CP violation in *b*-hadron decays at LHCb

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on behalf of the LHCb collaboration

Rencontres du Vietnam, Quy Nhon, 18th August 2025

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LHCb

Outline

- Introduction
  - CP violation in b-hadron decays
  - The LHCb experiment
- B decays to open charm
  - $B^0 \to D^+D^-$ and $B_s^0 \to D_s^+D_s^-$
  - Model-independent measurement of γ
- Charmless $B \to VV$ decays
  - $B_{(s)}^0 \to \phi\phi$
  - $B^+ \to \rho K^{*+}$
- CP violation in b-baryon decays
  - $\Lambda_b^0 \to pK^-\pi^+\pi^-$
  - $\Lambda_b^0(\Xi_b^0) \to pK_S^0h^-$

Interested in decays to charmonium? See Yinghua's talk!

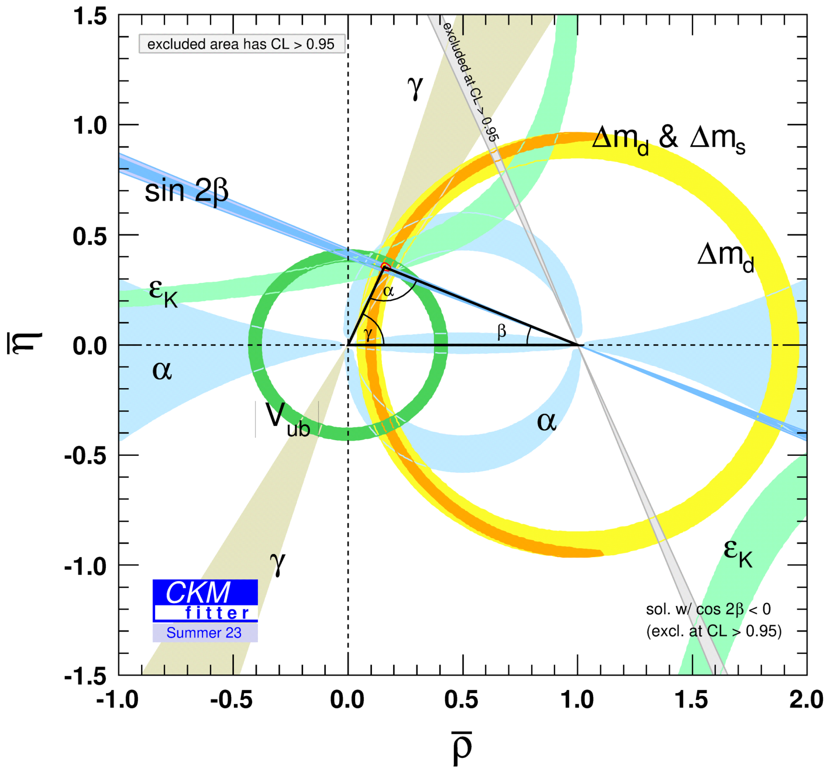
CP violation in the SM: the CKM matrix

- Quark flavour mixing determined by **CKM matrix** – connects mass and flavour eigenstates
- CP-violation in SM – complex phase in CKM
- Unitarity of CKM matrix ⇒ unitarity relations

$$\sum_k V_{ik} V_{jk}^* = 0$$

- Form **triangles** in the complex plane

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



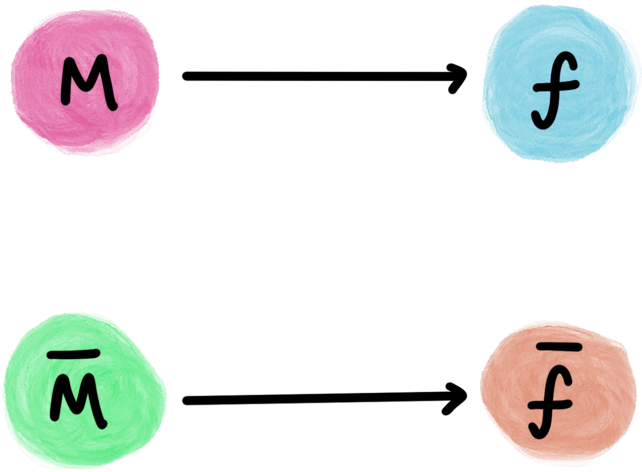
CKMfitter Group (J. Charles *et al.*), Eur. Phys. J. C41, 1-131 (2005) [hep-ph/0406184], updated results and plots available at: http://ckmfitter.in2p3.fr

Measuring *CP* violation

“indirect”

Direct *CP* violation

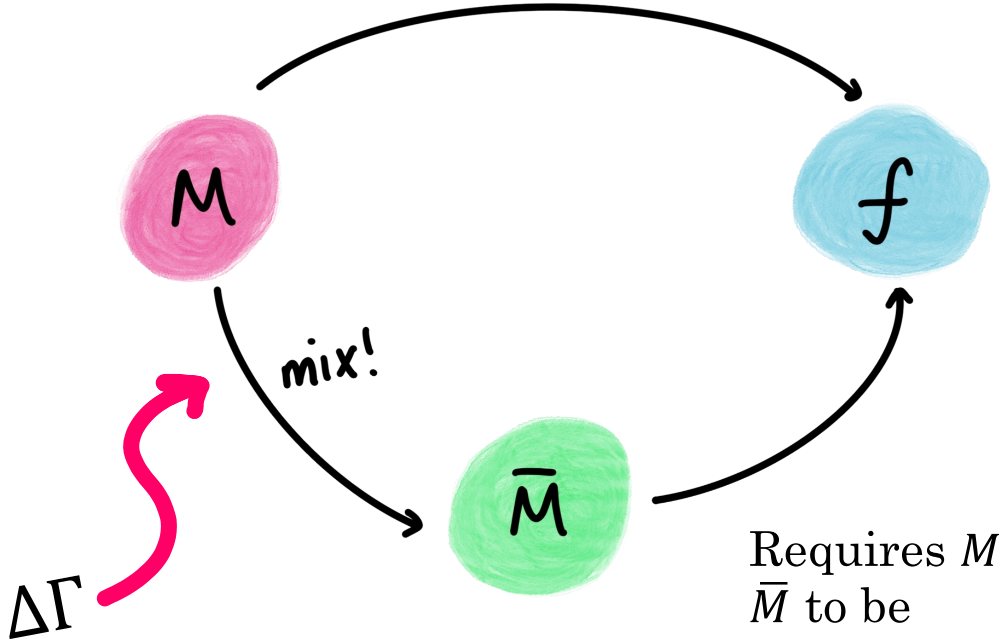
$$\mathcal{A}_f = |\mathcal{A}_1| e^{i(\delta_1+\varphi_1)} + |\mathcal{A}_2| e^{i(\delta_2+\varphi_2)} \dots$$



$$\bar{\mathcal{A}}_{\bar{f}} = |\mathcal{A}_1| e^{i(\delta_1-\varphi_1)} + |\mathcal{A}_2| e^{i(\delta_2-\varphi_2)}$$

Requires multiple contributing amplitudes with different strong and weak phases

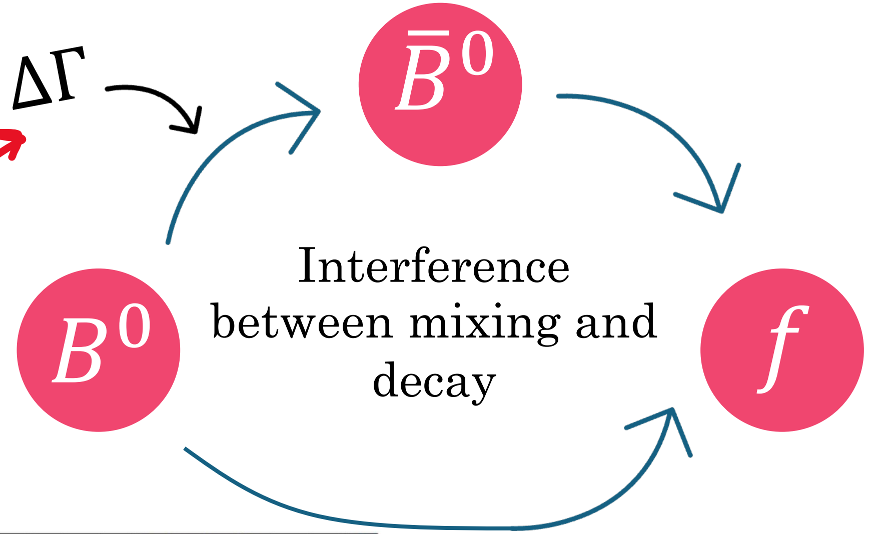
Mixing–induced *CP* violation



Requires M and $\bar{M}$ to be accessible to same final state

Measuring the CKM parameters

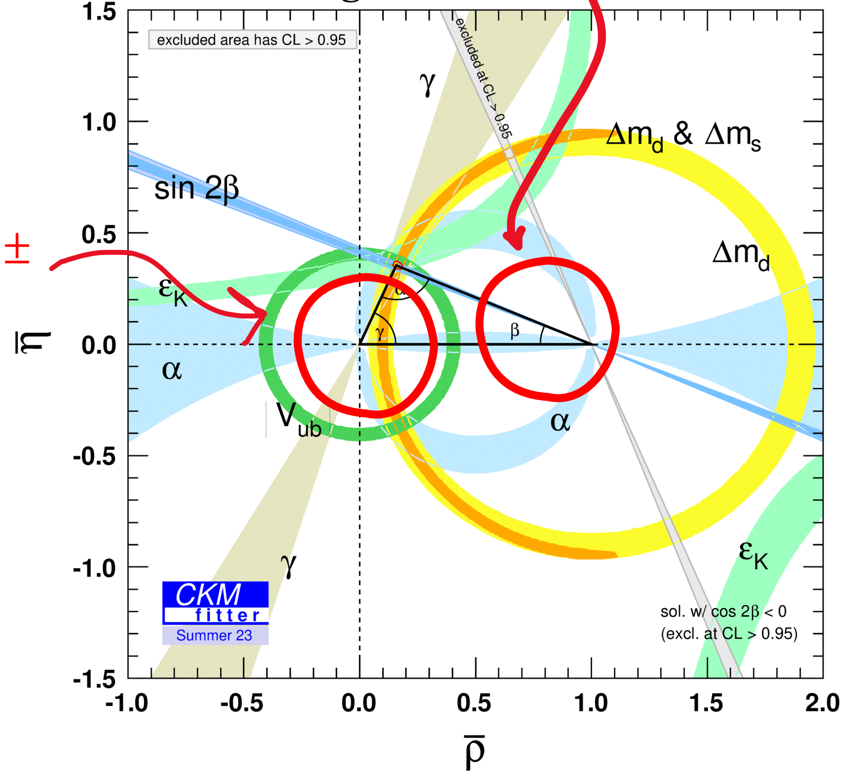
$B_s^0 \to J/\psi\eta'$ and
$B_s^0 \to J/\psi\pi^+\pi^-$



