Lepton Flavour Universality Violation and semileptonic decays

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

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Lepton Flavour Universality

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

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

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

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

- 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

Lepton Flavour Universality

Why is LFU often assumed to hold in BSM physics?

Lepton Flavour Universality

Why is LFU often assumed to hold in BSM physics?

- Many strong experimental constraints!

$\tau \to \ell \nu \bar{\nu}$

$\psi \to \ell \bar{\ell}$

$W \to \ell \bar{\nu}$

$Z \to \ell \bar{\ell}$

$K \to \pi \ell \bar{\ell}$

$\Upsilon \to \ell \bar{\ell}$

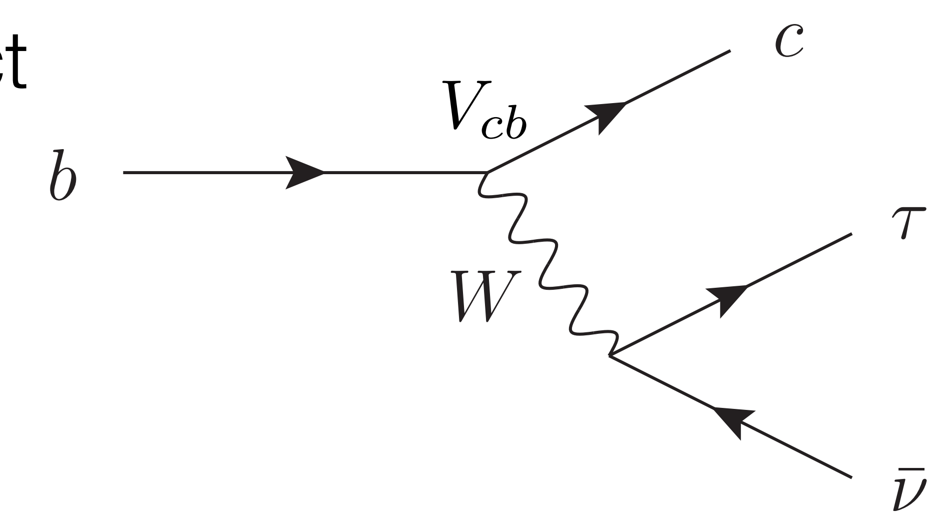
$\pi \to \ell \bar{\nu}$

- The most stringent bounds involve 1st and 2nd generation fermions.

What if – *like the Higgs* – New Physics interacts mostly with 3rd generation?

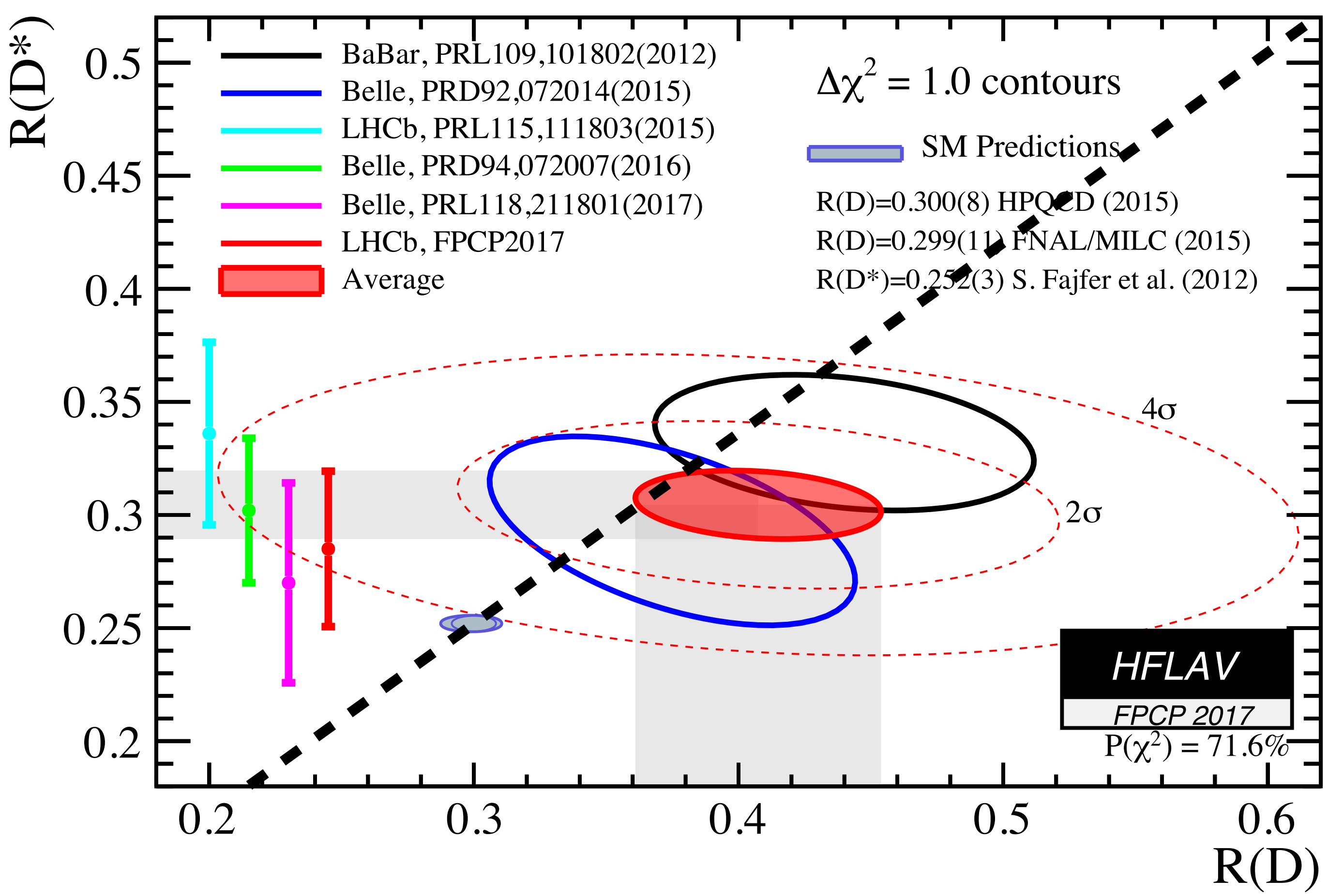
Semi-leptonic b to c decays

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



~ 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

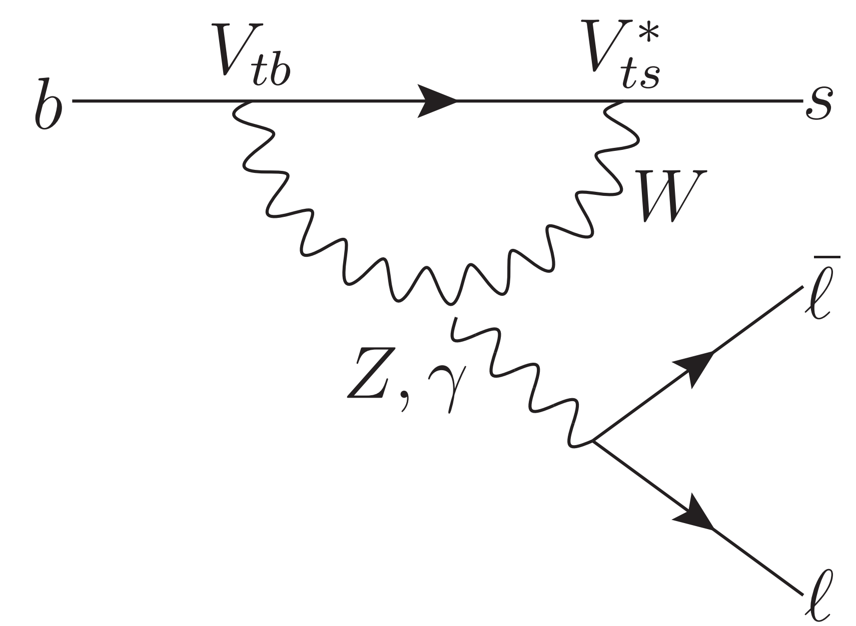
Semi-leptonic *b* to *s* decays

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

+ **CKM** suppressed

Semi-leptonic effective Lagrangian:

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



Deviations from SM in several observables

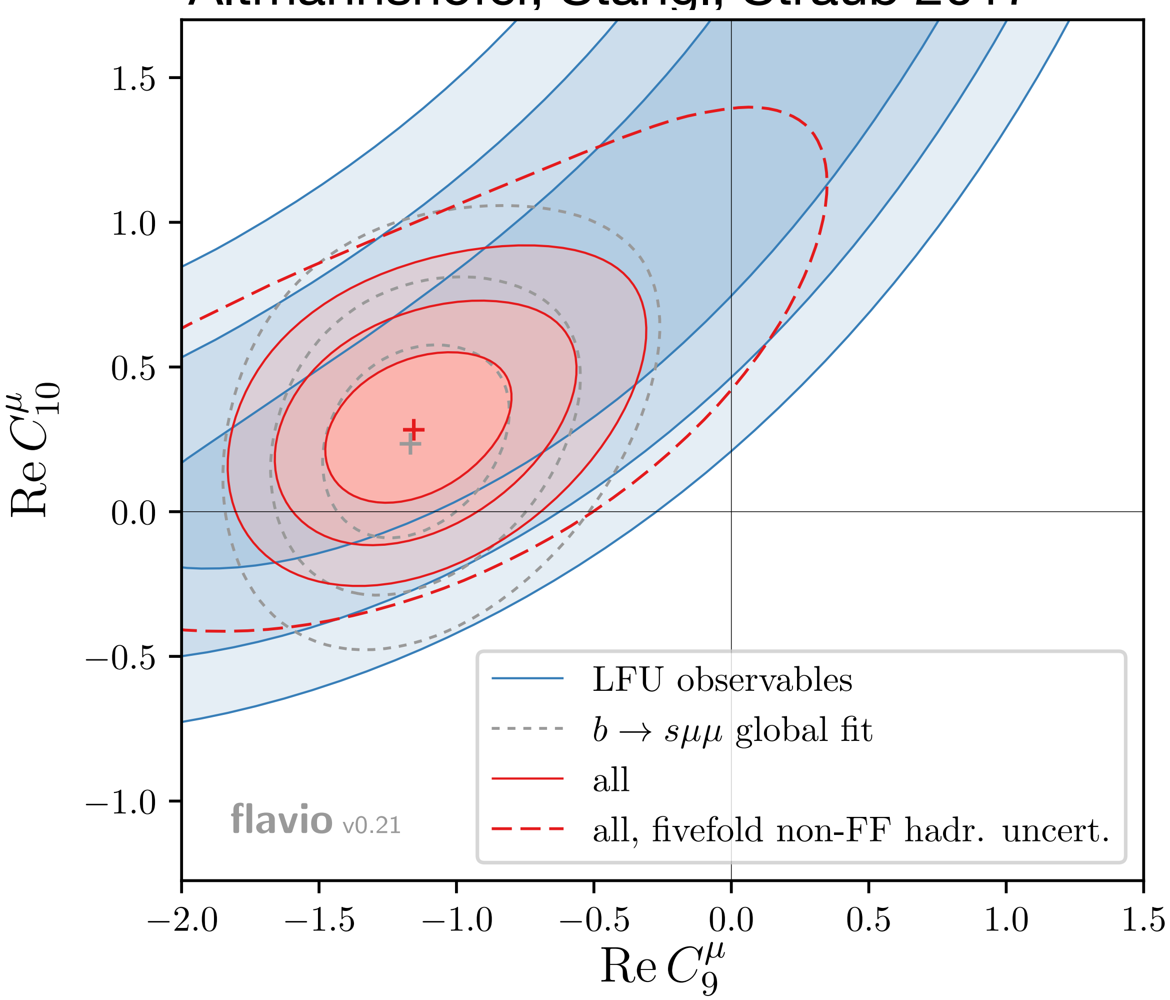
- Angular distributions in $B \rightarrow K^* \mu\mu$
- Various branching ratios $B_{(s)} \rightarrow X_s \mu\mu$
- LFU in R(K) and R(K^*) (very clean prediction!)

Consistency between the various results:

~ 20% NP contribution to LH current

Globally 5-6σ

Altmannshofer, Stangl, Straub 2017



Semi-leptonic b to s decays

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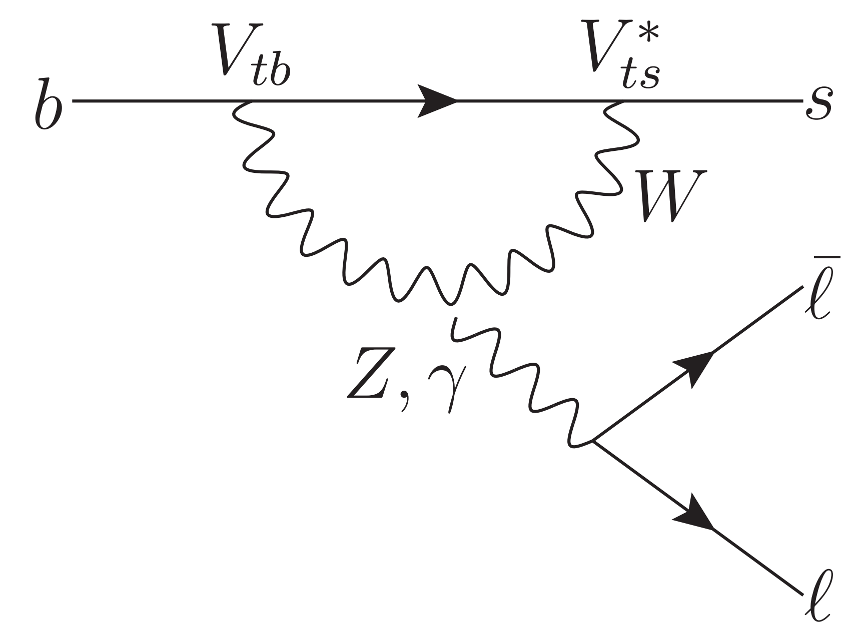

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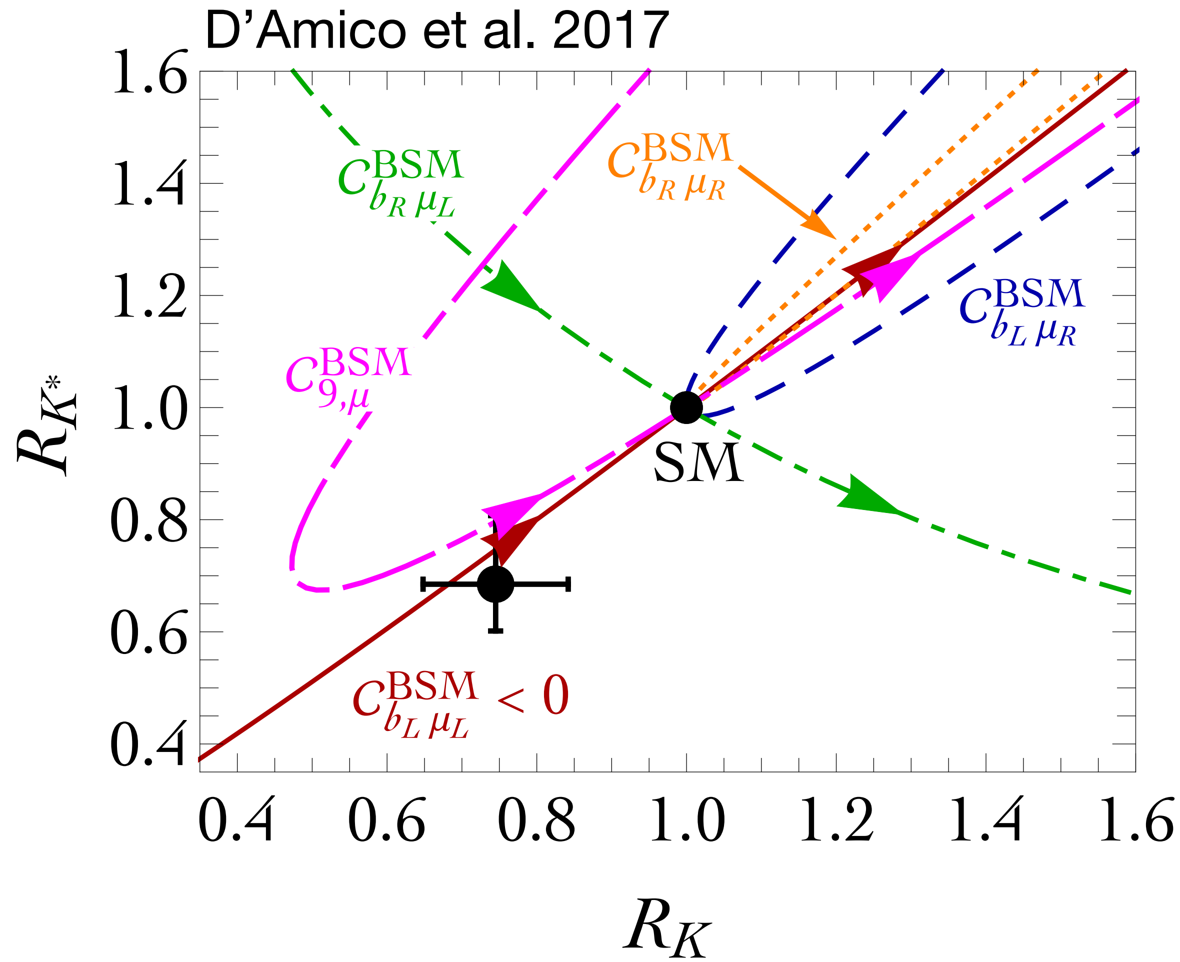


What do we know?

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

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

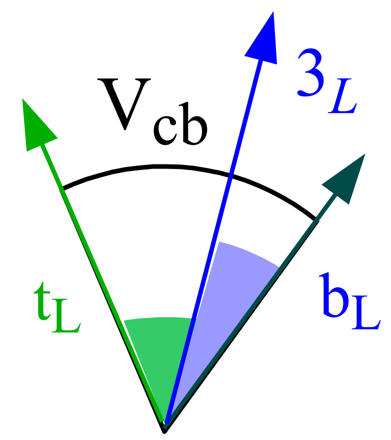
2. Large effect in **3rd generation**: b quarks, $\tau\nu$ competes with SM tree-level

   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

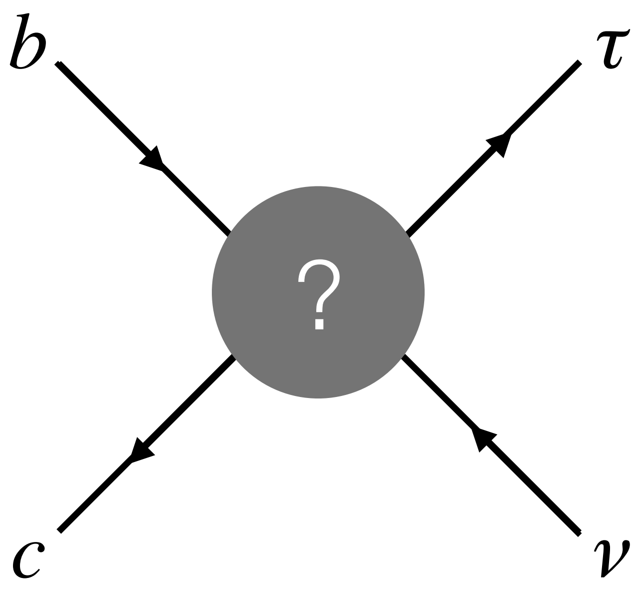
   to avoid large FCNC (true in general for BSM physics)



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

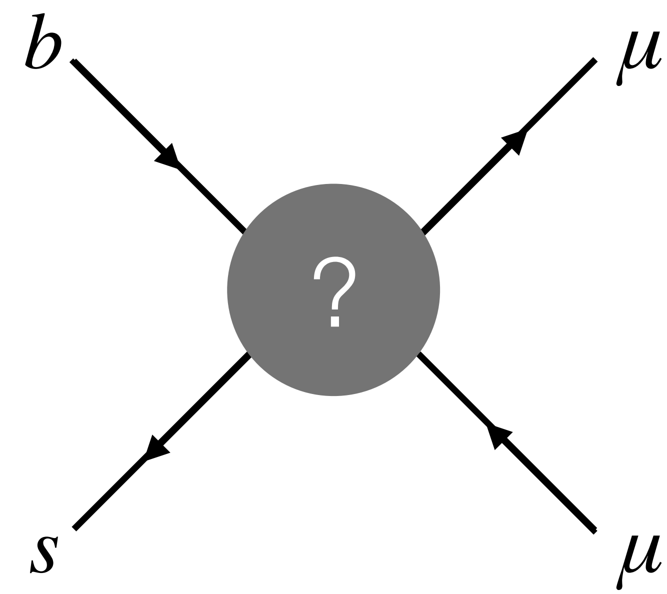
   RH and scalar currents disfavoured: can be present, but do not fit the anomalies (both in charged and neutral current), Higgs-current small or not relevant

Simultaneous explanations



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

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



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

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

1. **“vertical” structure:** the two operators are related by gauge $SU(2)_L$

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

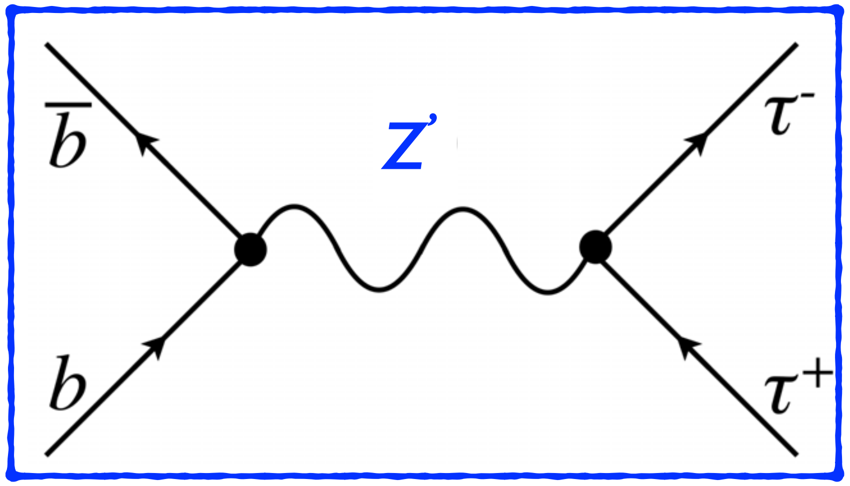
2. **“horizontal” structure:** NP structure reminds of the Yukawa hierarchy

