Imperial College London

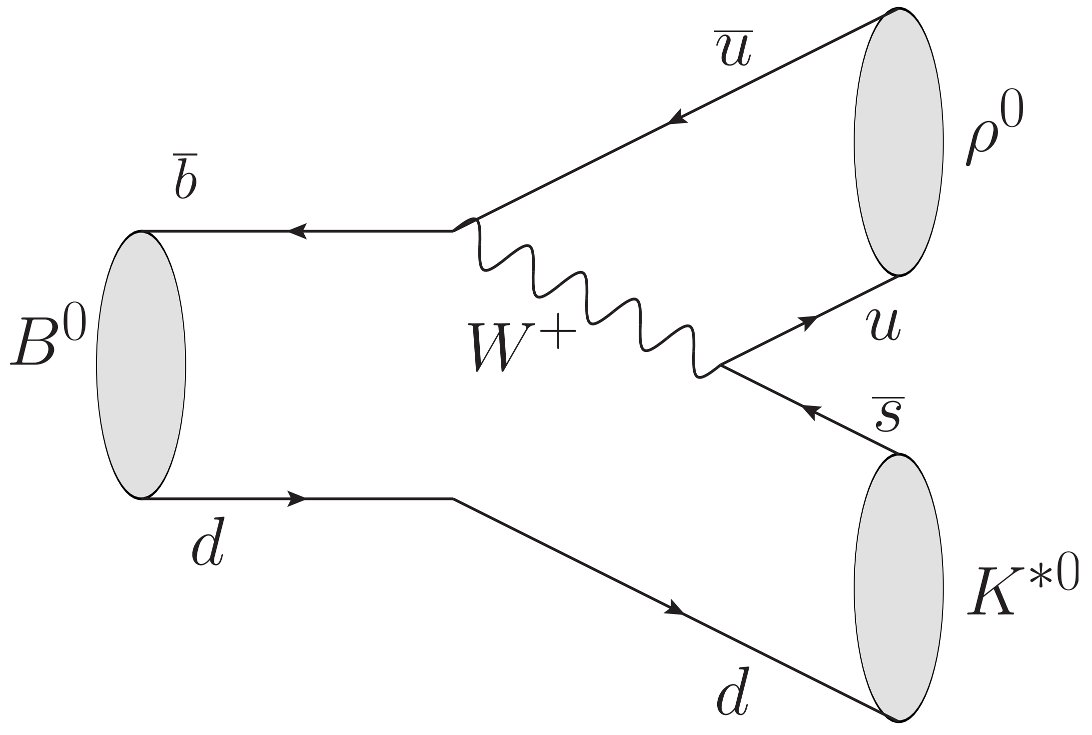
Recent results on $B \to VV$ decays at LHCb

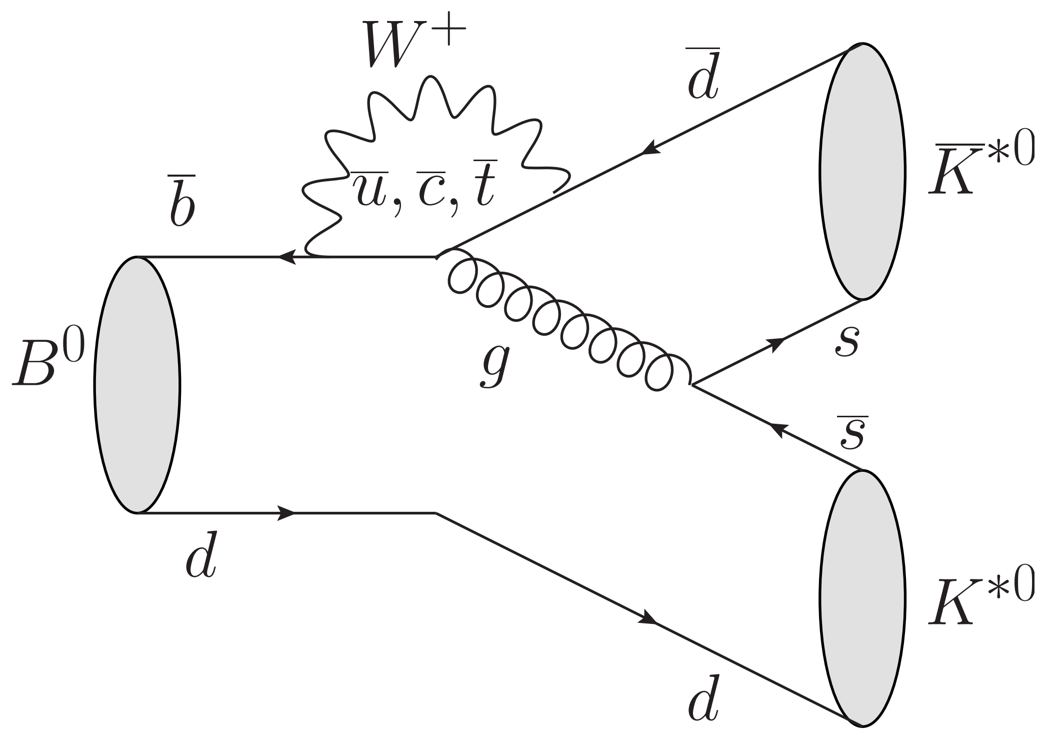
Nonleptonic decays of heavy mesons Workshop,
IPPP Durham, 24.03.26

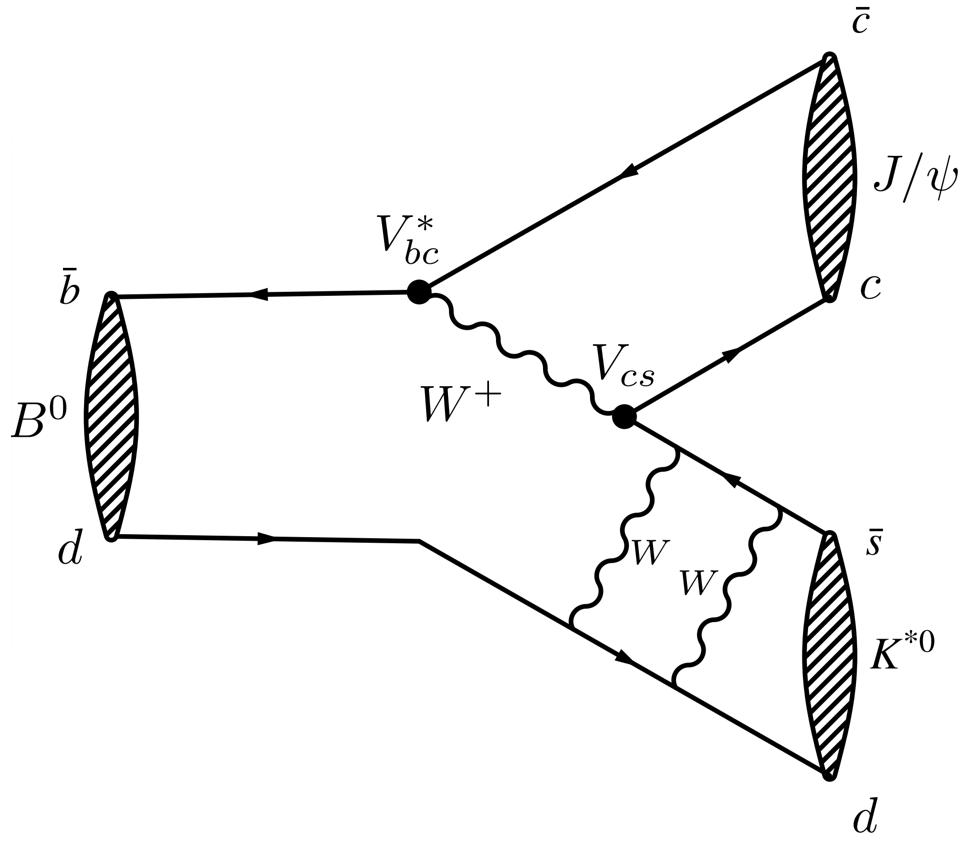
Davide Lancierini (ICL)

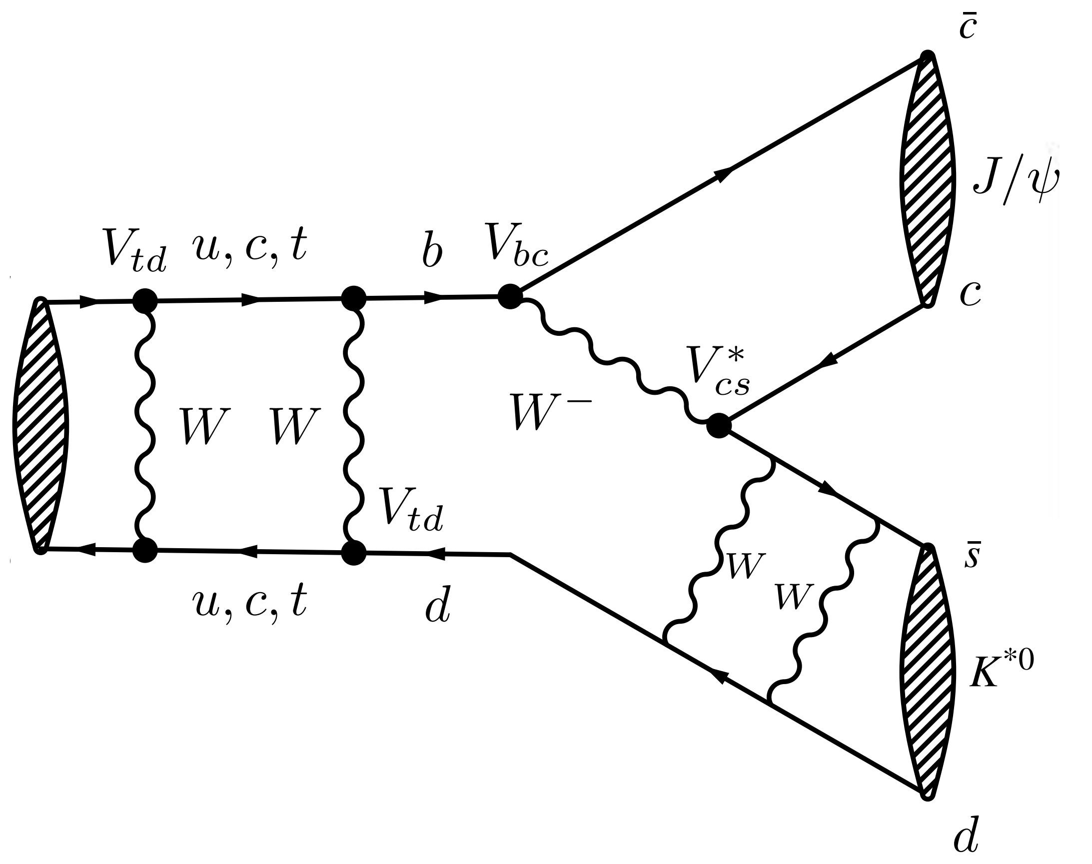
$B \to V_1 V_2$ decays

- Diverse range of decays of a B-meson to two spin-1 (V) mesons
- Spin structure → amplitude analysis: plethora of accessible observables
- Rich test-bed for the Standard Model (SM)
  - Measurement of highly suppressed decays (CKM, loop and OZI)
  - What it the origin of the tension btw SM prediction and experiment in polarisation fractions of hadronic $B \to VV$ decays?
  - Is ϕ_s consistent with its SM precise prediction?
- And many more…









$B \to V_1 V_2$ measurements

Level of difficulty, statistical power needed

○ Integrated branching ratios

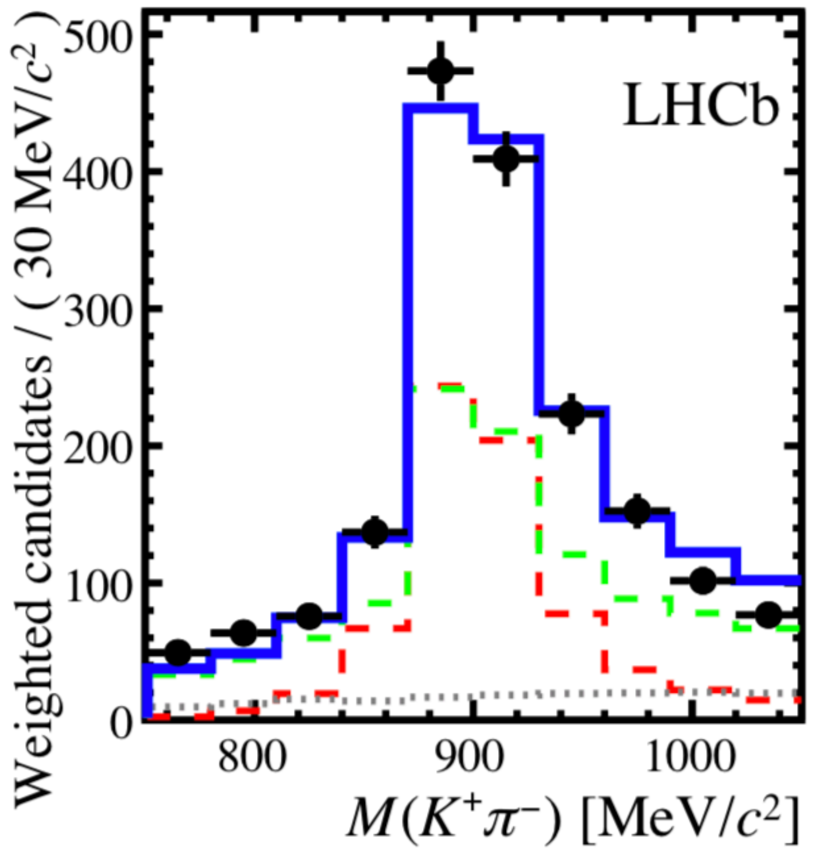
- At LHCb branching ratios are accessed relatively to control modes with same final state to cancel systematic uncertainties (detection effs., $\sigma_{b\bar{b}}$, L …)

$B \to V_1 V_2$ measurements

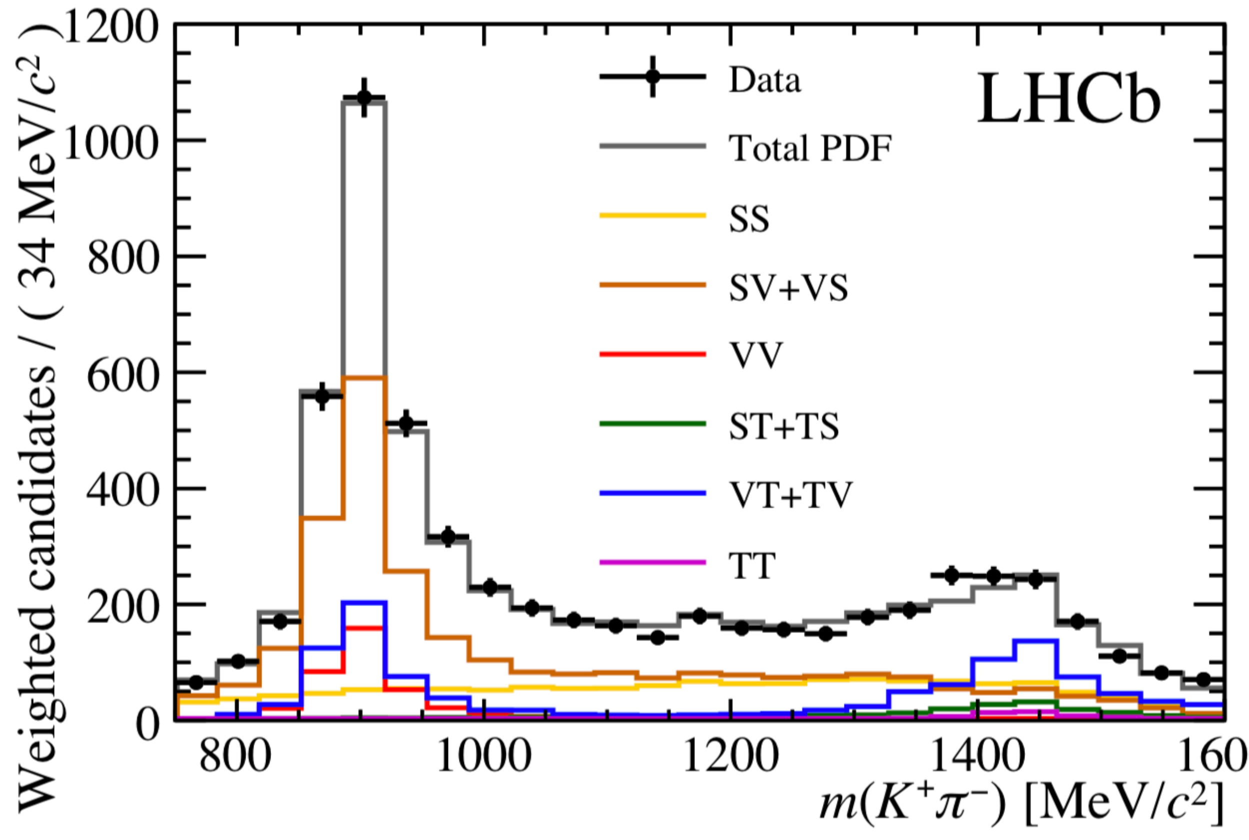
Level of difficulty, statistical power needed

○ Integrated branching ratios

- At LHCb branching ratios are accessed relatively to control modes with same final state to cancel systematic uncertainties (detection effs., $\sigma_{b\bar{b}}$, L …)
- Require careful study of relative efficiencies and often need an amplitude analysis anyway to extract the desired component.
  - Eg:$K^{*0}(892) \to K^{\pm}\pi^{\mp}$ selected in $m_{K\pi}$ window →presence of broad $K^{*0}(800), K^{*0}(1430)$ and NR contributions to be included



[JHEP 07 (2019) 032]



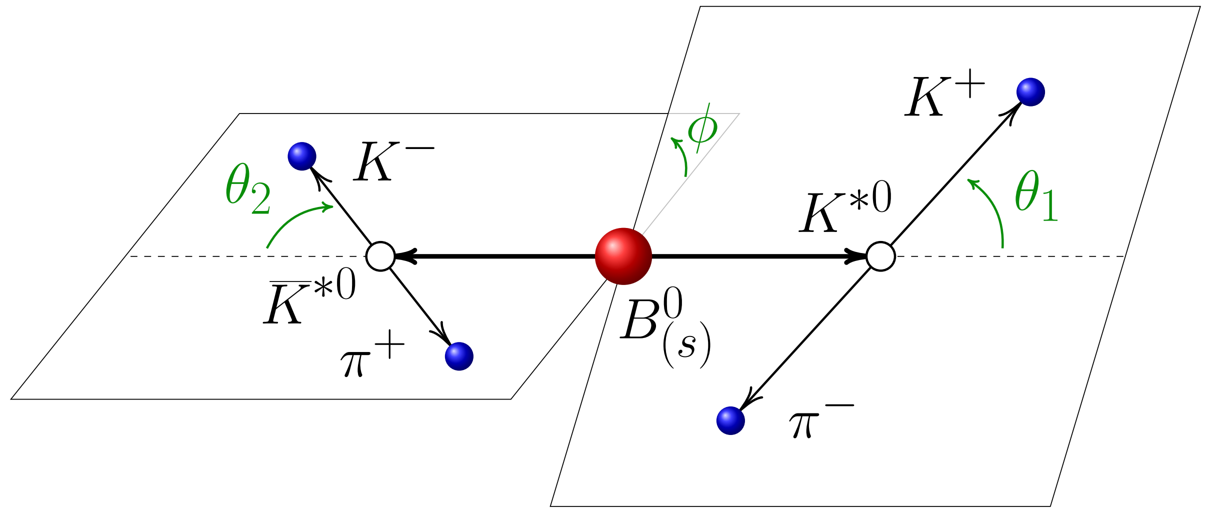
[JHEP 03 (2018) 140]

$B \to V_1 V_2$ measurements

Level of difficulty, statistical power needed

- ○ Integrated branching ratios
- ○ Angular analyses

- Study of differential distributions of $B \to V_1 V_2$ decays offer access to rich angular structure



$$\frac{d\Gamma}{d\Omega\, dm_1\, dm_2} \propto \left|\sum_i A_i g_i(m_1, m_2, \Omega)\right|^2$$

$P \to VV:$ 3 polarisation amplitudes, $A_0, A_\perp, A_\parallel$, extract their magnitude and phases together with their relative fractions

$$f_{L,\parallel,\perp} = \frac{|A_{0,\parallel,\perp}|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}$$

