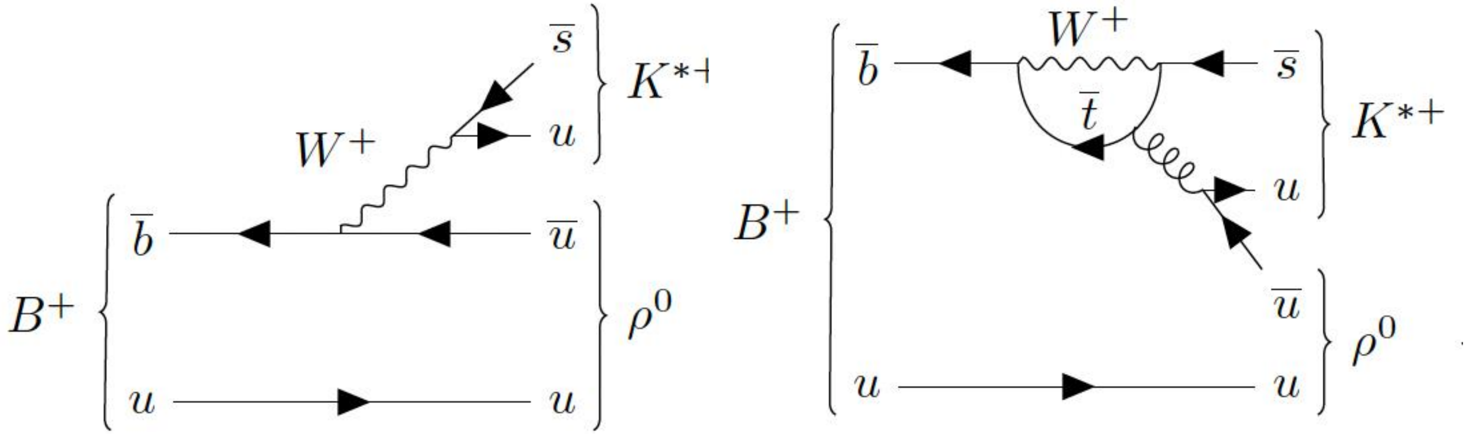
- Introduction
- First observation of CP violation and measurement of polarization in $B^+ \to \rho(770)^0 K^*(892)^+$
- Measurement of the branching fractions and longitudinal polarizations of $B^0_{(s)} \to K^*(892)^0 \overline{K}^*(892)^0$
- Measurement of CP violation of $B^0_s \to \phi\phi$ and search for $B^0 \to \phi\phi$
- Summary

Introduction on charmless $B \to VV$ decays

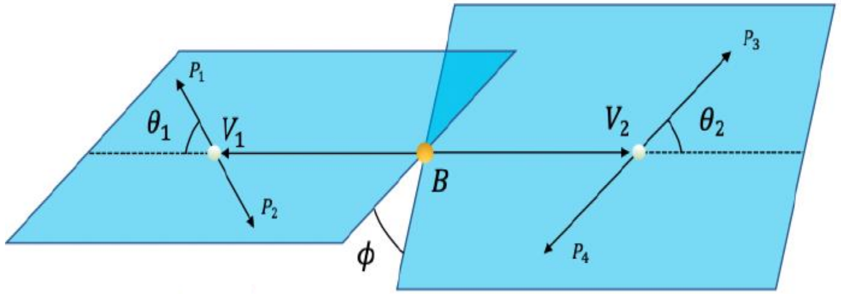
- Charmless B decays:
  - Tree level: Cabibbo suppressed
  - Loop level: similar amplitudes as tree level
  - Interference between them gives rise to direct *CP* violation



- Vector resonances: additional CP violating observables

Polarization puzzle

- Three contributing amplitudes in $B \to VV$ decays:
  - ➢ S-, P- or D- wave
  - ➢ Longitudinal, parallel, and perpendicular



$$f_L \equiv |A_0|^2/(|A_0|^2 + |A_\perp|^2 + |A_\parallel|^2)$$

- Discrepancy on the longitudinal polarization fraction between theoretical predictions and experimental results
- QCD effects or new physics?

Decay mode	f_L/percent	
	Theory	Exp
$B^- \to \rho^-\rho^0$	95.5 ± 1.1	95 ± 1.6
$\overline{B}^0 \to \rho^-\rho^+$	92.6 ± 1.6	98.8 ± 2.6
$B^- \to \rho^-\omega$	92.7 ± 1.4	90 ± 6
$\overline{B}_s^0 \to K^{*+}\rho^-$	94.4 ± 1.2	
$\overline{B}^0 \to \rho^0\rho^0$	81.7 ± 10.8	60 ± 23
$\overline{B}^0 \to \rho^0\omega$	82.7 ± 9.5	
$\overline{B}^0 \to \omega\omega$	92.2 ± 3.6	
$\overline{B}_s^0 \to K^{*0}\rho^0$	79.8 ± 8.0	
$\overline{B}_s^0 \to K^{*0}\omega$	77.9 ± 9.2	
$B^- \to \rho^-\overline{K}^{*0}$	46.0 ± 12.9	48 ± 8
$B^- \to \rho^0 K^{*-}$	40.7 ± 10.6	78 ± 12
$\overline{B}^0 \to \rho^0\overline{K}^{*0}$	48.7 ± 12.3	40 ± 14
$\overline{B}^0 \to \rho^+ K^{*-}$	38.9 ± 11.3	38 ± 13
$B^- \to \omega K^{*-}$	29.9 ± 6.8	41 ± 19
$\overline{B}^0 \to \omega\overline{K}^{*0}$	29.4 ± 17.5	69 ± 13
$B^- \to \phi K^{*-}$	48.0 ± 16.0	50 ± 5
$\overline{B}^0 \to \phi\overline{K}^{*0}$	48.0 ± 16.0	49.7 ± 1.7
$\overline{B}_s^0 \to \overline{K}^{*0}K^{*0}$	34.3 ± 12.6	
$\overline{B}_s^0 \to K^{*-}K^{*+}$	30.9 ± 10.4	
$\overline{B}_s^0 \to \phi\phi$	39.7 ± 16.0	36.2 ± 1.4
$B^- \to K^{*0}K^{*-}$	58.3 ± 11.1	75 ± 21
$\overline{B}^0 \to K^{*0}\overline{K}^{*0}$	58.3 ± 11.1	80 ± 13
$\overline{B}_s^0 \to \phi K^{*0}$	38.9 ± 14.7	51 ± 17

