Exploring Lepton Flavour with b-hadron Decays at LHCb:

Universality Tests and Searches for Violation

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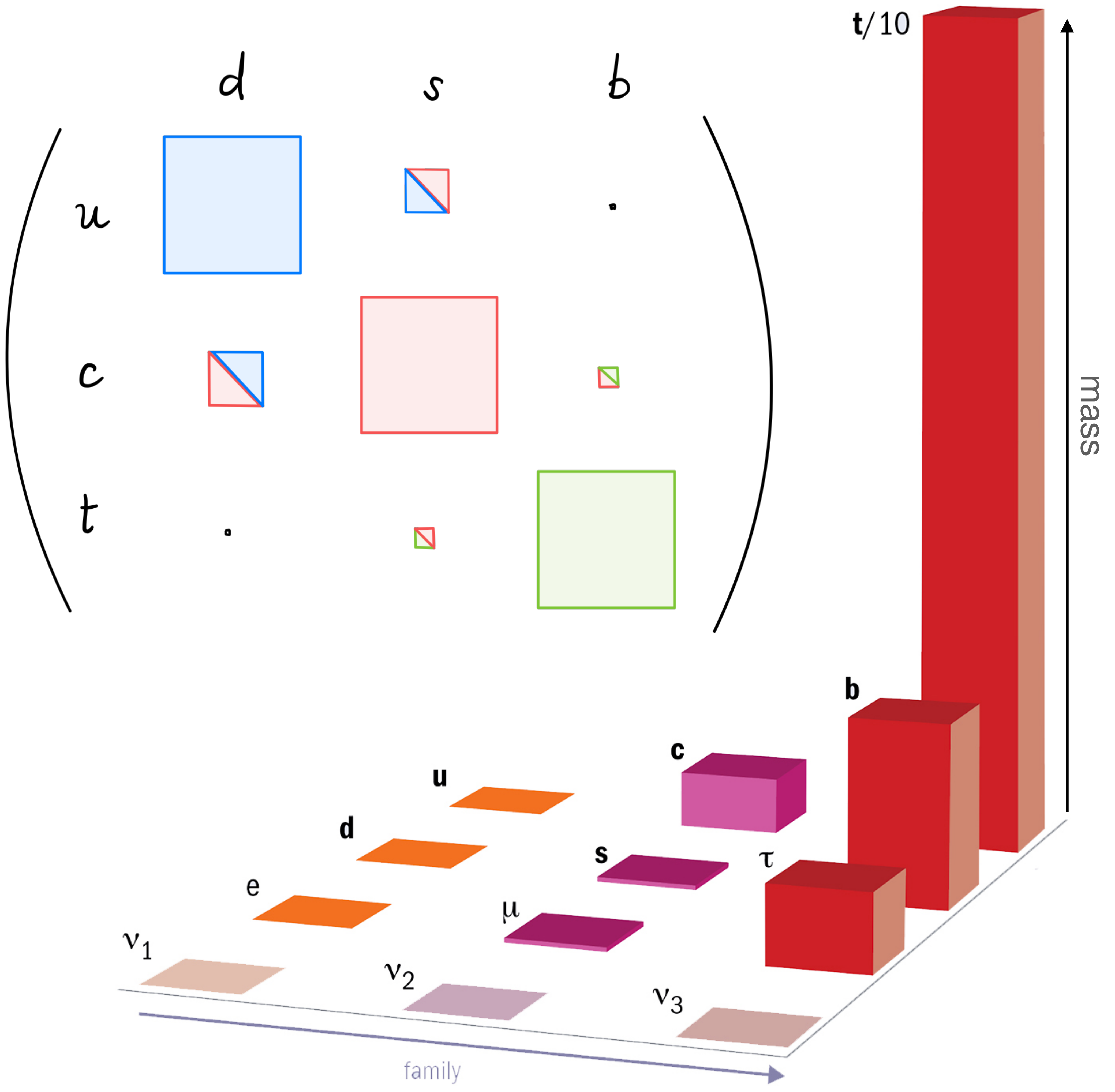
The Standard Model (SM) flavour problem

- Multiple free parameters in the SM: CKM matrix regulate transitions and between quarks, masses spanning several orders of magnitude
  - Peculiarly hierarchic flavour structure
  - Intimate connection with the Higgs and its hierarchical coupling to fermions

The flavour problem

- Studying the flavour structure of the SM at the intensity frontier can guide us on how to extend it



Accidental symmetries as New Physics (NP) probes

- The SM Lagrangian, considered as an effective field theory, can be written as

$$\mathcal{L}_{\text{eff}} = \underbrace{\mathcal{L}^{\text{SM}}_{\text{gauge}} + \mathcal{L}^{\text{SM}}_{\text{Higgs}} + \mathcal{L}^{\text{SM}}_{\text{Yukawa}}}_{\text{d=4}} + \mathcal{L}_{\text{d>4}}$$

- Global flavour symmetries of the $d = 4$ part regarded as accidental symmetries that arise as indirect consequences of the field content and the SM gauge symmetries
  - Processes that are interested by these symmetries are excellent laboratories to search for New Physics (NP) since the underlying theory might violate them

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Lepton number (L)

- Violation of lepton family number (LFV) arises from $d = 5$ operators → related to neutrino masses
- Due to their smallness, LFV processes are predicted to have very small BF in the SM $O(10^{-50})$ lower than any exp. sensitivity

Lepton Flavour Universality (LFU)

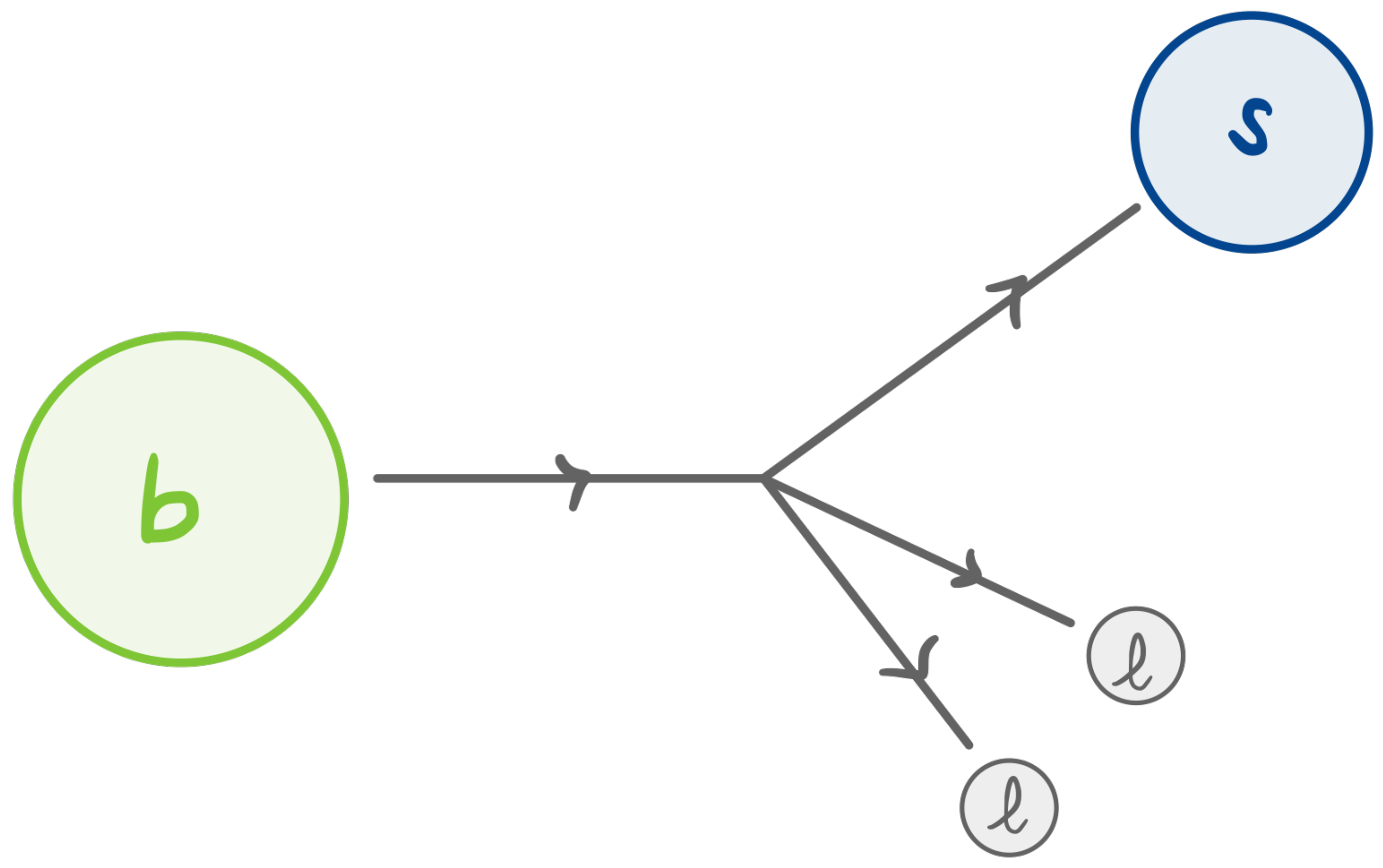
- Arises due to smallness of Yukawa terms w.r.t. weak coupling constants

$$\frac{\sqrt{2}m_\ell}{\langle v \rangle} \sim O(10^{-2} - 10^{-6}) \ll g, g'$$

- Within the SM, only kinematic effects due to lepton masses distinguish their flavour

Probing cLFV and LFUV in $b \to s\ell\ell^{(\prime)}$ transitions

- Flavour changing neutral currents (FCNC) involving the third quark family are extremely interesting NP probes since they are:
  - Initiated by a b quark which is heavy (various final states accessed) and long lived (rel. easy to detect)



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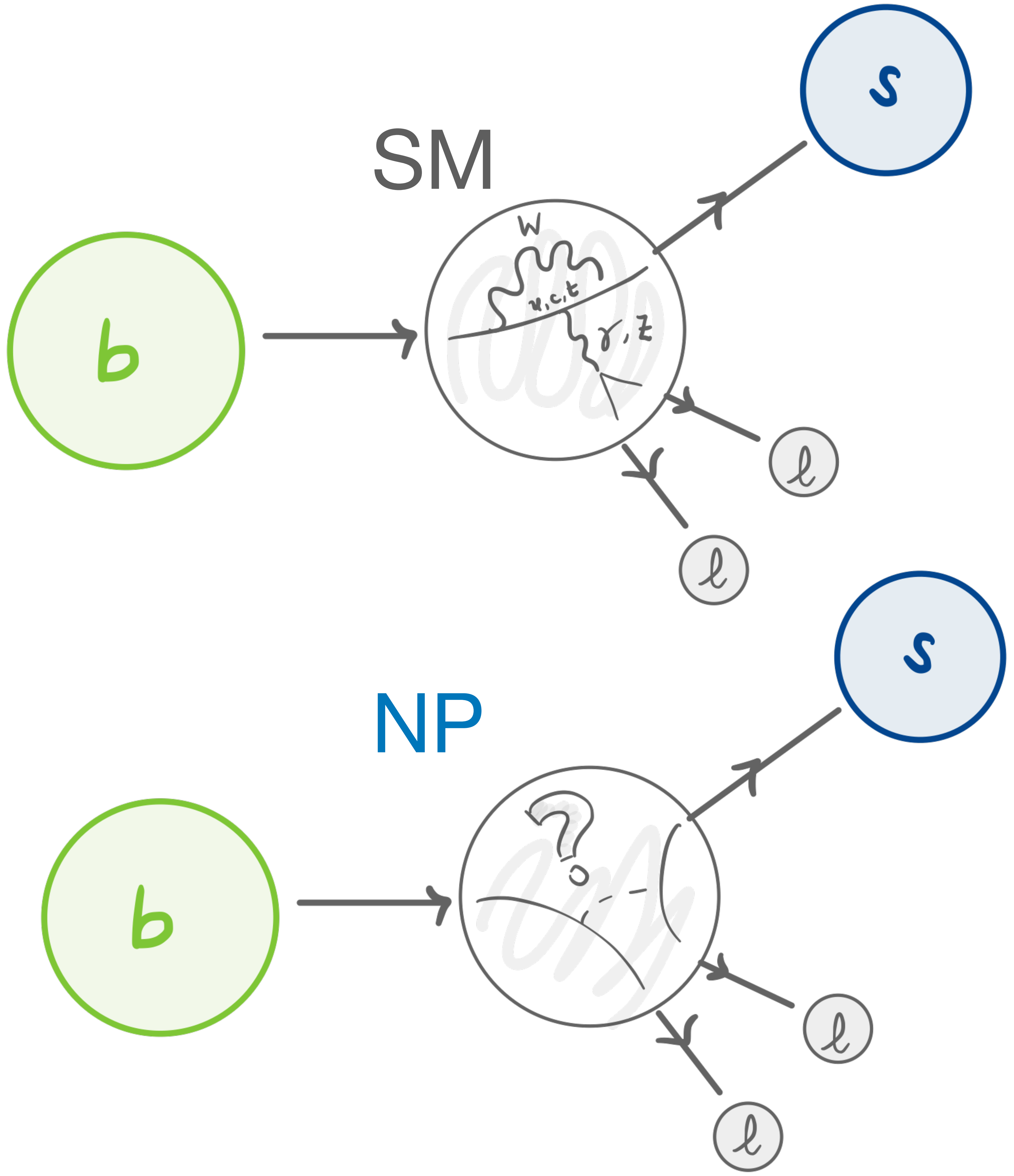
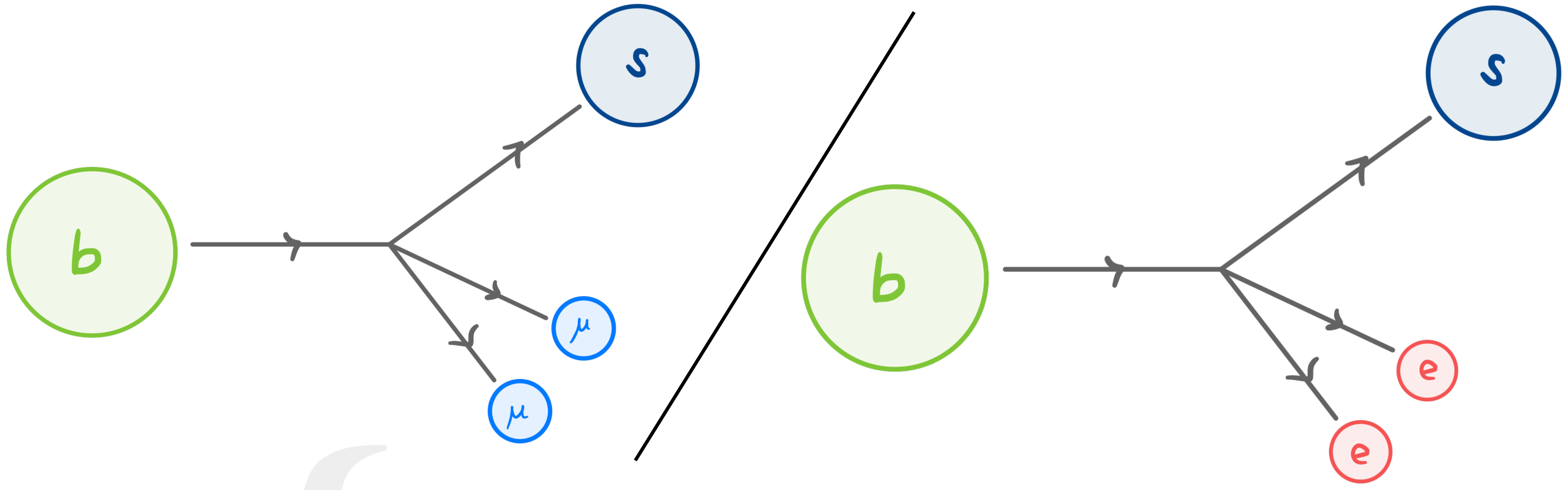
  - Initiated by a b quark which is heavy (various final states accessed) and long lived (rel. easy to detect)
  - Loop induced and CKM suppressed in the SM (BF of order $\sim 10^{-6} - 10^{-7}$):
    - NP contributions of same size as SM could modify decay properties (e.g. enhancing/suppressing branching fractions)
    - Probe higher energy scales than direct searches (of order $1 \sim 100$ TeV)



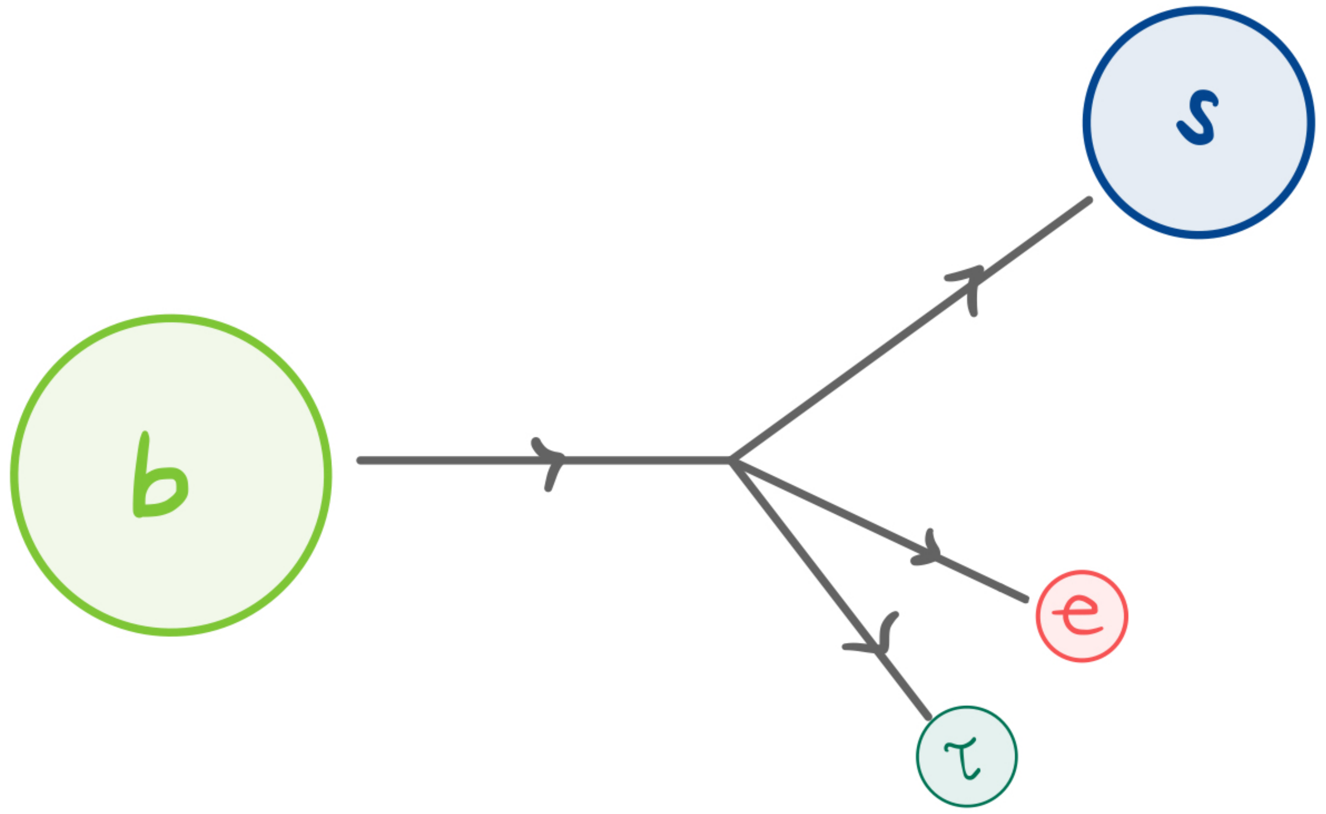
In this talk:

- Test of LFU with FCNC decays of b-quarks into light leptons



[PRL 134 (2025) 12, 121803]
[PRL 134 (2025) 18, 181803]
[arXiv:2505.03483]

- Search for cLFV decay $B \to K^{*0}\tau e$



[arXiv:2506.15347]

- For recent LHCb results on:
  - BF and angular analyses of $b \to s\ell\ell$ and $b \to d\ell\ell$ decays see [L. D. Carus' talk]
  - LFU decays involving flavour changing charged currents (FCCC) see [A. Brea's talk]

The LHCb detector (Run1,2)

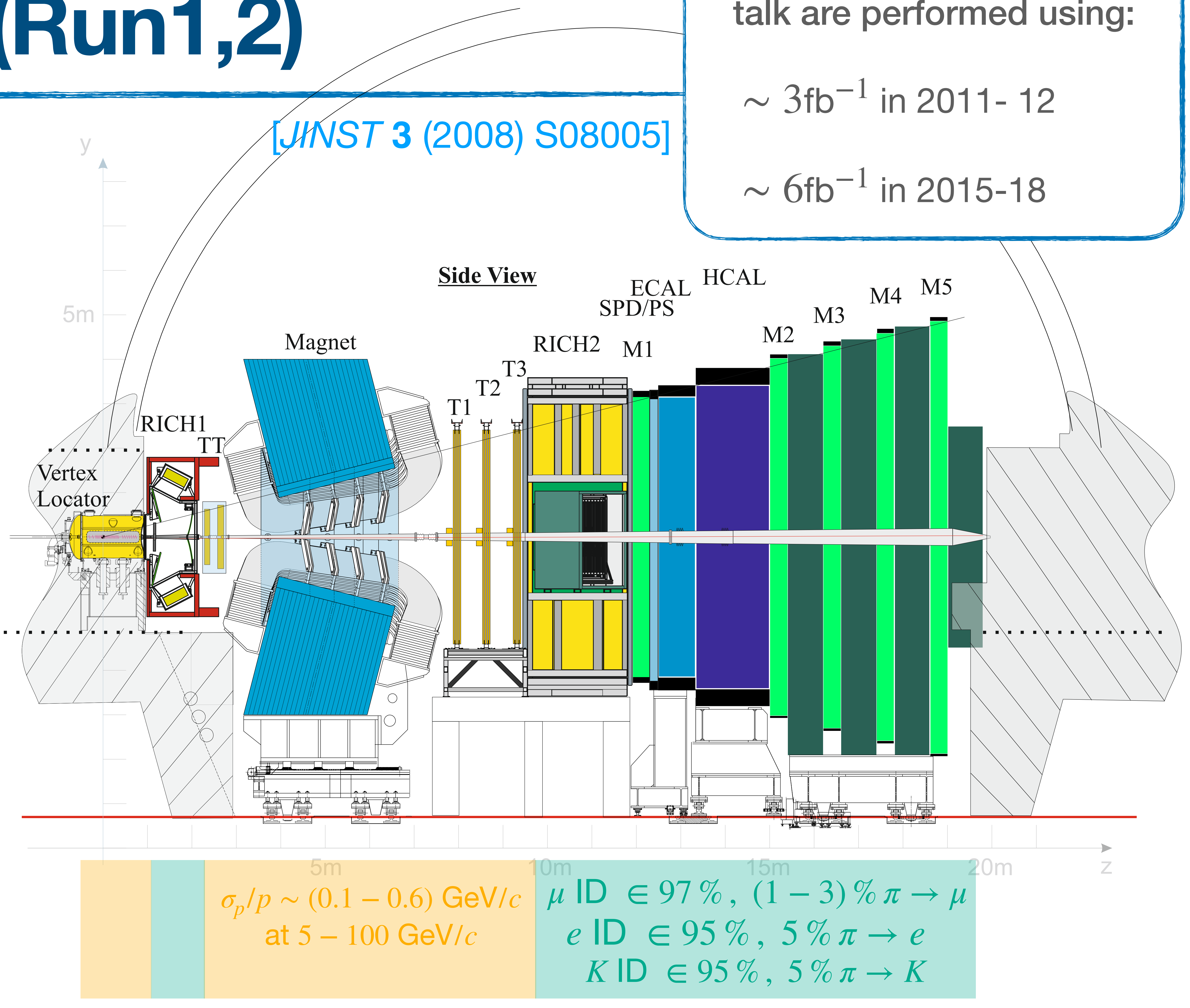
Analyses presented in this talk are performed using:

$\sim 3\text{fb}^{-1}$ in 2011- 12

$\sim 6\text{fb}^{-1}$ in 2015-18

- Forward arm GPD instrumented in the region where $\sigma(pp \to b\bar{b}X)$ is maximal
- In Run1+2, 100 thousand $b\bar{b}$ pairs per second produced in LHCb acceptance
- Excellent vertexing and PID capabilities to identify and reconstruct rare decays of displaced b-hadrons

[JINST **3** (2008) S08005]



LFU probes: the R_H observables

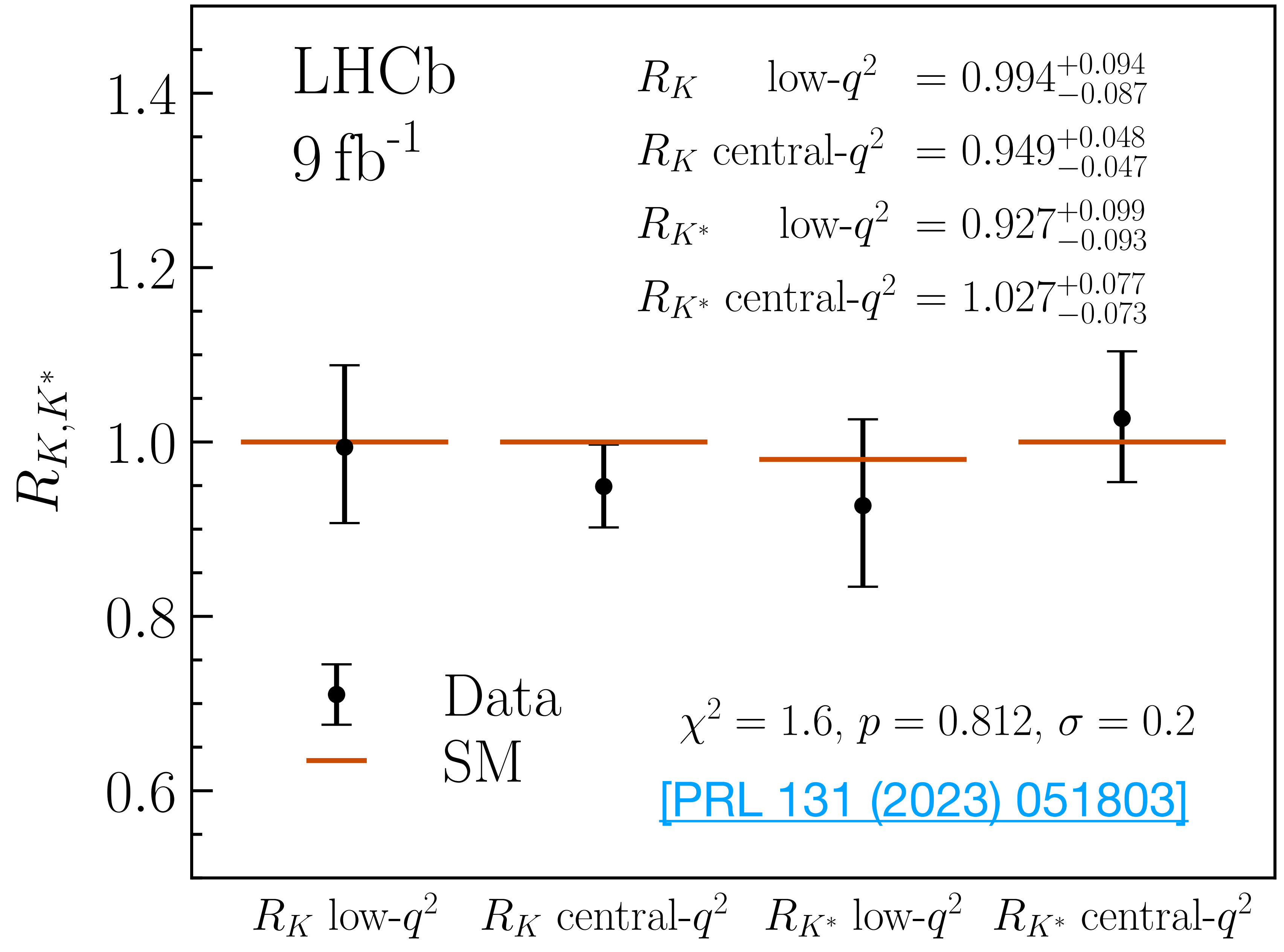
- SM distinguishes flavour only for mass effects, hadronic contributions are LFU
  → the value of R_{H_s} is predicted to be very close to 1 for μ/e ratios.

$q^2 \equiv$ momentum transfer to the pair of leptons

$$R_{H_s} = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\mathcal{B}(B\to H_s\mu^+\mu^-)}{dq^2}dq^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\mathcal{B}(B\to H_s e^+e^-)}{dq^2}dq^2} \overset{\rm SM}{=} 1 \pm \mathcal{O}(10^{-2})$$

QED

[EPJ C76 (2016) 8 440]

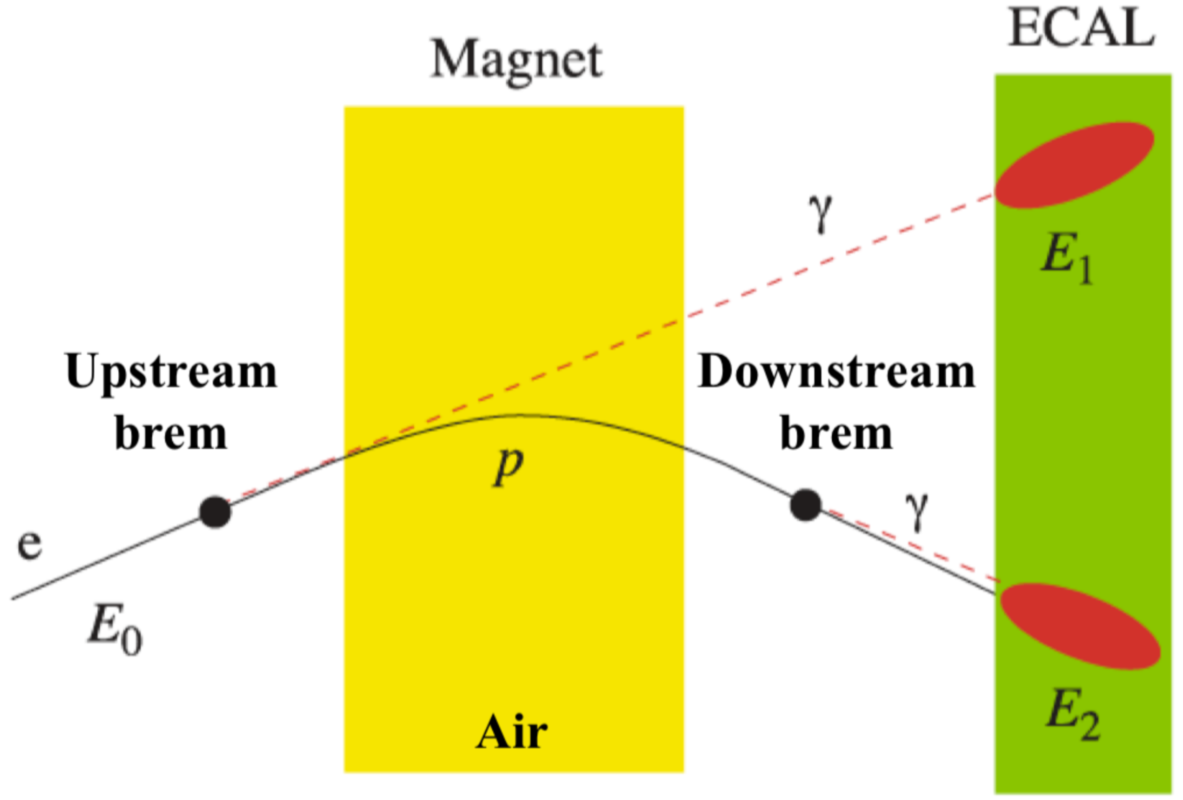


- Recent results from LHCb are in agreement with SM predictions within uncertainties, no competitive measurement of LFU ratio from LHCb above charm resonances, until now.

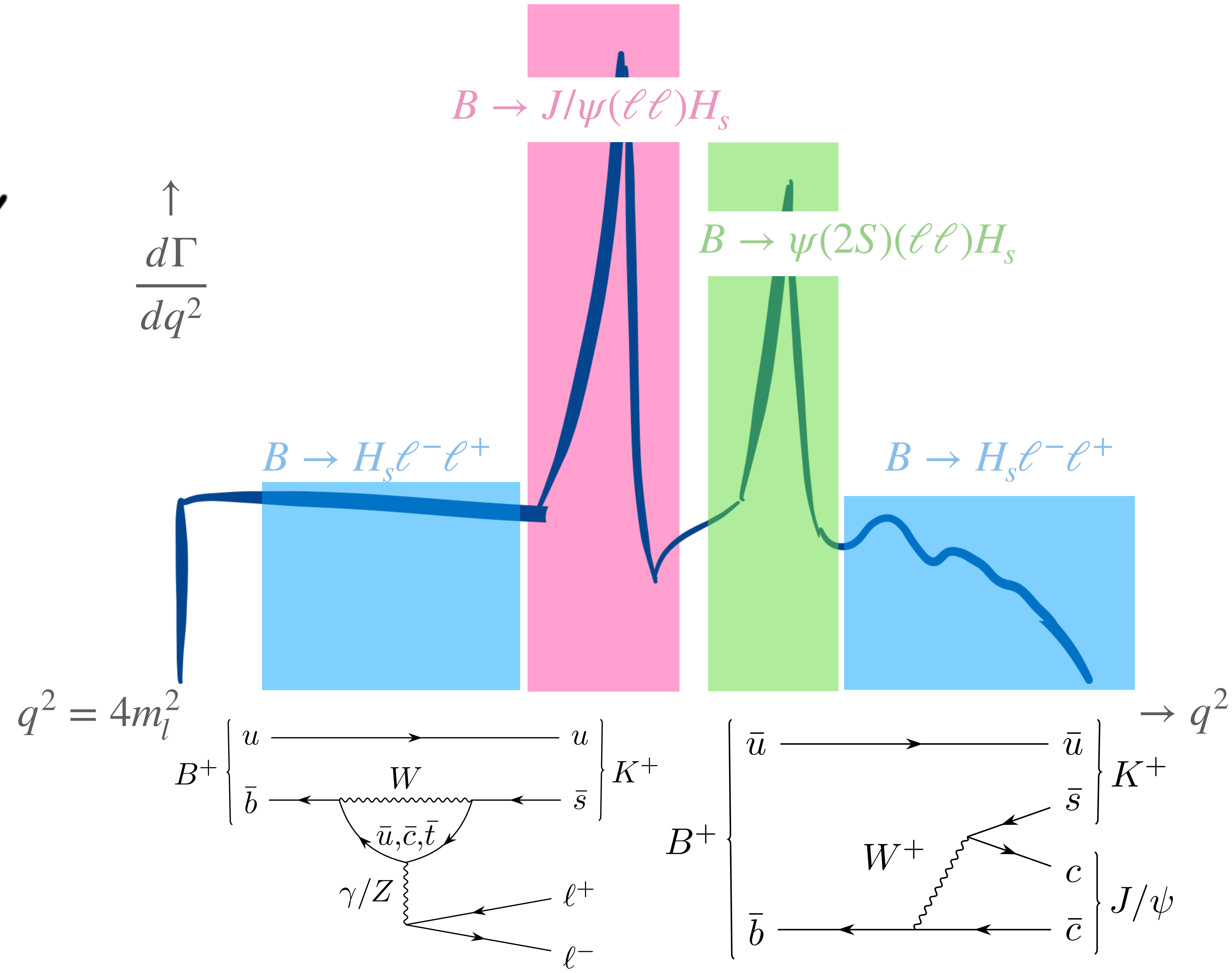
- Important to keep testing LFU with $b \to s\ell\ell$ processes involving different spectator quarks to fully exploit collected dataset and reduce orthogonal systematics

Strategy for R_H measurements at LHCb

- Experimentally challenging as sensitive to μ/e detection differences (e.g. trigger strategy, PID) + different occupancy → tighter requirements for e
- Significant energy loss to bremsstrahlung photons from e, mitigated by recovery algorithm
  → Degraded mass resolution and reconstruction efficiency for e w.r.t. μ



$$R_{H_s} = \frac{N(H_s\mu\mu)}{N(H_s ee)}\frac{\varepsilon(H_s ee)}{\varepsilon(H_s\mu\mu)} \Bigg/ \underbrace{\frac{N(H_s J/\psi(\mu\mu))}{N(H_s J/\psi(ee))}\frac{\varepsilon(H_s J/\psi(ee))}{\varepsilon(H_s J/\psi(\mu\mu))}}_{r^{H_s}_{J/\psi}}$$



