Lepton universality tests in B decays

FCCP 2025

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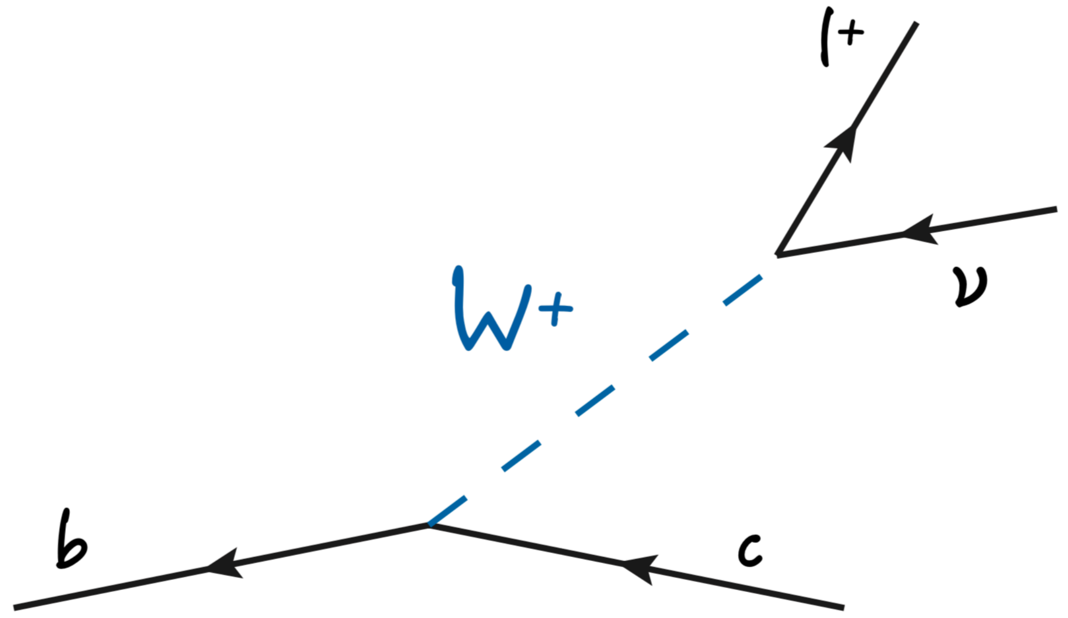
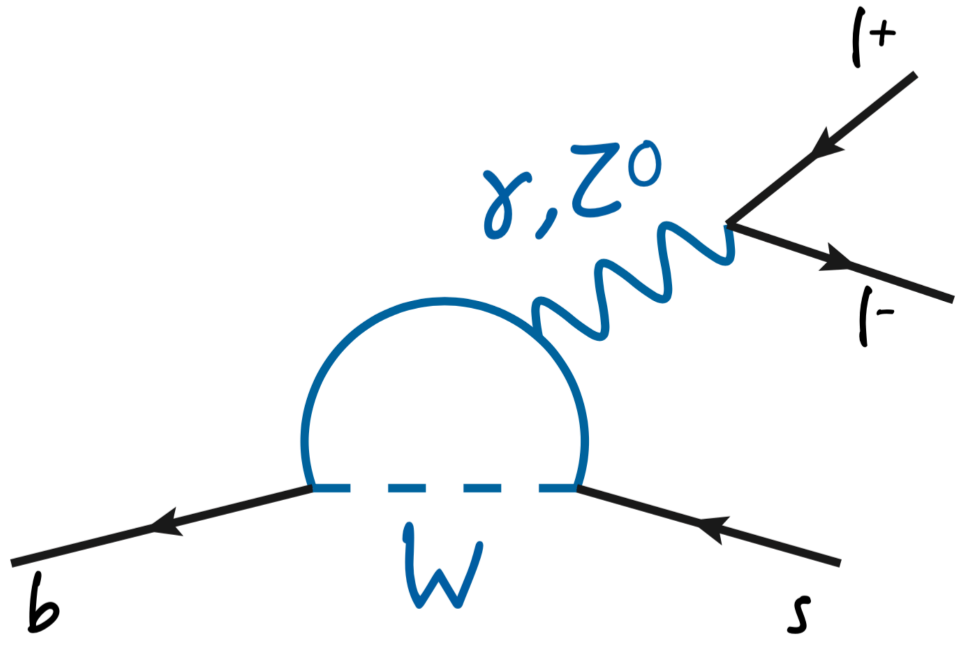
Lepton Flavour Universality

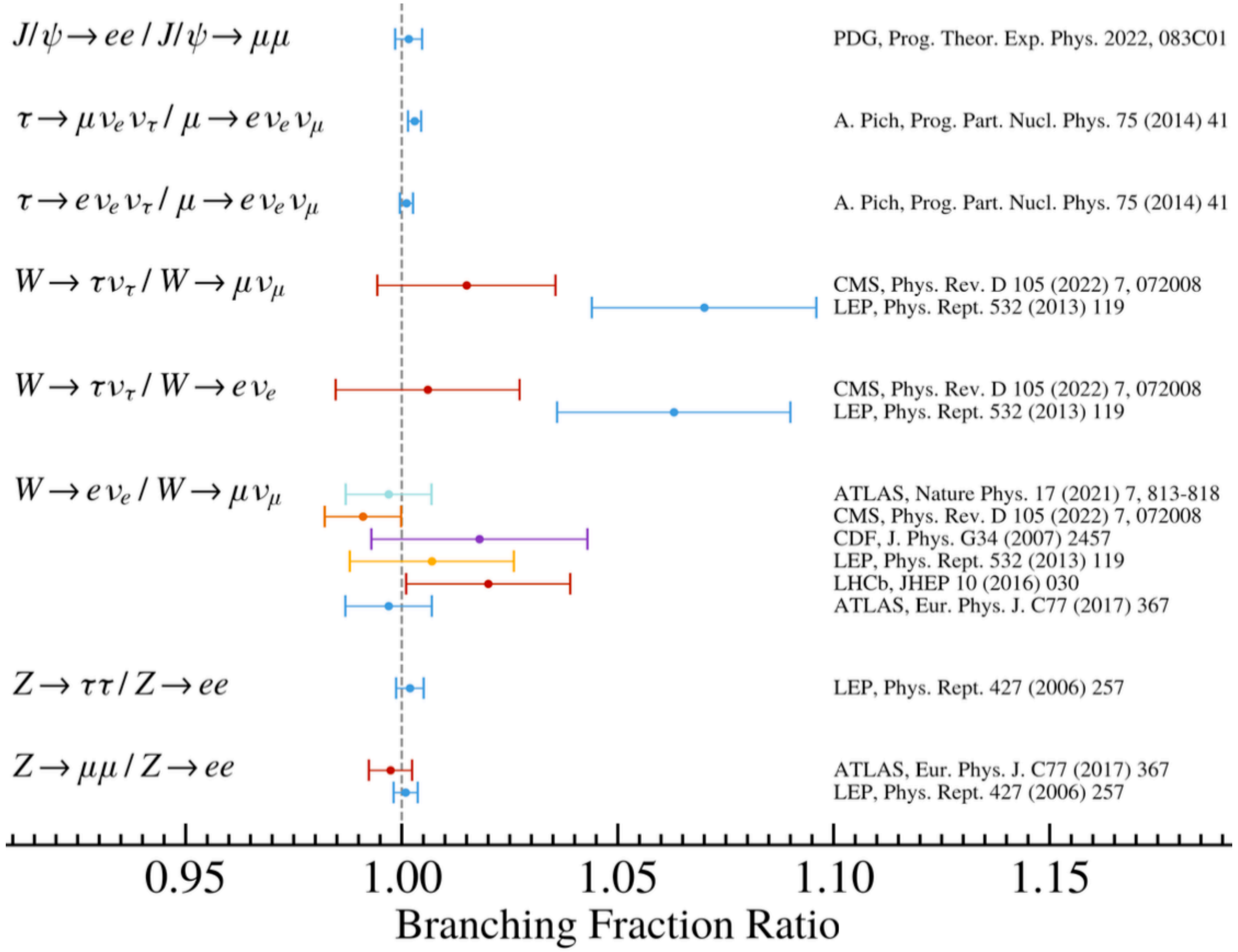
- In the Standard Model the couplings of the gauge bosons are lepton universal ⇒ provides a clean probe for New Physics



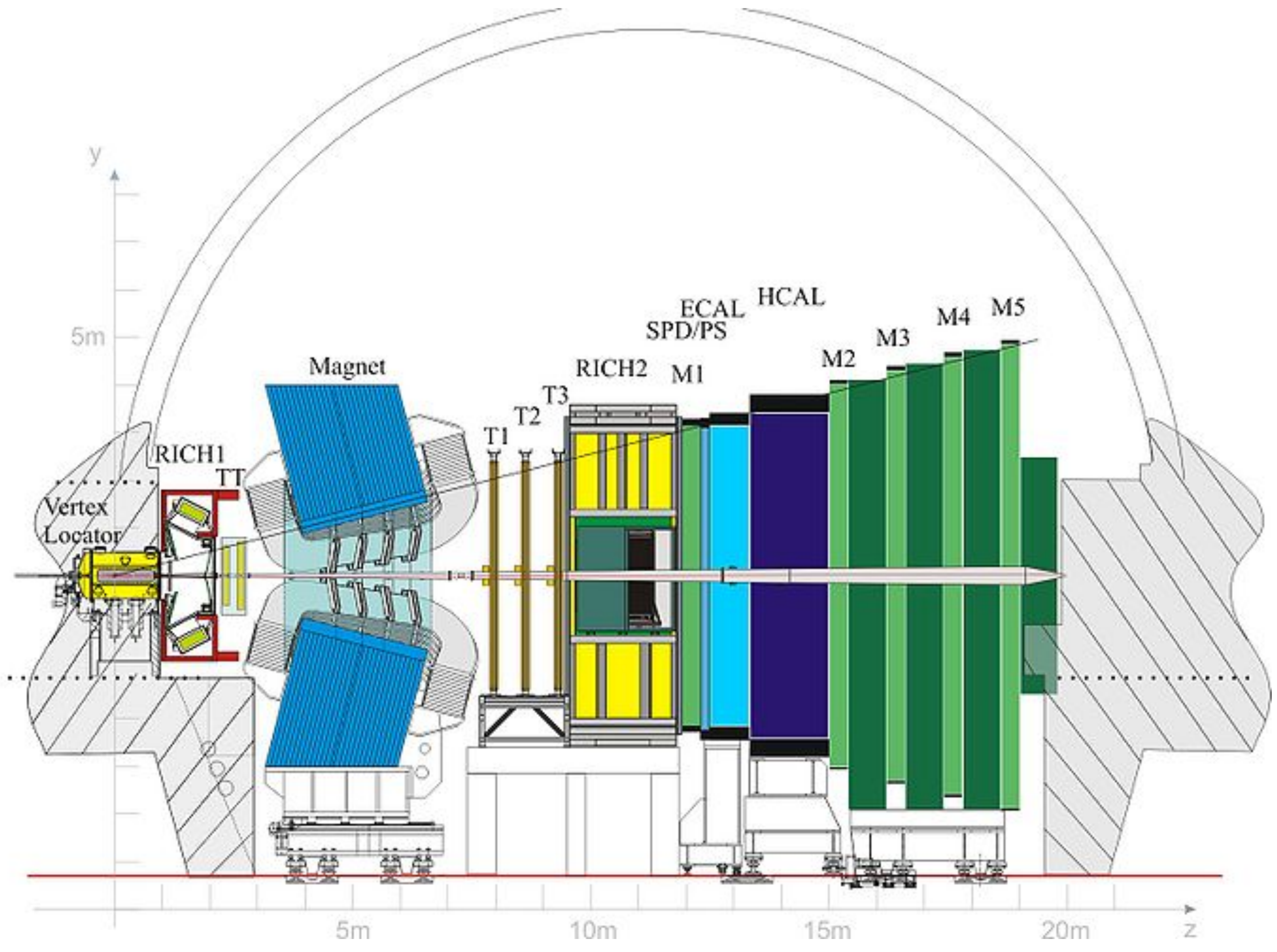
- Tests in **B-meson decays**
  - Flavour Changing Charged Current
    b→cℓν decays (tree-level)
    $B^{0,+} \to D^{(*)+,0}\ell\nu_\ell, \Lambda_b \to \Lambda_c\ell\nu_\ell, \ldots$



  - Flavour Changing Neutral Current
    b→sℓℓ transitions (loop-level)
    $B^{+,0} \to K^{+,0}\ell\ell, B^0_s \to \phi\ell\ell, \ldots$



The LHCb detector



[JINST 3 (2008) S08005]

- General purpose detector in the forward direction [flavour, EW, QCD, heavy ions…]
- Large $b\bar{b}$ and $c\bar{c}$ production at the LHC
  - 25% of the total $pp \to b\bar{b}$ cross-section in the LHCb acceptance
- Excellent tracking, vertexing and PID capabilities
  - Versatile and efficient trigger
- Three runs of data taking so far
  - Run 1 (2010 -12), Run 2 (2015 - 2018) ➝ 9/fb
  - LHCb upgrade, Run 3 (2022 - 2026) ➝ 25/fb

Neutral currents

$b \to s(d)\ \ell^+ \ell^-$ decays

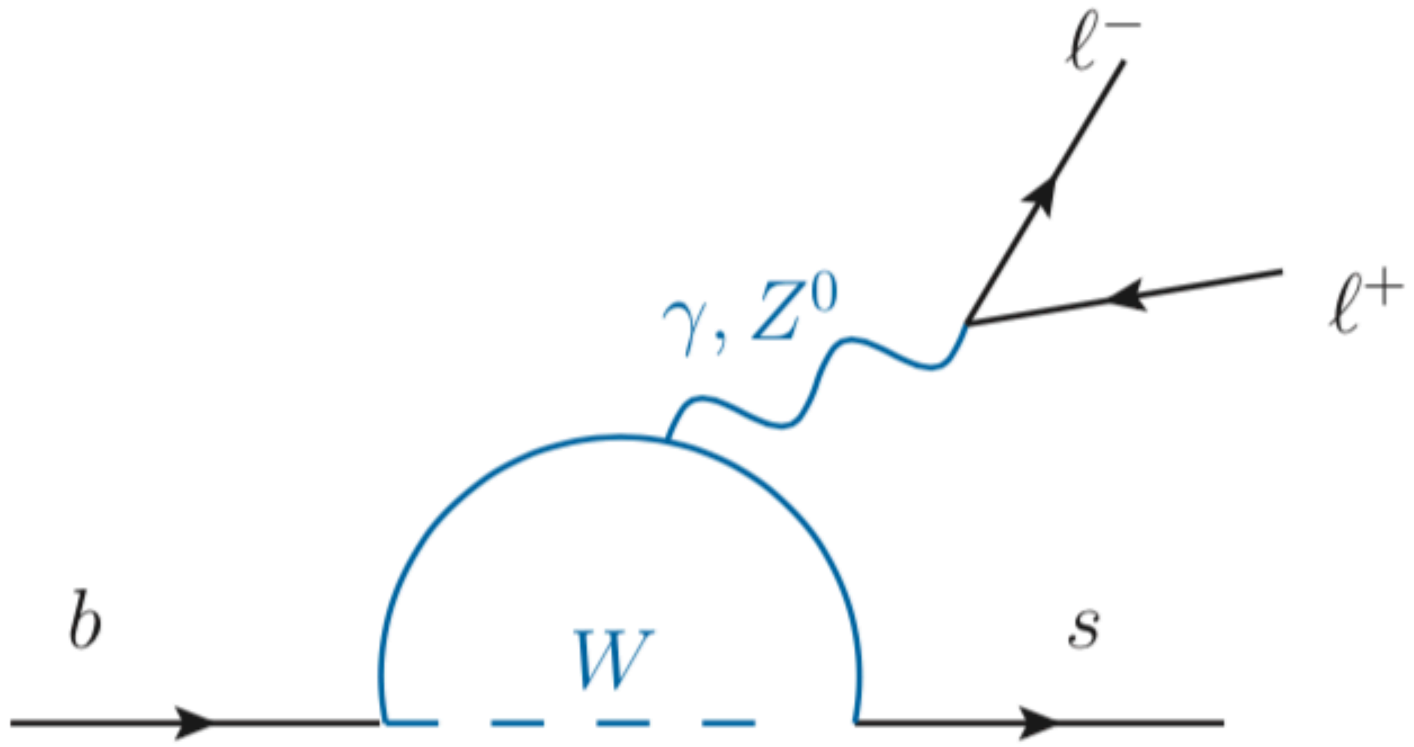
Suppressed in the SM

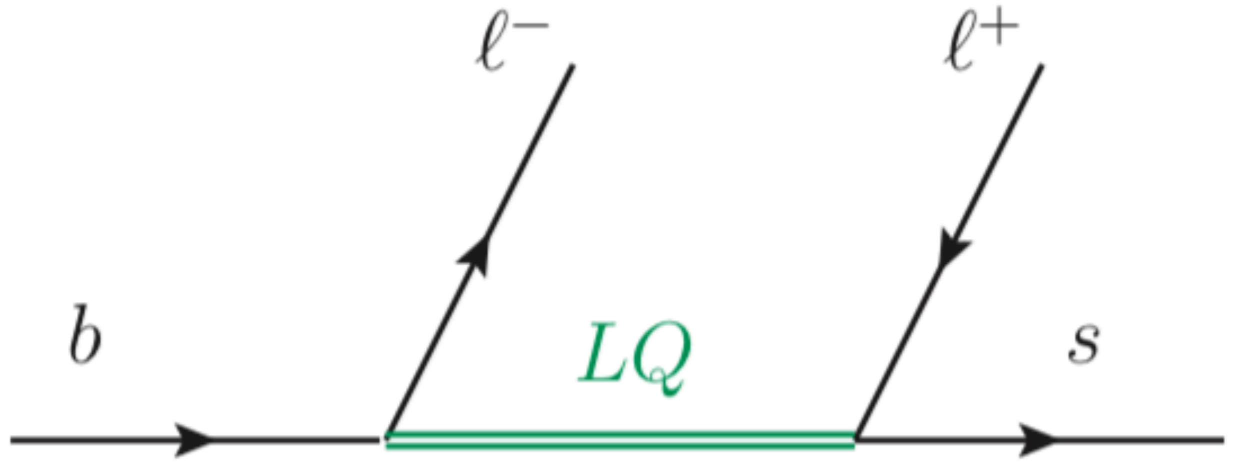
- Effects of new physics can be relatively large
- Access high mass scales, due to virtual contributions

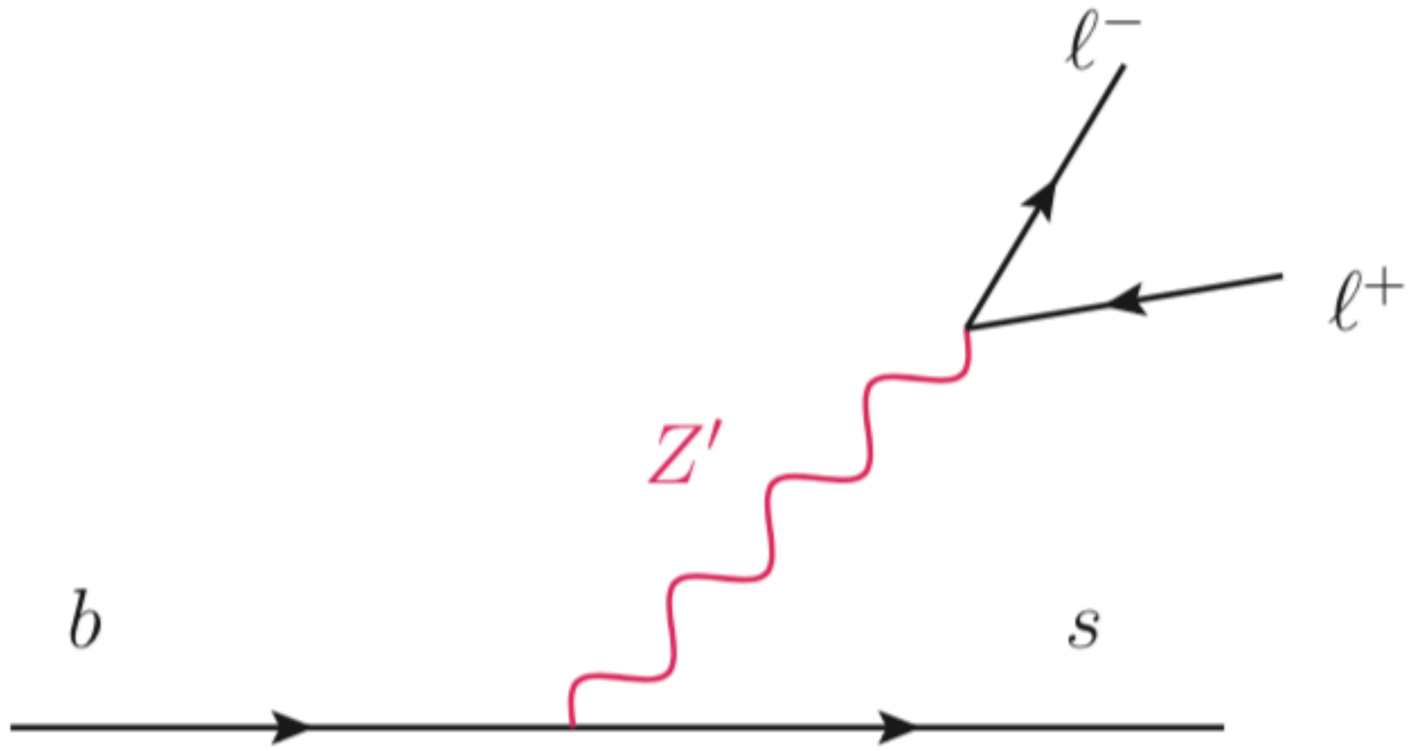
FCNC transitions, such as $b \to s(d)\ell\ell$ decays, are excellent candidates for indirect NP searches

Rare *B* decays offer rich phenomenology:

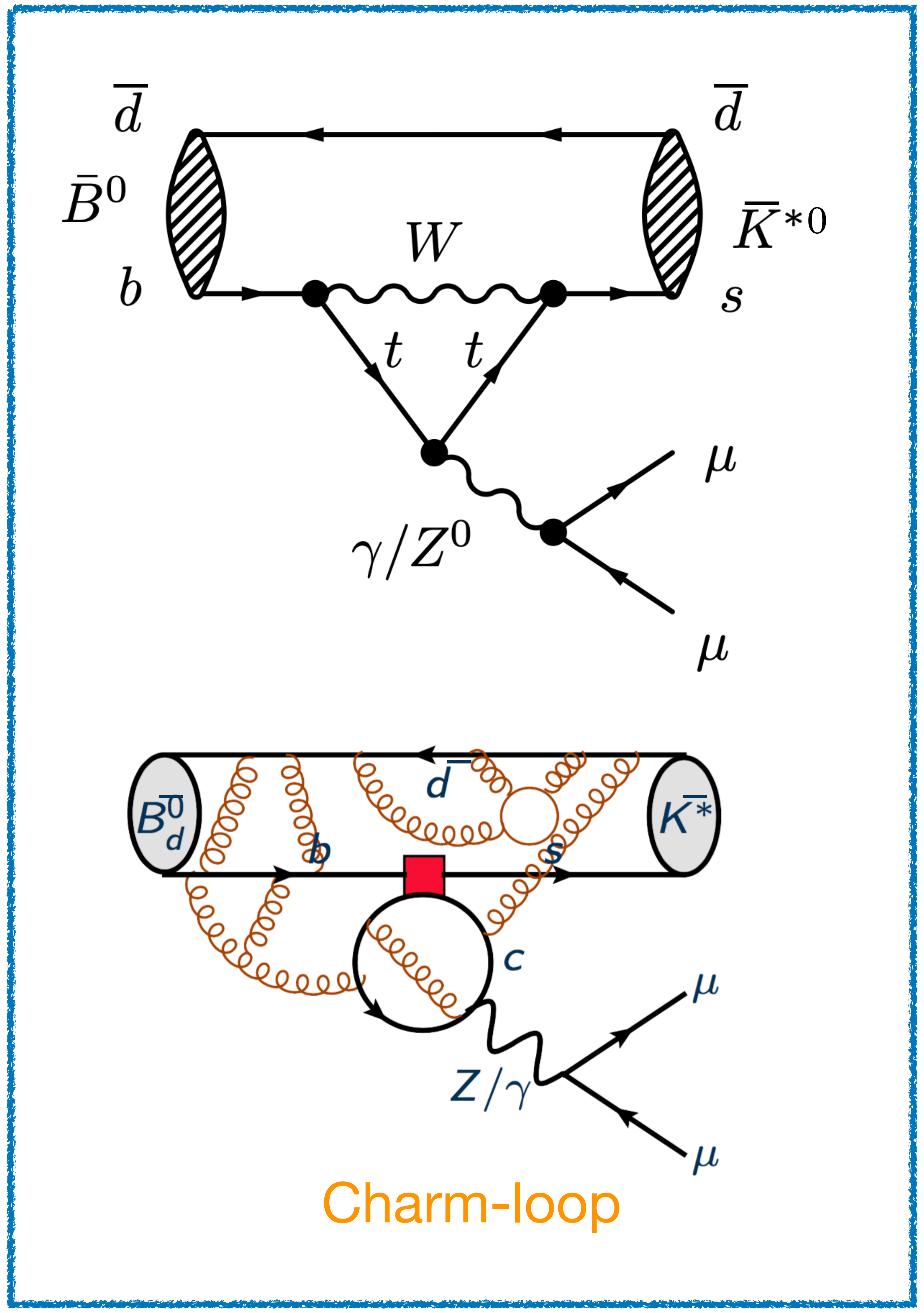
- Branching ratios, angular observables, LFU ratios…

