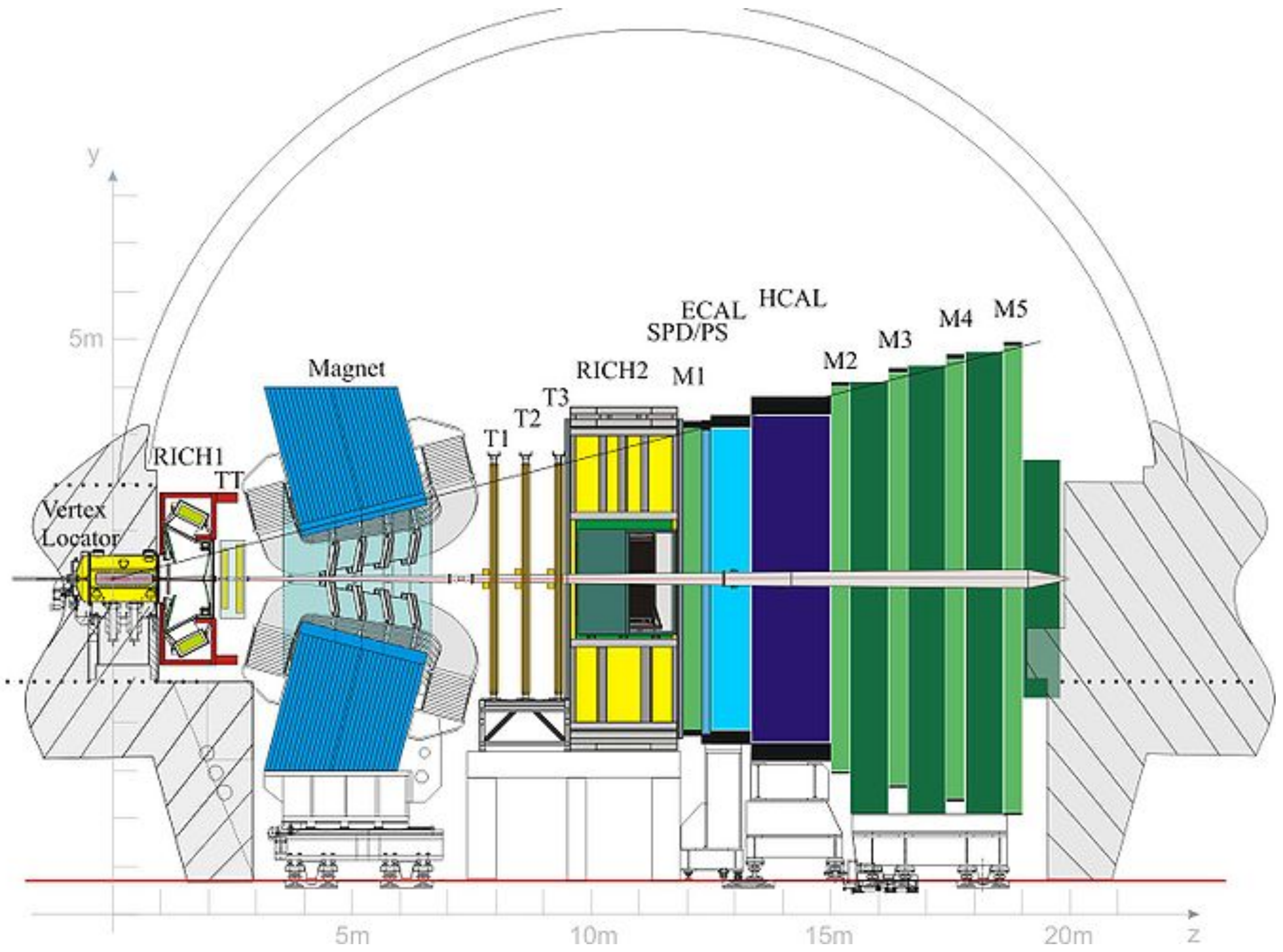
Latest news from LHCb - LFU

Flavour at the crossroads 2022

Paula Álvarez Cartelle, University of Cambridge

The LHCb detector

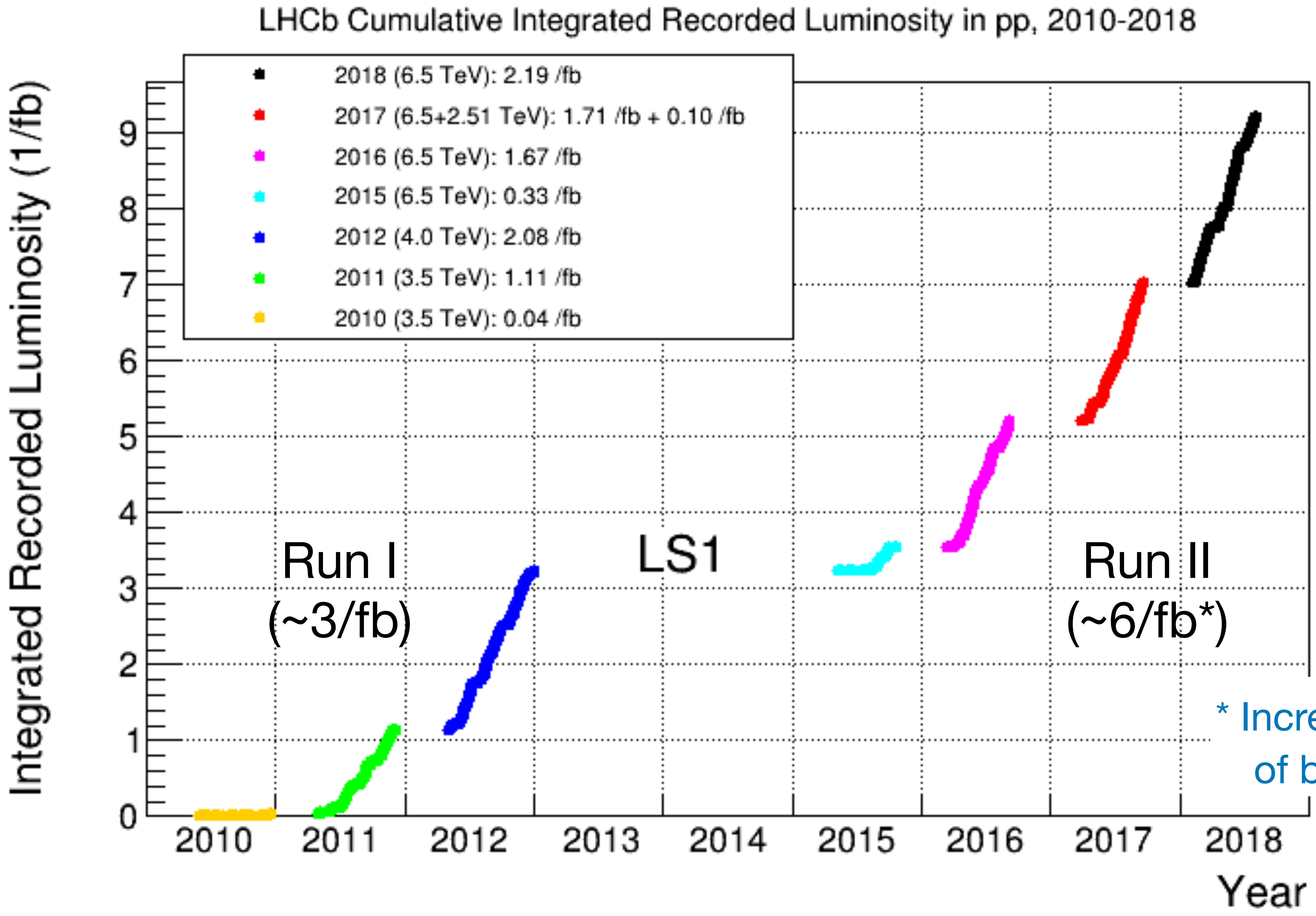


- General purpose detector in the forward direction [flavour, EW, QCD, heavy ions…]

- 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

The LHCb dataset

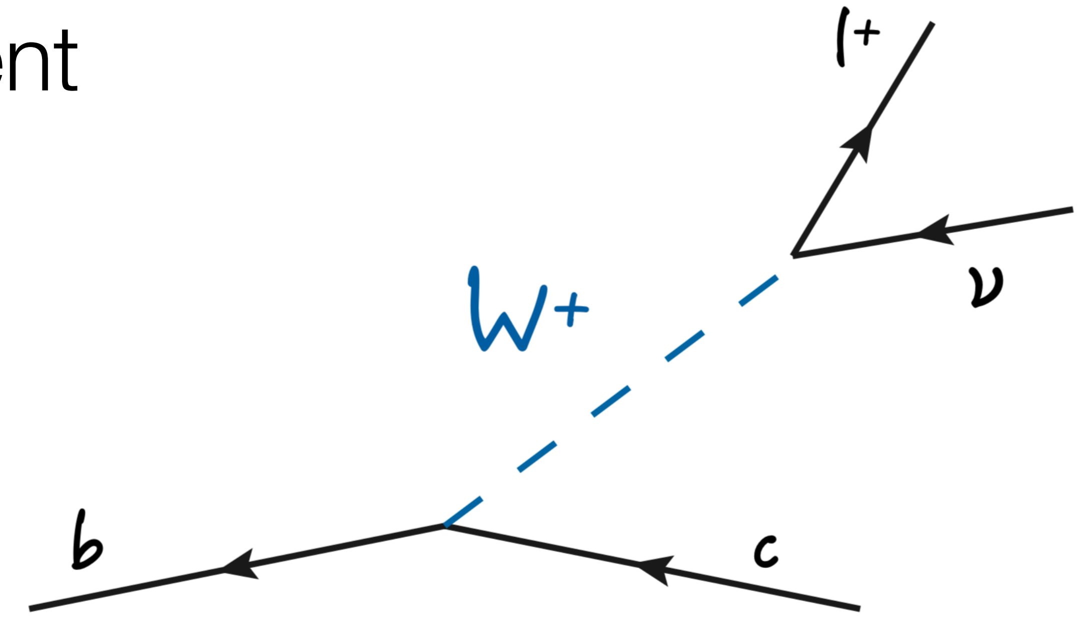


* Increased $\sqrt{s} \Rightarrow \sim 2\times$ number of b- and c- hadrons cf. Run I

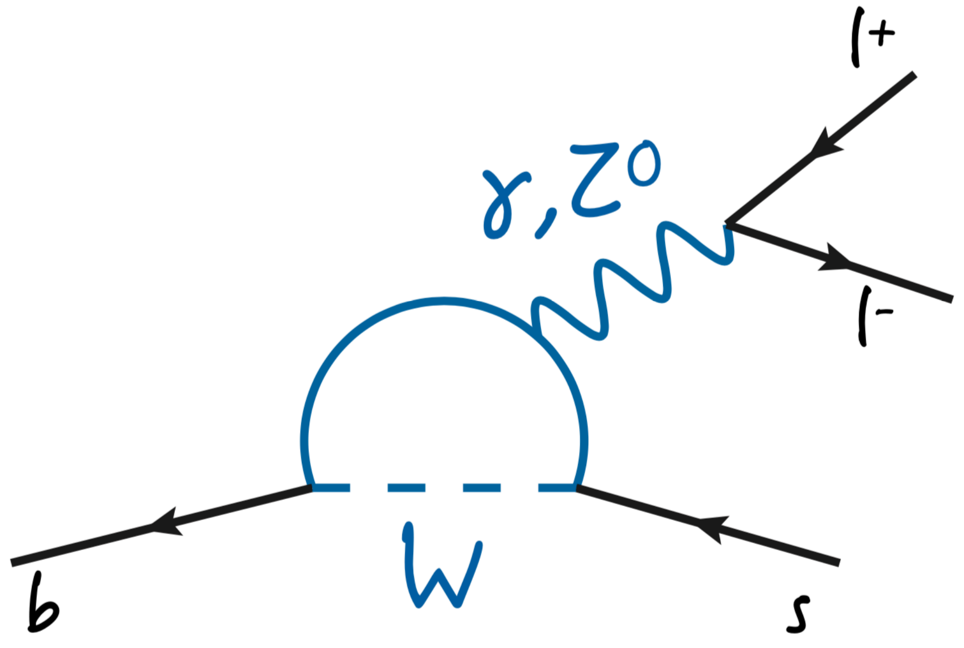
Lepton Flavour Universality

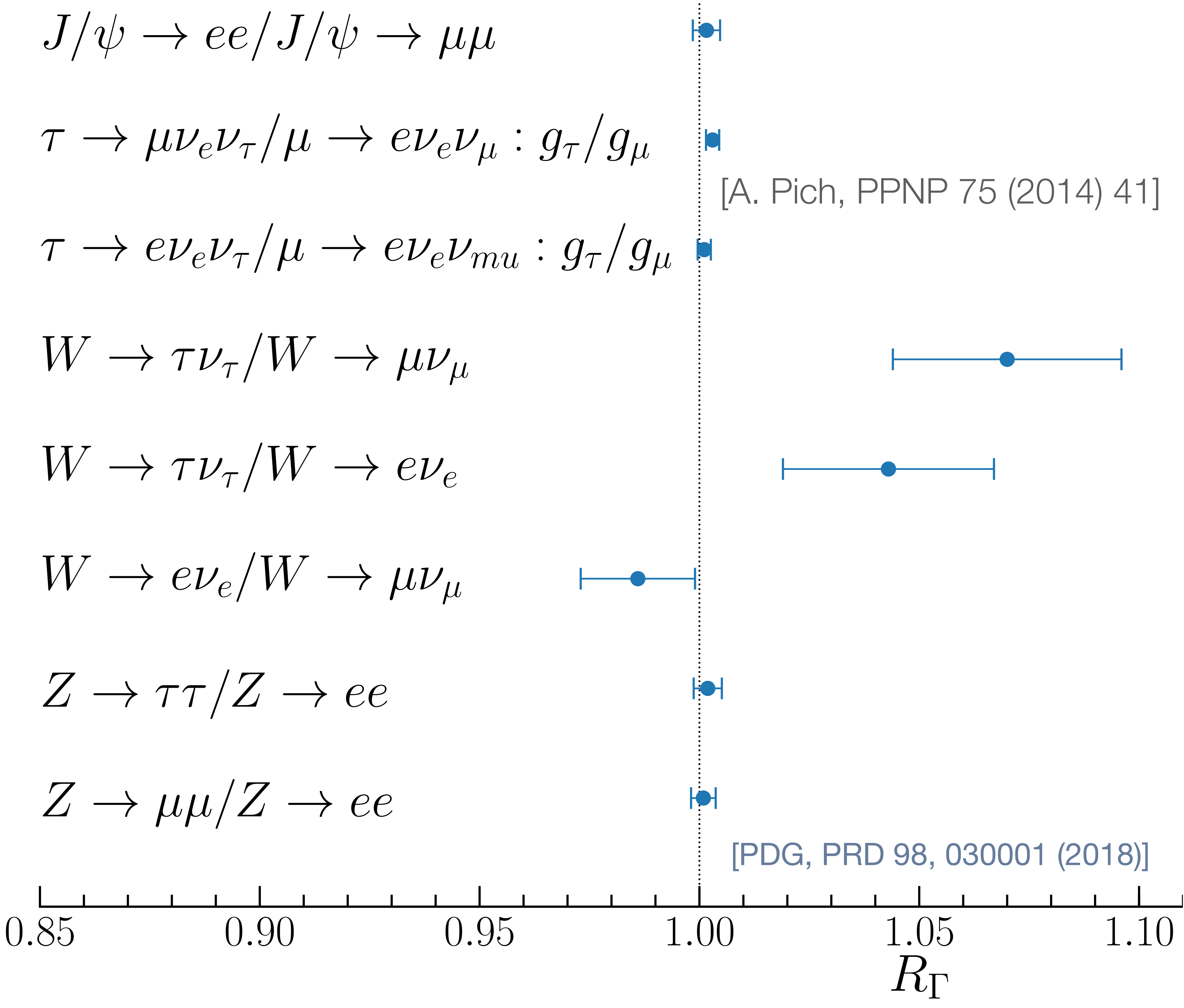
- In the Standard Model the couplings of the gauge bosons are lepton universal ⇒ provides a clean probe for New Physics

- Tests in **B-meson decays show some anomalies**
  - Flavour Changing Charged Current
    b→cℓν decays (tree-level)



  - Flavour Changing Neutral Current
    b→sℓℓ transitions (loop-level)



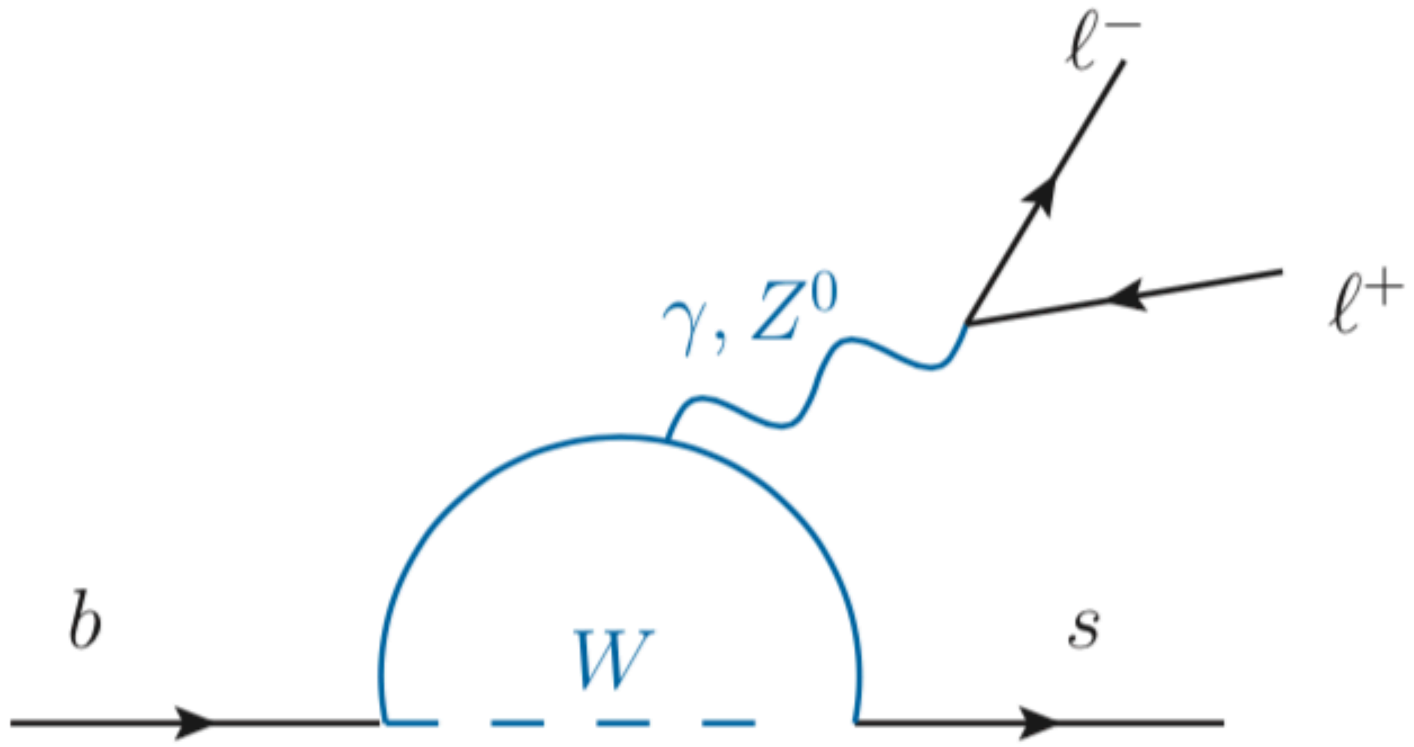


Neutral currents

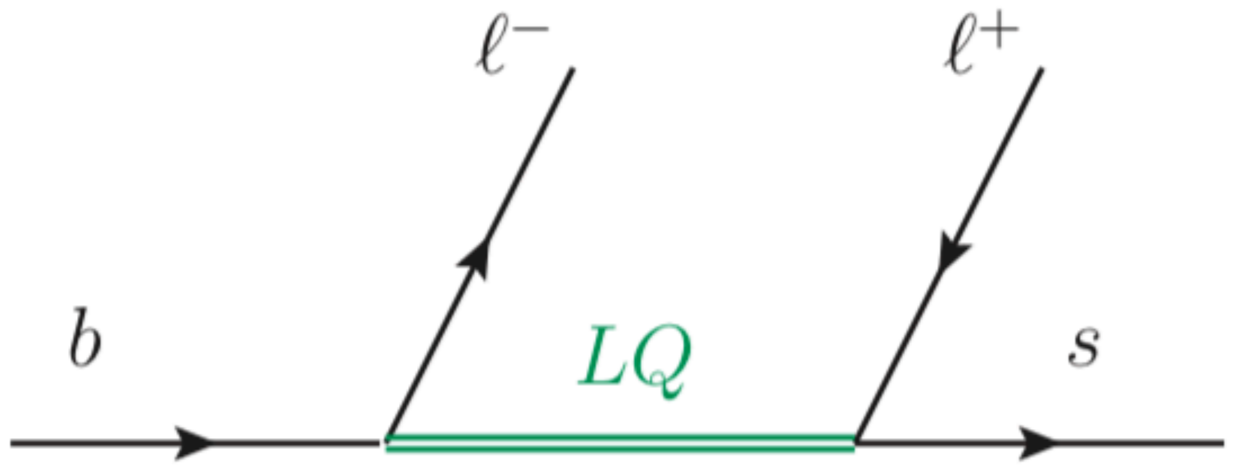
$b \to s\ \ell^+ \ell^-$ decays

Suppressed in the SM

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

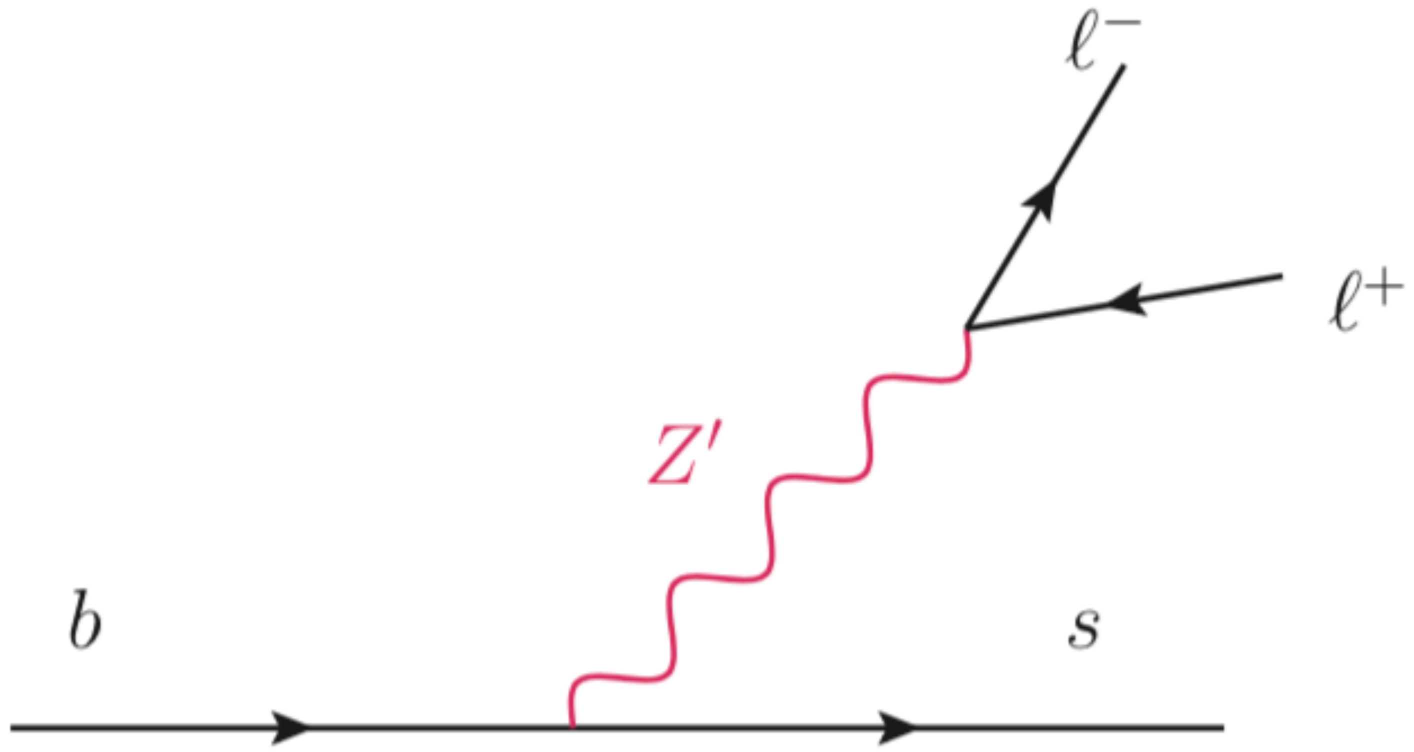


FCNC transitions, such as $b \to s(d)\ell\ell$ decays, are excellent candidates for indirect NP searches