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

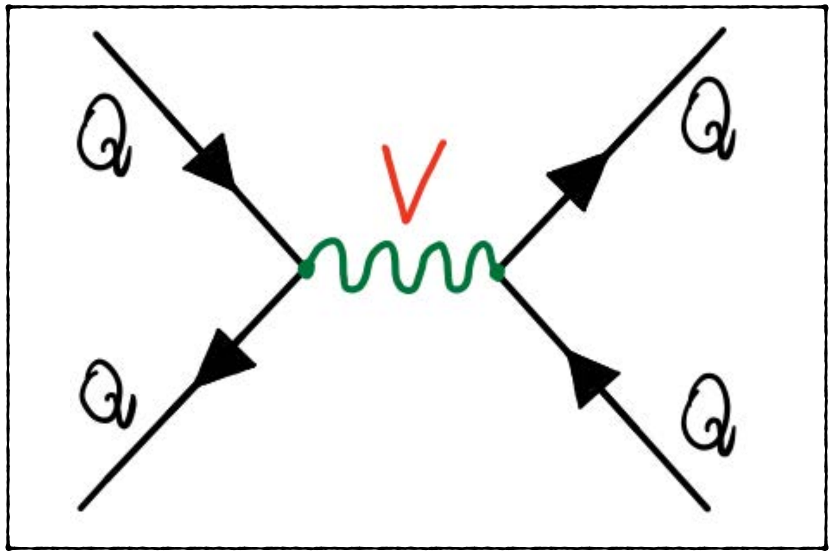
Problems

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

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

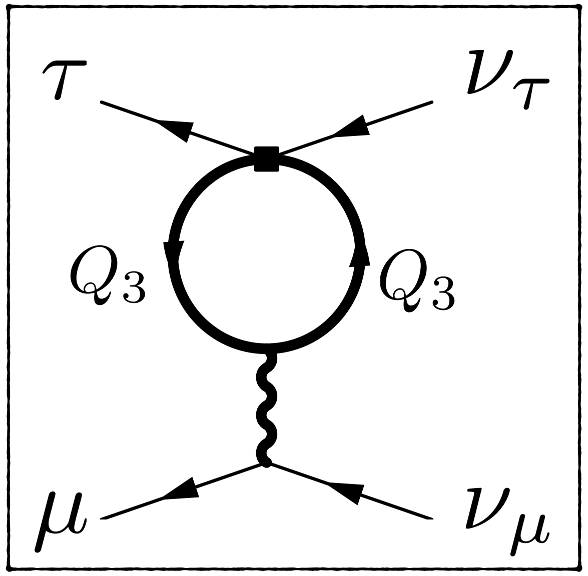


- **Flavour observables:**
  - other semi-leptonic observables
    model independent
  - meson mixing, lepton flavour violation
    depend on the model, generally present



- **ElectroWeak precision tests:**

  W, Z couplings, τ decays, …
  generated radiatively at one-loop



Effective Field Theory for semi-leptonic interactions

1. Left-handed semi-leptonic 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 —

assuming no light new particles, e.g. neutrinos!

(see e.g. 1807.10745 for a different approach)

Effective Field Theory for semi-leptonic interactions

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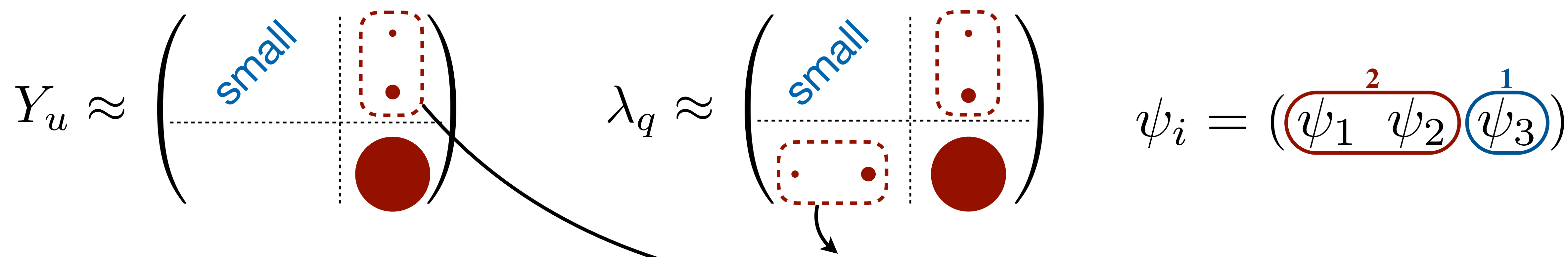
— SU(2) singlet —   — SU(2) triplet —

2. CKM-like flavour pattern: U(2) symmetry for both quarks & leptons



breaking of U(2)$_q$ symmetry

i.e. coupling to third generation only: $Q_L^{(3)} \sim \begin{pmatrix} V_{ib}^* u_L^i \\ b_L \end{pmatrix}$ + small terms (~ V_{CKM})

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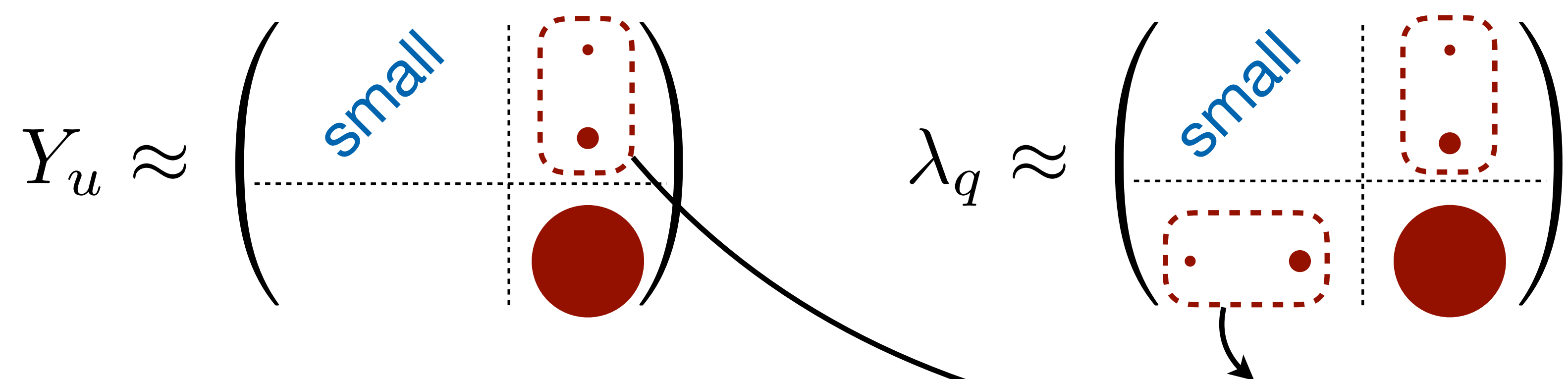

$$\psi_i = ((\psi_1 \;\; \psi_2)_{\mathbf{2}} (\psi_3)_{\mathbf{1}})$$

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i.e. coupling to third generation only: $Q_L^{(3)} \sim \begin{pmatrix} V^*_{ib} u^i_L \\ b_L \end{pmatrix}$ + small terms (~ V_{CKM})

$$\lambda^q_{ij} \approx \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & V_{ts} \\ \cdot & V^*_{ts} & 1 \end{pmatrix} \qquad \lambda^\ell_{\alpha\beta} \approx \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & |V_{\tau\mu}|^2 & V_{\tau\mu} \\ \cdot & V^*_{\tau\mu} & 1 \end{pmatrix}$$

4 parameters relevant for the anomalies

B, Greljo, Isidori, Marzocca, 2017

Effective Field Theory

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

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

***τ* vs *l*:** $$R^{\tau\ell}_{D^{(*)}} \simeq 1 + 2C_T\left(1 + \frac{\lambda^q_{bs}}{V_{cb}}\right) = 1.237 \pm 0.053$$

***μ* vs *e*:** $$R^{\mu e}_{D^{(*)}} \simeq 1 + 2C_T\left(1 + \frac{\lambda^q_{bs}}{V_{cb}}\right)\lambda_{\mu\mu} < 0.02 \quad \Rightarrow \quad \lambda_{\mu\mu} \lesssim 0.1$$

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Neutral currents: ***b* → *s*$\nu_\tau\nu_\tau$** 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* → *s*$\tau\tau$** ~ $C_T + C_S$ is large (100 x SM), weak experimental constraints

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→ $C_T \sim C_S$

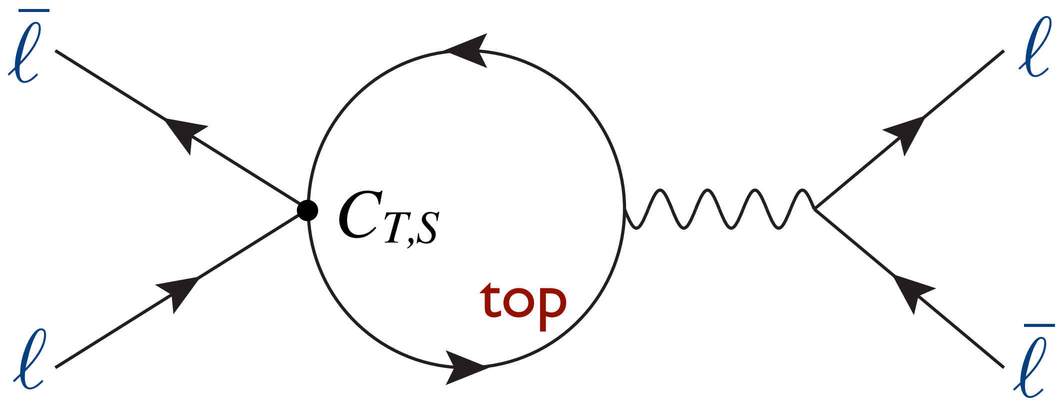
$b \to s\tau\tau$ ~ $C_T + C_S$ is large (100 x SM), weak experimental constraints

$b \to s\mu\mu$ is an independent quantity: fixes the size of $\lambda_{\mu\mu} \sim 10^{-2}$

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

Radiative corrections

- Purely leptonic operators generated at the EW scale by RG evolution



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

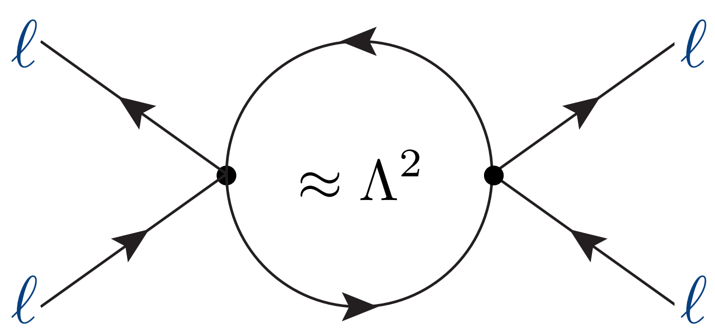
$$\delta g \approx \frac{v^2}{\Lambda^2} \log \frac{\Lambda}{m_W} \lesssim 10^{-3}$$ from LEP

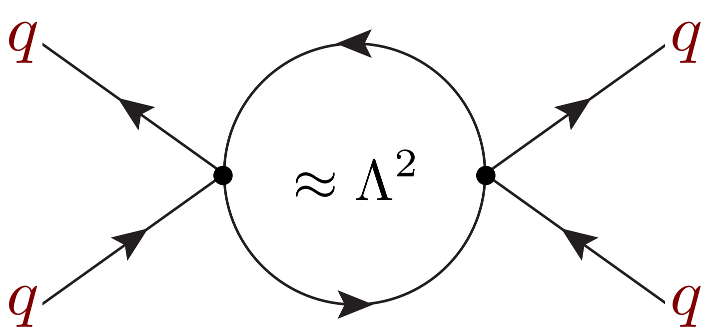
Feruglio et al. 2015

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

(RG-running corrections to four-quark operators suppressed by lepton masses)

- UV contributions (not log-enhanced) are model-dependent

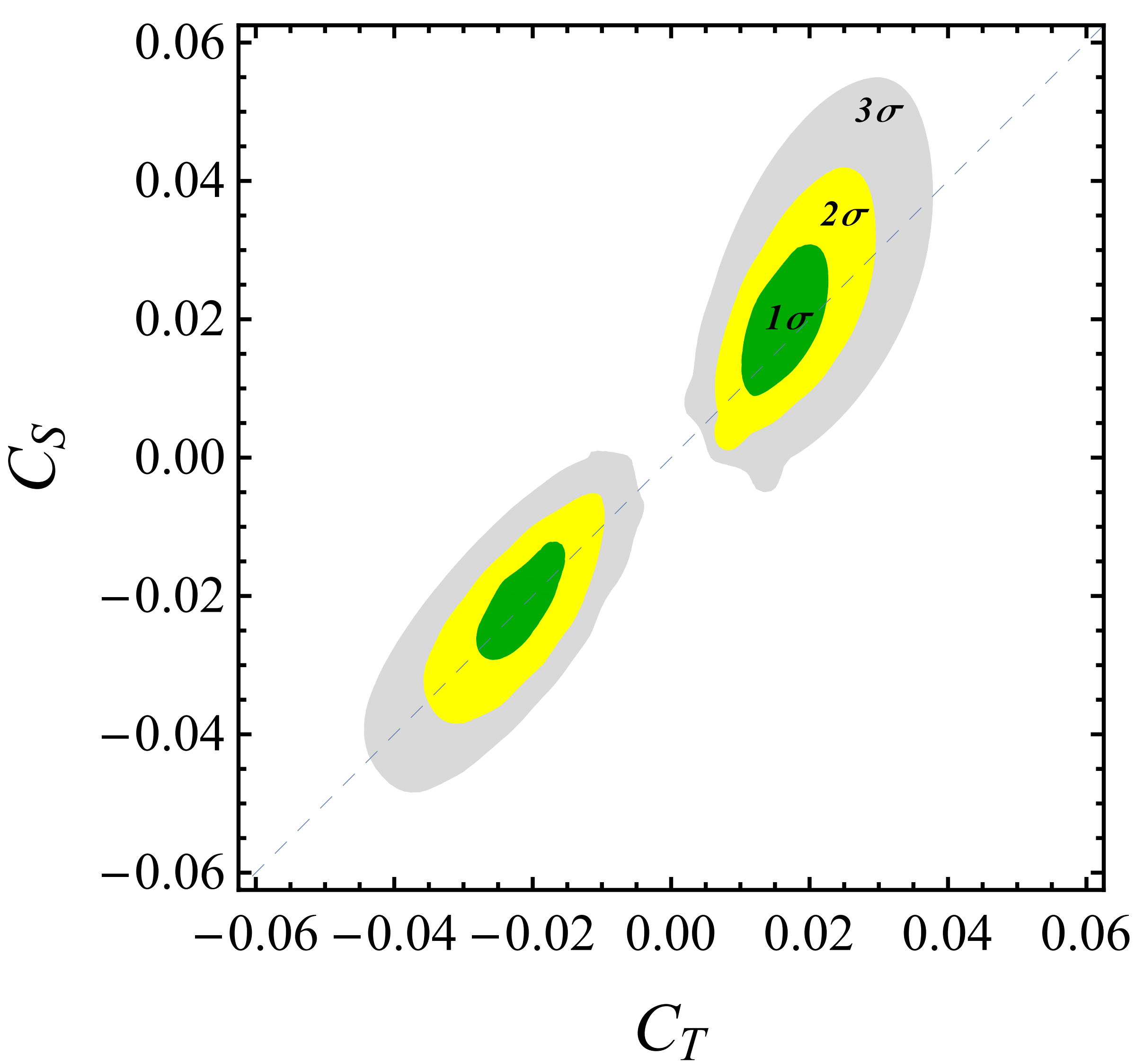


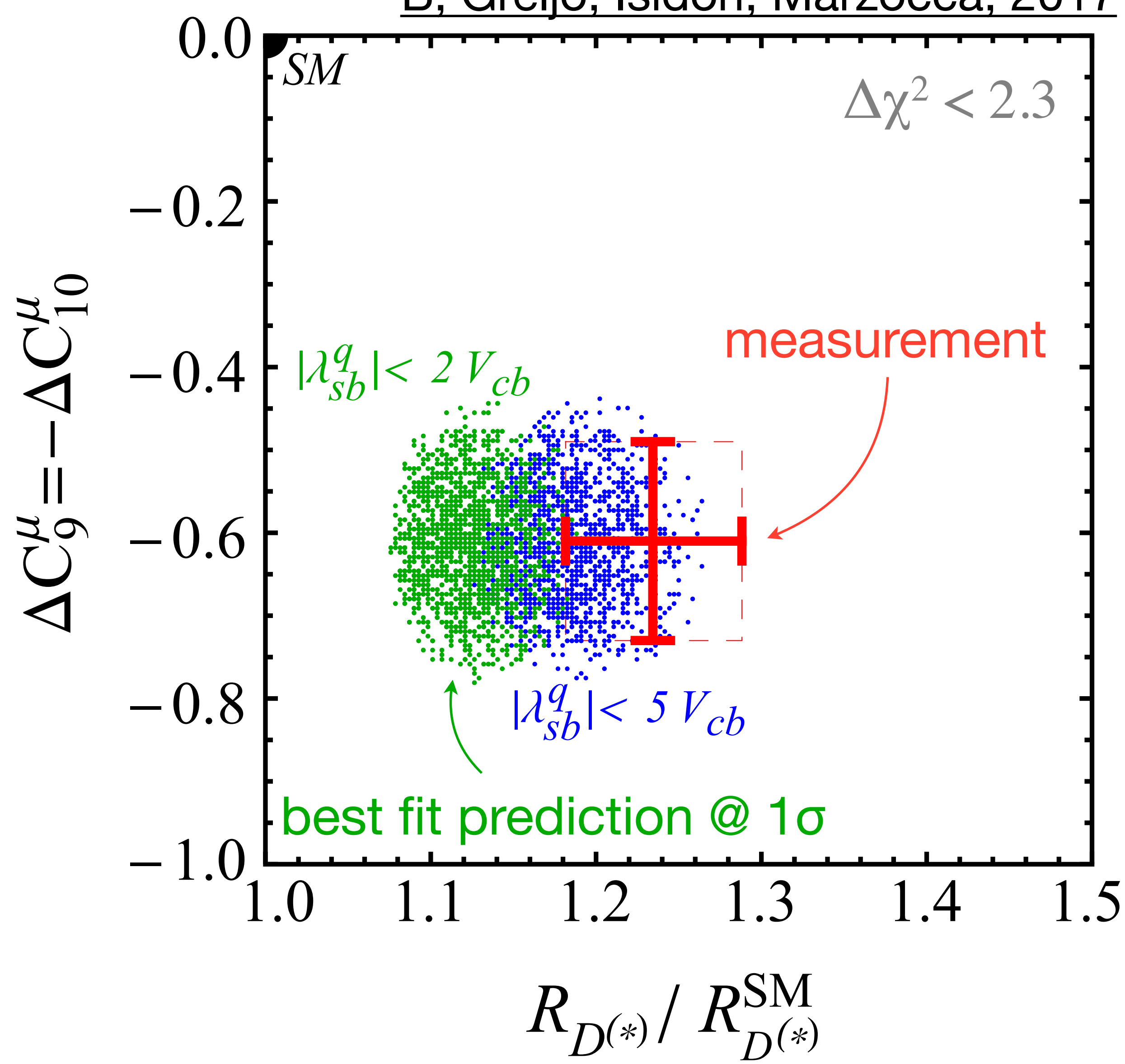


Fit to semi-leptonic observables

- 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)

B, Greljo, Isidori, Marzocca, 2017





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

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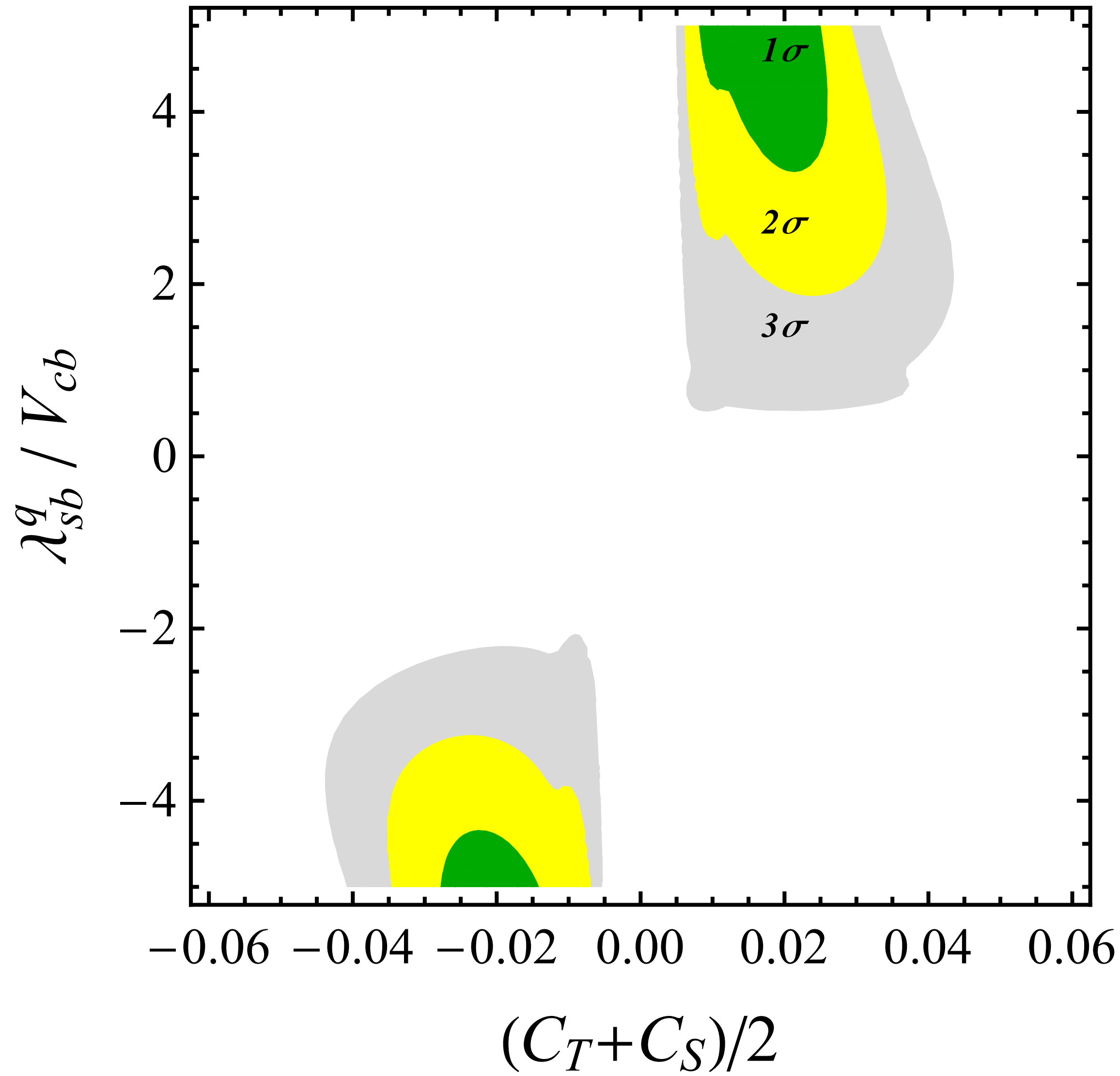

