Flavour anomalies in $b \to s\ell^+\ell^-$ and $b \to c\ell\nu$ transitions

11th Large Hadron Collider Physics Conference

Florian Reiss
on behalf of the ATLAS, CMS and LHCb collaborations

24.05.2023

The University of Manchester

Flavour anomalies

In recent years, tensions with the Standard Model (SM) have been observed in the flavour sector. If confirmed, would be clear indication of physics beyond the SM

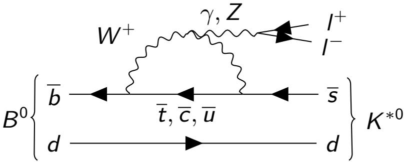
"flavor anomaly" interpreted by Stable Diffusion

Already touched upon in previous talks

- Carla Göbel
- Avital Dery
- Roger Jones

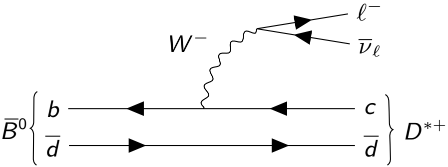
Flavour anomalies in tree- and loop-level *b*-hadron decays

Flavour changing neutral current



- rare penguin decays
- branching fraction $< 10^{-6}$
  - suppressed in SM
  - mediated via loops

Flavour changing charged current



- tree-level semileptonic decays
- branching fraction $\sim 10\%$

Flavour anomalies

Anomalies seen in different kinds of measurements

- differential branching fractions
- angular distributions
- relative branching fractions

⇓ increasing precision in theory predictions

Tests of lepton flavour universality (LFU) particularly appealing

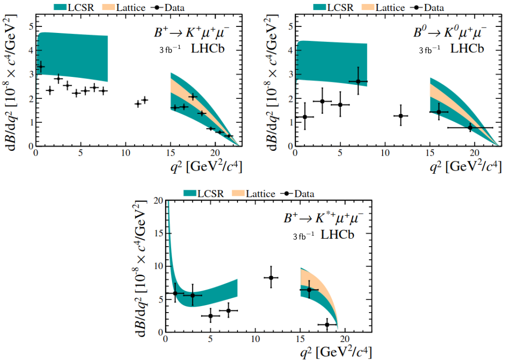
$$\frac{\mathcal{B}(B \to X\mu^+\mu^-)}{\mathcal{B}(B \to Xe^+e^-)}; \frac{\mathcal{B}(H_b \to H_c\tau\overline{\nu}_\tau)}{\mathcal{B}(H_b \to H_c\ell\overline{\nu}_\ell)}$$

- relative BFs with different lepton flavours
- small theoretical uncertainties
- some systematic uncertainties cancel in ratio measurement

$b \to s\mu^+\mu^-$ differential branching fractions

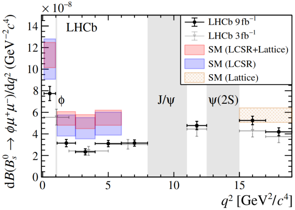
Various $b \to s\mu^+\mu^-$ differential branching fractions measured by LHCb

- differential BF in $q^2 = m^2(\mu^+\mu^-)$ bins



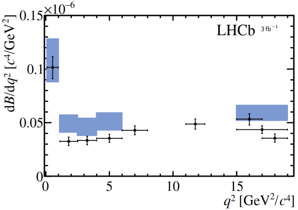
[JHEP 06 (2014) 133]

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



[PRL 127, 151801 (2021)]

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

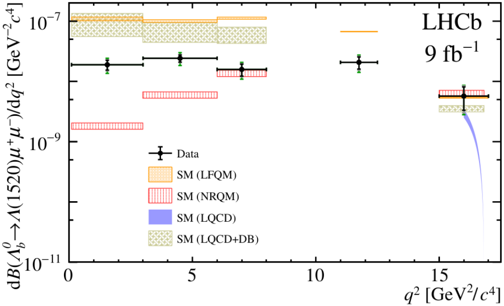


[JHEP 11 (2016) 047][JHEP 04 (2017) 142]

- measurements tend to lie below SM
- large theory uncertainties from form factors and charm loops

$b \to s\mu^+\mu^-$ differential branching fractions

Latest LHCb measurement using $\Lambda_b^0 \to \Lambda(1520)\mu^+\mu^-$ decays ($9\,\text{fb}^{-1}$)
[arXiv:2302.08262]



[arXiv:2302.08262]

- good agreement between measurement and theory in highest q^2 bin
  - better understanding of predictions needed at lower q^2

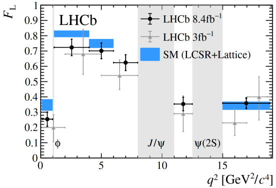
First-time measurement with excited Λ. Could help to refine predictions

