Flavor anomalies from a gauge extension

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Outline

1. Motivation: $b \to s\ell^+\ell^-$ and $b \to c\ell\nu$ anomalies
   A hint for new physics from flavor experiments?
2. Towards an unified explanation of the anomalies
   From an extended gauge sector
3. Phenomenological implications
   Gauge mixing effects, bounds from LHC and from flavor, diphoton anomaly
4. Summary

Lepton universality violation in $\mathrm{b} \to \mathrm{s}\ell^+\ell^-$

$$R_K = \frac{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} \frac{d\Gamma(B^+ \to K^+\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} \frac{d\Gamma(B^+ \to K^+e^+e^-)}{dq^2} dq^2} = 1 + \mathcal{O}(m_\mu^2/m_b^2)$$

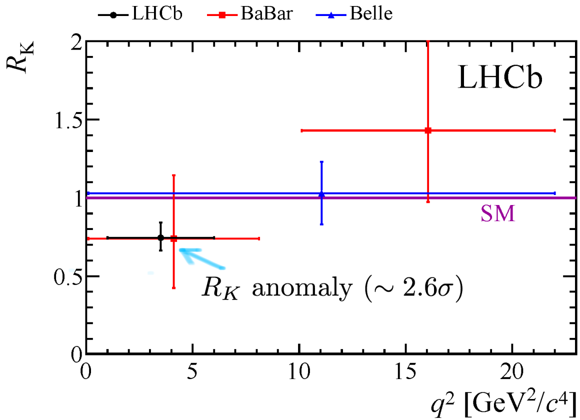
Key test to **lepton universality violations** in neutral currents

Hiller and Krüger, Phys.Rev. D69 (2004) 074020

The $\mathrm{R_K}$ anomaly

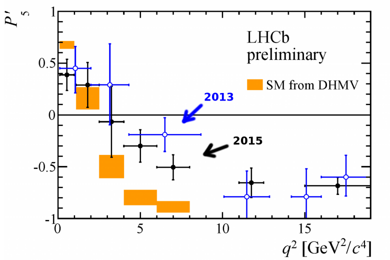
LHCb, Phys.Rev.Lett. 113 (2014)

$$R_K^{\mathsf{LHCb}}\Big|_{[1,6]} = 0.745^{+0.090}_{-0.074} \pm 0.036$$



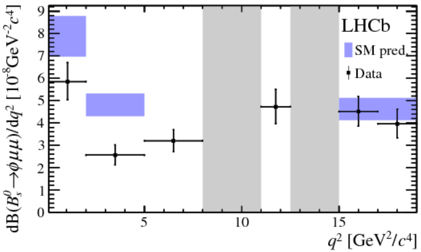
Other anomalies in $\mathrm{b} \to \mathrm{s}\mu^+\mu^-$ transitions

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



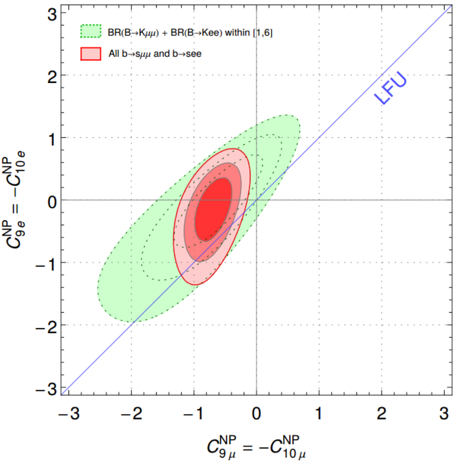
LHCb-CONF-2015-002

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



LHCb, JHEP 09 (2015) 179

Global fits to $b \to s\ell^+\ell^-$ data



Allow for **New Physics in muons**

$$\mathcal{O}_9^\mu = (\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \mu)$$
$$\mathcal{O}_{10}^\mu = (\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \gamma_5 \mu)$$

Global fit:

- $\mathcal{C}_9^\mu$ plays a central role in the interpretation of the anomalies
- Large pull for the SM hypothesis, **above $4\,\sigma$**

Descotes-Genon et al., arXiv:1510.04239

Lepton universality violation in $\mathrm{b} \to \mathrm{c}\ell\nu$

$$R(D) = \frac{\Gamma(B \to D\tau\nu)}{\Gamma(B \to D\ell\nu)} \stackrel{\mathrm{SM}}{=} 0.297 \pm 0.017$$

