Building models for B physics anomalies

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based on work with A. Greljo, G. Isidori, D. Marzocca

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Introduction

$$\mathcal{L} \sim \Lambda^2 |H|^2 + \sum_i \lambda_i \mathcal{O}_i^{(4)} + \frac{1}{\Lambda^2} \sum_i c_i \mathcal{O}_i^{(6)} + \cdots$$

Naturalness of EW scale

$$\Lambda \lesssim 1\,\mathrm{TeV}$$

Flavour constraints

$$\Lambda \gg \mathrm{TeV}$$

- low Λ, small c's: flavour problem
- high Λ, c's ~ O(1): hierarchy problem

Pre-LHC:

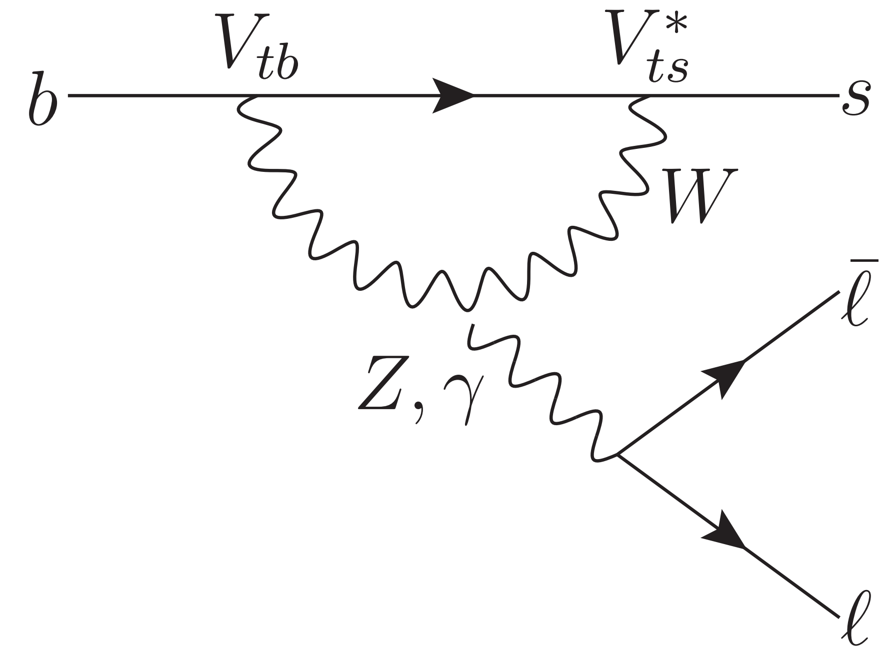
- exciting phenomena in high-pT experiments: ATLAS, CMS
- boring flavour physics (MFV)

Post-LHC:

- no light on-shell resonances
- very interesting anomalies in flavour observables

Semi-leptonic b to s decays

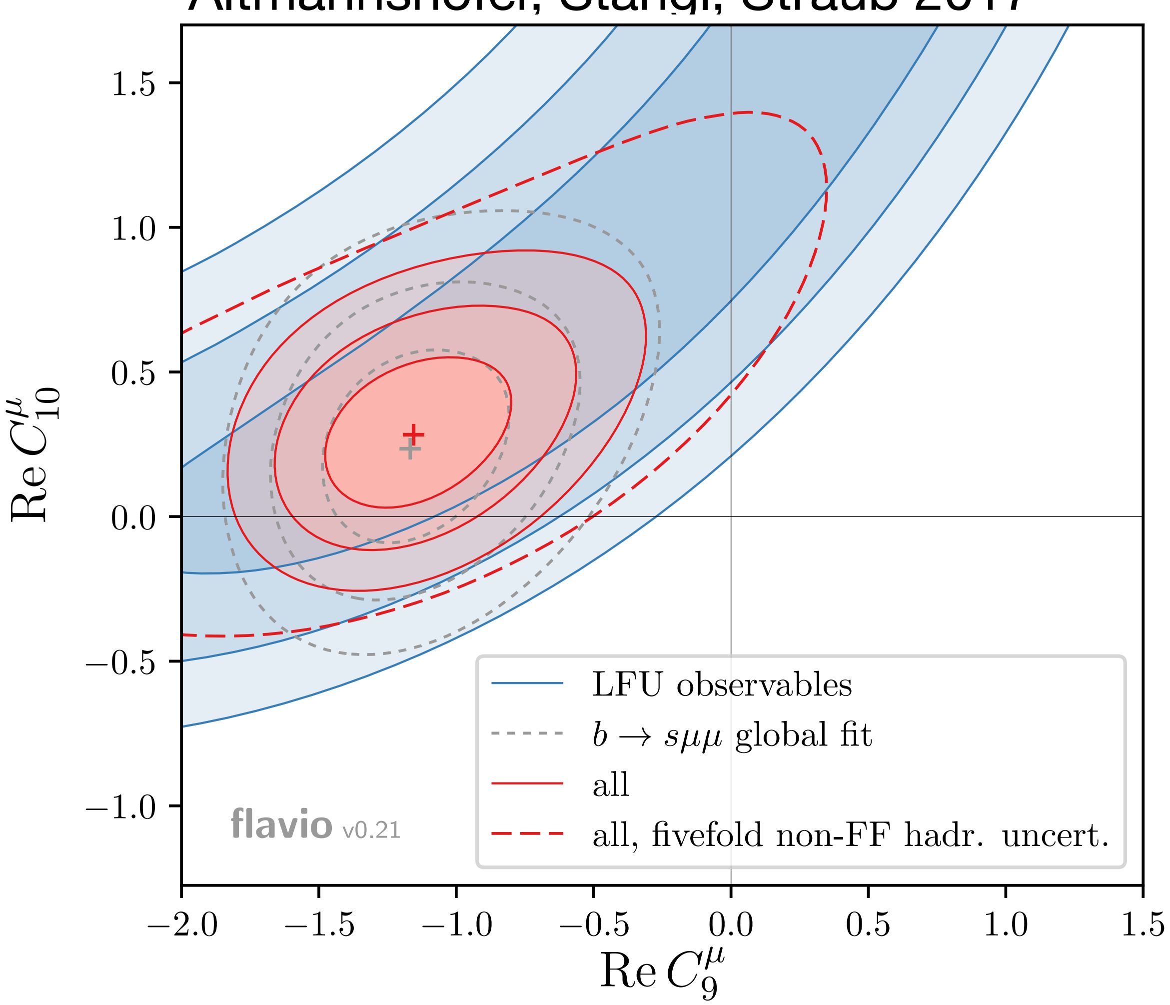
FCNC: occurs only at **loop-level** in the SM
+ **CKM** suppressed



Semi-leptonic effective Lagrangian:

$$\mathcal{L} = \frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi} V^*_{tb} V_{ts} \sum_i C_i \mathcal{O}_i + C'_i \mathcal{O}'_i$$

Altmannshofer, Stangl, Straub 2017



Deviations from SM in several observables

- Angular distributions in $B \to K^*\mu\mu$
- Various branching ratios $B_{(s)} \to X_s\,\mu\mu$
- LFU in R(K) and R(K^*) (very clean prediction!)