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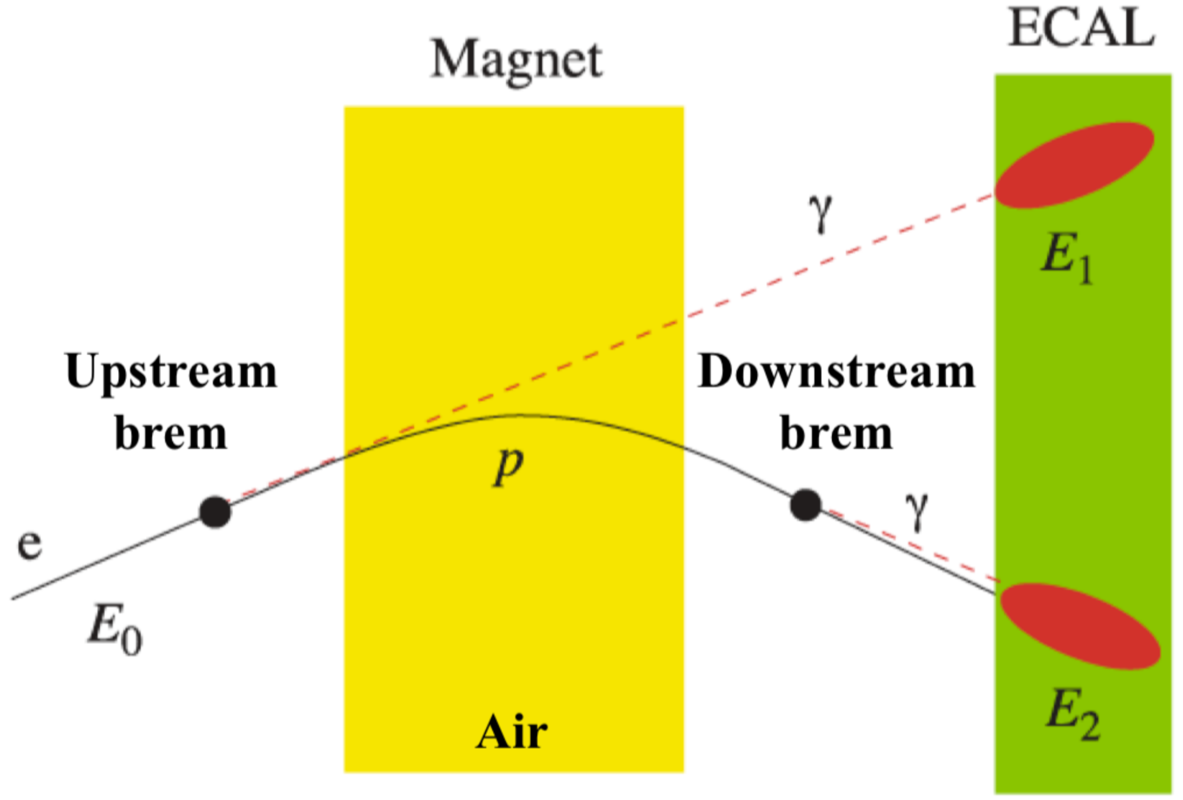
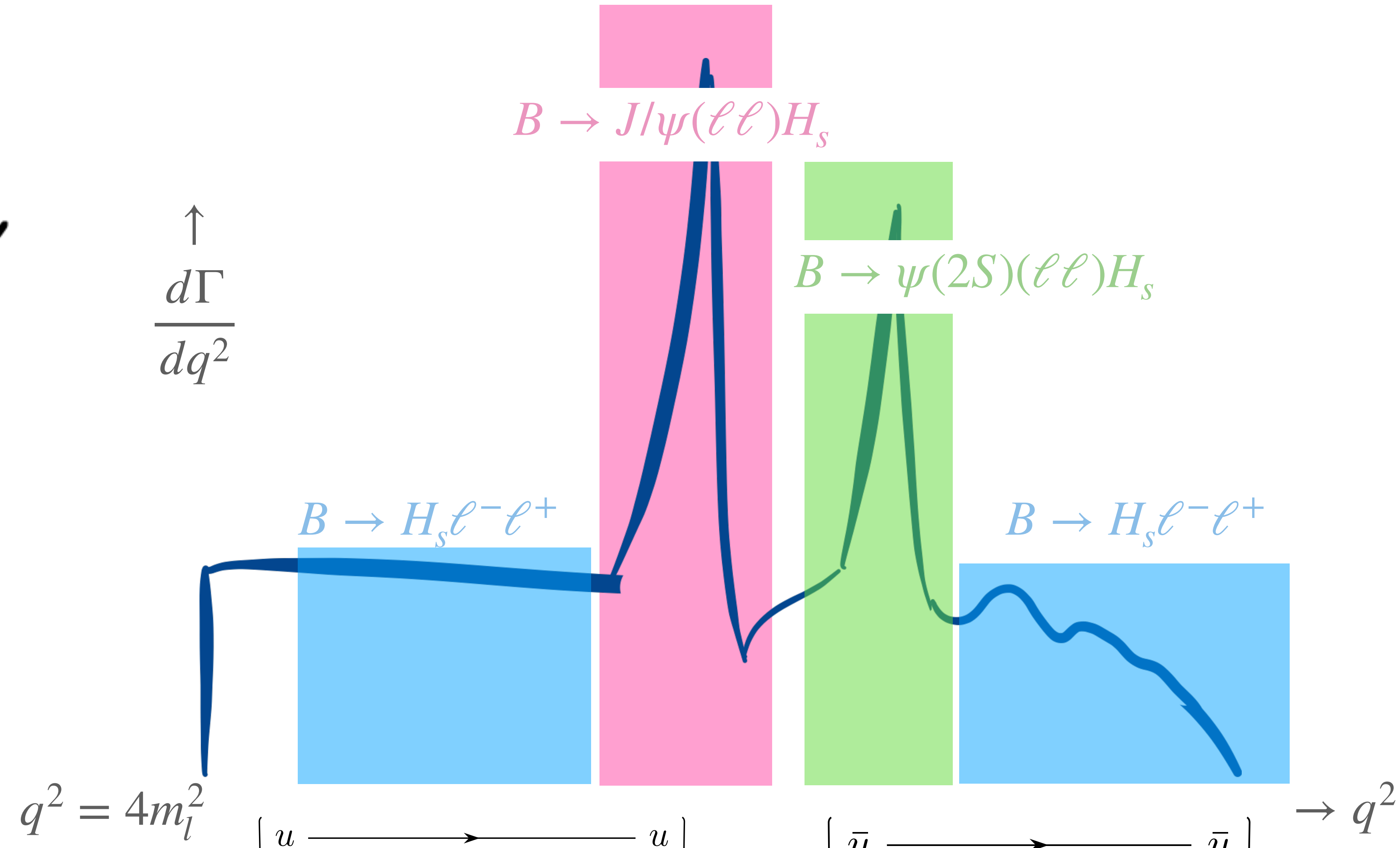


$$R_{H_s} = \frac{N(H_s\mu\mu)}{N(H_see)}\frac{\varepsilon(H_see)}{\varepsilon(H_s\mu\mu)} \Bigg/ \underbrace{\frac{N(H_sJ/\psi(\mu\mu))}{N(H_sJ/\psi(ee))}\frac{\varepsilon(H_sJ/\psi(ee))}{\varepsilon(H_sJ/\psi(\mu\mu))}}_{r^{H_s}_{J/\psi}}$$

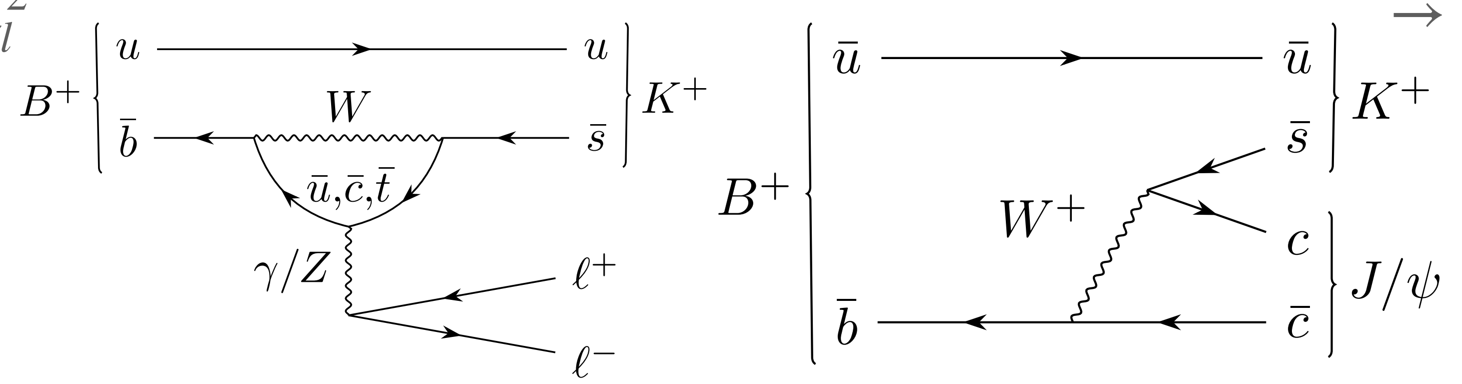


Efficiencies

- Excellent control of efficiencies in simulation thanks to double ratio w.r.t. control channels
- Standard candles since these decays are known to be LFU within 0.4% [PDG]

Yields

- Obtained from maximum likelihood fits to the B invariant mass
- Use data-driven techniques to obtain robust and conservative estimate of background contamination

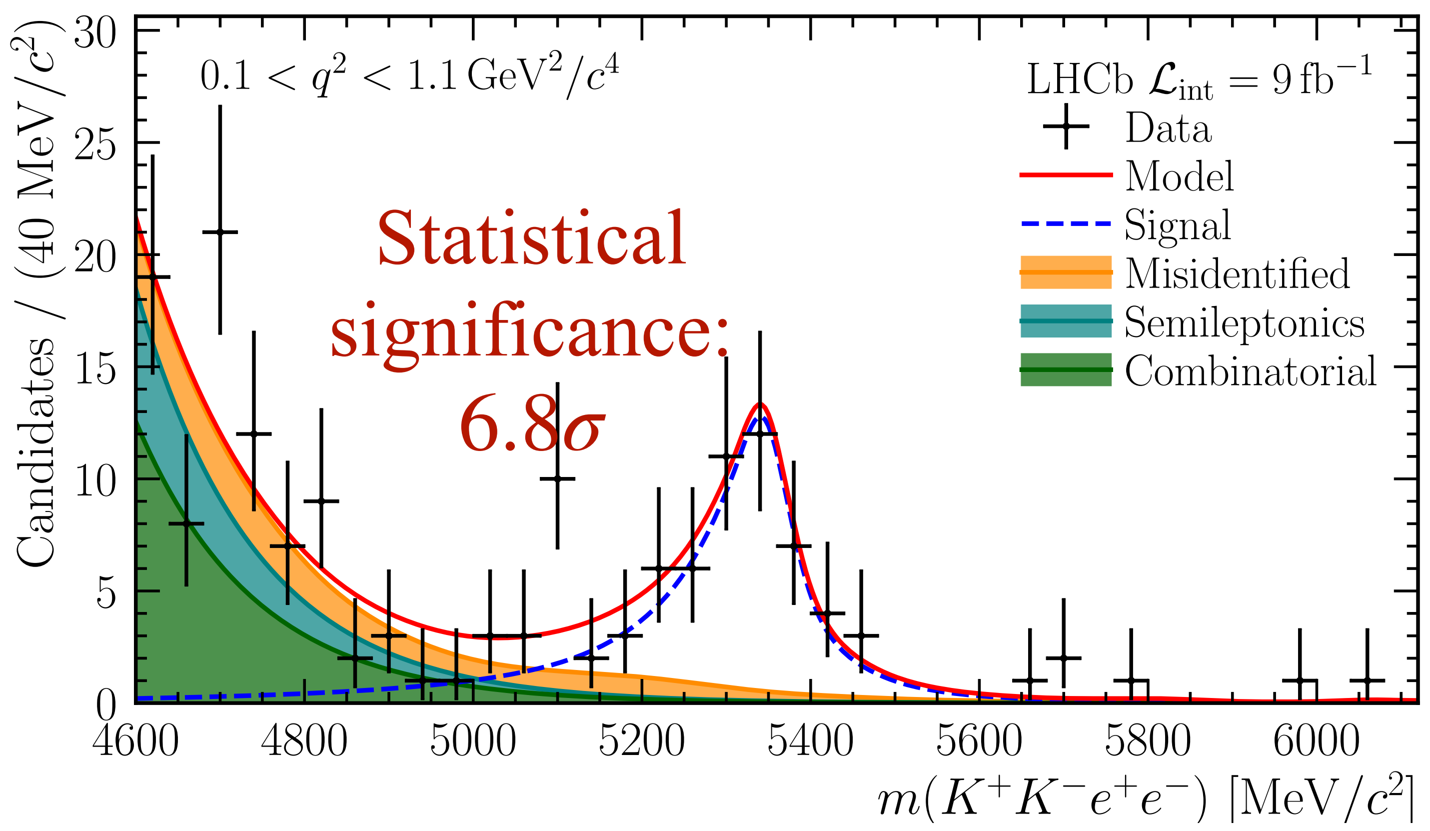


LFU ratio with $B_s^0 \to \phi \ell^+ \ell^-$ decays

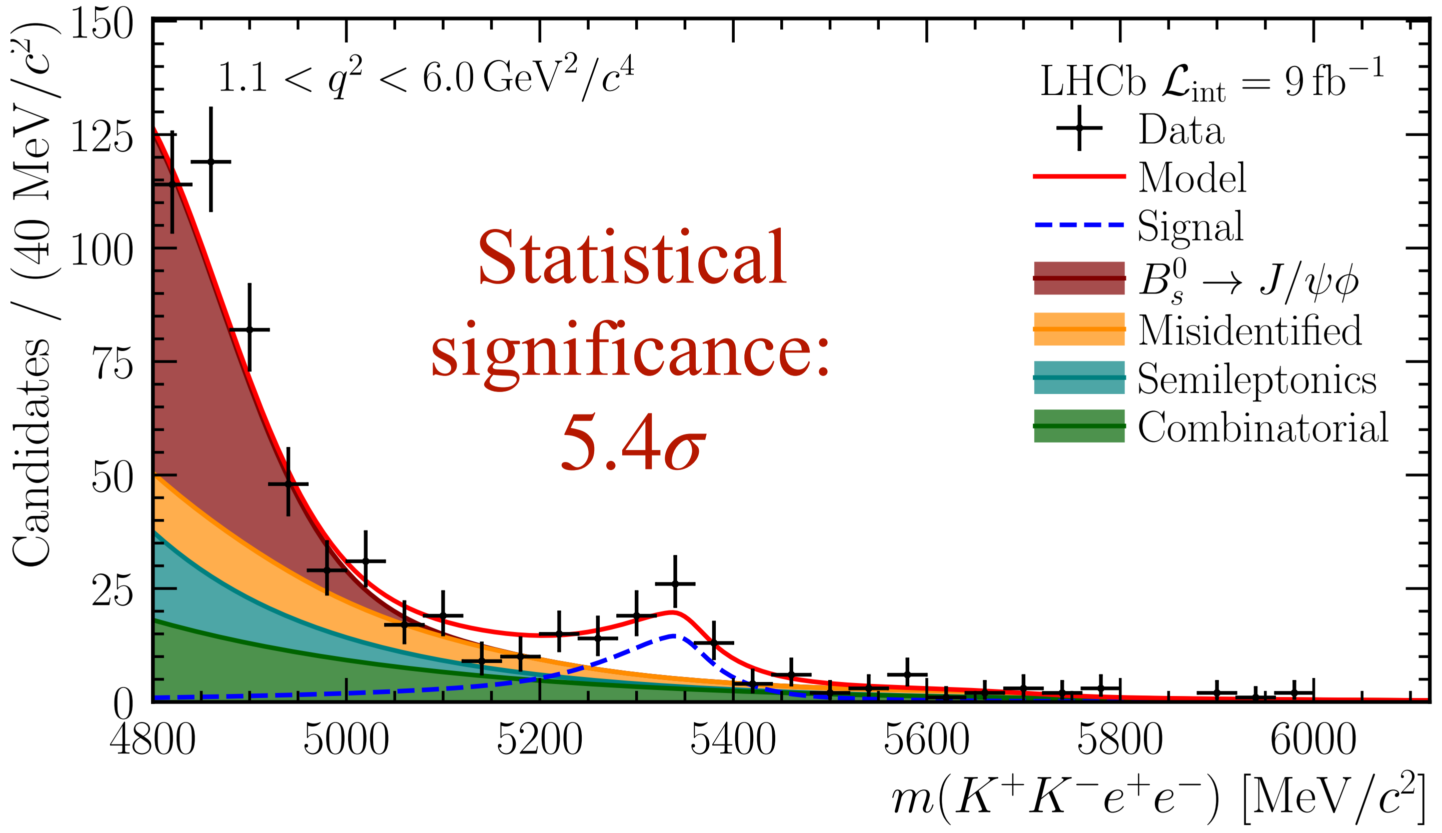
[PRL 134 (2025) 12, 121803]

- First LFU test in B_s^0 decays:
  - Measurement performed in low, central and high q^2 regions
  - Background is significantly reduced thanks to narrow width of ϕ
  - First LFU measurement at high q^2: challenging backgrounds due to vicinity of phase-space endpoint and charmonium resonances leakages

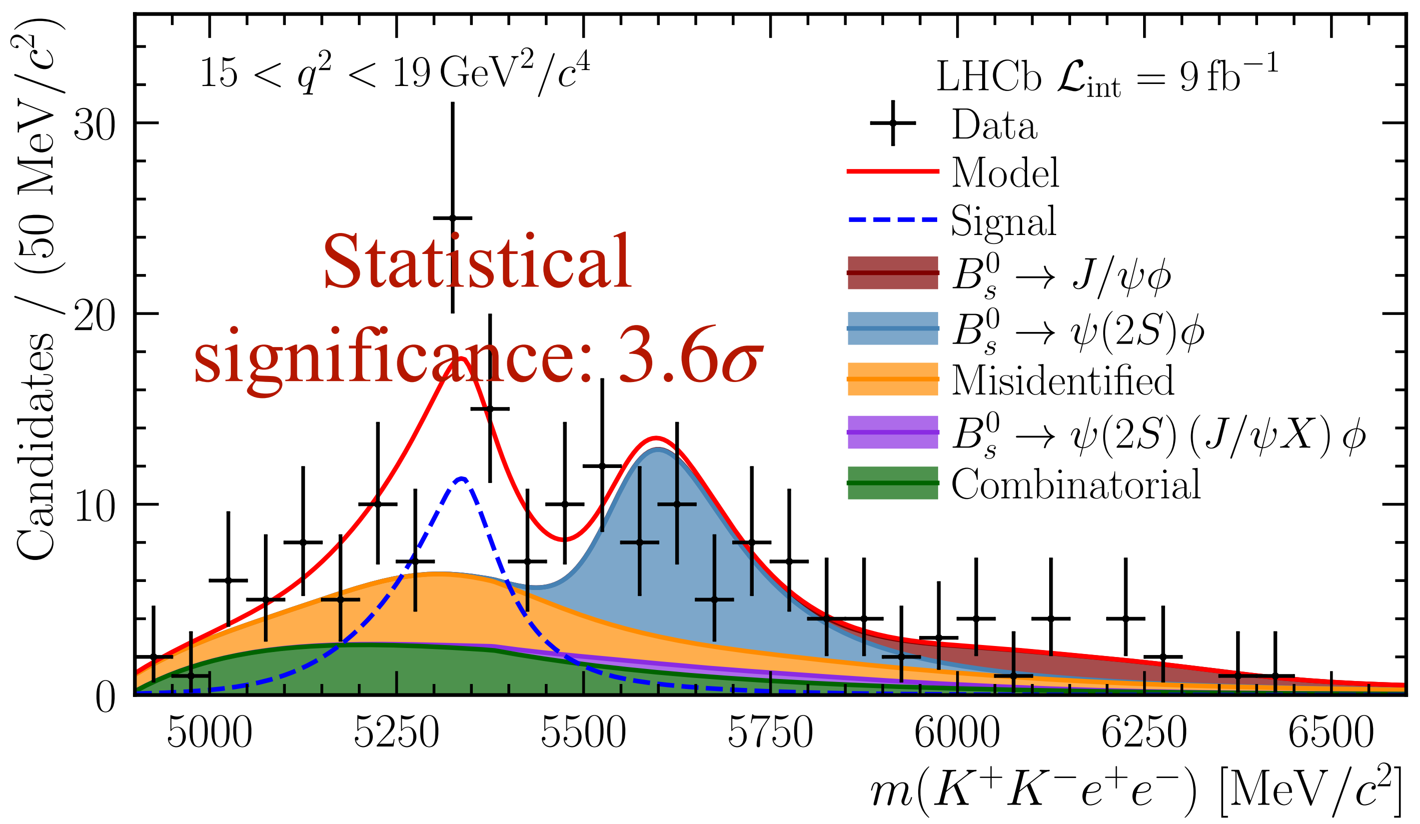
$$r^{\phi}_{J/\psi} = 0.997 \pm 0.013$$
$$r^{\phi}_{\psi(2S)} = 1.010 \pm 0.026$$