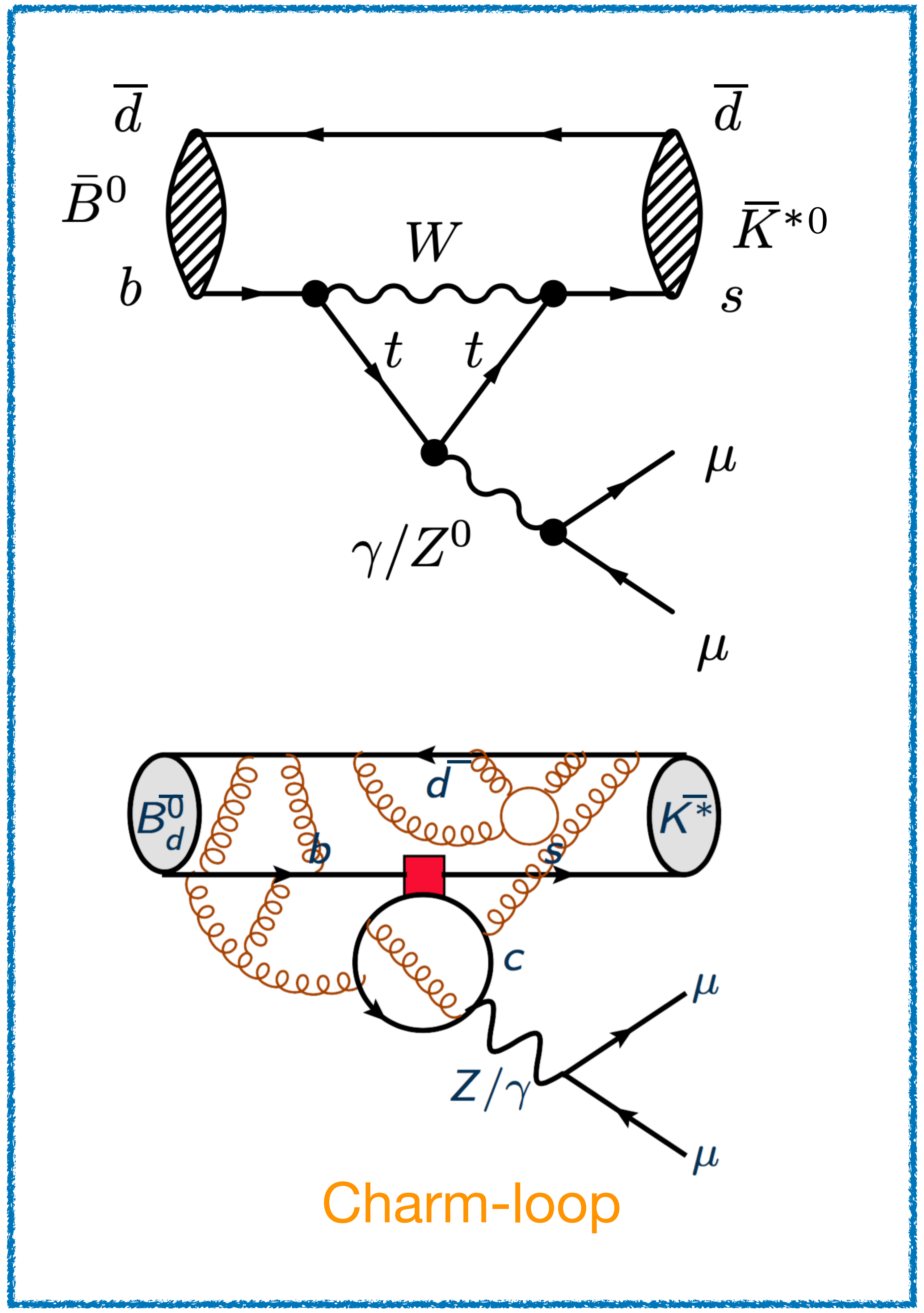


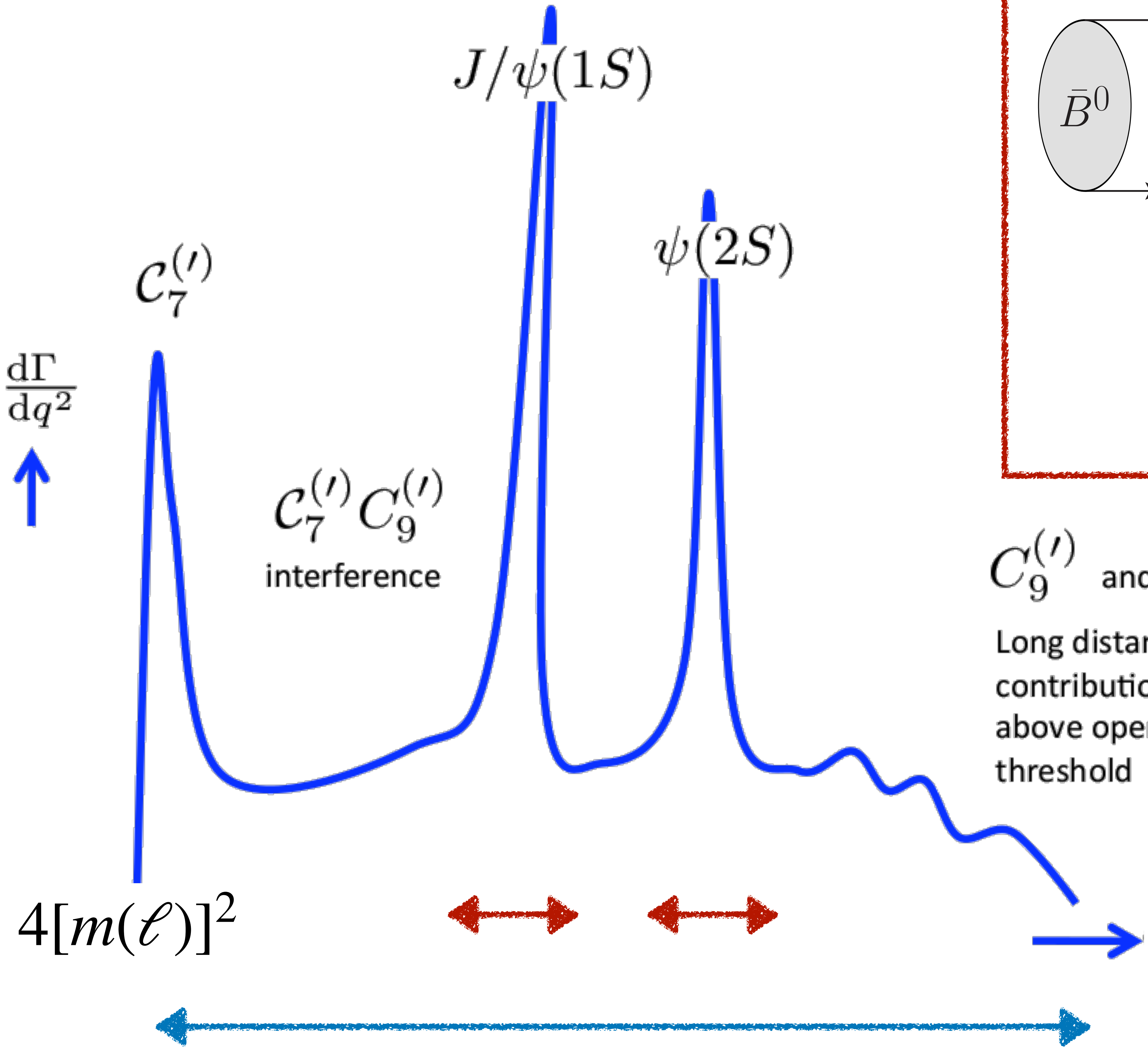
Rare *B* decays offer rich phenomenology:

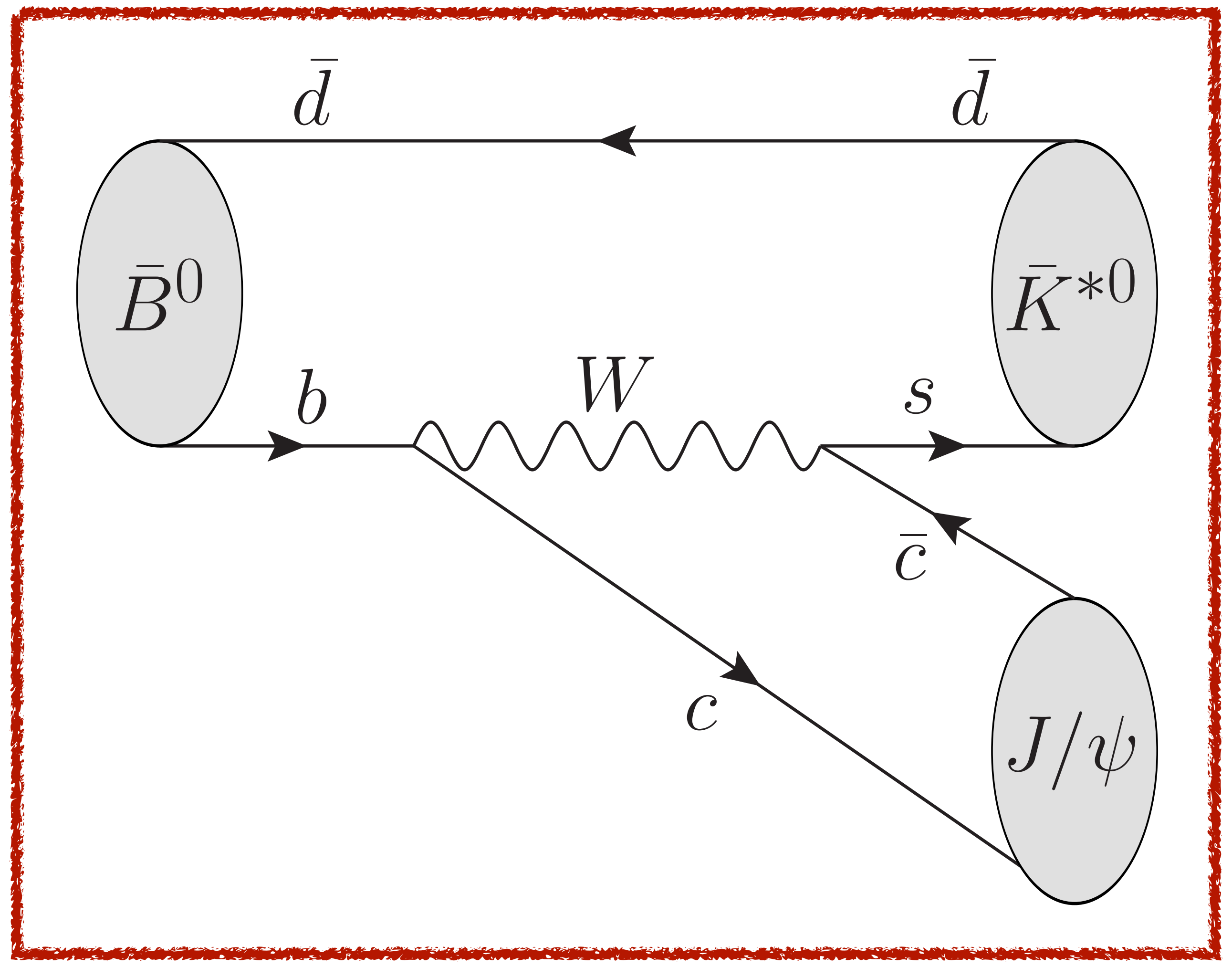
- Branching ratios, angular observables, LFU ratios…



The di-lepton spectrum







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

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

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

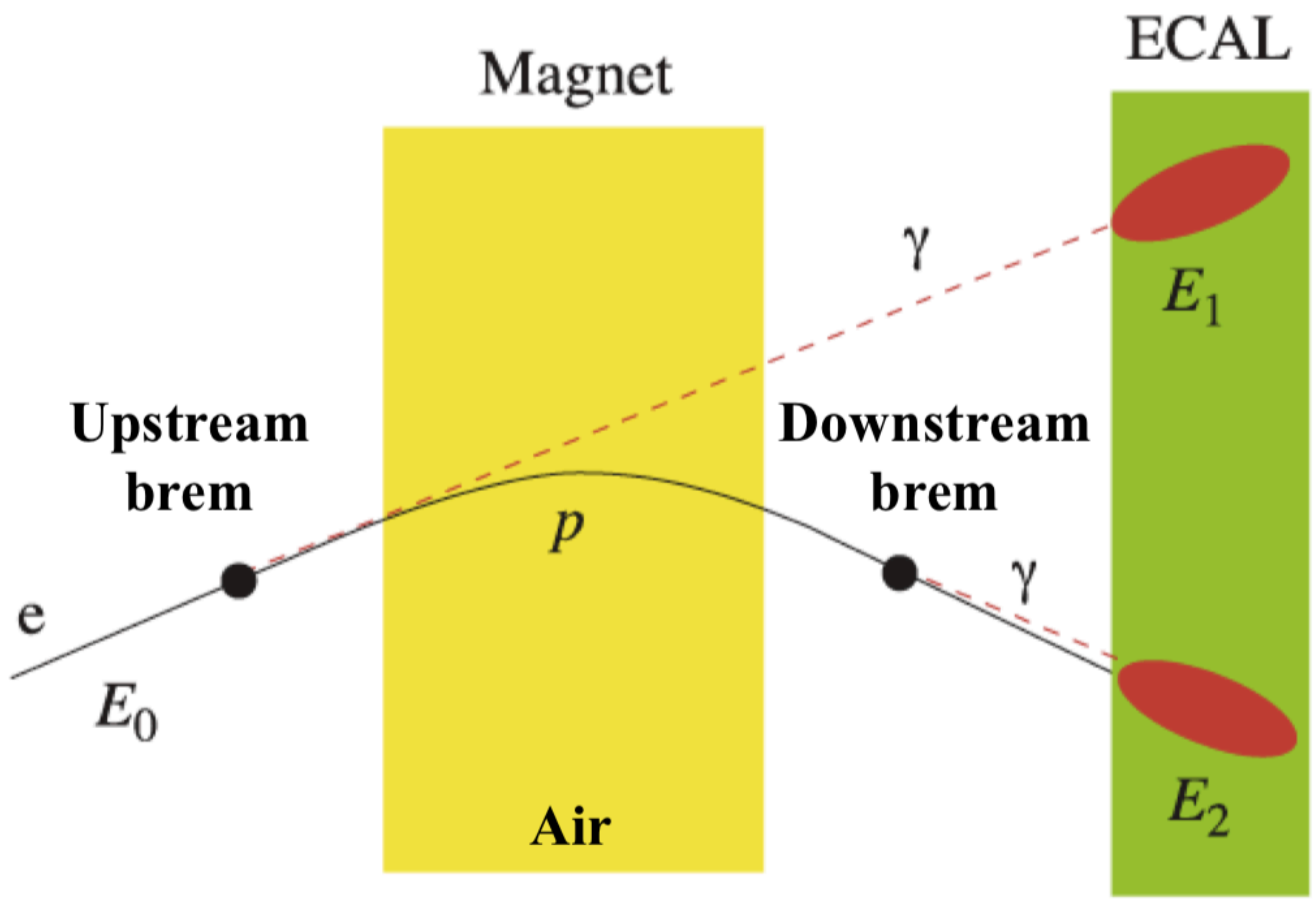
- Ratios of muons/electrons are extremely well predicted in the SM
  - Hadronic uncertainties of O(10-4)
  - QED uncertainties can be O(10-2)
- Any statistically significant deviation from 1 is a sign of New Physics

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)

See Martino's talk tomorrow for more details

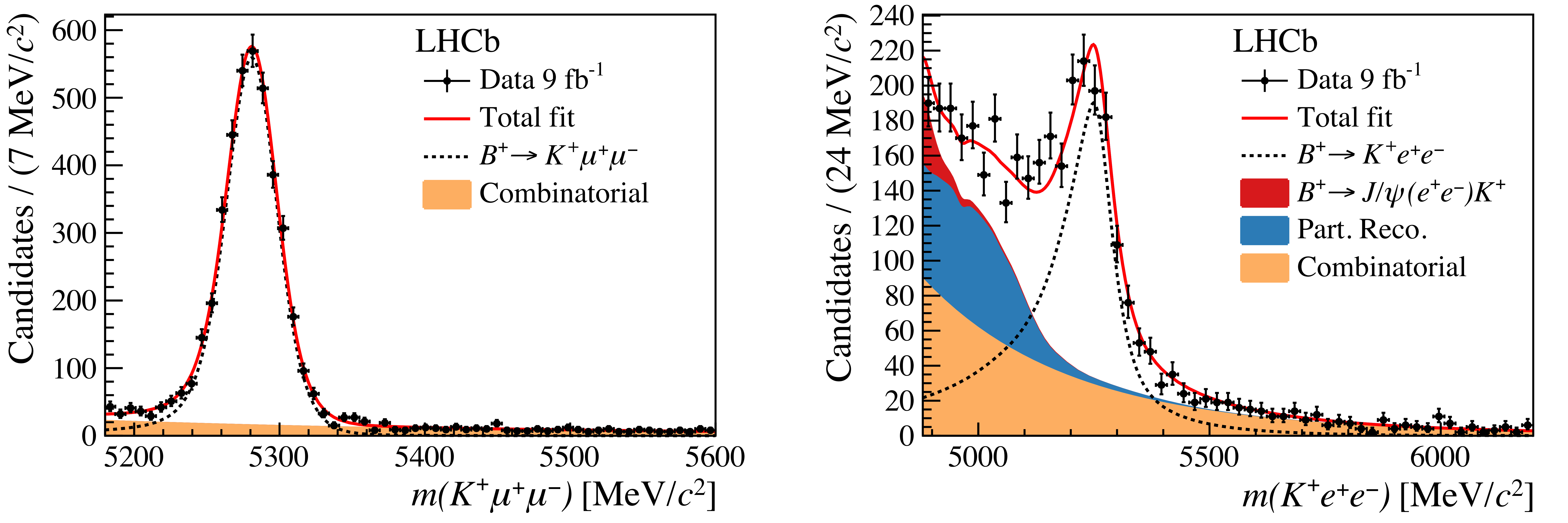


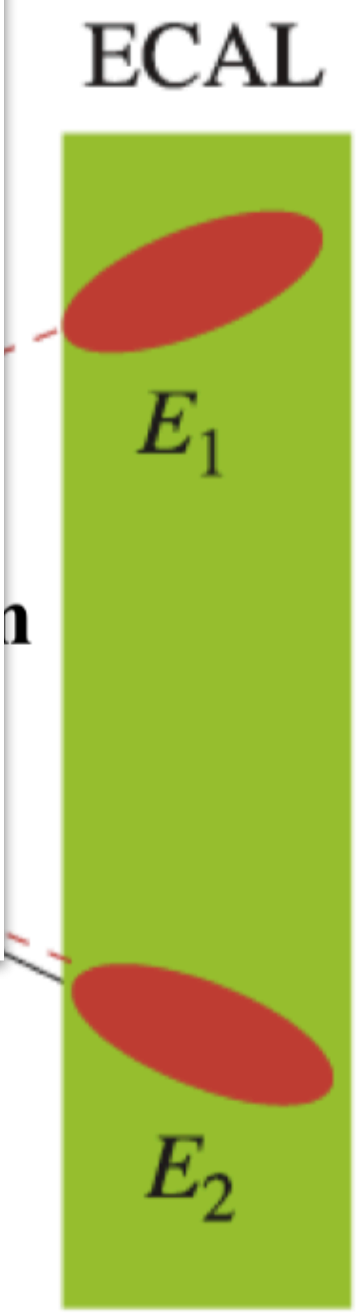
Electrons vs Muons at LHCb

- Electrons lose a large fraction of their energy through Bremsstrahlung radiation

- Af

[Nature Phys. 18 (2022) 277]

