$\mathcal{R} (D^{(*)})$, $\mathcal{R}_{K^{(*)}}$, and their cousins: update on the continued challenges to lepton flavor universality

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5th May 2021
Virtual joint
JHU/UMD seminar
The SM is pretty good

Assume Universe is $SU(3) \times SU(2)_L \times U(1)$ symmetric, put in a few particles, and bam!, most precise and comprehensive theory in the history of mankind.

Anomalous magnetic dipole moment

$$\frac{g_e - 2}{2} \left| \begin{array}{c} \text{SM} \\ \text{exp} \end{array} \right| = 0.001 \, 159 \, 652 \, 181 \, 606 \, (230)$$

$$\frac{g_e - 2}{2} \left| \begin{array}{c} \text{SM} \\ \text{exp} \end{array} \right| = 0.001 \, 159 \, 652 \, 180 \, 73 \, (28)$$

12,672 diagrams of 10th order

Atoms 7, 28 (2019)

Beyond the SM

Looking in many directions

Large Hadron Collider

Icecube

Sill, many questions left

Dark matter

MATTER universe, ANTIMATTER sign guest book

Neutrinos

Sill, many questions left

\( Q (D^{(*)}) , R_{K^{(*)}} \) and their cousins: update on the continued challenges to LFU
Testing the SM

~ Alas, no direct detection yet

~ Can access mass scales beyond the reach of current particle accelerators through precision tests

~ Flavor physics (study of quark and lepton species) is a key tool
Alas, no direct detection yet

Can access mass scales beyond the reach of current particle accelerators through precision tests

Flavor physics (study of quark and lepton species) is a key tool
Lepton Flavor Universality (LFU)

~ It is assumed that electroweak gauge couplings to 3 fermion generations are identical

\[
\begin{align*}
&Z & & e^-, \mu^-, \tau^- \\
&W^- & & e^-, \mu^-, \tau^- \\
&\gamma & & e^+, \mu^+, \tau^+ \\
&\gamma & & e^-, \mu^-, \tau^- \\
&W^+ & & e^+, \mu^+, \tau^+ \\
&H^0 & & e^-, \mu^-, \tau^- \\
\end{align*}
\]

In particle physics units...

If a neutrino was as heavy as an ant...

https://ghostsintheuniverse.org/theory/
LFU tested to great precision

**LFU tests with 1st/2nd gen.**

- **To 0.28% in Z decays**
  \[ \frac{\Gamma_{Z \to \mu\mu}}{\Gamma_{Z \to ee}} = 1.0009 \pm 0.0028 \]

- **To 0.8% in W decays**
  \[ \frac{\mathcal{B}(W \to e\nu)}{\mathcal{B}(W \to \mu\nu)} = 1.004 \pm 0.008 \]

- **To 0.31% in meson decays**
  \[ \frac{\Gamma_{J/\psi \to \mu\mu}}{\Gamma_{J/\psi \to ee}} = 1.0016 \pm 0.0031 \]

- **To 0.14% in \( \tau \to \ell\nu\nu \)**
  \[ g_\mu/g_e = 1.0018 \pm 0.0014 \]

**LFU tests with 3rd gen.**

- **To 0.32% in Z decays**
  \[ \frac{\Gamma_{Z \to \tau\tau}}{\Gamma_{Z \to ee}} = 1.0019 \pm 0.0032 \]

- **2.6\( \sigma \) tension in W decays**
  \[ \frac{\Gamma_{W \to \tau\nu}}{\Gamma_{W \to \mu\nu}} = 1.070 \pm 0.026 \]

- **To 1.3% in W decays**
  \[ \frac{\Gamma_{W \to \tau\nu}}{\Gamma_{W \to \mu\nu}} = 0.992 \pm 0.013 \]

- **To 6.1% in \( D_s \) decays**
  \[ \frac{\Gamma_{D_s \to \tau\nu}}{\Gamma_{D_s \to \mu\nu}} = 9.95 \pm 0.61 \]

- **To 0.15% in \( \tau \to \ell\nu\nu \) (with \( \tau_\ell \))**
  \[ g_\tau/g_\mu = 1.0030 \pm 0.0015 \]
Since 2012, hints of LFU in transitions involving 3rd gen. b quark

