Collider Implications of Flavour Anomalies

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Flavour Anomalies

$b \to s\mu\mu$ (LHCb from 2013)

1) Angular observables in $B \to K^* \mu^+ \mu^-$ $\sim 4\sigma$ (?!)

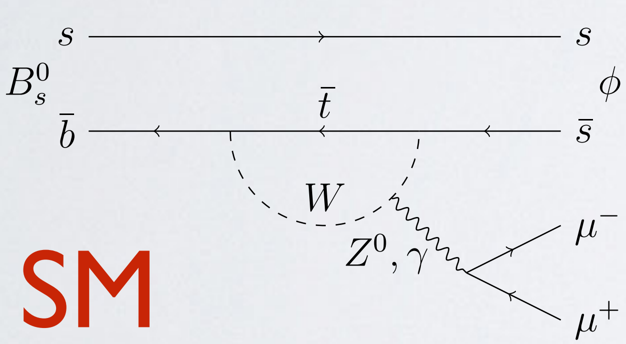
2) Branching ratios $\gtrsim 3.5\sigma$ (?!)

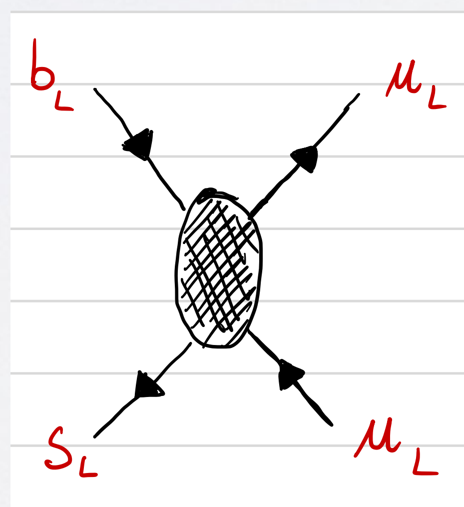
3) LFU violation in R_K 2.6σ

4) LFU violation in R_{K^*} (2 bins) $2.3\sigma,\ 2.6\sigma$

"clean" only $\approx 4\sigma$

SM

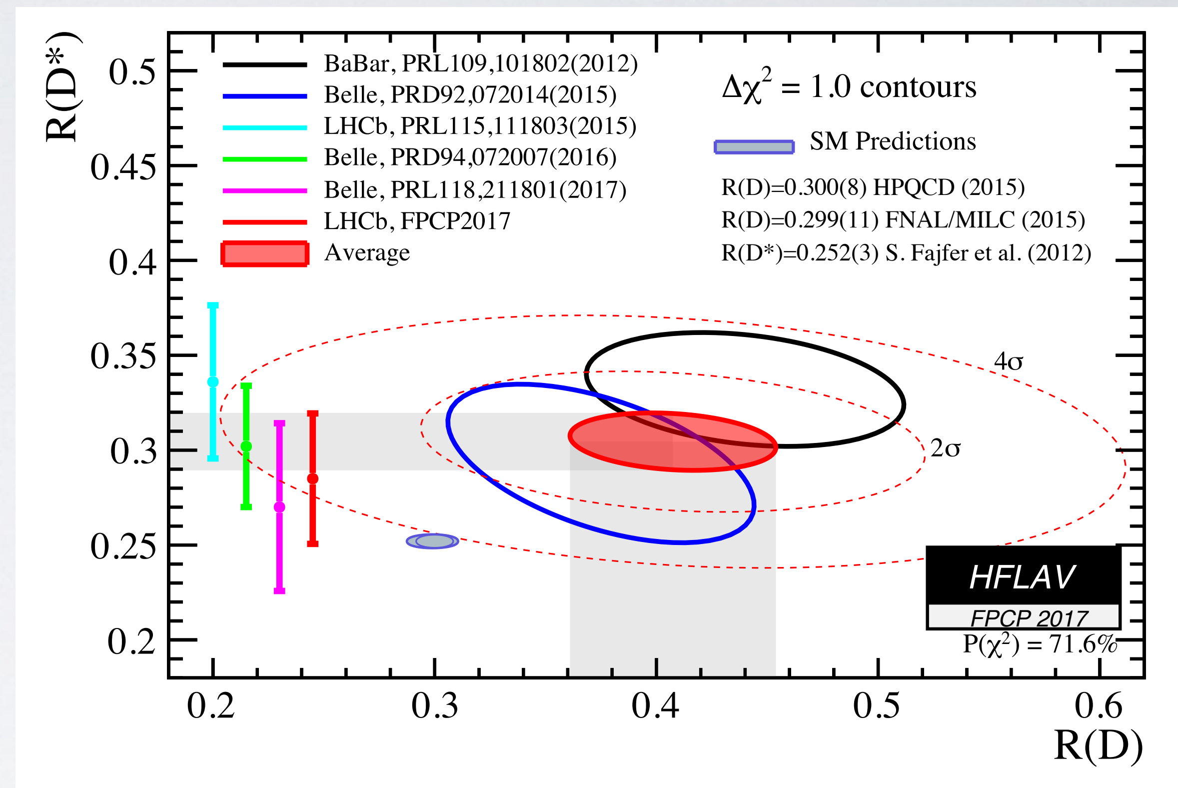


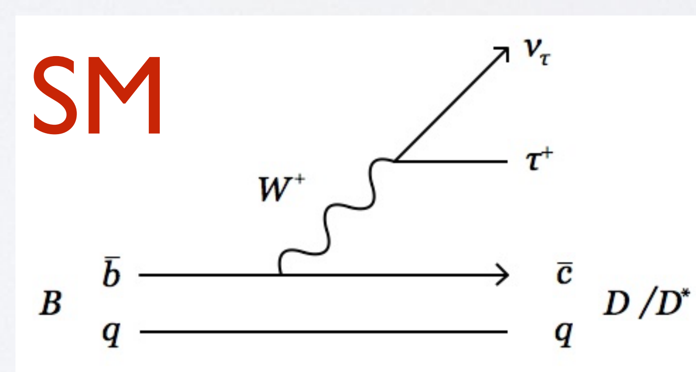


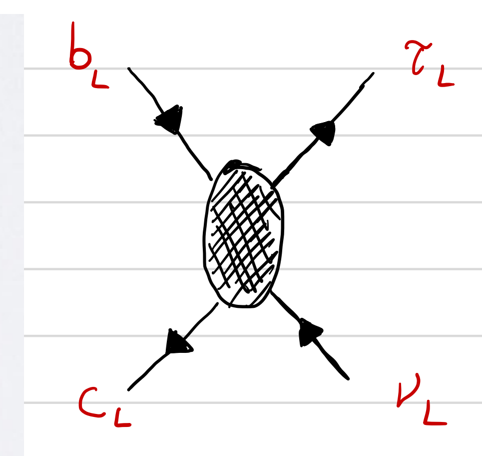