$0.1 < q^2 < 1.1$ GeV$^2/c^2$



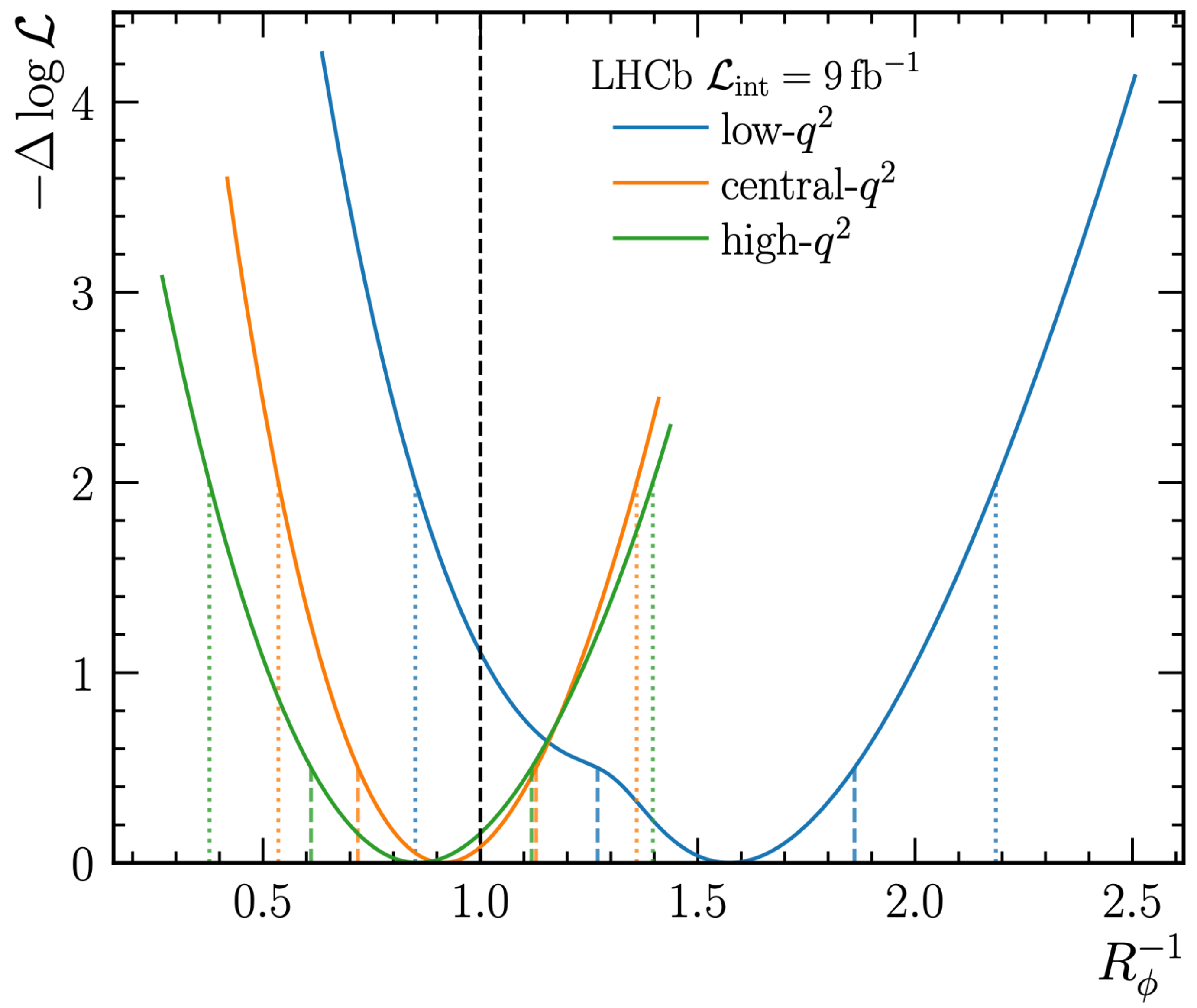
$1.1 < q^2 < 6.0$ GeV$^2/c^2$



$15.0 < q^2 < 19.0$ GeV$^2/c^2$

LFU ratio with $B_s^0 \to \phi\ell^+\ell^-$ decays [PRL 134 (2025) 12, 121803]

- First observation and measurement of BF of $B_s^0 \to \phi e^+e^-$ decays
- Results are compatible with SM, uncertainty on R_ϕ^{-1} is statistically dominated, main contributions to systematic come from misidentified background estimate



q^2 $[{\rm GeV}^2/c^4]$	R_ϕ^{-1}	${\rm d}\mathcal{B}(B_s^0 \to \phi e^+e^-)/{\rm d}q^2$ $[10^{-7}\,{\rm GeV}^{-2}c^4]$
$0.1 < q^2 < 1.1$	$1.57\,^{+0.28}_{-0.25} \pm 0.05$	$1.38\,^{+0.25}_{-0.22} \pm 0.04 \pm 0.19 \pm 0.06$
$1.1 < q^2 < 6.0$	$0.91\,^{+0.20}_{-0.19} \pm 0.05$	$0.26 \pm 0.06 \pm 0.01 \pm 0.01 \pm 0.01$
$15.0 < q^2 < 19.0$	$0.85\,^{+0.24}_{-0.23} \pm 0.10$	$0.39 \pm 0.11 \pm 0.04 \pm 0.02 \pm 0.02$

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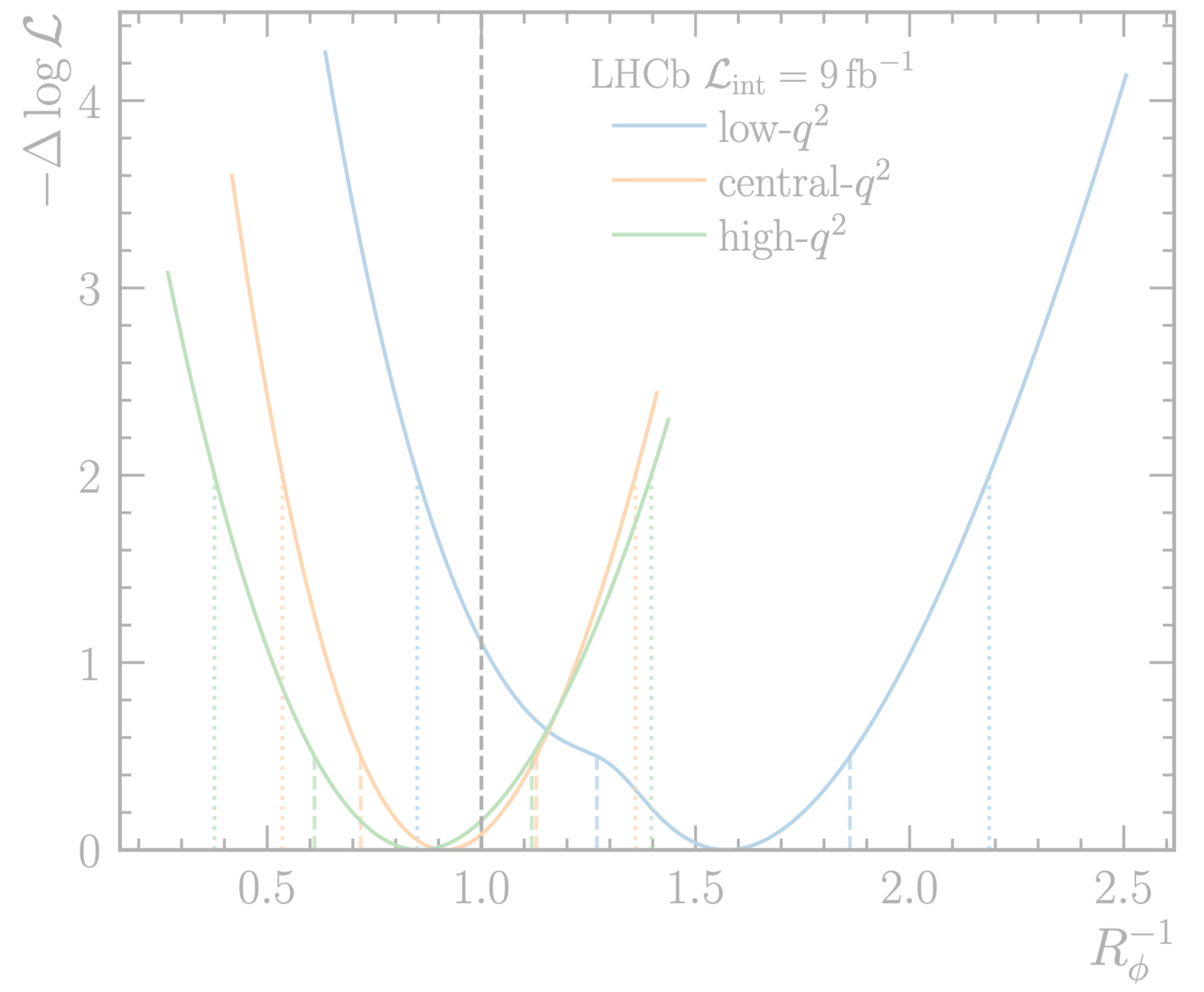

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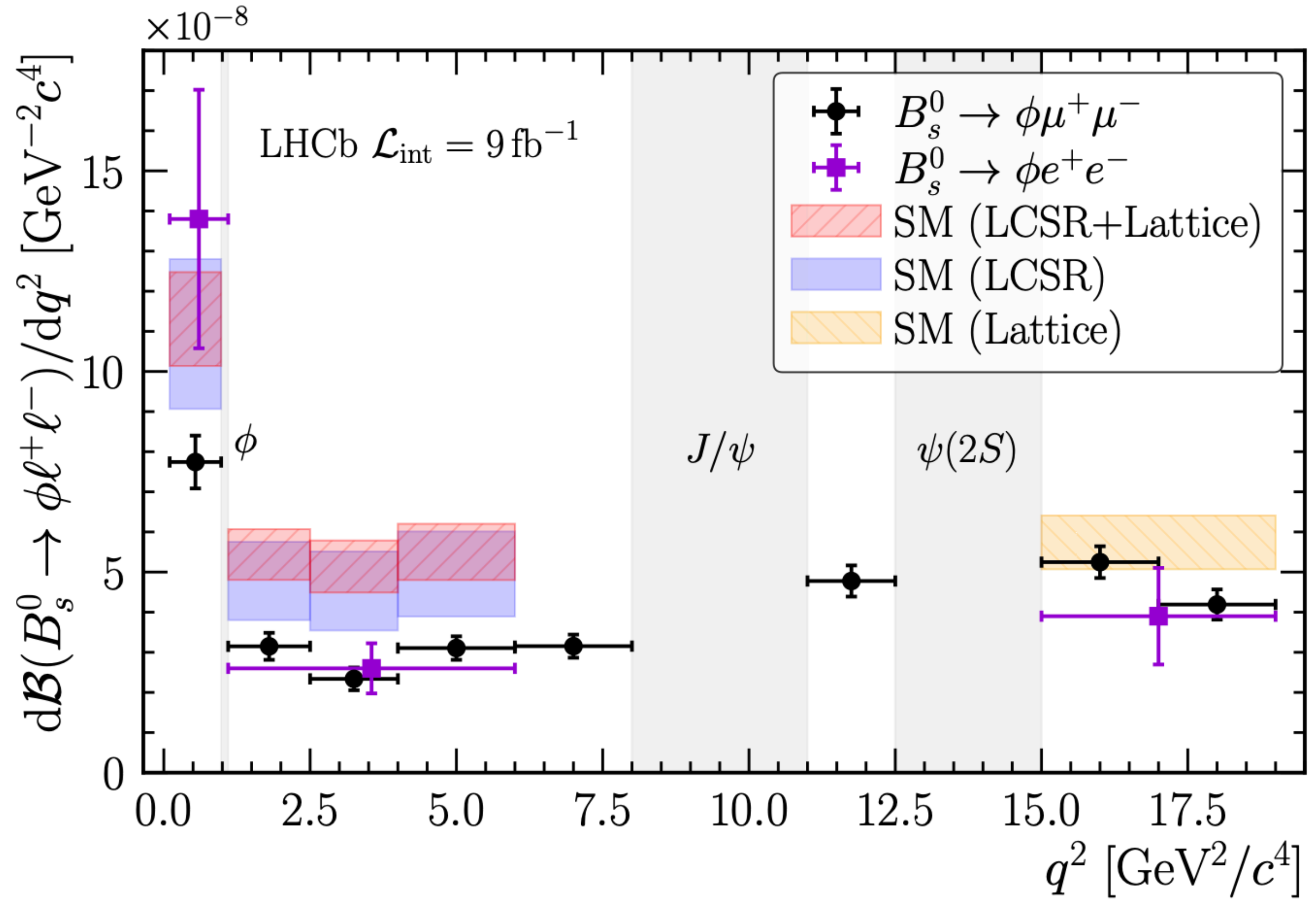
- The differential BF $B_s^0 \to \phi e^+e^-$ is obtained by combining R_ϕ^{-1} with $dB(B_s^0 \to \phi\mu^+\mu^-)/dq^2/B(B_s^0 \to J/\psi\phi)$ [PRL 127 (2021) 151801] and $B(B_s^0 \to J/\psi\phi)$ [PDG]



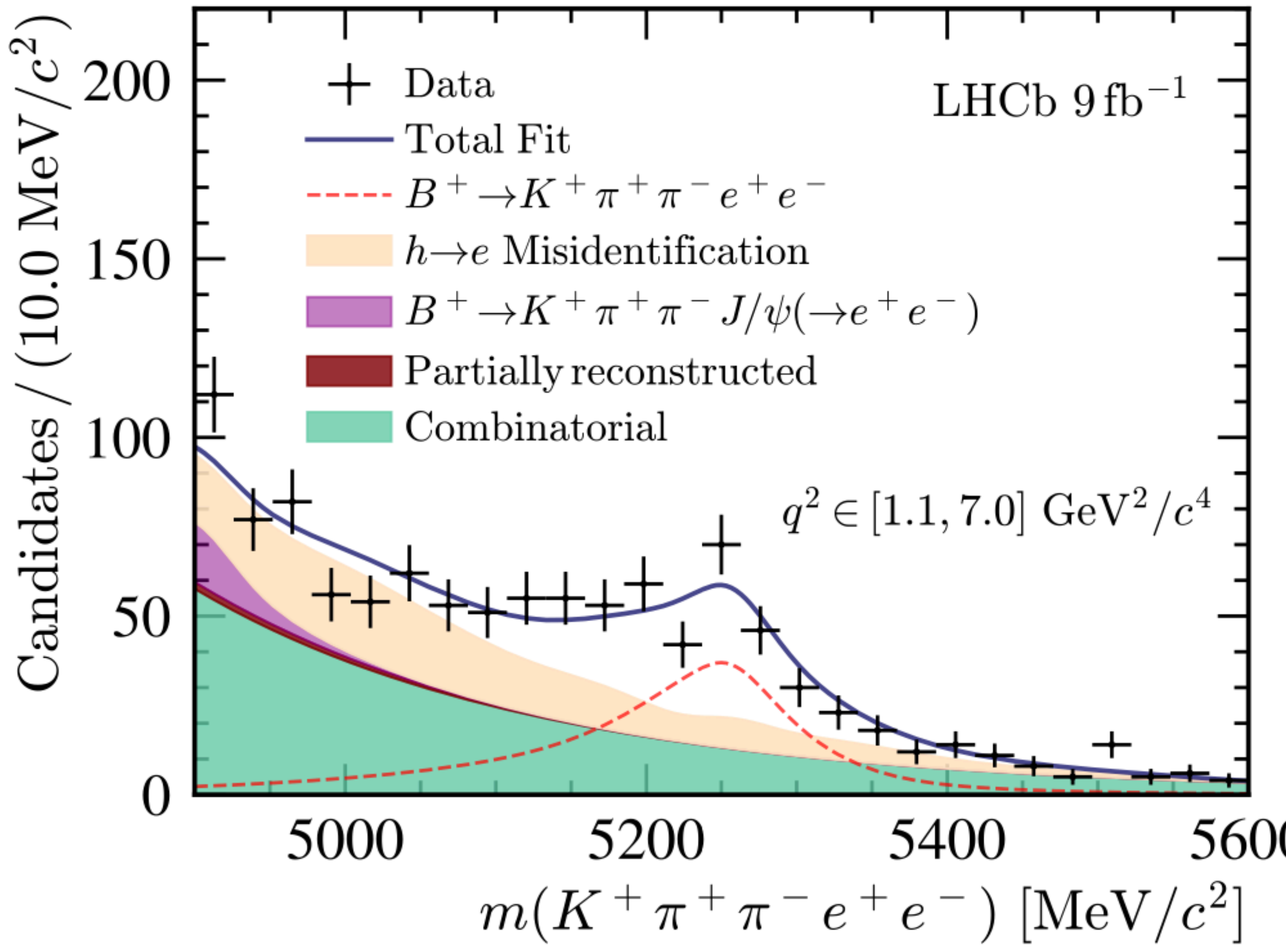
LFU ratio with $B^+ \to K^+\pi^+\pi^-\ell^+\ell^-$ decays

