Interplay Between B-Anomalies and High-p_T Physics

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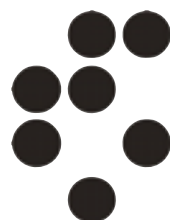
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Prelude: Lepton Flavor Universality in SM

SM gauge sector respects accidental flavor symmetry

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

LFU

*neutrino masses

Broken by Higgs Yukawas

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

$\Rightarrow$ 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
see also talk by Michele

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-curr

$$\frac{d^2}{} \qquad\qquad q^2) \qquad\qquad (\ell = e, \mu)$$

Hadronic
computed

shapes
data

*fit model dependence
Bernlochner et al., 1703.05330
Bigi et al., 1707.09509
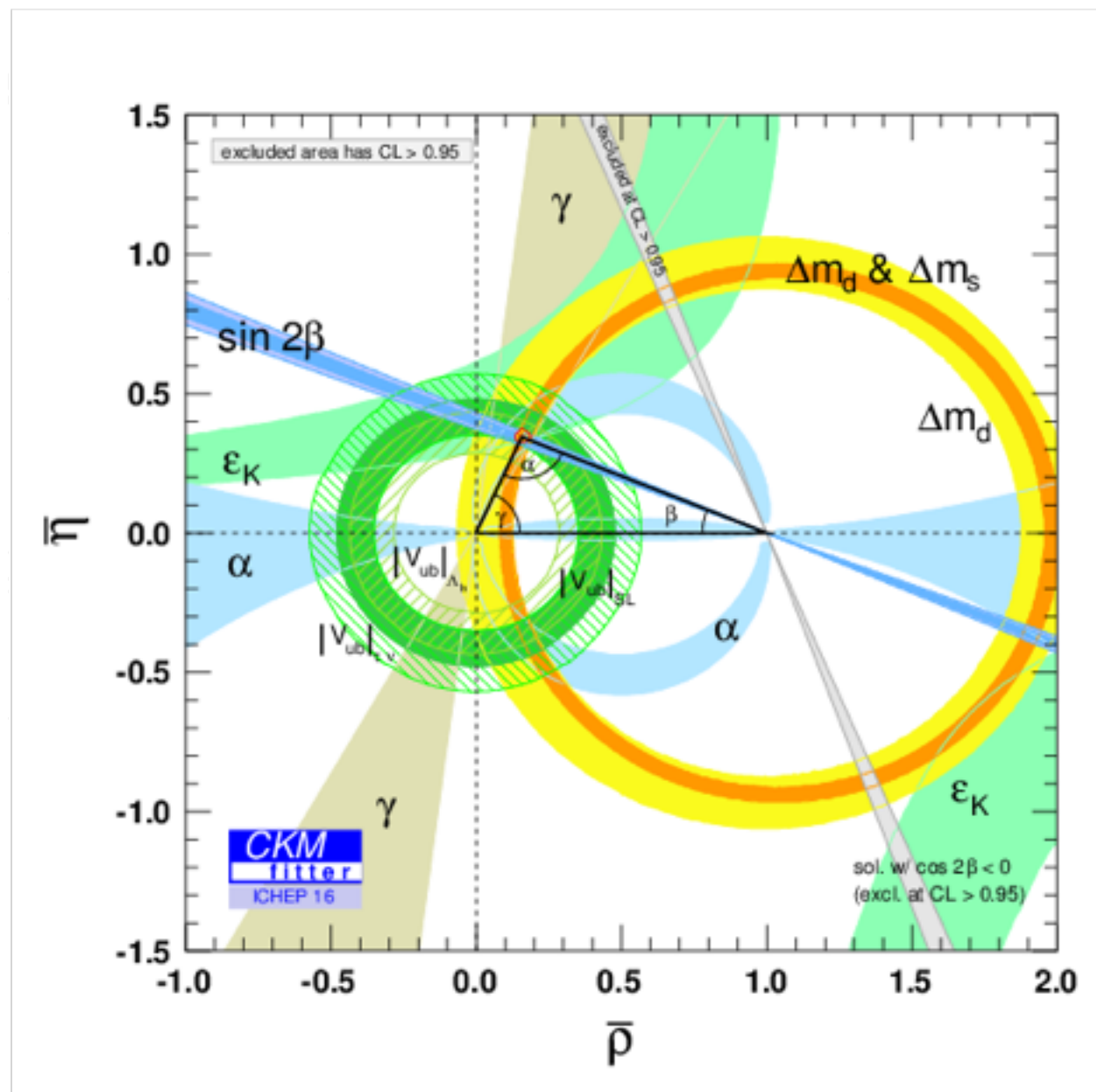see also talk by Michele