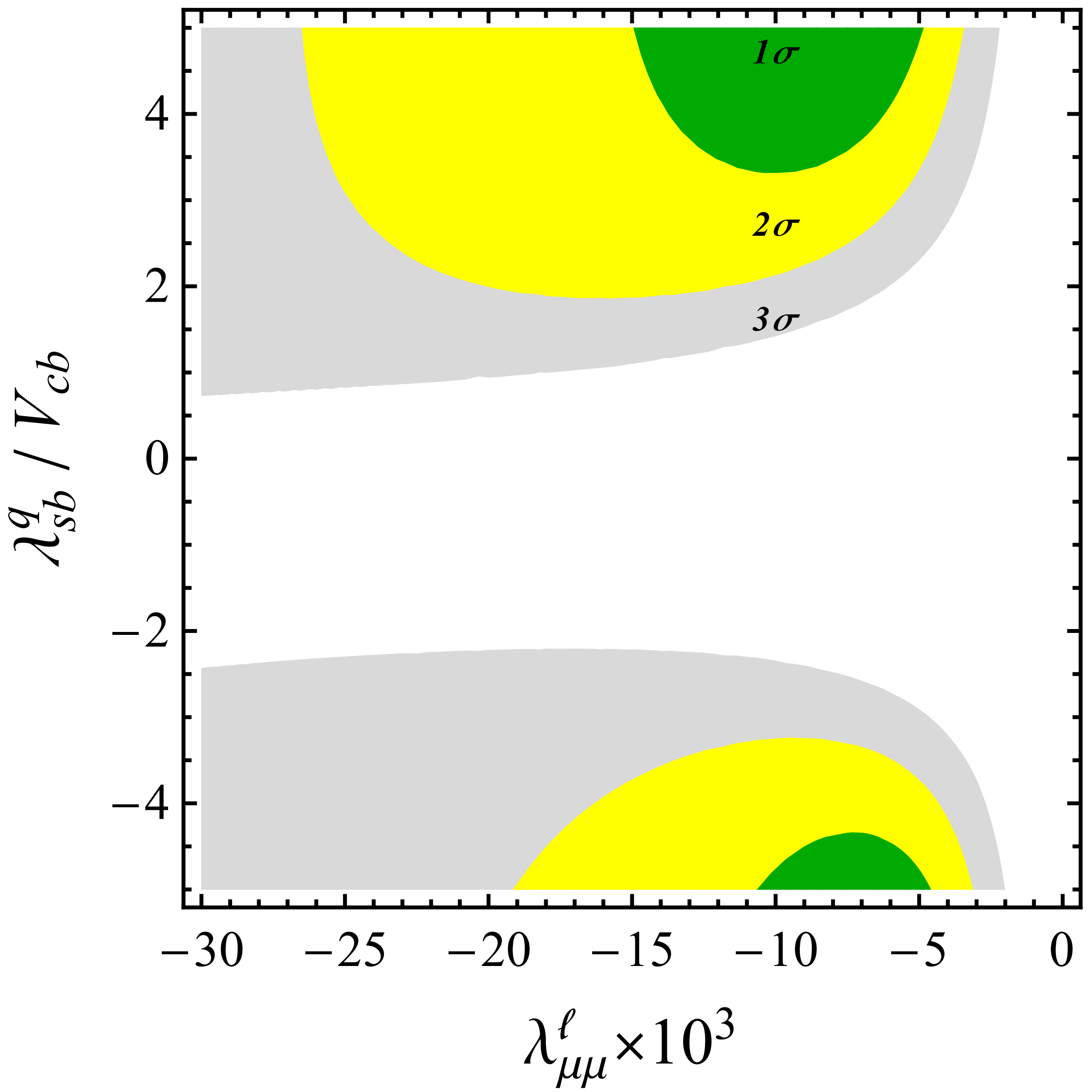

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Testing chirality and flavour structure: charged currents

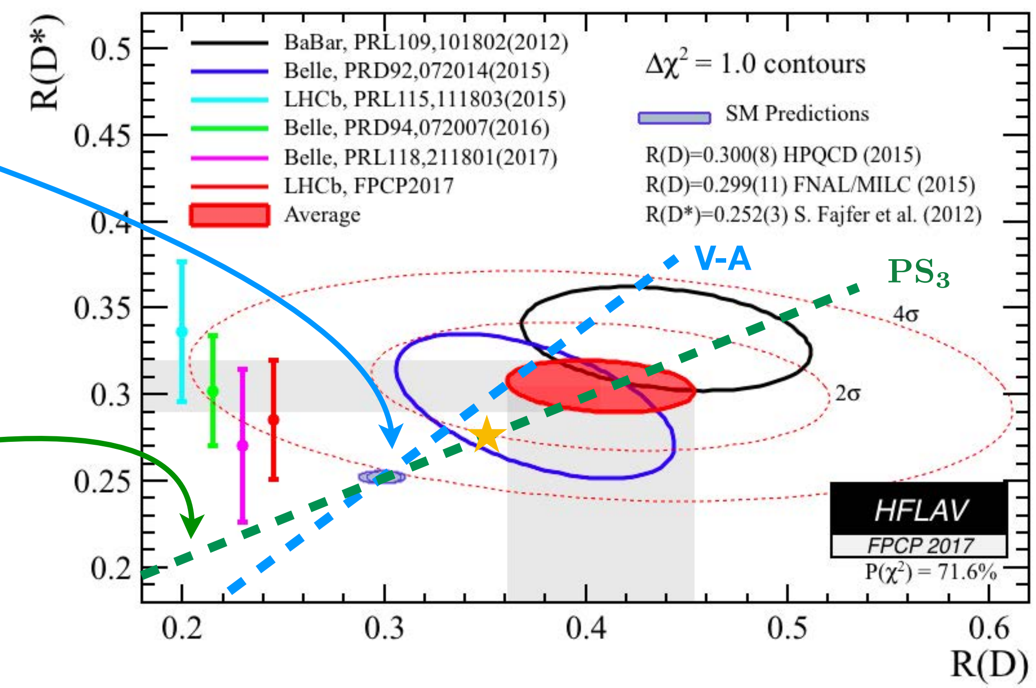
- **LH charged currents:** universality of all $b \to c$ transitions:

$$\mathrm{BR}(B \to D\tau\nu)/\mathrm{BR_{SM}} = \mathrm{BR}(B \to D^*\tau\nu)/\mathrm{BR_{SM}} = \mathrm{BR}(B_c \to \psi\tau\nu)/\mathrm{BR_{SM}}$$

$$= \mathrm{BR}(\Lambda_b \to \Lambda_c\tau\nu)/\mathrm{BR_{SM}} = \ldots$$

  - the presence of RH/scalar currents breaks the correlation

  example: Bordone et al. 1712.01368



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

$$\mathrm{BR}(B \to D^{(*)}\tau\nu)/\mathrm{BR_{SM}} = \mathrm{BR}(B \to \pi\tau\nu)/\mathrm{BR_{SM}} = \mathrm{BR}(B^+ \to \tau\nu)/\mathrm{BR_{SM}}$$

$$= \mathrm{BR}(B_s \to K^*\tau\nu)/\mathrm{BR_{SM}} = \mathrm{BR}(\Lambda_b \to p\tau\nu)/\mathrm{BR_{SM}} = \ldots$$

✓ $\mathrm{BR}(B_u \to \tau\nu)_{\mathrm{exp}}/\mathrm{BR_{SM}} = 1.31 \pm 0.27$ (UTfit 2016)

$$\lambda^q_{ij} \approx \begin{pmatrix} \cdot & \cdot & V_{td} \\ \cdot & \cdot & V_{ts} \\ V^*_{td} & V^*_{ts} & 1 \end{pmatrix}$$

small

CKM matrix

Relation to other observables: neutral currents

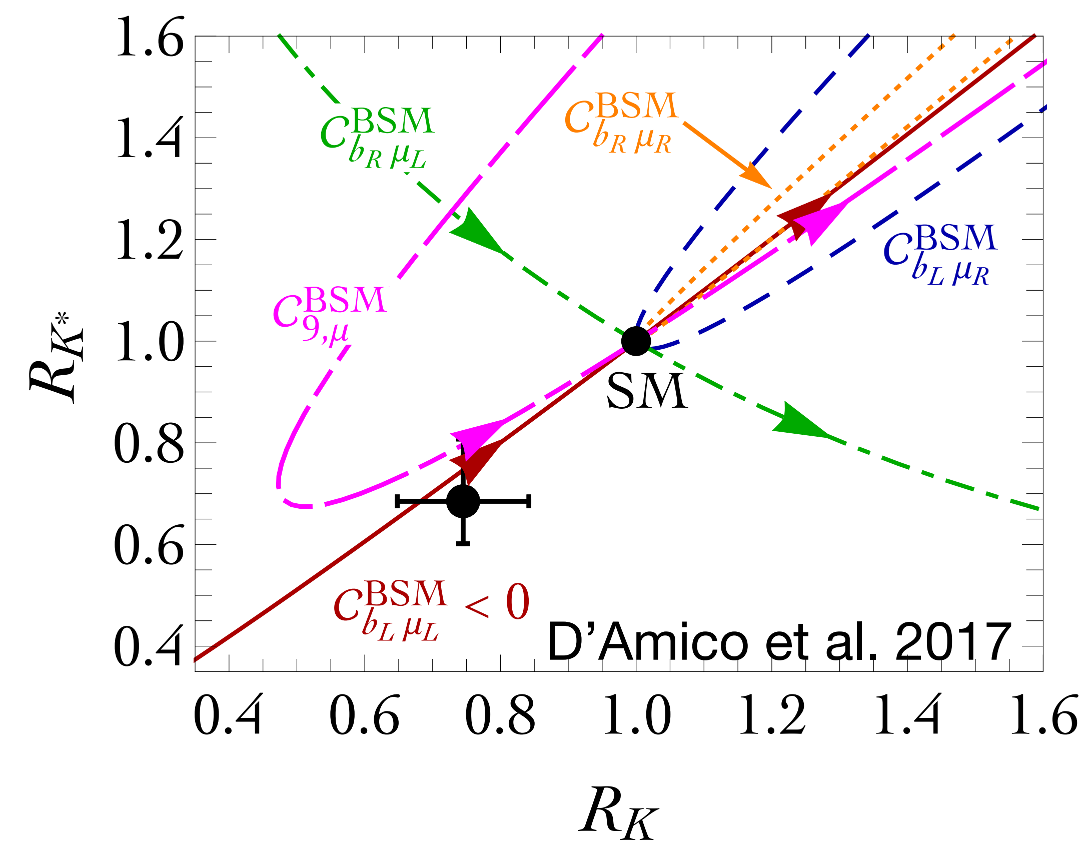
Isidori 2017

Quark flavour ↓ — U(2) symmetry

	μμ (ee)
b → s	R_K, R_{K^*} O(20%)
b → d	$B_d \to \mu\mu$ $B \to \pi\,\mu\mu$ $B_s \to K^{(*)}\,\mu\mu$ O(20%) [$R_K = R_\pi$]
s → d	*long-distance pollution*

\+ any other observable with the same quark-level transition…

independent of R_D



- ✦ the presence of RH/scalar currents breaks the correlation with the SM: e.g. $B \to \mu\mu$, $B \to \tau\tau$, $B \to \tau\mu$ could be enhanced

Relation to other observables: neutral currents

Lepton flavour →

<u>Isidori 2017</u>

Quark flavour ↓ (U(2) symmetry: $b \to s$, $b \to d$)

	$\mu\mu$ (ee)	$\tau\tau$ (SU(2))	$\nu\nu$ (SU(2))
$b \to s$	R_K, R_{K^*} O(20%)	$B \to K^{(*)} \tau\tau$ → 100×SM	$B \to K^{(*)} \nu\nu$ O(1)
$b \to d$	$B_d \to \mu\mu$ $B \to \pi\, \mu\mu$ $B_s \to K^{(*)} \mu\mu$ O(20%) [$R_K = R_\pi$]	$B \to \pi\, \tau\tau$ → 100×SM	$B \to \pi\, \nu\nu$ O(1)
$s \to d$	*long-distance pollution*	*NA*	$K \to \pi\, \nu\nu$ O(1)

SU(2) ($\tau\tau$, $\nu\nu$): cannot suppress both channels

size determined by $R_{D^{(*)}}$

Several correlated effects in other flavour observables.

<u>High-intensity program *is crucial* to test the flavour structure!</u>

Relation to other observables: neutral currents

Isidori 2017

Lepton flavour →

Quark flavour ↓

U(2) symmetry: $b \to s$, $b \to d$

SU(2): ττ, νν

	μμ (ee)	ττ	νν	τμ
$b \to s$	R_K, R_{K^*} O(20%)	$B \to K^{(*)} \tau\tau$ $\to$ 100×SM	$B \to K^{(*)} \nu\nu$ O(1)	$B \to K \tau\mu$ $\to \sim 10^{-6}$
$b \to d$	$B_d \to \mu\mu$ $B \to \pi \mu\mu$ $B_s \to K^{(*)} \mu\mu$ O(20%) $[R_K = R_\pi]$	$B \to \pi \tau\tau$ $\to$ 100×SM	$B \to \pi \nu\nu$ O(1)	$B \to \pi \tau\mu$ $\to \sim 10^{-7}$
$s \to d$	*long-distance pollution*	*NA*	$K \to \pi \nu\nu$ O(1)	*NA*

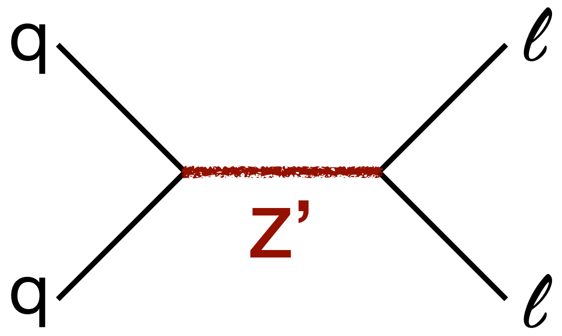
Several correlated effects in other flavour observables.

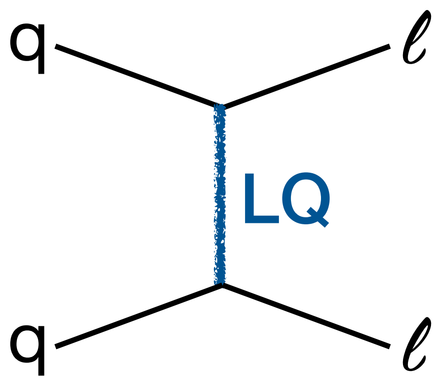
High-intensity program *is crucial* to test the flavour structure!

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	Vector resonance
Colour triplet	Scalar lepto-quark	Vector lepto-quark

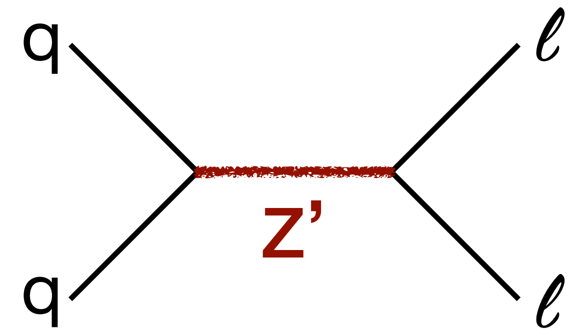


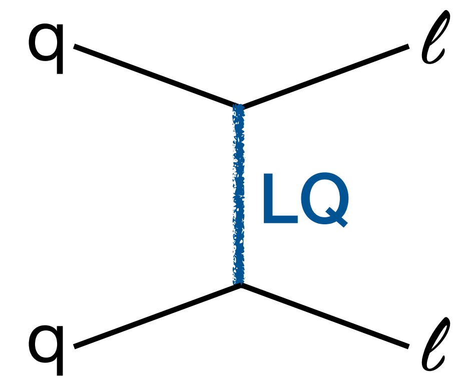


Simplified models

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





$$W' \sim (\mathbf{1}, \mathbf{3}, 0)$$
$$B' \sim (\mathbf{1}, \mathbf{1}, 0)$$

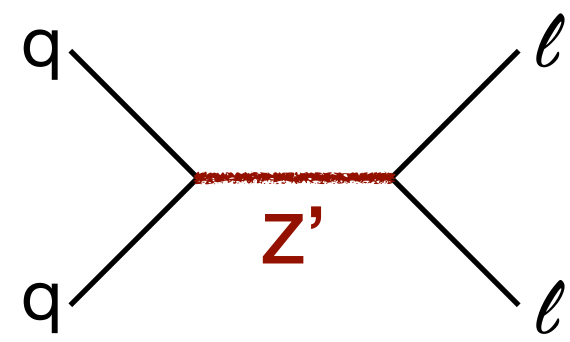
$$S_1 \sim (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$$
$$S_3 \sim (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$$

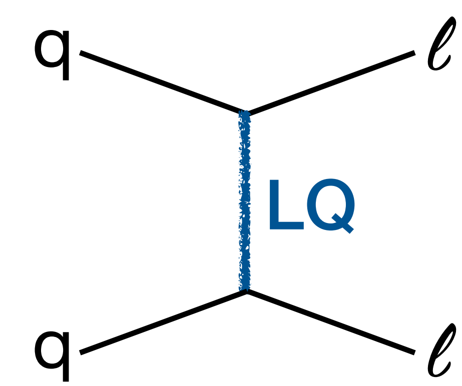
$$U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$$
$$U_3 \sim (\mathbf{3}, \mathbf{3}, 2/3)$$

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

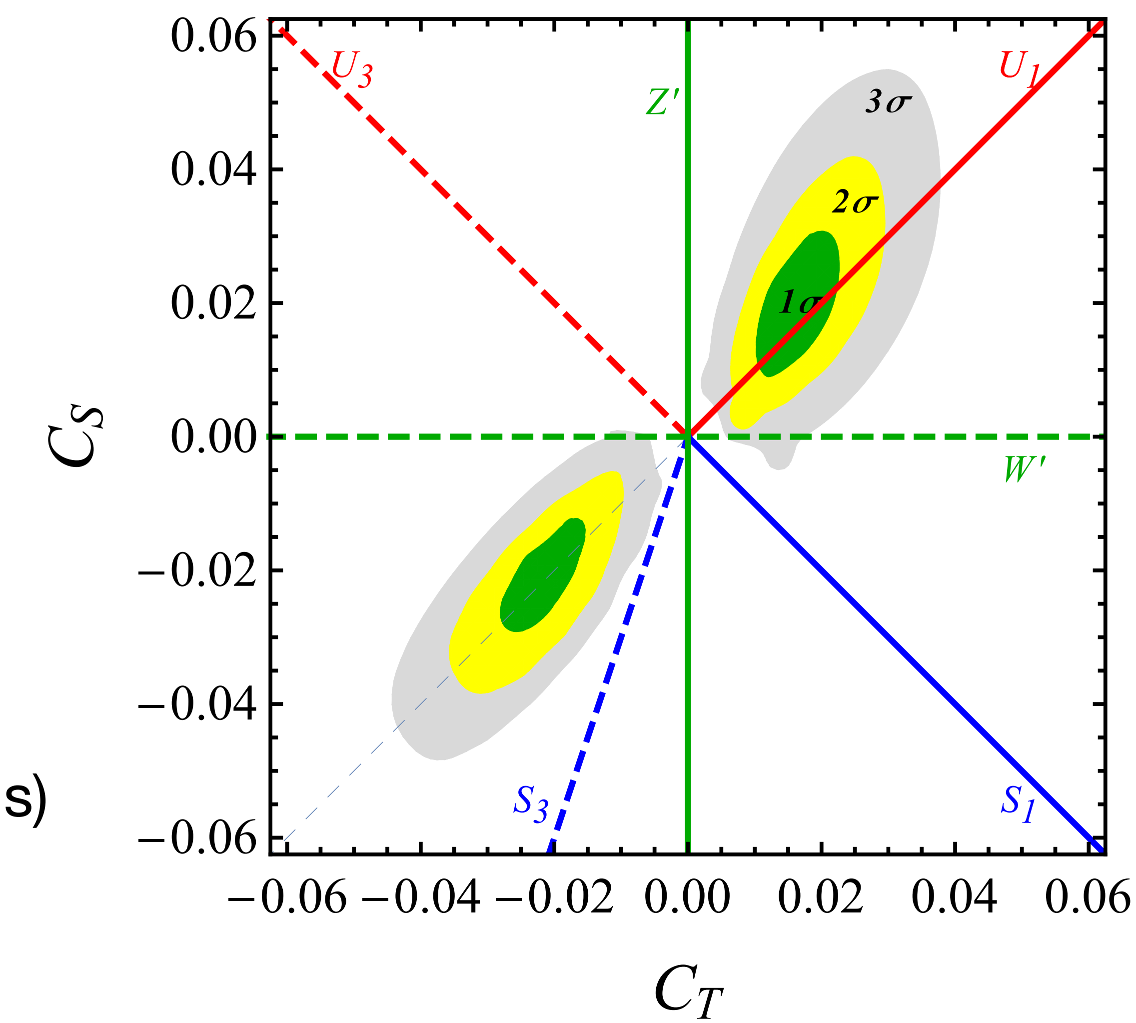




Contributions to C_T and C_S from different mediators:

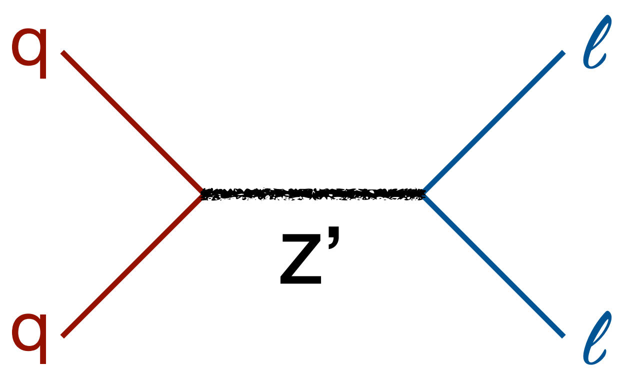
- A **vector leptoquark** is the only single mediator that can fit all the anomalies alone: $C_T \sim C_S$
- Combinations of two or more mediators also possible (often the case in concrete models)

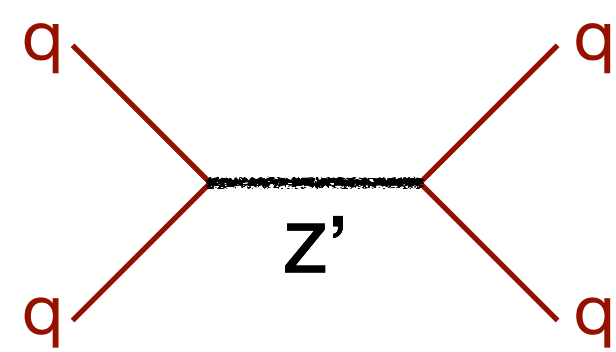
  large $b \to s\nu\nu$ expected in this case!