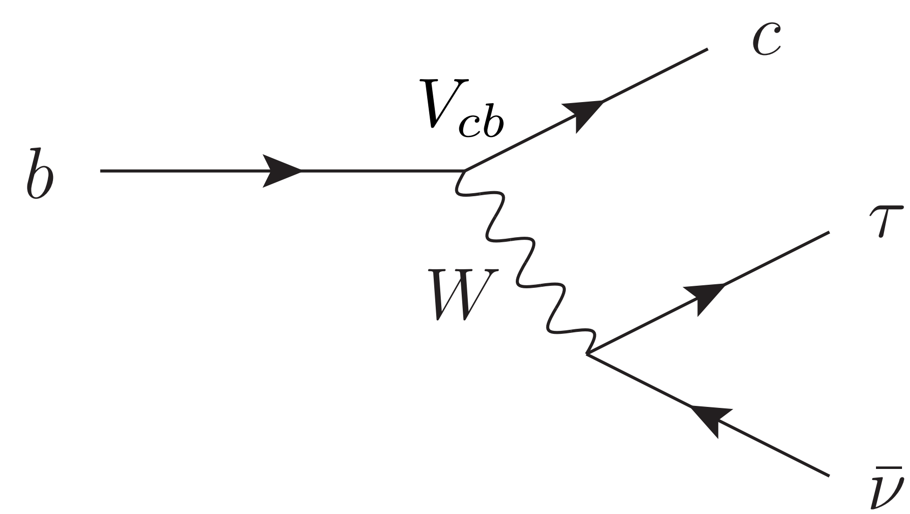
~ 20% NP contribution to LH current

Globally 5-6σ

➡ see Nazila's talk

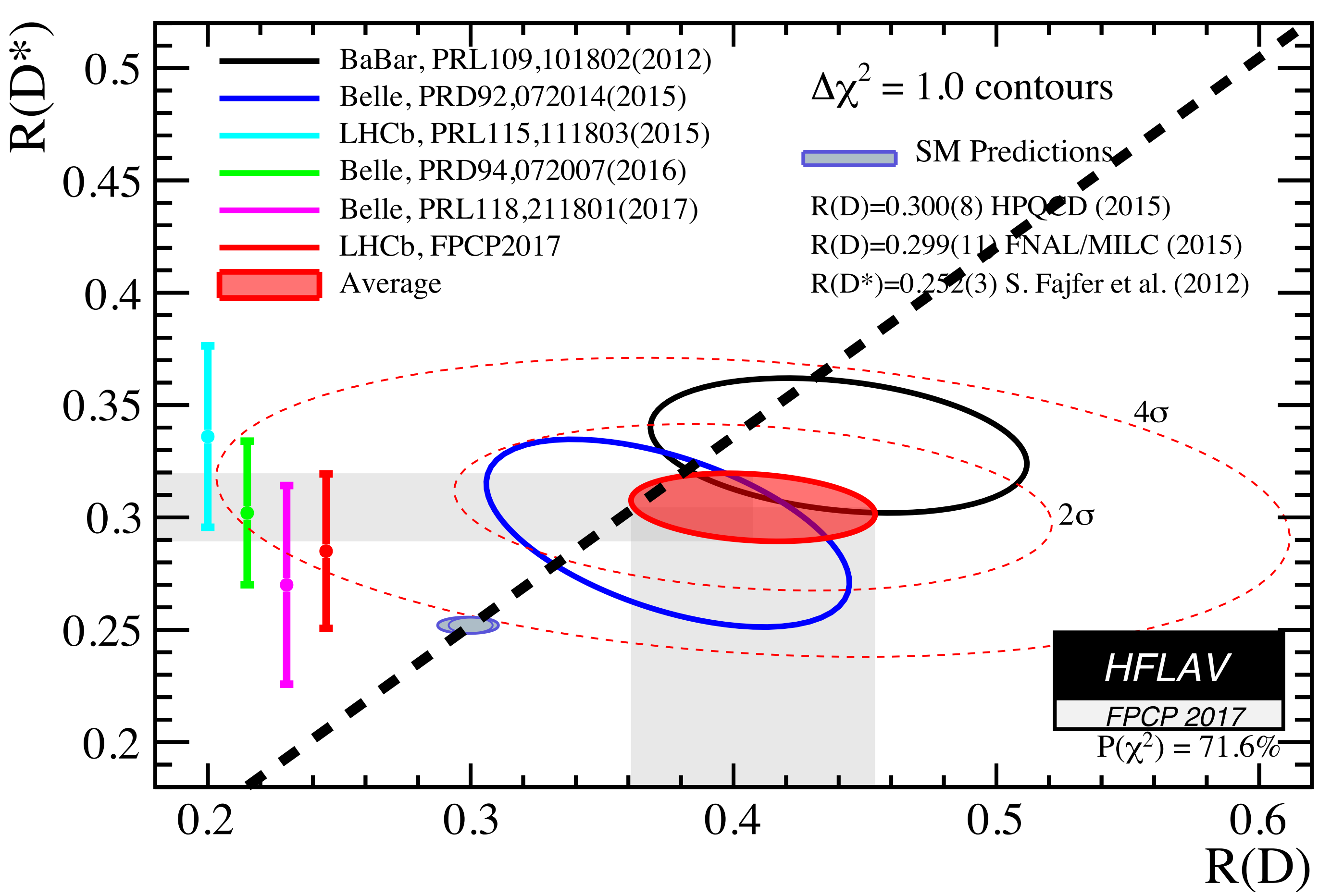
Semi-leptonic *b* to *c* decays

Charged-current interaction: **tree-level** effect in the SM, with mild CKM suppression



$$\mathcal{H}_{\rm eff} = \frac{G_F}{\sqrt{2}} V_{cb}^* (\bar{b}_L \gamma_\mu c_L)(\bar{\tau}_L \gamma^\mu \nu_\tau)$$

LFU ratios: $$R_{D^{(*)}} = \frac{\mathrm{BR}(B \to D^{(*)}\tau\bar{\nu})/\mathrm{SM}}{\mathrm{BR}(B \to D^{(*)}\ell\bar{\nu})/\mathrm{SM}} = 1.237 \pm 0.053$$

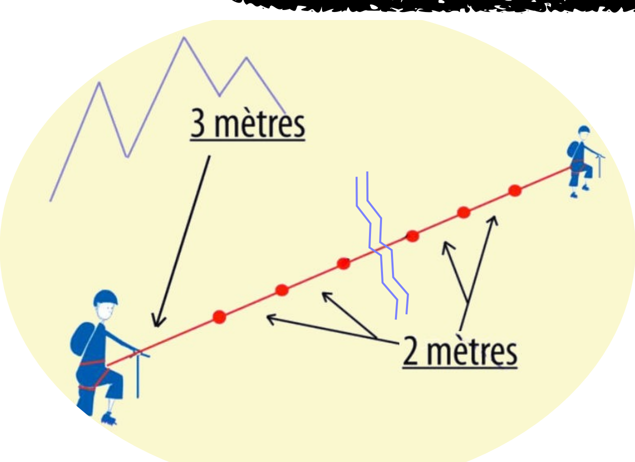


~ 20% enhancement in LH currents
~ 4σ from SM

- RH & scalar currents disfavoured
- SM predictions robust: form factors cancel in the ratio (to a good extent)
- Consistent results by three very different experiments, in different channels
- Large backgrounds & systematic errors

Is it possible to explain the whole set of anomalies in a coherent picture?

Effective Field Theory with flavour symmetry



Simplified models

UV completion

Lepton Flavour Universality

- (Lepton) flavour universality is an accidental property of the gauge Lagrangian, not a fundamental symmetry of nature

$$\mathcal{L}_{\text{gauge}} = i \sum_{j=1}^{3} \sum_{q,u,d,\ell,e} \bar{\psi}_j \not{D} \psi_j$$

- The only non-gauge interaction in the SM violates LFU maximally

$$\mathcal{L}_{\text{Yuk}} = \bar{q}_L Y_u u_R H^* + \bar{d}_L Y_d d_R H + \bar{\ell}_L Y_e e_R H \qquad Y_{u,d,e} \approx \text{diag}(0,0,1)$$

- LFU approximately satisfied in SM processes because Yukawa couplings are small

$$y_\mu \approx 10^{-3} \qquad y_\tau \approx 10^{-2}$$

➡ natural to expect LFU and flavour violations in BSM physics

What do we know?