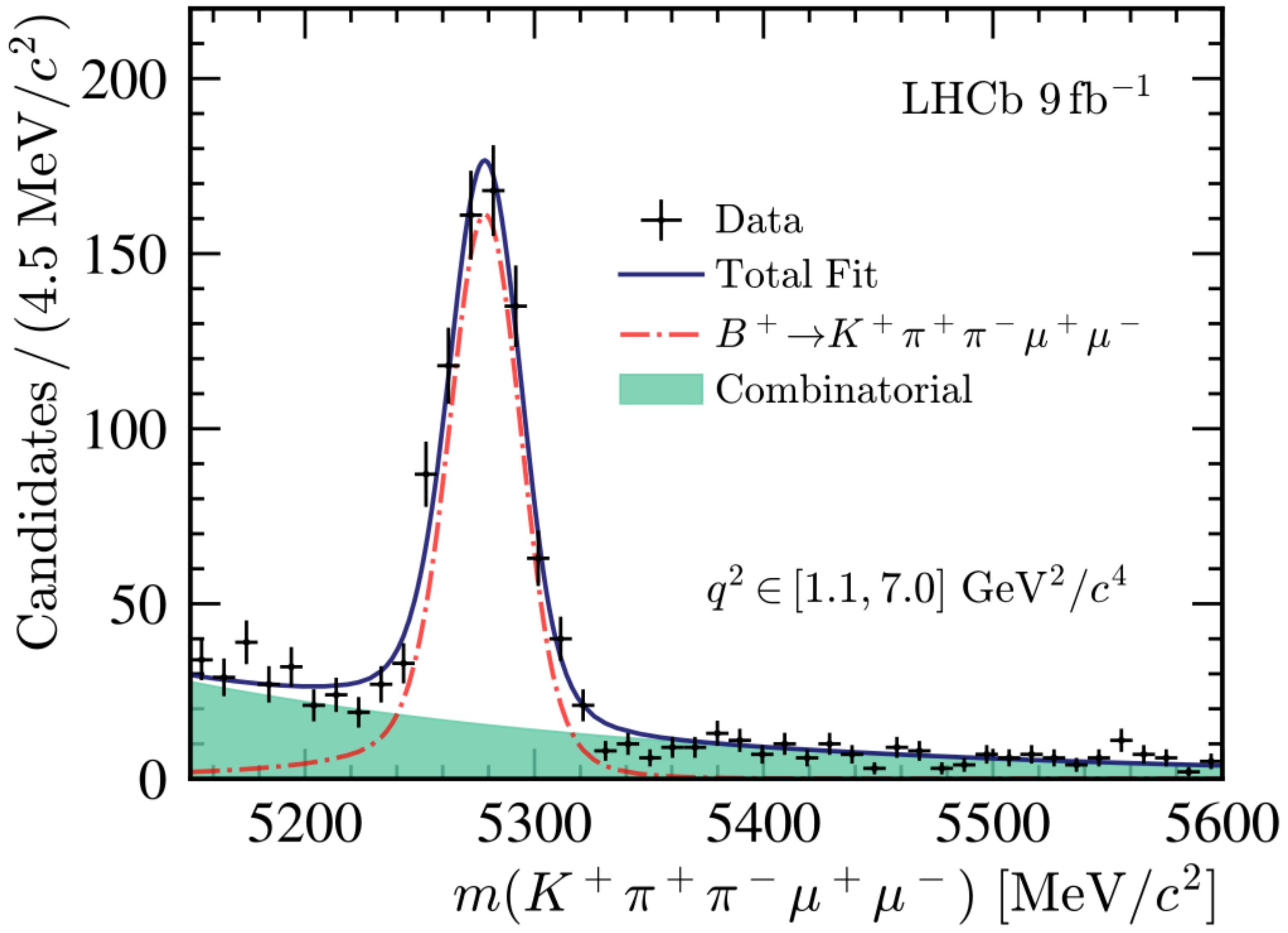
$$r_{J/\psi}^{K\pi\pi} = 1.033 \pm 0.017$$
$$r_{\psi(2S)}^{K\pi\pi} = 1.040 \pm 0.030$$

- First LFU test in these decays:
  - Measurement in central-q^2: $1.1 < q^2 < 7.0$ GeV$^2/c^2$, inclusive in $1.1 < m(K\pi\pi) < 2.4$ GeV$/c$
  - First observation of $B^+ \to K^+\pi^+\pi^-e^+e^-$ decay, $> 10\sigma$

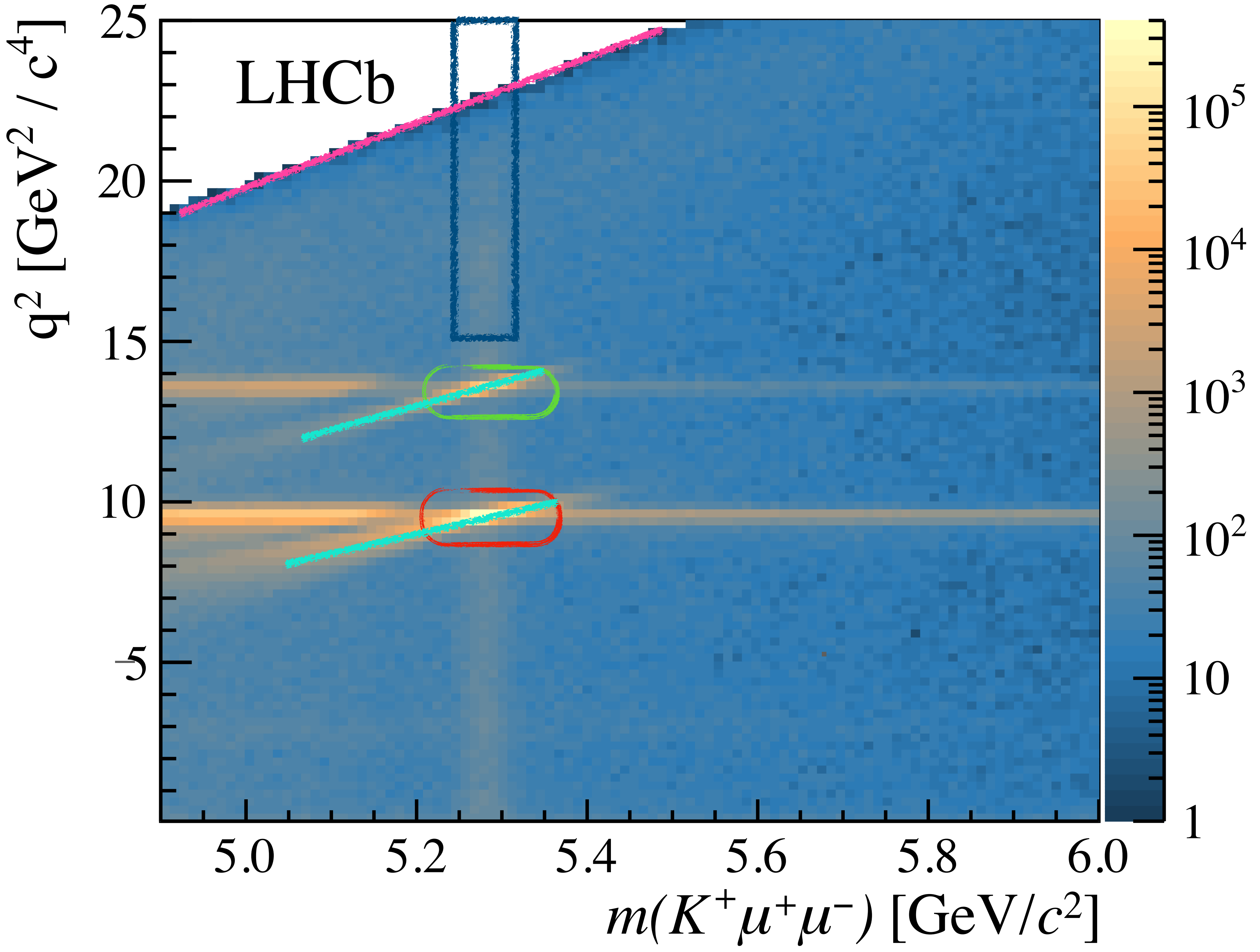
$$R_{K\pi\pi}^{-1} = 1.31^{+0.18}_{-0.17}\,(\text{stat})\,^{+0.12}_{-0.09}\,(\text{syst})$$

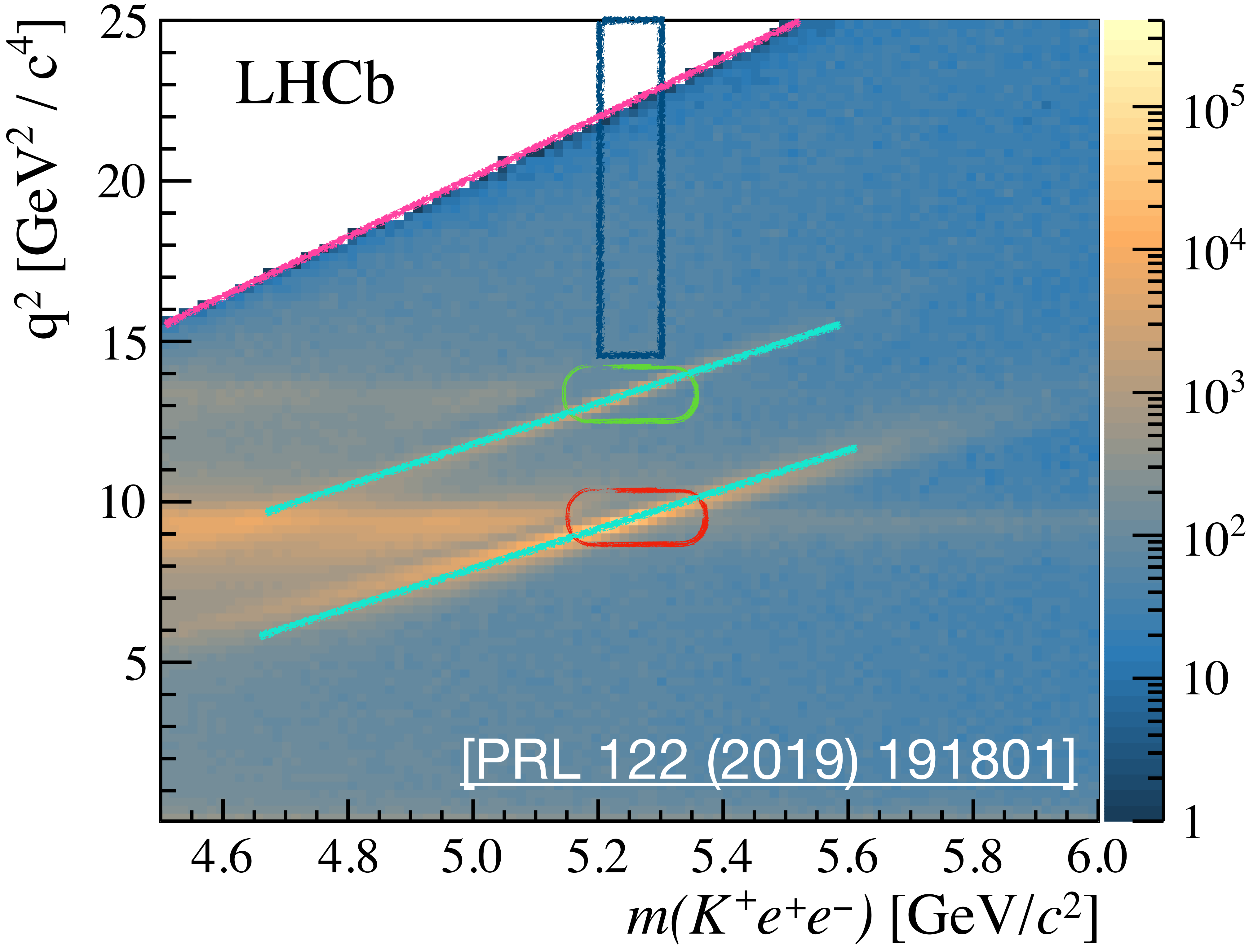
  - Result is compatible with SM
  - Still dominated by statistical uncertainty
  - Main systematics contributions come from mis-ID background shape and contamination estimate





LFU ratio with $B^+ \to K^+\ell^+\ell^-$: challenges at high q^2





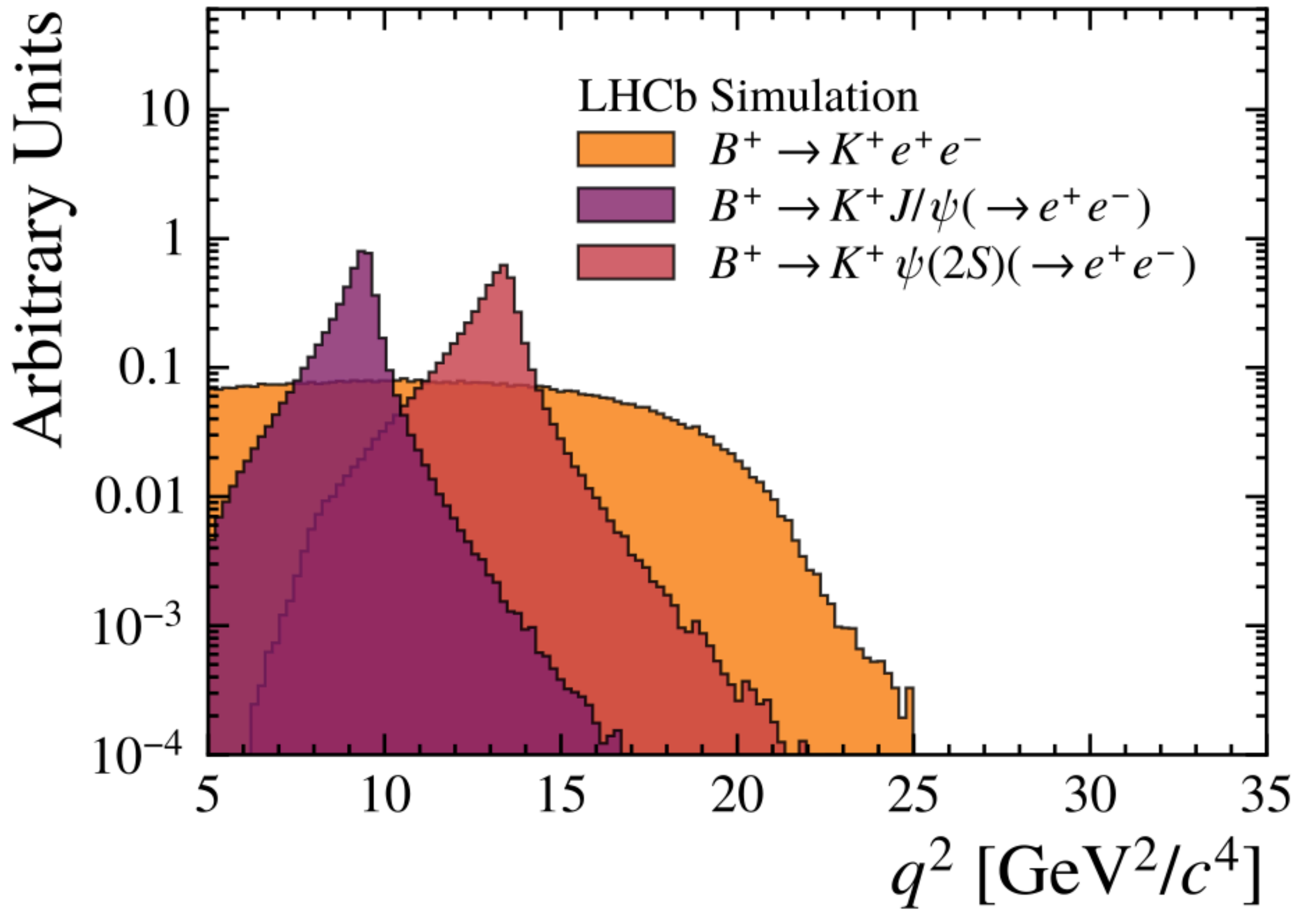
- Peaking structures: $B^+ \to K^+J/\psi(\ell^+\ell^-)$ and $B^+ \to K^+\psi(2S)(\ell^+\ell^-)$ (resonant decay modes)
- Vertical band: $B^+ \to K^+\ell^+\ell^-$ (rare decay mode) in high q^2 region
- Radiative tails + incorrectly-added bremsstrahlung $\to$ most prominent background at high q^2 is $B^+ \to K^+\psi(2S)(\ell^+\ell^-)$ leakage
- White triangle: kinematically inaccessible $\to$ pink line: phase space cutoff

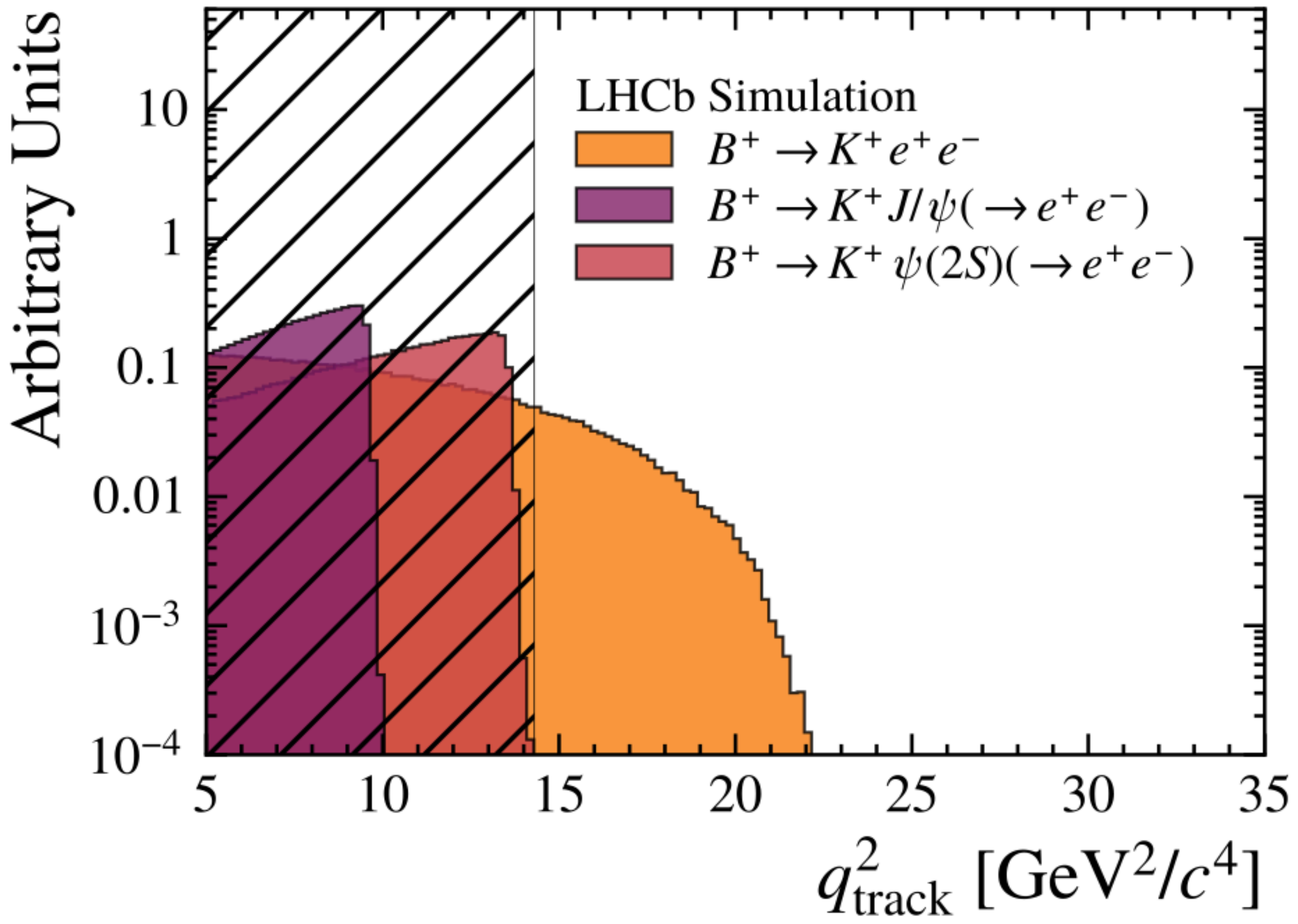
[arXiv:2505.03483]

LFU ratio with $B^+ \to K^+\ell^+\ell^-$ decays at high q^2

Aim at most precise measurement of R_K in high q^2 region:

- Pursue a maximum signal purity strategy:
  - Select electron signal decays requiring $q^2 > 14.3\ \text{GeV}^2/c^2$ prior to any bremsstrahlung recovery
  - Significant reduction of resonant leakages and misID backgrounds