**b → cτν transitions**
Charged currents (FCCC), tree diagram in SM → frequent

\[ R(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \rightarrow D^{(*)} \tau \nu_{\tau})}{\mathcal{B}(\bar{B} \rightarrow D^{(*)} \ell \nu_{\ell})} \]

with \( \ell = \mu, e \)

\[ R(D)^{SM} = 0.299 \pm 0.003 \quad R(D^{*})^{SM} = 0.258 \pm 0.005 \]

**b → sℓℓ transitions**
Neutral currents (FCNC), loop (penguin, box...) diagrams in SM → rare

\[ R_{K^{(*)}} = \frac{\mathcal{B}(\bar{B} \rightarrow K^{(*)} \mu^+ \mu^-)}{\mathcal{B}(\bar{B} \rightarrow K^{(*)} e^+ e^-)} \]

\[ R_{K}^{SM} \approx R_{K^{*}}^{SM} \approx 1.00 \pm 0.01 \] (at low-ish \( q^2 \))

Very solid SM predictions with 1-2% uncertainty, established deviations would be clear indications of BSM physics
Outline

Overview of experiments

LFU results with $b \to c\tau\nu$
- $p_B$ reconstruction
- B-factory and LHCb measurements of $\mathcal{R} \left( D^{(*)} \right)$
- Beyond $\mathcal{R} \left( D^{(*)} \right)$
- Future prospects

LFU results with $b \to s\ell\ell$
- $B_{(s)}^0 \to \mu^+\mu^-$
- Differential BF rates
- $B \to K^*\ell\ell$ angular observables
- LFU ratios $\mathcal{R}_{K^{(*)}}$
- Future prospects

One elegant interpretation
Contributions from several experiments

**BaBar** and **Belle** contributions:

- **$\mathcal{O}(10^9)$ $B^{0/+}$ mesons**
  - Low uncertainty on absolute rates,
  - 100% $\varepsilon$ (trigger), PID, low e-brem,
  - knowledge of collision momentum

**B-factories**

- With $\mathcal{O}(10^8)$ $B^{0/+}$ mesons already competitive search for $B \to K\nu\bar{\nu}$ (backup)!

**LHC** contributions:

- **$\mathcal{O}(10^{11})$ $B^{0/+}_{(s)}$ mesons**
  - Triggers primarily for flavor, PID, VELO,
  - all b-hadron species

- **$\mathcal{O}(10^{12})$ $B^{0/+}_{(s)}$ mesons**
  - All b-hadron species
LHC environment is slightly busier

LHC

$pp \rightarrow X_b B_s^0 X$

$B_s^0 \rightarrow \mu^+ \mu^-$

B-factories

Clean $e^+e^-$ collisions only produce two B mesons (for the most part)

$e^+e^- \rightarrow B^+_{\text{tag}} B^-_{\text{sig}}$

$B^- \rightarrow \rho^0 \mu^- \nu_{\mu}$
Vertexing and isolation key to LHC

\[ pp \rightarrow X_b B_s^0 X \]
\[ B_s^0 \rightarrow \mu^+ \mu^- \]

\~B mesons can fly \~cm thanks to large boost

\~Excellent trackers in CMS and ATLAS

\~Superb vertexing by VELO in LHCb
- Only 8.2 mm from IP, reduced to 5.1 in upgrade

\~Multivariate algorithms ensure tracks isolated
- Based on track impact parameter, other variables
LFU results with $b \rightarrow c\tau\nu$ transitions
Leptonic $\tau$

$\tau^- \rightarrow \ell^- \nu_\tau \bar{\nu}_\ell$

Same reco particles as normalization

$B \rightarrow D^{(*)}\ell\nu$, many uncertainties cancel on $\mathcal{R}(D^{(*)})$

Hadronic $\tau$

$\tau^- \rightarrow \pi^- \nu_\tau, \rho^- \nu_\tau, \pi^-\pi^+\pi^-\nu_\tau$

Better measurement of $\tau$ kinematics

$\mathcal{R}(D^{*+})$ depends on external branching fractions

Measure this ratio

$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \rightarrow D^{(*)}\tau\nu_\tau)}{\mathcal{B}(\bar{B} \rightarrow D^{(*)}\ell\nu_\ell)} = \frac{N_{\text{sig}}}{N_{\text{norm}}} \frac{\epsilon_{\text{norm}}}{\epsilon_{\text{sig}}}$