[Eur.Phys.J.C77(2017)333]

Study of $B^+ \to \rho(770)^0 K^*(892)^+$

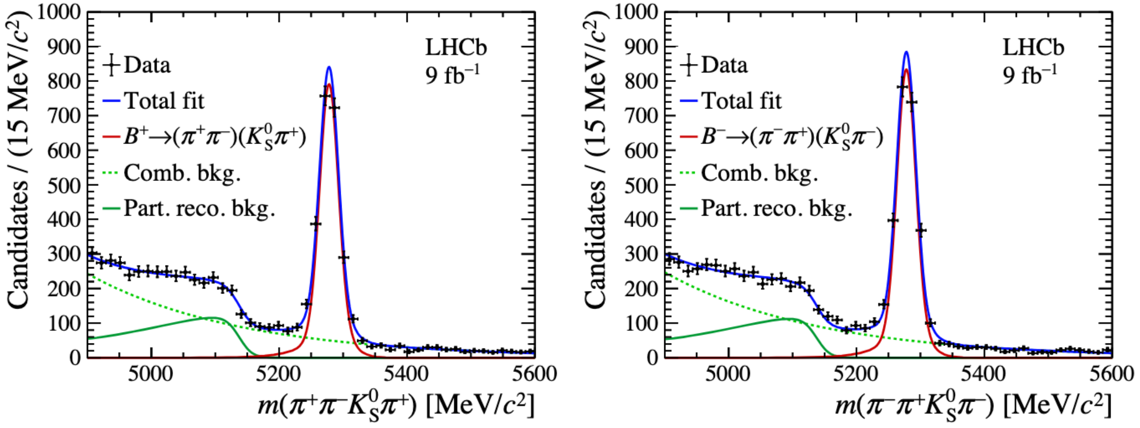
- Observed and measured by BaBar [Phys.Rev.D83(2011)051101]

Mode	Y	$\epsilon(\%)$	$\Pi\mathcal{B}_i(\%)$	S(σ)	$\mathcal{B}$ ($\times 10^{-6}$)	UL ($\times 10^{-6}$)	f_L	$\mathcal{A}_{CP}$
$B^+ \to \rho^0 K^{*+}$				5.3	$4.6 \pm 1.0 \pm 0.4$	6.0	$0.78 \pm 0.12 \pm 0.03$	$0.31 \pm 0.13 \pm 0.03$
$K^{*+} \to K_S^0 \pi^+$	85 ± 24	17.1	23.1	4.1	$4.6 \pm 1.2 \pm 0.5$	6.4	$0.74 \pm 0.13 \pm 0.03$	$0.25 \pm 0.14 \pm 0.03$
$K^{*+} \to K^+ \pi^0$	67 ± 31	9.9	33.3	3.3	$4.4 \pm 2.0 \pm 0.5$	7.1	$0.94 \pm 0.27 \pm 0.03$	$0.59 \pm 0.31 \pm 0.03$

- Study of $B^+ \to \rho(770)^0 K^*(892)^+$ decay with LHCb run1+2 data

  $\hookrightarrow \pi^+\pi^-$ $\hookrightarrow K_S^0\pi^+$

- Submitted to PRL [arXiv:2508.13563]
- Larger statistics(>2000 signal for each B+ and B-)



Amplitude analysis of $B^+ \to \rho(770)^0 K^*(892)^+$

- Amplitude analysis: 5D c-fit

$$\frac{\mathrm{d}^5\Gamma}{\mathrm{d}(m_{\pi^+\pi^-})\mathrm{d}(m_{K_S^0\pi^+})\mathrm{d}(\cos\theta_{\pi^+\pi^-})\mathrm{d}(\cos\theta_{K_S^0\pi^+})\mathrm{d}\phi}$$
$$\propto \Phi \cdot \left|\sum_{i=1}^{N} A_i \cdot g_i(\cos\theta_{\pi^+\pi^-}, \cos\theta_{K_S^0\pi^+}, \phi) \cdot M_i(m_{\pi^+\pi^-}, m_{K_S^0\pi^+})\right|^2,$$

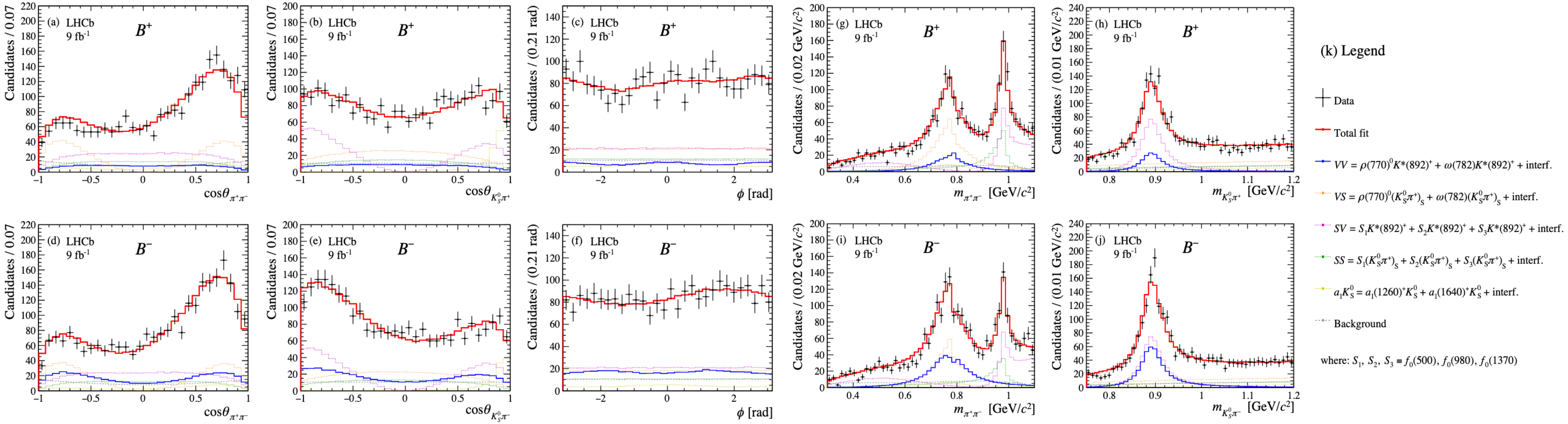
- Resonances considered:

$B^+ \to (\pi^+\pi^-)(K_S^0\pi^+)$

$\boxed{\rho(770)^0,\ \omega(782),\ f_0(500),\ f_0(980),\ f_0(1370)} \times \boxed{K^*(892)^+,\ (K\pi)_S}$

$B^+ \to (\pi^+\pi^-\pi^+)K_S^0$

$\boxed{a_1(1260),\ a_1(1640)} \times \boxed{K_S^0}$



CPV in $B^+ \to \rho(770)^0 K^*(892)^+$

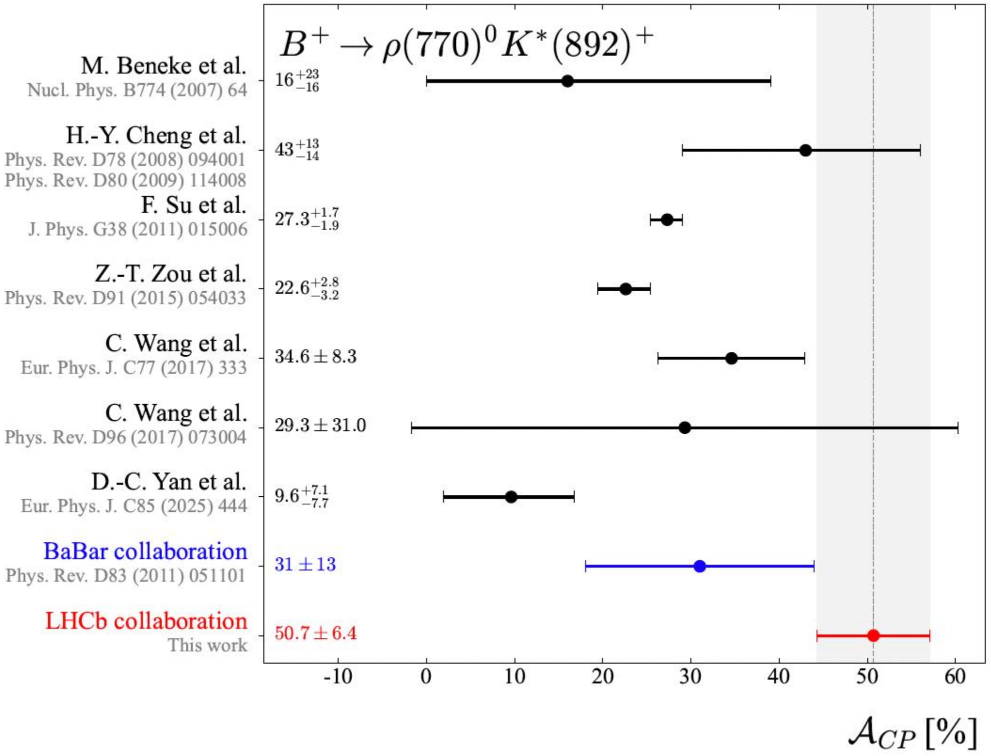
- Direct CP asymmetry: $\mathcal{A}_{CP} \equiv \frac{\sum_\lambda (|\bar{A}_\lambda|^2 - |A_\lambda|^2)}{\sum_\lambda (|\bar{A}_\lambda|^2 + |A_\lambda|^2)} = 0.507 \pm 0.062 \pm 0.017$

- Significance of direct CP violation: >9σ
  - ➢ First observation of CP violation in this channel !

- CP asymmetry for each component:

$$\mathcal{A}_{CP}(A_0) \equiv \frac{|\bar{A}_0|^2 - |A_0|^2}{|\bar{A}_0|^2 + |A_0|^2} = 0.664 \pm 0.083 \pm 0.025,$$
$$\Delta_{CP}(A_0) \equiv \arg(\bar{A}_0) - \arg(A_0) = 0.720 \pm 0.177 \pm 0.048\,\text{rad},$$

$$\mathcal{A}_{CP}(A_{\|}) = -0.063 \pm 0.137 \pm 0.024,$$
$$\Delta_{CP}(A_{\|}) = 0.477 \pm 0.187 \pm 0.040\,\text{rad},$$
$$\mathcal{A}_{CP}(A_\perp) = 0.284 \pm 0.140 \pm 0.022,$$
$$\Delta_{CP}(A_\perp) = 0.412 \pm 0.180 \pm 0.048\,\text{rad}.$$



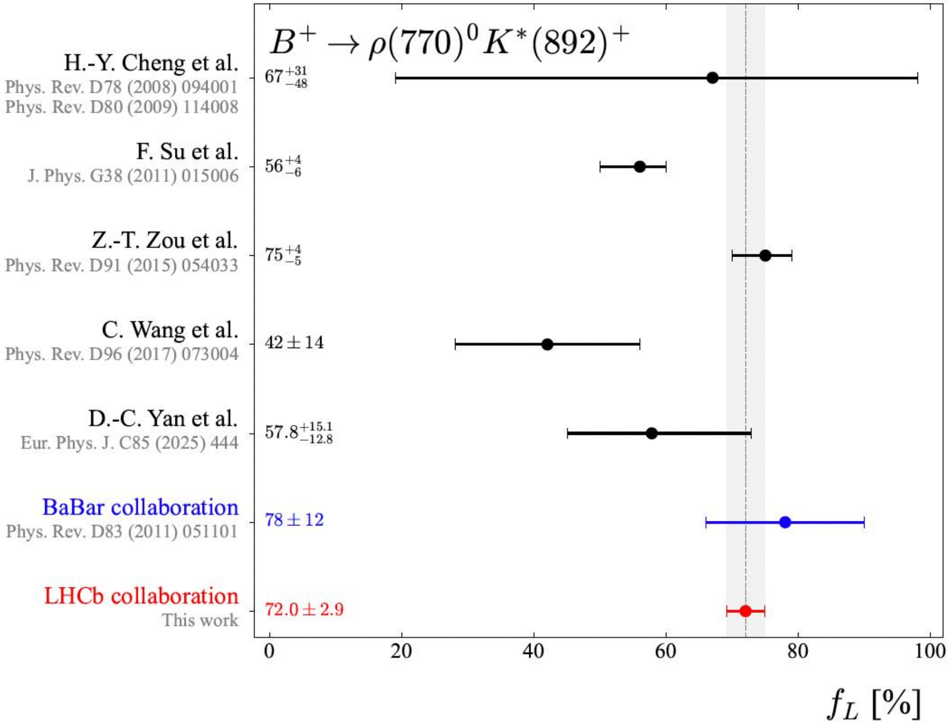
TPA and polarization in $B^+ \to \rho(770)^0 K^*(892)^+$