$$\mathcal{L}_{eff} = \frac{1}{\Lambda^2_{R_K}} \bar{s}_L \gamma^\mu b_L \ \bar{\mu}_L \gamma_\mu \mu_L + h.c.$$

$|C_\mu^{NP}| \gg |C_e^{NP}|$ $\Lambda_{R_K} = 31$ TeV

$b \to c\tau\nu$ Babar+Belle+LHCb from 2012







$$\mathcal{L}_{eff} = -\frac{2}{\Lambda^2_{R_D}} \bar{c}_L \gamma^\mu b_L \ \bar{\tau}_L \gamma_\mu \nu_L + h.c.$$

$|C_\tau^{NP}| \gg |C_\mu^{NP}|, |C_e^{NP}|$ $\Lambda_{R_D} = 3.4$ TeV

Outline of the talk

Theoretical input / bias

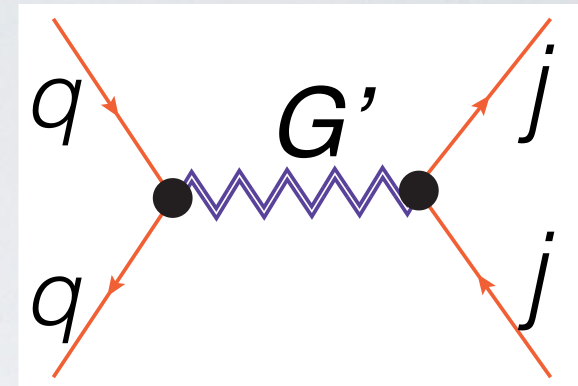
"Complete" Models — Address more questions/open problems: renormalizability, naturalness, origin of flavour,…

