ENIGMASS Annual Plenary Meeting, Annecy, 28 November 2018

Recent work on Flavour Physics at LAPTh

Presented by Peter Stangl

Laboratoire d'Annecy-le-Vieux
de Physique Théorique

Outline

1. Flavour in SUSY models
2. Flavour anomalies
   - Overview
   - Gauged horizontal SU(2) and $R_{K^{(*)}}$
   - Effects in Kaons from B anomalies
3. A global likelihood for analysing new physics models
4. Summary

Outline

Flavour in SUSY models

Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello, arXiv:1808.07488
Bernigaud, Herrmann, arXiv:1809.04370

Squark decays

- Important for SUSY searches at hadron colliders
- Squarks are flavoured $\rightarrow$ 3 generations, up-type, down-type
- Lightest up-type squark $\tilde{u}_1$ is lightest squark in many SUSY scenarios

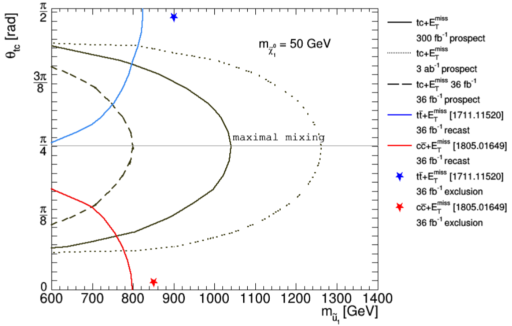
Squark flavour structure

Different options for flavour violation in squark sector:

- Only flavour violation from Standard Model CKM matrix
  - Minimal Flavour violation (MFV)
  - $\tilde{u}_1$ couples only to one quark generation
- Additional flavour violation in squark mass matrices
  - Non-Minimal Flavour violation (NMFV)
  - $\tilde{u}_1$ can couple to more than one generation, e.g. mainly to top and charm quarks

Mixed top-charm squarks at the LHC

Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello, arXiv:1808.07488



- Consider $\tilde{u}_1$ coupling to top and charm quarks
- Pair produced $pp \to \bar{\tilde{u}}_1 \tilde{u}_1$
- Existing searches for decays
  - $\bar{\tilde{u}}_1 \tilde{u}_1 \to \bar{t}t + E_T^{miss}$
  - $\bar{\tilde{u}}_1 \tilde{u}_1 \to \bar{c}c + E_T^{miss}$
- Proposed new search for $\bar{\tilde{u}}_1 \tilde{u}_1 \to \bar{t}c, \bar{c}t + E_T^{miss}$

Accessing the squark flavour structure

Assuming

Bernigaud, Herrmann, arXiv:1809.04370

- SUSY particles have been observed
- Masses have been measured for
  - Lightest up-type squark $\tilde{u}_1$
  - Lightest neutralino $\tilde{\chi}_1^0$
  - Lightest chargino $\tilde{\chi}_1^\pm$
- $\tilde{u}_1$ couples only to 2. and 3. generation quarks $\rightarrow$ $\tilde{u}_1$ is mixture of $\tilde{t}$ and $\tilde{c}$
- Ratios of branching ratios of squark $\tilde{u}_1$ have been measured:

$$R_{c/t} = \frac{BR(\tilde{u}_1 \rightarrow c\tilde{\chi}_1^0)}{BR(\tilde{u}_1 \rightarrow t\tilde{\chi}_1^0)}, \qquad R_{b/t} = \frac{BR(\tilde{u}_1 \rightarrow b\tilde{\chi}_1^+)}{BR(\tilde{u}_1 \rightarrow t\tilde{\chi}_1^0)}$$

Question: How large is amount of stop $\tilde{t}$ in lightet squark $\tilde{u}_1$?

- Quantified by stop flavour content $x_{\tilde{t}}$
- Try to infer $x_{\tilde{t}}$ from experimentally measured Observables $\mathcal{O}_i^{\text{exp}}$, $i \in \{m_{\tilde{u}_1}, m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_1^\pm}, R_{c/t}, R_{b/t}\}$

Accessing the squark flavour structure

Likelihood inference

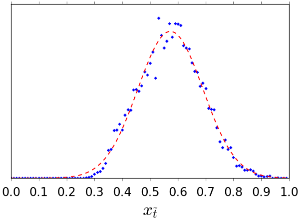
- Scanning over model parameters θ_j, calculate large set of theoretically predicted observables $\mathcal{O}_i^{\text{th}}(\theta_j), \quad i \in \{m_{\tilde{u}_1}, m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_1^\pm}, R_{c/t}, R_{b/t}\}$
- Stop flavour content $x_{\tilde{t}}$ is one of these parameters: $j \in \{x_{\tilde{t}}, \ldots\}$
- Construct likelihood for each scanned parameter point:

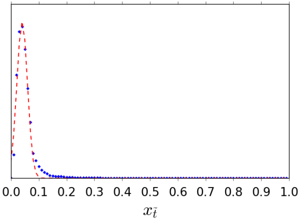
$$\ln \mathcal{L}(\theta_j) = -\frac{1}{2} \sum_i \left(\frac{\mathcal{O}_i^{\text{th}}(\theta_j) - \mathcal{O}_i^{\text{exp}}}{\sigma_i} \right)$$

- Average over likelihoods in bins of the scanned parameter $x_{\tilde{t}}$ $\to$ binned averaged likelihood $\hat{\mathcal{L}}(x_{\tilde{t}})$
- Fit Gaussian to binned likelihood $\hat{\mathcal{L}}(x_{\tilde{t}})$ to get value of $x_{\tilde{t}}$ that has highest averaged likelihood for given measured observables $\mathcal{O}_i^{\text{exp}}$

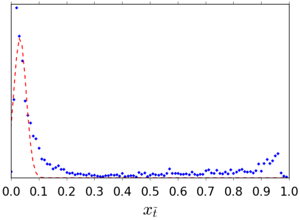
Accessing the squark flavour structure

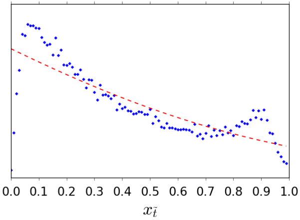
- Specific $\tilde{\chi}$ mixing





- General $\tilde{\chi}$ mixing





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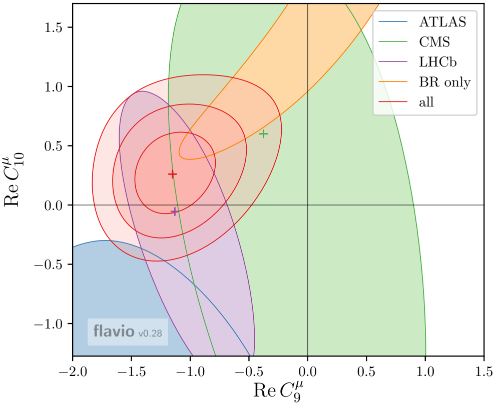
$b \to s\,\mu^+\mu^-$ anomaly

Several LHCb measurements deviate from Standard model (SM) predictions by 2-3σ:

- Angular observable P_5' in $B \to K^*\mu^+\mu^-$. LHCb, arXiv:1512.04442
- Branching ratios of $B \to K\mu^+\mu^-$, $B \to K^*\mu^+\mu^-$, and $B_s \to \phi\mu^+\mu^-$.

LHCb, arXiv:1403.8044, arXiv:1506.08777, arXiv:1606.04731

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



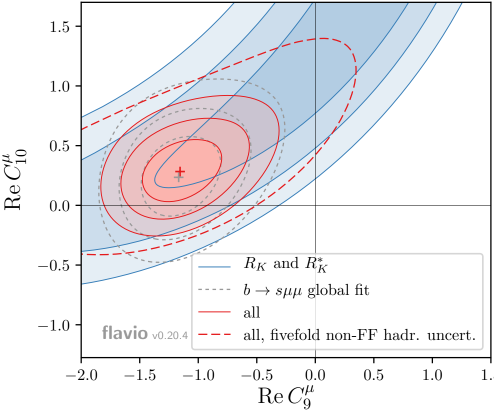
Altmannshofer, Niehoff, PS, Straub, arXiv:1703.09189

see also fits by other groups:
Capdevila et al., arXiv:1704.05340
D'Amico et al., arXiv:1704.05438
Geng et al., arXiv:1704.05446
Ciuchini et al., arXiv:1704.05447
Mahmoudi et al., arXiv:1611.05060

Hints for LFU violation in neutral current decays

Measurements of lepton flavour universality (LFU) ratios $R_K^{[1,6]}$, $R_{K^*}^{[0.045,1.1]}$, $R_{K^*}^{[1.1,6]}$ show deviations from SM by about 2.5σ each. LHCb, arXiv:1406.6482, arXiv:1705.05802