$b \to s\mu^+\mu^-$ angular measurements

Angular analyses allows access to various observables

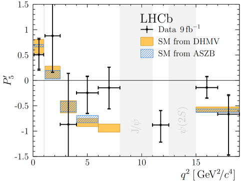
- forward-backward asymmetry A_{FB}
- longitudinal polarisation F_L
- P_5'
  - optimised to cancel hadronic uncertainty [JHEP 01 (2013) 048]

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



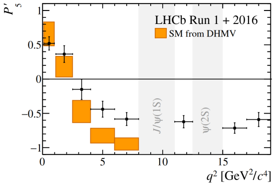
[JHEP 11 (2021) 043]

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



[PRL 126, 161802 (2021)]

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



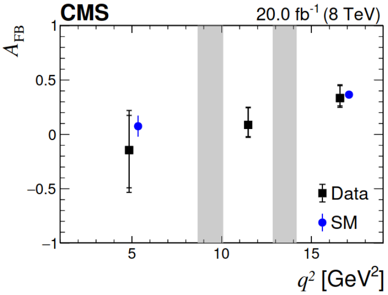
[PRL 125, 011802 (2020)]

Tension seen in P_5' angular observable in some q^2 bins

- real effect or contribution from charm loops?

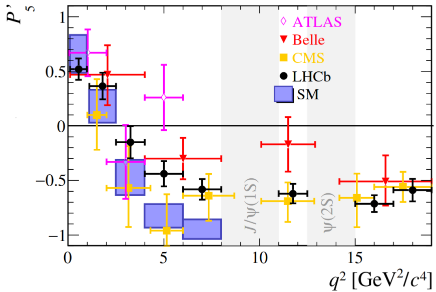
Angular analyses performed by ATLAS and CMS

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



[JHEP 04 (2021) 124]

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



Complementary measurements by ATLAS and CMS

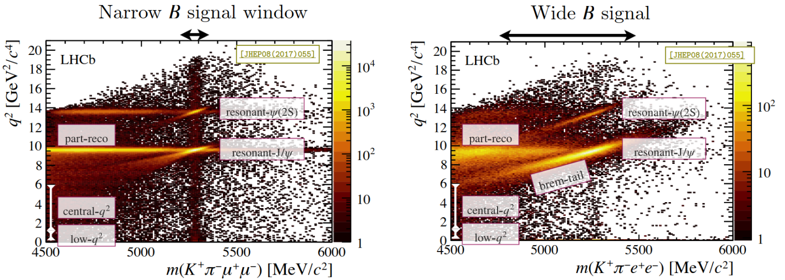
LFU tests with rare decays

Test LFU by measuring ratio in q^2 region $q^2_{min} < q^2 < q^2_{max}$

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

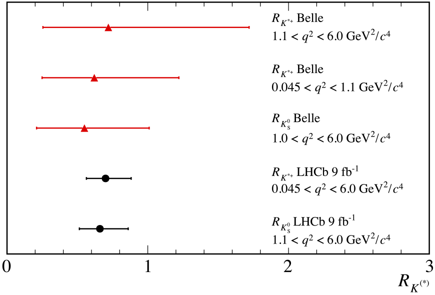
Experimental challenges at LHCb:

- corrections to simulation
- background modelling
- electrons and muons behave differently in detector



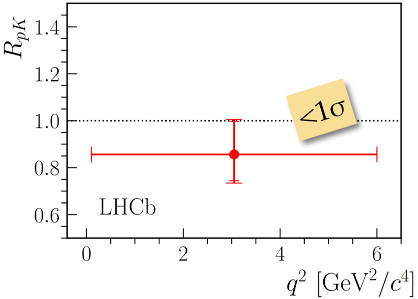
Various measurements by LHCb of complementary final states

$B^0 \to K^0_S \ell^+\ell^-$, $B^+ \to K^{*+}\ell^+\ell^-$ (9 fb^{-1})



[PRL 128 (2022) 191802]

$\Lambda^0_b \to pK^-\ell^+\ell^-$ (4.7 fb^{-1})



[JHEP 2020, 40 (2020)]

Recent combined LHCb measurements of $R(K)$ and $R(K^*)$

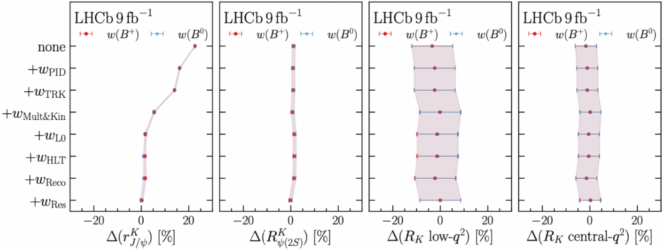
LFU tests with rare decays

Test of lepton universality in $b \to s\ell^+\ell^-$ ($9\,\text{fb}^{-1}$) [arXiv:2212.09153] [arXiv:2212.09152]