1. Anomalies seen only in semi-leptonic processes: **quarks** x **leptons**

   nothing observed in pure **quark** or **lepton** processes

2. Large effect in **3rd generation**: b quarks, $\tau\nu$ competes with SM tree-level

   smaller non-zero effect in **2nd generation**: $\mu\mu$ competes with SM FCNC,

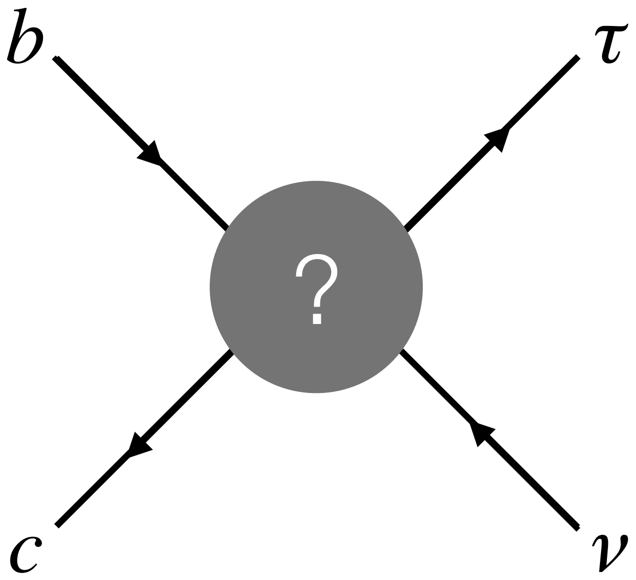
   no effect in 1st generation

3. **Flavour alignment** with down-quark mass basis (to avoid large FCNC)

4. **Left-handed** four-fermion interactions

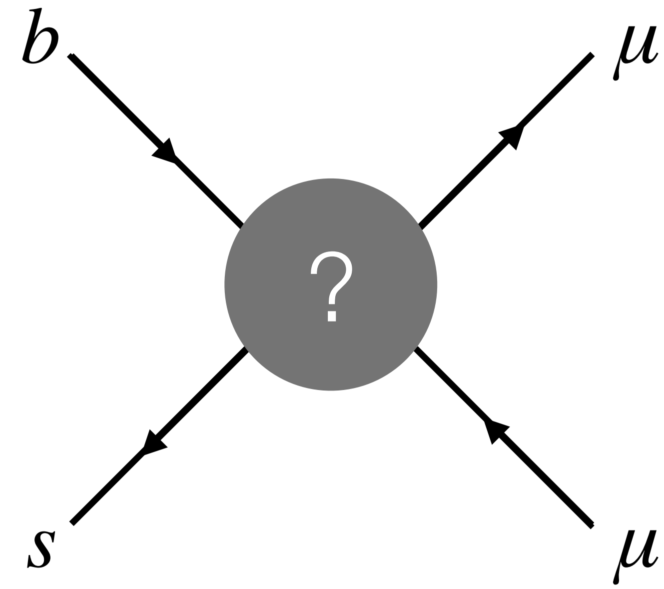
   RH and scalar currents disfavoured: can be present, but do not fit the anomalies (both in charged and neutral current), Higgs-current small or not relevant

Simultaneous explanations



$$\frac{1}{\Lambda_D^2}(\bar{b}_L\gamma_\mu c_L)(\bar{\tau}_L\gamma^\mu\nu_\tau)$$

$$\Lambda_D = 3.4\,\mathrm{TeV}$$



$$\frac{1}{\Lambda_K^2}(\bar{b}_L\gamma_\mu s_L)(\bar{\mu}_L\gamma^\mu\mu_L)$$

$$\Lambda_K = 31\,\mathrm{TeV}$$

- <u>I. “vertical” structure:</u> the two operators can be related by $SU(2)_L$

$$(\bar{q}_L\gamma_\mu\sigma^a q_L)(\bar{\ell}_L\gamma^\mu\sigma^a\ell_L)$$

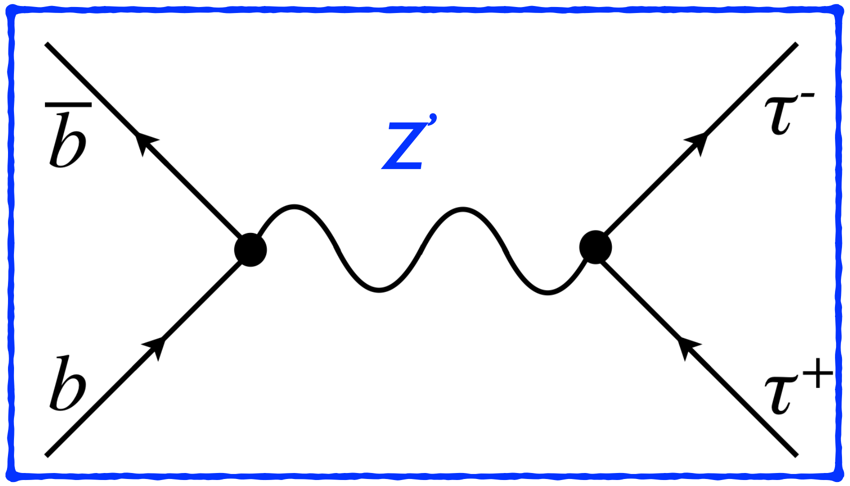
- <u>II. “horizontal” structure:</u> NP structure reminds of the Yukawa hierarchy

$$\Lambda_D \ll \Lambda_K, \qquad \lambda_{\tau\tau} \gg \lambda_{\mu\mu}$$

Problems

- **Direct searches:** large signal at high-pT

  $\Lambda_D \simeq 3.4\,\mathrm{TeV}$

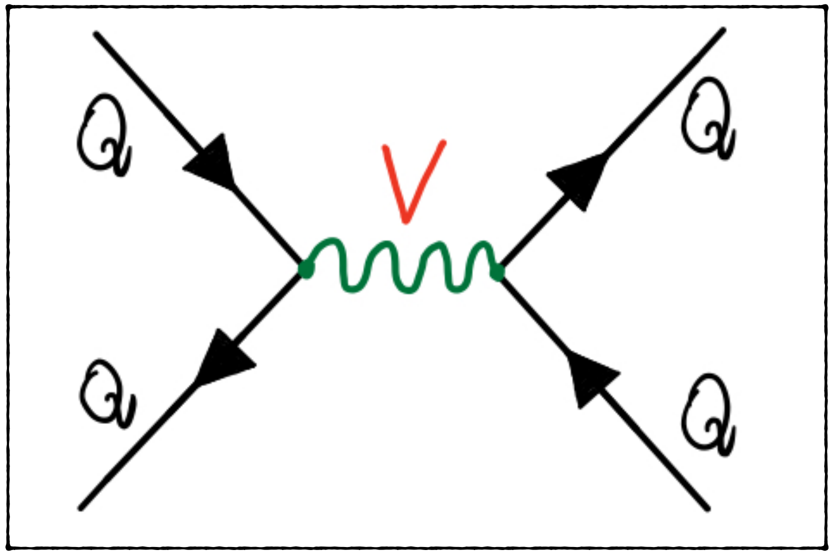


- **Flavour observables:**
  - other semi-leptonic observables

    model independent

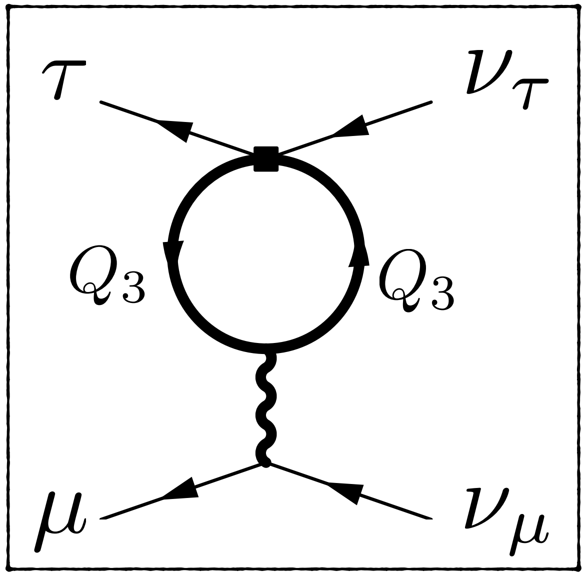
  - meson mixing, lepton flavour violation

    depend on the model, generally present



- **ElectroWeak precision tests:**
  W, Z couplings, τ decays

  generated radiatively at one-loop



Constructing the Effective Field Theory

1. Left-handed four-fermion interactions: two possible operators in SM-EFT

$$C_S(\bar{q}^i_L \gamma_\mu q^j_L)(\bar{\ell}^\alpha_L \gamma^\mu \ell^\beta_L)$$

— SU(2) singlet —

$$C_T(\bar{q}^i_L \gamma_\mu \sigma^a q^j_L)(\bar{\ell}^\alpha_L \gamma^\mu \sigma^a \ell^\beta_L)$$