$\epsilon$ ratio easy, yields are key
**B tagging:** $p_{B_{\text{sig}}} = p_{e^+e^-} - p_{B_{\text{tag}}}$

**Hadronic:** best $\sigma(p_B)$, $\varepsilon_{\text{had}} \sim 0.2\text{-}0.4\%$

**Semileptonic:** worse $\sigma(p_B)$, $\varepsilon_{\text{sl}} \sim 0.3\text{-}0.6\%$

**FEI:** bottom-up approach based on BDTs with $\varepsilon_{\text{FEI}}$ up to 3x the corresponding $\varepsilon_{\text{had}}$ or $\varepsilon_{\text{sl}}$
$$\mathcal{R}(D^{(*)})$$

Hadrionic $B_{\text{tag}},$ leptonic $\tau$


$$D^{*\pm} \rightarrow D^{(*)} \pi(\pi)$$

Check brown bkg well estimated

$$D^{0\ell}$$

$$D^{\pm\ell}$$

Check yellow bkg well estimated

$$D^{*\ell}$$

Check result stable as a function of lepton flavor, run period, and purity

$$\chi^2: 5.1/7$$
$p = 64.7\%$

$$\chi^2: 5.9/7$$
$p = 55.5\%$

$$\chi^2: 4.3/3$$
$p = 23.4\%$

$$\chi^2: 4.2/3$$
$p = 23.7\%$
Belle 2015 $R(D^{(*)})$, $q^2$ distributions

~ Similar strategy to BaBar
- Hadronic $B_{tag}$, leptonic $\tau$
~ Also excess, consistent with BaBar
~ $q^2$ distributions rule out 2HDM
Assume proper velocity of $B$ and reco particles ($\mu D^*$) along $z$ is the same to find $p_z(B)$

$$p_z(B) = \frac{m_B}{m(\mu D^*)} p_z(\mu D^*)$$

Find $B$ vertex assuming muon comes from it, scale $p_z(B)$ with angle $\alpha$

$$|p(B)| = p_z(B) \sqrt{1 + \tan^2 \alpha}$$

Use $\tau$ direction between $B$ and $\tau$ vertices, solve $(p_\tau - p_{\pi\pi\pi})^2 = 0$, then solve $(p_B - p_\tau - p_{D^*})^2 = 2$
LHCb 2015 and 2018 $\mathcal{R}(D^{(*)})$

Leptonic-$\tau$


Hadronic-$\tau$

*Phys. Rev. D 97, 072013 (2018)*

$\mathcal{R}(D^{(*)})$, $\mathcal{R}_{K^{*\mu}}$ and their cousins: update on the continued challenges to LFU

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Belle 2019 $\mathcal{R}(D^{(*)})$, current status


$\sim$ **Leptonic-$\tau$ and semileptonic $B_{\text{tag}}$ with super-efficient FEI**

Recent measurements closer to SM, but bkg/signal understanding has not meaningfully changed
Even a 5σ on $\mathcal{R}(D^{(*)})$ would not be sufficient to convince ourselves of NP

- Indirect measurement with broad signal distributions due to multiple $\nu$ in final state

It will be important to have

- Confirmation by independent experiments
- Confirmation in different decays
- Characterization in kinematic distributions

LHCb has a unique ability to study $b \to c\tau\nu$ transitions because $b\bar{b}$ production at the LHC hadronizes into all species of b-hadrons

Belle II and upgraded LHCb both sensitive to angular distributions

LHCb already published first non-$\mathcal{R}(D^{(*)})$ measurement $\mathcal{R}(J/\Psi) = 0.71 \pm 0.17 \pm 0.18$, 1.8σ above SM


Currently, world-averaged $\mathcal{R}(D^{(*)})$ exceeds SM by ~14%

With Belle II and upgraded LHCb, could get uncertainties below 3% in a few years

- In addition to $\mathcal{R}(D^{(*)})$ and $\mathcal{R}(J/\Psi)$, LHCb has $\mathcal{R}(D^{**})$, $\mathcal{R}(p\bar{p})$, $\mathcal{R}(D_s)$, $\mathcal{R}(D_s^*)$, and $\mathcal{R}(\Lambda_c)$ ongoing!

