CP violation at LHCb

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第二十二届全国重味物理和CP破坏研讨会

北京，西郊宾馆

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Outlines

- LHCb experiment makes significant progress in CP violation studies over the past year

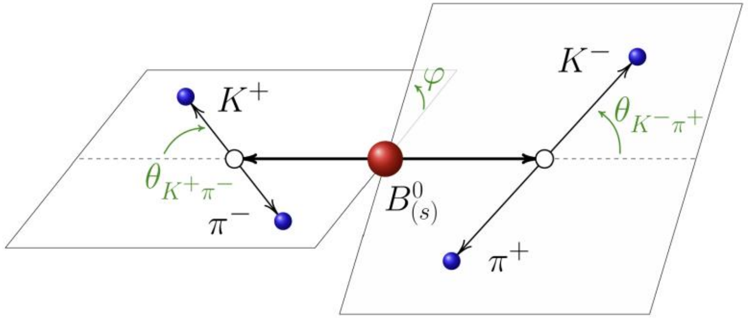
- Selected topics for today's presentation
  - **The Polarization puzzle in $B \to VV$ decays**
  - **CP violation in Baryon decays**

- CP violation in Charm decays (Talk by Prof. Liang Sun)
- CP violation in b-hadron to charmonium decays (Talk by Dr. XiaoFan Hu)

LHCb实验综述	孙亮	大会报告	10月25日
LHCb实验底强子到粲偶素衰变的CP破坏	胡晓凡	（一分会场）	10月25日

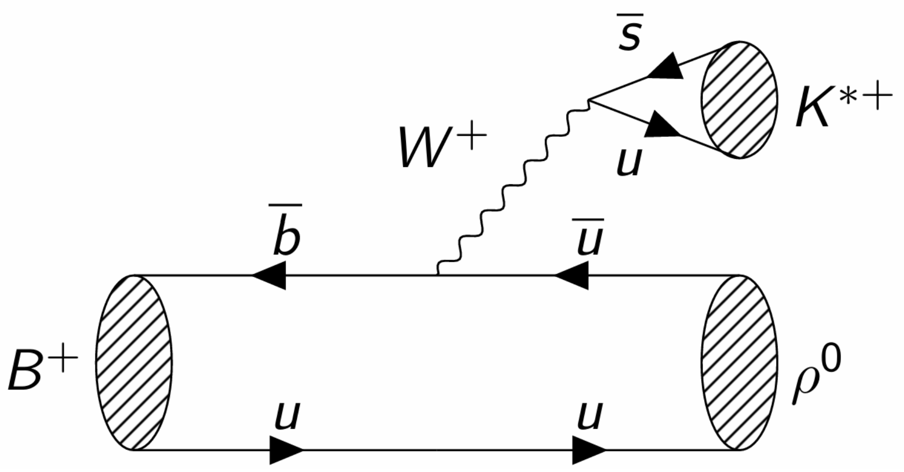
$B \to VV$ analyses: charmless

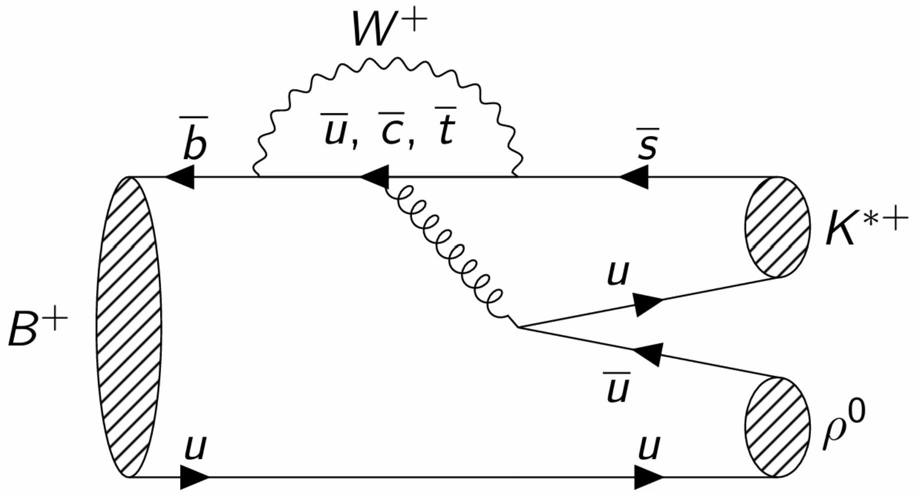
- B meson decays into two spin-1 vector (V) mesons provide a sensitive probe of CP-violation
  - Stringent tests of the SM through angular analyses and CP asymmetry measurements
- The Polarization Puzzle: A long-standing puzzle
  - Three helicity amplitudes: longitudinal (A_0), parallel ($A_\parallel$), and perpendicular ($A_\perp$)
  - Theoretical predictions: the longitudinal polarization $f_L \approx 1$
  - Experimental measurements: vary widely from 0.1 to 1



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

- First measurement from LHCb: observation and amplitude analysis from Babar
- Decay modes: $\rho(770)^0 \to \pi^+\pi^-, K^*(892)^+ \to K_S^0\pi^+$
- Full Run-1 + Run-2 LHCb datasets:
- Analysis approach: simultaneous fit to B^- and B^+ decays

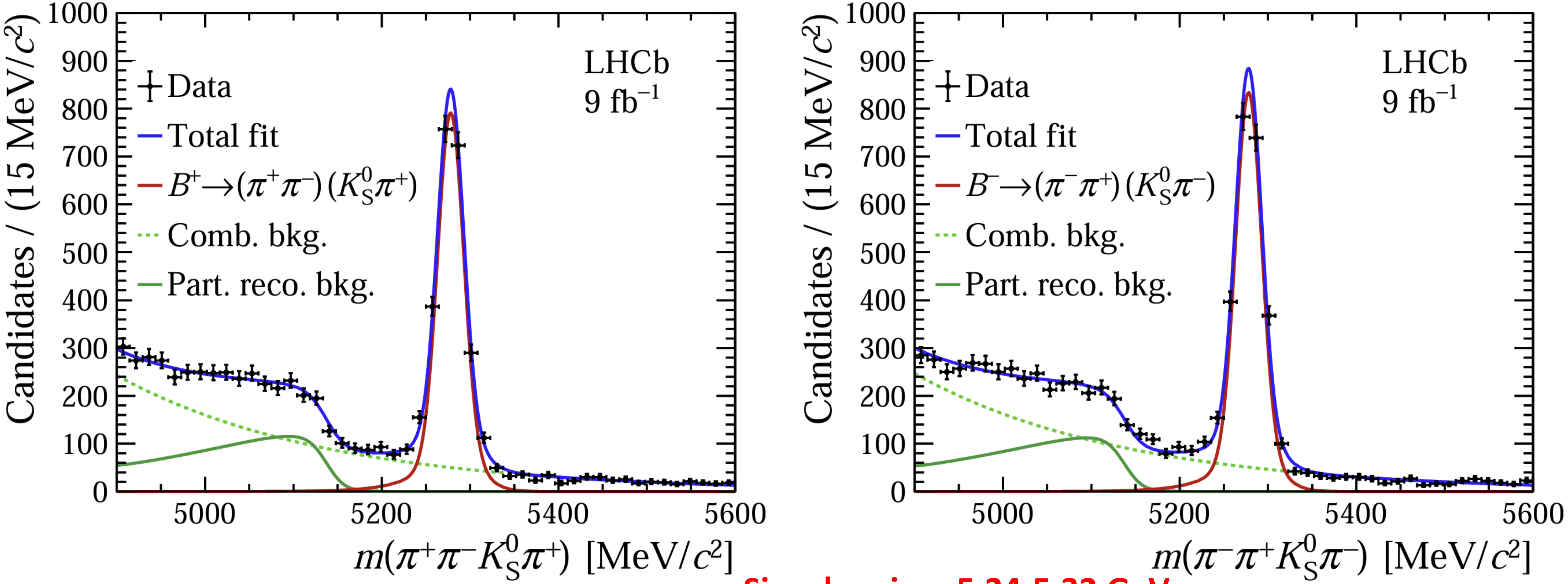




CP violation in $B^+ \to \rho(770)^0 K^*(892)^+$

Submitted to Phys. Rev. Lett.
arXiv: 2508.13563

$N(B^+) = 2208 \pm 53$ $\quad$ $N(B^-) = 2333 \pm 55$

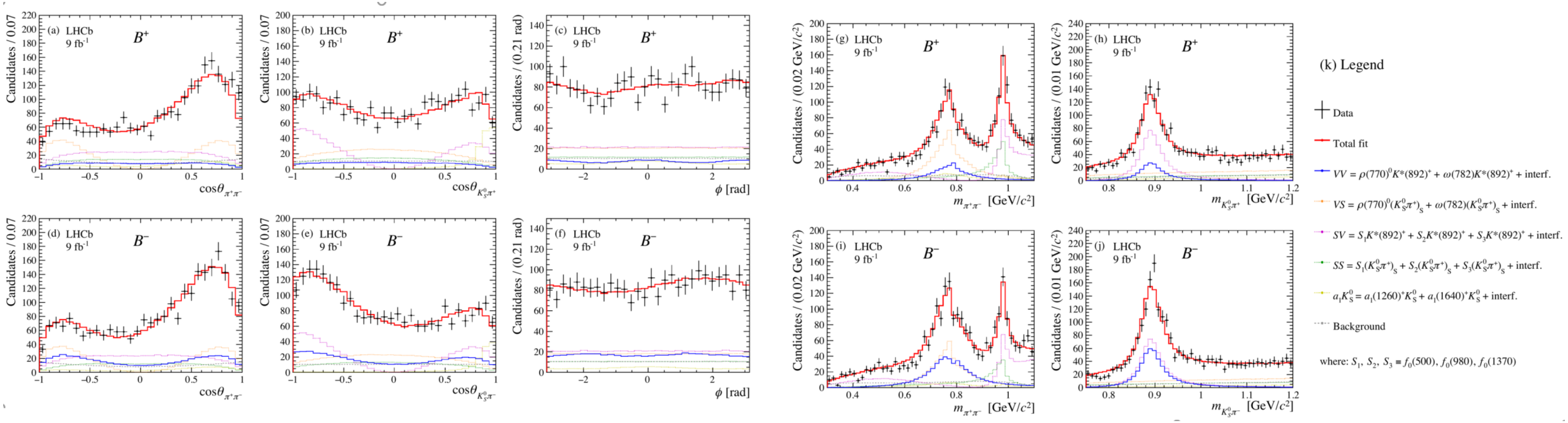


Signal region: 5.24-5.32 GeV

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

Submitted to Phys. Rev. Lett.
arXiv: 2508.13563

- 5-D amplitude analysis in the phase-space region:
  - $0.3 < m(\pi^+\pi^-) < 1.1\ GeV/c^2$
  - $0.75 < m(K_S^0\pi^-) < 1.2\ GeV/c^2$