— SU(2) triplet —

2. Flavour structure:

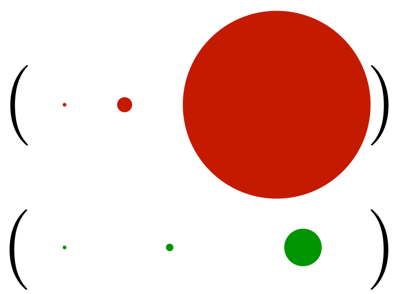
- Large effect in 3rd generation
- Smaller effect in 2nd generation
- Flavour alignment with CKM

→ connection with Yukawa coupling hierarchies: U(2) symmetry

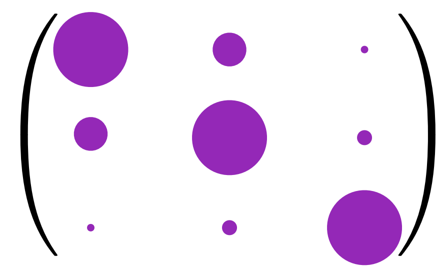
U(2) flavour symmetry

SM Yukawa couplings exhibit an approximate U(2)[3] flavour symmetry:

$m_u \sim$
$m_d \sim$



$V_{\rm CKM} \sim$



$$U(2)_{q_L} \times U(2)_{u_R} \times U(2)_{d_R}$$

$$\psi_i = (\underbrace{\psi_1 \;\; \psi_2}_{\mathbf{2}} \; \underbrace{\psi_3}_{\mathbf{1}})$$

1. Good approximation of SM spectrum: $m_{\rm light} \sim 0$, $V_{\rm CKM} \sim 1$

Breaking pattern: $Y_{u,d} \approx \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \longrightarrow Y_{u,d} \approx \begin{pmatrix} \Delta & V_q \\ 0 & 1 \end{pmatrix}$

$$\Delta \sim (\mathbf{2}, \mathbf{2}, \mathbf{1})$$
$$V_q \sim (\mathbf{2}, \mathbf{1}, \mathbf{1})$$

<u>Barbieri et al. 2011, 2012</u>

2. The *assumption* of a single spurion V_q connecting the 3rd generation with the other two ensures MFV-like FCNC protection
3. The most general symmetry that gives "CKM-like" interactions in a model-independent way

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2. Flavour structure: minimally broken $U(2)_q \times U(2)_\ell$ symmetry

$U(2)_q \times U(2)_\ell$ breaking pattern:

$V_q = (V_{td}^*, V_{ts}^*)$ CKM structure for quarks

$V_\ell \approx (0, V_{\tau\mu})$ strong LFV constraints for electrons

no flavour-conserving coupling to light generations

$$Q_L^{(3)} \sim \begin{pmatrix} V_{ib}^* u_L^i \\ b_L \end{pmatrix}$$ + small terms (~ V_{CKM})

$$\lambda_{ij}^q \approx \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & V_{ts} \\ \cdot & V_{ts}^* & 1 \end{pmatrix} \qquad \lambda_{\alpha\beta}^\ell \approx \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & |V_{\tau\mu}|^2 & V_{\tau\mu} \\ \cdot & V_{\tau\mu}^* & 1 \end{pmatrix}$$

(small) (small)

B, Greljo, Isidori, Marzocca, 2017

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small small

B, Greljo, Isidori, Marzocca, 2017

Effective Field Theory

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} - \frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T(\bar{q}^i_L\gamma_\mu\sigma^a q^j_L)(\bar{\ell}^\alpha_L\gamma^\mu\sigma^a\ell^\beta_L) + C_S(\bar{q}^i_L\gamma_\mu q^j_L)(\bar{\ell}^\alpha_L\gamma^\mu\ell^\beta_L)\right]$$

B, Greljo, Isidori, Marzocca, 2017

LFU ratios in ***b* → *c*** charged currents:

- ***τ***: $R^{\tau\ell}_{D^{(*)}} \simeq 1 + 2C_T\left(1 + \frac{\lambda^q_{bs}}{V_{cb}}\right) = 1.237 \pm 0.053$
- ***μ* vs. *e***: $R^{\mu e}_{D^{(*)}} \simeq 1 + 2C_T\left(1 + \frac{\lambda^q_{bs}}{V_{cb}}\right)\lambda_{\mu\mu} < 0.02$ ➡ $\lambda_{\mu\mu} \lesssim 0.1$

Effective Field Theory

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Neutral currents: ***b* → *sν_τν_τ*** transitions not suppressed by lepton spurion

$$\Delta C_\nu \simeq \frac{\pi}{\alpha V^*_{ts}V_{tb}}\lambda^q_{sb}(C_S - C_T)$$

strong bounds from $B \to K^*\nu\nu$

➡ $C_T \sim C_S$

b* → *sττ ~ $C_T + C_S$ is large (100 x SM), weak experimental constraints

Effective Field Theory

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strong bounds from $B \to K^*\nu\nu$

➡ $C_T \sim C_S$

$b \to s\tau\tau$ ~ $C_T + C_S$ is large (100 x SM), weak experimental constraints

$b \to s\mu\mu$ is an independent quantity: fixes the size of $\lambda_{\mu\mu}$

$$\Delta C_{9,\mu} = -\frac{\pi}{\alpha V^*_{ts}V_{tb}}\lambda^q_{sb}\lambda_{\mu\mu}(C_T + C_S)$$

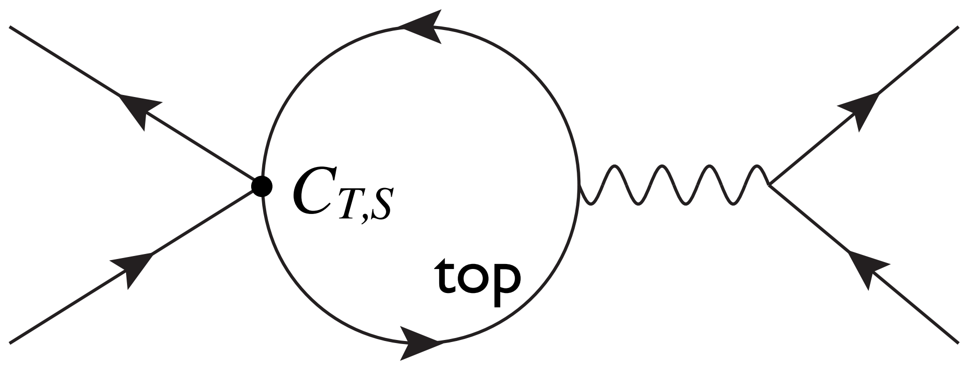
Radiative corrections

Purely leptonic operators generated at the EW scale by RG evolution

Feruglio et al. 2015

- **LFU in τ decays** $\tau \to \mu\nu\nu$ vs. $\tau \to e\nu\nu$ (effectively deviation in W couplings)

$$\delta g_\tau^W = -0.084\, C_T = (9.7 \pm 9.8) \times 10^{-4}$$



- ***Z$\tau\tau$* couplings**

$$\delta g_{\tau_L}^Z = -0.047 C_S + 0.038 C_T = -0.0002 \pm 0.0006$$

- ***Z$\nu\nu$* couplings** (number of neutrinos)