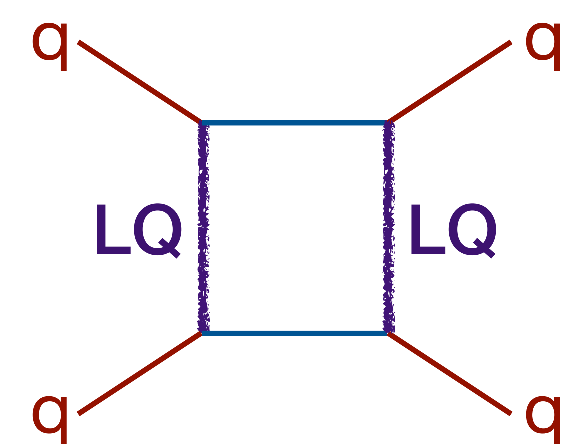


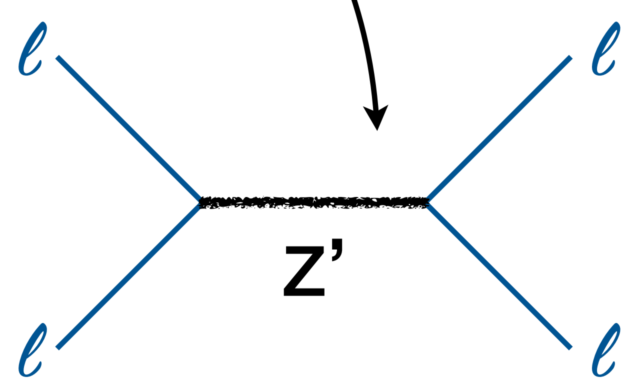
Other observables

In most explicit models, four-quark and four-lepton operators are also present



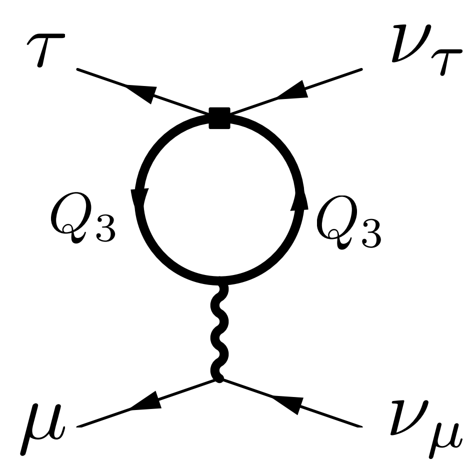






- Bd and Bs mixing:
  O(few %) deviations from SM expected, already in tension with present bounds in most models (vector resonances ☠)
- CP violation in D mixing:
  O(0.1 %) effects

- τ → 3μ:
  large effect expected, possibly close to experimental bound, BR ~ 10^{-9}
- τ vs μ LFU:
  O(0.1 %) deviation in τ → μνν vs. τ → eνν and in $G_F(\tau)$ vs. $G_F(\mu)$

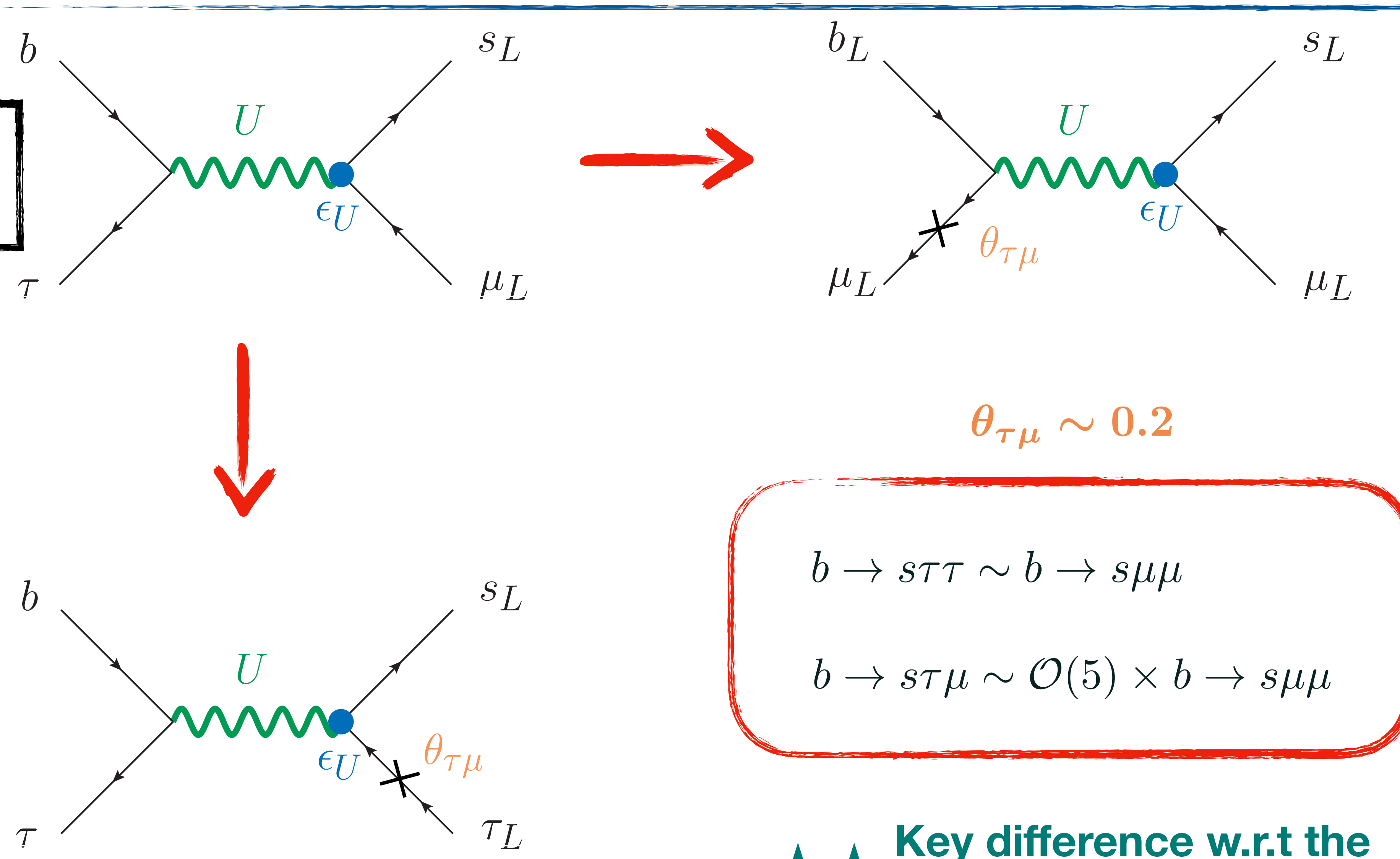


Lepton vs quark couplings: beyond U(2)

A *small* FV coupling to quarks required by meson mixing:
implies lower scale, or large lepton-flavour violation to fit the anomalies

(In concrete models, contributions to EWPT can be calculated beyond leading log approximation… less tension)

Example:
arXiv:1712.01368



$b \to s\tau\tau \sim b \to s\mu\mu$

$b \to s\tau\mu \sim \mathcal{O}(5) \times b \to s\mu\mu$

★★ **Key difference w.r.t the "standard" solutions**

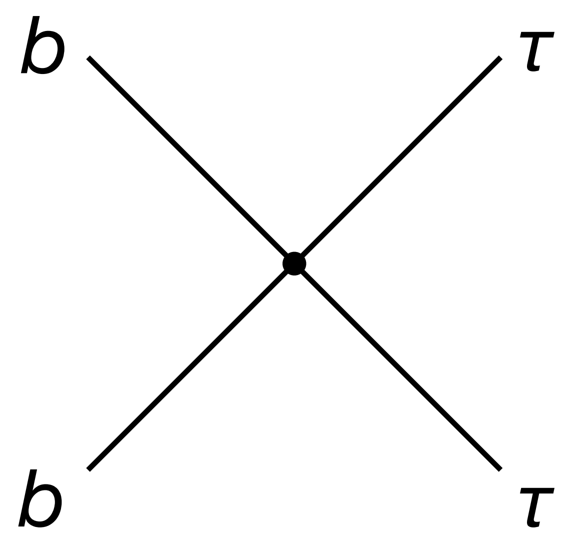
Fuentes (Moriond 2018)

High-pT searches at LHC

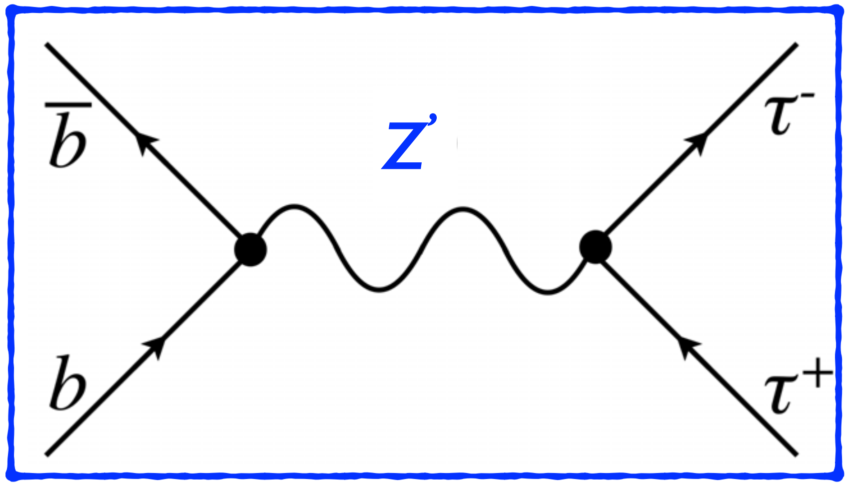
A general feature of any model: large coupling to *b* and *τ*

➡ searches in *ττ* final state at high energy at LHC

PDF of *b* quark small, but still dominant
if compared to flavour suppression

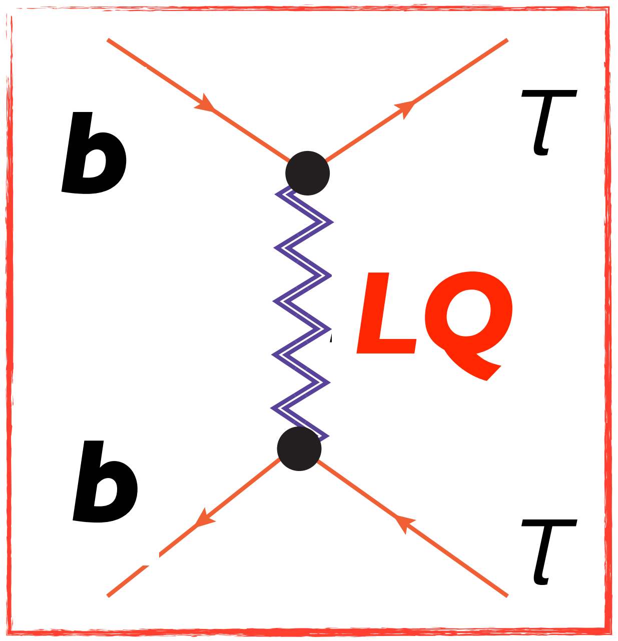


✦ s-channel resonances



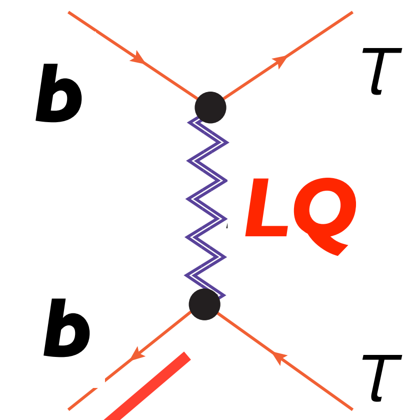
must be broad to escape searches
if below ~ 2 TeV

✦ t-channel exchange: leptoquarks



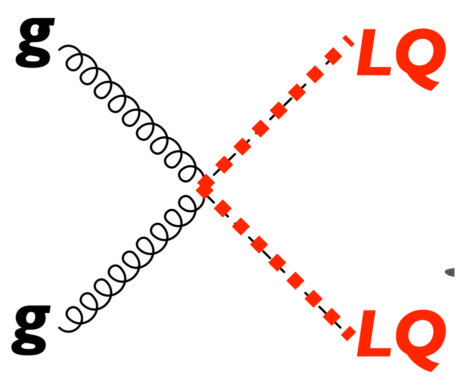
High-pT searches at LHC: leptoquarks

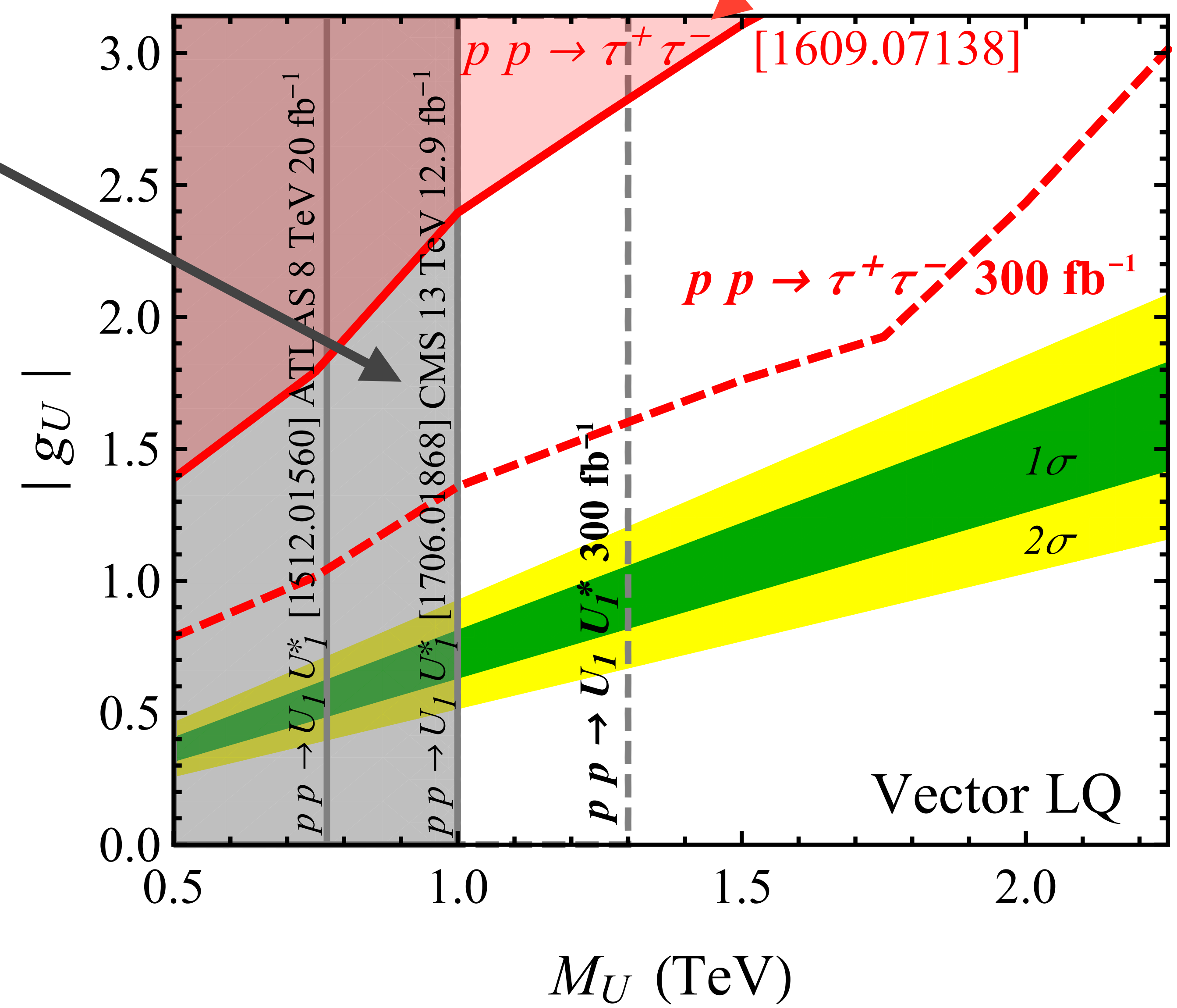
- *bb*-fusion, searches in *ττ* invariant mass distribution



- Pair-production through QCD interaction

Faroughy, Greljo Kamenik 2016





If heavier than ~ 1.3 TeV, could not be visible at LHC!

→ HL-LHC or HE-LHC needed to probe the best-fit region

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

$$\begin{pmatrix} (G_\mu^a)^\alpha_\beta & U_\mu^\alpha \\ (U_\mu^\alpha)^\dagger & Z'_\mu \end{pmatrix}$$

- ✦ No proton decay: protected by gauge $U(1)_{B-L} \subset SU(4)$
- ✦ U_μ gauge vector: universal 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:** extended gauge group

  color can't be completely embedded in SU(4)

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

  Di Luzio et al. 2017
  Isidori et al. 2017

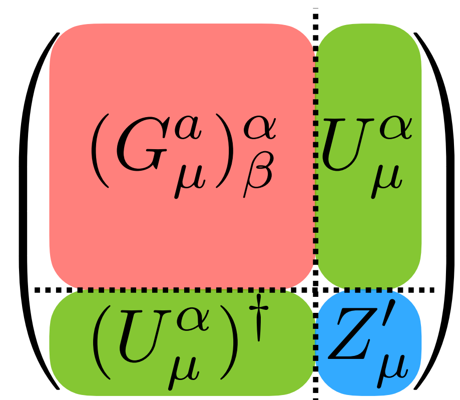
  only the 3rd generation is charged under SU(4)

- **Composite vectors:** resonances of a strongly interacting sector

  with global $SU(4) \times SU(2) \times SU(2)$ Barbieri, Tesi 2017

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

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



Searches at LHC!

A composite UV completion: scalar leptoquarks

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

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

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

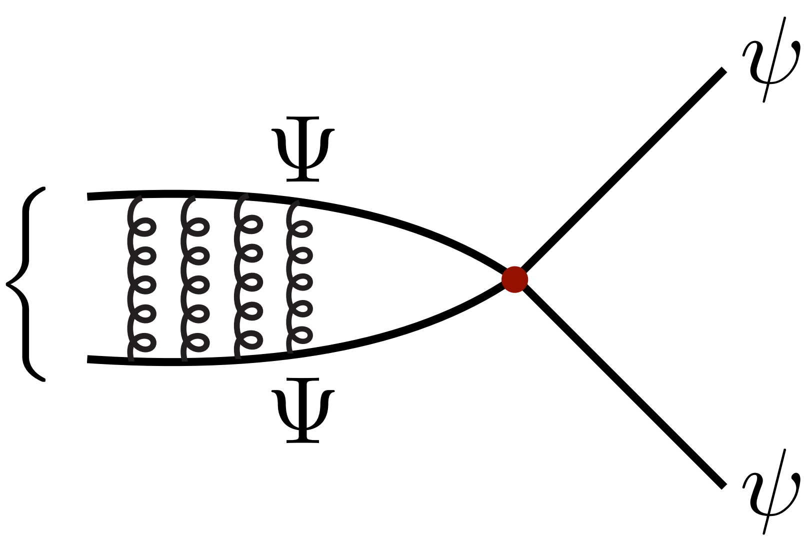
- If the fermions are charged under SM gauge group, then also the pseudo Nambu-Goldstone bosons have SM charges:

$$\Psi_Q \sim (\mathbf{3}, \mathbf{2}, Y_Q), \qquad \Psi_L \sim (\mathbf{1}, \mathbf{2}, Y_L) \longrightarrow$$

$$S_1 \sim (\mathbf{3}, \mathbf{1}, Y_Q - Y_L),$$
$$S_3 \sim (\mathbf{3}, \mathbf{3}, Y_Q - Y_L),$$
$$\eta \sim (\mathbf{1}, \mathbf{1}, 0),$$
$$\pi \sim (\mathbf{1}, \mathbf{3}, 0), \quad \cdots$$
$$H \sim (\mathbf{1}, \mathbf{2}, \pm 1/2)$$

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

$\varphi = [\bar{\Psi}\Psi]$



- **composite Higgs** as a pNGB can be included in the picture

B, Greljo, Isidori, Marzocca 2017
➡ Marzocca, 2018

Summary

- Lepton Flavour Universality violations: natural possibility in BSM physics. Present hints consistent with Yukawa-like couplings.
  Data of the coming years (months?) will confirm/disprove the picture

- **High-precision program** is essential to probe the flavour structure of the new interactions. Pure LH currents? U(2) symmetry? tau physics?