CP violation in $B^+ \rightarrow \rho(770)^0 K^*(892)^+$

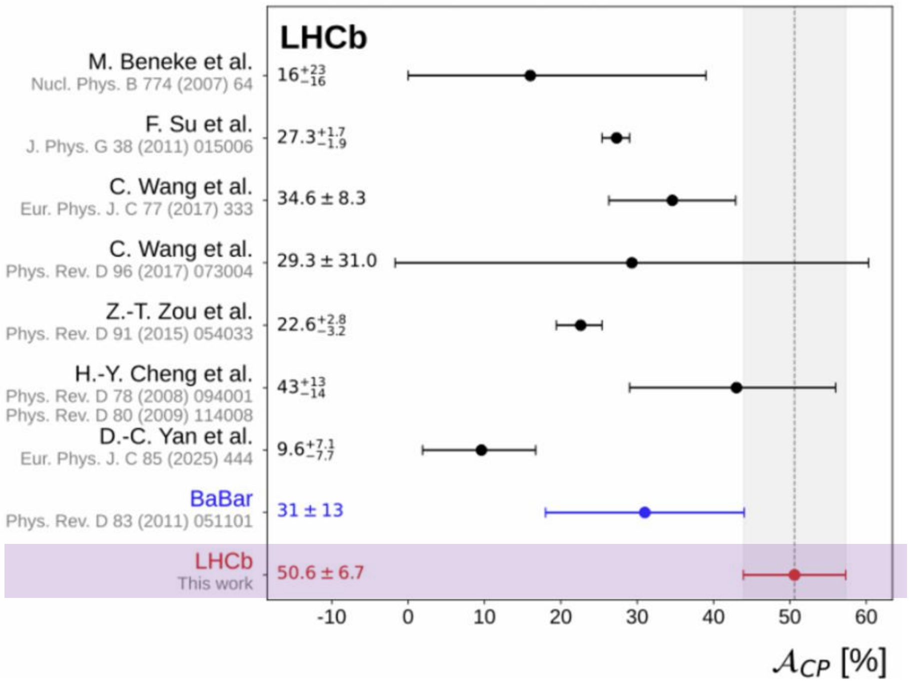
Submitted to Phys. Rev. Lett.
arXiv: 2508.13563

- CP-averaged longitudinal fraction
  - $f_L = 0.720 \pm 0.028\ (stat.) \pm 0.009\ (syst.)$
  - Input to understand the polarization puzzle

$$f_L = \frac{|A_0|^2 + |\bar{A}_0|^2}{\sum_\lambda \left(|\bar{A}_\lambda|^2 + |A_\lambda|^2\right)}$$

- Direct CP asymmetry:
  - $A_{CP} = 0.507 \pm 0.062\ (stat.) \pm 0.017\ (syst.)$
  - $\lambda \in (0, \parallel, \perp)$

$$A_{CP} = \frac{\sum_\lambda \left(|\bar{A}_\lambda|^2 - |A_\lambda|^2\right)}{\sum_\lambda \left(|\bar{A}_\lambda|^2 + |A_\lambda|^2\right)}$$

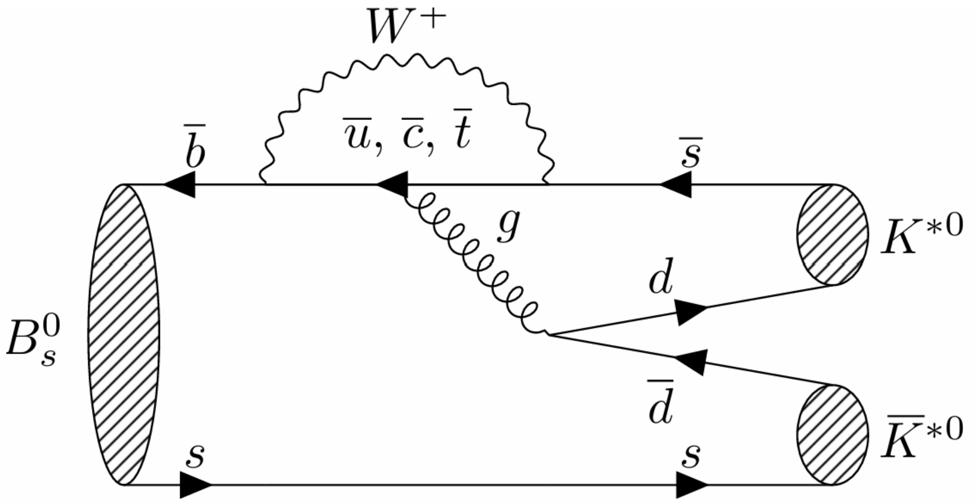


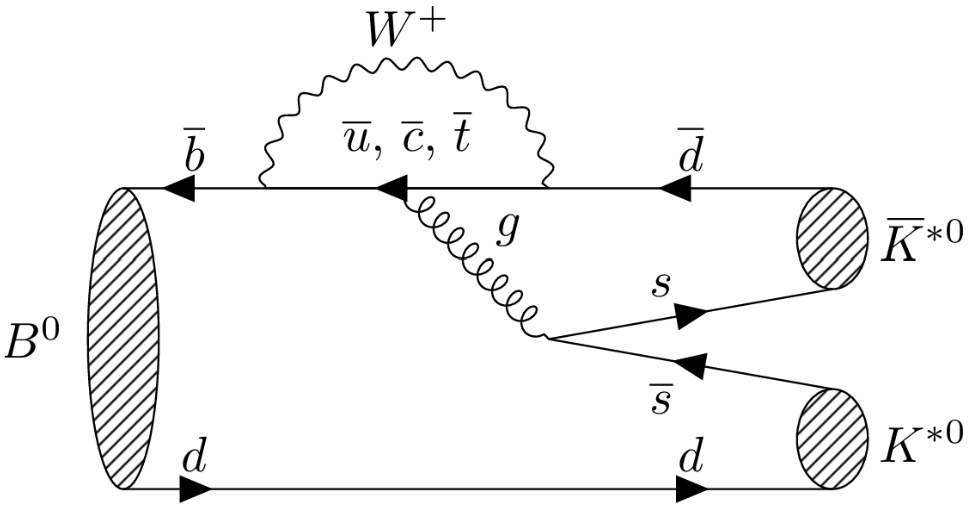
- First observation of CP violation in this decay
  - More than 9σ

$B^0_{(s)} \to K^{*0}\overline{K}^{*0}$ decay

- $B^0_s \to K^{*0}\overline{K}^{*0}$ and $B^0 \to K^{*0}\overline{K}^{*0}$ decays loop level at lowest order
- Closely related by U-spin symmetry: swap of $s \leftrightarrow d$
- A theory-motivated observable
  - $L = \mathcal{G}\frac{\mathcal{B}(B^0_s\to K^{*0}\overline{K}^{*0})f_L^s}{\mathcal{B}(B^0\to K^{*0}\overline{K}^{*0})f_L^d}$, where $\mathcal{G}$ is a lifetime and phase-space factors
  - $L^I = 18.34^{+7.47}_{-5.83}$, $L^{II} = 26.08^{+5.70}_{-4.72}$