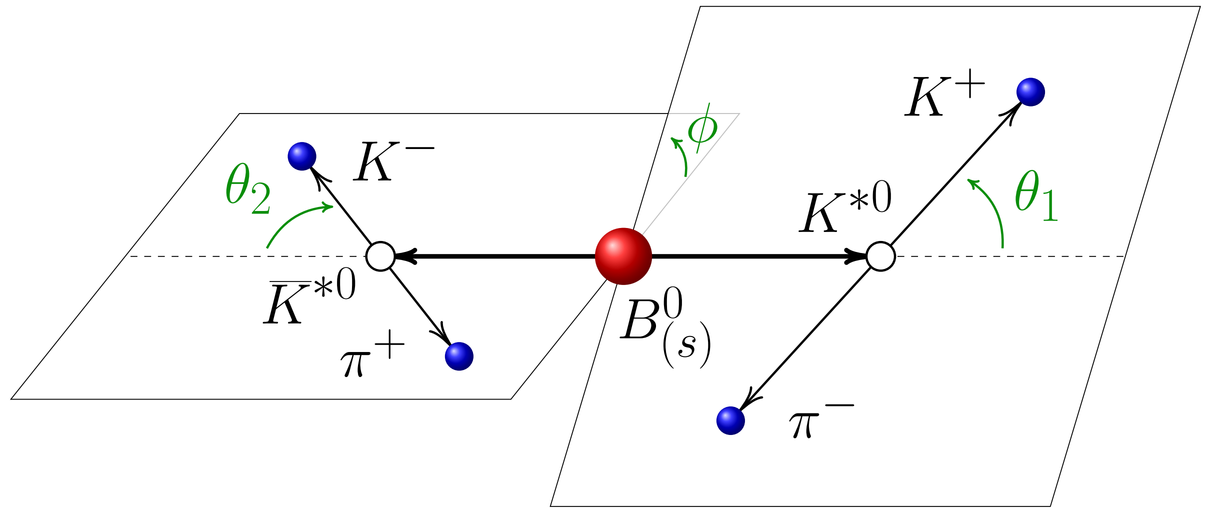
- This is not the only parametrisation on the market! Covariant formalism also used (although less common)

$B \to V_1 V_2$ measurements

Level of difficulty, statistical power needed

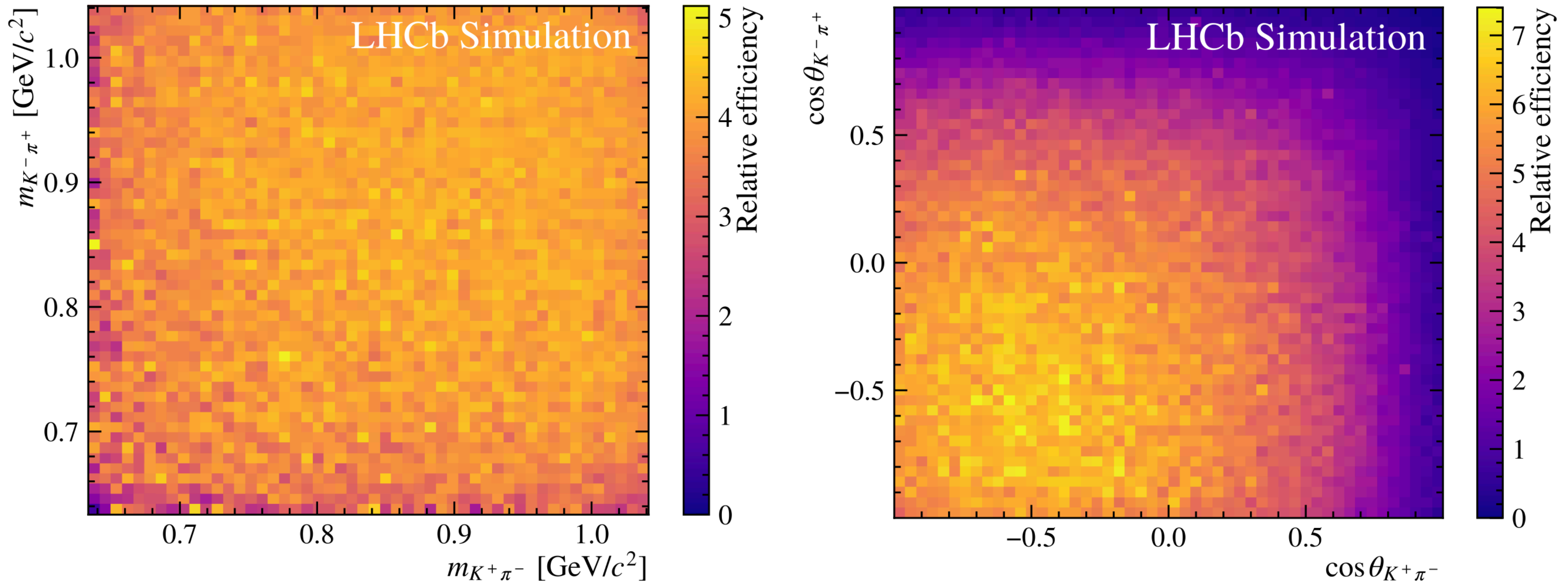
- ○ Integrated branching ratios
- ○ Angular analyses

- Study of differential distributions of $B \to V_1 V_2$ decays offer access to rich angular structure



$$\frac{d\Gamma}{d\Omega dm_1 dm_2} \propto |\sum_i A_i g_i(m_1, m_2, \Omega)|^2$$

- Require control of the differential rate “warping” effects due to angular acceptance (forward region) mass requirements and finite detector resolution



$B \to V_1 V_2$ measurements

Level of difficulty, statistical power needed

- Integrated branching ratios
- Angular analyses
- Time integrated CP asymmetries

- For self tagged modes, one can perform ΔA_{CP} of branching ratios or polarisation fractions either integrated or in regions of phase-space
  - Require control of production and detection asymmetries, often a control mode where these are known is used
- For untagged modes, time independent and untagged angular analyses allow to access direct and mixing induced CP observables: [PRD.88.016007]
- Triple product asymmetries involving products of the kind:

$$\vec{p}_{V_1} \cdot (\vec{\varepsilon}_1 \times \vec{\varepsilon}_2)$$

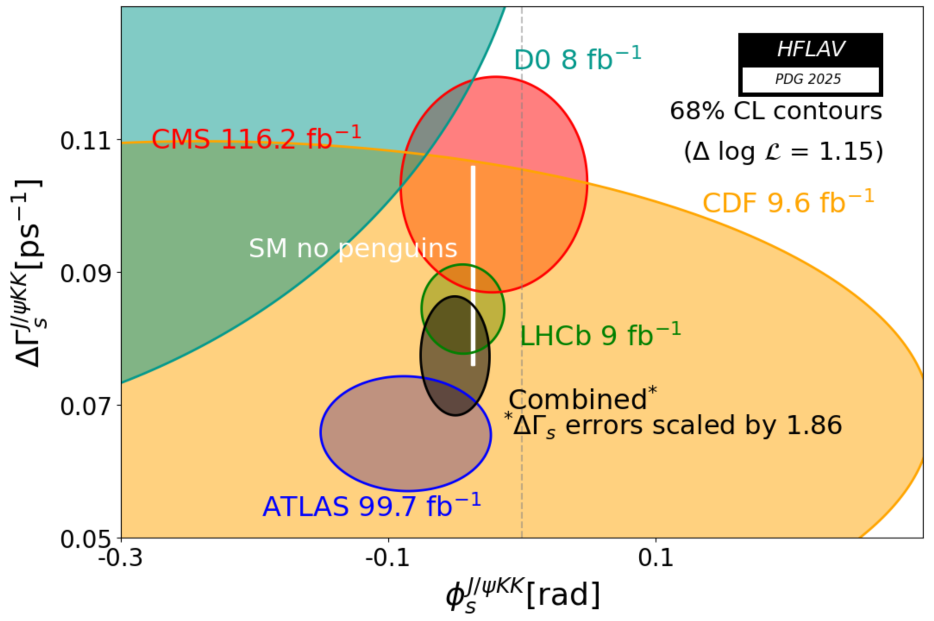
  - Can be as "easy" as a counting experiment for some exceptionally clean channels such as $B^0_{(s)} \to \phi\phi$ and $B^0_{(s)} \to K^{*0}\bar{K}^{*0}$

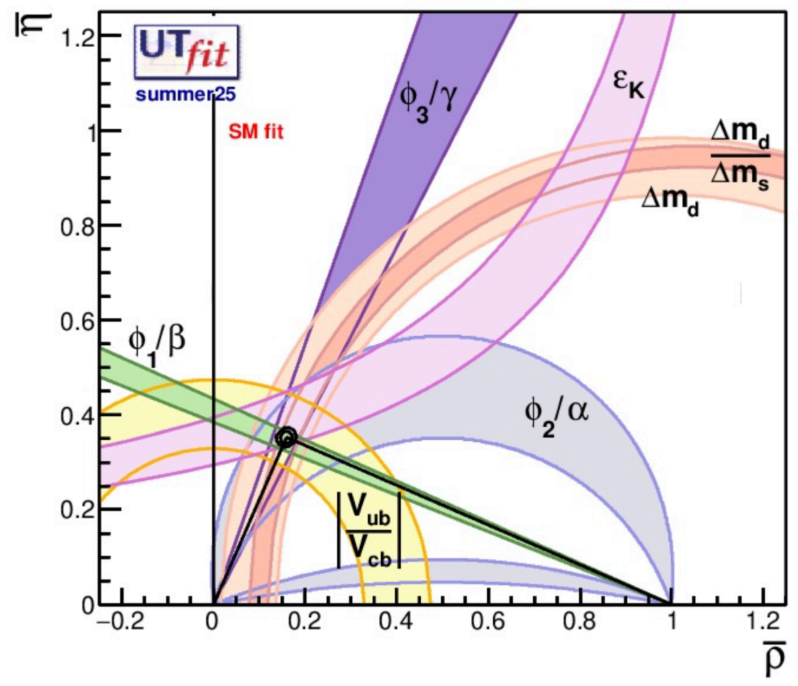
$B \to V_1 V_2$ measurements

Level of difficulty, statistical power needed

- Integrated branching ratios
- Angular analyses
- Time integrated CP asymmetries
- Time dependent CP asymmetries

- Usually the most complex analyses as they factor all previous experimental difficulties together
  - Require control of production and detection asymmetries, often a control mode where these are known is used
  - Require control of flavour tagging performance and B decay time resolution
- Allow access to observables in time dependent decay width such as CKM angles and mixing parameters :



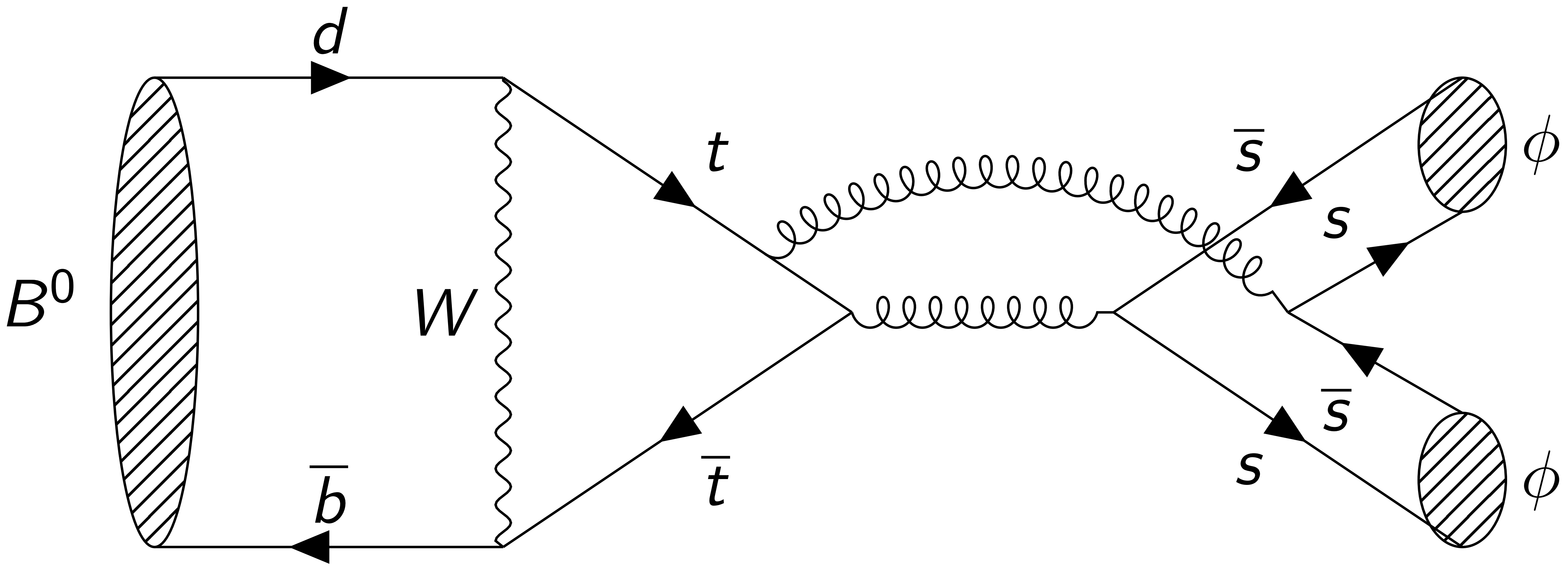


$$B^0 \to \phi\phi$$

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

[JHEP 12 (2025) 026]

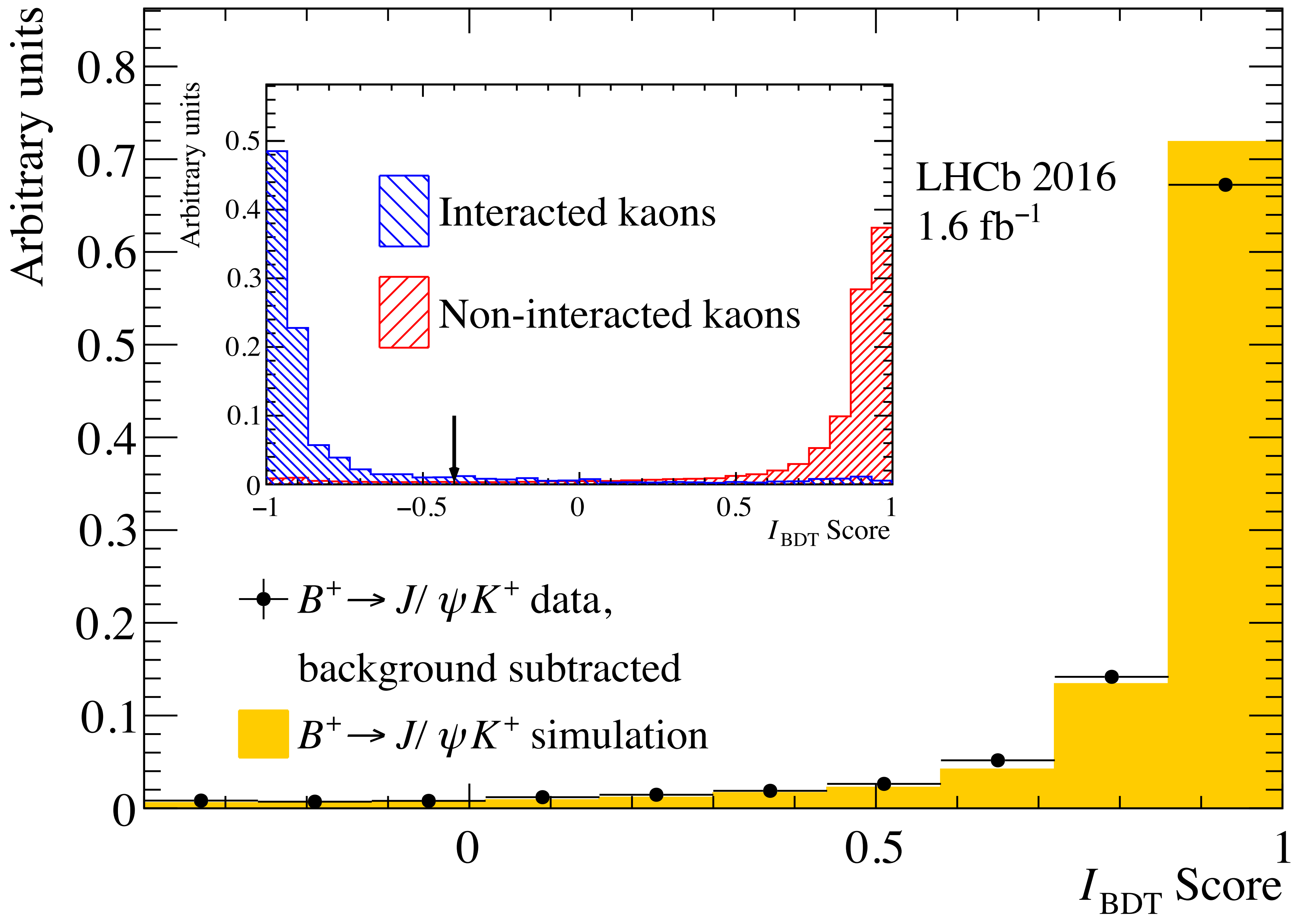
- $B_s^0 \to \phi\phi$ flaghisp charmless $B \to VV$ decay for its clean signature and relatively background free environment measurements of β_s
- $B^0 \to \phi\phi$ was never observed
  - $\bar{b}d \to s\bar{s}$ annihilation: loop, CKM and OZI suppressed
  - Small expt BF within the SM $\sim O(10^{-8})$ excellent SM probe
- Previous searches with LHCb Run1 data → world best limit at $Br(B^0 \to \phi\phi) < 2.7 \times 10^{-8}$ at $90\,\%$ CL

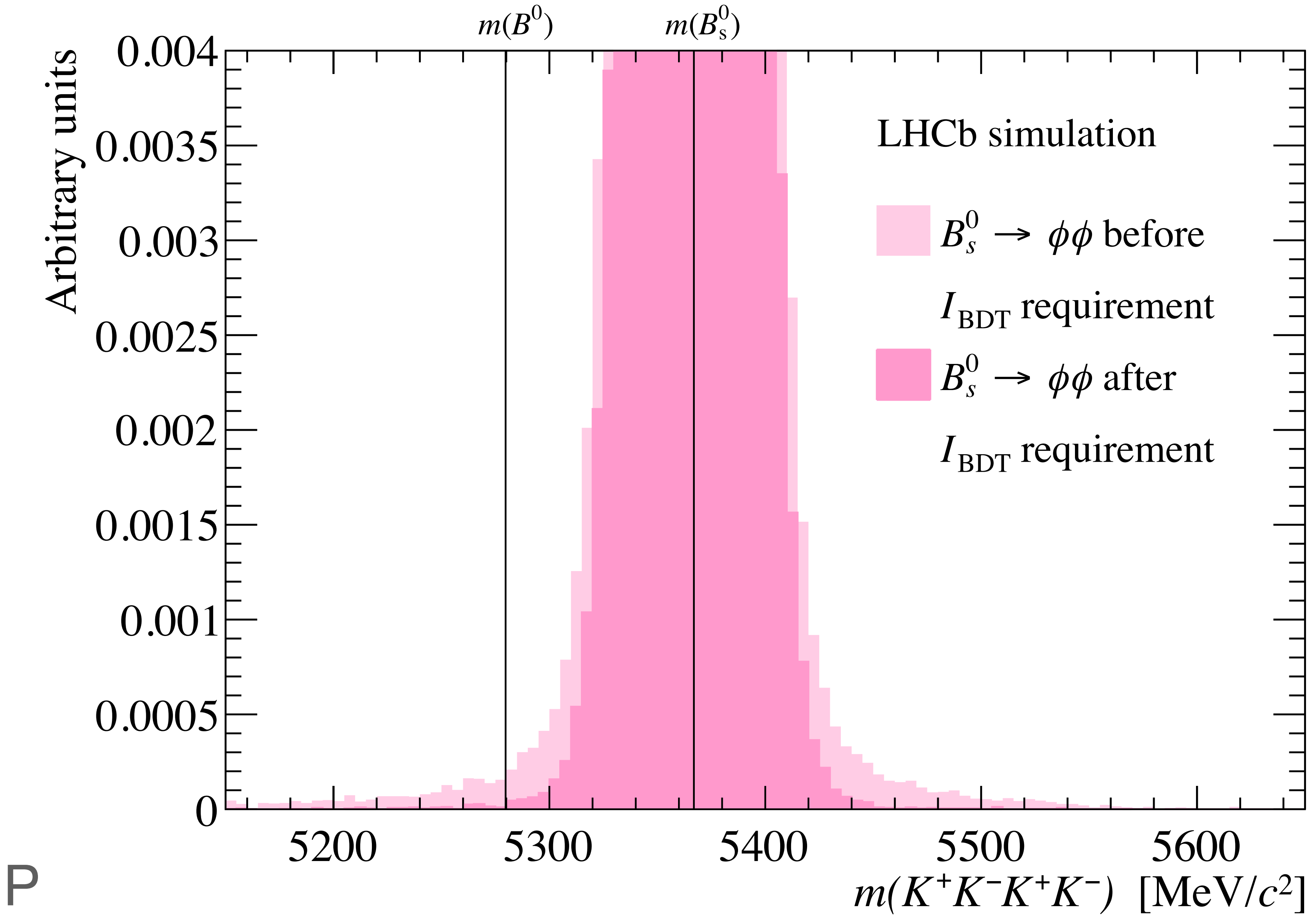


[JHEP 12 (2025) 026]