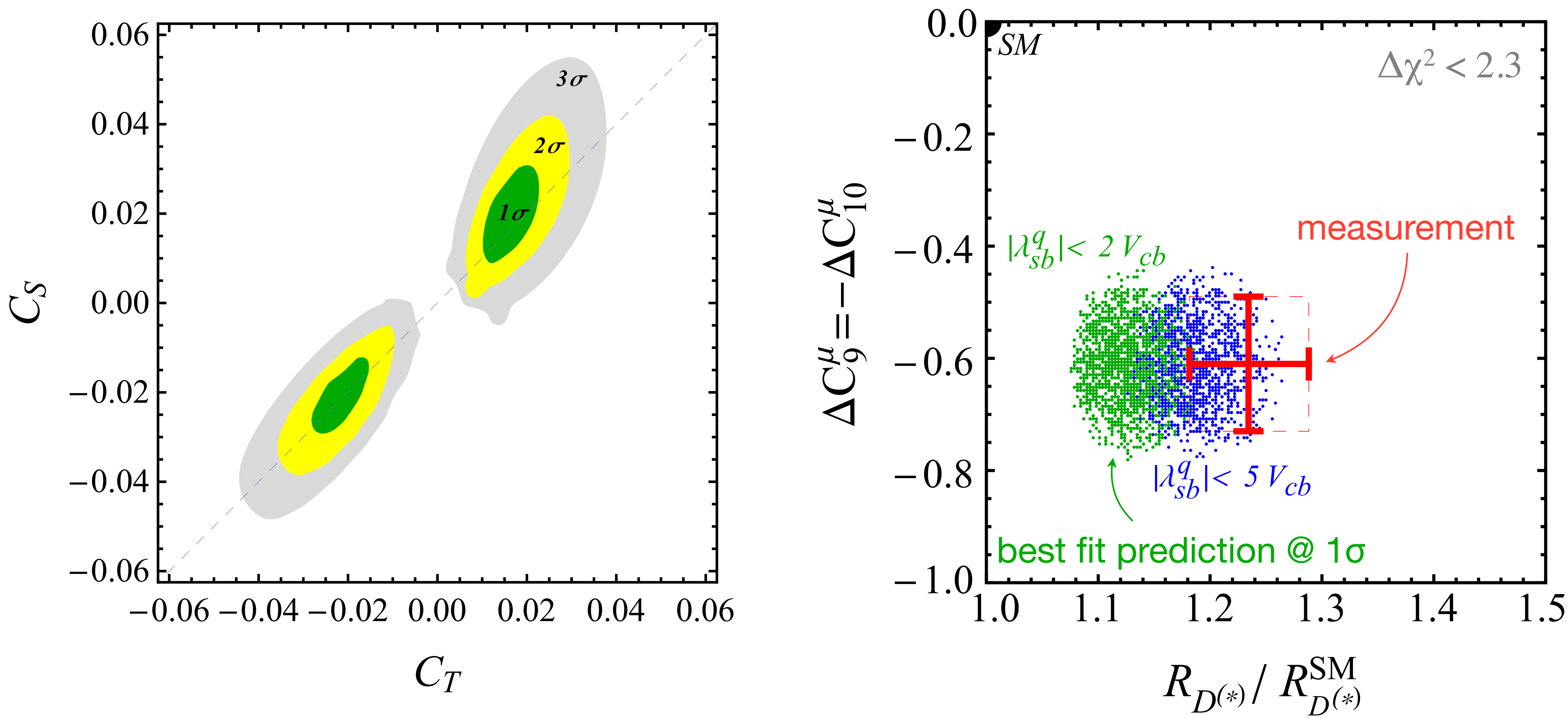
$$N_\nu = 3 - 0.19\, C_S - 0.15\, C_T = 2.9840 \pm 0.0082$$

(RG-running corrections to four-quark operators suppressed by the τ mass)

→ strong bounds on the scale of NP ($C_{S,T} \lesssim$ 0.02-0.03)

Fit results

- EFT fit to all semi-leptonic observables + radiative corrections to EWPT
- Don't include any UV contribution to other operators
  (they will depend on the dynamics of the specific model)



Good fit to all anomalies, with couplings compatible with the U(2) assumption

Other observables

- LH currents: universality of all $b \to c$ transitions:

  $BR(B \to D\tau\nu)/SM = BR(B \to D^*\tau\nu)/SM = BR(B_c \to \psi\tau\nu)/SM = BR(\Lambda_b \to \Lambda_c\tau\nu)/SM$ …

- U(2) symmetry: $b \to c$ vs. $b \to u$ universality:

  $BR(B \to D^{(*)}\tau\nu)/SM = BR(B \to \pi\tau\nu)/SM = BR(B^+ \to \tau\nu)/SM = BR(B_s \to K^*\tau\nu)/SM$ …

Other observables

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  BR($B \to D\tau\nu$)/SM = BR($B \to D^*\tau\nu$)/SM = BR($B_c \to \psi\tau\nu$)/SM = BR($\Lambda_b \to \Lambda_c\tau\nu$)/SM …

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  BR($B \to D^{(*)}\tau\nu$)/SM = BR($B \to \pi\tau\nu$)/SM = BR($B^+ \to \tau\nu$)/SM = BR($B_s \to K^*\tau\nu$)/SM …

- Neutral currents: several correlated effects in many observables

Lepton flavour →

Isidori 2017

SU(2) [ττ, νν]

Quark flavour ↓ / U(2) symmetry

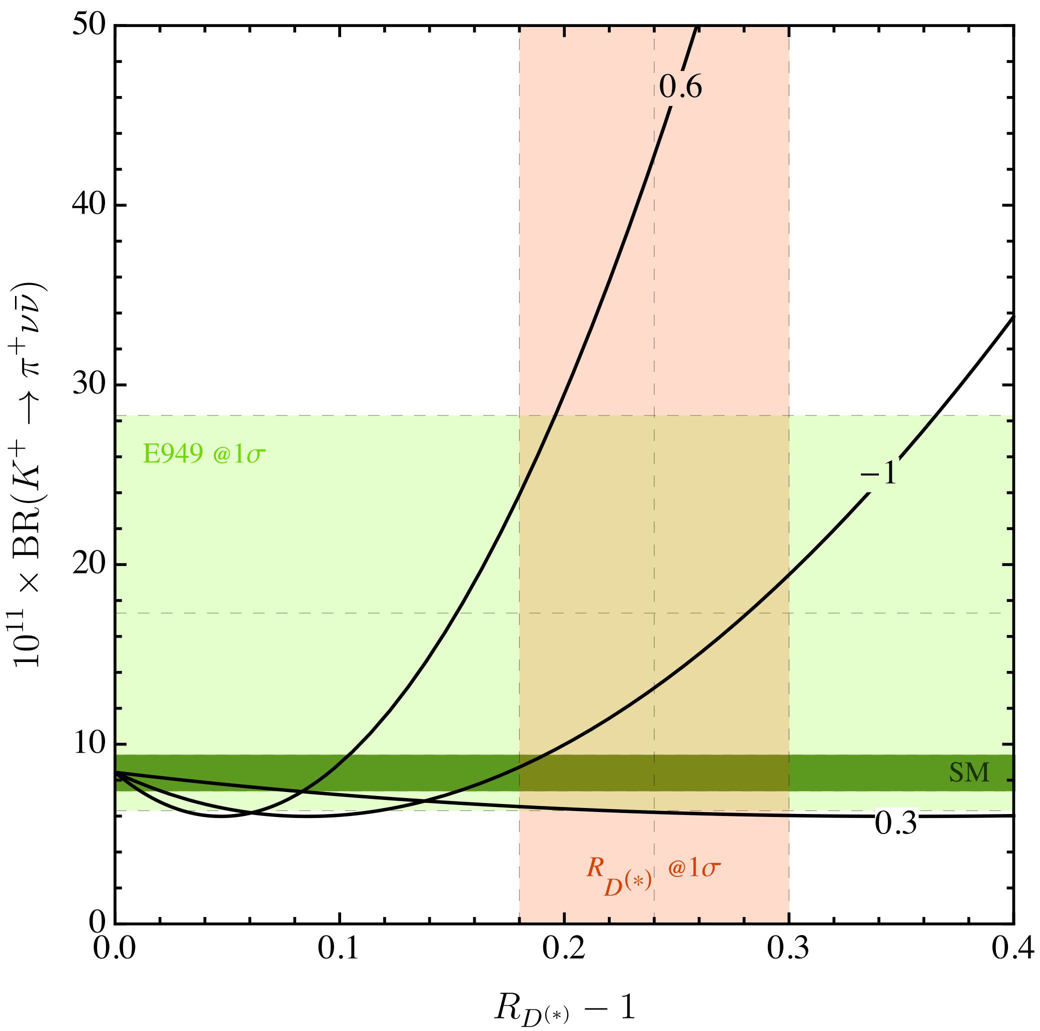
	$\mu\mu$ (ee)	$\tau\tau$	$\nu\nu$	$\tau\mu$
$b \to s$	R_K, R_{K^*} O(20%)	$B \to K^{(*)}\tau\tau$ → 100×SM	$B \to K^{(*)}\nu\nu$ O(1)	$B \to K\tau\mu$ → ~10^{-6}
$b \to d$	$B_d \to \mu\mu$ $B \to \pi\mu\mu$ $B_s \to K^{(*)}\mu\mu$ O(20%) [R_K=R_π]	$B \to \pi\tau\tau$ → 100×SM	$B \to \pi\nu\nu$ O(1)	$B \to \pi\tau\mu$ → ~10^{-7}

