B theory and Lepton Flavor Universality overview

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Split
18/9/2018

(Interplay Between B-Anomalies and High-p_T Physics)

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Prelude: Lepton Flavor Universality in SM

SM gauge sector respects accidental flavor symmetry

$$G_F^{\mathrm{SM}} = U(3)_Q \times U(3)_U \times U(3)_D \times \underbrace{\boxed{U(3)_L \times U(3)_E}}_{\text{LFU}}$$

*neutrino masses

Broken by Higgs Yukawas

$$G_{\mathrm{acc.}}^{\mathrm{SM}} = U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$$

⇒ Unique source of LFU breaking: $m_e \neq m_\mu \neq m_\tau$

Any LFU violation beyond lepton mass effects sign of NP!

*Higgs boson processes

Crash course on B-anomalies: charged currents

Charged-current semileptonic B decays:

$$\frac{d^2\Gamma(B \to D^{(*)}\ell\nu)}{dq^2 d\cos\theta} = |V_{cb}|^2 \mathcal{N}_0 \sum_\lambda h_\lambda(\cos\theta)\Phi_\lambda(q^2) \qquad (\ell = e, \mu)$$

Hadronic form factor normalization computed using Lattice QCD

Helicity basis functions (determine angular distributions)

(Relative) form factor shapes extracted (fitted) from data

*fit model dependence
Bernlochner et al., 1703.05330
Bigi et al., 1707.09509

Comparison with measured rates yields

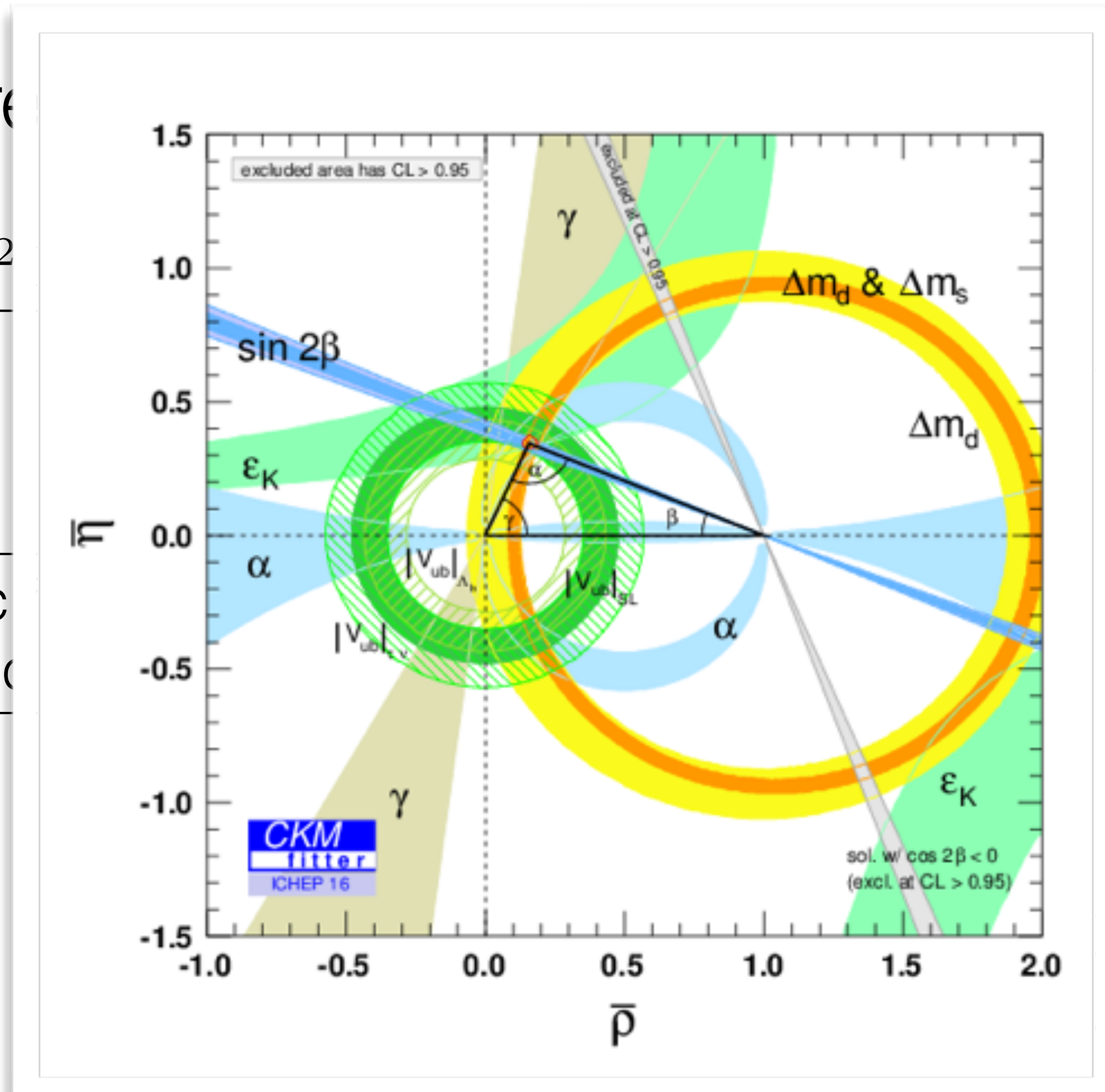
$$|V_{cb}|_{\text{excl.}} = (38.99 \pm 1.27) \times 10^{-3}$$

HFAG, CKMFitter

Crash course on B-anomalies: charged currents

Charged-curre

d^2 … $q^2)$ $\qquad (\ell = e, \mu)$



Hadronic
computed

shapes
data

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HFAG, CKMFitter

Crash course on B-anomalies: charged currents

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$$\frac{d^2\Gamma(B \to D^{(*)}\tau\nu)}{dq^2 d\cos\theta} = |V_{cb}|^2 \mathcal{N}_0 \sum_\lambda h_\lambda(\cos\theta)\Phi_\lambda(q^2, m_\tau)$$