$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu^+\mu^-)}{BR(B \to K^{(*)}e^+e^-)}$$



Altmannshofer, PS, Straub, arXiv:1704.05435

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Ciuchini et al., arXiv:1704.05447

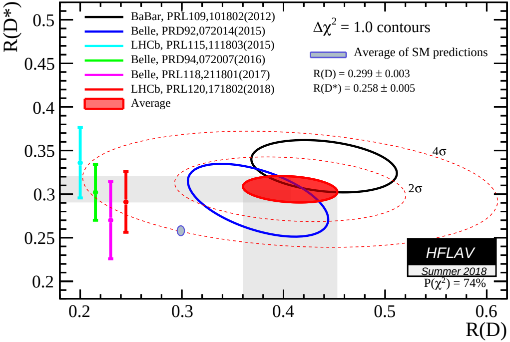
Hints for LFU violation in charged current decays

Measurements of LFU ratios R_D and R_{D^*} by BaBar, Belle, and LHCb show combined deviation from SM by 3.6-3.8σ.

BaBar, arXiv:1205.5442, arXiv:1303.0571
LHCb, arXiv:1506.08614, arXiv:1708.08856
Belle, arXiv:1507.03233, arXiv:1607.07923, arXiv:1612.00529

$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}\ell\nu)}$$

$$\ell \in \{e, \mu\}$$

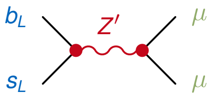


HFLAV, arXiv:1612.07233

Outline

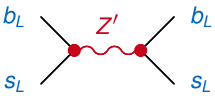
Z' solution for $R_{K^{(*)}}$ and B_s-$\bar{B}_s$ mixing

Heavy Z' vector boson can explain $R_{K^{(*)}}$ measurements



$\rightarrow$

But Z'-b_L-s_L coupling yields contribution to B_s-$\bar{B}_s$ mixing
$\rightarrow$ strong constraint!



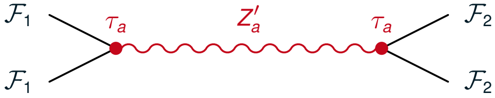
Gauged horizontal SU(2) and $R_{K^{(*)}}$

Guadagnoli, Reboud, Sumensari, arXiv:1807.03285

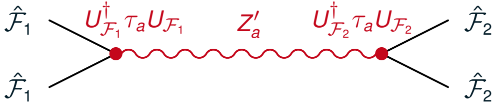
- **Idea:** instead of a single Z', use three Z's from a horizontal $SU(2)$ gauge group
- 2. and 3. generation fermions transform as doublets $\mathcal{F}$ under this $SU(2)$

$$\mathcal{F} \in \left\{ \begin{pmatrix} b \\ s \end{pmatrix}, \begin{pmatrix} \tau \\ \mu \end{pmatrix}, \ldots \right\}$$

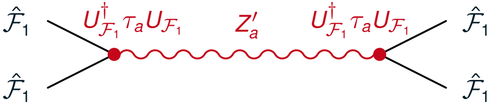
- In gauge basis, one gets diagrams like



- After rotating to mass basis with mass eigenstates $\hat{\mathcal{F}} = U^\dagger_{\mathcal{F}}\,\mathcal{F}$



Gauged horizontal SU(2) and $R_{K^{(*)}}$



Special feature of mass basis diagram if $\mathcal{F}_2 = \mathcal{F}_1$ and Z'_a masses degenerate:

- $SU(2)$ symmetry can be used to make couplings flavour diagonal!
- No contribution to B_s-$\bar{B}_s$ mixing at tree level since $\mathcal{F}_{(b,s)}$ on both sides
- Flavour violation to get $bs\mu\mu$ still possible since $\mathcal{F}_{(b,s)} \neq \mathcal{F}_{(\mu,\tau)}$

Model still constrained by other observables, but strong constraints from B_s-$\bar{B}_s$ are avoided

Outline

Effects in Kaons from B anomalies

Borsato, Gligorov, Guadagnoli, Santos, Sumensari, arXiv:1808.02006

- Assume B meson anomalies are explained by purely left-handed operator

$$\lambda^q_{ij}\,\lambda^\ell_{mn}\left(\bar{d}^i_L\,\gamma^\alpha\,d^j_L\right)\left(\bar{\ell}^m_L\,\gamma_\alpha\ell^n_L\right)$$

