Lepton flavour universality tests

SM@LHC 11-14 April 2022

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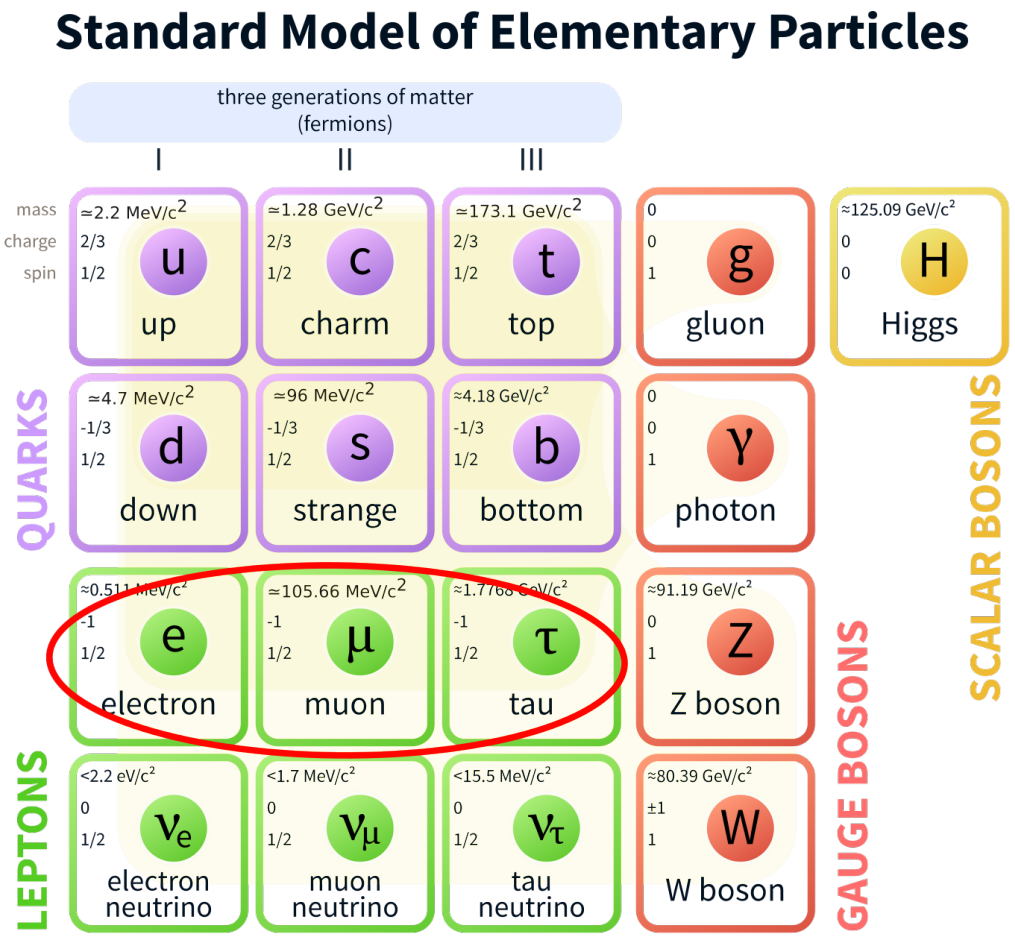
on behalf of the LHCb collaboration
with results from ATLAS & CMS

12.04.2022

The University of Manchester

Lepton flavour universality



[link]

In the Standard Model (SM)

- leptons almost the same
  - same electroweak couplings
  - but different masses

$\rightarrow$ lepton flavour universality

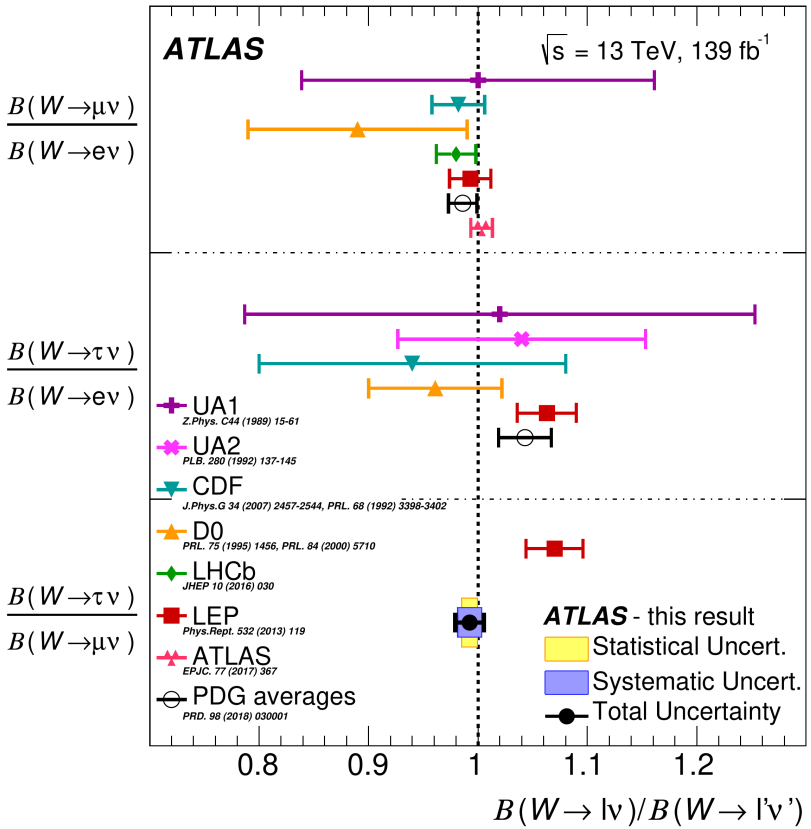
Lepton flavour universality

Lepton flavour universality in weak coupling well established

- $Z \to \ell^+\ell^-$
  - $\frac{\Gamma_{Z\to\mu^+\mu^-}}{\Gamma_{Z\to e^+e^-}} = 1.0009 \pm 0.0028$
  - $\frac{\Gamma_{Z\to\tau^+\tau^-}}{\Gamma_{Z\to\mu^+\mu^-}} = 1.0019 \pm 0.0032$

[Phys. Rept. 427 (2006) 257]

- $W \to \ell\nu_\ell$



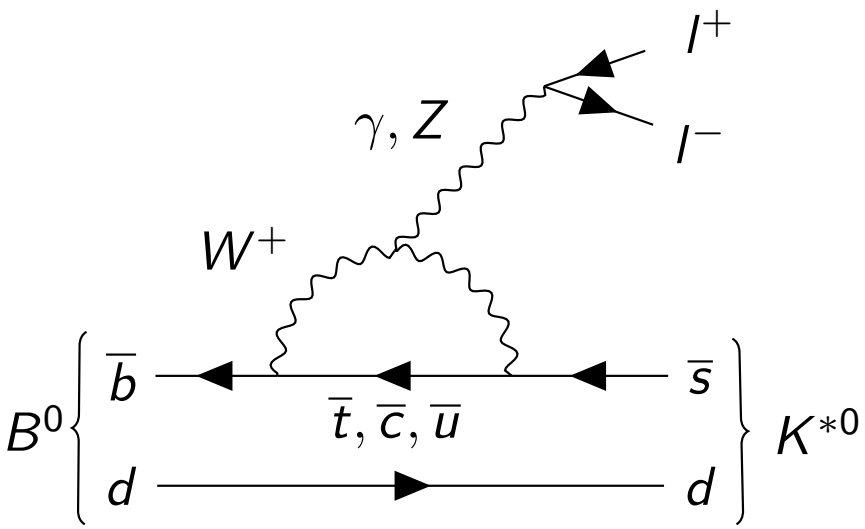
[Nature Physics 17, 813-818 (2021)]