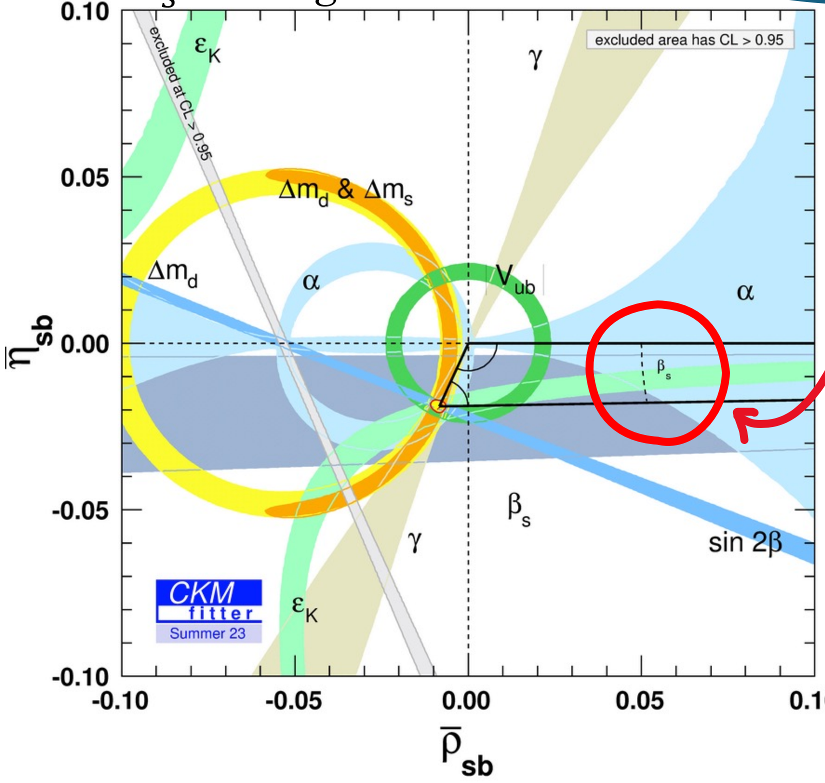
B^0 triangle

$B^0 \to J/\psi K_S^0$

$B_s^0 \to D_s^\mp K^\pm$



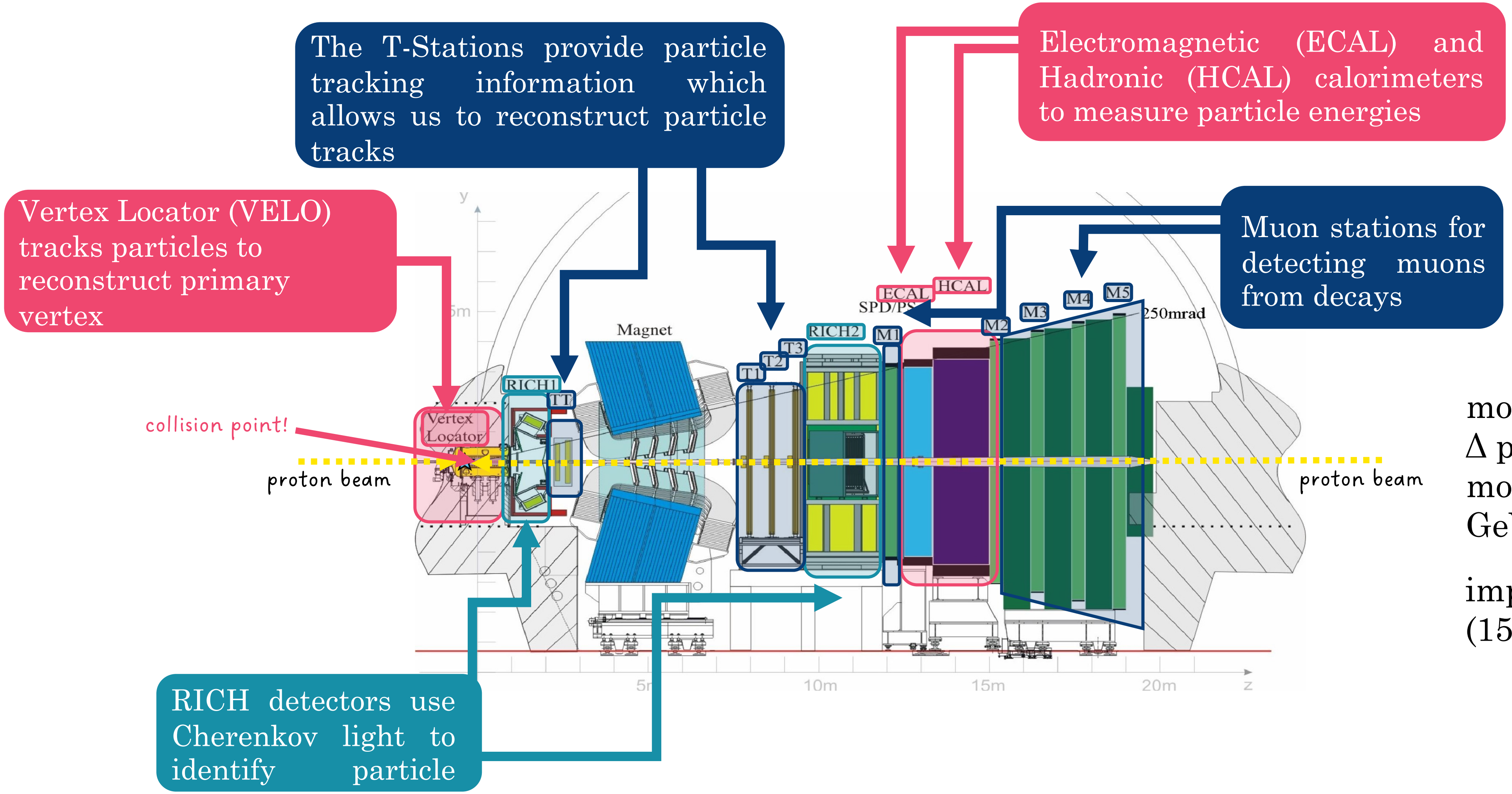
B_s^0 triangle



$B_s^0 \to J/\psi\phi$ and
$B_s^0 \to D_s^+ D_s^-$

The LHCb experiment – Run 1 and Run 2

Alves, A., & others (2008). The LHCb Detector at the LHC. *JINST, 3, S08005.*



momentum resolution: Δ p / p = 0.5 % at low momentum to 1.0% at 200 GeV/c

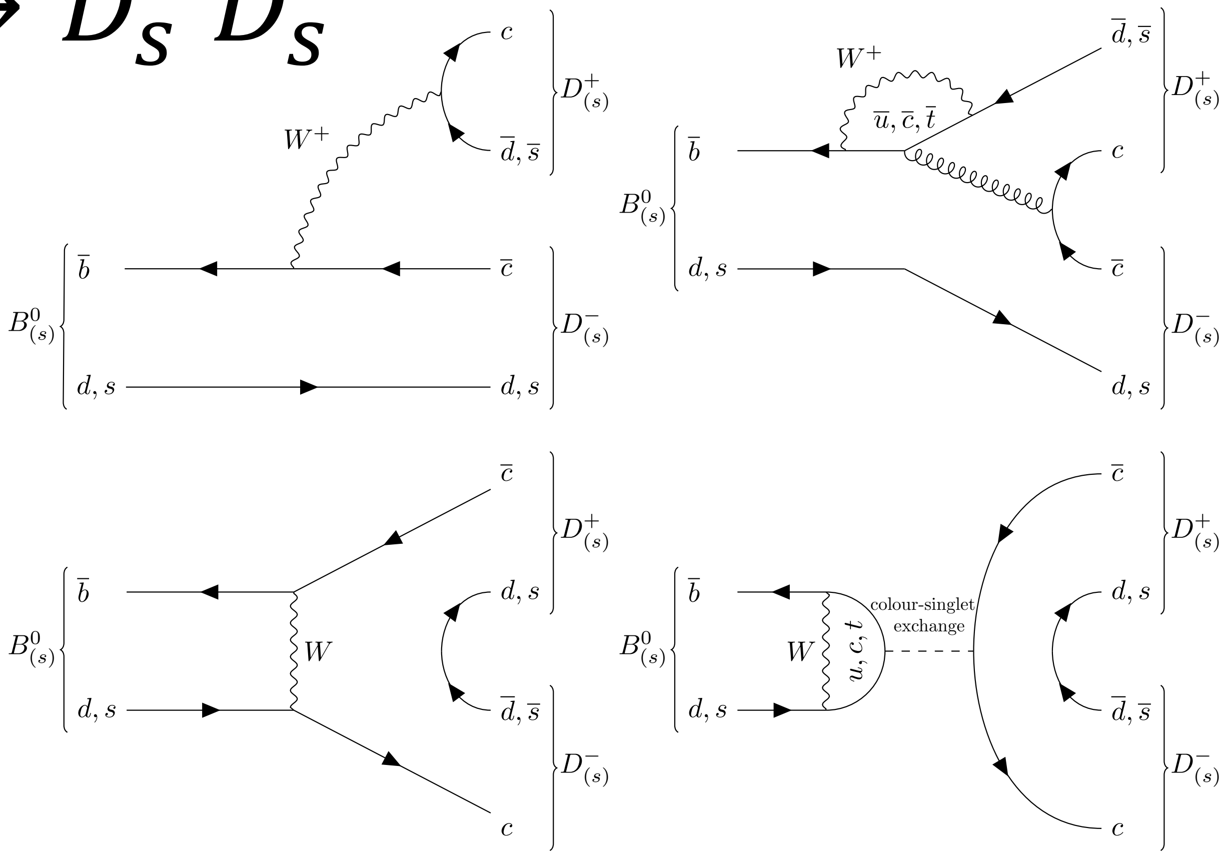
impact parameter resolution: (15 +29/pT[GeV]) μm

B decays to open charm

JHEP 01 (2025) 061

Measurement of CP violation in $B^0 \to D^+D^-$ and $B_s^0 \to D_s^+D_s^-$

- Time-dependent flavour-tagged analysis
- Relate to CKM angles β and β_s where $\phi_s = -2\beta_s$



$$\frac{\mathrm{d}\Gamma(t,d)}{\mathrm{d}t} \propto e^{-t/\tau_{B^0_{(s)}}} \left(\cosh \frac{\Delta\Gamma_q t}{2} + D_f \sinh \frac{\Delta\Gamma_q t}{2} + d\, C_f \cos \Delta m_q t - d\, S_f \sin \Delta m_q t \right)$$

$$D_f = -\frac{2|\lambda_f| \cos\phi_q}{1+|\lambda_f|^2},\quad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2},\quad S_f = -\frac{2|\lambda_f| \sin\phi_q}{1+|\lambda_f|^2},$$

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} \text{ and } \phi_q = -\arg\lambda_f,$$

Extract $S_{D^+D^-}$, $C_{D^+D^-}$, ϕ_s and $|\lambda_{D_s^+D_s^-}|$

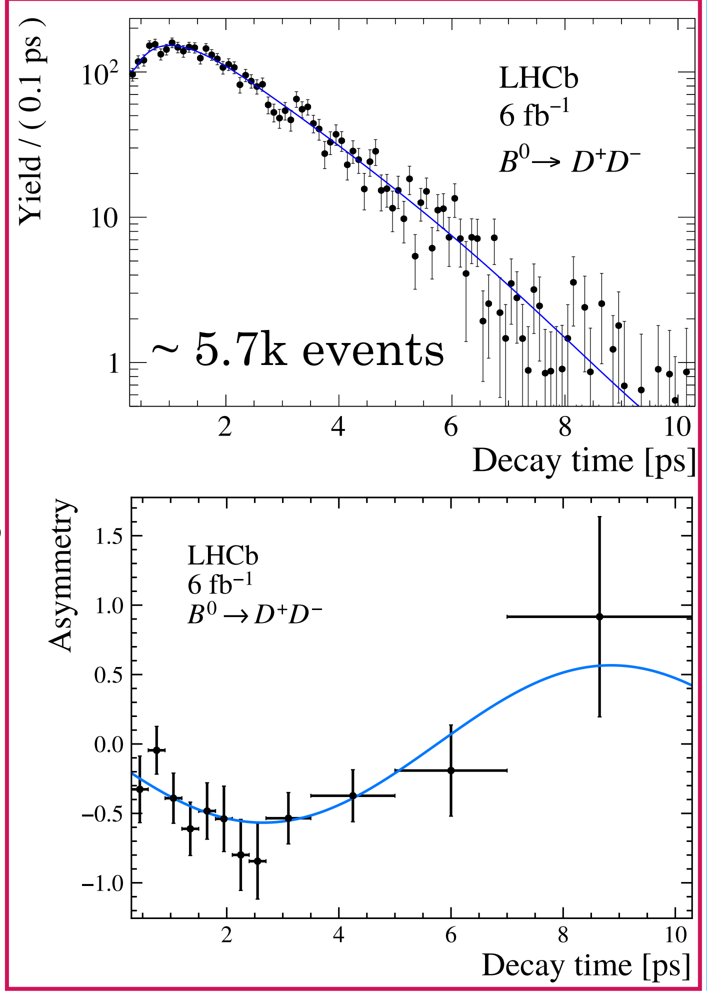
Measurement of CP violation in $B^0 \to D^+D^-$ and $B_s^0 \to D_s^+D_s^-$