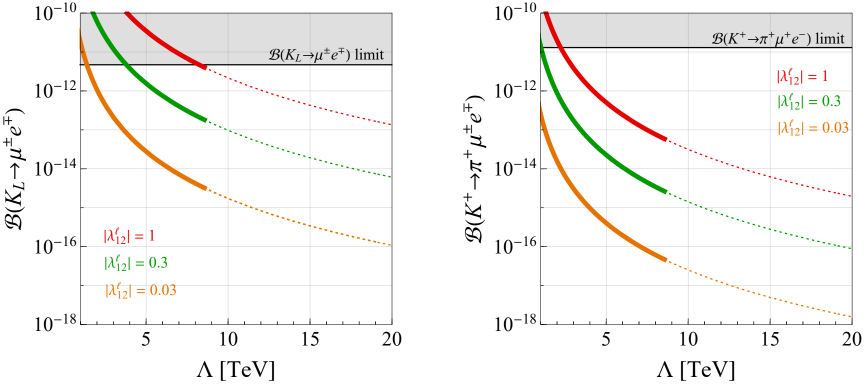
- Well-motivated case that can explain anomalies is if quark couplings are proportional to CKM elements:

$$\lambda^q_{ij} \propto V^*_{ti}V_{tj}$$

- This yields effects in Kaon decays from

$$\lambda^q_{sd} \propto V^*_{ts}V_{td}$$

Effects in Kaons from B anomalies



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Analysing a model

- Compute *all relevant* observables $\vec{O}$ (flavour, EWPO, ...) in terms of Lagrangian parameters $\vec{\theta}$

$$\mathcal{L}_{\rm NP}(\vec{\theta}) \to \vec{O}(\vec{\theta})$$

- Take into account loop / RGE effects

$$\mathcal{L}_{\rm NP}(\vec{\theta}) \xrightarrow{\Lambda_{\rm NP} \to \Lambda_{\rm IR}} \vec{O}(\vec{\theta})$$

- Compare to experiment

$$\vec{O}(\vec{\theta}) \to \underbrace{L(\vec{O}(\vec{\theta}), \vec{O}_{\rm exp})}_{\text{Likelihood}}$$

Tedious to do this for each model...

Analysing a model

- Assuming $\Lambda_{\text{NP}} \gg v$, NP effects in flavour, EWPO, Higgs, top,. . . can be expressed in terms of SMEFT Wilson coefficients

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{n>4} \sum_{i} \frac{c_i}{\Lambda^{n-4}} O_i$$

Buchmuller, Wyler, Nucl. Phys. B 268 (1986) 621
Grzadkowski, Iskrzynski, Misiak, Rosiek, arXiv:1008.4884

- Powerful tool to connect model-building to phenomenology without needing to recompute hundreds of observables in each model
  - Model building:

$$\mathcal{L}_{\text{NP}}(\vec{\theta}) \to \vec{C}(\vec{\theta}) \;\; @ \;\; \Lambda_{\text{NP}}$$

  - *Model-independent* pheno:

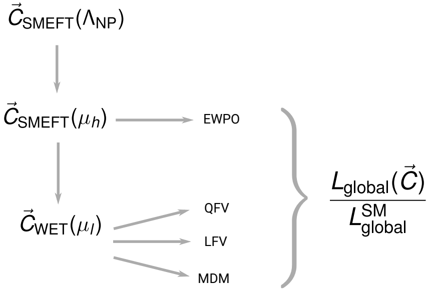
$$\vec{C} \xrightarrow{\Lambda_{\text{NP}} \to \Lambda_{\text{IR}}} \vec{O}(\vec{C}) \to L(\vec{O}(\vec{C}), \vec{O}_{\text{exp}})$$

Building a global SMEFT likelihood

Aebischer, Kumar, PS, Straub, arXiv:1810.07698

- Based on the tools
  - **flavio** for computing observables — Straub, arXiv:1810.08132
  - **wilson** for RG running and matching — Aebischer, Kumar, Straub, arXiv:1804.05033
- We have started building the **SM**EFT **L**ike**LI**hood
  - **smelli** `https://github.com/smelli`

- So far, 257 observables included
  - Rare B decays
  - Semi-leptonic B and K decays
  - Meson-antimeson mixing
  - FCNC K decays
  - (LFV) tau and muon decays
  - Z and W pole EWPOs
  - $g-2$



