UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

Null Tests in B Decays
LFU, LFV, rare searches

Sara Celani, on behalf of the LHCb collaboration

LHCb Implications Workshop

CERN, 23-25 Oct, 2024

Lepton Flavour Universality

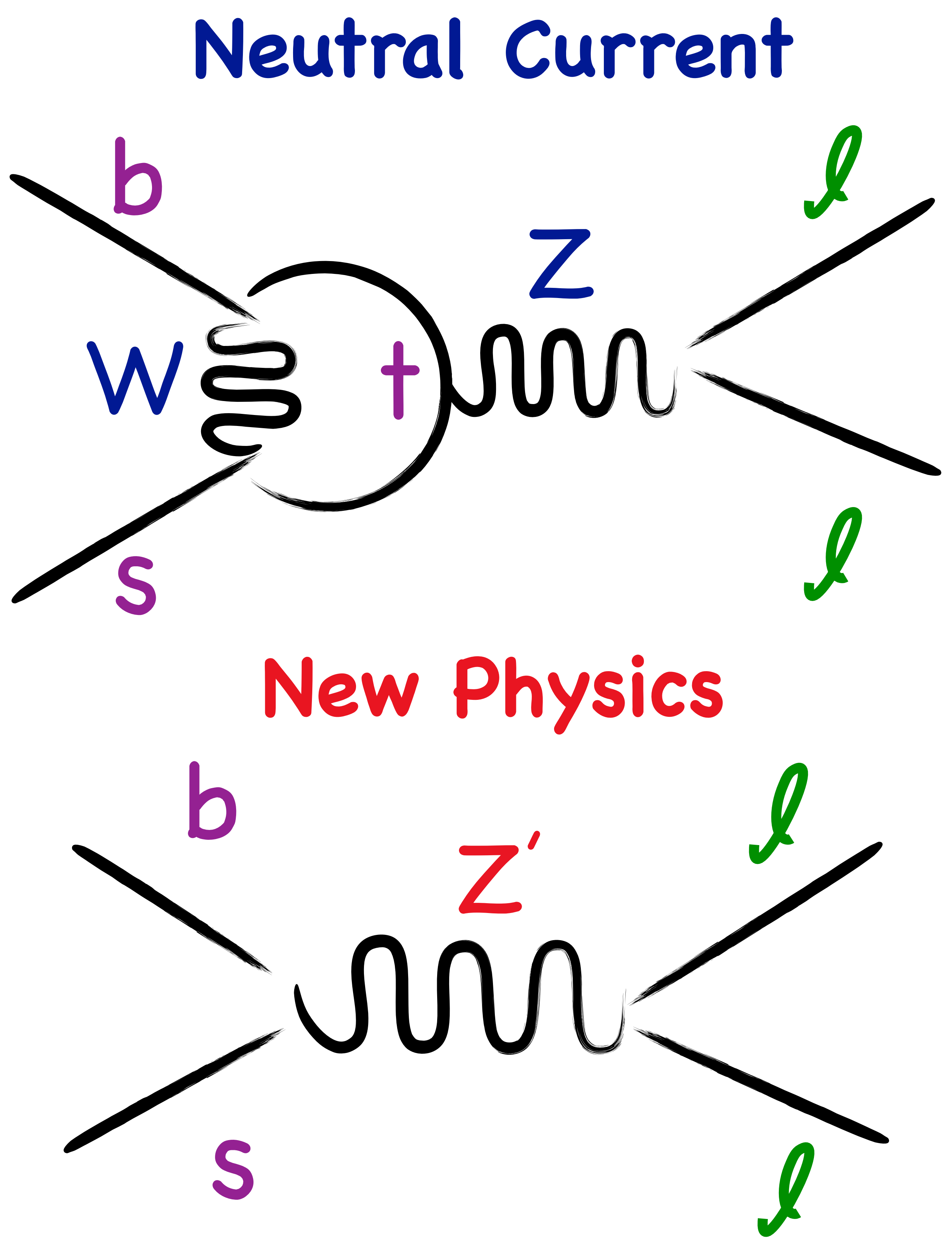
LFU

- $b \to s\ell\ell$ transitions extensively used to test the lepton universality of the SM
  - Rare processes, happen only via loop or boxes, $\mathscr{B} \sim 10^{-7} - 10^{-6}$
  - **New** non-LFU **physics** mediators can contribute with comparable amplitudes
- Test LFU by measuring **relative rates**

$q^2 = m^2(\ell^+\ell^-)$

$$R_X = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{\mathscr{B}(B \to X\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{\mathscr{B}(B \to Xe^+e^-)}{dq^2} dq^2} \overset{\rm SM}{\equiv} 1 \quad \text{if } m_\ell^2 \ll q^2$$

  - are clean: hadronic uncertainties cancels out in the ratio
  - are predicted by the SM with very high precision



LFU

- LHCb dominates the precision on LFU tests with different hadronic systems $X = K, K^*, pK....$
- Today's talk:

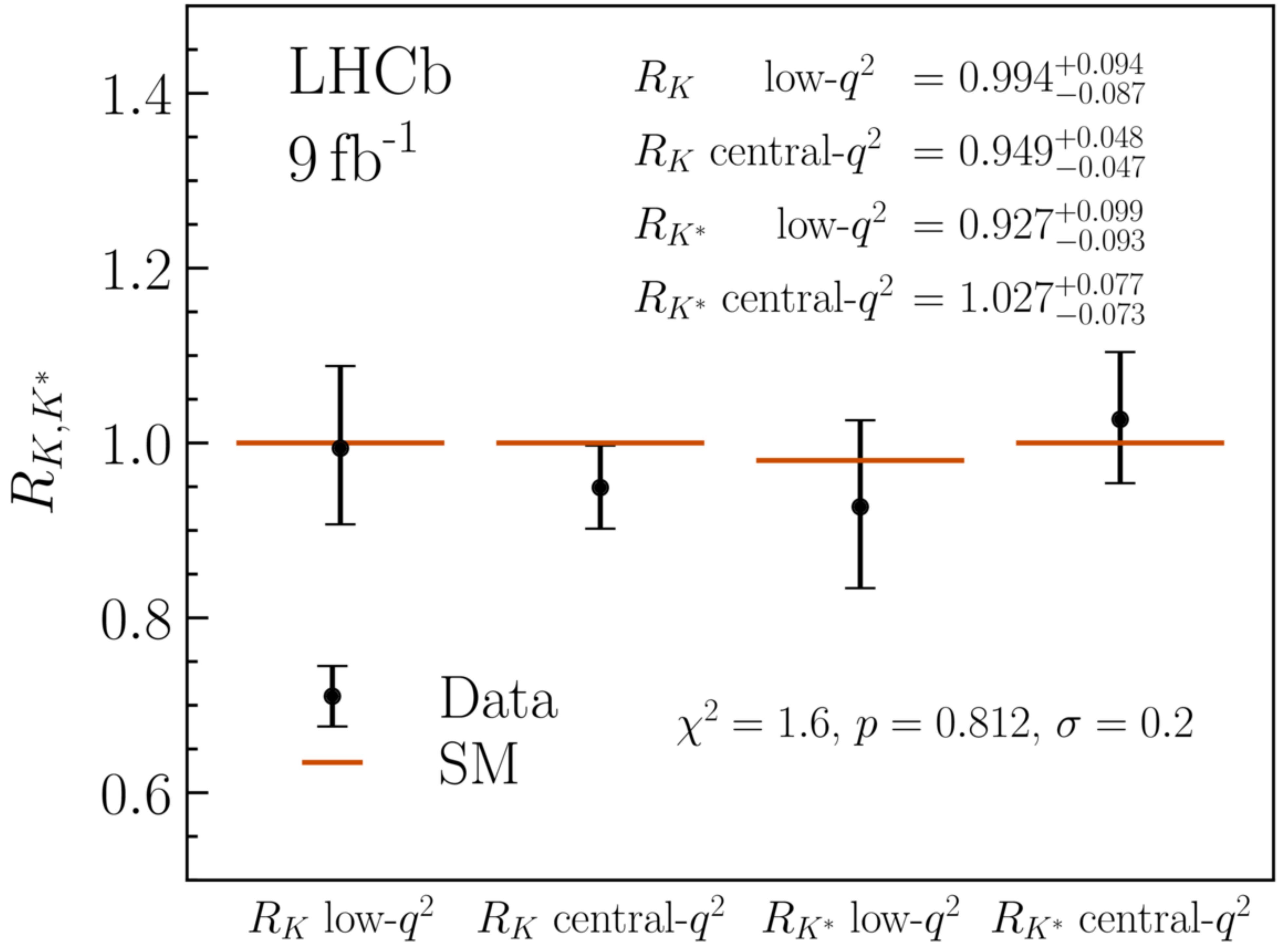
NEW! ▸ LFU test with $B_s \to \phi_{(\to K^+K^-)}\ell^+\ell^+$ decays — CERN seminar

- ❖ First LFU test with a B_s decay
- ❖ First LHCb high-q^2 LFU test
- ❖ First observation of $B_s \to \phi e^+e^+$ decay*

NEW! ▸ LFU test with $B^+ \to K^+\pi^+\pi^-\ell^+\ell^-$ decays

- ❖ First inclusive LFU test with 5-body decays
- ❖ First observation of $B^+ \to K^+\pi^+\pi^-e^+e^-$ decay

PRL 131 (2023) 051803



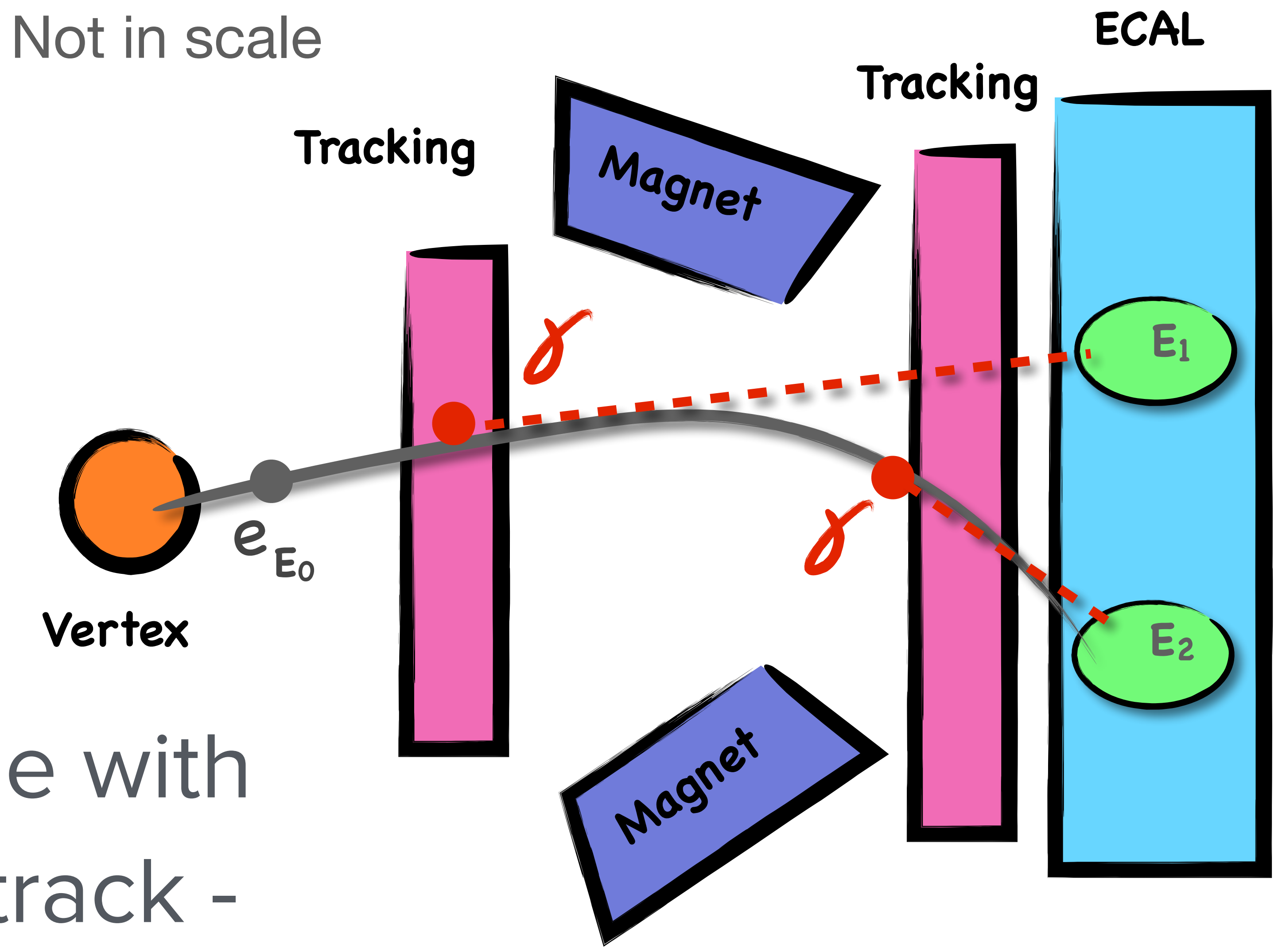
*together with very low q^2 analysis [LHCb-PAPER-2024-030], in preparation, see Lakshan Madhan talk

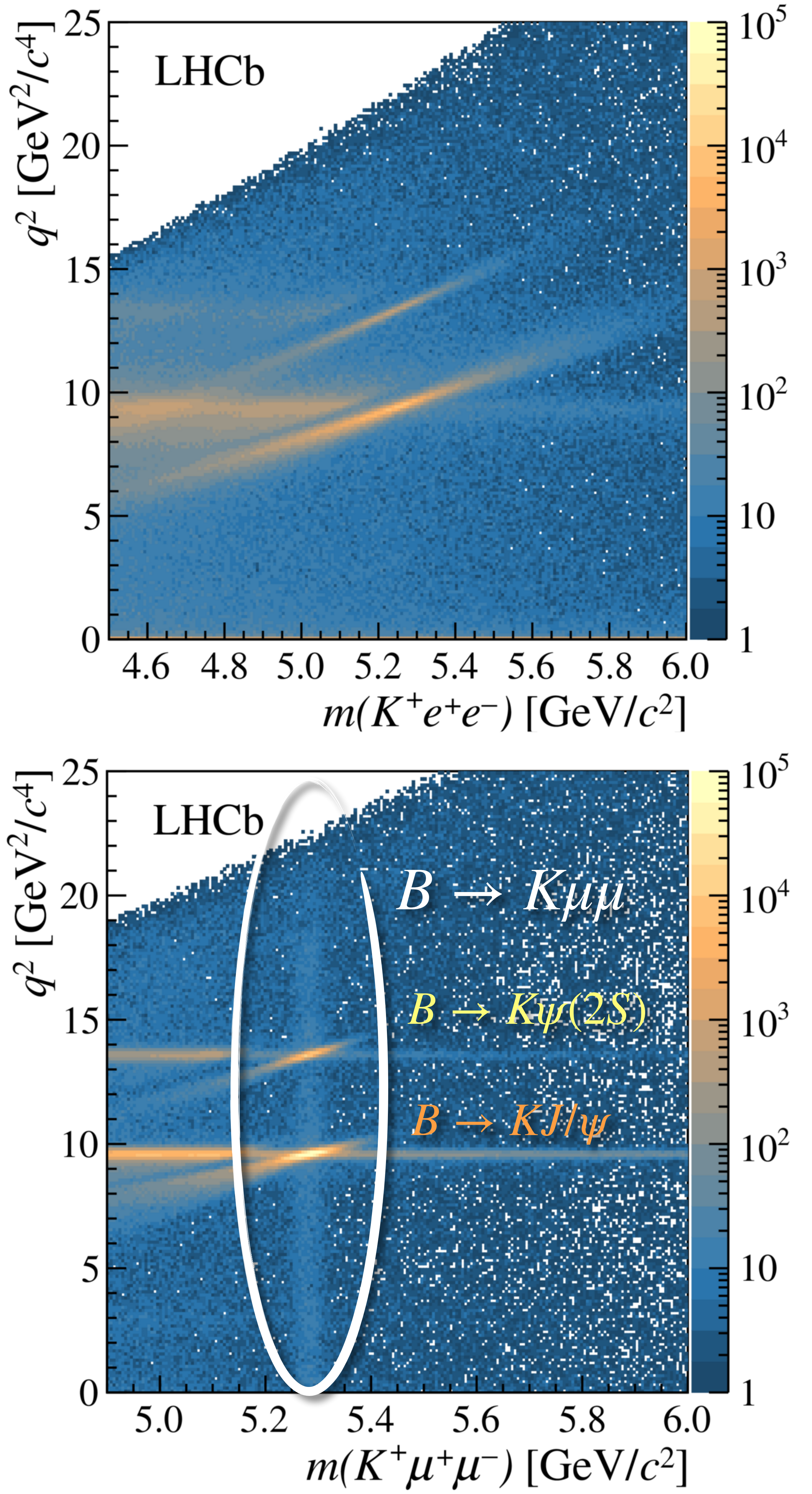
LFU ratios challenges: e vs μ

$q^2 = m^2(\ell^+\ell^-)$

PRL 122 (2019) 191801

- Most electrons emit **bremsstrahlung** photons:
  - Need to recover the photon cluster energy
  - Photon added if compatible with the extrapolated electron track - $\mathcal{O}(50\%)$ efficient
- High occupancy in the ECAL
  - Higher energy thresholds ➞ lower statistics