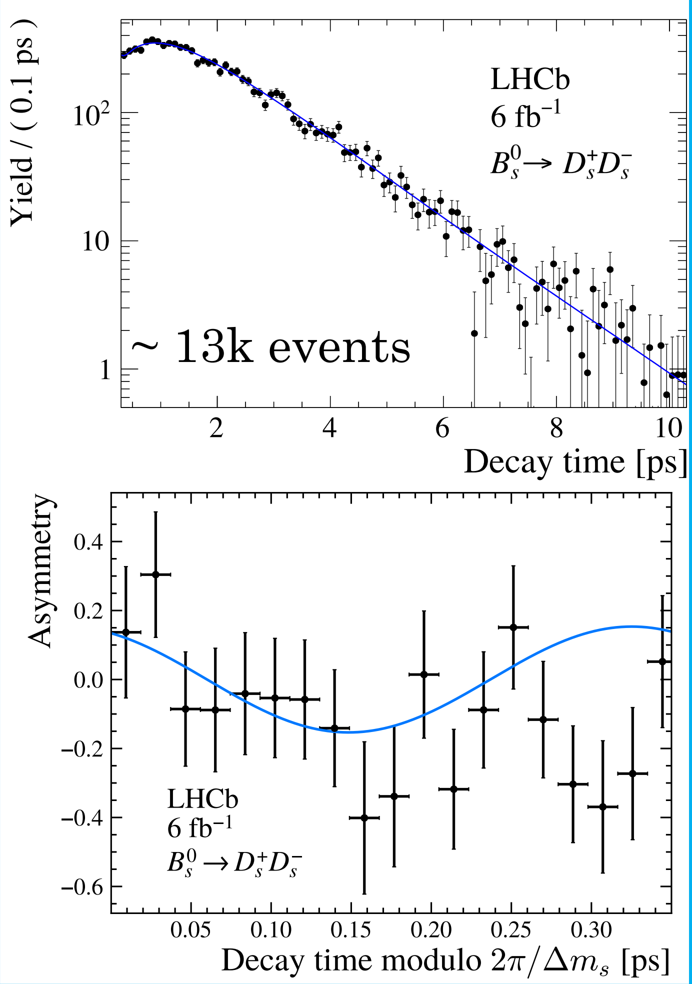
- Unbinned maximum likelihood fit to signal-weighted decay time distributions

$$S_{D^+D^-} = -0.552 \pm 0.100\,(\text{stat}) \pm 0.010\,(\text{syst}),$$
$$C_{D^+D^-} = 0.128 \pm 0.103\,(\text{stat}) \pm 0.010\,(\text{syst}),$$

$$\phi_s = -0.055 \pm 0.090\,(\text{stat}) \pm 0.021\,(\text{syst})\ \text{rad},$$
$$|\lambda_{D_s^+D_s^-}| = 1.054 \pm 0.099\,(\text{stat}) \pm 0.020\,(\text{syst}),$$

- ***CP* symmetry excluded by more than 6σ in $B^0 \to D^+D^-$**

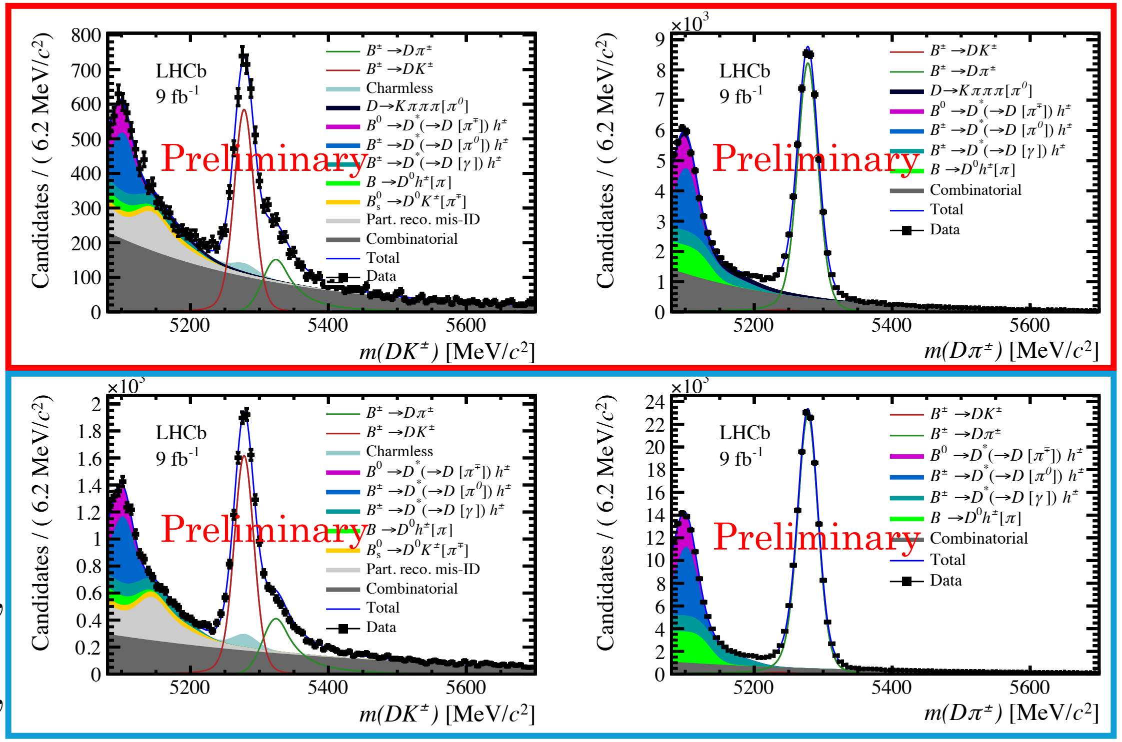




Model-independent measurement of CKM angle γ

NEW!

- Using decays $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D h^{\pm}$ and $B^{\pm} \to [\pi^+\pi^-\pi^+\pi^-]_D h^{\pm}$
  - $h = K, \pi$
- Binned in phase space – strong phases taken from BESIII measurements



$$N^{+}_{+i} = h^{DK}_{B^+}\left(F_{-i} + \left((x^{DK}_{+})^2 + (y^{DK}_{+})^2\right)F_i + 2\sqrt{F_{-i}F_i}(x^{DK}_{+} c_i + y^{DK}_{+} s_i)\right),$$

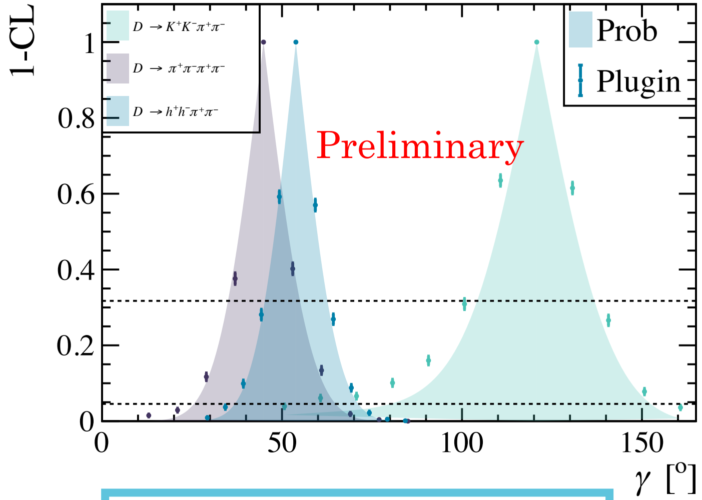
$$N^{-}_{-i} = h^{DK}_{B^-}\left(F_{-i} + \left((x^{DK}_{-})^2 + (y^{DK}_{-})^2\right)F_i + 2\sqrt{F_{-i}F_i}(x^{DK}_{-} c_i + y^{DK}_{-} s_i)\right),$$

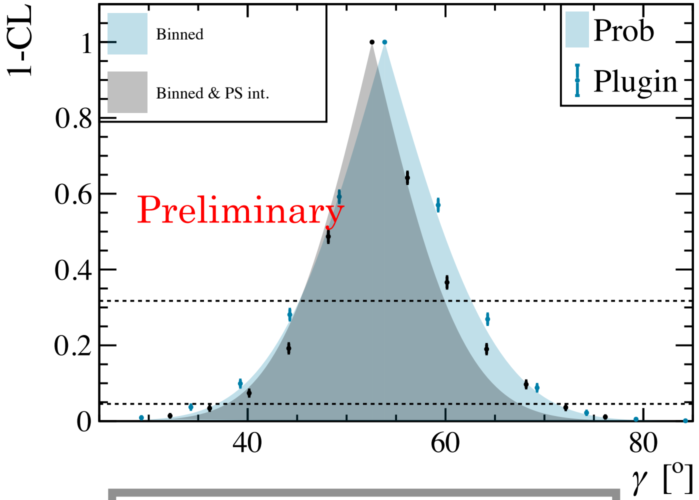
$$x^{DK}_{\pm} \equiv r^{DK}_B \cos(\delta^{DK}_B \pm \gamma), \quad y^{DK}_{\pm} \equiv r^{DK}_B \sin(\delta^{DK}_B \pm \gamma).$$

Model-independent measurement of CKM angle γ

NEW!

- Extract physics parameters from fit to each D decay and simultaneously for both modes
- Combination with phase-space integrated measurements
- **First standalone model-independent measurement of γ in the $B^{\pm} \to Dh^{\pm}$ decay with these D-meson final states**





$$
\begin{aligned}
\gamma &= (53.9^{+9.5}_{-8.9})^{\circ}, \\
\delta_B^{DK} &= (111.0^{+8.0}_{-7.9})^{\circ}, \\
r_B^{DK} &= 0.101^{+0.021}_{-0.018}, \\
\delta_B^{D\pi} &= (241^{+103}_{-98})^{\circ}, \\
r_B^{D\pi} &= 0.0022^{+0.0041}_{-0.0022}.
\end{aligned}
$$

$$
\begin{aligned}
\gamma &= (52.6^{+8.5}_{-6.4})^{\circ}, \\
\delta_B^{DK} &= (112.6^{+6.1}_{-7.8})^{\circ}, \\
r_B^{DK} &= 0.102^{+0.014}_{-0.017}, \\
\delta_B^{D\pi} &= (262^{+40}_{-52})^{\circ}, \\
r_B^{D\pi} &= 0.0043^{+0.0033}_{-0.0043},
\end{aligned}
$$

Charmless $B \to VV$ decays

Charmless $B \to VV$ decays particularly interesting

- Decays of $B^0_{(s)} \to V_1 V_2$ with $V_{1,2}$ in $\{\phi,\ K^*, \rho\}$
- Three contributing amplitudes – mixture of CP states
  - $A_{\parallel}, A_0, A_{\perp}$
    $\underbrace{A_{\parallel}, A_0}_{CP \text{ even}}$, $\underbrace{A_{\perp}}_{\text{odd}}$
- Polarization puzzle - expect longitudinal polarization, A_0, to dominate due to helicity suppression
  - Holds for decays at tree-level but not penguin-dominated
- Indirect CP violation in penguin $B \to VV$ susceptible to new physics entering in loops

Phys. Rev. Lett. 131, 171802 (2023)

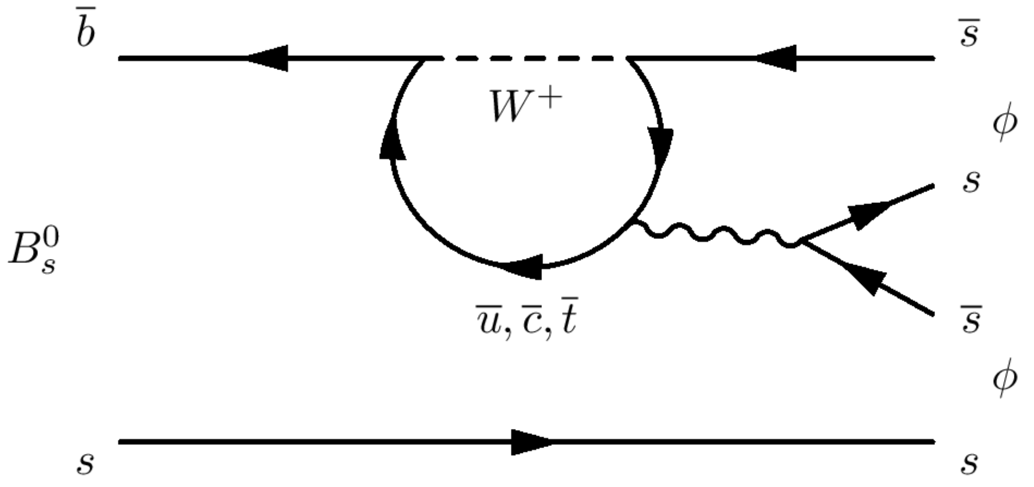
Measurement of $\phi_s^{s\bar{s}s}$ with $B_s^0 \to \phi\phi$

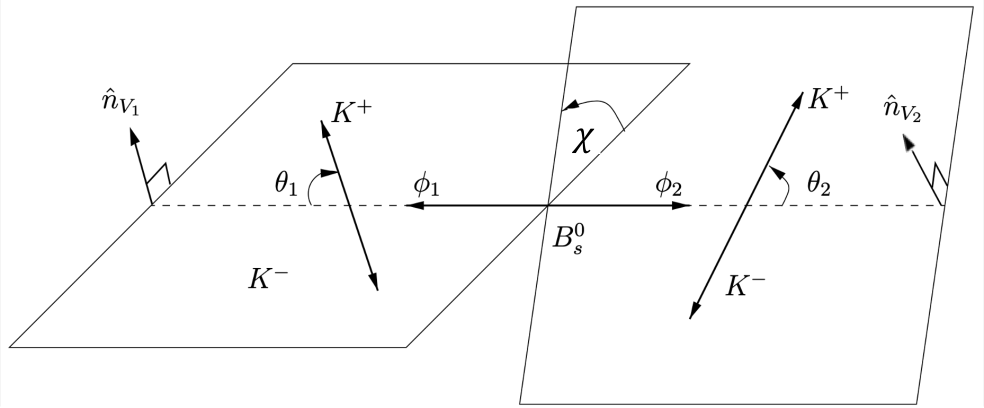
- A golden mode of LHCb - experimentally clean
- Probe of CP violation in penguin-dominated decays
- CP violation in mixing and decay predicted to cancel in the SM

$$\phi_s^{s\bar{s}s} = \phi^M - \phi^D \approx 0$$

Upper limit: 0.02 rad.[1]

- Significant deviation from zero is clear signature of new physics





[1] Matthaeus Bartsch, Gerhard Buchalla, & Christina Kraus. (2008). B -> V_L V_L Decays at Next-to-Leading Order in QCD.