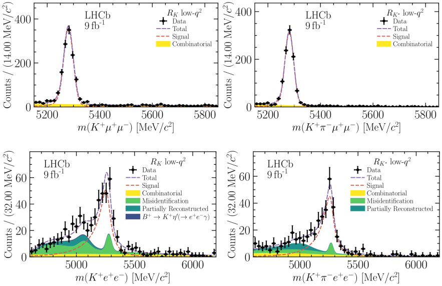
Measure double-ratio using resonant mode

$$R_X = \frac{\mathcal{B}(B \to X\mu^+\mu^-)}{\mathcal{B}(B \to Xe^+e^-)} \times \underbrace{\frac{\mathcal{B}(B \to XJ/\psi(\to e^+e^-))}{\mathcal{B}(B \to XJ/\psi(\to \mu^+\mu^-))}}_{r(J/\psi)^{-1}}, X = K^+, K^{*0}$$

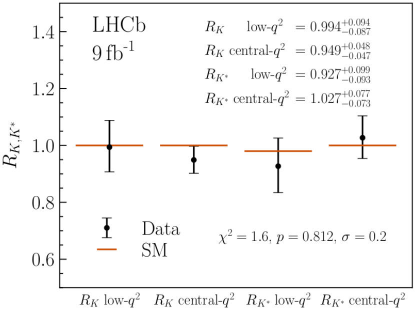
- measured in two $q^2 = m^2(\ell^+\ell^-)$ bins
- systematic uncertainties related to efficiencies cancel in double-ratio
- compatibility of $r(J/\psi)$ with unity for validation



[arXiv:2212.09153] [arXiv:2212.09152]



[arXiv:2212.09153] [arXiv:2212.09152]



Both R_K and R_{K^*} in agreement with Standard Model

Improvements to previous publications [Nature Physics 18 (2022) 277]

- improved understanding of misidentified hadronic backgrounds in e^+e^- mode
  - tighter electron particle identification requirements
  - improved modelling of residual hadronic background

LFU tests with semileptonic decays

Test LFU by measuring ratio

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

Semileptonic decays challenging at hadron colliders

- missing neutrino(s)
- many background sources
- signal yield needs to be extracted with template fits
- large and precisely calibrated simulated samples required

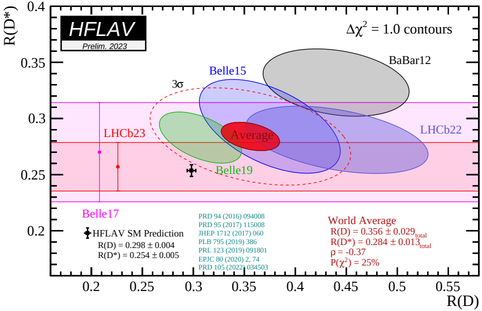
But profit from large sample sizes and production of various b-hadron species

Tests of LFU with complementary final states

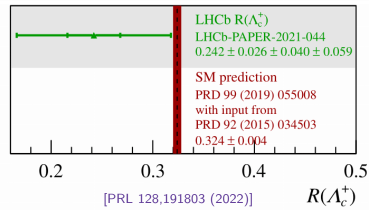
Two ways of reconstructing τ at LHCb:

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

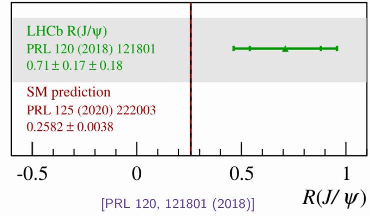
$B \to D^{(*)}\ell^-\overline{\nu}_\ell$



$\Lambda_b^0 \to \Lambda_c^+\ell^-\overline{\nu}_\ell$ (3 fb^{-1})



$B_c^- \to J/\psi\,\ell^-\overline{\nu}_\ell$ (3 fb^{-1})



Recent LHCb measurements of $R(D^{(*)})$ using muonic and hadronic modes

More details in talk by Rizwaan Mohammed tomorrow

LFU tests with semileptonic decays

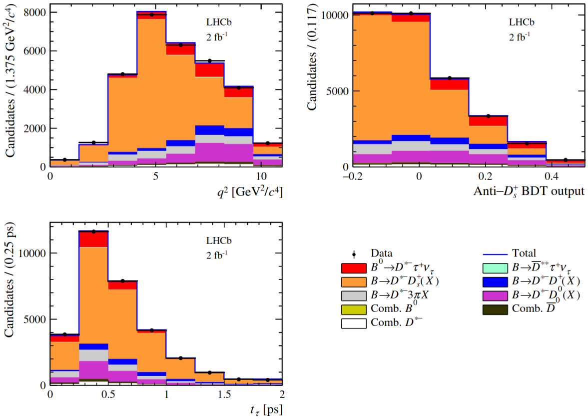
Measurement of $R(D^{*-})$ with hadronic τ decay at LHCb ($2\,\text{fb}^{-1}$)
[arXiv:2305.01463]

$$\mathcal{R}(D^{*-}) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

- use hadronic τ decay $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\overline{\nu}_\tau$
  - use displaced 3π vertex to suppress prompt background
- measure w.r.t normalisation channel $B^0 \to D^{*-}\pi^+\pi^-\pi^+$

$$\mathcal{R}(D^{*-}) = \underbrace{\left[\frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}\right]}_{\mathcal{K}(D^{*-}),\textit{measured}} \times \underbrace{\left[\frac{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}\right]}_{\textit{external}}$$