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

- New analysis uses full Run1+2 data
  - 2x the dataset. + 2x sensitivity wrt previous search
- Increase in sensitivity from improved control of backgrounds
  - Innovative techniques to reduce impact of decay in flight and final state interactions from $B_s \to \phi\phi$
  - These effects yield kinked tracks, worse momentum resolution, smear of mass peak → B_s leaking into B region
  - Kaon interaction boosted decision tree (BDT) to reject candidates with hadronic interactions
    - Use muons from $B^+ \to J/\psi(\to \mu\mu)K^+$ as proxy for non-interacted kaon tracks





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

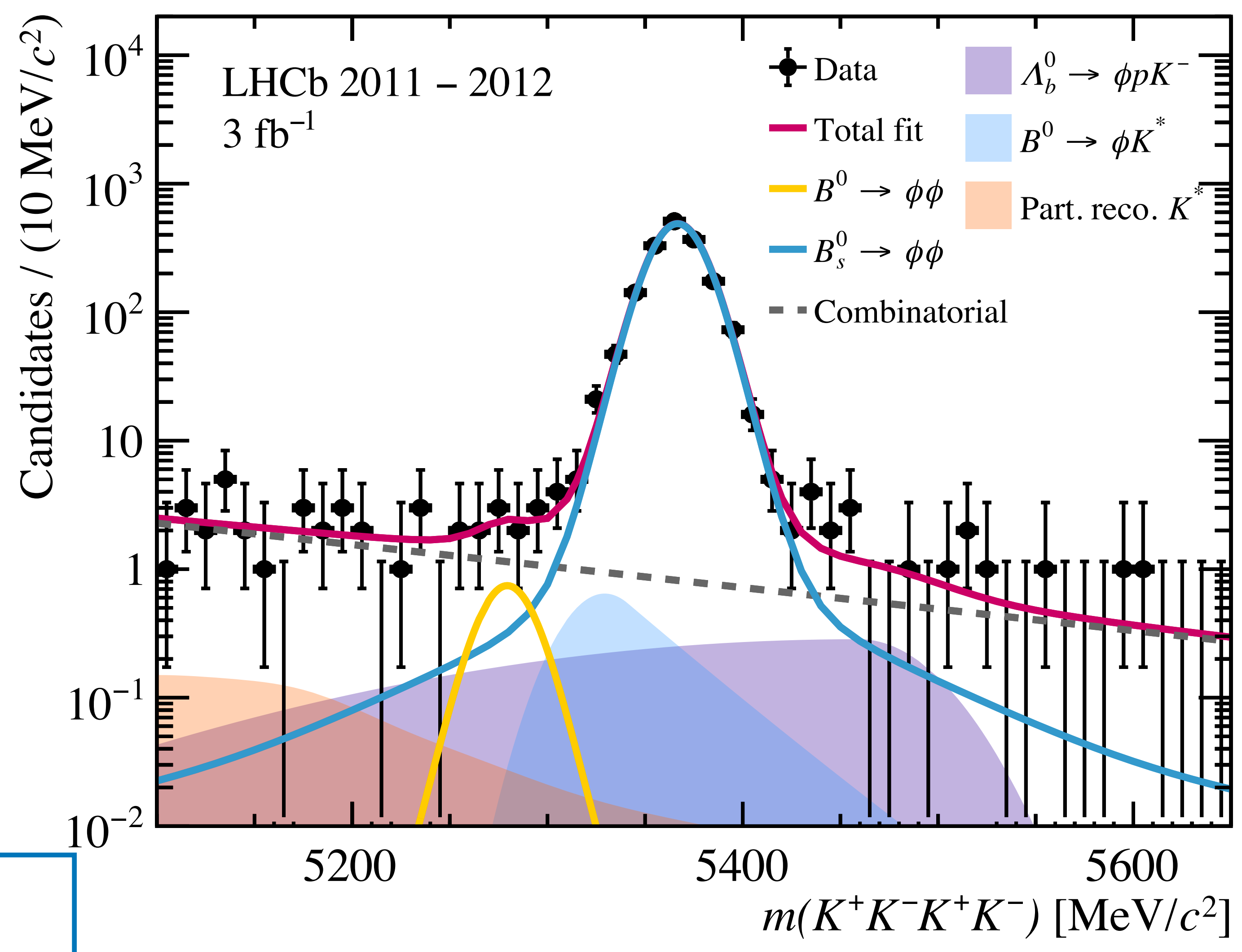
[JHEP 12 (2025) 026]

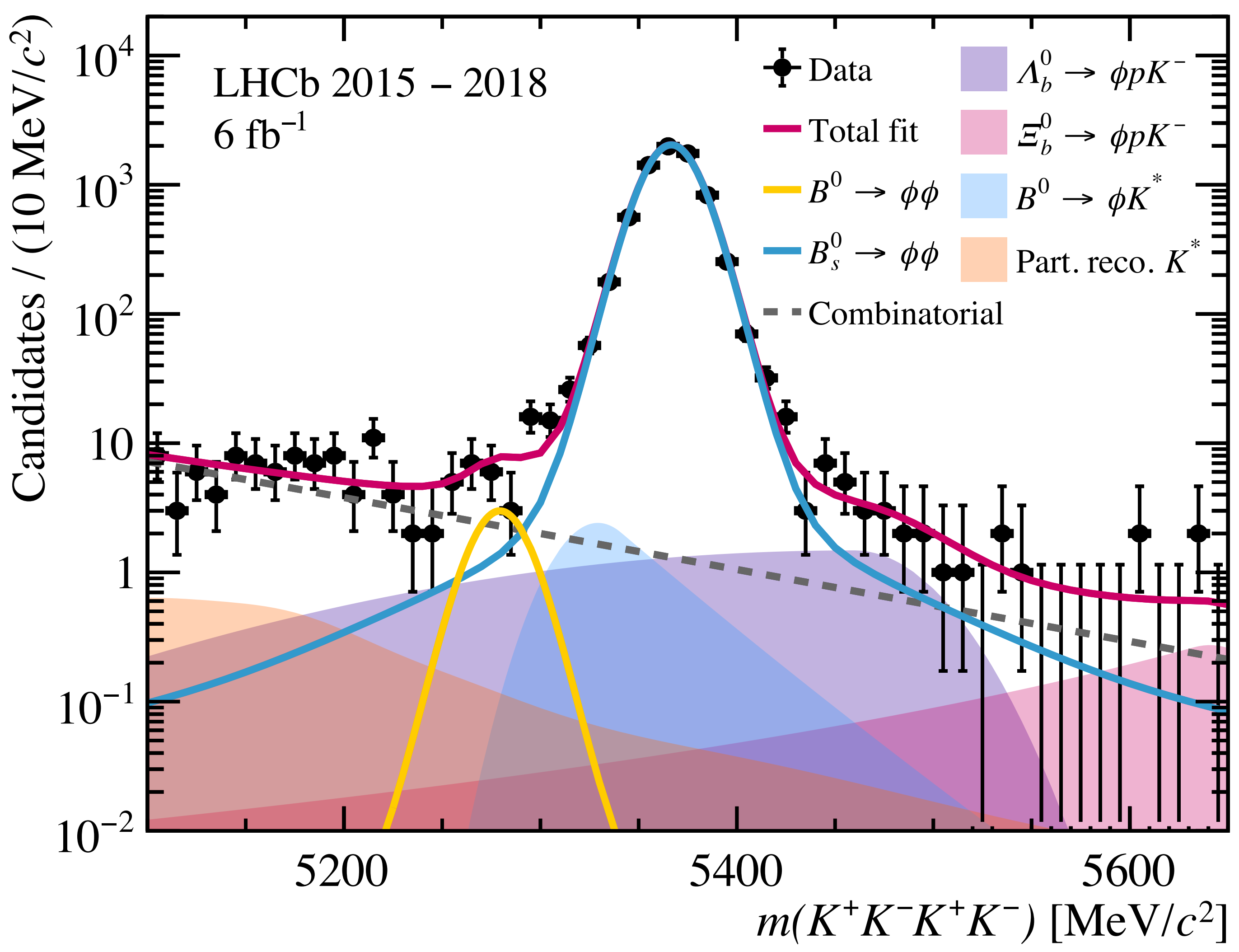
- Signal is consistent with the background only hypothesis at 1.9σ
- Decay not observed → set upper limit with CLs
- New limit is at:

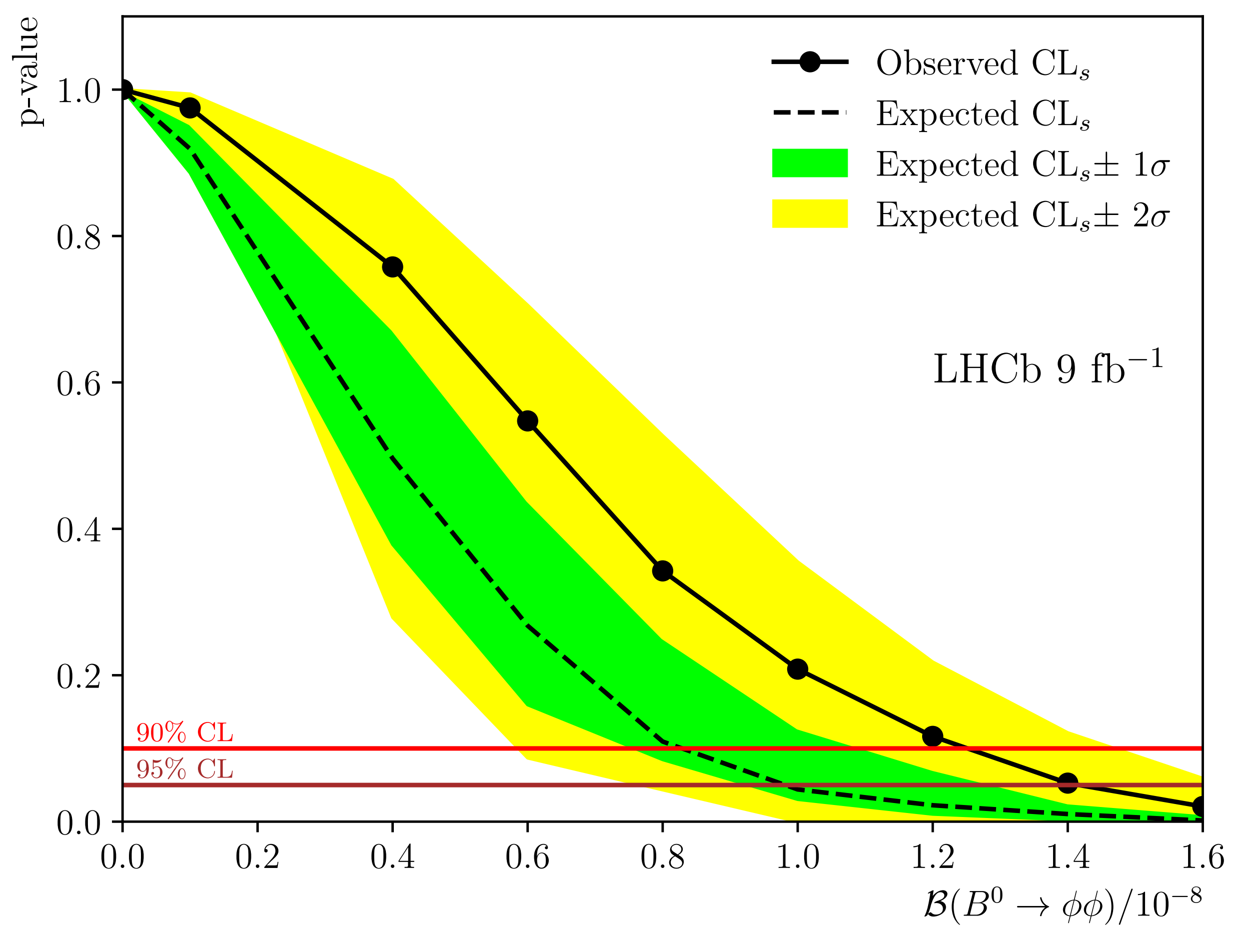
$$Br(B^0 \to \phi\phi) < 1.3(1.4) \times 10^{-8}$$

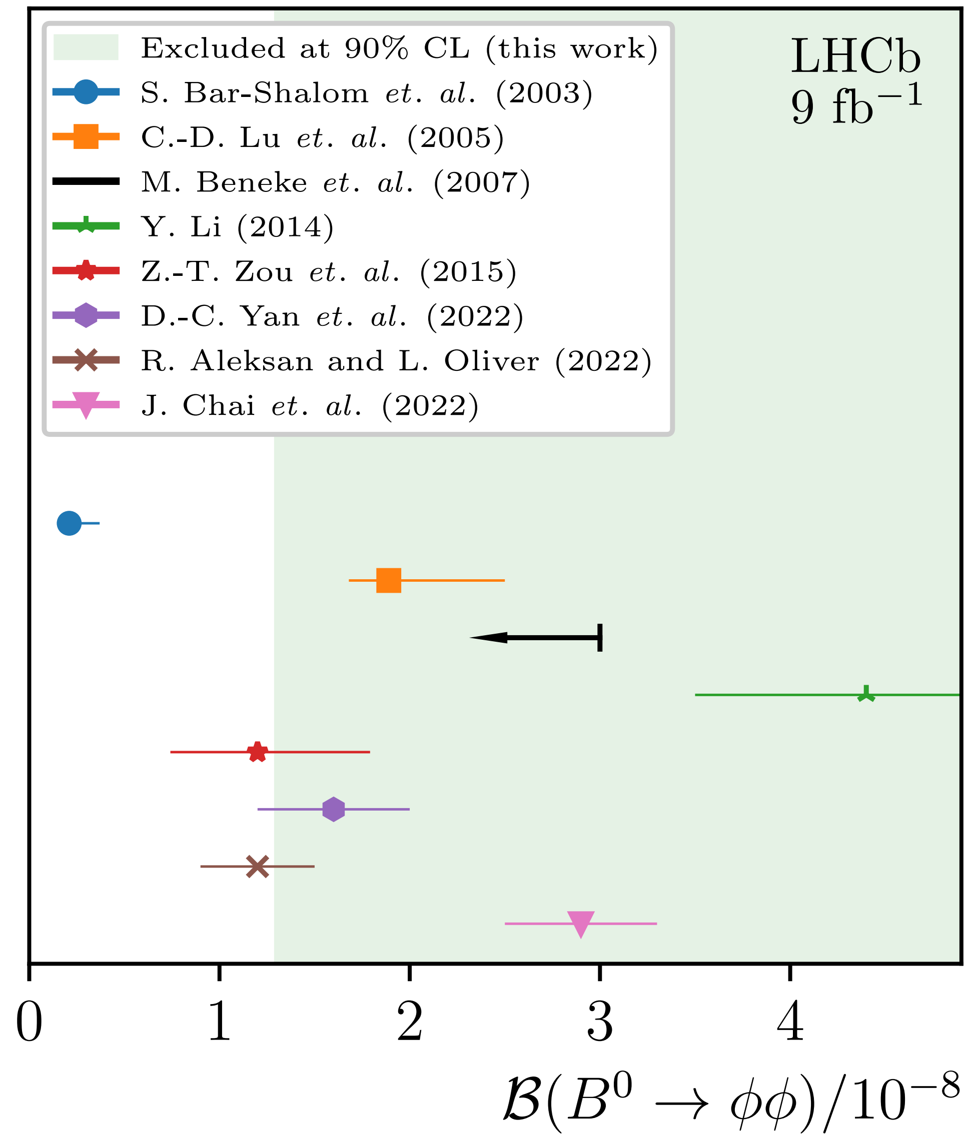
at 90% (95%) CL

- Factor 2 improvement over prev. result
- Approaching lower limit of theoretical predictions
- Exciting prospects for Run 3









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

Amplitdue analysis of $B^+ \to \rho^0 K^{*+}$

[PRL 136 (2026) 021803]

- $B \to VV$ decay , higher branching ratio allows amplitude analysis → performed in the helicty basis: three independent helicity states: A_0, A_+, A_-
  - Working in transversity basis where: $A_0, A_\perp = \dfrac{A_+ - A_-}{\sqrt{2}}, A_\parallel = \dfrac{A_+ + A_-}{\sqrt{2}}$,
  - Transversity amplitdutes have definited CP eigenstates with $A_0, A_\parallel$ CP even and $A_\perp$ CP odd
- Expectation from heavy quark symmetry is that A_0 should prevail over the other two

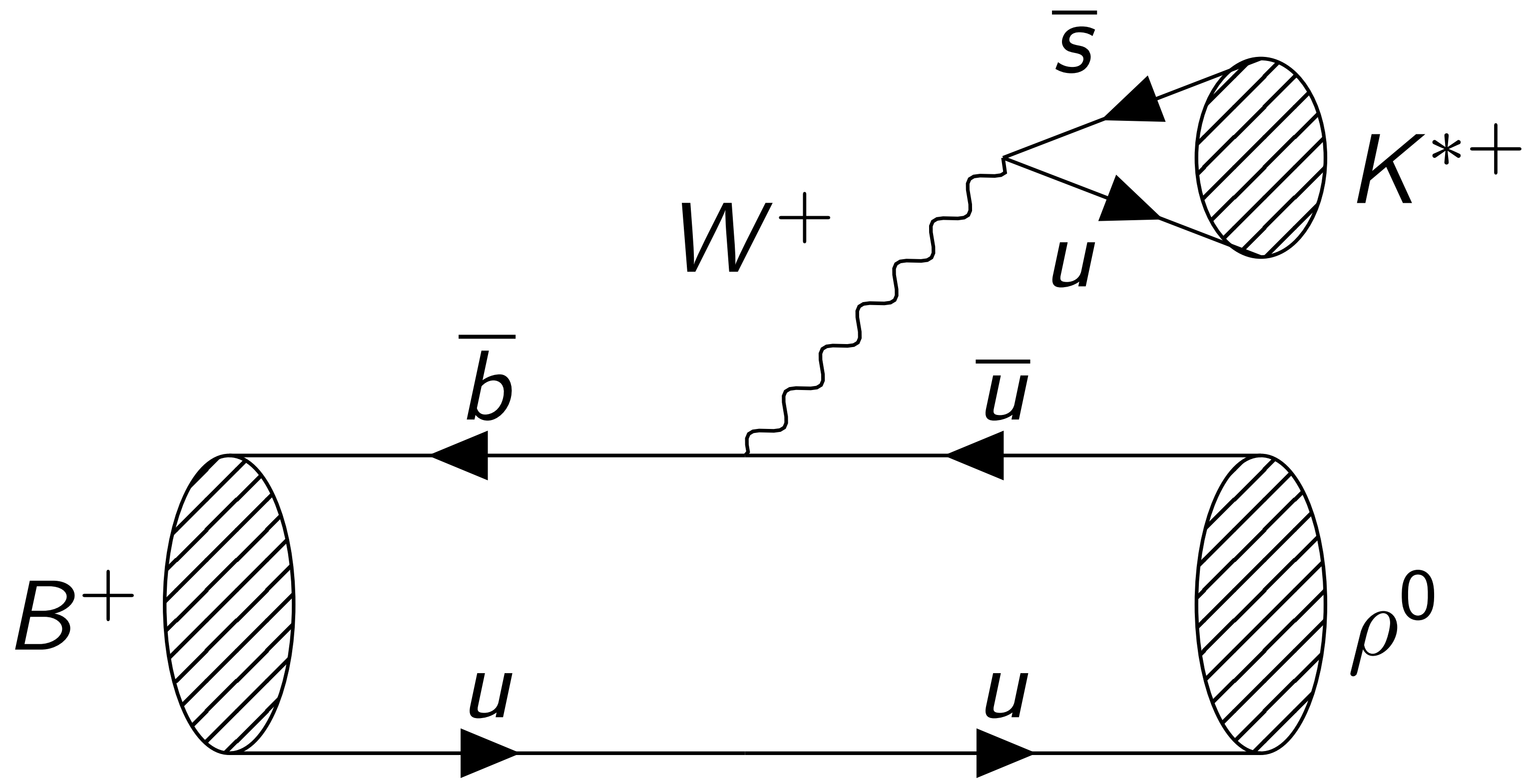
$$f_L = \frac{|A_0|^2}{|A_0|^2 + |A_\perp|^2 + |A_\parallel|^2} \approx 1$$