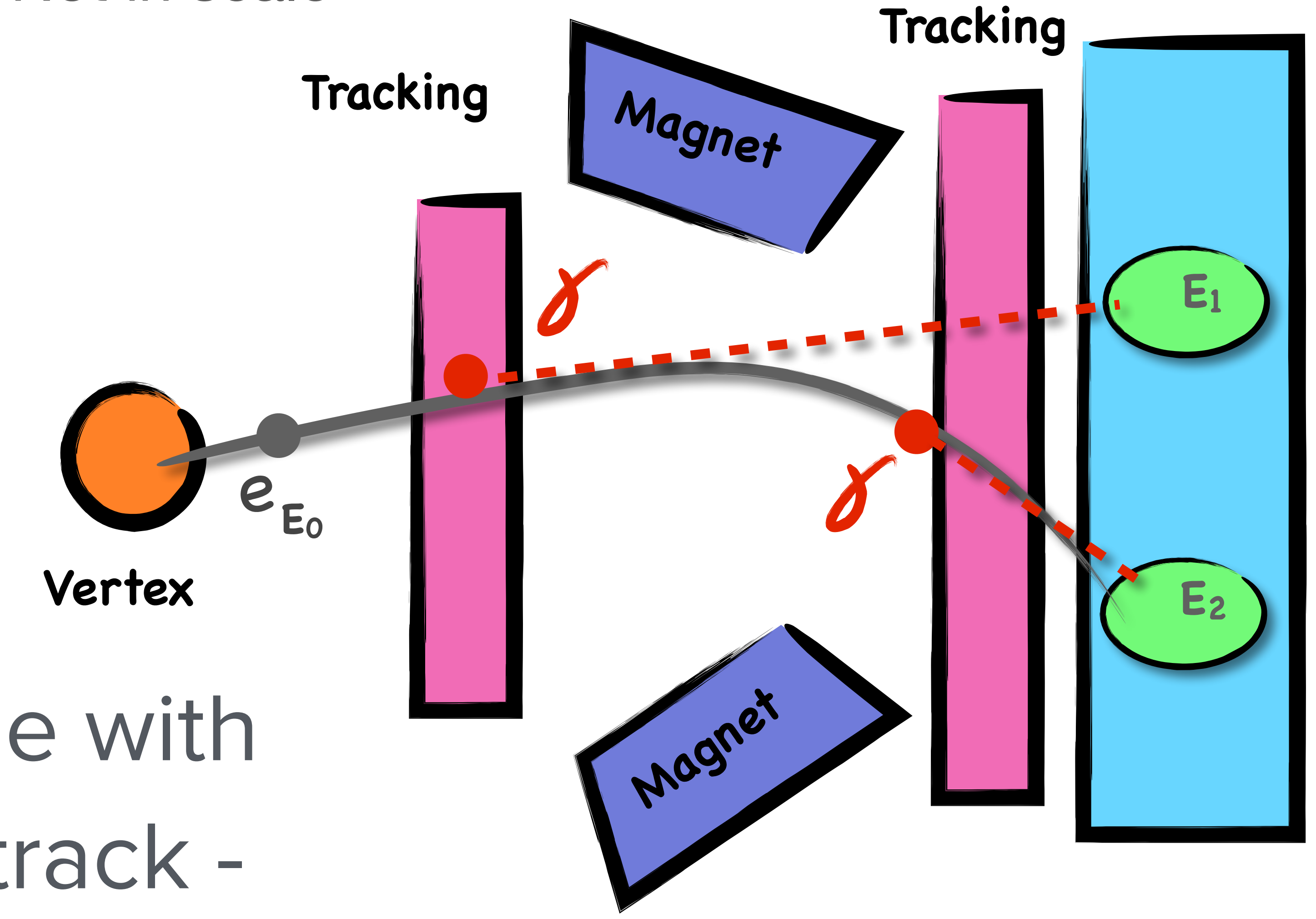


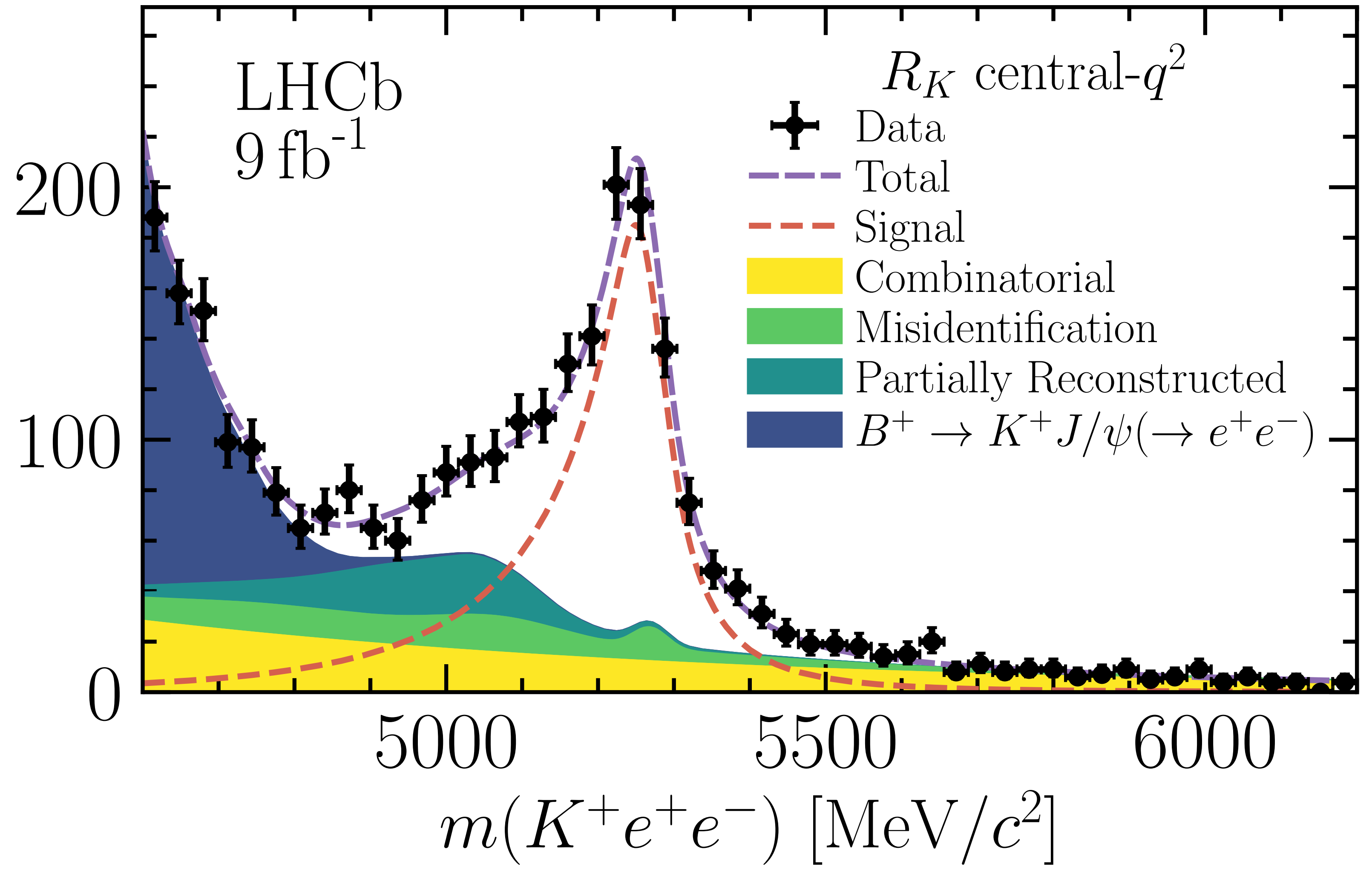
LFU ratios challenges: e vs μ

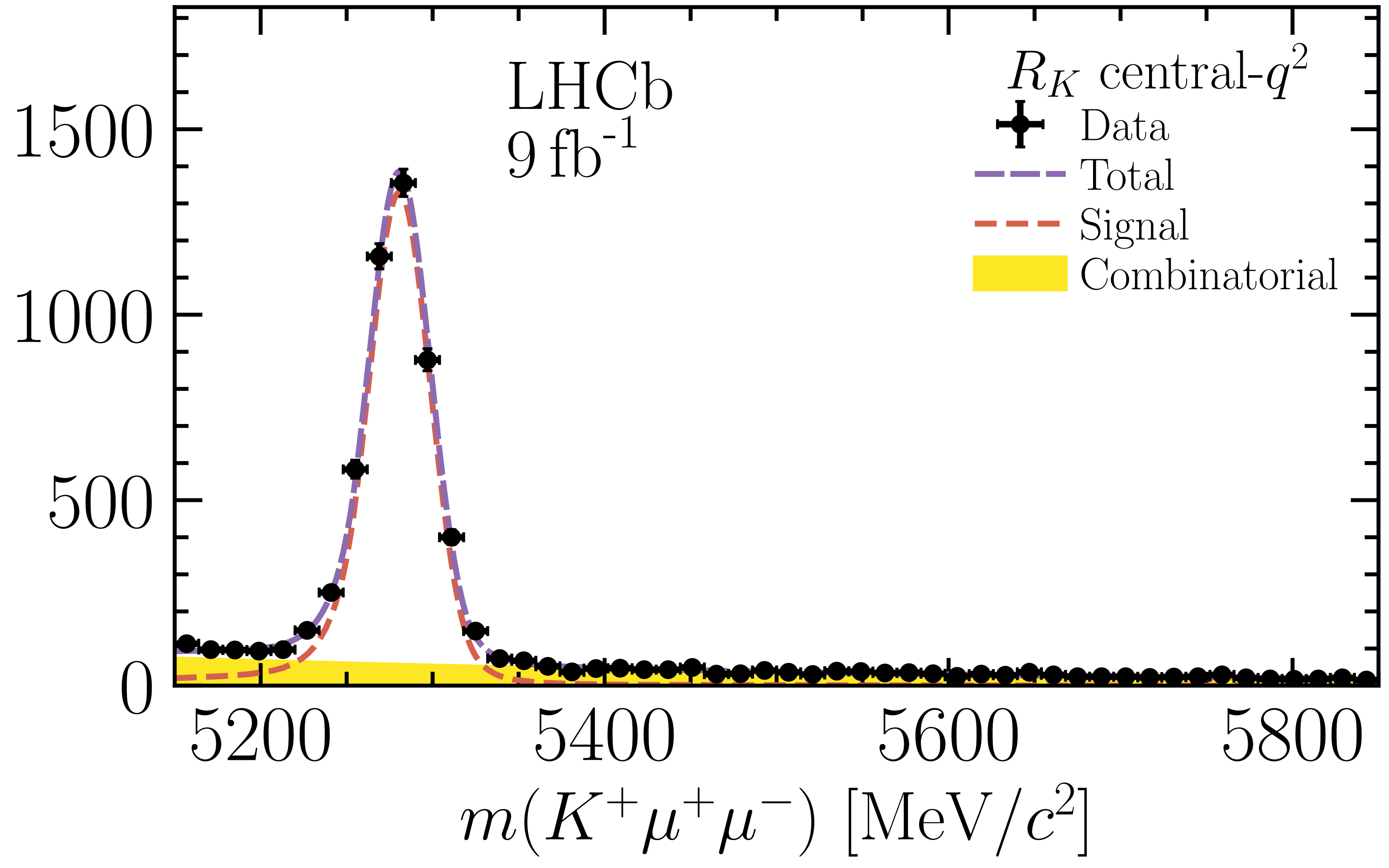
$q^2 = m^2(\ell^+\ell^-)$

PRL 131 (2023) 051803

- Most electrons emit **bremsstrahlung** photons:
  - Need to recover the photon cluster energy
  - Photon added if compatible with the extrapolated electron track - $\mathcal{O}(50\%)$ efficient





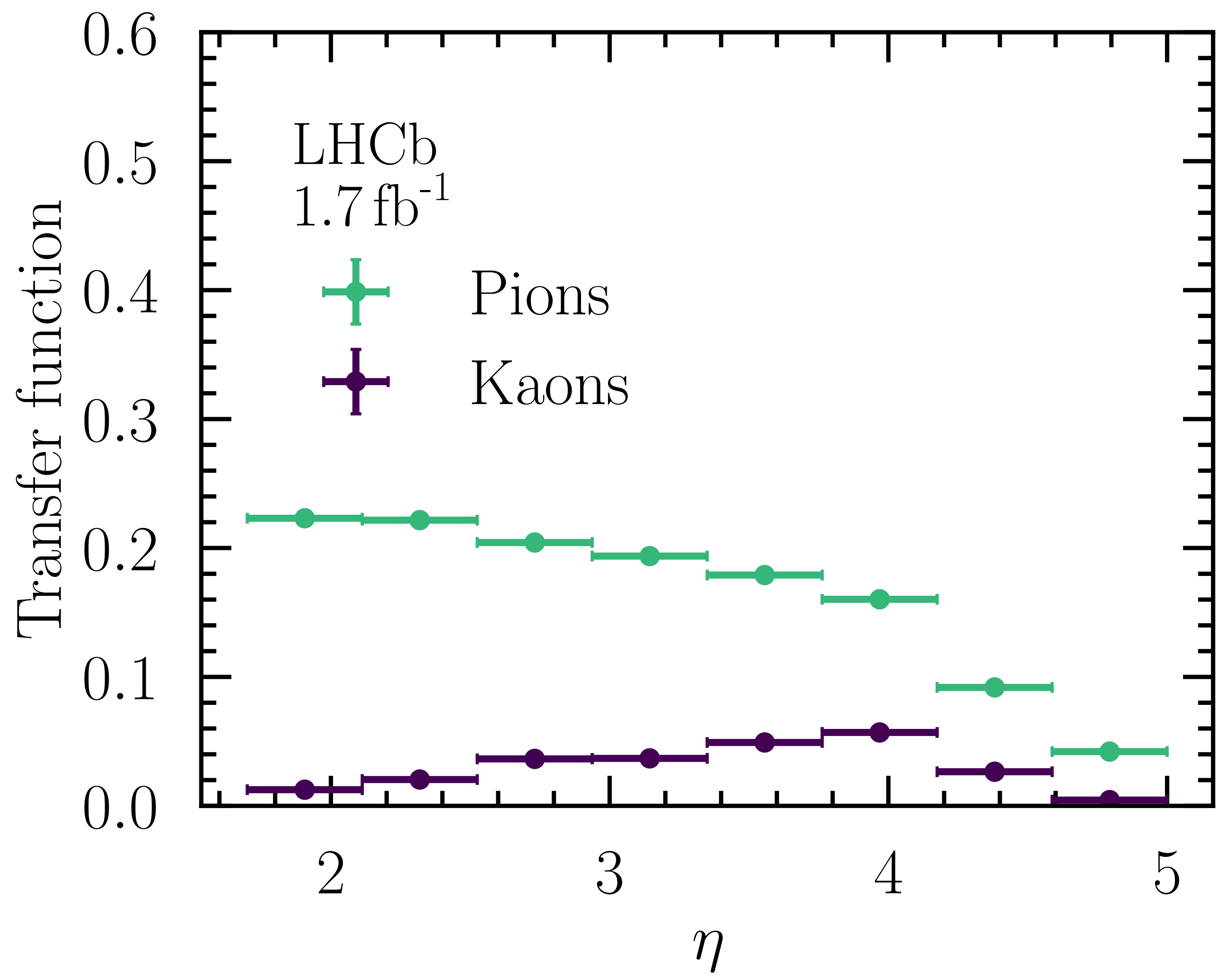


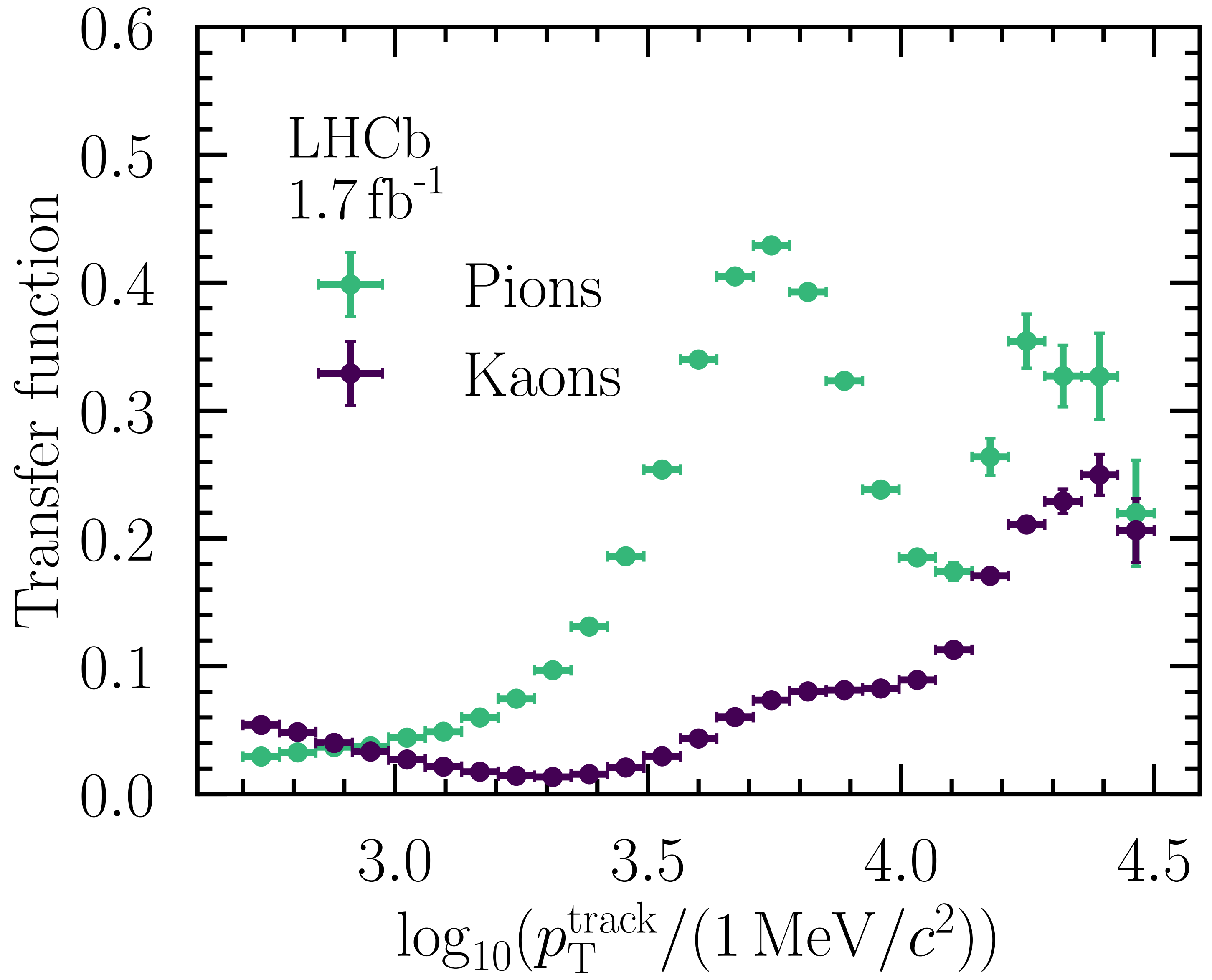
- High occupancy in the ECAL
  - Higher energy thresholds ➞ lower statistics
- Additional backgrounds in the electron modes
  - Partially reconstructed decays, misID $h \to e$, leakage from resonant decays

$h \to e$ misID background

PRD 108 (2023) 032002

- Data driven method developed in R_K & R_{K^*} analysis
- Basic principles:
  - Define control regions enriched in misID, by inverting PID criteria on the electrons
  - Compute weights to transfer knowledge from control to signal regions



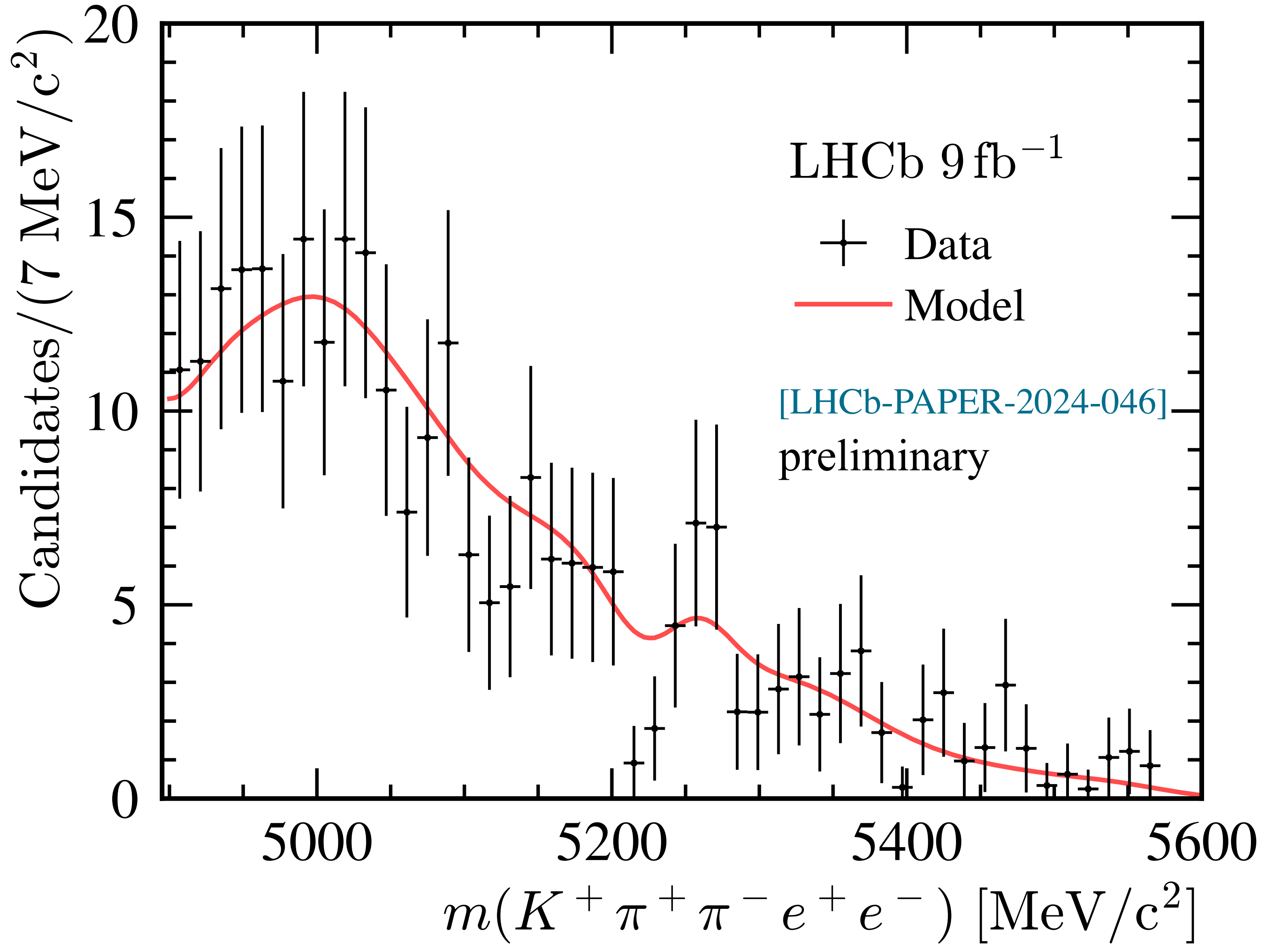


$h \to e$ misID background

$X = K\pi\pi$

[LHCb-PAPER-2024-046], in preparation

- Data driven method developed in R_K & R_{K*} analysis
- Basic principles:
  - Define control regions enriched in misID, by inverting PID criteria on the electrons
  - Compute weights to transfer knowledge from control to signal regions
  - Use the mis-ID weighted events in the control regions to estimate lineshape and amount of misID background