LFU tests with semileptonic decays



[arXiv:2305.01463]

- extract signal yield using 3D template fit
  - $q^2 = m^2(\tau^+\nu_\tau)$, τ^+ decay time t_{τ^+}, output of BDT against $B^0 \to D^{*-} D_s^+$

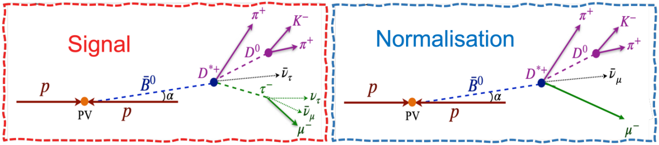
$$\mathcal{R}(D^{*-}) = 0.247 \pm 0.015\,(\text{stat}) \pm 0.015\,(\text{syst}) \pm 0.012(ext)$$

- in agreement with Standard Model and world average

LFU tests with semileptonic decays

Simultaneous measurement of $R(D^*)$ and $R(D^0)$ with muonic τ decay at LHCb ($3\,\mathrm{fb}^{-1}$) [arXiv:2302.02886]

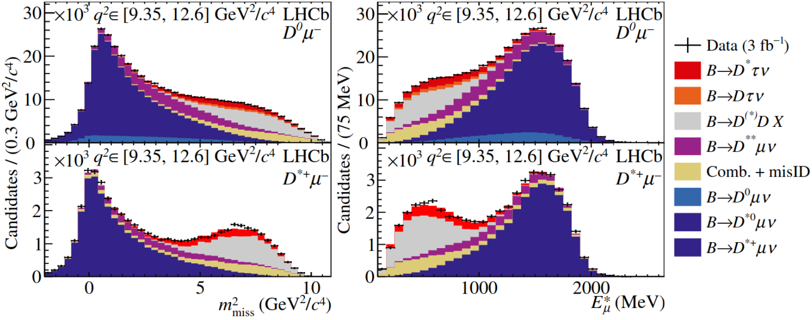
- signal and normalisation sample same final state
  - no need for external BFs
- backgrounds from $B \to D^{**}\mu\nu_\mu$, $B \to DD(X)$



Two independent samples

- $D^0\mu^-$
  - $B^- \to D^0\tau^-\overline{\nu}_\tau$
  - $B^- \to D^{*0}\tau^-\overline{\nu}_\tau$
  - $\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$
- $D^{*+}\mu^-$ (vetoed in $D^0\mu^-$ sample)
  - $\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$

LFU tests with semileptonic decays



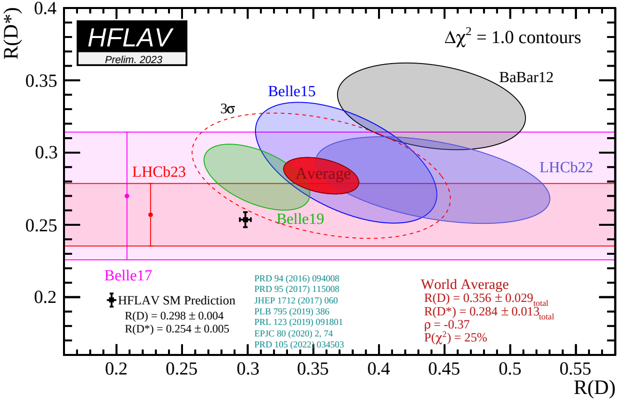
[arXiv:2302.02886]

- extract signal yield using 3D template fit
  - $q^2 = m^2(\tau^+\nu_\tau)$, E_μ, m^2_{miss}

$$\mathcal{R}(D^*) = 0.281 \pm 0.018 \pm 0.024$$
$$\mathcal{R}(D^0) = 0.441 \pm 0.060 \pm 0.066$$
$$\text{correlation } \rho = -0.43$$

- in agreement with Standard Model at 1.9σ

LFU tests with semileptonic decays



- tension between world average and SM prediction $> 3\sigma$

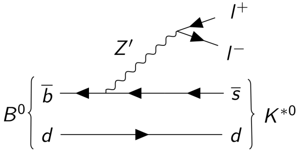
LHCb can make competitive measurements

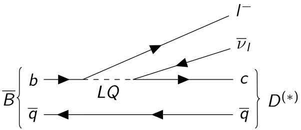
Interpretation of anomalies

- tension with SM in $R(K)$ and $R(K^*)$ not confirmed in latest measurement
- several anomalies still persist
  - differential branching fraction
  - angular observables
  - relative branching fractions of semileptonic decays to τ and light leptons

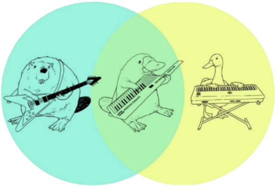
How to interpret them?