arXiv: 2506.12478

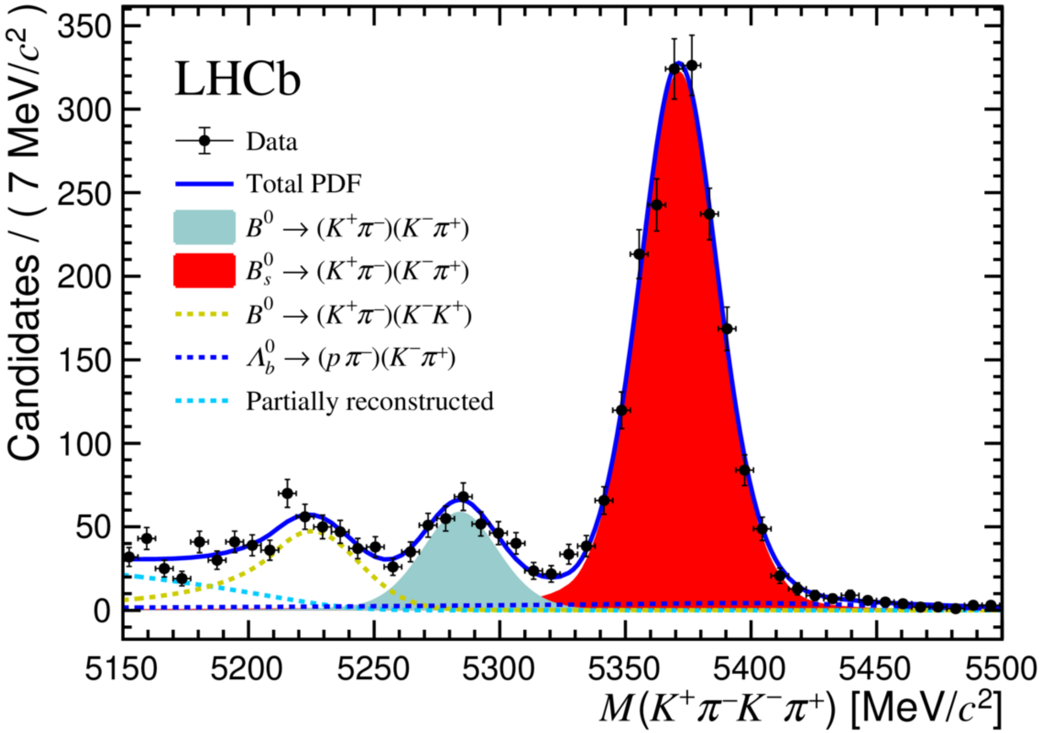




Previous $B^0_{(s)} \to K^{*0}\bar{K}^{*0}$ decay

LHCb-PAPER-2019-004
JHEP 07 (2019) 032

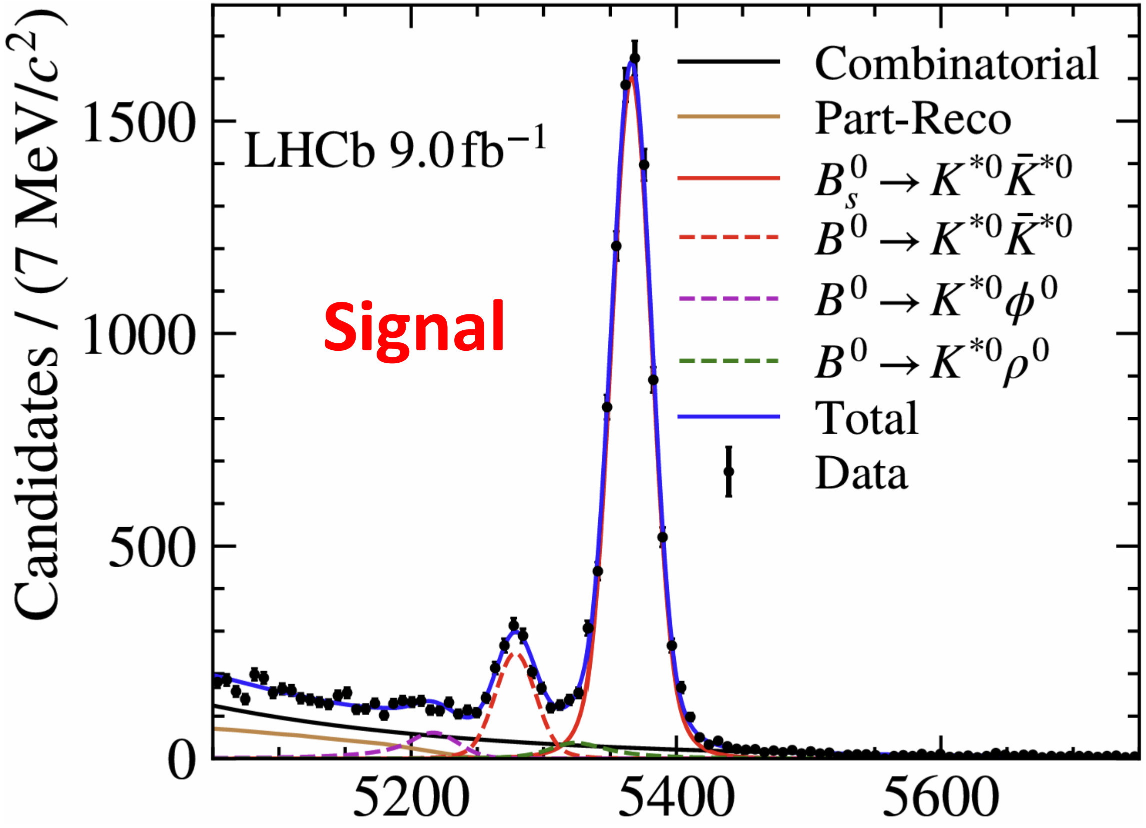
- Using LHCb Run-1 data-set
- Polarization puzzle:
  - $f_L^s = 0.240 \pm 0.040$
  - $f_L^d = 0.724 \pm 0.053$
- Experimental value of L
  - $L = 4.43 \pm 0.92$
  - Tension of $2.3 - 4.4\sigma$ depending on form factor treatment



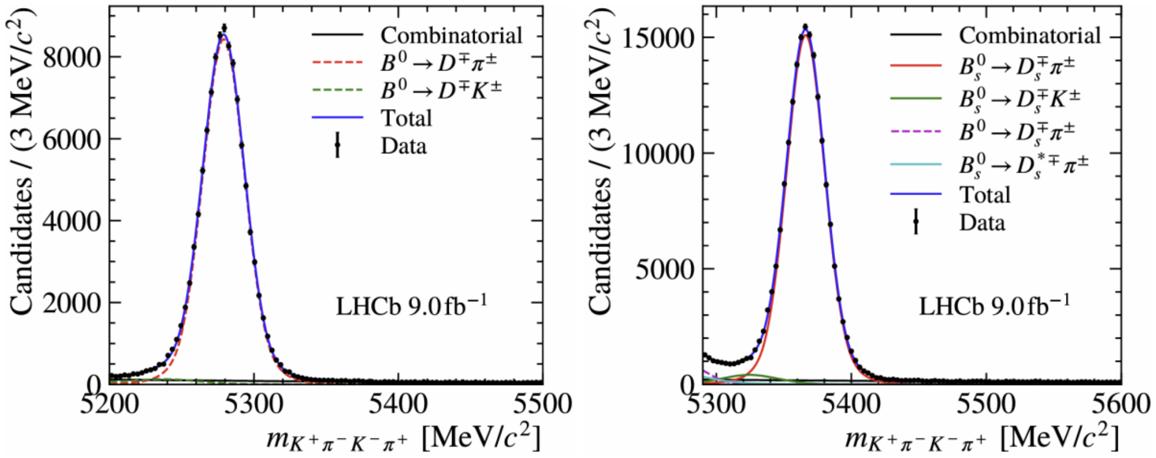
$B^0_{(s)} \to K^{*0}\overline{K}^{*0}$ decay