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-current semitauonic B decays:

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

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

JFK & Mescia, 0802.3790
Fajfer et al., 1203.2654
Bernlochner et al., 1703.05330
Bigi et al., 1707.09509
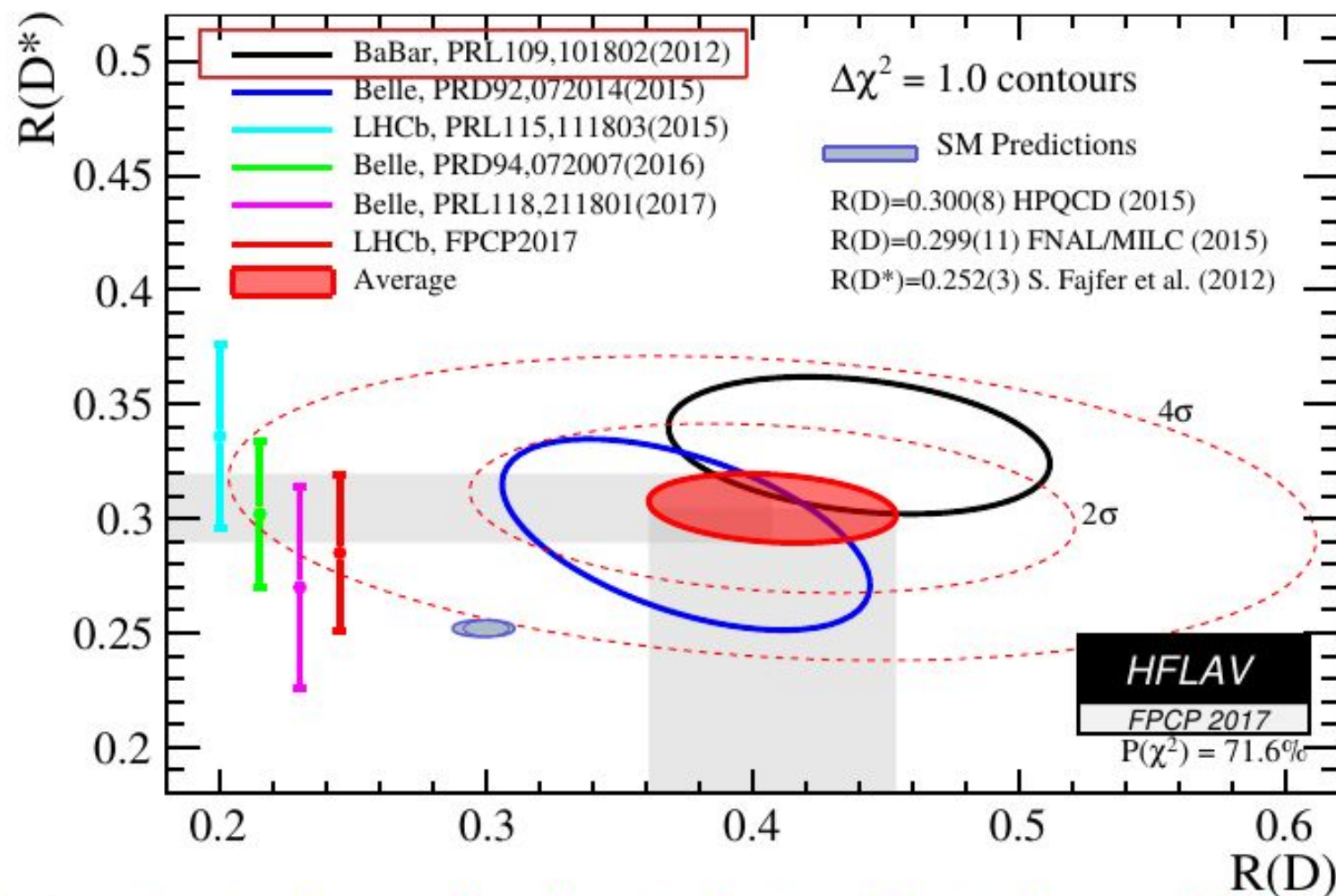see also talk by Michele

Can be systematically computed
(Lattice QCD, HQET)

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

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

Crash course on B-Anomalies: neutral currents

Neutral-current mediated rare semileptonic B decays:

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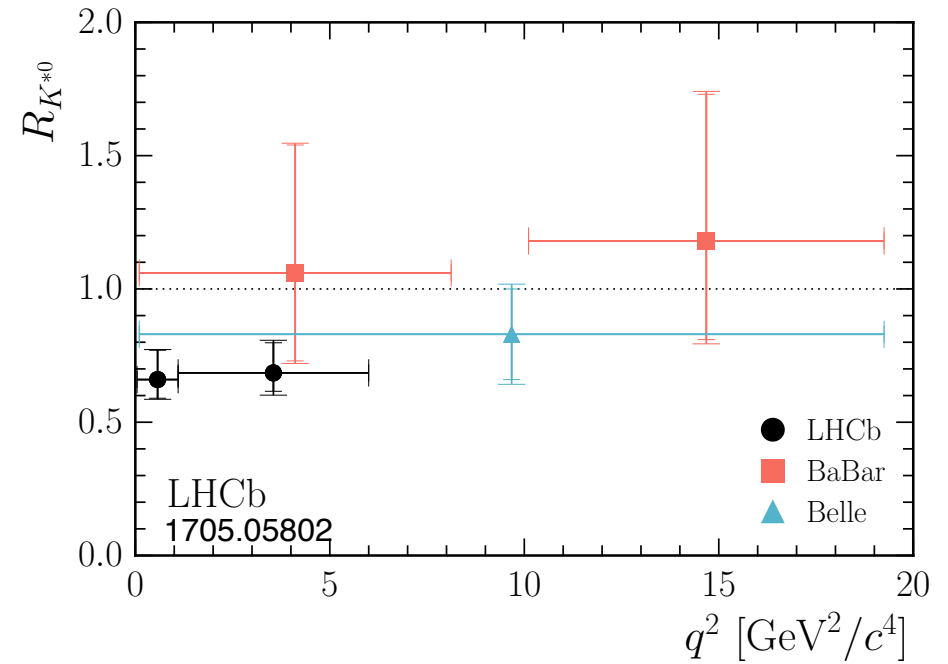
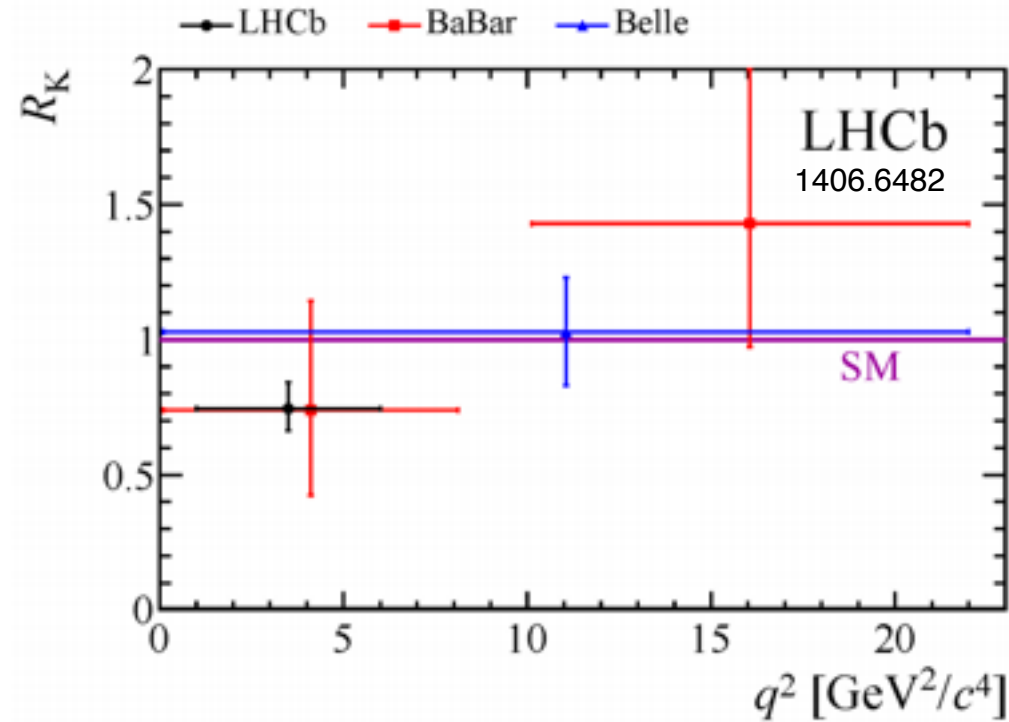FCNCs - loop suppressed in SM

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:

$$R_{K^{(*)}} \equiv \frac{\Gamma(B \to K^{(*)}\mu\mu)}{\Gamma(B \to K^{(*)}ee)}\bigg|_{q^2_{\min}}^{q^2_{\max}}$$

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

to be suppresse
dimension-six o
either by modif
change or via lo
lass of deviation
-shell Z produc
ee e.g. Ref. [13
gh energies, sca

$\sim v^-/\Lambda^-$, where $v \simeq 246$ GeV.

