Flavour anomalies

Konstantinos A. Petridis
on behalf of LHCb

University of Bristol

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Questions

How can gravity be accommodated?

What are Dark Matter and Dark Energy?

Where did all the anti-matter go?

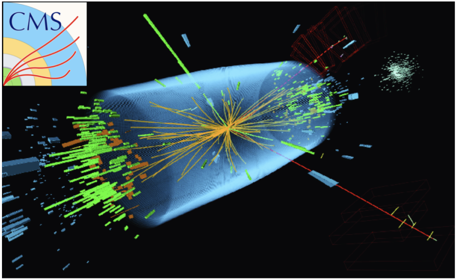
Why is the Higgs so light?

Why the spread in fermion masses and quark couplings?

Experimental approaches

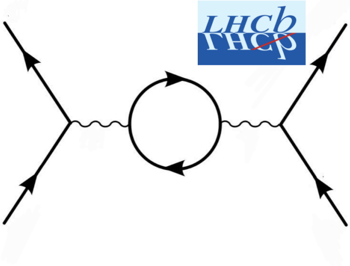
SM could be a low-energy effective theory of a more fundamental theory at higher energy scale with new particles, dynamics/symmetries.

$$E = mc^2$$



- Limited by collision energy
- Unambiguous evidence of new particle

$$m \gg E/c^2$$



- Not limited by collision energy
- Requires precise predictions (and measurements)

Indirect probe of high NP scales

Look at observables that:

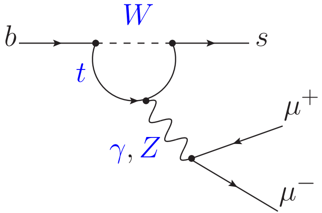
1. The SM contribution is either small or accidental
2. Can be measured to high precision
3. Can be predicted to high precision

$\rightarrow$ Flavour Changing Neutral Currents in SM

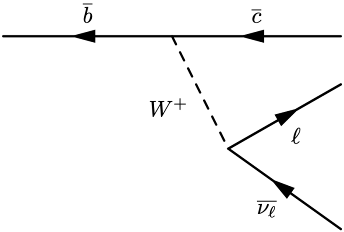
- Loop level, GIM suppressed
- Left-handed chirality
- Lepton universal couplings

$\rightarrow$ NP could violate any of these

$\Delta F = 1$ Rare B decays



Tree level B decay



Indirect probe of high NP scales

Look at observables that:

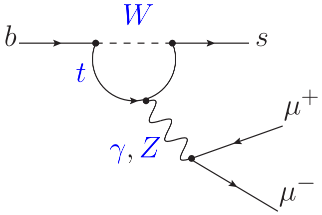
1. The SM contribution is either small or accidental
2. Can be measured to high precision
3. Can be predicted to high precision

$\rightarrow$ Tree level $b \rightarrow c\ell\nu$ in SM

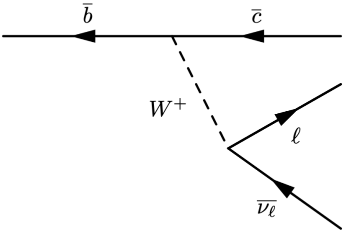
- Left-handed chirality
- Lepton universal couplings

$\rightarrow$ NP could violate any of these

$\Delta F = 1$ Rare B decays



Tree level B decay

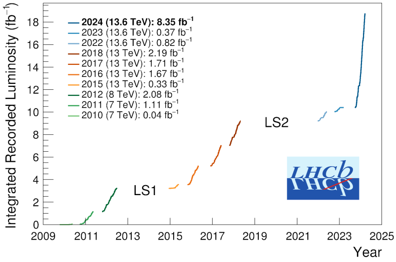


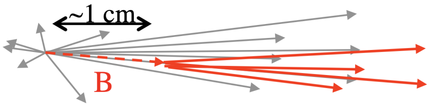
B production at the LHC

- Huge production cross-section: $\sigma_{b\bar{b}} = \mathcal{O}(100)\mu b$ at the LHC
- B-hadron decays well separated owing to boost
- "Easy" to identify due to secondary vertex
- LHCb: Excellent IP and momentum resolution, and PID capabilities

  $\rightarrow$ World leading precision in many final states

LHCb: Recorded $\mathcal{L} > 18\text{fb}^{-1}$, doubling our Run1,2 dataset in 2024





Flavour Anomalies

Over the past decade we have observed a coherent set of tensions with SM predictions