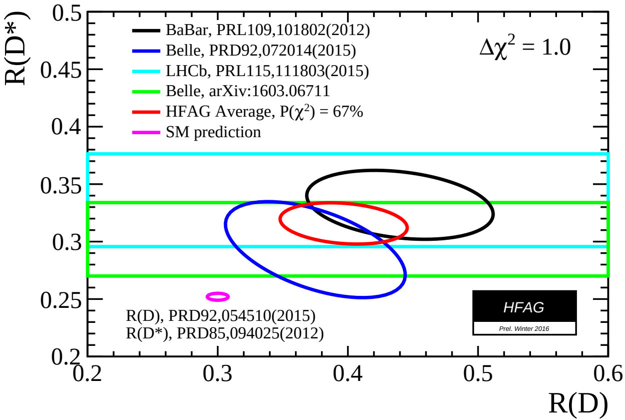
$$R(D^*) = \frac{\Gamma(B \to D^*\tau\nu)}{\Gamma(B \to D^*\ell\nu)} \stackrel{\mathrm{SM}}{=} 0.252 \pm 0.003$$

Fajfer et al., Phys.Rev.D85(2012) 094025

Key test to **lepton universality violations** in charged currents

The $\mathrm{R}(\mathrm{D}^{(*)})$ anomalies

$$R(D)_{exp} = 0.397 \pm 0.049 \qquad R(D^*)_{exp} = 0.316 \pm 0.019$$



Deviation from the SM prediction at the $4\,\sigma$ level

More about the $\mathrm{R}(\mathrm{D}^{(*)})$ anomalies

- Angular analysis by BaBar compatible with a spin-1 mediator

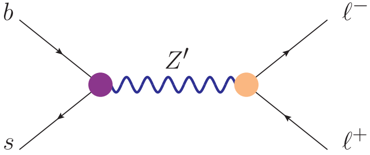
- Data compatible with an universal scaling of the $R(D^{(*)})$ excesses

$$\frac{R(D)_{exp}}{R(D)_{SM}} = 1.34 \pm 0.17 \qquad \frac{R(D^*)_{exp}}{R(D^*)_{SM}} = 1.25 \pm 0.08$$

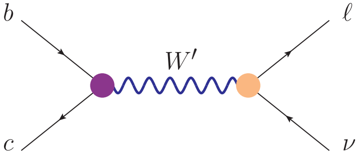
as expected for NP from left-handed current interactions

Are the two anomalies hinting to the same new physics?

Towards a gauge explanation of the anomalies



Flavor violating couplings to quarks



Lepton-flavor universality violation

Minimal possible gauge explanation:

- Add an extra $\mathrm{SU}(2)$ factor to the SM gauge group
- Null or negligible couplings to electrons, as suggested by data
- Couplings to left-handed fermions, as suggested by $b \to s\ell\ell$, and $R(D^{(*)})$ apparent universal scaling
- An effective dynamical model in this direction

Greljo et al., JHEP 1507 (2015) 142

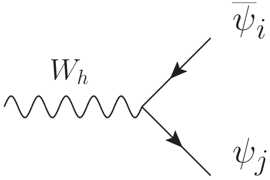
Possible model classification

Breaking patterns:

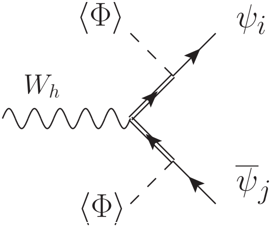
- $\mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_H \otimes \mathrm{U}(1)_H \to \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$
- $\mathrm{SU}(2)_1 \otimes \mathrm{SU}(2)_2 \otimes \mathrm{U}(1)_Y \to \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$

Source of non-universality:

- Non-universal gauge couplings

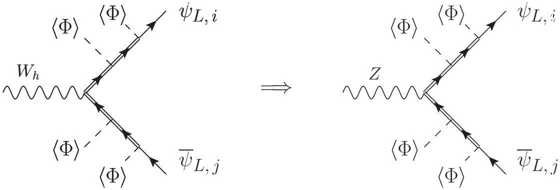


- Through mixing with other fermions



$\mathbf{SU(2)_L \otimes SU(2)_H \otimes U(1)_H \to SU(2)_L \otimes U(1)_Y}$

- Non-universal gauge couplings:
  - ✓ Able to accommodate $R(D^{(*)})$ (with some tensions)
    He and Valencia, Phys.Rev.D87 (2013) no.1, 014014
  - ✗ Right-handed currents, cannot accommodate the $b \to s\ell\ell$ anomalies
- Non-universality through mixing with other fermions:
  - ✓ Left-handed neutral currents are possible...
  - ✗ ... but not for the charged currents (without introducing large FCNCs)



$\mathbf{SU(2)_1 \otimes SU(2)_2 \otimes U(1)_Y \to SU(2)_L \otimes U(1)_Y}$

- Non-universal gauge couplings:
  - ✓ Left-handed currents
  - ✗ $g_2 \gg g_1 \sim g$ to have the necessary lepton couplings
    - ⋆ With the SM fermion content, in conflict with proton decay
      JF, J. Portolés and P. Ruiz-Femenía, JHEP 1501 (2015) 134
    - ⋆ Even if we extend the fermion content, in conflict with perturbativity

- Non-universality through mixing with other fermions:
  - ✓ Left-handed currents
  - ✓ Enough freedom to accommodate the necessary couplings
    (controlled non-universality, no Z'/W' couplings to the first family...)

A minimal example

$$\mathrm{SU}(2)_1 \otimes \mathrm{SU}(2)_2 \otimes \mathrm{U}(1)_Y$$

$\langle \Phi \rangle \sim u \gg v$ ↓ $M_{Z'}, M_{W'} \sim \mathcal{O}(u)$

$$\mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$$

$\langle \phi \rangle \sim v$ ↓ $M_Z, M_W \sim \mathcal{O}(v)$

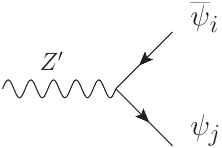
$$\mathrm{U}(1)_{\mathrm{em}}$$

Particle content

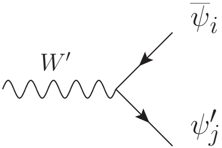
- A Higgs doublet: $\phi \sim (1,2)_{1/2}$
- A (self-dual) bidoublet: $\Phi \sim (2,\bar{2})_0$
- SM fermions (charged **universally** under $\mathrm{SU}(2)_2$)
- Vector-like fermions: Q, L (charged **universally** under $\mathrm{SU}(2)_1$)

$$\mathcal{L}_{\text{mix}} = \lambda_q \, \overline{Q}_R \, \Phi \, q_L + \lambda_\ell \, \overline{L}_R \, \Phi \, \ell_L$$

A minimal example cont'd



$$\sim \Delta_L^{q,\ell} = \mathbb{1} - \underbrace{\lambda_{q,\ell}\frac{u^2}{M_{Q,L}^2}\lambda_{q,\ell}^\dagger}_{\mathcal{O}(1)} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1-\Delta_1^2 & \Delta_1\Delta_2 \\ 0 & \Delta_1\Delta_2 & 1-\Delta_2^2 \end{pmatrix}$$

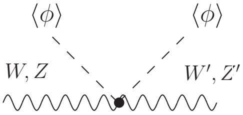


$$\sim V_{q,\ell}\,\Delta_L^{q,\ell} \qquad (V_{q,\ell} = V_{\mathsf{CKM}},\, \mathbb{1})$$

Free parameters for flavor: $\{g_2,\, M_{Z'},\, \Delta_s,\, \Delta_b,\, \Delta_\mu,\, \Delta_\tau\}$

✓ The model reproduces the required structure for the couplings

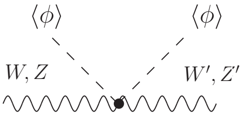
Gauge mixing effects



$$\sim \xi \, \frac{M_{Z,W}^2}{M_{Z'}^2} \qquad\qquad \xi \sim \mathcal{O}(1)$$

- Mixing effects are constrained by LEP at the per-mile level
  - The mass hierarchy suppresses NP corrections to Z/W couplings: $M_Z^2/M_{Z'}^2 = 8.3 \times 10^{-3} \left(\frac{1\,\mathrm{TeV}}{M_{Z'}}\right)^2$
  - An additional parametric suppression from ξ might be necessary
- For unsuppressed ξ, gauge mixing effects are potentially of the same size as Z'/W' tree-level exchange in certain flavor observables:
  - Potential to spoil the desired couplings (Anomalous couplings to electrons, departure from $\delta\mathcal{C}_9^{\mathrm{NP}} = -\delta\mathcal{C}_{10}^{\mathrm{NP}}$)