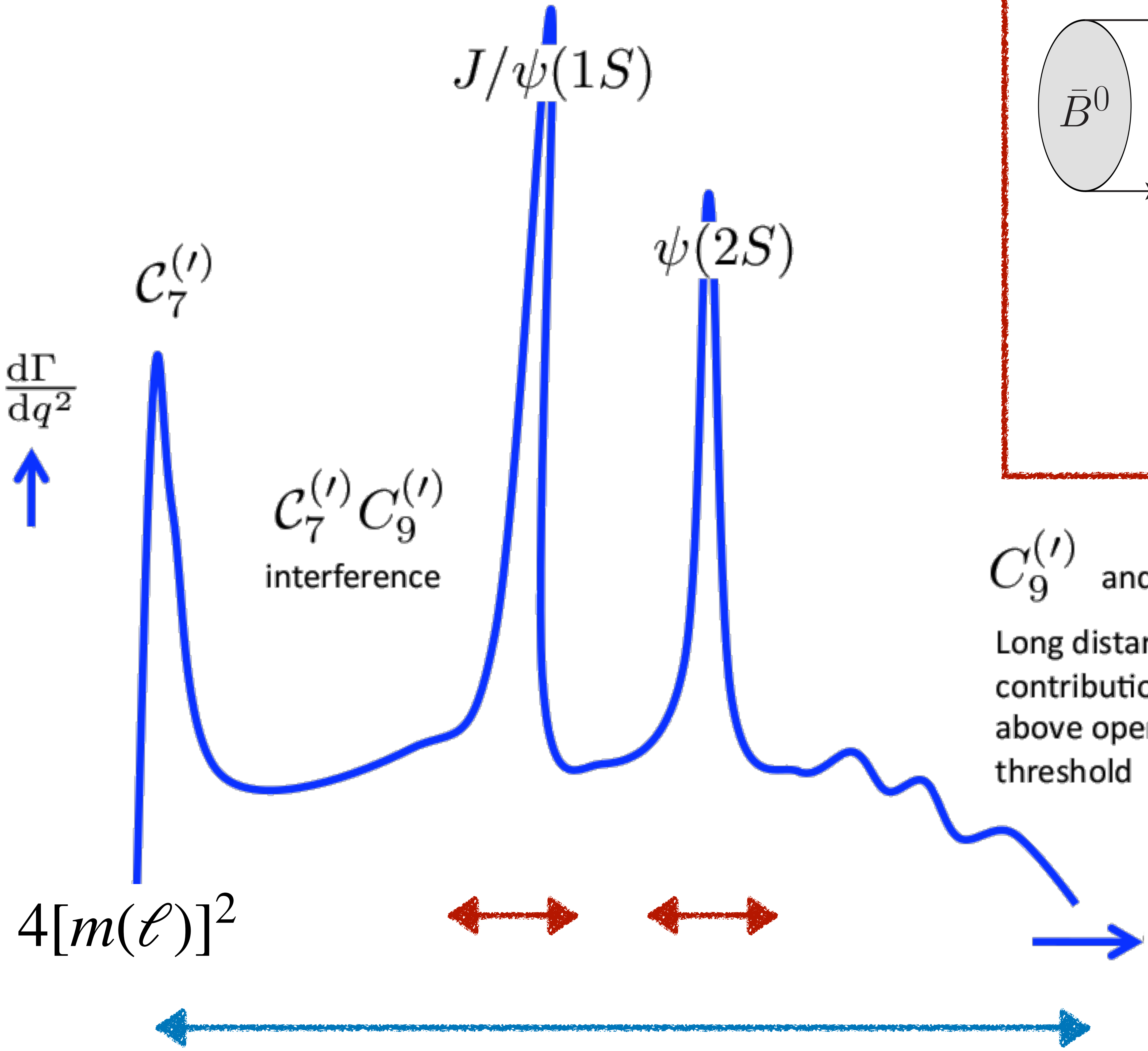


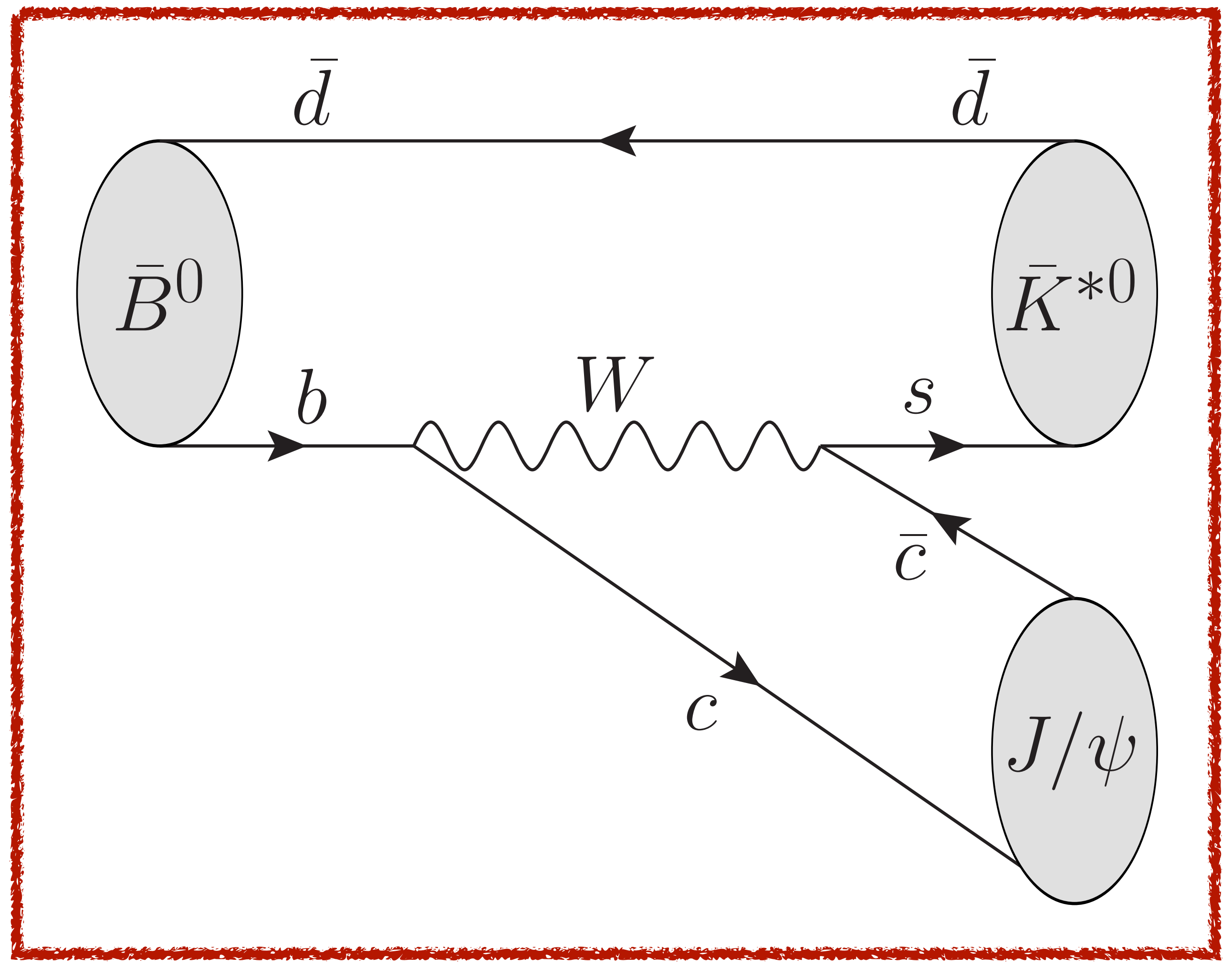




The di-lepton spectrum







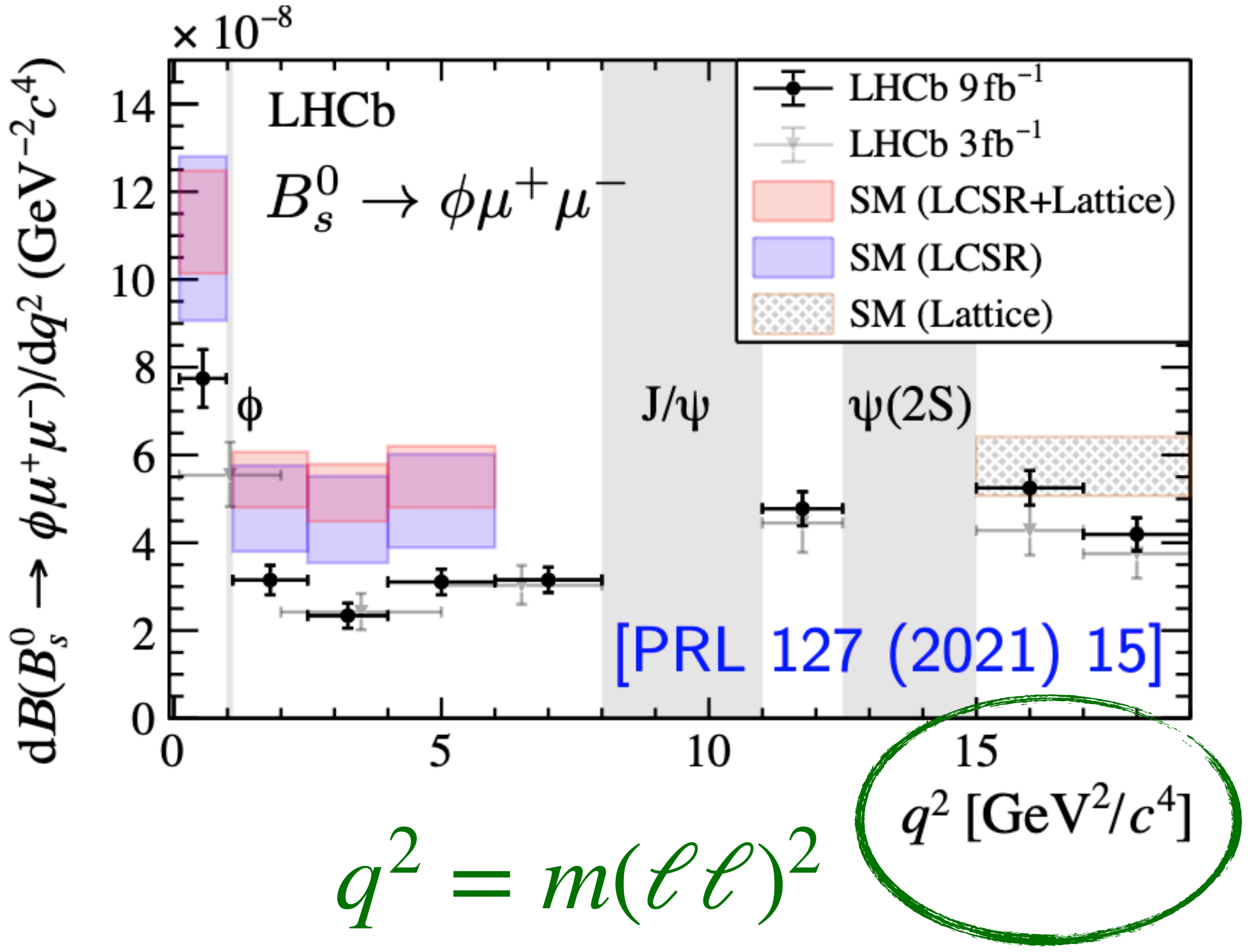
$C_9^{(\prime)}$ and $C_{10}^{(\prime)}$

Long distance contributions from $c\bar{c}$ above open charm threshold

$b \to s\ \mu^+ \mu^-$ anomalies

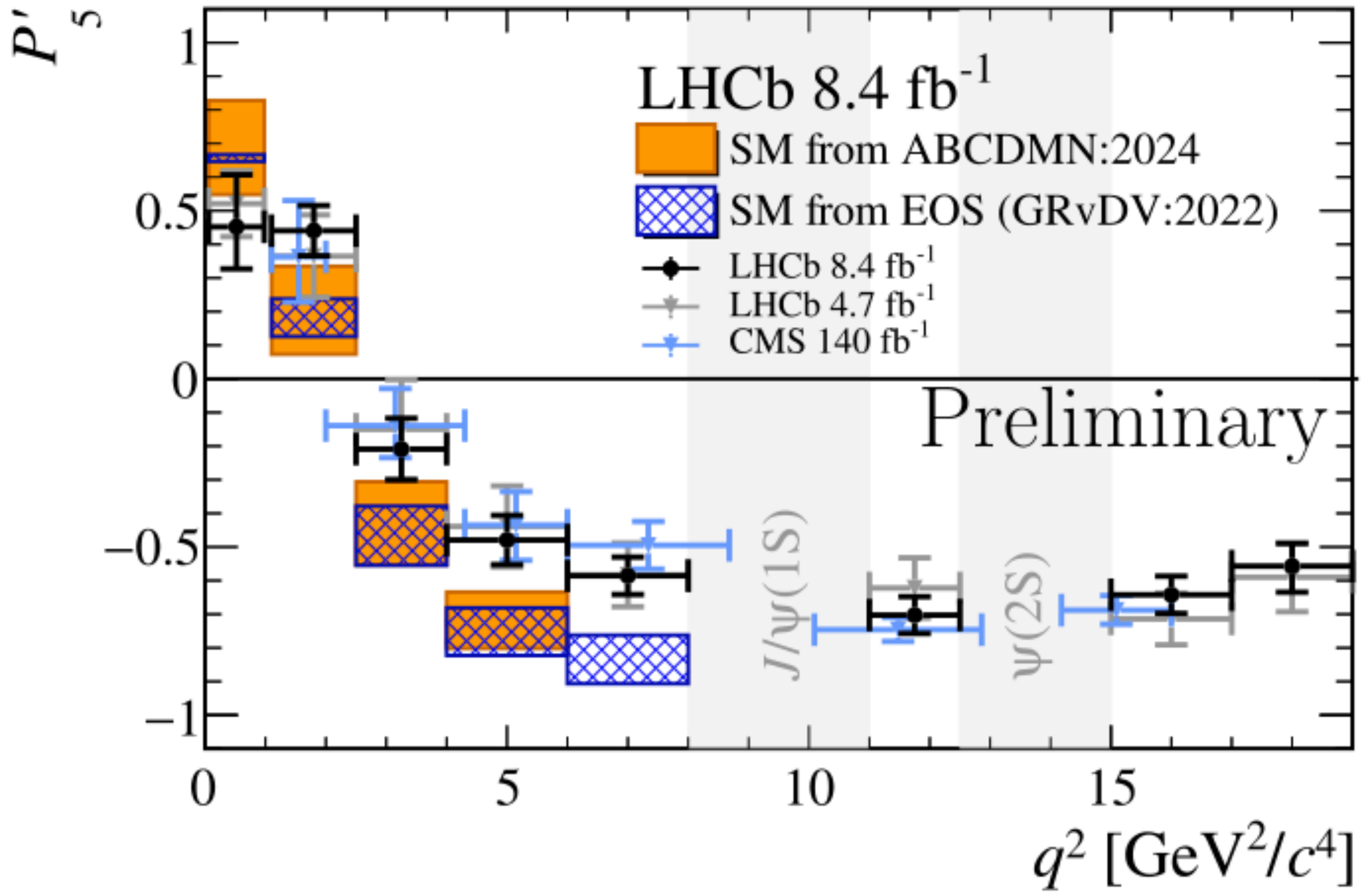
[arxiv: 2309.01311]

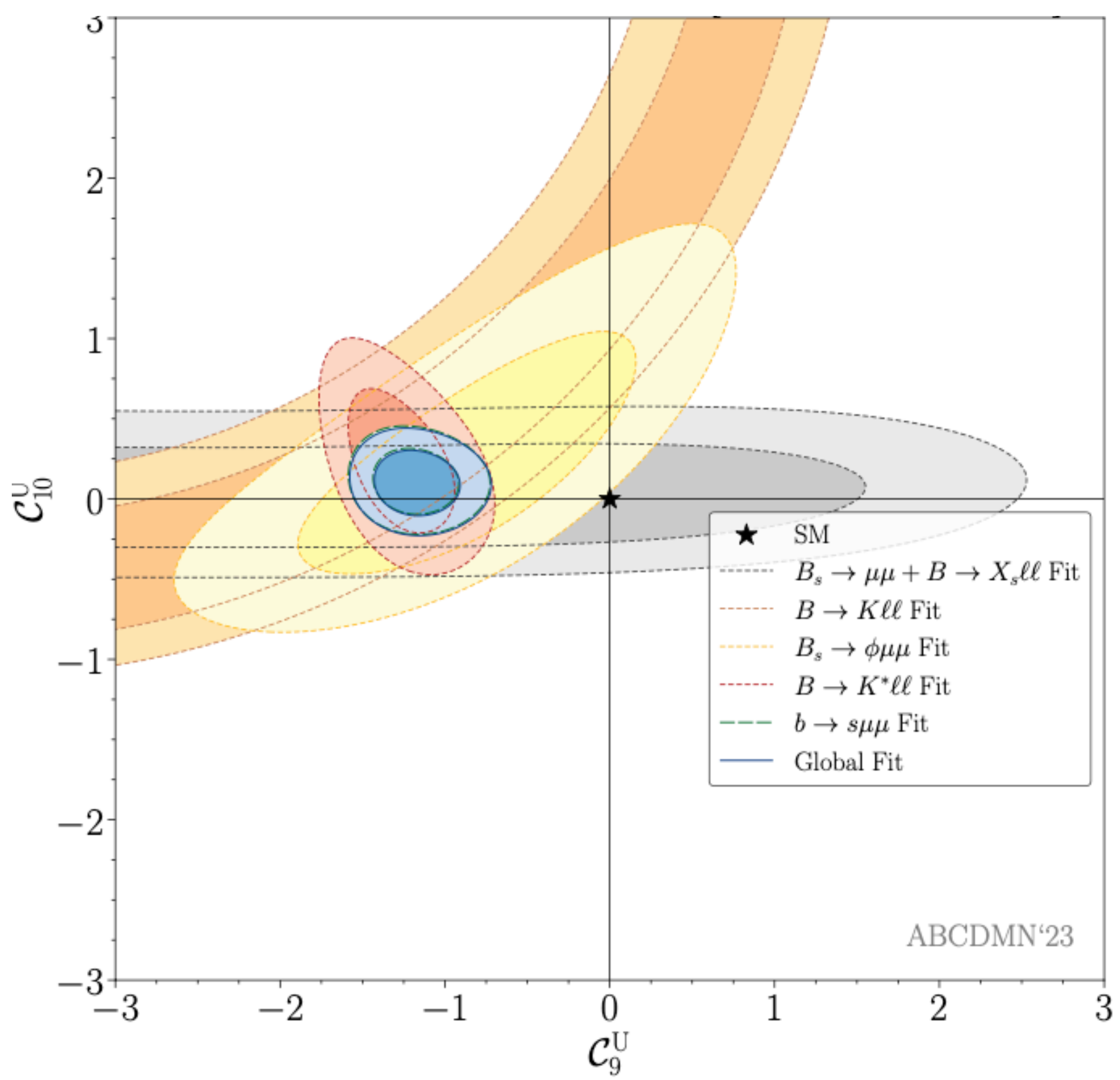
$B_s^0 \to \phi\mu\mu$



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

$B^0 \to K^{*0}\mu\mu$



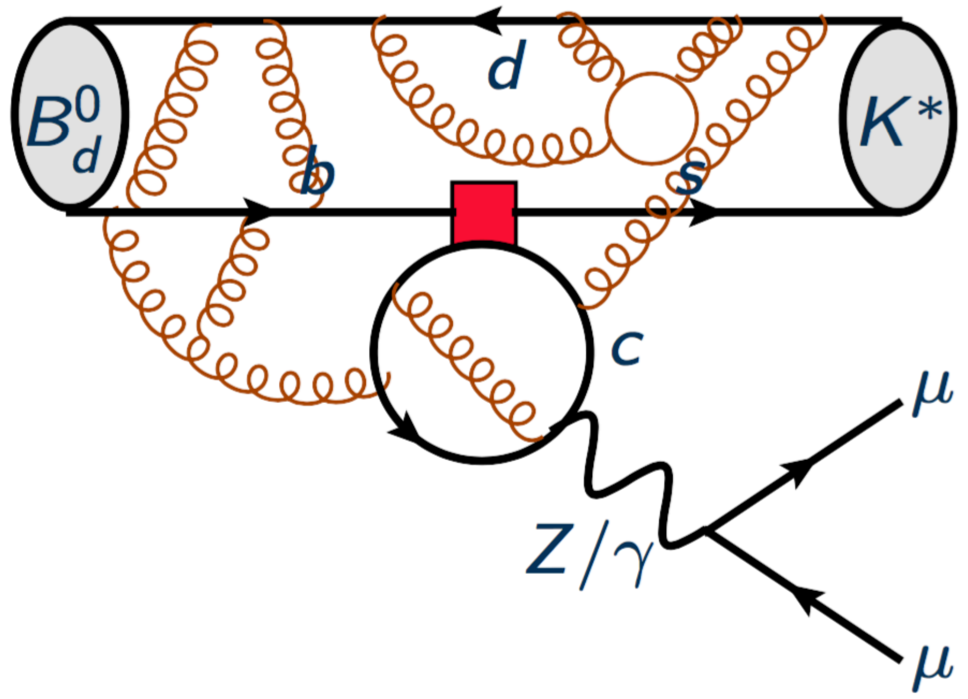


Set of anomalies observed in multiple measurement of b→sμμ decays

Global fits to all these observables in terms of Effective Field Theories, point point to a **non-SM vector coupling** (C_9)

Could unexpectedly large long-distance hadronic contributions (cc-loops) mimic this effect?

See Martino Borsato's talk later for more details



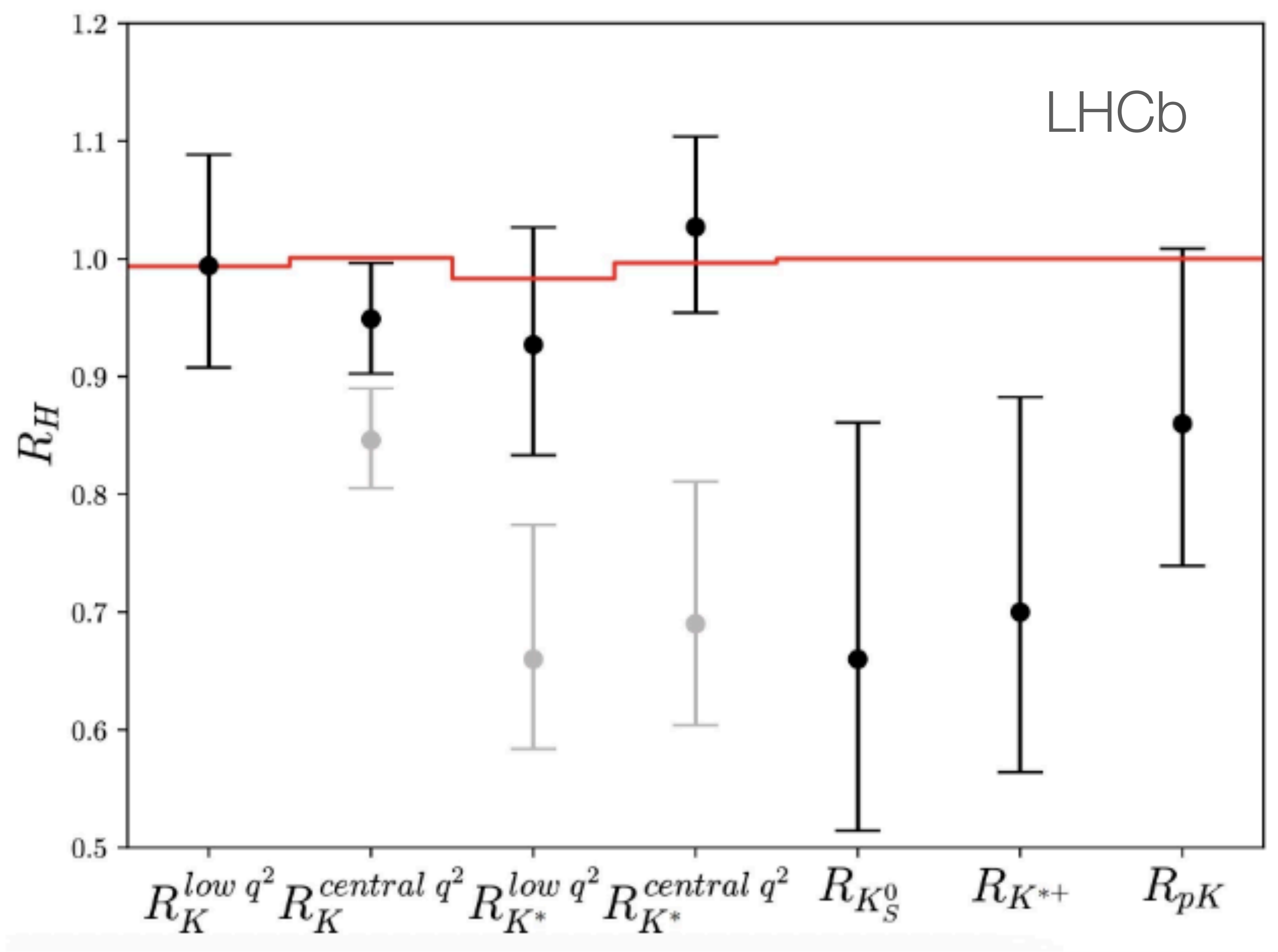
LFU tests in $b \to s \ell^+ \ell^-$

[Phys.Rev.D 108 (2023) 3, 032002]
[Nature Physics volume 19, page1517 (2023)]
[JHEP 05 (2020) 040]
[Phys.Rev.Lett. 128 (2022) 19, 191802]
[JHEP 08 (2017) 055]

$B^{+,0}$, B_S, Λ_b — $K, K^*, \phi, pK \ldots$

$$R_{H_s} = \frac{\int \frac{\mathrm{d}\Gamma(B \to H_s \mu^+ \mu^-)}{\mathrm{d}q^2} \mathrm{d}q^2}{\int \frac{\mathrm{d}\Gamma(B \to H_s e^+ e^-)}{\mathrm{d}q^2} \mathrm{d}q^2} \overset{SM}{\cong} 1$$