LHCb-Paper-2025-046, in preparation
To be submitted to PRD

- Normalization channels: $B_s^0 \to D_s^-\pi^+$, $B^0 \to D^-\pi^+$



	Signal	Normalization
B^0	1424 ± 59	105666 ± 348
B_s^0	9190 ± 114	180807 ± 483

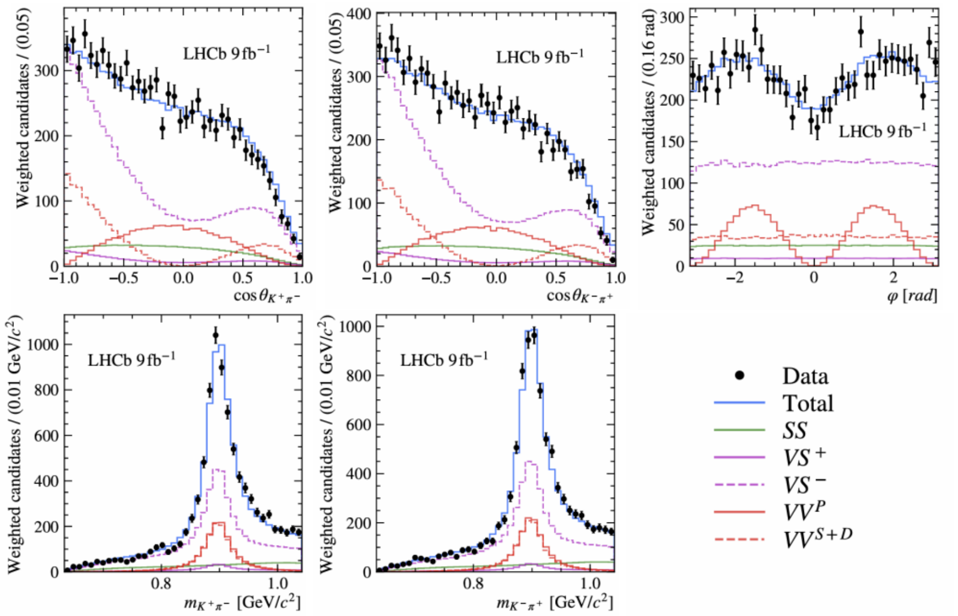


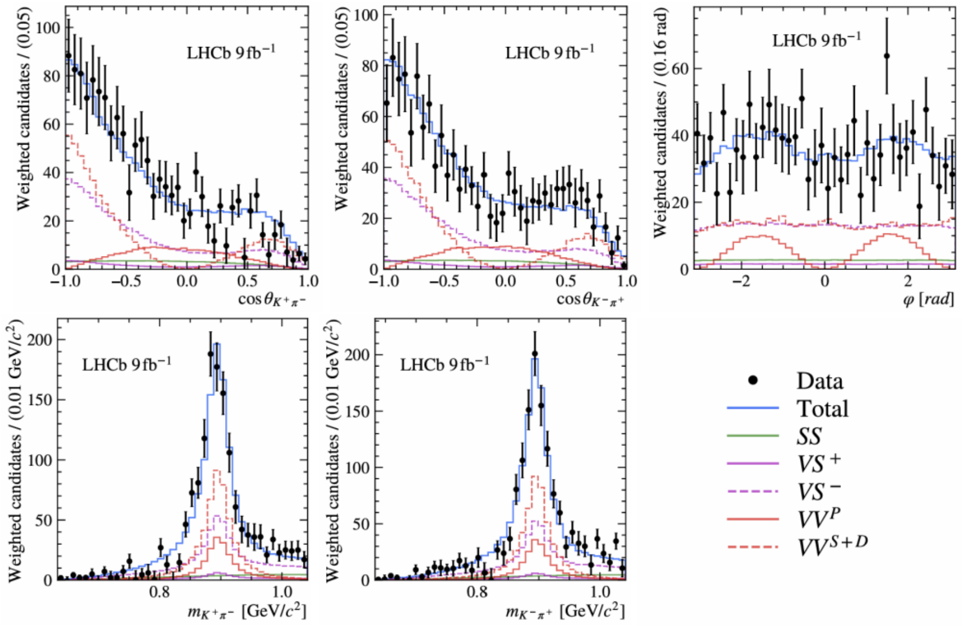
Normalization

Angular analysis

LHCb-Paper-2025-046, in preparation
To be submitted to PRD

- Consider scalar (S) and vector (V) contributions for each ($K\pi$)
- Fit down to $K\pi$ production threshold, use S-wave parameterization from dispersive scattering relations rather than LASS





$B^0_{(s)} \to K^{*0}\overline{K}^{*0}$ results

LHCb-Paper-2025-046,
in preparation
To be submitted to PRD

- Polarization puzzle:
  - $f_L^s = (14.6 \pm 0.9 \pm 2.5)\%$
  - $f_L^d = (61 \pm 2 \pm 4)\%$
- Branching fraction:

$$\mathcal{B}(B_s^0 \to K^{*0}\overline{K}^{*0}) = (0.943 \pm 0.030\,(\text{stat}) \pm 0.020\,(\text{syst}) \pm 0.037\,(\text{ext})) \times 10^{-5},$$

$$\mathcal{B}(B^0 \to K^{*0}\overline{K}^{*0}) = (4.70 \pm 0.30\,(\text{stat}) \pm 0.53\,(\text{syst}) \pm 0.16\,(\text{ext})) \times 10^{-7},$$

$$\frac{\mathcal{B}(B^0 \to K^{*0}\overline{K}^{*0})}{\mathcal{B}(B_s^0 \to K^{*0}\overline{K}^{*0})} = 0.054 \pm 0.004\,(\text{stat}) \pm 0.008\,(\text{syst}) \pm 0.002\,(f_s/f_d),$$

- $L = 4.45 \pm 0.45(stat) \pm 0.57(syst) \pm 0.02(ext) \pm 0.09(f_s/f_d)$
  - Still at $2.3 - 4.4\ \sigma$ from the SM prediction

Baryon CP violation

- CP violation well established in meson decays
  - b quark particular promising: heavy and long lived
- Only direct CP violation measurements in baryon decays
  - No oscillation or interference
- Lack of clear theoretical predictions
  - Non-perturbative QCD contributions

$\Lambda_b^0 \to ph^-$: PRD 111 (2025) 092004
$\Lambda_b^0(\Xi_b^0) \to \Lambda h^+ h^-$: PRL 134 (2025)101802
$\Lambda_b^0 \to pK^-\pi^+\pi^-$: Nature 643 (2025) 1223
$\Lambda_b^0(\Xi_b^0) \to pK_S^0 h^-$: LHCb-PAPER-2025-016
$\Lambda_b^0(\Xi_b^0) \to J/\psi\, ph^-$: LHCb-PAPER-2025-016

General strategy

- CP violation observable A_{CP} not directly accessible

$$A_{CP}(\Lambda_b^0 \to f) = \frac{\Gamma(\Lambda_b^0 \to f) - \Gamma(\overline{\Lambda}_b^0 \to \bar{f})}{\Gamma(\Lambda_b^0 \to f) + \Gamma(\overline{\Lambda}_b^0 \to \bar{f})}$$

- A_{CP} can be related to the observable counting in the detector accounting for experimental asymmetry effects (A_i)

$$A_{raw}(\Lambda_b^0 \to f) = \frac{\mathrm{N}(\Lambda_b^0 \to f) - \mathrm{N}(\overline{\Lambda}_b^0 \to \bar{f})}{\mathrm{N}(\Lambda_b^0 \to f) + \mathrm{N}(\overline{\Lambda}_b^0 \to \bar{f})} \cong A_{CP} + \sum_i A_i$$

- **Production asymmetry**
- **Final state f detection asymmetry**
- **Trigger asymmetry**
- **Particle-ID asymmetry**

- **Control channel:**
  - **Partial cancellation of experimental effects**
  - **The control channel usually negligible wrt to final measurement precision (Cabibbo-favoured decays, intermediate charmed state)**