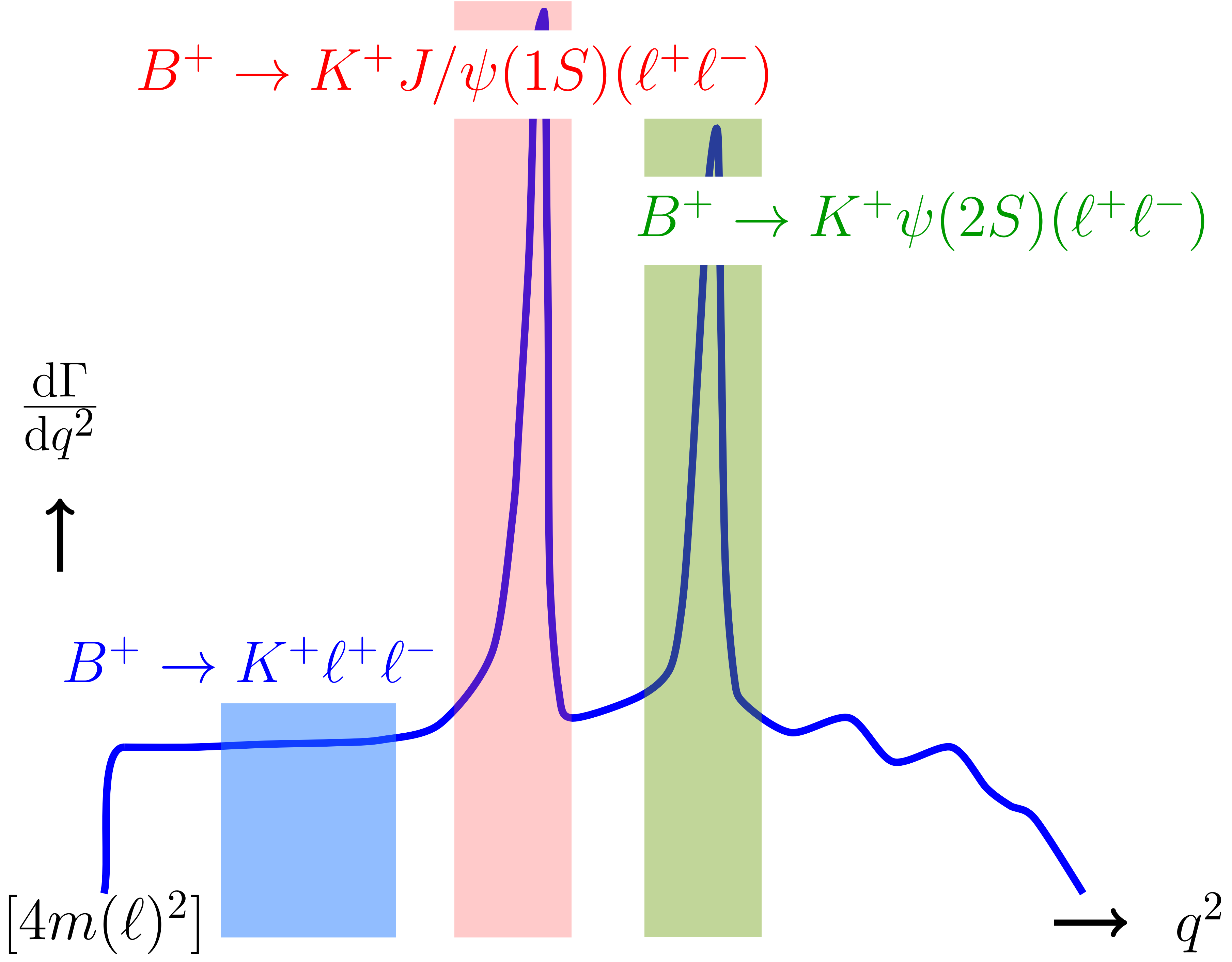




See Martino's talk tomorrow for more details

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



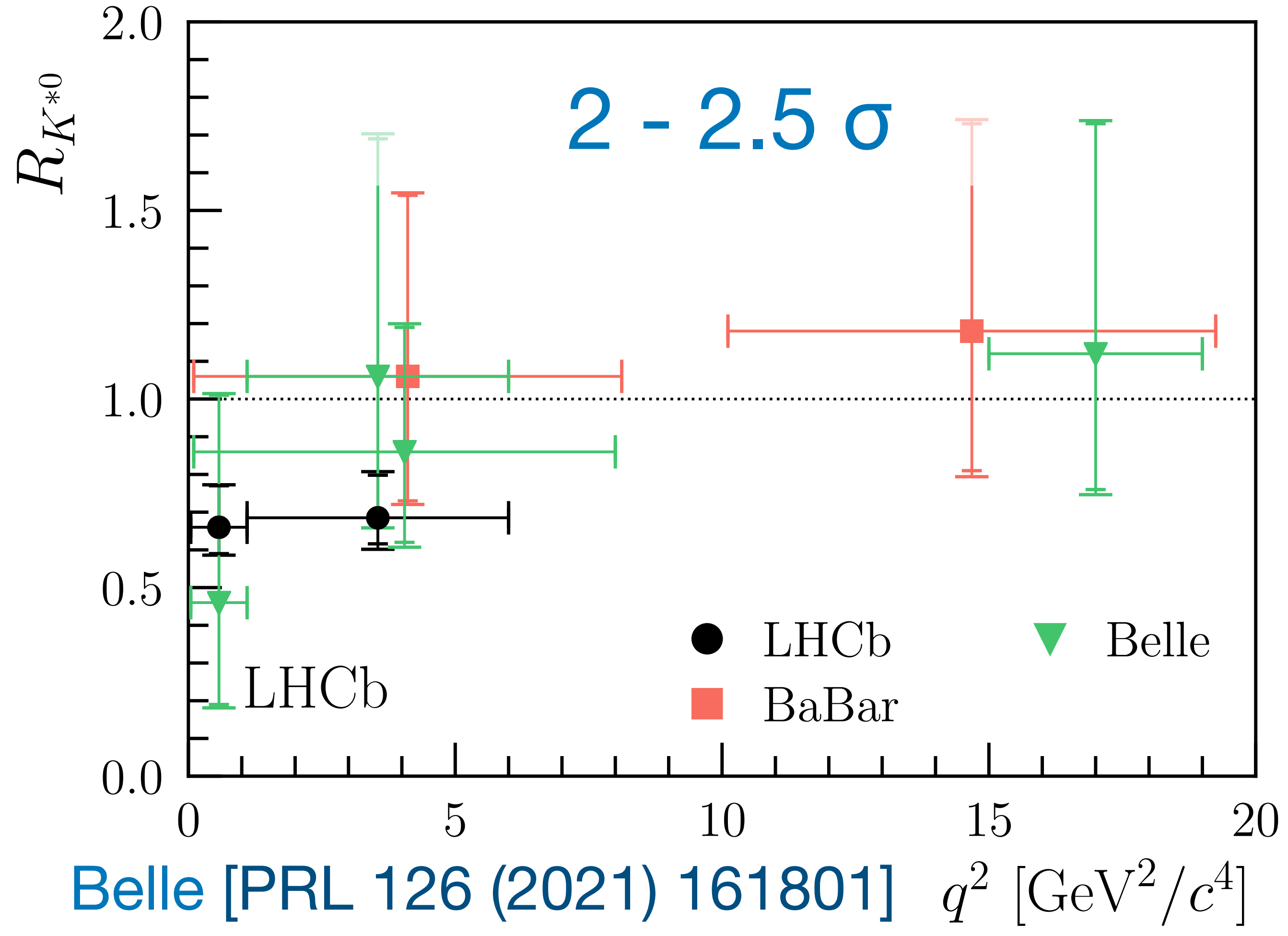
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))}$$

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

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

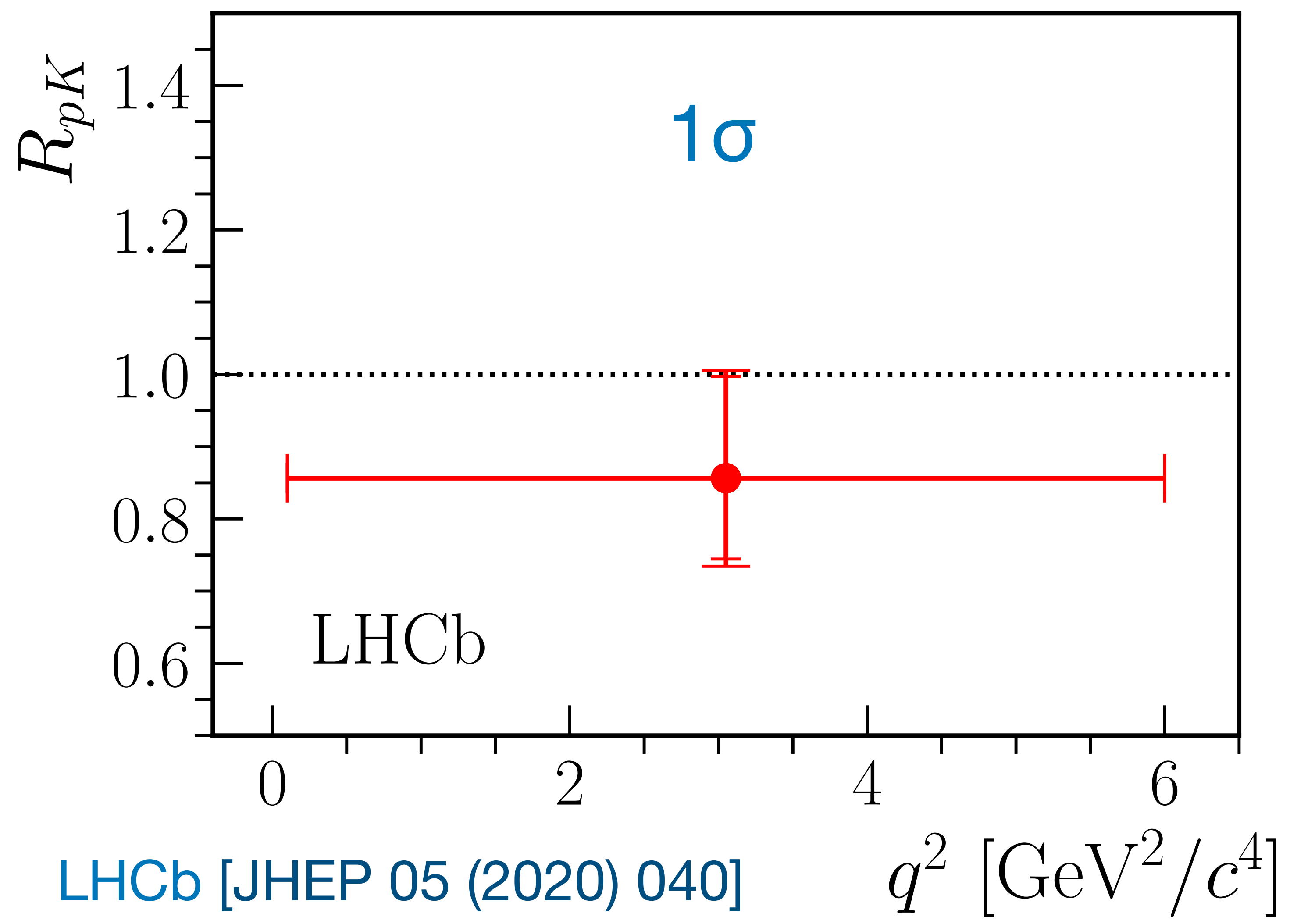
LFU tests at LHCb

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



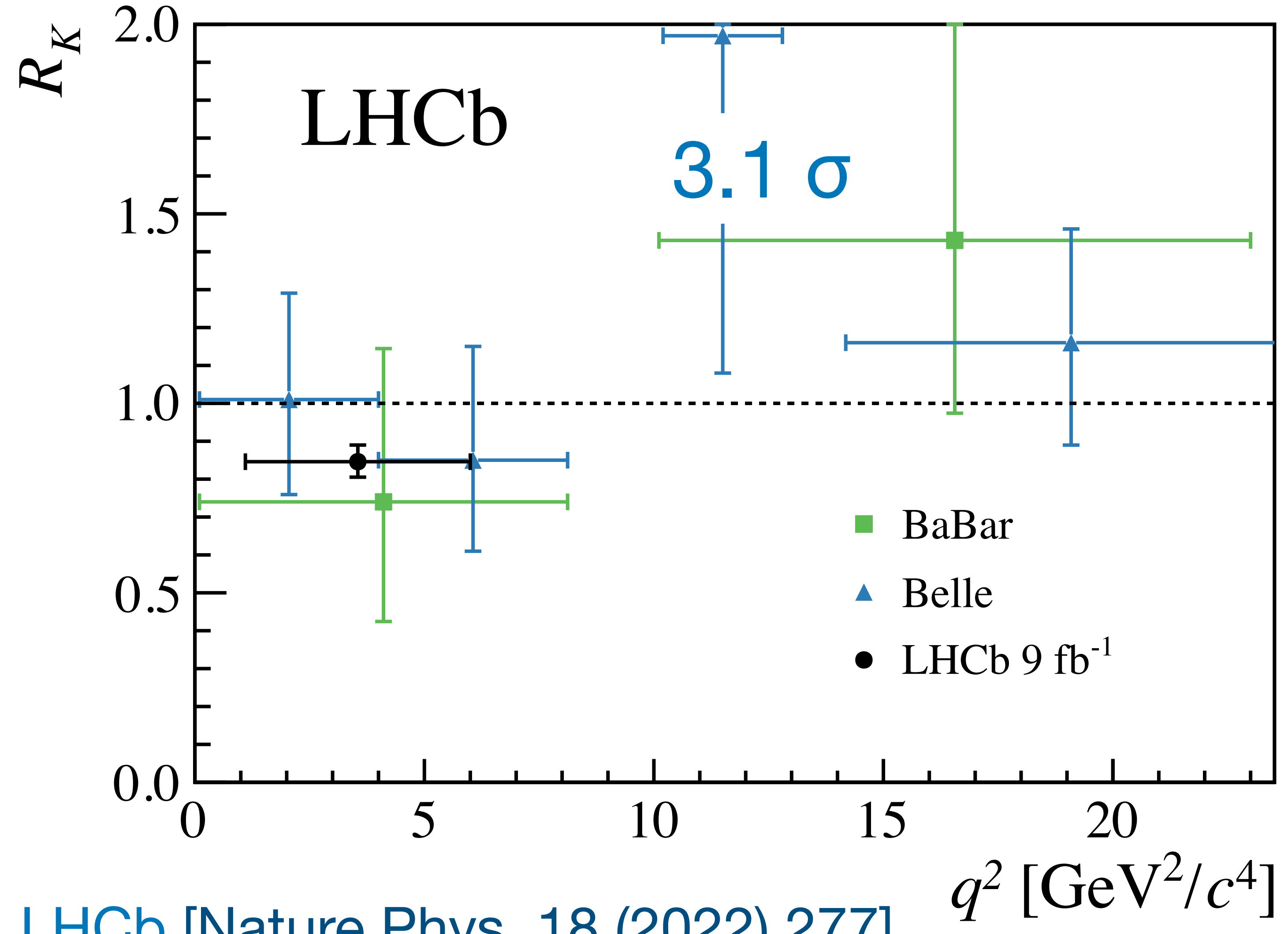
Belle [PRL 126 (2021) 161801]
BaBar [PRD 86 (2012) 032012]
LHCb [JHEP 08 (2017) 055]

$\Lambda_b \to pK^-\ell^+\ell^-$



LHCb [JHEP 05 (2020) 040]

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



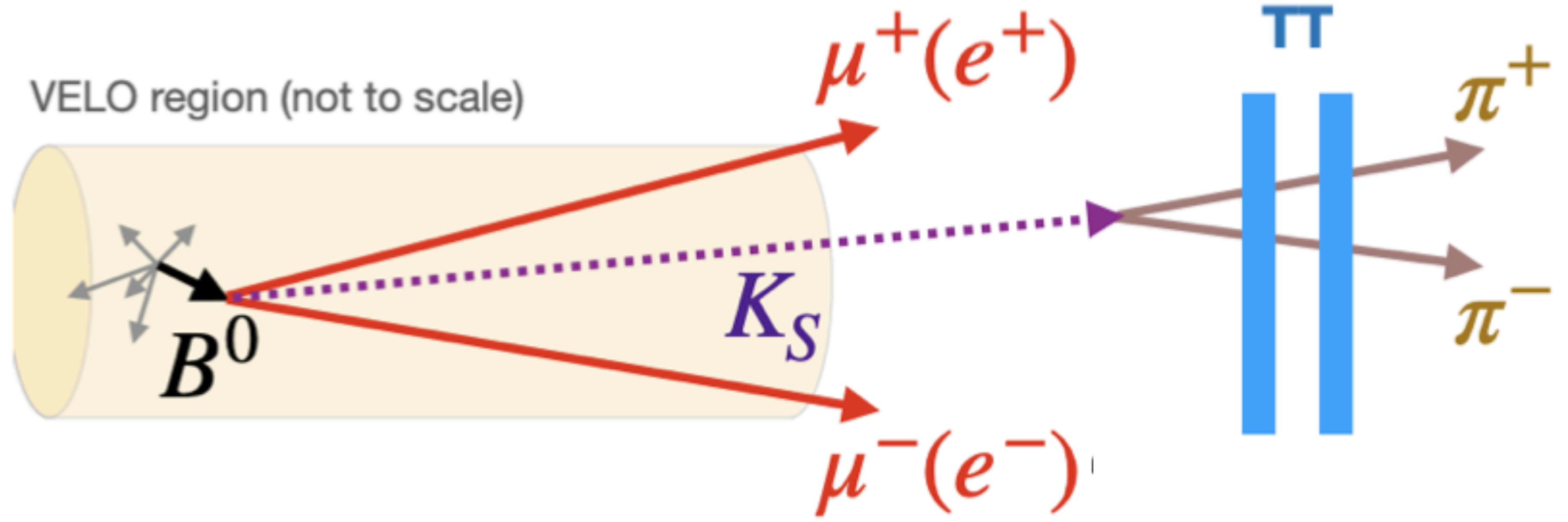
LHCb [Nature Phys. 18 (2022) 277]
BaBar [PRD 86 (2012) 03]
Belle [JHEP 03 (2021) 105]

New measurements of $R_{K^{*+}}$ and R_{KS} LHCb [arXiv:2110.09501]

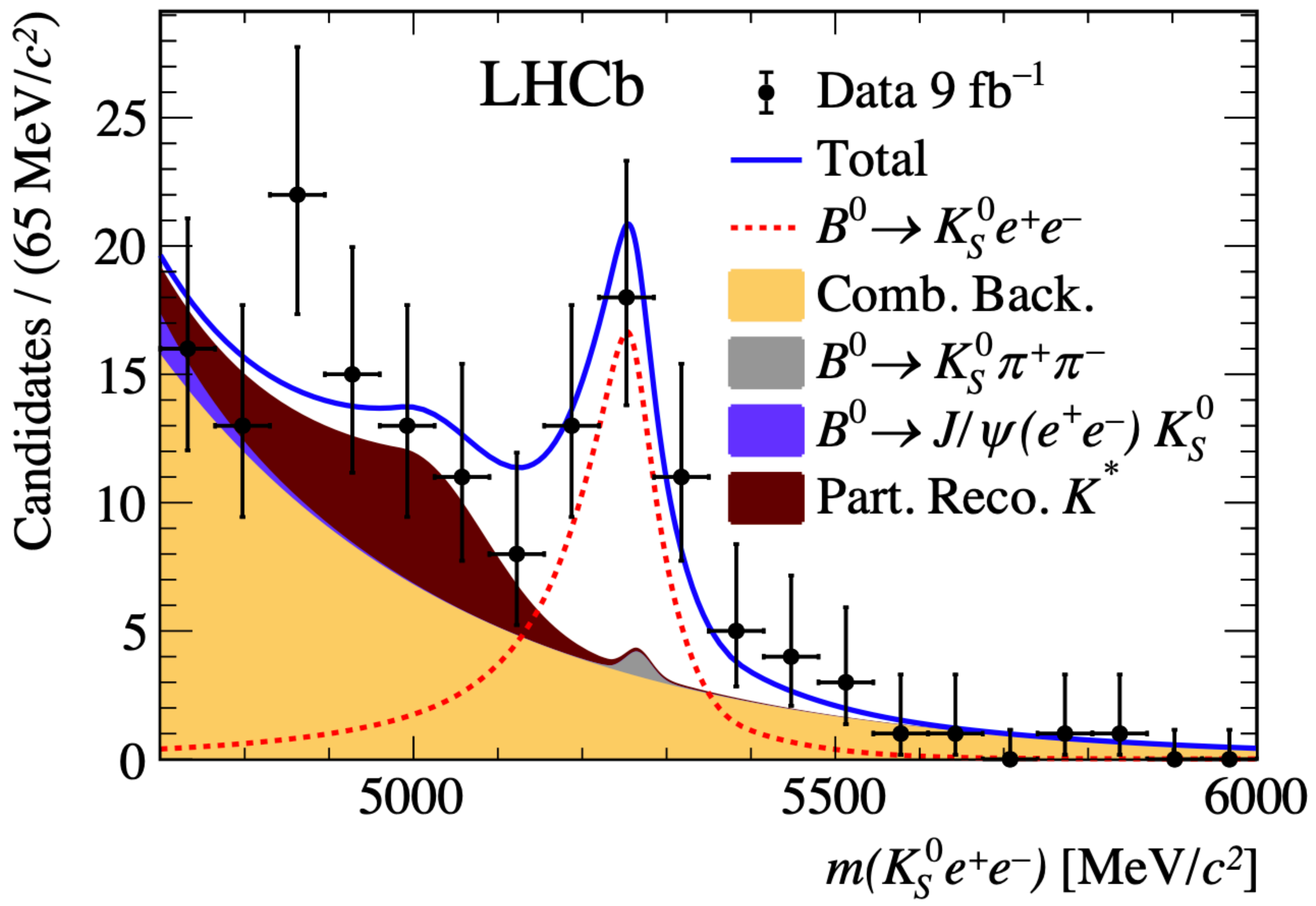
LFU in $B^0 \to K_S \ell\ell$ and $B^+ \to K^{*+} \ell\ell$

[LHCb, arXiv:2110.09501]

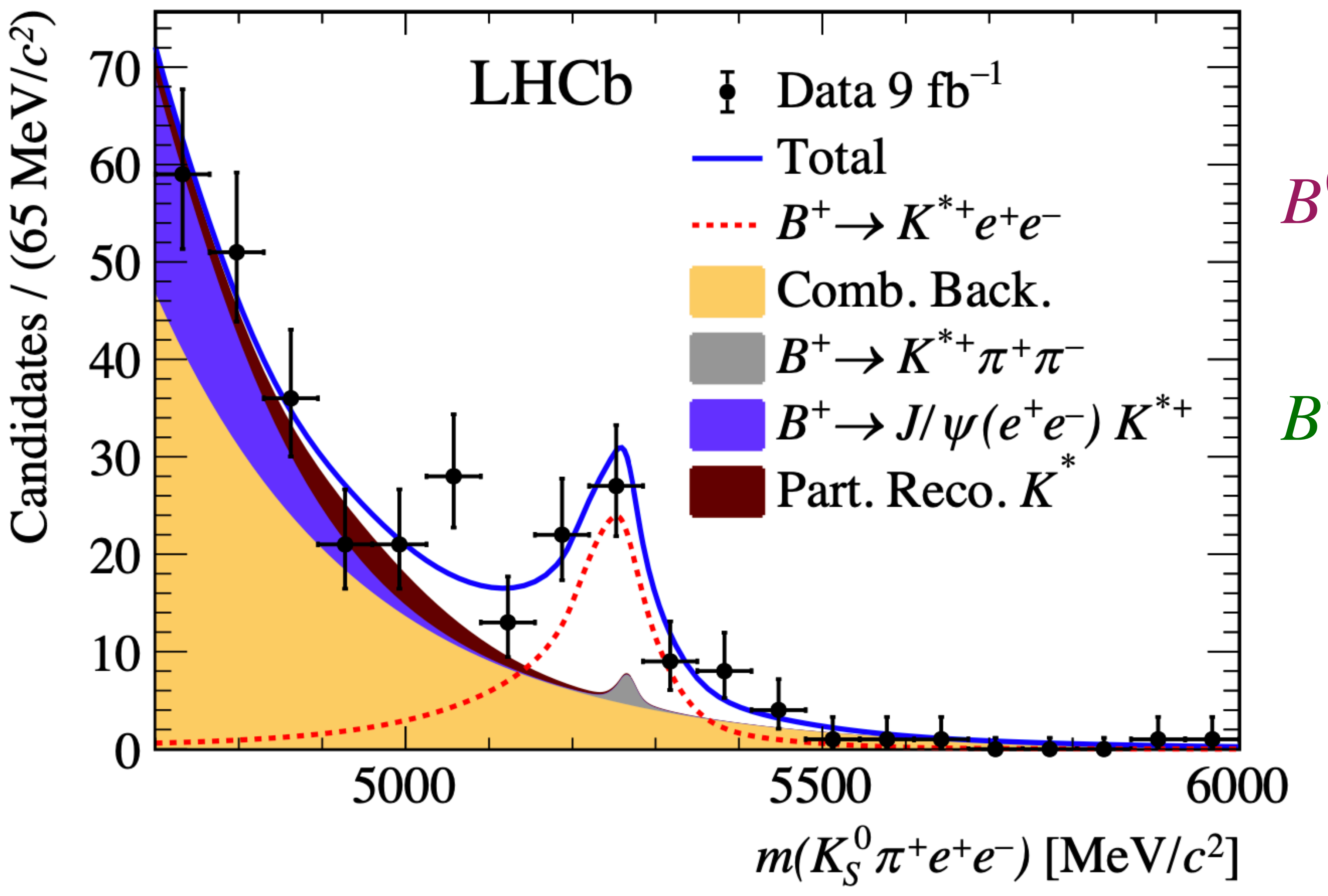
- Isospin partners of RK and RK*
- Reconstruct $K_S \to \pi^+\pi^-$ and $K^{*+} \to K_S\,\pi^+$
  - More challenging due to long-lived Ks in final state



$B^0 \to K_S\, \ell\ell$



$B^+ \to K^{*+}\, \ell\ell$



B^0 : $q^2 \in [1.1,\ 6.0]\ \mathrm{GeV}^2/c^4$

B^+ : $q^2 \in [0.045,\ 6.0]\ \mathrm{GeV}^2/c^4$

$|m(K_S\,\pi) - m_{K^{*+}}| < 300\ \mathrm{MeV}/c^2$

First observation of electron modes!