Phys. Rev. Lett. 131, 171802 (2023)

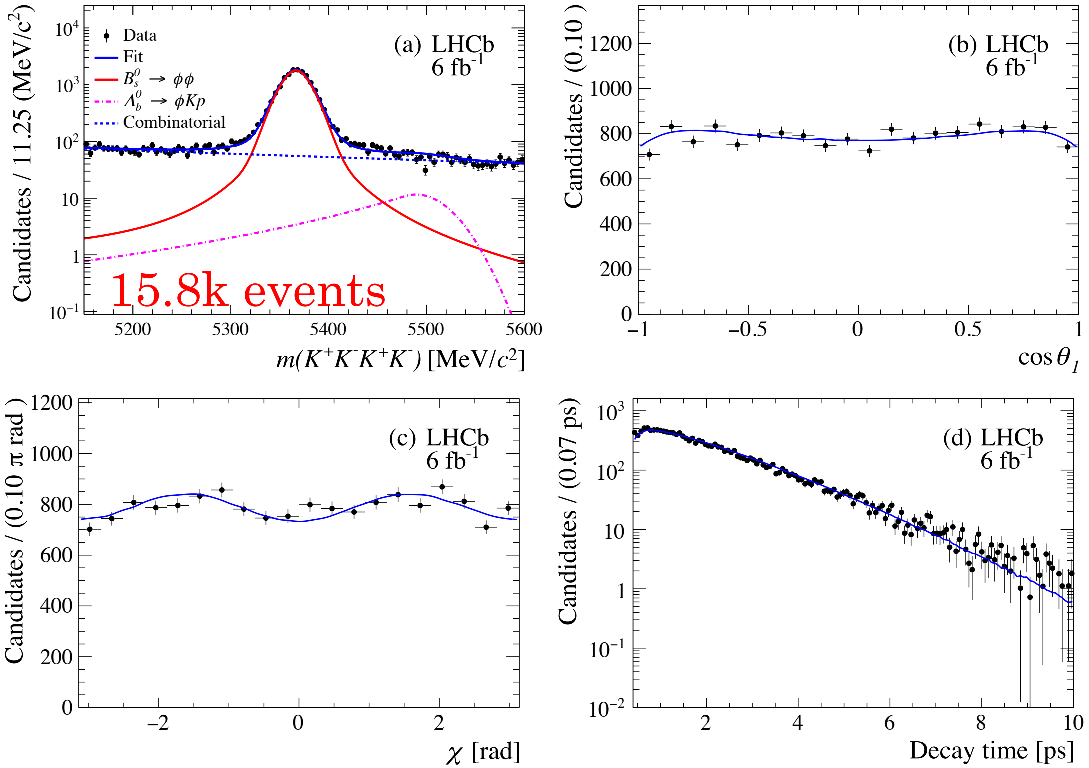
Measurement of $\phi_s^{s\bar{s}s}$ with $B_s^0 \to \phi\phi$

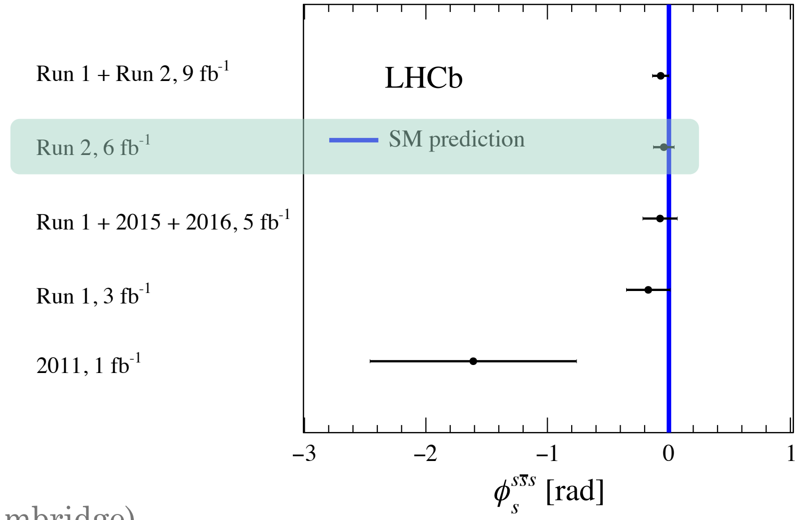
- Value of $\phi_s^{s\bar{s}s}$ extracted from 4D fit to decay time and three helicity angle distributions

- Fit results using full Run 2 dataset with 15.8k events:

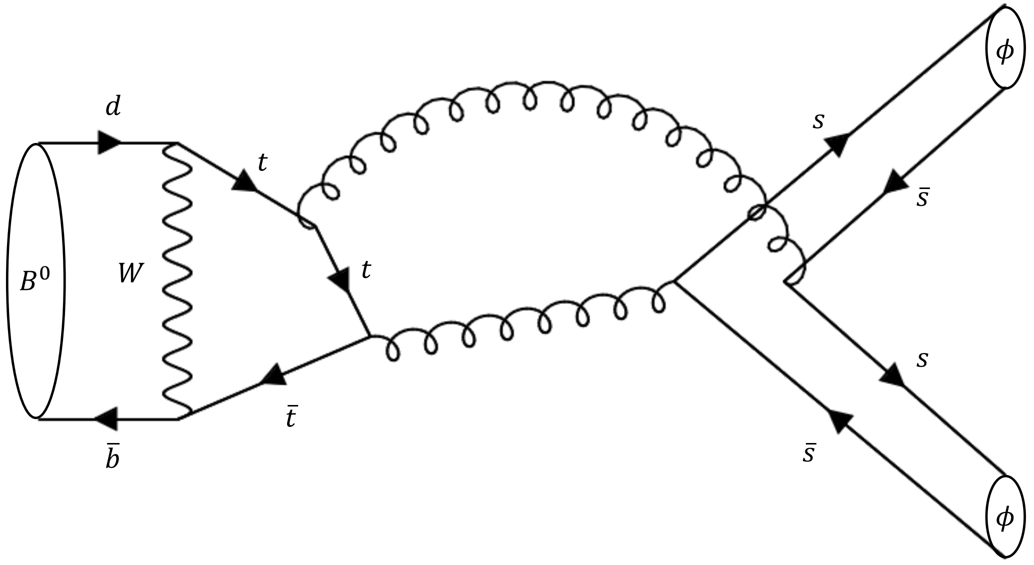
$$\phi_s^{s\bar{s}s} = -0.042 \pm 0.075\ (\text{stat.}) \pm 0.009\ (\text{syst.})\ \text{rad}$$

- **Most precise measurement of time-dependent *CP* asymmetry in penguin dominated *B* decays to date and consistent with the SM prediction**



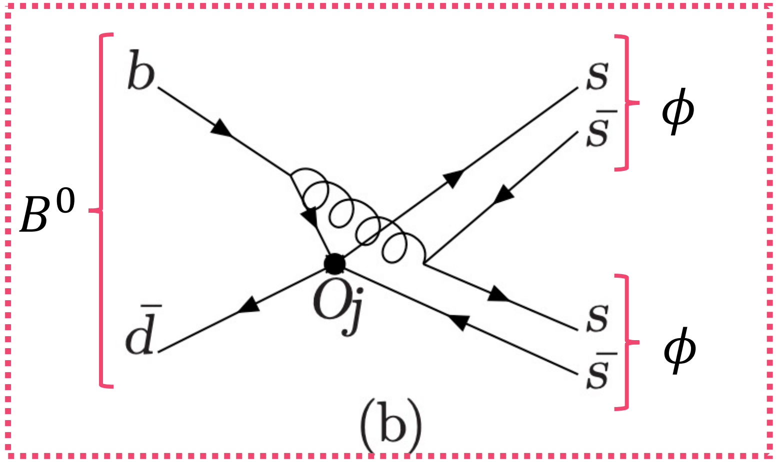


Search for $B^0 \to \phi\phi$



- **Complementary study**
- $\bar{b}d \to s\bar{s}$ annihilation: loop, Cabibbo and OZI suppressed
- Branching fraction may be enhanced in many scenarios: new physics, $\omega - \phi$ mixing…
- Predictions at $\sim 10^{-8}$ level - vary by order of magnitude
- Leading-order non-factorizable contributions to $B^0 \to \phi\phi$ are higher-order corrections to $B_s^0 \to \phi\phi$

non-factorizable



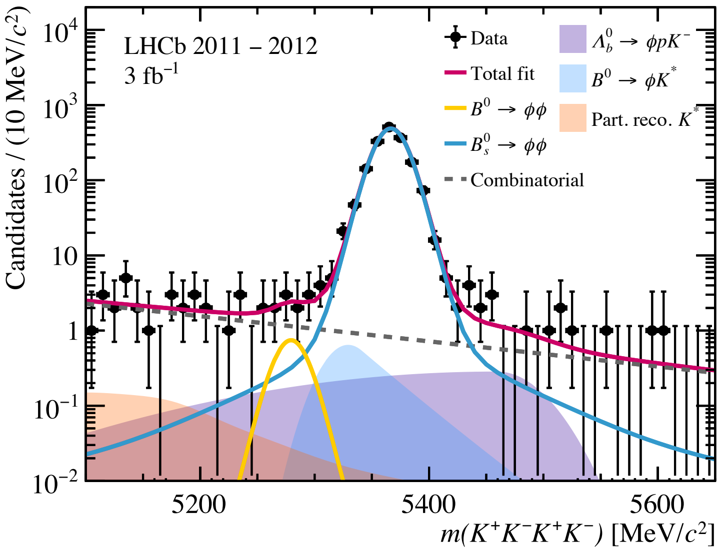
Bar-Shalom, S., Eilam, G., & Yang, Y.-D. (2003). $B \to \phi\pi$ and $B^0 \to \phi\phi$ the standard model and new bounds on R-parity violation. Physical Review D, 67(1). https://doi.org/10.1103/physrevd.67.014007