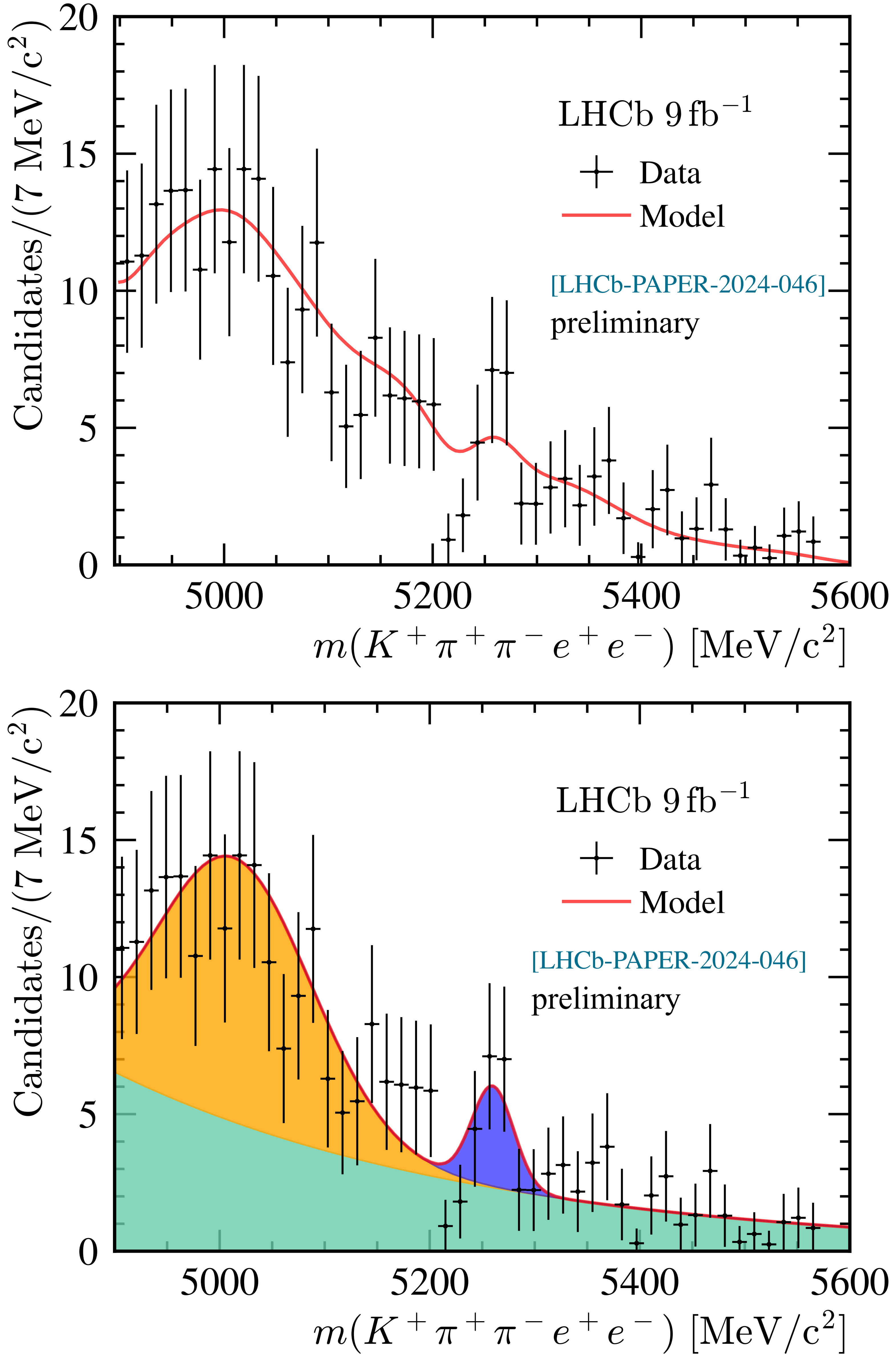


$h \to e$ misID background

- Data driven method developed in R_K & R_{K^*} analysis
- Basic principles:
  - Define control regions enriched in misID, by inverting PID criteria on the electrons
  - Compute weights to transfer knowledge from control to signal regions
  - Use the mis-ID weighted events in the control regions to estimate lineshape and amount of misID background
- Main source of systematics, assessed by varying
  - The size of the contribution
  - The lineshape models
  - The PID criteria to decide it was a K or a π misID

$X = K\pi\pi$

[LHCb-PAPER-2024-046], in preparation

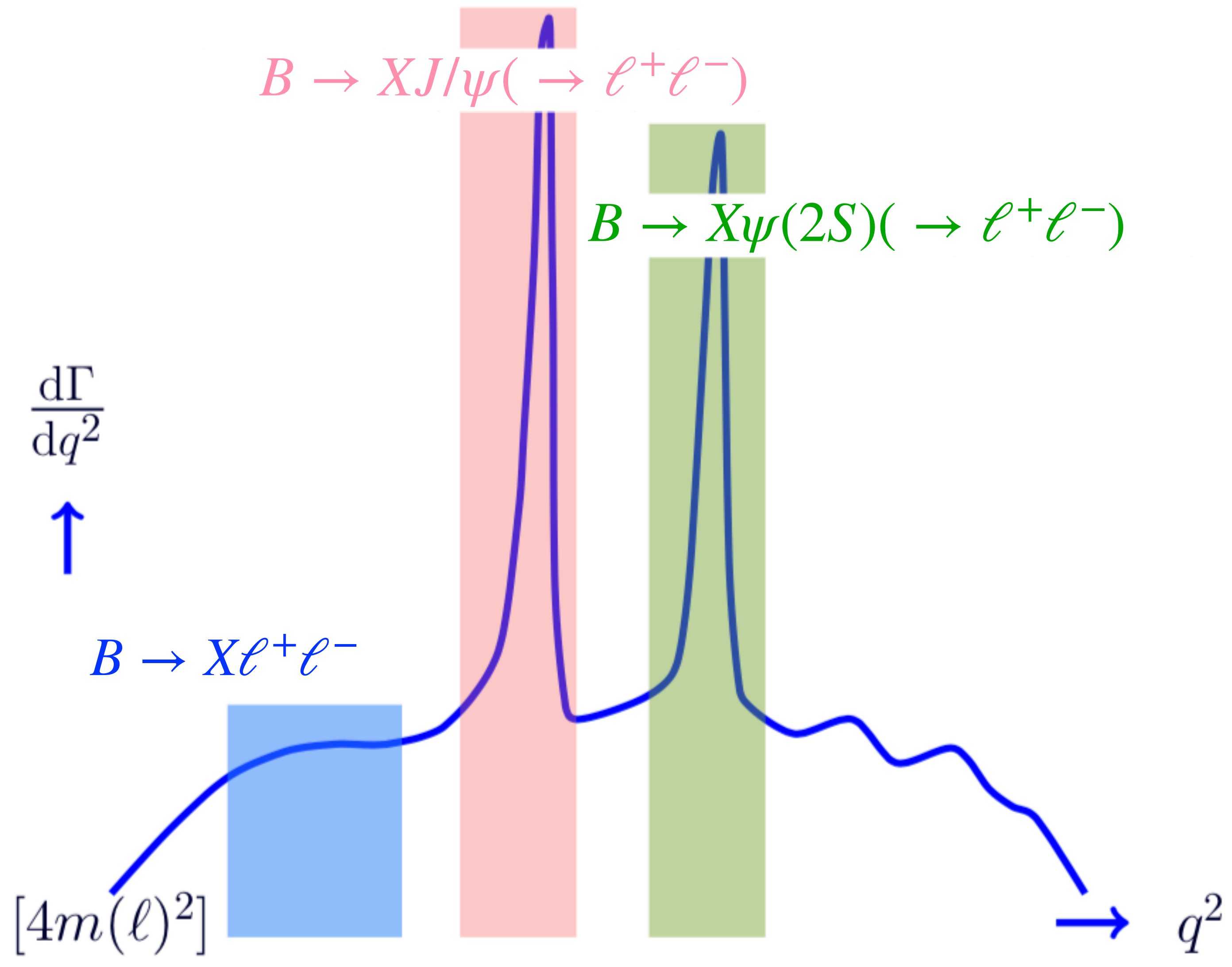


LFU ratio: Experimental strategy

- R_X are measured as double ratios, to mitigate e/μ reconstruction differences

$$R_X = \frac{\mathcal{N}_{B\to X\mu^+\mu^-}}{\mathcal{N}_{B\to XJ/\psi(\to\mu^+\mu^-)}} \cdot \frac{\mathcal{N}_{B\to XJ/\psi(\to e^+e^-)}}{\mathcal{N}_{B\to Xe^+e^-}} \cdot \frac{\epsilon_{B\to XJ/\psi(\to\mu^+\mu^-)}}{\epsilon_{B\to X\mu^+\mu^-}} \cdot \frac{\epsilon_{B\to Xe^+e^-}}{\epsilon_{B\to XJ/\psi(\to e^+e^-)}}$$

- Yields: unbinned maximum-likelihood fits to the B invariant mass
- Efficiencies: simulation corrected for well-known MC/data differences

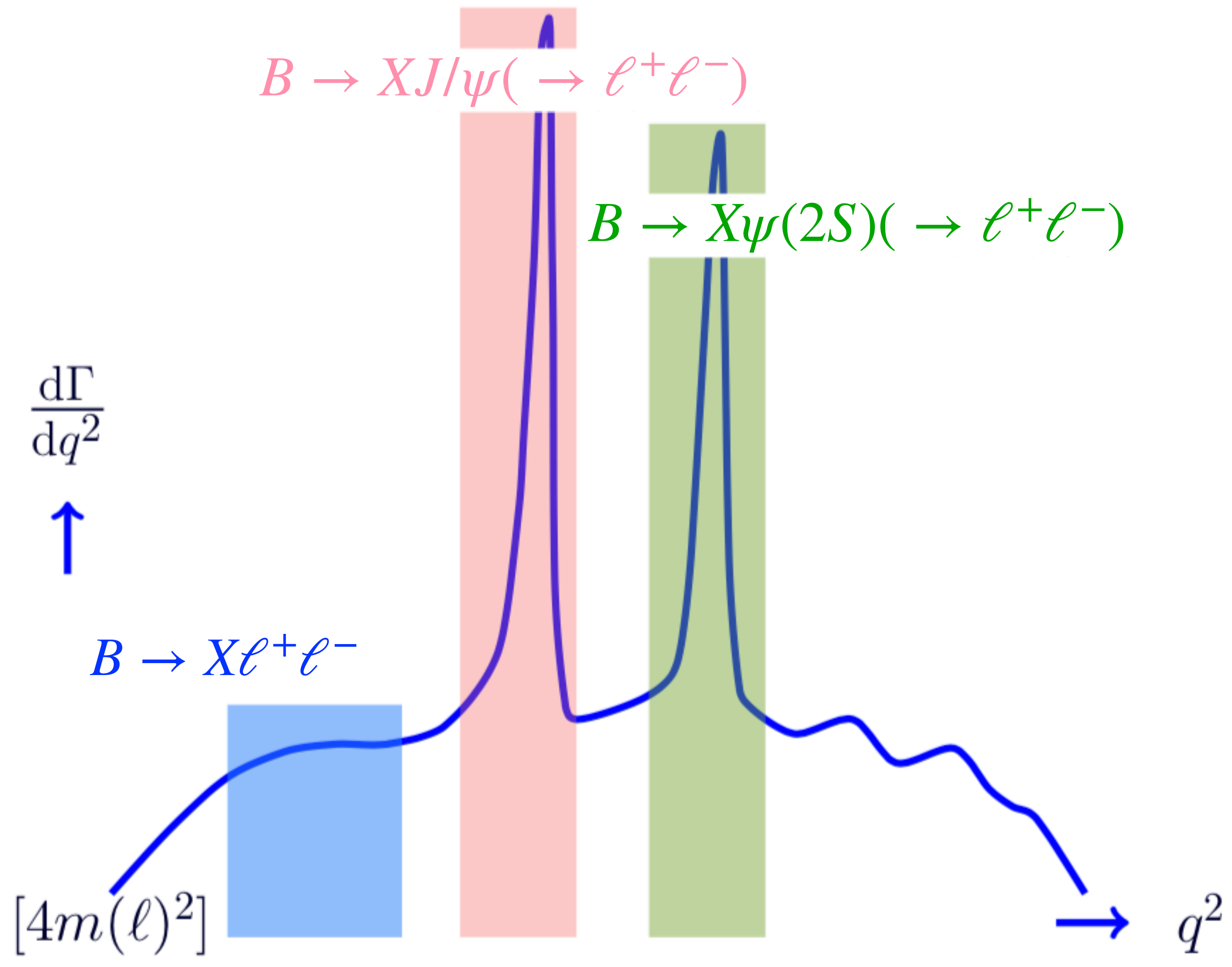


LFU ratio: Experimental strategy

- R_X are measured as double ratios, to mitigate e/μ reconstruction differences

$$R_X = \frac{\mathcal{N}_{B\to X\mu^+\mu^-}}{\mathcal{N}_{B\to XJ/\psi(\to\mu^+\mu^-)}} \cdot \frac{\mathcal{N}_{B\to XJ/\psi(\to e^+e^-)}}{\mathcal{N}_{B\to Xe^+e^-}} \cdot \frac{\epsilon_{B\to XJ/\psi(\to\mu^+\mu^-)}}{\epsilon_{B\to X\mu^+\mu^-}} \cdot \frac{\epsilon_{B\to Xe^+e^-}}{\epsilon_{B\to XJ/\psi(\to e^+e^-)}}$$

- Yields: unbinned maximum-likelihood fits to the B invariant mass
- Efficiencies: simulation corrected for well-known MC/data differences

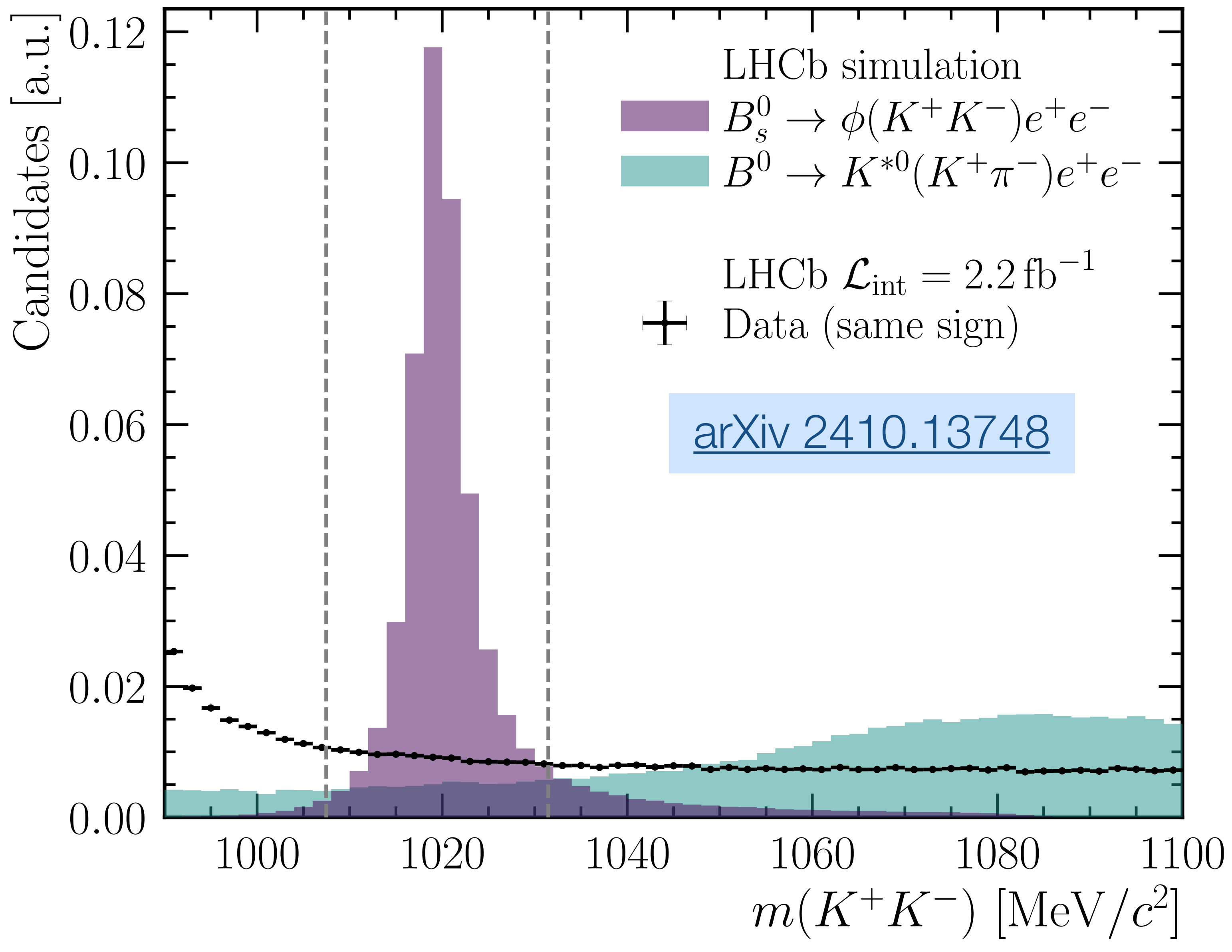


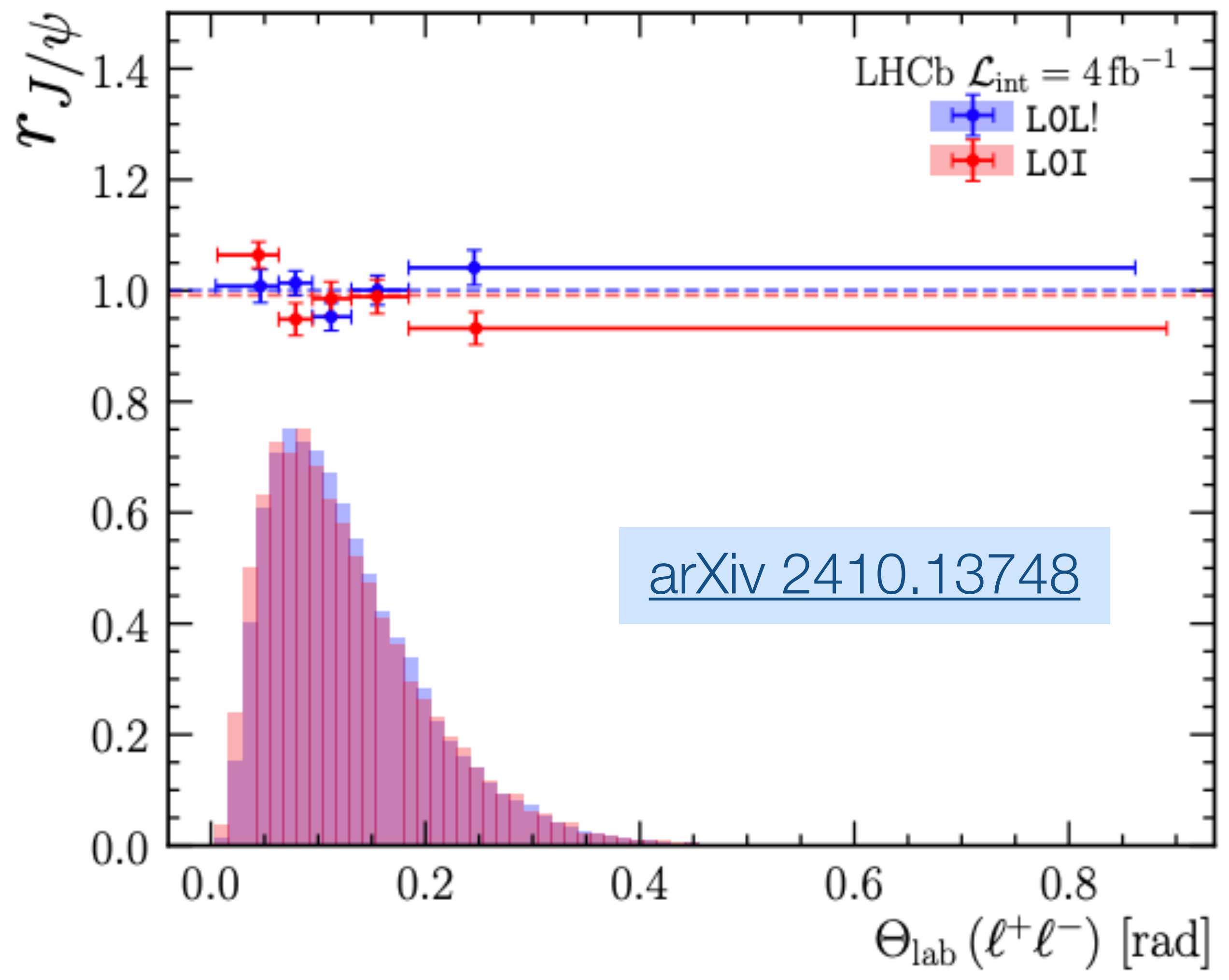
- Resonant channels also used for checks/data driven studies
  - J/ψ and $\psi(2S)$ satisfy LFU, not mediated by $b \to s\ell\ell$
    - $r_{J/\psi} = \frac{\mathcal{B}(B\to XJ/\psi(\to\mu\mu))}{\mathcal{B}(B\to XJ/\psi(\to ee))} \equiv 1$ Sensitive to e, μ differences
    - $R_{\psi(2S)} = \frac{\mathcal{B}(B\to X(\psi(2S)\to\mu\mu))}{\mathcal{B}(B\to X(J/\psi\to\mu\mu))} \cdot \frac{\mathcal{B}(B\to X(J/\psi\to ee))}{\mathcal{B}(B\to X(\psi(2S)\to ee))} \equiv 1$ Efficiency related systematics cancel in double ratio