Analysis validation

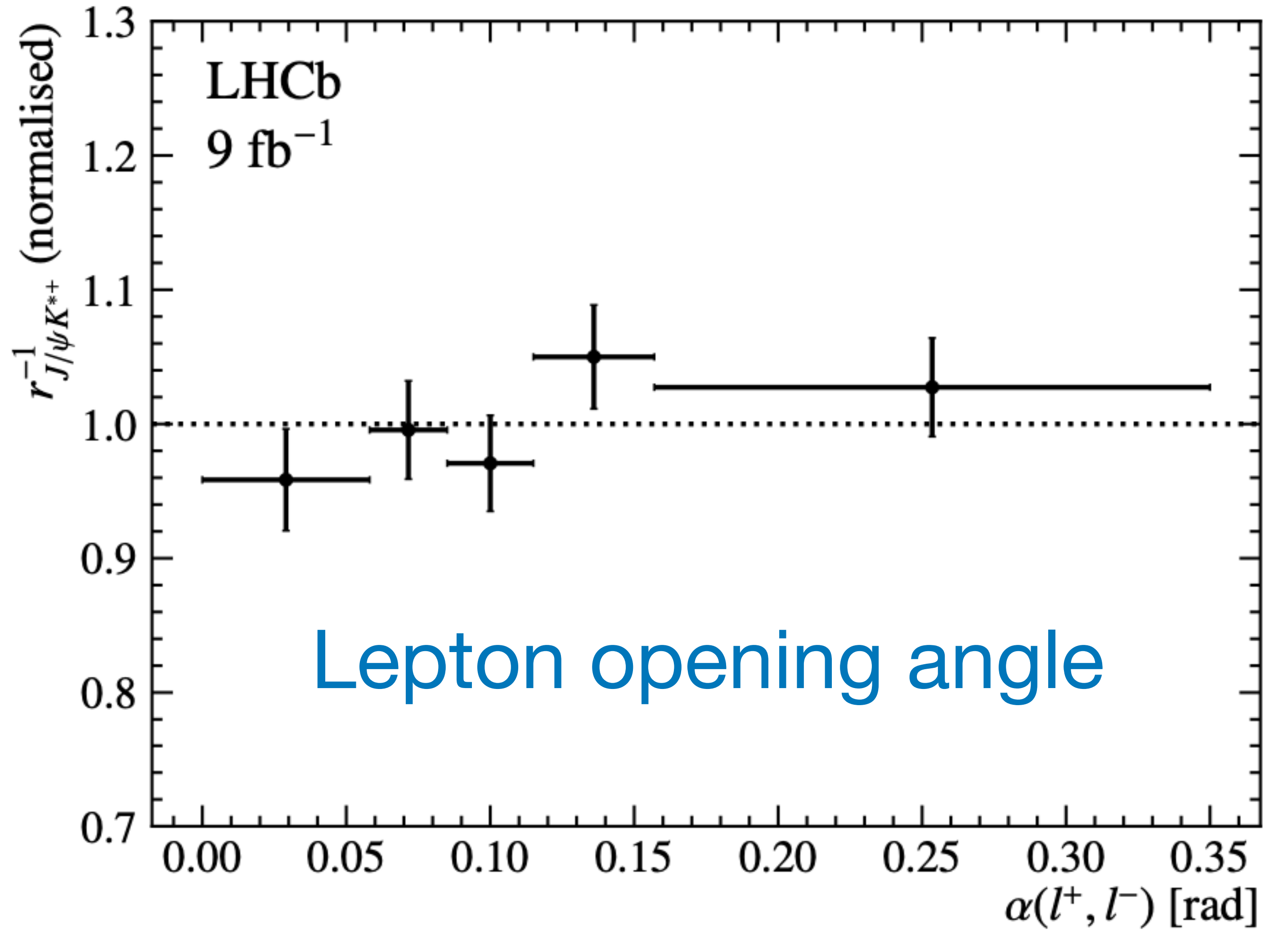
[LHCb, arXiv:2110.09501]

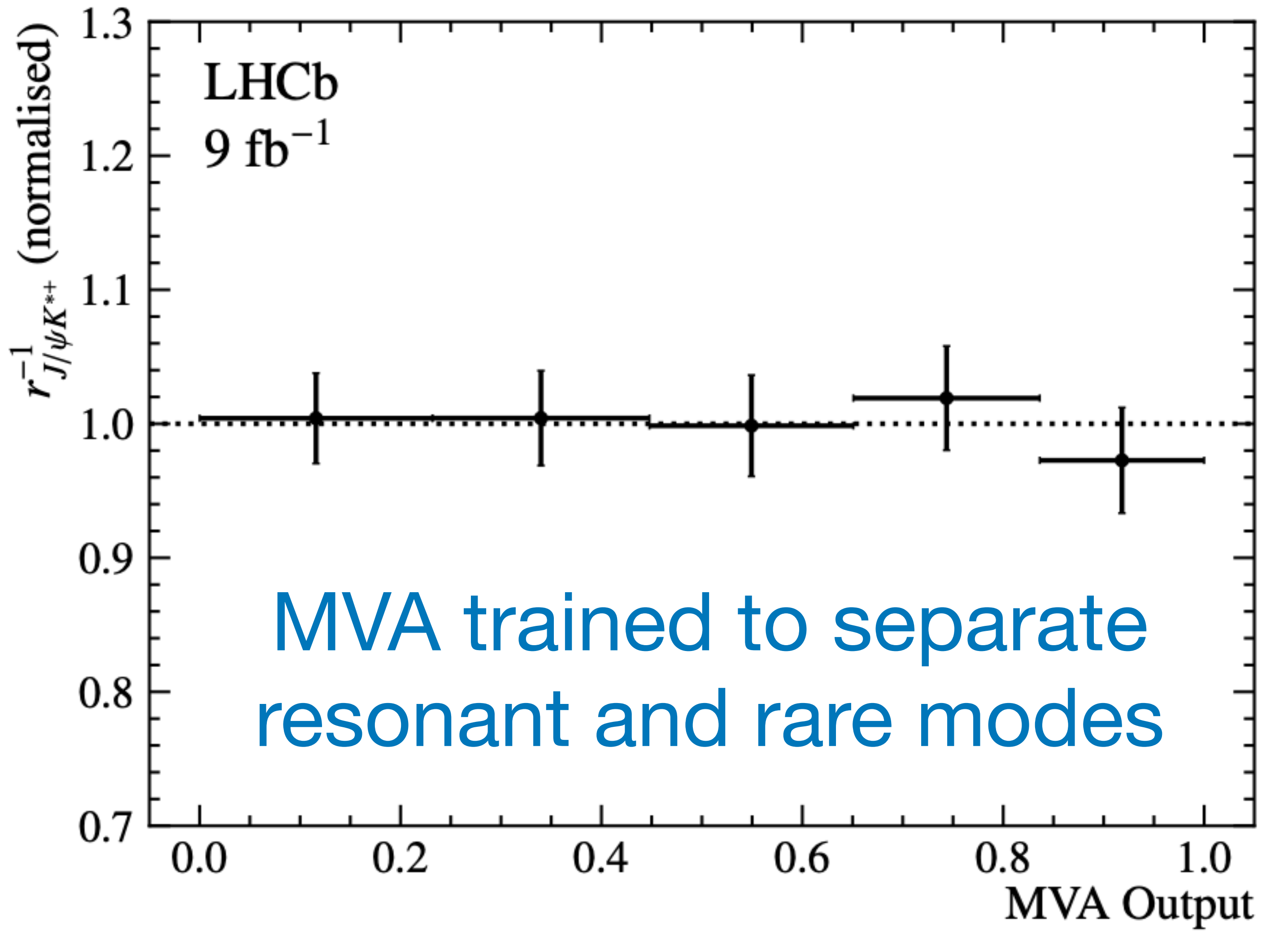
- Analysis uses double ratios w.r.t. $B \to K^{(*)}\ J/\psi(\ell\ell)$ to cancel most μ/e differences
- Single ratios, $r_{J/\psi\ K^{(*)}}$, are used to check the understanding of the efficiencies

$$r^{-1}_{J/\psi\ K^{(*)}} = \frac{B \to K^{(*)}\ J/\psi(ee)}{B_x \to K^{(*)}\ J/\psi(\mu\mu)}$$

$$r^{-1}_{J/\psi\ K_S} = 0.977 \pm 0.008\ (\text{stat}) \pm 0.027\ (\text{syst})$$
$$r^{-1}_{J/\psi\ K^{*+}} = 0.965 \pm 0.011\ (\text{stat}) \pm 0.045\ (\text{syst})$$

- Also checks vs variables relevant to the detector response and double ratios using $B \to K^{(*)}\ \psi(2S)(\ell\ell)$ decays





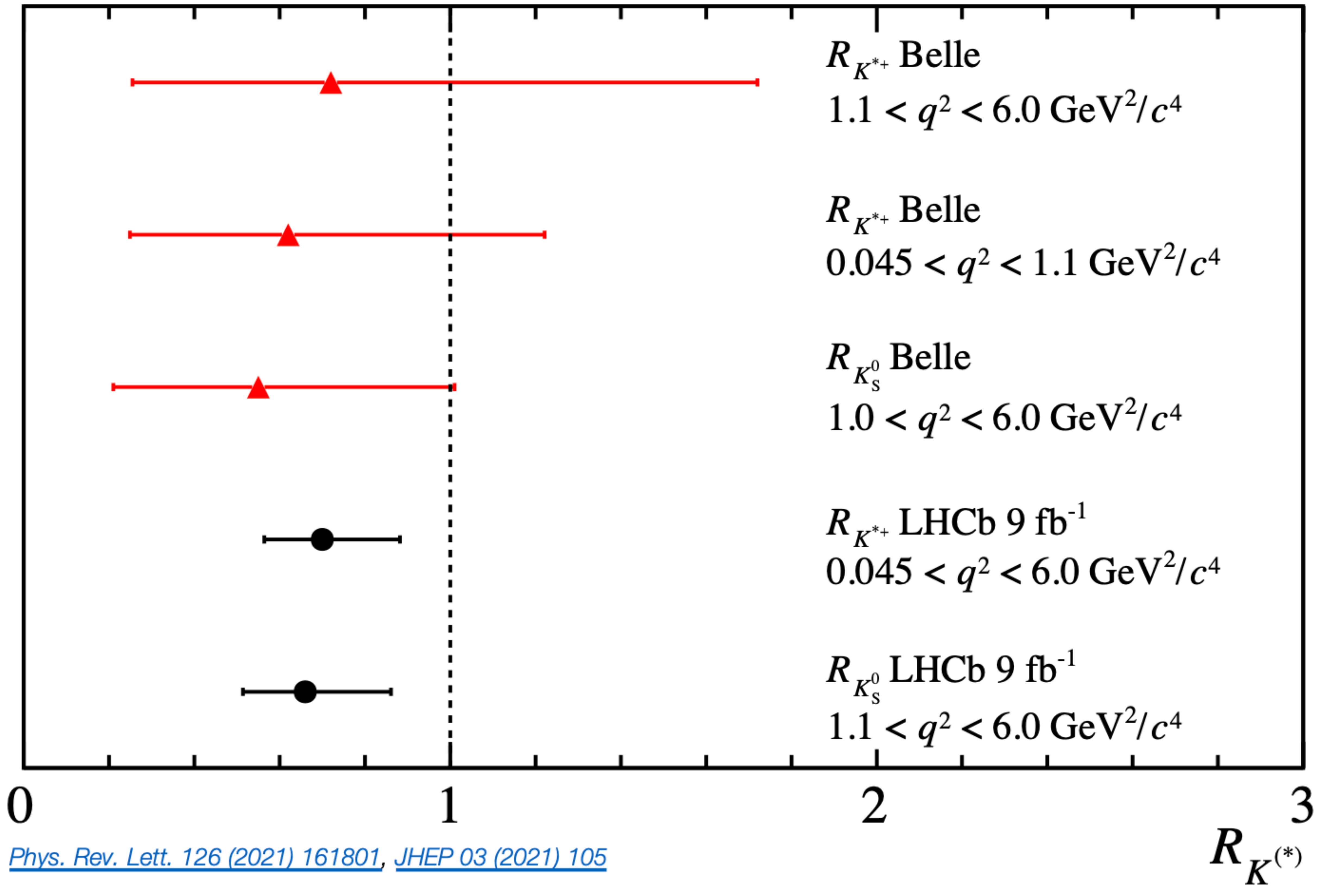
Results for R_{KS} and $R_{K^{*+}}$

[LHCb, arXiv:2110.09501]

$$R_{K_S}^{-1} = 1.51 \ {}^{+0.40}_{-0.35} \ (\text{stat}) \ {}^{+0.09}_{-0.04} \ (\text{syst})$$

$$R_{K^{*+}}^{-1} = 1.44 \ {}^{+0.32}_{-0.29} \ (\text{stat}) \ {}^{+0.09}_{-0.06} \ (\text{syst})$$

Compatible with the SM prediction at ~1.5 σ

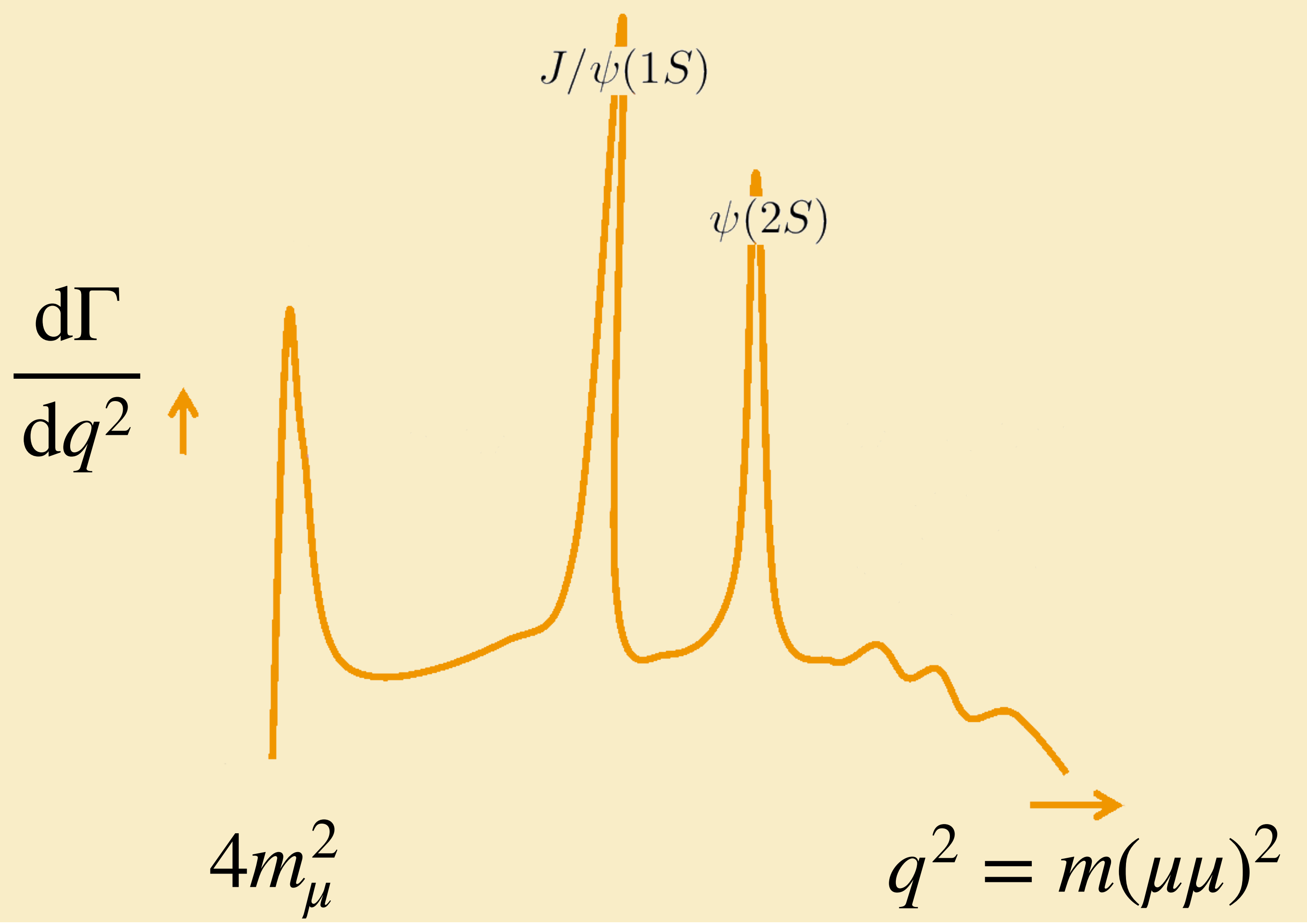


Phys. Rev. Lett. 126 (2021) 161801, JHEP 03 (2021) 105

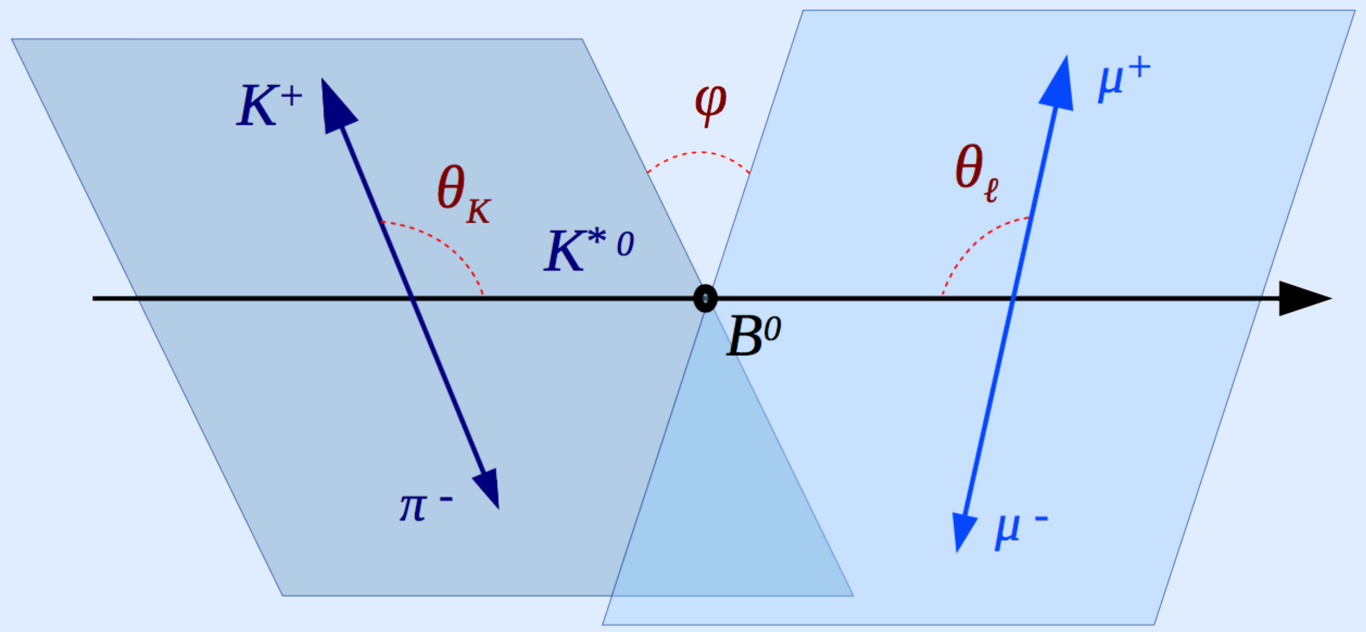
$b \to s\ \ell^+\ell^-$ anomalies

- Pattern of tensions with the SM predictions in several observables

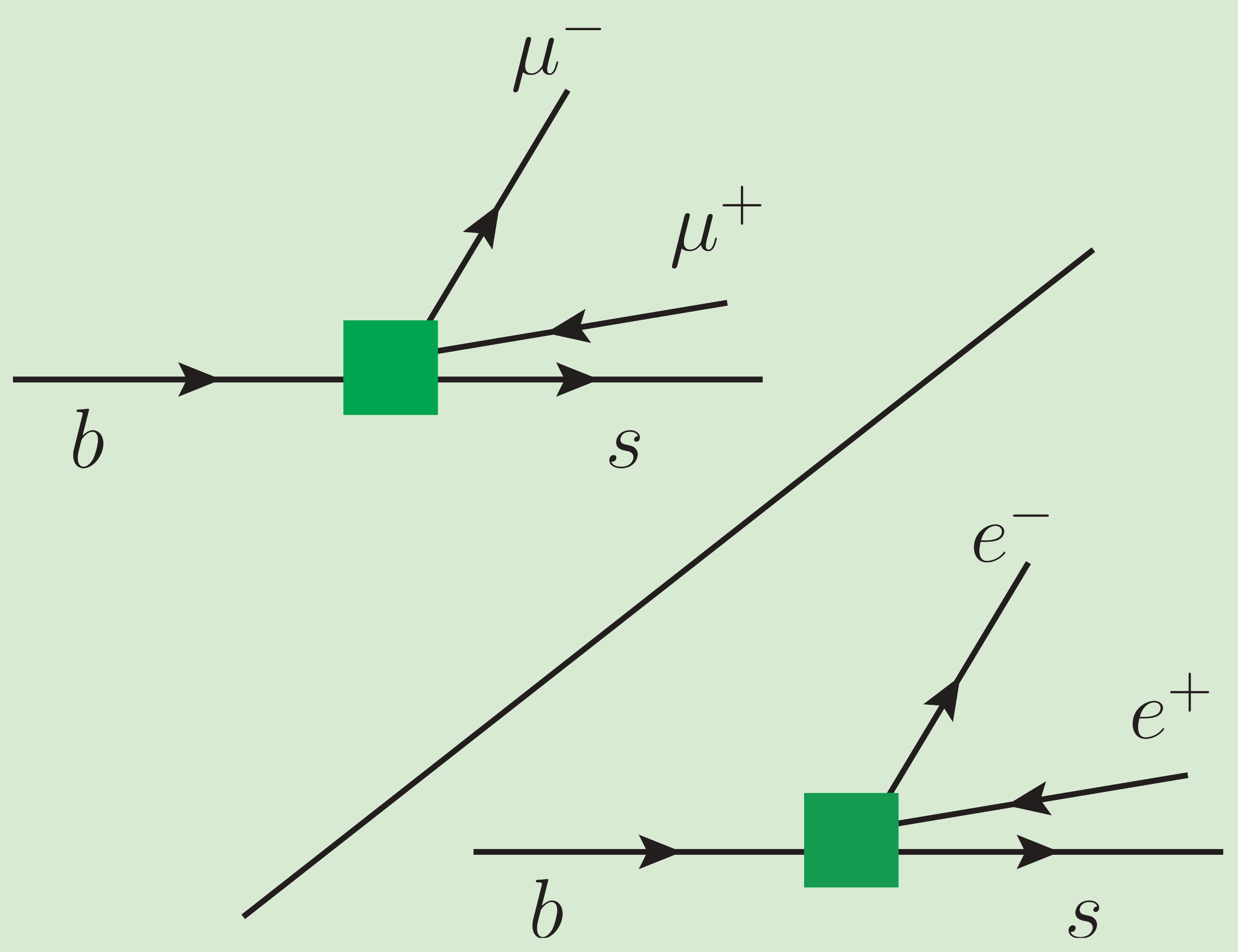
Low branching ratios



Angular observables



Lepton Flavour Universality

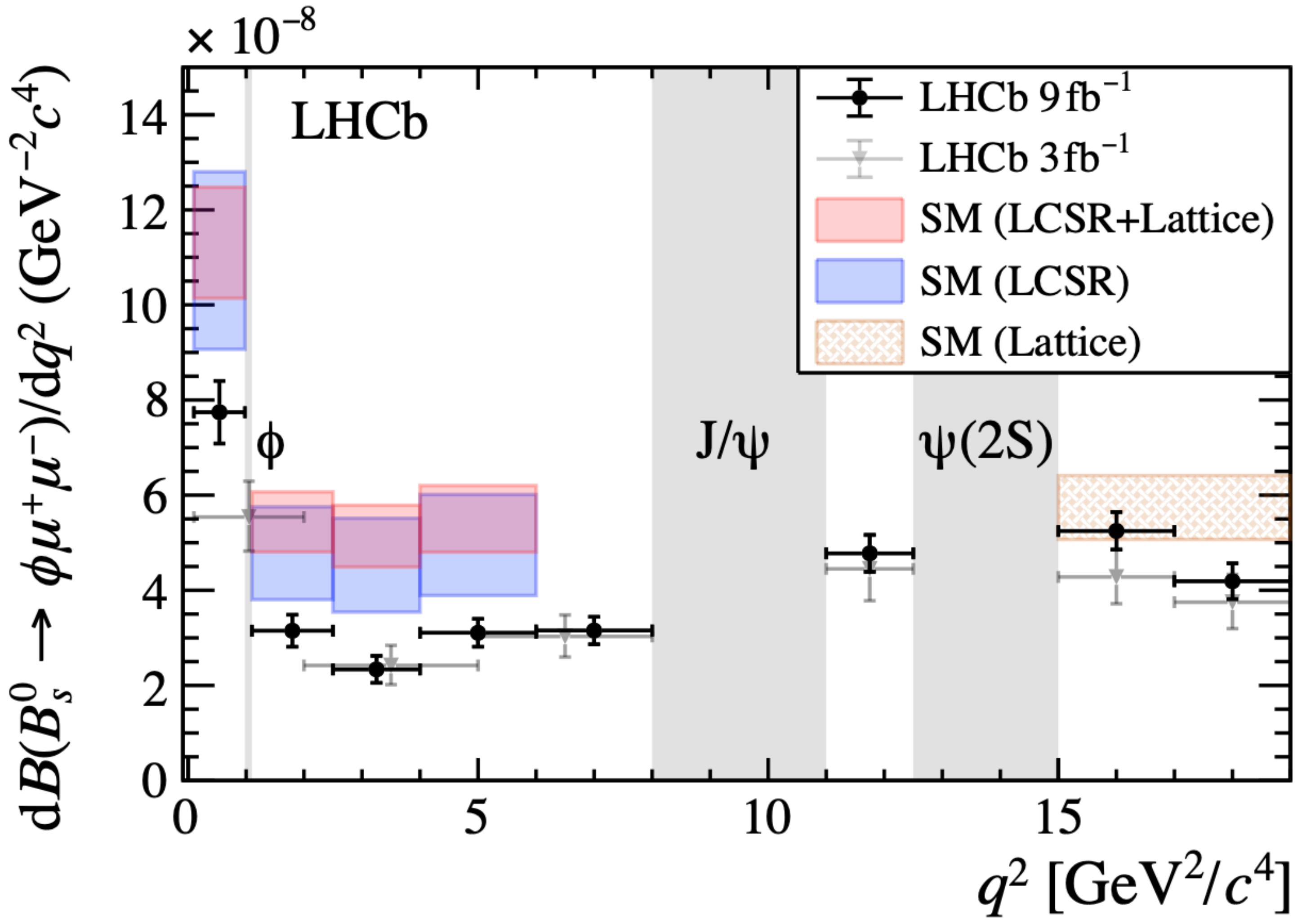


Theoretically ‘cleaner’