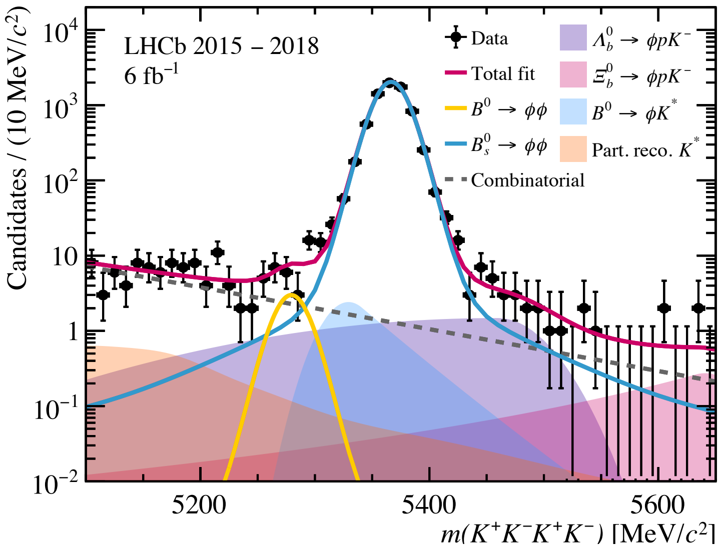
New limit set on branching fraction

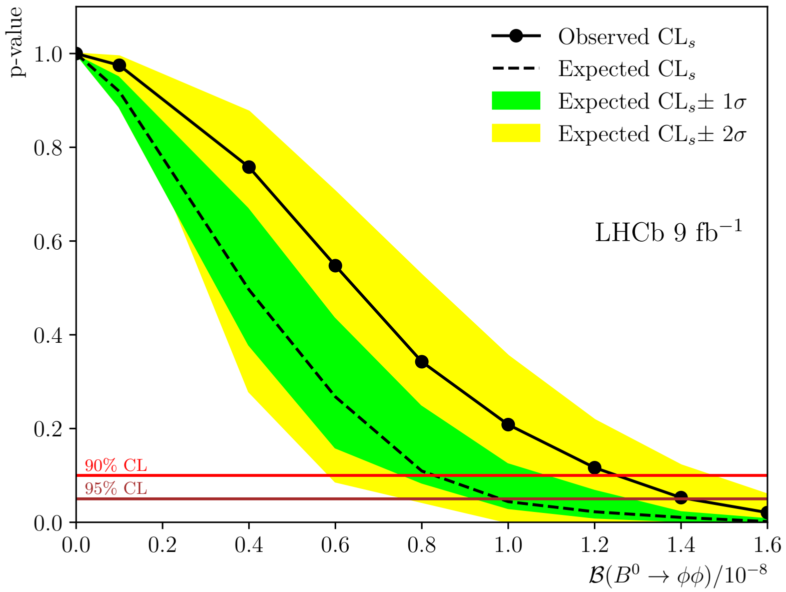
- BF from fit to invariant mass, relative to $B_s^0 \to \phi\phi$
- Set a new limit on the branching fraction at 90% confidence level

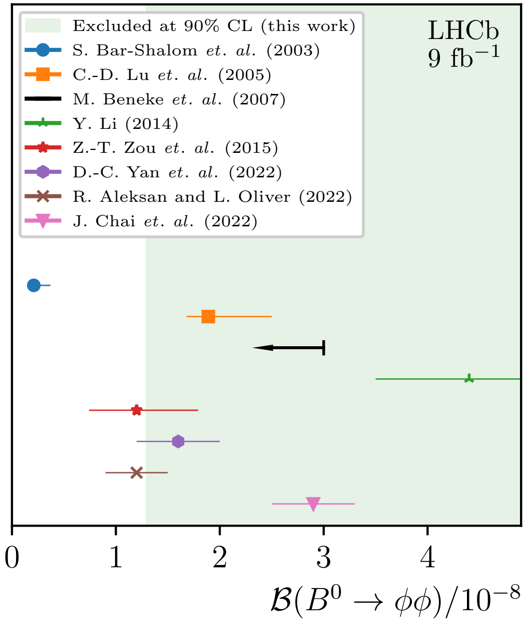
$$\mathcal{B}(B^0 \to \phi\phi) < 1.3 \times 10^{-8}$$

- **factor of two better than previous limit**



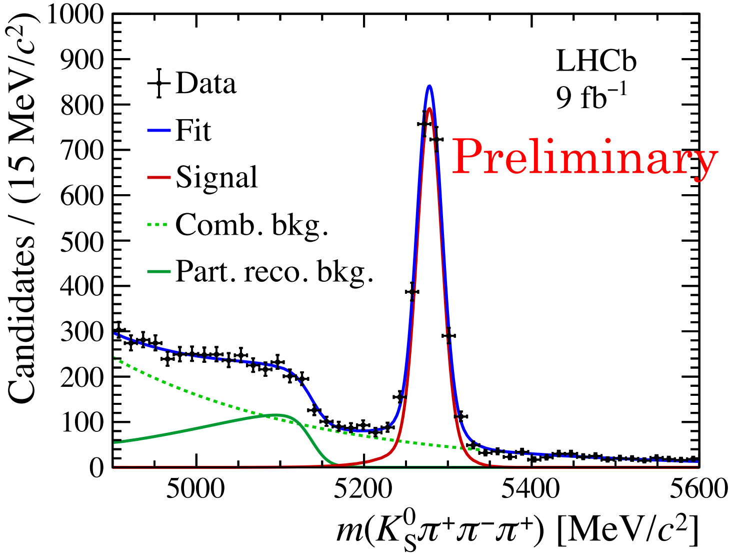




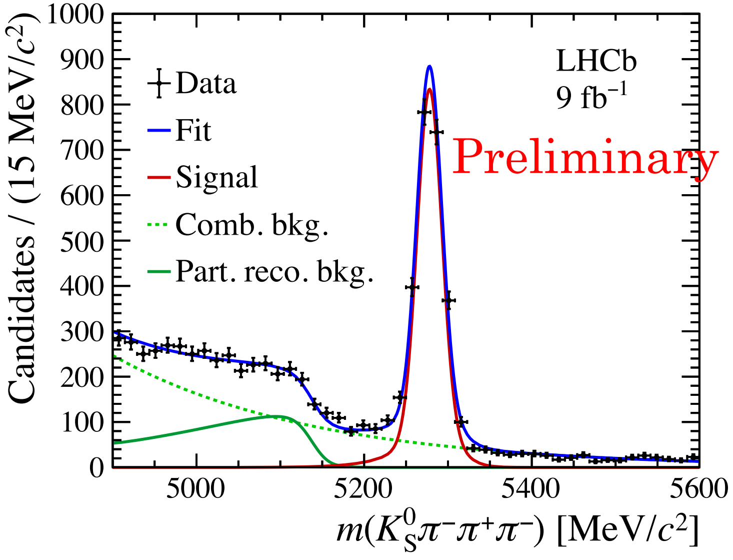


Amplitude analysis of $B^+ \to \rho K^{*+}$

- $B^+ \to \rho K^{*+}$
  - K^{*+} ($\to K_S \pi^+$)
  - ρ ($\to \pi^+ \pi^-$)
- Extract
  - longitudinal fraction, f_L
  - CP asymmetry, $\mathcal{A}_{CP}$
  - Triple product asymmetries
- 5-dimensional fit to $m(K_S\pi^+)$, $m(\pi^+\pi^-)$, and helicity angles $\cos\theta_{K_S\pi^+}$, $\cos\pi^+\pi^-$ and ϕ



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



$B^- \to \rho K^{*-}$

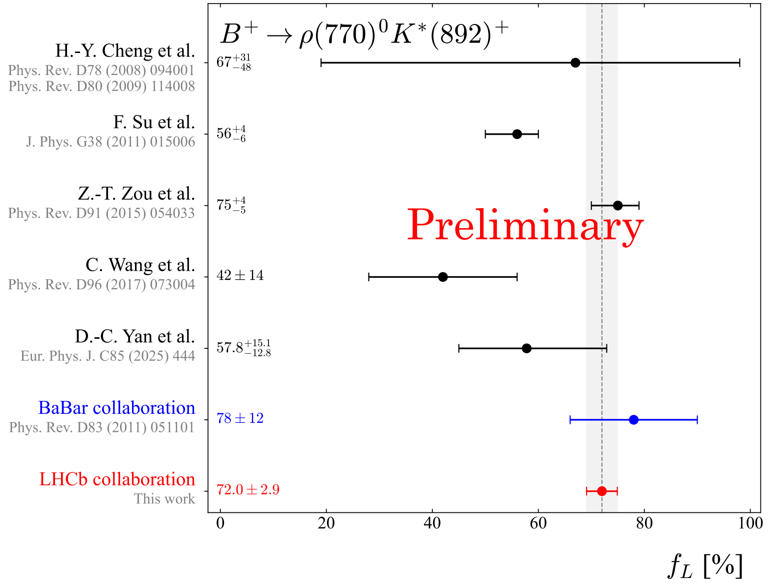
Select signal candidates from simultaneous fit to $m(K_S\pi\pi\pi)$ within 2.5σ of $B^\pm$ mass

$$N_{B^+} = 2208 \pm 53\,,\, N_{B^-} = 2333 \pm 55$$

$B^+ \to \rho K^{*+}$ results

- Theory
- BaBar
- This work

LHCb-PAPER-2025-026 in preparation



- Charge-averaged longitudinal fraction

$$f_L \equiv \frac{|A_0|^2 + |\overline{A_0}|^2}{\sum_\lambda (|A_\lambda|^2 + |\overline{A_\lambda}|^2)} \quad \lambda \text{ in } \{0, \parallel \perp\}$$

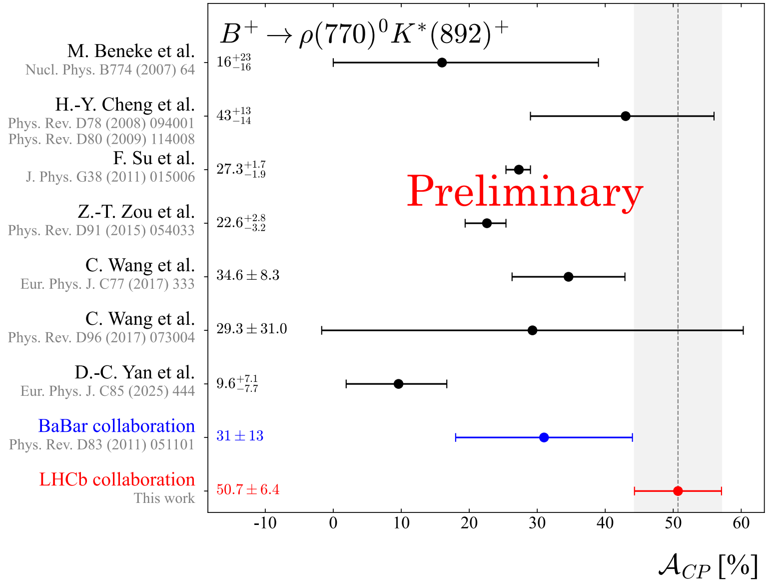
$$= 0.720 \pm 0.028 \pm 0.009$$

- Direct CP asymmetry

$$\mathcal{A}_{CP} \equiv \frac{\sum_\lambda (|\overline{A_\lambda}|^2 - |A_\lambda|^2)}{\sum_\lambda (|\overline{A_\lambda}|^2 + |A_\lambda|^2)} \quad \lambda \text{ in } \{0, \parallel \perp\}$$

$$= 0.507 \pm 0.062 \pm 0.017$$

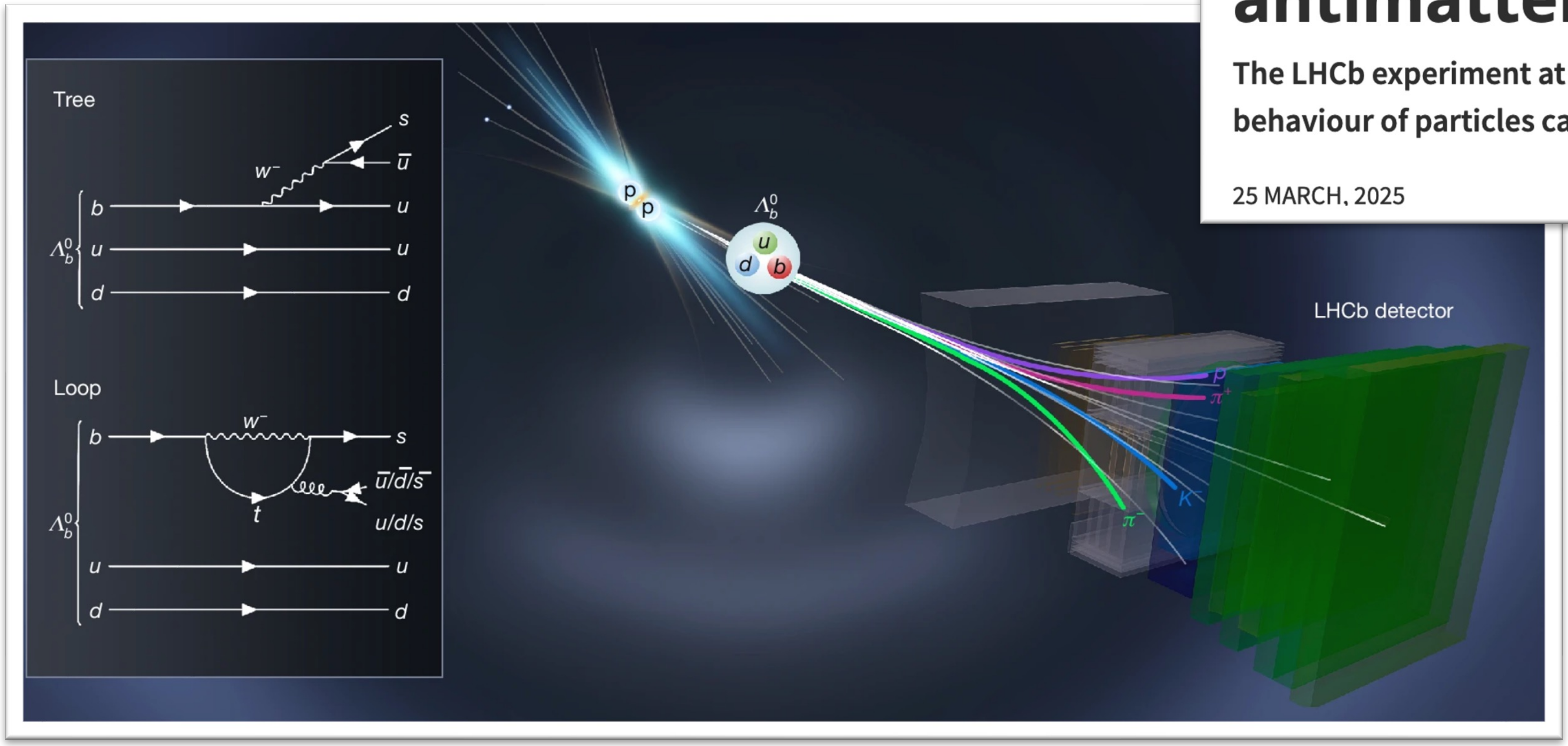
9σ with likelihood-ratio test!