R_ϕ - Strategy

$X = \phi$

- Measurement performed in in three q^2 regions
  - low-q^2 : $0.1 < q^2 < 1.1$ Gev$^2/c^4$
  - central-q^2 : $1.1 < q^2 < 6.0$ Gev$^2/c^4$
  - high-q^2 : $15 < q^2 < 19$ Gev$^2/c^4$
- Use full LHCb dataset ($9\,\mathrm{fb}^{-1}$)
- Take advantage of the narrow ϕ resonance and excellent $m(K^+K^-)$ resolution at LHCb



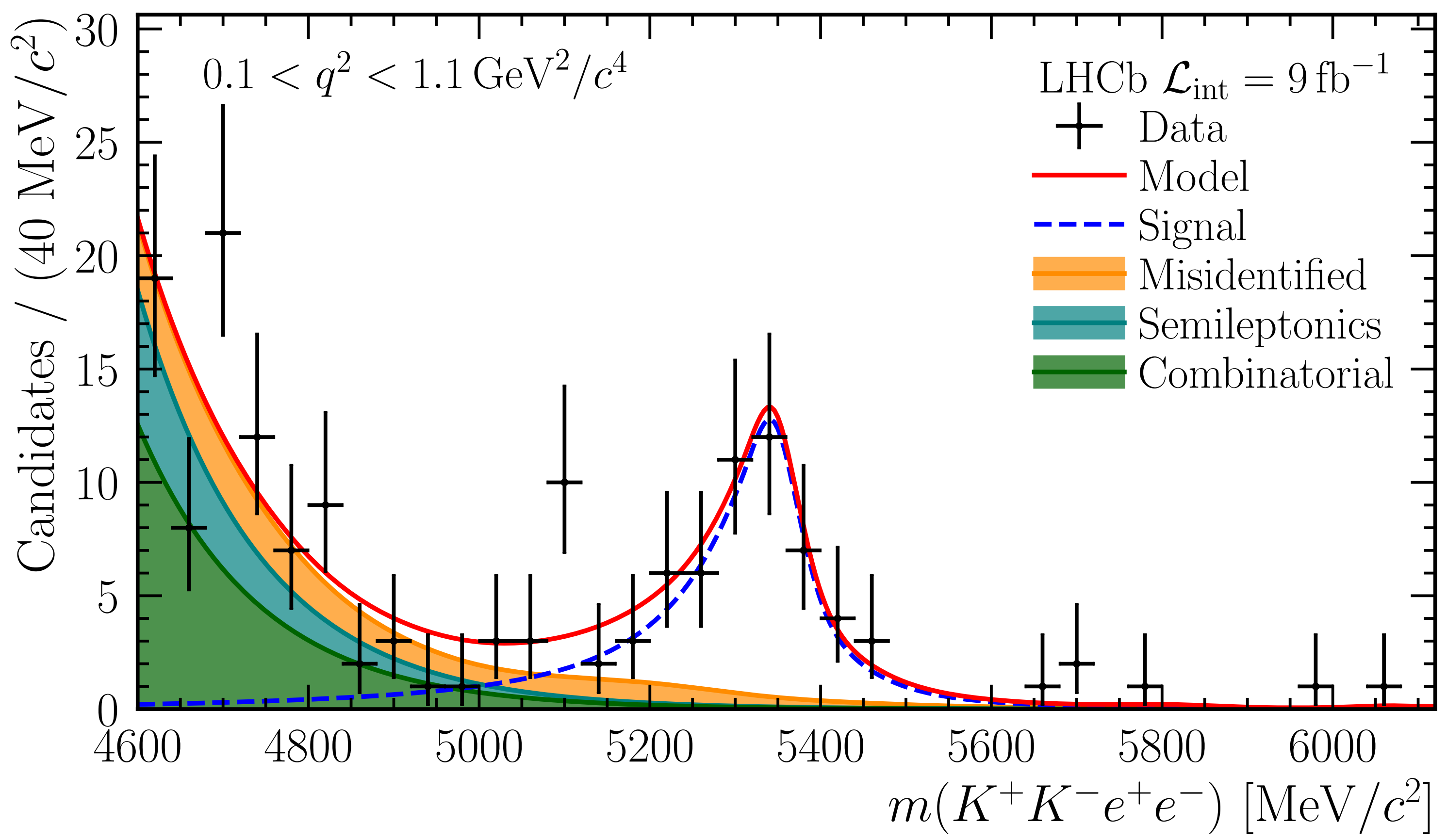


- Cross checks:
  - $r_{J/\psi} = 0.997 \pm 0.013$
  - $R_{\psi(2S)} = 1.010 \pm 0.026$
- Uncertainties includes systematics due to the calibration sample size

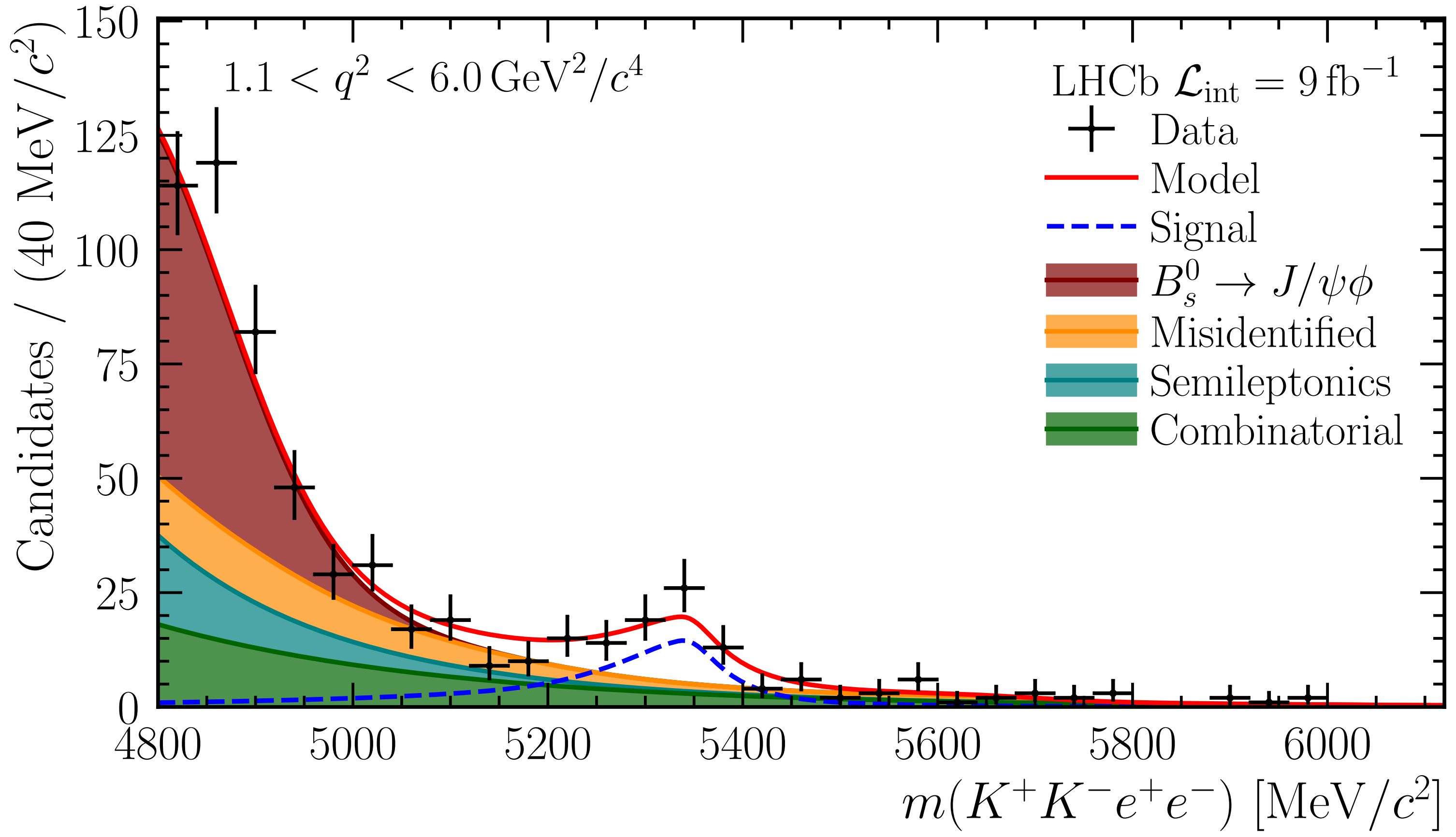
$B_s \to \phi e^+ e^-$ observation*

arXiv 2410.13748

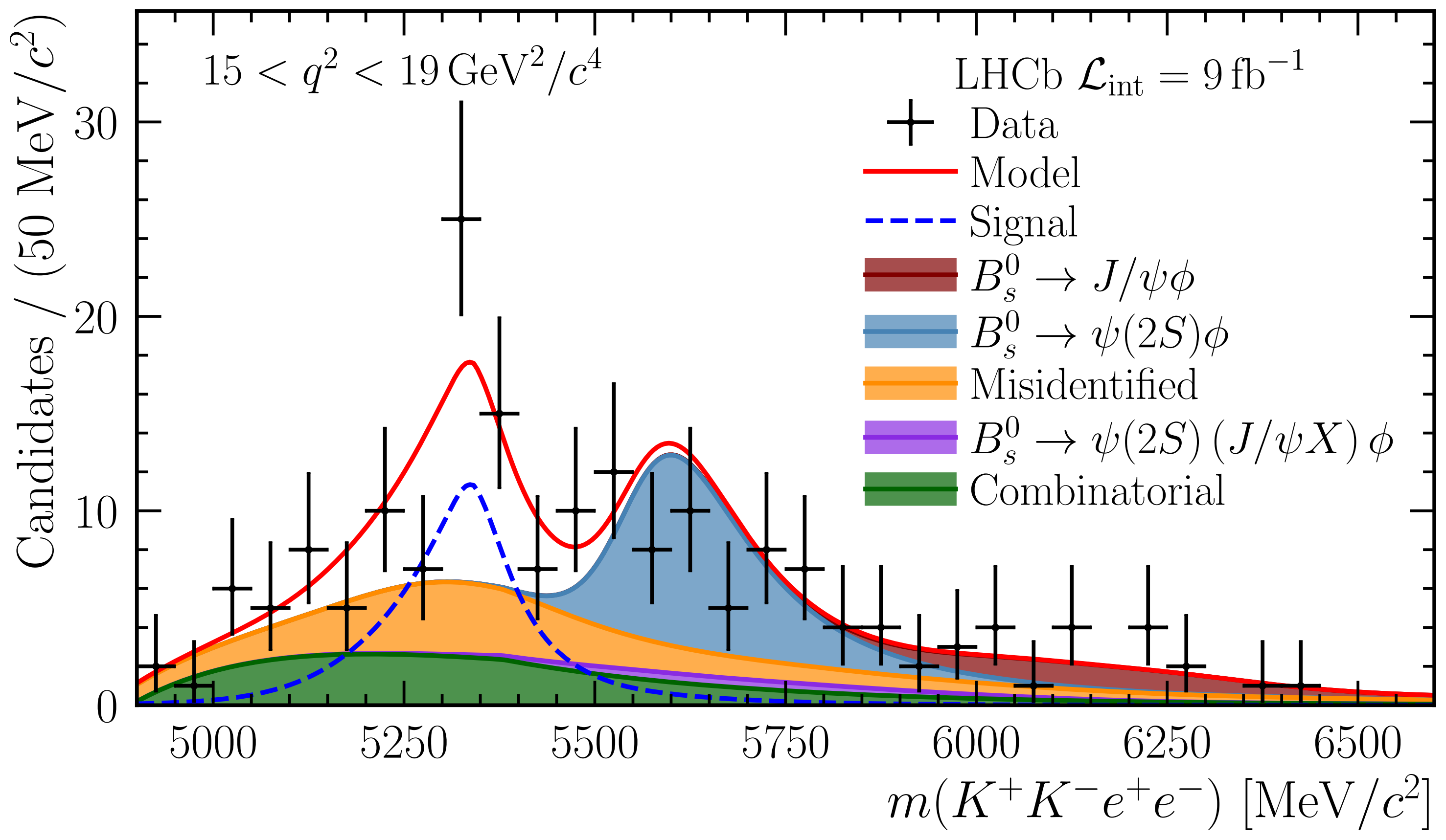
- $h \to e$ mis-identification modeled with pass-fail method
- Tree-level $B_s^0 \to D_s^- e^+ \nu_e$ in central and low-q^2
- Leakage from $B_s^0 \to \phi J/\psi(\to e^+e^-)$ in central and high-q^2
- Leakage from $B_s^0 \to \phi \psi(2S)(\to e^+e^-)$ in high-q^2
- Challenges in combinatorial high-q^2 due to the limited phase space after the selection
  - Use "acceptance" function validated on same-sign data



Statistical significance: 6.8σ



Statistical significance: 5.4σ



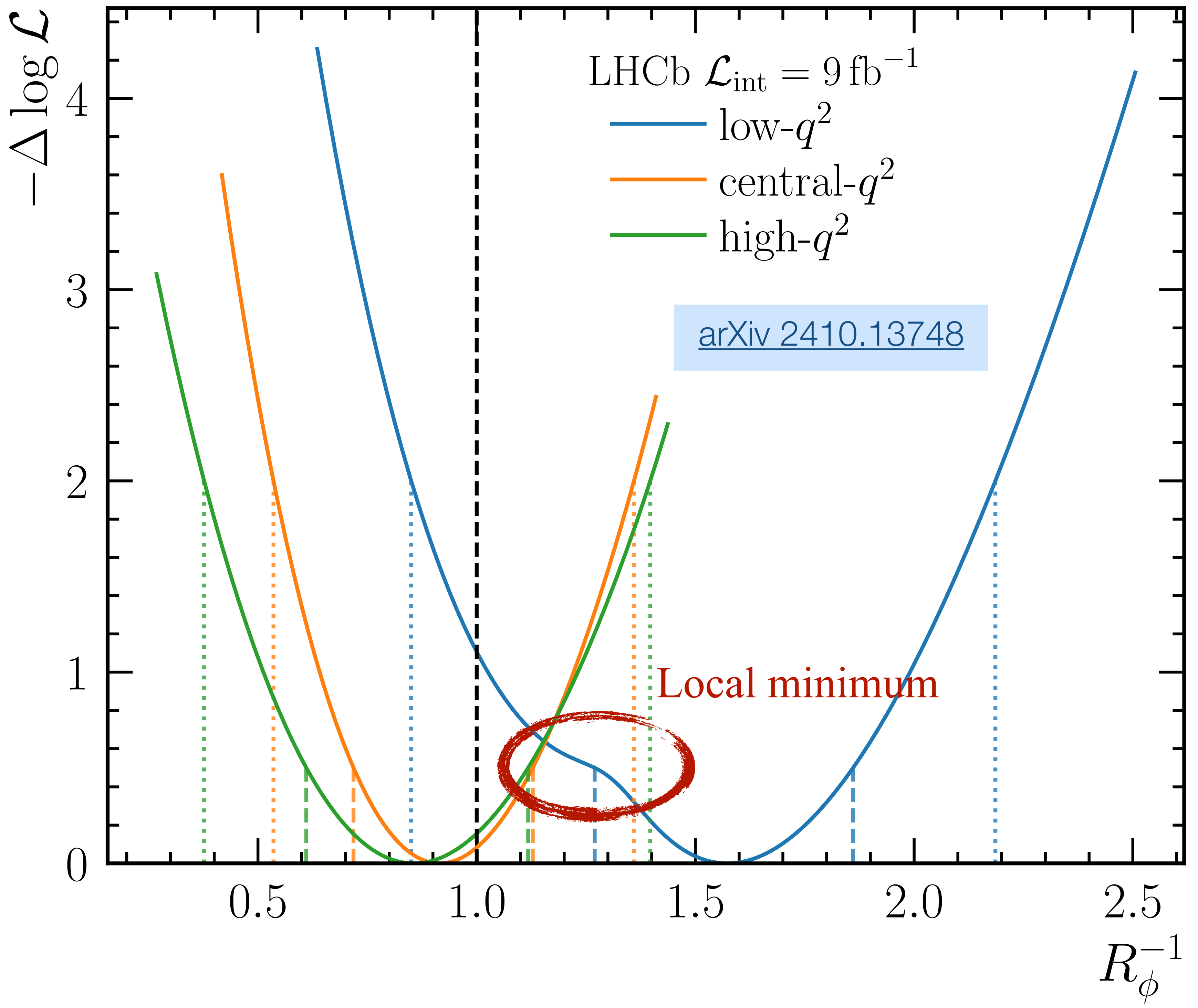
Statistical significance: 3.6σ

*together with very low q^2 analysis [LHCb-PAPER-2024-030], in preparation, see Lakshan Madhan talk

R_ϕ - Results

$X = \phi$

q^2 [GeV$^2/c^4$]	R_ϕ^{-1}
$0.1 < q^2 < 1.1$	$1.57\,^{+0.28}_{-0.25} \pm 0.05$
$1.1 < q^2 < 6.0$	$0.91\,^{+0.20}_{-0.19} \pm 0.05$
$15.0 < q^2 < 19.0$	$0.85\,^{+0.24}_{-0.23} \pm 0.10$

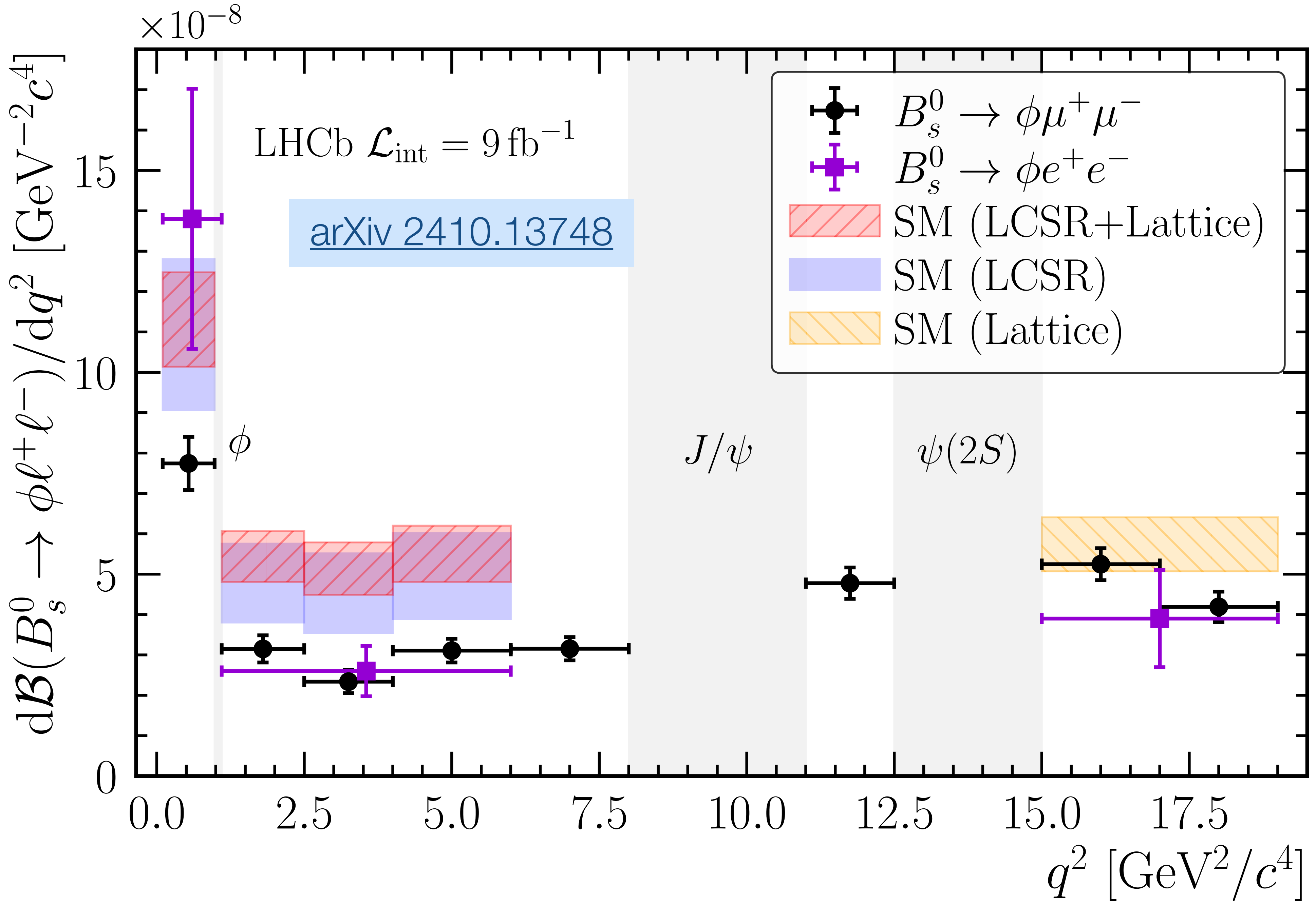


- In agreement with SM predictions
- Dominated by statistical uncertainty
- Main systematics due to signal and background modelling shapes