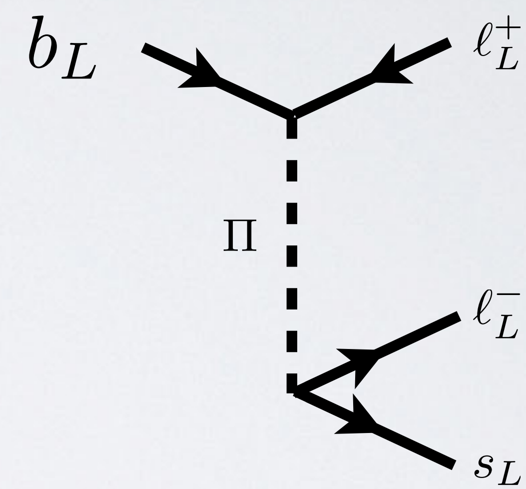
Simplified Models — Introducing explicitly New Physics, in the simplest way as possible

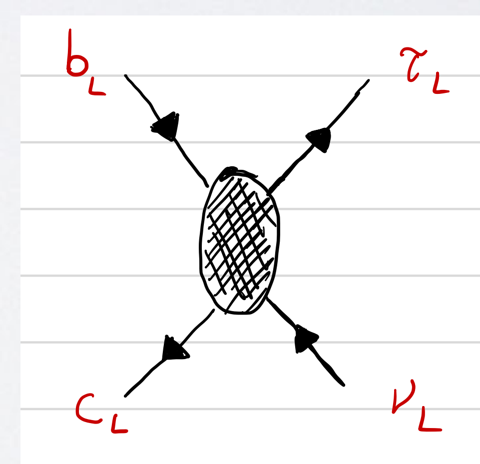
EFT at mZ — Correlation induced by SM gauge symmetry

EFT at mB — New Physics in a model independent way

Experimental input







$$\mathcal{L}_{eff} = -\frac{2}{\Lambda_{R_D}^2}\, \bar{c}_L \gamma^\mu b_L\, \bar{\tau}_L \gamma_\mu \nu_L + h.c.$$

$\Lambda_{R_D} = 3.4$ TeV

- *What is the scale of New Physics?*

$$\Lambda_{R_{D^{(*)}}} = 3.4 \pm 0.4 \text{ TeV}\,, \qquad \Lambda_{R_{K^{(*)}}} = 31 \pm 4 \text{ TeV}\,,$$

← "Measured" Fermi constant

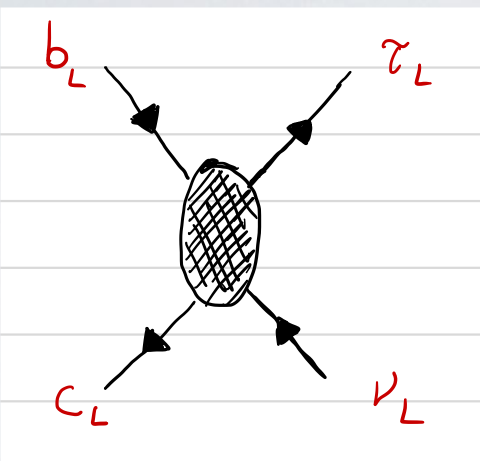
$$\frac{1}{\Lambda^2} = \frac{C}{M^2}$$

→ Model dependent part

C= (loops) x (couplings) x (flavour)

→ On-shell effects @ colliders

- *What do we expect?* (Worst case scenario)



$$\mathcal{A}(\psi\psi \to \psi\psi) \propto s$$

Tree-Level Pertubative Unitarity criterium

$$|\mathcal{A}_{J=0}| < 1/2$$

[Di Luzio, MN, 1706.01868]