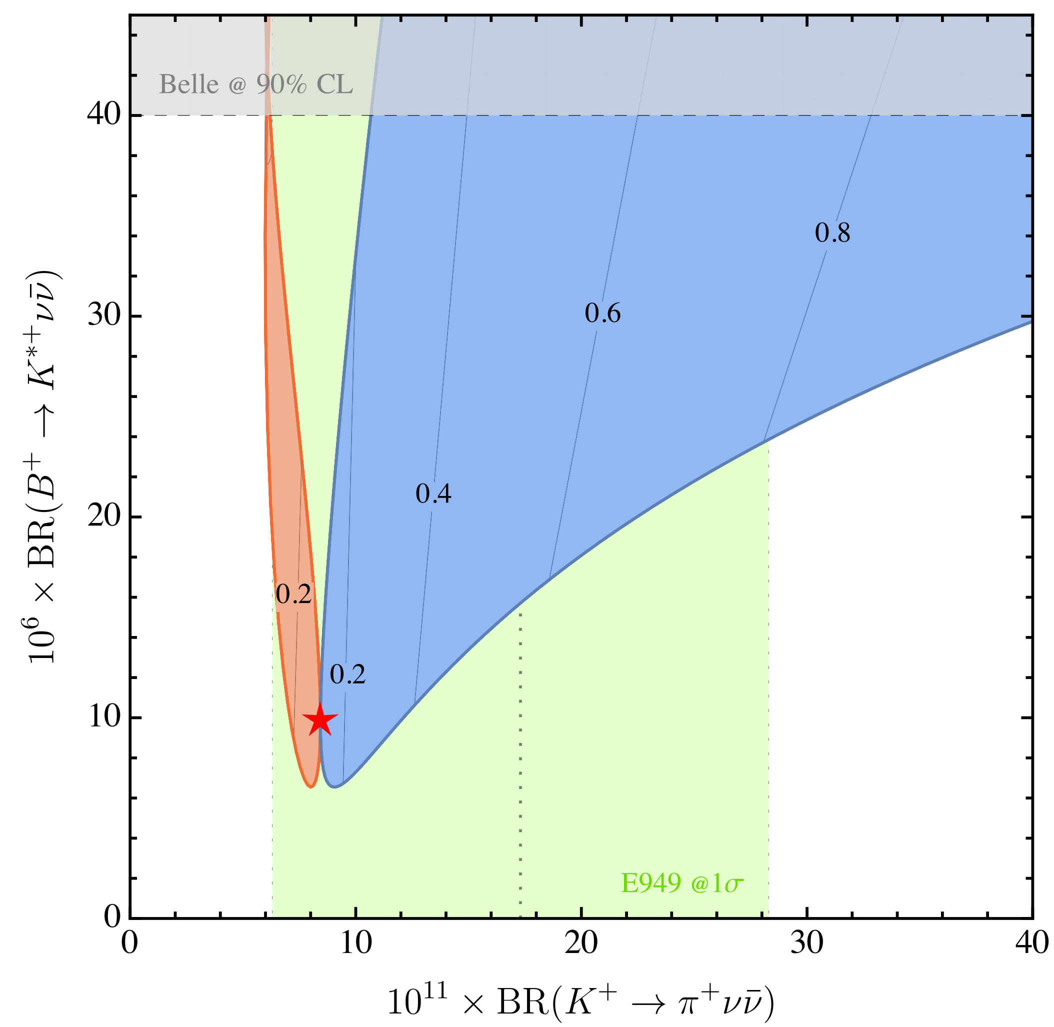
$K \to \pi\nu\nu$

- The only $s \to d$ decay with 3rd generation leptons in the final state: sizeable deviations can be expected

- U(2) symmetry relates $b \to q$ transitions to $s \to d$ (up to model-dependent parameters of order 1): $\lambda_{sd} \sim V_q V_q^* \sim V_{ts}^* V_{td}$ $\lambda_{bq} \sim V_q \sim V_{tq}^*$

Bordone, B, Isidori, Monnard 2017

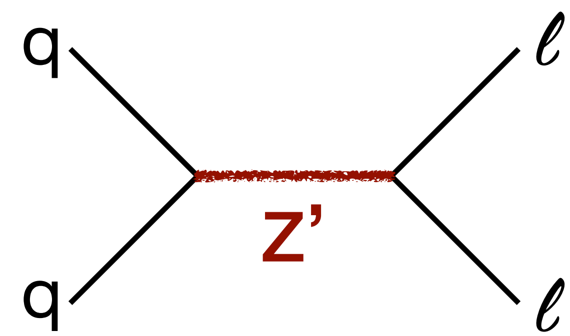


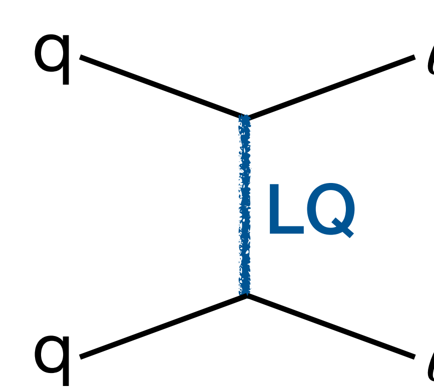


Simplified models

Mediators that can give rise to the $b \to c\ell\nu$ and $b \to s\ell\ell$ amplitudes:

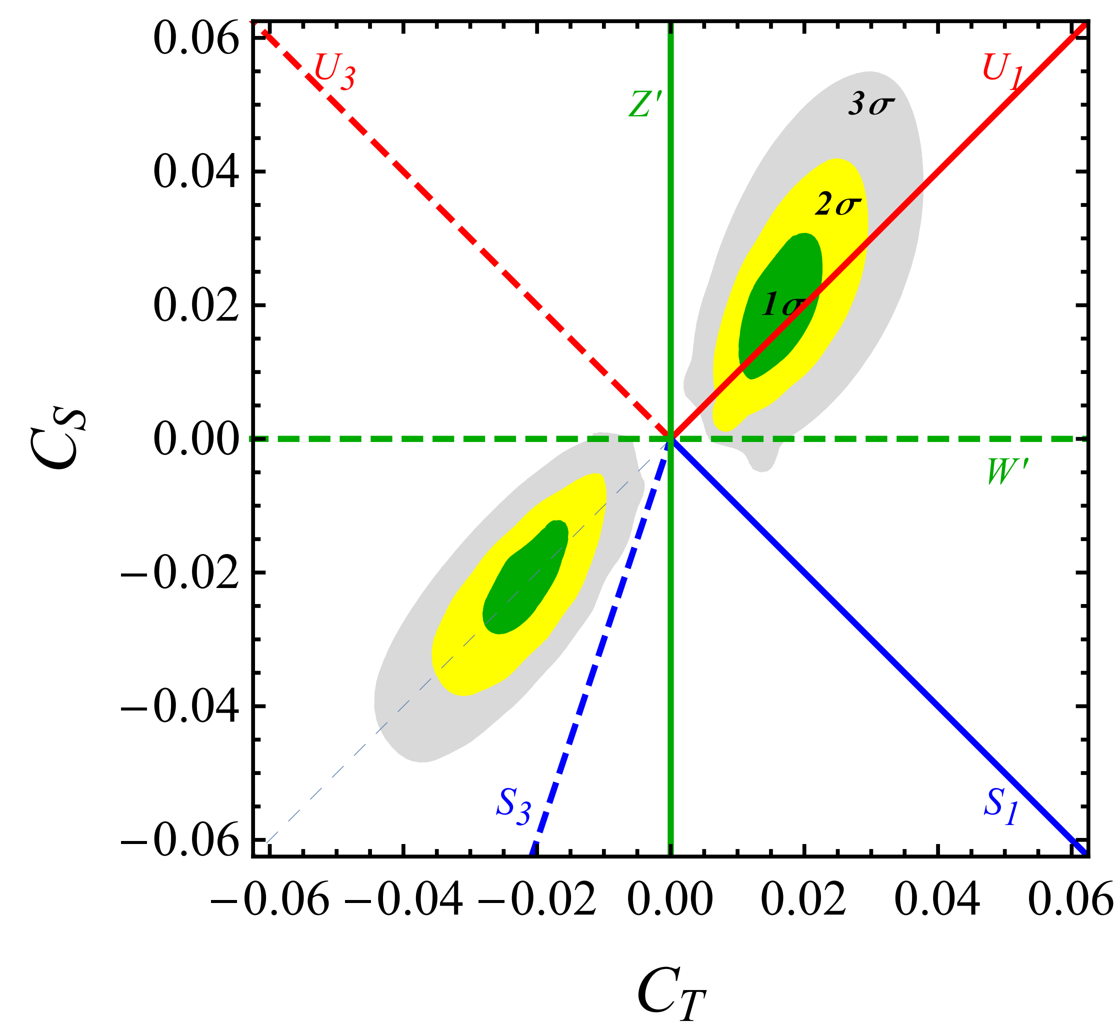
	Spin 0	Spin 1
Colour singlet	~~2HDM~~ no LL operator	Vector resonance
Colour triplet	Scalar lepto-quark	Vector lepto-quark