For these reasons we neglect them and focus on
fermion interactions which comprise four classes
ing on the chirality: $(\bar{L}L)(\bar{L}L)$, $(\bar{R}R)(\bar{R}R)$, $(\bar{R}R)($
$(\bar{L}L)(\bar{R}R)$. In particular, the relevant set of operato

Corroborating evidence
from angular analyses,
rate measurements:

$$b \to s\ell\bar{\ell}$$

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

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

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

Author Proof

$$\mathcal{L}^{\text{SMEFT}} \supset \frac{c_{Q_{ij}L_{kl}}^{(3)}}{\Lambda^2}(\bar{Q}_i\gamma_\mu\sigma_a Q_j)(\bar{L}_k\gamma^\mu\sigma_a L_l)$$

Altmannshofer et al.
1704.05435

$$+\frac{c_{Q_{ij}L_{kl}}^{(1)}}{\Lambda^2}(\bar{Q}_i\gamma_\mu Q_j)(\bar{L}_k\gamma^\mu L_l)$$

$$\frac{1}{-}(\bar{u}_i\gamma_\mu u_j)(\bar{e}_k\gamma^\mu e_l) + \frac{c_{d_{ij}L_{kl}}}{\Lambda^2}(\bar{d}_i\gamma_\mu d_j)($$

see also
Geng et al. 1704.05446
Capdevila et al., 1704.05340
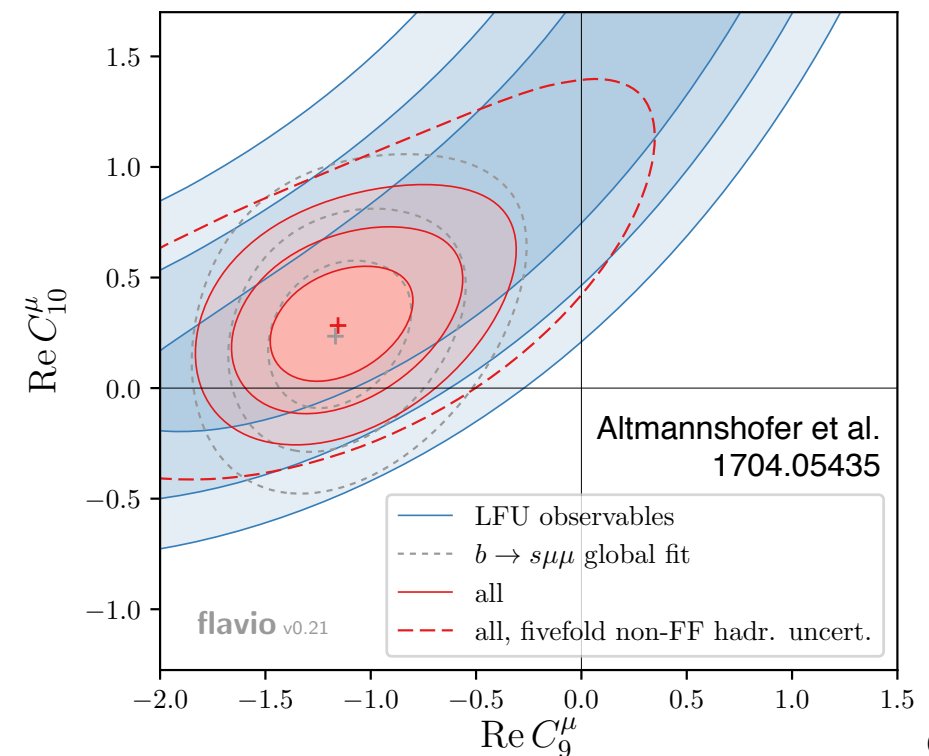
Implications for high p_T: general considerations

B-anomalies in presence of (heavy) NP:

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

Deviations in flavor $\Rightarrow$ indications of NP scale

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

Unitarity/Perturbativity

$\Rightarrow$ upper bound on coupling

Di Luzio & Nardecchia, 1706.01868

$\Rightarrow$ 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

$$R_{K^{(*)}} \quad \boxed{\begin{array}{c} \epsilon^L_{ij}\epsilon^Q_{kl}(\bar{L}_i L_j)(\bar{Q}_k Q_l) \\ \hline \epsilon^E_{ij}\epsilon^Q_{kl}(\bar{E}_i E_j)(\bar{Q}_k Q_l) \end{array}}$$