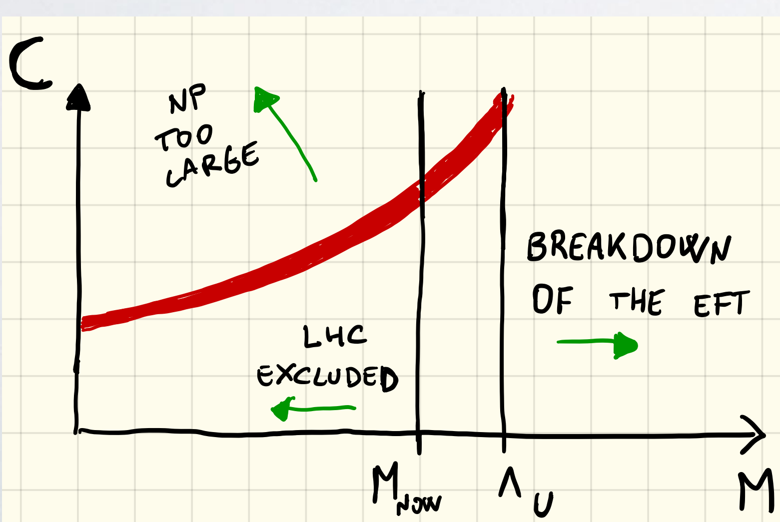
$$\begin{cases} \sqrt{s}_{max} \equiv \Lambda_U = 9 \text{ TeV} & b \to c\tau\nu \\ \sqrt{s}_{max} \equiv \Lambda_U = 80 \text{ TeV} & b \to s\mu\mu \end{cases}$$

An old lesson: VV scattering…

$\Lambda_U = 2 \text{ TeV}, m_h = 125 \text{ GeV}$

- *What do we expect?* (Warning: a simplified cartoon!)