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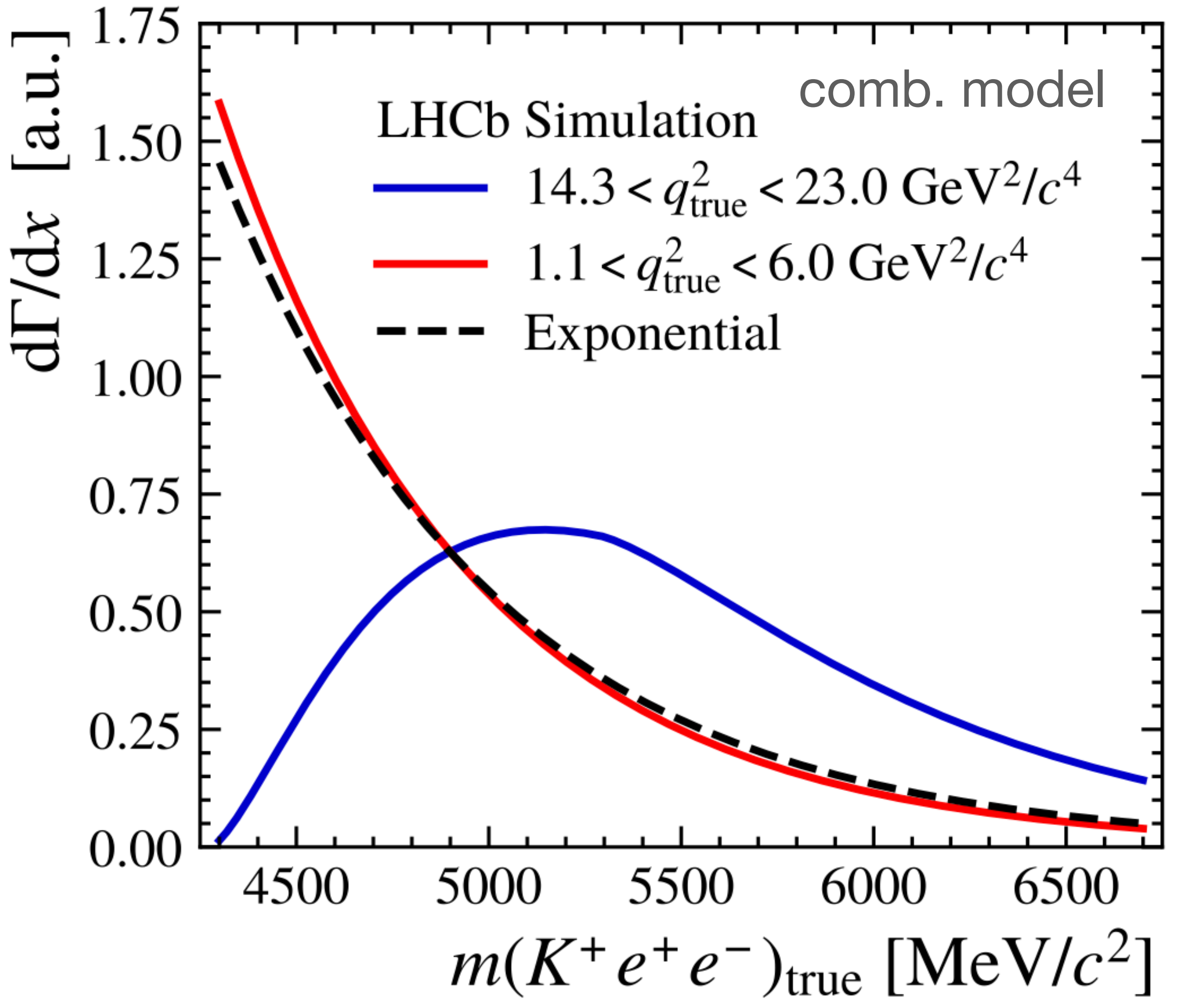
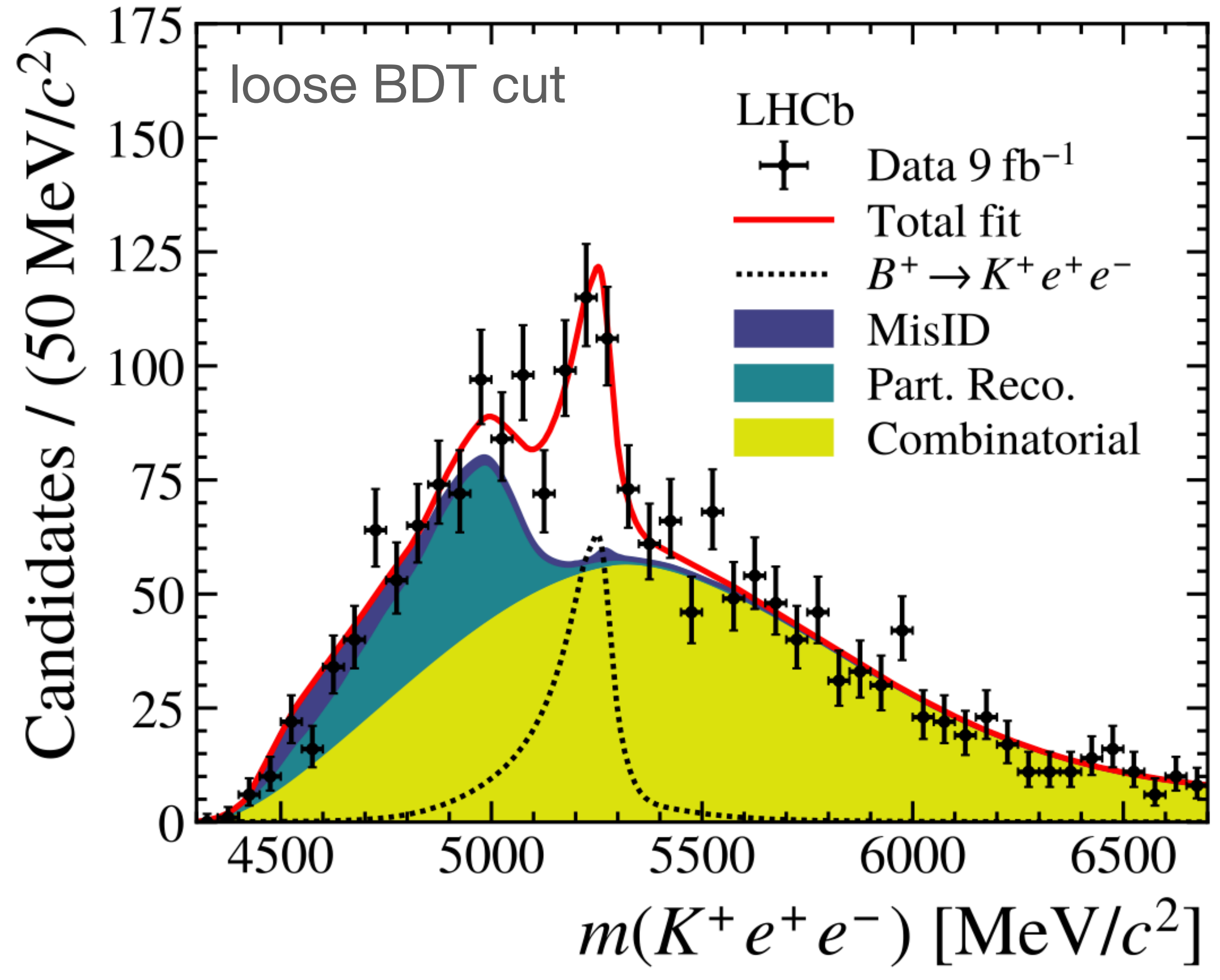
- Precise description of the sculpting induced by the high q^2 requirement:
  - Modelled phase-space cut on the combinatorial shape using kinematic ansatz
  - Verified that model well reproduces data with loose BDT requirement

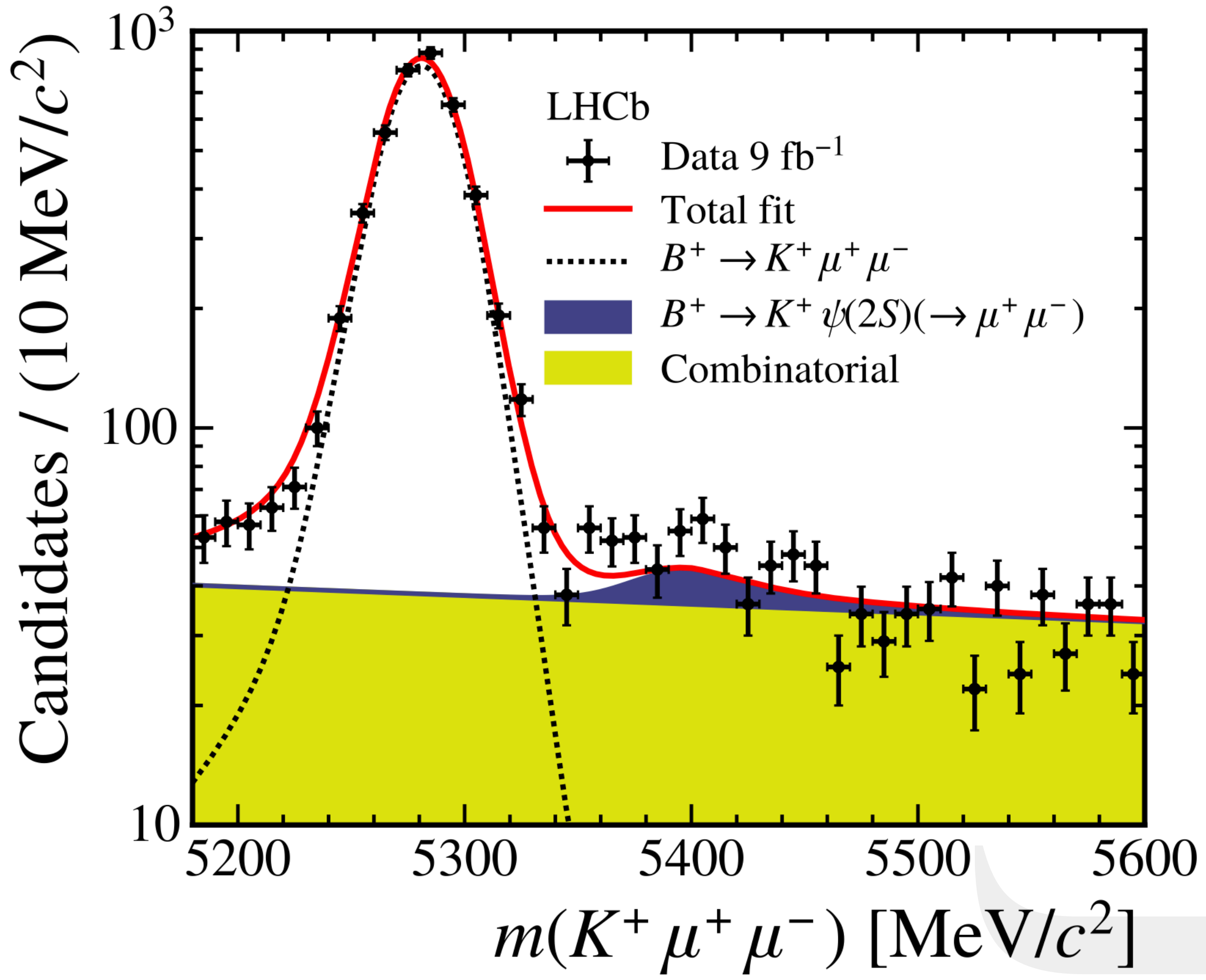


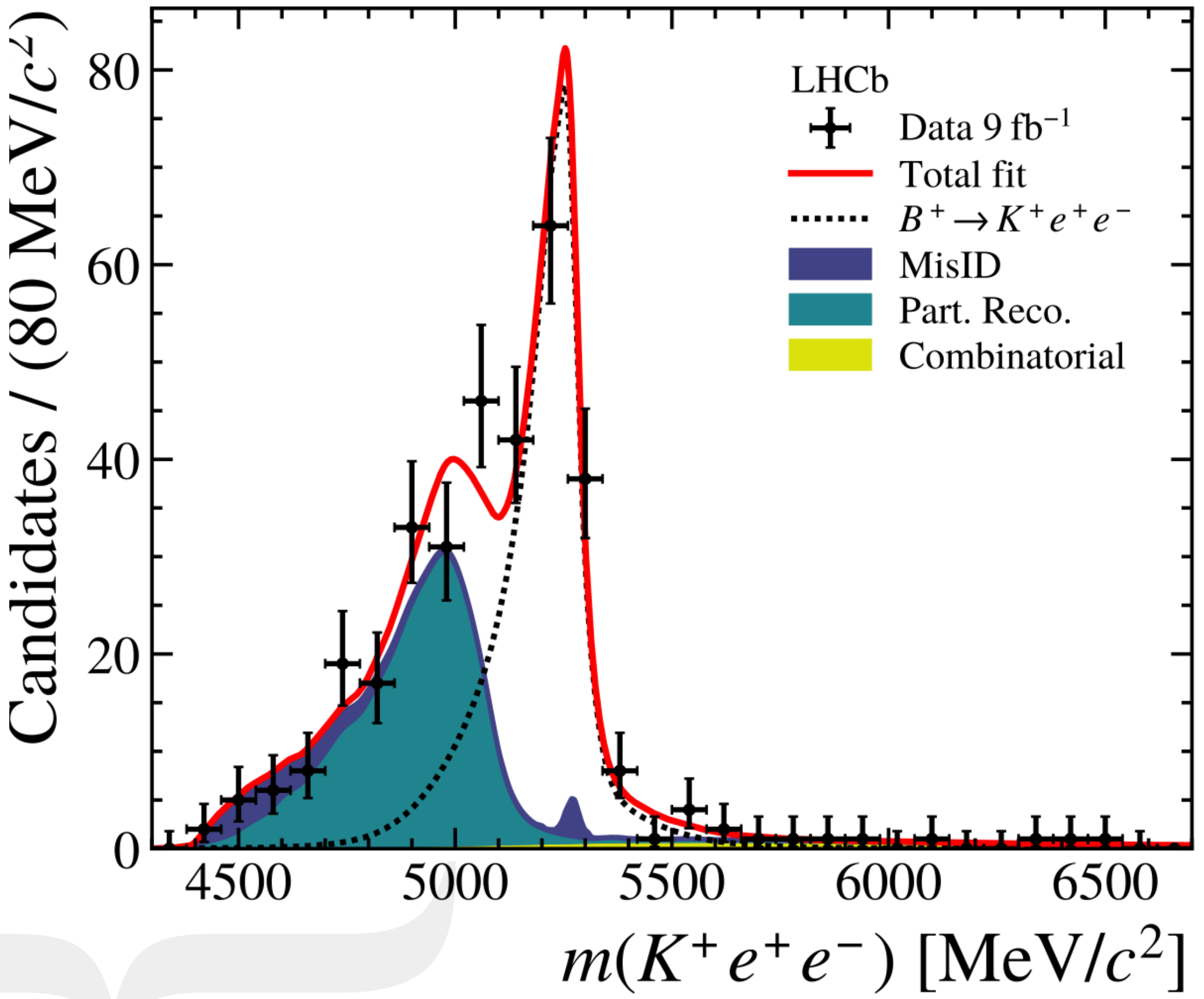


LFU ratio with $B^+ \to K^+\ell^+\ell^-$ decays at high q^2

- Most precise measurement of LFU ratio R_K at at high q^2:

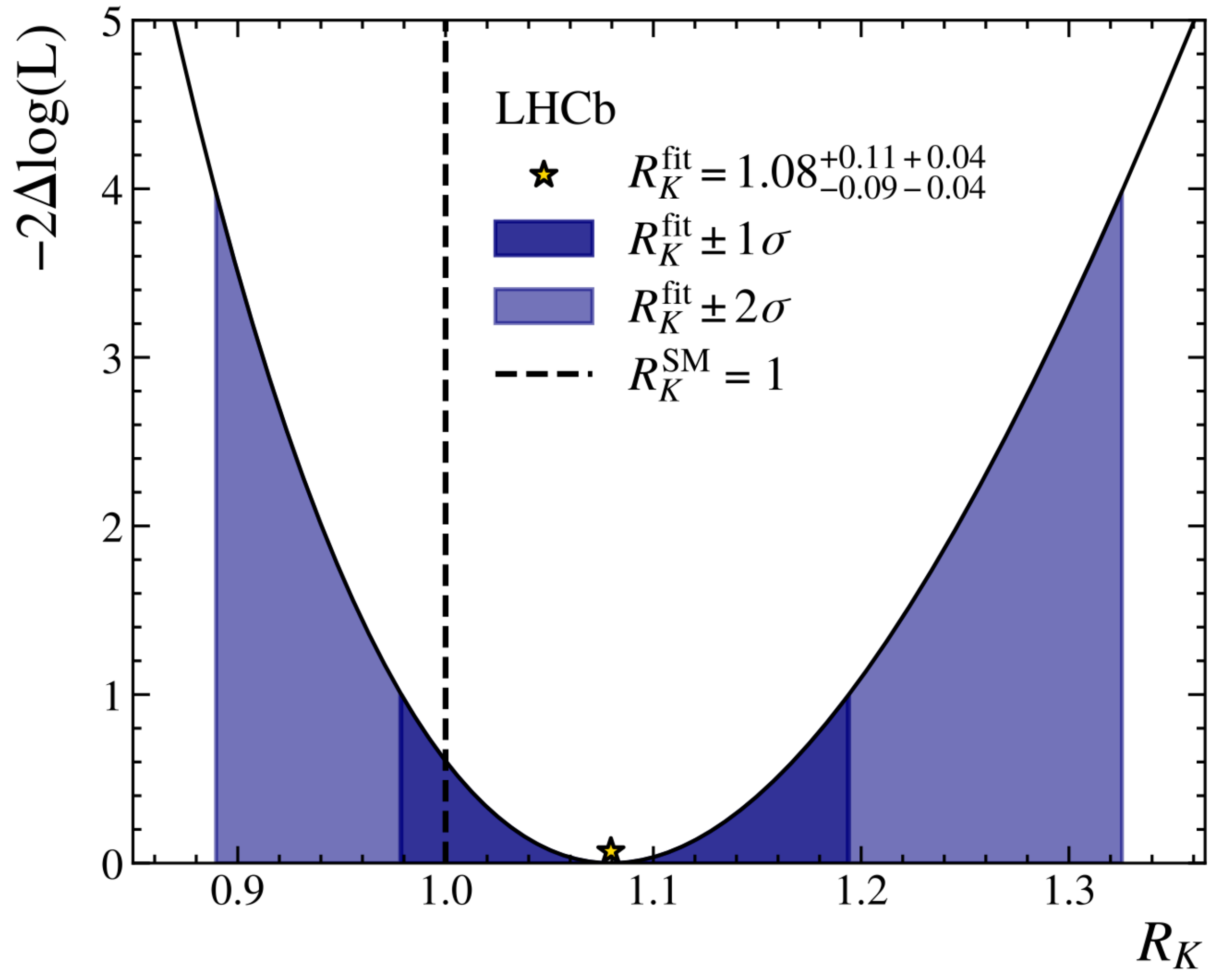
$$R_K(q^2 > 14.3\ \mathrm{GeV}^2/c^4) = 1.08^{+0.11\ +0.04}_{-0.09\ -0.04}$$





- Uncertainty is statistically dominated, systematic uncertainty driven by the partially reconstructed and misidentified backgrounds