CP violation in baryon decays

Nature **volume 643**, pages 1223–1228 (2025)

LHCb makes the headlines with first observation of CP violation in baryon decays



Measure of direct CP asymmetry in $\Lambda_b^0 \to pK^-\pi^+\pi^-$

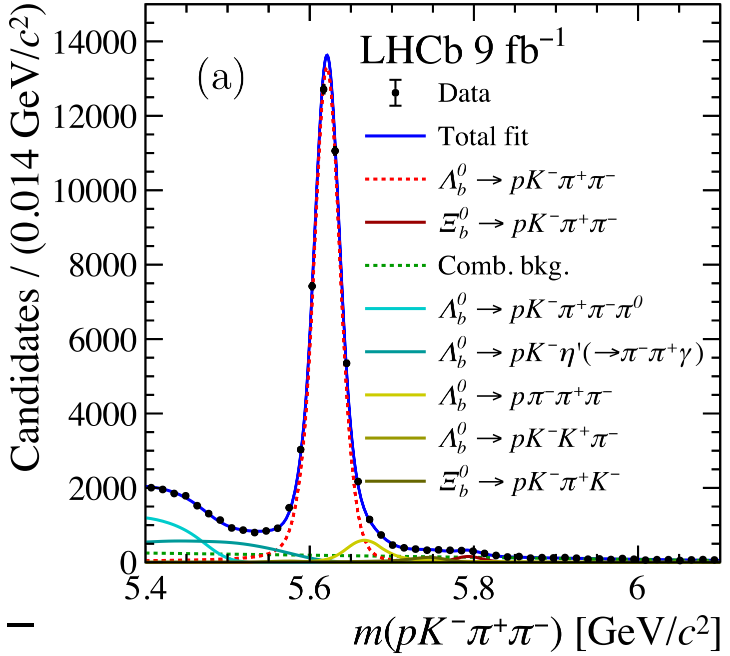
Nature **volume 643**, pages 1223–1228 (2025)

Direct CP asymmetry in $\Lambda_b^0 \to pK^-\pi^+\pi^-$

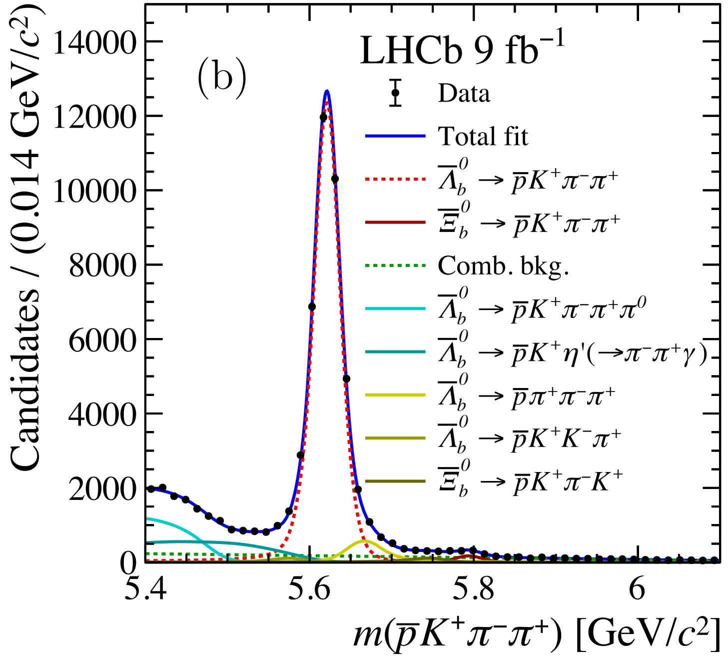
- Fit the $pK^-\pi^+\pi^-$ invariant mass distribution for the yields
- Global CP asymmetry is measured

$$\mathcal{A}_{CP} = (2.45 \pm 0.46 \pm 0.10)\%$$

- **differs from zero by 5.2σ**
- Across phase space, largest CP asymmetry in $\Lambda_b^0 \to R(p\pi^+\pi^-)K^-$ – more than 6σ



$N_{\Lambda_b^0} = (4.184 \pm 0.025)\times10^4$



$N_{\overline{\Lambda_b^0}} = (3.885 \pm 0.023)\times10^4$

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

- Four modes:
  - $\Lambda_b^0 \to pK_S^0\pi^-$
  - $\Lambda_b^0 \to pK_S^0K^-$
  - $\Xi_b^0 \to pK_S^0K^-$
  - $\Xi_b^0 \to pK_S^0\pi^-$

Observed for the first time!

Upper limit set

- $\Lambda_b^0 \to pK_S^0\pi^-$ proceeds through $\Lambda_b^0 \to pK^*(892)^-(\to K_S^0\pi^-)$

- Methods such as QCD factorisation predict large *CP* asymmetries for $\Lambda_b^0 \to pK^*(892)^-$ ($\mathcal{A}_{CP}$~20-30%)

- Perturbative QCD and final-state rescattering predict cancellation from partial waves ($\mathcal{A}_{CP}$ ~$-5 - 2\%$)

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

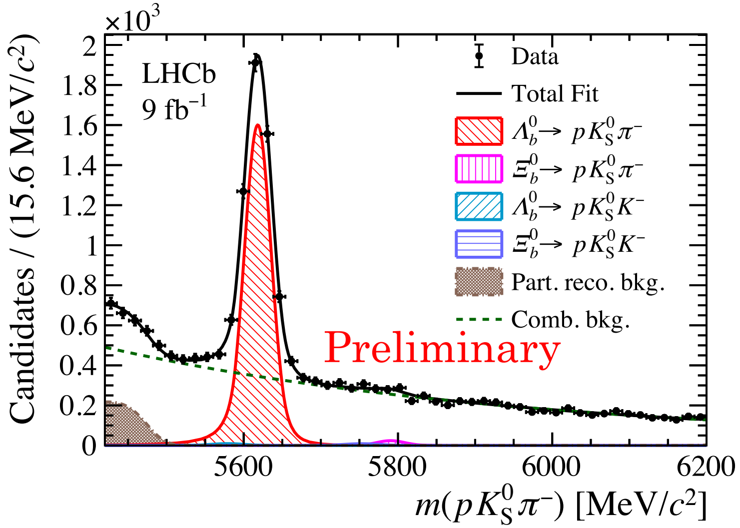
- Measurement of branching fractions – fit to $pK_S^0 h^-$ invariant mass distributions

Decay	Yield	Significance
$\Lambda_b^0 \to pK_S^0\pi^-$	4740 ± 90	-
$\Lambda_b^0 \to pK_S^0K^-$	127 ± 17	$8.1\,\sigma$
$\Xi_b^0 \to pK_S^0\pi^-$	70 ± 40	$1.0\,\sigma$
$\Xi_b^0 \to pK_S^0K^-$	88 ± 13	$8.0\,\sigma$
$\Lambda_b^0 \to \Lambda_c^+(\to pK_S^0)\pi^-$	$34\,680 \pm 200$	-

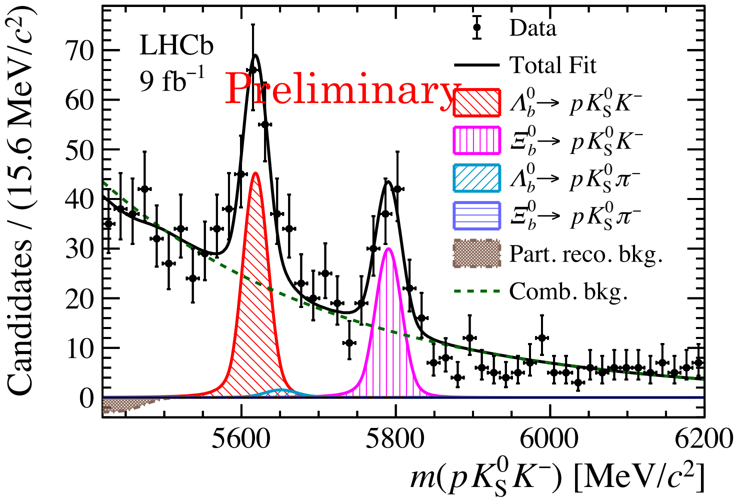
	Result $[\times 10^{-6}]$
$\mathcal{B}(\Lambda_b^0 \to pK_S^0\pi^-)$	$10.62 \pm 0.21 \pm 0.16 \pm 0.98$
$\mathcal{B}(\Lambda_b^0 \to pK_S^0K^-)$	$0.61 \pm 0.08 \pm 0.06 \pm 0.06$
$\mathcal{B}(\Xi_b^0 \to pK_S^0\pi^-)$	$< 2.8\ (3.2)$ at $90\ (95)\%$ CL
$\mathcal{B}(\Xi_b^0 \to pK_S^0K^-)$	$3.9 \pm 0.6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

(stat.) ± (syst.) ± (normalization) ± (b-quark fragmentation fractions)