- Kinematical (phase space) effects
- One additional relative f.f. shape (tau helicity suppressed)

Can be systematically computed (Lattice QCD, HQET)

JFK & Mescia, 0802.3790
Fajfer et al., 1203.2654
Bernlochner et al., 1703.05330
Bigi et al., 1707.09509

LFU ratios can be determined very precisely

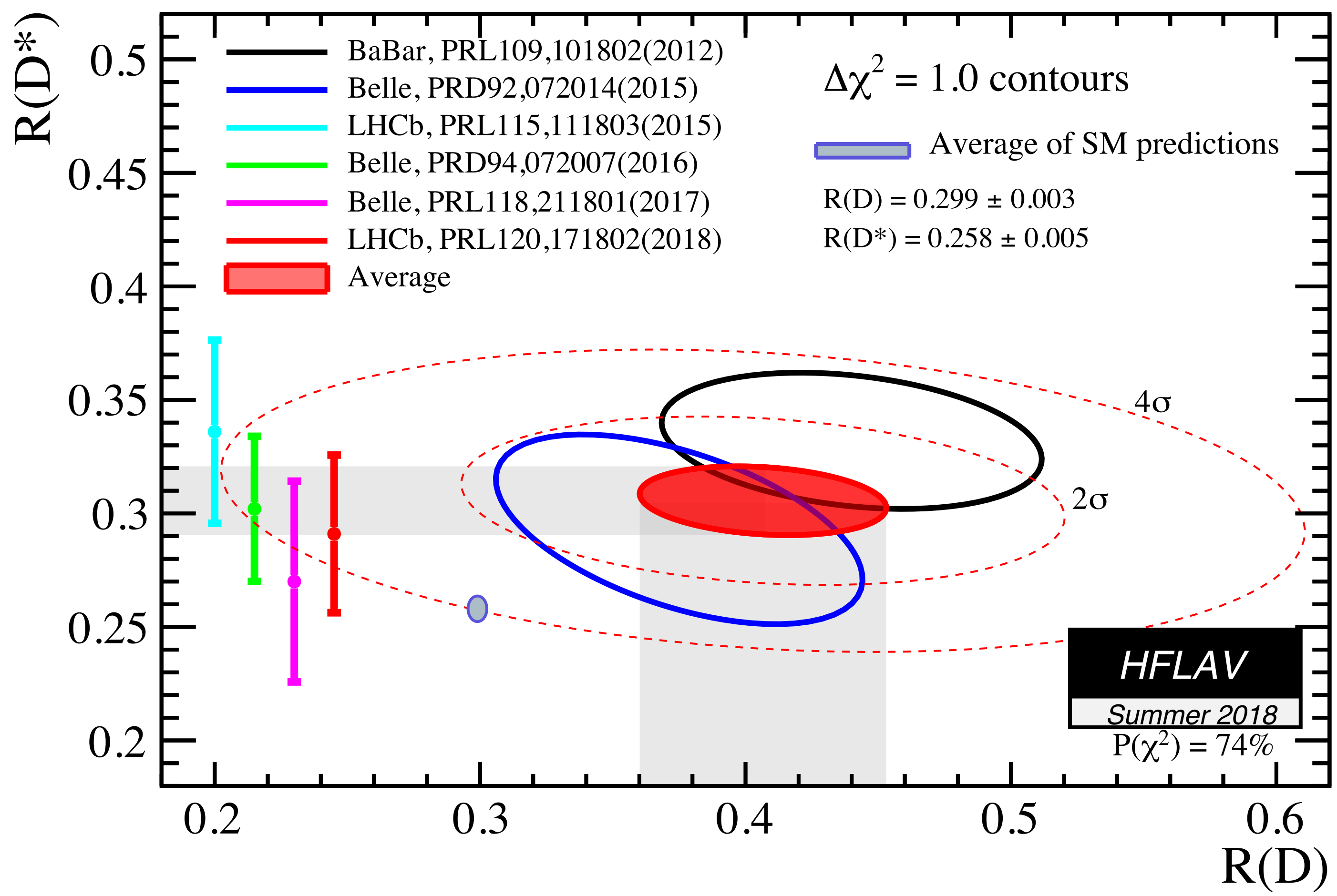
$$R(D^{(*)}) \equiv \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

*QED effects

de Boer at al., 1803.05881

Semileptonic B anomalies: LFU in charged currents

Intriguing experimental situation



$^*R(B_c \to J/\psi)$

LHCb, 1711.05623

see also talk by Capriotti

SM (subleading f.f.) uncertainties insignificant at this point

Crash course on B-Anomalies: neutral currents

Neutral-current mediated rare semileptonic B decays:

$$\frac{d^2\Gamma(B \to K^{(*)}\ell^+\ell^-)}{dq^2 d\Omega} = \frac{\alpha |V_{tb}V_{ts}|^2}{4\pi}\mathcal{N}_0 \sum_\lambda h_\lambda(\Omega) I_\lambda(q^2)$$

FCNCs - loop suppressed in SM

LD hadronic effects due to hadronic substructure of the photon not captured by local f.f.'s ($c\bar{c}$ res.)