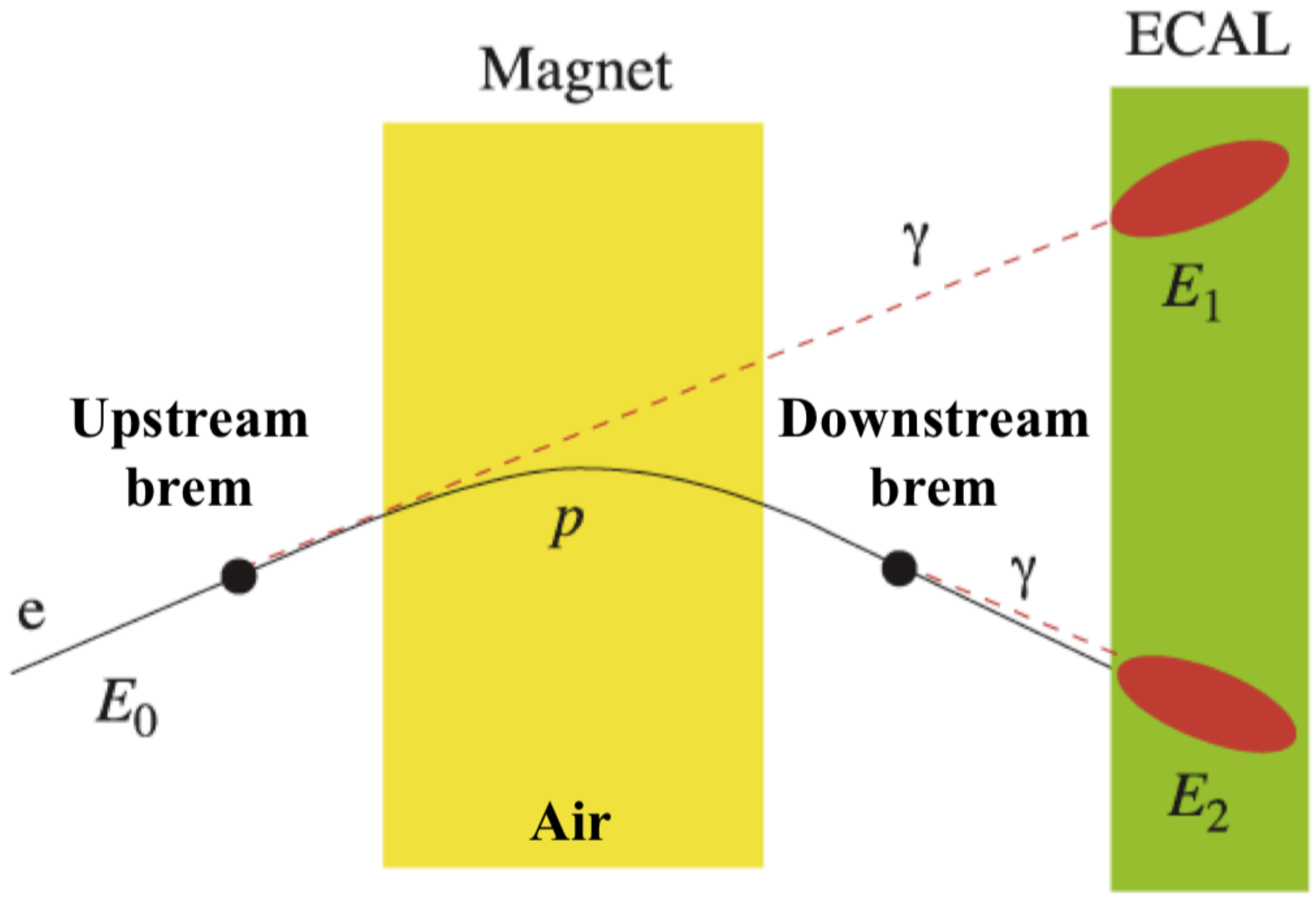
Picture at the start of 2024



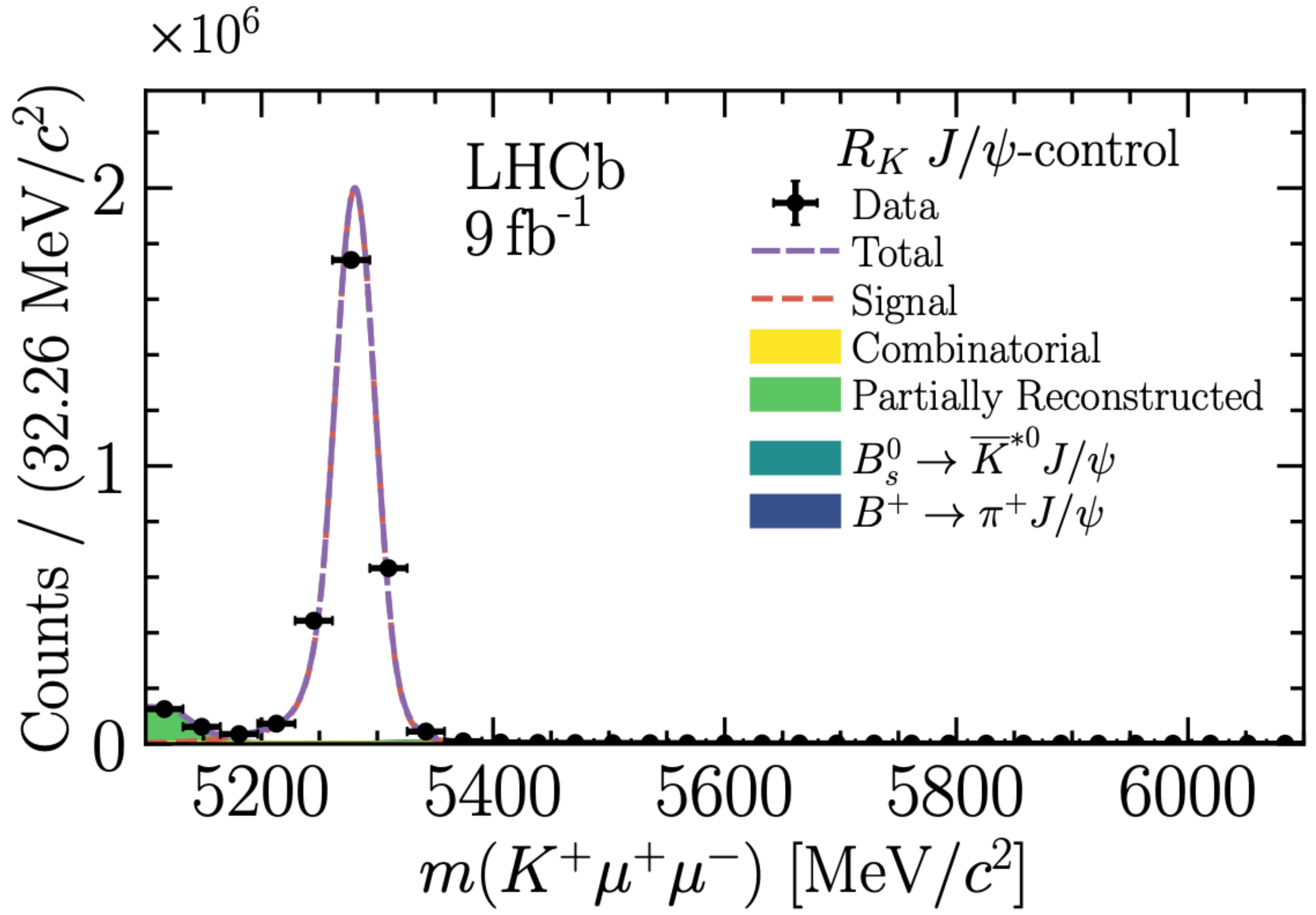
- Ratios of muons/electrons are extremely well predicted in the SM
  - Hadronic uncertainties of O(10-4)
  - QED uncertainties can be O(10-2)
- Any statistically significant deviation from 1 is a sign of New Physics

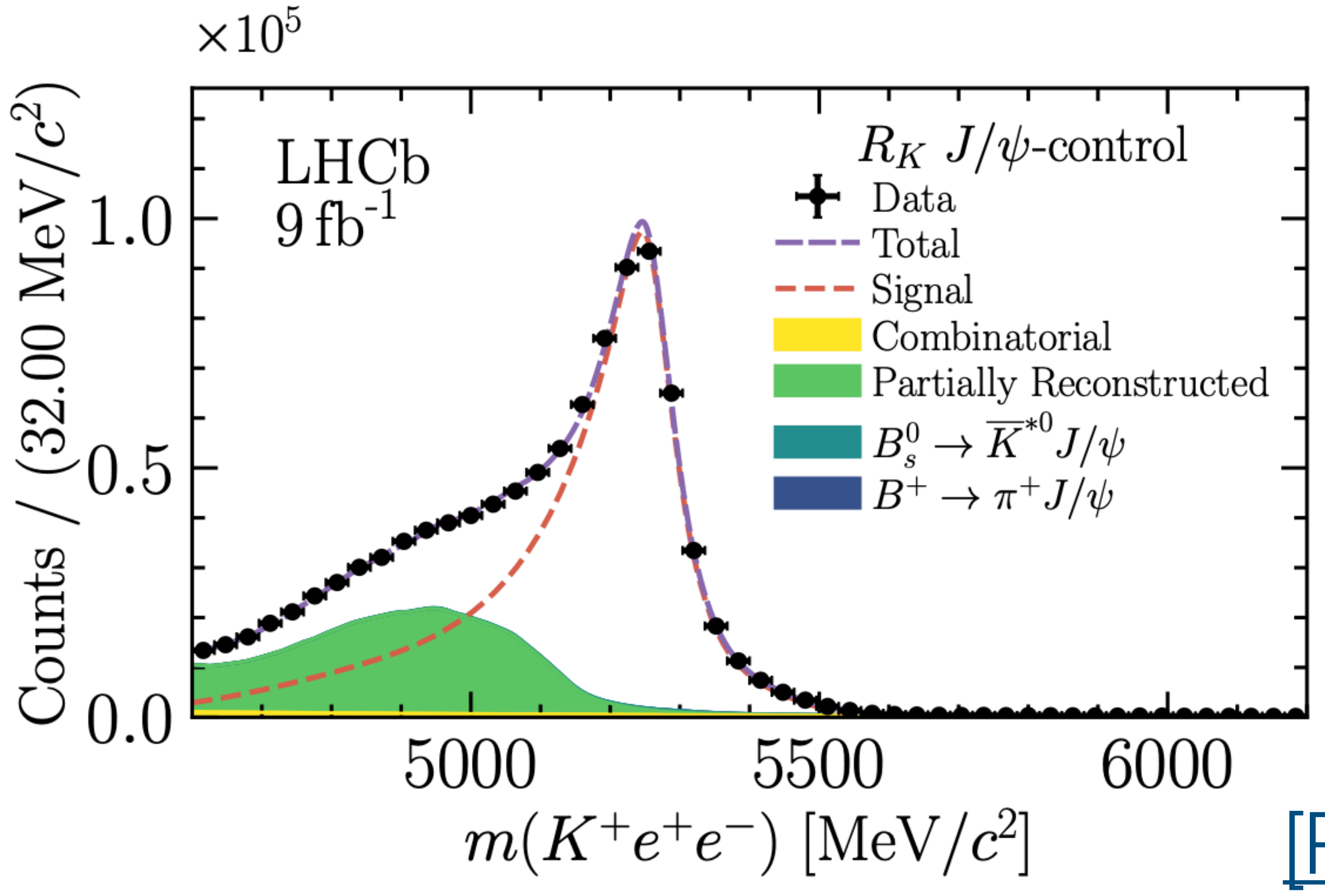
Electrons vs Muons at LHCb

- Electrons lose a large fraction of their energy through Bremsstrahlung radiation
  - Bremsstrahlung recovery: Look for photon clusters in the calorimeter (E_T > 75 MeV) compatible with electron direction before magnet
- After this correction electrons still have
  - Lower reconstruction/trigger/PID efficiency
  - Worse mass and q^2 resolution (more background)



$B^+ \to K^+\ell^+\ell^-$

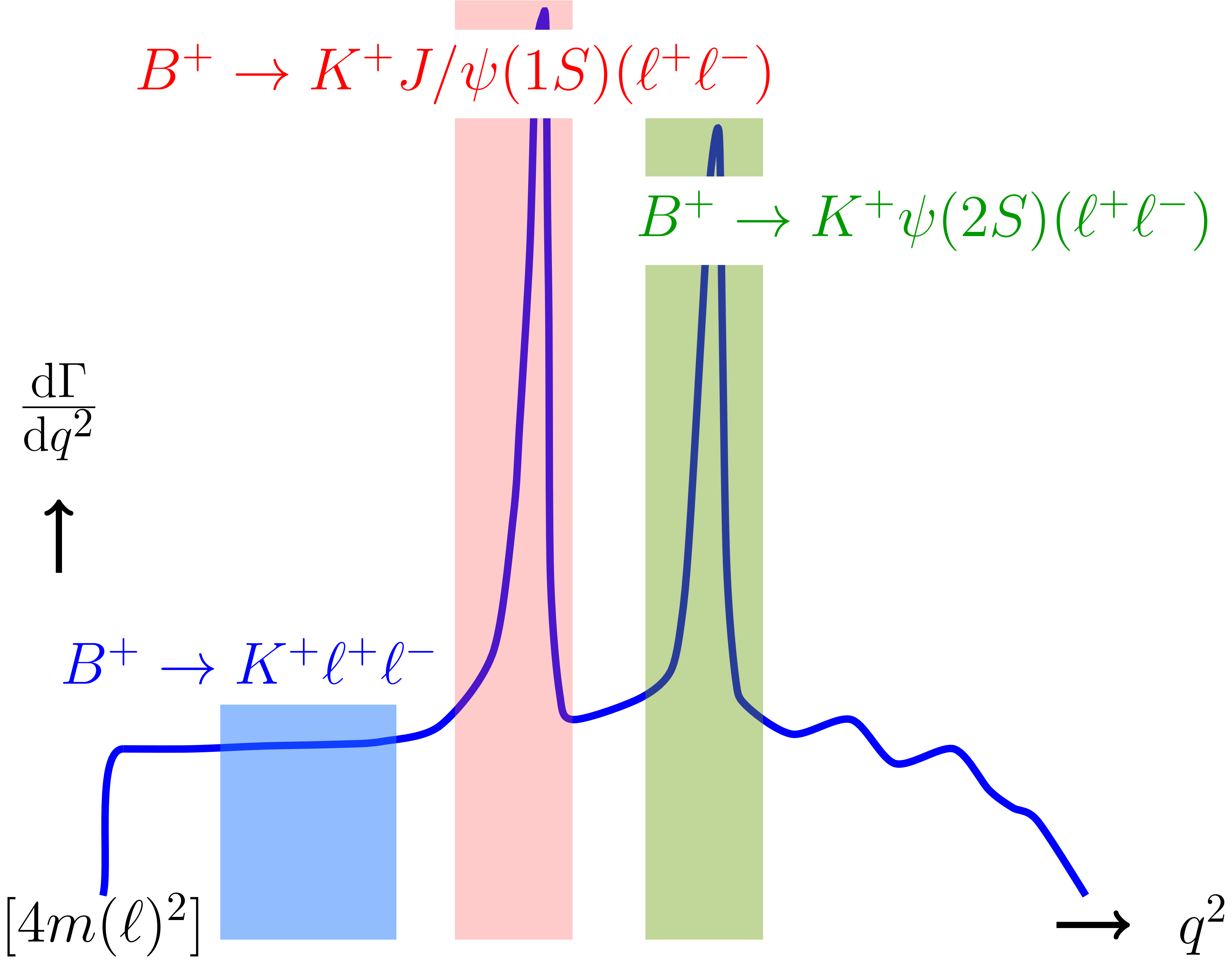




[PRL 131 (2023) 051803]

The double ratio

- Measure R_H as a double ratio, relative to equivalent ratio for $B \to H_s\, J/\psi(\ell\ell)$ decays
  - reduces impact of the differences in efficiency between electrons and muons



$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(\mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(e^+e^-))}$$

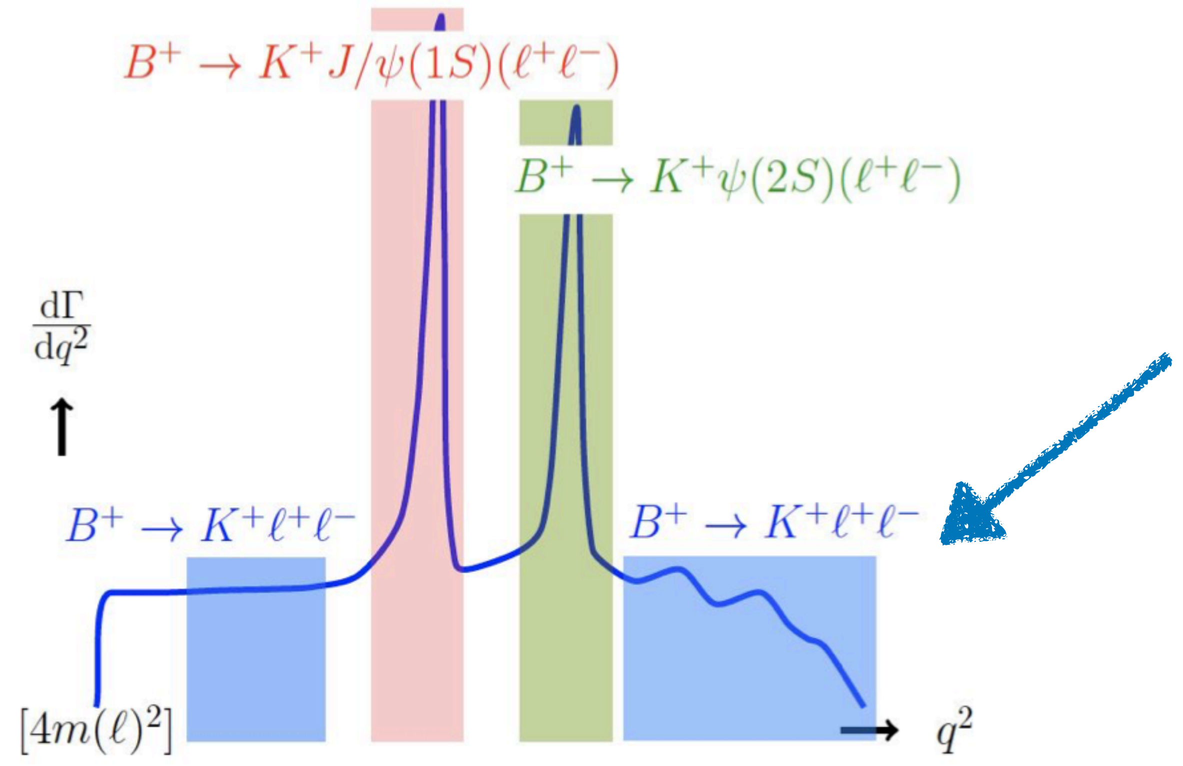
$$= \frac{N(K^+\mu^+\mu^-)}{N(K^+J/\psi(\mu^+\mu^-))} \cdot \frac{N(K^+J/\psi(e^+e^-))}{N(K^+e^+e^-)}$$

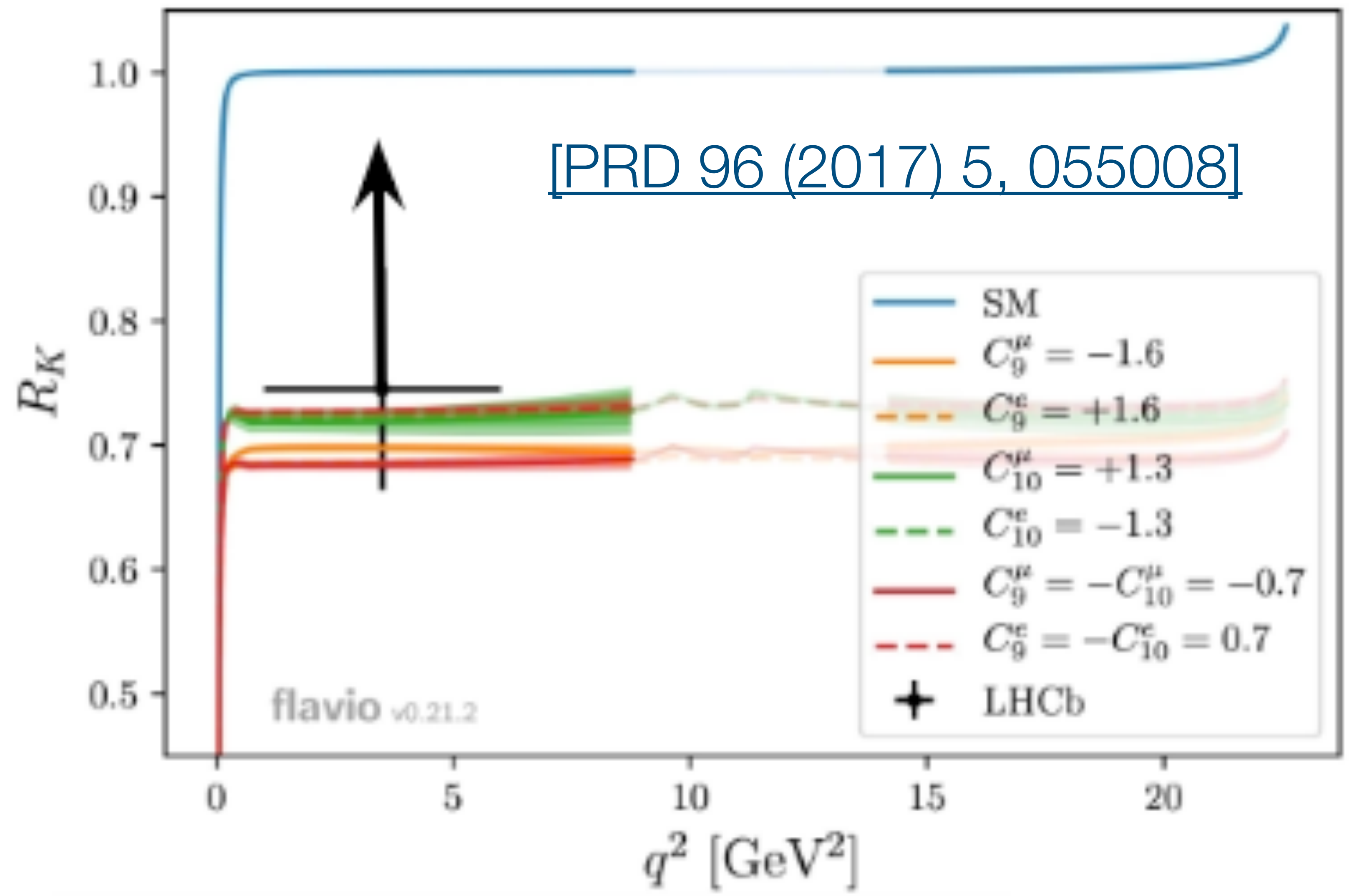
$$\cdot \frac{\varepsilon(K^+J/\psi(\mu^+\mu^-))}{\varepsilon(K^+\mu^+\mu^-)} \cdot \frac{\varepsilon(K^+e^+e^-)}{\varepsilon(K^+J/\psi(e^+e^-))}$$

Measurement of R_K at high-q^2

[JHEP 07 (2025) 198]

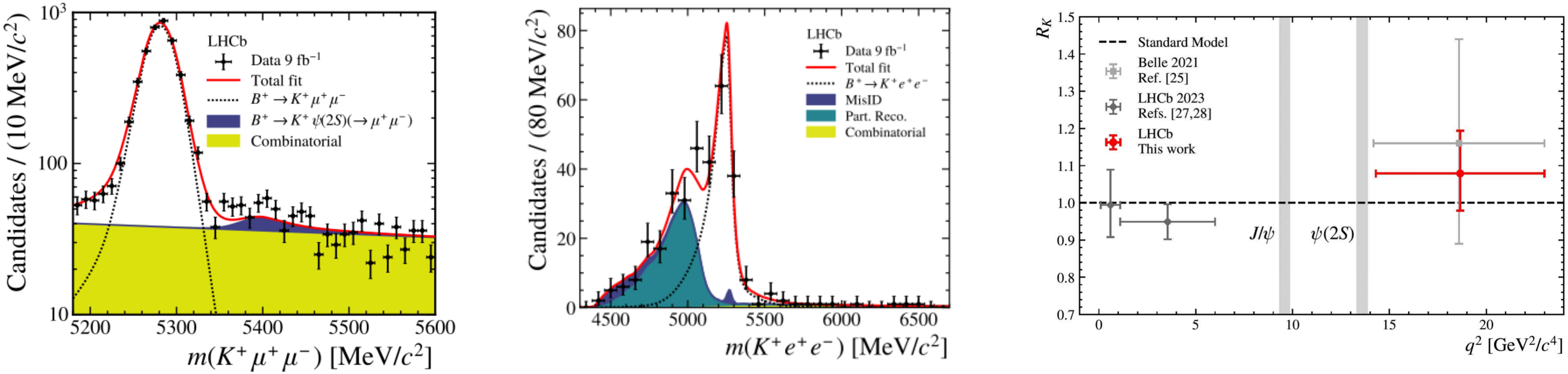
- Using the full Run 1 + Run 2 dataset
  - $q^2 > 14.3\ \mathrm{GeV}^2/c^4$
- Complementary to measurement at low q^2
  - Expected RK value in SM and many NP scenarios is independent of q^2
- Different background composition & systematics
  - Sculpting of the combinatorial background
  - Leakage of ψ(2S) due to erroneous added photons
  - Non-uniform efficiency ratio vs q^2





Measurement of R_K at high-q^2

[JHEP 07 (2025) 198]



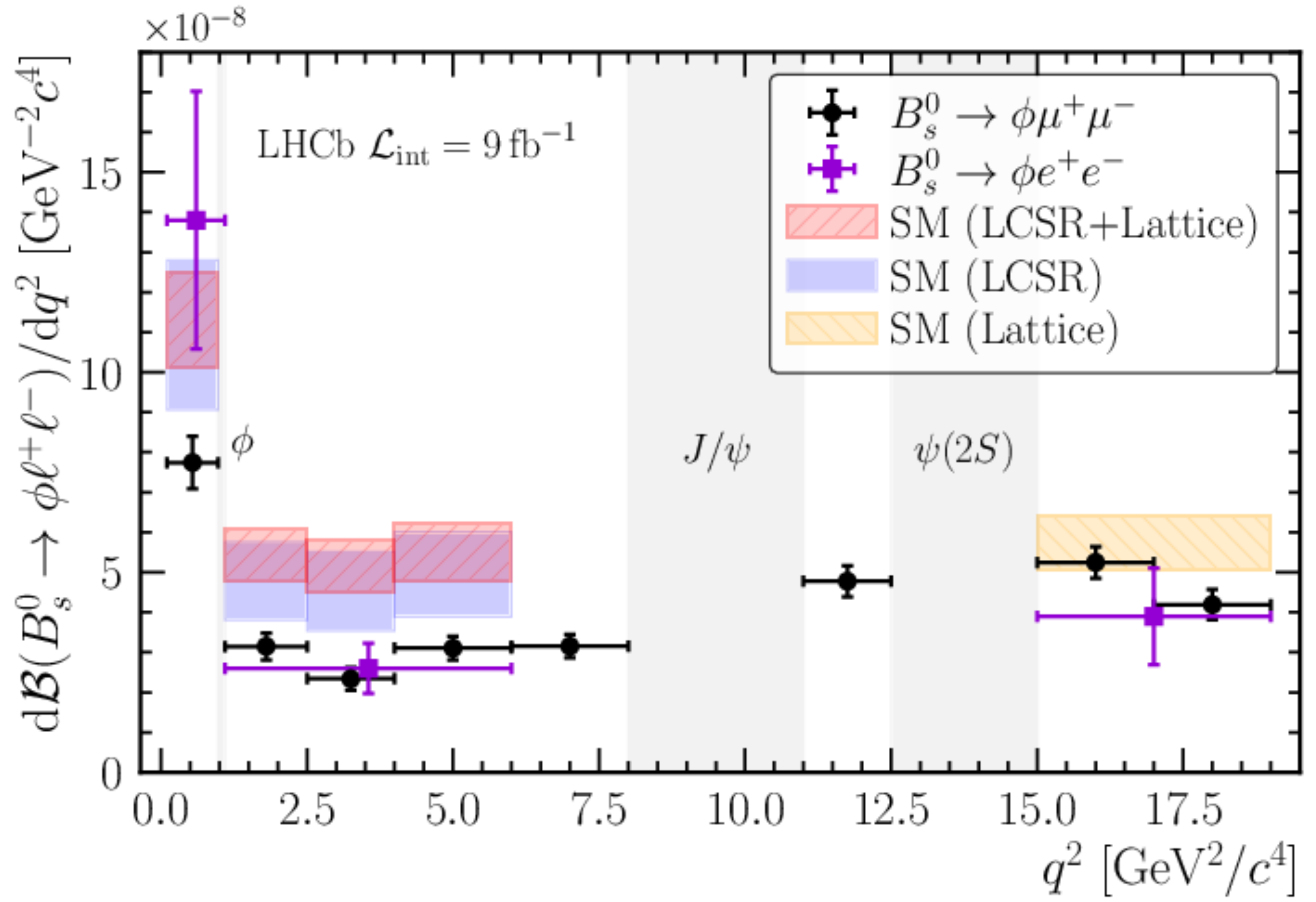
$$R_K(q^2 > 14.3\ \mathrm{GeV}^2/c^4) = 1.08\ ^{+0.11}_{-0.09}\ \pm 0.04$$