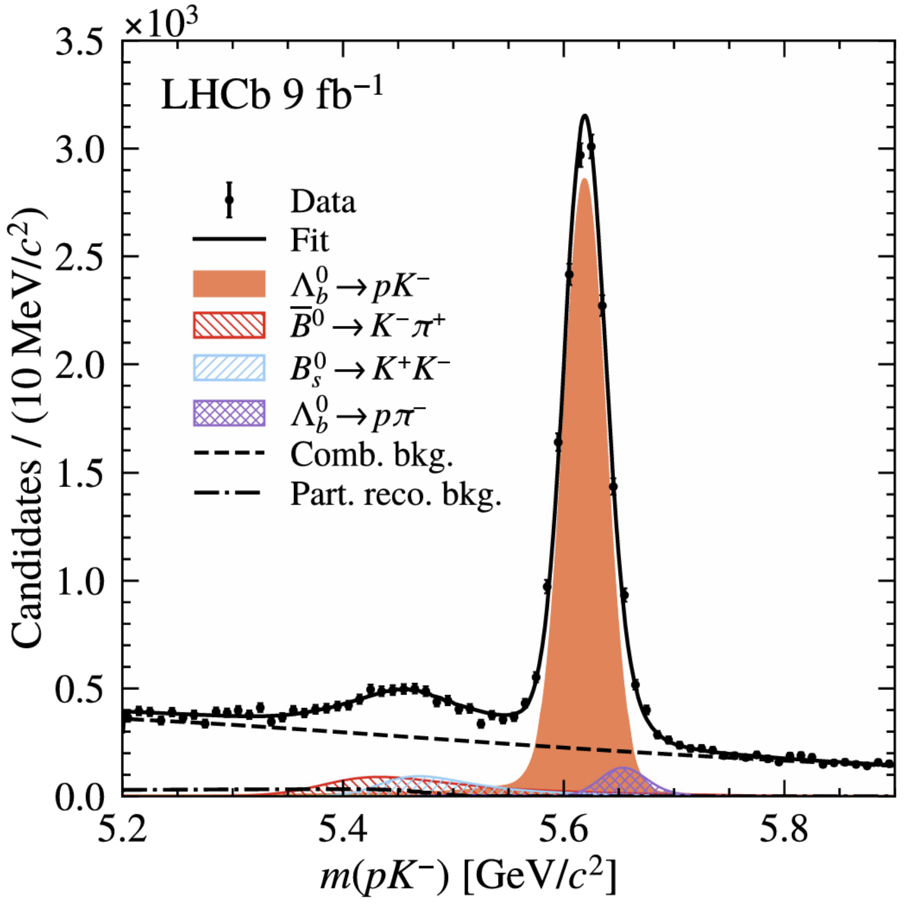
PRD 111 (2025) 092004

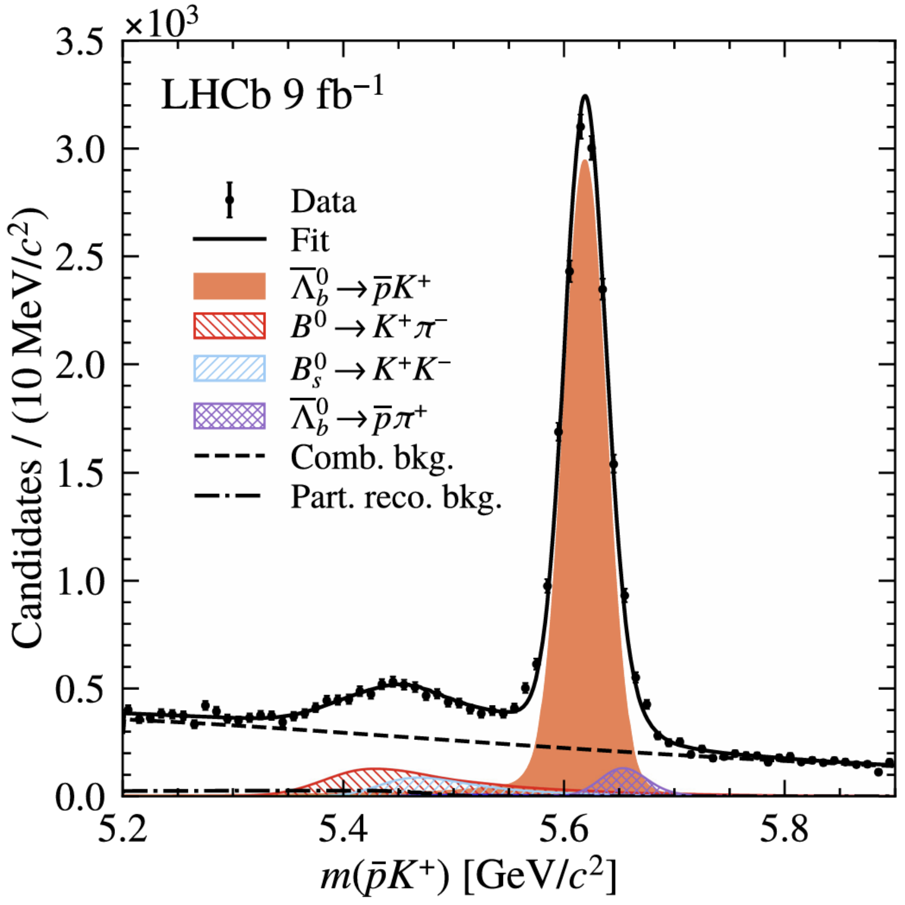
$\Lambda_b^0 \to ph^-$ decay

$A_{CP}^{pK^-} = (-1.1 \pm 0.7 \pm 0.4)\%$

- Similar diagrams to $B^0 \to K^+\pi^-$

No evidence of CP violation
Global averages improved by factor 3





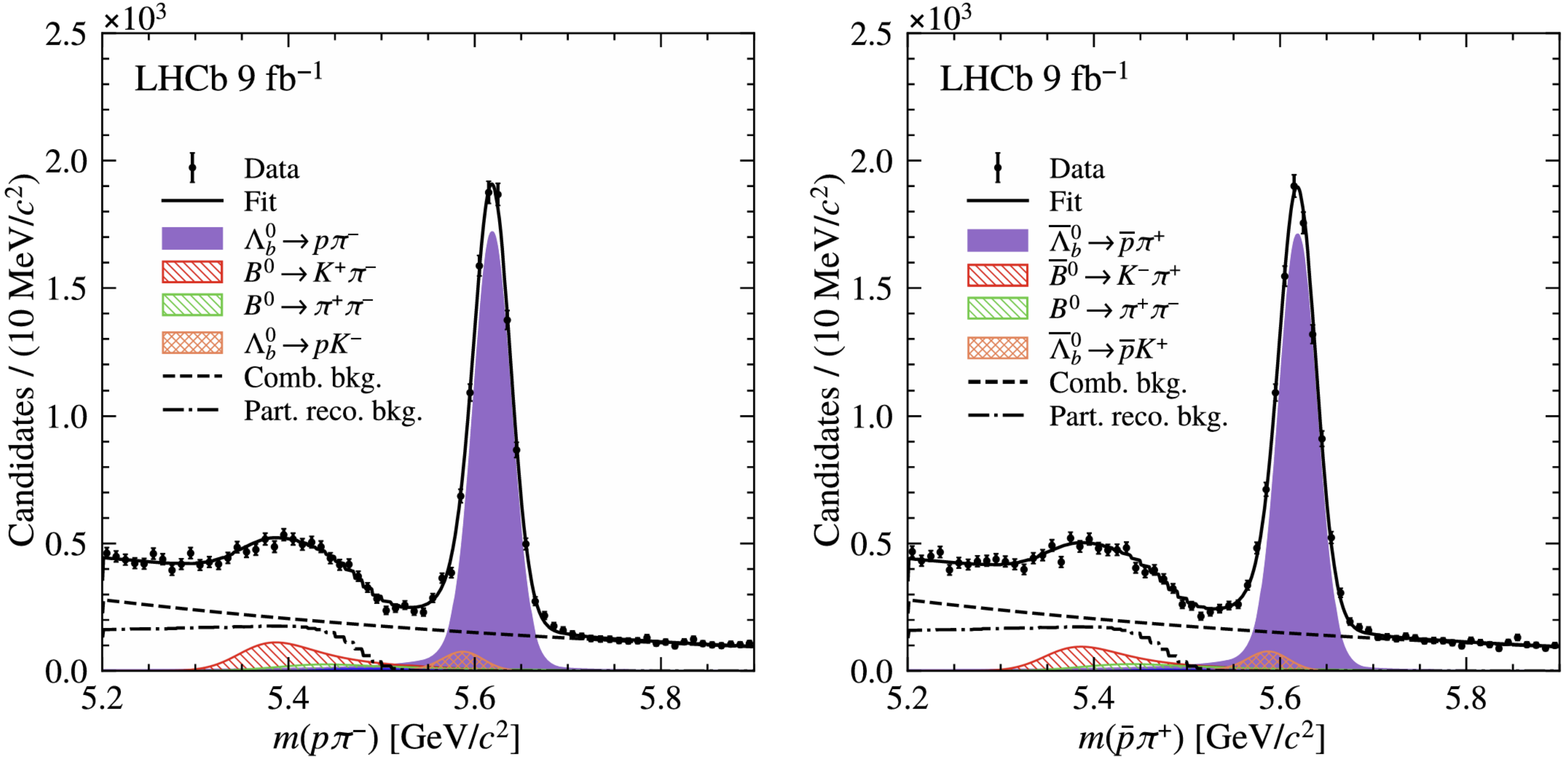
PRD 111 (2025) 092004

$\Lambda_b^0 \to ph^-$ decay

$$A_{CP}^{p\pi^-} = (0.2 \pm 0.8 \pm 0.4)\%$$

- Similar diagrams to $B^0 \to K^+\pi^-$

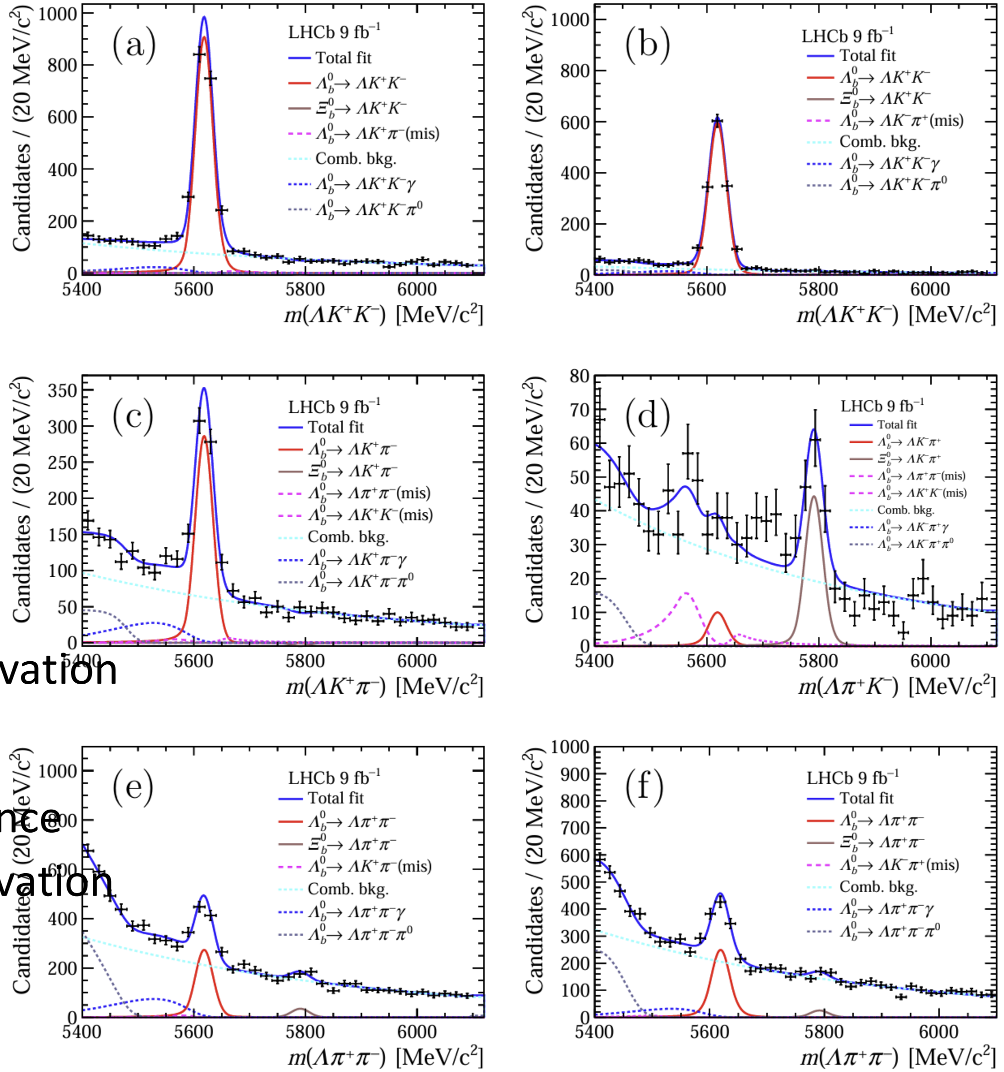
No evidence of CP violation
Global averages improved by factor 3



$\Lambda_b^0(\Xi_b^0) \to \Lambda h^+ h^-$ decay

PRL 134 (2025)101802

- CP violation enhancement in $\pi\pi \to KK$ re-scattering regions of $B^\pm \to h^\pm h'^+ h''^-$
- Light resonances contribution
- $\Lambda_b^0 \to (\Lambda_c^+\pi^+)\pi^-$ as control sample
  - Cabibbo favored