$\Lambda_b^0(\Xi_b^0) \to pK_S^0\pi^-$



$\Lambda_b^0(\Xi_b^0) \to pK_S^0K^-$

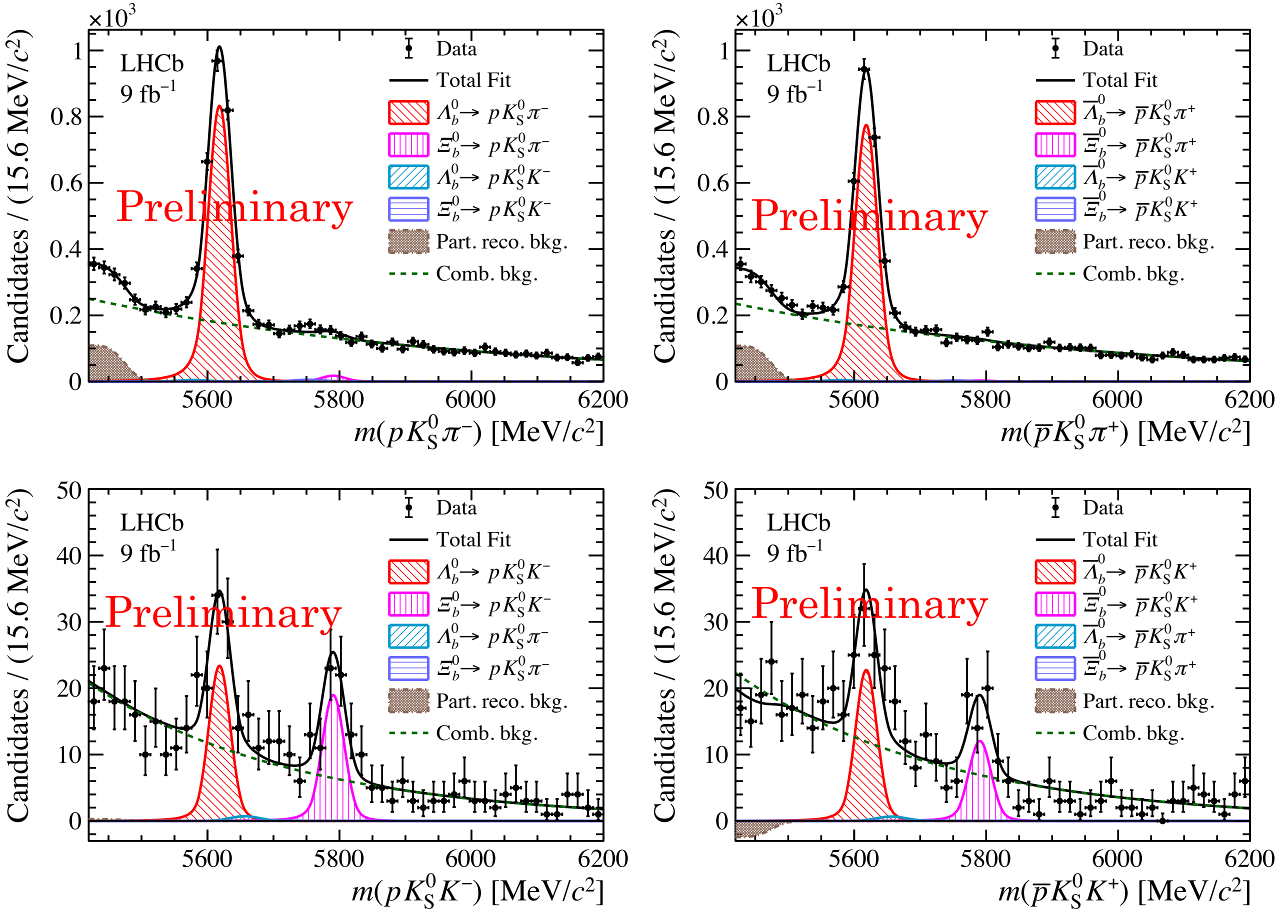


Measurement of $\Lambda_b^0(\Xi_b^0) \to pK_S^0 h^-$

- **No significant *CP* asymmetry in any channel**

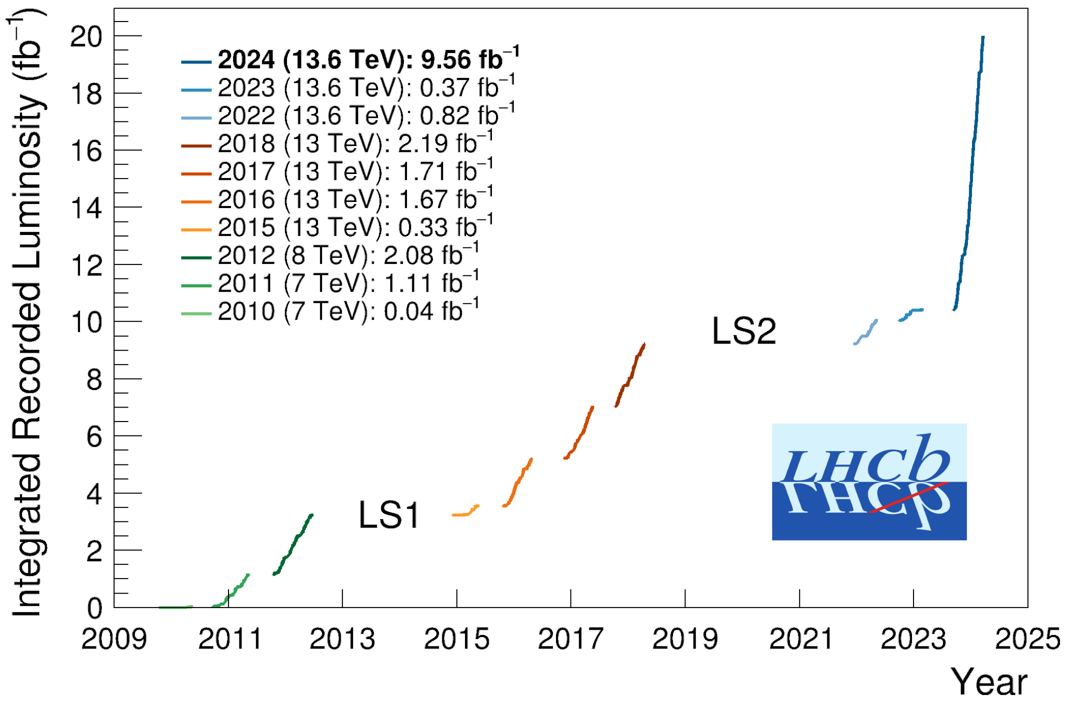
	Result [%]
$\mathcal{A}^{CP}$ $(\Lambda_b^0 \to pK_S^0\pi^-)$	$3.4 \pm 1.9 \pm 0.9$
$\mathcal{A}^{CP}$ $(\Lambda_b^0 \to pK_S^0K^-)$	$2 \pm 13 \pm 9$
$\mathcal{A}^{CP}$ $(\Xi_b^0 \to pK_S^0K^-)$	$22 \pm 15 \pm 11$

- Dalitz region of $\Lambda_b^0 \to pK_S^0\pi^-$ shows vanishing *CP* asymmetry of $\Lambda_b^0 \to pK^*(892)^-$



Thank you for your attention!

- LHCb has many results on *CP* violation with new results from Run 1 and Run 2 still coming out
- LHCb provides observation of *CP* violation in baryon decays for the first time – new avenue to constrain CKM
- We are taking our largest datasets yet with LHCb Run 3 – **stay tuned for LHCb Run 3 results**



Collecting our largest dataset yet!

Back-up material

$B_s^0 \to D_s^{\mp} K^{\pm}$ decay rate

$$\frac{\mathrm{d}\Gamma_{B_s^0\to f}(t)}{\mathrm{d}t} = \frac{1}{2}|A_f|^2(1+|\lambda_f|^2)e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_f\cos(\Delta m_s t) - S_f\sin(\Delta m_s t)\right],$$

$$\frac{\mathrm{d}\Gamma_{\overline{B}_s^0\to f}(t)}{\mathrm{d}t} = \frac{1}{2}|A_f|^2\left|\frac{p}{q}\right|^2(1+|\lambda_f|^2)e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - C_f\cos(\Delta m_s t) + S_f\sin(\Delta m_s t)\right],$$

$$C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} = -C_{\bar{f}} = -\frac{1-|\lambda_{\bar{f}}|^2}{1+|\lambda_{\bar{f}}|^2},$$

$$A_f^{\Delta\Gamma} = \frac{-2\mathcal{R}e(\lambda_f)}{1+|\lambda_f|^2},\quad A_{\bar{f}}^{\Delta\Gamma} = \frac{-2\mathcal{R}e(\lambda_{\bar{f}})}{1+|\lambda_{\bar{f}}|^2},$$

$$S_f = \frac{2\mathcal{I}m(\lambda_f)}{1+|\lambda_f|^2},\qquad S_{\bar{f}} = \frac{2\mathcal{I}m(\lambda_{\bar{f}})}{1+|\lambda_{\bar{f}}|^2}.$$

$$C_f = \frac{1-r_{D_sK}^2}{1+r_{D_sK}^2},$$

$$A_f^{\Delta\Gamma} = \frac{-2r_{D_sK}\cos(\delta-(\gamma-2\beta_s))}{1+r_{D_sK}^2},\quad A_{\bar{f}}^{\Delta\Gamma} = \frac{-2r_{D_sK}\cos(\delta+(\gamma-2\beta_s))}{1+r_{D_sK}^2},$$

$$S_f = \frac{2r_{D_sK}\sin(\delta-(\gamma-2\beta_s))}{1+r_{D_sK}^2},\quad S_{\bar{f}} = \frac{-2r_{D_sK}\sin(\delta+(\gamma-2\beta_s))}{1+r_{D_sK}^2}.$$

$B_s^0 \to \phi\phi$ differential decay rate

$$\frac{\mathrm{d}^4\Gamma(t,\vec{\Omega})}{\mathrm{d}t\mathrm{d}\vec{\Omega}} \propto \sum_{k=1}^{6} h_k(t) f_k(\vec{\Omega})$$

$$h_k(t) = N_k e^{-\Gamma_s t}\left[a_k \cosh\left(\frac{\Delta\Gamma_s}{2}t\right) + b_k \sinh\left(\frac{\Delta\Gamma_s}{2}t\right) + Qc_k \cos(\Delta m_\mathrm{s}\, t) + Qd_k \sin(\Delta m_\mathrm{s}\, t)\right]$$

i	N_i	a_i	b_i	c_i	d_i	f_i
1	$\lvert A_0\rvert^2$	$1+\lvert\lambda_0\rvert^2$	$-2\lvert\lambda_0\rvert\cos(\phi)$	$1-\lvert\lambda_0\rvert^2$	$2\lvert\lambda_0\rvert\sin(\phi)$	$4\cos^2\theta_1\cos^2\theta_2$
2	$\lvert A_\parallel\rvert^2$	$1+\lvert\lambda_\parallel\rvert^2$	$-2\lvert\lambda_\parallel\rvert\cos(\phi_{s,\parallel})$	$1-\lvert\lambda_\parallel\rvert^2$	$2\lvert\lambda_\parallel\rvert\sin(\phi_{s,\parallel})$	$\sin^2\theta_1\sin^2\theta_2(1+\cos 2\Phi)$
3	$\lvert A_\perp\rvert^2$	$1+\lvert\lambda_\perp\rvert^2$	$2\lvert\lambda_\perp\rvert\cos(\phi_{s,\perp})$	$1-\lvert\lambda_\perp\rvert^2$	$-2\lvert\lambda_\parallel\rvert\sin(\phi_{s,\perp})$	$\sin^2\theta_1\sin^2\theta_2(1-\cos 2\Phi)$
4	$\frac{\lvert A_\parallel\rvert\lvert A_\perp\rvert}{2}$	$\sin(\delta_\parallel-\delta_\perp)-\lvert\lambda_\parallel\rvert\lvert\lambda_\perp\rvert\cdot$ $\sin(\delta_\parallel-\delta_\perp-\phi_{s,\parallel}+\phi_{s,\perp})$	$-\lvert\lambda_\parallel\rvert\sin(\delta_\parallel-\delta_\perp-\phi_{s,\parallel})$ $+\lvert\lambda_\perp\rvert\sin(\delta_\parallel-\delta_\perp+\phi_{s,\perp})$	$\sin(\delta_\parallel-\delta_\perp)+\lvert\lambda_\parallel\rvert\lvert\lambda_\perp\rvert\cdot$ $\sin(\delta_\parallel-\delta_\perp-\phi_{s,\parallel}+\phi_{s,\perp})$	$\lvert\lambda_\parallel\rvert\cos(\delta_\parallel-\delta_\perp-\phi_{s,\parallel})$ $+\lvert\lambda_\perp\rvert\cos(\delta_\parallel-\delta_\perp+\phi_{s,\perp})$	$-2\sin^2\theta_1\sin^2\theta_2\sin 2\Phi$
5	$\frac{\lvert A_\parallel\rvert\lvert A_0\rvert}{2}$	$\cos(\delta_\parallel-\delta_0)+\lvert\lambda_\parallel\rvert\lvert\lambda_0\rvert\cdot$ $\cos(\delta_\parallel-\delta_0-\phi_{s,\parallel}+\phi)$	$-\lvert\lambda_\parallel\rvert\cos(\delta_\parallel-\delta_0-\phi_{s,\parallel})$ $+\lvert\lambda_0\rvert\cos(\delta_\parallel-\delta_0+\phi)$	$\cos(\delta_\parallel-\delta_0)-\lvert\lambda_\parallel\rvert\lvert\lambda_0\rvert\cdot$ $\sin(\delta_\parallel-\delta_0-\phi_{s,\parallel}+\phi)$	$-\lvert\lambda_\parallel\rvert\sin(\delta_\parallel-\delta_0-\phi_{s,\parallel})$ $+\lvert\lambda_0\rvert\sin(\delta_\parallel-\delta_0+\phi)$	$\sqrt{2}\sin 2\theta_1\sin 2\theta_2\cos\Phi$
6	$\frac{\lvert A_0\rvert\lvert A_\perp\rvert}{2}$	$\sin(\delta_0-\delta_\perp)-\lvert\lambda_0\rvert\lvert\lambda_\perp\rvert\cdot$ $\sin(\delta_0-\delta_\perp-\phi+\phi_{s,\perp})$	$-\lvert\lambda_0\rvert\sin(\delta_0-\delta_\perp-\phi)$ $+\lvert\lambda_\perp\rvert\sin(\delta_0-\delta_\perp+\phi_{s,\perp})$	$\sin(\delta_0-\delta_\perp)+\lvert\lambda_0\rvert\lvert\lambda_\perp\rvert\cdot$ $\sin(\delta_0-\delta_\perp-\phi+\phi_{s,\perp})$	$\lvert\lambda_0\rvert\cos(\delta_0-\delta_\perp-\phi)$ $+\lvert\lambda_\perp\rvert\cos(\delta_0-\delta_\perp+\phi_{s,\perp})$	$-\sqrt{2}\sin 2\theta_1\sin 2\theta_2\sin\Phi$