- Longitudinal polarization fractions:
  - Charge-specific: $f_L^+ \equiv \frac{|A_0|^2}{\sum_\lambda |A_\lambda|^2} = 0.491 \pm 0.083 \pm 0.025,\quad f_L^- \equiv \frac{|\bar{A}_0|^2}{\sum_\lambda |\bar{A}_\lambda|^2} = 0.794 \pm 0.025 \pm 0.007.$
  - Averaged: $f_L \equiv \frac{|A_0|^2 + |\bar{A}_0|^2}{\sum_\lambda (|A_\lambda|^2 + |\bar{A}_\lambda|^2)} = 0.720 \pm 0.028 \pm 0.009,$
  - Most precise measurement of f_L
  - Consistent with Babar results
- TPA measurements

$$\begin{aligned}
\mathcal{A}^{(1)}_{true} &= -0.105 \pm 0.024 \pm 0.006,\\
\mathcal{A}^{(2)}_{true} &= 0.007 \pm 0.019 \pm 0.003,\\
\mathcal{A}^{(1)}_{fake} &= -0.157 \pm 0.024 \pm 0.008,\\
\mathcal{A}^{(2)}_{fake} &= 0.008 \pm 0.018 \pm 0.004.
\end{aligned}$$

$$\mathcal{A}^{(1)}_{\substack{true\\fake}} \equiv -\frac{2\sqrt{2}}{\pi} \frac{\mathcal{I}m(A_\perp A_0^* \mp \bar{A}_\perp \bar{A}_0^*)}{\sum_{\lambda\in\{0,\parallel,\perp\}}(|A_\lambda|^2 + |\bar{A}_\lambda|^2)},$$

$$\mathcal{A}^{(2)}_{\substack{true\\fake}} \equiv -\frac{4}{\pi} \frac{\mathcal{I}m(A_\perp A_\parallel^* \mp \bar{A}_\perp \bar{A}_\parallel^*)}{\sum_{\lambda\in\{0,\parallel,\perp\}}(|A_\lambda|^2 + |\bar{A}_\lambda|^2)},$$



Study of $B^0_{(s)} \to K^*(892)^0 \overline{K}^*(892)^0$

- Analysis of $B^0_{(s)} \to K^*(892)^0 \overline{K}^*(892)^0$ decays with LHCb run1+2 data
  - ➢ Measure individual branching fractions of $B^0 \to K^*(892)^0 \overline{K}^*(892)^0$ and $B^0_s \to K^*(892)^0 \overline{K}^*(892)^0$
  - ➢ Measure longitudinal polarization f_L and $L_{K^{*0}\overline{K}^{*0}}$

$$L_{K^{*0}\overline{K}^{*0}} = \mathcal{G}\frac{\mathcal{B}(B^0_s \to K^{*0}\overline{K}^{*0})}{\mathcal{B}(B^0 \to K^{*0}\overline{K}^{*0})}\frac{f_L^s}{f_L^d}$$

[JHEP04(2021)066]

  - ➢ Tension on $L_{K^*\overline{K}^*}$: $L^{\mathrm{SM}}_{K^*\bar{K}^*} = 19.57^{+9.42}_{-6.70}\,, \quad L^{\exp}_{K^*\bar{K}^*} = 4.43 \pm 0.92\,,$
- LHCb run 1 results:

$$f_L^s = 0.240 \pm 0.031 \pm 0.025$$
$$f_L^d = 0.724 \pm 0.051 \pm 0.016$$
$$L_{K^{*0}\overline{K}^{*0}} = 3.48 \pm 0.38$$

[JHEP07(2019)032]

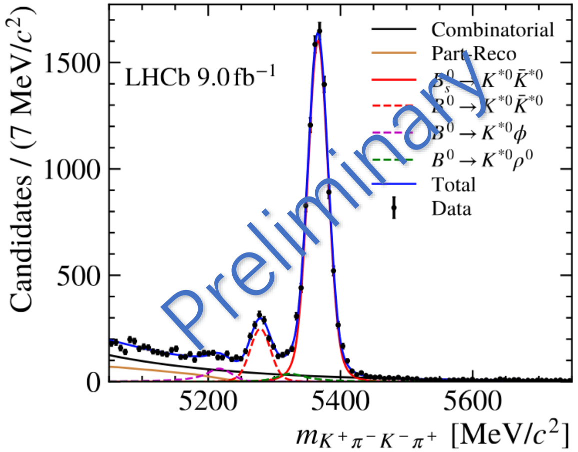
- Time-integrated, flavor-untagged amplitude analysis
- Paper in preparation [LHCb-PAPER-2025-046]

Amplitude analysis of $B^0_{(s)} \to K^*(892)^0 \overline{K}^*(892)^0$

- Covariant tensor formalism rather than helicity formalism
  - Set of four-momentum of final state particles, Φ_4, as the fit basis(instead of angles)
  - Spin amplitudes are eigenstates of orbital angular momentum

$$A(\Phi_4) \equiv F_{(K^+\pi^-)(K^-\pi^+)}(\Phi_4)[F_{K^+\pi^-}(\Phi_4)T_{K^+\pi^-}(\Phi_4)][F_{K^-\pi^+}(\Phi_4)T_{K^-\pi^+}(\Phi_4)]Z(\Phi_4)$$

  - F: barrier factor; T: mass propagator; Z: angular amplitude
- Backgrounds removed by sPlot