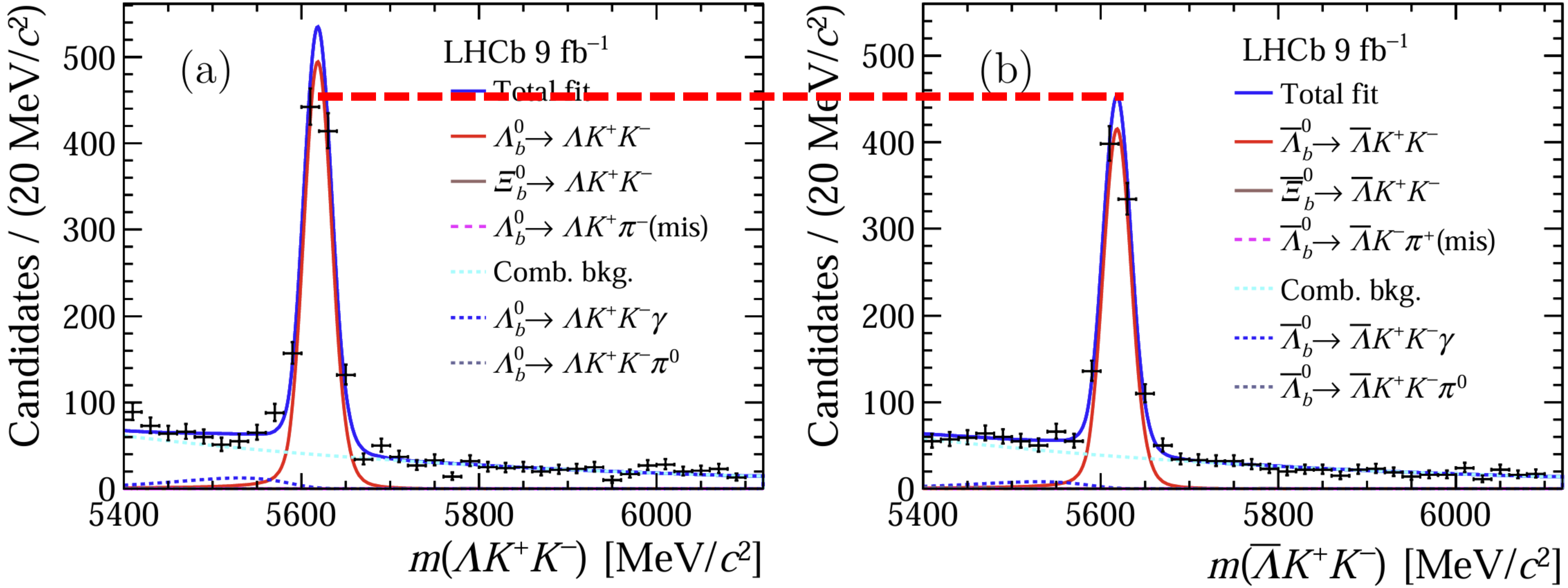
Decay	Yield	$\mathcal{B}$ $(\times 10^{-6})$	
$\Lambda_b^0 \to \Lambda\pi^+\pi^-$	$(6.4 \pm 0.4) \times 10^2$	$5.3 \pm 0.4 \pm 0.5 \pm 0.5$	First observation
$\Lambda_b^0 \to \Lambda K^+\pi^-$	$(6.18 \pm 0.32) \times 10^2$	$4.6 \pm 0.2 \pm 0.4 \pm 0.5$	
$\Lambda_b^0 \to \Lambda K^+K^-$	$(1.92 \pm 0.05) \times 10^3$	$10.7 \pm 0.3 \pm 0.4 \pm 1.1$	
$\Xi_b^0 \to \Lambda\pi^+\pi^-$	$(5.6 \pm 2.7) \times 10^1$	$11.0 \pm 2.6 \pm 1.4 \pm 3.8$	First evidence
$\Xi_b^0 \to \Lambda K^-\pi^+$	$(1.19 \pm 0.15) \times 10^2$	$10.4 \pm 1.4 \pm 1.2 \pm 3.5$	First observation
$\Xi_b^0 \to \Lambda K^+K^-$	$(1.2 \pm 0.9) \times 10^1$	< 2.4 (2.8) at 90% (95%) CL	
$\Lambda_b^0 \to \Lambda_c^+(\to \Lambda\pi^+)\pi^-$	$(5.25 \pm 0.07) \times 10^3$	—	

First CP violation evidence

PRL 134 (2025)101802

$$\Delta\mathcal{A}^{CP}\left(\Lambda_b^0 \to \Lambda\pi^+\pi^-\right) = -0.013 \pm 0.053 \pm 0.018,$$
$$\Delta\mathcal{A}^{CP}\left(\Lambda_b^0 \to \Lambda K^+\pi^-\right) = -0.118 \pm 0.045 \pm 0.021,$$
$$\Delta\mathcal{A}^{CP}\left(\Lambda_b^0 \to \Lambda K^+K^-\right) = 0.083 \pm 0.023 \pm 0.016,$$
$$\Delta\mathcal{A}^{CP}\left(\Xi_b^0 \to \Lambda K^-\pi^+\right) = 0.27 \pm 0.12 \pm 0.05,$$

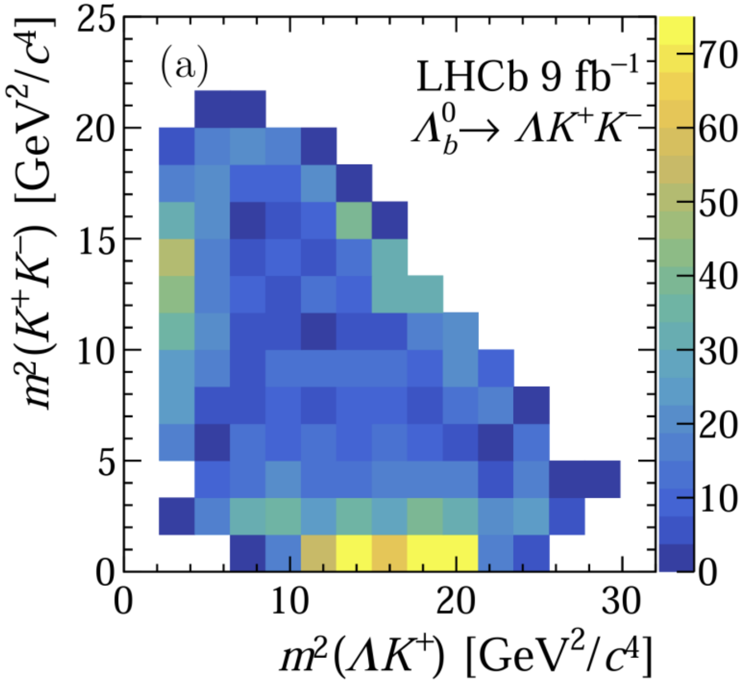
3.1σ

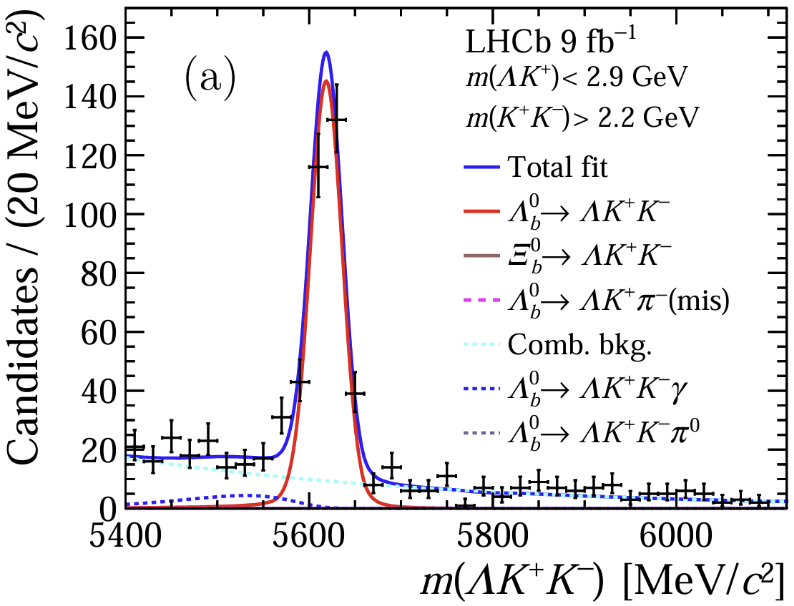


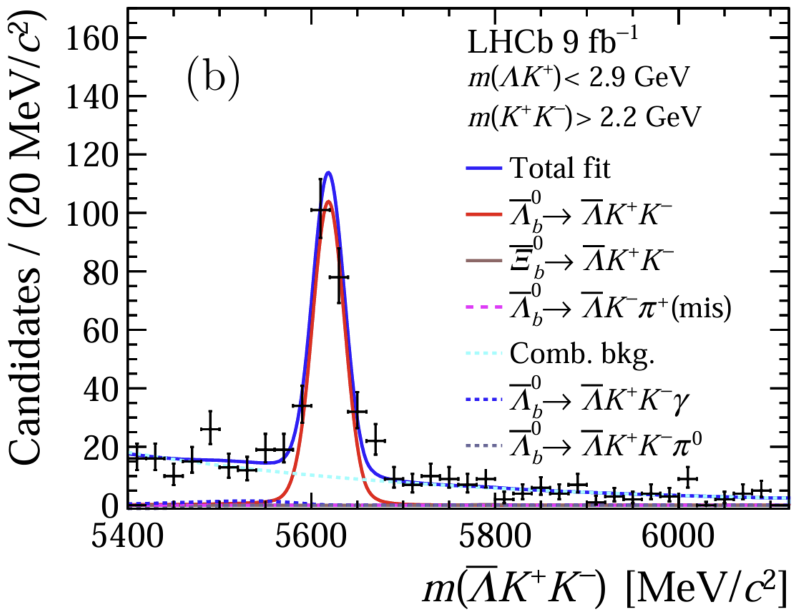
$\Lambda_b^0 \to \Lambda K^+ K^-$

PRL 134 (2025)101802

- Structures in the $N^{*+} \to \Lambda K^+$ and $\phi \to K^+ K^-$ regions
- Enhancement of the asymmetry in the N^{*+} region ($m_{KK} > 2.2, m_{\Lambda K^+} < 2.9\ GeV/c^2$)
  - $\Delta A_{CP} = 0.165 \pm 0.048 \pm 0.017$: 3.2$\sigma$