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

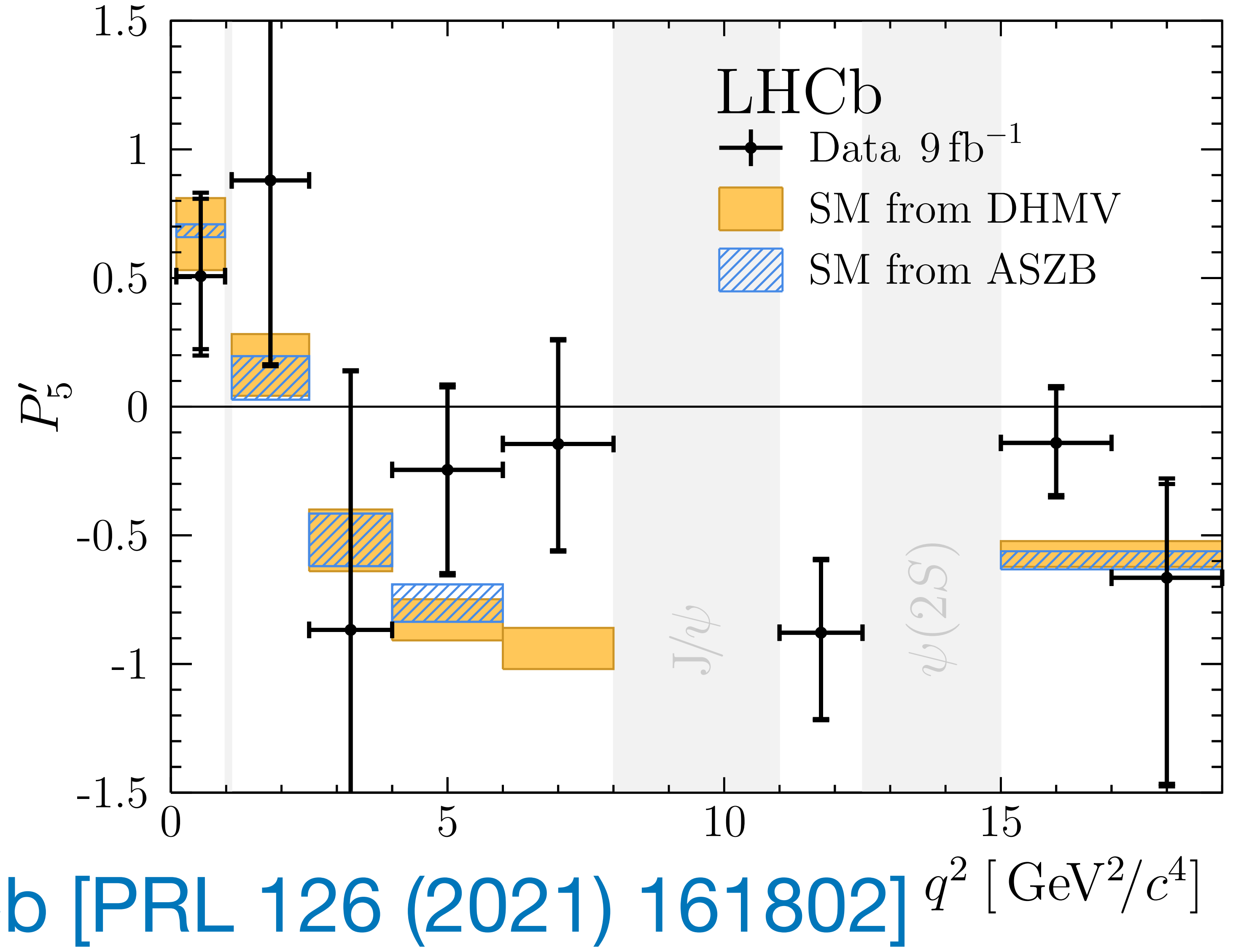
- Pattern of tensions with the SM predictions in several observables

Branching ratio of $B_s^0 \to \phi\, \mu^+\mu^-$



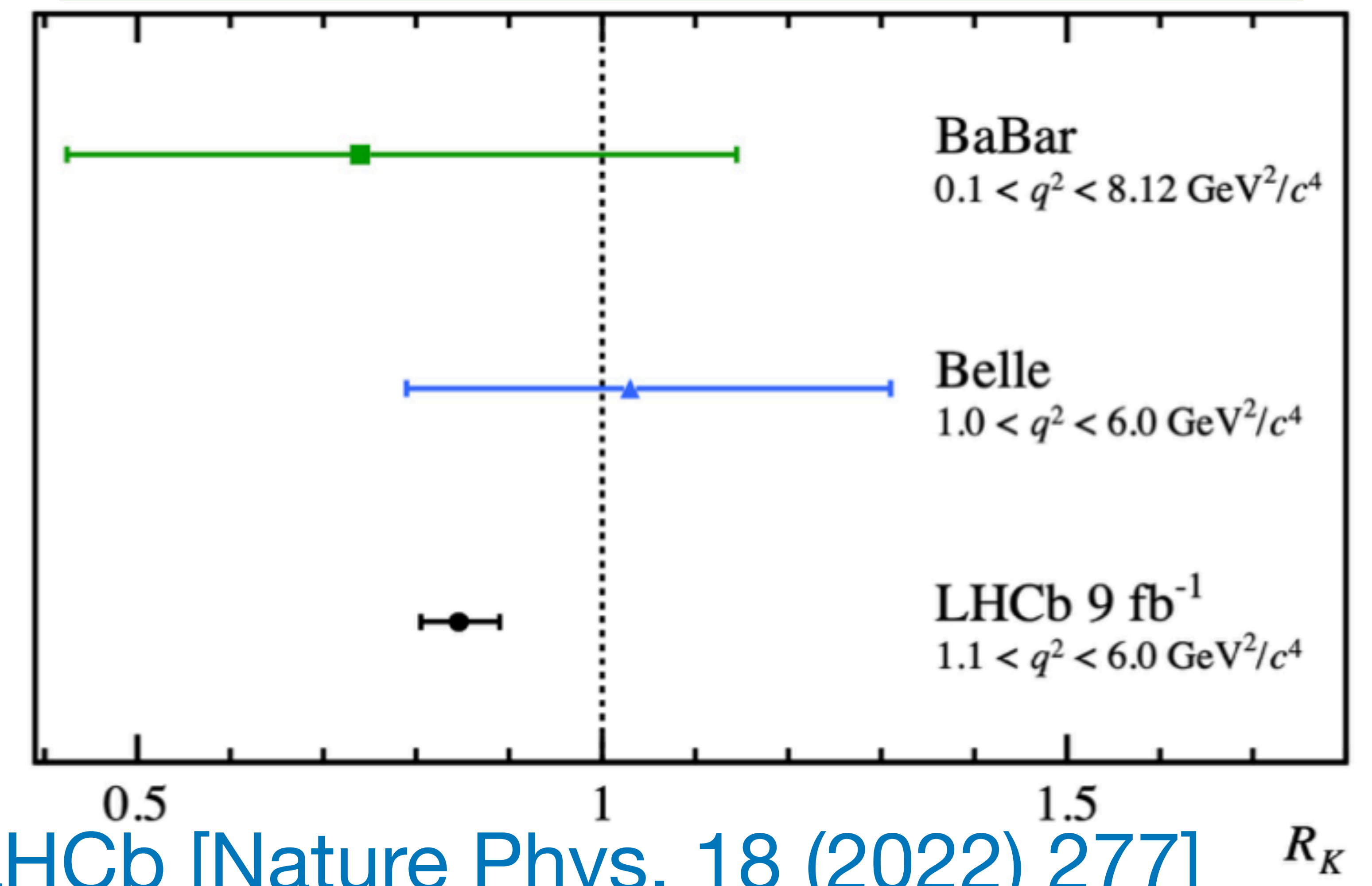
[LHCb, arXiv:2105.14007]

Angular analysis of $B^+ \to K^{*+}\mu^+\mu^-$



LHCb [PRL 126 (2021) 161802]

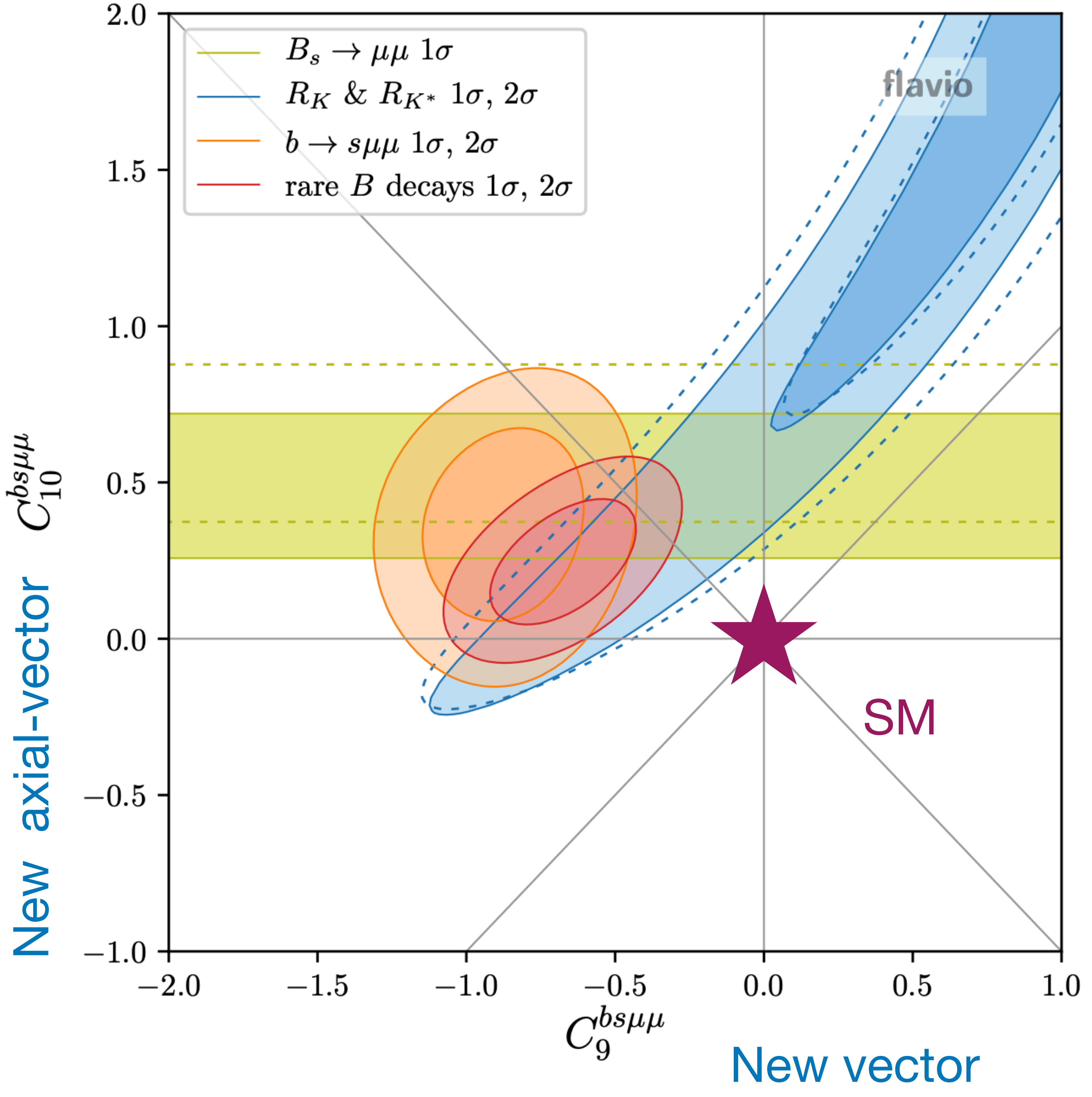
LFU ratios



LHCb [Nature Phys. 18 (2022) 277]

Theoretically 'cleaner'

$b \to s\, \ell^+ \ell^-$ anomalies



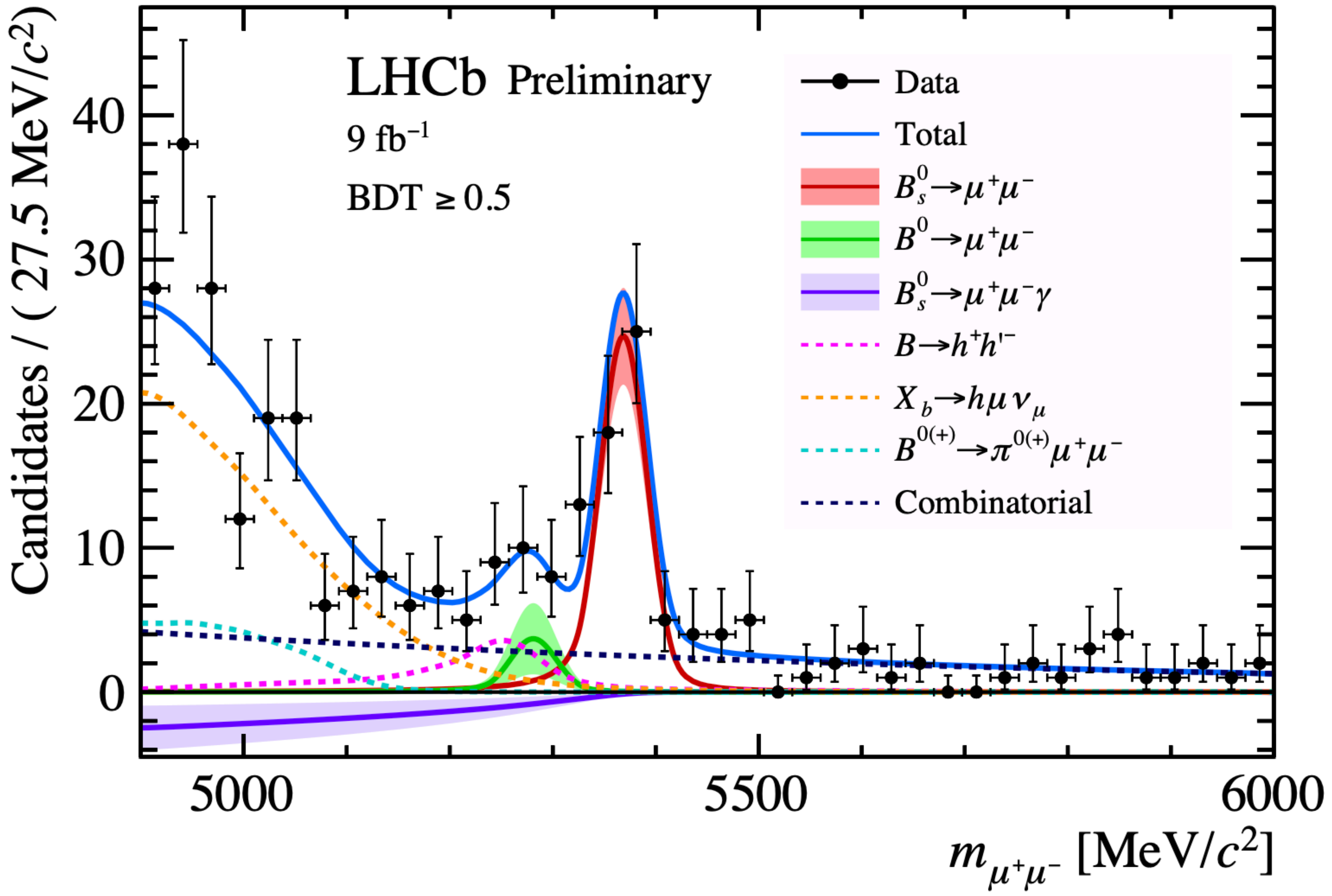
[W. Altmannshofer et al., arXiv:2103.13370]

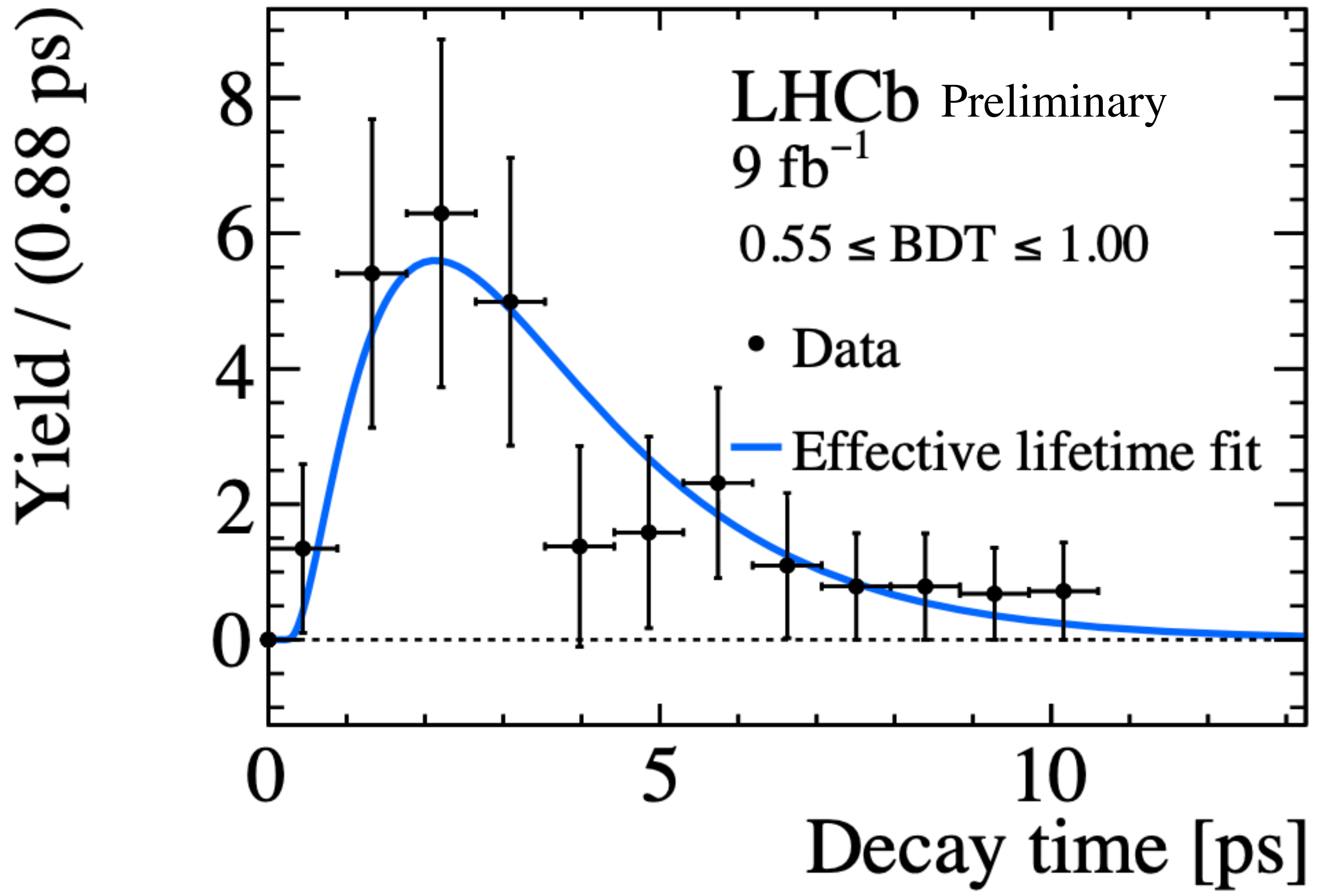
[Similar fits by
Algueró et al: arXiv:2104.08921,
Hurth et al: arXiv:2104.10058,
Ciucchini et al: arXiv:1903.09632,
Kowalska et al: arXiv:1903.10932,
Geng et al arXiv:2103.12738
and many others]

Critical to improve the precision in all of these measurements to clarify this picture

$B^0_{(S)} \to \mu^+\mu^-$ at LHCb

[PRL 128, (2022) 041801]





- Full Run1+2 LHCb sample
- Find $B_s \to \mu^+\mu^-$ with significance >10σ, but no evidence yet for $B^0 \to \mu^+\mu^-$ (1.7σ)

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.09\ {}^{+0.46}_{-0.43}\ {}^{+0.15}_{-0.11}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}\ (95\,\%\,\mathrm{CL})$$

- Set a limit also for the radiative decay (ISR) $\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{m_{\mu^+\mu^-}>4.9\mathrm{GeV}} < 2.0 \times 10^{-10}\ (95\,\%\,\mathrm{CL})$
- Updated effective lifetime $\tau_{\mathrm{eff}}(B_s^0 \to \mu^+\mu^-) = 2.07 \pm 0.29 \pm 0.03\ \mathrm{ps}$
- Main BR systematics from f_s/f_d (3%) improved from an updated hadronisation fraction [LHCb, arXiv:2103.06810]