- Correlations/cancellations can be present in explicit models.
  Predictions might be different from general "model independent" EFT

- Leptoquarks are interesting! Pati-Salam unification? Goldstone bosons?

- Interplay between flavour / high-pT searches important.

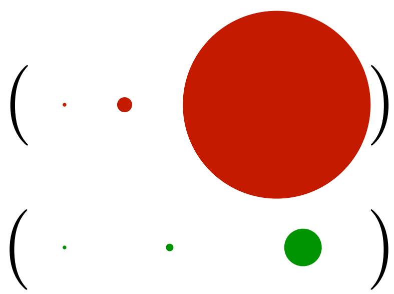

LE ZOO
Backup

U(2) flavour symmetry

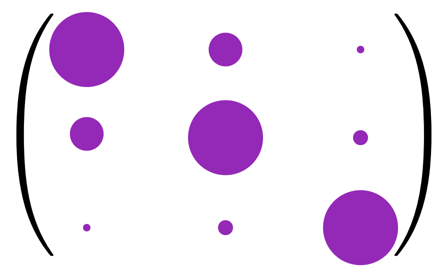
SM Yukawa couplings exhibit an approximate $U(2)^3$ flavour symmetry:

$m_u \sim$

$m_d \sim$



$V_{\mathrm{CKM}} \sim$



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

$$\psi_i = (\overbrace{\psi_1 \;\; \psi_2}^{\mathbf{2}} \; \overbrace{\psi_3}^{\mathbf{1}})$$

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

Breaking pattern:

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

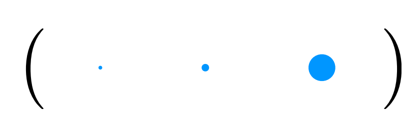
$$\Delta \sim (\mathbf{2}, \mathbf{2}, \mathbf{1})$$

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

Barbieri, B, Sala, Straub, 2012

2. The *assumption* of a single spurion V_q connecting the 3rd generation with the other two ensures MFV-like FCNC protection

3. Can be extended to the charged-lepton sector $m_\ell \sim$



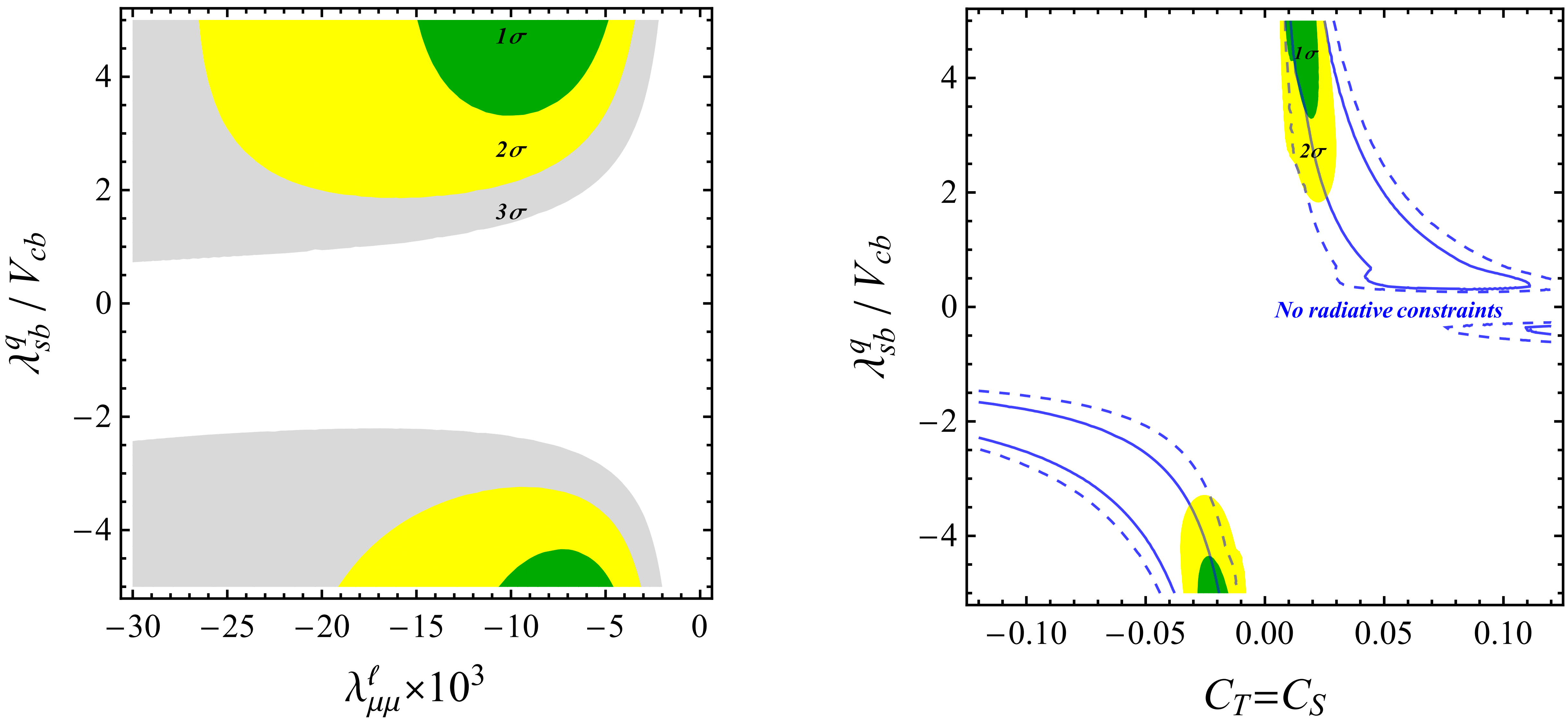
Fit to semi-leptonic operators

Observables that enter in the fit:

Observable	Exp. bound	Linearised expression
$R^{\tau\ell}_{D^{(*)}}$	1.237 ± 0.053	$1 + 2C_T(1 + \lambda^q_{sb}\frac{V_{cs}}{V_{cb}})(1 - \lambda^\ell_{\mu\mu}/2)$
$\Delta C^\mu_9 = -\Delta C^\mu_{10}$	-0.61 ± 0.12	$-\frac{\pi}{\alpha_{\rm em} V_{tb} V^*_{ts}}\lambda^\ell_{\mu\mu}\lambda^q_{sb}(C_T + C_S)$
$R^{\mu e}_{b\to c} - 1$	0.00 ± 0.02	$2C_T(1 + \lambda^q_{sb}\frac{V_{cs}}{V_{cb}})\lambda^\ell_{\mu\mu}$
$B_{K^{(*)}\nu\nu}$	0.0 ± 2.6	$1 + \frac{2}{3}\frac{\pi}{\alpha_{\rm em} V_{tb} V^*_{ts} C^{\rm SM}_\nu}(C_T - C_S)\lambda^q_{sb}(1 + \lambda_{\mu\mu})$
$\delta g^Z_{\tau_L}$	-0.0002 ± 0.0006	$0.38 C_T - 0.47 C_S$
N_ν	2.9840 ± 0.0082	$3 - 0.19 C_S - 0.15 C_T$
$\lvert g^W_\tau / g^W_\ell \rvert$	1.00097 ± 0.00098	$1 - 0.09 C_T$

- Include all the terms generated in the RG running
- Do not include any UV contribution to non-semi-leptonic operators
  (they will depend on the dynamics of the specific model)

Fit to semi-leptonic operators



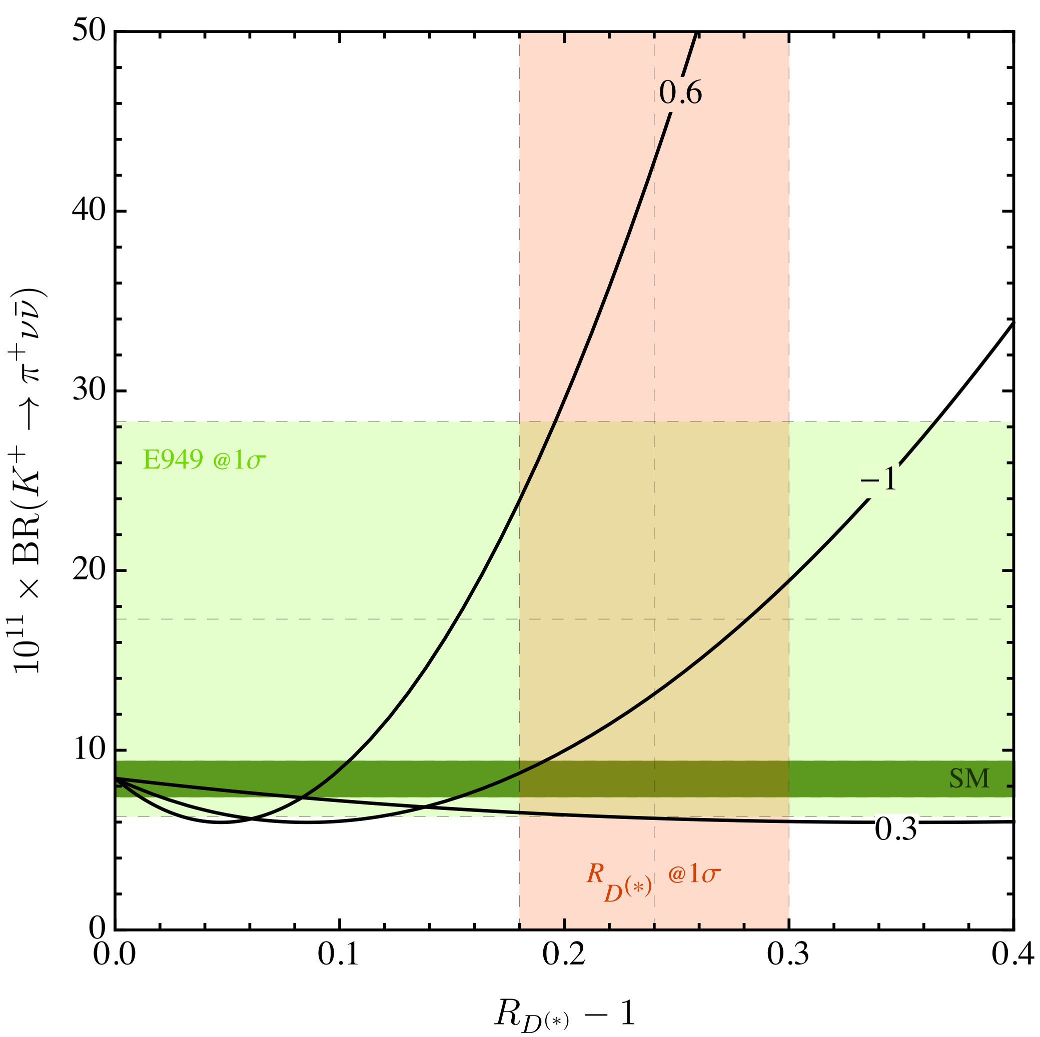
- Small values of C_T required by radiative constraints
- $\lambda_{\mu\mu}$ must be negative to fit C_9

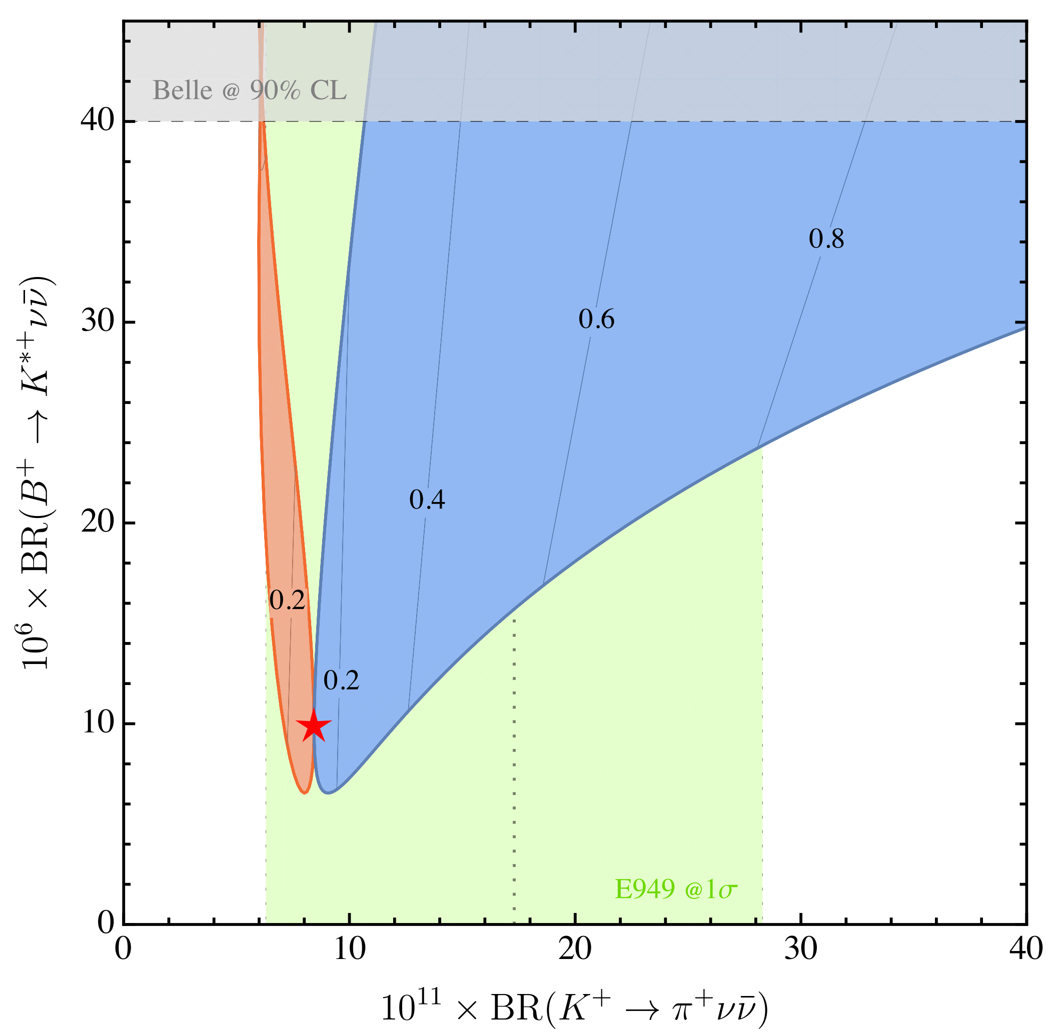
  this rules out the "pure mixing" scenario in the lepton sector (where $\lambda_{\mu\mu} \sim \sin\theta_{\tau\mu}^2$)

$K \to \pi\nu\nu$

- 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): $\lambda_{sd} \sim V_q V_q^* \sim V_{ts}^* V_{td}$ $\quad \lambda_{bq} \sim V_q \sim V_{tq}^*$

Bordone, B, Isidori, Monnard 2017



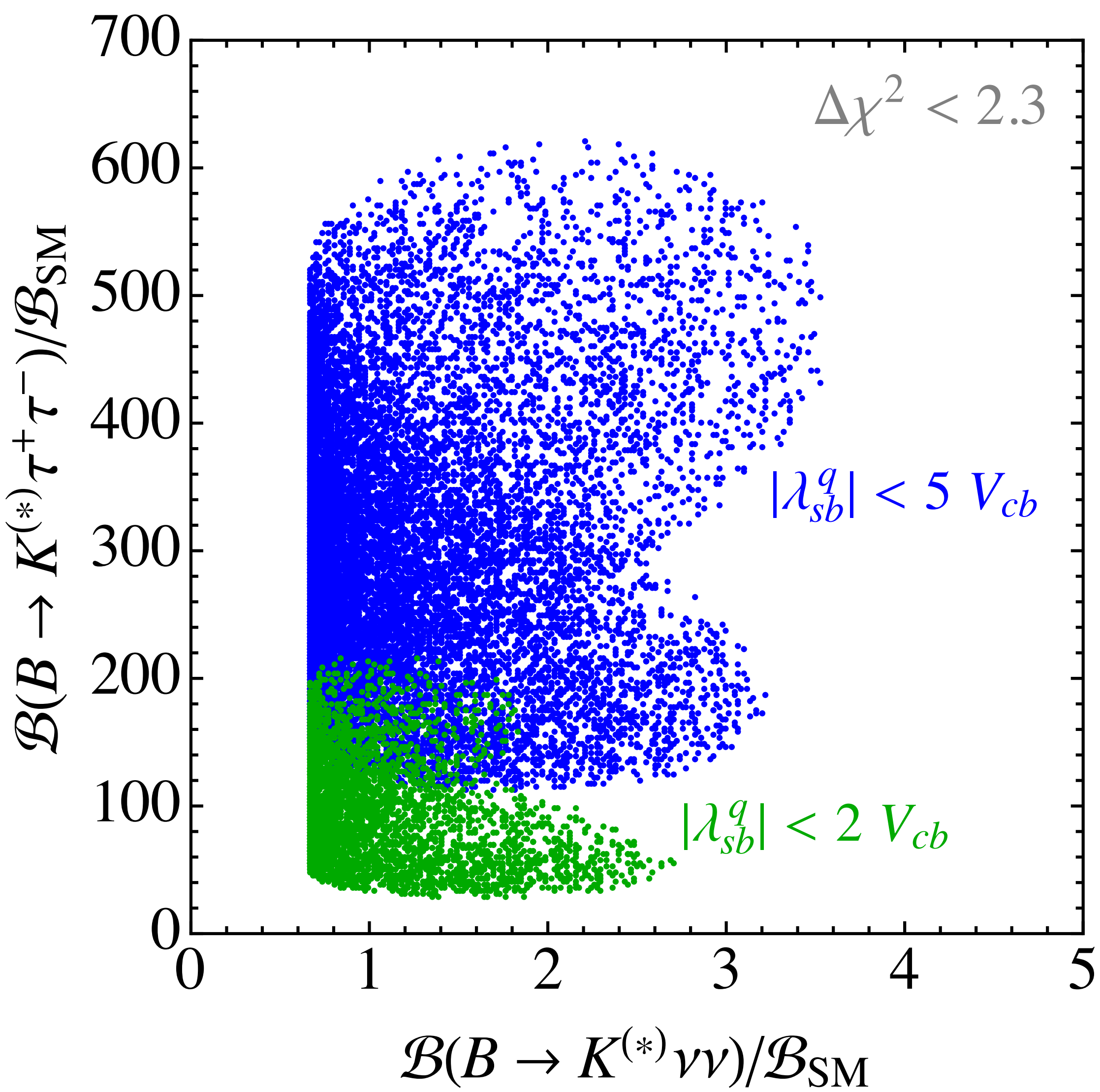


Relation to other observables: $b \to s\tau\tau$

- ***b* → *sττ*** is determined by (λ_{bs}, C_T, C_S) only

$$\Delta C_{9,\tau} = -\frac{\pi}{\alpha V_{ts}^* V_{tb}} \lambda_{sb}^q (C_T + C_S) = \Delta C_{9,\mu}/\lambda_{\mu\mu}^\ell$$

large enhancements possible (up to 10^2-10^3): maybe in reach of Belle II



- SM value: BR($B \to K\tau\tau$) ~ 10^{-7}
- Exp. bounds:

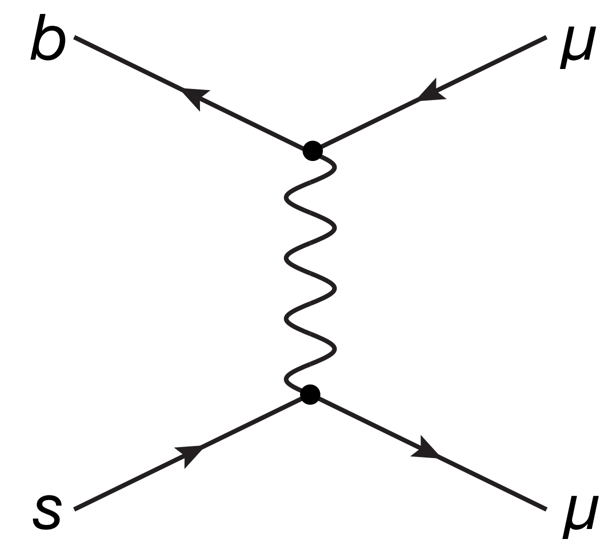
  Belle: BR($B \to K\tau\tau$) < 10^{-3}

  Belle II: ΔBR($B \to K\tau\tau$) ~ 10^{-4}–10^{-5}

  possible at LHCb?