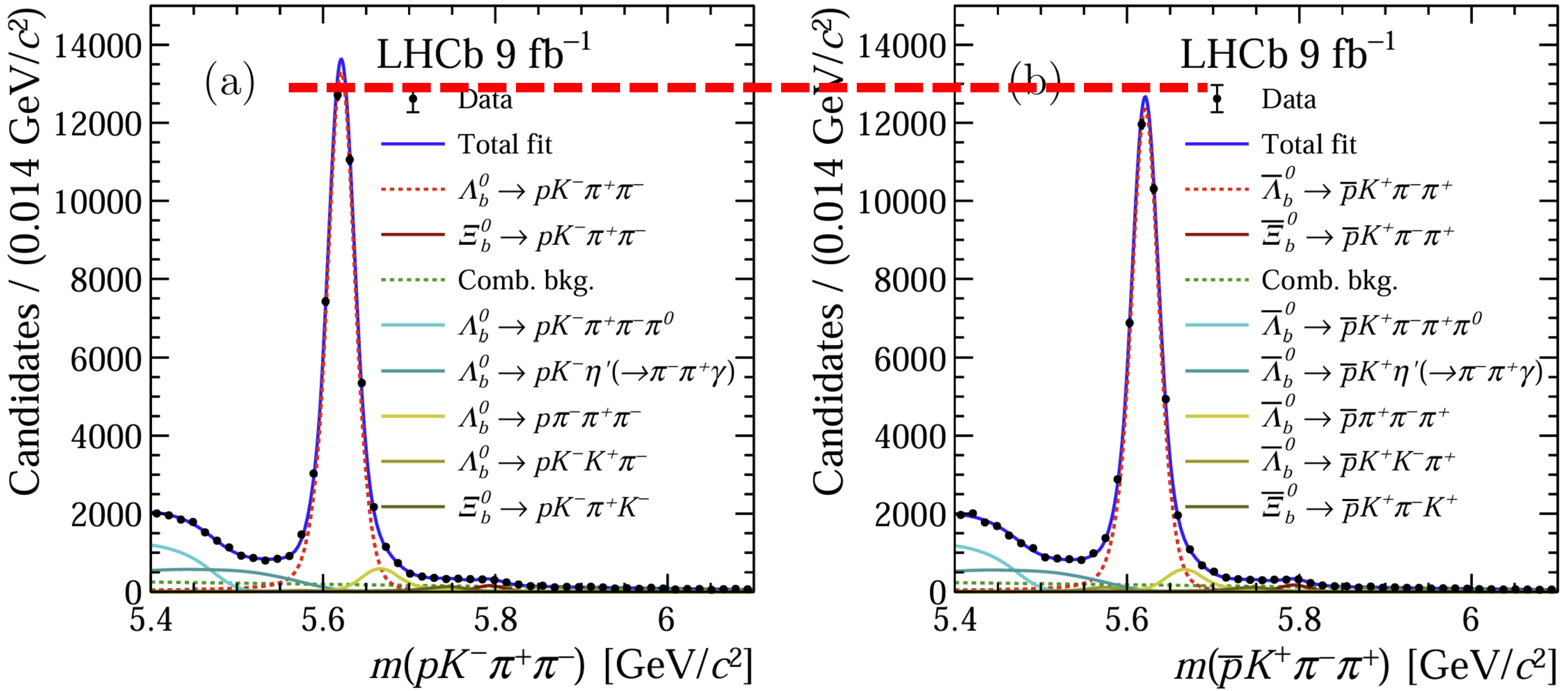


CP violation in $\Lambda_b^0 \to pK^-\pi^+\pi^-$ decay

Nature 643 (2025) 1223

- First observation (5.2σ) of CPV in baryon decays

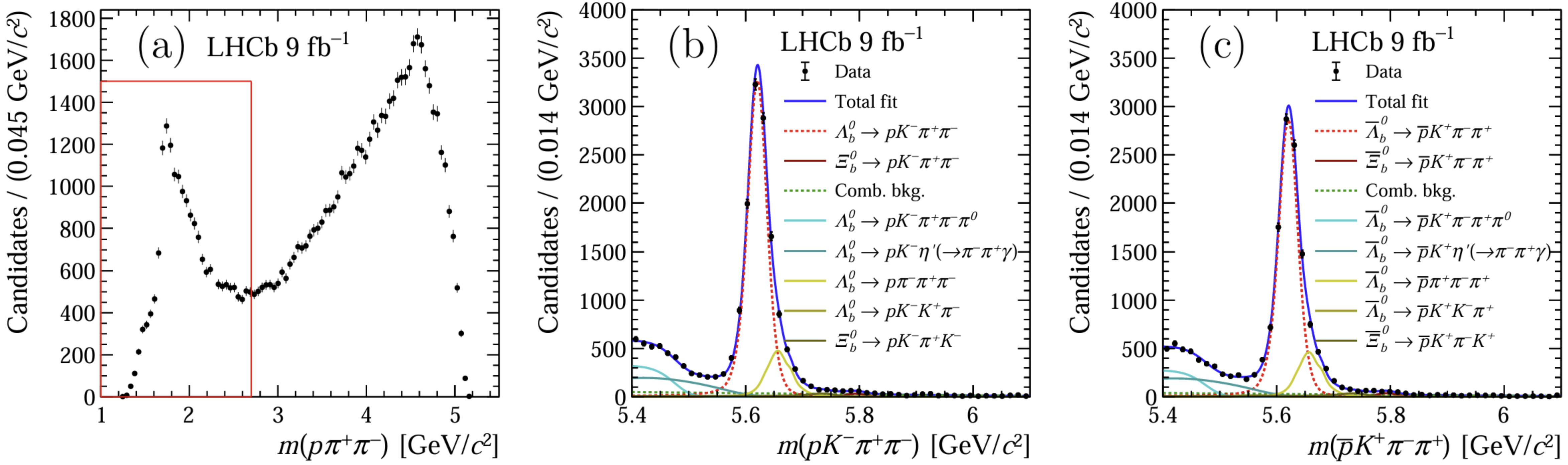
$$A_{CP} = (2.45 \pm 0.46 \pm 0.10)\%$$



CP violation in $\Lambda_b^0 \to pK^-\pi^+\pi^-$ decay

Nature 643 (2025) 1223

- Check different kinematic regions
  - Enhancements are observed: $A_{CP} = (5.4 \pm 0.9 \pm 0.1)\%,\ 6.0\sigma$



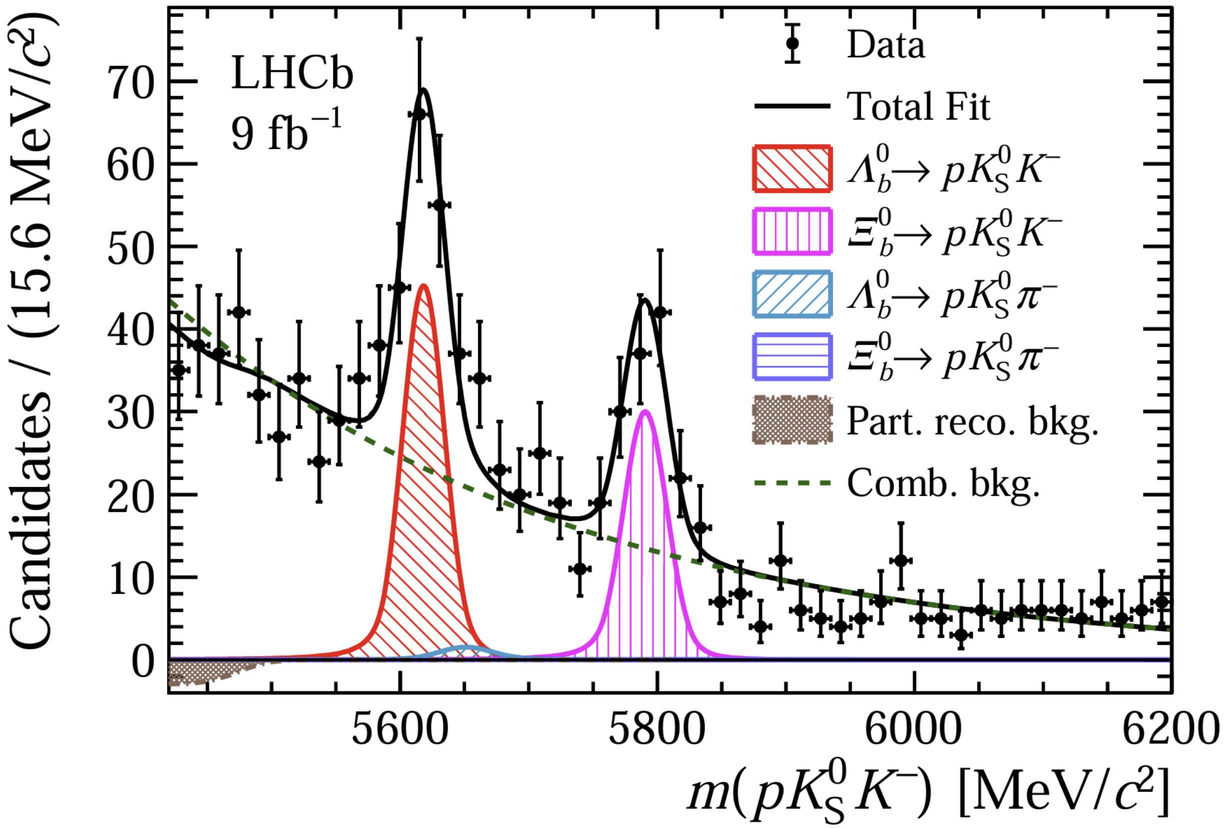
$\Lambda_b^0(\Xi_b^0) \to pK_S^0 h^-$ decay