- tensions with SM seen in LEP measurement resolved by LHC

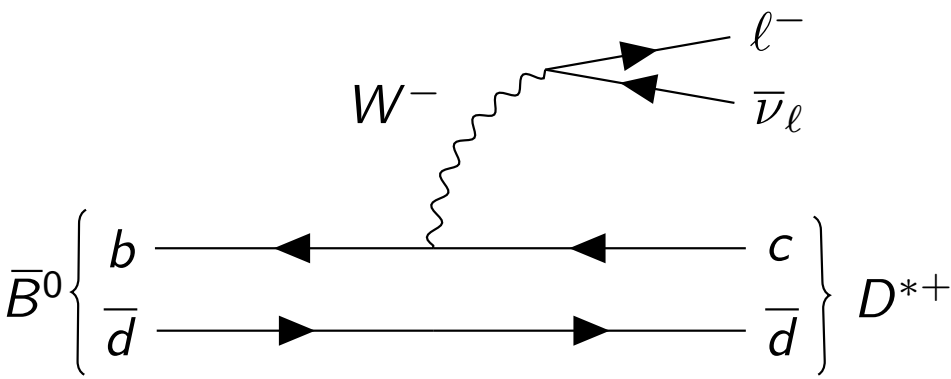
Lepton flavour universality

In past years tensions with Standard Model observed in B-hadron decays
#CautiouslyExcited

- rare penguin decays



- tree-level semileptonic decays



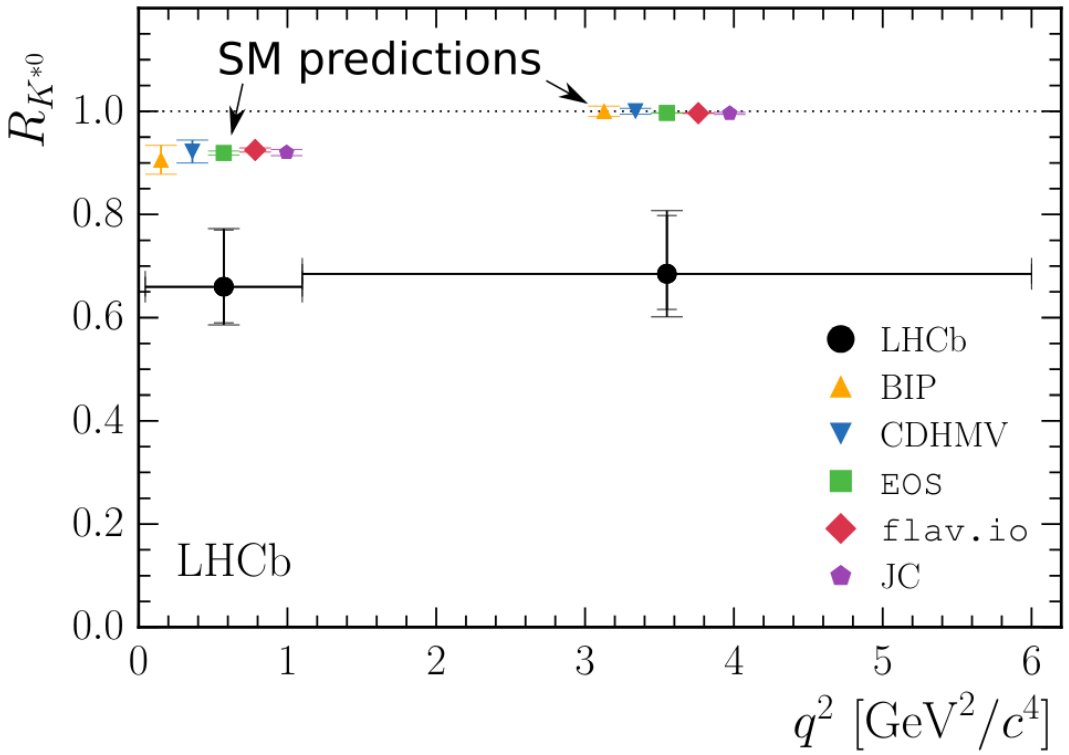
- flavour changing neutral current
  - suppressed in SM
  - mediated via loops

LFU tests in rare decays

Test LFU by measuring ratio

$$R(H) = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(H_b \to H\mu^+\mu^-)}{dq^2}}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(H_b \to He^+e^-)}{dq^2}}; \quad H = K^0_S, K^+, K^{*+}, K^{*0}, pK, \ldots$$

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

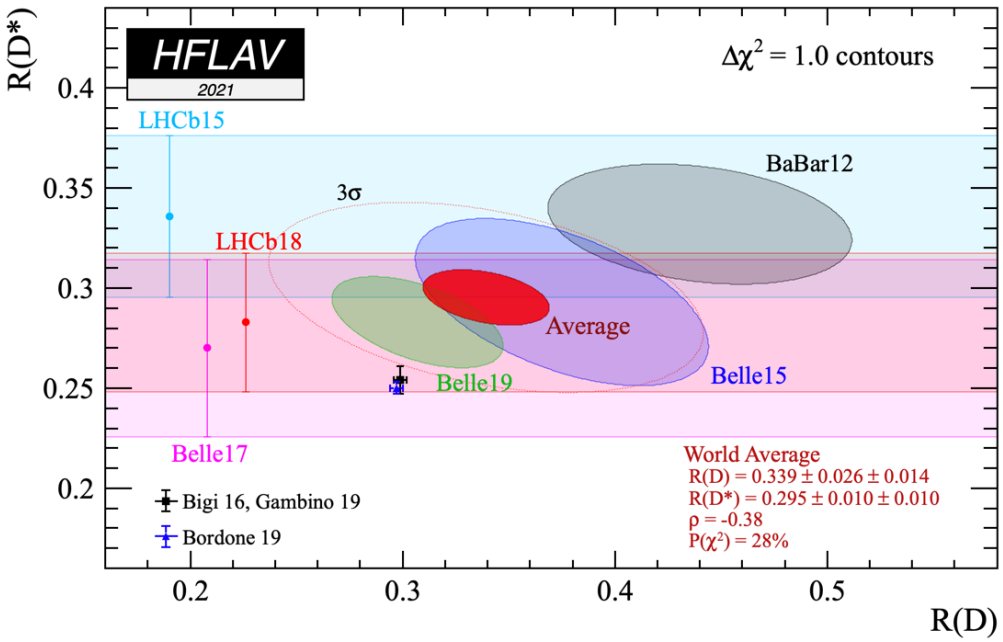


[JHEP 08 (2017), 055]

LFU tests in semileptonic decays

Test LFU by measuring ratio

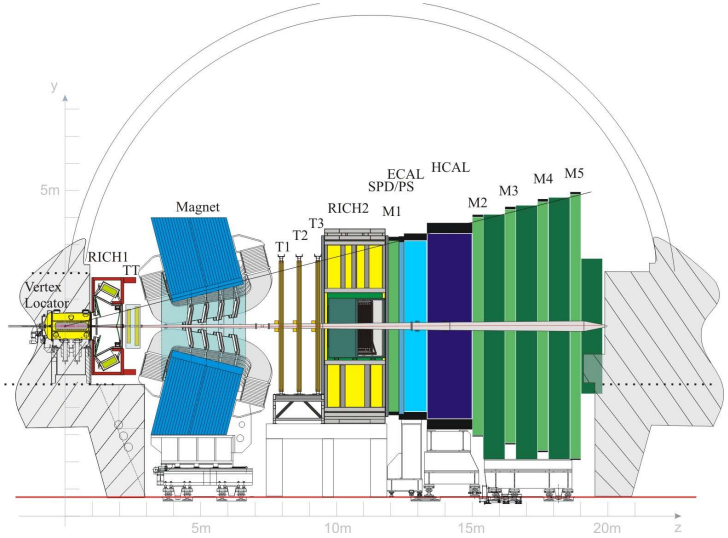
$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau \overline{\nu}_\tau)}{\mathcal{B}(H_b \to H_c \ell \overline{\nu}_\ell)}; \quad H_c = D^{*+}, D^0, D^+, D_s^+, \Lambda_c^+, \ldots$$



[Eur. Phys. J. C (2021) 81: 22]

- $\ell = e, \mu$ B-factories
- $\ell = \mu$ LHCb

LFU@LHCb



[JINST 3 (2008) S08005]

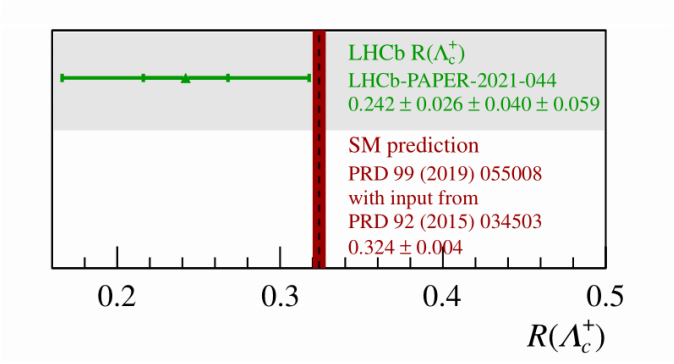
Ratios measured at LHCb:

- $b \to c\ell\overline{\nu}$
  - $R(J/\psi)$ $B_c^- \to J/\psi\,\ell^-\overline{\nu}_\ell$
  - $R(D^{*+})$ $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_\ell$
  - $R(\Lambda_c^+)$ $\Lambda_b^0 \to \Lambda_c^+\ell^-\overline{\nu}_\ell$
- $b \to s\ell^+\ell^-$
  - $R(K^{*0})$ $B^0 \to K^{*0}\ell^+\ell^-$
  - $R(pK)$ $\Lambda_b^0 \to pK^-\ell^+\ell^-$
  - $R(K_S^0)$ $B^0 \to K_S^0\ell^+\ell^-$
  - $R(K^{*+})$ $B^+ \to K^{*+}\ell^+\ell^-$
  - $R(K^+)$ $B^+ \to K^+\ell^+\ell^-$

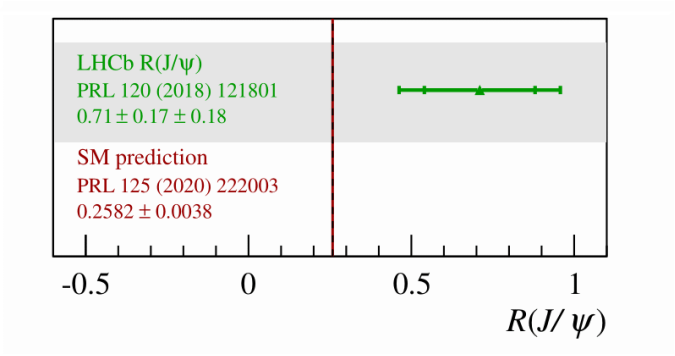
$b \to c\ell\overline{\nu}$ @LHCb

Two ways of reconstructing τ:

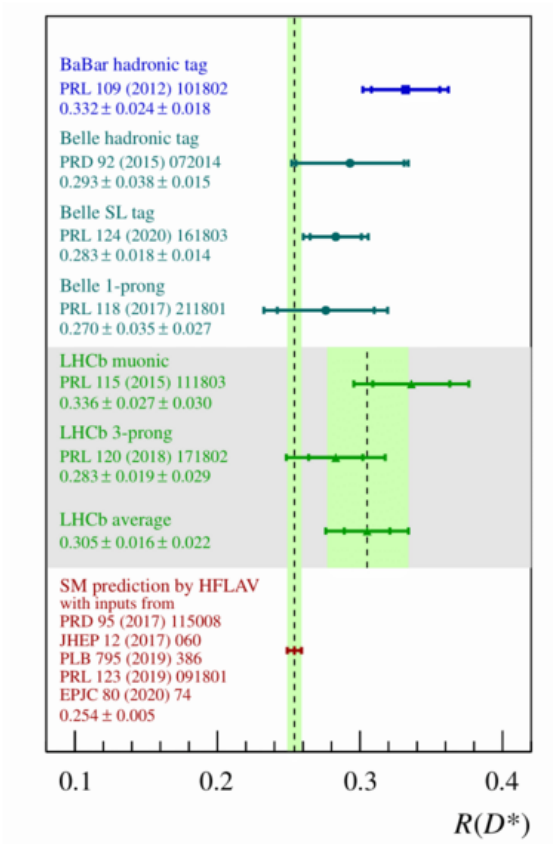
- $\tau^+ \to \pi^+\pi^+\pi^-(\pi^0)\overline{\nu}_\tau$ (hadronic)
- $\tau^+ \to \mu^+\nu_\mu\overline{\nu}_\tau$ (muonic)



$\Lambda_b^0 \to \Lambda_c^+\ell^-\overline{\nu}_\ell$



$B_c^- \to J/\psi\,\ell^-\overline{\nu}_\ell$



$\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_\ell$

experimental challenges:

- missing neutrino(s)
- many background sources
- large MC samples required for template shapes

$R(\Lambda_c^+)$ $(3\,\mathbf{fb}^{-1})$ [arXiv:2201.03497]

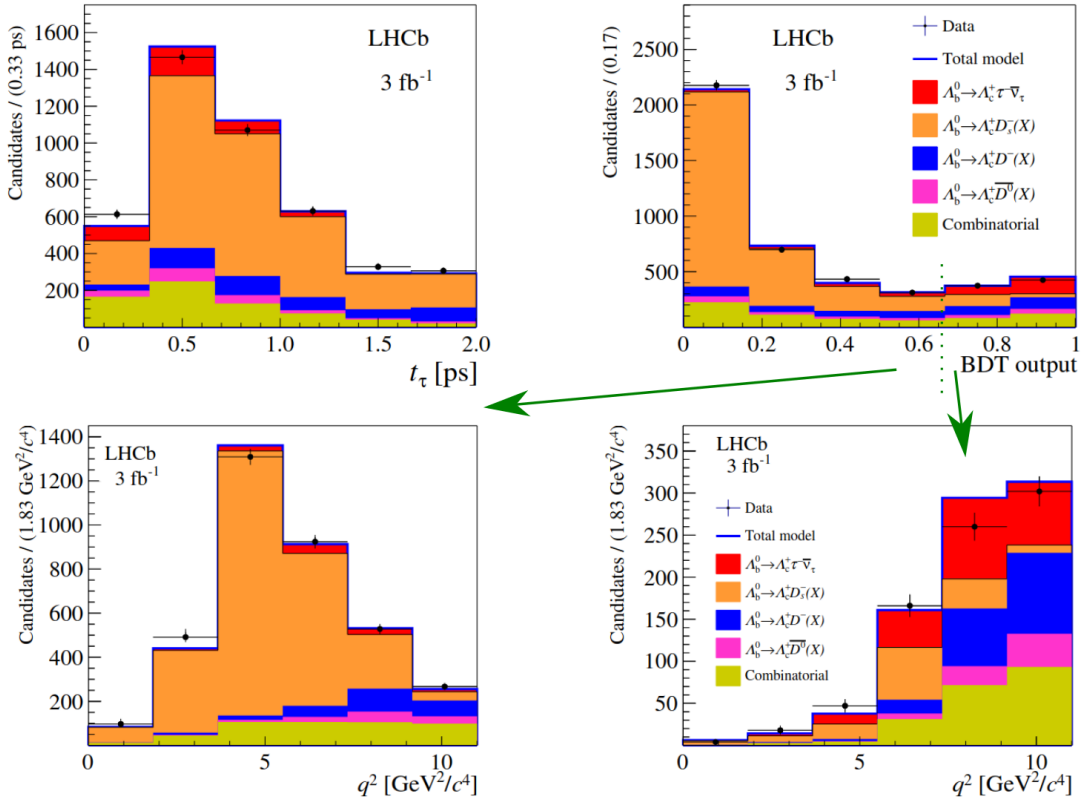
$$R(\Lambda_c^+) = \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu)}$$

- first LFU test using semileptonic baryon decay
  - spin $\frac{1}{2}$ $\to$ different BSM physics could contribute
- use hadronic τ decay
  - exploit displaced 3π vertex to suppress prompt background
- measure w.r.t normalization channel $\Lambda_b^0 \to \Lambda_c^+ 3\pi$

$$R(\Lambda_c^+) = \underbrace{\left[\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ 3\pi)}\right]}_{K(\Lambda_c^+),\mathit{measured}} \times \underbrace{\left[\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ 3\pi)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu)}\right]}_{\mathit{external}}$$

$R(\Lambda_c^+)$ $(3\,\mathbf{fb}^{-1})$ [arXiv:2201.03497]

- three-dimensional fit to t_τ, q^2 and BDT output to extract signal yield
  - $q^2 = (p_\ell + p_\nu)^2$
  - BDT trained to distinguish $\Lambda_b^0 \to \Lambda_c^+ D_s^-(X)$ decays