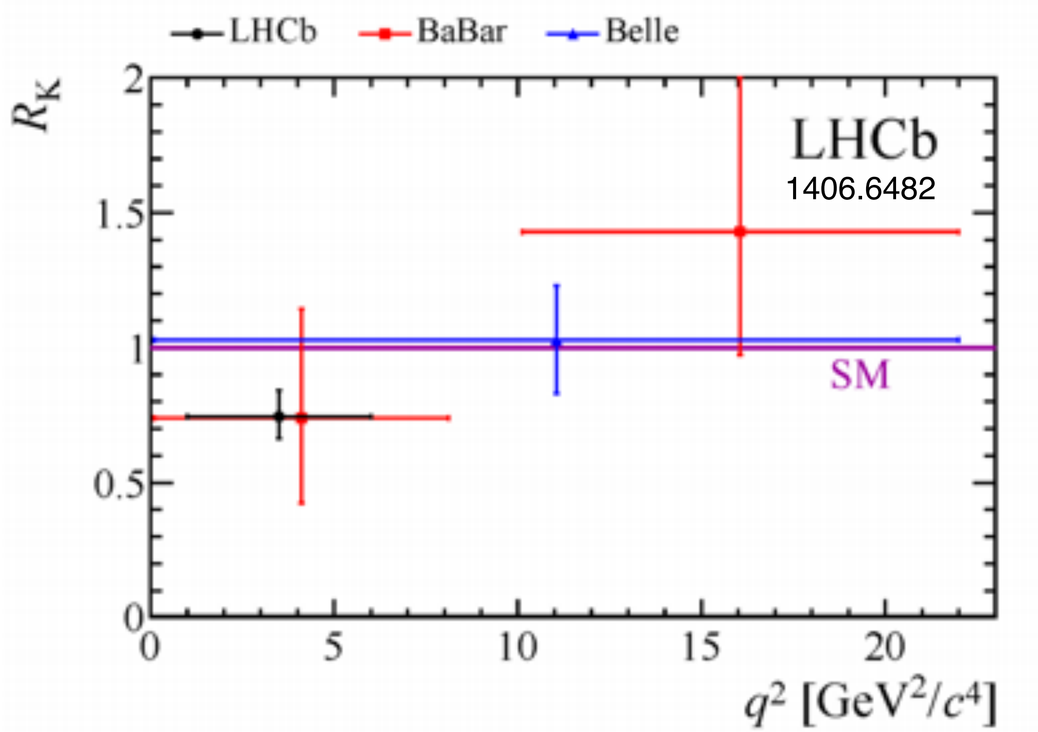
Can form th. clean LFU ratios: $$R_{K^{(*)}} \equiv \left.\frac{\Gamma(B \to K^{(*)}\mu\mu)}{\Gamma(B \to K^{(*)}ee)}\right|_{q^2_{\rm min}}^{q^2_{\rm max}}$$

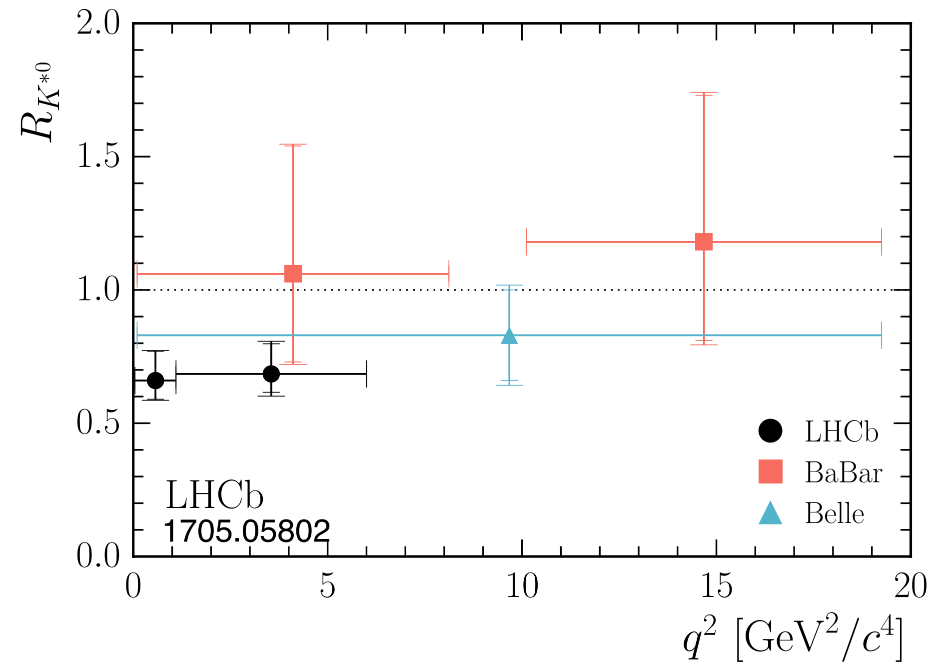
Non LFU effects tiny away from threshold $R_{K^{(*)}} = 1 + \mathcal{O}(m_\mu^2/m_B^2)$