- Even CMS trying to get out a measurement with ingenious trigger strategy

Wherever this ends up, very exciting times ahead!
LFU results with $b \rightarrow s\ell\ell$ transitions
Leptonic $B^0_{(S)} \to \mu^+\mu^-$ (very rare)

~ FCNC and helicity/Cabibbo suppressed $\Rightarrow$ very rare $\mathcal{B} \sim 10^{-9}$

$$\mathcal{B}(B^0_q \to \mu^+\mu^-)_{\text{SM}} = \frac{\tau_{B_q} G_{F} M_W^4 \sin^4 \theta_W}{8\pi^3} |C_{10}^{SM}|^2 v^*_{ub} V_{ts} \sqrt{1 - \frac{4m_{\mu}^2}{m_{B_q}^2} \frac{1}{1 - y_q}}$$

$\frac{1}{q = d, s}$

single Wilson coefficient & single hadronic constant (known at $\approx 0.5\%$!)

\[ \text{SM Predictions} \]

\[ \mathcal{B} \left( B^0_s \to \mu^+\mu^- \right) = (3.66 \pm 0.14) \times 10^{-9} \rightarrow 4\% \text{ uncertainty} \]

\[ \mathcal{B} \left( B^0 \to \mu^+\mu^- \right) = (1.03 \pm 0.05) \times 10^{-9} \rightarrow 5\% \text{ uncertainty} \]

~ BFIs out of reach from B-factories, but their measurements are key

Normalization from $B^+ \to J/\psi K^+$ (and $B^0 \to K^+\pi^-$ in LHCb)

$$\mathcal{B}(B^0_{s} \to \mu^+\mu^-) = \frac{N_S}{N_{B^+}} \frac{f_{B^+}}{f_{S}} \frac{\varepsilon_{\text{B+}}}{\varepsilon_{\text{tot}}}^{B^+(\to J/\psi K^+)} \mathcal{B}(J/\psi \to \mu^+\mu^-)$$

2.4% uncert. \( \text{BaBar} \) 0.6% uncert. \( \text{BESIII} \)

3.2% uncert. from 2103.06810 (7% until this March)

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\( \mathcal{R}(D^{(*)}), \mathcal{R}_{K^{*n}} \) and their cousins: update on the continued challenges to LFU
\(B_{(S)}^{0} \rightarrow \mu^{+}\mu^{-}: \text{ATLAS and CMS}\)

**Normalization**

**Signal**

25% of \(B_s\) in Run 1+2 dataset

\[ \mathcal{B}\left(B_{s}^{0} \rightarrow \mu^{+}\mu^{-}\right) = \left(2.8^{+0.8}_{-0.7}\right) \times 10^{-9} \rightarrow 4.6\sigma \]

\[ \mathcal{B}\left(B_{s}^{0} \rightarrow \mu^{+}\mu^{-}\right) < 2.1 \times 10^{-10} \quad \text{(95 \% CL)} \]

JHEP 04 (2019) 098

32% of \(B_s\) in Run 1+2 dataset

\[ \mathcal{B}\left(B_{s}^{0} \rightarrow \mu^{+}\mu^{-}\right) = \left(2.9^{+0.7}_{-0.8}\right) \times 10^{-9} \rightarrow 5.6\sigma \]

\[ \mathcal{B}\left(B_{s}^{0} \rightarrow \mu^{+}\mu^{-}\right) < 3.6 \times 10^{-10} \quad \text{(95 \% CL)} \]

JHEP 04 (2020) 188
$B^0_{(S)} \to \mu^+\mu^-$: LHCb

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

 normalization

 signal

~ Combination with ATLAS/CMS

$\mathcal{B} (B^0_s \to \mu^+\mu^-)_{WA} = (2.84 \pm 0.33) \times 10^{-9}$

~ 22% below SM prediction

~ 2.3σ tension with SM

100% of $B_s$ in Run 1+2 dataset

PAPER-2021-007 forthcoming

$\mathcal{B} (B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}$ (95% CL)
Semileptonic $B_s \rightarrow H\ell^+\ell^-$ (medium rare)