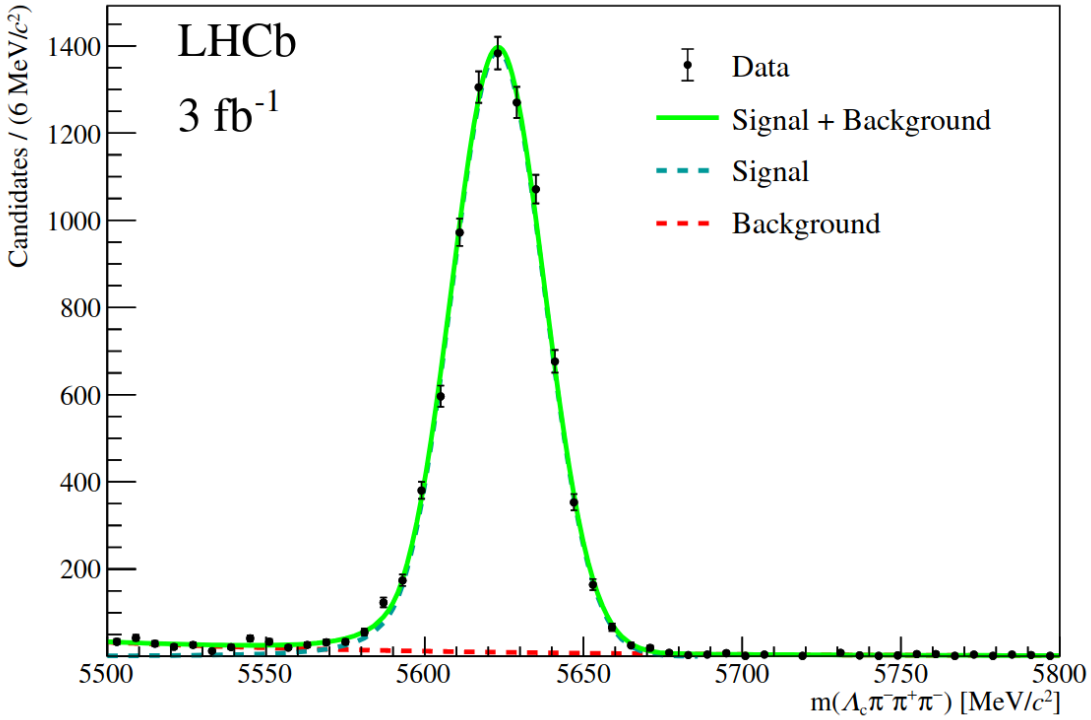


- first observation of $\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau$

$R(\Lambda_c^+)$ $(3\,\mathbf{fb}^{-1})$ [arXiv:2201.03497]

$$K(\Lambda_c^+) = \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ 3\pi)} = \frac{N_{sig}}{N_{norm}} \frac{\epsilon_{norm}}{\epsilon_{sig}} \frac{1}{\mathcal{B}(\tau^- \to 3\pi(\pi^0)\nu_\tau)}$$

- fit to extract normalisation yield after removing Λ^* decays



$$K(\Lambda_c^+) = 2.46 \pm 0.27\,(\text{stat}) \pm 0.40\,(\text{syst})$$

$R(\Lambda_c^+)$ (3 **fb**$^{-1}$) [arXiv:2201.03497]

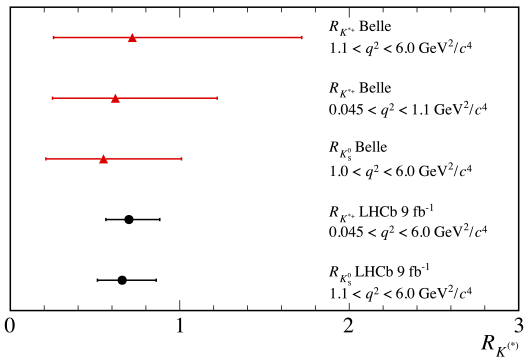
$$R(\Lambda_c^+) = 0.242 \pm 0.026\,(\text{stat}) \pm 0.040\,(\text{syst}) \pm 0.059(ext)$$

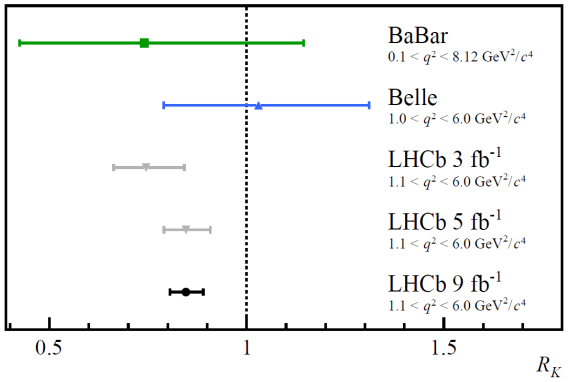
Source	$\delta\mathcal{K}(\Lambda_c^+)/\mathcal{K}(\Lambda_c^+)[\%]$
Simulated sample size	3.8
Fit bias	3.9
Signal modelling	2.0
$\Lambda_b^0 \to \Lambda_c^{*+}\tau^-\overline{\nu}_\tau$ feeddown	2.5
$D_s^- \to 3\pi Y$ decay model	2.5
$\Lambda_b^0 \to \Lambda_c^+ D_s^- X$, $\Lambda_b^0 \to \Lambda_c^+ D^- X$, $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 X$ background	4.7
Combinatorial background	0.5
Particle identification and trigger corrections	1.5
Isolation BDT classifier and vertex selection requirements	4.5
D_s^-, D^-, $\overline{D}^0$ template shapes	13.0
Efficiency ratio	2.8
Normalisation channel efficiency (modelling of $\Lambda_b^0 \to \Lambda_c^+ 3\pi$)	3.0
Total uncertainty	16.5

SM prediction $R^{SM}(\Lambda_c^+) = 0.324 \pm 0.004$ [Phys. Rev. D99 (2019) 055008]

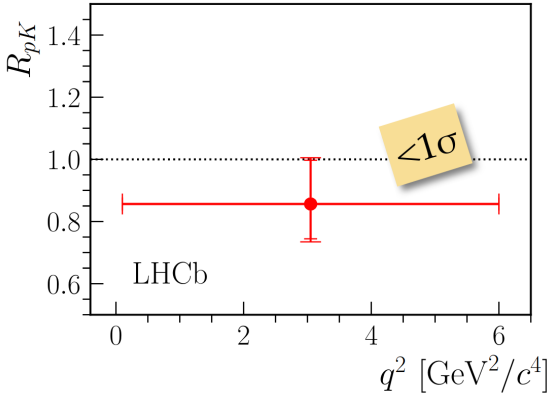
- in agreement within 1σ

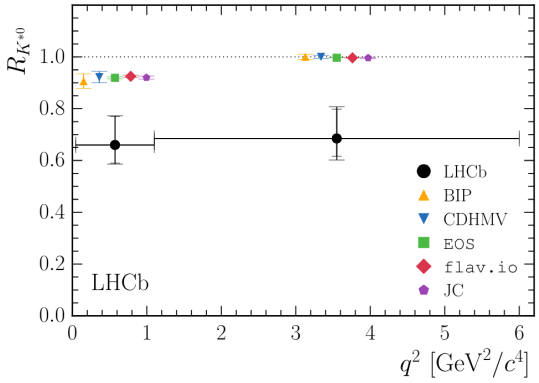
$b \to s\ell^+\ell^-$ @LHCb





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





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

experimental challenges:

- electrons and muons behave differently in detector
  - Bremsstrahlung
  - trigger efficiency

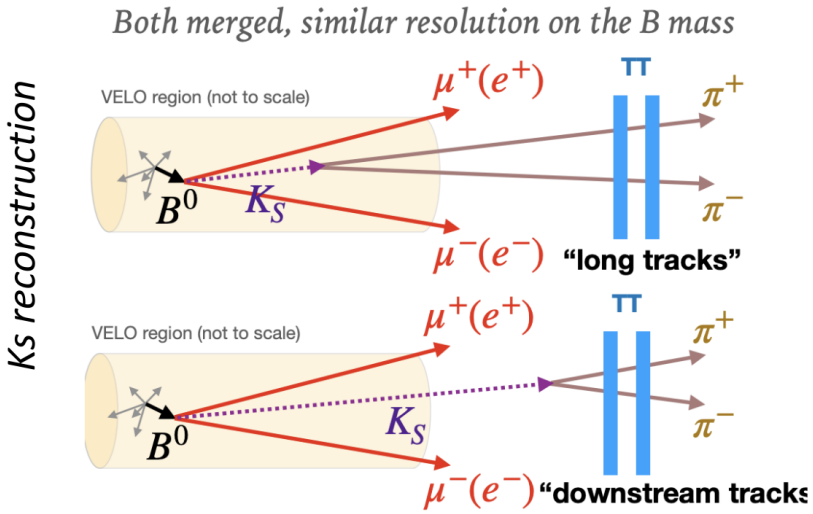
$R(K^0_S)$ and $R(K^{*+})$ ($9\,\mathrm{fb}^{-1}$) [arXiv:2110.09501]