Bordone et al., 1605.07633

Semileptonic B anomalies: neutral currents

see also talk by Capriotti

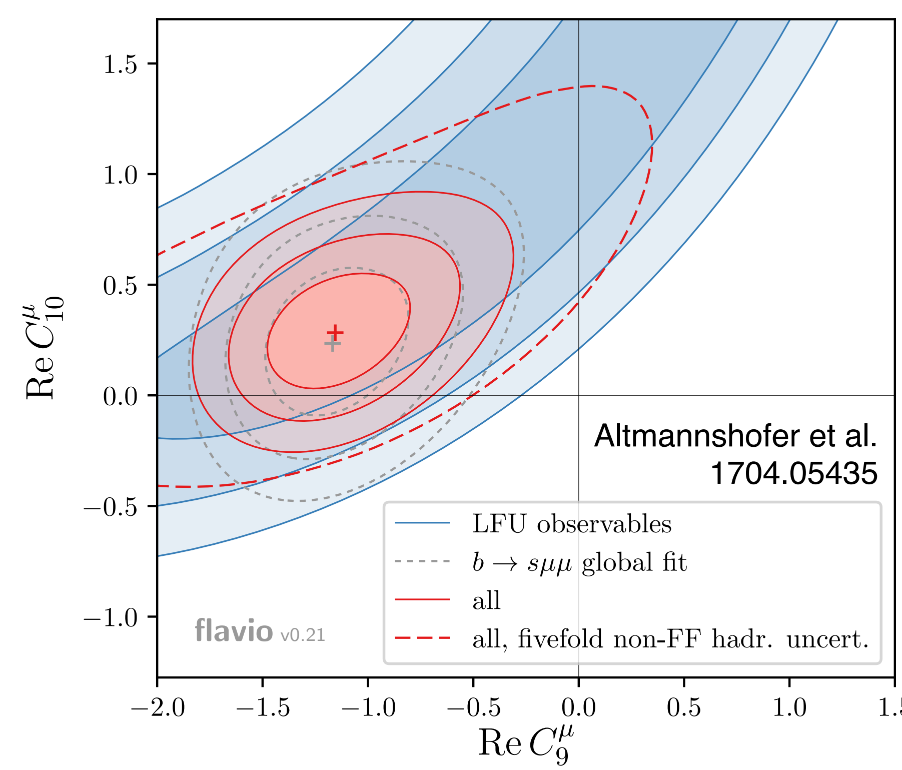




Corroborating evidence from angular analyses, rate measurements:

$$\mathcal{H}_{\text{eff}}^{\text{NP}} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_{i,\ell} (C_i^\ell O_i^\ell + C_i'^{\,\ell} O_i'^{\,\ell}) + \text{h.c.}\,,$$

$$O_9^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,,$$
$$O_{10}^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,,$$



see also
Geng et al., 1704.05446
Capdevila et al., 1704.05340

Implications for high p_T: general considerations

B-anomalies in presence of (heavy) NP:

$$\mathcal{L}_{\rm BSM} \to \mathcal{L}_{\nu{\rm SM}} + \sum_{i,(d>4)} \frac{\mathcal{Q}_i^{(d)}}{\Lambda^{d-4}}$$

Deviations in flavor ⇒ indications of NP scale

$$[\text{scale}] = \frac{[\text{mass}]}{[\text{coupling}]}$$

Unitarity/Perturbativity

⇒ upper bound on coupling

Di Luzio & Nardecchia, 1706.01868

⇒ upper bound on NP d.o.f. mass

Implications for high p_T: general considerations

LFUV in $R(D^{(*)})$: $\Lambda \simeq 2.5\,\mathrm{TeV}$

e.g. $\mathcal{Q} = (\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma_\mu P_L \nu)$

$\Rightarrow$ tree-unitarity $M_{\mathrm{NP}} \lesssim 6.5\mathrm{TeV}$

up to the edge of LHC kinematical reach

see e.g.
Altmannshofer et al., 1704.06659

LFUV in $R_{K^{(*)}}$ (& other obs.) : $\Lambda \sim 40\mathrm{TeV}$

e.g. $\mathcal{Q} = (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu P_L \mu)$

$\Rightarrow$ NP d.o.f.s accessible at LHC only if their couplings to bs and/or $\mu\mu$ suppressed!

Implications of LFUV for NP flavor breaking

NP needs to respect SM gauge symmetry

$$\mathcal{Q}_i[Q, D, U, L, E]$$

At EW scale: in terms of four-fermion operators

$$R_{K^{(*)}} \quad \boxed{\boxed{\epsilon^L_{ij}\epsilon^Q_{kl}(\bar{L}_i L_j)(\bar{Q}_k Q_l)} \quad \epsilon^E_{ij}\epsilon^Q_{kl}(\bar{E}_i E_j)(\bar{Q}_k Q_l)} \qquad \boxed{\begin{array}{c}\epsilon^{EL}_{ij}\epsilon^{QD}_{kl}(\bar{E}_i H^\dagger L_j)(\bar{Q}_k H D_l) \\ \epsilon^{LE}_{ij}\epsilon^{QU}_{kl}(\bar{L}_i H E_j)(\bar{Q}_k \tilde{H} U_l)\end{array}} \quad R(D^{(*)})$$

Buttazzo et al., 1706.07808

$$\epsilon^{L,E}_{\mu\mu},\ \epsilon^Q_{sb} \neq 0 \qquad \epsilon^{L,EL}_{\tau i},\ \epsilon^{Q,QD}_{cb} \neq 0$$

$$\epsilon^{LE}_{i\tau},\ \epsilon^{QU}_{bc} \neq 0$$

*B_c lifetime, decays
Alonso et al., 1611.06676
Akeroyd & Chen, 1708.04072

*right-handed currents
Asadi et al., 1804.04135
Greljo et al., 1804.04642
Azatov et al., 1807.10745
Robinson et al., 1807.04753

Simplest UV: Z'/W' $\qquad$ $\mathrm{LQ's}$ $\qquad$ $H^\pm$

Implications of LFUV for NP flavor breaking

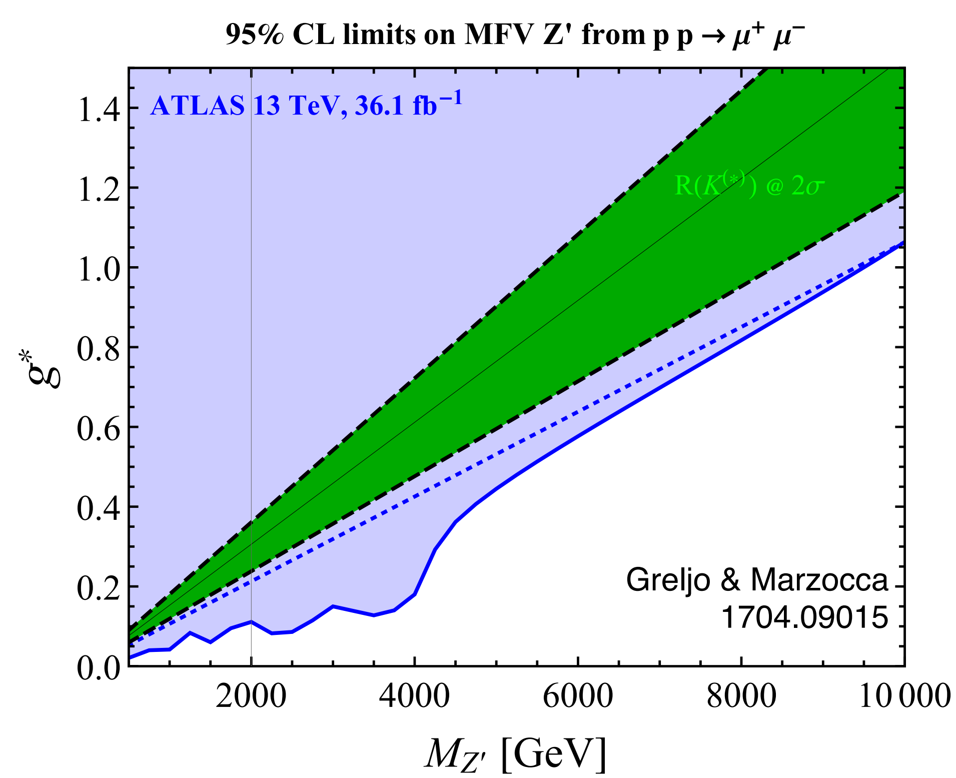
Absence of BSM LFUV, FCNCs in Kaon, Charm,Tau decays requires approximate alignment with the 3rd generation