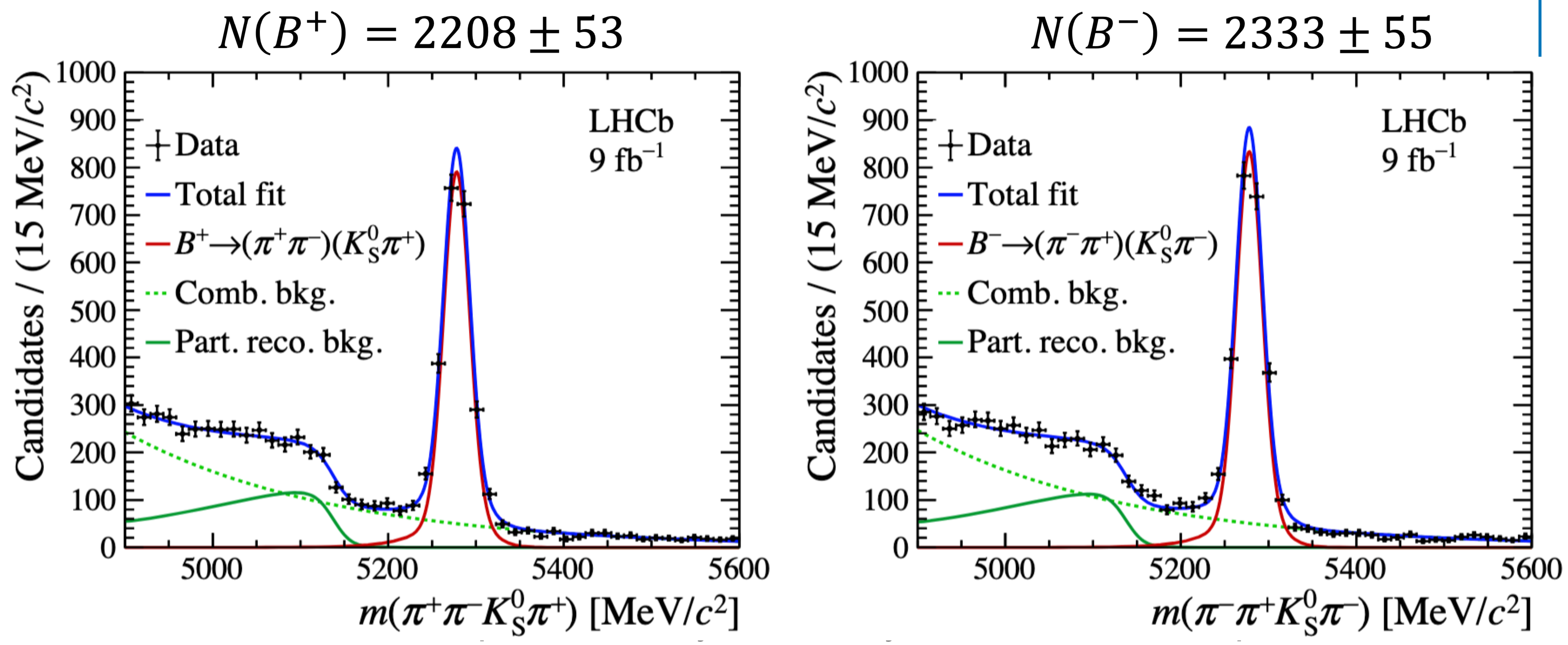
- Part of long standing polarisation puzzle — this amplitude herarchy seems to be respected in tree level $B \to VV$ decays but not in loop induced $B \to VV$ decays

Amplitdue analysis of $B^+ \to \rho^0 K^{*+}$

[PRL 136 (2026) 021803]

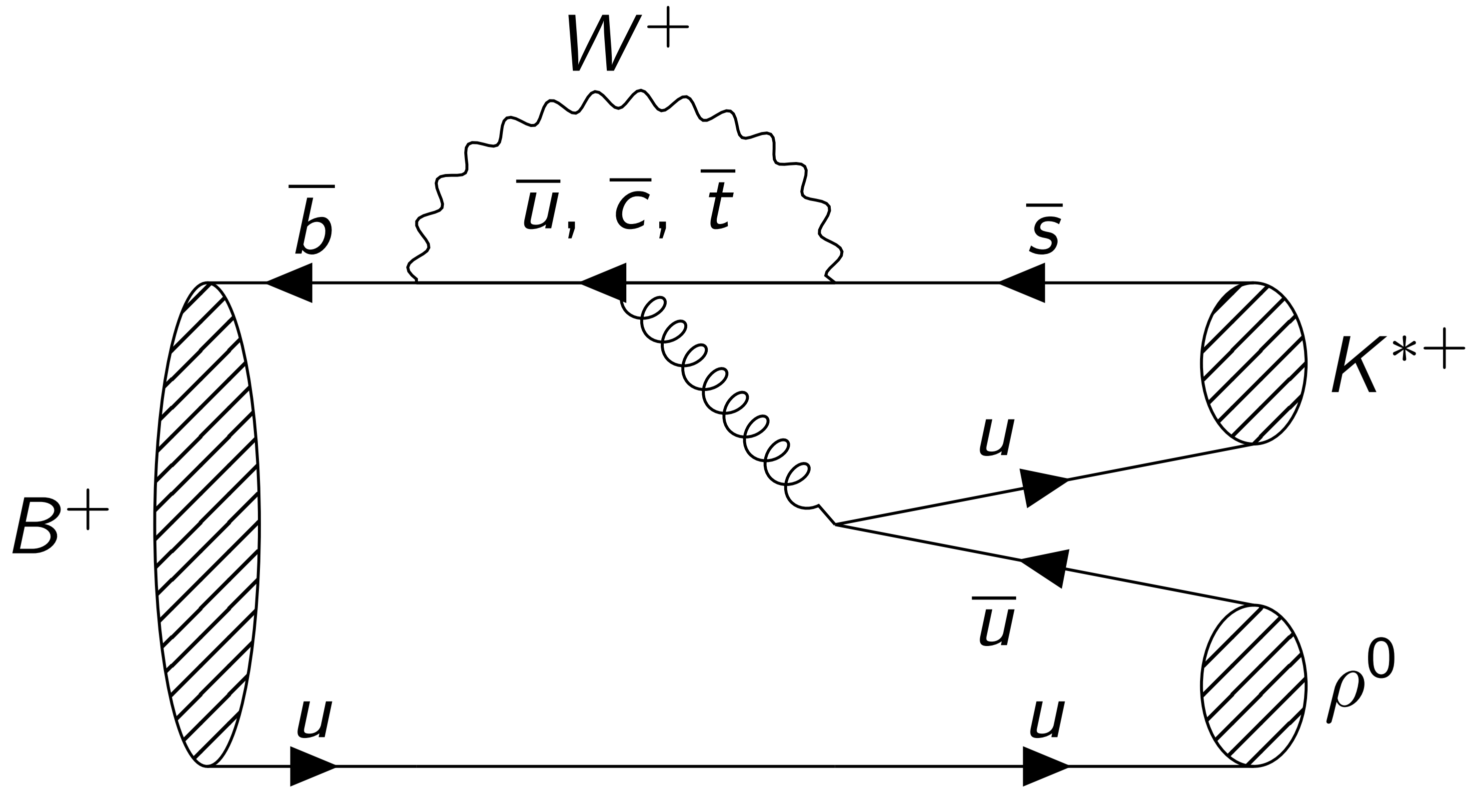
- The $B^+ \to \rho^0 K^{*+}$ decay was not studied at LHCb before
  - Amplitude analysis from BaBar: branching fraction, polarisation and CP asymmetry were measured ($f_L = 0.78 \pm 0.12$)
  - New analysis with full Run1 + Run2 LHCb datasets
- Recostructed with $\rho^0 \to \pi^+\pi^-$, $K^{*+} \to K^0_S\pi^+$
- Simultaneous fit to B^+ and B^- candidates, share e.g. common intermediate resonance parameters





$N(B^+) = 2208 \pm 53$

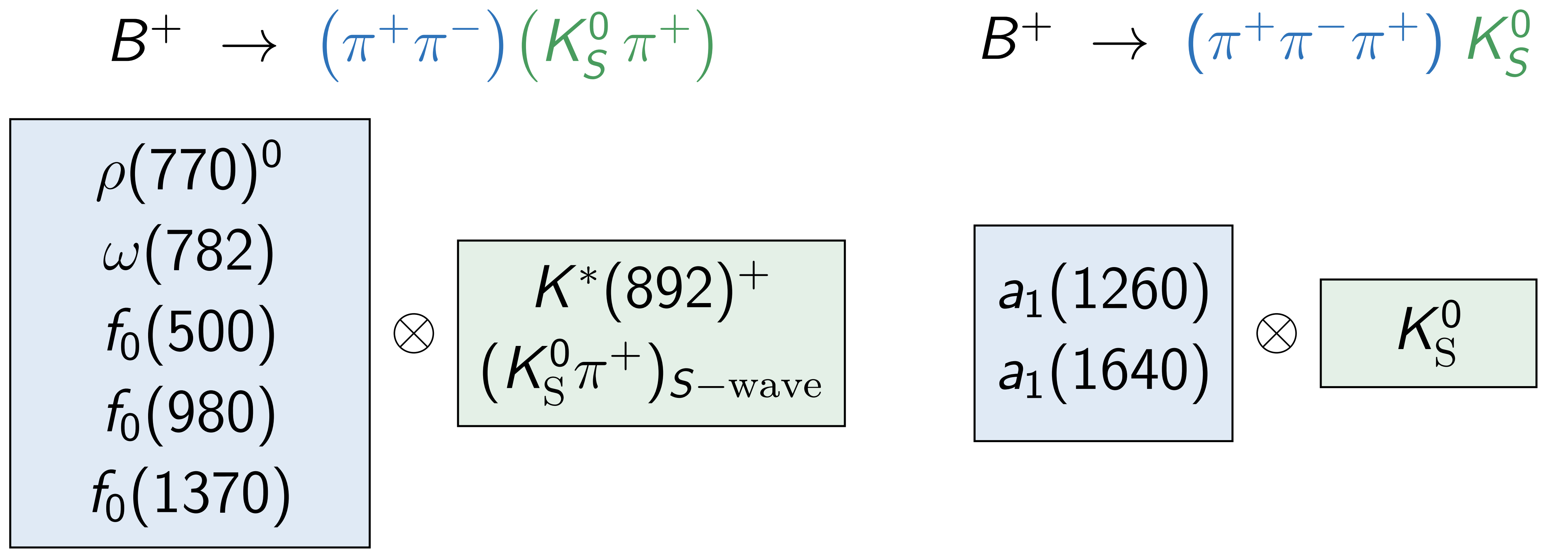
$N(B^-) = 2333 \pm 55$



Amplitdue analysis of $B^+ \to \rho^0 K^{*+}$

[PRL 136 (2026) 021803]

- 5D amplitude analysis of $B^+ \to (\pi^+\pi^-)(K^0_S\pi^+)$ in the phase-space regions of
  - $(0.3 < m(\pi^+\pi^-) < 1.1)$ GeV/c^2
  - $(0.75 < m(K^0_S\pi^+) < 1.2)$ GeV/c^2



$B^+ \to (\pi^+\pi^-)(K^0_S\pi^+)$

$\rho(770)^0$
$\omega(782)$
$f_0(500)$
$f_0(980)$
$f_0(1370)$

$\otimes$

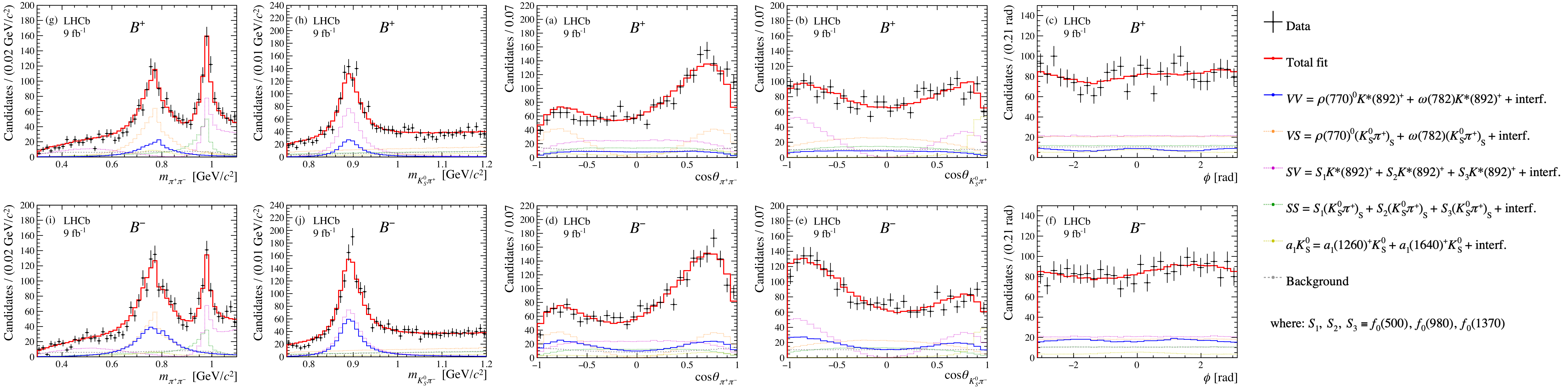
$K^*(892)^+$
$(K^0_S\pi^+)_{S\text{-wave}}$

$B^+ \to (\pi^+\pi^-\pi^+)\,K^0_S$

$a_1(1260)$
$a_1(1640)$

$\otimes$

K^0_S



Amplitdue analysis of $B^+ \to \rho^0 K^{*+}$

[PRL 136 (2026) 021803]

- Most precise CP averaged longitudinal polarisation fraction:

$$f_L^{\text{avg}} = \frac{|A_0|^2 + |\bar{A}_0|^2}{\sum_{\lambda\in\{0,\perp,\|\}} (|\bar{A}_\lambda|^2 + |A_\lambda|^2)} = 0.721 \pm 0.027 \text{ (stat)} \ \pm 0.030 \text{ (syst)}$$

  - Consistent with BaBar and most theory predictions

- Direct CP asymmetry (first observation at > 5σ in this decay)

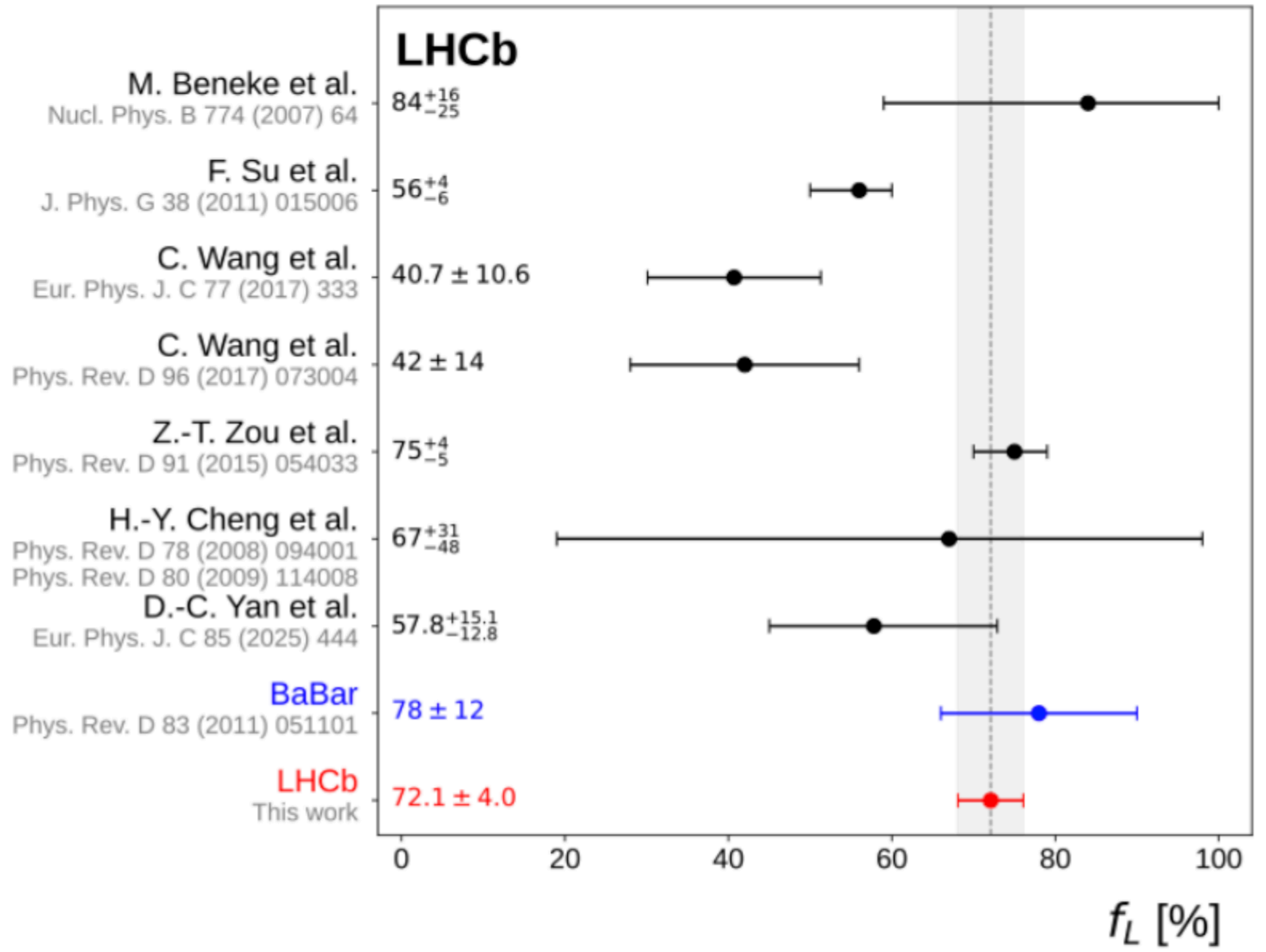
$$A_{CP} = \frac{\sum_{\lambda\in\{0,\perp,\|\}} (|\bar{A}_\lambda|^2 - |A_\lambda|^2)}{\sum_{\lambda\in\{0,\perp,\|\}} (|\bar{A}_\lambda|^2 + |A_\lambda|^2)} = 0.506 \pm 0.062 \text{ (stat.)} \ \pm 0.025 \text{ (syst.)}$$