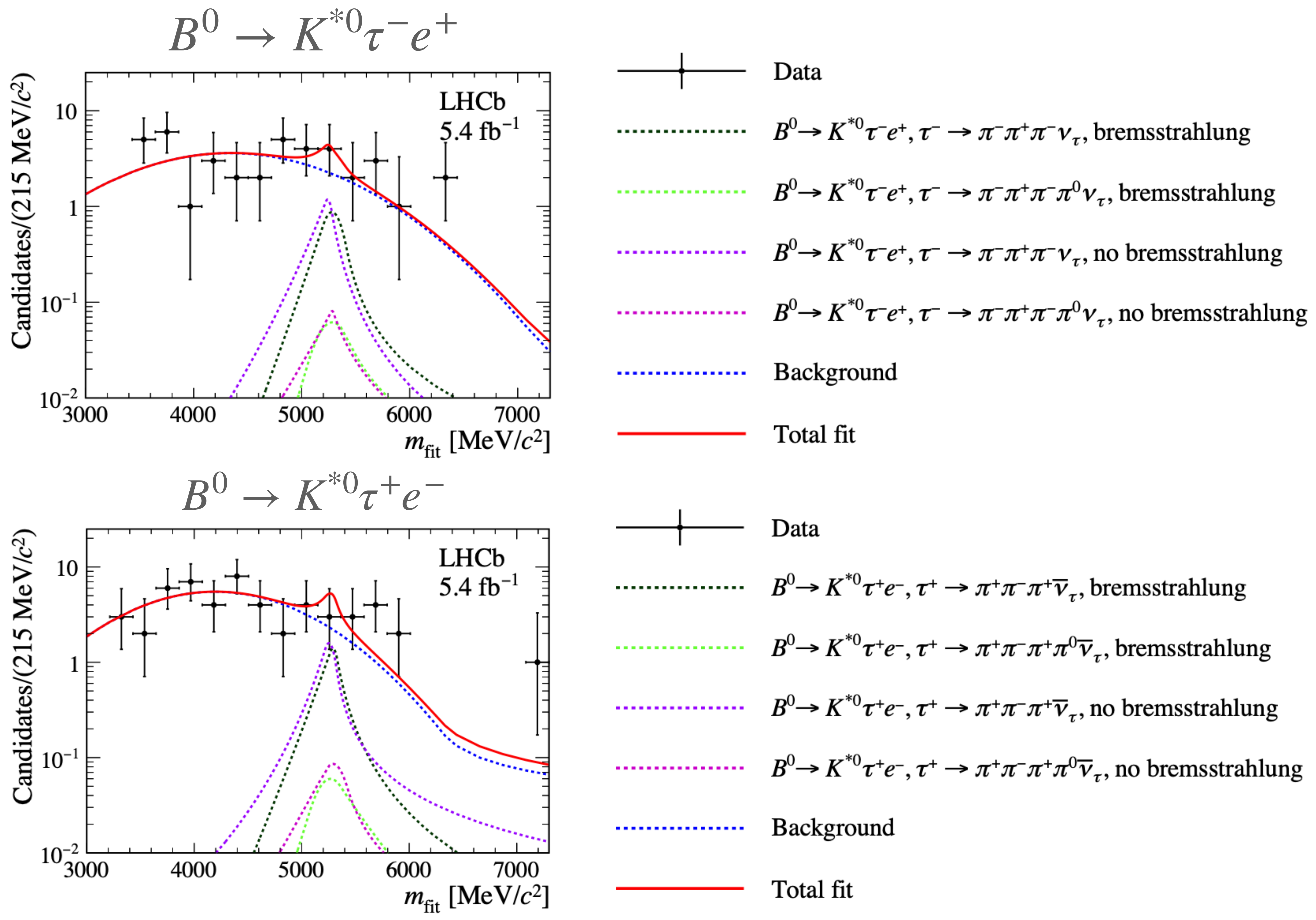
- Leakages from charmonia resonances are excluded from systematic uncertainties, otherwise hard to evaluate



LFV searches in $B^0 \to K^{*0}\tau^{\pm}e^{\mp}$

[arXiv:2506.15347]

- LFV has been observed in neutral leptons through neutrino oscillations
  - For charged leptons however, SM predicts that LFV is beyond current experimental sensitivity
  - Search for LFV violation helps constraining NP models that predict it
- Reconstructed B mass is refitted via a decay chain fit with kinematic constraints to correct for the missing ν momentum
- $B^0 \to D^-(K\pi\pi)D_s^+(KK\pi)$ used as normalisation + corrections to simulated efficiencies
- Most stringent limits on $b \to s\tau e$ are obtained:



@ 90(95) % C.L.

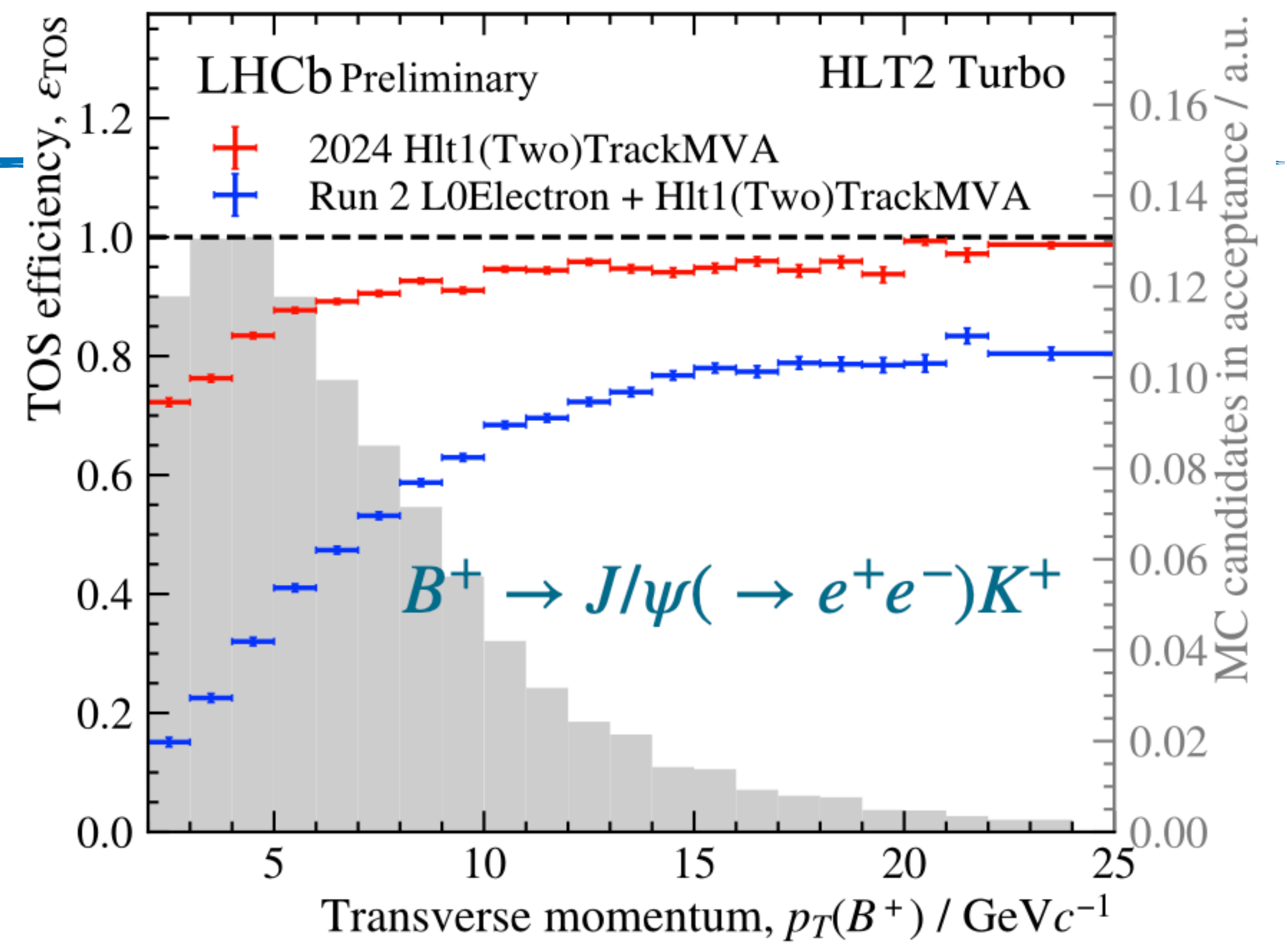
$$\mathcal{B}(B^0 \to K^{*0}\tau^-e^+) < 5.9\ (7.1) \times 10^{-6}$$

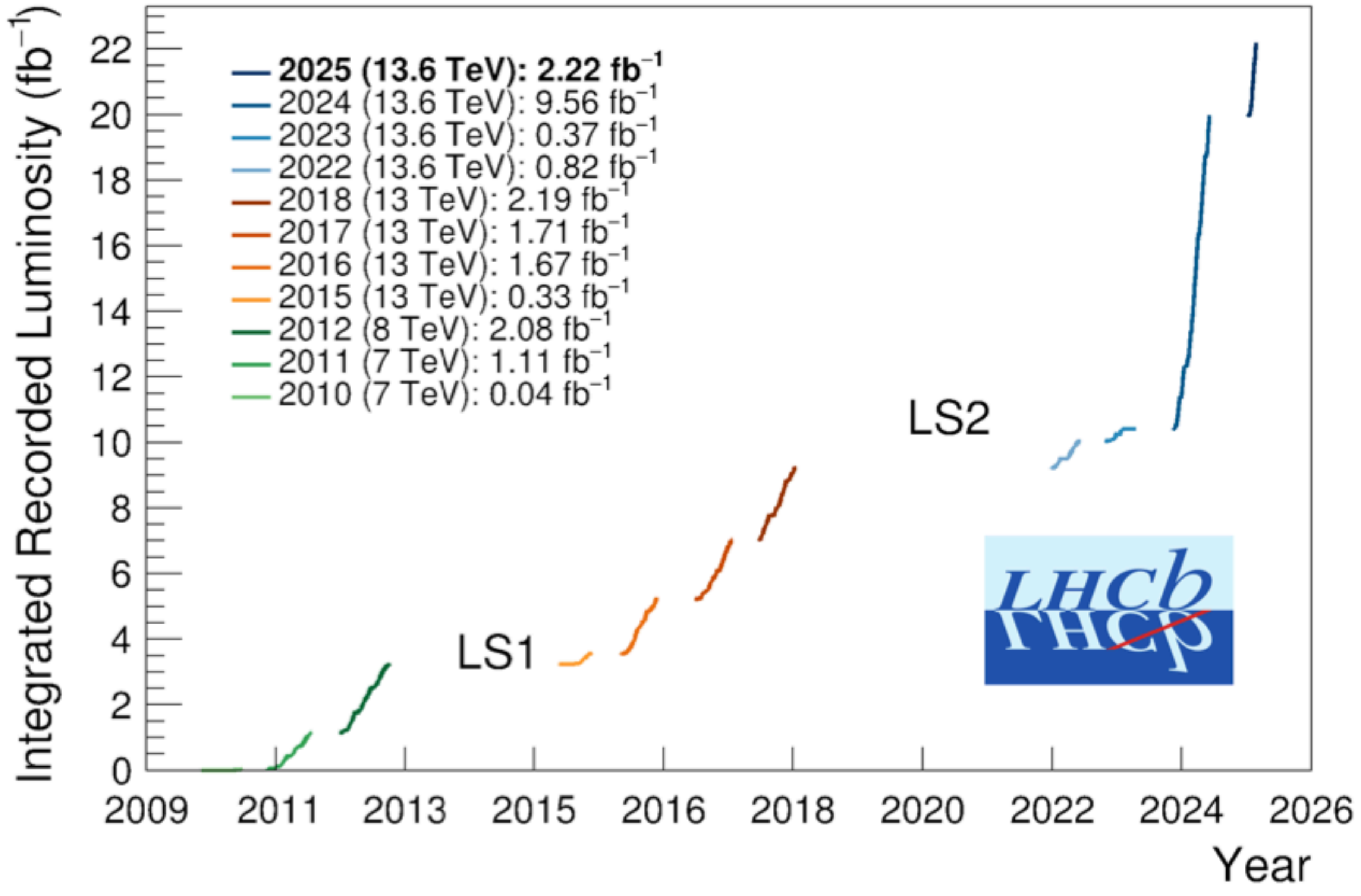
$$\mathcal{B}(B^0 \to K^{*0}\tau^+e^-) < 4.9\ (5.9) \times 10^{-6}$$

Conclusions and outlook

- Approximate and accidental symmetries offer unique opportunities to hunt for SM extensions:
  - LHCb is leading the precision measurements of observables that probe the violation of such symmetries in $b \to s\ell\ell^{(\prime)}$ transitions:
    - Pioneering LFU measurements in new modes
    - Improving LFU precision in new kinematic regions
    - Setting most stringent limits on cLFV transitions
- Already collected more than 13fb^{-1} in Run3
  - Upgraded detector with higher efficiency trigger system
    → Stay tuned for further updates!!

[LHCB-FIGURE-2024-030]





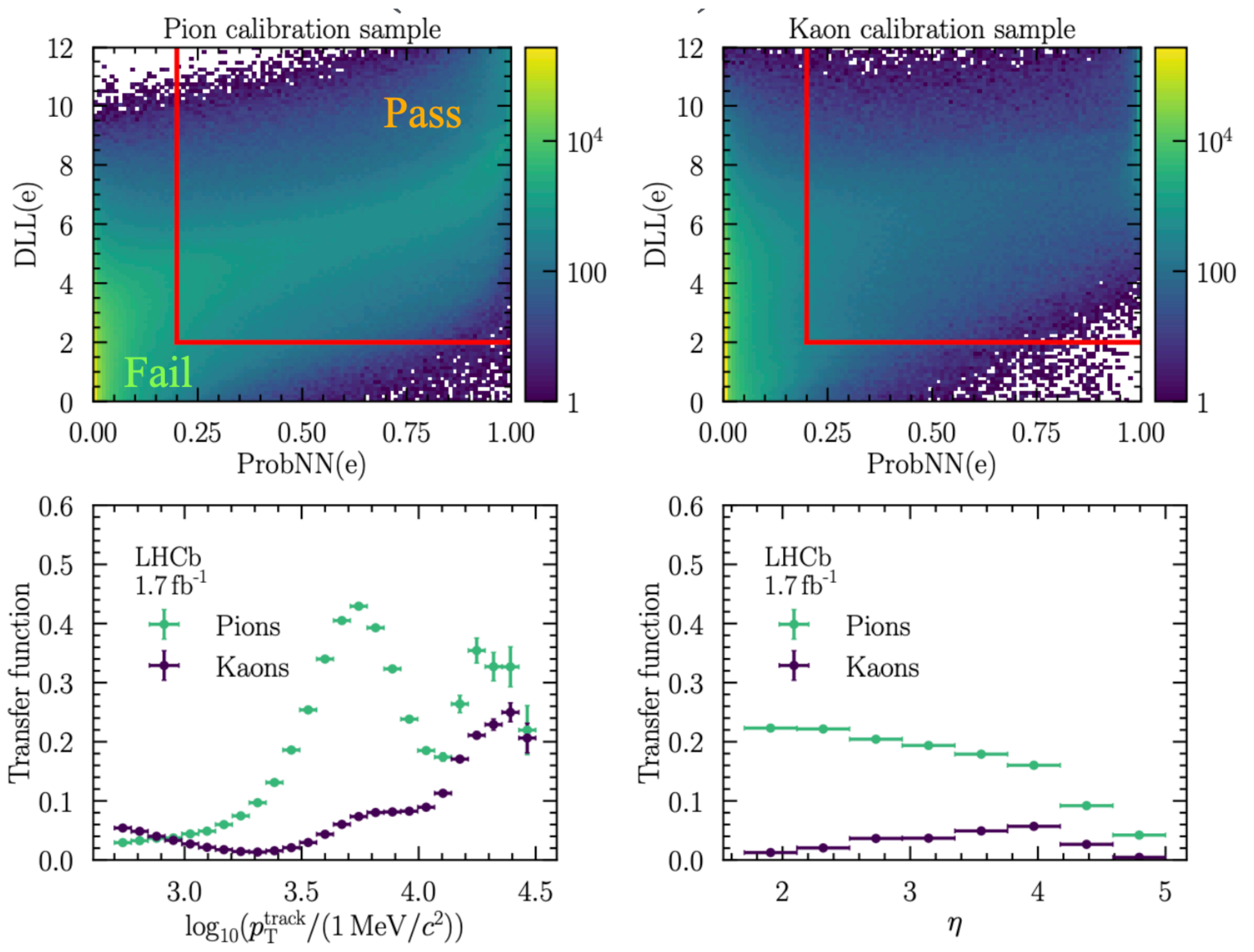
Thanks for listening!