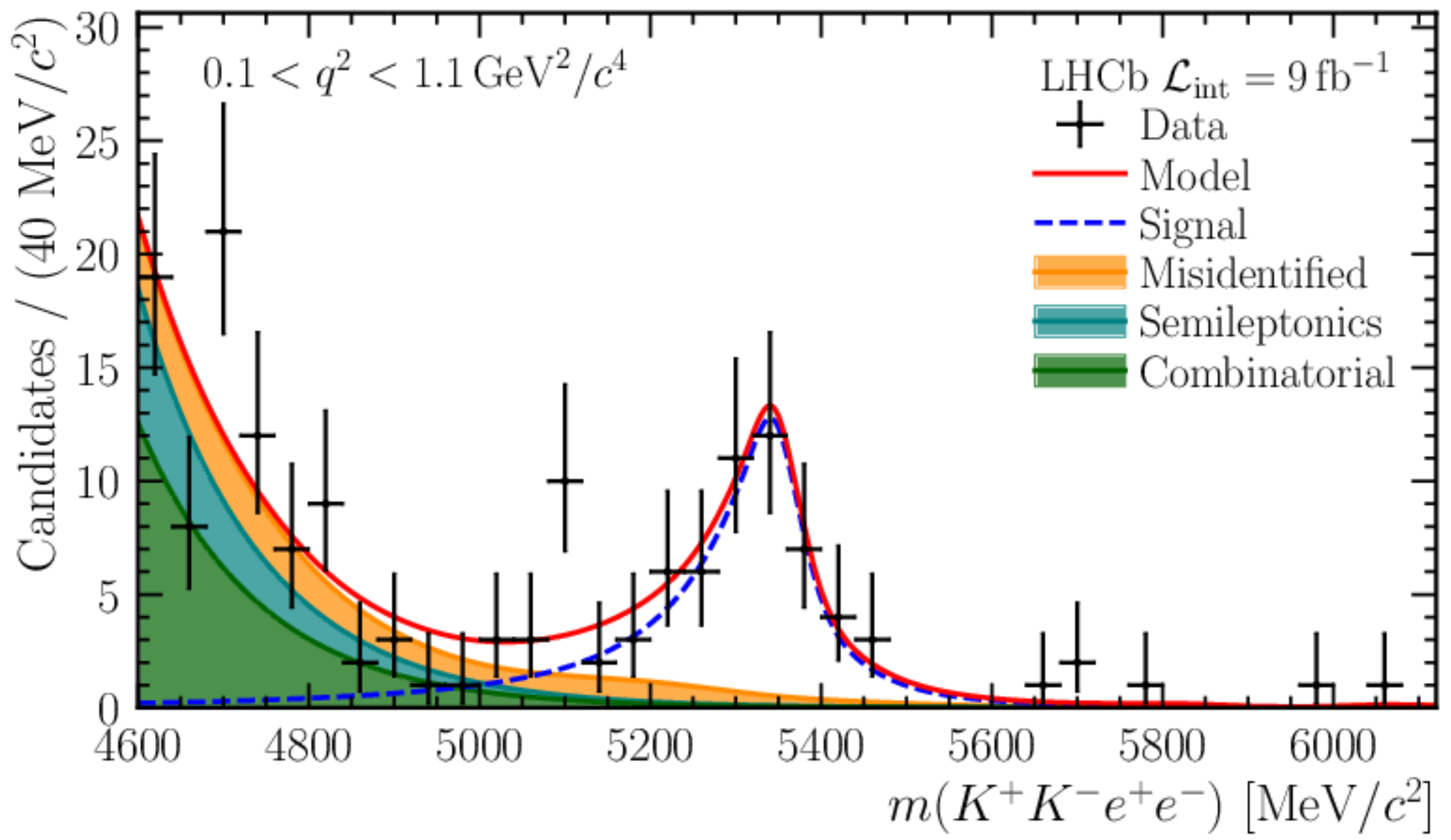
- Result is compatible with the SM prediction and the low/central-q^2 value

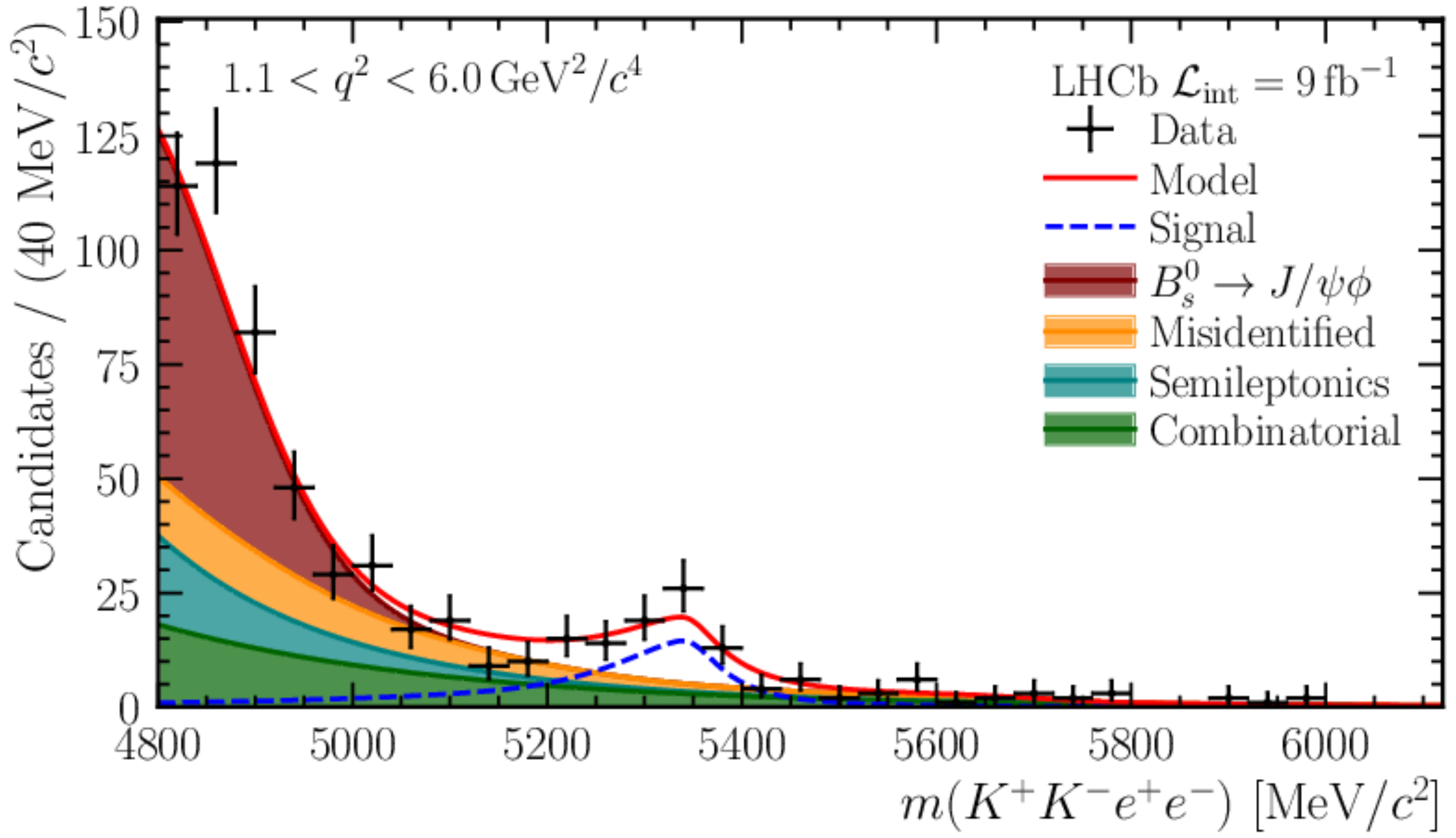
LFU test with $B_s^0 \to \phi \ell^+ \ell^-$ decays

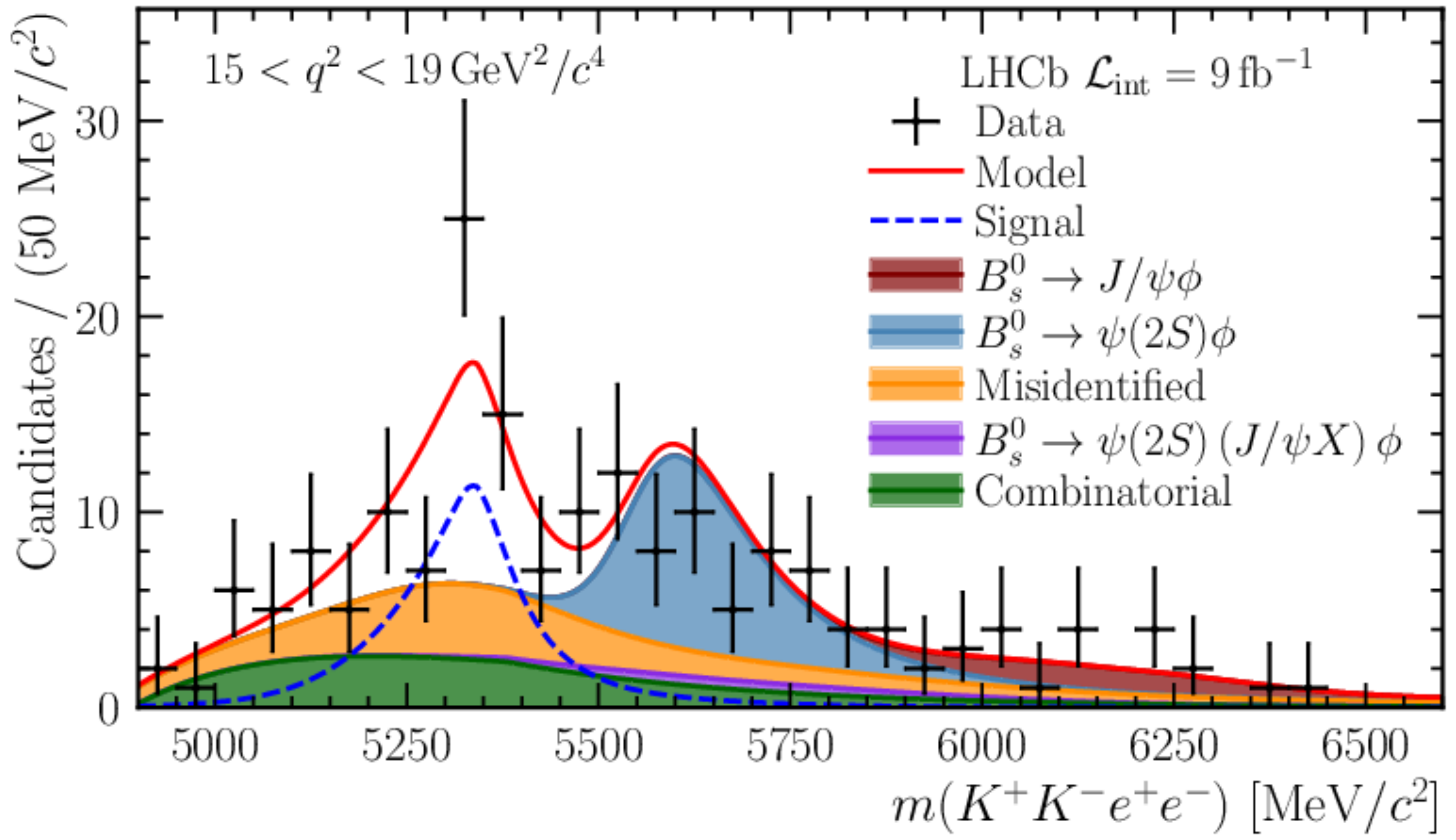
[PRL 134 (2025) 12, 121803]

- Measurement in three regions of q²
  - Low: $R_\phi^{-1}(0.1 < q^2 < 1.1\ \mathrm{GeV}^2/c^4) = 1.57\ ^{+0.28}_{-0.25} \pm 0.05$
  - Central: $R_\phi^{-1}(1.1 < q^2 < 6.0\ \mathrm{GeV}^2/c^4) = 0.91\ ^{+0.20}_{-0.19} \pm 0.05$
  - High: $R_\phi^{-1}(15 < q^2 < 19\ \mathrm{GeV}^2/c^4) = 0.85\ ^{+0.24}_{-0.23} \pm 0.10$
- Double ratio with $B_s^0 \to \phi J/\psi(\ell\ell)$
- Result compatible with the SM

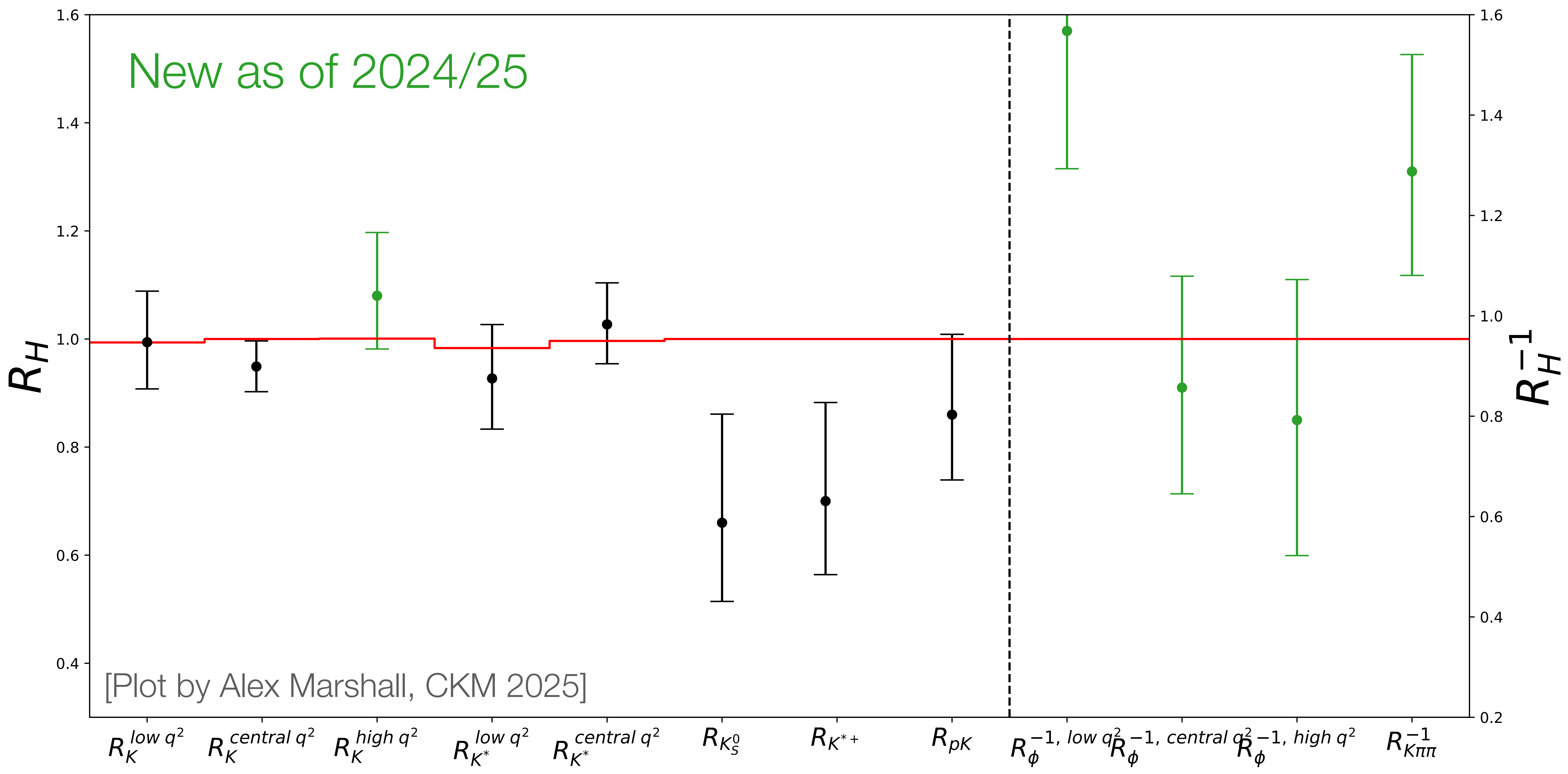








Summary of LFU ratios



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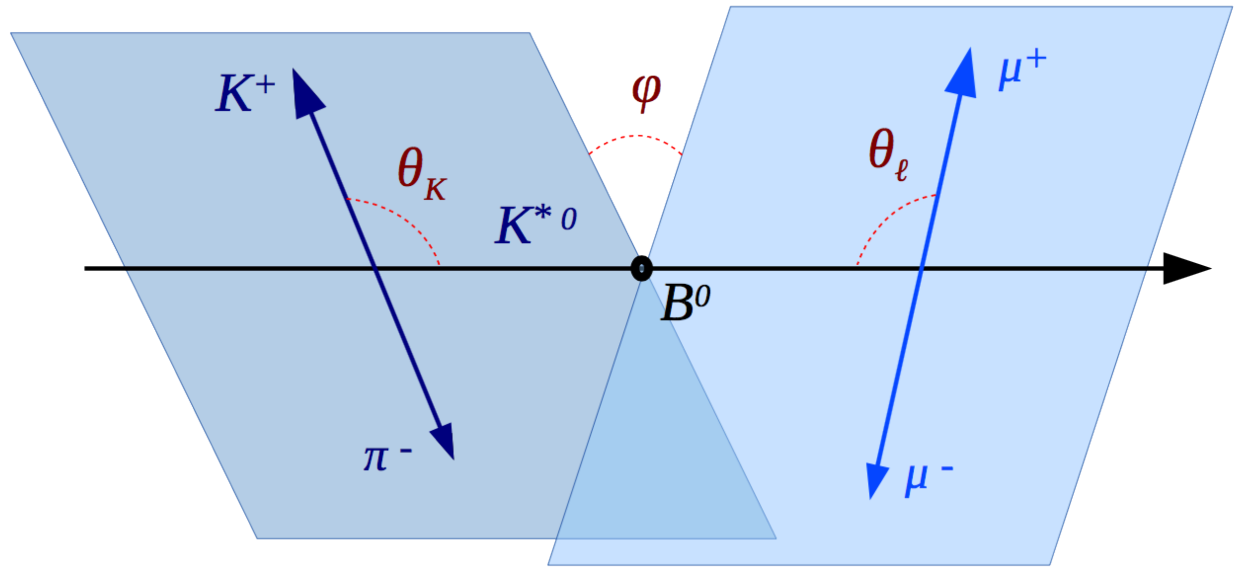
[JHEP 07 (2025) 198]
[Phys.Rev.Lett. 134 (2025) 18, 181803]
[Phys.Rev.Lett. 134 (2025) 12, 121803]

Whatever is affecting the muons, seems to be affecting the electrons in the same way!

Testing LFU with angular analyses

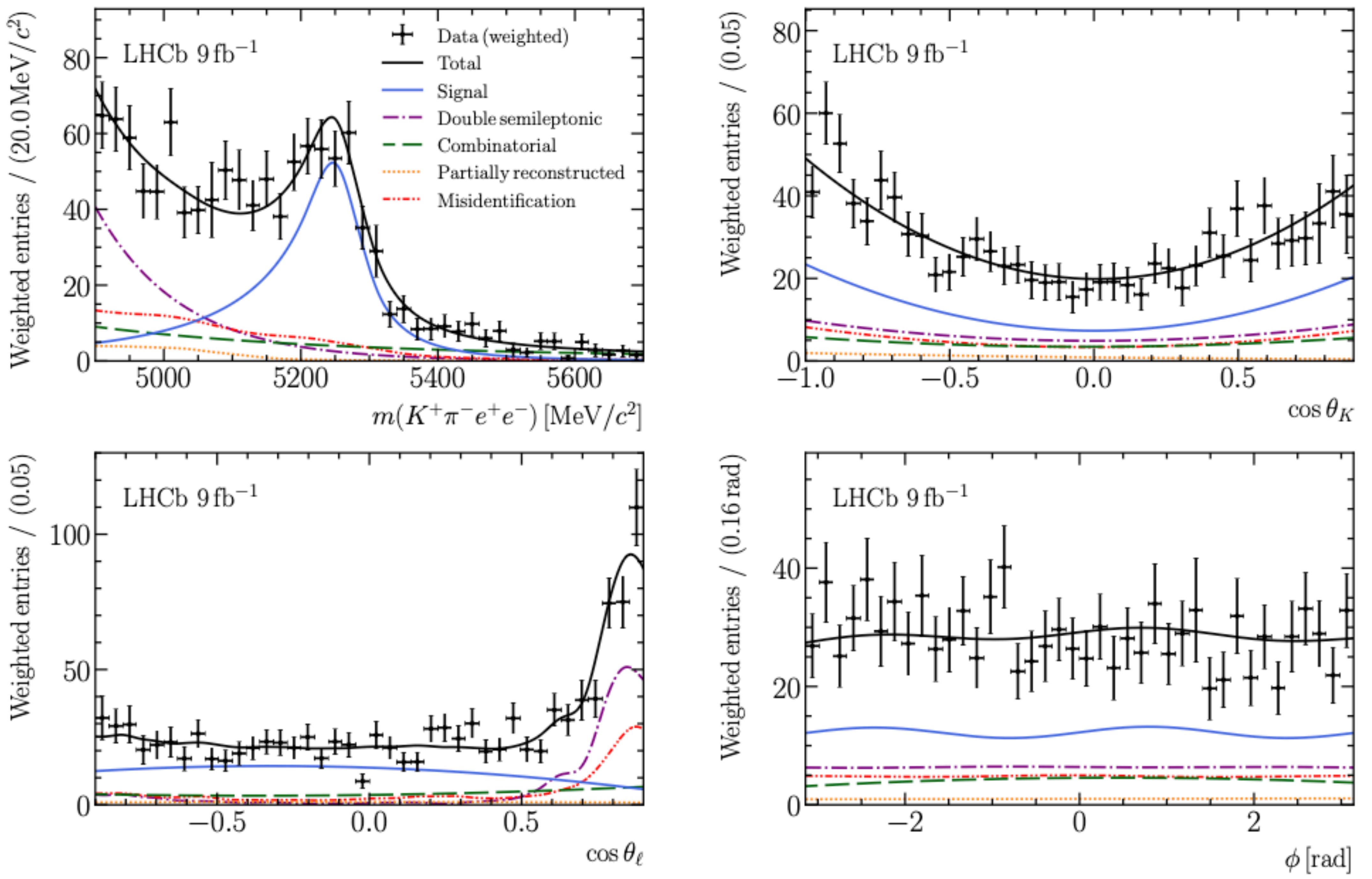
$$
\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K
+\frac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell
- F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi
+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi
+\frac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi
+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]
$$



- Coefficients describing the differential angular distributions are also sensitive to new physics
  - To test LFU, compare them for muons and electrons
- Worse resolution wrt muon channel
  - Additional backgrounds that need to be carefully accounted for

$B^0 \to K^{*0} e^+ e^-$

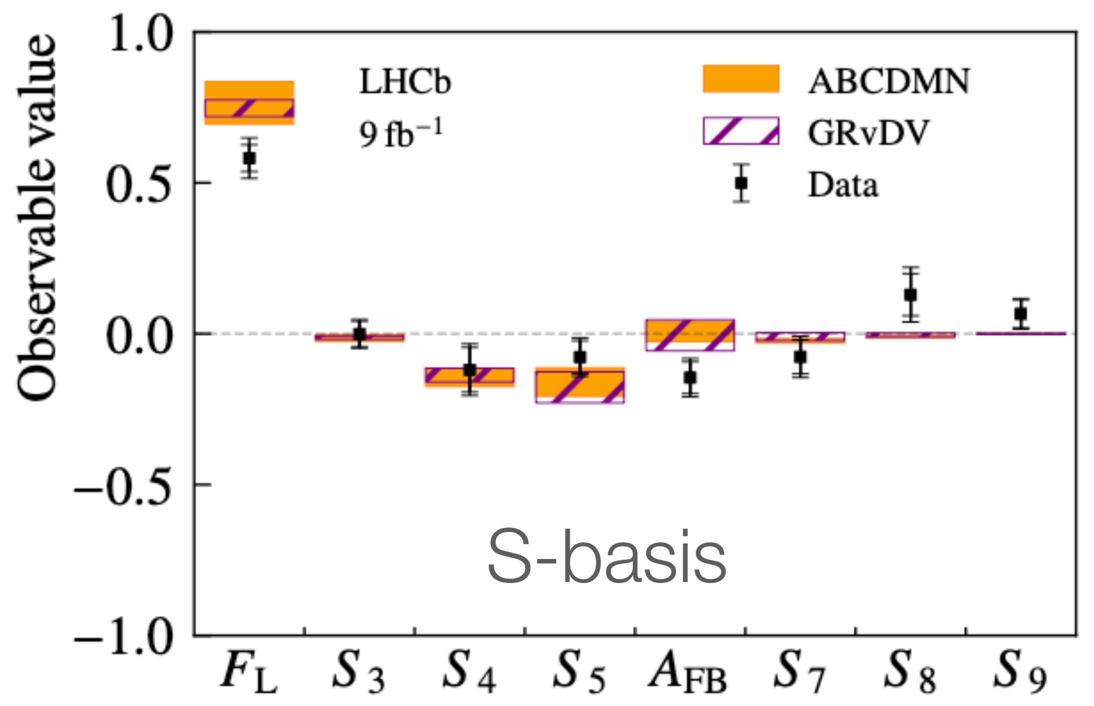
[JHEP 06 (2025) 140]

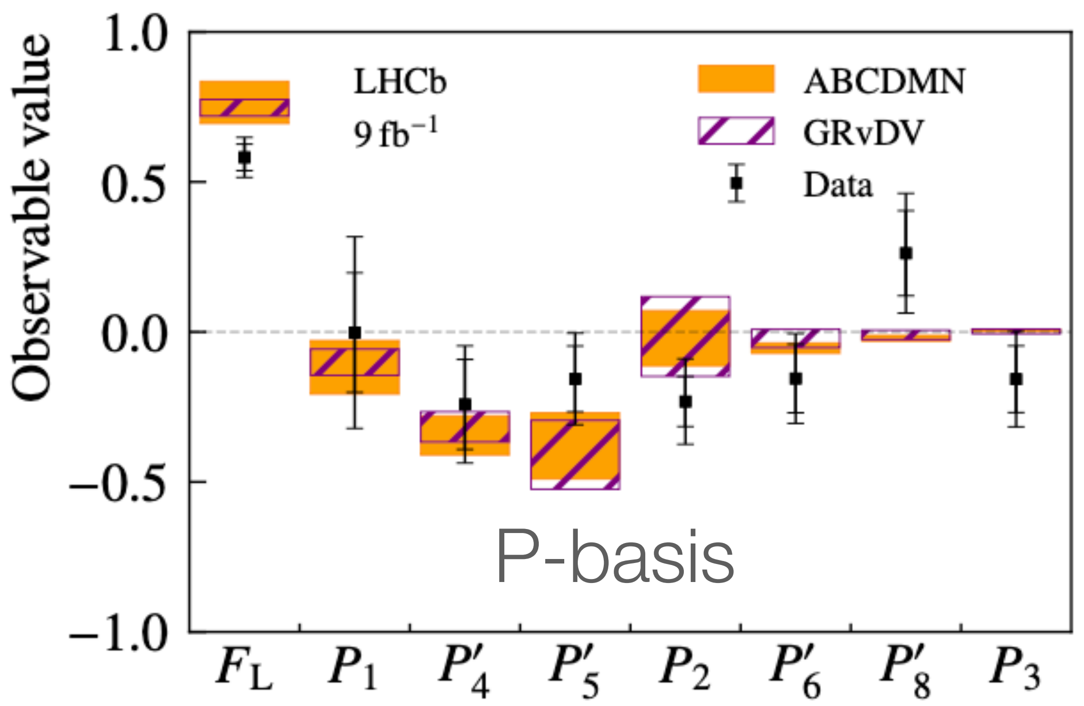


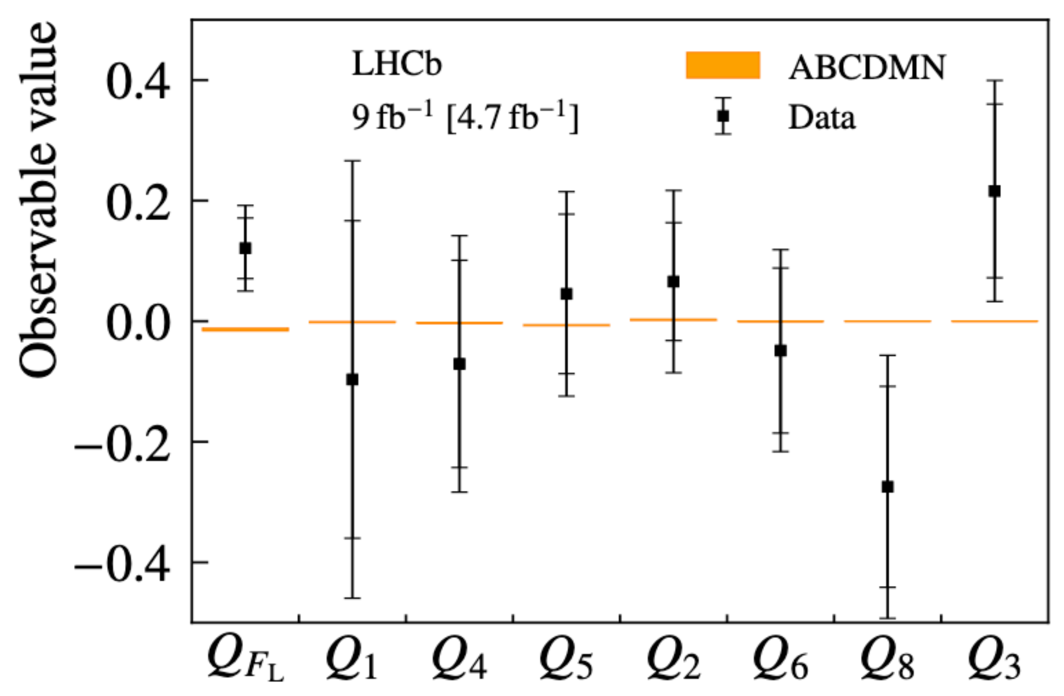
Two new angular analyses…

$B^0 \to K^{*0} e^+ e^-$ [JHEP 06 (2025) 140]