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

$$\epsilon^{L,E}_{\mu\mu}, \; \epsilon^Q_{sb} \neq 0$$

$$\epsilon^{L,EL}_{\tau i}, \; \epsilon^{Q,QD}_{cb} \neq 0$$

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

Simplest UV: $\qquad Z'/W' \qquad\qquad$ LQ's $\qquad\qquad H^\pm$
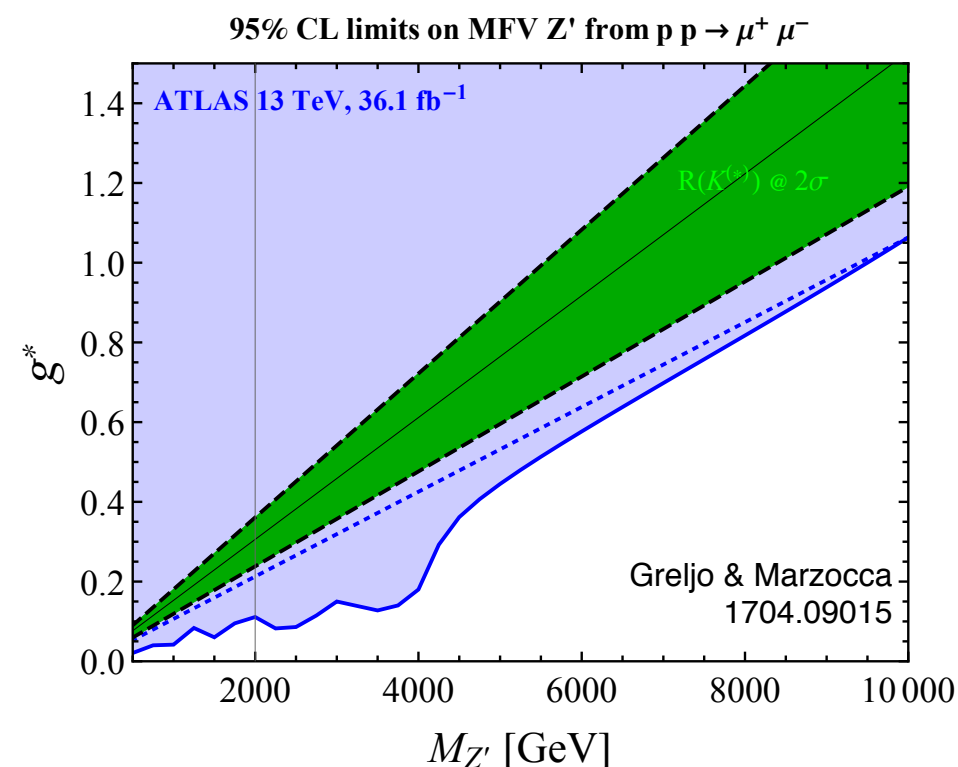
Implications of LFUV for NP flavor breaking

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

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

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

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

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

Not universal! High pT di-muon searches

95% CL limits on MFV Z' from p p → μ⁺ μ⁻

ATLAS 13 TeV, 36.1 fb⁻¹

$R(K^{(*)})$ @ 2σ

Greljo & Marzocca
1704.09015

Immediate implications for LHC

Flavor alignment implies lower NP scale:

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

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

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

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

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

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

Well within LHC reach!   Still only marginally!

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

Enhanced LFUV in top processes:

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

Vector Leptoquark (**3**,**1**,2/3)

Currently tested to O(10%)