Not as suppressed as leptonic decays, but still rare with $\mathcal{B} \sim 10^{-7}$

$Q^2 \equiv m(\ell^+\ell^-)$
Precision test strategies

Experimental and theoretical uncertainties depend on strategy

Branching fractions
Simpler for LHC (focus on \( \mu \)), but large theory uncertainties

Angular observables
Minimal FF uncertainties, though sensitive to charm loops

LFU ratios \( R_{H_s} = \frac{\mathcal{B}(H_b \rightarrow H_s \mu\mu)}{\mathcal{B}(H_b \rightarrow H_s ee)} \)
Theory uncertainty of \( \sim 1\% \), but electrons harder at the LHC
**Differential BF rates**

~ First measurements of $B \rightarrow K(\ast) \ell \ell$ at Tevatron and the B-factories

- Consistent with expectations though large uncertainties

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**Deficit** in LHCb measurements with muons at low $q^2$

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PRL 107, 201802 (2011)
PRL 103, 171801 (2009)
PRD 86, 032012 (2012)

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R (D(*)), R_{K} and their cousins: update on the continued challenges to LFU
Angular observables in $B \rightarrow K^* \ell \ell$

3 angles
$\theta_\ell, \theta_K, \phi$

\[
\frac{1}{\Gamma} \frac{d^3(\Gamma + \bar{\Gamma})}{\cos \theta_\ell \cos \theta_K \, d\phi} = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell 
- F_L \cos^2 \theta_K \cos 2\theta_\ell + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi + S_6^\phi \sin^2 \theta_K \cos \theta_\ell + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi + S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right].
\]

P-wave

~ Optimized $P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_L (1 - F_L)}}$ observables make a clever use of the symmetries to cancel soft FF at LO

~ Also, LFU $Q_i = P^\mu_i - P^e_i$ observables independent of long distance charm contributions

JHEP 10, 075 (2016)
$P'_5$ and $Q_{4,5}$ in $B \rightarrow K^* \ell \ell$

Possible discrepancies at low $q^2$, driven by muons
\( \mathcal{R}_{K^*(\ast)} \) at Belle

~ Measured all isospin variants for \( \mathcal{R}_{K^*(\ast)} = \frac{\mathcal{B}(B \to K(\ast)\mu\mu)}{\mathcal{B}(B \to K(\ast)ee)} \)

~ Fit \( M_{bc} = \sqrt{E_{\text{beam}}^2 - p_B^2} \)

~ \( \mathcal{R}_K \) also fits NN and \( \Delta E = E_B - E_{\text{beam}} \), \( \mathcal{R}_{K^*} \) cuts on them

~ Similar mass resolution for \( \mu \) and \( e \)

~ Powerful check with \( B \to J/\psi(\to \ell \ell') K(\ast) \)

\[ r^K_{J/\psi} = \frac{\mathcal{B}[B \to K J/\psi(\to \mu\mu)]}{\mathcal{B}[B \to K J/\psi(\to ee)]} = 0.994 \pm 0.015 \]

\[ r^{K*}_{J/\psi} = \frac{\mathcal{B}[B \to K^* J/\psi(\to \mu\mu)]}{\mathcal{B}[B \to K^* J/\psi(\to ee)]} = 1.015 \pm 0.045 \]

Aside: most precise \( \mathcal{B}(B \to J/\psi K) \) in the world, just added to PDG

\[ \mathcal{B}(B^+ \to J/\psi K^+) = (1.032 \pm 0.025) \times 10^{-3} \]

\[ \mathcal{B}(B^0 \to J/\psi K^0) = (0.902 \pm 0.028) \times 10^{-3} \]
deviation along this direction is observed in the lowest 
predictive estimation of uncertainty is performed to account 
for residual correlations with the top-level classifiers.