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

- $K^0_S \to \pi^+\pi^-$
- $K^{*+} \to K^0_S \pi^+$

experimental challenges:

- electron Bremsstrahlung
- K^0_S reconstruction



Typical strategy: measure double-ratio using resonant mode

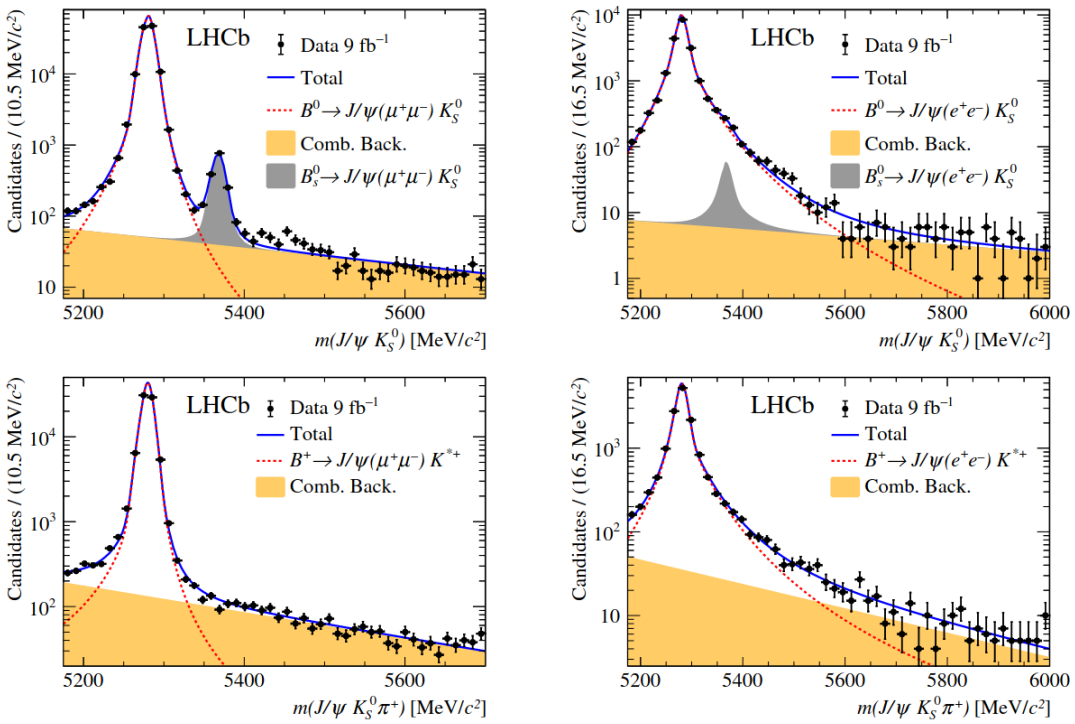
$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \times \frac{\mathcal{B}(B \to K^{(*)}J/\psi(\to e^+e^-))}{\mathcal{B}(B \to K^{(*)}J/\psi(\to \mu^+\mu^-))}$$

- systematic uncertainties cancel in ratio

$R(K^0_S)$ and $R(K^{*+})$ ($9\,\mathrm{fb}^{-1}$) [arXiv:2110.09501]

validation by measuring ratio of control modes

$$r^{-1}_{J/\psi\,K^{(*)}} = \frac{N(B\to K^{(*)}J/\psi\,(\to e^+e^-))}{N(B\to K^{(*)}J/\psi\,(\to \mu^+\mu^-))}\,\frac{\epsilon(B\to K^{(*)}J/\psi\,(\to \mu^+\mu^-))}{\epsilon(B\to K^{(*)}J/\psi\,(\to e^+e^-))}$$



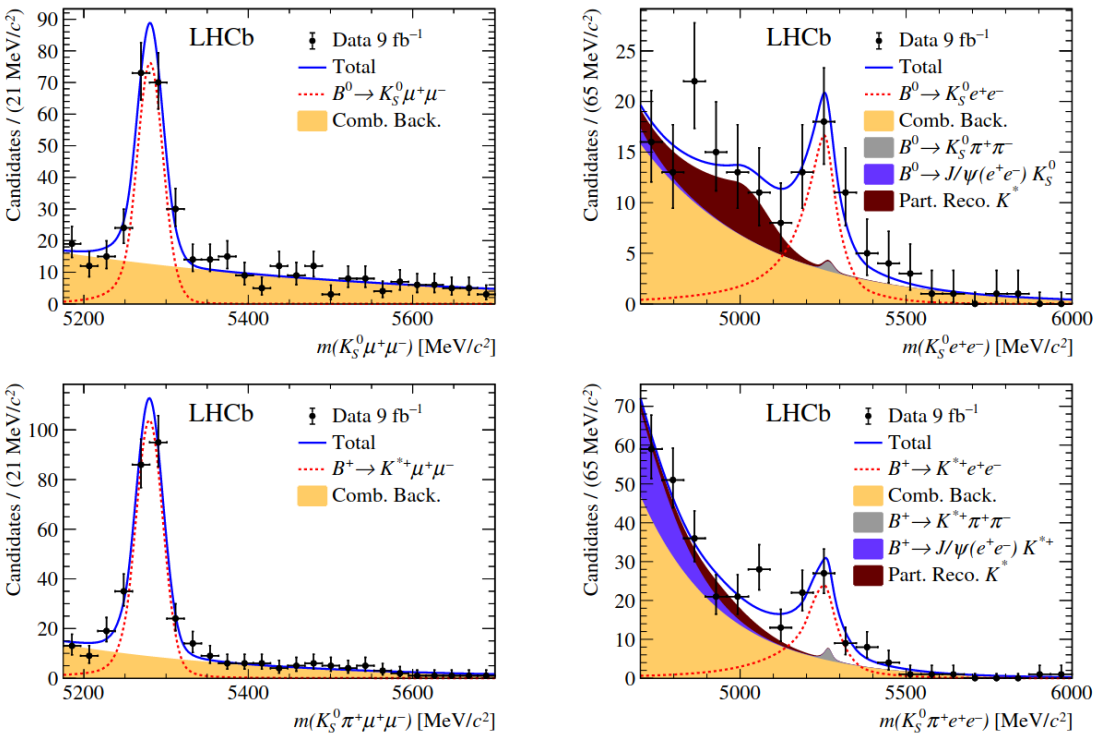
$$r^{-1}_{J/\psi\,K^0_S} = 0.977 \pm 0.008\,(\mathrm{stat}) \pm 0.027\,(\mathrm{syst})$$

$$r^{-1}_{J/\psi\,K^{*+}} = 0.965 \pm 0.011\,(\mathrm{stat}) \pm 0.045\,(\mathrm{syst})$$

$\rightarrow$ in good agreement with SM expectation of unity

$R(K^0_S)$ and $R(K^{*+})$ ($9\,\mathrm{fb}^{-1}$) [arXiv:2110.09501]