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

ATLAS, 1506.05074

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

(JFK, Katz & Stolarski, to appear)
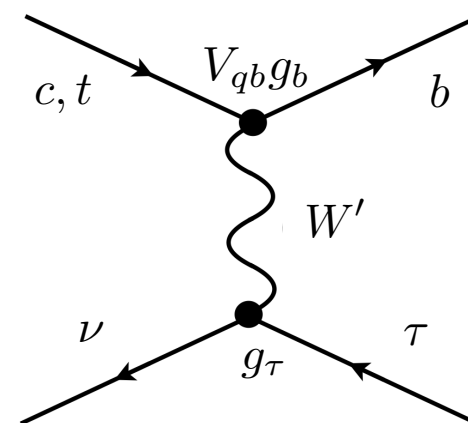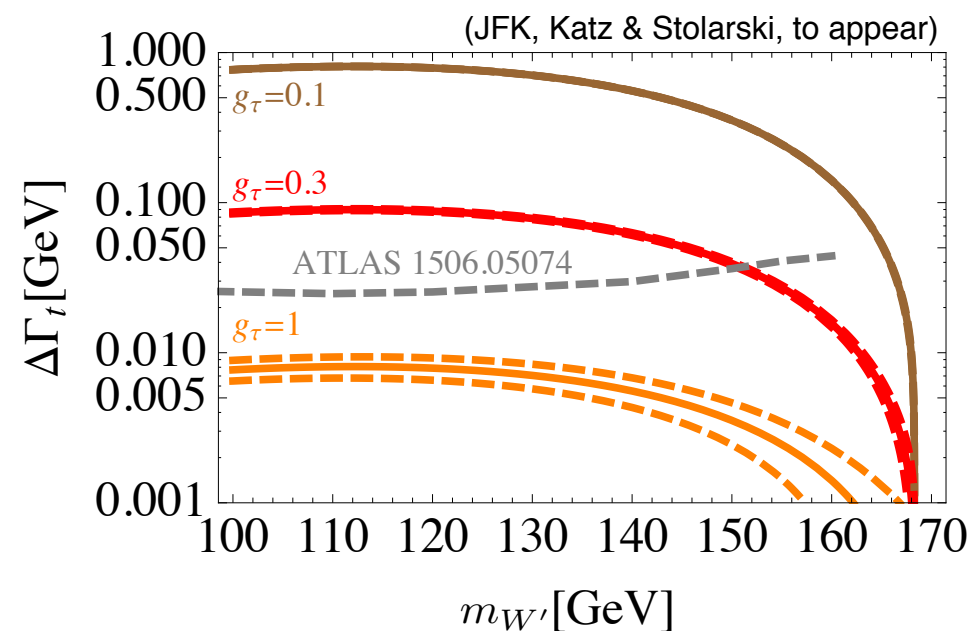
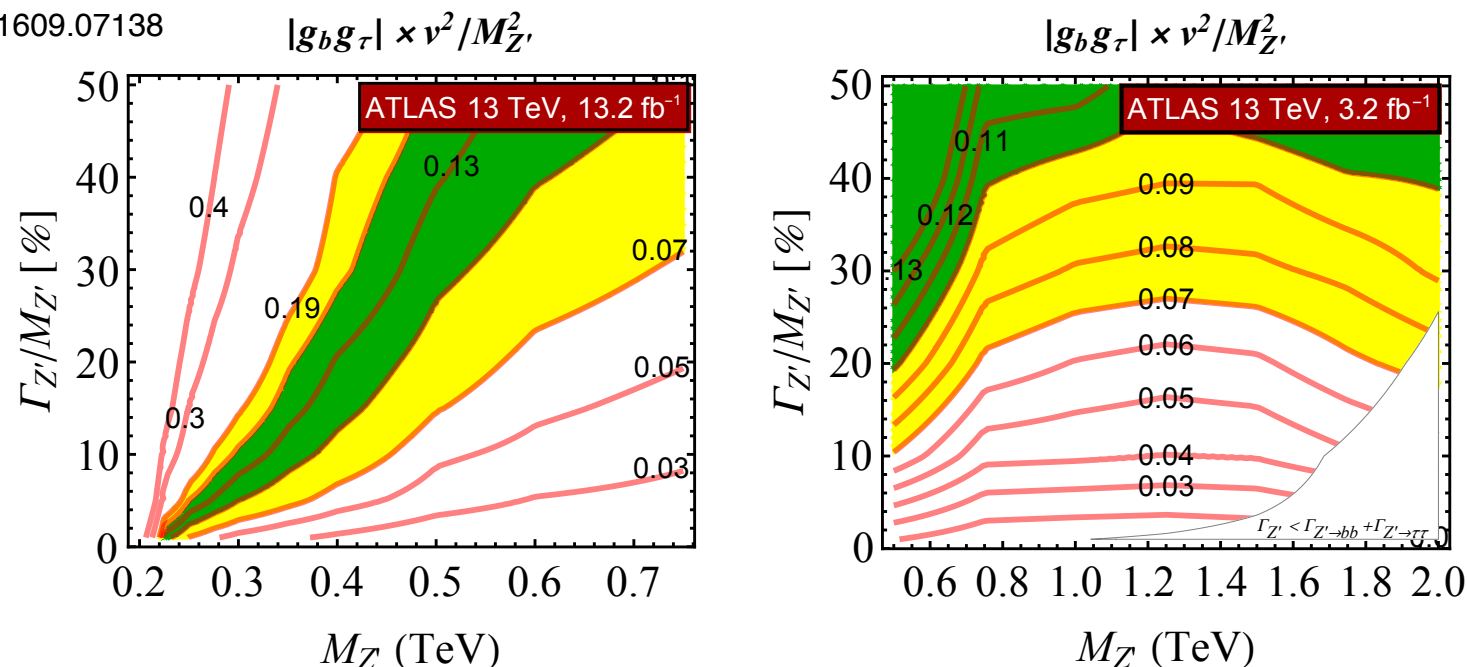LHC measurements starting to constrain $m_{W'} < m_t$ region.