- Effective Field Theory interpretation (see talk by Patrick Owen)
- specific new models



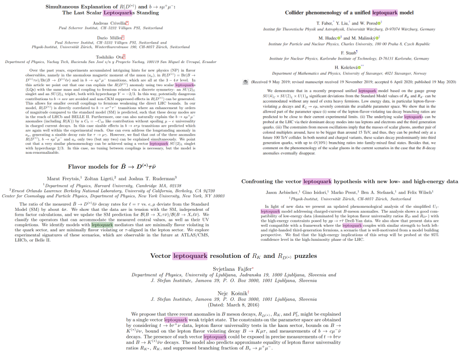


- charged Higgs?
- new heavy gauge bosons?
- leptoquarks (LQ)?
  - coupling quarks and leptons



Search for leptoquarks

A lot of theory interest in leptoquarks (arbitrary selection)



Simultaneous Explanation of $R(D^{(*)})$ and $b \to s\mu^+\mu^-$: The Last Scalar Leptoquarks Standing

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Over the past years, experiments accumulated intriguing hints for new physics (NP) in flavor observables, namely in the anomalous magnetic moment of the muon (a_μ), in $R(D^{(*)}) = \mathrm{Br}(B \to D^{(*)}\tau\nu)/\mathrm{Br}(B \to D^{(*)}\ell\nu)$ and in $b \to s\mu^+\mu^-$ transitions, which are all at the $3-4\sigma$ level. In this article we point out that one can explain the $R(D^{(*)})$ anomaly using two scalar leptoquarks (LQs) with the same mass and coupling to fermions related via a discrete symmetry: an $SU(2)_L$ singlet and an $SU(2)_L$ triplet, both with hypercharge $Y = -2/3$. In this way, potentially dangerous contributions to $b \to s\nu\nu$ are avoided and non-CKM suppressed effects in $R(D^{(*)})$ can be generated. This allows for smaller overall couplings to fermions weakening the direct LHC bounds. In our model, $R(D^{(*)})$ is directly correlated to $b \to s\tau^+\tau^-$ transitions where an enhancement by orders of magnitude compared to the standard model (SM) is predicted, such that these decay modes are in the reach of LHCb and BELLE II. Furthermore, one can also naturally explain the $b \to s\mu^+\mu^-$ anomalies (including $R(K)$) by a $C_9 = -C_{10}$ like contribution without spoiling $\mu - e$ universality in charged current decays. In this case sizable effects in $b \to s\tau\mu$ transitions are predicted which are again well within the experimental reach. One can even address the longstanding anomaly in a_μ, generating a sizable decay rate for $\tau \to \mu\gamma$. However, we find that out of the three anomalies $R(D^{(*)})$, $b \to s\mu^+\mu^-$ and a_μ only two (but any two) can be explained simultaneously. We point out that a very similar phenomenology can be achieved using a vector leptoquark $SU(2)_L$ singlet with hypercharge 2/3. In this case, no tuning between couplings is necessary, but the model is non-renormalizable.

Collider phenomenology of a unified leptoquark model

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(Received 9 May 2019; revised manuscript received 19 November 2019; accepted 6 April 2020; published 19 May 2020)

We demonstrate that in a recently proposed unified leptoquark model based on the gauge group $SU(4)_C \times SU(2)_L \times U(1)_R$ significant deviations from the Standard Model values of R_K and R_{K^*} can be accommodated without any need of extra heavy fermions. Low energy data, in particular lepton-flavor-violating μ decays and $K_L \to e\mu$, severely constrain the available parameter space. We show that in the allowed part of the parameter space (i) some of the lepton-flavor-violating tau decay branching ratios are predicted to be close to their current experimental limits. (ii) The underlying scalar leptoquarks can be probed at the LHC via their dominant decay modes into tau leptons and electrons and the third generation quarks. (iii) The constraints from meson oscillations imply that the masses of scalar gluons, another pair of colored multiplets around, have to be bigger than around 15 TeV, and thus, they can be probed only at a future 100 TeV collider. In both neutral and charged variants, these scalars decay predominantly into third generation quarks, with up to $O(10\%)$ branching ratios into family-mixed final states. Besides that, we comment on the phenomenology of the scalar gluons in the current scenarios in the case that the B-decay anomalies eventually disappear.