In $b \to s\ell^+\ell^-$ transitions (4-5σ)

1. **Branching Fractions**
   $B \to K^{(*)}\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$, $\Lambda_b \to \Lambda\mu^+\mu^-$
2. **Angular analyses**
   $B \to K^{(*)}\mu^+\mu^-$, $\Lambda_b \to \Lambda\mu^+\mu^-$
3. ~~**Lepton Flavour Universality involving μ/e ratios**~~
   ~~$B^0 \to K^{*0}\ell^+\ell^-$, $B^+ \to K^+\ell^+\ell^-$~~

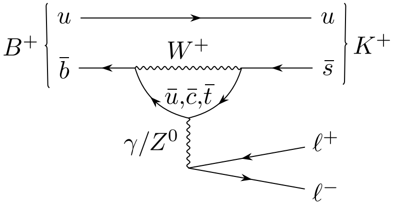
In $b \to c\ell\nu$ transitions (3σ)

4. **Lepton Flavour Universality involving μ/τ ratios**
   $B \to D^{(*)}\ell\nu$

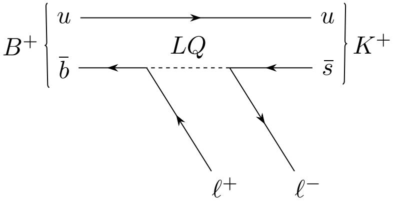
Types of $b \to s\ell^+\ell^-$ decays

- Decays of form: $B^+ \to K^+\ell^+\ell^-$, $B^0 \to K^{*0}\ell^+\ell^-$, $B_s \to \phi\mu^+\mu^-$, $\Lambda_b \to \Lambda^*\ell^+\ell^-$...

SM



NP example

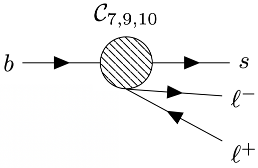


- Offer multitude of observables.

Interpreting results

- Rely on an Effective Field Theory to interpret our measurements
- Integrate out heavy ($\mu \geq m_W$) field(s) and introduce set of:
  - Wilson coefficients C_i describing the short distance part
  - Operators $\mathcal{O}_i$ containing the (non-perturbative) long distance part

Weak effective theory



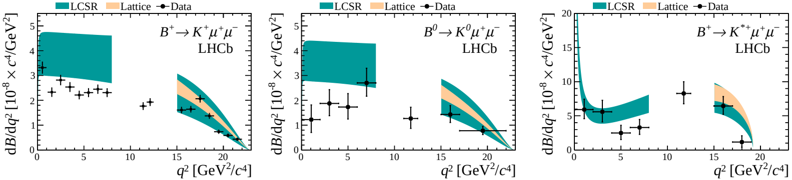
Operator $\mathcal{O}_i$	$B_{s(d)} \to X_{s(d)}\mu^+\mu^-$
$\mathcal{O}_7 \sim (\bar{s}_L \sigma^{\mu\nu} b_R)F_{\mu\nu}$ EM	✓
$\mathcal{O}_9 \sim (\bar{s}_L \gamma^{\mu} b_L)(\bar{\ell}\gamma_\mu \ell)$ Vector $\ell\bar{\ell}$	✓
$\mathcal{O}_{10} \sim (\bar{s}_L \gamma^{\mu} b_L)(\bar{\ell}\gamma_5\gamma_\mu \ell)$ Axial vector $\ell\bar{\ell}$	✓
$\mathcal{O}_{S,P} \sim (\bar{s}b)_{S,P}(\bar{\ell}\ell)_{S,P}$ (Pseudo-)Scalar $\ell\bar{\ell}$	(✓)

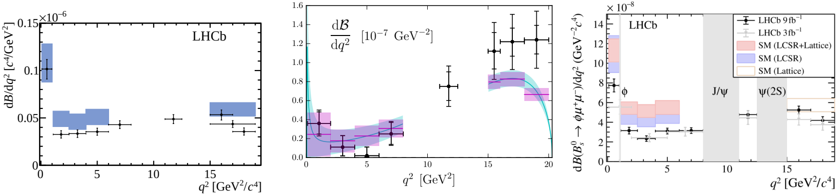
Can also get quark chirality flipped counterparts

1. Decay Rates

- Measurements consistently below theory predictions at low $q^2 \equiv p^2_{\ell\ell}$ for many $b \to s\mu^+\mu^-$ decays

[JHEP06(2014)133]