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

Weak gauge invariance $\Rightarrow$ neutral currents

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

Constraints from existing $pp \rightarrow \tau^+\tau^-$ 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

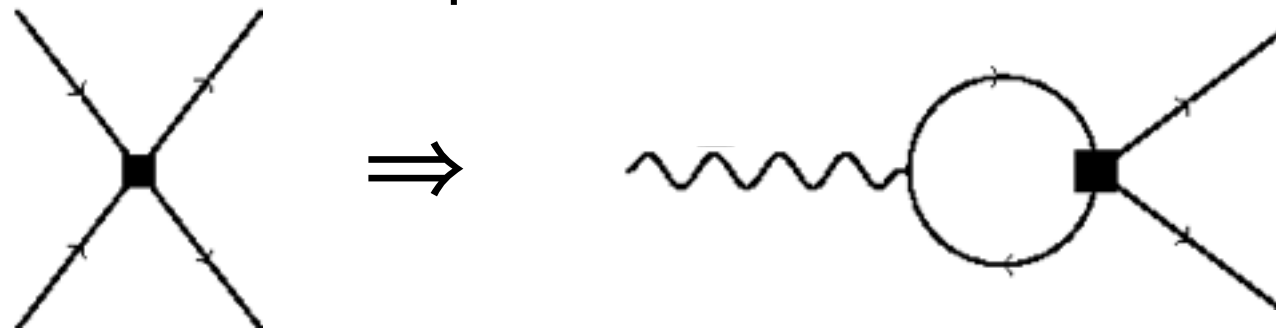# Importance of EW radiative corrections: LFV

LFUV in absence of LFV:

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

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
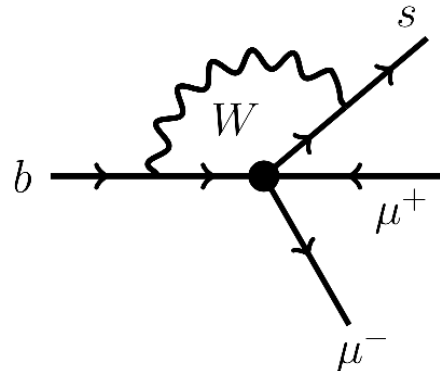
⇒ Implications for UV model building (cancelations)

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:

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

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: $\quad \Lambda \dfrac{\sqrt{|V_{ts}|}}{4\pi} \sim 600\,\mathrm{GeV}$

⇒ automatically respects 3rd gen. alignment
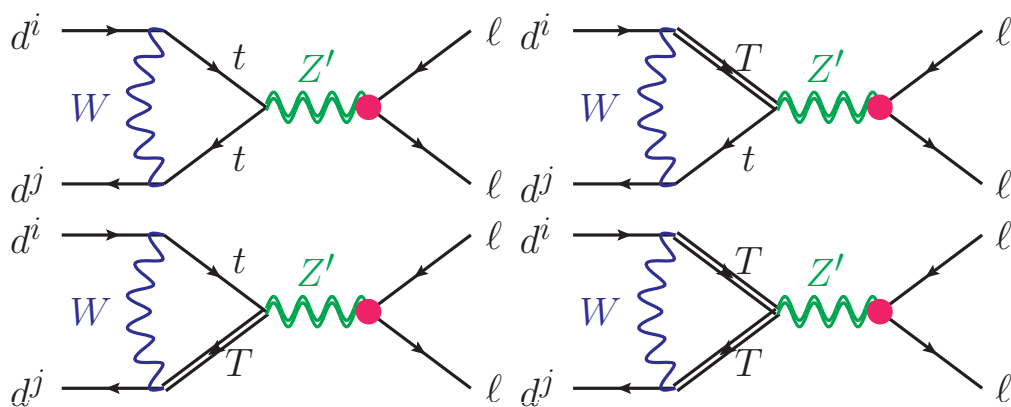
⇒ d.o.f.'s mediating R$_K$ well within LHC kinematical reach

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

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)