- first observation of rare electron modes

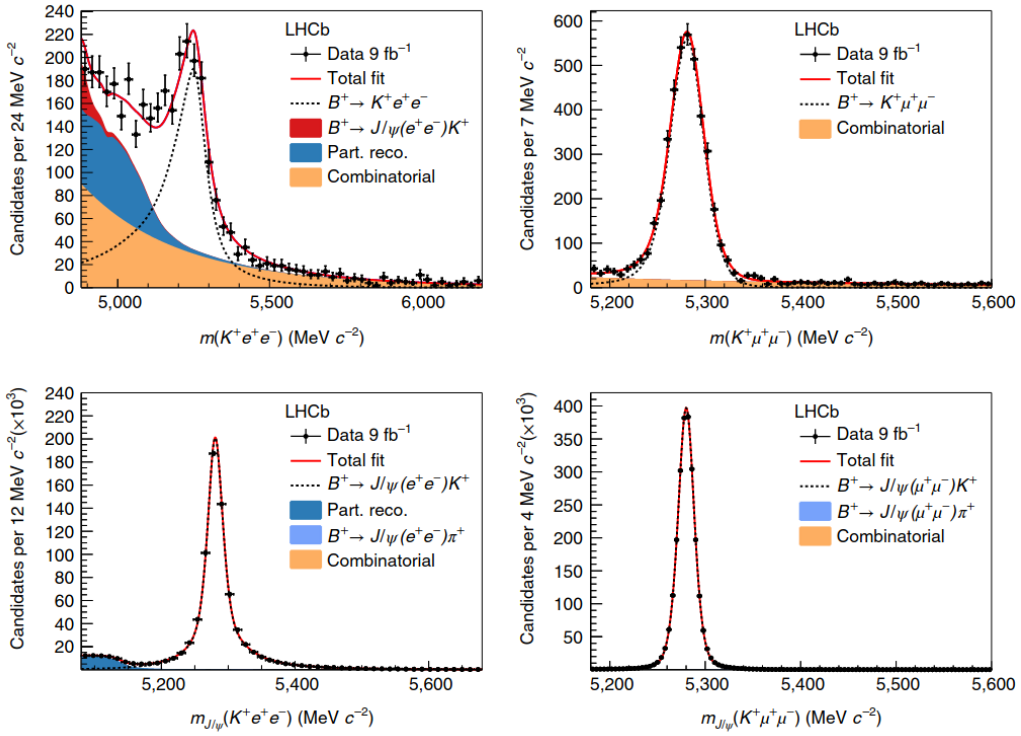


$$R(K^0_S) = 0.66^{+0.20}_{-0.14}\,(\mathrm{stat})^{+0.02}_{-0.04}\,(\mathrm{syst})$$
$$R(K^{*+}) = 0.70^{+0.18}_{-0.13}\,(\mathrm{stat})^{+0.03}_{-0.04}\,(\mathrm{syst})$$

- consistent with SM at 1.5 and 1.4σ

$R(K^+)$ (9 **fb**$^{-1}$) [Nat. Phys. 18, 277-282 (2022)]

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

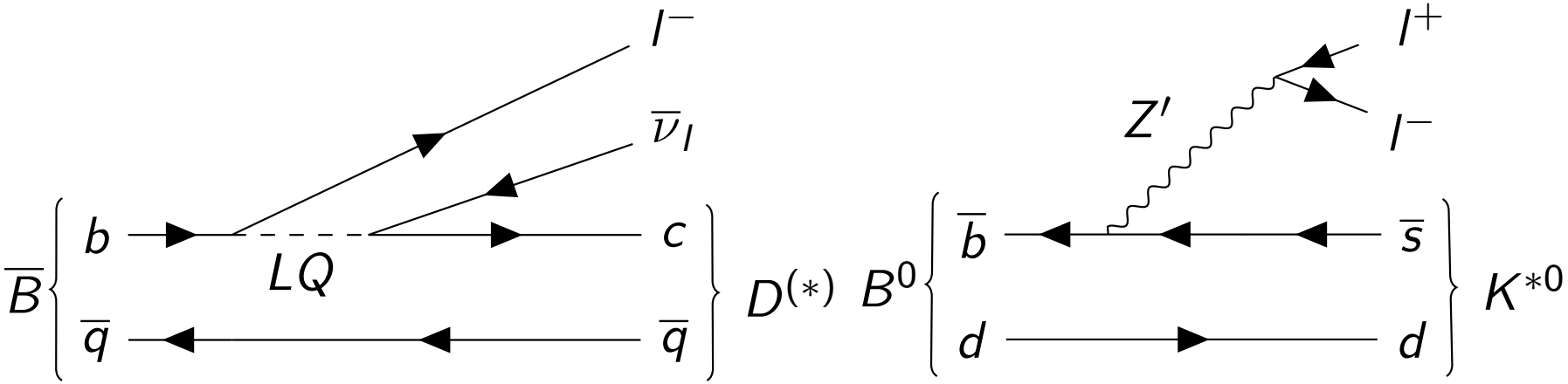


$$R(K^+) = 0.846^{+0.042}_{-0.039}\,(\text{stat})^{+0.013}_{-0.012}\,(\text{syst})$$

- 3.1σ tension with SM

LFU interpretation

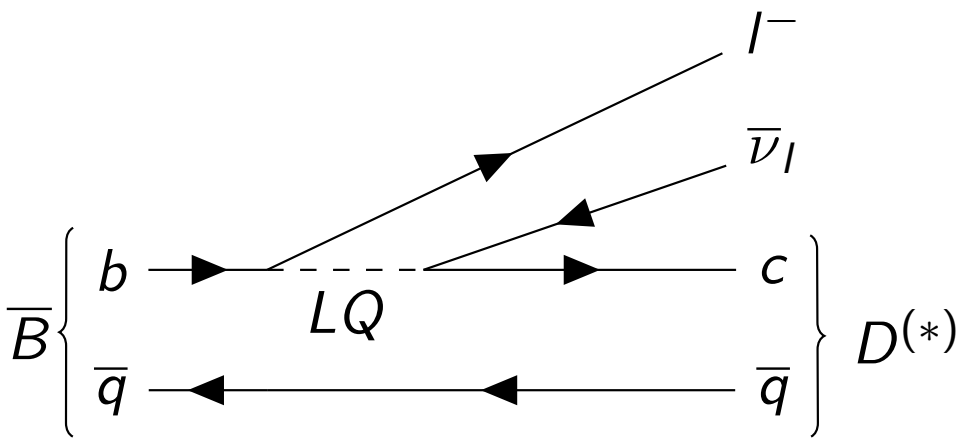
If tensions are confirmed, the big questions is:
What could beyond the SM physics look like?

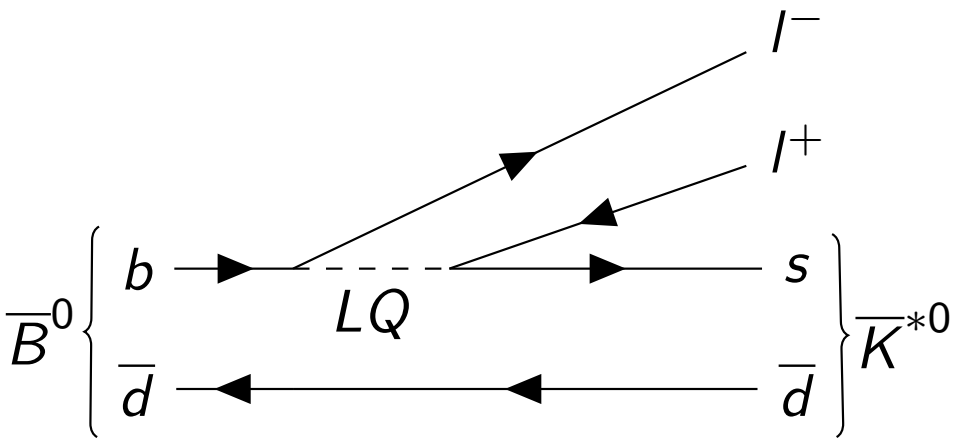


- leptoquarks?
- new heavy gauge bosons?
- charged Higgs?

LFU interpretation

Can we explain tension in rare and semileptonic decays with same model?





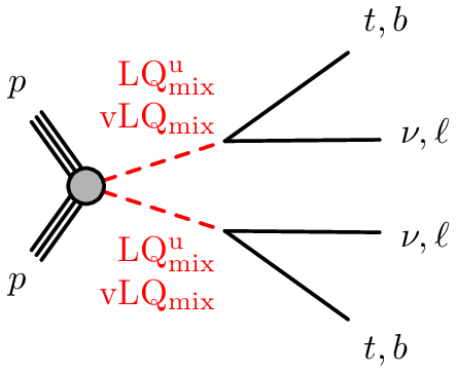
Can leptoquark model work? [PRD101,095024 (2020)]