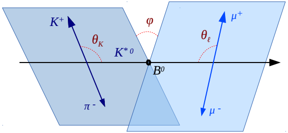


$B^0 \to K^{*0}\mu^+\mu^-$ [JHEP11(2016)047], $\Lambda_b \to \Lambda\mu^+\mu^-$ [JHEP06(2015)115] $B_s \to \phi\mu^+\mu^-$ [PRL127.151801]

Theory: Bobeth et al [JHEP07(2011)067], Bharucha et al [JHEP08(2016)098], Detmold et al [PRD93,074501(2016)], Horgan et al [PRD89(2014)]

- SM predictions limited by $B \to K^{(*)}$ form-factor uncertainties

2. Angular analysis of $B \to K^*\mu^+\mu^-$



- Differential decay rate of $B^0 \to K^{*0}\mu^+\mu^-$ and $\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$:

$$\frac{1}{\Gamma'_{full}}\frac{d^4\Gamma}{dq^2\,d\cos\theta_K\,d\cos\theta_l\,d\phi} =$$

Matias et al
JHEP05(2013)137

$$\frac{9}{32\pi}\Big[\frac{3}{4}F_T\sin^2\theta_K + F_L\cos^2\theta_K + (\frac{1}{4}F_T\sin^2\theta_K - F_L\cos^2\theta_K)\cos 2\theta_l$$

$$+\frac{1}{2}P_1F_T\sin^2\theta_K\sin^2\theta_l\cos 2\phi + \sqrt{F_TF_L}\left(\frac{1}{2}P_4'\sin 2\theta_K\sin 2\theta_l\cos\phi + P_5'\sin 2\theta_K\sin\theta_l\cos\phi\right)$$

$$+2P_2F_T\sin^2\theta_K\cos\theta_l - \sqrt{F_TF_L}\left(P_6'\sin 2\theta_K\sin\theta_l\sin\phi - \frac{1}{2}Q'\sin 2\theta_K\sin 2\theta_l\sin\phi\right)$$

$$-P_3F_T\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big](1 - F_S) + \frac{1}{\Gamma'_{full}}W_S$$

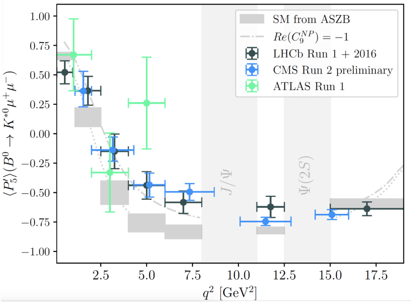
The coefficients of the polluting term can be parametrized as

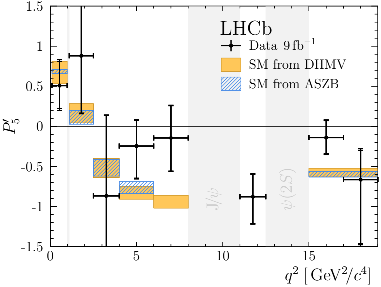
$$\frac{W_S}{\Gamma'_{full}} = \frac{3}{16\pi}\big[F_S\sin^2\theta_\ell + A_S\sin^2\theta_\ell\cos\theta_K + A_S^4\sin\theta_K\sin 2\theta_\ell\cos\phi$$
$$+A_S^5\sin\theta_K\sin\theta_\ell\cos\phi + A_S^7\sin\theta_K\sin\theta_\ell\sin\phi + A_S^8\sin\theta_K\sin 2\theta_\ell\sin\phi\big]$$

- Measure 16 observables (CP symmetric and asymmetric) through a quasi 4D angular and $m_{K\pi}$ fit in bins of q^2
- Each observable sensitive to different types of new physics couplings

Latest $B \to K^*\mu^+\mu^-$ results

- The large number of observables cover full spectrum of new physics models
  - Orthogonal expt. systematics and more precise theory predictions





- Combination of angular observables: $\sim 2-3\sigma$ tension per mode and experiment

$B^0 \to K^{*0}\mu^+\mu^-$[PRL125(2020)011802] $B^+ \to K^{*+}\mu^+\mu^-$ [PRL126(2021)161802]

CMS, ATLAS $B^0 \to K^{*0}\mu^+\mu^-$ [CMS-PAS-BPH-21-002], [JHEP10(2018)047]

3. Lepton Flavour Universality tests

- In the SM couplings of gauge bosons to leptons are independent of lepton flavour
  $\rightarrow$ Branching fractions differ only by phase space and helicity-suppressed contributions