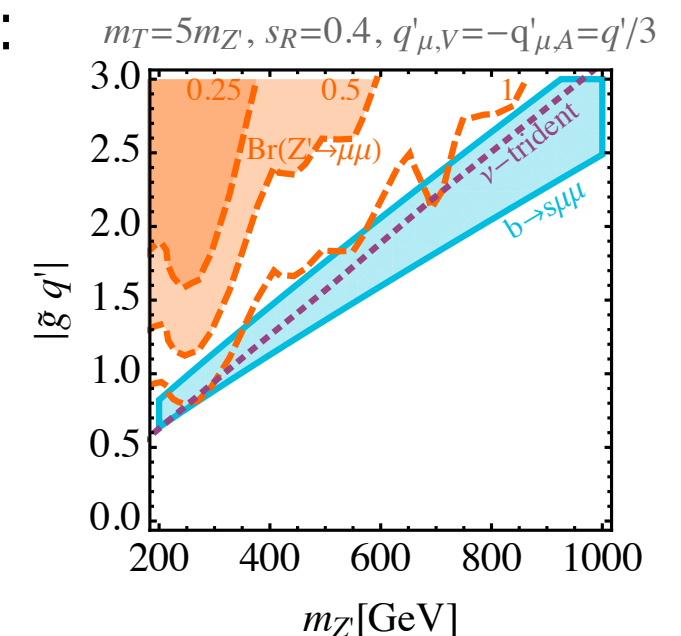R$_K$ induced through W loops

Dominant signatures:

- neutrino trident

- $pp \rightarrow 4t$
  Alvarez et al., 1611.05032

- $pp \rightarrow 2\mu 2t$
  see also
  Fox et al., 1801.03505

$m_T = 5 m_{Z'}$, $s_R = 0.4$, $q'_{\mu,V} = -q'_{\mu,A} = q'/3$

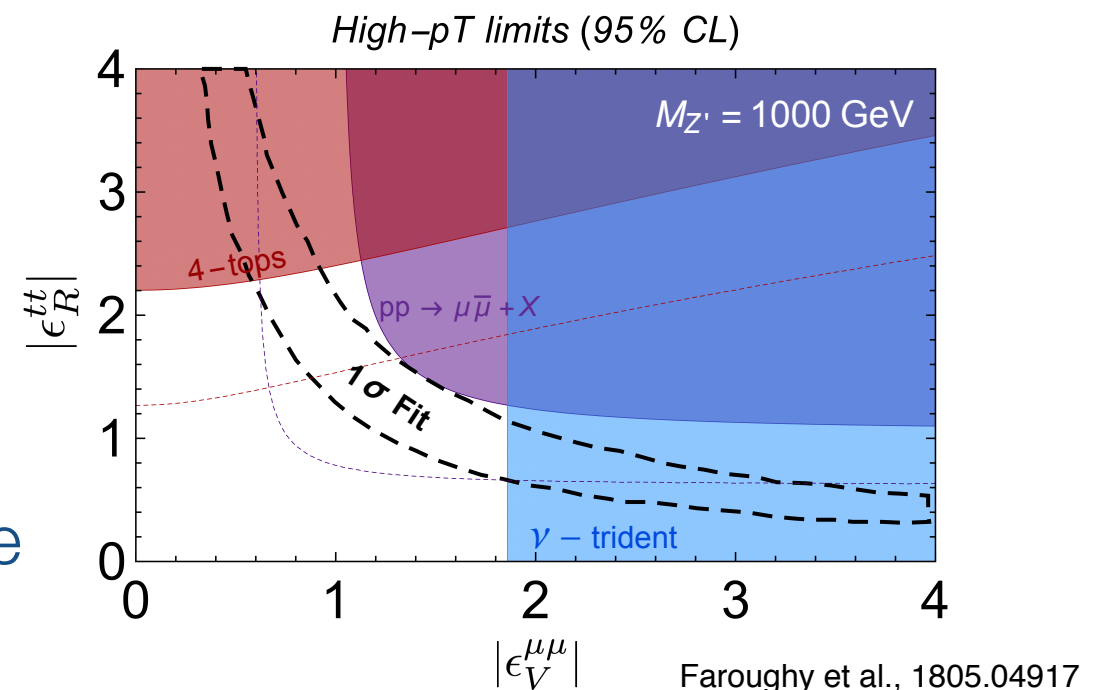# $R_{K^{(*)}}$ without new flavor violation: a UV completion

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Complementary constraints:

- Flavor (LHCb, BelleII)

- LHC top & muon production

- Low energy colliders: neutrino trident

Existing experiments should confirm/exclude

High−pT limits (95% CL)

$M_{Z'}$ = 1000 GeV

4−tops

$pp \rightarrow \mu\bar{\mu} + X$

1σ Fit

ν − trident

$|\epsilon_R^{tt}|$

$|\epsilon_V^{\mu\mu}|$

Faroughy et al., 1805.04917

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