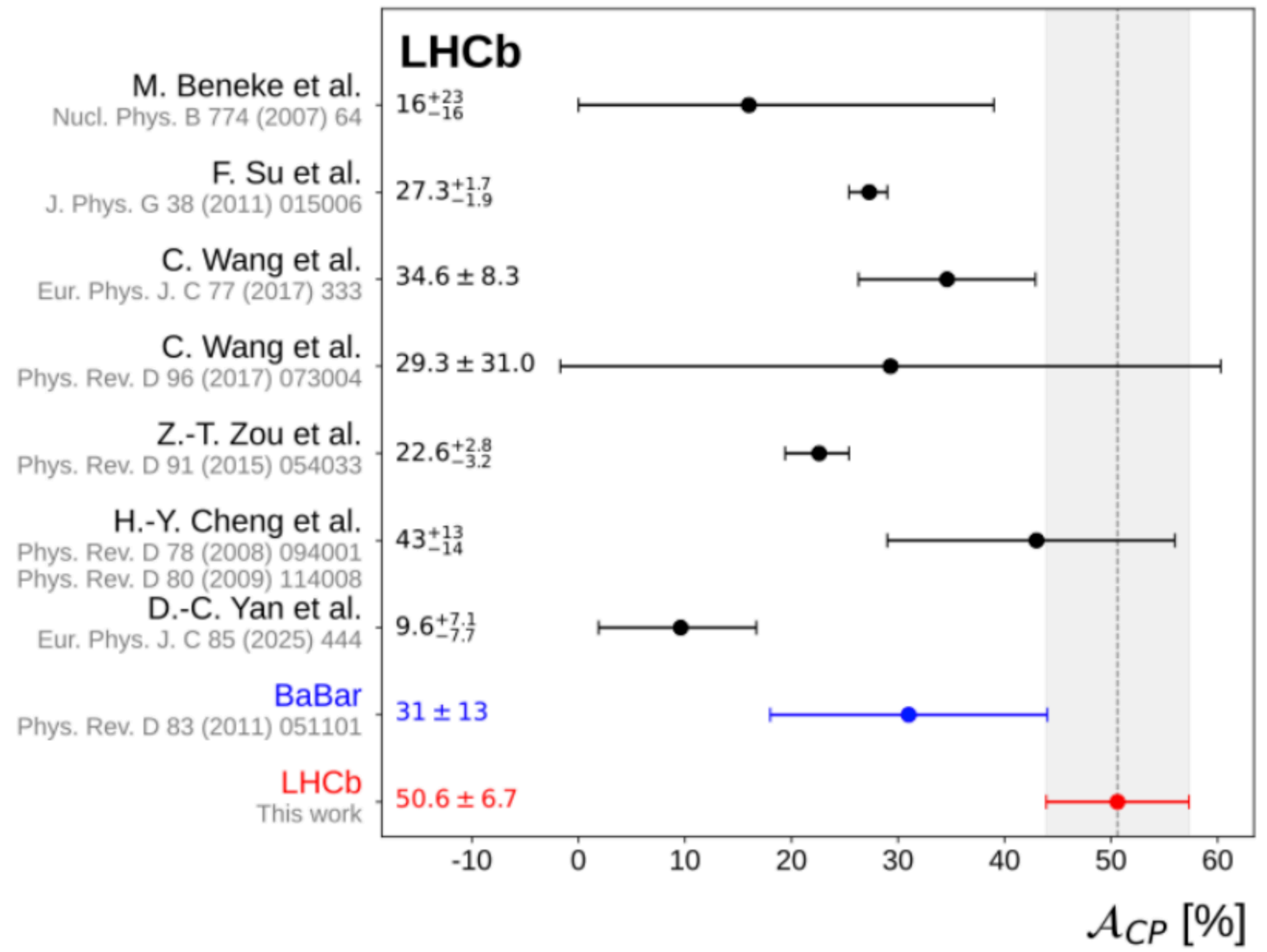
- Magnitude and phase of CP asymmetries for single polarisation amplitudes and fractions:
  CP violation is driven by the longitudinal component:

$$\mathcal{A}_{CP}(|A_0|^2) \equiv \frac{|\bar{A}_0|^2 - |A_0|^2}{|\bar{A}_0|^2 + |A_0|^2} = 0.666 \pm 0.081 \pm 0.048,$$

$$\Delta_{CP}(\delta_0) \equiv \bar{\delta}_0 - \delta_0 = 0.774 \pm 0.172 \pm 0.078$$

$$\mathcal{A}_{CP}(f_L) \equiv \frac{\bar{f}_L - f_L}{\bar{f}_L + f_L} = 0.241 \pm 0.083 \pm 0.050$$





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

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

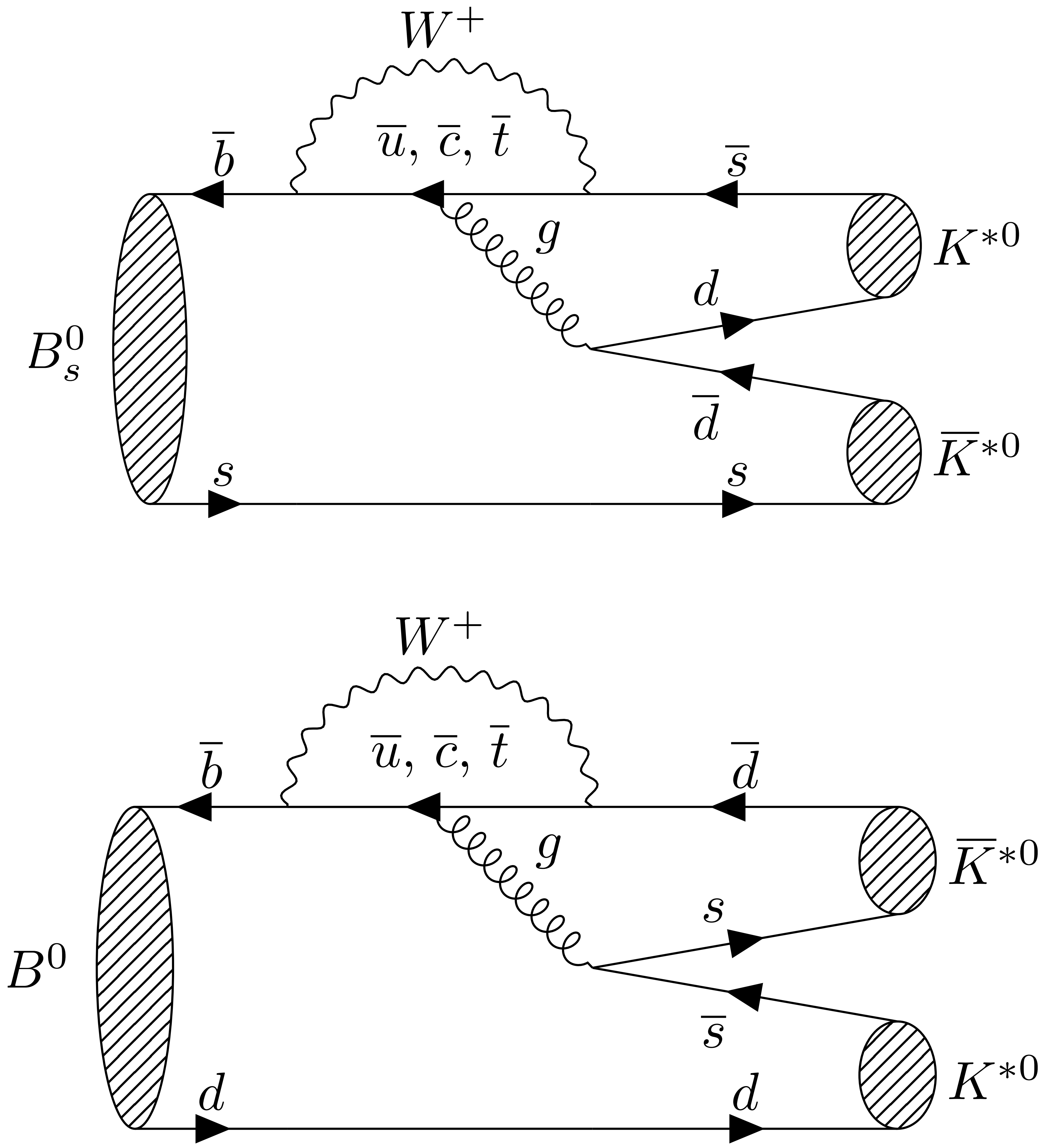
- $B^0 \to K^{*0}\bar{K}^{*0}$ and $B^0_s \to K^{*0}\bar{K}^{*0}$ decays loop-level mediated at lowest order
- Closely related by U-spin swap of s ↔ d
- Under QCD factorisation hypothesis, cancellation of QCD uncertainties motivate the measurement of a clean ratio of longitudinal branching ratio:

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

- Latest $L_{K^{*0}\bar{K}^{*0}}$ predictions with different form factor treatments:
  I : predicitions based solely on LCSR, II : LCSR and lattice QCD

$$L^{I,\mathrm{SM}}_{K^*\bar{K}^*} = 18.34^{+7.47}_{-5.83}\,, \qquad L^{II,\mathrm{SM}}_{K^*\bar{K}^*} = 26.08^{+5.70}_{-4.72}$$

[JHEP 09 (2025) 188]



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

[JHEP 07 (2019) 032]

- Latest results from LHCb: time independent angular analysis determined for both B^0 and B_s with 3fb^{-1} of data

$$f_L^{B_s^0} = 0.240 \pm 0.031(\text{stat}) \pm 0.025(\text{syst})$$

$$f_L^{B^0} = 0.724 \pm 0.051(\text{stat}) \pm 0.016(\text{syst})$$

- $f_L^{B^0}$ well compatible with SM prediction!

- Using naive luminosity scaling the measurement on $f_L^{B_s}$ is going to be systematically dominated:
  - Major contributions to syst. budget are from simulation sample size and S-wave mass model
  - Reduce the latter by decomposing the amplitudes using angular momentum eigenfunctions rather than helicity basis

Decay mode	
Parameter	f_L
Bias data-simulation	0.004
Fit method	0.001
Kinematic acceptance	0.011
Resolution	0.002
P–wave mass model	0.001
S–wave mass model	0.021
Differences data-simulation	0.002
Background subtraction	0.000
Peaking backgrounds	0.003
Time acceptance	0.008
Total systematic unc.	0.025

$B^0_{(s)} \to K^{*0}\bar{K}^{*0}$: covariant tensor formalism

- The angular model in helicity formalism is fine, the problem arises in the mass variables:
    - Longitudinal and parallel amplitudes are not eigenstates of angular momentum but rather a superposition of $L = 0,\ 2$
    - In Blatt-Weisskopf barrier factors set $L = 0$ as baseline and trial $L = 2$ as systematic

$$B(q, L) \equiv \begin{cases} 1 & \text{if } L = 0\,, \\ \dfrac{1}{\sqrt{1 + (qr)^2}} & \text{if } L = 1\,, \\ \dfrac{1}{\sqrt{9 + 3(qr)^2 + (qr)^4}} & \text{if } L = 2\,. \end{cases}$$

- In covariant tensor formalism amplitudes are built from spin amplitudes, which are eigenstates of ang. mom.:

$$A(\Phi_4) = \sum_i a_i S_i(\Phi_4) T_i(\Phi_4) B_i(\Phi_4)$$

- a_i complex coefficients, $S_i(\Phi_4)$ spin amplitudes $T_i(\Phi_4)$ mass lineshapes of the resonances (Breit-Wigner, LASS, dispersive scattering model..) and $B_i(\Phi_4)$ are the Blatt-Weisskopf factors

- Rather than angles and masses use Φ_4, the of four-momenta of final state particles as fit basis

$B^0_{(s)} \to K^{*0}\bar{K}^{*0}$: covariant tensor formalism

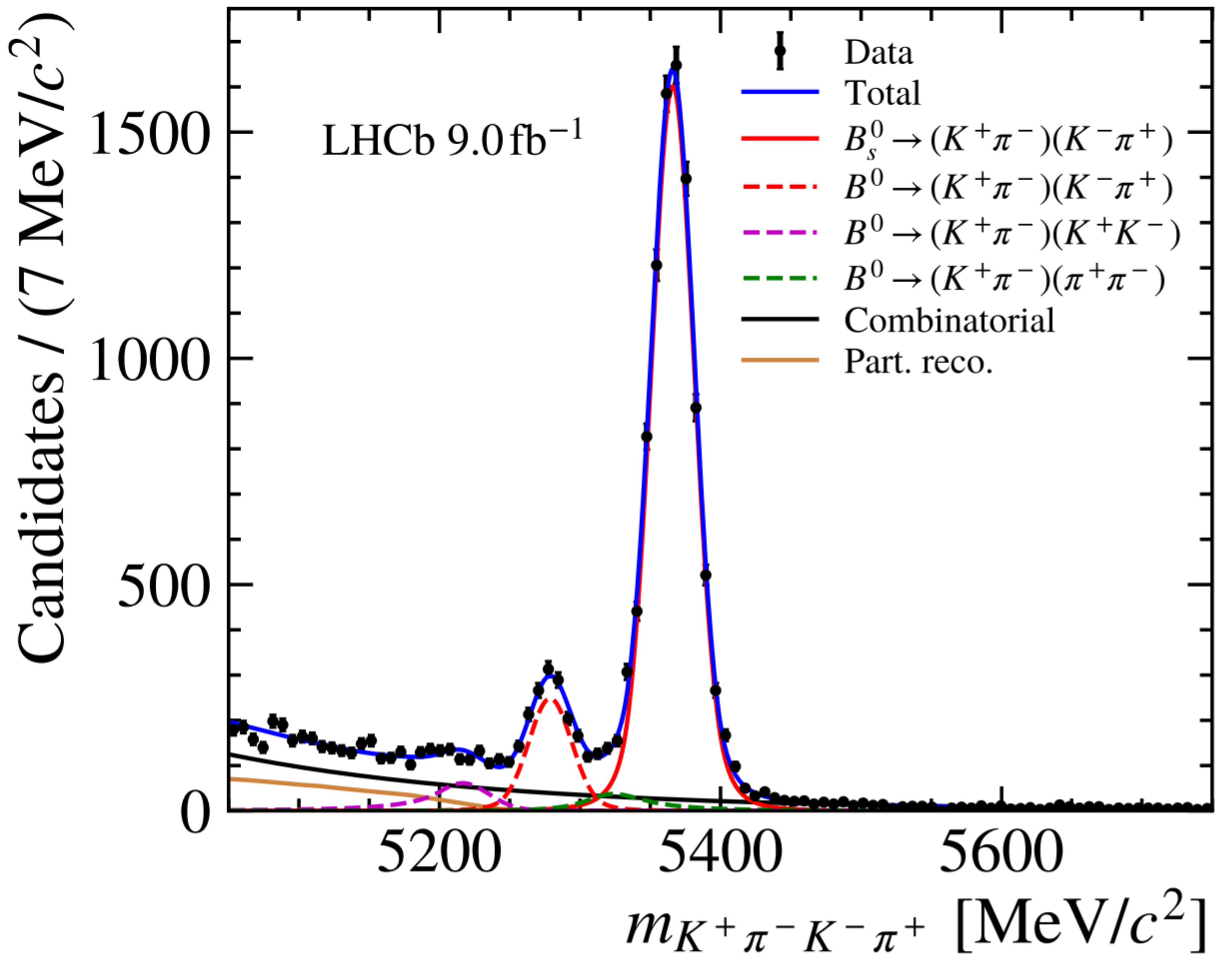
$$A(\Phi_4) = \sum_i a_i S_i(\Phi_4) T_i(\Phi_4) B_i(\Phi_4)$$

- Sum runs over $i = 6$ amplitudes, each $K\pi$ can be in a vector (V) or scalar (S) state:
  - SS (S-wave only)
  - VS and SV (P-wave only)
  - VV ($S-$, $P-$ and $D-$ wave)
- Region in $m(K\pi)$ considered ($(K^\pm\pi^\mp)_{\text{threshold}} < m(K^\pm\pi^\mp) < 1042$) MeV/$c^2$
  - Upper limit is set to keep us in the elastic region (i.e. below $K\eta$ production) since the S-wave parametrisation is simpler
  - First time at LHCb fitting the $K^\pm\pi^\mp$ S-wave down to threshold
- Higher order spins (e.g. tensors) not included as nominal but considered as systematics
- $V_{K\pi}$ mass modelled by a relativistic Breit-Wigner line-shape
- $S_{K\pi}$ mass modelled with dispersive scattering model (Peláez-Rodas parametrisation [arXiv:2010.11222]

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

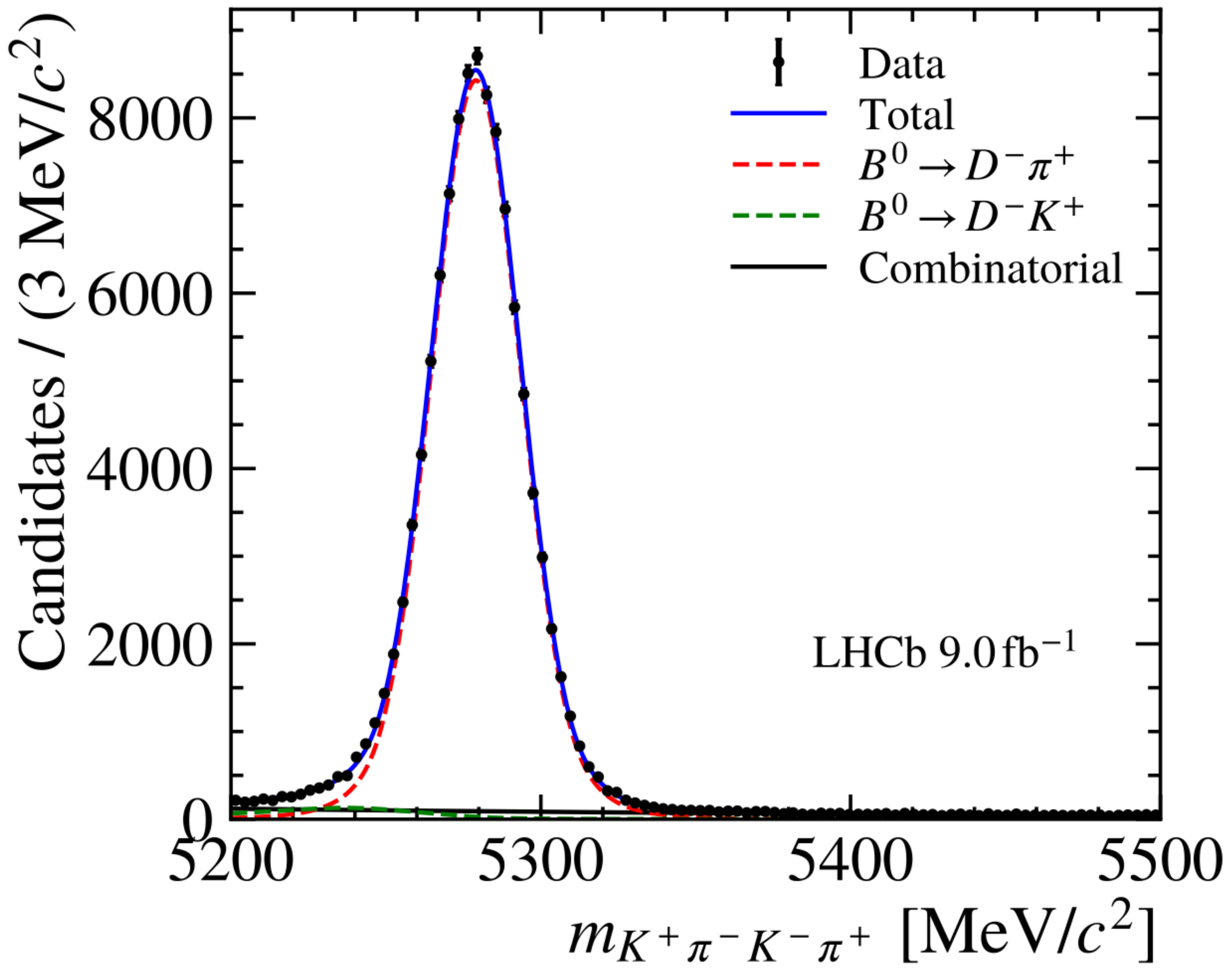
[arXiv:2512.05102]

- Before we can proceed for the angular fit, first isolate the signal of interest with a fit to $m(K\pi K\pi)$
- The branching ratio of $B_s^0 \to K^{*0}\bar{K}^{*0}$ and $B^0 \to K^{*0}\bar{K}^{*0}$ is also provided separately:
  - Normalise with respect to open charm decays $B_s^0 \to D_s^-\pi^+$ and $B^0 \to D^-\pi^+$ with the same number of K and π in the final state:

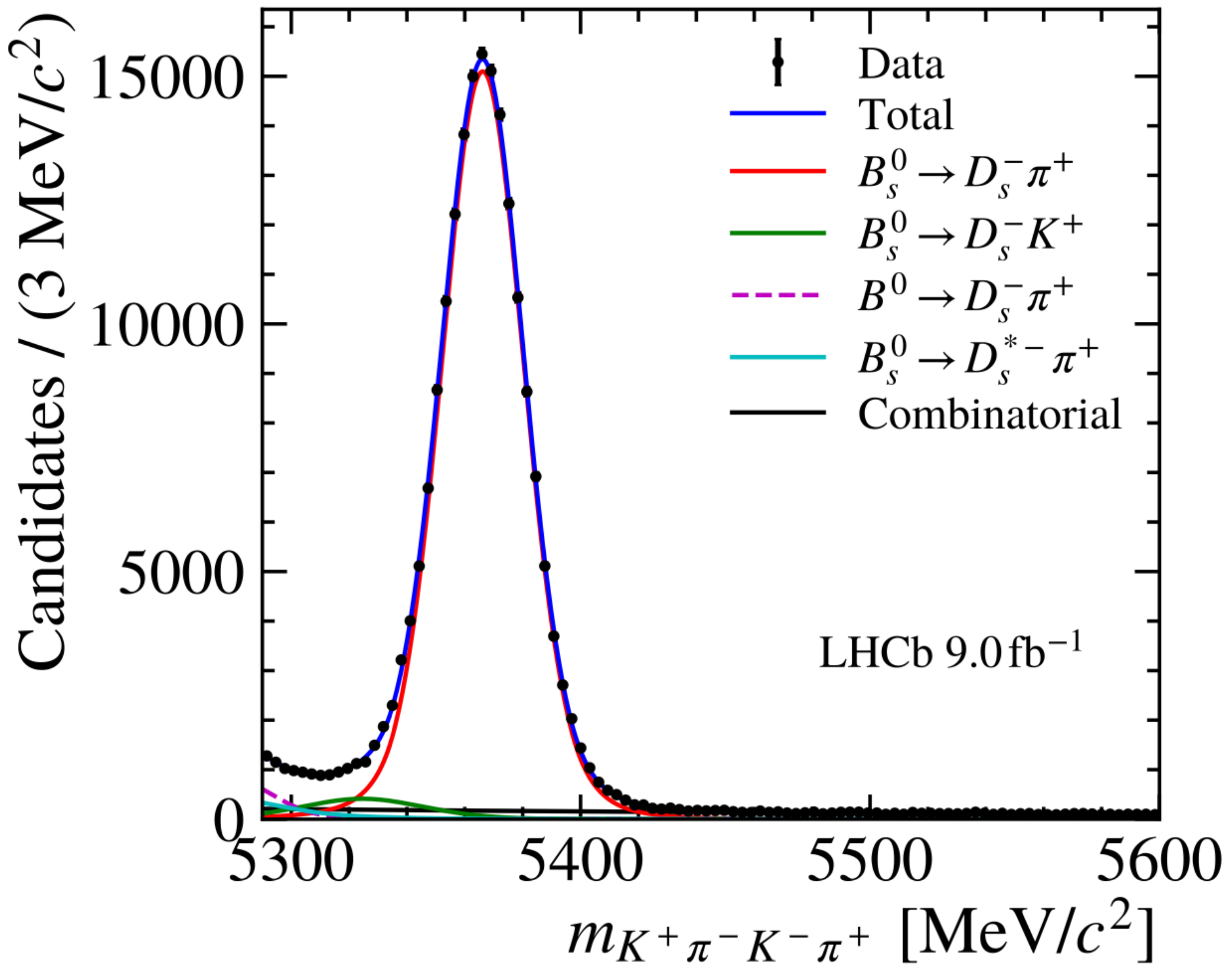


$N^{B_s^0\to K^{*0}\bar{K}^{*0}} = 9190 \pm 114,$

$N^{B^0\to K^{*0}\bar{K}^{*0}} = 1424 \pm 59,$



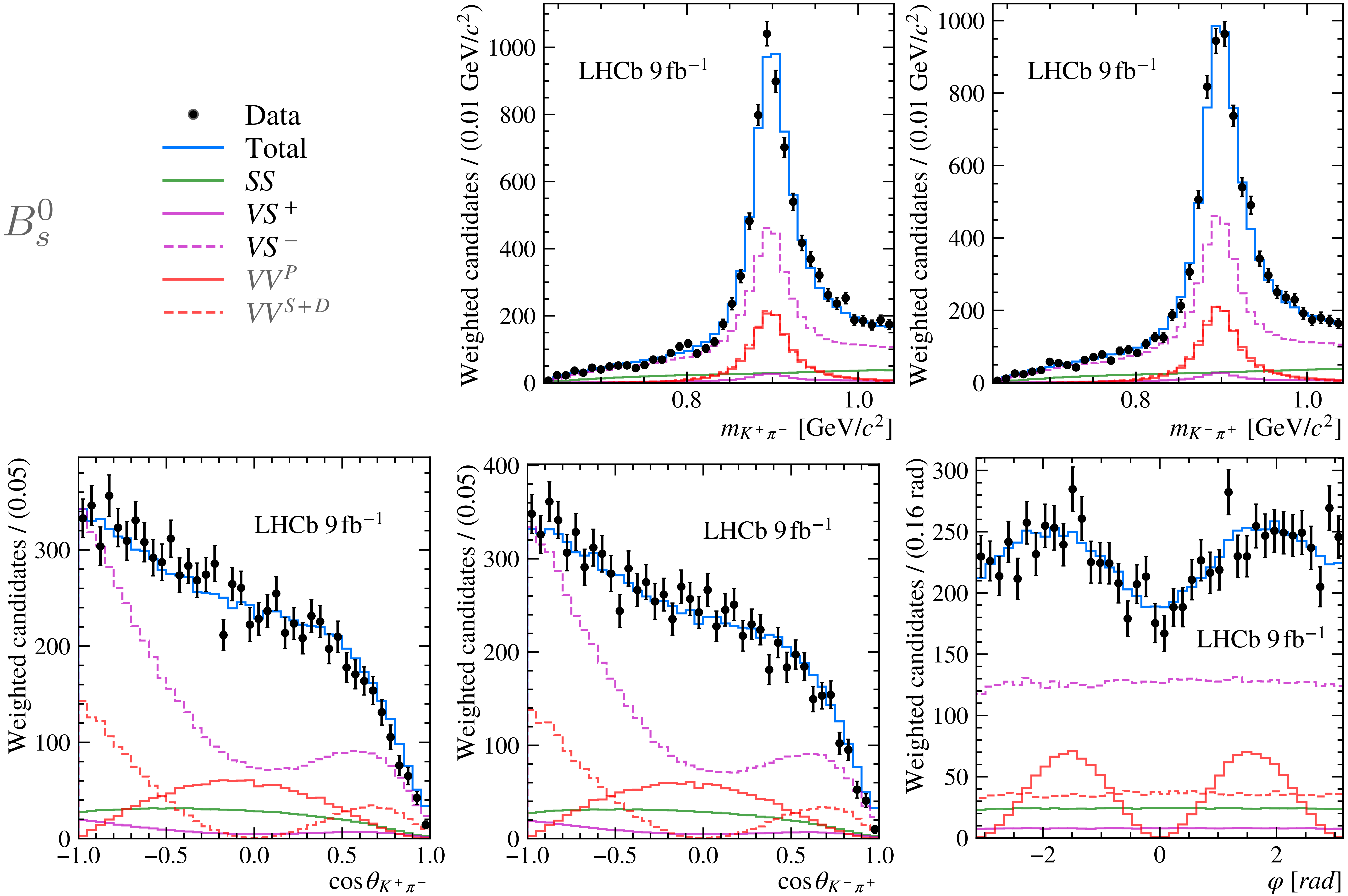
$N^{B^0\to D^-\pi^+} = 105\,666 \pm 348$



$N^{B_s^0\to D_s^-\pi^+} = 180\,807 \pm 483$

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

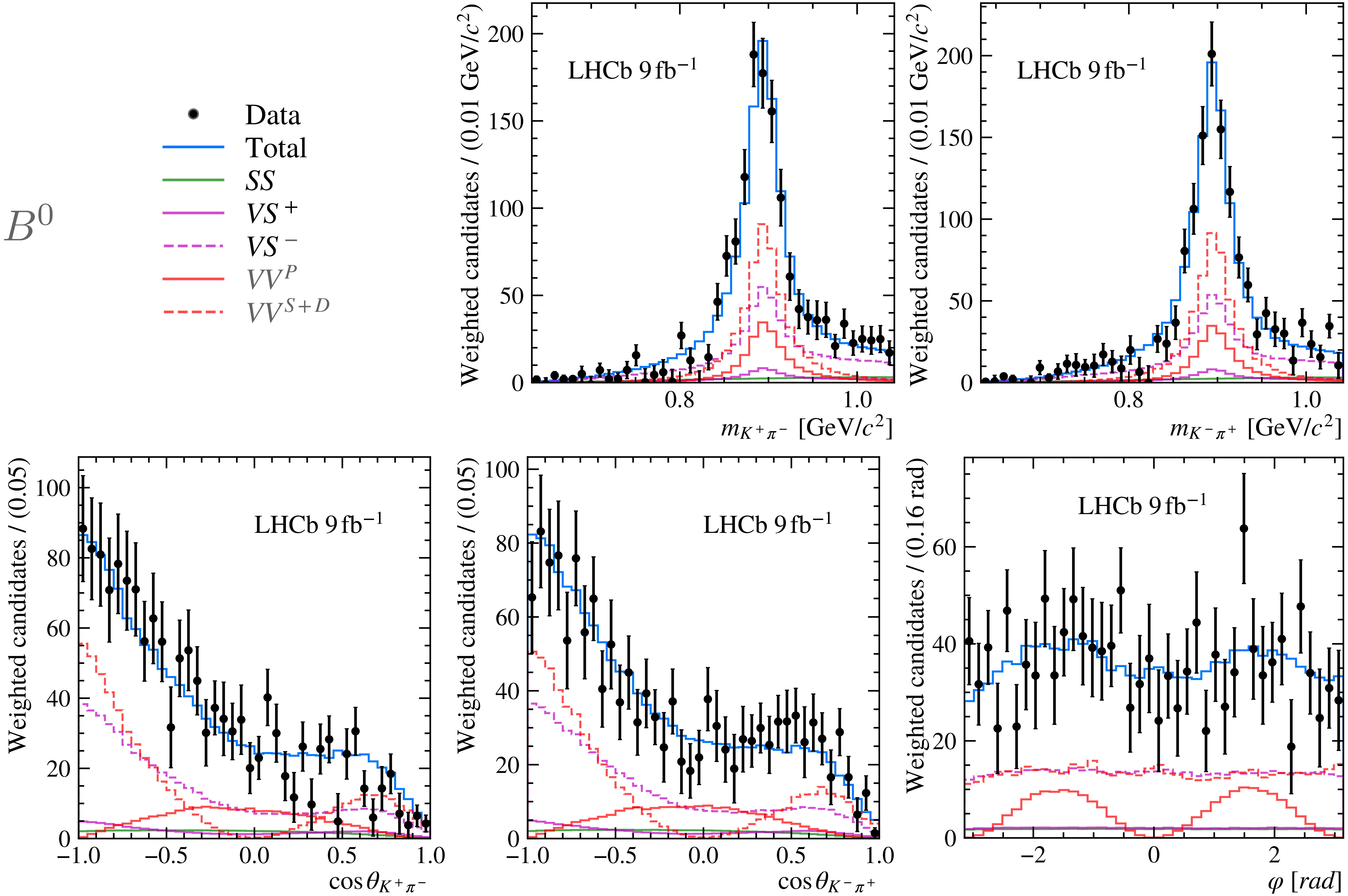
[arXiv:2512.05102]



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

[arXiv:2512.05102]

B^0



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

- Spin amplitudes for $B^0_{(s)} \to K^{*0}\bar{K}^{*0}$

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

- Where $L_{\mu_1..\mu_L}(p, q)$ is the relative orbital angular momentum tensor of initial state with momentum p decaying to a two body with relative momentum $q = p_1 - p_2$ between decay products

Result are fit frations of the kind

	Parameter	Value	Parameter	Value
B^0	$\mathcal{F}^{S+D}_{VV}$ (%)	$37 \pm 2 \pm 2$	$\mathcal{F}^{P}_{VV}$ (%)	$14 \pm 1 \pm 0.7$
B^0_s	$\mathcal{F}^{S+D}_{VV}$ (%)	$15.6 \pm 0.63 \pm 0.26$	$\mathcal{F}^{P}_{VV}$ (%)	$15.55 \pm 0.56 \pm 0.38$

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

[arXiv:2512.05102]

- To recast results in transversity basis generate pseudoexperiments from the fit result:
  - Fit back with angular amplitude in trasversity basis in 3D

$$A_{V\overline{V}}(\theta_{K^+\pi^-}, \theta_{K^-\pi^+}, \varphi) \propto A_L \cos\theta_{K^+\pi^-} \cos\theta_{K^-\pi^+} + \frac{A_\parallel}{\sqrt{2}} \sin\theta_{K^+\pi^-} \sin\theta_{K^-\pi^+} \cos\varphi + \frac{A_\perp}{\sqrt{2}} \sin\theta_{K^+\pi^-} \sin\theta_{K^-\pi^+} \sin\varphi$$

- Most precise branching fractions measurements, improving over the PDG uncertainties a factor 5 for $B^0_s \to K^{*0}\bar{K}^{*0}$ and 4 for $B^0 \to K^{*0}\bar{K}^{*0}$
- $L_{K^{*0}\bar{K}^{*0}}$ in good agreement with previous exp value of $L_{K^{*0}\bar{K}^{*0}} = 4.43 \pm 0.92$
- Now stat dominated (syst uncert driven by background modelling)
- Tension with SM persists

$$f_L^{B^0_s} = 0.159 \pm 0.010(\text{stat}) \pm 0.007(\text{syst})$$

$$f_L^{B^0} = 0.600 \pm 0.022(\text{stat}) \pm 0.017(\text{syst})$$

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

$$\mathcal{B}(B^0_s \to K^{*0}\overline{K}^{*0}) = (0.932 \pm 0.025\,(\text{stat}) \pm 0.018\,(\text{syst}) \pm 0.036\,(\text{ext})) \times 10^{-5},$$

$$\mathcal{B}(B^0 \to K^{*0}\overline{K}^{*0}) = (4.69 \pm 0.29\,(\text{stat}) \pm 0.43\,(\text{syst}) \pm 0.16\,(\text{ext})) \times 10^{-7},$$

$$B_s^0 \to J/\psi \overline{K}^*(892)^0$$

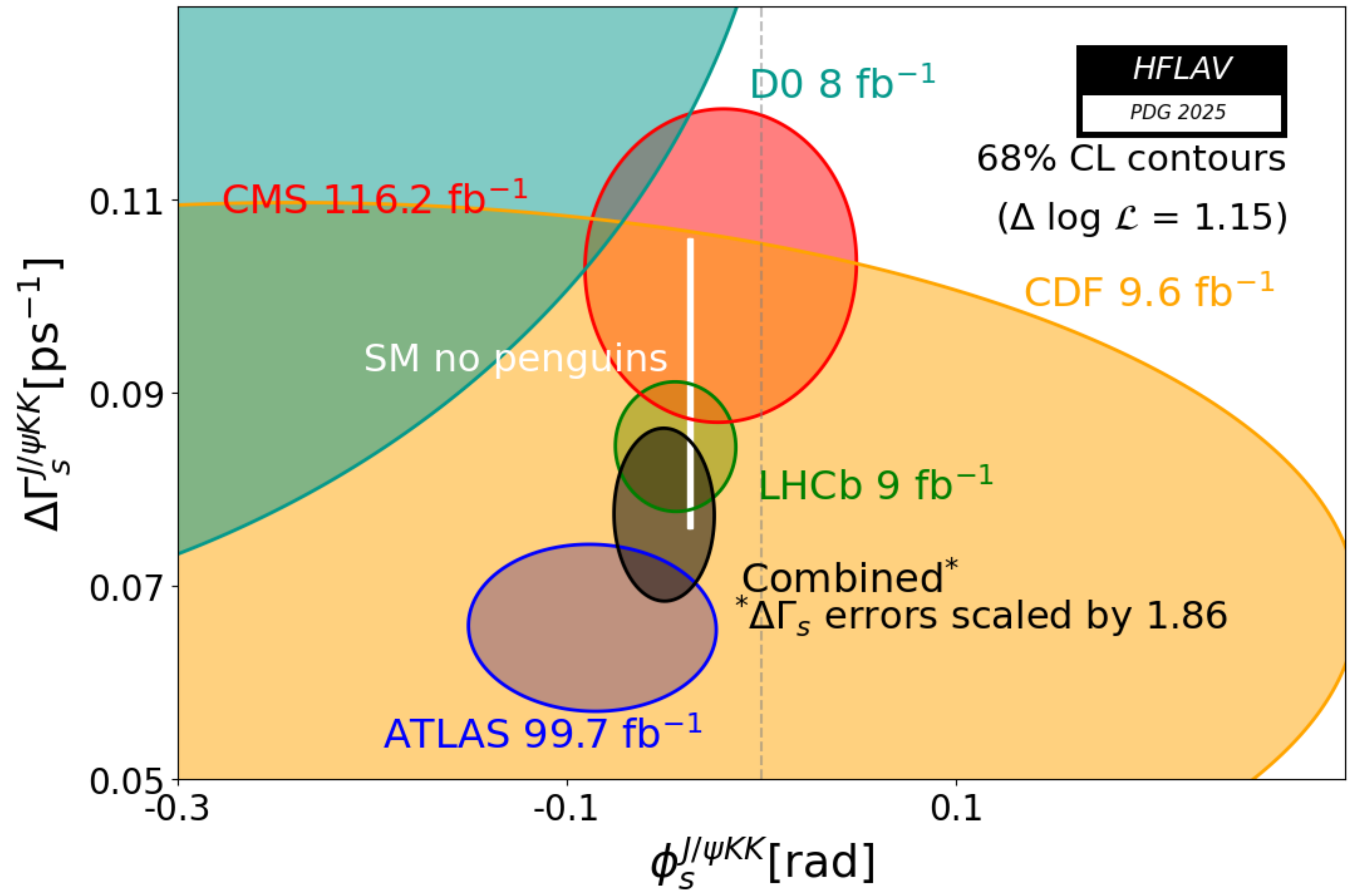
The run for ϕ_s

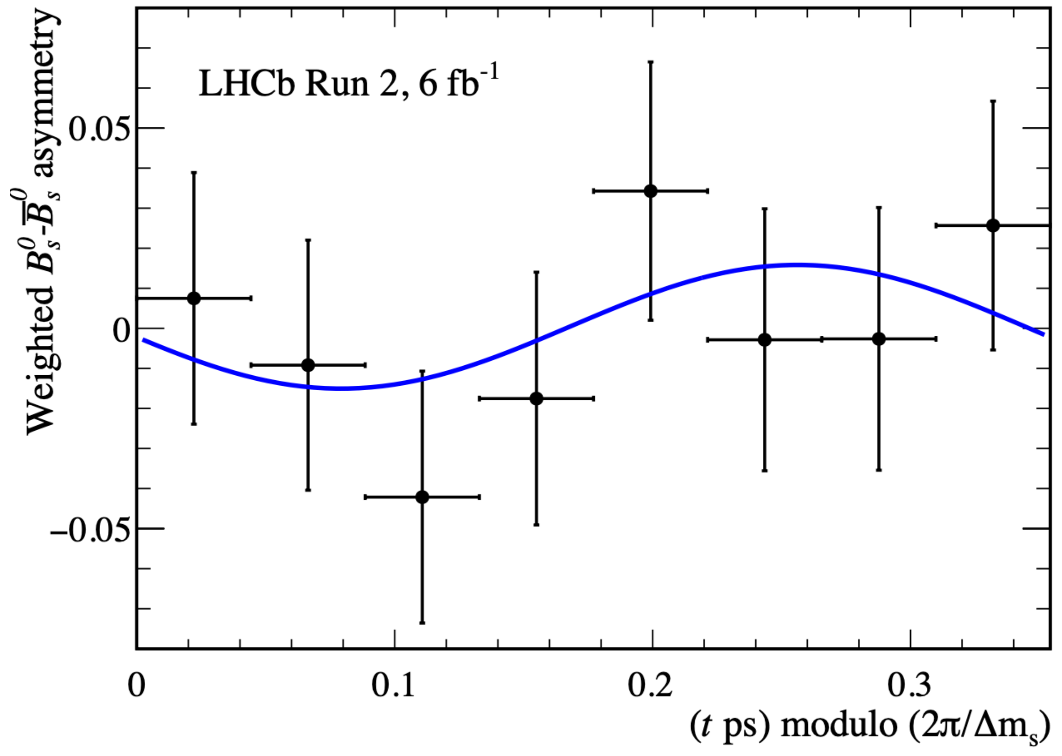
- SM prediction for mixing induced CPV effects in $b \to c\bar{c}s$ decays is very precise

  $\phi_s = -2\beta_s = -0.0376^{+.0006}_{-.0005}$ [CKMfitter] $\phi_s = -0.0367 \pm 0.0010$ [UTfit]
- Sensitive to NP contributions in mixing
- $B_s \to J/\psi\phi$ is the golden mode for ϕ_s measurements:
  - Penguin amplitudes are subdominant
  - Requires a flavour-tagged, angular and time-dependent analysis
- World average is dominated by LHCb measurement [PRL 132 (2024) 051802]