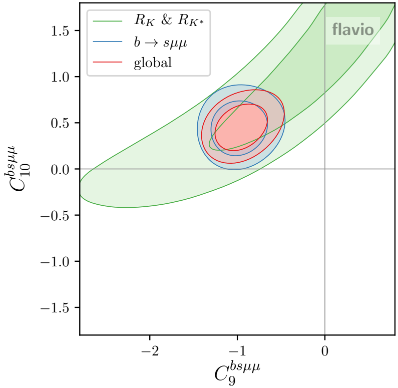
Outline

Summary

- Squarks with NMFV flavour structure have interesting phenomenology that could be probed by the LHC if SUSY is discovered
- Flavour anomalies hint at new physics that violates lepton flavour universality
- Explanation of anomalies in rare B decays by gauged horizontal symmetry could avoid stringent constraints from B_s-$\bar{B}_s$ mixing
- Anomalies in B decays could imply new effects in Kaon decays
- New global likelihood in SMEFT can be used to analyse models using more than 250 flavour and other precision observables

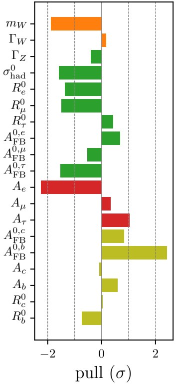
Backup slides

Likelihood maps: $b \to s\ell\ell$ anomalies



- Since *B* phyiscs constraints are included in the likelihood, the usual $b \to s\ell\ell$ Wilson coefficient are one example application (using WET WCs here)
- Disclaimer: this and the following two-coefficient plots are only meant for illustration – main point of the global likelihood is to *not* be restricted to 2D subspaces

Electroweak precision tests



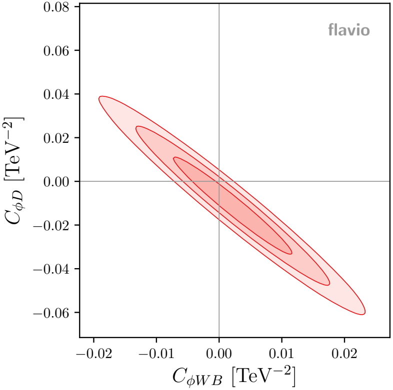
- We have implemented all the relevant Z and W pole observables, not assuming LFU, in `flavio`

  Efrati, Falkowski, Soreq, arXiv:1503.07872
  Brivio, Trott, arXiv:1706.08945

- SM pulls in good agreement e.g. with Gfitter

  Baak et al., arXiv:1407.3792

Oblique parameters

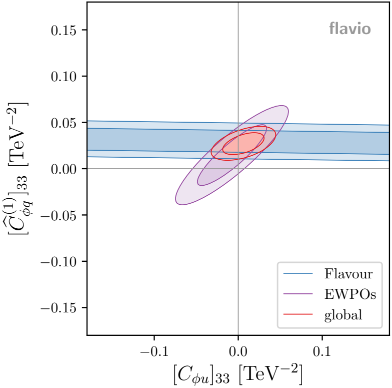


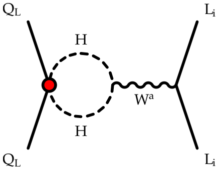
- Reproducing the EWPO constraint on the electrowewak S and T parameters

$$S \propto C_{\phi WB}, \quad T \propto -C_{\phi D}$$

$$O_{\phi D} = \left(\phi^\dagger D^\mu \phi\right)^* \left(\phi^\dagger D_\mu \phi\right)$$
$$O_{\phi WB} = \phi^\dagger \tau^I \phi W^I_{\mu\nu} B^{\mu\nu}$$

EWPT vs. *B* constraints on modified *t* couplings

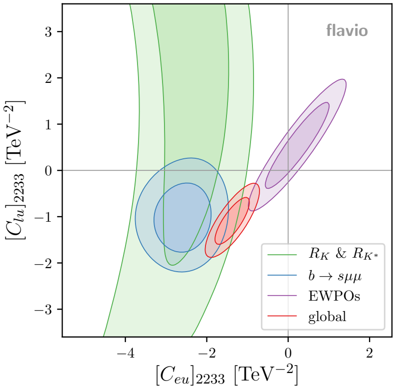


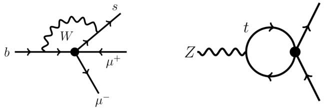


- Modfications of LH vs. RH $Zt\bar{t}$ couplings (in basis where up-type quark mass matrix is diagonal)
- Complementarity between flavour ($B_s \to \mu^+\mu^-$) and EW ($Z \to b\bar{b}$, T) constraints

  Brod, Greljo, Stamou, Uttayarat, arXiv:1408.0792
- Plot: WC at 1 TeV, up-aligned basis