Vector leptoquarks

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



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

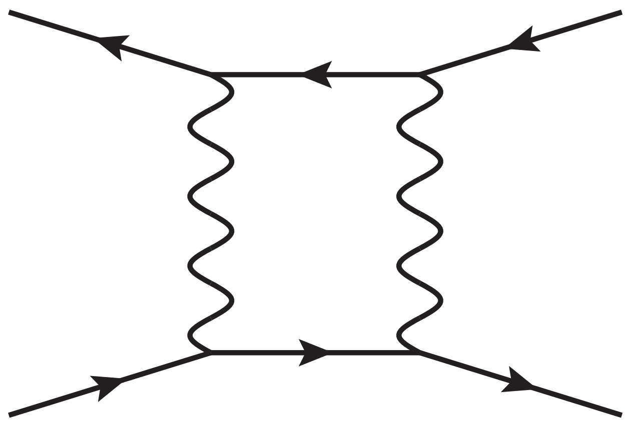
- $C_T = C_S$ automatically satisfied at tree-level

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

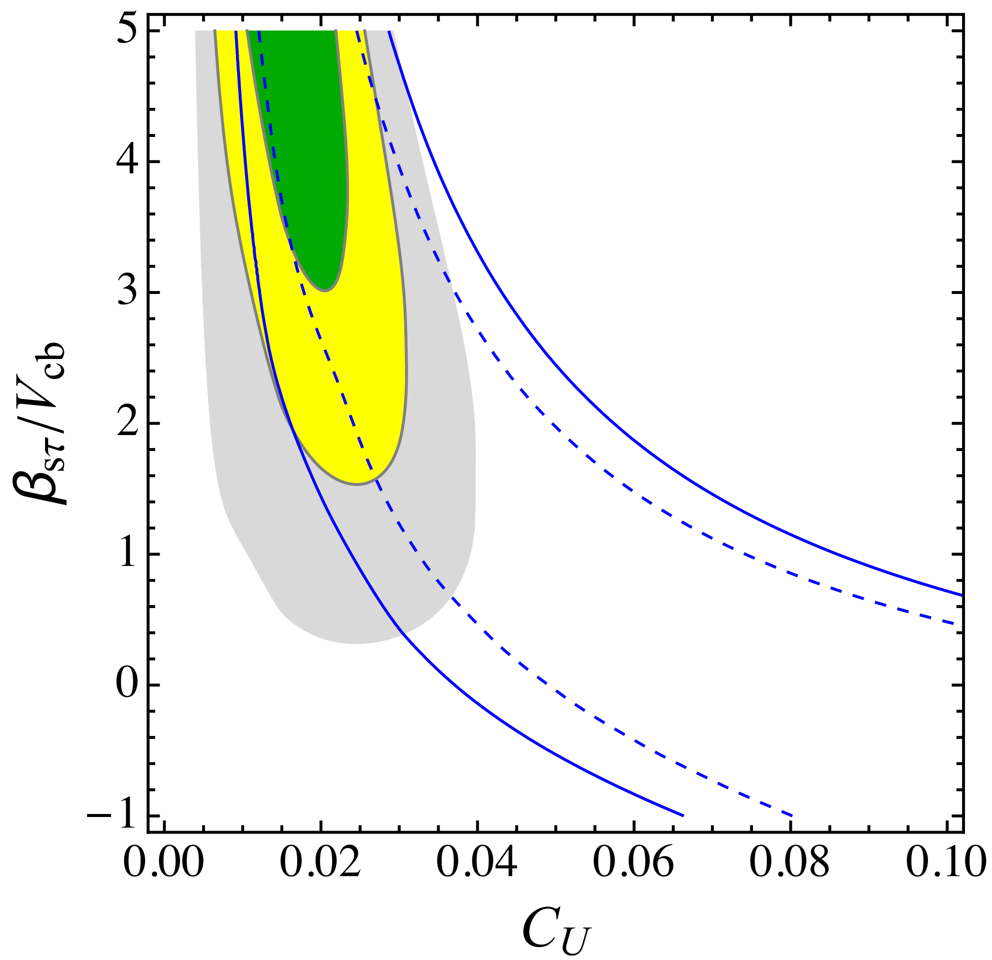
$$C_U = \frac{v^2 |g_U|^2}{2 m_U^2}$$

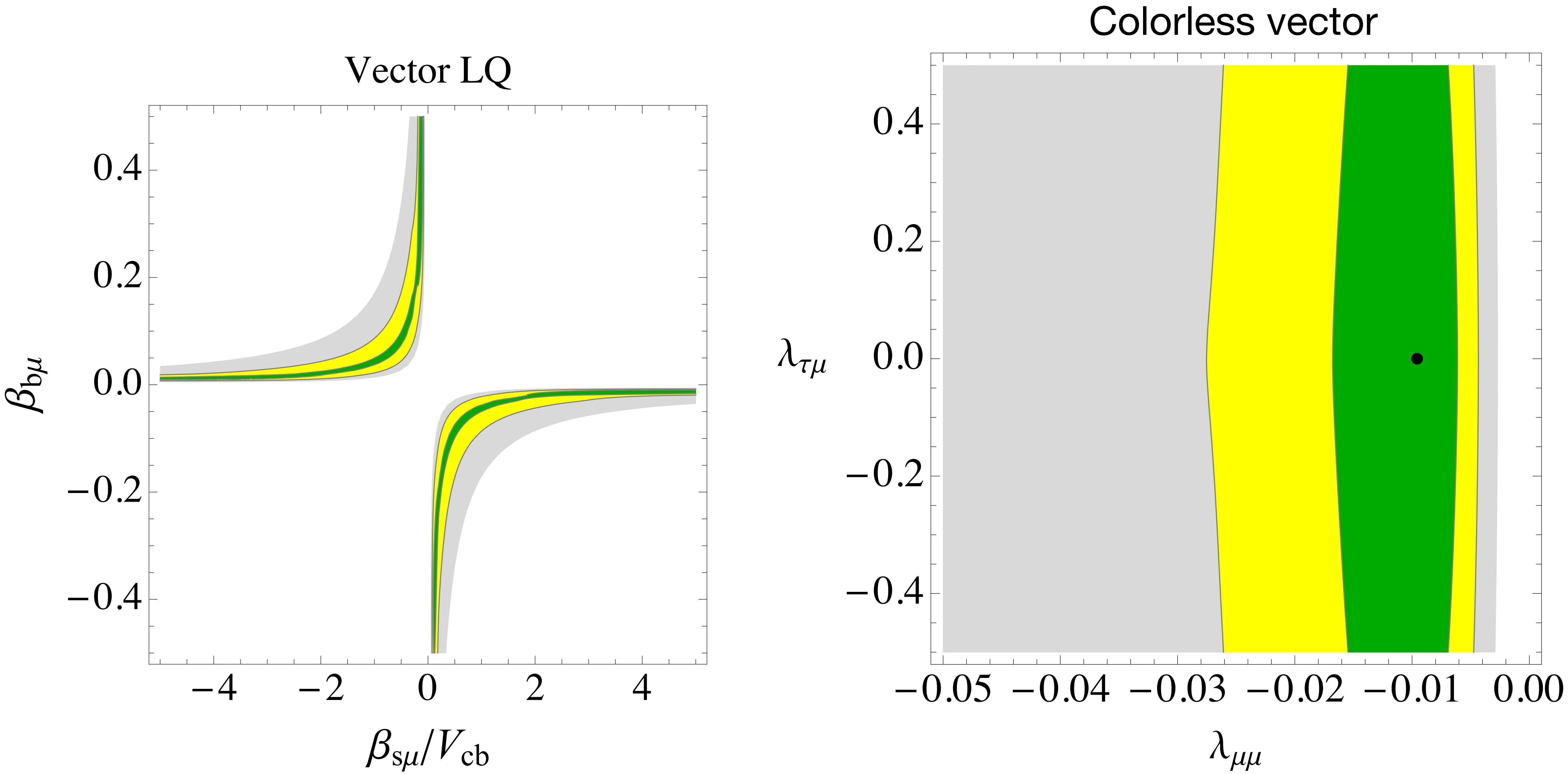
- No tree-level contribution to B$_{(s)}$-$\bar{\rm B}_{(s)}$ mixing, but UV contributions not calculable

naïve estimate:



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





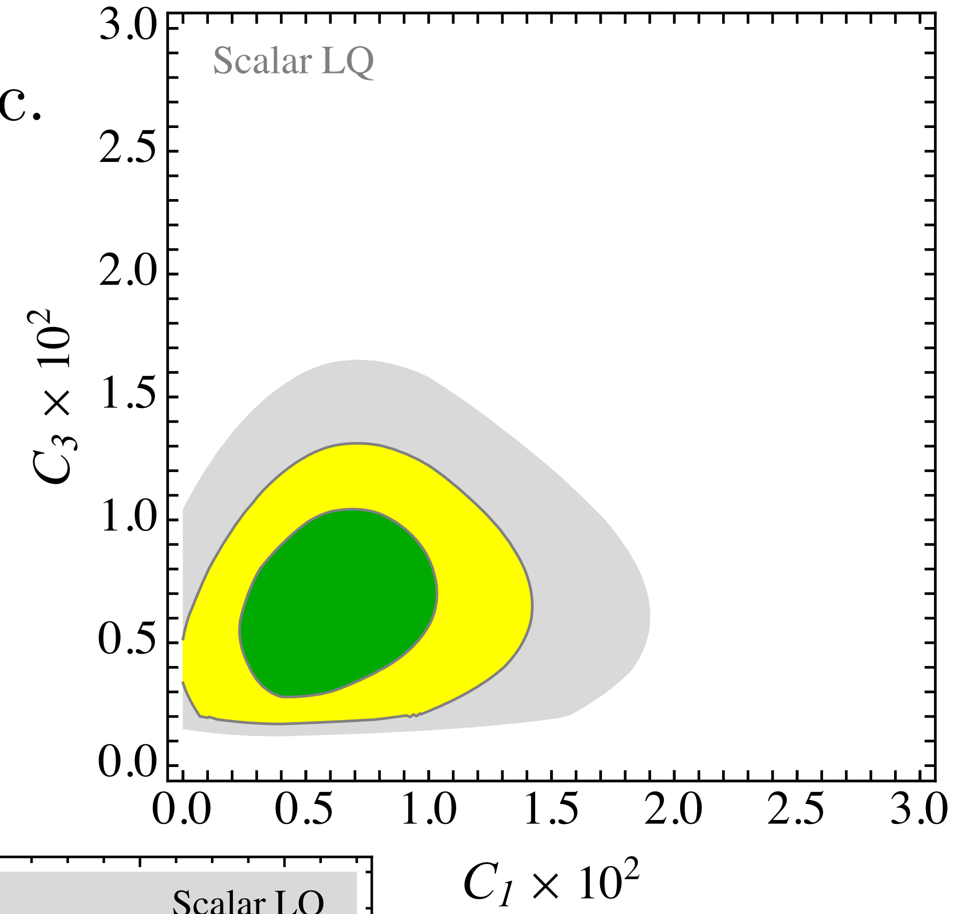
Vector LQ
0.4
0.2
0.0
−0.2
−0.4
−4
−2
0
2
4
$\beta_{b\mu}$
$\beta_{s\mu}/V_{cb}$
Colorless vector
0.4
0.2
0.0
−0.2
−0.4
−0.05
−0.04
−0.03
−0.02
−0.01
0.00
$\lambda_{\tau\mu}$
$\lambda_{\mu\mu}$

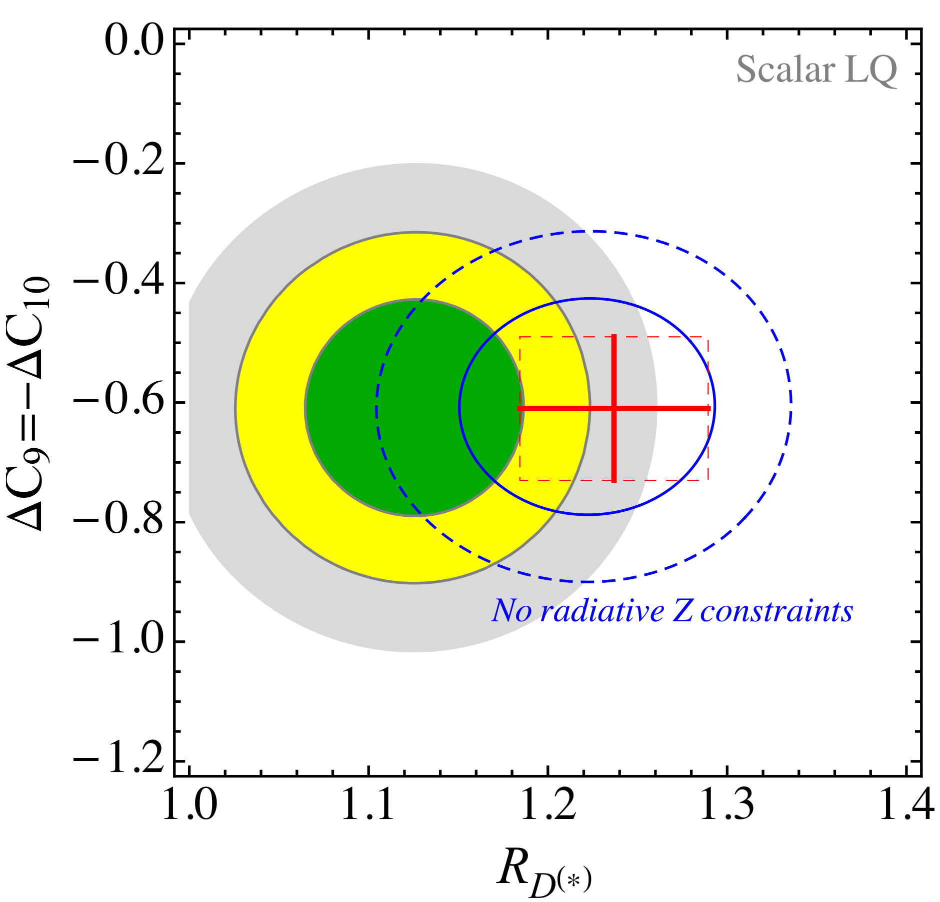
Scalar leptoquarks

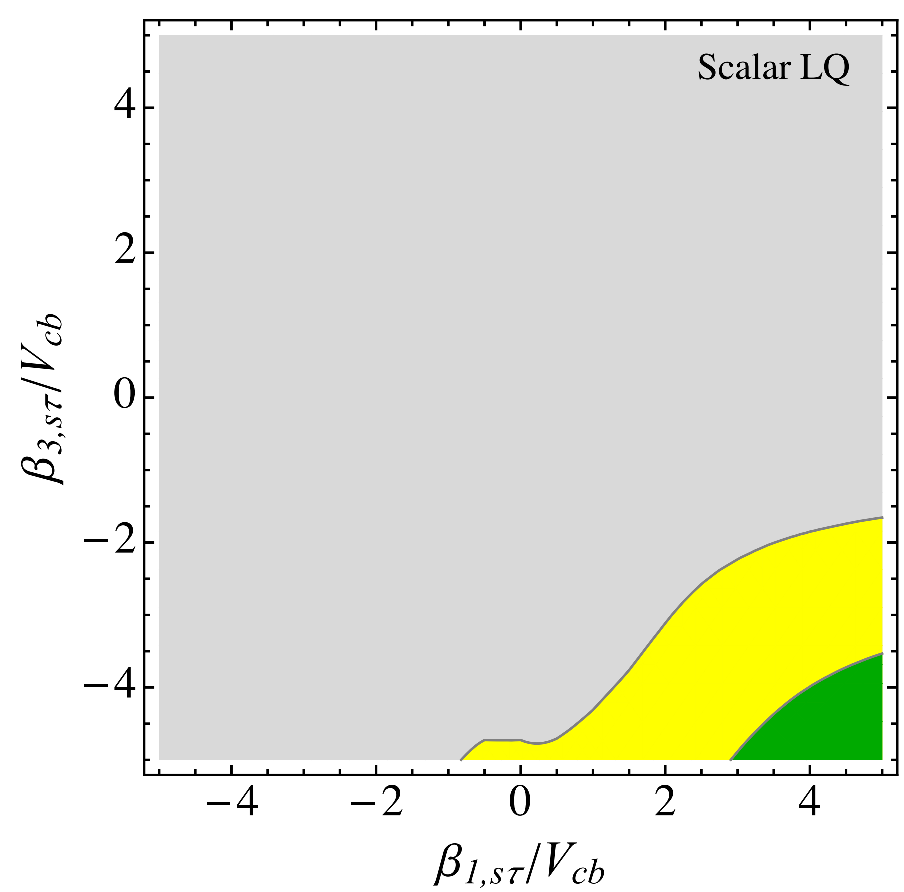
$$\mathcal{L} \supset g_1 y_{1\,i\alpha} (\bar{Q}_L^{c\,i} \epsilon L_L^\alpha) S_1 + g_3 y_{3\,i\alpha} (\bar{Q}_L^{c\,i} \epsilon \sigma^a L_L^\alpha) S_3^a + \text{h.c.}$$

In general, different flavour couplings of singlet and triplet

✓ Renormalisable model:
no contribution to meson mixing



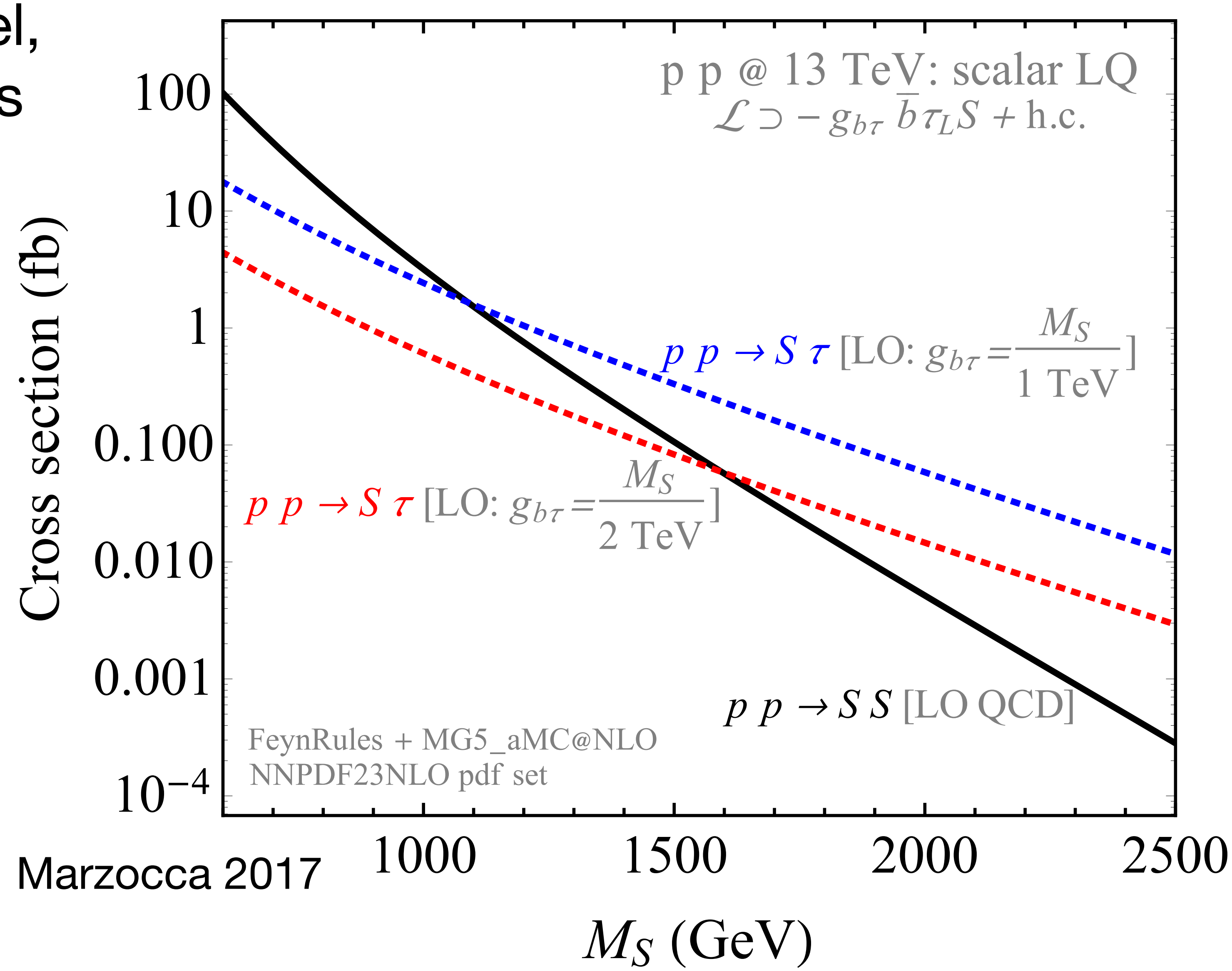




High-pT searches at LHC

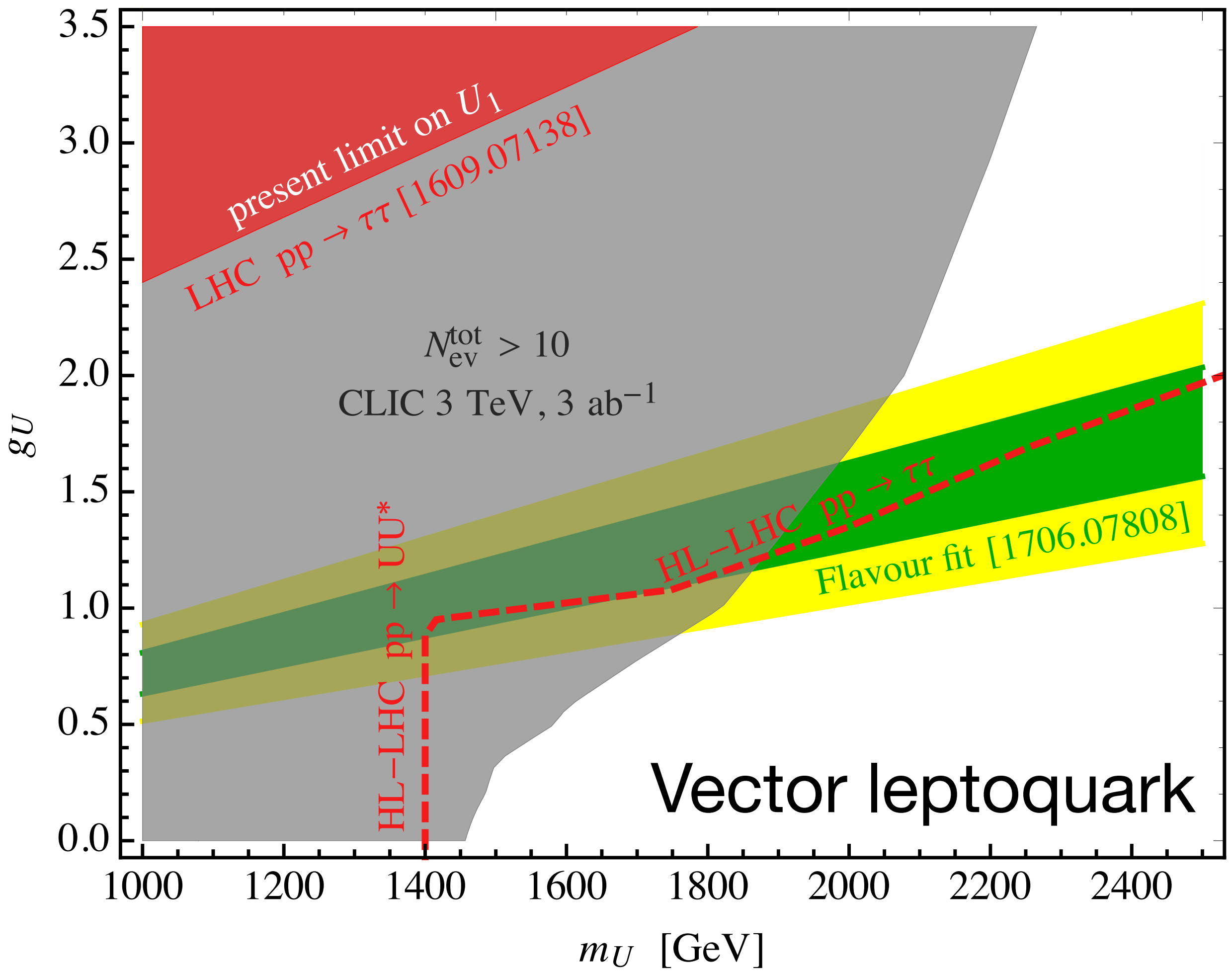
- Single LQ production depends on the coupling to fermions
- For high masses (above the LHC reach in double production) single production becomes the dominant production mechanism