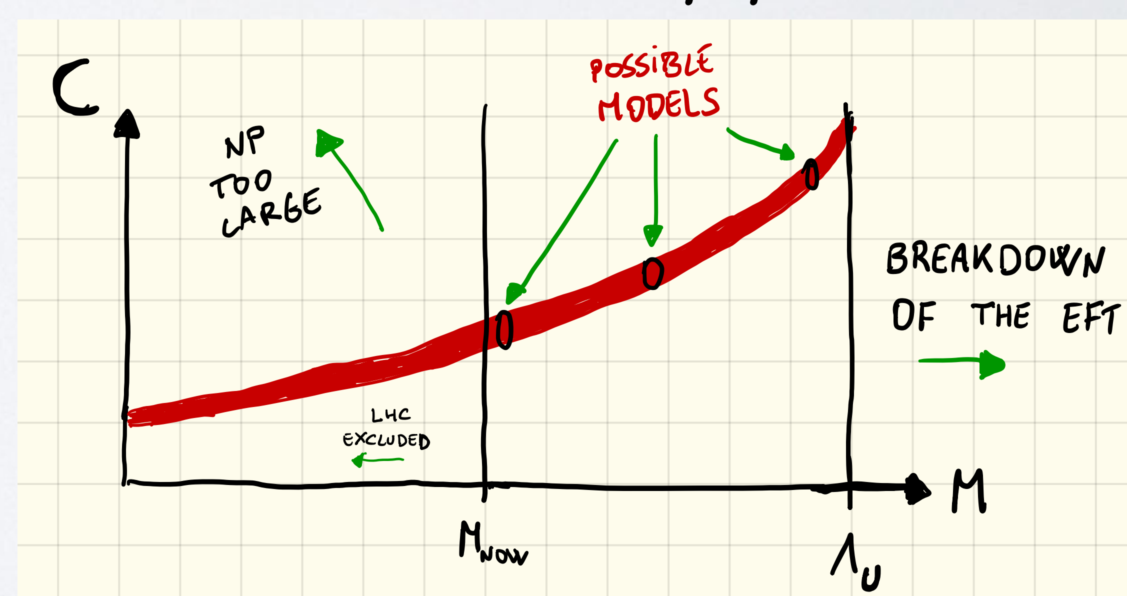
$b \to c\tau\nu$



Absence of New Physics at high energy

$$M_{now} \gtrsim 1 \text{ TeV}$$

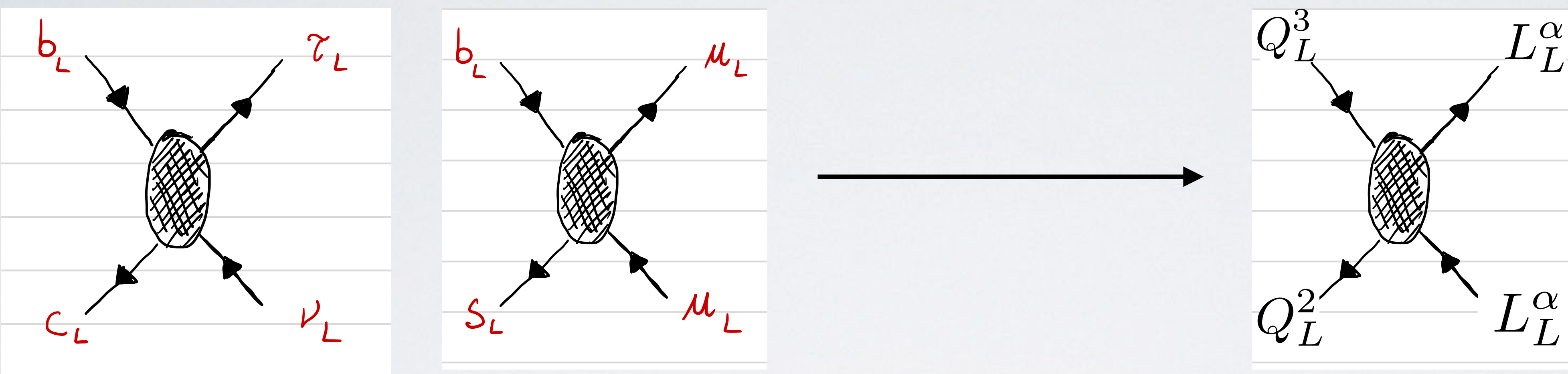
$b \to s\mu\mu$



Vertical (gauge) structure

- Fits to data suggest a sizeable (most likely dominant) contribution of the New Physics to left currents for both quarks and leptons

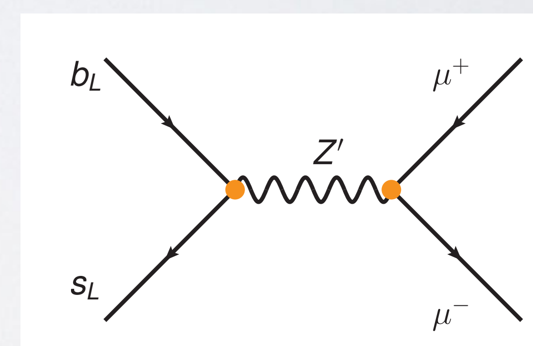
$$C_S(\overline{Q}^i_L\gamma^\mu Q^j_L)(\overline{L}^\alpha_L\gamma^\mu L^\beta_L) + C_T(\overline{Q}^i_L\gamma^\mu\sigma^a Q^j_L)(\overline{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L)$$

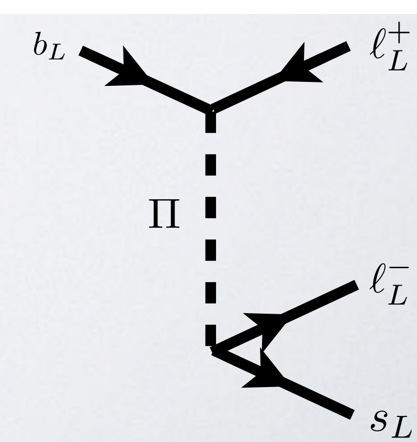


SU(2) structure induce correlations

- *Collider implication: Quantum numbers of tree level mediators restricted*

Mediator	Spin	SM irrep	c_1/c_3	$R_{D^{(*)}}$	$R_{K^{(*)}}$	No $d_i \to d_j\nu\overline{\nu}$
Z'	1	$(1,1,0)$	∞	×	✓	×
V'	1	$(1,3,0)$	0	✓	✓	×
S_1	0	$(\overline{3},1,1/3)$	-1	✓	×	×
S_3	0	$(\overline{3},3,1/3)$	3	✓	✓	×
U_1	1	$(3,1,2/3)$	1	✓	✓	✓
U_3	1	$(3,3,2/3)$	-3	✓	✓	×