- Integrated over $q^2 \in [1.1, 6.0]\ \mathrm{GeV}^2/c^4$
- Fit to the B-mass and 3D angular distribution





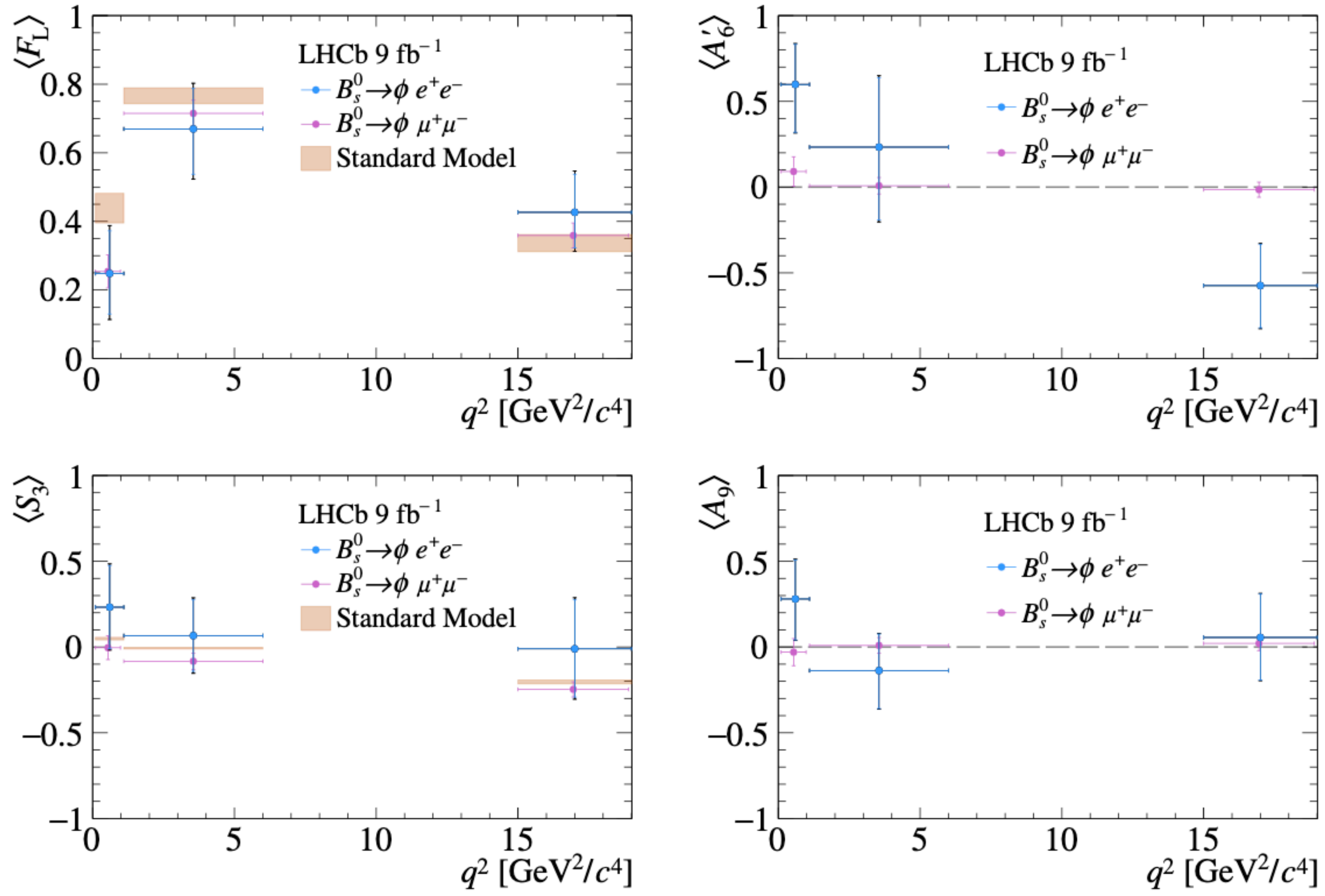


Simultaneous fit to $B^0 \to K^{*0}\mu\mu$ to extract:

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

$B_s^0 \to \phi e^+ e^-$ [JHEP 07 (2025) 069]

- Three q2 bins (low, central, high)
- Simplified fit to handle lower sample size

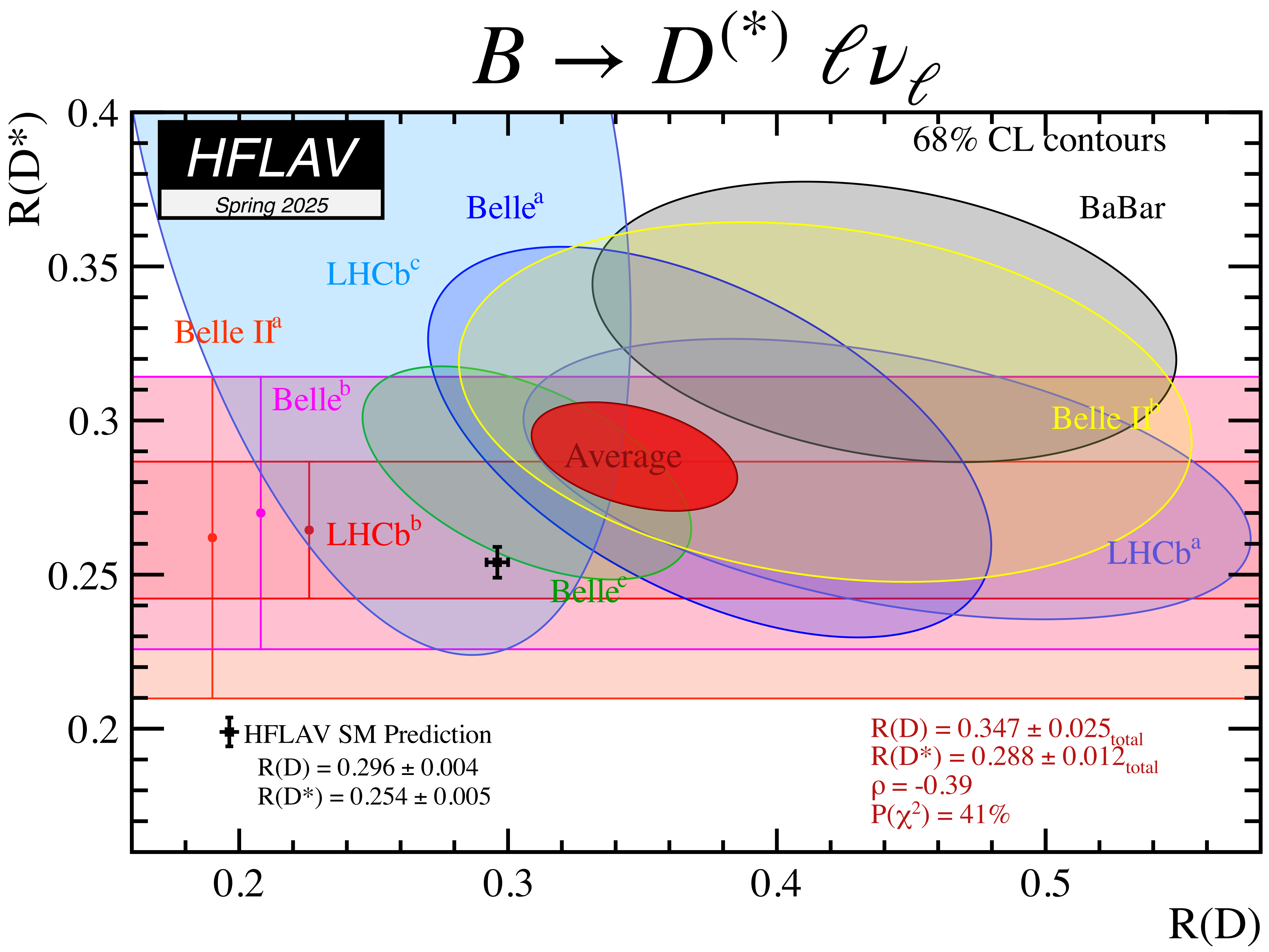


Results compatible with the SM predictions and the corresponding muon modes

Charged currents

LFU in $b \to c \ell \nu$ transitions

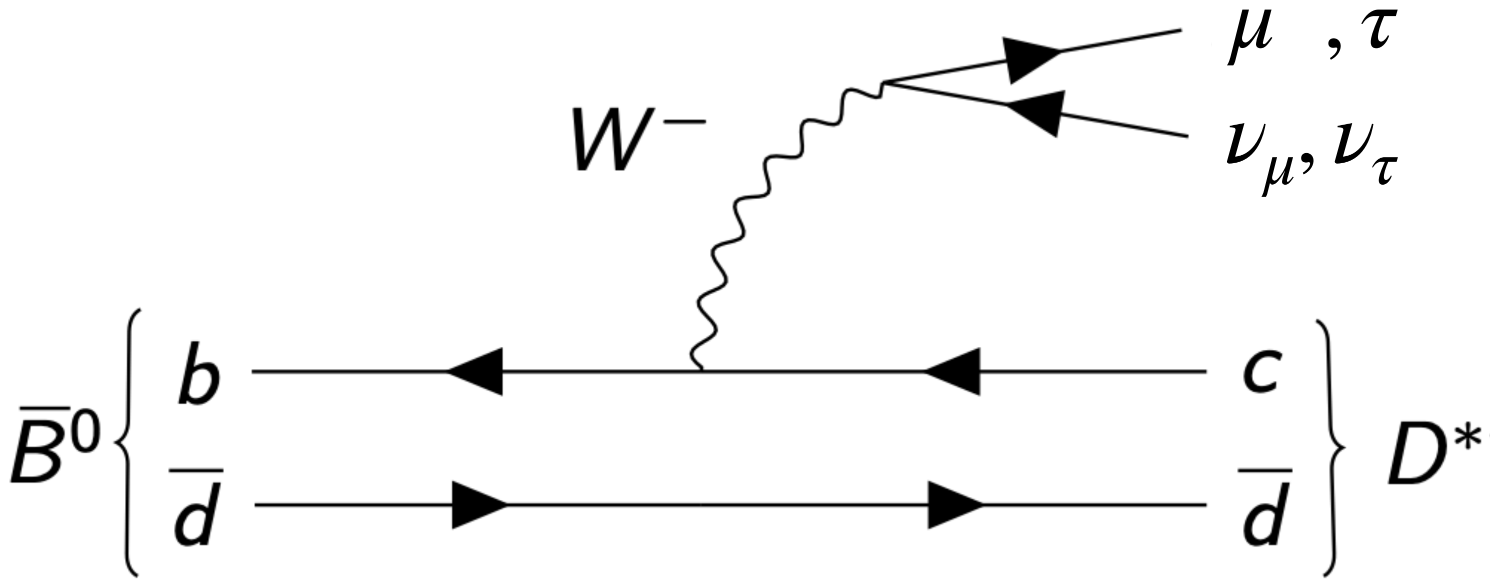
- Tree level transition already in the SM
  - High-statistics tests
  - NP scale could be order few TeV
- Different observables of interest
  - Ratios between rates of τ and μ (or μ and e)
  - Comparison of angular observables
  - Family of semileptonic decays
- Currently, R(D)-R(D*) show 3.7σ deviation from the SM

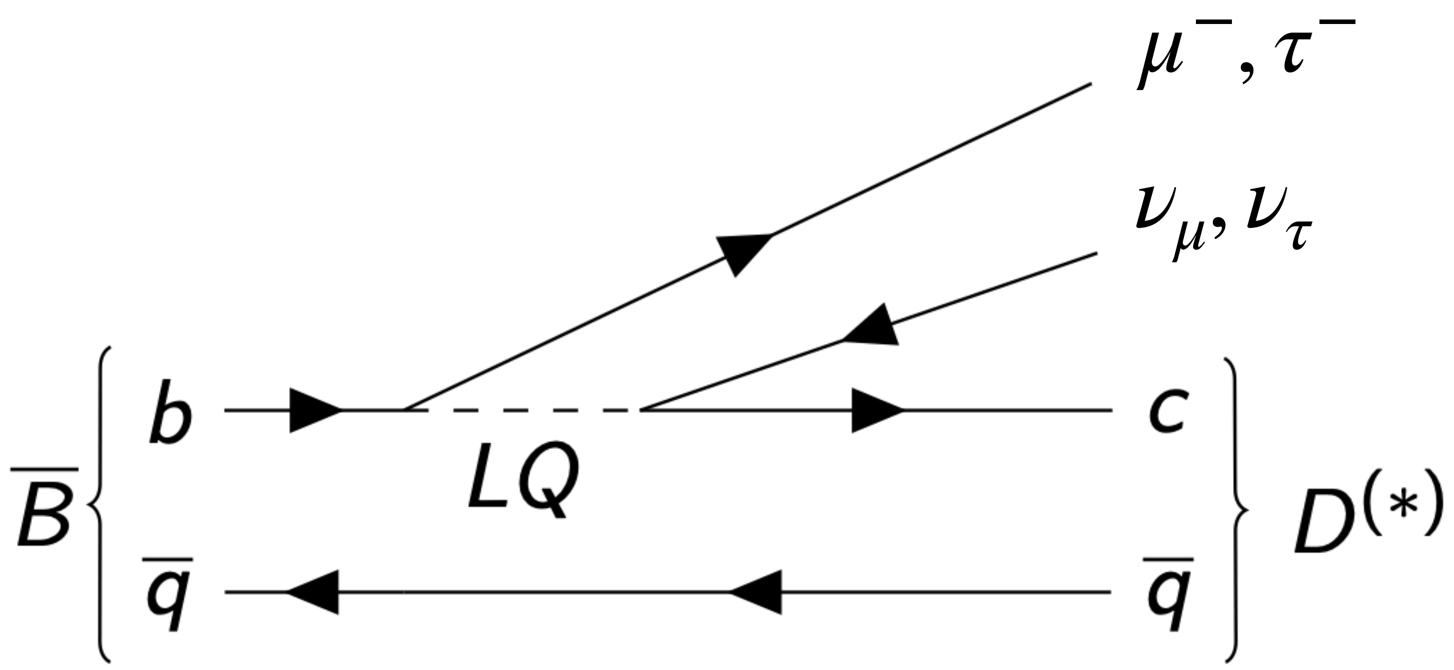


$B^{+,0}$, B_c, Λ_b — $D^{(*)}$, J/ψ, Λ_c…

$$R(H_c) = \frac{H_b \to H_c\, \tau\, \nu_\tau}{H_b \to H_c\, \ell\, \nu_\ell}$$

e, μ





R(D+) and R(D*+) with muonic τ

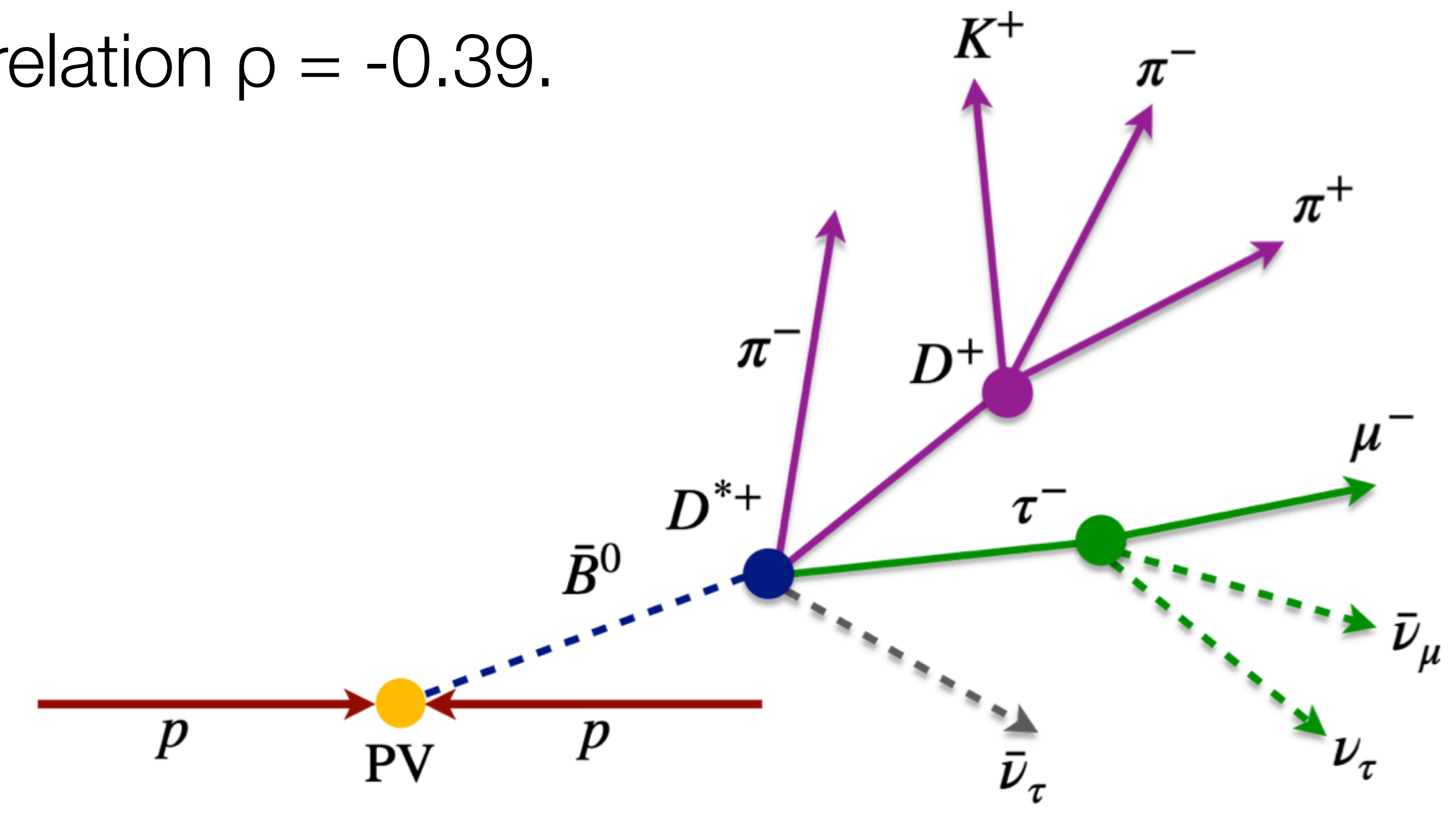
PRL 134 (2025) 061801

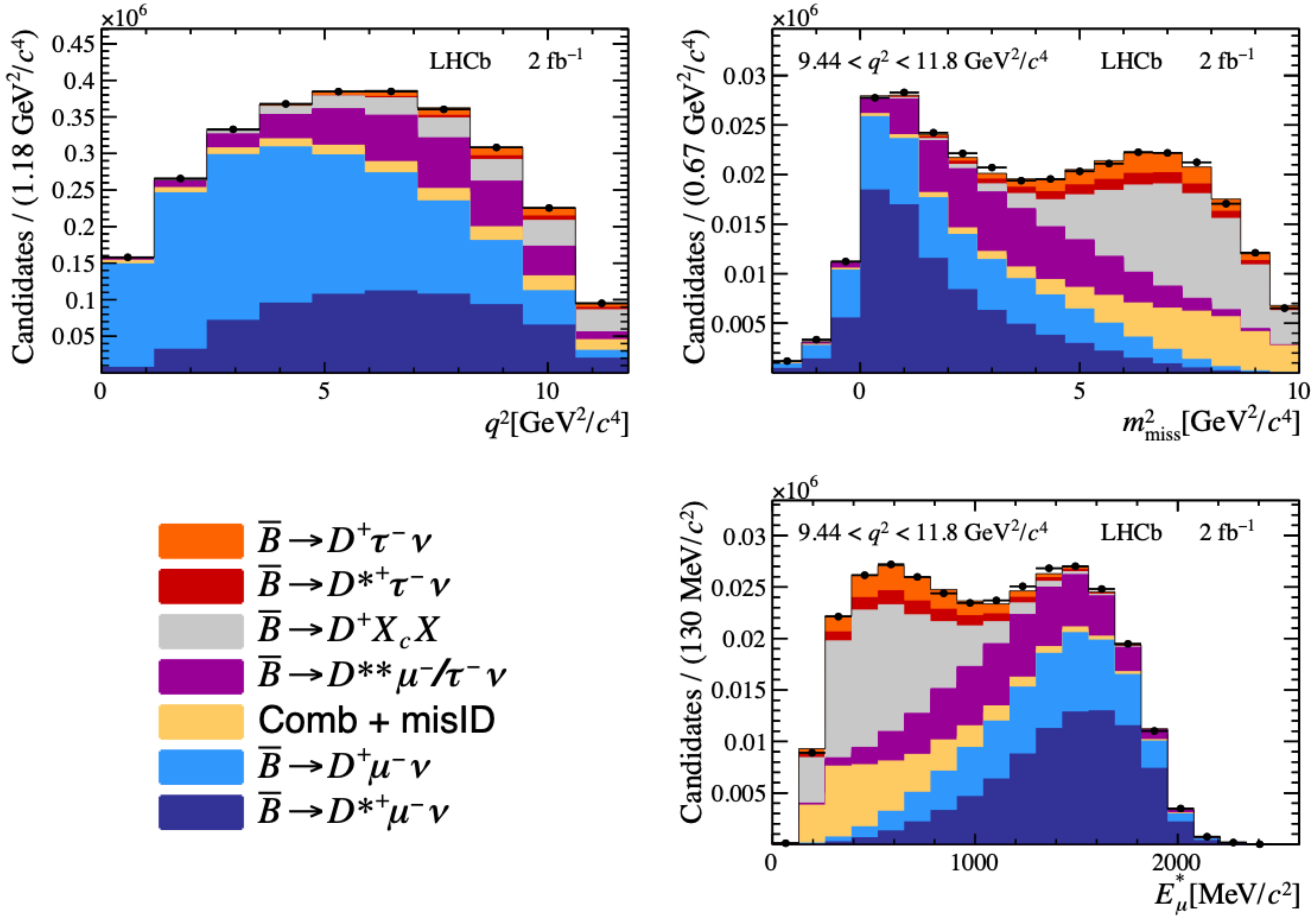
- Measure $\mathcal{B}(B^+ \to D^{(*)+}\tau^-\nu_\tau) / \mathcal{B}(B^+ \to D^{(*)+}\mu^-\nu_\mu)$
  - $D^+ \to K^+\pi^-\pi^+$
  - $D^{(*)+} \to D^+\pi^0$ (π^0 not reconstructed)

- Result in good agreement with the SM prediction and world average:

$$R(D^+) = 0.249 \pm 0.043 \text{ (stat)} \pm 0.047 \text{ (syst)}$$
$$R(D^{*+}) = 0.402 \pm 0.081 \text{ (stat)} \pm 0.085 \text{ (syst)}$$

with correlation ρ = -0.39.





