Strange penguins at LHCb

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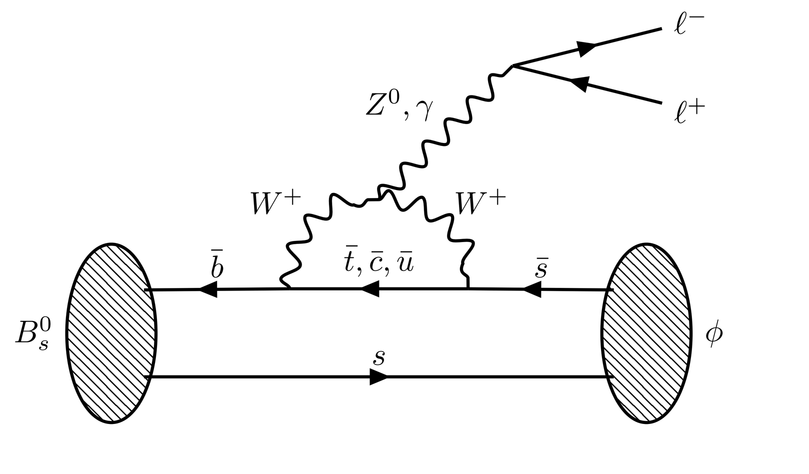
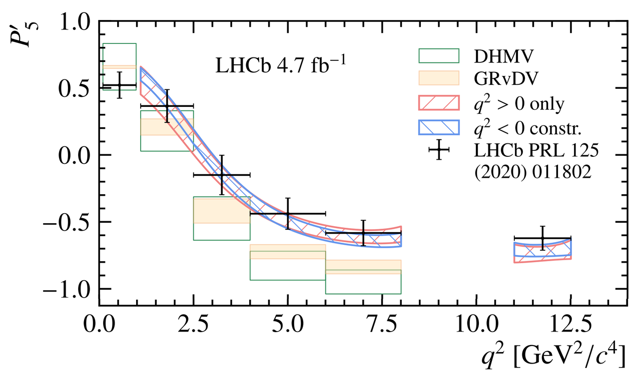
Testing lepton flavour universality with $B_s^0 \to \phi\ell^+\ell^-$ decays and steps towards an angular analysis of $B_s^0 \to \phi e^+e^-$

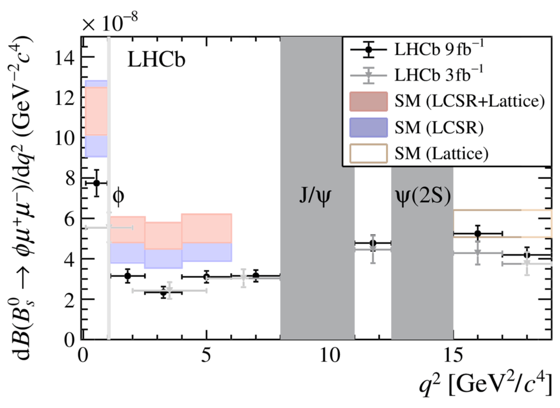
The penguin landscape



- **Flavour changing neutral current**, only loops in SM.
- Sensitive to New Physics contributions in loop amplitudes.
- **Various tensions** have been reported, picture remains unclear.



PHYS. REV. LETT. 132 (2024) 131801



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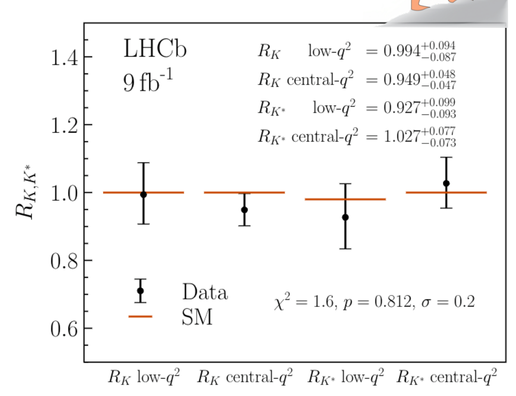