Contributions to C_T and C_S from different mediators:

- A **vector leptoquark** is the only single mediator that can fit all the anomalies alone: $C_T \sim C_S$
- Combinations of two or more mediators also possible
  (often the case in concrete models)



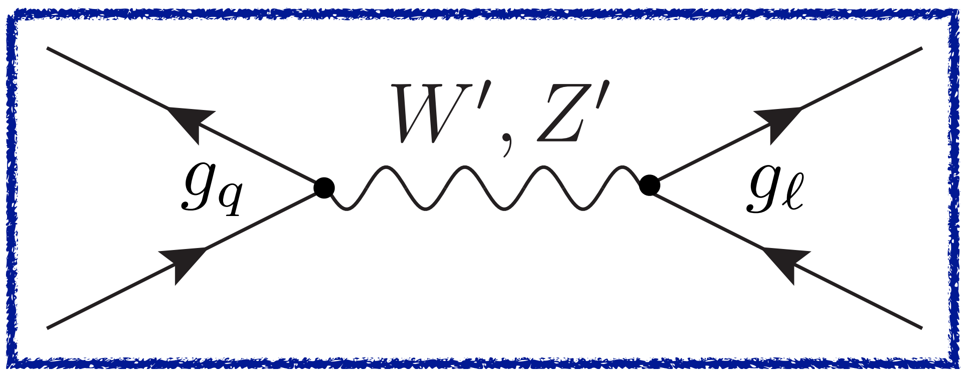
Vector resonances

Triplet and singlet colourless vectors:

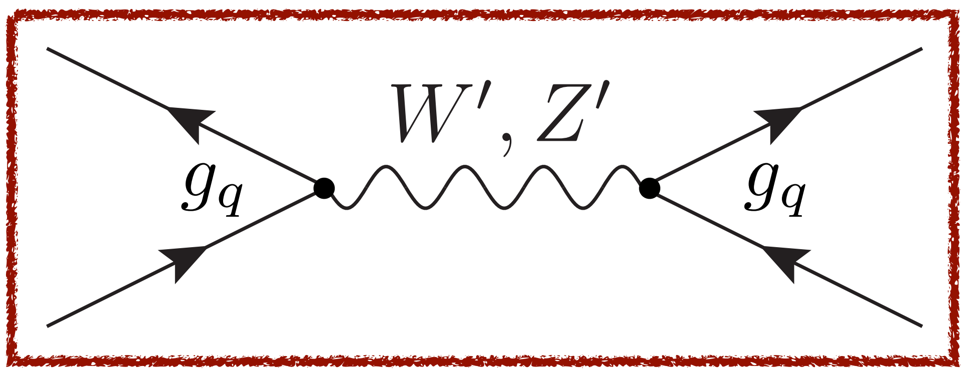
$$\mathcal{L}_{\rm int} = W'^{a}_{\mu} J^{a}_{\mu} + B'_{\mu} J^{0}_{\mu}$$

$$J^a_\mu = g_q \lambda^q_{ij} \left(\bar{Q}^i_L \gamma_\mu T^a Q^j_L \right) + g_\ell \lambda^\ell_{\alpha\beta} \left(\bar{L}^\alpha_L \gamma_\mu T^a L^\beta_L \right)$$

$$J^0_\mu = \frac{g^0_q}{2} \lambda^q_{ij} \left(\bar{Q}^i_L \gamma_\mu Q^j_L \right) + \frac{g^0_\ell}{2} \lambda^\ell_{\alpha\beta} \left(\bar{L}^\alpha_L \gamma_\mu L^\beta_L \right)$$



$$C_{T,S} = \frac{4v^2}{m_V^2} g_q g_\ell$$



Large contribution to B_s mixing

$$\Delta \mathcal{A}_{B_s\text{-}\bar{B}_s} \approx \frac{v^2}{m_V^2} \lambda^2_{bs} \left(g_q^2 + (g_q^0)^2 \right)$$

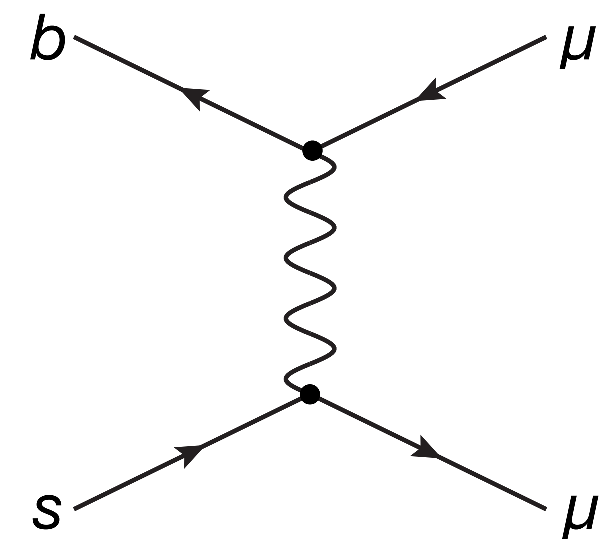
$$\approx \left(C_T + C_S \right) \lambda^2_{bs}$$

Problem less severe for large $C_{T,S}$ — stronger tension with EW precision tests.

In models with more couplings (e.g. Higgs current) can partially cancel the contributions

Vector leptoquarks

SU(2)$_L$ singlet vector LQ: $U_\mu \sim (\mathbf{3}, \mathbf{1}, 2/3)$



$$\mathcal{L}_{\rm LQ} = g_U U_\mu \beta_{i\alpha} \left(\bar{Q}^i_L \gamma^\mu L^\alpha_L\right) + \text{h.c.}$$

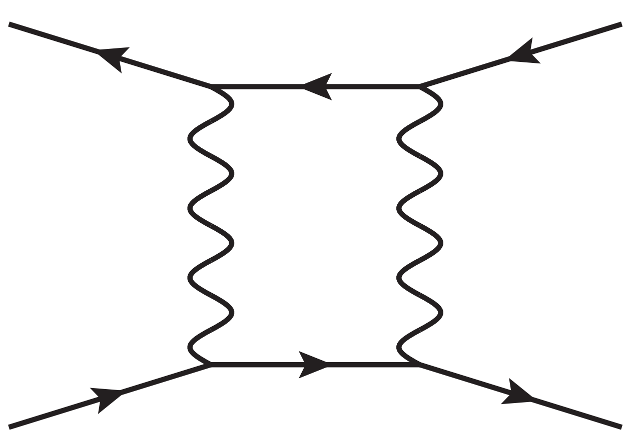
- $C_T = C_S$ automatically satisfied at tree-level

$$\mathcal{L}_{\rm eff} \supset -\frac{1}{v^2} C_U \beta_{i\alpha}\beta^*_{j\beta} \left[(\bar{Q}^i\gamma_\mu\sigma^a Q^j)(\bar{L}^\alpha\gamma^\mu\sigma^a L^\beta) + (\bar{Q}^i\gamma_\mu Q^j)(\bar{L}^\alpha\gamma^\mu L^\beta)\right]$$