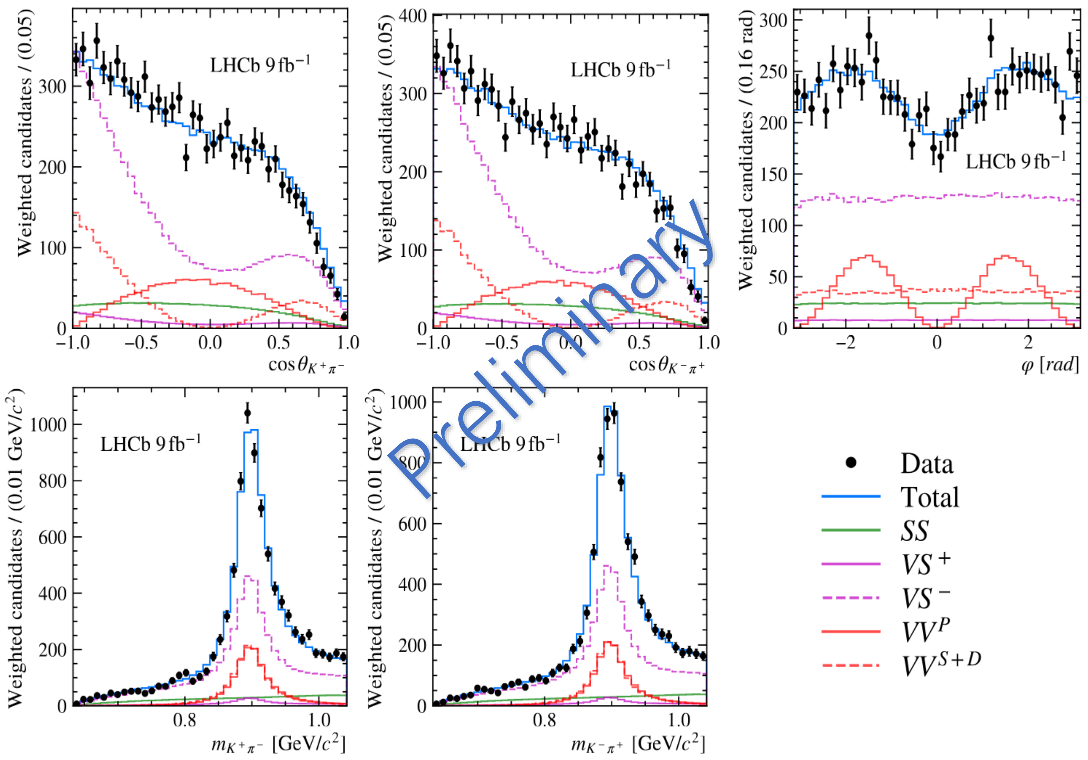


$B^0_{(s)}$ decay topology	Angular amplitude $Z(\Phi_4)$
$B \to V\bar{V}[S]$	$L_a(p_V, q_V)L^a(p_{\bar{V}}, q_{\bar{V}})$
$B \to V\bar{V}[P]$	$\epsilon_{abcd}p^d_B L^c(p_B, q_B)L^b(p_V, q_V)L^a(p_{\bar{V}}, q_{\bar{V}})$
$B \to V\bar{V}[D]$	$L_{ab}(p_B, q_B)L^b(p_V, q_V)L^a(p_{\bar{V}}, q_{\bar{V}})$
$B \to V\bar{S}$	$L_a(p_B, q_B)L^a(p_V, q_V)$
$B \to S\bar{V}$	$L_a(p_B, q_B)L^a(p_{\bar{V}}, q_{\bar{V}})$
$B \to S\bar{S}$	1

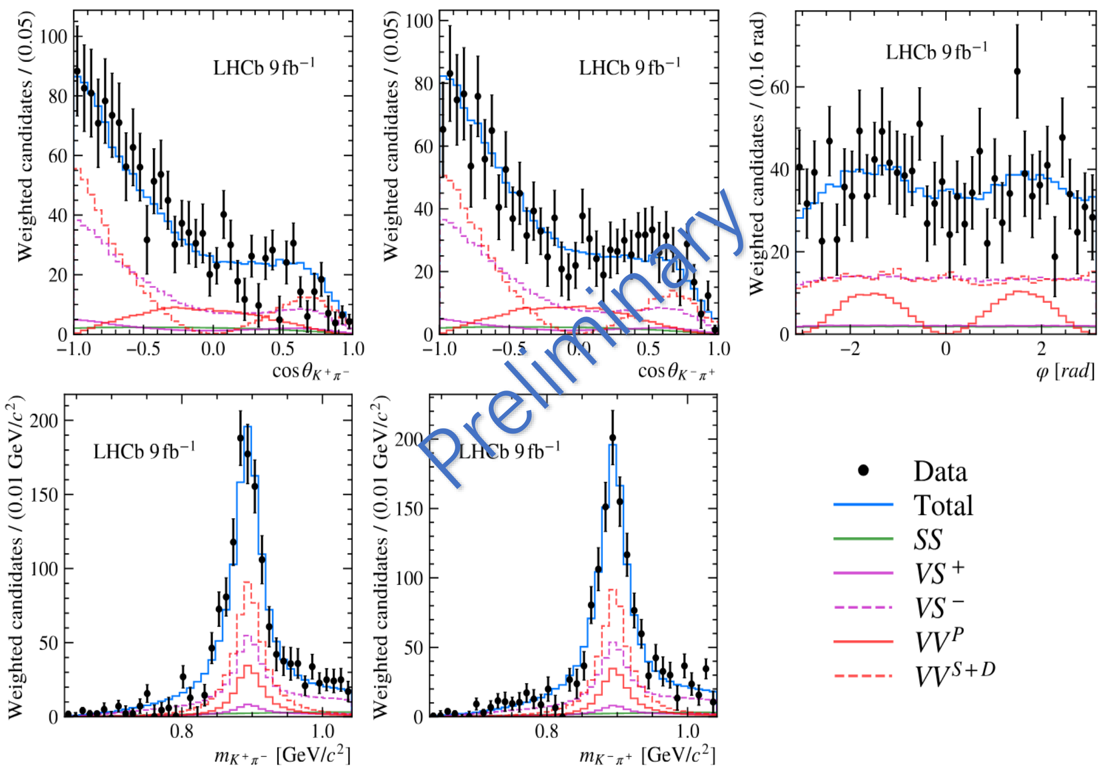
Amplitude analysis of $B^0_{(s)} \to K^*(892)^0 \overline{K}^*(892)^0$