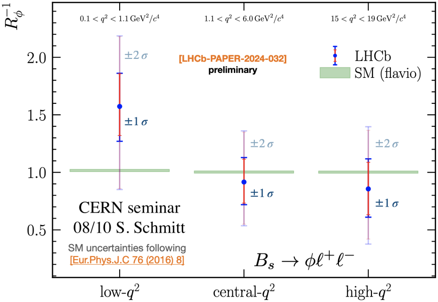
- Ratios of the form:

$$R_{K^{(*)}} := \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \overset{\mathrm{SM}}{\cong} 1$$

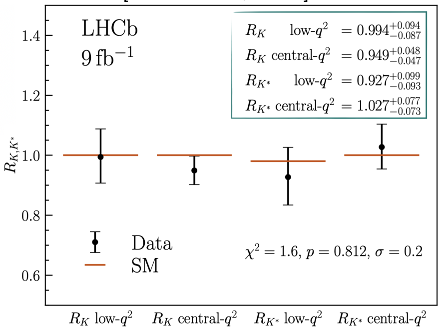
- In SM free from QCD uncertainties affecting other observables
  $\rightarrow \mathcal{O}(10^{-4})$ uncertainty [JHEP07(2007)040]
- Up to $\mathcal{O}(1\%)$ QED corrections [EPJC76(2016)8,440]

$\rightarrow$ **Any significant deviation is a smoking gun for New Physics.**

Latest R_X results

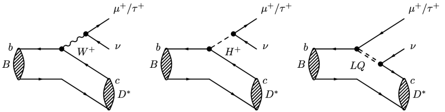


[LHCb PRL131,051803]



- New measurements in $B_s \to \phi\ell^+\ell^-$!
- Good compatibility with SM
  $\rightarrow$ Electron and muon BFs consistently below SM prediction

4. Tree level LFUV



$$R_{D^{(*)}} := \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\mu\nu_\mu)}$$

- Persistent hint of LFUV involving 3rd generation in $b \to c\ell\nu$ tree-level transitions

NEW: $R_{D^{(*)+}}$ in $D^+\mu-$ using 2fb^{-1} of Run2 data [LHCb-PAPER-2024-007]

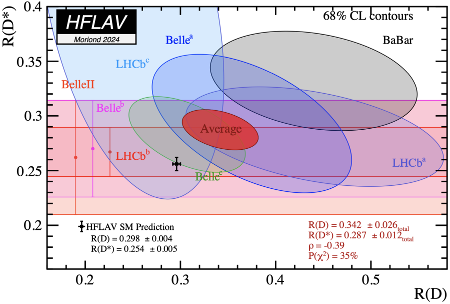
$R_{D^{(*)}}$ in $D^0\mu-$ using Run1 data[PRL131,111802(2023)]

$R_{D^{(*+)}}$ in $D^0 3\pi$ [PRL131,111802(2023)]

- LHCb measurement uncertainty equal split between stat. and syst.

$\to$ $B \to D^*$ form-factors and background modelling largest systematic of Run2 analysis

$\to$ Simulation sample size largest systematic for Run1 analysis



- Global fit to LHCb Belle and BaBar measurements at $\sim 3.1\sigma$ from SM

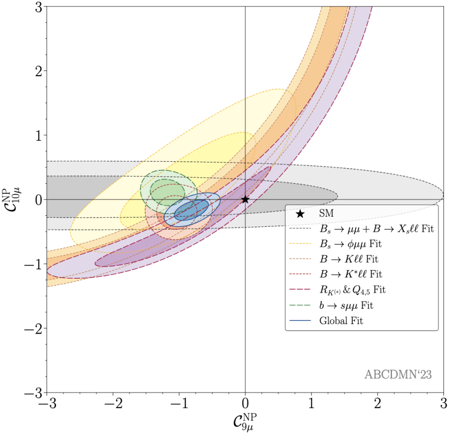
Putting it all together

- Combination of $b \to s\ell^+\ell^-$ measurements

  $\sim 5\sigma$ from SM

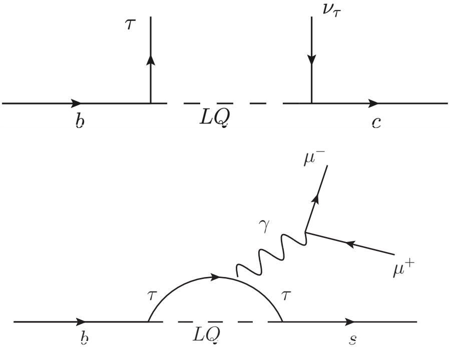
- Measurements point to new physics with vector dilepton coupling (C_9)