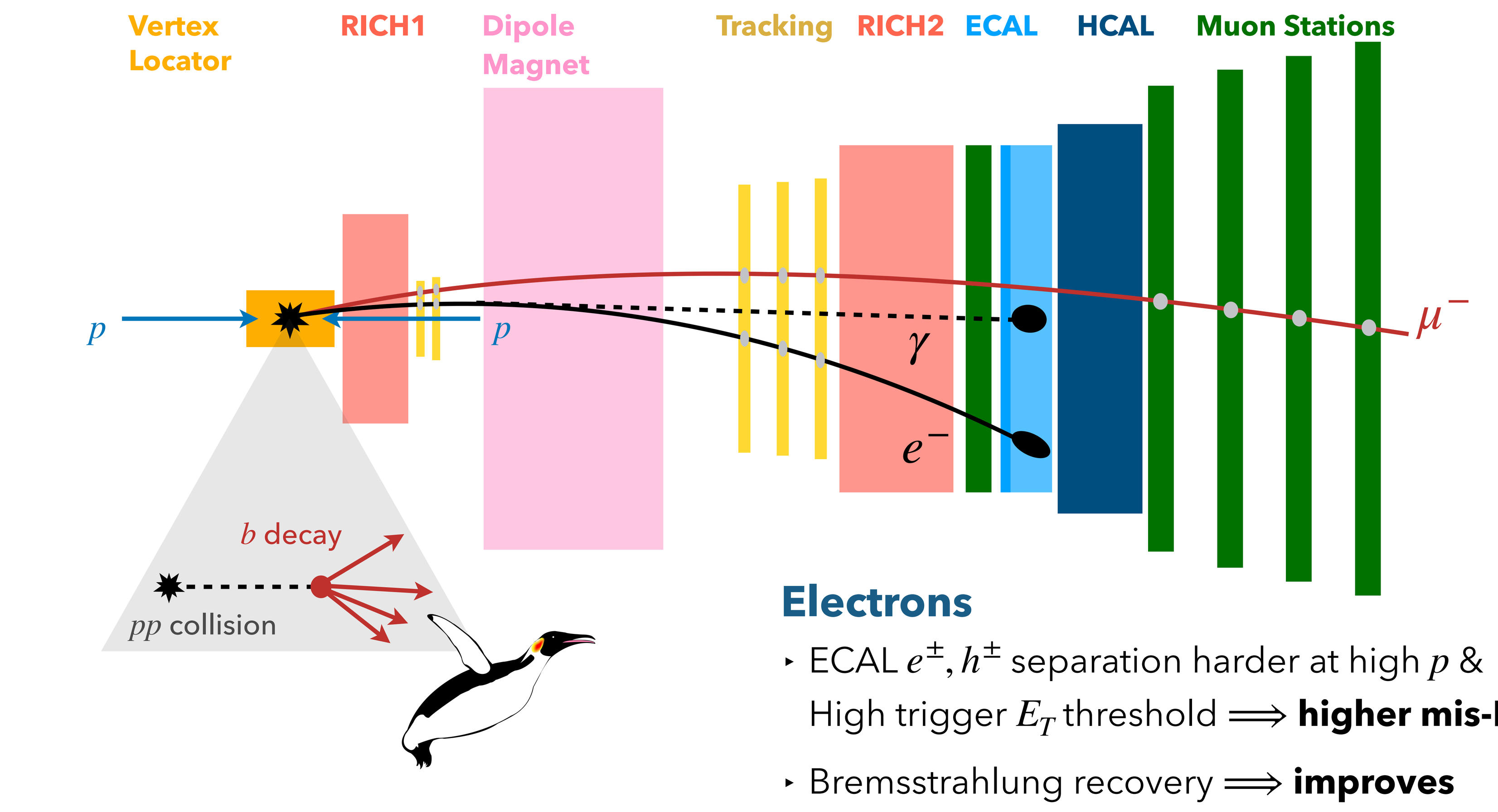
PHYS. REV. LETT. 131 (2023) 051803
PHYS. REV. D 108 (2023) 032002

- Unbinned amplitude analysis of $B^0 \to K^{*0}\mu^+\mu^-$ decays.
- Measurement of $B_s^0 \to \phi\mu^+\mu^-$ branching fraction.
- Lepton flavour universality tests:

$$R_H = \frac{\mathcal{B}(H_b \to H_s\mu^+\mu^-)}{\mathcal{B}(H_b \to H_s e^+e^-)} \overset{\text{SM}}{=} 1$$

theoretically clean.

Signatures in the LHCb detector



- Excellent decay vertex resolution.
- Clean $\phi \to K^+K^-$ peak shields from partially reconstructed backgrounds.