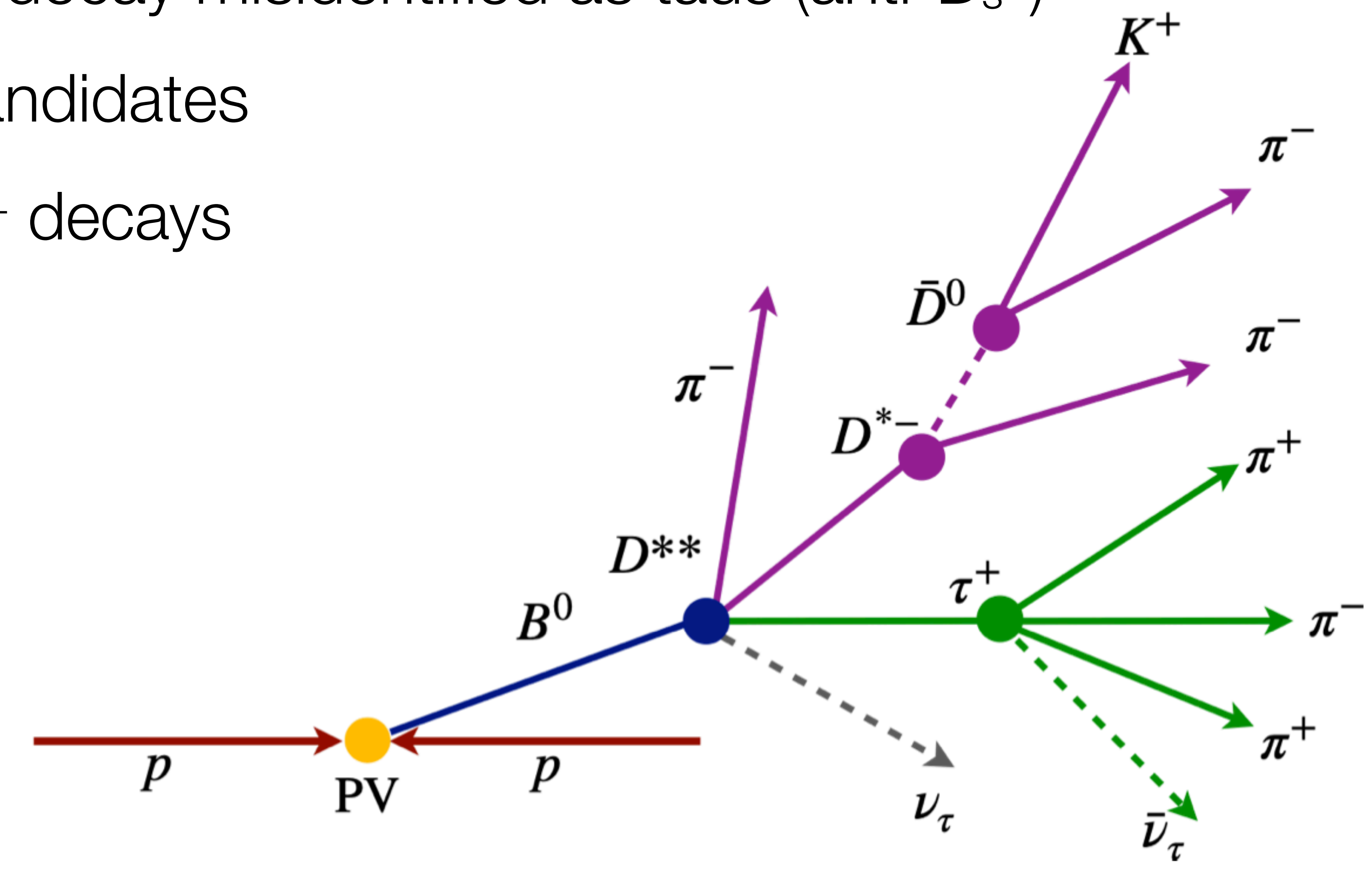
Signal and background templates extracted from simulation

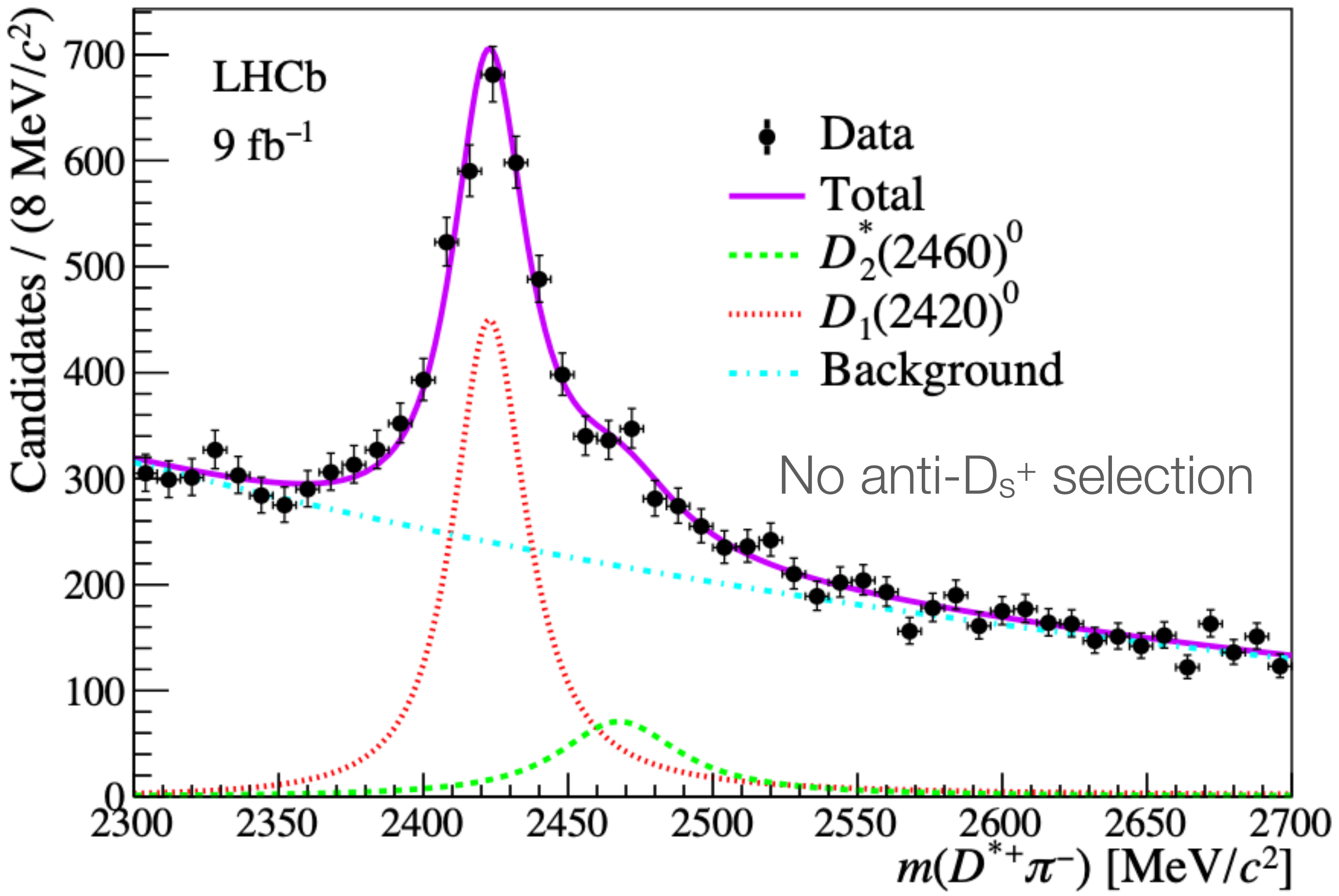
- Uncertainties associated to FF parameters included in the fit using RooHammerModel [arXiv:2007.12605]

Study of $B^+ \to D^{**0}\tau^+\nu$ decays

PRL 135 (2025) 021802

- Large systematic in R(D(*)) measurement comes from $D^{**} \to D^{*+}\pi^-$ feed-down in the τ-mode
  - $D^{**}: D_1(2420)^0, D_2(2460)^0, D_1'(2400)$
  - Wide $D_1'(2400)$ cannot be distinguished from combinatorial background
- Three multivariate classifiers discriminate against:
  - $D_s^+ \to \pi\pi\pi X$ decay misidentified as taus (anti-D_s^+)
  - Fake D** candidates
  - 5-prong D_s^+ decays





PDG:

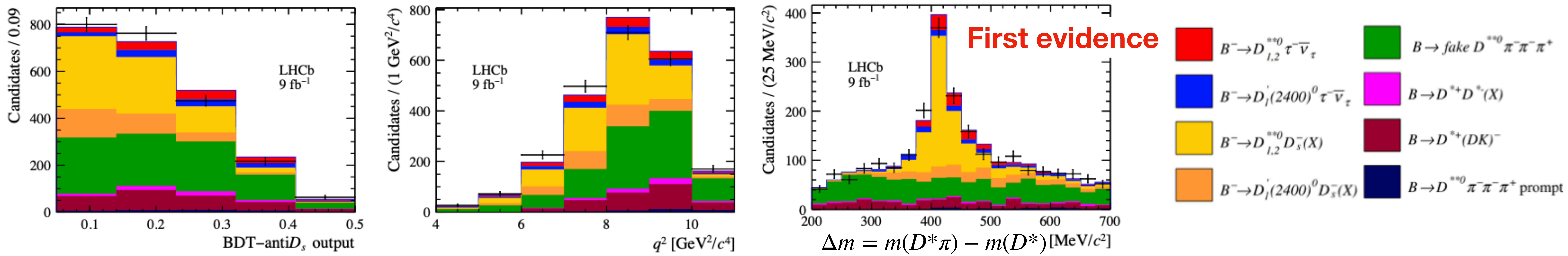
$D_1'(2400)^0$, $m = 2412 \pm 9$ MeV/c^2, $\Gamma = 314 \pm 29$ MeV/c^2

$D_1(2420)^0$, $m = 2422.1 \pm 0.6$ MeV/c^2, $\Gamma = 31.3 \pm 1.9$ MeV/c^2

$D_2(2460)^0$, $m = 2461.1 \pm 0.8$ MeV/c^2, $\Gamma = 47.3 \pm 0.8$ MeV/c^2

Study of $B^+ \to D^{**0}\, \tau^+\, \nu$ decays

PRL 135 (2025) 021802



- Normalising to $B^+ \to D^{**0} D_s$, the branching ratio is measured to be

$$\mathcal{B}(B^- \to D^{**0}_{1,2}\tau^-\nu_\tau) \times \mathcal{B}(D^{**0}_{1,2} \to D^{*+}\pi^-) = (0.051 \pm 0.013\ (\text{stat}) \pm 0.006\ (\text{syst}) \pm 0.009\ (\text{ext}))\,\%$$

- LFU ratio

$$R(D^{**0}_{1,2}) = \frac{\mathcal{B}(B^- \to D^{**0}_{1,2}\tau^-\nu_\tau)}{\mathcal{B}(B^- \to D^{**0}_{1,2}\mu^-\nu_\mu)} = 0.13 \pm 0.03\ (\text{stat}) \pm 0.01\ (\text{syst}) \pm 0.02\ (\text{ext})$$

compatible with SM prediction of $R(D^{**}_{1,2}) = 0.09 \pm 0.02$ [PRD 97 (2018) 075011]

Connection between $b \to c\ell\nu$ and $b \to s\,\ell^+\ell^-$?

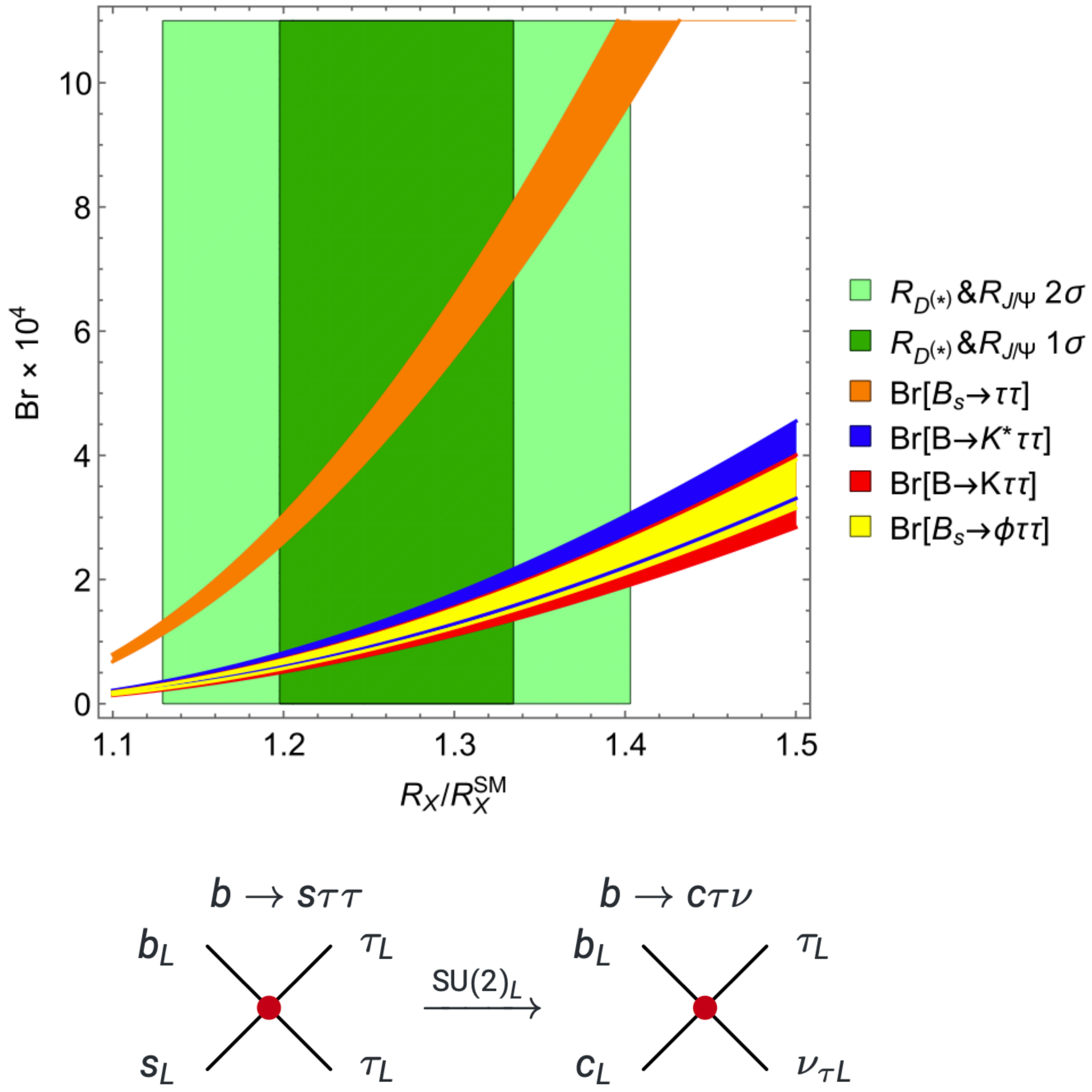
- Attempts to explain LFU violating effects in R(D)-R(D*) tend to **enhance $b \to s\tau\tau$ couplings** by 10^3-10^4 compared to the SM value

- As a bonus, one obtains higher order corrections to $b \to s\ell\ell$, causing a LFU shift in C_9

		SM prediction
$B_s \to \tau\tau$		$(7.73 \pm 0.49) \times 10^{-7}$
$B \to K\tau\tau$	$[15, 22]\text{GeV}^2/c^2$	$(1.20 \pm 0.12) \times 10^{-7}$
$B \to K^*\tau\tau$	$[15, 19]\text{GeV}^2/c^2$	$(0.98 \pm 0.10) \times 10^{-7}$
$B_s \to \phi\tau\tau$	$[15, 18.8]\text{GeV}^2/c^2$	$(0.86 \pm 0.06) \times 10^{-7}$

Bobeth et al, PRL 112 (2014) 101801, Capdevila et al, PRL120 (2018) 181802

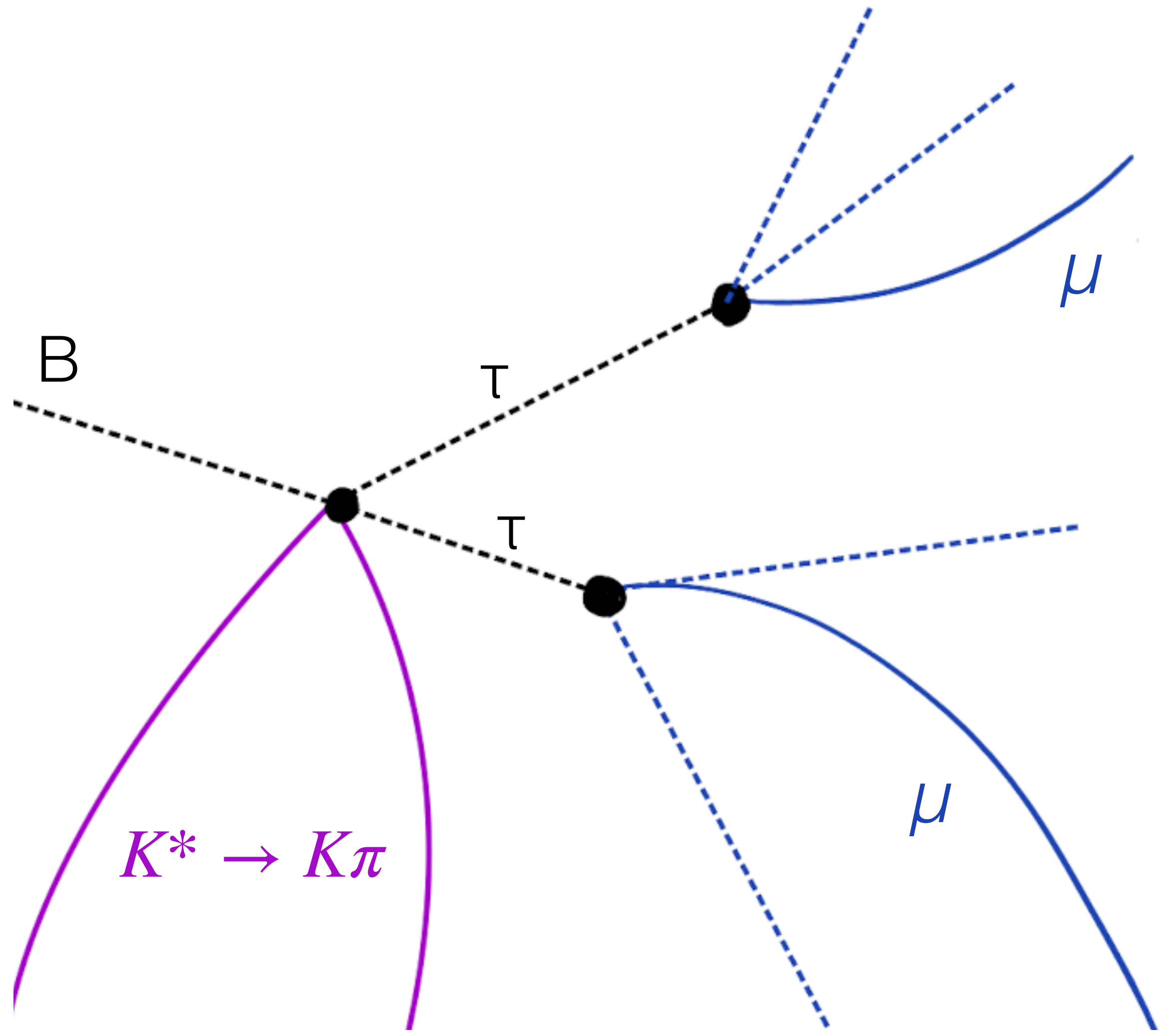
Capdevila et al, PRL120 (2018) 181802



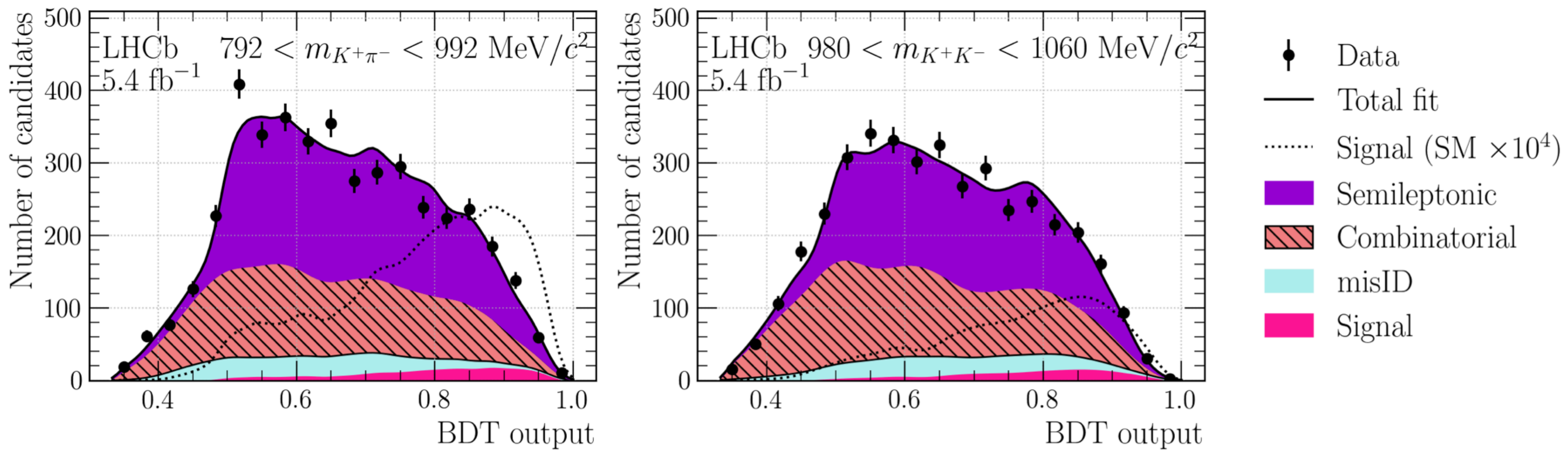
Search for $b \to s\,\tau^+\tau^-$ decays

[LHCb-PAPER-2025-048 in preparation]

- New LHCb search for $B^0 \to K^+\pi^-\tau^+\tau^-$ and $B_s^0 \to K^+K^-\tau^+\tau^-$
  - Using muonic taus
- Experimentally very challenging, due to the multiple neutrinos
  - partially reconstructed signal and high background contamination
- Analysis strategy:
  - Search performed in bins of the di-hadron mass (model independent)
  - Multi-class BDT to fight different background sources



No signal is observed



Search for $b \to s\, \tau^+ \tau^-$ decays

[LHCb-PAPER-2025-048 in preparation]

Confidence level	Upper limit on $\mathcal{B}(B^0 \to K^+\pi^-\tau^+\tau^-)$			
$m_{K^+\pi^-}$ (MeV/c^2)	[792, 992]	[992, 1330]	[1330, 1530]	[1530, 1726]
90%	1.4×10^{-4}	2.7×10^{-5}	1.0×10^{-5}	2.7×10^{-6}
95%	1.6×10^{-4}	3.4×10^{-5}	1.1×10^{-5}	3.3×10^{-6}

Confidence level	Upper limit on $\mathcal{B}(B_s^0 \to K^+K^-\tau^+\tau^-)$				
$m_{K^+K^-}$ (MeV/c^2)	[980, 1060]	[1060, 1200]	[1200, 1400]	[1400, 1600]	[1600, 1813]
90%	2.0×10^{-4}	1.3×10^{-4}	1.2×10^{-4}	6.8×10^{-5}	3.2×10^{-5}
95%	2.3×10^{-4}	1.5×10^{-4}	1.4×10^{-4}	7.6×10^{-5}	3.6×10^{-5}

- Upper limits obtained are either new or the world's best!
- Results can be recasted in terms of the resonant decays

$$\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-) < 2.8 \times 10^{-4}\ (2.5 \times 10^{-4}) \text{ at } 95\%\ (90\%) \text{ CL},$$
$$\mathcal{B}(B_s^0 \to \phi\tau^+\tau^-) < 4.7 \times 10^{-4}\ (4.1 \times 10^{-4}) \text{ at } 95\%\ (90\%) \text{ CL}.$$

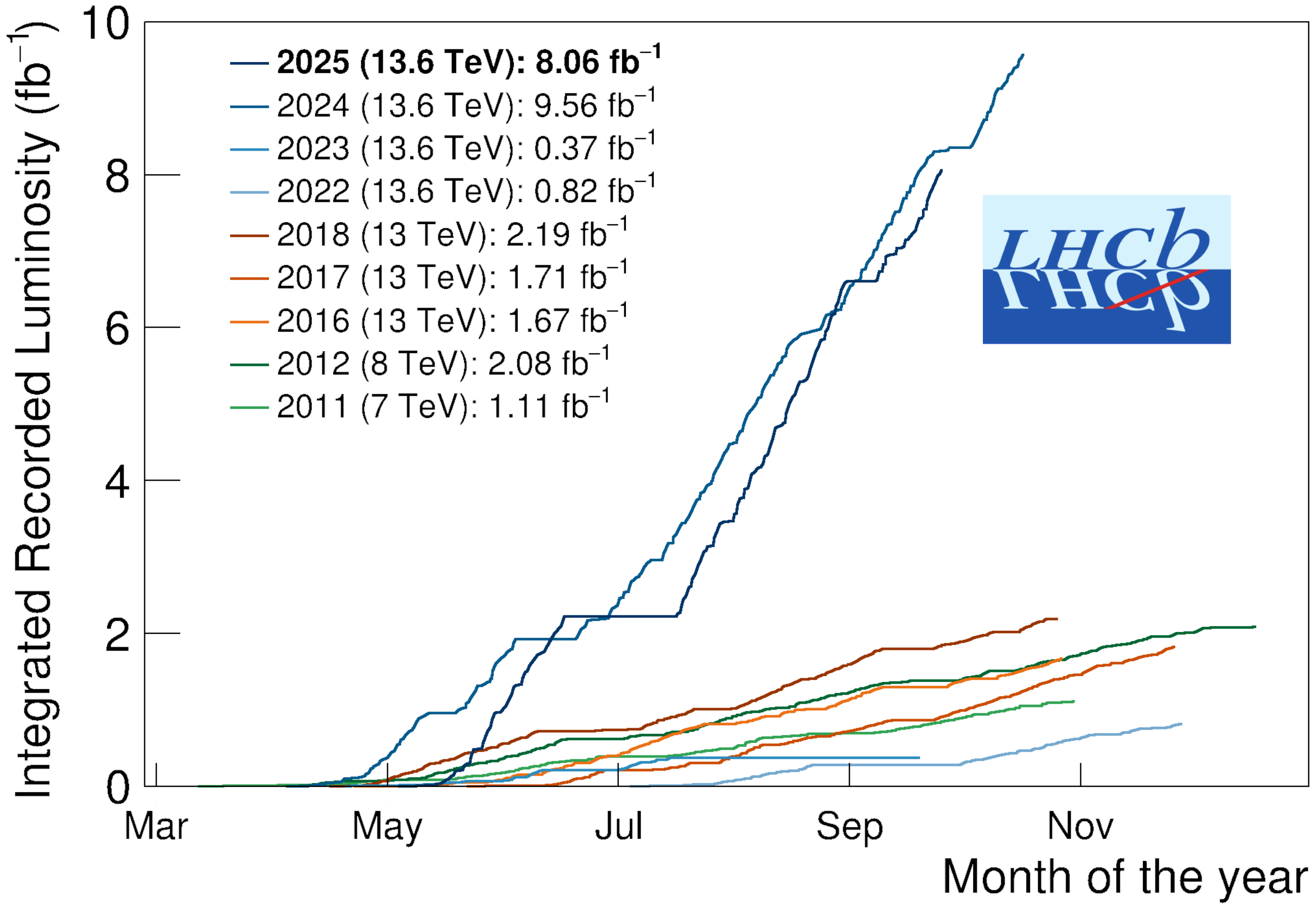
Improves by approx a factor 10 the recent best limit from Belle II [arxiv: 2504.10042]

Summary & Outlook

- Large number of new LFU tests from LHCb
  - Anomalies in charged currents still standing
  - Neutral currents show compatibility with LFU (similar deviations seen in muons and electrons)

- Many analyses still in the pipeline for Run 1 & 2

- The upgraded LHCb detector is accumulating data at much higher rate in Run 3
  - Significant improvements in statistically limited measurement
  - New possibilities for precision LFU measurements (rarer decays, finer binnings, …)