$$\epsilon^Q_{sb} \propto V_{tb} V_{ts} \qquad \epsilon^Q_{cb} \propto V_{cb}$$

$\boxed{U(2)_F,\ \text{MFV}}$

$$\epsilon^Q_{ij} \simeq \cancel{\mathbf{1}} + \mathcal{O}(\mathbf{Y}\mathbf{Y}^\dagger)$$

Not universal! High pT di-muon searches



see also
Fajfer et al., 1206.1872
Bordone et al., 1702.07238

Immediate implications for LHC

Flavor alignment implies lower NP scale:

$$(\bar{Q}_3 Q_3)(\bar{L}_3 L_3) \to V_{cb}(\bar{c}b)(\bar{\tau}\nu)$$

$\Rightarrow \; R(D^{(*)})$ anomaly

$$\Lambda\sqrt{|V_{cb}|} \sim 500\,\mathrm{GeV}$$

Well within LHC reach!

see e.g. Abdullah et al., 1805.01869
Robinson et al., 1807.04753

$$(\bar{Q}_3 Q_3)(\bar{L}_2 L_2) \to V_{tb}V_{ts}(\bar{s}b)(\bar{\mu}\mu)$$

$\Rightarrow \; R_{K^{(*)}}$ anomaly

$$\Lambda\sqrt{|V_{ts}|} \sim 8\,\mathrm{TeV}$$

Still only marginally!

Immediate implications for LHC: $R(D^{(*)})$

Enhanced LFUV in top processes:

$$(\bar{Q}_3 Q_3)(\bar{L}_3 L_3) \to V_{cb}(\bar{c}b)(\bar{\tau}\nu) + \boxed{V_{tb}(\bar{t}b)(\bar{\tau}\nu)}$$

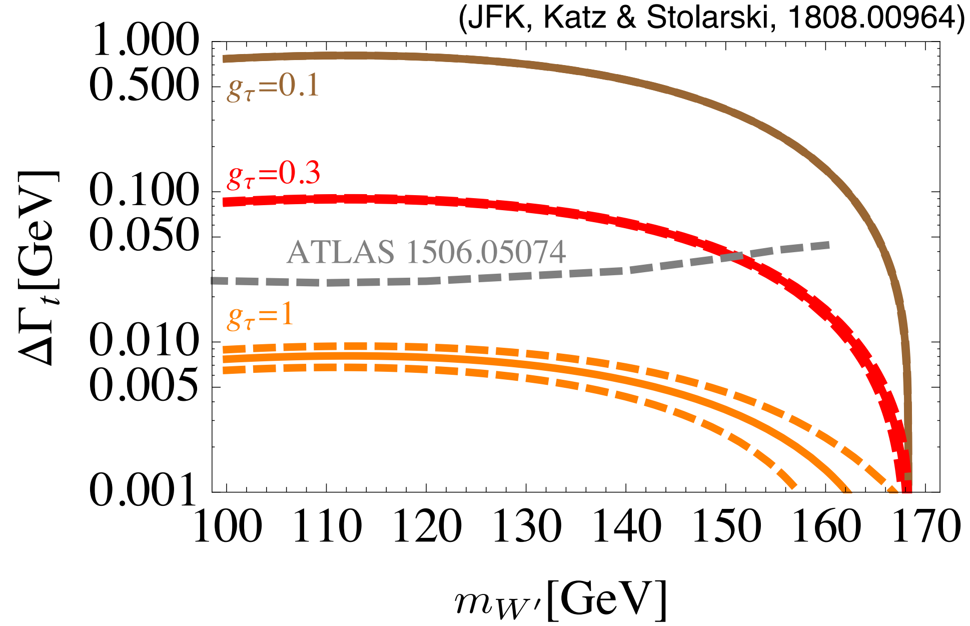
Currently tested to O(10%)

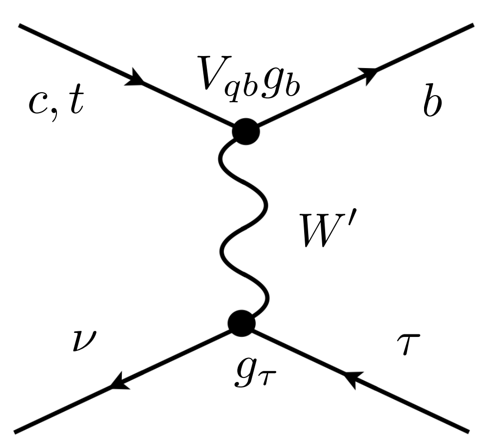
$$\mathcal{B}_e = 13.3(4)(4)\%\,,\ \mathcal{B}_\mu = 13.4(3)(5)\%\,,\ \mathcal{B}_{\tau_h} = 7.0(3)(5)\%\,,$$

ATLAS, 1506.05074

Example simplified model: charged spin-1 boson (W')

(JFK, Katz & Stolarski, 1808.00964)





LHC measurements starting to constrain $m_{W'} < m_t$ region.