Charged currents

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

- Tree level transition already in the SM
  - NP scale could be order few TeV

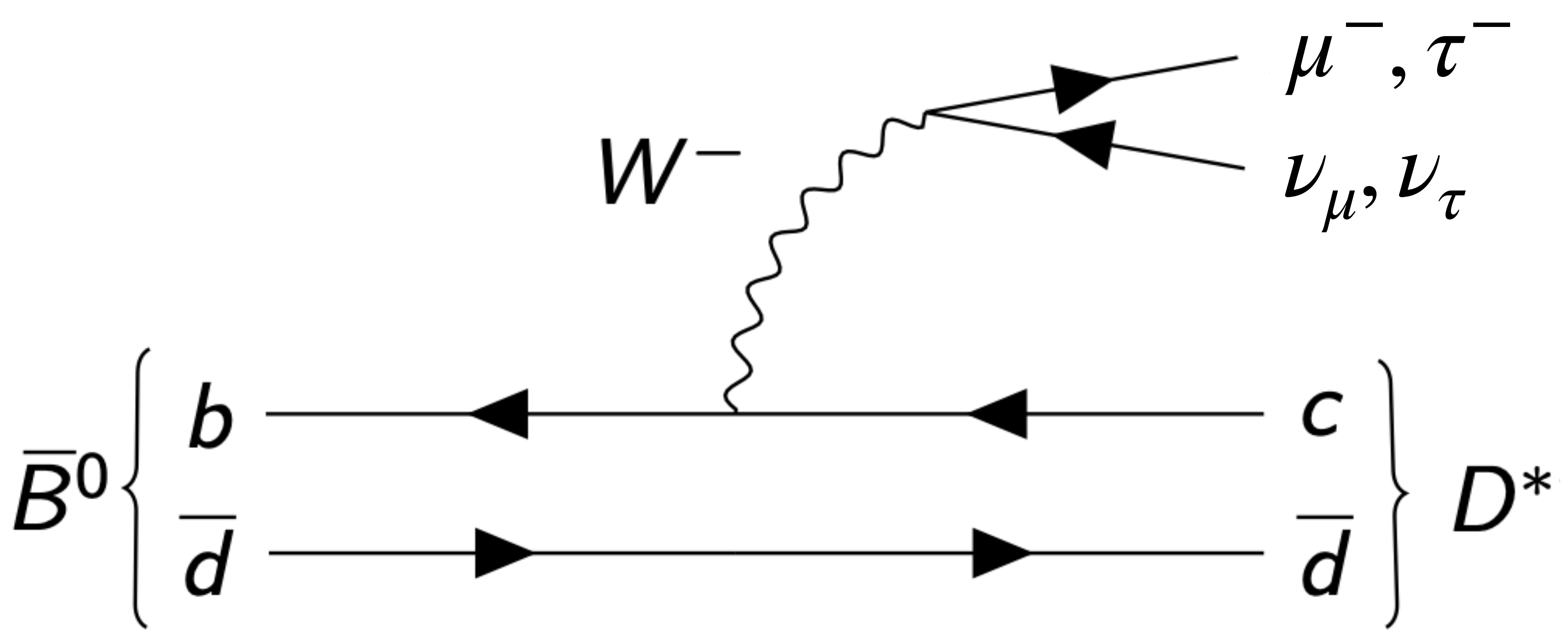
- LFU tests measure ratios between τ and μ (LHCb) or e+μ (B-factories)

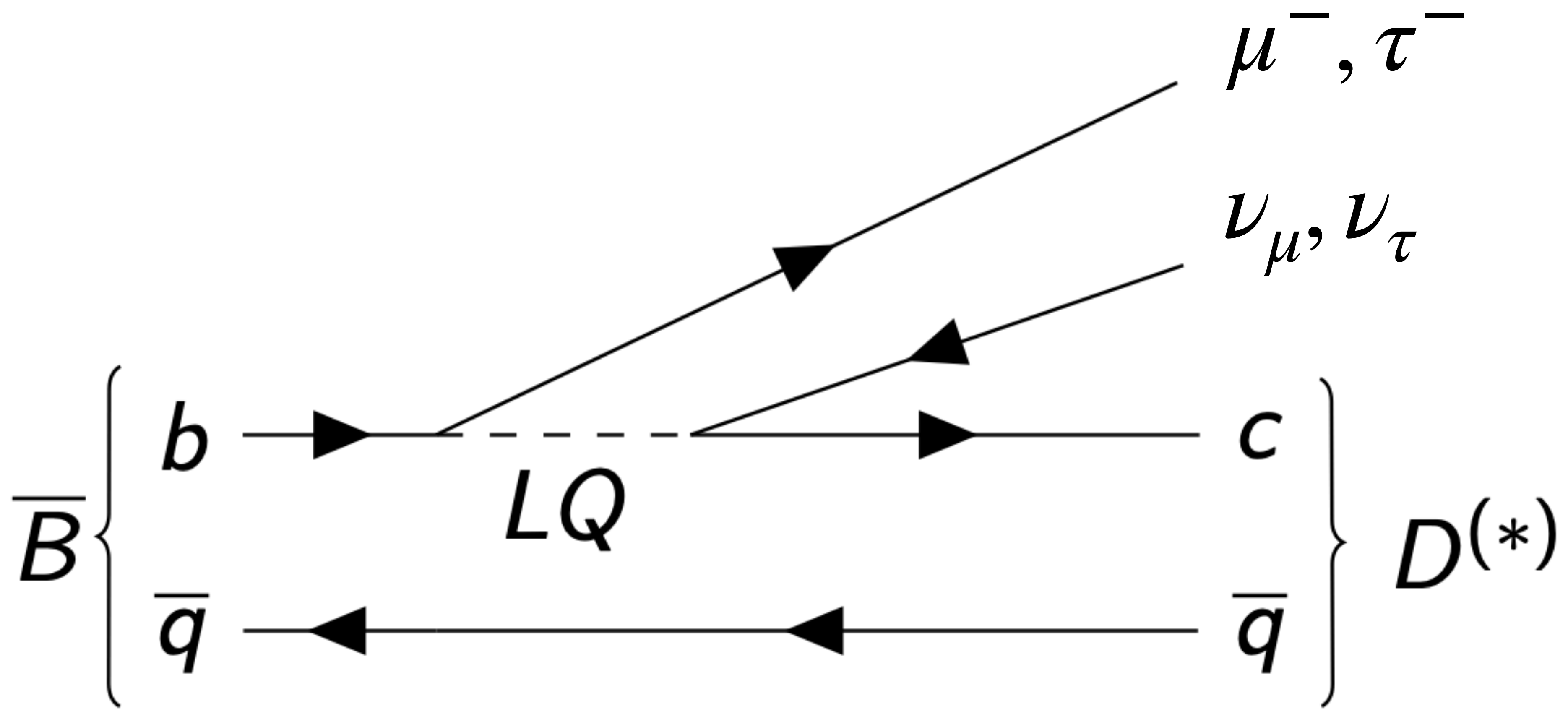
$B^{+,0}$, B_c, Λ_b → H_b

$D^{(*)}$, J/ψ, Λ_c… → H_c

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

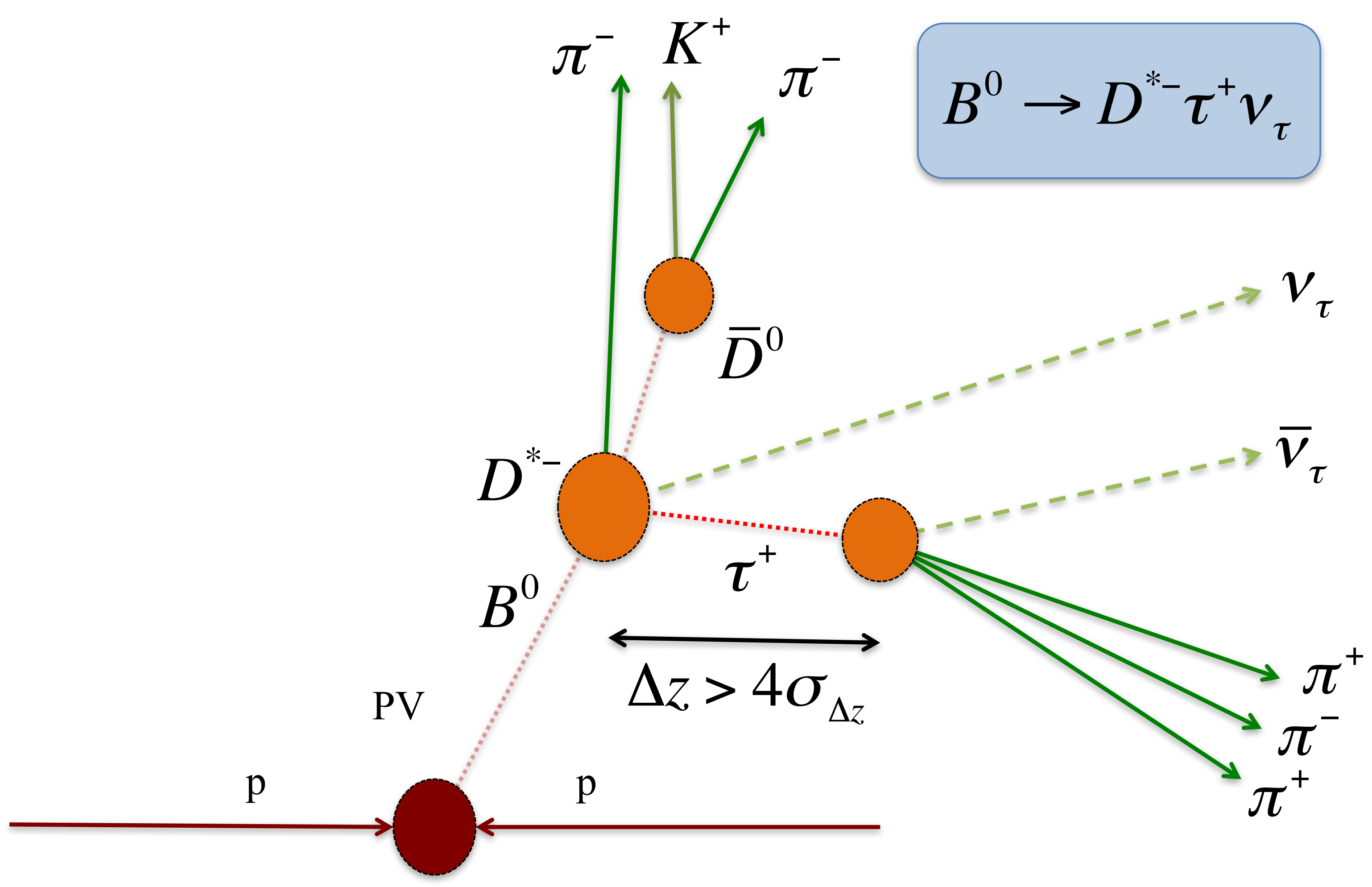
e, μ → ℓ

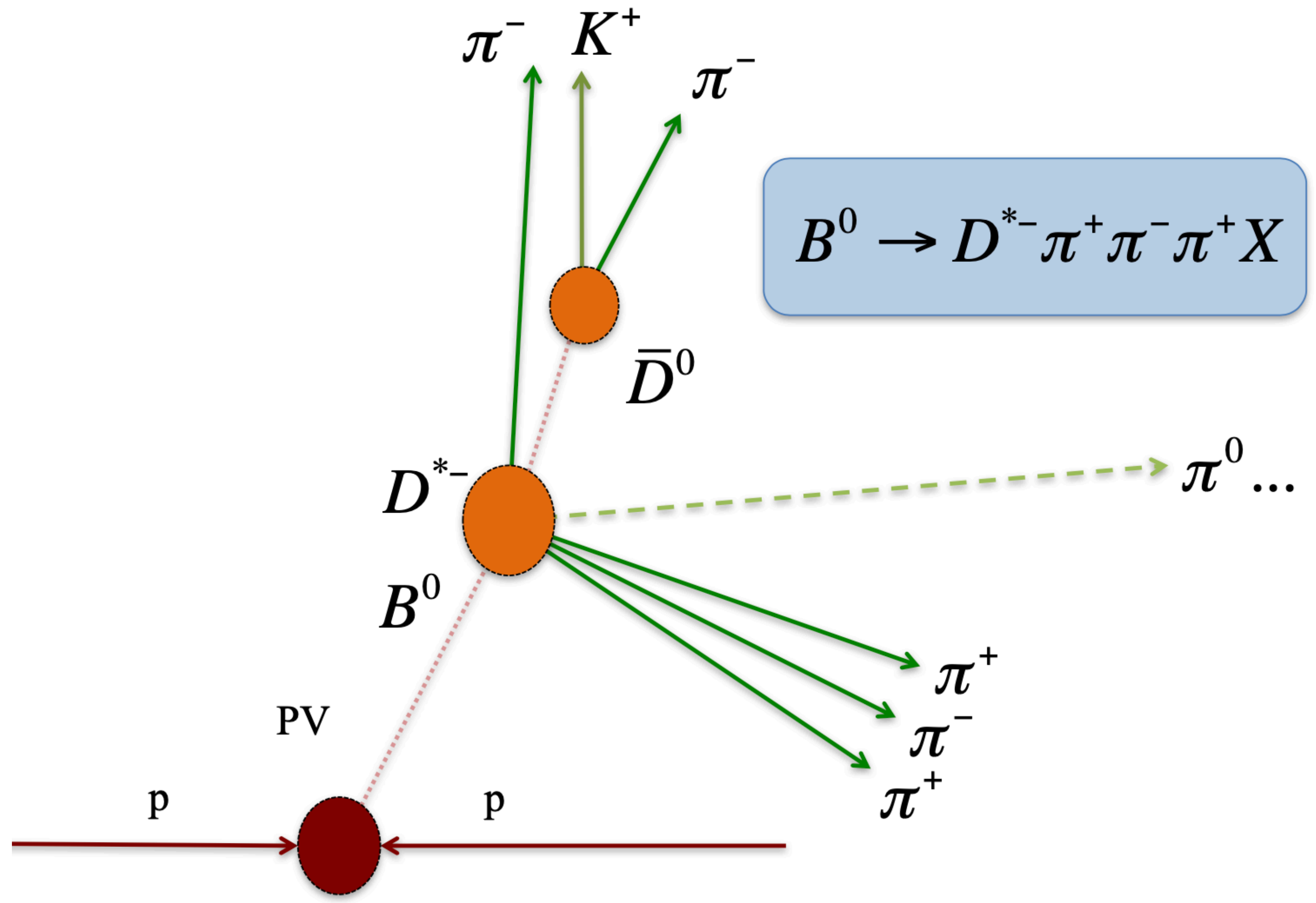


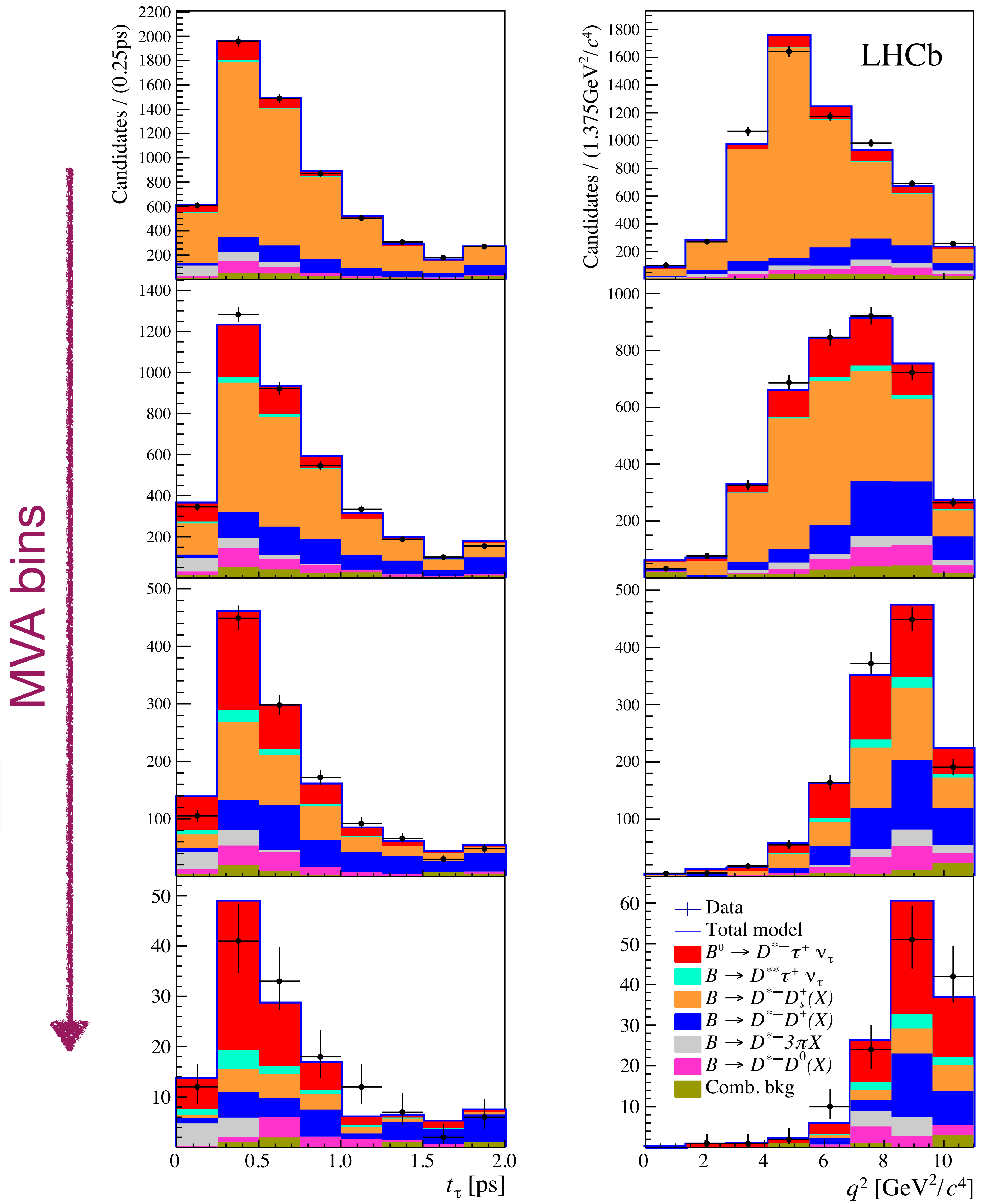


LFU in $b \to c \ell \nu$ transitions at LHCb

- Experimentally challenging for LHCb due to the presence of multiple neutrinos
  - Use both $\tau \to \mu\nu\nu$, $\tau \to \pi\pi\pi\nu$
- Multidimensional template fits use topological and kinematic information to discriminate signal from multiple backgrounds







[LHCb, PRL 120 (2018) 171802]

R(Λ_c^+)

[LHCb, arXiv:2201.03497]

- LFU test using baryonic decays $\Lambda_b^0 \to \Lambda_c^+ \ell^- \nu_\ell$
  - Complementary NP sensitivity compared *R(D(*))*
- Measure the BR of the tau decay mode and normalise to $\Lambda_b^0 \to \Lambda_c^+ 3\pi$
  - Run I dataset (3/fb)
  - Reconstruct the tau in hadronic mode

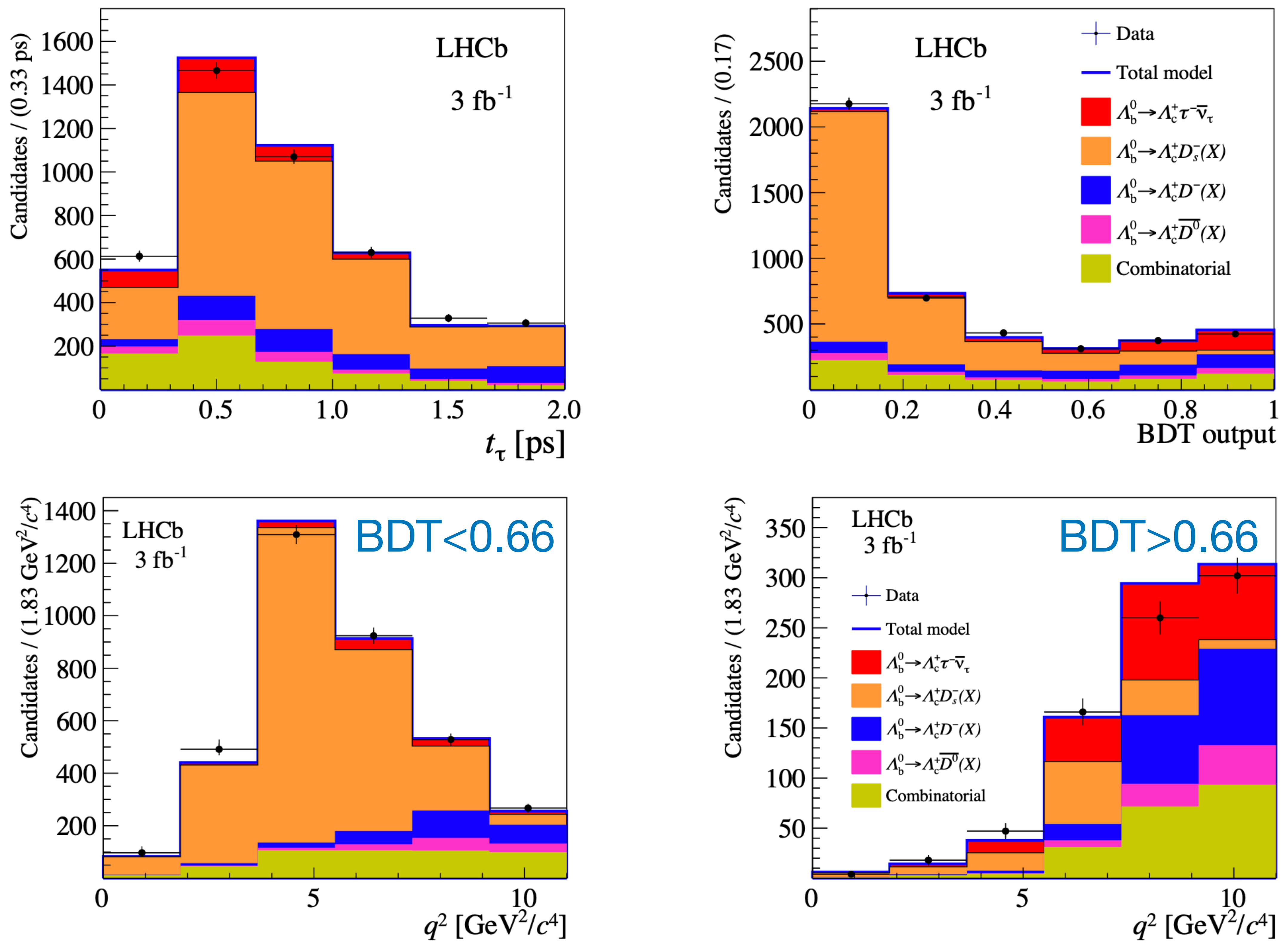
$$R(\Lambda_c^+) = \frac{B(\Lambda_b^0 \to \Lambda_c^+ \tau\nu)}{B(\Lambda_b^0 \to \Lambda_c^+ 3\pi)} \times \frac{B(\Lambda_b^0 \to \Lambda_c^+ 3\pi)}{B(\Lambda_b^0 \to \Lambda_c^+ \mu\nu)}$$

external input

R(Λ_c^+)

[LHCb, arXiv:2201.03497]