Horizontal (flavour) structure

- Considering the whole set of data (neutral and charged currents), a possible link with the SM flavour structure is emerging

$$b \to c\tau\nu \qquad 3_q \to 2_q 3_\ell 3_\ell$$
$$b \to s\mu\mu \qquad 3_q \to 2_q 2_\ell 2_\ell$$

SM VS NP
A link?

$$|C_\tau^{\rm NP}| \gg |C_\mu^{\rm NP}| \gg |C_e^{\rm NP}|$$
$$|Y_\tau^{SM}| \gg |Y_\mu^{SM}| \gg |Y_e^{SM}|$$

- Motivated flavour ansatz in the quark sector (MFV, U(2),Partial Compositeness, Froggat-Nielsen) predicts dominant coupling of the New Physics with the third family.

$$\frac{\bar{c}\gamma^\mu b}{\bar{t}\gamma^\mu b} = \mathcal{O}(\lambda^2) \quad , \quad \frac{\bar{s}\gamma^\mu b}{\bar{b}\gamma^\mu b} = \mathcal{O}(\lambda^2) \qquad \lambda = 0.23$$

(Cabibbo angle)

- *Collider implications*

  - NP getting closer
$$\begin{cases} M \lesssim 3~\text{TeV} & b \to c\tau\nu \\ M \lesssim 20~\text{TeV} & b \to s\mu\mu \end{cases}$$

  - Better to look for resonant decays of the mediators into SM fermions of the third family

Where to look at LHC?

Simplified Model	Spin	SM irrep	c_1/c_3	$R_{D^{(*)}}$	$R_{K^{(*)}}$	No $d_i \to d_j \nu\bar{\nu}$
Z'	1	$(1, 1, 0)$	∞	$\times$	$\checkmark$	$\times$
V'	1	$(1, 3, 0)$	0	$\checkmark$	$\checkmark$	$\times$
S_1	0	$(\overline{3}, 1, 1/3)$	-1	$\checkmark$	$\times$	$\times$
S_3	0	$(\overline{3}, 3, 1/3)$	3	$\checkmark$	$\checkmark$	$\times$
U_1	1	$(3, 1, 2/3)$	1	$\checkmark$	$\checkmark$	$\checkmark$
U_3	1	$(3, 3, 2/3)$	-3	$\checkmark$	$\checkmark$	$\times$

Colourless mediators (Z', V')

Leptoquarks (S_1, S_3, U_1, U_3)

1) Resonance searches for charged current anomalies

- Colourless mediator Z'+V' not viable (excluded already $Z' \to \tau\tau$)
- Vector Leptoquark, U1, decaying into SM fermions of the third family
- Scalar Leptoquarks, S1+ S3, decaying into SM fermions of the third family
- More complicated linear combinations can be thought

2) Resonance searches for neutral current anomalies only (and no flavour bias)

- Z' to muons
- Leptoquark in final states with muons

3) Non-resonant searches

- High-pT dilepton tails $pp \to \tau\tau, pp \to \mu\mu$ *[See Greljo, Marzocca 1704.09015]*

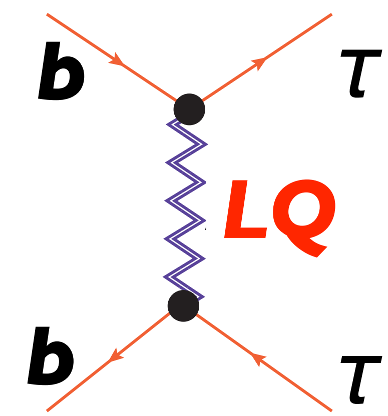
Vector Leptoquark $U_1^\mu \equiv (\mathbf{3}, \mathbf{1}, 2/3)$