Immediate implications for LHC: $R(D^{(*)})$

Enhanced LFUV in top processes:

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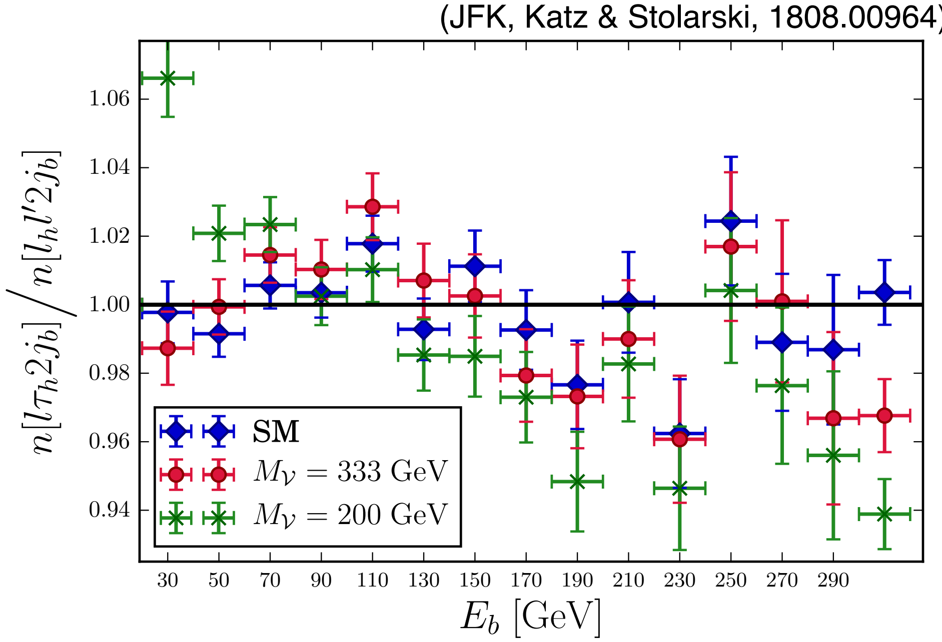


Features around the SM peak of b-jet energy distribution

$$E_b^* = \frac{m_t^2 - m_{l\nu}^2}{2m_t}$$

HL-LHC prospects for testing (sub-)percent level LFU

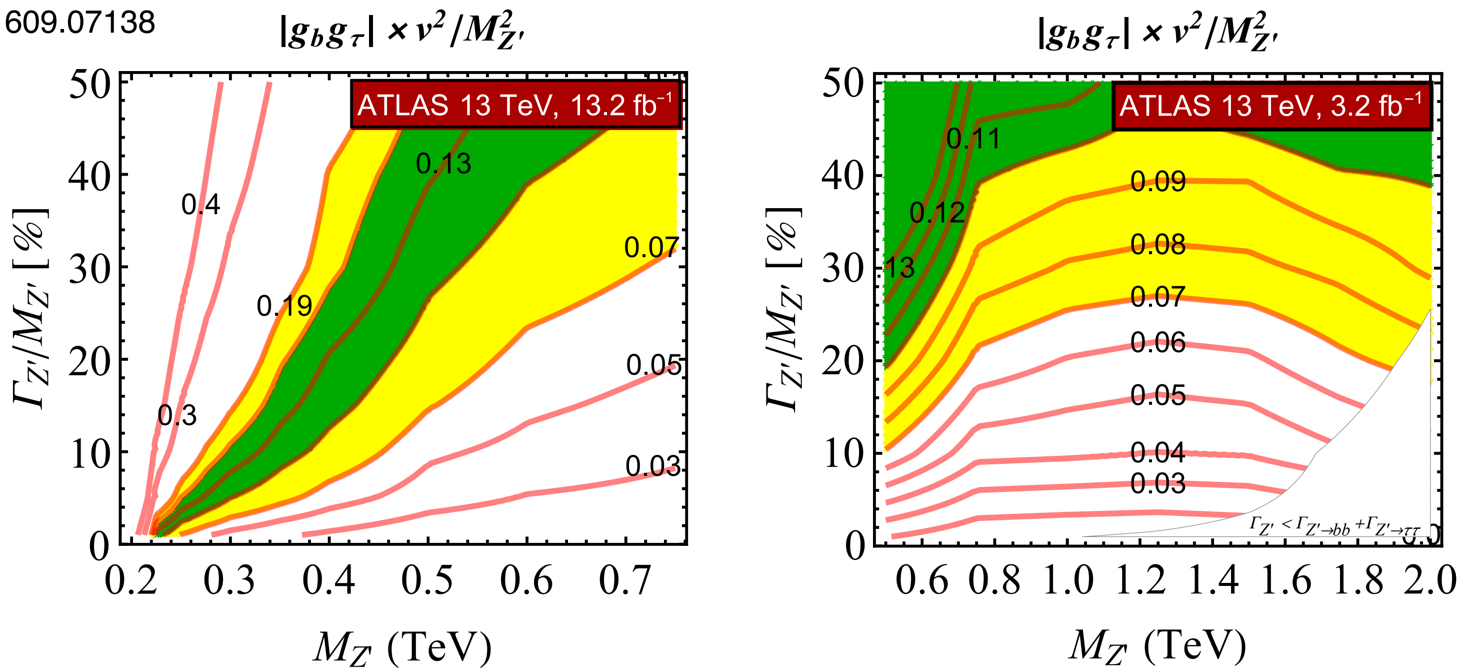
Immediate implications for LHC: $R(D^{(*)})$