- Fit results in transversity basis:

B_s^0



B_d^0



Branching fraction of $B_{(s)}^0 \to K^*(892)^0 \overline{K}^*(892)^0$

- Control channel: $B_{(s)}^0 \to D_{(s)}^- (\to K^+ K^- \pi^-)\pi^+$

$$\frac{\mathcal{B}(B_{(s)}^0 \to K^{*0}\overline{K}^{*0})}{\mathcal{B}(B_{(s)}^0 \to D_{(s)}^-\pi^+)} = \frac{N_{B_{(s)}^0 \to K^{*0}\overline{K}^{*0}}}{N_{B_{(s)}^0 \to D_{(s)}^-\pi^+}} \frac{\epsilon_{B_{(s)}^0 \to D_{(s)}^-\pi^+}}{\epsilon_{B_{(s)}^0 \to K^{*0}\overline{K}^{*0}}} \frac{1}{\mathcal{B}(K^{*0} \to K^+\pi^-)^2}$$

  - $N_{B_{(s)}^0 \to K^{*0}\overline{K}^{*0}}$: from fit on $B_{(s)}^0$ mass and *VV* fraction in amplitude analysis
  - $N_{B_{(s)}^0 \to D_{(s)}^-\pi+}$: from fit on $B_{(s)}^0$ mass
  - ϵ: Efficiency estimated by MC

- Results of vector-vector branching fractions

$$\begin{aligned}
\mathcal{B}^{\text{Mix}}(B_s^0 \to K^{*0}\overline{K}^{*0}) &= (0.937 \pm 0.025\,(\text{stat}) \pm 0.018\,(\text{syst}) \pm 0.036\,(\text{ext})) \times 10^{-5}, \\
\mathcal{B}(B_s^0 \to K^{*0}\overline{K}^{*0}) &= (0.932 \pm 0.025\,(\text{stat}) \pm 0.018\,(\text{syst}) \pm 0.036\,(\text{ext})) \times 10^{-5}, \\
\mathcal{B}(B^0 \to K^{*0}\overline{K}^{*0}) &= (4.69 \pm 0.29\,(\text{stat}) \pm 0.43\,(\text{syst}) \pm 0.16\,(\text{ext})) \times 10^{-7},
\end{aligned}$$

Preliminary

Polarization fraction of $B^0_{(s)} \to K^*(892)^0 \bar{K}^*(892)^0$

- Fit fractions and phases:

	Parameter	Value	Parameter	Value	Parameter	Value
B^0_s	$\mathcal{F}^{S+D}_{VV}$ (%)	$15.6 \pm 0.63 \pm 0.26$	$\mathcal{F}^{P}_{VV}$ (%)	$15.55 \pm 0.56 \pm 0.38$	$\mathcal{F}^{+}_{VS}$ (%)	$3.57 \pm 0.59 \pm 2.3$
	$\mathcal{F}^{-}_{VS}$ (%)	$54.75 \pm 0.89 \pm 1.1$	$\mathcal{F}_{SS}$ (%)	$10.55 \pm 0.56 \pm 0.23$	δ^{D}_{VV} (rad)	$-0.074 \pm 0.005 \pm 0.008$
	δ^{+}_{VS} (rad)	$-1.92 \pm 0.11 \pm 0.84$	δ^{-}_{VS} (rad)	$-2.98 \pm 0.04 \pm 0.12$	δ_{SS} (rad)	$0.12 \pm 0.06 \pm 0.25$
	f_L (%)	$15.9 \pm 1.0 \pm 0.7$	$f_{\parallel}$ (%)	$34.2 \pm 1.3 \pm 1.0$	$f_{\perp}$ (%)	$50.0 \pm 1.4 \pm 0.3$
	$\delta_{\parallel}$ (rad)	$0.73 \pm 0.08 \pm 0.12$				
B^0	$\mathcal{F}^{S+D}_{VV}$ (%)	$37 \pm 2 \pm 2$	$\mathcal{F}^{P}_{VV}$ (%)	$14 \pm 1 \pm 0.7$	$\mathcal{F}^{+}_{VS}$ (%)	$6 \pm 2 \pm 1$
	$\mathcal{F}^{-}_{VS}$ (%)	$38 \pm 2 \pm 3$	$\mathcal{F}_{SS}$ (%)	$5 \pm 1 \pm 0.2$	δ^{D}_{VV} (rad)	$-0.10 \pm 0.04 \pm 0.02$
	δ^{+}_{VS} (rad)	$2.1 \pm 0.2 \pm 0.3$	δ^{-}_{VS} (rad)	$-0.4 \pm 0.1 \pm 0.1$	δ_{SS} (rad)	$-1.7 \pm 0.2 \pm 0.3$
	f_L (%)	$60 \pm 2 \pm 2$	$f_{\parallel}$ (%)	$17 \pm 2 \pm 2$	$f_{\perp}$ (%)	$24 \pm 2 \pm 2$
	$\delta_{\parallel}$ (rad)	$0.3 \pm 0.2 \pm 0.1$				

Preliminary

- Theory-motivated $L_{K^{*0}\bar{K}^{*0}}$ observable

$$L_{K^{*0}\bar{K}^{*0}} = 4.92 \pm 0.55\,(\text{stat}) \pm 0.47\,(\text{syst}) \pm 0.02\,(\text{ext}) \pm 0.10\,(f_s/f_d)$$

Preliminary

- ➢ Consistent with previous experimental results
- ➢ Latest SM prediction $L^{I,\text{SM}}_{K^*\bar{K}^*} = 18.34^{+7.47}_{-5.83}\,,$ $L^{II,\text{SM}}_{K^*\bar{K}^*} = 26.08^{+5.70}_{-4.72}$ [arXiv:2506.12478]
- ➢ A 2.4~3.5σ tension between this results and the SM prediction

CPV in $B_s^0 \to \phi\phi$ [Phys.Rev.Lett.131(2023)171802]