The dominant uncertainty originates from lepton 
identification, ranging between 5% and 10% depending 
onational uncertainties from tracking (0.35% per track) and 
region. As discussed in the beginning, this uncertainty 
applying to the branching fractions not to the LFU 
this model dependence using di 

The Belle II experiment \[\text{in the SM}\] is predicted to 
express \(R_{K}^{(*)}\) with 100% of Belle's dataset: 711 fb\(^{-1}\)

Compatible with \(R_{K}^{SM} \approx 1\)

Compatible with \(R_{K^{*}}^{SM} \approx 1\)
Measurements of $R_{K^{*0}}$ (3 fb$^{-1}$) and $R_{K^+}$ (9 fb$^{-1}$)

~ At LHCb, electrons are major challenge

~ Use double ratio with $B \rightarrow K^{(*)} J/\psi(\rightarrow e^+ e^-)$

$$R_K = \frac{N_{\text{rare}}^{\mu^+ \mu^-}}{N_{\text{rare}}^{e^+ e^-}} \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)/\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)}{\mathcal{B}(B^+ \rightarrow K^+ J/\psi(\mu^+ \mu^-))/\mathcal{B}(B^+ \rightarrow K^+ J/\psi(e^+ e^-))}$$

Electrons have worse mass resolution and are more difficult to trigger on.
A large number of cross-checks were performed before unblinding the result. The control central...

**Figure 7**

- Backgrounds reduced with
  - Tight PID
  - Vetoes on invariant masses, eg $m(K^+e) > m(D^0)$
  - Multivariate classifiers

- Combinatorial and partially-reco bkgds free in fit

- $B \rightarrow K^{(*)} J/\psi(\rightarrow \ell\ell)$ contamination from resonant fit

- Signal shapes taken from simulation
  - Small corrections obtained from clean $B \rightarrow K^{(*)} J/\psi(\rightarrow \ell\ell)$
Rare and J/ψ events have **identical final states**, difference only q²

- **Check if we understand** ε with \( r_{f/\psi}^{K(*)} = \frac{\mathcal{B} \left[ B \rightarrow K^{(*)} J/\psi(\rightarrow \mu\mu) \right]}{\mathcal{B} \left[ B \rightarrow K^{(*)} J/\psi(\rightarrow ee) \right]} = 1 \)

- **Apply J/ψ mass constraint**, but check without as well

\( r_{f/\psi}^{K^*} = 1.043 \pm 0.045 \)

\( r_{\psi(2S)/f/\psi}^{K^*} = 0.980 \pm 0.040 \)

\( r_{f/\psi}^{K} = 0.981 \pm 0.020 \)

\( r_{\psi(2S)/f/\psi}^{K} = 0.997 \pm 0.011 \)

**Also in bins of lab angle, p_T**
**LFU $R_{K^{(*)}}$ at LHCb: results**

**$B \rightarrow K^{(*)}\mu^+\mu^-$**

- LHCb
- $B^0 \rightarrow K^0\mu^+\mu^-$
- Combinatorial
- $N_{\mu\mu}^{Tot} = 638 \pm 28$
- $1.1 < q^2 < 6.0$ [GeV$^2$/c$^4$]

**$B \rightarrow K^{(*)}e^+e^-$**

- $K^0$
- LHCb
- $B^0 \rightarrow K^0e^+e^-$
- Combinatorial
- $B \rightarrow Xe^+e^-$
- $B^0 \rightarrow K^0J/\psi$
- $1.1 < q^2 < 6.0$ [GeV$^2$/c$^4$]
- $N_{ee}^{Tot} = 200 \pm 18$

**$K^+$**

- $K^+$
- LHCb
- Data 9 fb$^{-1}$
- Total fit
- $B^+ \rightarrow K^+\mu^+\mu^-$
- Combinatorial
- $N_{\mu\mu}^{Tot} = 3850 \pm 70$

**$R_{K^{*0}}$ with 25% of Run 1+2**

- $R_{K^{*0}}^{[0.045, 1.1]} = 0.66^{+0.11}_{-0.07} \pm 0.03$
- 2.1σ below SM
- JHEP 08, 055 (2017)

- $R_{K^{*0}}^{[1.1, 6]} = 0.69^{+0.11}_{-0.07} \pm 0.05$
- 2.4σ below SM

**$R_{K^+}$ with 100% of Run 1+2**

- Fresh!
- $R_{K^+}^{[1.1, 6]} = 0.846^{+0.042+0.013}_{-0.039-0.012}$
- 3.1σ below SM
- arXiv 2103.11769
Currently, $\mathcal{R}_{K(*)} \sim 15\text{-}30\%$ below SM

~Uncertainties on LFU ratios expected to reach about 2\text{-}3\% with 2025 LHCb dataset