Weak gauge invariance ⇒ neutral currents

$$(\bar{Q}_3 Q_3)(\bar{L}_3 L_3) \to V_{cb}(\bar{c}b)(\bar{\tau}\nu) + V_{tb}(\bar{t}b)(\bar{\tau}\nu) + \boxed{(\bar{b}b)(\bar{\tau}\tau)}$$

Constraints from existing $pp \to \tau^+\tau^-$ searches at LHC

Faroughy, Greljo & JFK, 1609.07138



W'/Z' explanation only allowed if light (M < 400 GeV) or broad (Γ/M > 20%)

Leptoquark, charged scalar explanations disfavored

Departures from strict $U(2)_F$ limit can ameliorate the bounds

see e.g.
Buttazzo et al., 1706.07808

Importance of EW radiative corrections: LFV

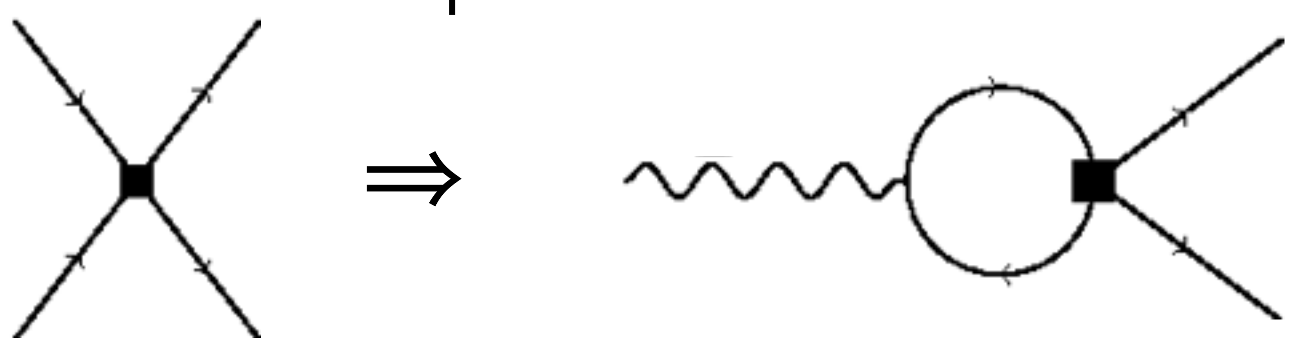
LFUV in absence of LFV:

$\boxed{\text{MLFV}}$ $\epsilon^L_{\mu i} \propto \delta_{\mu i}$ $\epsilon^L_{\tau i} \propto \delta_{\tau i}$

See e.g.
Alonso et al., 1505.05164

see also
Glashow et al., 1411.0565

Mixing of 4-fermion operators under EW RGE evolution



Feruglio et al., 1606.00524
1705.00929

Induces LFUV in decays of heavy leptons; in Z,W couplings

⇒ Severely constrains combined explanations of LFUV in charged and neutral current B decays

see also
Buttazzo et al., 1706.07808
Cornella et al., 1803.00945

⇒ Implications for UV model building (cancelations)

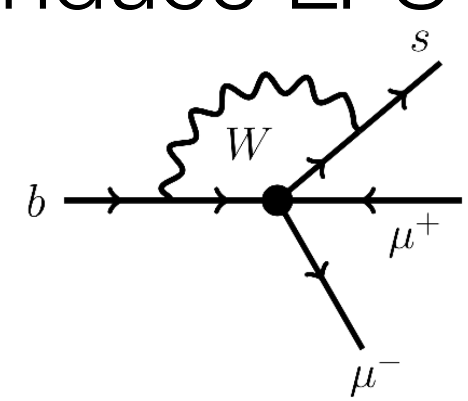
di Luzio et al., 1708.08450
Bordone et al., 1712.01368
1805.09328

Importance of EW radiative corrections:
B-anomalies without new quark flavor violation

Starting with flavor conserving non-universal operators:

$$(\bar{L}_2 L_2)(\bar{U}_3 U_3) \qquad (\bar{E}_2 E_2)(\bar{U}_3 U_3)$$

EW matching & RGE induce LFUV in rare FCNC B decays



Aebischer et al., 1512.02830
Faroughy et al., 1805.04917

see also
Blanger, Delaunay, & Westhoff, 1507.06660
Bauer et al., 1511.01900
Becirevic & Sumensari, 1704.05835

Effective NP scale now loop-suppressed: $\Lambda \frac{\sqrt{|V_{ts}|}}{4\pi} \sim 600\,\mathrm{GeV}$

⇒ automatically respects 3rd gen. alignment

⇒ d.o.f.'s mediating R_K well within LHC kinematical reach

$R_{K^{(*)}}$ without new flavor violation: a UV completion

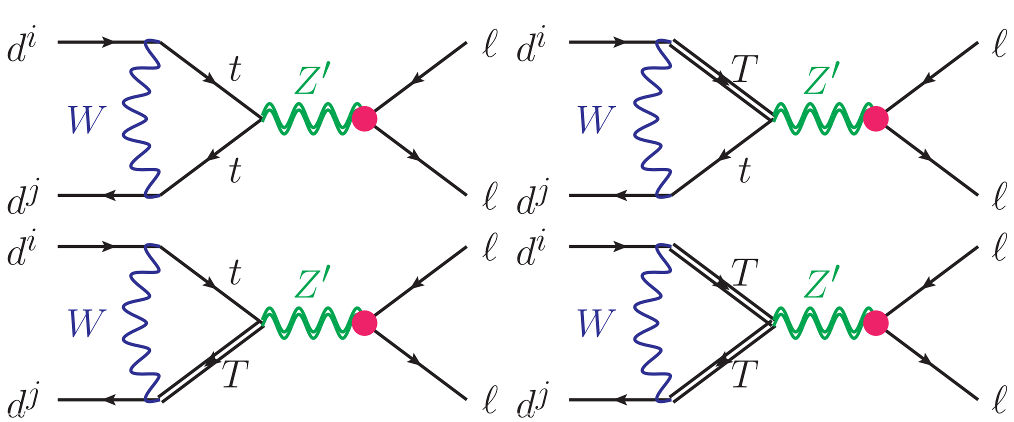
JFK, Soreq & Zupan, 1704.06005

VL quark partner of right-handed top (T),

- charged under gauged $U(1)'$ (Z', h')
- T-t_R mix after $U(1)'$ breaking - induced $U(1)'$ charge of t_R