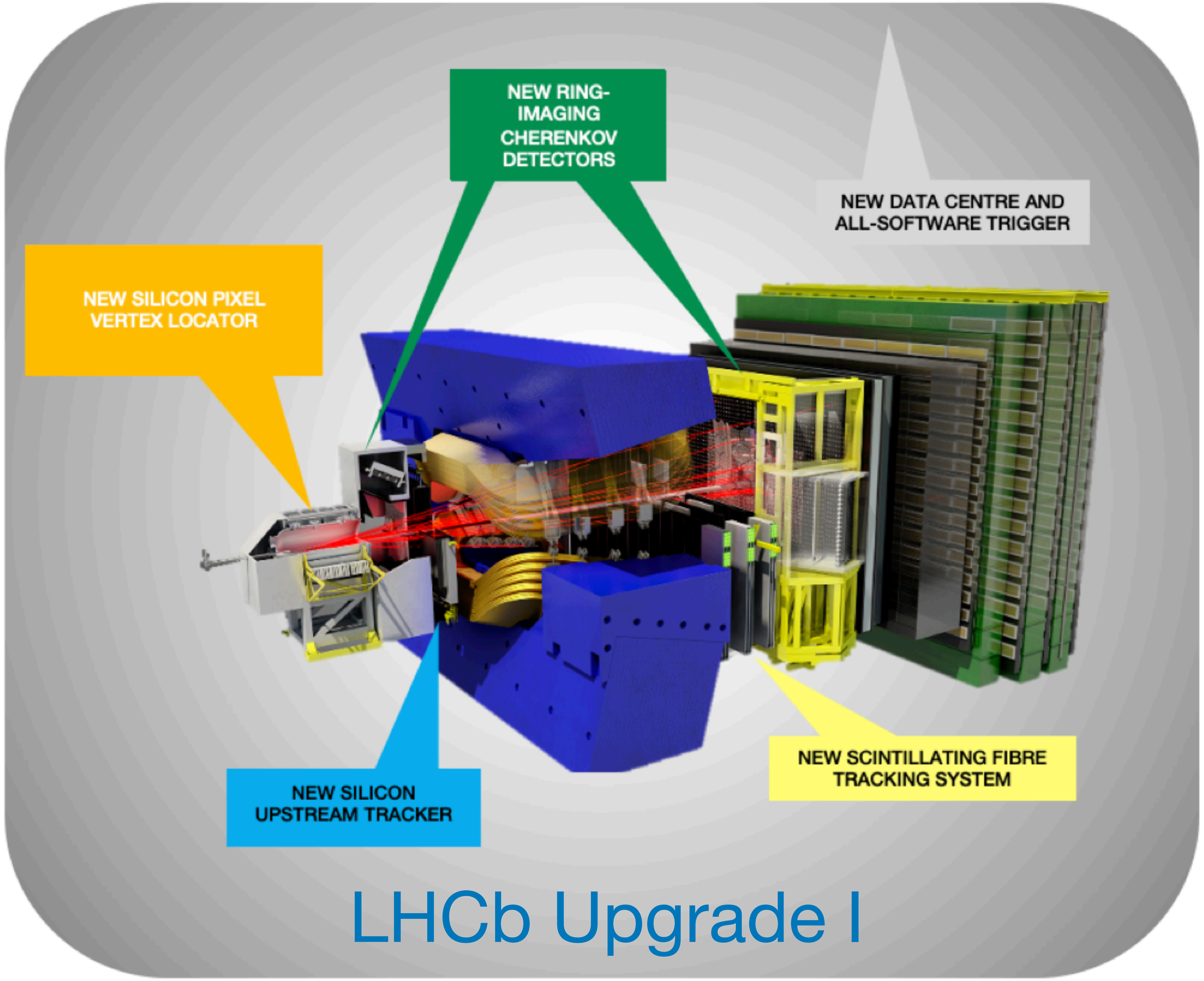


Backup

LHCb Upgrade I

The LHCb Upgrade I in Run3 and Run4

- Almost brand new detector
- Full software trigger [readout at 30 MHz]
- Accumulate at least 50/fb

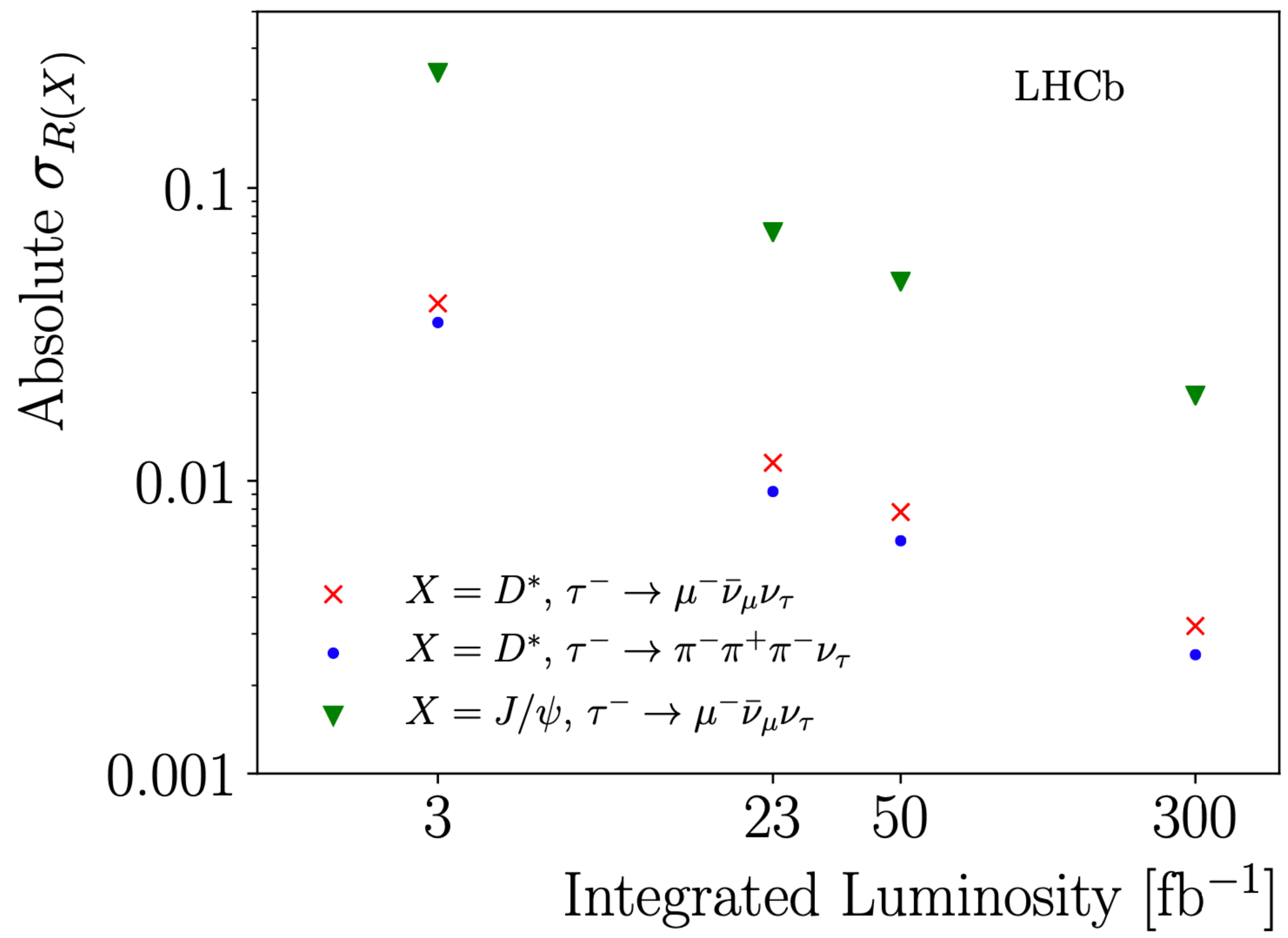


LFU with LHCb Upgrade I

[LHCb, arXiv:1808.08865]

R_X precision	$9\,\text{fb}^{-1}$	$23\,\text{fb}^{-1}$	$50\,\text{fb}^{-1}$
R_K	0.043	0.025	0.017
$R_{K^{*0}}$	0.052	0.031	0.020
R_ϕ	0.130	0.076	0.050
R_{pK}	0.105	0.061	0.041
R_π	0.302	0.176	0.117

[LHCb, arXiv:1808.08865]



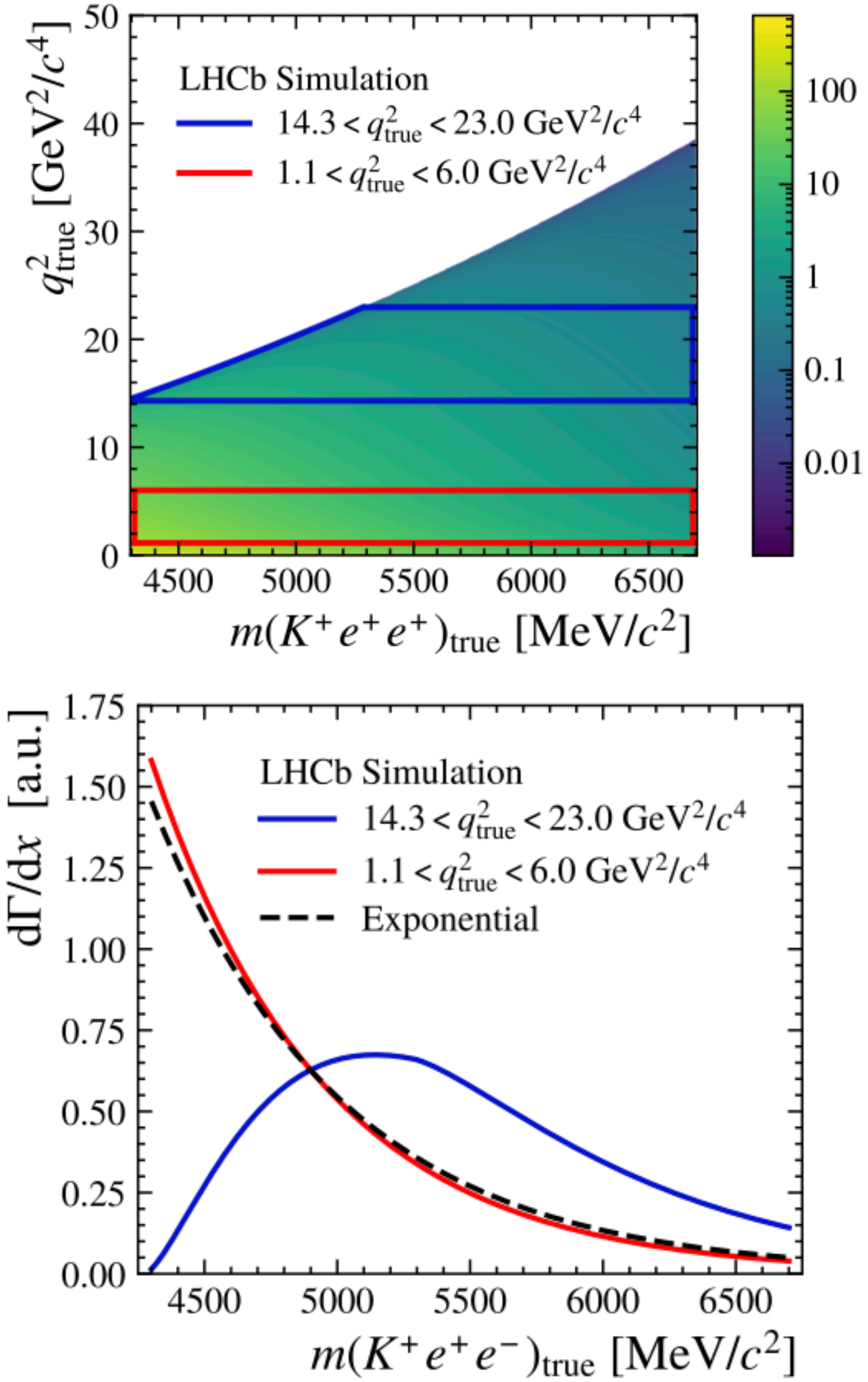
Significant increase in data opens the door to a very significant jump in precision and access to 'rarer' processes

For $b \to c\ell\nu$ transitions, apart from the statistical gain, many systematics expected to scale with luminosity [background templates, normalisation BRs,…]

Measurement of R_K at high-q^2

[JHEP 07 (2025) 198]

- Using the full Run 1 + Run 2 dataset
  - $q^2 > 14.3\ \mathrm{GeV}^2/c^4$
- Complementary to measurement at low q2
  - Expected RK value in SM and many NP scenarios is independent of q2
- Different background composition & systematics
  - Sculpting of the combinatorial background
    - Developed a parameterisation based on a phase-space model
    - Validated using control samples in data



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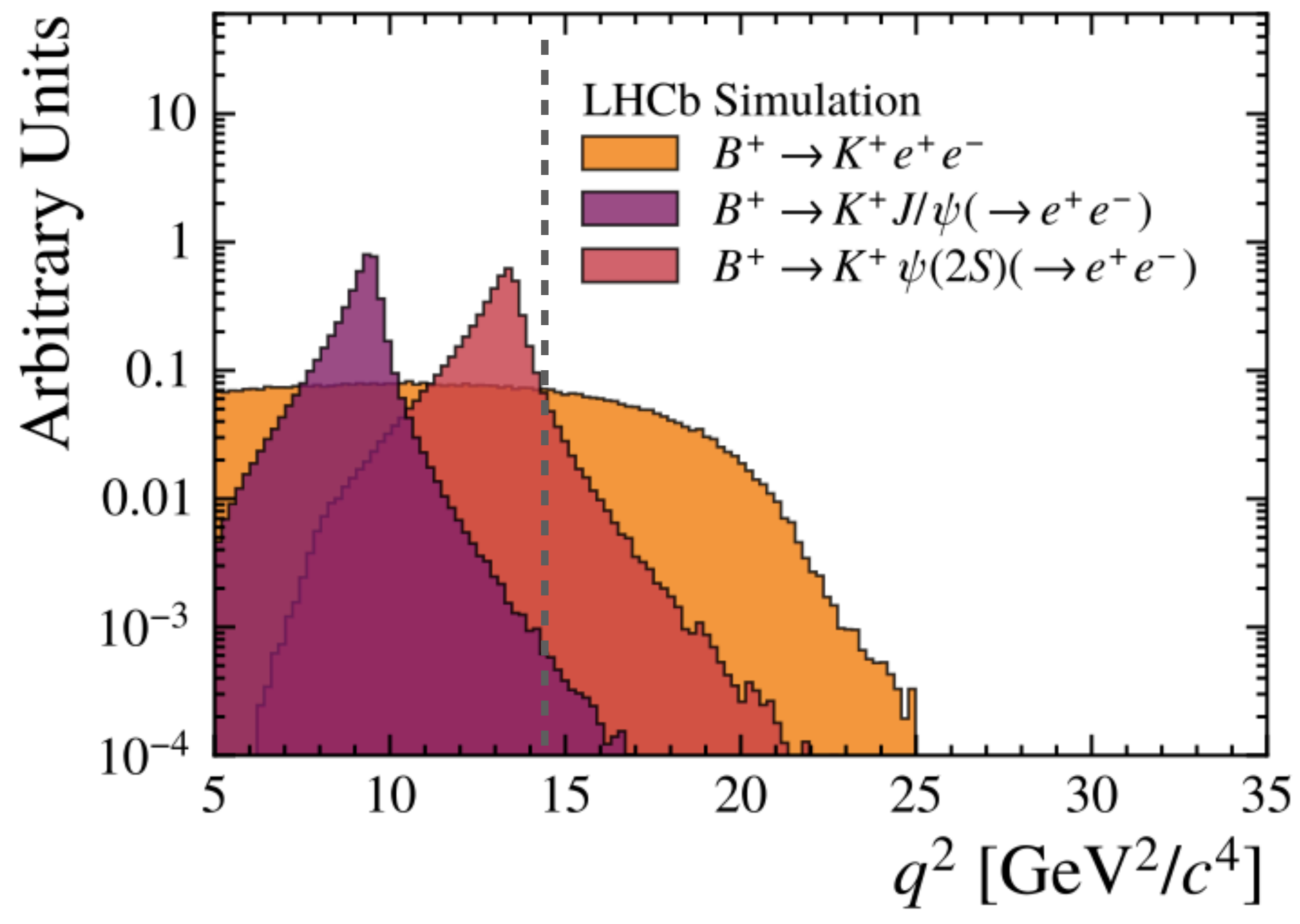
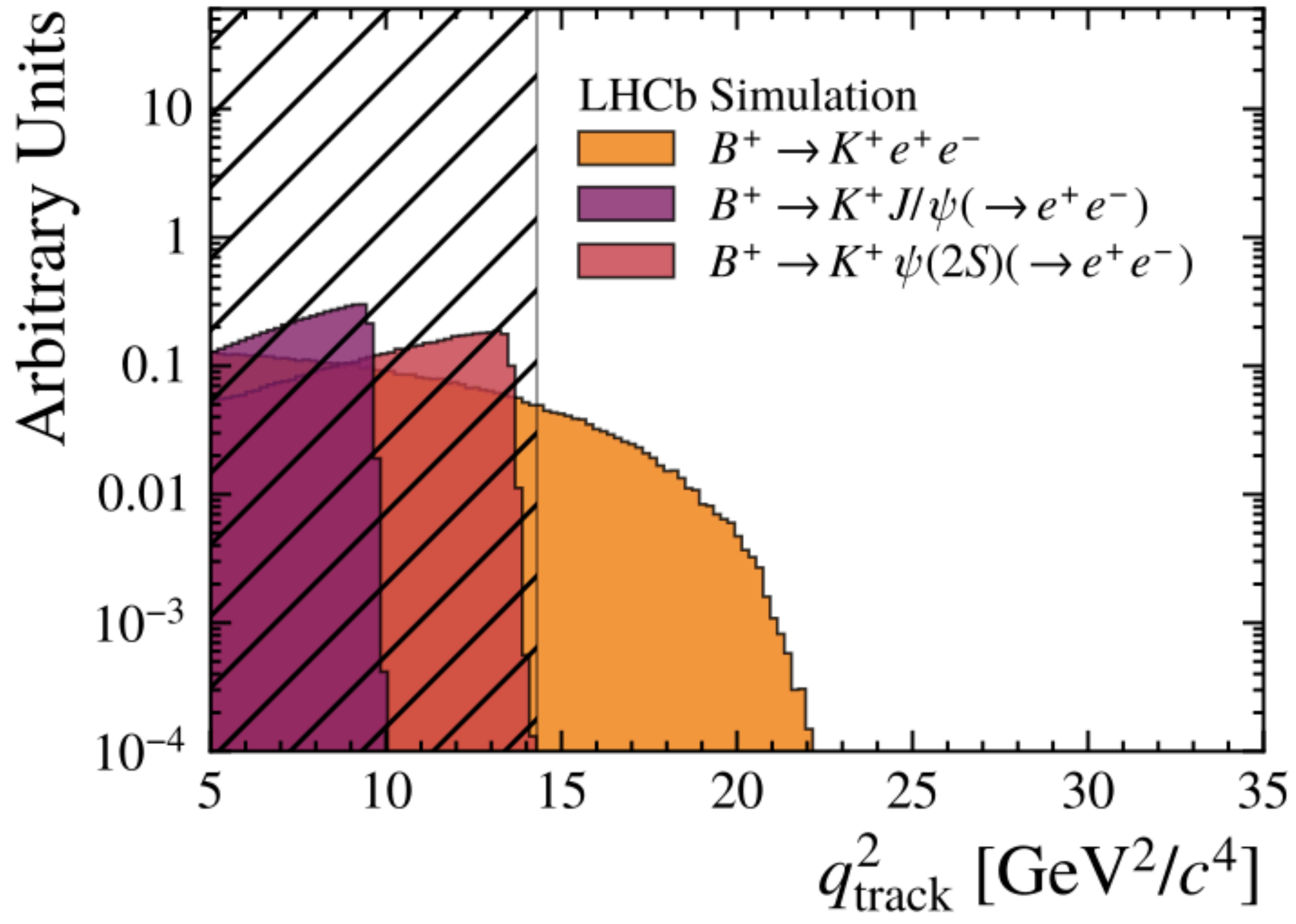
- Complementary to measurement at low q2
  - Expected RK value in SM and many NP scenarios is independent of q2
- Different background composition & systematics
  - Sculpting of the combinatorial background
  - Leakage of ψ(2S) due to erroneous added photons
    - Suppressed using q^2_{track}: q^2 calculated before bremsstrahlung recovery





Measurement of R_K at high-q^2

[JHEP 07 (2025) 198]

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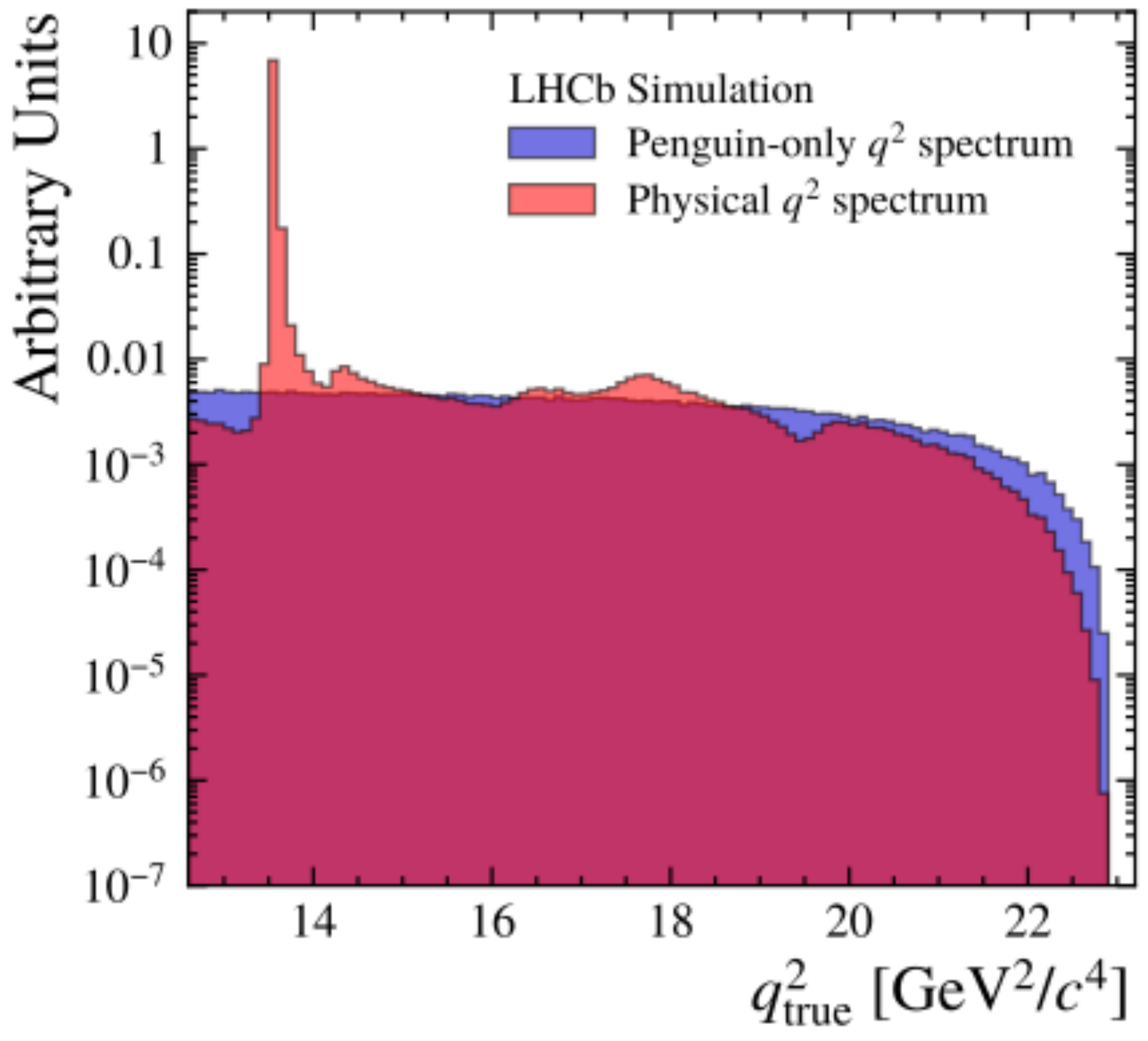
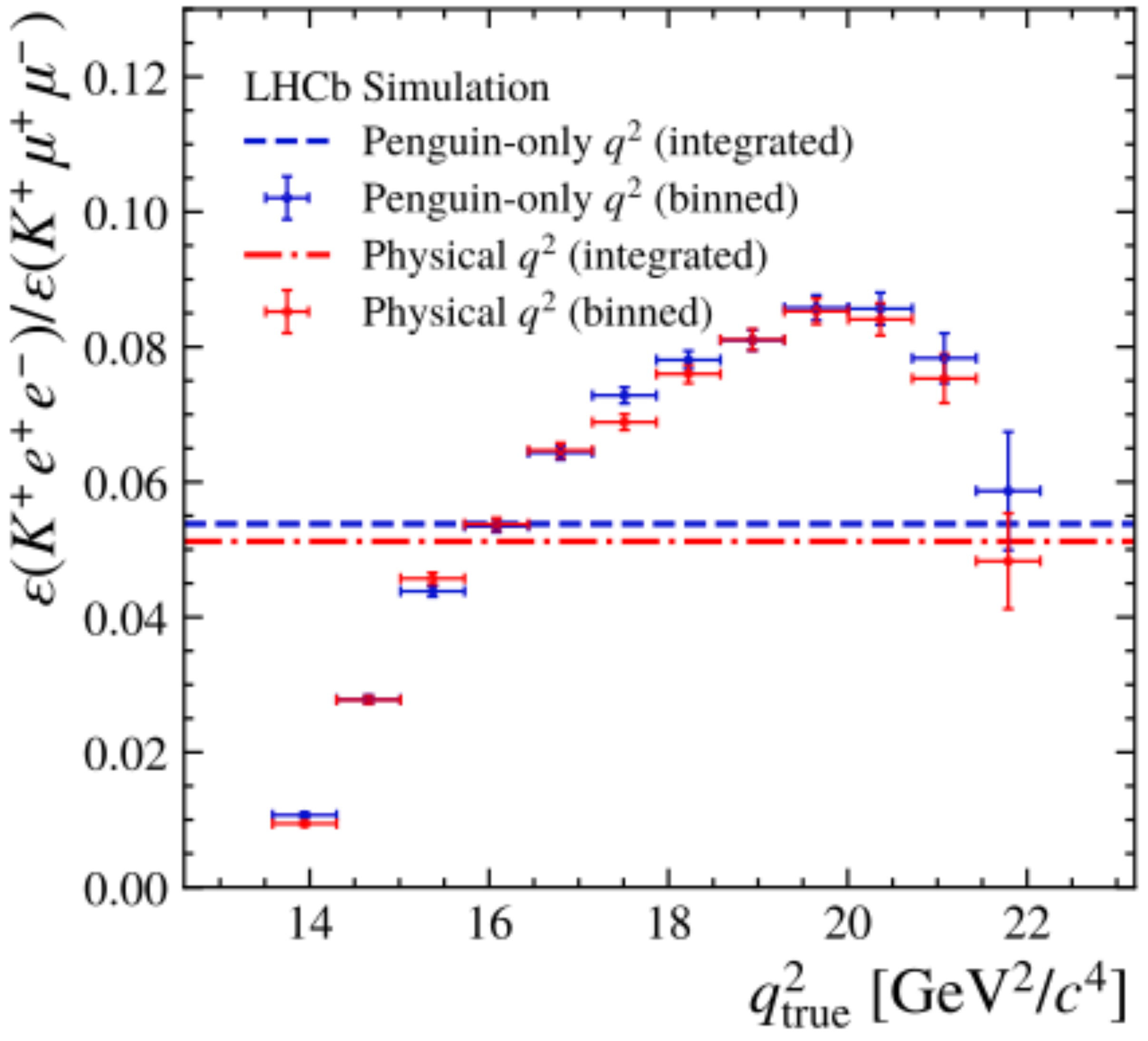
  - $q^2 > 14.3\ \text{GeV}^2/c^4$
- Complementary to measurement at low q2
  - Expected RK value in SM and many NP scenarios is independent of q2
- Different background composition & systematics
  - Sculpting of the combinatorial background
  - Leakage of ψ(2S) due to erroneous brem. recovery
  - Non-uniform efficiency ratio vs q^2
    - Reweighing procedure to eliminate model dependence





$B^0 \to K^{*0} e^+ e^-$ angular analysis

[JHEP 06 (2025) 140]

- Global fit to all observables, allowing only for a C9 shift, shows compatibility between muons and electrons

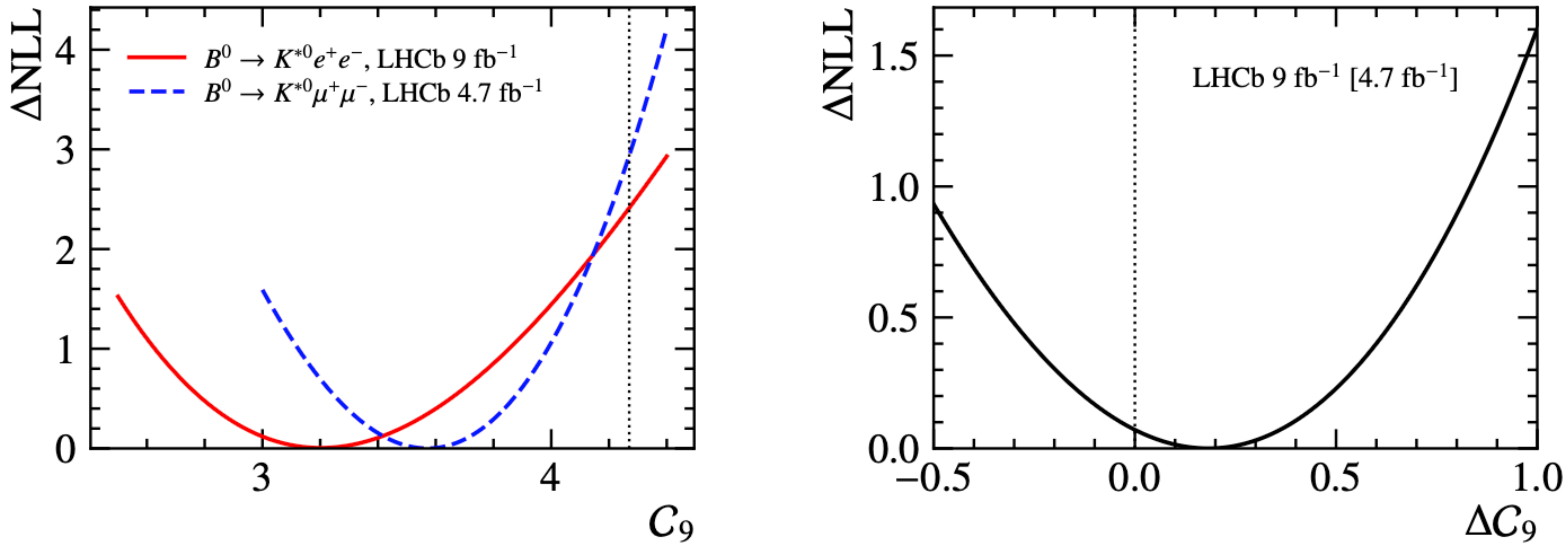


Figure 8. Negative log-likelihood scan of (left) C_9^e and C_9^μ and (right) $\Delta C_9 = C_9^{(\mu)} - C_9^{(e)}$. The dotted vertical line corresponds to the SM prediction [78, 79].