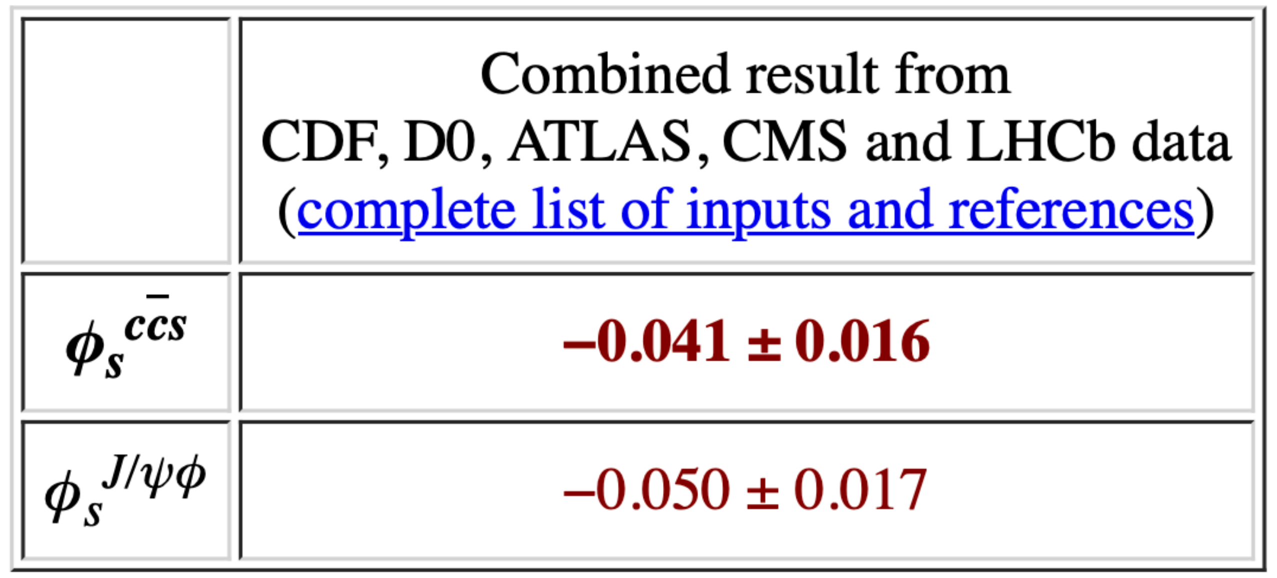
$$\phi_s^{J/\psi KK} = -0.044 \pm 0.020 \text{ rad}$$

- New modes governed by the same underlying transition will tighten the room for NP contributions





[HFLAV] averaging group



	Combined result from CDF, D0, ATLAS, CMS and LHCb data (complete list of inputs and references)
$\phi_s^{c\bar{c}s}$	**−0.041 ± 0.016**
$\phi_s^{J/\psi\phi}$	−0.050 ± 0.017

[arXiv:2506.22090] submitted to JHEP

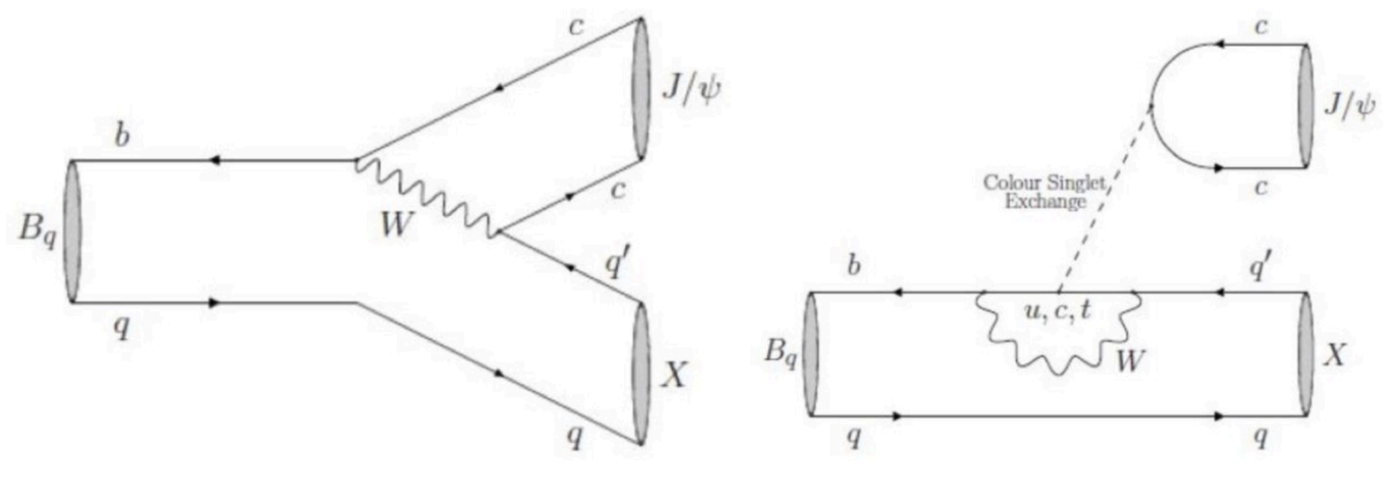
CPV and polarisation measurements in $B_s^0 \to J/\psi \overline{K}{}^*(892)^0$ decays

- Subleading SM loop contributions in $B_s \to J/\psi\phi$ decay complicate the interpretation of experimental measurements in terms of ϕ_s

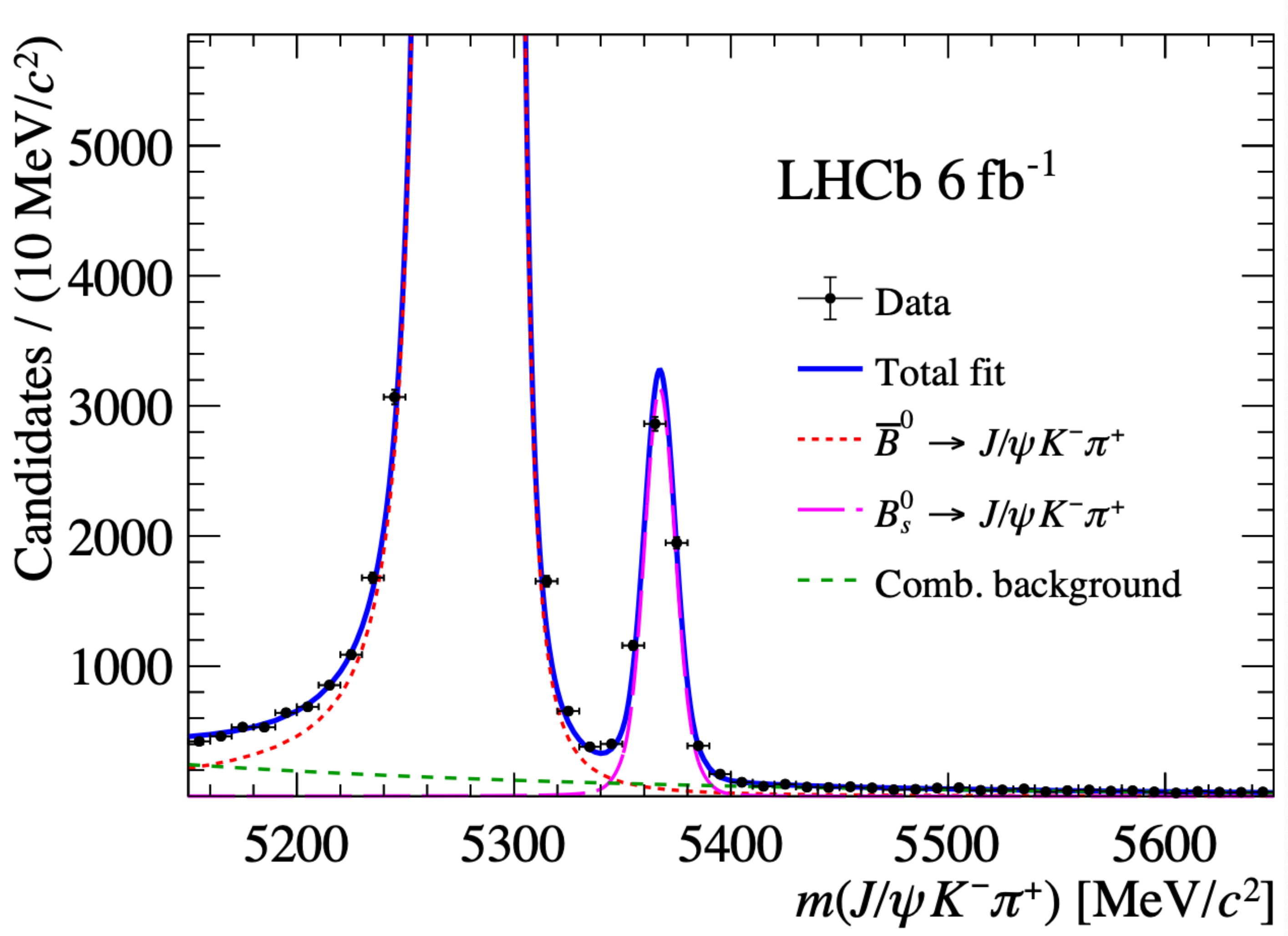
$$\phi_{s,i} = -2\beta_s + \phi_s^{\mathrm{BSM}} + \boxed{\Delta\phi_{s,i}^{J/\psi\,\phi}(a_i', \theta_i')}$$

Contrib. from SM loops

- Goal: measure CP asymmetry of CKM suppressed $b \to c\bar{c}d$ decays, e.g. $B_s^0 \to J/\psi \overline{K}{}^{*0}$, to constrain penguin parameters in $B_s \to J/\psi\phi$ via approximate $SU(3)_F$
- Run2 Time-Integrated angular analysis of $B_s^0 \to J/\psi \overline{K}{}^{*0}$ allows to:
  - Fit for P-wave amplitudes to extract polarisation fractions (combine with Run1 results to obtain most precise values to date)
  - Update the branching ratio of $B_s^0 \to J/\psi \overline{K}{}^{*0}$
  - Measurement of A_{CP} and constrain penguin parameters (a', θ')



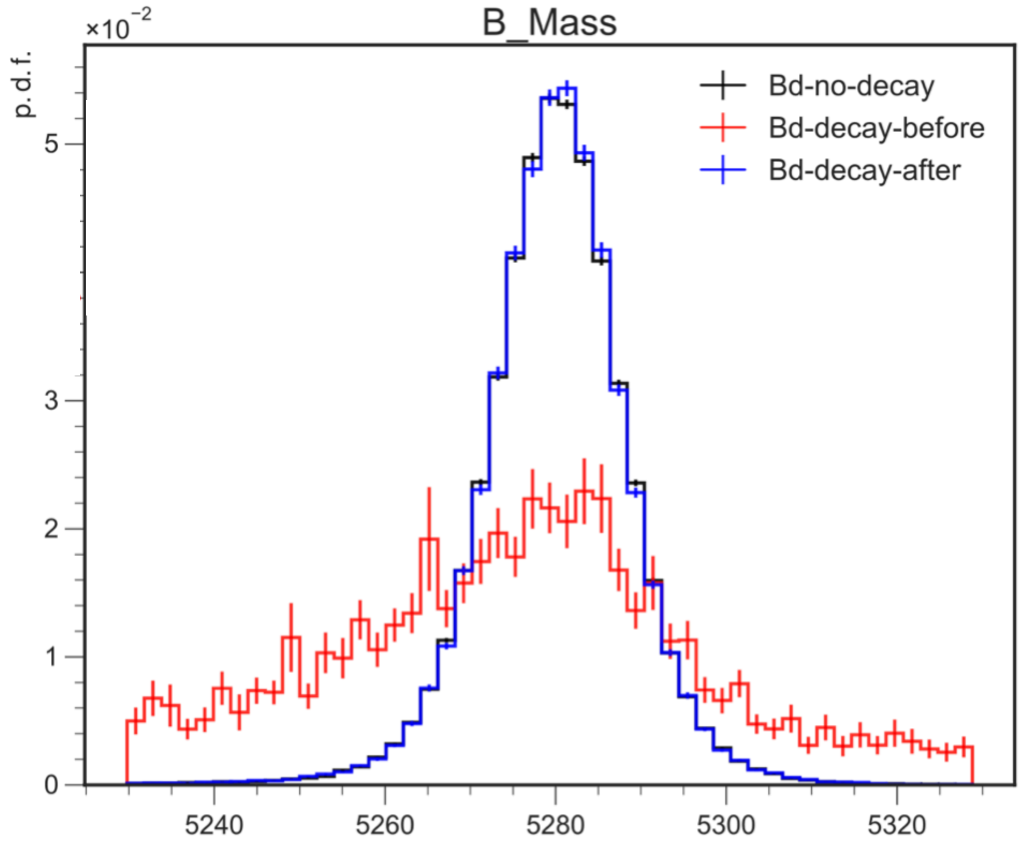
process	tree level coupling	loop level coupling
$B_s \to J/\psi\phi$	$\sim \lambda^2$	$\sim \lambda^4$
$B_s \to J/\psi K^{*0}$	$\sim \lambda^4$	$\sim \lambda^4$

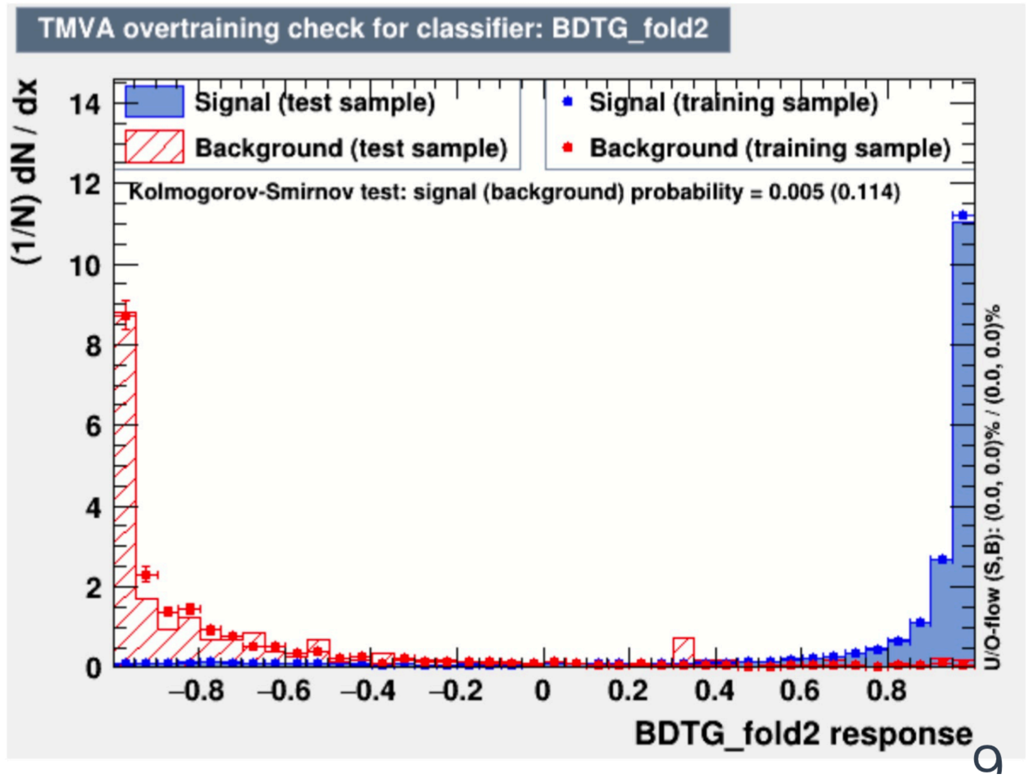


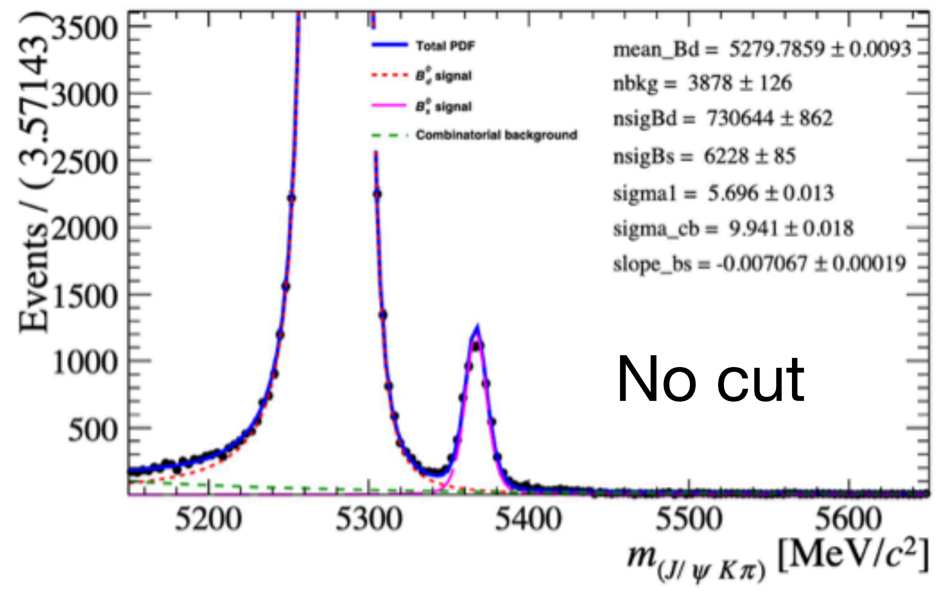
[arXiv:2506.22090] submitted to JHEP

CPV and polarisation measurements in $B_s^0 \to J/\psi \overline{K}{}^*(892)^0$ decays

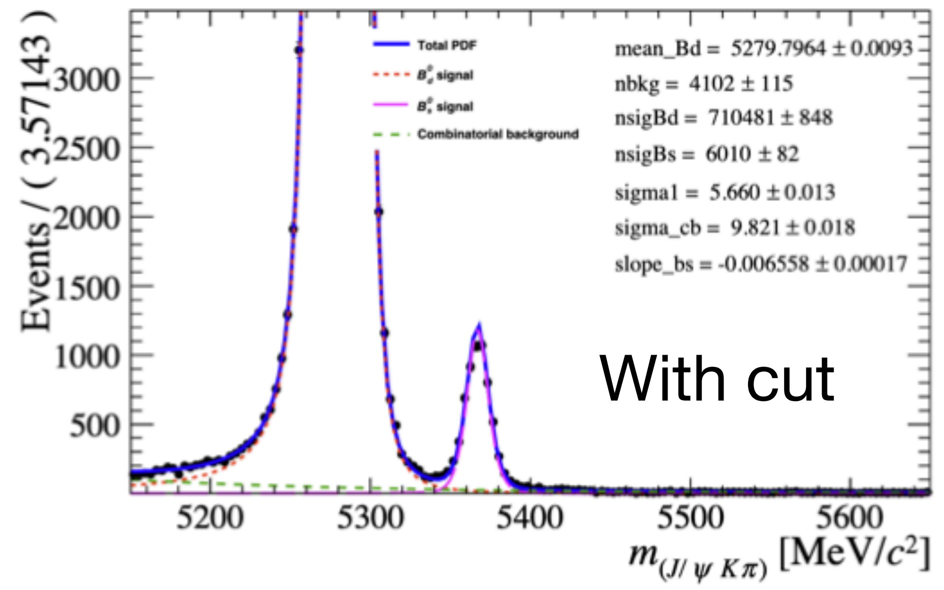
- Event selection and mass fit:
  - Selection: PID, kinematic cuts, $80(70)$ MeV/c^2 window around the $J/\psi(K^{*0})$ mass, veto of $\Lambda_b^0 \to J/\psi p_{\to K^+}\pi^-$ and $B_{d/s}^0 \to J/\psi \pi_{\to K}\pi$ misID
  - In addition to combinatorial BDT, train another BDT using simulation:
    - Based on tracking reconstruction quality variables in B_d decays after (before) T2 as a proxy for sig. (bkg), allowing to:
      - Improve B_s purity in signal region
      - Remove badly reconstructed candidates (e.g. decay in flight)
  - $m(\mu\mu K^-\pi^-)$ mass fit to extract B_s^0 sWeights for angular fit