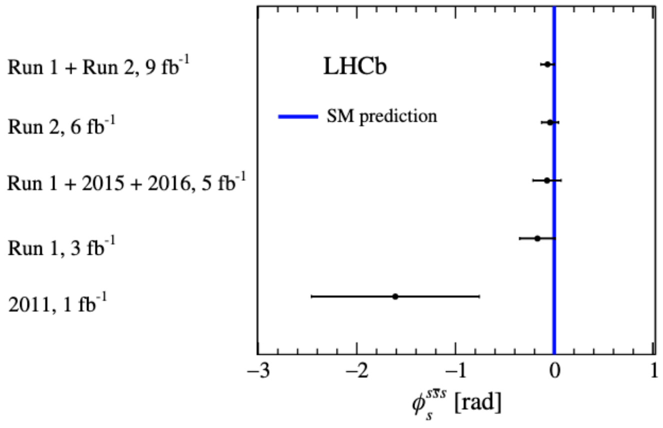
- Time-dependent *CP* violation
- Penguin-mediated decay
- Precise measurement (LHCb run2 data)

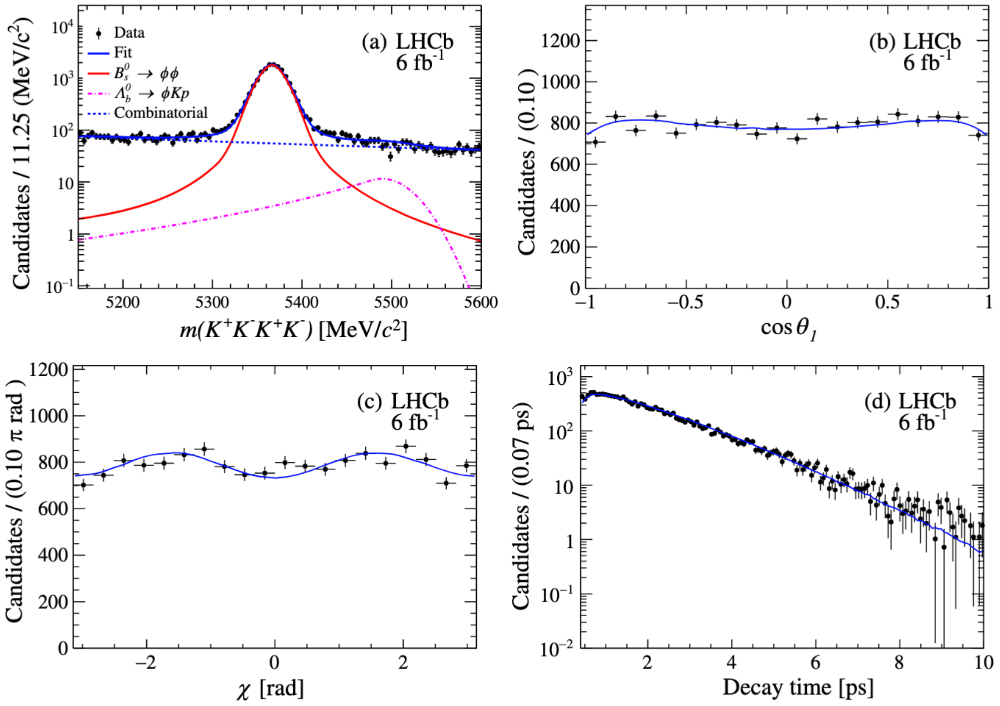
$$\frac{q}{p}\frac{\bar{A}_i}{A_i} = \eta_i|\lambda_i|e^{-i\phi_{s,i}},$$

- Measurement of the the *CP*-violating parameter $|\lambda|$ and the phase $\phi_s^{s\bar{s}s}$

$$\phi_s^{s\bar{s}s} = -0.042 \pm 0.075 \pm 0.009 \text{ rad},$$
$$|\lambda| = 1.004 \pm 0.030 \pm 0.009,$$