~Belle II expected to take longer than in plot

Bifani, Descotes-Genon, Romero Vidal, Schune
Journal of Physics G: Nuclear and Particle Physics, 46, 2 (2018)
One elegant interpretation

Anomalies recap

**LFU results with $b \to c\tau\nu$**

- $1.8\sigma$ excess in $\mathcal{R}(J/\Psi)$
- 14% excess in $\mathcal{R}(D)$
- 14% excess in $\mathcal{R}(D^*)$

**LFU results with $b \to s\ell\ell$**

- Deficit in differential BF rates with $\mu$
- 22% deficit in $B_{(s)}^0 \to \mu^+\mu^-$
- 15% deficit in $\mathcal{R}_K$
- ~30% deficit in $\mathcal{R}_{K^*}$
- Disagreement in $B \to K^{*}\ell\ell$ angular $P'_5$

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Slide 39
EFT for $b \to s \ell \ell$

Dimension-6 operators identified as relevant set for combined explanation of both anomalies

$$\mathcal{L}_{b \to s \ell^+ \ell^-} = \frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_i C_i^\ell \mathcal{O}_i^\ell$$

**FCNC operators:**
- $\mathcal{O}_{10}^\ell = (\bar{s}_L \gamma \mu b_L)(\bar{\ell} \gamma \mu \gamma_5 \ell)$
- $\mathcal{O}_9^\ell = (\bar{s}_L \gamma \mu b_L)(\bar{\ell} \gamma \mu \ell)$

**Four-quark operators:**
- $\mathcal{O}_2 = (\bar{s}_L \gamma \mu b_L)(\bar{\ell} \gamma \mu c_L)$

Separate NP contributions between

Lepton Flavor Universal

$$\Delta C_{9,10}^U \equiv C_{9,10}^e - C_{9,10}^{SM}$$

and LFU-breaking

$$\Delta C_{9,10}^\mu \equiv C_{9,10}^\mu - C_{9,10}^e = C_{9,10}^\mu - (C_{9,10}^{SM} + \Delta C_{9,10}^U)$$

Induce $\Delta C_{9}^U$ but no LFU breaking terms

$(\mathcal{R}_{K^{(*)}})$ or axial-current contributions

$$(B_s^0 \to \mu^+ \mu^-)$$
EFT fits for $b \to s \ell \ell$

Fit to **clean observables** ($\mathcal{R}_{K^{(*)}}$ and $B^0_s \to \mu^+\mu^-$) consistent with single NP parameter $\Delta C_9^\mu = - \Delta C_{10}^\mu$, discrepancy very significant

$$\sigma^{ij\alpha\beta}_{LL} = (q_L^i \gamma_{\mu} \gamma_{\nu L}^\dagger)(q_R^j \gamma_{\mu} \gamma_{\nu L}^\dagger) = \frac{1}{2} [Q_{ij}^{(1)} + Q_{ij}^{(3)} \beta_{\alpha\beta}]$$

Fits to **clean and other observables** also consistent, away from SM

$C_{LL}^{23\mu\mu} \times 10^3$

$C_{LL}^{23\tau\tau} \times 10$

$C_{LL}^{23\tau\tau} \approx 10^2 \times C_{LL}^{23\mu\mu}$ points to scaling with fermion generation

Isidori at APS April 2021, arXiv:2103.16558
\( b \rightarrow s \ell \ell \) and \( b \rightarrow c \tau \nu \) give remarkably consistent results

\( \sim b \rightarrow s \ell \ell \) and \( b \rightarrow c \tau \nu \) give remarkably consistent results

\( \sim 10^{-1} \) for each 2\textsuperscript{nd} gen. \( q_L \) or \( l_L \)
\( \rightarrow |C_{23}^{\mu \mu}| \sim 10^{-3} |C_{33}^{\tau \tau}| \)
\( \rightarrow |V_{ts}| \sim 0.4 \times 10^{-1} \)

\( \checkmark \) Nice consistency among the two sets of anomalies

\( \checkmark \) Remarkably consistent

I. \( \Delta F=2 \) and \( \tau \rightarrow l \nu \)

II. Direct searches: \( 3^{\text{rd}} \) gen. \( LQ \) are also in better shape as far as direct searches are concerned (\textit{contrary to Z'...}).