[Alguero et al EPJC83(2023)7,648]



Putting it all together: Optimistic

- Leptoquark with 3rd generation couplings
- Expect large enhancement of $b \to s\tau^+\tau^-$
- Generates radiatively anomalies in $b \to s\ell^+\ell^-$ $(\ell = e, \mu)$



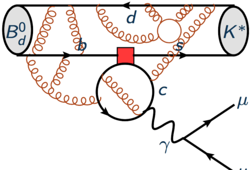
[Fuentes-Martin et al '22], [Bordone et al 17',18'], [Cornella et al 19'], [Greljo et al 18'], [Matias et al '18]

Putting it all together: Pessimistic

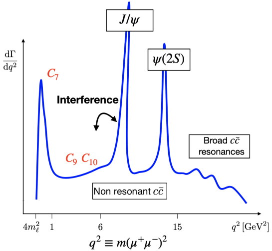
- Theory input required to compute contribution of $b \to c\bar{c}s$ hadronic amplitude (non-local)
  e.g [Khodjamirian et al 2010], [Gubernari et al 2018,2021,2022]
  $$C_9^{\rm eff} = C_9^{\rm SM} + C_9^{\rm NP} + Y_{c\bar{c}}(q^2)$$
- Unexpectedly large $b \to c\bar{c}s$, can mimic new physics in C_9

  $\rightarrow$ Use data to determine both $C_9^{\rm NP}$ and $Y_{c\bar{c}}(q^2)$ components
  [Cornella et al EPJC80(2020)12:1095], [Bobeth et al EPJC(2018)78:451], [Pomery et al EPJC(2018)78:453]

  $\rightarrow$ Requires model for $Y_{c\bar{c}}(q^2)$



Charm loop contribution that is difficult to calculate



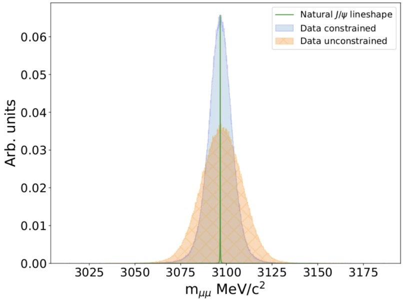
Determining non-local contributions from data

$$\frac{d^5\Gamma}{dq^2 d\vec{\Omega} dm^2_{K\pi}} = \sum_i S_i(q^2, m^2_{K\pi}) f(\vec{\Omega})$$

S_i bilinear combinations of K^* helicity amplitudes $\mathcal{A}^{\lambda}_{L,R}(C^{\mathrm{NP}\,(\prime)}_{7,9,10}, Y^{\lambda}(q^2), F_i(q^2))$
Wilson Coefficients, $B \to K^*$ non local amp., $B \to K^*$ form factors

- Maximise sensitivity by fitting q^2 spectrum continuously

- Narrow dimuon resonances ϕ, ψ, ψ' etc require excellent control of resolution
  $\to$ Kinematic constraint using known B^0 mass to improve q^2 resolution
  $\to$ Obtain resolution parameters from fit to data



Latest measurement

- Unbinned amplitude analysis of entire $B^0 \to K^{*0}\mu^+\mu^-$ q^2 spectrum
- First measurement using entire Run1+Run2 result

Dispersion relation-like model

Local — Non-local contributions

$$C_9^{\mathrm{eff},\lambda}(q^2) = C_9^{\mu} + Y_{c\bar{c}}^{(0),\lambda} + Y_{c\bar{c}}^{1P,\lambda}(q^2) + Y_{\mathrm{light}}^{1P,\lambda}(q^2) + Y_{c\bar{c}}^{2P,\lambda}(q^2) + Y_{\tau\bar{\tau}}(q^2)$$

$$C_7^{\mathrm{eff},\lambda}(q^2) = C_7^{\mu} + \epsilon^{\lambda} e^{i\omega^0}$$

ΔC_7^{λ}

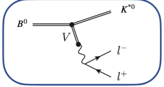
Polarisation dependent shift to C_7

This is determined theoretically at negative q^2 values

Subtraction term

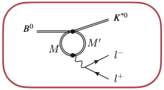
Asatrian, Greub, Virto [JHEP 04 (2020) 012]