- Template fit in 3-dimensions: t_τ, q^2 and BDT
  - BDT trained using kinematic distributions to exploit resonant structure of the 3π system in τ decays



$$R(\Lambda_c^+) = 0.242 \pm 0.026 \pm 0.040 \pm 0.059$$

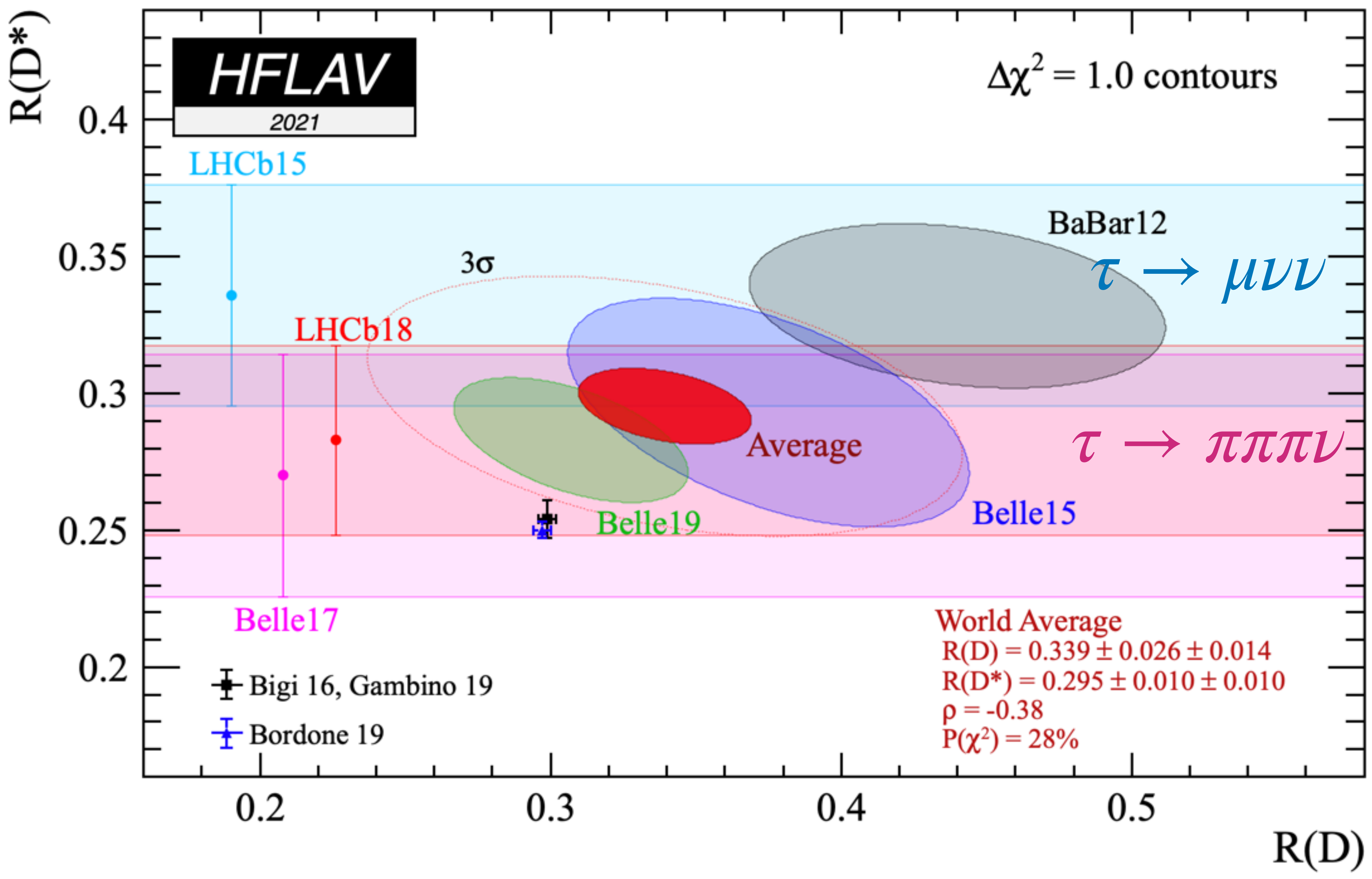
Statistical

Systematics:
- background fit templates

$B(\Lambda_b^0 \to \Lambda_c\, \mu\nu_\mu)$

Result compatible with SM prediction at 1σ

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

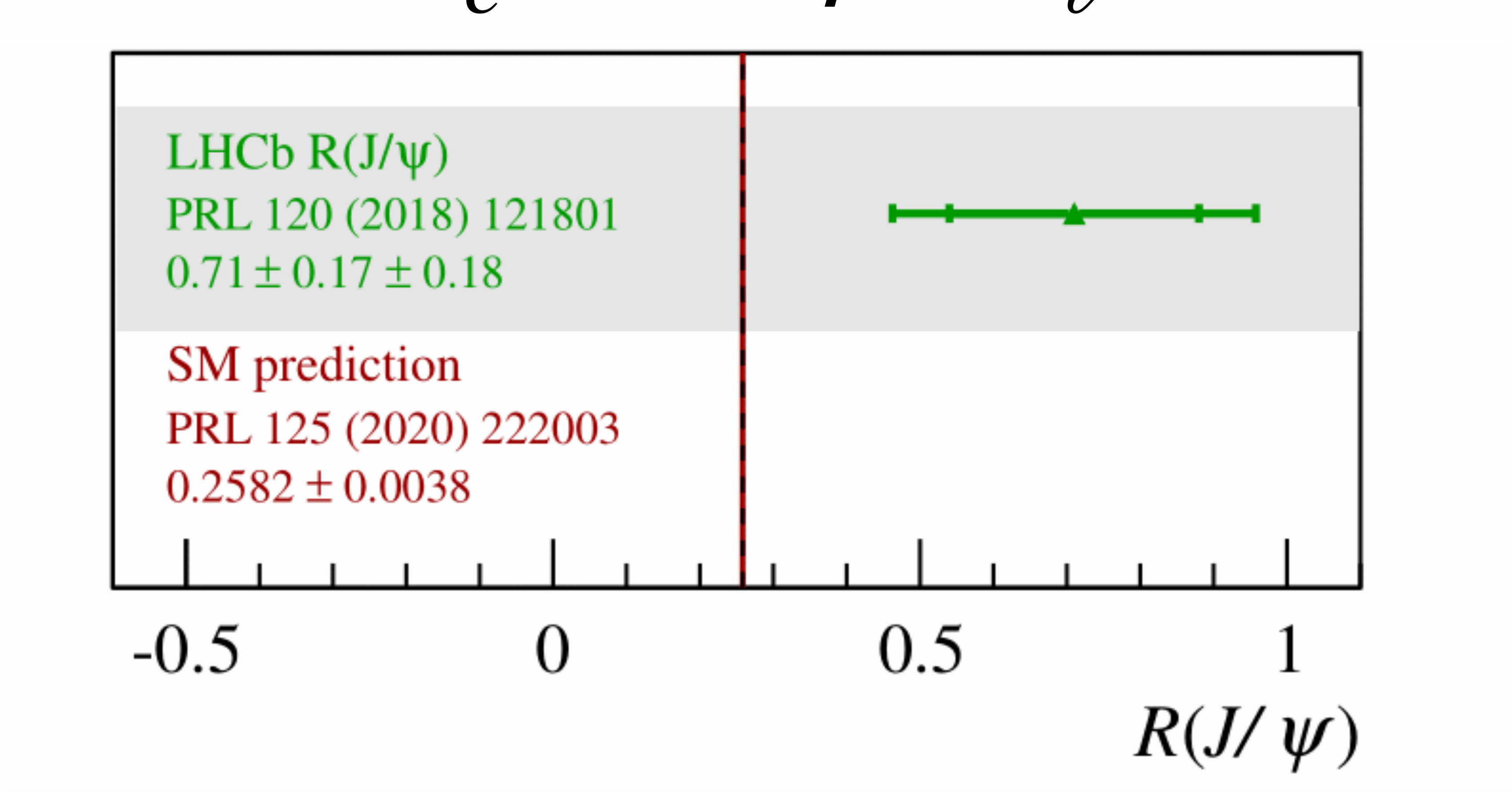


$B \to D^{(*)} \ell\nu_\ell$

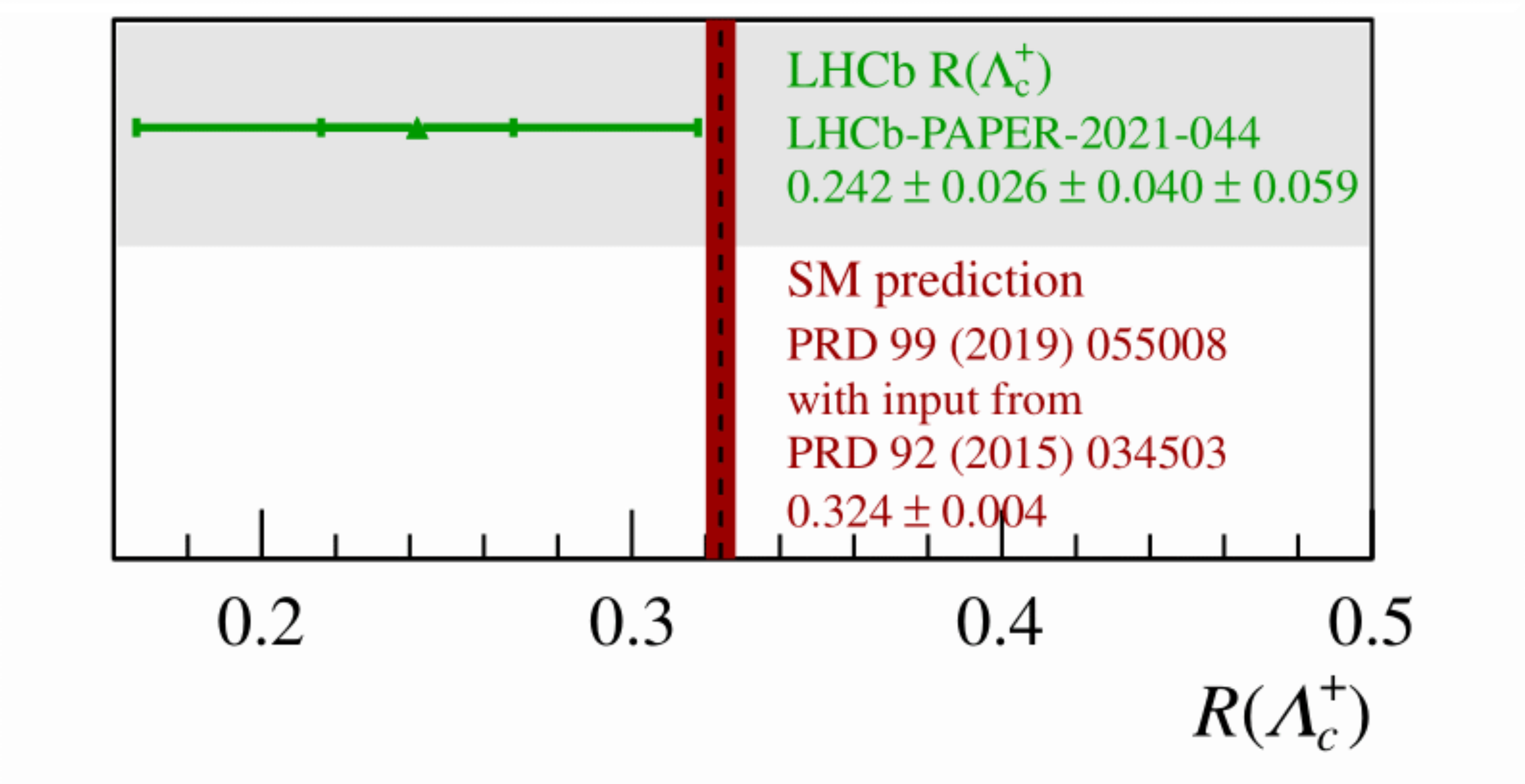
LHCb15: PRL 115 (2015) 111803
LHCb18: PRL 120 (2018) 171802
BaBar12: PRL 109 (2012) 101802

Belle15: PRD 92 (2015) 072014
Belle17: PRL 118 (2017) 211801
Belle 19: PRL 124 (2020) 161803

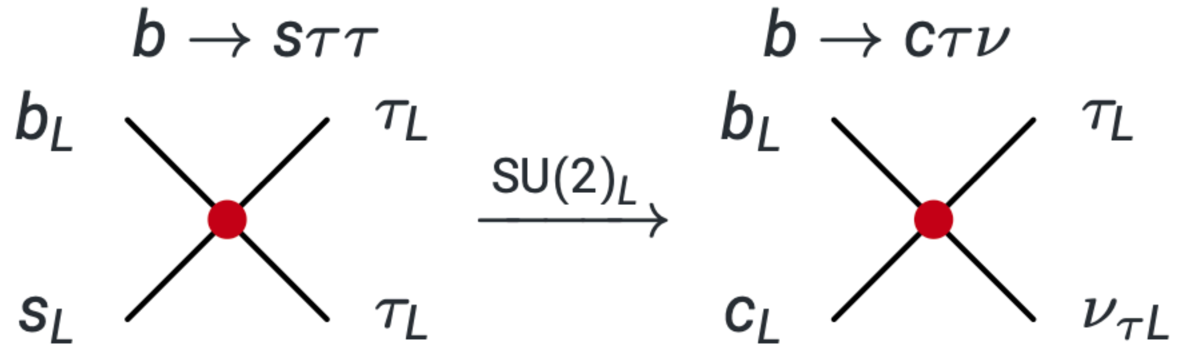
$B_c \to J/\psi\, \ell\nu_\ell$



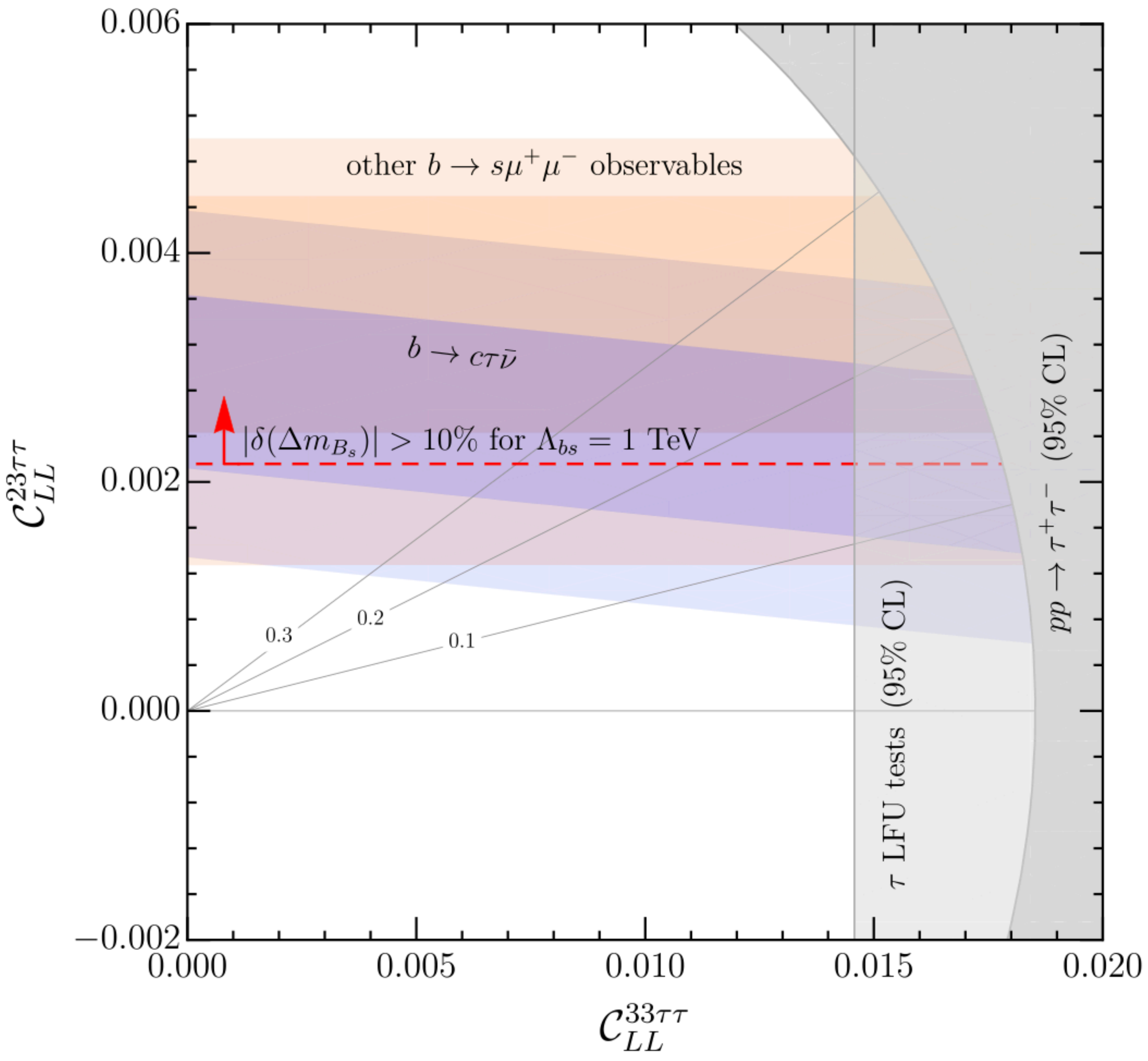
$\Lambda_b \to \Lambda_c\, \ell\nu_\ell$

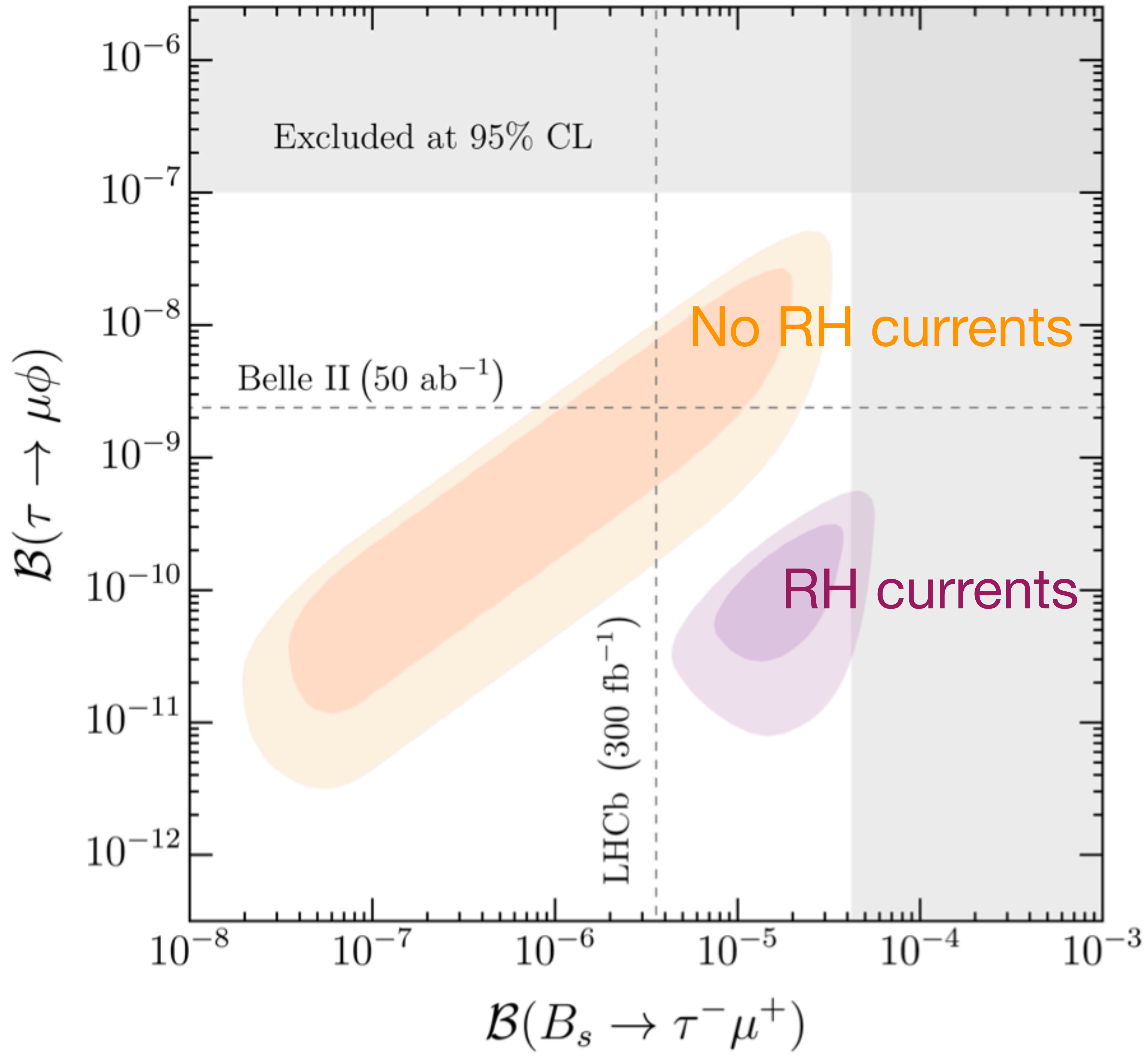


Common origin?



- Effective Field Theory fits can accommodate both sets of anomalies (left-handed, semi-leptonic operators)
- Simplified models, such as leptoquarks, usually point to **Lepton Flavour Violation** too





[Cornella et al., arXiv:2103.16558]

Lepton flavour violation at LHCb

Decay	Limit @ 90% C.L.	Luminosity	Reference
$B^0 \to e\,\mu$	1.0×10^{-9}	3 fb^{-1} (Run1)	*JHEP 03 (2018) 078*
$B_s \to e\,\mu$	5.4×10^{-9}		
$B^+ \to K^+ e^+ \mu^-$	7.0×10^{-9}	3 fb^{-1} (Run1)	*Phys. Rev. Lett. 123 (2019) 241802*
$B^+ \to K^+ e^- \mu^+$	6.4×10^{-9}		
$B^0 \to K^{*0} \mu^{\pm} e$	9.9×10^{-9}	9 fb^{-1} (Run1+2)	*LHCb-PAPER-2022-008 (preliminary)*
$B^0 \to K^{*0} \mu^- e^+$	6.7×10^{-9}		
$B^0 \to K^{*0} \mu^+ e^-$	5.7×10^{-9}		
$B_s \to \phi\, \mu^{\pm} e$	1.6×10^{-8}		
$B^0 \to \tau\,\mu$	1.2×10^{-5}	3 fb^{-1} (Run1)	*Phys. Rev. Lett. 123 (2019) 211801*
$B_s \to \tau\,\mu$	3.4×10^{-5}		
$B^+ \to K^+ \tau\,\mu$	3.9×10^{-5}	9 fb^{-1} (Run1+2)	*JHEP 06 (2020) 129*

Also: *$BR(\tau \to \mu\mu\mu) < 4.6 \times 10^{-8}$ at 90% C.L. with* 3 fb^{-1} (Run1)*[JHEP 02 (2015) 121]*

Compilation by F. Polci, Moriond QCD 22

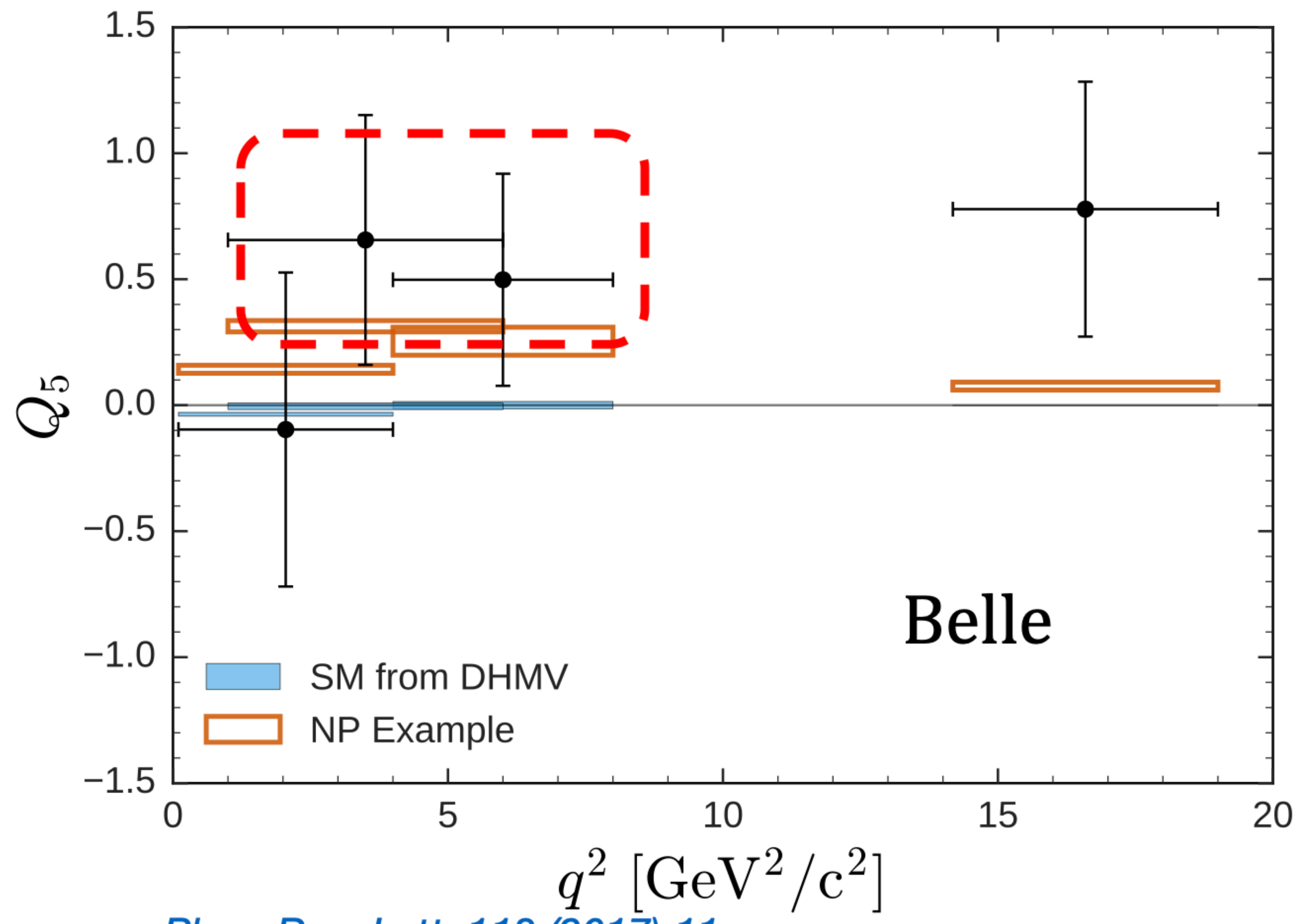
More data is on its way!