R_ϕ - Results

$X = \phi$

q^2 [GeV^2/c^4]	$\mathrm{d}\mathcal{B}(B_s^0 \to \phi e^+ e^-)/\mathrm{d}q^2$ [10^{-7} GeV$^{-2}c^4$]
$0.1 < q^2 < 1.1$	$1.38\ ^{+0.25}_{-0.22} \pm 0.04 \pm 0.19 \pm 0.06$
$1.1 < q^2 < 6.0$	$0.26 \pm 0.06 \pm 0.01 \pm 0.01 \pm 0.01$
$15.0 < q^2 < 19.0$	$0.39 \pm 0.11 \pm 0.04 \pm 0.02 \pm 0.02$



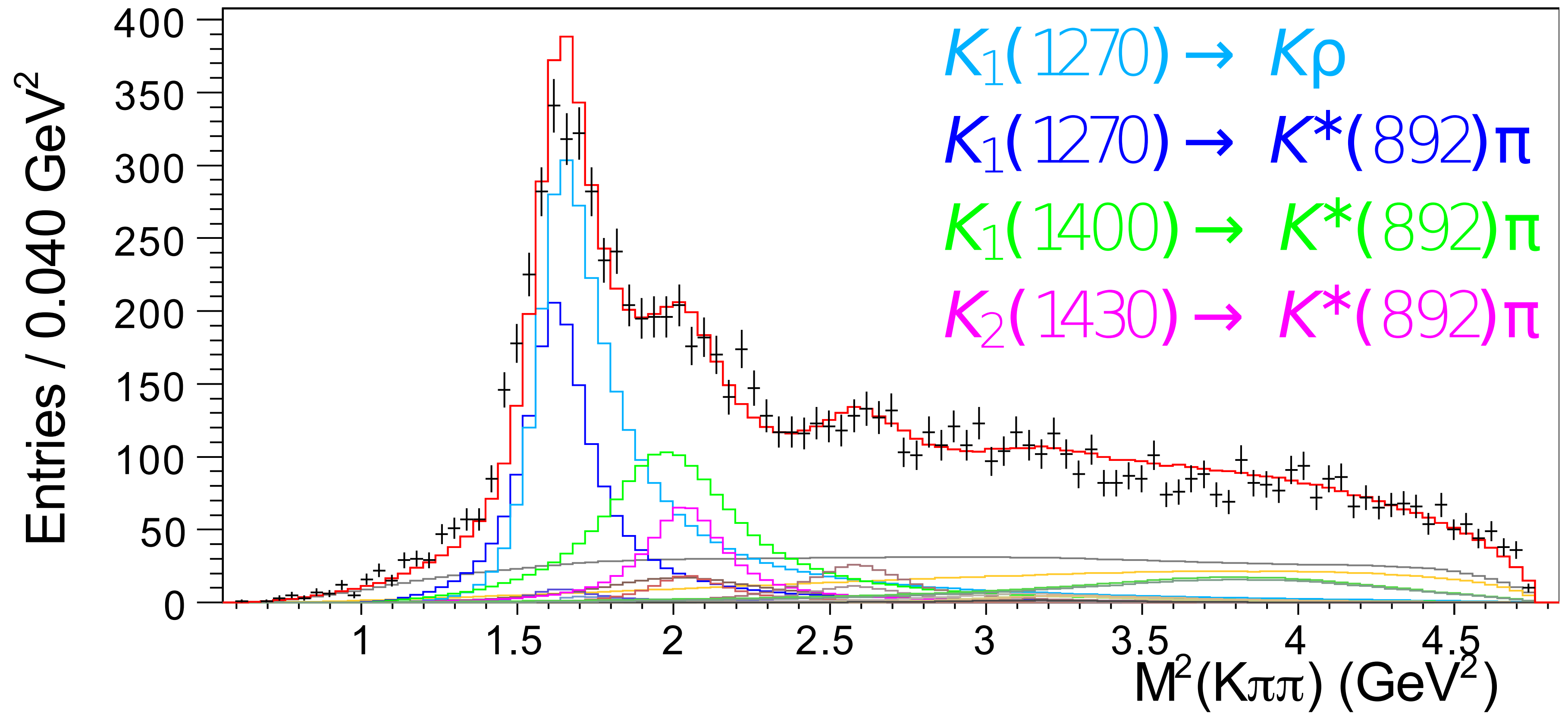
- In agreement with SM predictions
- Dominated by statistical uncertainty
- Main systematics due to signal and background modelling shapes
- $\mathscr{B}(B_s^- \to \phi e^+ e^-)$ agrees with measured $\mathscr{B}(B_s^- \to \phi \mu^+ \mu^-)$

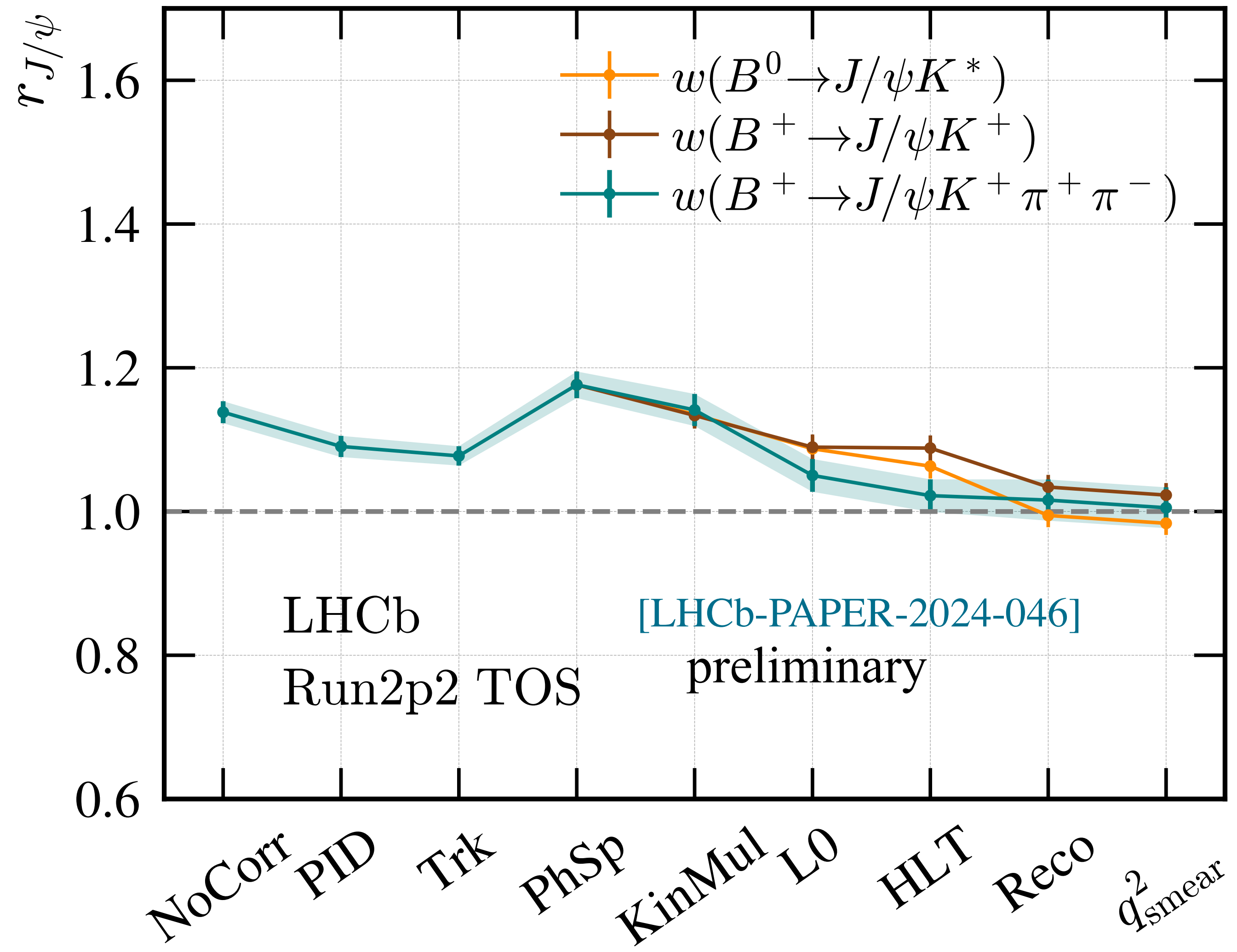
$R_{K\pi\pi}$ - Strategy [LHCb-PAPER-2024-046], in preparation

$X = K\pi\pi$

- Measurement performed in central-q^2 : $1.1 < q^2 < 7.0$ Gev$^2/c^4$
- Use full LHCb dataset ($9\,\text{fb}^{-1}$)
- Inclusive in the very complex $K\pi\pi$ system
- Simulated with phase-space model
  - Reweighted to match resonance structures seen in J/ψ resonant channel
  - Extensive systematics studied

PRD 83 (2011) 032005



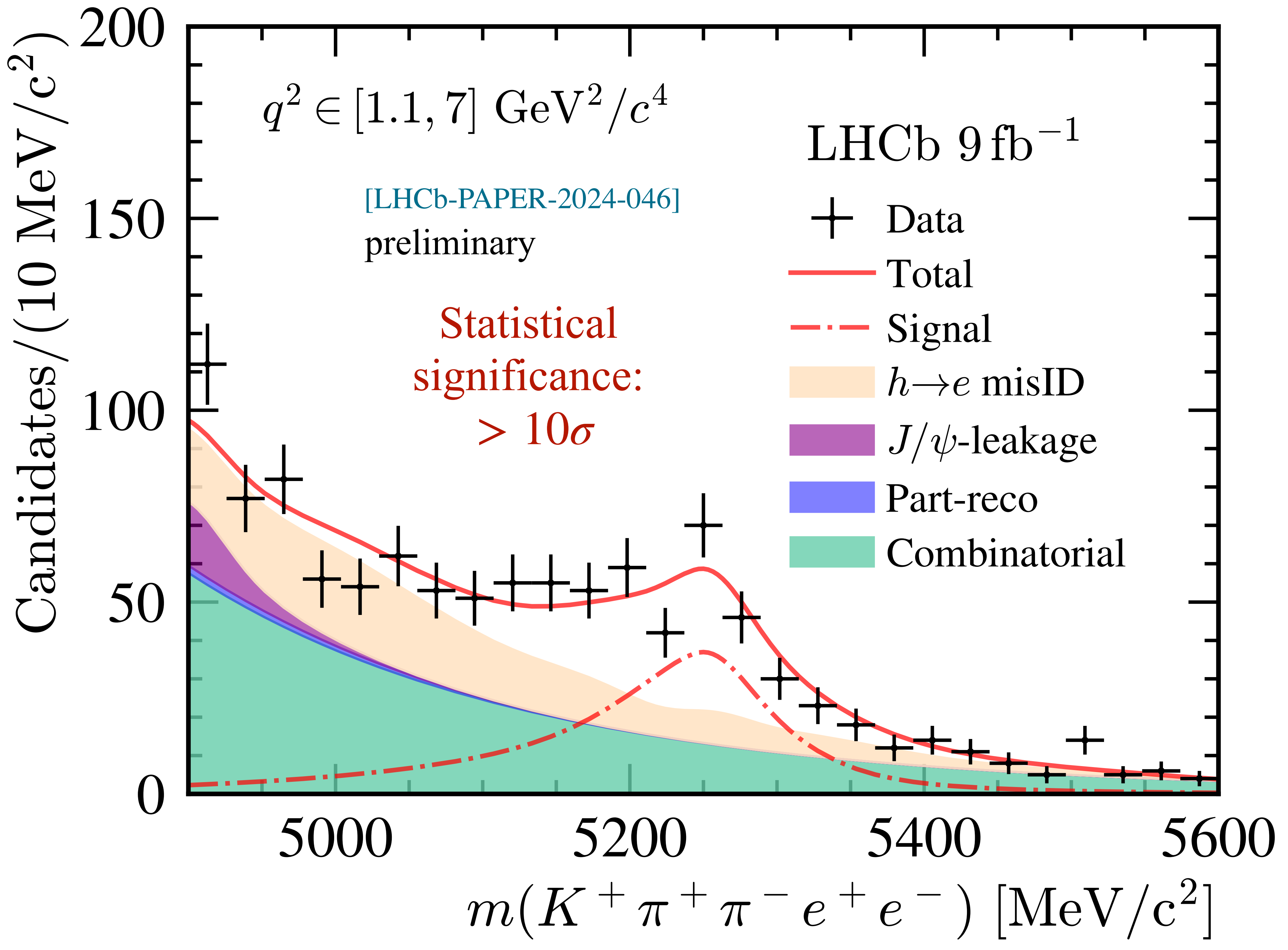


- Cross checks:
  - $r_{J/\psi} = 1.033 \pm 0.017$
  - $R_{\psi(2S)} = 1.040 \pm 0.030$
- Uncertainties includes only systematics due to the calibration sample size

$B^+ \to K^+\pi^+\pi^-e^+e^-$ observation

$X = K\pi\pi$

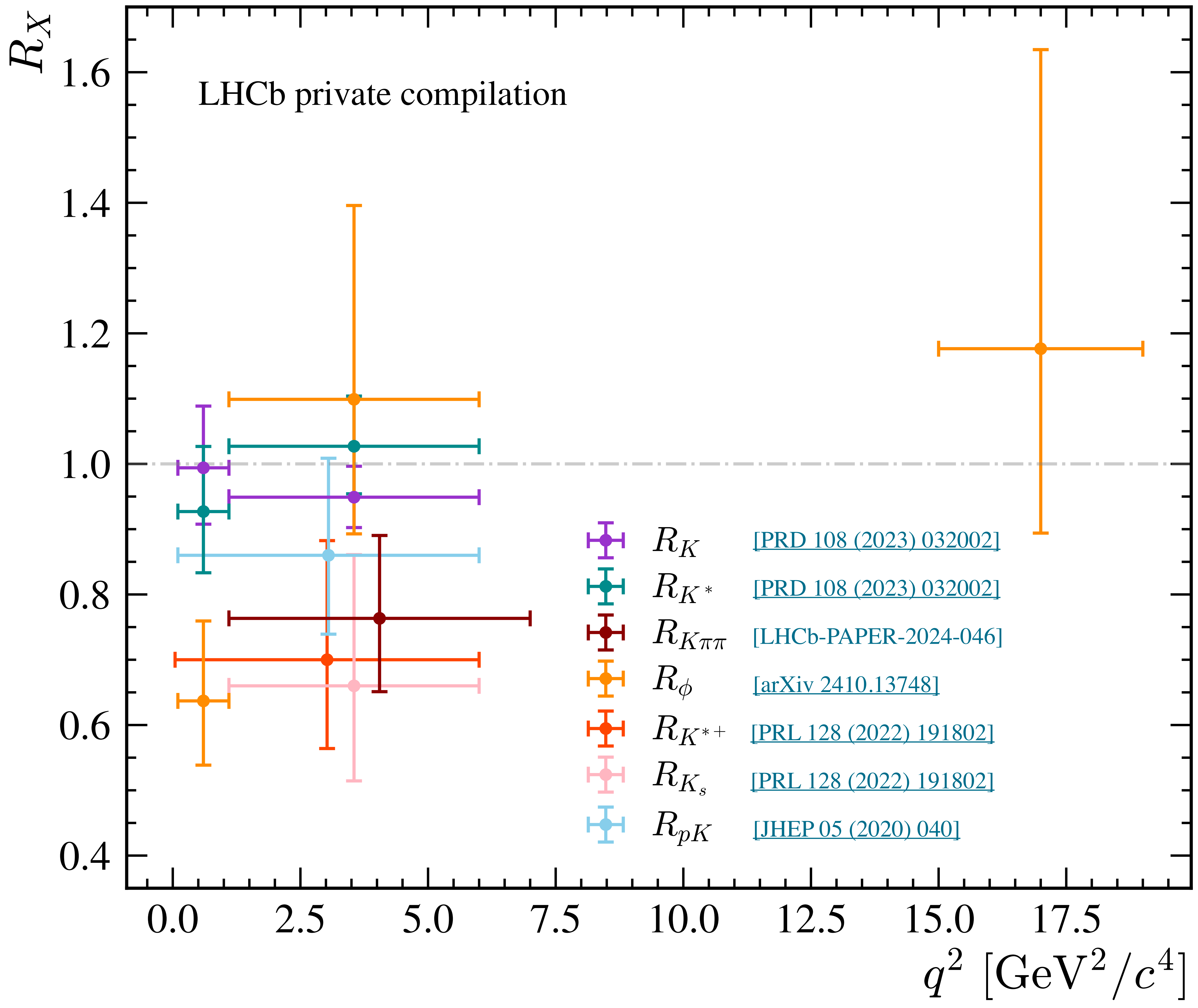
- $h \to e$ mis-identification modeled with pass-fail method
- Leakage from $B^+ \to K^+\pi^+\pi^- J/\psi(\to e^+e^-)$
- Partially-reconstructed background
  - Challenging, no a priori information on underlying structure
  - Shape and amount extracted from J/ψ resonant data



$R_{K\pi\pi}$ - Results

$$R_{K\pi\pi}^{-1} = 1.31^{+0.18}_{-0.17}\,(\text{stat})\,^{+0.12}_{-0.09}\,(\text{syst})$$

- In agreement with the SM predictions
- Main source of systematics:
  - Background modelling
  - Reweighting of the simulated phase-space



Rare searches and Lepton Flavour Violation

Rare searches

- Strongly suppressed decays $\mathscr{B} < \mathcal{O}(10^{-7})$, sensitive to NP contributions