Negligible impact from light quarks



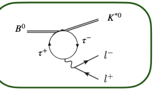
1-particle contributions

Includes:
$\omega(782)$, $\rho(770)$, $\phi(1020)$, J/ψ, $\psi(2S)$, $\psi(3770)$, $\psi(4040)$, $\psi(4160)$



2-particle contributions

Includes:
$D\bar{D}$, $D^*\bar{D}$, $D^*\bar{D}^*$



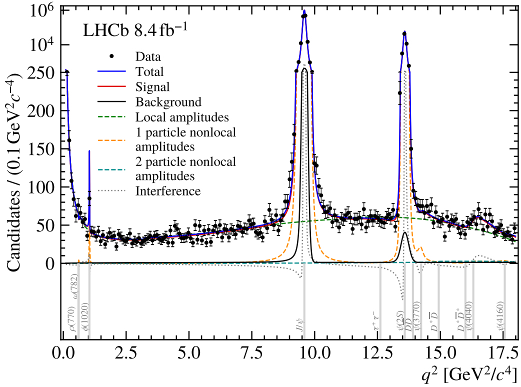
Tau loop contribution

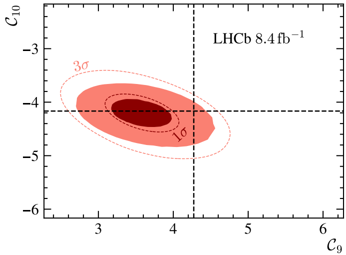
Sensitive to C_9^{τ}

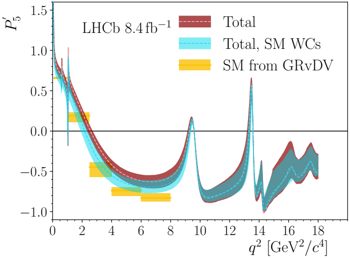
C. Cornella, G. Isidori, M. König, S. Liechti, P. Owen, N. Serra [Eur.Phys.J.C 80 (2020) 12, 1095]

Latest results

LHCb [JHEP09(2024)026]





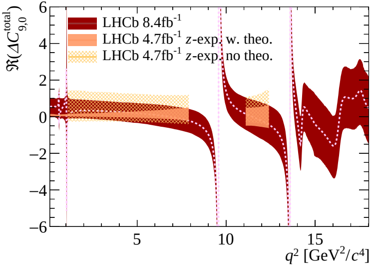


- Excellent agreement with global fits
- Tesion in C_9 at 2.1σ from SM
- Non-local amplitude plays clear role
- First determination of $C_9^\tau = -116 \pm 264 \pm 98$

Latest results contd.

- Good agreement with previous unbinned LHCb measurement [PRL132(2024)13180]
  - ▷ Using "polynomial" model for non-local amplitudes (z-expansion) [Bobeth et al EPJC(2018)78:451] in limited q^2 range
    $\rightarrow$ Less model dependent and more formal theoretically

LHCb [JHEP09(2024)026]



Conclusions

- Intriguing set of coherent anomalies in $b \to s\ell\ell$ and $b \to c\tau\ell\nu$ persist a decade on
  - Evaporation of LFUV in $b \to s\ell\ell$ ($\ell \equiv \mu, e$) means no irrefutible NP evidence

- Understanding hadronic contributions is critical
- First results promising but are we missing other effects?
  eg large hadronic rescattering $B \to D^* D_s \to K^{(*)}\ell\ell$ [Ciuchini et al 22]
  [Isidori et al 24] suggests maybe not?.
  - Both theory and experiment work ongoing

- Improved experimental precision in R_{D,D^*} and $B \to K^{(*)}\tau\tau$ is critical
  - Run3 LHCb and Belle2 data are key to this endeavour
- Potential R_{D,D^*} links with V_{cb} puzzle means further theory and experiment work ongoing here as well

One last thing...

- Keep close eye on Belle2 $B \to K\nu\bar{\nu}$ excess [PRD109,112006(2024)]
  - Leptoquark can also enhance $b \to s\nu_\tau\bar{\nu}_\tau$
  - No charm-loop arguments

- Potential tensions also in non-leptonic $b \to s(d)$ $b \to c$ measurements
  eg [Biswas et al JHEP06(2023)108], [Bordone et al EPJC80 10 951(2020)]
  - Significant theory and experimental work needed here

Thanks for listening

Backup