Flavor models for $\bar{B} \to D^{(*)}\tau\bar{\nu}$

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The ratio of the measured $\bar{B} \to D^{(*)}\ell\bar{\nu}$ decay rates for $\ell = \tau$ vs. e, μ deviate from the Standard Model (SM) by about 4σ. We show that the data are in tension with the SM, independent of form factor calculations, and we update the SM prediction for $\mathcal{B}(B \to X_c\tau\bar{\nu})/\mathcal{B}(B \to X_c\ell\bar{\nu})$. We classify the operators that can accommodate the measured central values, as well as their UV completions. We identify models with leptoquark mediators that are minimally flavor violating in the quark sector, and are minimally flavor violating or τ-aligned in the lepton sector. We explore experimental signatures of these scenarios, which are observable in the future at ATLAS/CMS, LHCb, or Belle II.

Confronting the vector leptoquark hypothesis with new low- and high-energy data

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In light of new data we present an updated phenomenological analysis of the simplified U_1-leptoquark model addressing charged-current B-meson anomalies. The analysis shows a good compatibility of low-energy data (dominated by the lepton flavor universality ratios R_D and R_{D^*}) with the high-energy constraints posed by $pp \to \tau\bar{\tau}$ Drell-Yan data. We also show that present data are well compatible with a framework where the leptoquark couples with similar strength to both left- and right-handed third-generation fermions, a scenario that is well-motivated from a model building perspective. We find that the high-energy implications of this setup will be probed at the 95% confidence level in the high-luminosity phase of the LHC.

Vector leptoquark resolution of R_K and $R_{D^{(*)}}$ puzzles

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(Dated: March 8, 2016)

We propose that three recent anomalies in B meson decays, $R_{D^{(*)}}$, R_K, and P_5', might be explained by a single vector leptoquark weak triplet state. The constraints on the parameter space are obtained by considering $t \to b\tau^+\nu$ data, lepton flavor universality tests in the kaon sector, bounds on $B \to K^{(*)}\bar{\nu}\nu$, bound on the lepton flavor violating decay $B \to K\mu\tau$, and measurements of $b \to c\mu^-\bar{\nu}$ decays. The presence of such vector leptoquark could be exposed in precise measurements of $t \to b\tau\nu$ and $B \to K^{(*)}\bar{\nu}\nu$ decays. The model also predicts approximate equality of lepton flavor universality ratios R_{K^*}, R_K, and suppressed branching fraction of $B_s \to \mu^+\mu^-$.

Leptoquarks@LHCP

- Ben Stefanek
- Giovanni Padovano
- Halil Saka
- Nejc Košnik

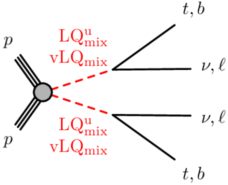
Can leptoquarks explain flavour anomalies?

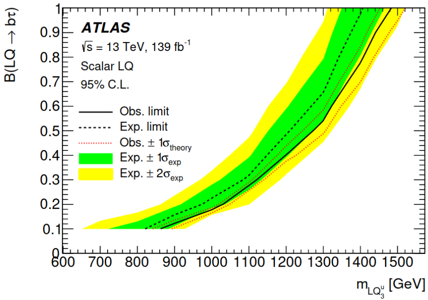
- difficult to accommodate all measurements
- constrained by limits on lepton flavour violating decays (talk by Lex Greeven)

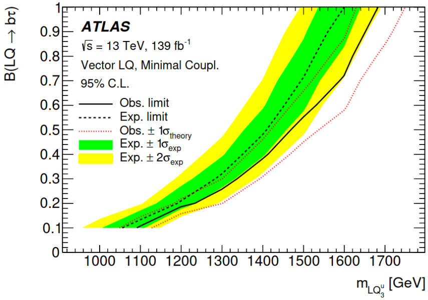
Leptoquarks with mass around TeV scale and preferential coupling to third generation well-motivated

ATLAS + CMS can directly search for leptoquarks

- included in searches for new phenomena

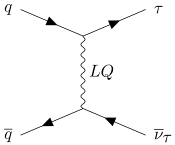


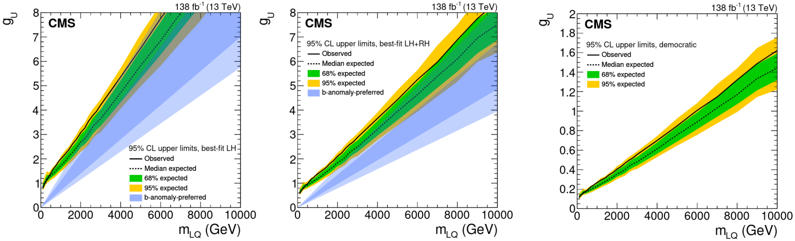




[arXiv:2303.01294]

Search for NP in τ + missing energy final state by CMS ($138\,\text{fb}^{-1}$)
[arXiv:2212.12604]





[arXiv:2212.12604]

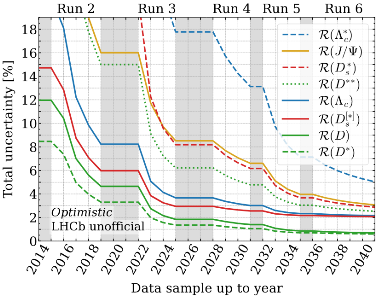
- first time upper limits on the cross section of t-channel leptoquark exchange

Limits on LQ interpretation of flavour anomalies

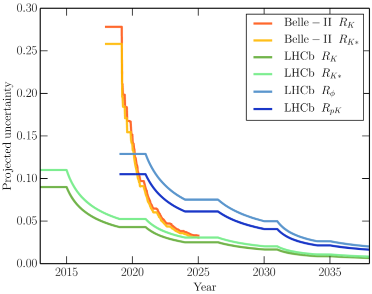
Outlook

Additional measurements needed to paint definite picture!