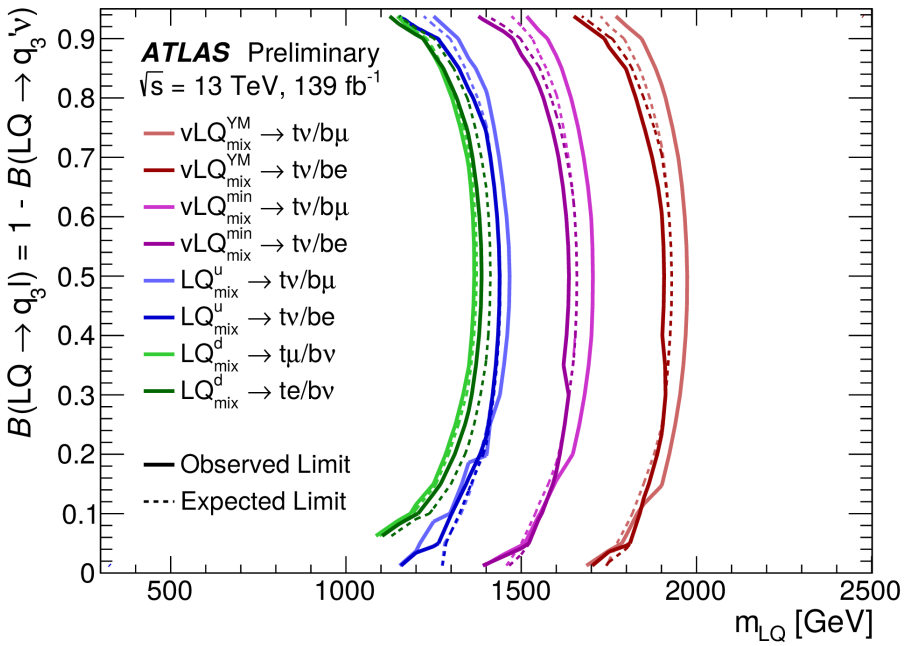
- difficult to get all measured values right
- constrained by limits on lepton flavour violating decays

Search for leptoquarks

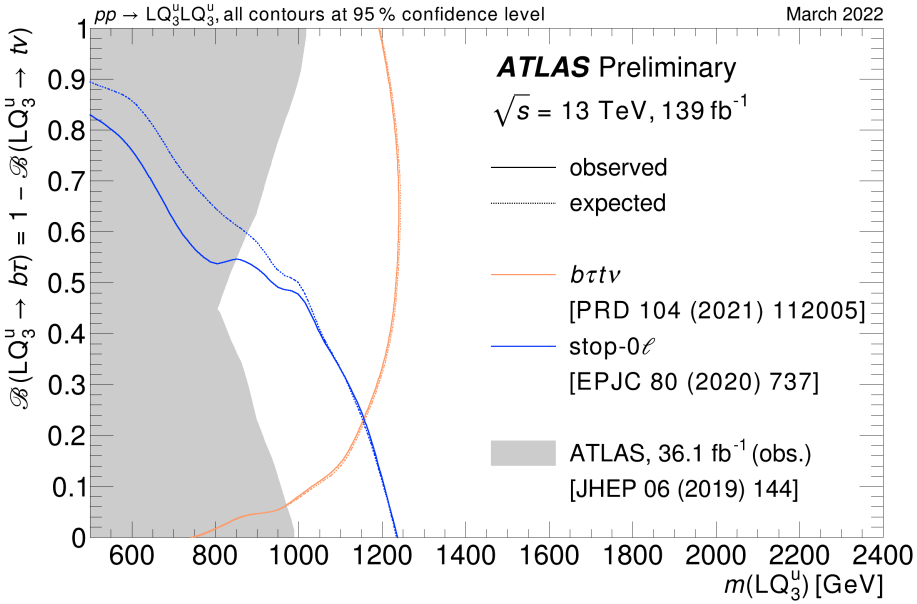
ATLAS + CMS can directly search for leptoquarks

- included in searches for new phenomena





[ATLAS-CONF-2022-009]

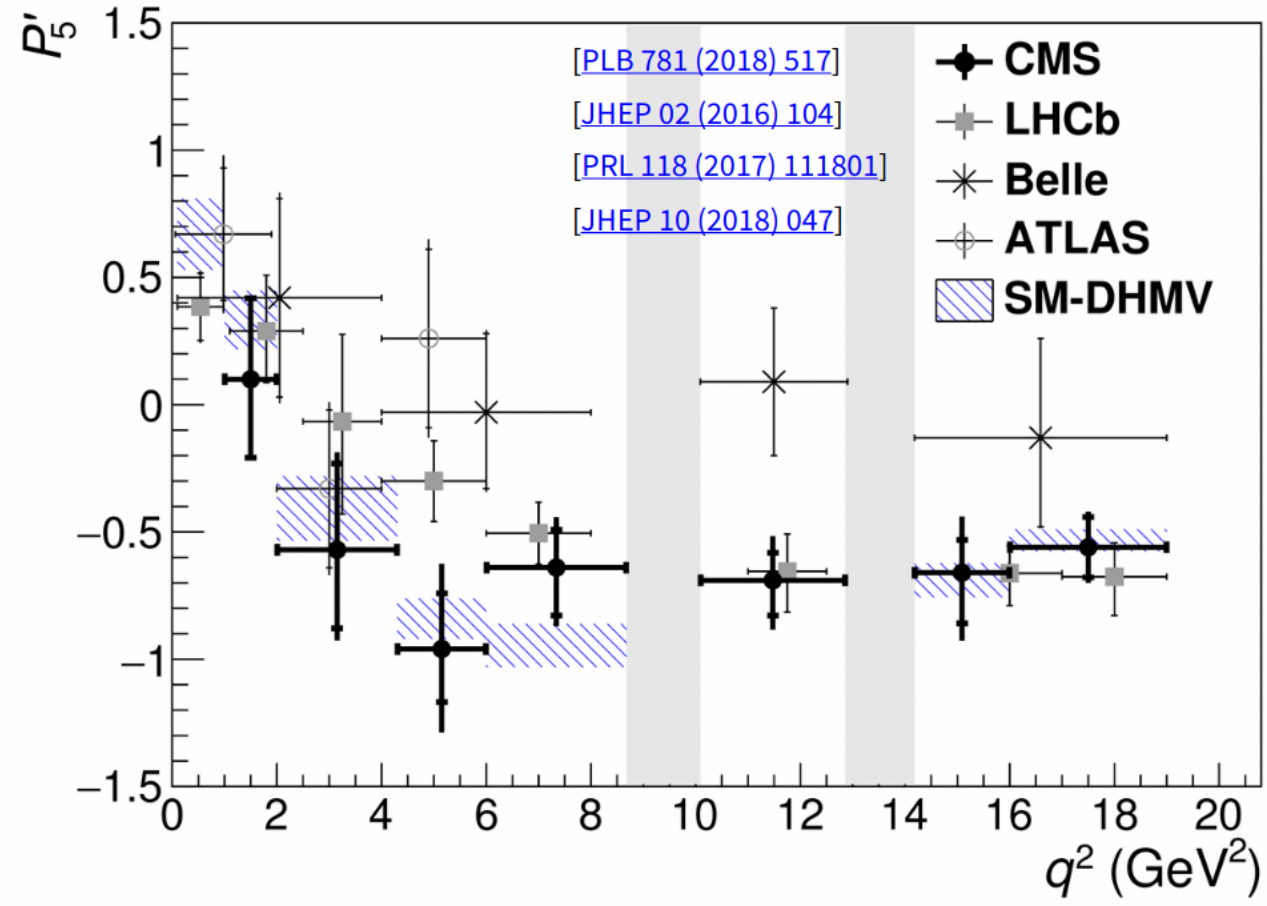


[ATL-PHYS-PUB-2022-012]

Angular measurements

Another hint to understand LFU tensions are angular measurements

- tension seen in P_5' angular observable in $B^0 \to K^{*0}\mu^+\mu^-$
  - ▶ optimised to cancel hadronic uncertainty [JHEP 01 (2013) 048]



taken from Yuta Takahashi's talk @ Flavour Anomaly Workshop 2021

Summary

LHCb

- has measured several LFU observables
  - tensions with SM observed in some of them
  - $b \to c\ell\nu$: $R(J/\psi)$, $R(D^{*+})$, $R(\Lambda_c^+)$
  - $b \to s\ell^+\ell^-$: $R(K^{*0})$, $R(pK)$, $R(K_S^0)$, $R(K^{*+})$, $R(K^+)$
- more measurements using full Run 1+2 dataset in preparation
- LHCb Upgrade for Run 3 to take even more data