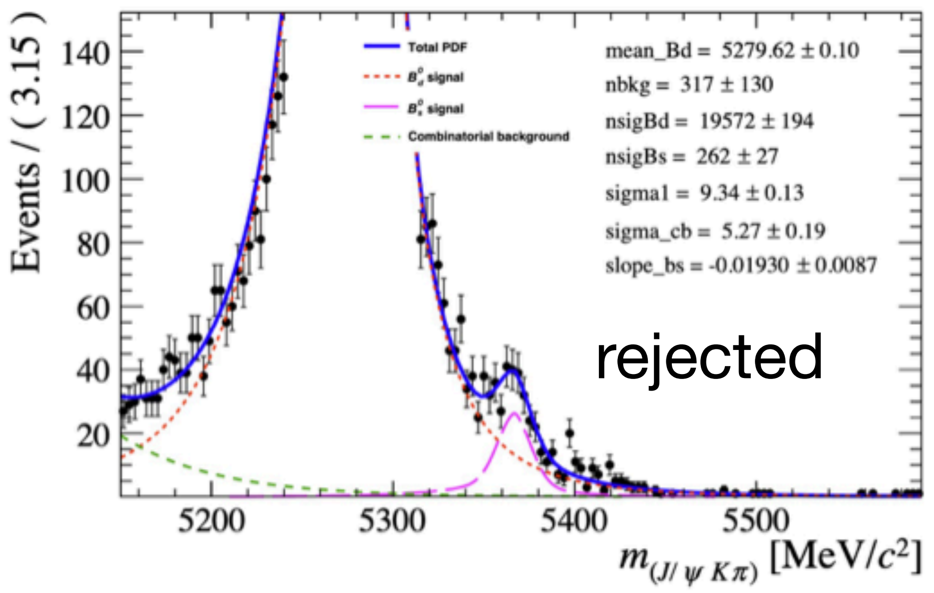




No cut



With cut



rejected

Sig. eff. $98.3\,\%$
bkg rej. eff. $42\,\%$

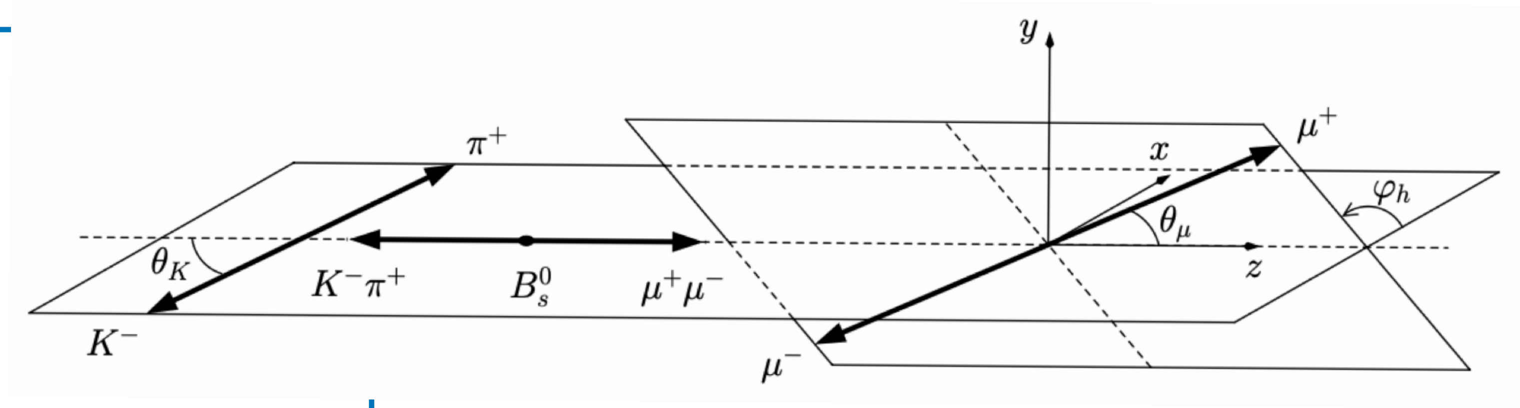
[arXiv:2506.22090] submitted to JHEP

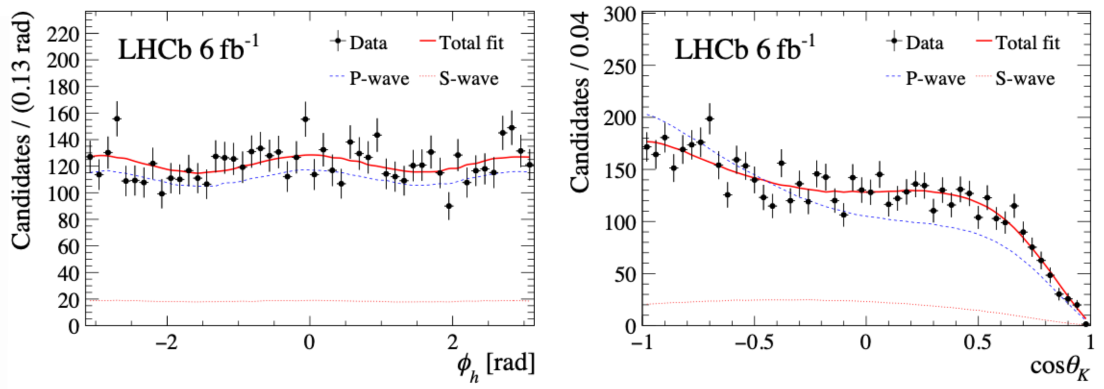
CPV and polarisation measurements in $B_s^0 \to J/\psi \overline{K}{}^*(892)^0$ decays

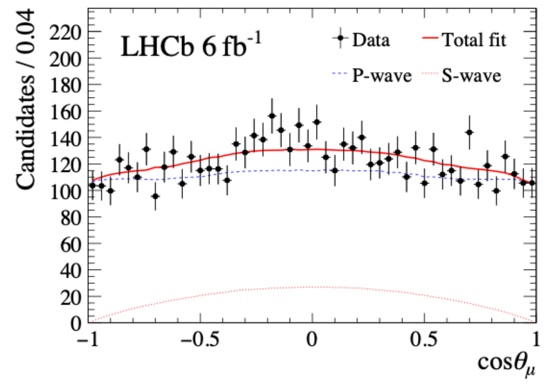
- Angular analysis:
  - Simultaneous fit for S and P wave amplitudes in 8 categories: 4 $m_{K\pi}$ mass bins x 2 meson charges,
    - S-P wave interference effects taken from Run1 analysis
  - Angular acceptance evaluated from simulation samples, in bins of $m_{K\pi}$ and kaon charge
  - Physics quantities of interest:
    - CP averaged P-wave polarisation fractions, CP averaged S-wave fraction and CP asymmetries A_k^{CP}
    - Systematics considered include error on simulation corrections, fit model biases, contributions from external CP asymmetries
  - Combine with Run1 result for most precise determination of:

$$Br(B_s^0 \to J/\psi \overline{K}{}^*(892)^0) = (4.13 \pm \underset{\text{stat}}{0.12} \pm \underset{\text{syst}}{0.07} \pm \underset{f_s/f_d}{0.14} \pm \underset{Br(B^0)}{0.45}) \times 10^{-5}$$

  - Using all measured quantities, recast result in terms of constraints on $\delta\phi_s^{\text{loop}}$



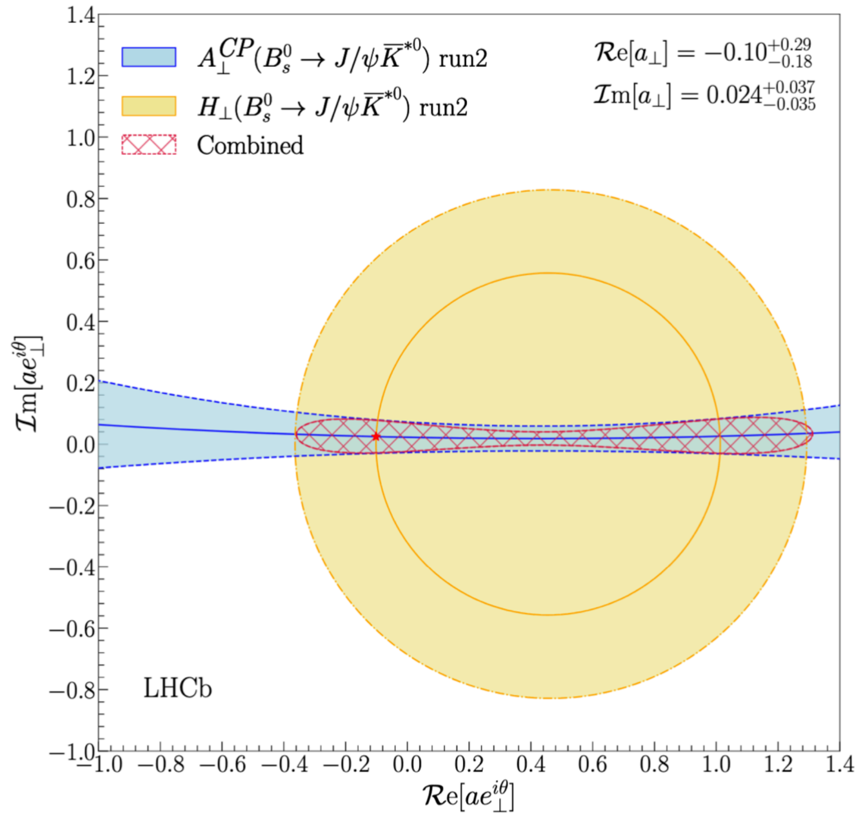




$$\Gamma_k = \int \overbrace{\boxed{a_k}}^{\text{Bilinear combinations of } A_{0,\|,\perp,S}} \underbrace{\boxed{G_k(\Omega)}}_{\text{Spherical harmonics}} d\Omega \qquad (k = 0, \|, \perp, S).$$

$$A_k^{CP} = \frac{\overline{\Gamma}_k - \Gamma_k}{\overline{\Gamma}_k + \Gamma_k} \qquad f_k = \frac{\Gamma_k^{\text{avg}}}{\Gamma_{\text{P}}^{\text{avg}}} \qquad F_S = \frac{\Gamma_S^{\text{avg}}}{\Gamma_{\text{tot}}^{\text{avg}}}$$

$$\begin{aligned}
f_0 &= 0.528 \pm 0.011\,(\text{stat}) \pm 0.009\,(\text{syst}),\\
f_\| &= 0.205 \pm 0.012\,(\text{stat}) \pm 0.005\,(\text{syst}),\\
A_0^{CP} &= 0.021 \pm 0.026\,(\text{stat}) \pm 0.007\,(\text{syst}),\\
A_\|^{CP} &= -0.073 \pm 0.060\,(\text{stat}) \pm 0.007\,(\text{syst}),\\
A_\perp^{CP} &= 0.057 \pm 0.049\,(\text{stat}) \pm 0.014\,(\text{syst}).
\end{aligned}$$



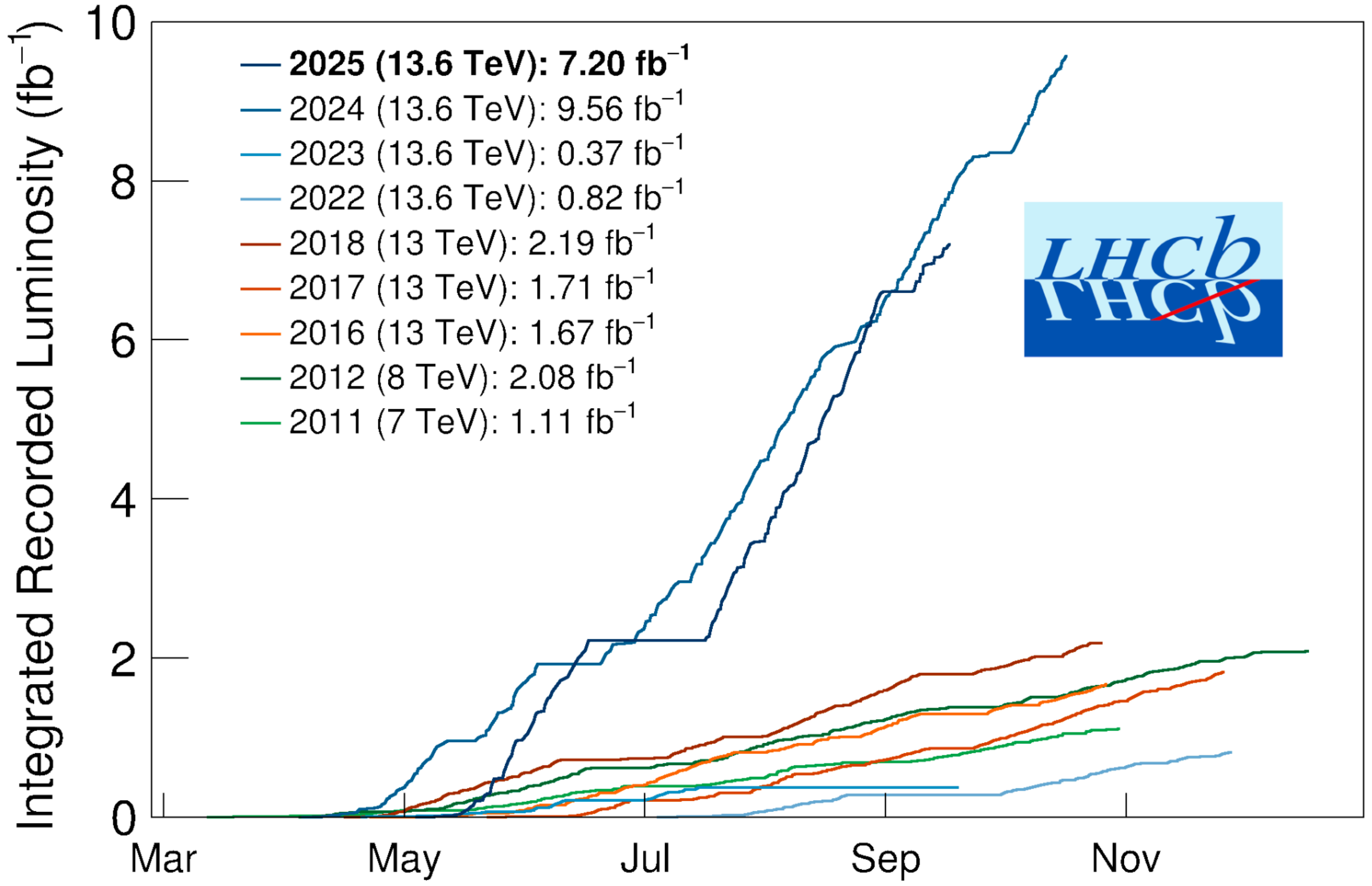
Conclusions and prospects

- Several Run 1 + Run 2 $B \to VV$ analyses are ongoing including:
  - $B^0_{(s)} \to \phi K^{*0}$
  - $B^0_{(s)} \to \rho^0 K^{*0}$
  - $B^+ \to \phi K^{*+}$
  - Time-dependent $B^0_{(s)} \to K^{*0}\bar{K}^{*0}$

Shed more light on the polarisation puzzle

Most precise determination of ϕ_s^{dd} in a $b \to d\bar{d}s$ transition

- Run 3 likely to have double the luminosity of Run 1 + Run 2
- Having moved to fully software based trigger roughly doubles the number of signal candidates per pb^{-1} → huge dataset of charmless $B \to VV$ decays to explore



Thanks for listening

Spare slides

$B^0_{(s)} \to K^{*0}\bar{K}^{*0}$: amplitude analysis and branching fraction measurement

- The heavy-quark limit implies the polarisation hierarchy $f_L \gg f_{\|,\perp}$ in $B_{(s)} \to K^{*0}\bar{K}^{0*}$ decays, with QCDF predicting [Nucl.Phys.B774:64-101,2007] :

$$f_L^{B_0} = 0.69^{+0.16}_{-0.20} \qquad f_L^{B_s} = 0.72^{+0.16}_{-0.21}$$

$B_{(s)} \to K^{*0}\bar{K}^{0*}$

[LHCb: JHEP 07 (2015) 166]

[LHCb: JHEP 03 (2018) 140]

[LHCb: JHEP 07 (2019) 032]

TI CP asymmetries in $B_s \to K^{*0}\bar{K}^{0*}$ with 1fb^{-1} of data

- Within uncertainties consistent with no CP violation
- Low value of $f_L^{B_s}$ confirmed

$$f_L^{B_s} = 0.201 \pm 0.057(\text{stat}) \pm 0.040(\text{syst})$$

$B^0_{(s)} \to K^{*0}\bar{K}^{*0}$: amplitude analysis and branching fraction measurement

- The heavy-quark limit implies the polarisation hierarchy $f_L \gg f_{\|,\perp}$ in $B_{(s)} \to K^{*0}\bar{K}^{0*}$ decays, with QCDF predicting [Nucl.Phys.B774:64-101,2007] :

$$f_L^{B_0} = 0.69^{+0.16}_{-0.20} \qquad f_L^{B_s} = 0.72^{+0.16}_{-0.21}$$

$B_{(s)} \to K^{*0}\bar{K}^{0*}$

[LHCb: JHEP 07 (2015) 166]

[LHCb: JHEP 03 (2018) 140]

[LHCb: JHEP 07 (2019) 032]

TD CP asymmetries in $B_s \to K^{*0}\bar{K}^{0*}$ with $3\mathrm{fb}^{-1}$ of data

- First measurement of the CP-violating phase

$$\phi_s^{s\bar{s}} = -0.10 \pm 0.13(\mathrm{stat}) \pm 0.14(\mathrm{syst})$$

- Low value of $f_L^{B_s}$ confirmed

$$f_L^{B_s} = 0.208 \pm 0.032(\mathrm{stat}) \pm 0.046(\mathrm{syst})$$

$B^0_{(s)} \to K^{*0}\bar{K}^{*0}$: amplitude analysis and branching fraction measurement

- The heavy-quark limit implies the polarisation hierarchy $f_L \gg f_{\|,\perp}$ in $B_{(s)} \to K^{*0}\bar{K}^{0*}$ decays, with QCDF predicting [Nucl.Phys.B774:64-101,2007] :

$$f_L^{B_0} = 0.69^{+0.16}_{-0.20} \qquad f_L^{B_s} = 0.72^{+0.16}_{-0.21}$$

$B_{(s)} \to K^{*0}\bar{K}^{0*}$

[LHCb: JHEP 07 (2015) 166]

[LHCb: JHEP 03 (2018) 140]

[LHCb: JHEP 07 (2019) 032]

TD CP asymmetries in $B_s \to K^{*0}\bar{K}^{0*}$ with 3fb^{-1} of data

- First measurement of the CP-violating phase

$$\phi_s^{s\bar{s}} = -0.10 \pm 0.13(\text{stat}) \pm 0.14(\text{syst})$$

- Low value of $f_L^{B_s}$ confirmed

$$f_L^{B_s} = 0.208 \pm 0.032(\text{stat}) \pm 0.046(\text{syst})$$

$B^0_{(s)} \to K^{*0}\bar{K}^{*0}$: covariant tensor formalism

- $\varepsilon_{\mu_1..\mu_L}(p,\lambda)$ rank J polarisation tensor with Lorentz indices μ_i.
- Rarita-Schwinger polarisation tensor symmetric traceless and orthogonal to p
- Reduce 4^J components to $2J+1$
- P projection operator, L contraction with relative momentum in 2 body decay
- Square brackets relative angular momentum between intermediate states

$$P_{\mu_1\ldots\mu_J,\nu_1\ldots\nu_J}(p) = \sum_\lambda \epsilon_{\mu_1\ldots\mu_J}(p,\lambda)\epsilon^*_{\nu_1\ldots\nu_J}(p,\lambda)\,,$$

$$L_{\mu_1\ldots\mu_L}(p,q) = P_{\mu_1\ldots\mu_L,\nu_1\ldots\nu_L}(p)q^{\nu_1}\ldots q^{\nu_L}\,.$$

$B^0_{(s)}$ decay topology	Angular amplitude $Z(\Phi_4)$
$B \to V\bar{V}[S],\quad V \to K_1^+\pi_2^-,\quad \bar{V} \to K_3^-\pi_4^+$	$L_a(p_V,q_V)L^a(p_{\bar{V}},q_{\bar{V}})$
$B \to V\bar{V}[P],\quad V \to K_1^+\pi_2^-,\quad \bar{V} \to K_3^-\pi_4^+$	$\epsilon_{abcd}p_B^d L^c(p_B,q_B)L^b(p_V,q_V)L^a(p_{\bar{V}},q_{\bar{V}})$
$B \to V\bar{V}[D],\quad V \to K_1^+\pi_2^-,\quad \bar{V} \to K_3^-\pi_4^+$	$L_{ab}(p_B,q_B)L^b(p_V,q_V)L^a(p_{\bar{V}},q_{\bar{V}})$
$B \to V\bar{S},\quad V \to K_1^+\pi_2^-,\quad \bar{S} \to K_3^-\pi_4^+$	$L_a(p_B,q_B)L^a(p_V,q_V)$
$B \to S\bar{V},\quad S \to K_1^+\pi_2^-,\quad \bar{V} \to K_3^-\pi_4^+$	$L_a(p_B,q_B)L^a(p_{\bar{V}},q_{\bar{V}})$
$B \to S\bar{S},\quad S \to K_1^+\pi_2^-,\quad \bar{S} \to K_3^-\pi_4^+$	1