- more LHCb measurements ongoing using full Run 1+2 data
- Run 3 will further improve sensitivity
  - many measurements statistically limited



[Rev. Mod. Phys. 94, 015003 (2022)]



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

Novel approaches to reconstruction and triggering will allow ATLAS and CMS to make LFU measurements as well (talk by Keith Ulmer)

- e.g. CMS B-parking

Summary

LHCb

- differential and angular measurements of $b \to s\mu^+\mu^-$ decays
- tests of lepton flavour universality
  - $b \to c\ell\nu$: $R(J/\psi)$, $R(D^*)$, $R(D)$, $R(\Lambda_c^+)$
  - $b \to s\ell^+\ell^-$: $R(K^{*0})$, $R(pK)$, $R(K_S^0)$, $R(K^{*+})$, $R(K^+)$
- more measurements using full Run 1+2 dataset in preparation
- LHCb Upgrade for Run 3 to take even more data

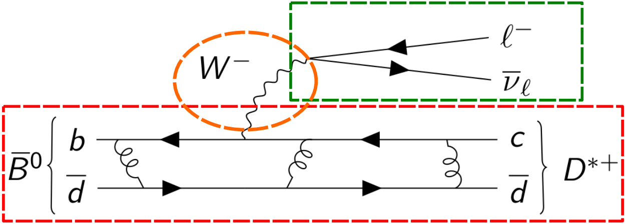
ATLAS + CMS

- angular measurements of $b \to s\mu^+\mu^-$ decays
- gearing up to perform LFU tests with taus and electrons
- direct and indirect searches for leptoquarks constrain NP scenarios

The future will remain flavourful!

Thanks for your attention!

Backup



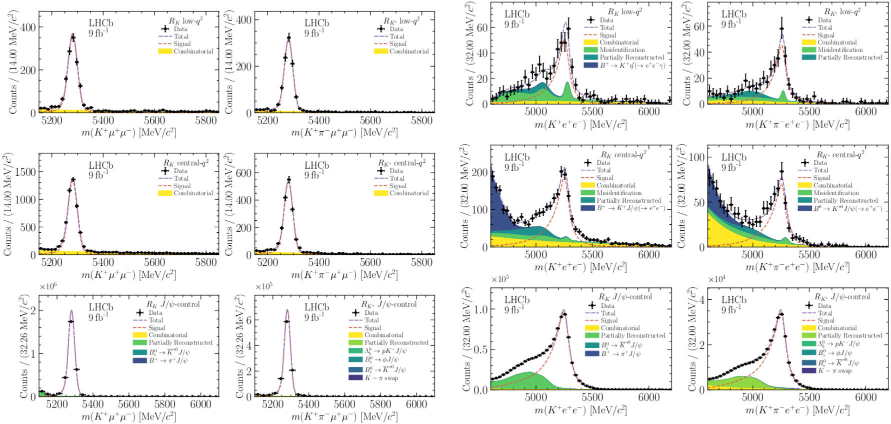
description of hadronic current more difficult

- bound state
- non-perturbative QCD

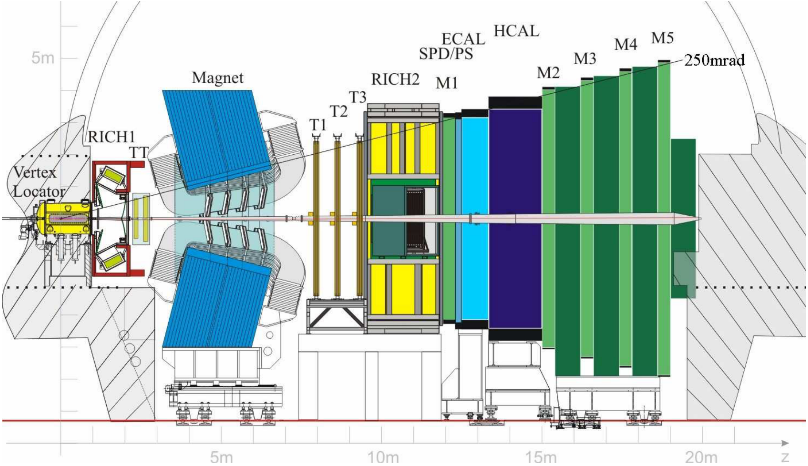
$\rightarrow$ absorbed into 'form factors'