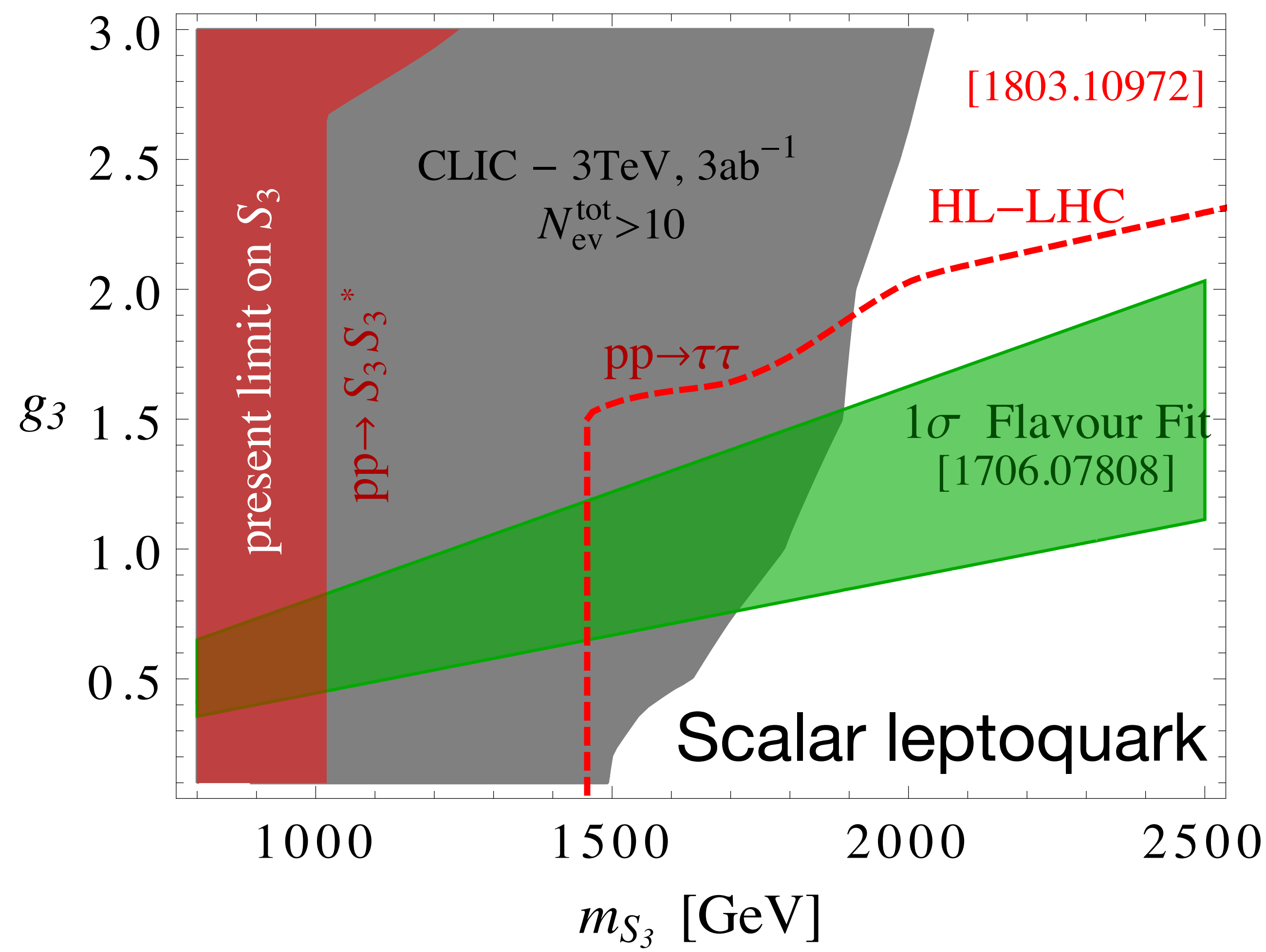
$pp \to S\tau$ important search channel, for couplings that fit the anomalies



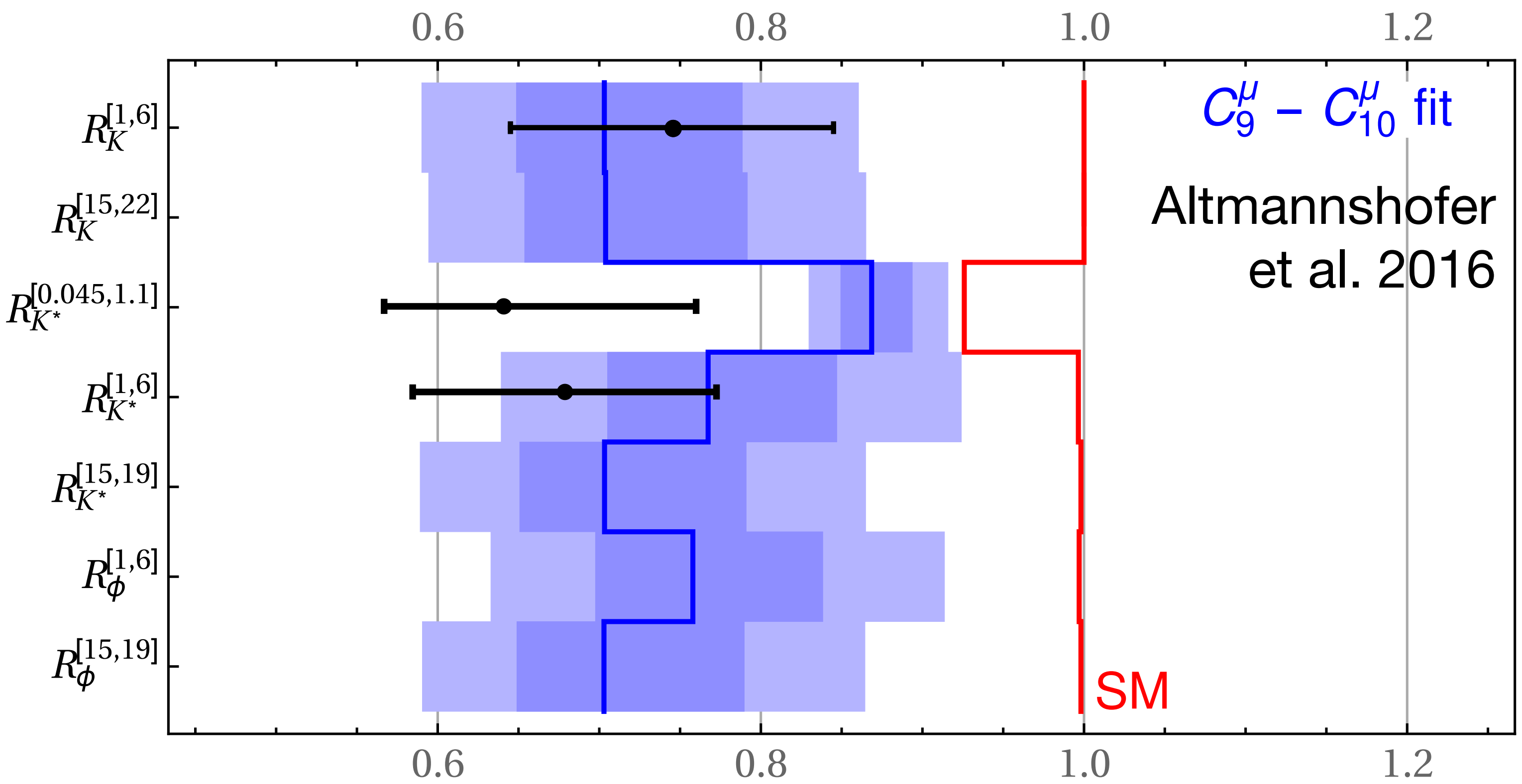
B, Greljo, Isidori, Marzocca 2017

High-pT searches



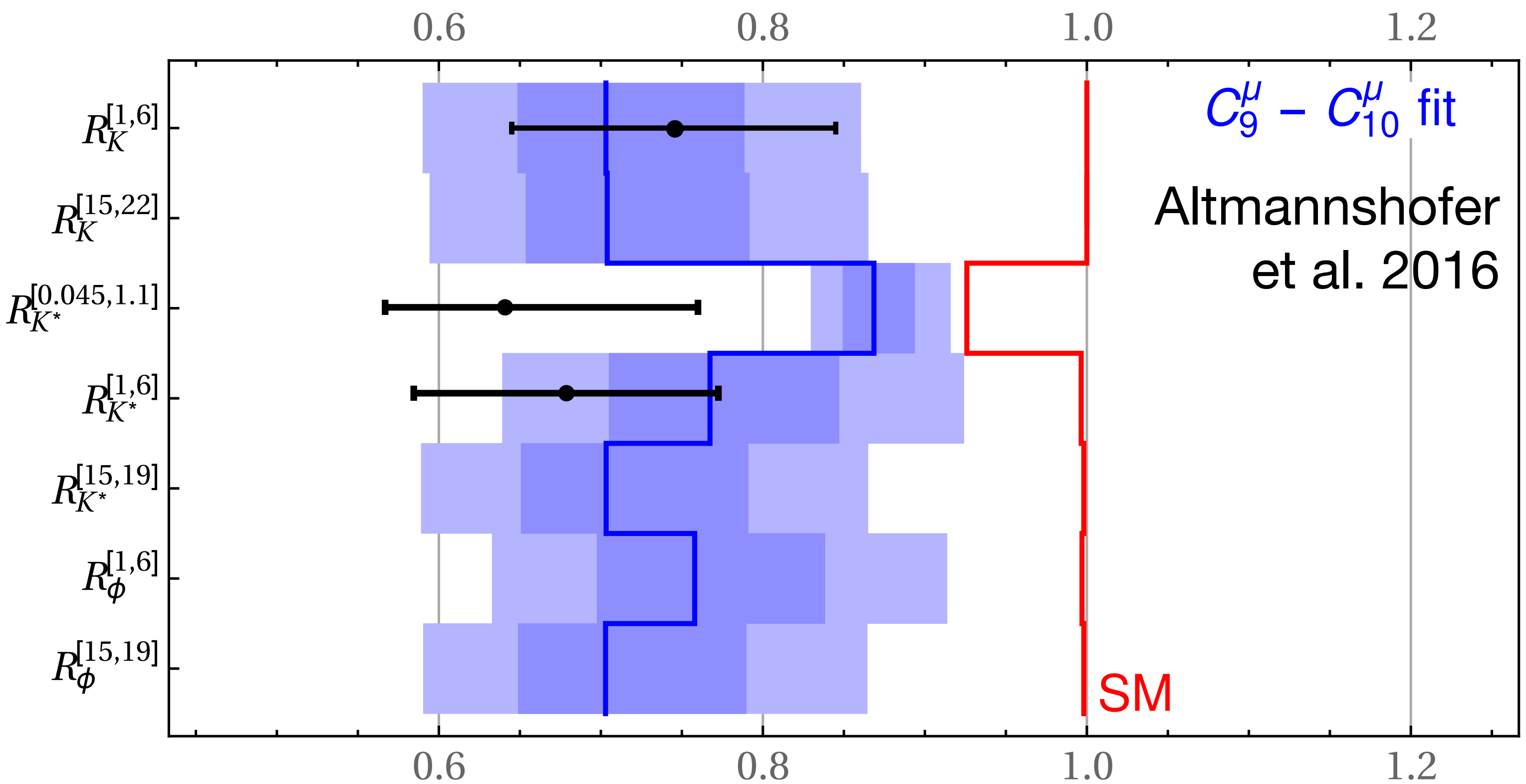


LFU ratios: R(K) & R(K^*)

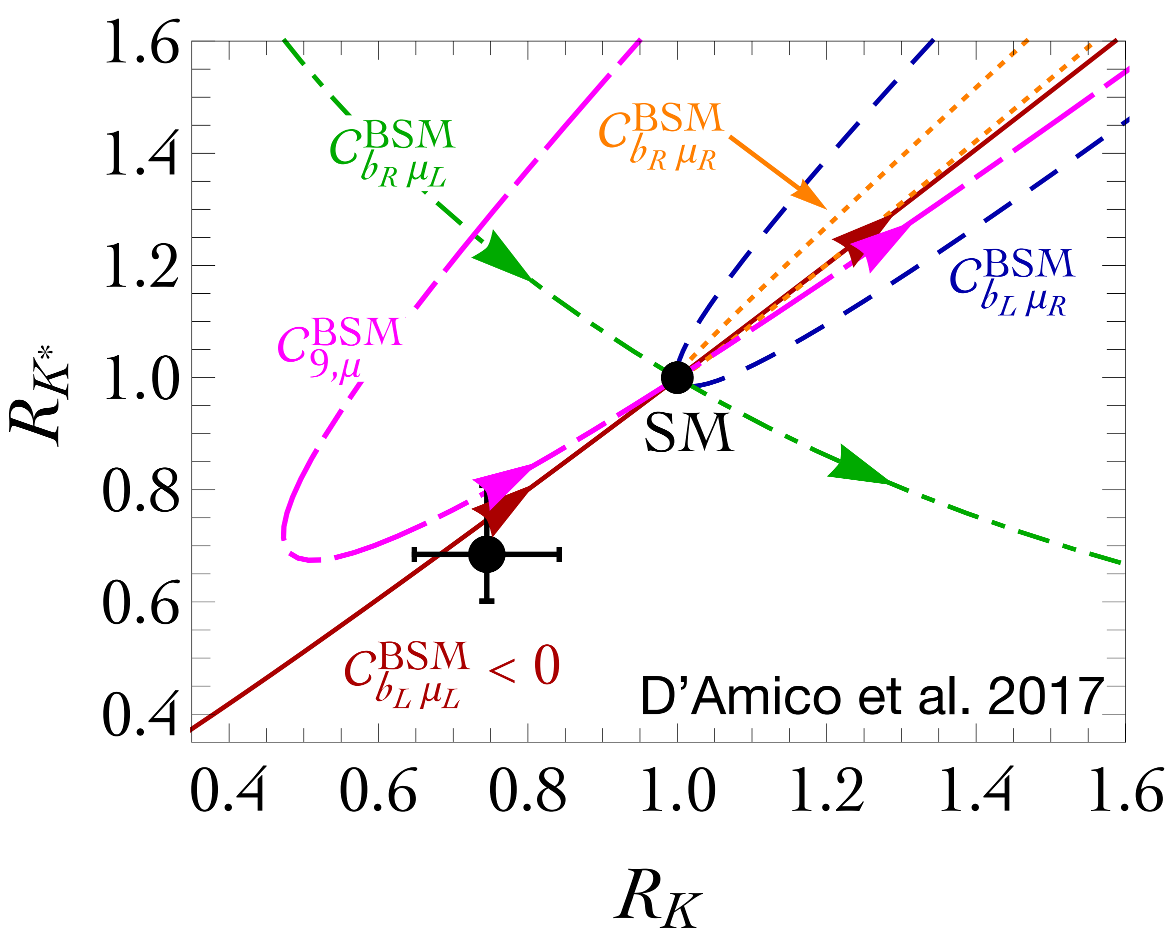


- LFU ratios are consistent with predictions from a fit to $b \to s\mu\mu$ data only

LFU ratios: R(*K*) & R(*K**)



- LFU ratios are consistent with predictions from a fit to $b \to s\mu\mu$ data only



- Left-Handed current necessary to have both R_K and $R_{K^*} < 1$

Semi-leptonic effective operators

Two simple current-current structures:

1. **QQ x LL** $\mathcal{L}_{\rm eff} \propto J_{QQ} J_{LL} + {\rm h.c.}$

$$J^\mu_{QQ} = \left(\bar q^i_L \gamma^\mu q^j_L\right) \left[\delta_{i3}\delta_{j3} + a_q \delta_{i3}(V_q^*)_j + a_q^*(V_q)_i\delta_{j3} + b_q\,(V_q)_i(V_q^*)_j\right] \equiv \lambda^q_{ij} \bar q^i_L \gamma^\mu q^j_L$$

$$J^\mu_{LL} = \left(\bar \ell^\alpha_L \gamma^\mu \ell^\beta_L\right) \left[\delta_{\alpha 3}\delta_{\beta 3} + a_\ell \delta_{\alpha 3}(V_\ell^*)_\beta + a_\ell^*(V_\ell)_\alpha\delta_{\beta 3} + b_\ell\,(V_\ell)_\alpha(V_\ell^*)_\beta\right] \equiv \lambda^\ell_{\alpha\beta} \bar \ell^\alpha_L \gamma^\mu \ell^\beta_L$$

4 + 2 free parameters: $\lambda^q_{bs} = a_q V_{ts}$, $\lambda^\ell_{\tau\mu} = a_\ell V_{\tau\mu}$, $\lambda^\ell_{\mu\mu} = b_\ell |V_{\tau\mu}|^2$, $\lambda^q_{sd} = b_q V^*_{ts} V_{td}$

2. **LQ x QL** $\mathcal{L}_{\rm eff} \propto J_{LQ} J^\dagger_{LQ}$

$$J^\mu_{LQ} = \left(\bar q^i_L \gamma^\mu \ell^\alpha_L\right) \left[\delta_{i3}\delta_{\alpha 3} + a_q^*(V_q)_i\delta_{\alpha 3} + a_\ell \delta_{i3}(V_\ell^*)_\alpha + b\,(V_q)_i(V_\ell^*)_\alpha\right] \equiv \beta_{i\alpha} \bar q^i_L \gamma^\mu \ell^\alpha_L$$

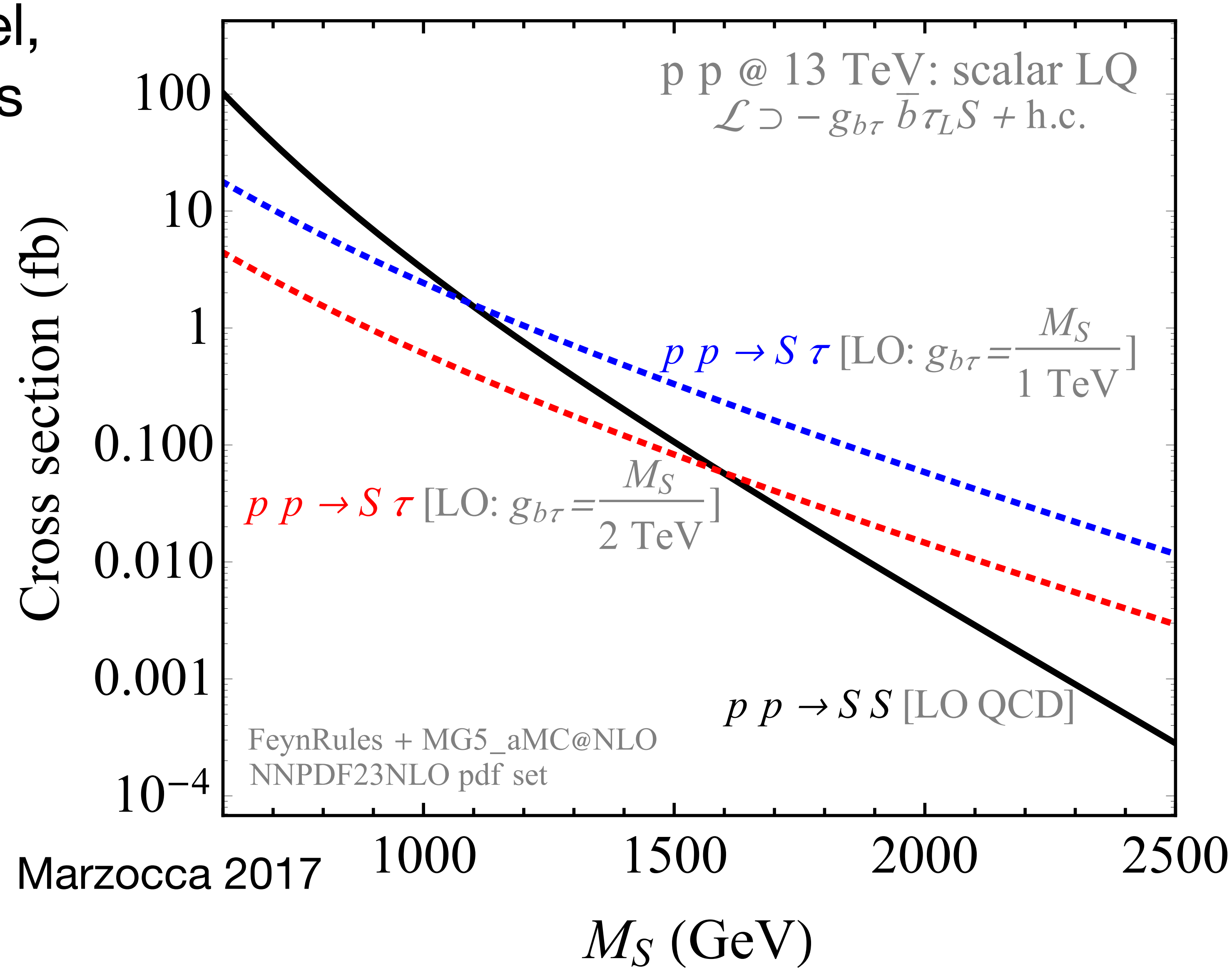
3 + 3 free parameters: $\beta^*_{s\tau} = a_q V_{ts}$, $\beta_{b\mu} = a_\ell V_{\tau\mu}$, $\beta_{b\mu}\beta^*_{s\mu} = a_\ell\, b |V_{\tau\mu}|^2$

Non-equivalent, if terms with more than one spurion are considered!