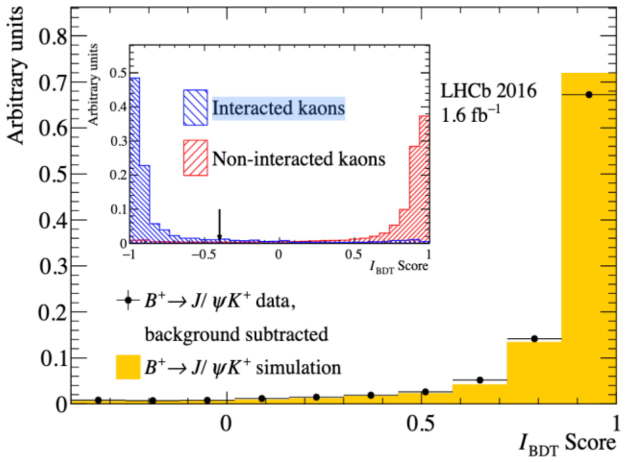
- Consistent with the SM prediction

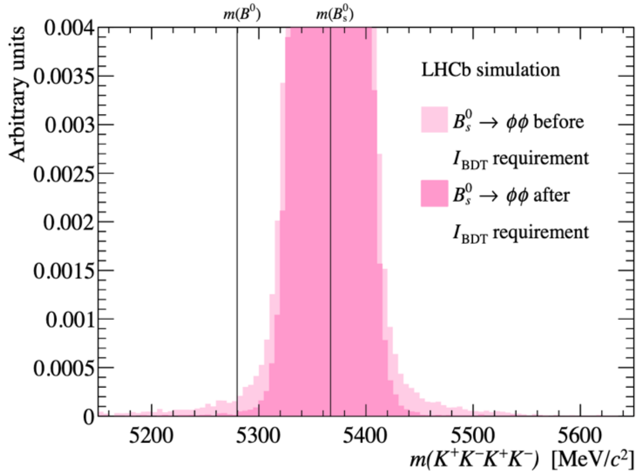


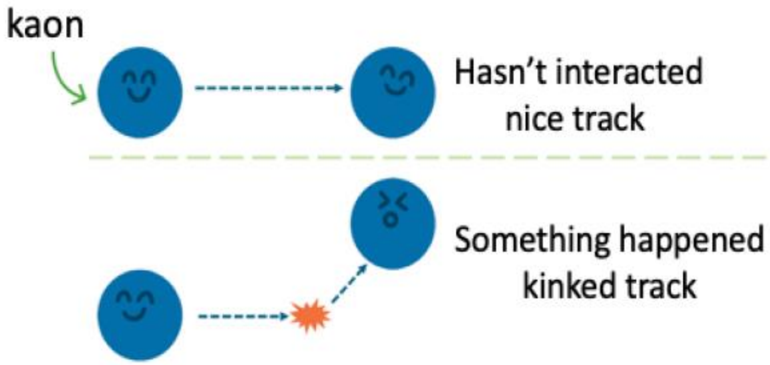


Search for $B^0 \to \phi\phi$

- $B^0 \to \phi\phi$ decay proceeds via a $b\bar{d} \to s\bar{s}$ annihilation process
  - ➢ At least one loop, Cabibbo suppressed, and Okubo–Zweig–Iizuka (OZI) suppressed
- Not observed yet $\mathcal{B}(B^0 \to \phi\phi) < 2.7\,(3.0) \times 10^{-8}$ at 90 % (95 %) CL, [JHEP12(2019)155]
- Low branching fraction compared to $\mathcal{B}(B_s^0 \to \phi\phi) = (1.84 \pm 0.14) \times 10^{-5}$
  - ➢ Important to control the tail of the B_s^0 mass
  - ➢ BDT classifier to suppress interacted kaons

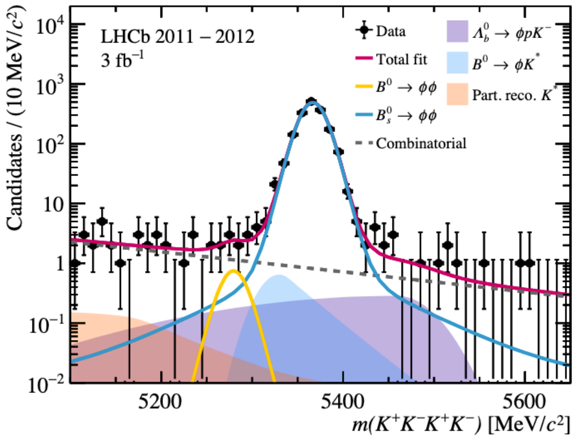


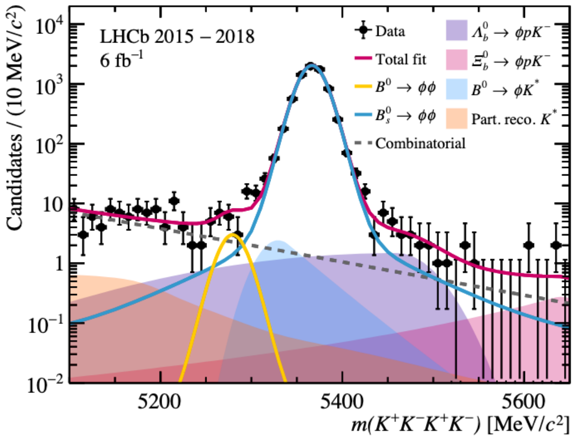




Search for $B^0 \to \phi\phi$

- Mass fits (run1 and run2):
  - ➢ Consistent with the background-only hypothesis (1.9σ)



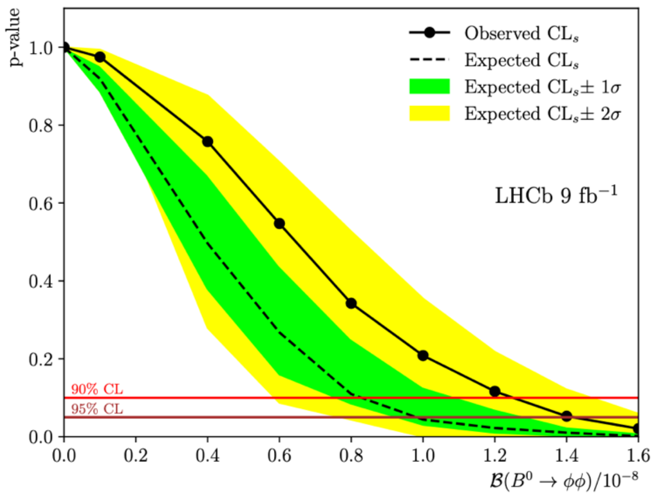


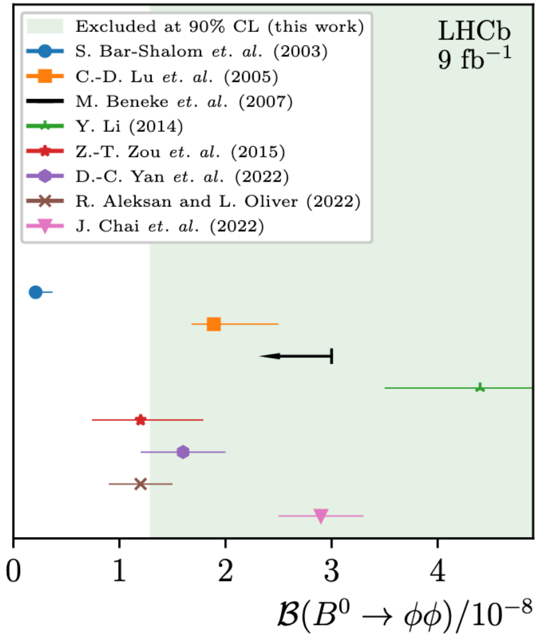
- Upper limit:

$$\mathcal{B}(B^0 \to \phi\phi) < 1.3\ (1.4) \times 10^{-8} \text{ at } 90\%\ (95\%) \text{ confidence level.}$$

  - ➢ Improve the previous LHCb limit by a factor of two

- Submitted to JHEP [arXiv:2507.20945]





Summary

- Recent results about charmless $B \rightarrow VV$ decays at LHCb
- $B^+ \rightarrow \rho(770)^0 K^*(892)^+$:
  - First observation of direct CP violation
  - Most precise measurement of f_L
- $B^0_{(s)} \rightarrow K^*(892)^0 \overline{K}^*(892)^0$
  - Vector-vector branching fractions measured
  - Tension on longitudinal polarization $L_{K^{*0}\overline{K}^{*0}}$
- $B^0_{(s)} \rightarrow \phi\phi$
  - Precise measurement of time-dependent *CP* violation in $B^0_s \rightarrow \phi\phi$
  - Upper limit of $B^0 \rightarrow \phi\phi$ improved
- Mamy more results are coming soon

Thank you!