Test of lepton universality in $b \to s\ell^+\ell^-$

[arXiv:2212.09153] [arXiv:2212.09152] [LHCb-PAPER-2022-046] [LHCb-PAPER-2022-045]

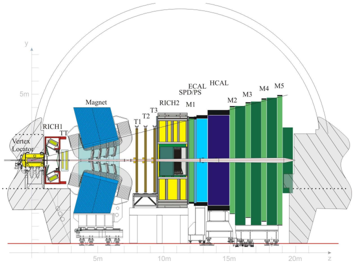


LHCb detector (Run 1+2)



[JINST 3 (2008) S08005]

Major upgrade of LHCb detector for Run 3



[JINST 3 (2008) S08005]

Ratios measured at LHCb:

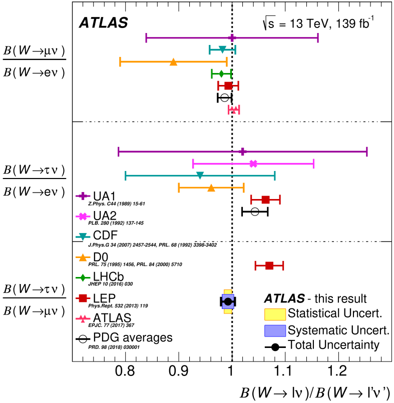
- $b \to c\ell\overline{\nu}$
  - $R(J/\psi)$ $B_c^- \to J/\psi\,\ell^-\overline{\nu}_\ell$
  - $R(D^*)$ $B^0 \to D^*\ell^-\overline{\nu}_\ell$
  - $R(D^0)$ $B^+ \to D^0\ell^-\overline{\nu}_\ell$
  - $R(\Lambda_c^+)$ $\Lambda_b^0 \to \Lambda_c^+\ell^-\overline{\nu}_\ell$
- $b \to s\ell^+\ell^-$
  - $R(K^{*0})$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

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]

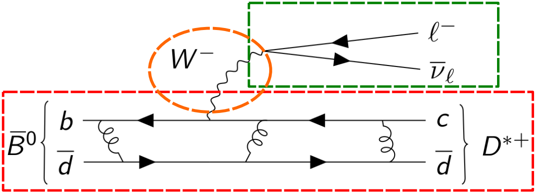
- $W \to \ell\nu_\ell$



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

- tensions with SM seen in LEP measurement resolved by LHC

Interpretation of flavour anomalies with Effective Field Theory



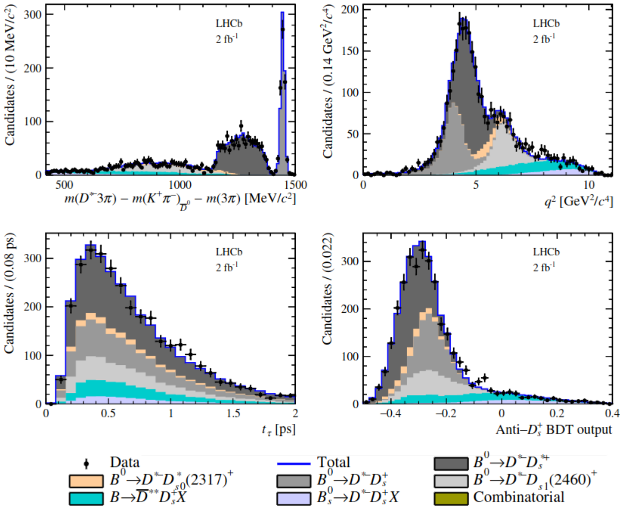
Factorise into

- lepton current
- hadronic current
  - non-perturbative QCD described by form factors

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

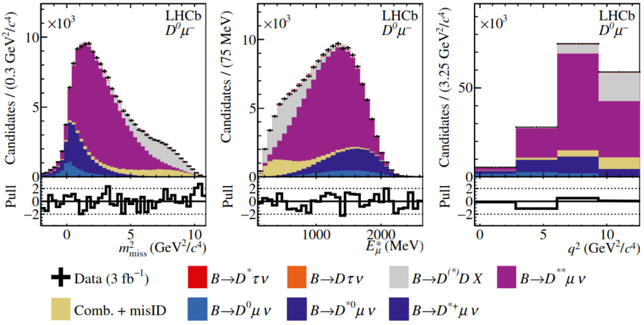
- $\mathcal{C}_i$ Wilson coefficients
- $\mathcal{O}_i$ operator
- in SM $O_{V_L} = (\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu)$, $C_{V_L} = 1$

LFU tests with semileptonic decays



- use $D^* D_s^+$ control sample to constrain $B \to D^* D_s^+(X)$ background

LFU tests with semileptonic decays



[arXiv:2302.02886]

- control backgrounds using control sample with additional pions and kaons
- enriched in $B \to DDX$ and $B \to D^{**}\mu\nu$
- fit simultaneously with signal sample