Electrons

- ECAL $e^\pm, h^\pm$ separation harder at high p & High trigger E_T threshold $\Longrightarrow$ **higher mis-ID.**
- Bremsstrahlung recovery $\Longrightarrow$ **improves momentum resolution.**
- Higher multiple scattering.

Muons

- Clear signature in Muon Stations.
- Negligible bremsstrahlung.

Testing lepton flavour universality

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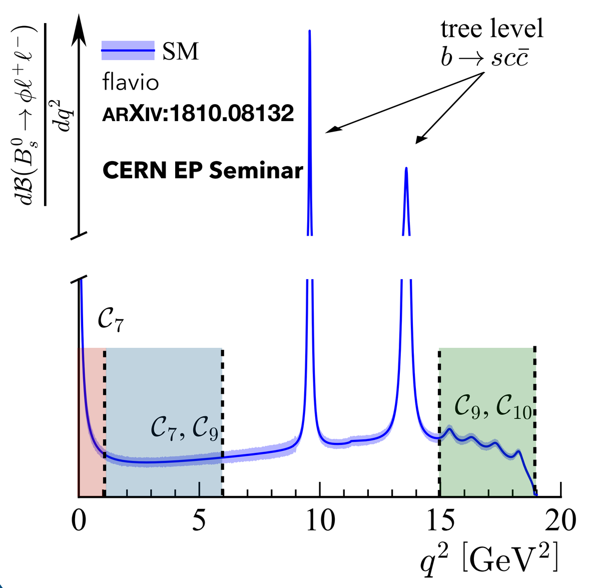
$$R_\phi^{-1} = \frac{\mathcal{B}(B_s^0 \to \phi e^+e^-)}{\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)} \frac{\mathcal{B}(B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi)}{\mathcal{B}(B_s^0 \to J/\psi(\to e^+e^-)\phi)} = \frac{N(B_s^0 \to \phi e^+e^-)}{N(B_s^0 \to \phi\mu^+\mu^-)} \frac{N(B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi)}{N(B_s^0 \to J/\psi(\to e^+e^-)\phi)} \frac{\epsilon_{\mu^+\mu^-}}{\epsilon_{e^+e^-}} \frac{\epsilon^{J/\psi}_{e^+e^-}}{\epsilon^{J/\psi}_{\mu^+\mu^-}}$$

Rare mode **Normalisation mode**

- **Double ratio** reduces many systematic uncertainties related to reconstruction.

$\Longrightarrow$ **Experimentally**

- Double ratio of **efficiency corrected yields.**



- The process is sensitive to different possible NP contributions depending on the **di-lepton mass squared.**
- R_ϕ is measured in three bins:

First ever LFU ratio at high-q^2!

Low Central High

$$q^2 \equiv m^2(e^+e^-) \in [0.1, 1.1], [1.1, 6.0], [15, 19] \text{ GeV}^2/c^4$$

- **Resonant modes offer powerful cross-check**, known to respect LFU.

J/ψ $\psi(2S)$

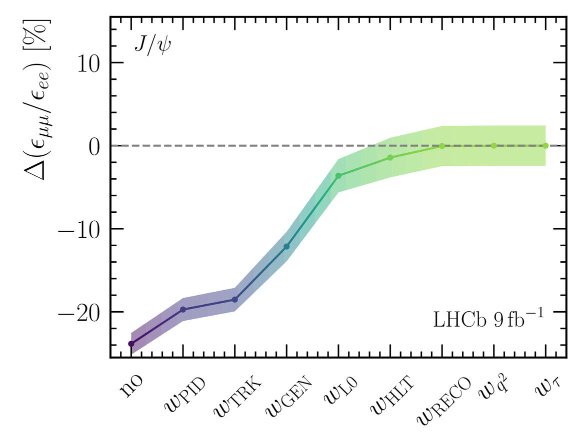
$$q^2 \in [6.0, 11], [11, 15] \text{ GeV}^2/c^4$$