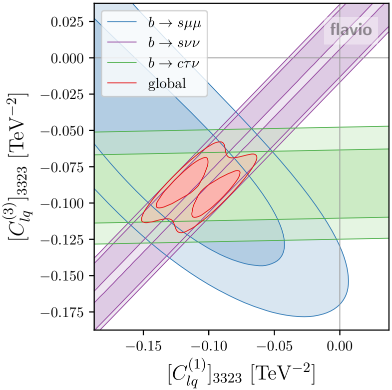
B anomalies from NP in top





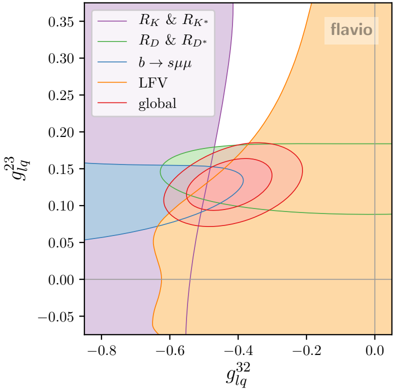
- $[C_{eu}]_{2233}$, i.e. RH $tt\mu\mu$ operator, suggested as solution to $b \to s\ell\ell$ anomalies in Celis et al., arXiv:1704.05672
  - see Z' model in Kamenik et al., arXiv:1704.06005
- Later realized that there are strong constraints from $Z \to \mu\mu$ Camargo-Molina, Celis, Faroughy, arXiv:1805.04917
- Plot: WC at 1 TeV

LLLL solutions to B anomalies



- Using models that generate $C_{lq}^{(3)}$ with flavour $\tau\tau sb$ are prime candidates to explain $R_{D^{(*)}}$
- Strong constraint from bounds on $B \to K\nu\nu$ probing $b \to s\nu_\tau\bar{\nu}_\tau$ unless $C_{lq}^{(1)} \approx C_{lq}^{(3)}$ Buras et al., arXiv:1409.4557
- Radiatevely induced lepton flavour *universal* conntribution to $b \to s\mu\mu$ and thus also explain $B \to K^*\mu\mu$ anomalies Bobeth, Haisch, arXiv:1109.1826 Crivellin, Greub, Müller, Saturnino, arXiv:1807.02068
- (Explaining $R_{K^{(*)}}$ possible by directly coupling to muons)
- Plot: WC at 1 TeV

Vector leptoquark (U_1) solution to B anomalies



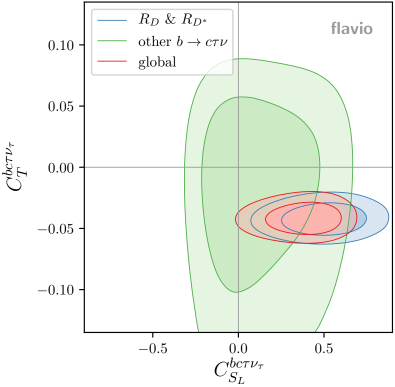
- Suggested in Barbieri et al., arXiv:1512.01560
- Does not generate $B \to K\nu\nu$ at tree level
  Buras, Girrbach-Noe, Niehoff, Straub, arXiv:1409.4557
- Couplings:

$$\mathcal{L}_{U_1} \supset g_{lq}^{ij} \left(\bar{l}_L^i \gamma^\mu q_L^j\right) U_\mu + \text{h.c.}$$

  - $b \to s\mu\mu$ requires $g_{lq}^{22} g_{lq}^{23*}$
  - $b \to c\tau\nu$ requires $g_{lq}^{32} g_{lq}^{33*}$
  - $\tau \to \phi\mu$ constrains $g_{lq}^{32} g_{lq}^{22*}$

$m_{U_1} = 1$ TeV $\quad g_{lq}^{33} = 1 \quad g_{lq}^{22} = 0.04^2 \approx V_{cb}^2$

Scalar and tensor operator explanation of $R_{D^{(*)}}$



- This combination is generated with $C_{S_L}^{bc\tau\nu_\tau} = -4C_T^{bc\tau\nu_\tau}$ at matching scale by S_1 leptoquark
  Becirevic, Sumensari, arXiv:1704.05835
- New result:
  second, disjoint solution with large tensor Wilson coefficient excluded by new, preliminary Belle measurement of longitudinal polarization fraction F_L in $B \to D^* \tau\nu$ Nishida, Talk given at CKM 2018