@90% CL

EPJ 84 (2024) 468

- First search for $B_c^+ \to \pi^+\mu^+\mu^-$

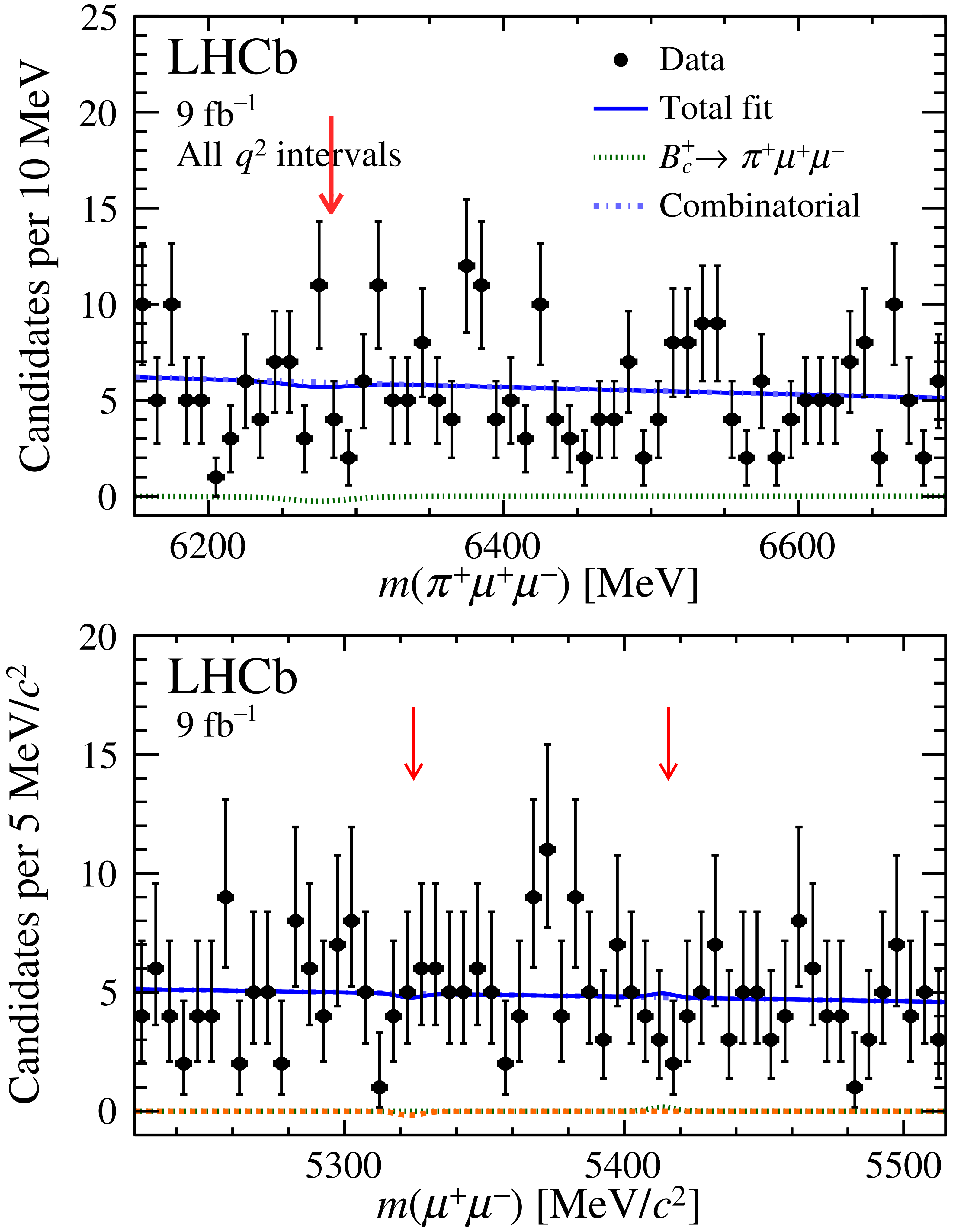
$$R_{\pi^+\mu^+\mu^-/J/\psi\pi^+} < 2.1 \times 10^{-4}$$

  - No theory predictions, can provide insights to QCD
  - Fit to $m(\pi^+\mu^+\mu^-)$ in q^2 intervals
- First search of $B^{*0}_{(s)} \to \mu^+\mu^-$ decays in $B_c^+ \to B^{*0}_{(s)}(\mu^+\mu^-)\pi^+$
  - Accurate SM predictions $\mathscr{B} \sim 10^{-11}$ PRL 116 (2016) 14, 141801
  - Exploit B_c^+ displaced vertex to reduce combinatorial bkg
  - Simultaneous fit to $m(\mu^+\mu^-)$ and $m(\pi^+\mu^+\mu^-)$

LHCb-CONF-2024-003

$$R_{B^{*0}(\mu^+\mu^-)\pi^+/J/\psi\pi^+} < 3.8 \times 10^{-5}$$
$$R_{B_s^{*0}(\mu^+\mu^-)\pi^+/J/\psi\pi^+} < 5.0 \times 10^{-5}$$

@90% CL



Rare searches

- Search for $B \to D\mu^+\mu^-$
  - Different interactions: Annihilation, penguins, W^+ exchange....
  - Studied with and without a J/ψ intermediate resonance
- Selected in $q^2 \in [0.044, 8.0]\,\mathrm{GeV}^2/c^4$
- World's best limits at 95% of CL
- Improved precision of $\mathcal{B}(B_c^+ \to D_s^+ J/\psi)$

$$\frac{f_c}{f_u} \cdot \mathcal{B}(B_c^+ \to D_s^+ J/\psi) = (1.63 \pm 0.15 \pm 0.13) \times 10^{-5}$$

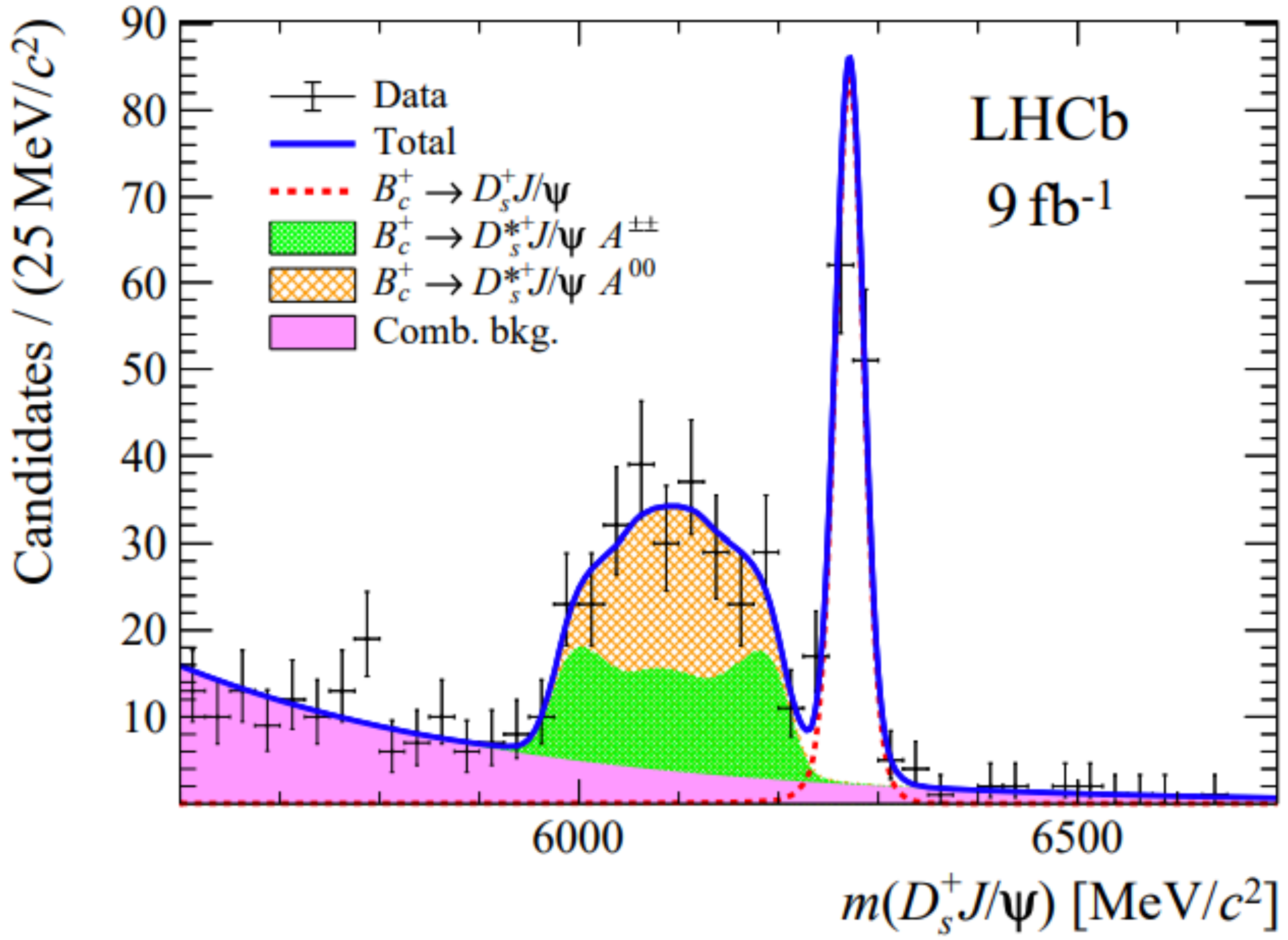
$\mathcal{B}(B^0 \to \bar{D}^0\mu^+\mu^-) < 5.1\times10^{-8}$ | $\mathcal{B}(B^0 \to \bar{D}^0 J/\psi) < 1.1\times10^{-6}$

$\mathcal{B}(B^+ \to D_s^+\mu^+\mu^-) < 3.2\times10^{-8}$ | $\mathcal{B}(B^+ \to D_s^+ J/\psi) < 3.5\times10^{-7}$

$\mathcal{B}(B_s^0 \to \bar{D}^0\mu^+\mu^-) < 1.6\times10^{-7}$ | $\mathcal{B}(B_s^0 \to \bar{D}^0 J/\psi) < 1.5\times10^{-6}$

$f_c/f_u \cdot \mathcal{B}(B_c^+ \to D_s^+\mu^+\mu^-) < 9.6\times10^{-8}$

JHEP 02 (2024) 032



LFV

JHEP 06 (2023) 073

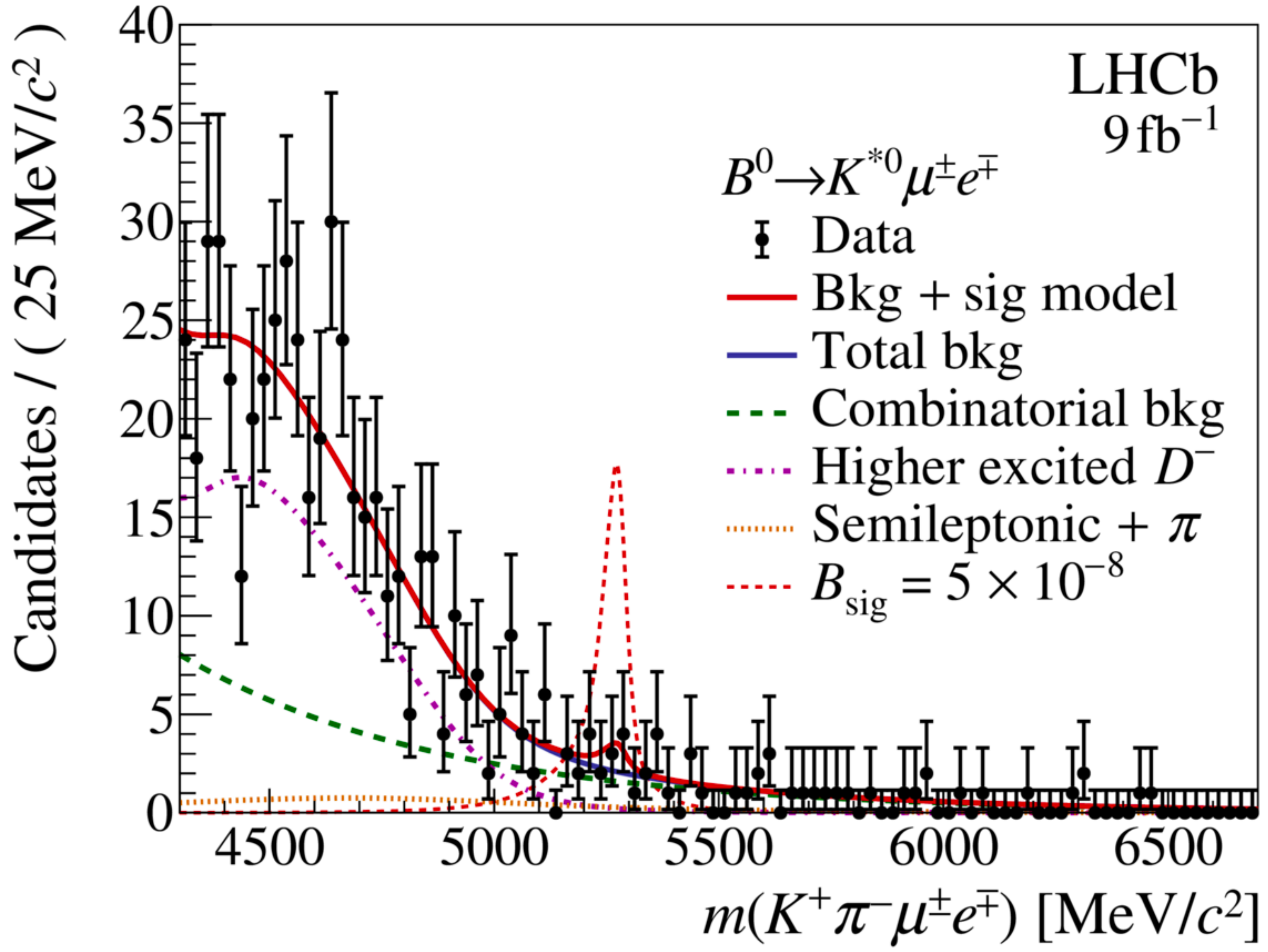
- $b \to s\ell\ell$ transitions also used to look for LFV decays
  - Related to possible LFUV
  - Can help constraining NP models
- Search for $B^0 \to K^{*0}\mu^\pm e^\mp$ and $B_s^0 \to \phi\mu^\pm e^\mp$
  - Results also for $b \to s\mu^+e^-$ and $b \to s\mu^-e^+$ separately
  - No access found, best limits set

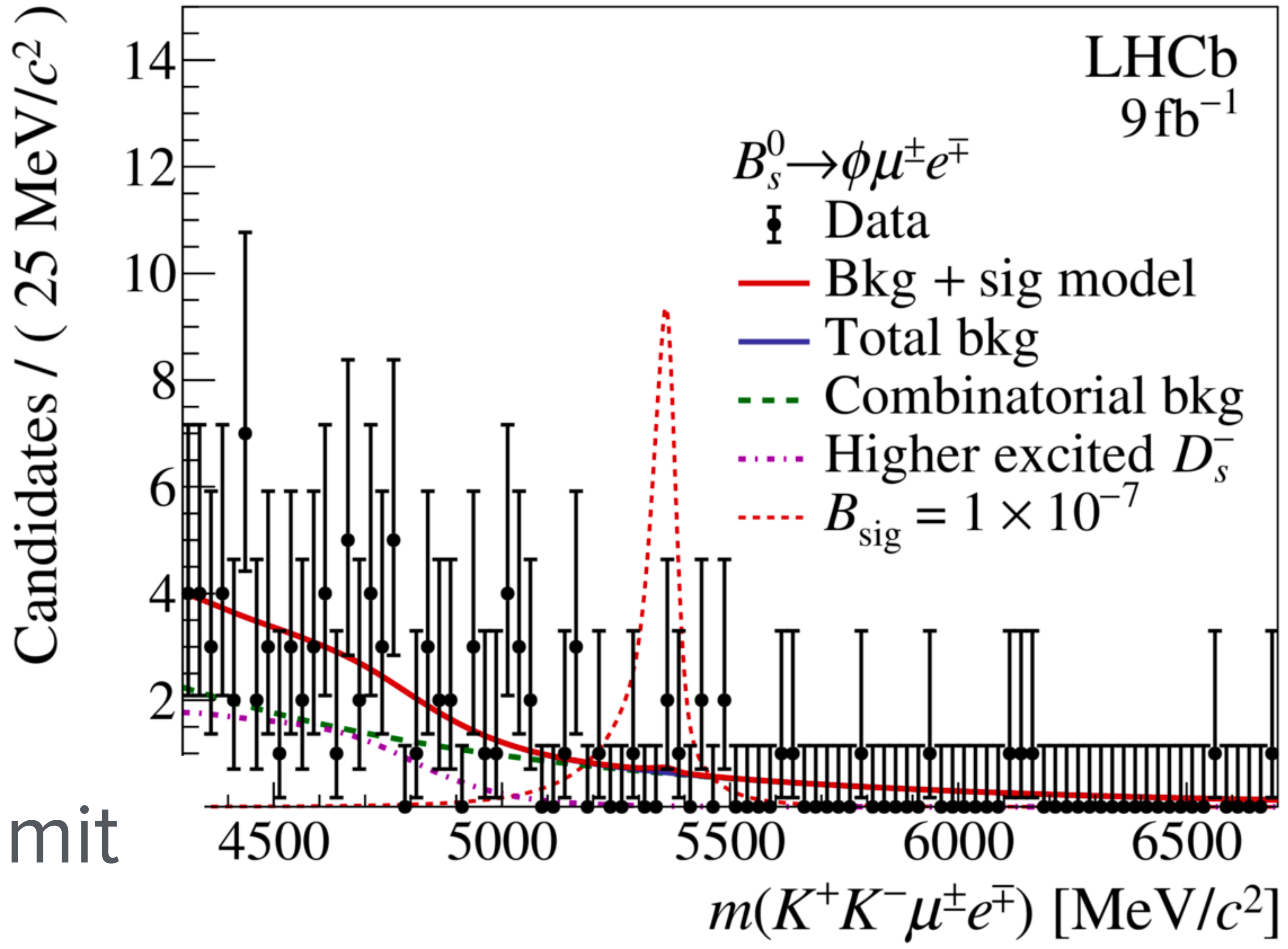
@90% (95%) CL

$$\mathcal{B}(B^0 \to K^{*0}\mu^+e^-) < 5.7\times10^{-9}\ (6.9\times10^{-9}),$$
$$\mathcal{B}(B^0 \to K^{*0}\mu^-e^+) < 6.8\times10^{-9}\ (7.9\times10^{-9}),$$
$$\mathcal{B}(B^0 \to K^{*0}\mu^\pm e^\mp) < 10.1\times10^{-9}\ (11.7\times10^{-9}),$$
$$\mathcal{B}(B_s^0 \to \phi\mu^\pm e^\mp) < 16.0\times10^{-9}\ (19.8\times10^{-9})$$

World first limit

  - Provided limits on a scalar and left-handed NP scenario





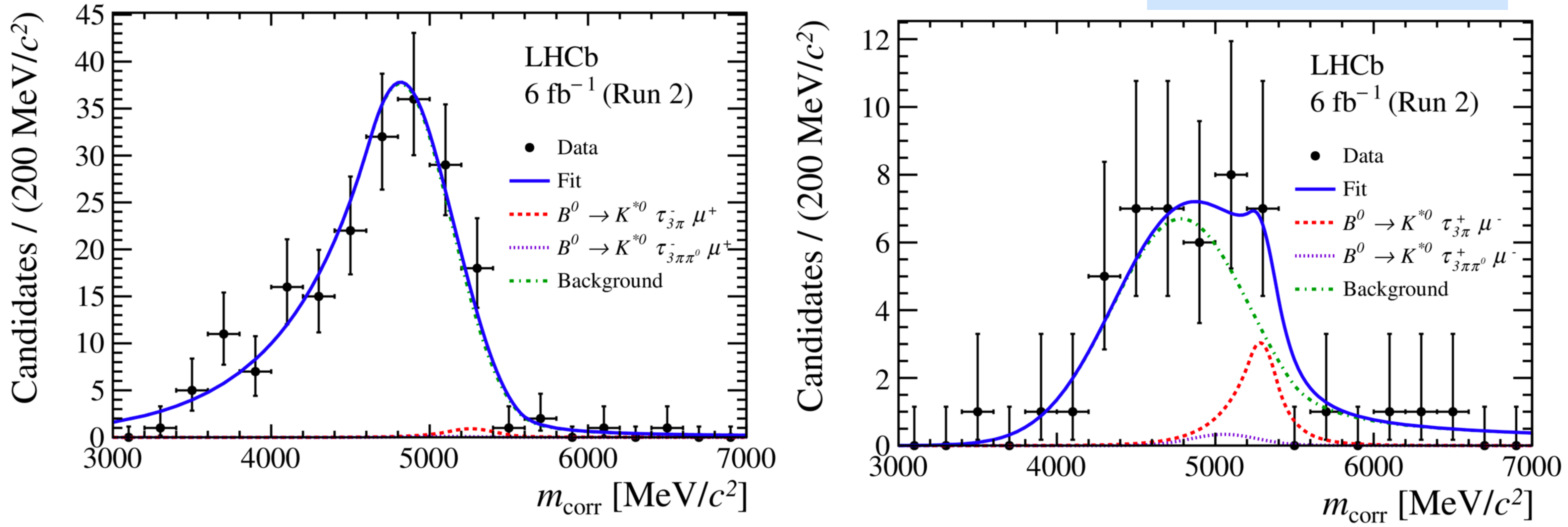
LFV with taus

- Use $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$
- Search for $B^+ \to K^{*0}\tau^\pm\mu^\mp$
  - Separated treatment for charges combinations
  - Corrected mass used to recover neutrinos energies: $m_{\text{corr}} = \sqrt{p_\perp^2 + m_{K^*\tau\mu}^2} + p_\perp$