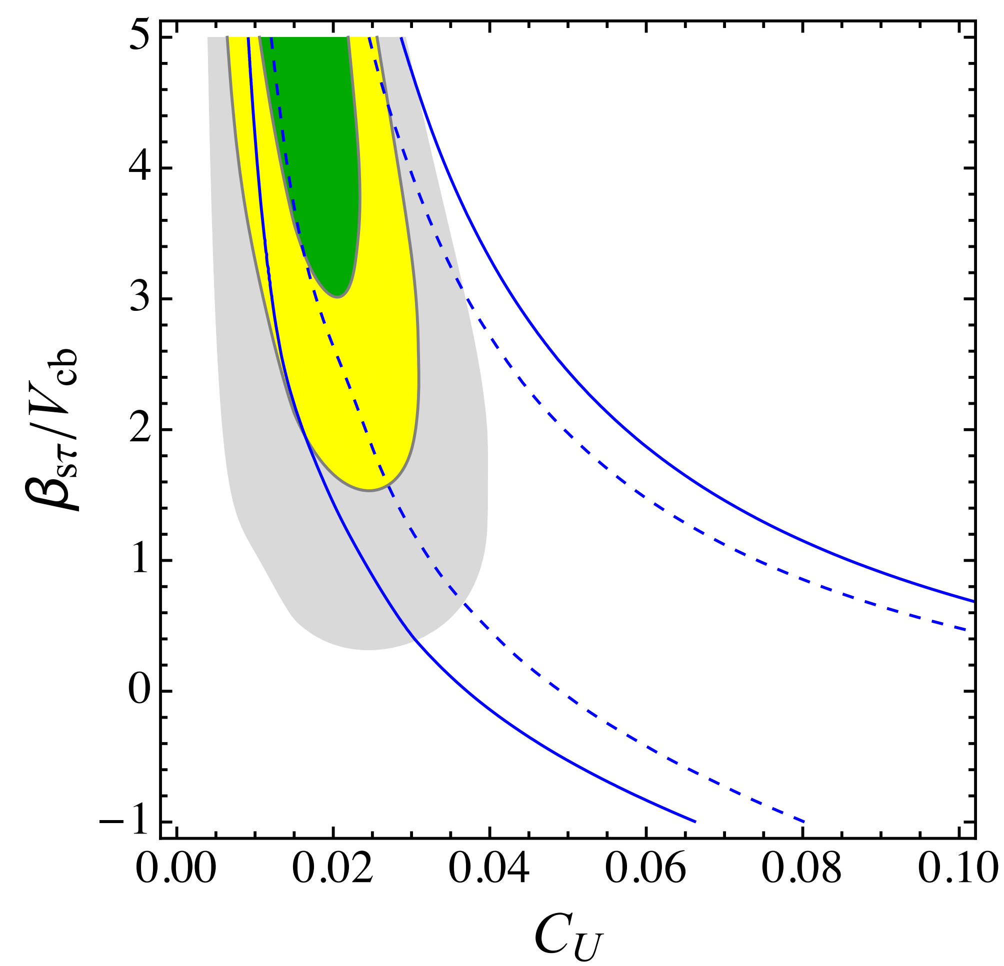
$$C_U = \frac{v^2|g_U|^2}{2m_U^2}$$

- No tree-level contribution to $B_{(s)}$-$\bar{B}_{(s)}$ mixing, but UV contributions not calculable

naïve estimate:



$$\approx C_U |\beta_{s\tau}|^2 \frac{g_U^2}{(4\pi)^2}$$



UV completions: vector leptoquark

Leptoquark quantum numbers are consistent with Pati-Salam unification

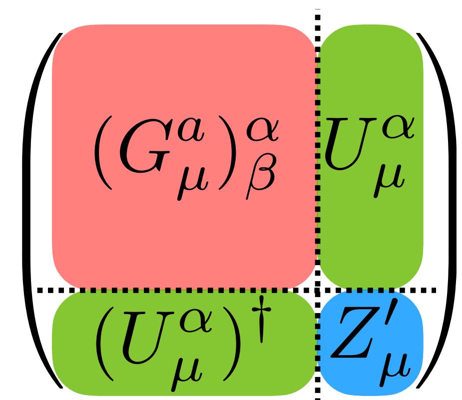
$$SU(4) \times SU(2)_L \times SU(2)_R \supset SU(3)_c \times SU(2)_L \times U(1)_Y$$

Lepton number = 4th color

$$\psi_L = (q_L^1, q_L^2, q_L^3, \ell_L) \sim (\mathbf{4}, \mathbf{2}, \mathbf{1}),$$
$$\psi_R = (q_R^1, q_R^2, q_R^3, \ell_R) \sim (\mathbf{4}, \mathbf{1}, \mathbf{2}).$$

Gauge fields: $\mathbf{15} = \mathbf{8}_0 \oplus \mathbf{3}_{2/3} \oplus \bar{\mathbf{3}}_{-2/3} \oplus \mathbf{1}_0$

→ vector leptoquark U_1^μ (the $\mathbf{3}_{2/3}$)



- No proton decay: protected by gauge $U(1)_{B-L} \subset SU(4)$
- U_μ gauge vector: unitary couplings to fermions

➡ bounds of O(100 TeV) from light fermion processes, e.g. $K \to \mu e$

UV completions: vector leptoquark

Non-universal couplings to fermions needed!

- **Elementary vectors:** color can't be completely embedded in SU(4)

$$SU(4) \times SU(3) \to SU(3)_c$$

Di Luzio et al. 2017
Isidori et al. 2017

only the 3rd generation is charged under SU(4)

- **Composite vectors:** resonances of a strongly interacting sector with global $SU(4) \times SU(2) \times SU(2)$

the couplings to fermions can be different (e.g. partial compositeness)

Barbieri, Tesi 2017

In all cases, additional heavy vector resonances (color octet and Z') are present

$$\begin{pmatrix} (G^a_\mu)^\alpha_\beta & U^\alpha_\mu \\ (U^\alpha_\mu)^\dagger & Z'_\mu \end{pmatrix}$$

Searches at LHC!

➡ see M. Nardecchia's talk

Composite scalar leptoquarks

- New strong interaction that confines at a scale Λ ~ few TeV

$$\Psi \sim \Box, \qquad \bar{\Psi} \sim \bar{\Box}$$ N new (vector-like) fermions

$$\langle \bar{\Psi}^i \Psi^j \rangle = -f^2 B_0 \delta^{ij} \longrightarrow \mathrm{SU}(N)_L \times \mathrm{SU}(N)_R \to \mathrm{SU}(N)_V$$

(more in general *G* → *F*)

- If the fermions transform under SM gauge group, also the Pseudo Nambu-Goldstone bosons have SM charges:

$$\Psi_Q \sim (\mathbf{3}, \mathbf{2}, Y_Q), \qquad \Psi_L \sim (\mathbf{1}, \mathbf{2}, Y_L) \longrightarrow \begin{array}{l} S_1 \sim (\mathbf{3}, \mathbf{1}, Y_Q - Y_L), \\ S_3 \sim (\mathbf{3}, \mathbf{3}, Y_Q - Y_L), \\ \eta \sim (\mathbf{1}, \mathbf{1}, 0), \\ \pi \sim (\mathbf{1}, \mathbf{3}, 0), \ \cdots \end{array}$$

the scalar LQ are naturally light (pNGB) and couple to fermions

$$\Psi_E \sim (\mathbf{1}, \mathbf{1}, -1), \qquad \Psi_N \sim (\mathbf{1}, \mathbf{1}, 0) \longrightarrow H \sim (\mathbf{1}, \mathbf{2}, \pm 1/2)$$

composite Higgs as a pNGB can be included in the picture

- Vector resonances (with the same quantum numbers) are heavier

$$W'_\mu, B'_\mu, U_\mu, \cdots$$

B, Greljo, Isidori, Marzocca 2017
Marzocca, to appear

Conclusions & outlook

Is the SM breaking down in the flavour sector? We don't know…

- ➡ many new data in the coming years
- ➡ low scale: flavour measurements VS high-pT searches

Model-independent description: EFT

- CKM-like flavour violation
- Triplet and Singlet operators with similar size
- EWPT and meson mixing give important constraints

Leptoquarks are interesting!

Pati-Salam unification?!


Thank you for your attention!