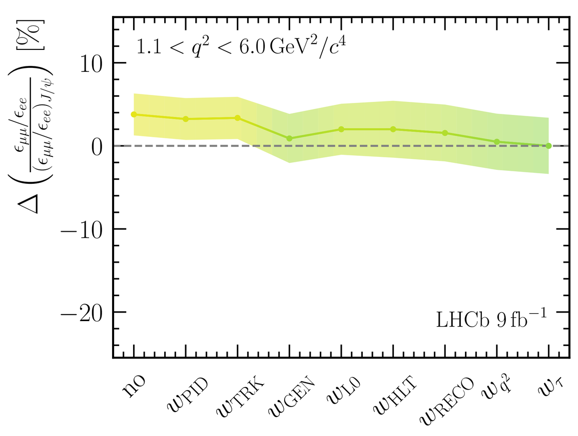
$$r_{J/\psi} = \frac{\mathcal{B}(B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi)}{\mathcal{B}(B_s^0 \to J/\psi(\to e^+e^-)\phi)} = 0.997 \pm 0.013$$

$$R_{\psi(2S)} = \frac{\mathcal{B}(B_s^0 \to \psi(2S)(\to \mu^+\mu^-)\phi)}{\mathcal{B}(B_s^0 \to \psi(2S)(\to e^+e^-)\phi)} \cdot r_{J/\psi}^{-1} = 1.010 \pm 0.026$$

➡ Single ratio, cross-check of simulation corrections.

➡ Double ratio, cross-check of analysis strategy.





Robustness of the double-ratio approach against simulation corrections

Towards an angular analysis

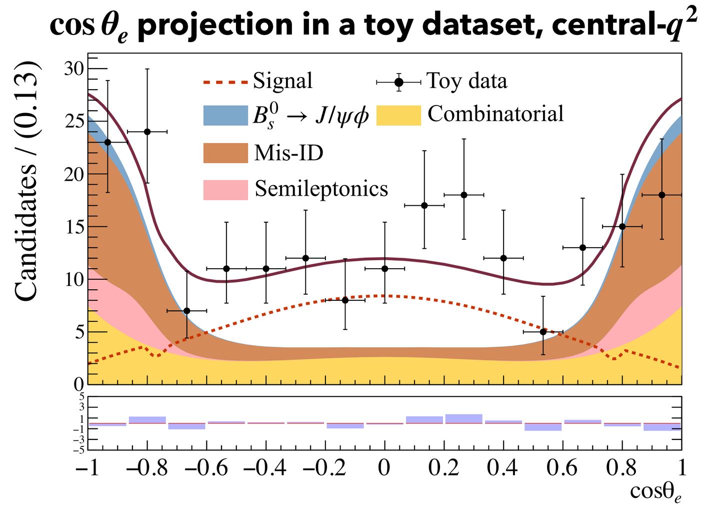
$$\frac{d\Gamma}{dq^2 d\cos\theta_K d\cos\theta_e d\Phi} = \sum_i J_i(q^2)\, f_i(\cos\theta_K, \cos\theta_e, \Phi)$$

Encodes decay amplitudes — Encodes spin structure

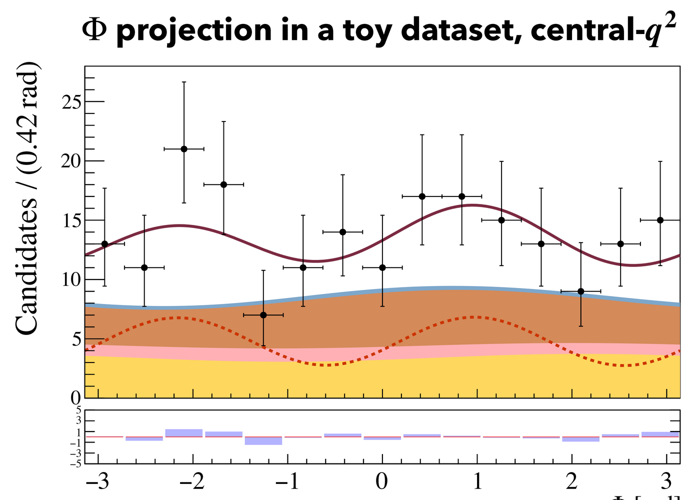
CP-averaged rate

$$\Longrightarrow \frac{1}{d(\Gamma+\bar\Gamma)/dq^2}\frac{d(\Gamma+\bar\Gamma)}{dq^2 d\cos\theta_K d\cos\theta_e d\Phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K(1+\frac{1}{3}\cos 2\theta_e) + F_L\cos^2\theta_K(1-\cos 2\theta_e) + S_3\sin^2\theta_K\sin^2\theta_e\cos 2\Phi + S_4\sin 2\theta_K\sin 2\theta_e\cos\Phi + A_5\sin 2\theta_K\sin\theta_e\cos\Phi + A_6\sin^2\theta_K\cos\theta_e + S_7\sin 2\theta_K\sin\theta_e\sin\Phi + A_8\sin^2\theta_K\sin 2\theta_e\sin\Phi + A_9\sin^2\theta_K\sin^2\theta_e\sin 2\Phi\Big]$$