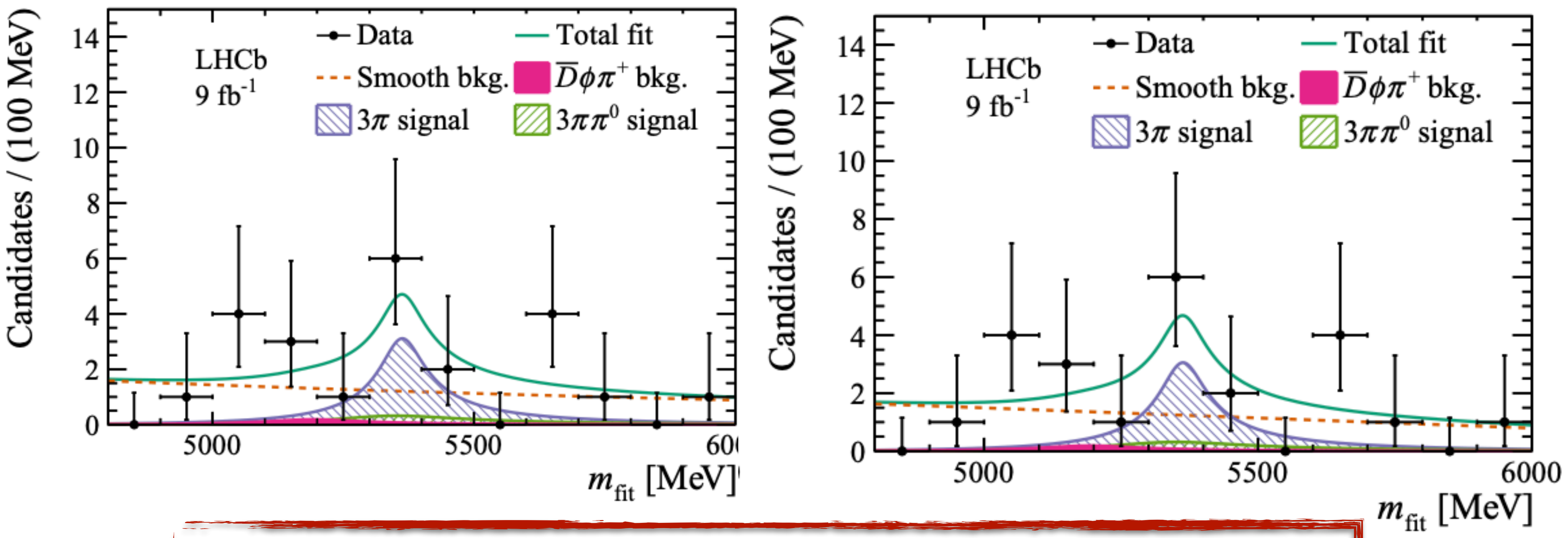
@90% CL

$$\mathcal{B}(B^0 \to K^{*0}\tau^+\mu^-) < 1.0 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K^{*0}\tau^-\mu^+) < 8.2 \times 10^{-6}$$

JHEP 06 (2023) 143



arXiv:2405.13103



- Search for $B_s^0 \to \phi\tau\mu$
  - Mass re-fitted including missing neutrino momentum and kinematic constraints
  - No charge separation possible

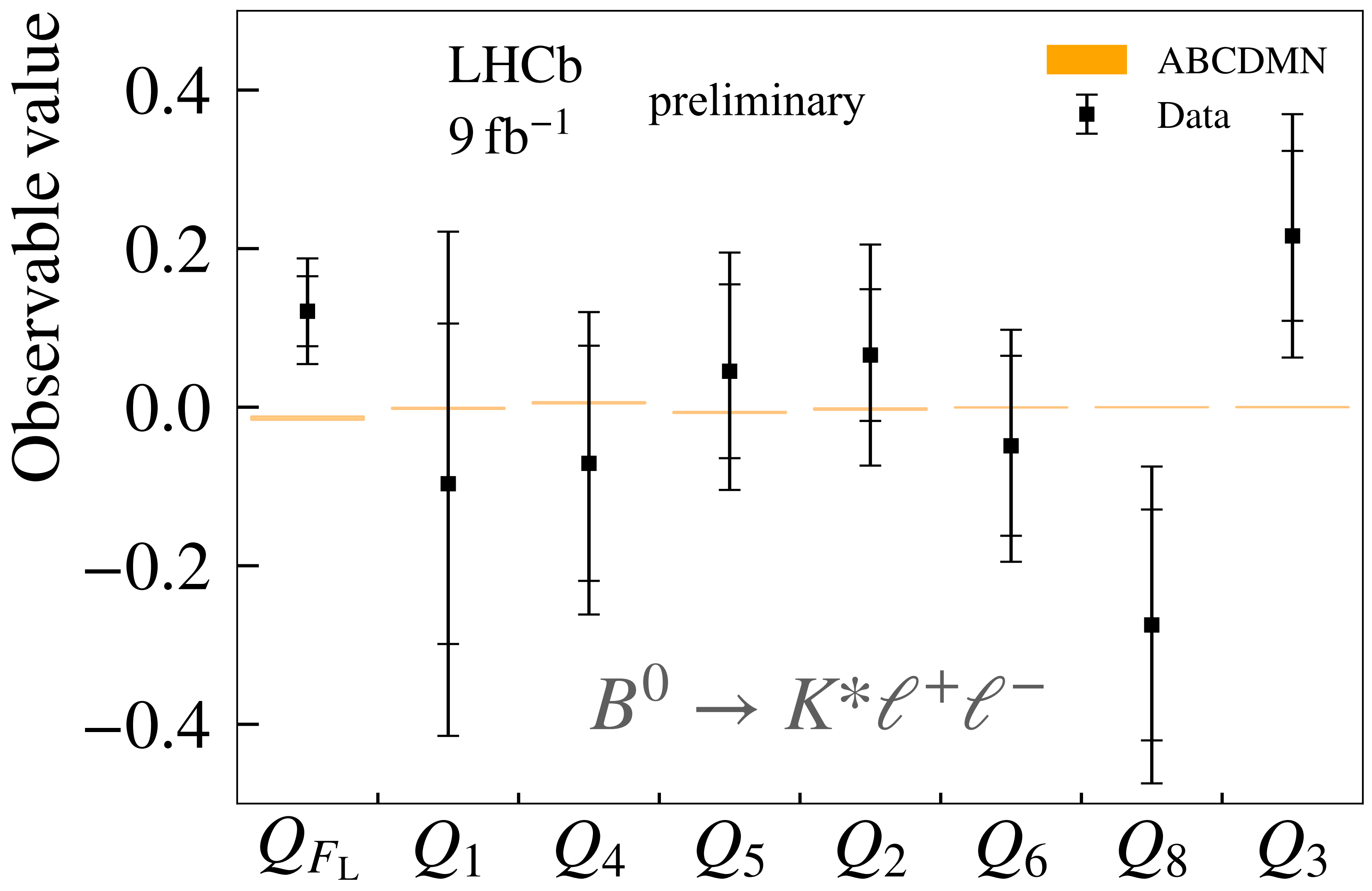
$$\mathcal{B}(B_s^0 \to \phi\mu^+\tau^-) < 1.0 \times 10^{-5}$$ @90% CL

Outlook

- More updating/searches ongoing with Run2 data
  - Direct searches in $\tau \to 3\mu$ (under internal review), $\tau \to \phi\mu, \tau \to p\mu\mu$

    see Lakshan Madhan talk
  - LFU observables in angular analysis

$Q_i = P_i^{\mu} - P_i^{e}$

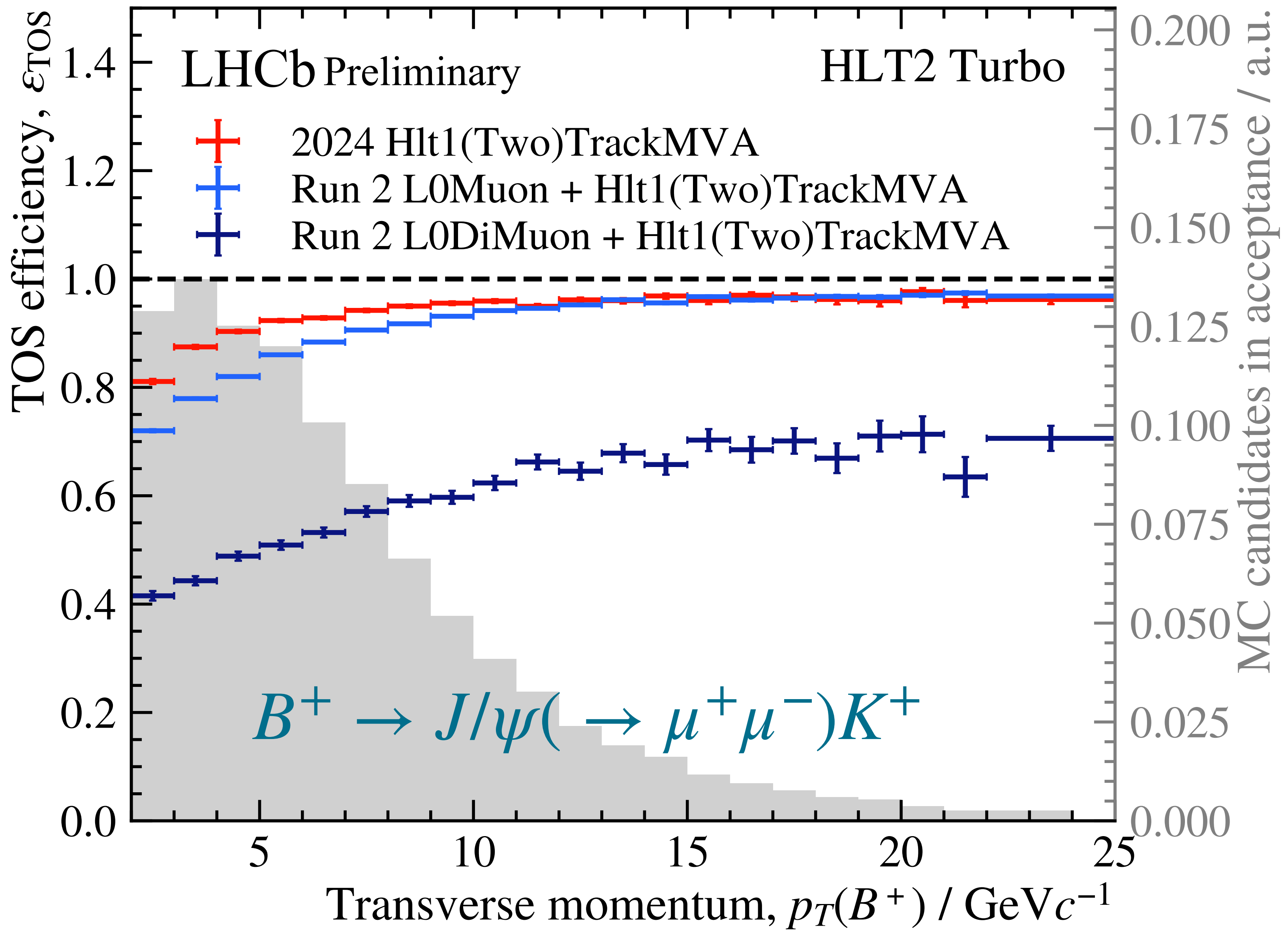


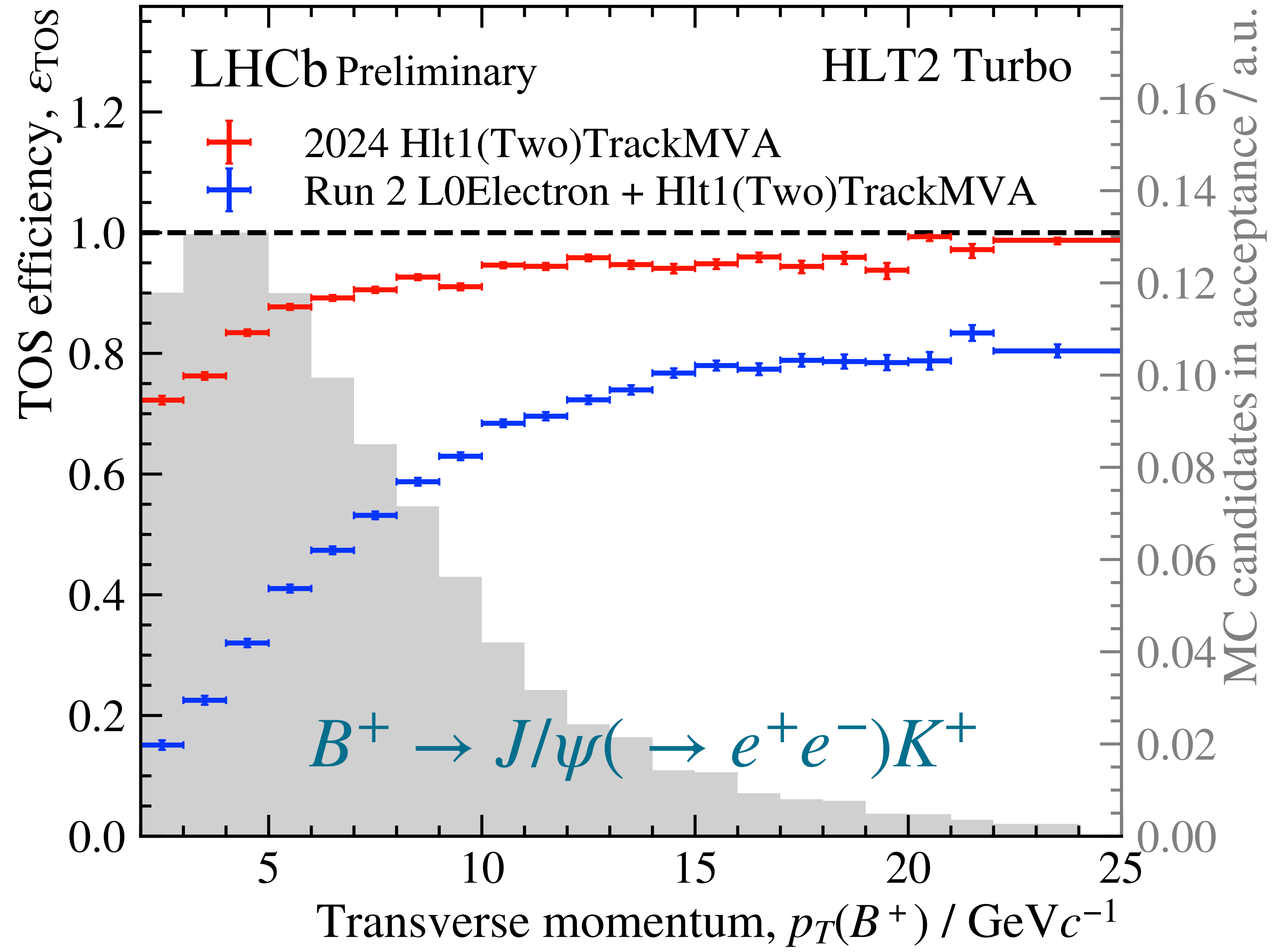
[LHCb-PAPER-2024-046], in preparation

Outlook

LHCB-FIGURE-2024-030

- More updating/searches ongoing with Run2 data
  - Direct searches in $\tau \to 3\mu$ (under internal review), $\tau \to \phi\mu, \tau \to p\mu\mu$
    see Lakshan Madhan talk
  - LFU observables in angular analysis
- New data from Run3!
  - Collected with an upgraded detector and trigger system
  - Reducing systematics due to data driven methods
  - Better sensitivities for LFV and rare searches