LHCb-PAPER-2025-026 in preparation

$B^+ \to \rho K^{*+}$ 5D fit

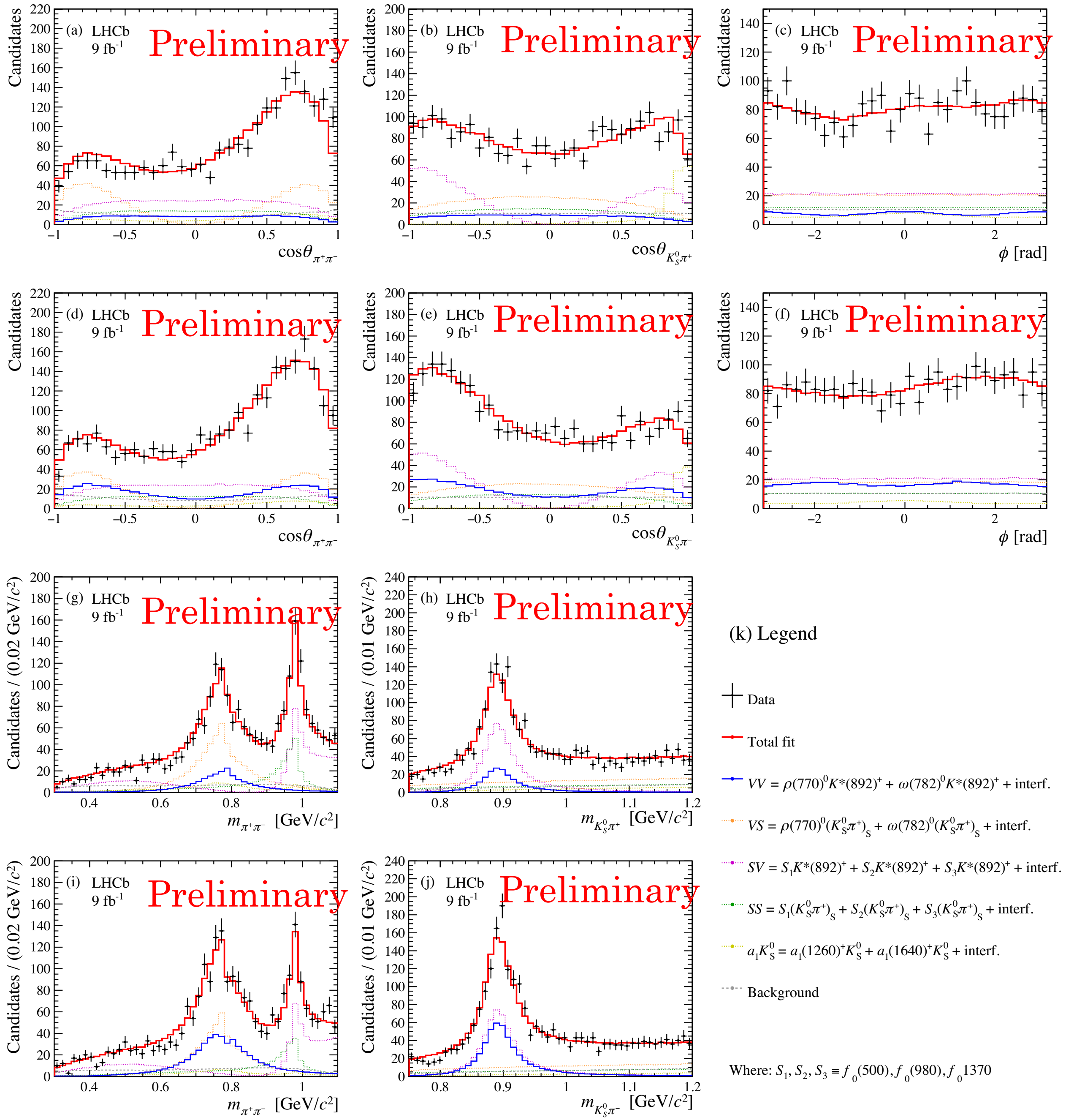
- Consider several resonances

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

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

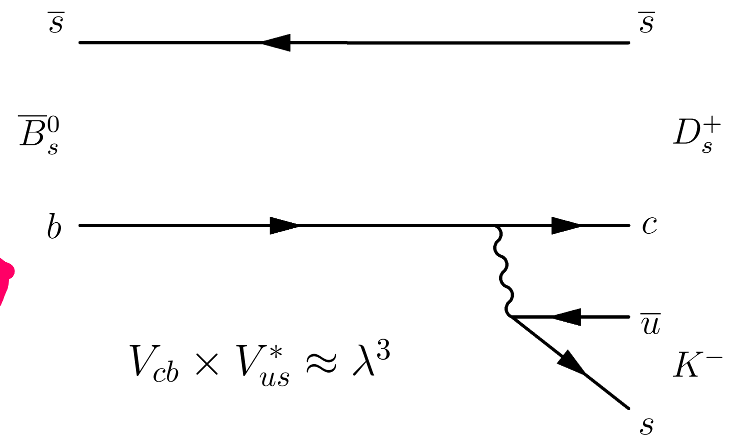
$B^+ \to (\pi^+\pi^-\pi^+)(K_S)$

$a_1(1260)$ K_S
$a_1(164)$



Measurement of CP violation in $B_s^0 \to D_s^{\mp} K^{\pm}$

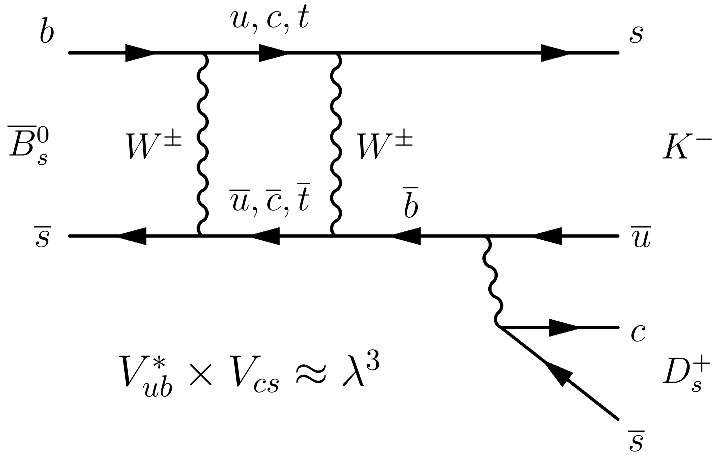
- CP violation parameters are function of CKM angles β_s and γ
- Sensitivity to γ is achieved since interfering amplitudes have similar magnitudes $r_{D_sK} \sim \mathcal{O}(\lambda^3)$



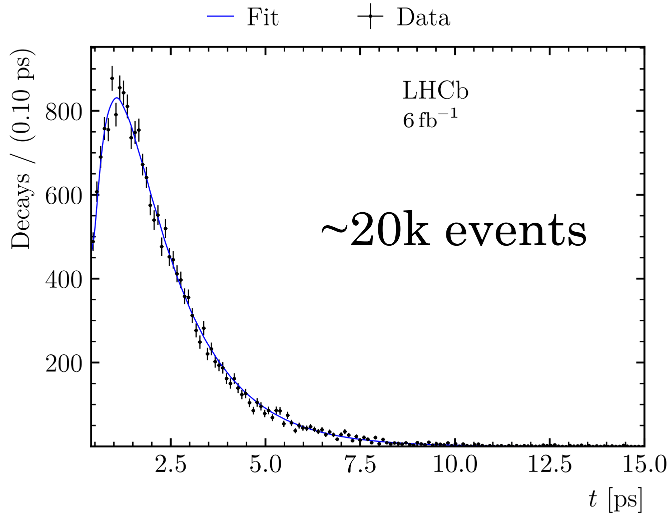
$$\frac{d\Gamma_{B_s^0 \to f}(t)}{dt} = \frac{1}{2}|A_f|^2(1+|\lambda_f|^2)e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_f\cos(\Delta m_s t) - S_f\sin(\Delta m_s t)\right],$$

$$\frac{d\Gamma_{\overline{B}_s^0 \to f}(t)}{dt} = \frac{1}{2}|A_f|^2\left|\frac{p}{q}\right|^2(1+|\lambda_f|^2)e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - C_f\cos(\Delta m_s t) + S_f\sin(\Delta m_s t)\right],$$

CP violation parameters relate to γ and β_s

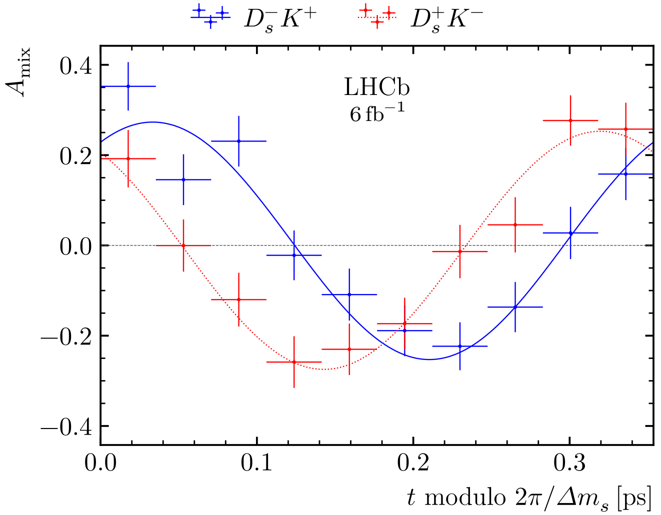


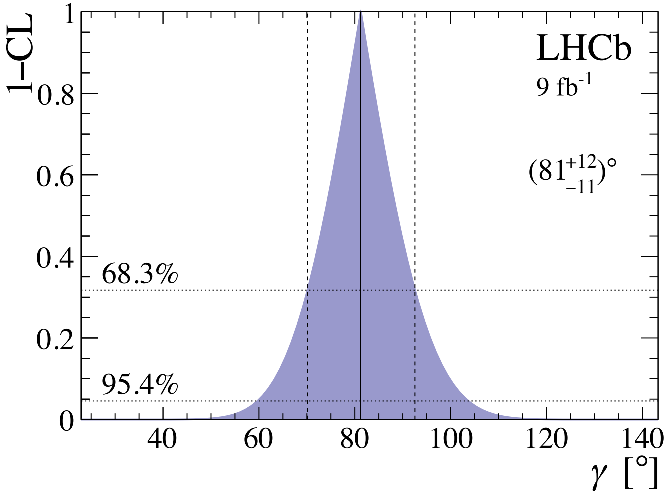
Measurement of CP violation in $B_s^0 \to D_s^{\mp} K^{\pm}$



$$
\begin{aligned}
C_f &= 0.791 \pm 0.061 \pm 0.022 \,, \\
A_f^{\Delta\Gamma} &= -0.051 \pm 0.134 \pm 0.058 \,, \\
A_{\bar{f}}^{\Delta\Gamma} &= -0.303 \pm 0.125 \pm 0.055 \,, \\
S_f &= -0.571 \pm 0.084 \pm 0.023 \,, \\
S_{\bar{f}} &= -0.503 \pm 0.084 \pm 0.025 \,,
\end{aligned}
$$

- Unbinned maximum likelihood fit to signal-weighted decay time distribution
- 8.6σ from CP symmetry
- Combination with Run 1 and taking β_s from LHCb $B_s^0 \to J/\psi\phi$





$$
\begin{aligned}
\gamma &= (81^{+12}_{-11})^\circ \,, \\
\delta &= (347.6 \pm 6.3)^\circ \,, \\
r_{D_s K} &= 0.318^{+0.034}_{-0.033} \,.
\end{aligned}
$$