LHCb-PAPER-2025-016

- Improvement on 2011 measurement:
  - Statistics uncertainty improved by factor of 9 for $\Lambda_b^0 \to pK_S^0\pi^-$
- $\Lambda_b^0 \to (\Lambda_c^+ \to pK_S^0)\pi^-$ as control channel

	Result $[\times 10^{-6}]$
$\mathcal{B}(\Lambda_b^0 \to pK_S^0\pi^-)$	$10.62 \pm 0.21 \pm 0.16 \pm 0.98$
$\mathcal{B}(\Lambda_b^0 \to pK_S^0K^-)$	$0.61 \pm 0.08 \pm 0.06 \pm 0.06$
$\mathcal{B}(\Xi_b^0 \to pK_S^0\pi^-)$	$< 2.8\,(3.2)$ at $90\,(95)\%$ CL
$\mathcal{B}(\Xi_b^0 \to pK_S^0K^-)$	$3.9 \pm 0.6 \pm 0.5 \pm 0.4 \pm 1.4$

First observation

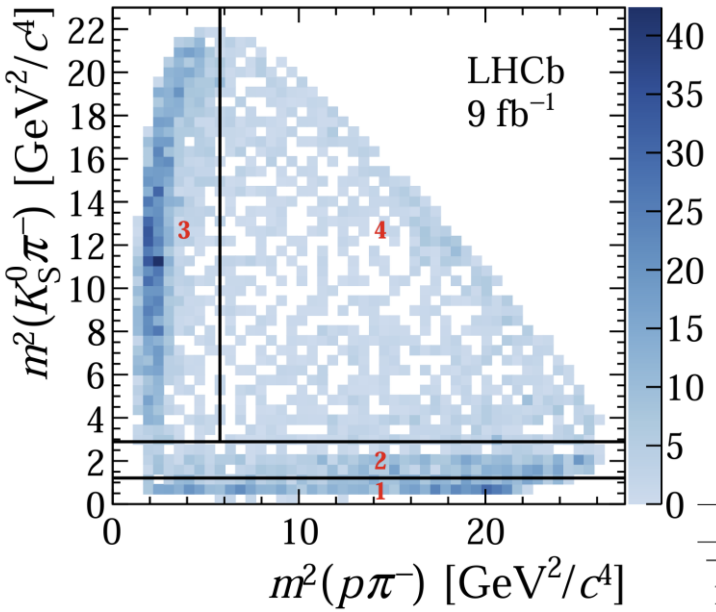


$\Lambda_b^0(\Xi_b^0) \to pK_S^0 h^-$ decay

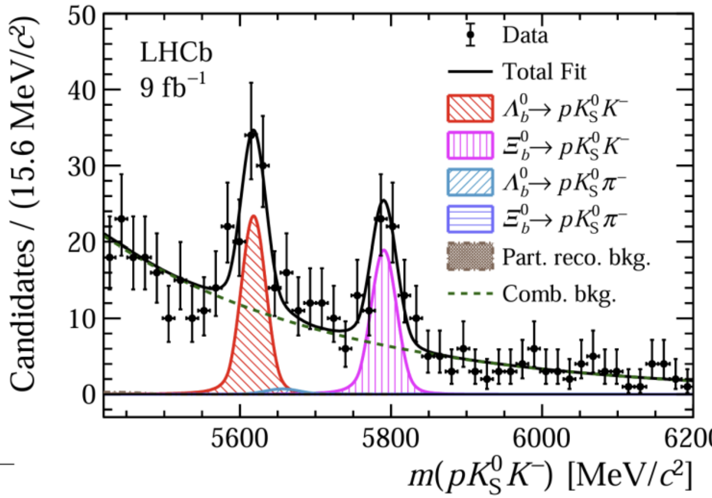
LHCb-PAPER-2025-016

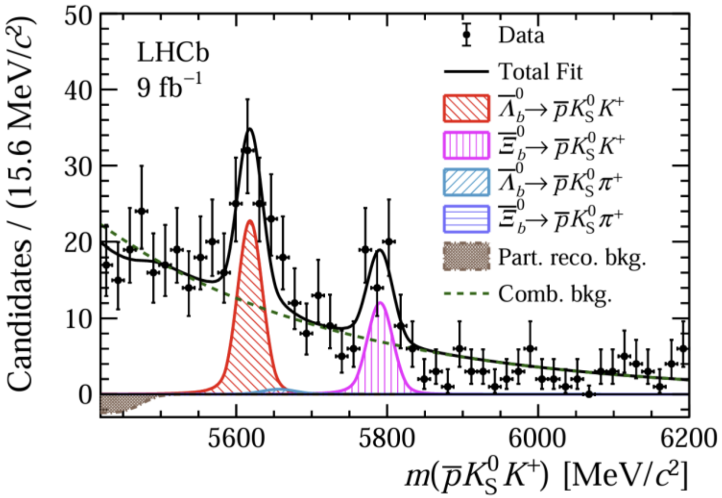
- Search parameter space for possible local CP violation
- No hints of CP violation
- Enough statistics to explore different $\Lambda_b^0 \to pK_S^0\pi^-$ kinematic bins

	Result [%]
$\mathcal{A}^{CP}$ $(\Lambda_b^0 \to pK_S^0\pi^-)$	$3.4 \pm 1.9 \pm 0.9$
$\mathcal{A}^{CP}$ $(\Lambda_b^0 \to pK_S^0K^-)$	$2 \pm 13 \pm 9$
$\mathcal{A}^{CP}$ $(\Xi_b^0 \to pK_S^0K^-)$	$22 \pm 15 \pm 11$



$\mathcal{A}^{CP}$ [%]
$-0.6 \pm 4.0 \pm 1.9$
$12.4 \pm 4.2 \pm 1.8$
$0.5 \pm 2.4 \pm 1.1$
$3.3 \pm 5.5 \pm 2.0$





Summary

- LHCb has made significant progress in CP violation in B hadron decays

- The Polarization puzzle:
  - Ongoing investigations in charmless $B \to VV$ decays continue to challenge theoretical understanding
- CP violation in b-baryon decays:
  - An emerging and promising frontier for probing CP violation
  - Offers complementary insights to B-meson channels and sensitivity to new physics

- Several new analyses based on the full Run 1 + Run 2 dataset are forthcoming
- Exciting prospects for LHCb Run-3 analyses

Backup

Results since HFCPV-2024:

CPV in $\Lambda_b^0(\Xi_b^0) \to pK_S^0h^-$: 2508.17836, submitted to PRL

CPV in $B^+ \to \rho(770)^0K^*(892)^+$: 2508.16259, submitted to PRL

Observation of Baryon CPV: Nature 643 (2025) 1223

CPV in $\Lambda_b^0 \to ph^-$: PRD 111 (2025) 092004

CPV in $\Lambda_b^0 \to \Lambda K^+K^-$: PRL 134 (2025) 101802

CPV in $\Lambda_b^0 \to J/\psi\, p\pi^-$: 2509.16103, submitted to Science Bullets

CPV in $B_s^0 \to J/\psi\, K^{*0}(892)$: JHEP 10 (2025) 173

CPV in $B_s^0 \to J/\psi\, K^+$: PRL 134 (2025) 101801

CPV in $B^+ \to K_S^0h^+$: LHCb-PAPER-2025-049, to be submitted to PRL

CPV in $B_{(s)}^0 \to K^{*0}\overline{K}^{*0}$: LHCb-PAPRE-2025-046, to be submitted to PRD

....

$\Lambda_b^0 \to ph^-$ decay

	Run 1		Run 2	
	$\Lambda_b^0 \to pK^-$	$\Lambda_b^0 \to p\pi^-$	$\Lambda_b^0 \to pK^-$	$\Lambda_b^0 \to p\pi^-$
Fit model	0.1	0.2	0.1	0.2
Particle identification	0.3	0.3	0.2	0.2
TIS trigger	0.1	0.1	<0.1	<0.1
TOS hardware trigger	0.2	0.2	0.1	0.1
TOS software trigger	0.3	0.3	0.2	0.2
Proton detection	0.1	0.1	<0.1	<0.1
Kaon detection	0.3	...	0.1	<0.1
Pion detection	...	0.10	<0.1	<0.1
Λ_b^0 production	0.1	0.1	...	...
$\Lambda_b^0 \to \Lambda_c^+\pi^-$ sample size	...	...	0.3	0.3
Total systematic	0.6	0.5	0.4	0.4
Statistical	1.5	1.9	0.7	0.9