[LHCb, arXiv:1808.08865]

R_X precision	$9\,\text{fb}^{-1}$
R_K	0.043
$R_{K^{*0}}$	0.052
R_ϕ	0.130
R_{pK}	0.105
R_π	0.302

From LHCb many results still to come from Run1+2 data

- LFU test in different channels/kinematic regions
  [$R_{K^{*0}}$, R_ϕ, high-q^2, R(D), …]
- Angular observables of $b \to s\mu^+\mu^-$ decays
  [parameterising hadronic contributions, LFU…]
- Measurements of $b \to s\tau\tau$ processes and LFV involving τ's

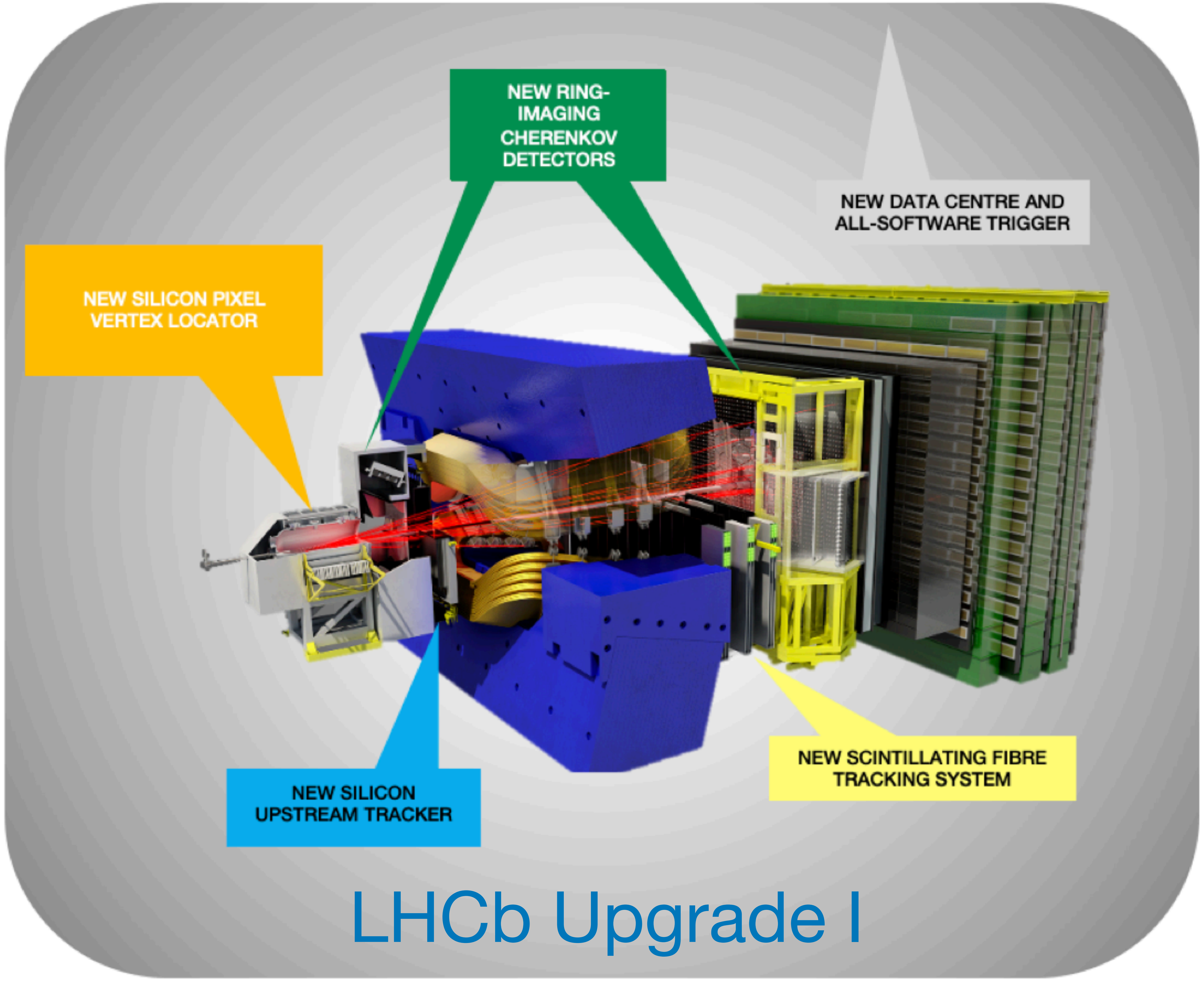


Phys. Rev. Lett. 118 (2017) 11

More data is on its way!

The LHCb Upgrade I in Run3 and Run4

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

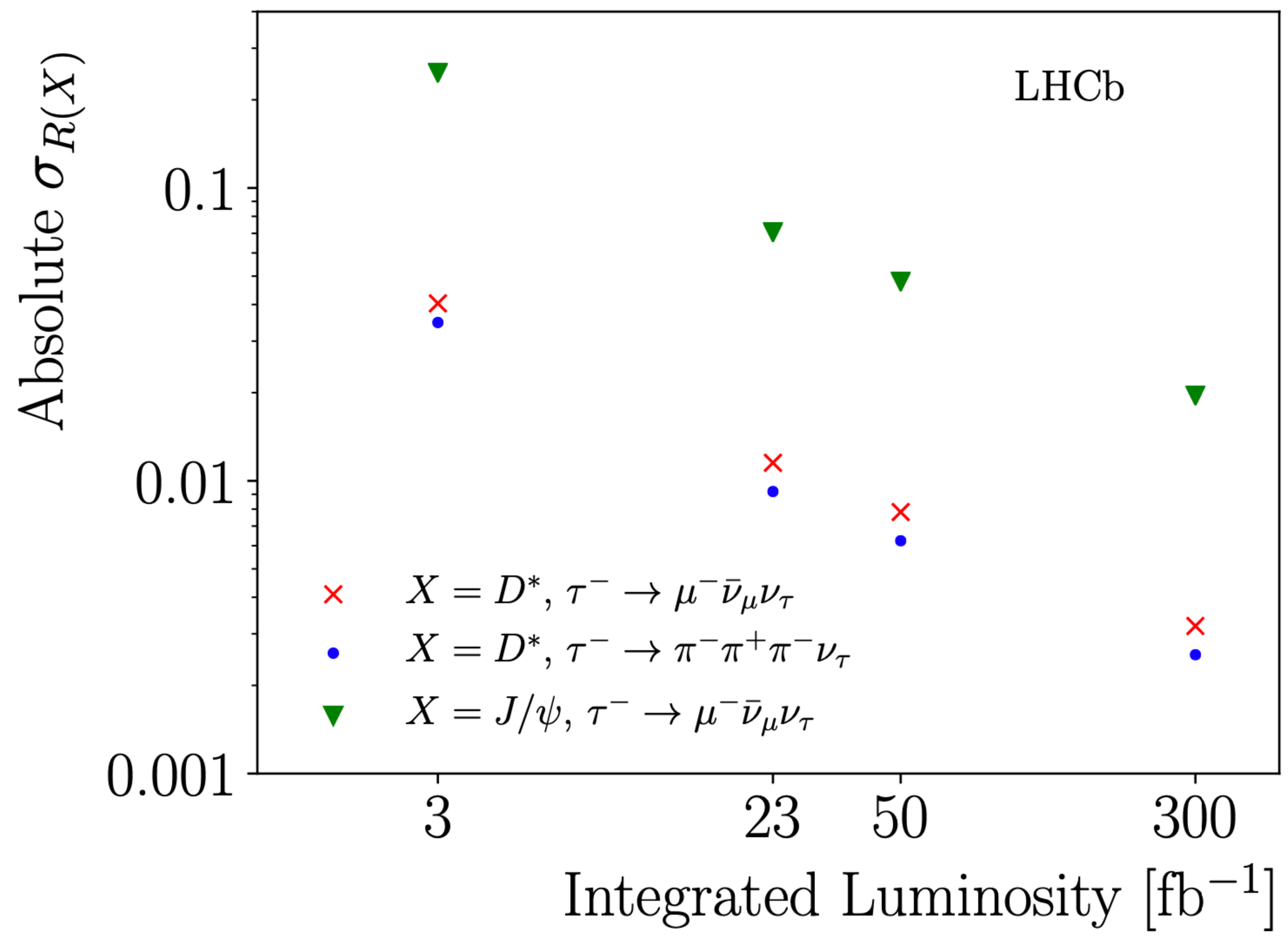


LFU with LHCb Upgrade I

[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

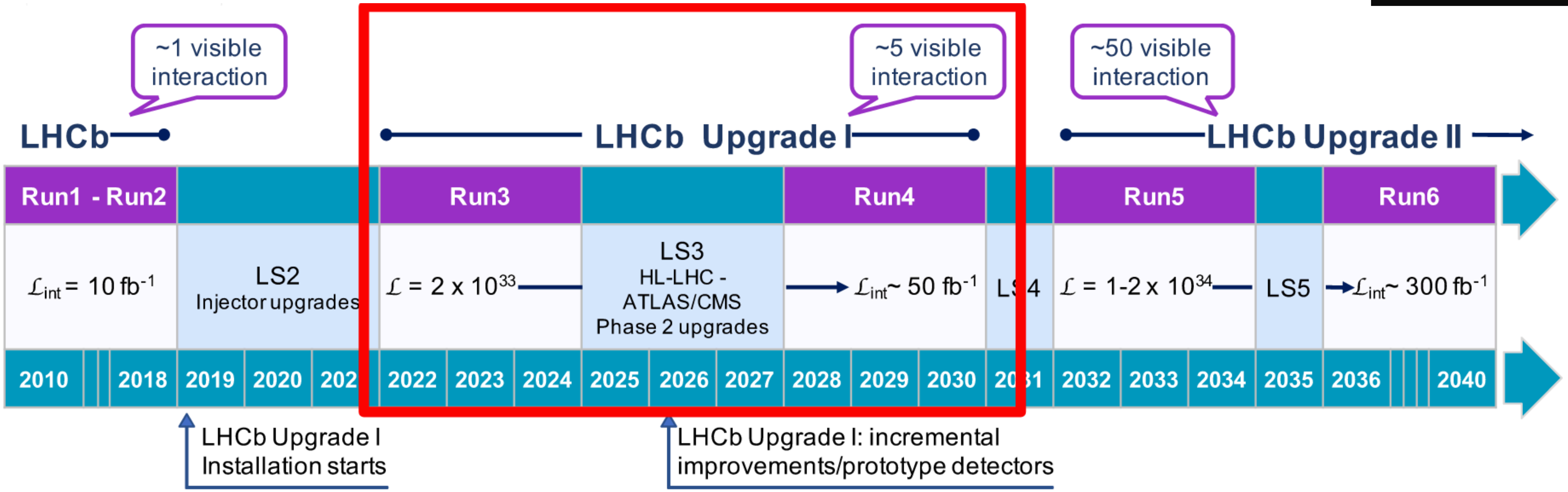
For $b \to c\ell\nu$ transitions, apart from the statistical gain, many systematics expected to scale with luminosity [background templates, normalisation BRs,…]

LHCb Upgrade II

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

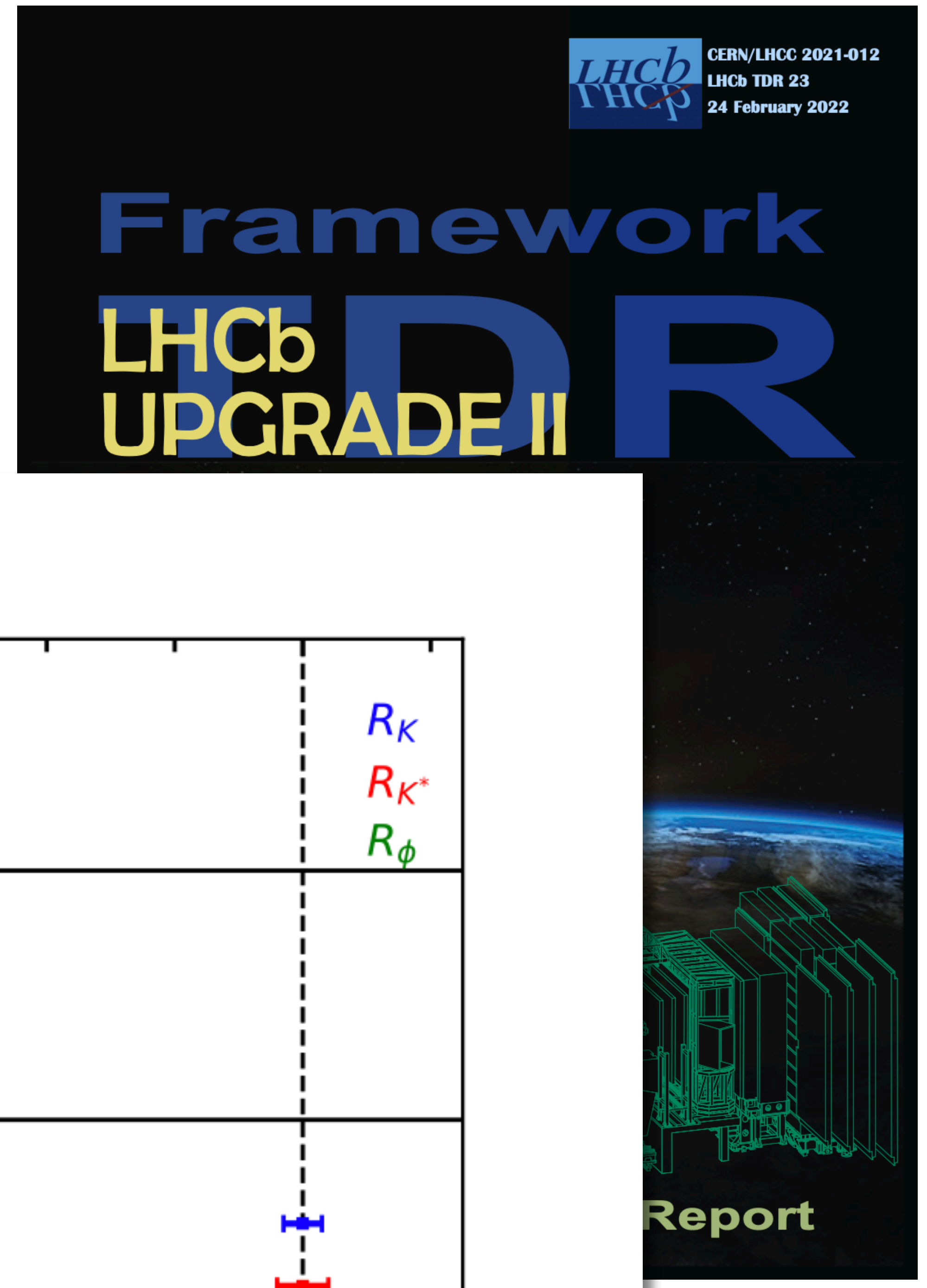
- Maintain performance in a much more challenging environment [new technologies, adding timing information]
- Expect to collect 10x more data than phase I

[LHCb, CERN-LHCC-2021-012]



LHCb Upgrade II

CC-2021-012]



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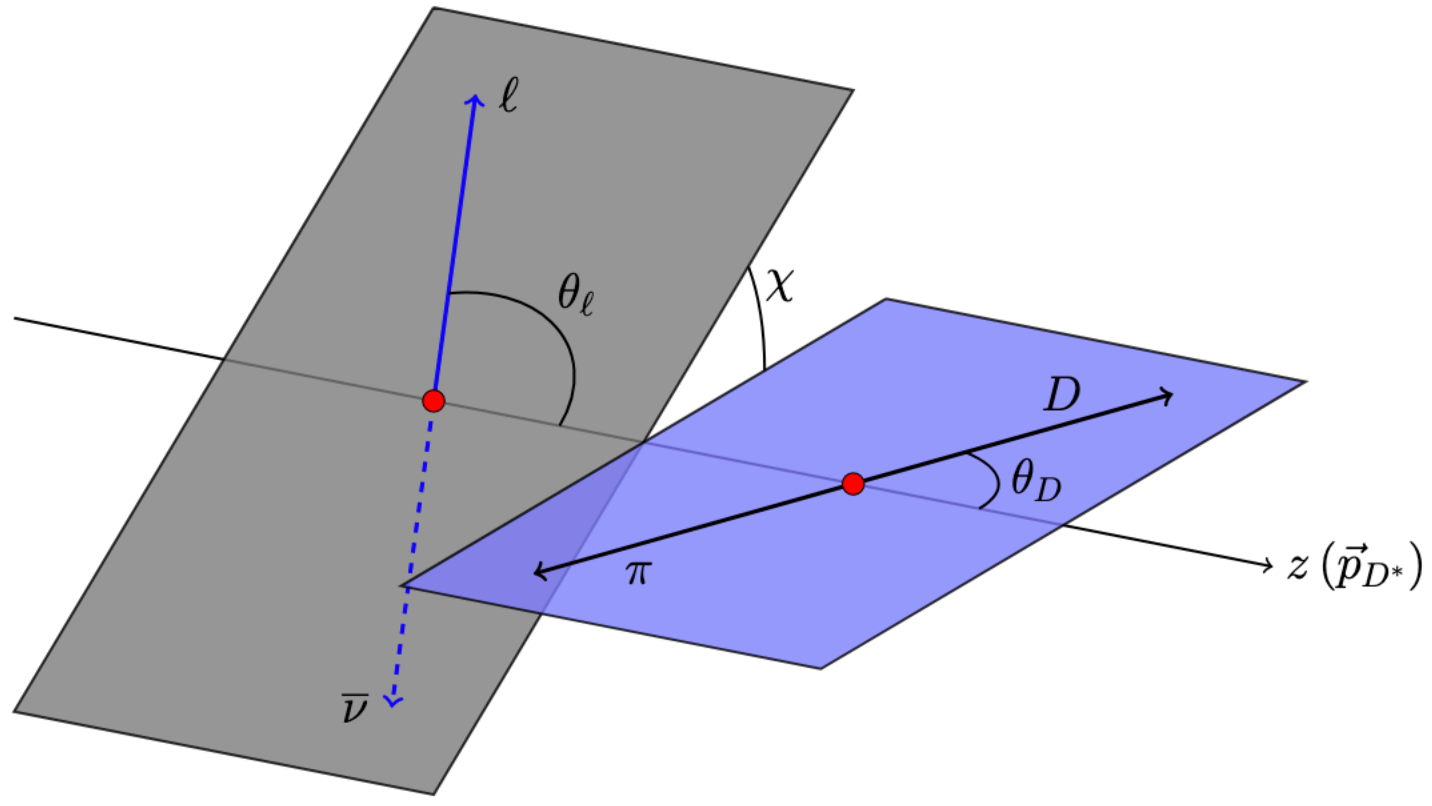
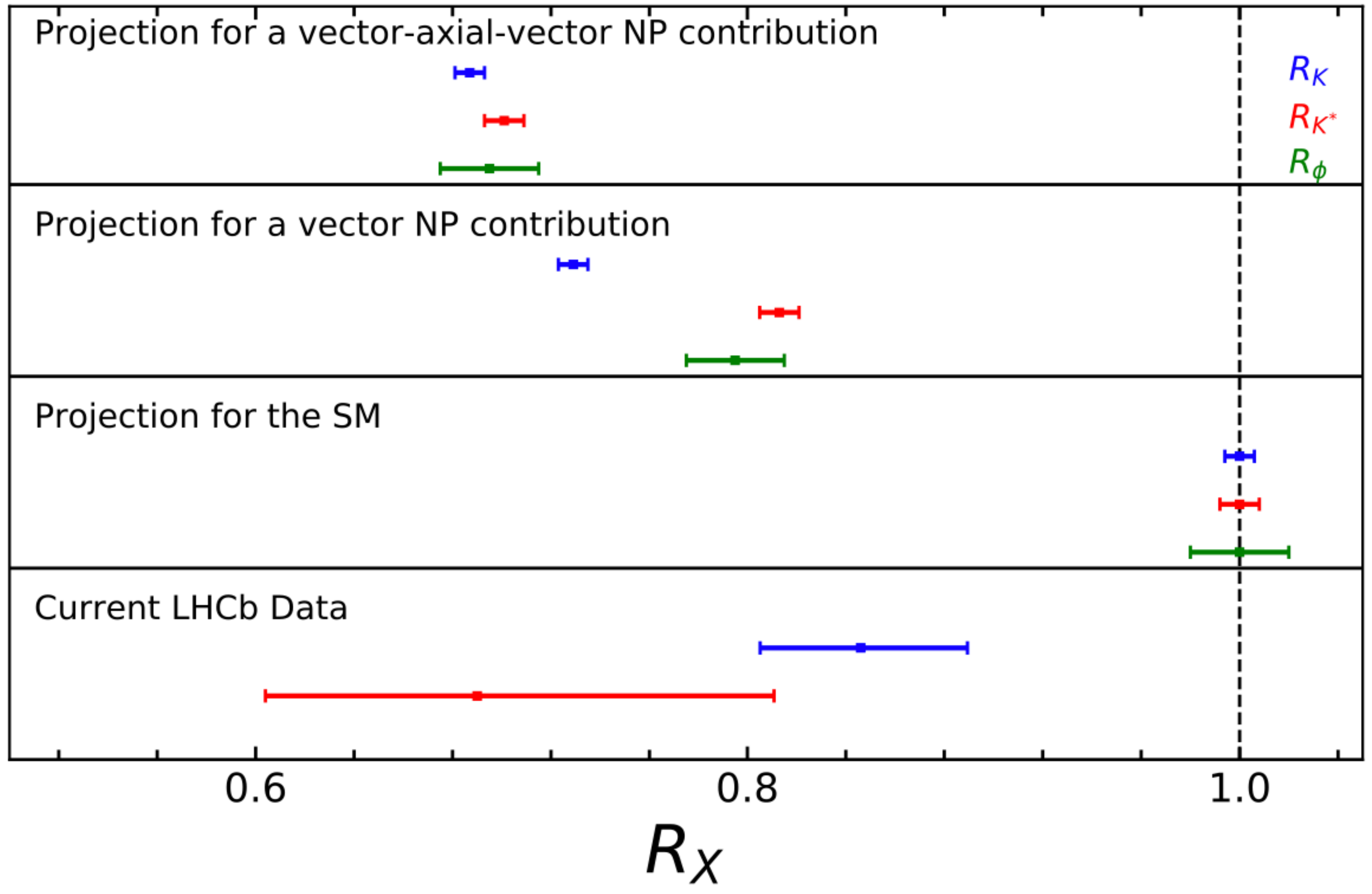


Access amplitudes for B->D* τ ν



Clearly distinguish New Physics scenarios

LHCb Upgrade I
Installation starts

LHCb Upgrade I: incremental
improvements/prototype detectors

Summary

- LHCb's Run1+2 dataset leaves us with an interesting pattern of anomalies
  - Understanding what these mean requires more data

- Luckily, many results expected with the full exploitation of LHC's Run2 dataset, and Run3 just started!

Backup