R(D+) and R(D*+) with muonic τ

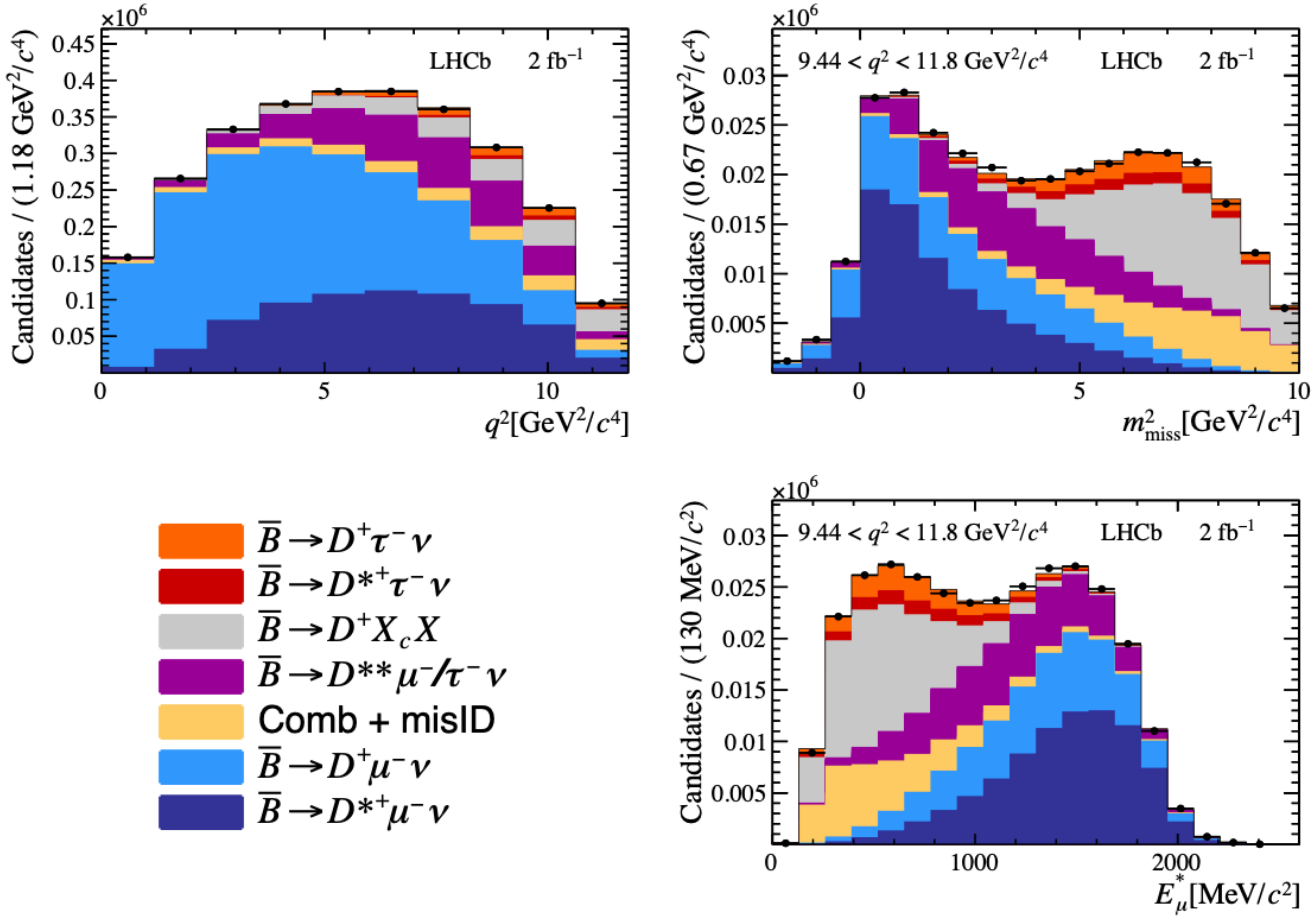
PRL 134 (2025) 061801

- Measure $\mathcal{B}(B^+ \to D^{(*)+}\tau^-\nu_\tau) / \mathcal{B}(B^+ \to D^{(*)+}\mu^-\nu_\mu)$
  - $D^+ \to K^+\pi^-\pi^+$
  - $D^{(*)+} \to D^+\pi^0$ (π^0 not reconstructed)
- Three dimensional template fit:
  - $q^2 = (\mathbf{p}_B - \mathbf{p}_D)^2$
  - Energy of the muon in the B rest frame (E^*_μ)
  - Missing mass squared ($m^2_{\rm mis}$)
- Result in good agreement with the SM prediction and world average:

$$R(D^+) = 0.249 \pm 0.043 \ (\text{stat}) \pm 0.047 \ (\text{syst})$$

$$R(D^{*+}) = 0.402 \pm 0.081 \ (\text{stat}) \pm 0.085 \ (\text{syst})$$

with correlation ρ = -0.39.



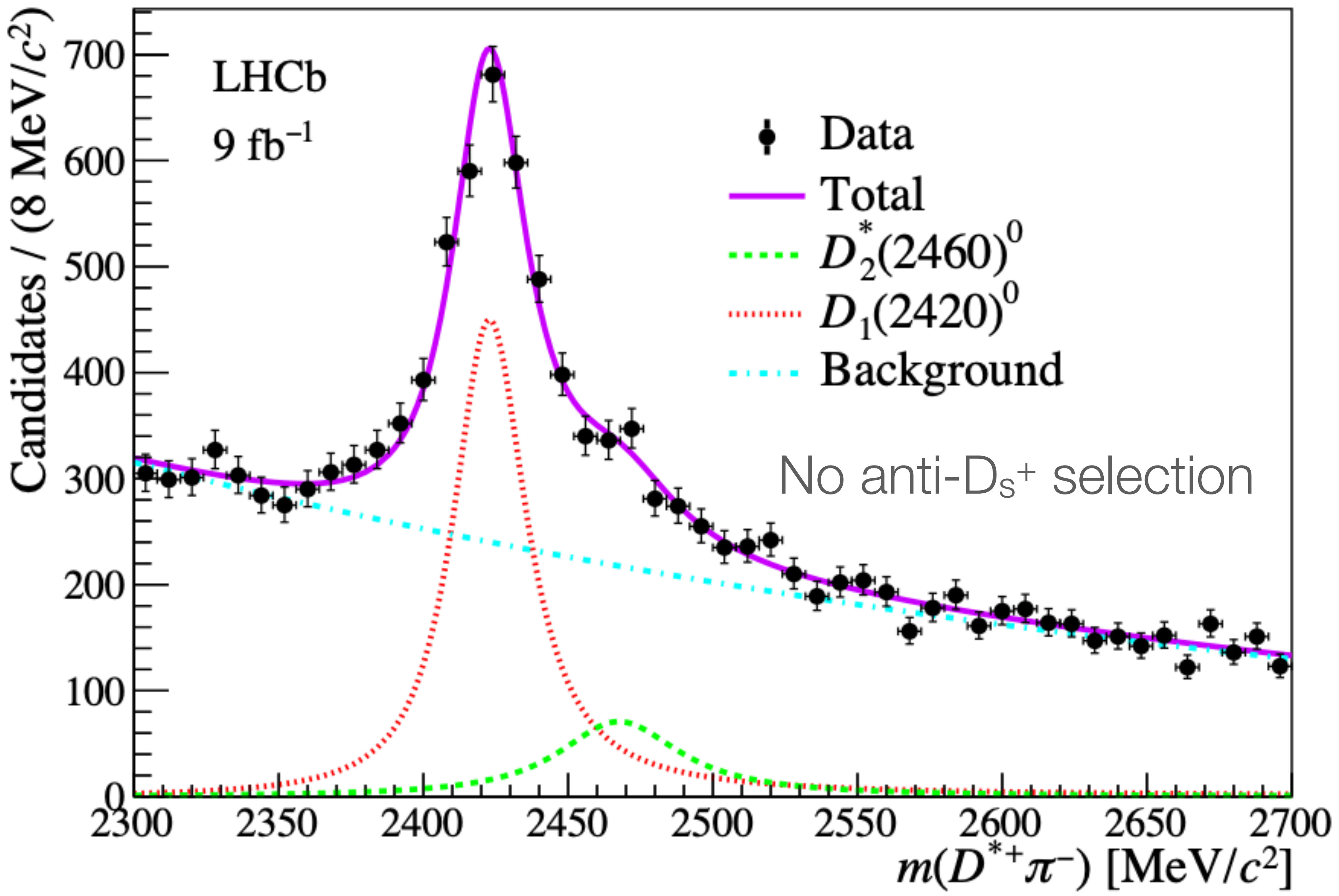
Signal and background templates extracted from simulation

- Uncertainties associated to FF parameters included in the fit using RooHammerModel [arXiv:2007.12605]

Study of $B^+ \to D^{**0}\, \tau^+\, \nu$ decays

PRL 135 (2025) 021802

- Large systematic in R(D(*)) measurement comes from $D^{**} \to D^{*+}\pi^-$ feed-down in the τ-mode
  - D^{**} : $D_1(2420)^0, D_2(2460)^0, D_1'(2400)$
  - Wide $D_1'(2400)$ cannot be distinguished from combinatorial background
- Using hadronic τ, this analysis provides
  - Measurement of $\mathscr{B}(B^- \to D_{1,2}^{**0}\, \tau^-\, \bar{\nu}_\tau) \times \mathscr{B}(D_{1,2}^{**0} \to D^{*+}\pi^-)$
  - Test of LFU by comparing to $\mathscr{B}(B^- \to D_{1,2}^{**0}\, \mu^-\, \bar{\nu}_\mu)$
- Three multivariate classifiers discriminate against:
  - Fake D** candidates
  - 5-prong D_s^+ decays
  - $D_s^+ \to \pi\pi\pi X$ decay misidentified as taus (anti-D_s^+)



PDG: $D_1'(2400)^0$, $m = 2412 \pm 9$ MeV/c², $\Gamma = 314 \pm 29$ MeV/c²

$D_1(2420)^0$, $m = 2422.1 \pm 0.6$ MeV/c², $\Gamma = 31.3 \pm 1.9$ MeV/c²

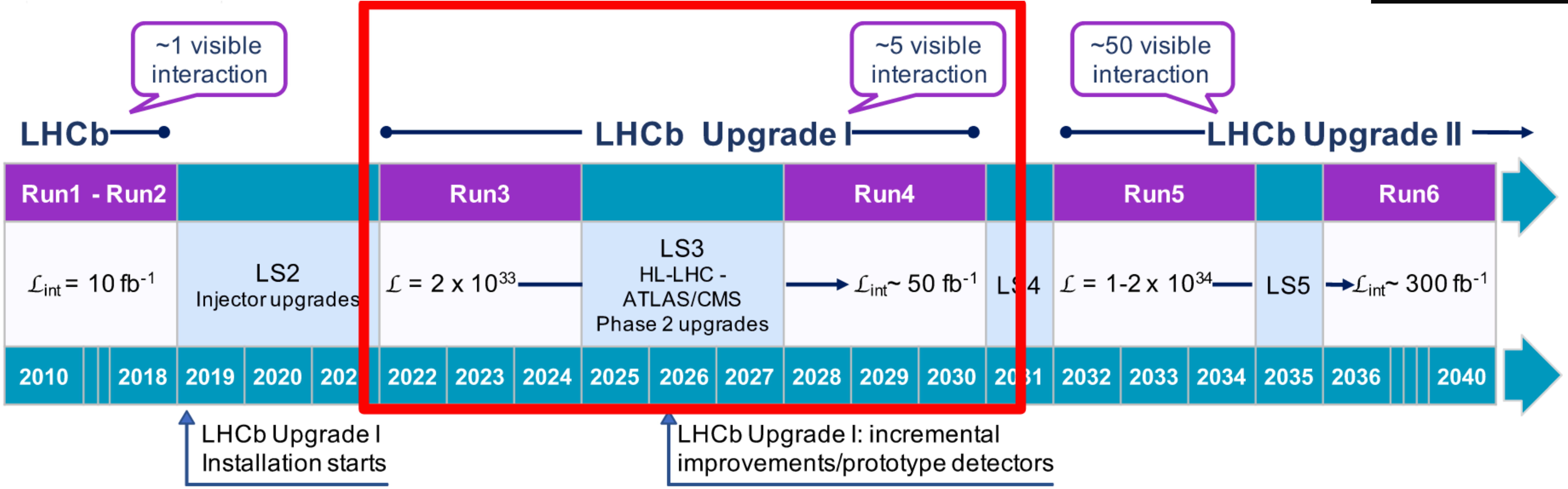
$D_2(2460)^0$, $m = 2461.1 \pm 0.8$ MeV/c², $\Gamma = 47.3 \pm 0.8$ MeV/c²

LHCb Upgrade II

LHCb Upgrade II will profit from the boost in Lumi from HL-LHC

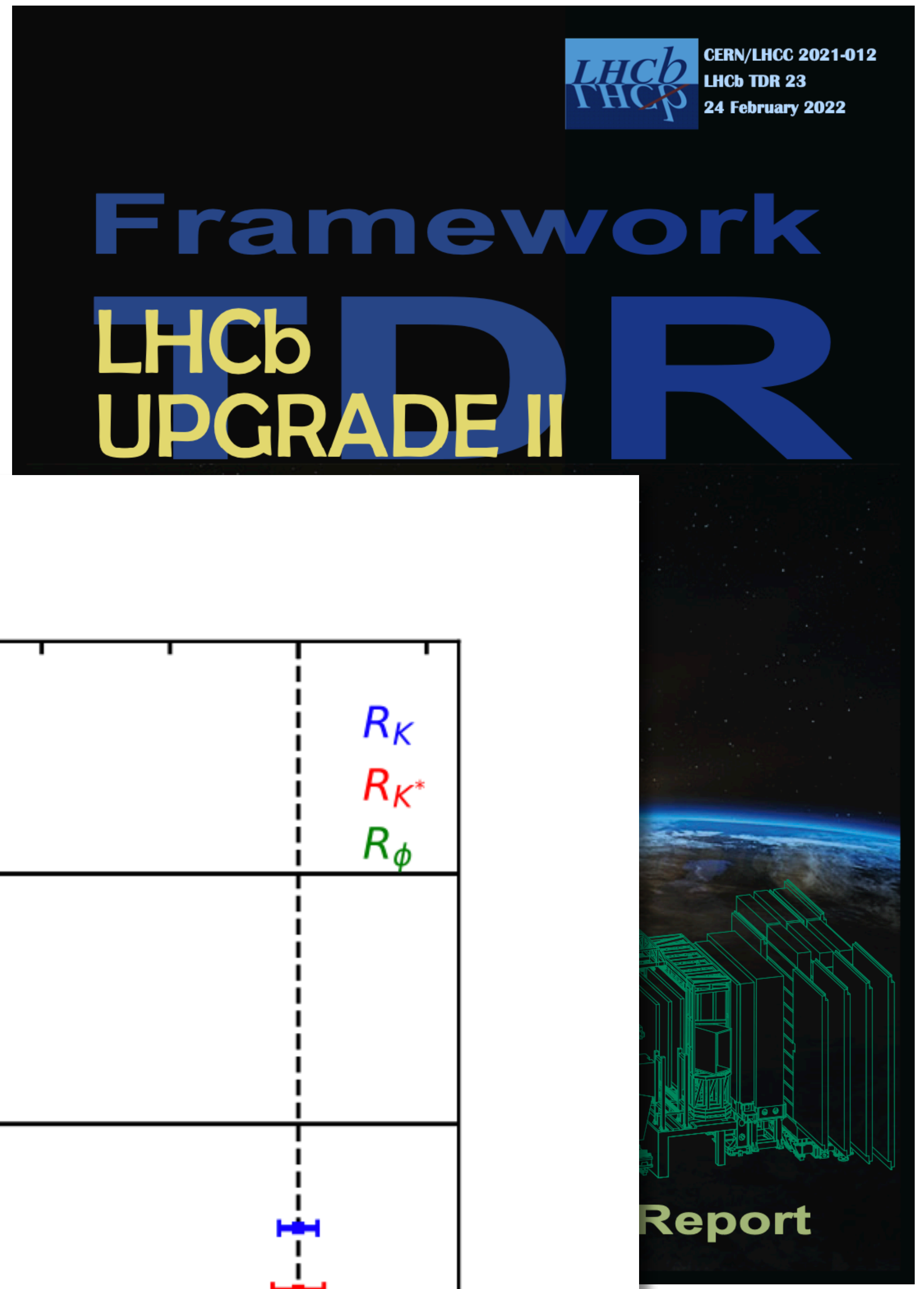
- Maintain performance in a much more challenging environment [new technologies, adding timing information]
- Expect to collect 10x more data than phase I

[LHCb, CERN-LHCC-2021-012]



LHCb Upgrade II

CC-2021-012]



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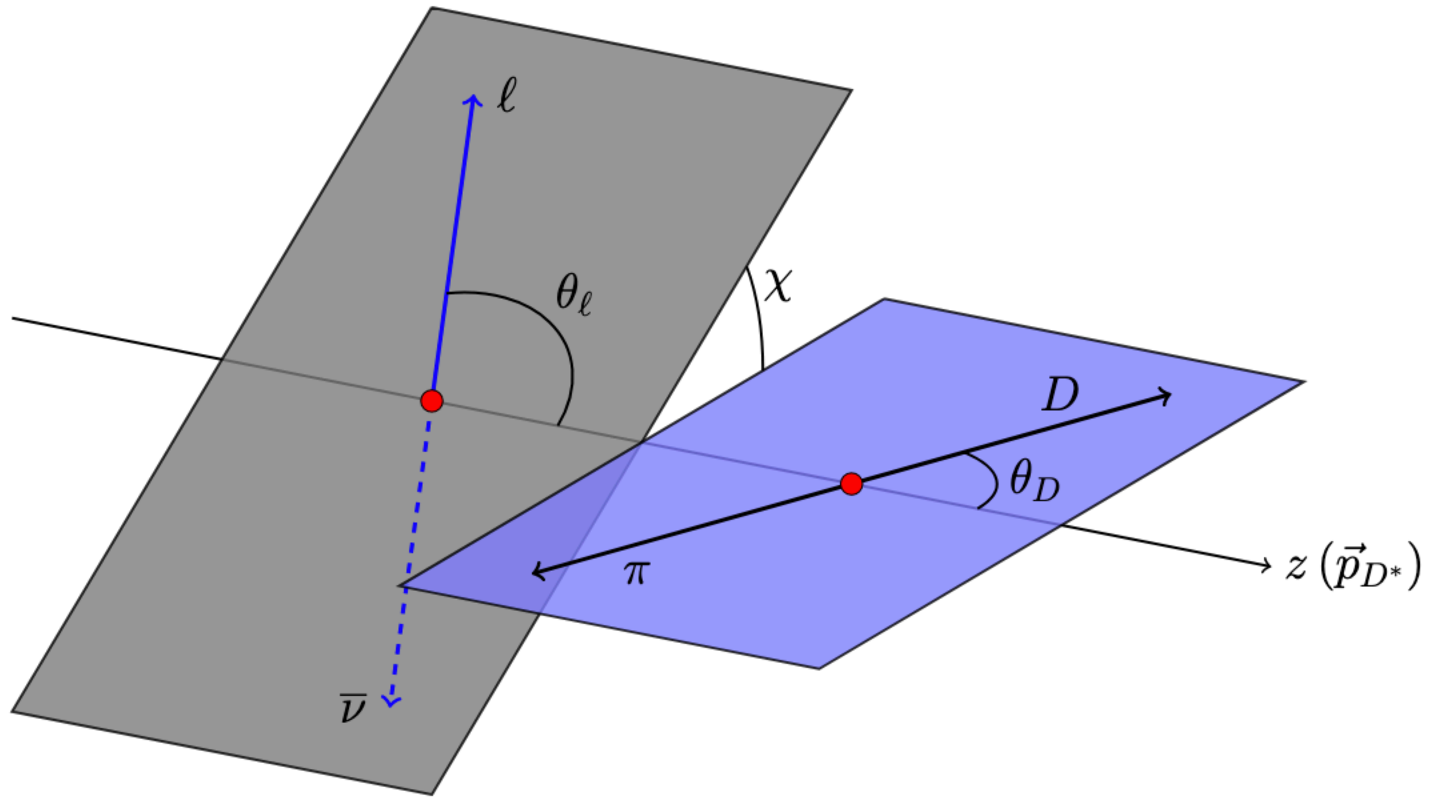
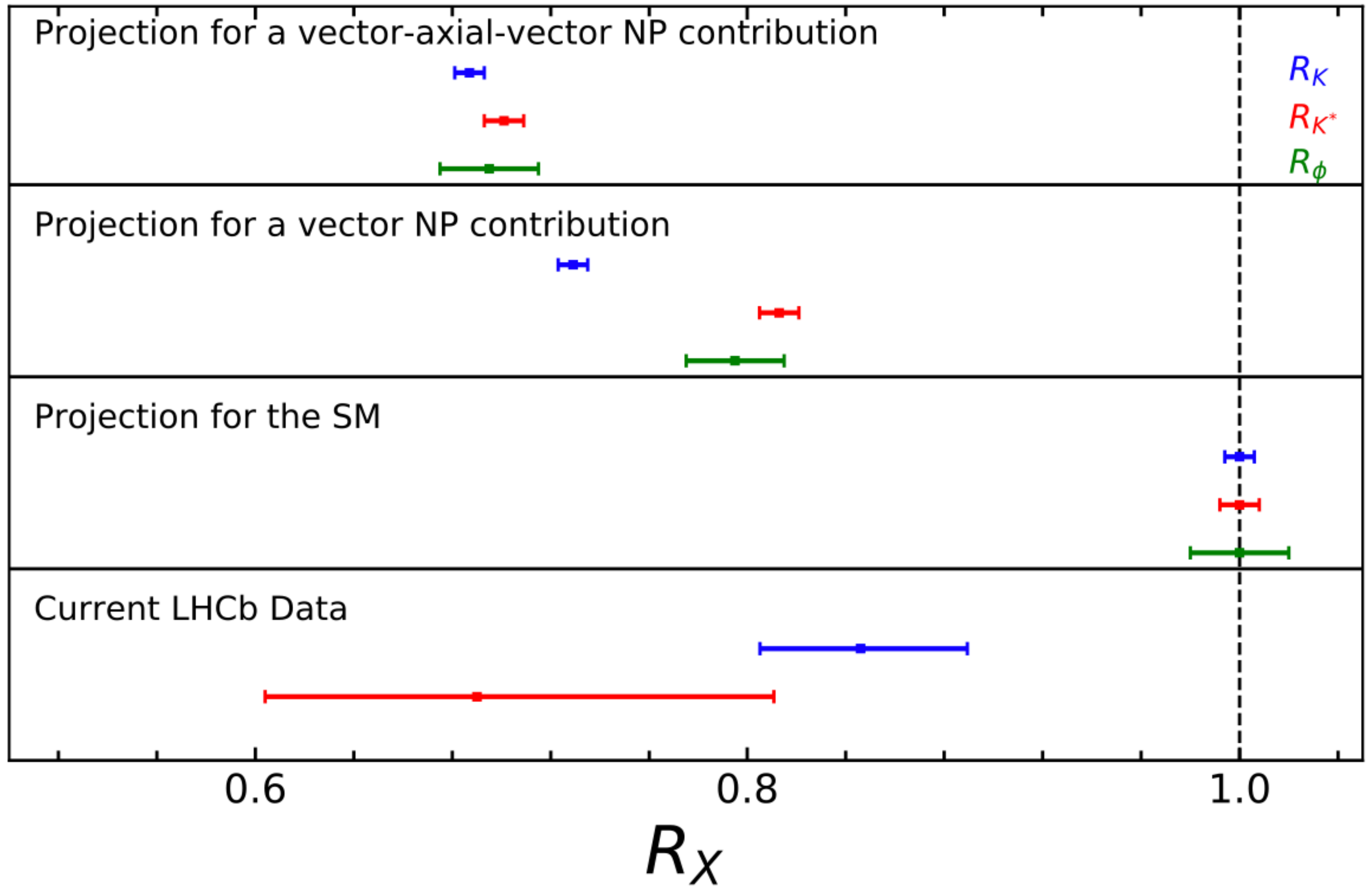


Precision measurements of amplitudes for B->D* τ ν



Clearly distinguish New Physics scenarios

LHCb Upgrade I
Installation starts

LHCb Upgrade I: incremental
improvements/prototype detectors