High-pT searches at LHC

- Single LQ production depends on the coupling to fermions
- For high masses (above the LHC reach in double production) single production becomes the dominant production mechanism

$pp \to S\tau$ important search channel, for couplings that fit the anomalies

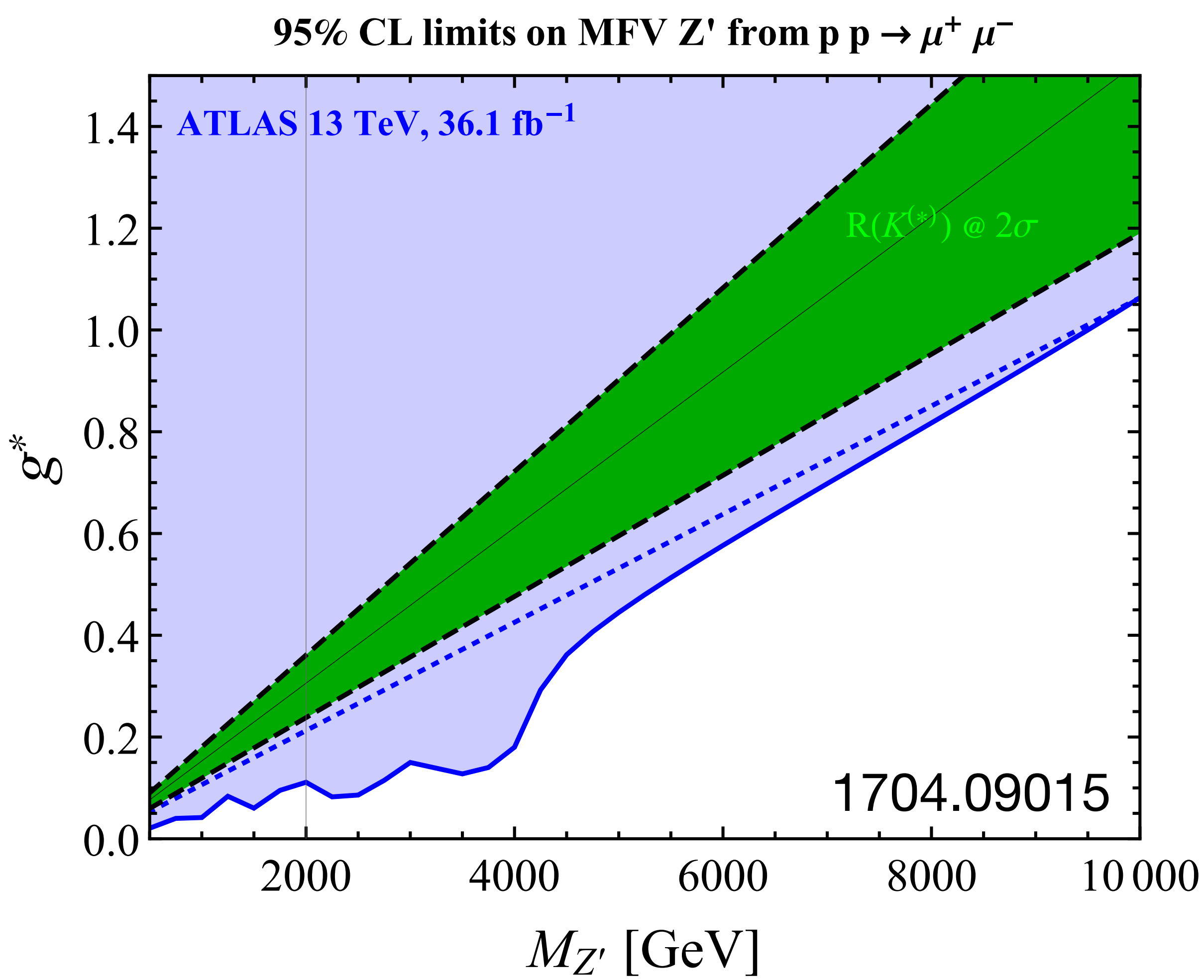


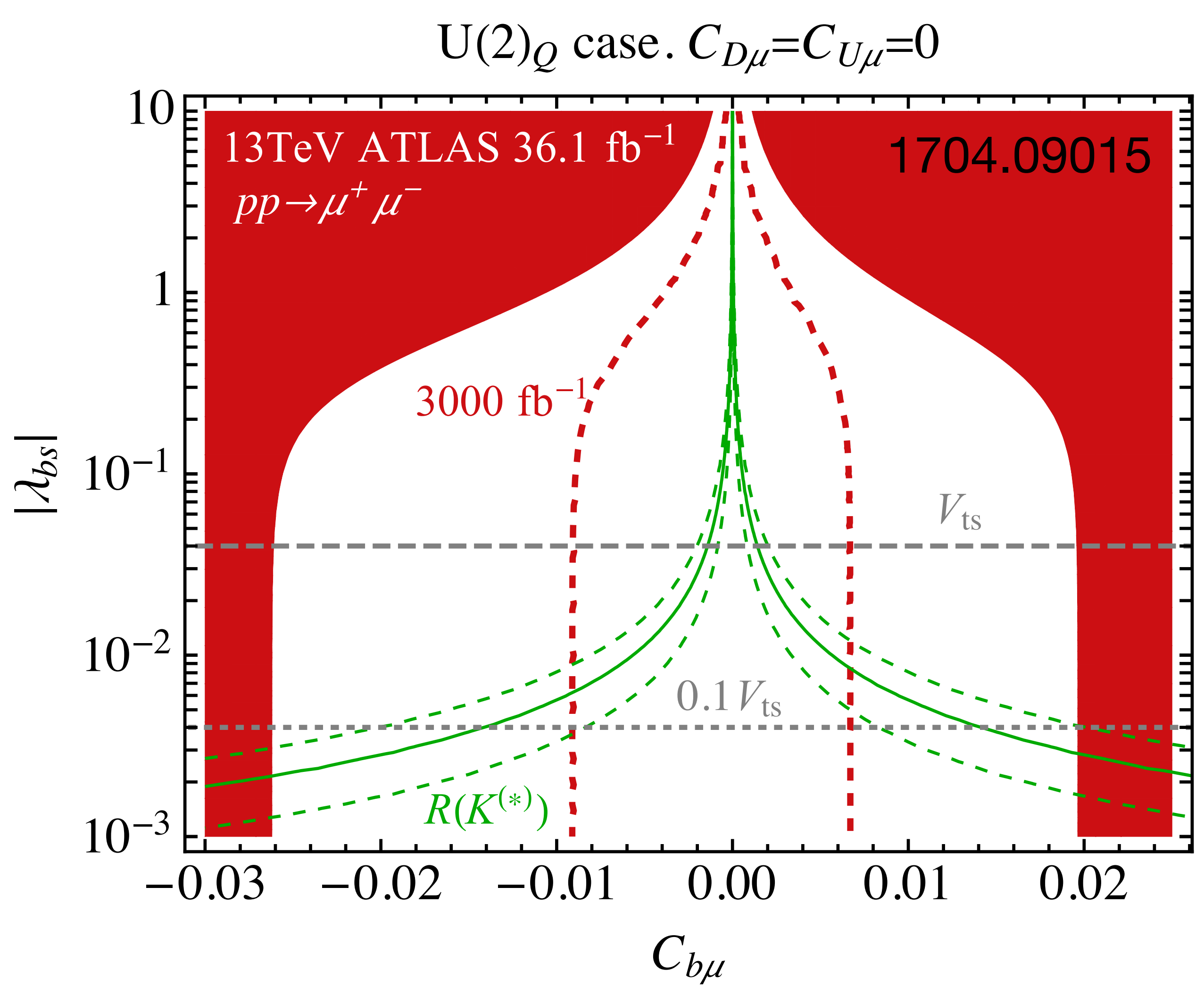
B, Greljo, Isidori, Marzocca 2017

High-pT searches at LHC

- $bb \to \mu\mu$ suppressed by small $\lambda_{\mu\mu}$ (but better experimental sensitivity)
- Searches in tails of the $\mu\mu$ invariant mass distribution:
    - MFV case already excluded
    - Not a relevant bound for U(2) models

Greljo & Marzocca 2017





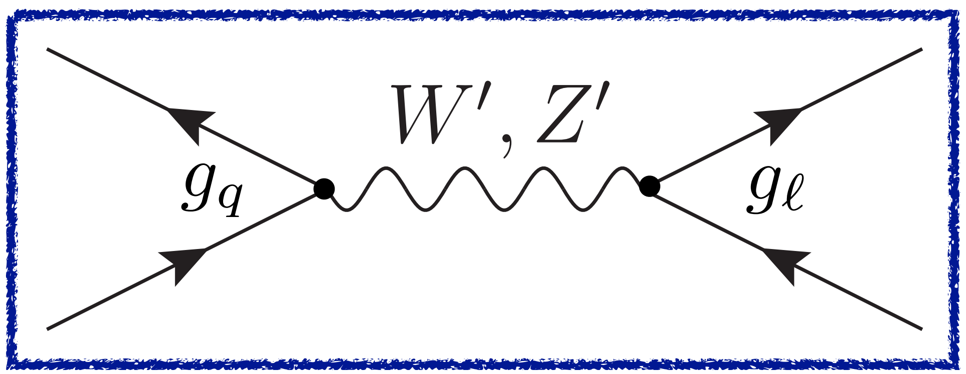
Vector resonances

Triplet and singlet colourless vectors:

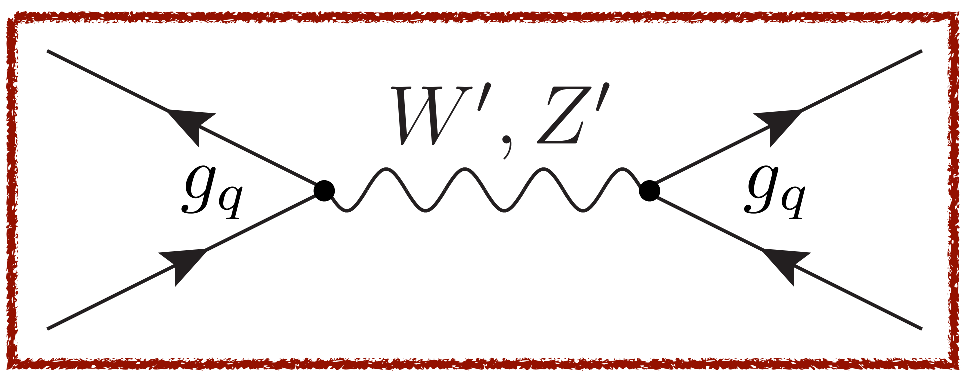
$$\mathcal{L}_{\rm int} = W'^a_\mu J^a_\mu + B'_\mu J^0_\mu$$

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

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



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



Large contribution to B_s mixing

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

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

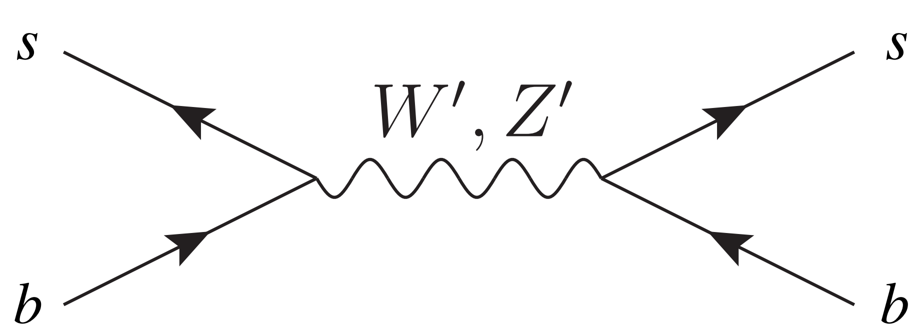
Problem less severe for large $C_{T,S}$ — stronger tension with EW precision tests.

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

$B_{(s)}$-$\bar{B}_{(s)}$ mixing

- Tree-level contribution to ΔF = 2 amplitudes

$$\Delta A_{B_s}^{\Delta F=2} \simeq \frac{154}{(V_{tb}^* V_{ts})^2} \left[\epsilon_q^2 \lambda_{bs}^2 + (\epsilon_q^0)^2 (\lambda_{bs}^2 + (\lambda_{bs}^d)^2 - 7.14 \lambda_{bs} \lambda_{bs}^d)\right] = 0.07 \pm 0.09$$



tuning of ~ few x 10^{-3}
to satisfy the constraint

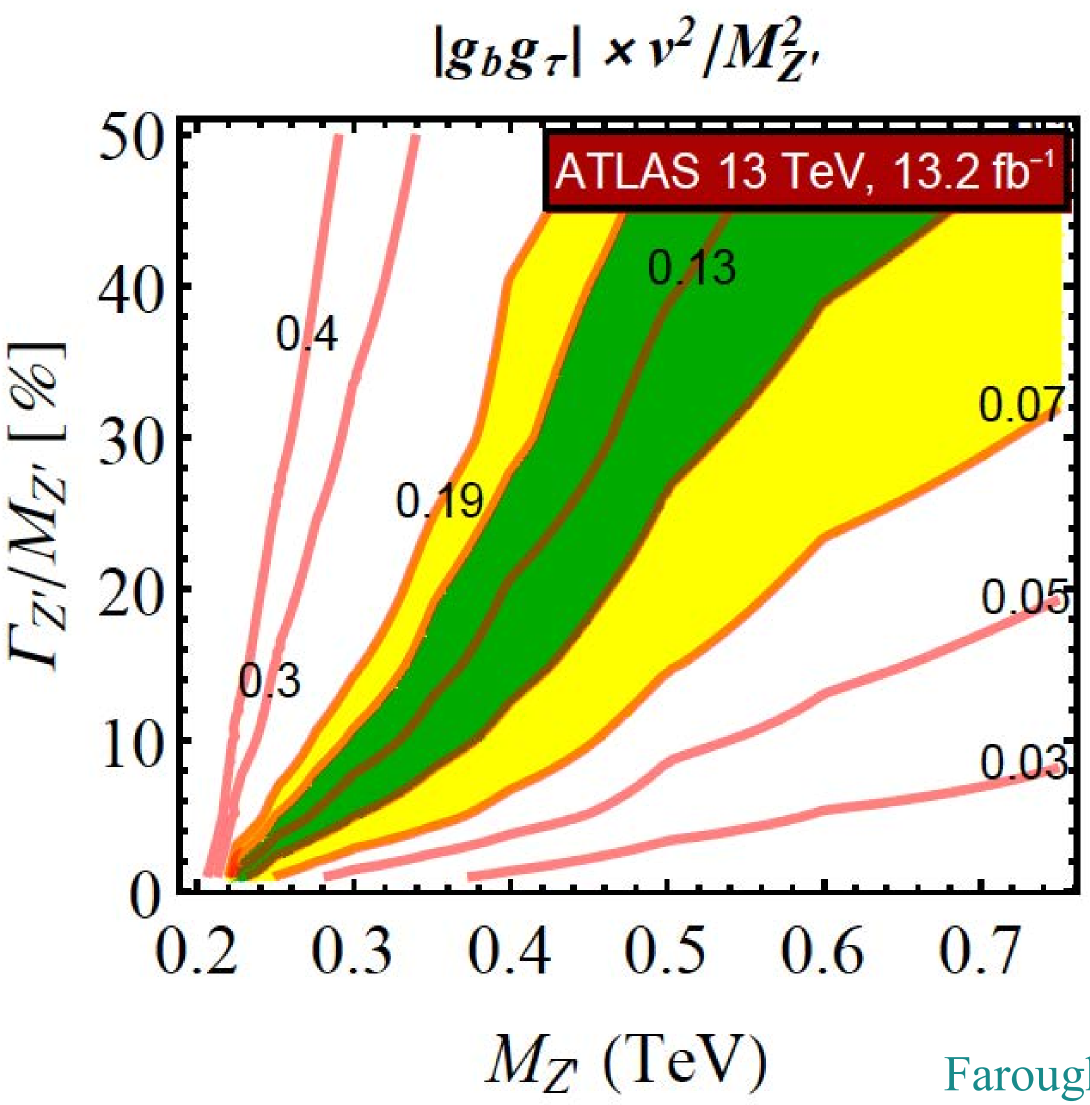
- Can have a mild tuning if C_T is large. Solve the tension with radiative corrections introducing a coupling to the Higgs current…

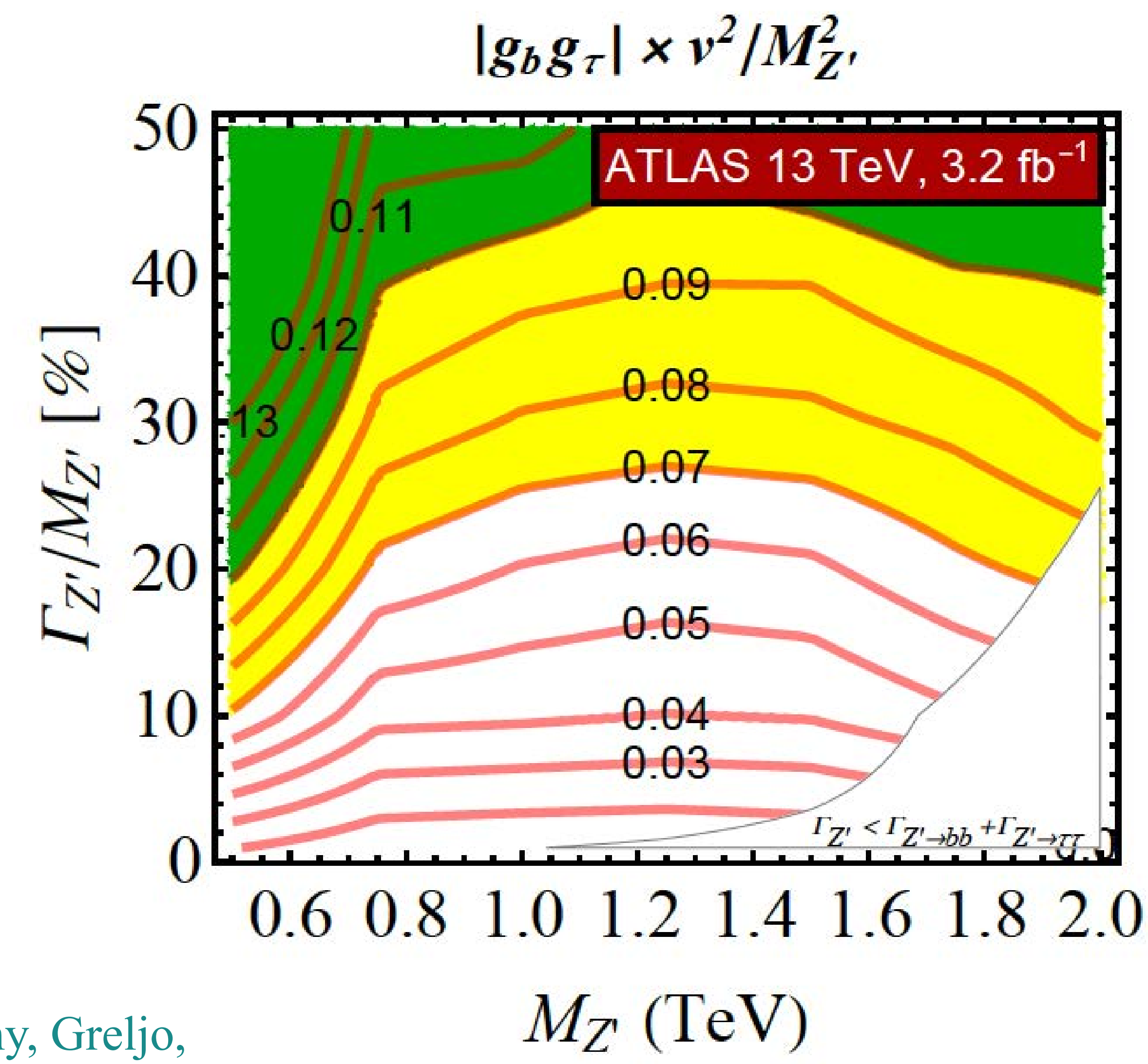
$$\Delta J_\mu^a = \frac{1}{2}\epsilon_H \left(i H^\dagger \overleftrightarrow{D}^a{}_\mu\, H\right) , \qquad \Delta J_\mu^0 = \frac{1}{2}\epsilon_H^0 \left(i H^\dagger \overleftrightarrow{D}_\mu\, H\right)$$

Many free parameters, can find points with mild tuning satisfying the bounds

$$\begin{array}{llll} \epsilon_\ell \approx 0.2 \ , & \epsilon_q \approx 0.5 \ , & \epsilon_H \approx -0.01 \ , & \lambda_{sb}^q/|V_{cb}| \approx -0.07 \ , \\ \epsilon_\ell^0 \approx 0.1 \ , & \epsilon_q^0 \approx -0.1 \ , & \epsilon_H^0 \approx -0.03 \ , & \lambda_{\mu\mu}^\ell \approx 0.2 \ . \end{array}$$

ATLAS heavy vector searches





Faroughy, Greljo, Kamenik '16