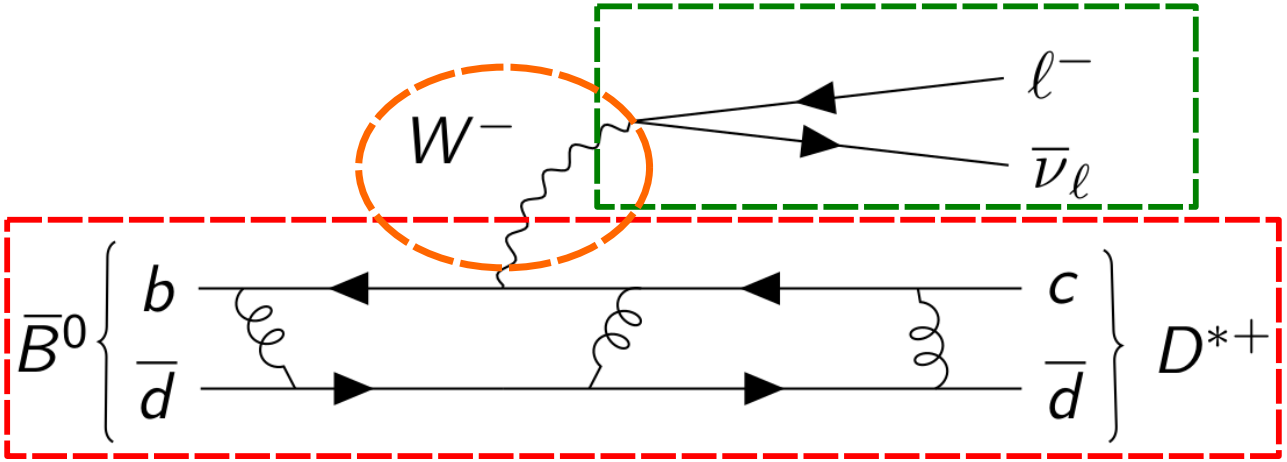
ATLAS + CMS

- gearing up to perform LFU tests with taus and electrons
- direct searches for leptoquarks constrain BSM scenarios

Thanks for your attention!

Backup

Lepton flavour universality



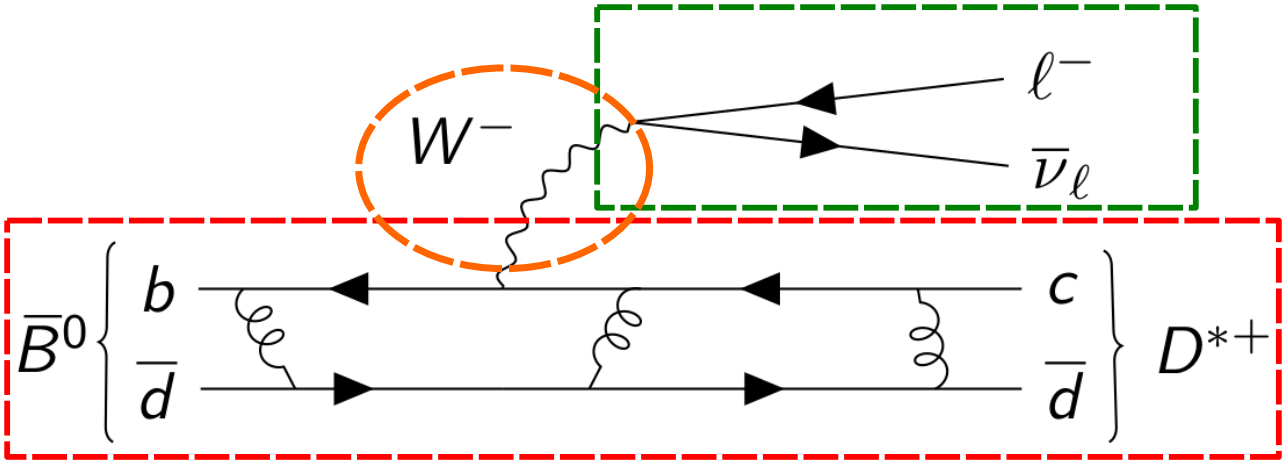
possible to factorise description of decay with effective field theory approach since $M_w^2 \gg q^2 = M^2(\ell\nu)$

- lepton current
- hadronic current
- 4-point interaction

$$\mathcal{H}_{eff}(b \to c\ell^-\overline{\nu}_\ell) = \frac{4G_F}{\sqrt{2}} V_{cb} \sum_i \mathcal{C}_i \mathcal{O}_i,$$

- $\mathcal{C}_i$ Wilson coefficients
- $\mathcal{O}_i$ operator
- in SM $O_{V_L} = (\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu)$, $C_{V_L} = 1$

Lepton flavour universality

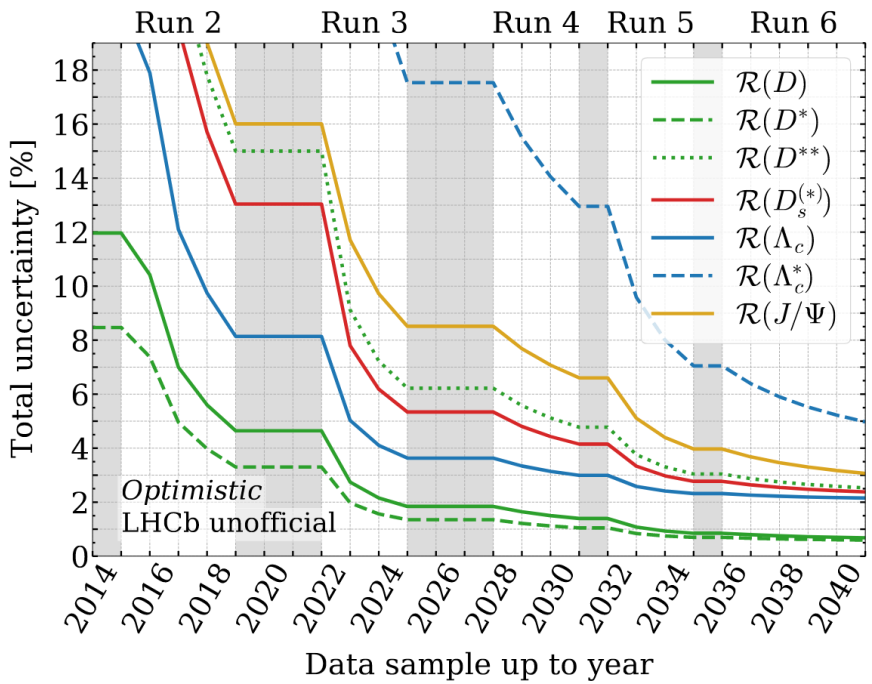


description of hadronic current more difficult

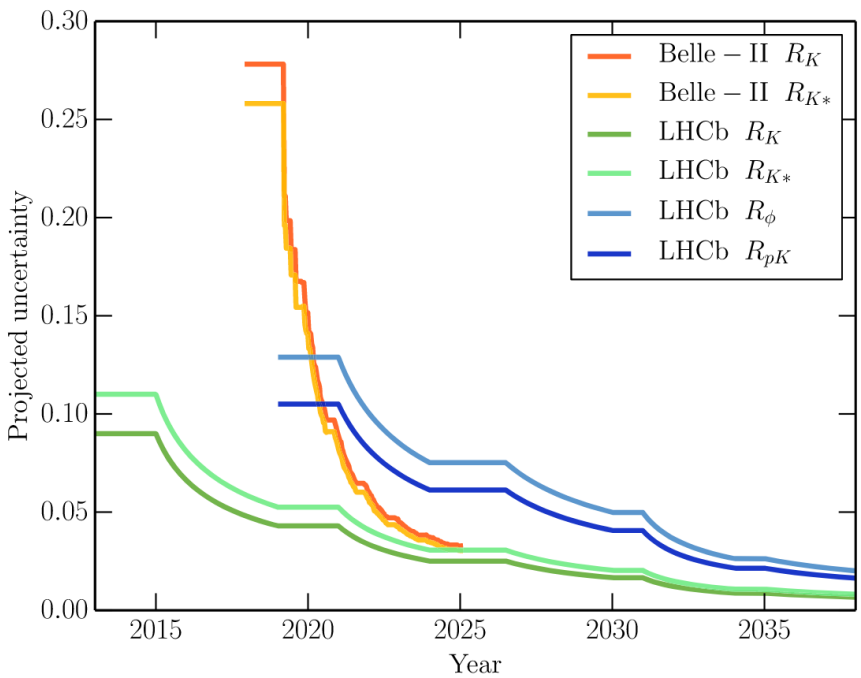
- bound state
- non-perturbative QCD

$\rightarrow$ absorbed into 'form factors'

Lepton flavour universality



[arXiv:2101.08326]



[J. Phys. G: Nucl. Part. Phys. 46 023001]