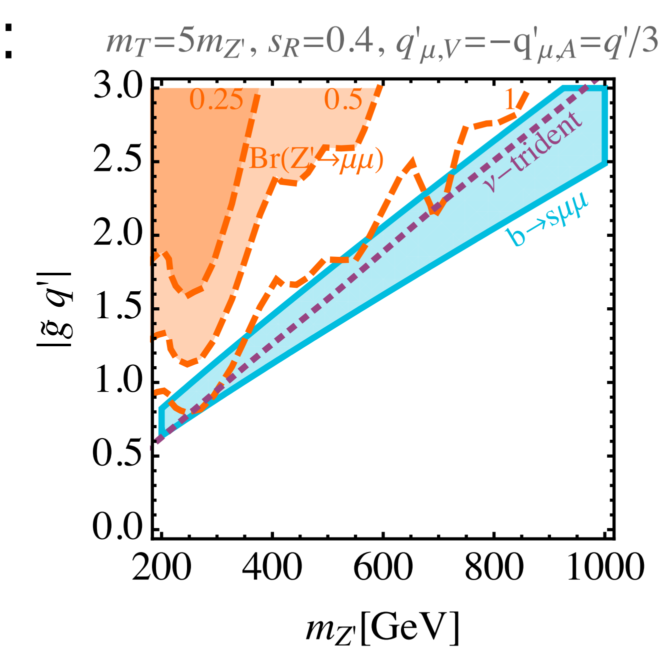
(similar mechanism possible to induce muon $U(1)'$ charge)

R$_K$ induced through W loops



Dominant signatures:

- neutrino trident
- $pp \to 4t$
  Alvarez et al., 1611.05032
- $pp \to 2\mu 2t$
  see also
  Fox et al., 1801.03505



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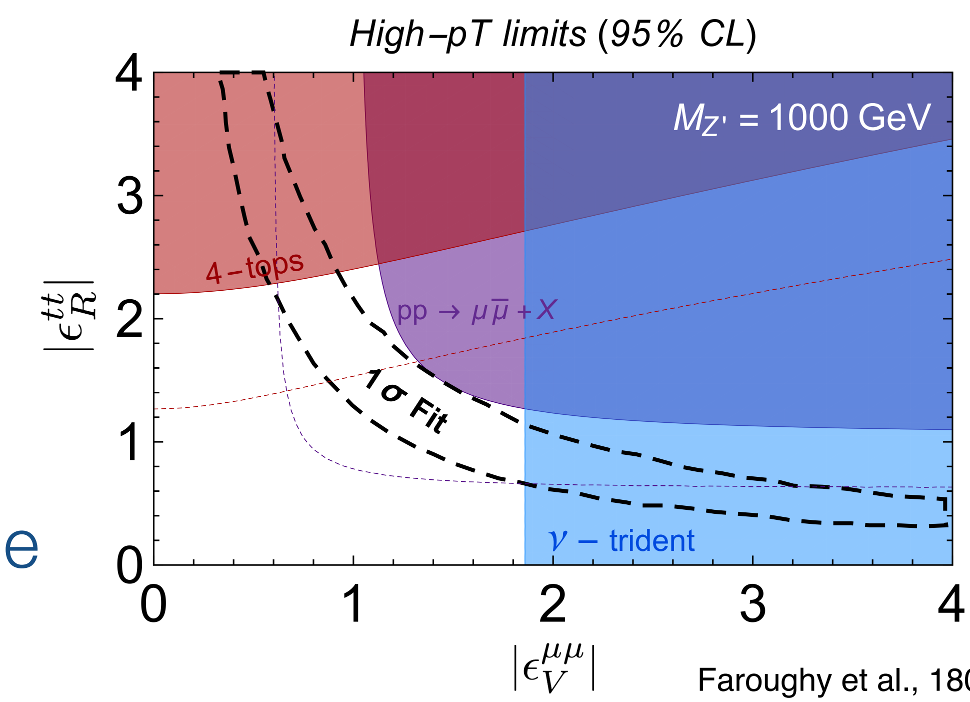
Complementary constraints:

- Flavor (LHCb, BelleII)
- LHC top & muon production
- Low energy colliders: neutrino trident

Existing experiments should confirm/exclude



Faroughy et al., 1805.04917

Conclusions

LFU tests among the theoretically cleanest probes of SM fundamentals

Imperative to resolve experimental status of current anomalies

- other B-hadron modes ($R(D_s)$, $R(\Lambda_c)$), q^2 spectra

see also talk by Capriotti

- LFU in angular observables $Q_i \equiv P_i^\mu - P_i^e$

Capdevila et al., 1605.03156

Important implications for LFV ($b \to s\tau\mu$), $b \to s\tau\tau$, $q \to q'\nu\bar{\nu}$

see e.g. Angelescu et al., 1808.08179

JFK, Monteil, Semkiv & Vale Silva, 1705.11106
Capdevilla et al., 1712.01919

JFK, Soreq & Zupan, 1704.06005
Bordone et al., 1705.10729

Conclusions

Flavor is powerful guide to high-p_T searches at LHC:

- In case of significant signals of NP in flavor observables can identify prospective LHC experimental targets

Generally, NP d.o.f.'s accommodating tentative B-anomalies could be beyond LHC reach.

Phenomenological and model-building considerations point towards more optimistic scenarios

- Low energy constraints can point to lighter mediators!
- Example of fruitful interplay between NP searches at energy and intensity frontiers

BSM penguin at high p