Gauge mixing effects



$$\sim \xi \, \frac{M_{Z,W}^2}{M_{Z'}^2}$$

ξ free parameter if we add:

$$\phi' \sim (2,1)_{1/2}$$

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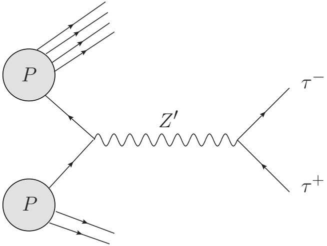
LHC bounds



- A Z' with mass above 2 TeV do not get any bounds from LHC direct searches for s/c-induced production
- In case of b-mediated production, Z' masses as low as 1.5 TeV are allowed without any limit on the Z' couplings, in agreement with previous analyses

  Greljo et al., JHEP 1507 (2015) 142
- These bounds can be relaxed by adding more decay channels, which increases the decay width

Bounds from flavor observables

At this point a fit to flavor data is necessary:

- $b \to s\ell\ell$ and $b \to c\ell\nu$ data

- Leptonic τ decays
  - $\Gamma\left(\tau \to e\nu\bar{\nu}\right)/\Gamma\left(\mu \to e\nu\bar{\nu}\right)$
  - $\Gamma\left(\tau \to \mu\nu\bar{\nu}\right)/\Gamma\left(\mu \to e\nu\bar{\nu}\right)$

- $s \to u$ transitions
  - $\Gamma\left(K \to \mu\nu\right)/\Gamma\left(K \to e\nu\right)$
  - $\Gamma\left(\tau \to K\nu\right)/\Gamma\left(K \to e\nu\right)$
  - $\Gamma\left(K \to \pi\mu\nu\right)/\Gamma\left(K \to \pi e\nu\right)$

- $b \to s$ transitions
  - $\Delta M_s/\Delta M_d$

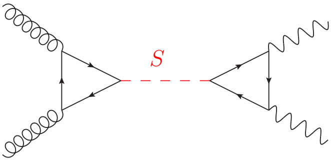
- $d \to u$ transitions
  - $\Gamma\left(\pi \to \mu\nu\right)/\Gamma\left(\pi \to e\nu\right)$
  - $\Gamma\left(\tau \to \pi\nu\right)/\Gamma\left(\pi \to e\nu\right)$

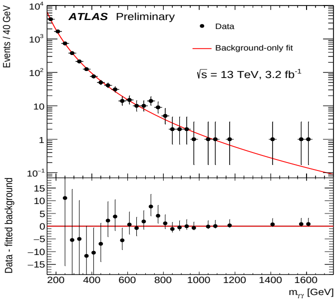
- $c \to s$ transitions
  - $\Gamma\left(D \to K\mu\nu\right)/\Gamma\left(D \to Ke\nu\right)$
  - $\Gamma\left(D_s \to \tau\nu\right)/\Gamma\left(D_s \to \mu\nu\right)$

- LFV observables
  - $\Gamma\left(\tau \to 3\mu\right)$
  - $Z \to \tau\mu$


Work in progress

One slide about the diphoton anomaly





A candidate for S

- Singlet component of Φ
- A scalar or a pseudo-scalar from ϕ'
- An 'ad-hoc' scalar singlet

A dedicated flavor analysis is needed to test these possibilities

Summary

- Motivated by the flavor anomalies we have explored specific $\mathrm{SU}(2)$ model realizations with the potential to accommodate them.
- We have seen that, in order to achieve the required patterns for the gauge couplings, one should introduce non-universality through the mixing with an extended fermion sector
- The scalar sector of the minimal model should be further extended in order to control potentially dangerous mixing effects
- These extra fermion and scalar degrees of freedom provide a rich phenomenology that will be further explored

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Thank you!