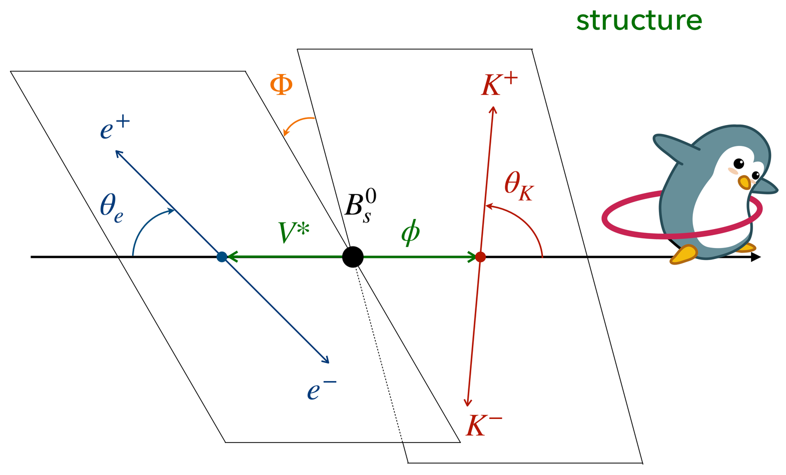
Symmetric or **Antisymmetric** under CP.



cos θ_e projection in a toy dataset, central-q^2



Φ projection in a toy dataset, central-q^2



- Small sample size $\Longrightarrow$ **fit angular projections.**
- Mass-angle fit for improved background separation.
- Fitting ($\cos\theta_K, \cos\theta_e$) and, separately, Φ gives access to F_L, A_6, S_3, A_9 in the same q^2 bins.
- Use control mode to validate angular fit strategy.
- Cross check against published LHCb analyses of $B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi$ and $B_s^0 \to \psi(2S)(\to \mu^+\mu^-)\phi$ decays, gives consistent results.
- Promising results for the angular analysis of the rare mode.