Backup

Pass-Fail method in LFU tests

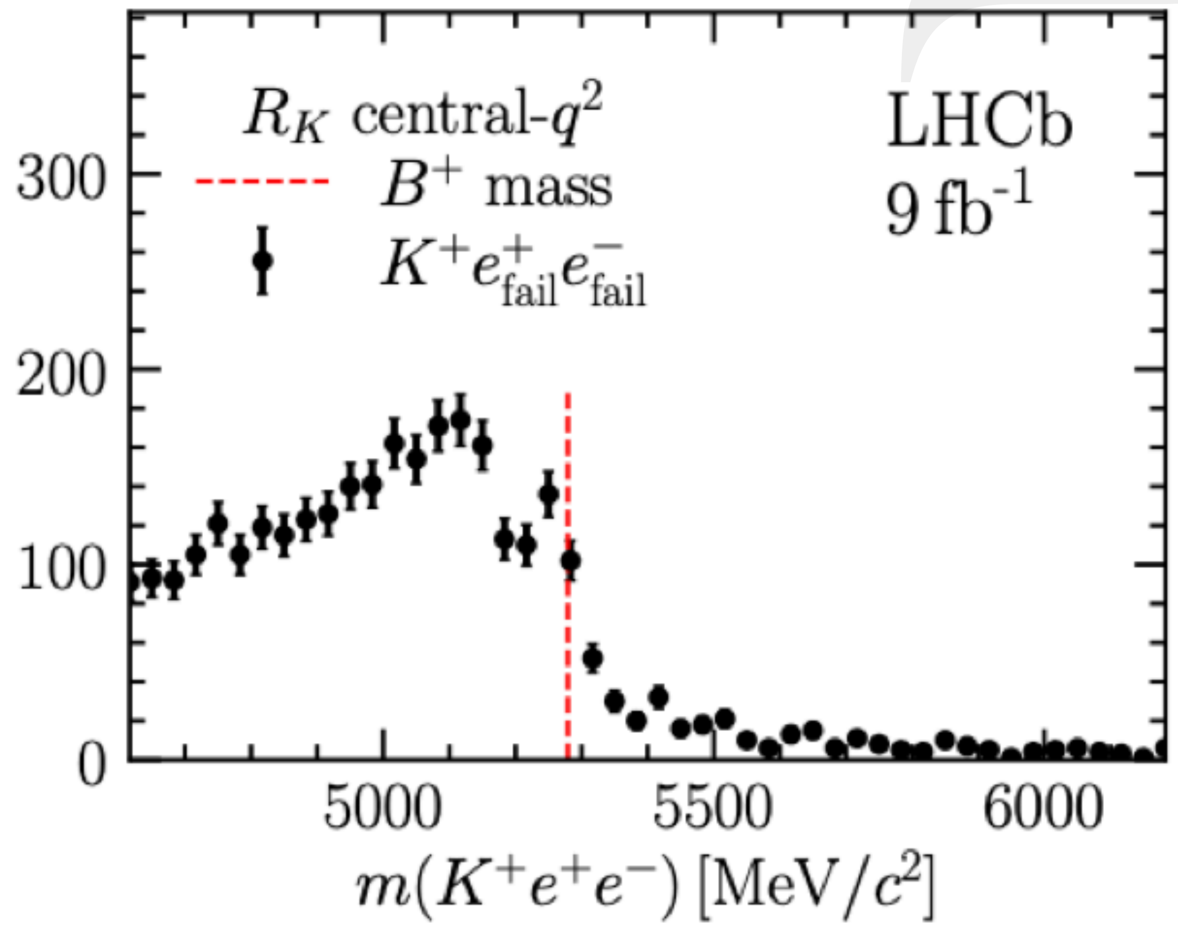
[PRD 108 (2023) 032002]
[arXiv:2505.03483]

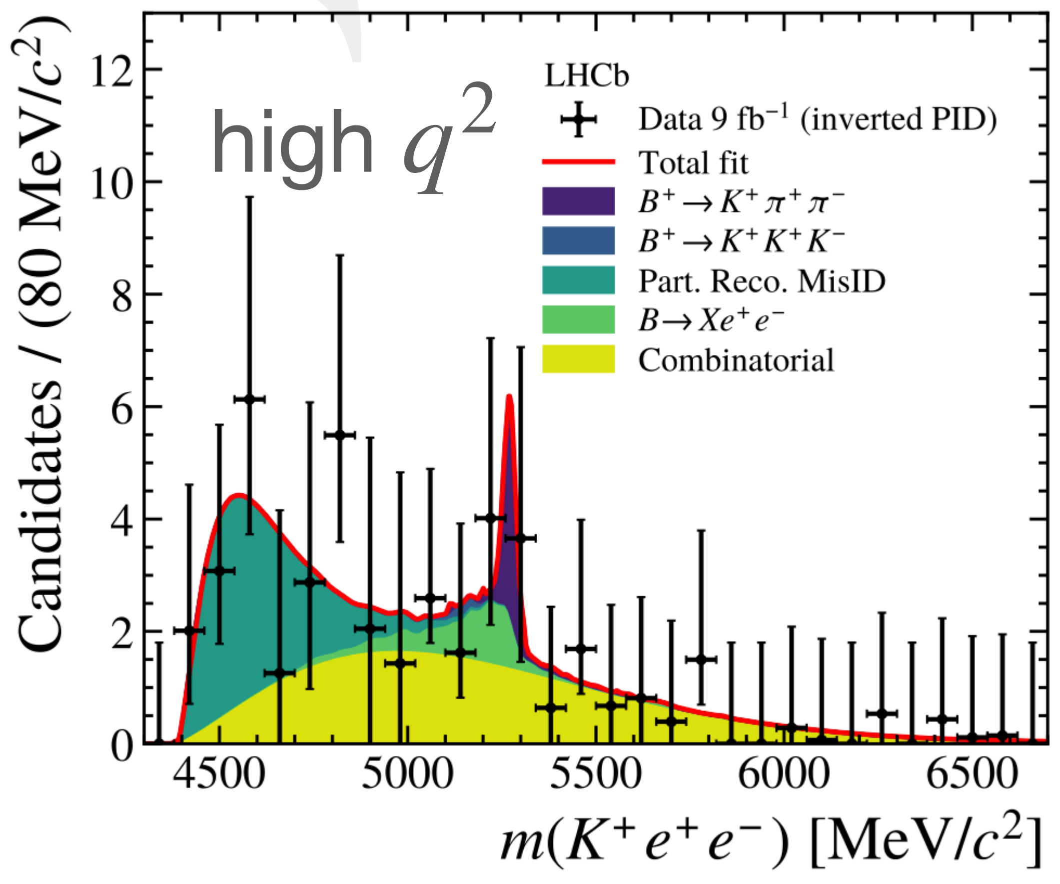
- $h \to e$ misidentification estimates using data-driven methods



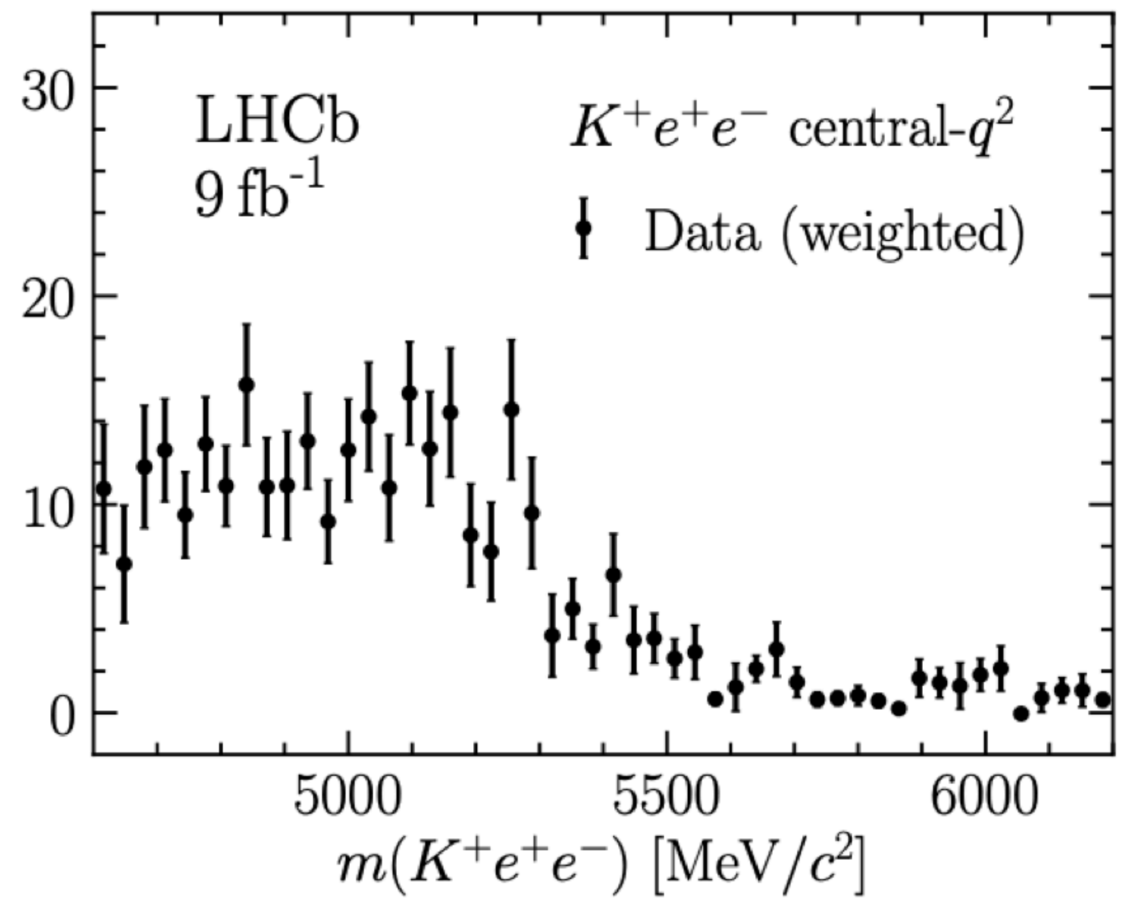
$$w = \frac{\varepsilon_{\text{pass}}}{\varepsilon_{\text{fail}}}(\eta, p_T, \text{L0})$$

Inverted PID control regions





Weights from PID calib. samples are used to transfer the inverted PID data to nominal region

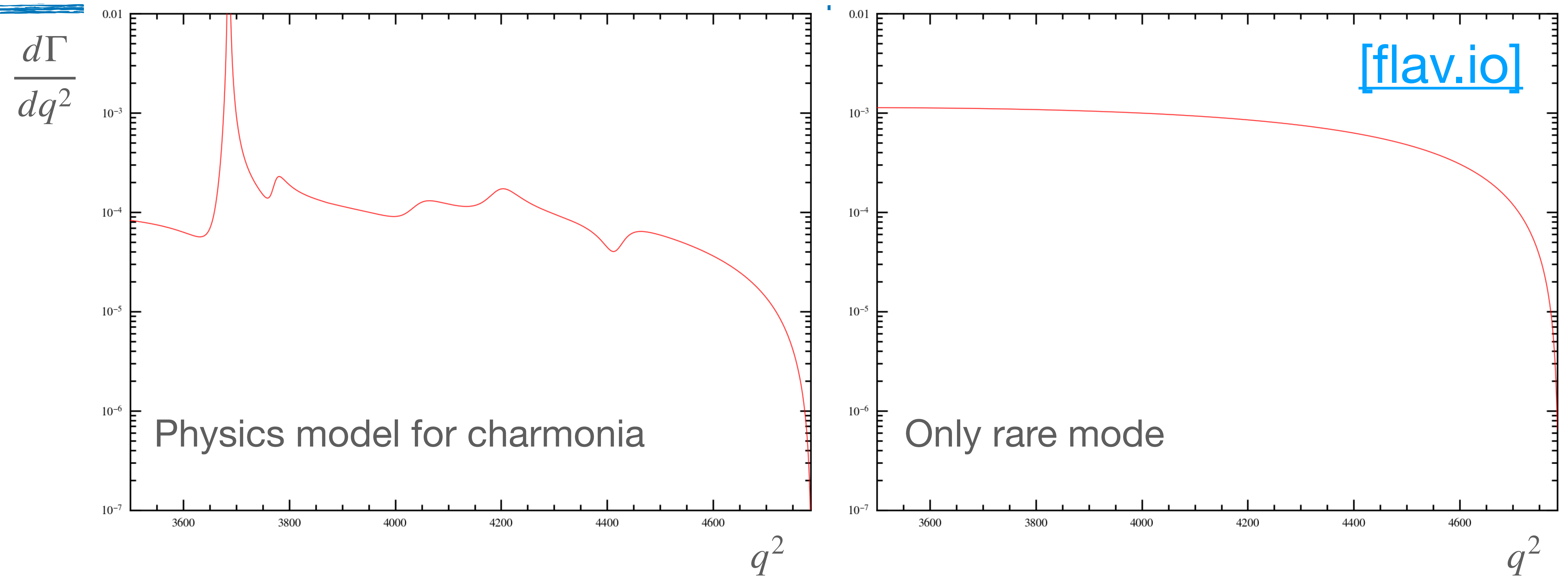


R_K at high q^2: model independence

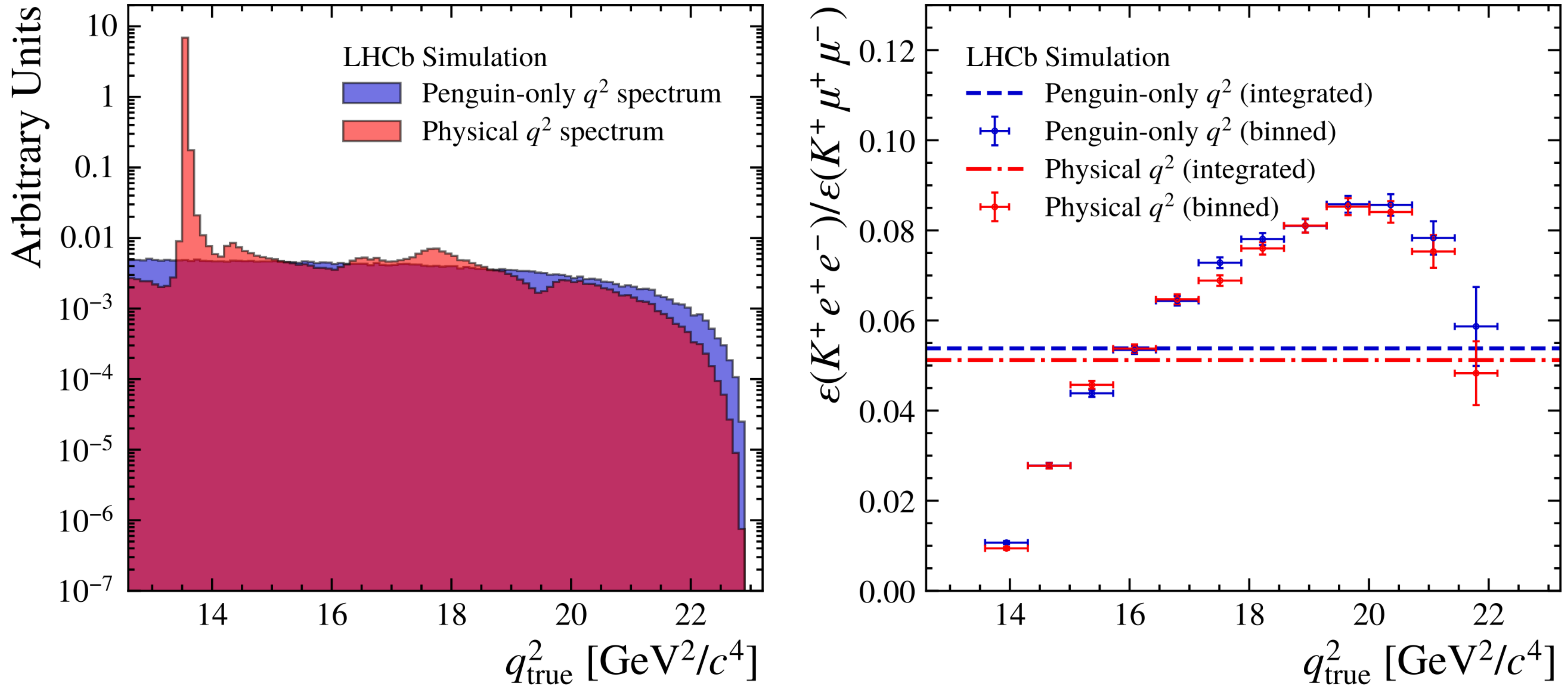
[arXiv:2505.03483]

- At high q^2 presence of multiple wide charm resonances as well as open charm
- Assumed q^2 distribution introduces model dependence when computing integrated efficiencies for $q^2_{\text{noBrem}} > 14.3\ \text{GeV}^2$

(two extreme cases →)



- Use of q^2_{noBrem} cut yields different $\varepsilon(q^2_{\text{true}})$ for electrons and muons → inaccuracies in the q^2 dependence of model will induce a bias on R_K
- Remove model dependence by weighting muon data and MC to have same $\varepsilon(q^2_{\text{true}})$ as electrons*
- R_K no longer extracted as simultaneous fit to both electron and muon data

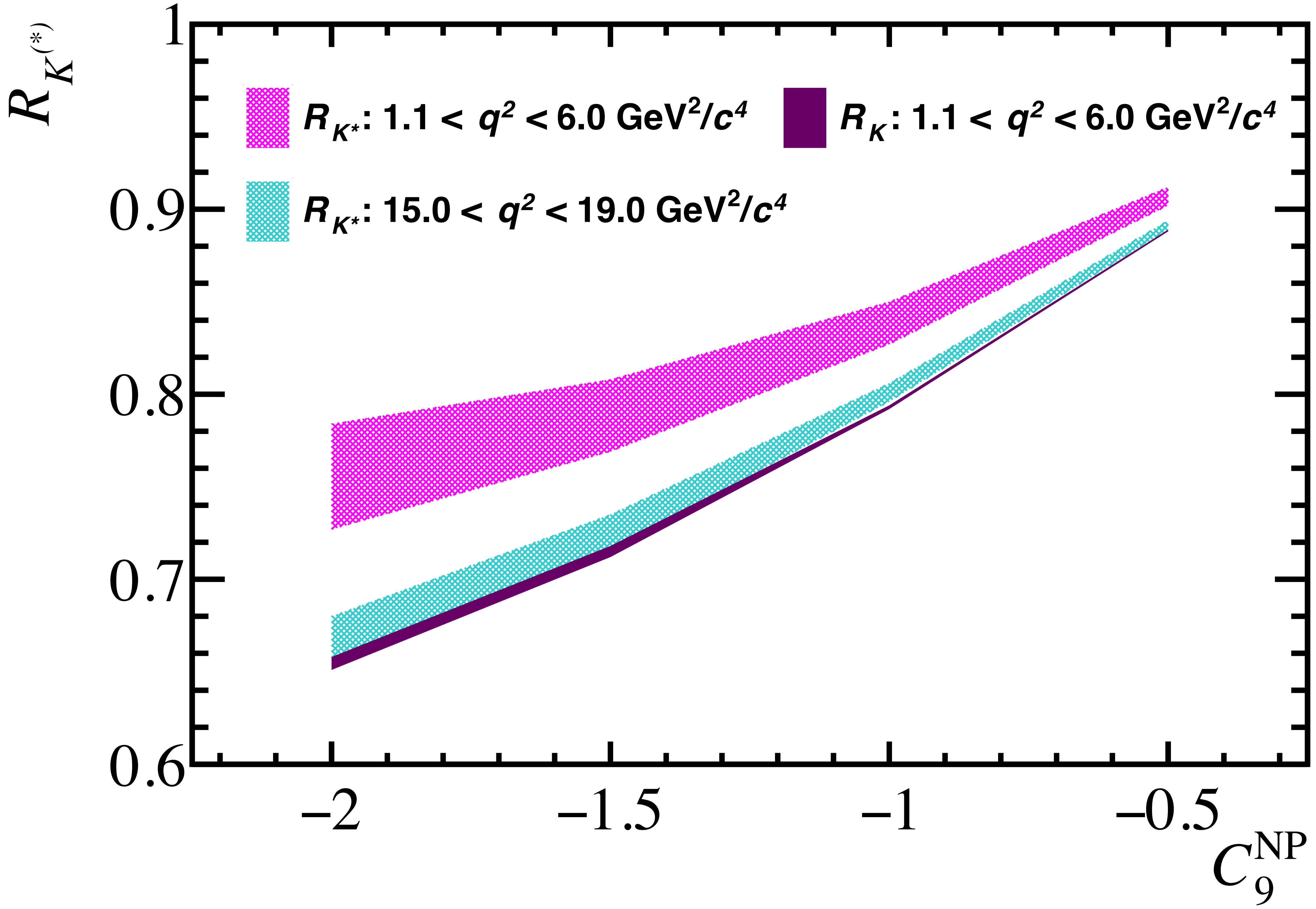


* Requires two assumptions: $q^2_{\text{true}} = q^2_{\text{reco}}$ in muons and the $(p_B - p_K)^2 = q^2_{\text{true}}$ distribution in SM is LFU

R_K sensitivity to NP at high q^2

[arXiv:1709.03921]

- Presence of charmonium resonances at high q^2 doesn't dilute the NP sensitivity of R_K in this kinematic region
- Higher charmonium states have sizeable interference with the rare mode which can be LFU violating
- Error bands on R_K are obtained using the measured non local contributions in $B^+ \to K^+\mu^+\mu^-$



R_K values at low recoil are same as at high recoil

Improving B^0 mass resolution with m_{fit}

[arXiv:2506.15347]

- ν_τ not reconstructed, π^0 is ignored during reconstruction: poor resolution of B^0 invariant mass
- Kinematic fit to calculate B^0 invariant mass obtained by reconstructing the entire decay chain constraining:
  - Three tracks from pions originate from τ vertex
  - τ candidate mass is constrained to known mass
  - τ is required to point to the B^0 vertex which is reconstructed from charged decay products of K^{*0}