Additional \( \sim 10^{-2} \) (\textit{\sim} loop) suppression for:

- Four-quarks (\( \Delta F=2 \))
- Four-leptons (\( \tau \rightarrow \mu \nu \nu \))
- Semi-leptonic \( O^{(1-3)} \) (\( b \rightarrow s \nu \nu \))
“Renaissance” of LQ models (to explain the anomalies, but not only...):

- **Scalar LQ as PNG**
  - Gripiños, '10
  - Gripiños, Nardecchia, Rennier, '14
  - Marzocca '18

- **Scalar LQ from GUTs & SUSY**
  - Hiller & Schmaltz, '14
  - Becirevic et al. '16
  - Fajfer et al. '15-'17
  - Dorsner et al. '17
  - Crivellin et al. '17
  - Altmannshofer et al. '17
  - Trifinopoulos '18, Becirevic et al. '18 + ...

- **Vector LQ as techni-fermion resonances**
  - Barbieri et al. '15
  - Buttazzo et al. '16
  - Barbieri, Murphy, Senia, '17

- **Scalar LQ as PNG**
  - Marzocca '18
  - Gripaios, Nardecchia, Renner, '14
  - Marzocca '18

- **Scalar LQ from GUTs & SUSY**
  - Hiller & Schmaltz, '14
  - Becirevic et al. '16
  - Fajfer et al. '15-'17
  - Dorsner et al. '17
  - Crivellin et al. '17
  - Altmannshofer et al. '17
  - Trifinopoulos '18, Becirevic et al. '18 + ...

- **Vector LQ in GUT gauge models**
  - Assad et al. '17
  - Di Luzio et al. '17
  - Bordone et al. '17
  - Hecck & Teresi '18 + ...

**Which LQ explains which anomaly?**

<table>
<thead>
<tr>
<th>Model</th>
<th>$R_K(\times)$</th>
<th>$R_D(\times)$</th>
<th>$R_K(\times) &amp; R_D(\times)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_1 = (3, 1)_{-1/3}$</td>
<td>$\times$</td>
<td>$\checkmark$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$S_2 = (3, 2)_{-1/6}$</td>
<td>$\times$</td>
<td>$\checkmark$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$\bar{S}<em>2 = (3, 2)</em>{1/6}$</td>
<td>$\times$</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$S_3 = (3, 3)_{-1/3}$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$U_1 = (3, 1)_{2/3}$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
</tr>
<tr>
<td>$\bar{U}<em>1 = (3, 2)</em>{2/3}$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
<td>$\times$</td>
</tr>
</tbody>
</table>

LQ of the Pati-Salam gauge group: $SU(4) \times SU(2)_L \times SU(2)_R$

**Figure 3.2:**

- **Figure 3.2a:**
  - $U_1$ leptoquark fits all low-energy data

- **Figure 3.2b:**
  - $U_1$ leptoquark fits all low-energy data

- **Figure 3.2c:**
  - $U_1$ leptoquark fits all low-energy data

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Isidori at APS April 2021, arXiv:2103.16558
Study of high $p_T$ tails in $\tau\tau$ events from ATLAS, PRL 125, 051801 (2020)

Direct LQ searches at LHC have limited mass reach, but high $p_T$ tails in $\tau\tau$ events would have sensitivity at HL-LHC

Also, $b \rightarrow d\mu\mu$, $b \rightarrow s\tau\tau$, $b \rightarrow s\tau\mu$, $B_s$ mixing, $b \rightarrow s\nu\nu$, $\tau \rightarrow \mu\mu$

Direct LQ search from CMS, arXiv:2012.04178
~ **Excesses** in decays involving $b \to c\tau\nu$ transitions
  - 3.1σ significance

~ **Deficits** in decays involving $b \to s\mu\mu$ transitions
  - At least 3.9σ significant

~ **$U_1$ leptoquark** could explain both
  - Within reach at HL-LHC

~ **Exciting times ahead**
  - **LHC** still analyzing Runs 1+2 data
  - Run 3 to start next year with 5x inst. lumi at LHCb
  - **Belle II** will increase $B$-factories dataset by 50x
  - **HL-LHC** will increase current dataset by 100x