A new penguin on the block

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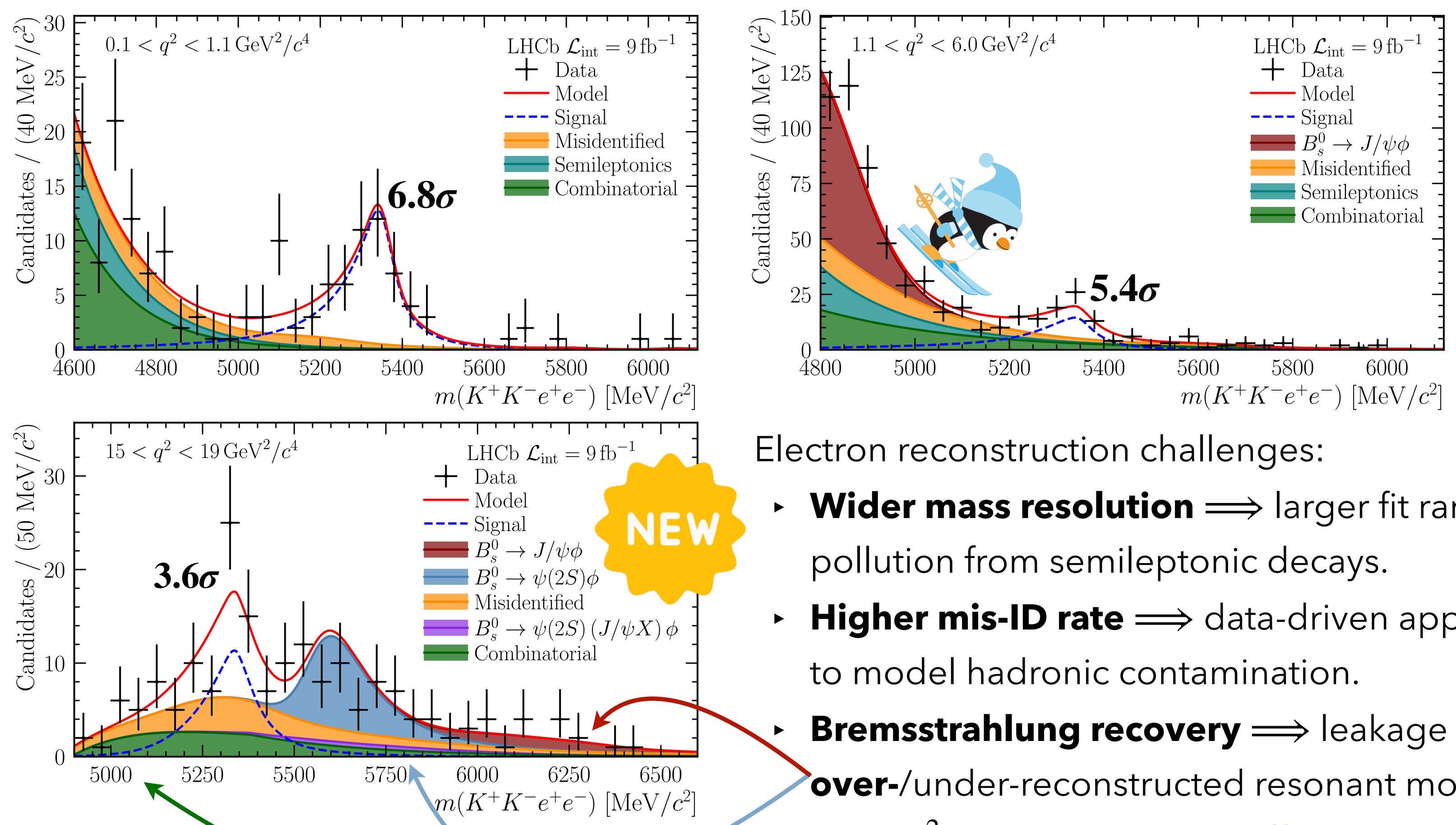
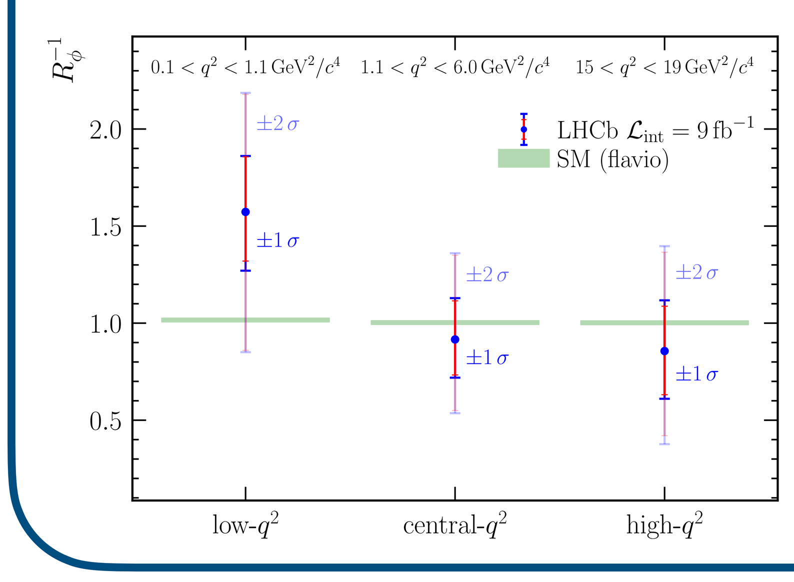
Observation of the $B_s^0 \to \phi e^+e^-$ channel!



Electron reconstruction challenges:

- **Wider mass resolution** $\Longrightarrow$ larger fit range, pollution from semileptonic decays.
- **Higher mis-ID rate** $\Longrightarrow$ data-driven approach to model hadronic contamination.
- **Bremsstrahlung recovery** $\Longrightarrow$ leakage from **over-**/under-reconstructed resonant modes.
- **High-q^2** $\Longrightarrow$ **phase-space effects** at low mass.



$$R_\phi^{-1}(\text{low-}q^2) = 1.57^{+0.28}_{-0.25}\text{ (stat.)} \pm 0.05\text{ (syst.)}$$

$$R_\phi^{-1}(\text{central-}q^2) = 0.91^{+0.20}_{-0.19}\text{ (stat.)} \pm 0.05\text{ (syst.)}$$

$$R_\phi^{-1}(\text{high-}q^2) = 0.85^{+0.24}_{-0.23}\text{ (stat.)} \pm 0.09\text{ (syst.)}$$

- **Statistically dominated measurement.**
- **Good agreement with SM.**