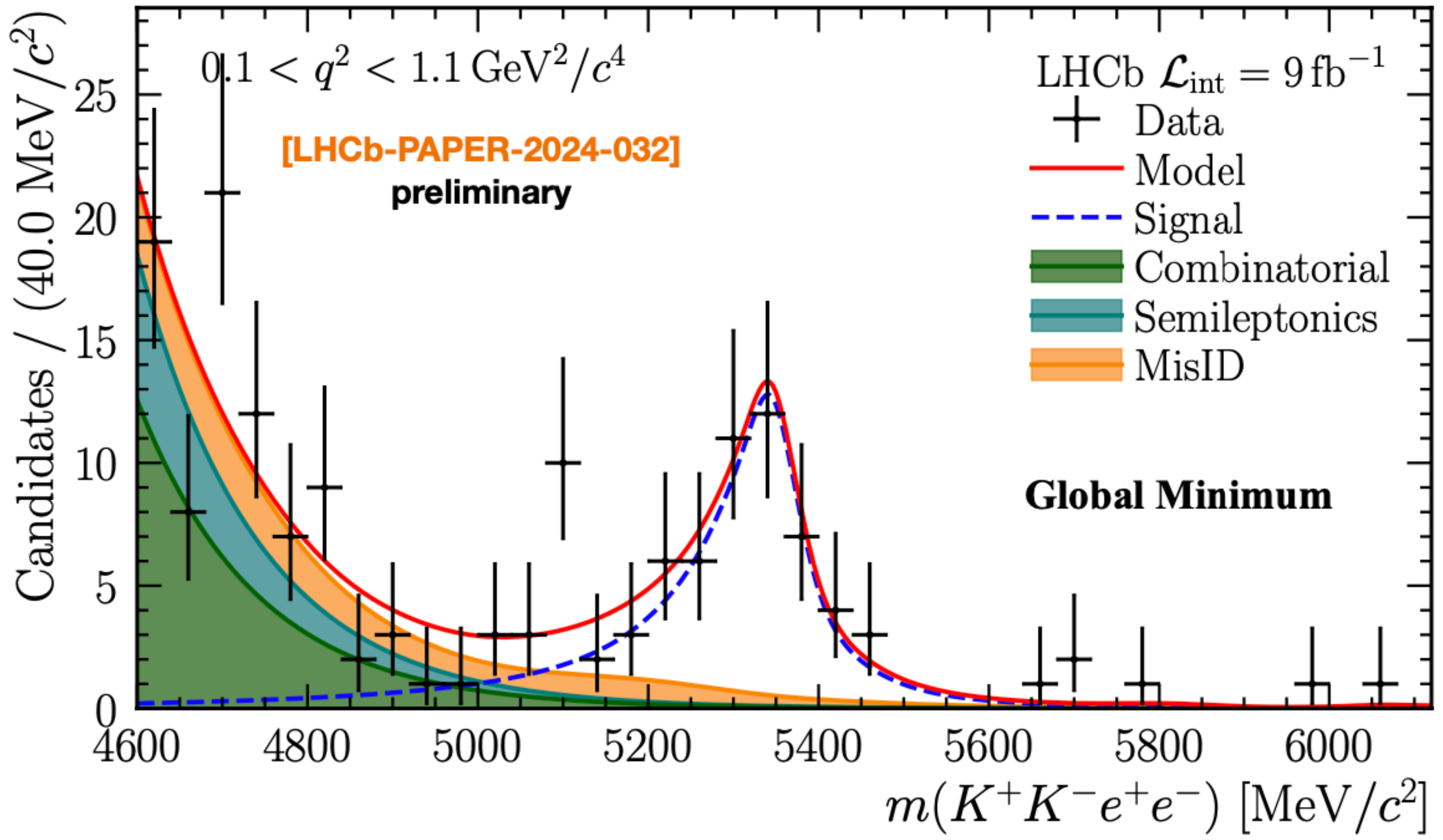


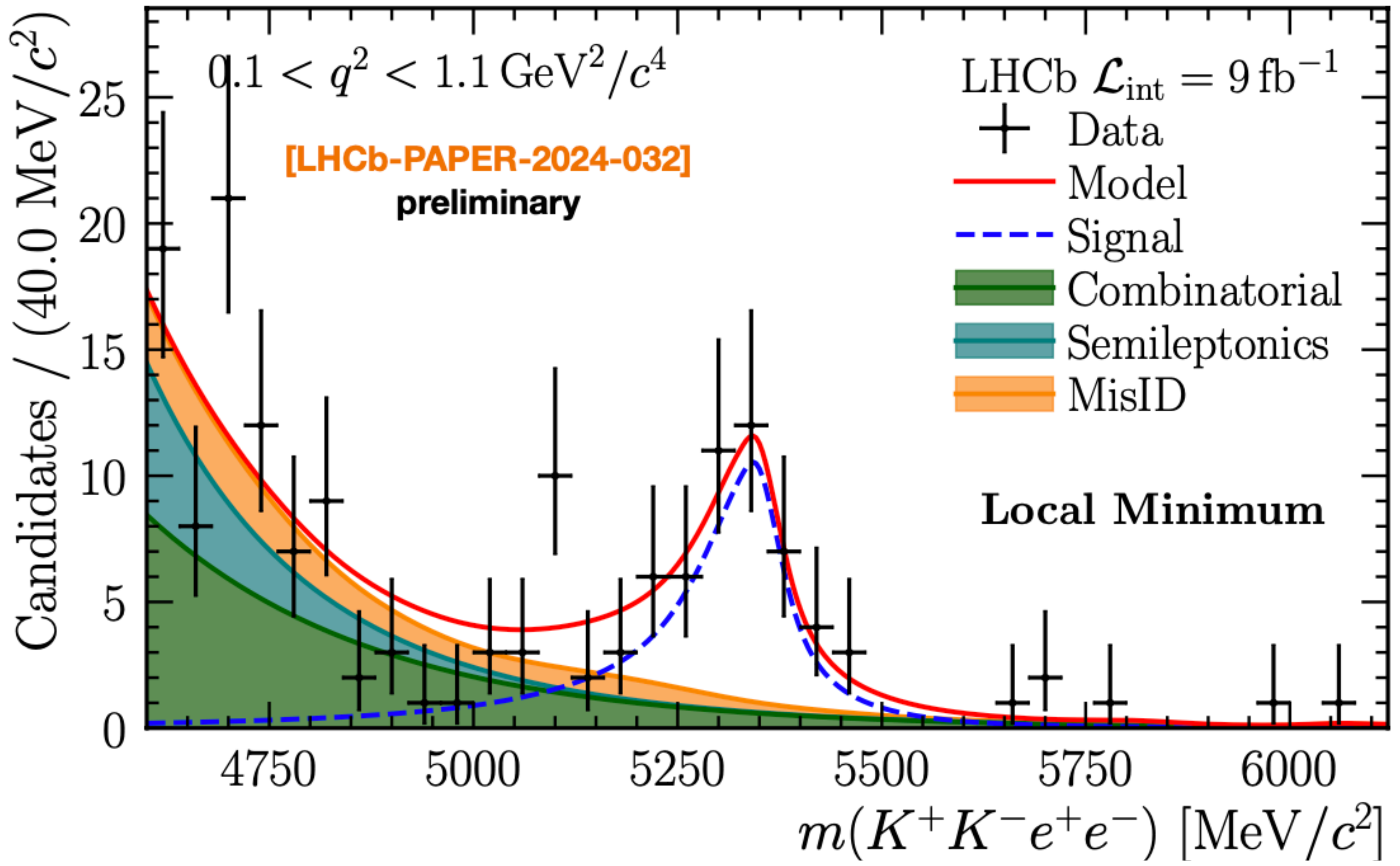


Back-up

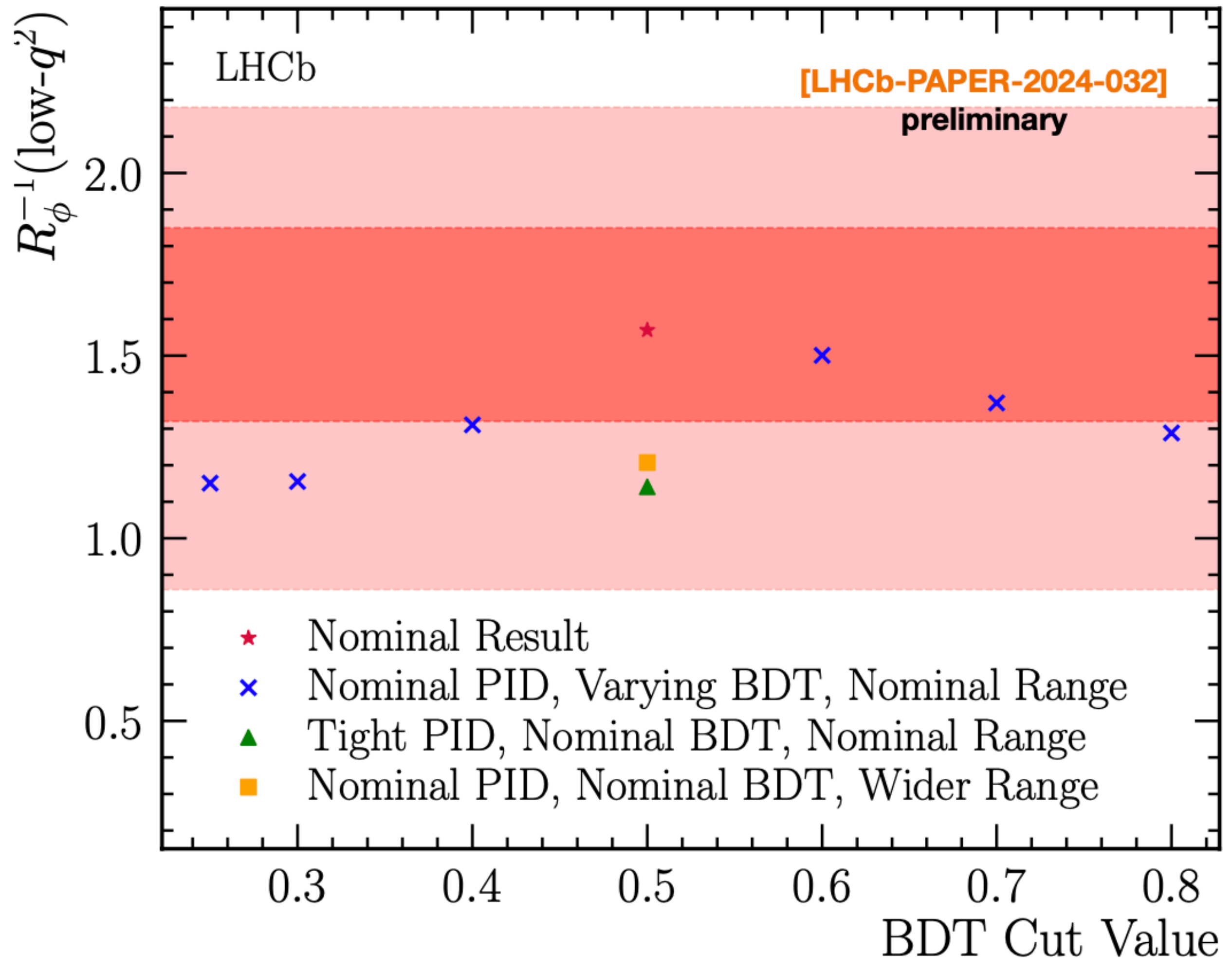
R_ϕ Secondary minimum

- Secondary minimum characterised by flatter combinatorial



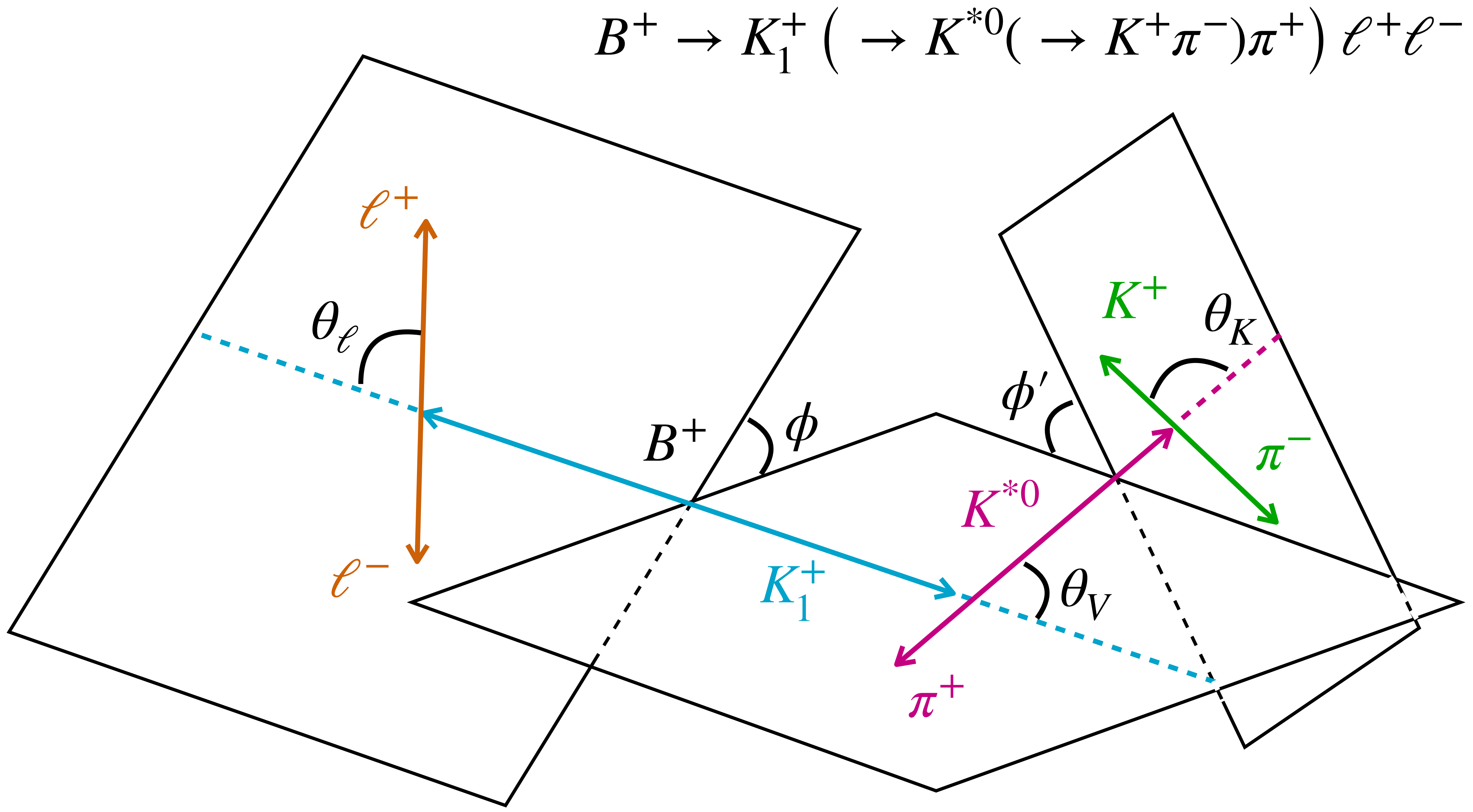


- Variations of analysis choices affect which minimum is global



$R_{K\pi\pi}$ Phase-space correction

- BDT reweighter comparing simulation and $B \to K^+\pi^+\pi^- J/\psi(\to \mu^+\mu^-)$ s-weighted data
  - Trained on $m(K\pi), m(\pi\pi), m(K\pi\pi), \cos\theta_L, \cos\theta_K, \cos\theta_V$
  - 10-fold cross validation
  - Also transferred to electrons
  - Data unfolded with efficiencies maps to take ir account acceptance effects

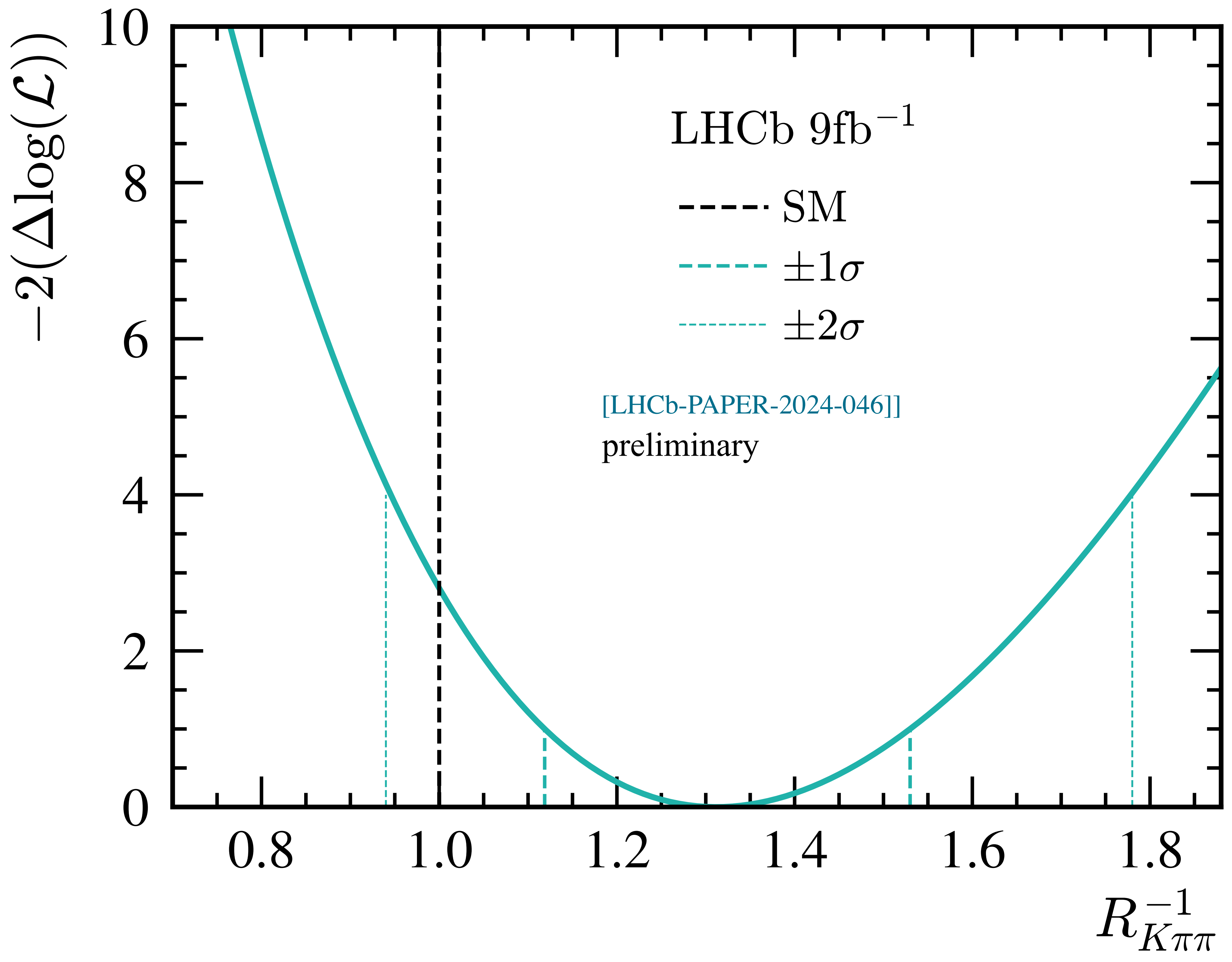


- Systematics uncertainties are assigned by:
  - Training the reweighters on $B^+ \to K^+\pi^+\pi^-\gamma$ decays
  - Using no angular information in the training
  - Training on custom simulation where the $K\pi\pi$ system is in different spin configuration

$R_{K\pi\pi}$ Phase-space correction

$$R_{K\pi\pi}^{-1} = 1.31^{+0.18}_{-0.17}\,(\text{stat})\,^{+0.12}_{-0.09}\,(\text{syst})$$

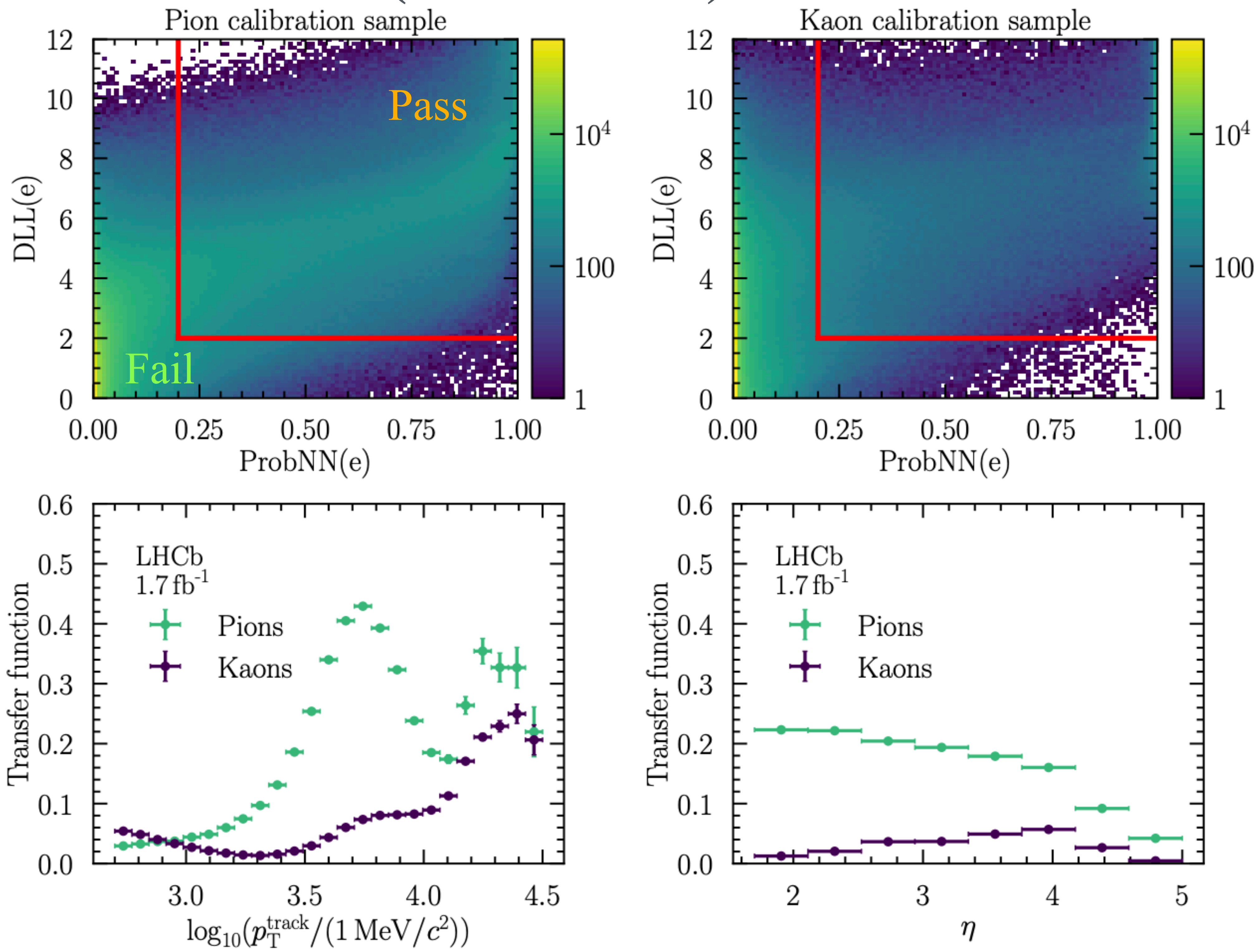
- Profile log likelihood used to evaluate the **agreement with SM**: 1.7σ
- **First observation** of $B^+ \to K^+\pi^+\pi^-e^+e^-$ decay, significance $> 10\sigma$ (Wilk's theorem)
- Systematics directly added by convoluting the likelihood with a Gaussian kernel



Pass-Fail

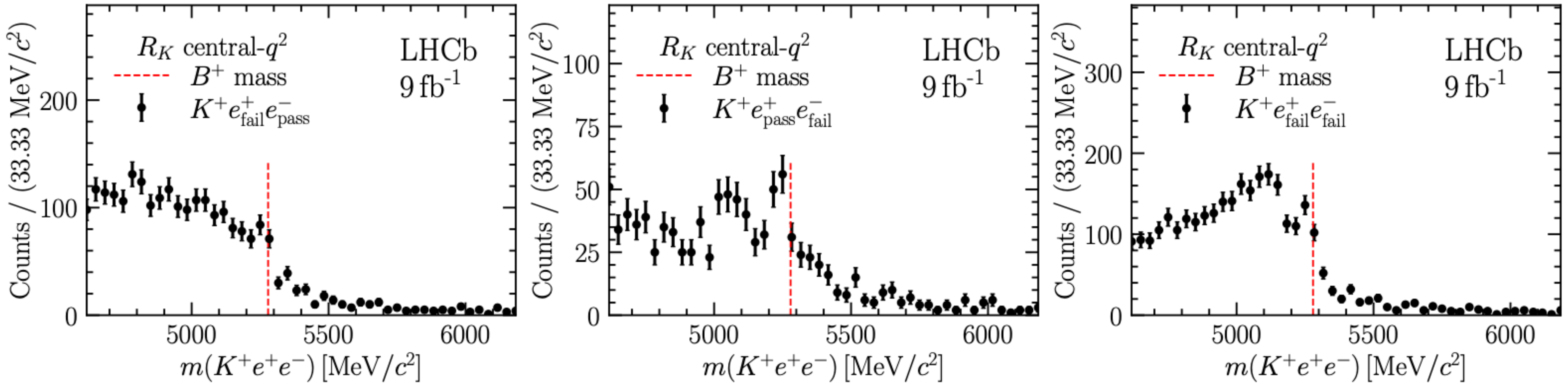
[PRD 108 (2023) 032002]

$D^{*+} \to D^0(\to K^-\pi^+)\pi^+$



$$w_{\text{fake}} = \frac{\varepsilon_{\text{pass}}}{\varepsilon_{\text{fail}}}(p_t, \eta)$$

Control regions



Combined and weighted for transfer functions