[Buttazzo, AG, Isidori, Marzocca], JHEP 1711 (2017) 044

$$\mathcal{L}_U = -\frac{1}{2}U_{1,\mu\nu}^\dagger U^{1,\mu\nu} + M_U^2 U_{1,\mu}^\dagger U_1^\mu + g_U (J_U^\mu U_{1,\mu} + \text{h.c.})$$

$$J_U^\mu \equiv \beta_{i\alpha}\, \bar{Q}_i \gamma^\mu L_\alpha \longrightarrow b\tau + t\nu$$

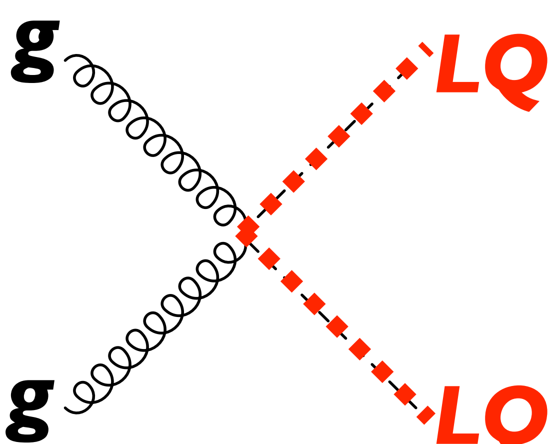
Flavour data: $\mathcal{B}(U \to t\nu) \approx \mathcal{B}(U \to b\tau) \approx 0.5$

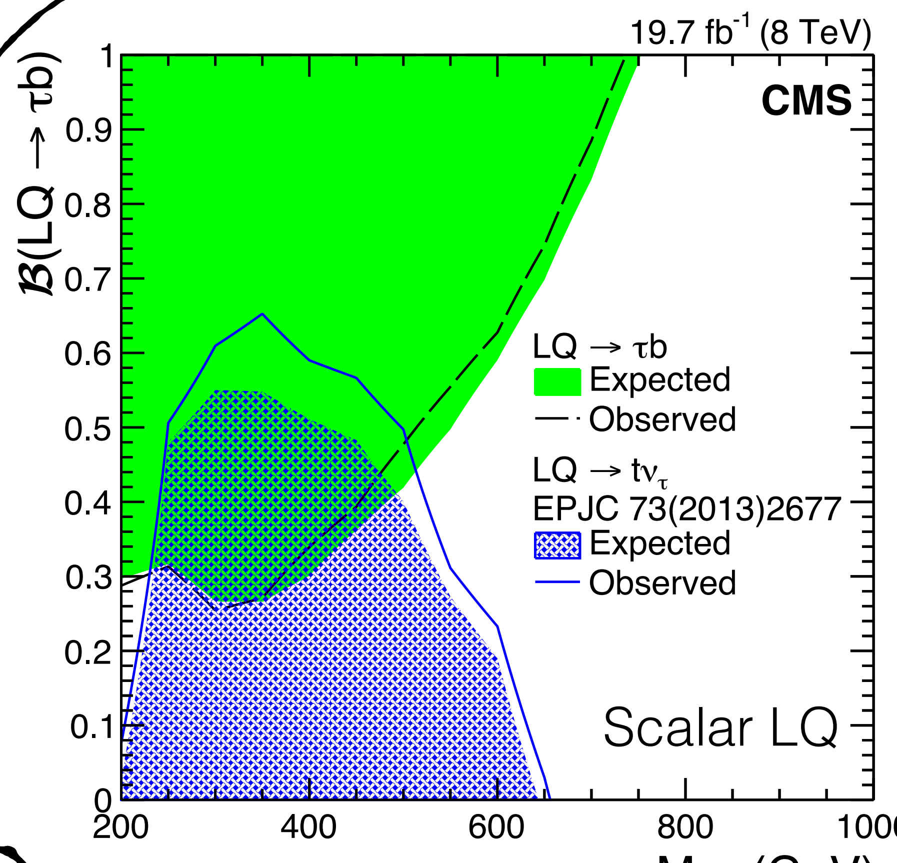


[Faroughy, AG, F. Kamenik] Phys.Lett. B764 (2017) 126-134

pp→LQLQ → **bτbτ 25%**, **tνtν 25%**, **bτtν 50%**

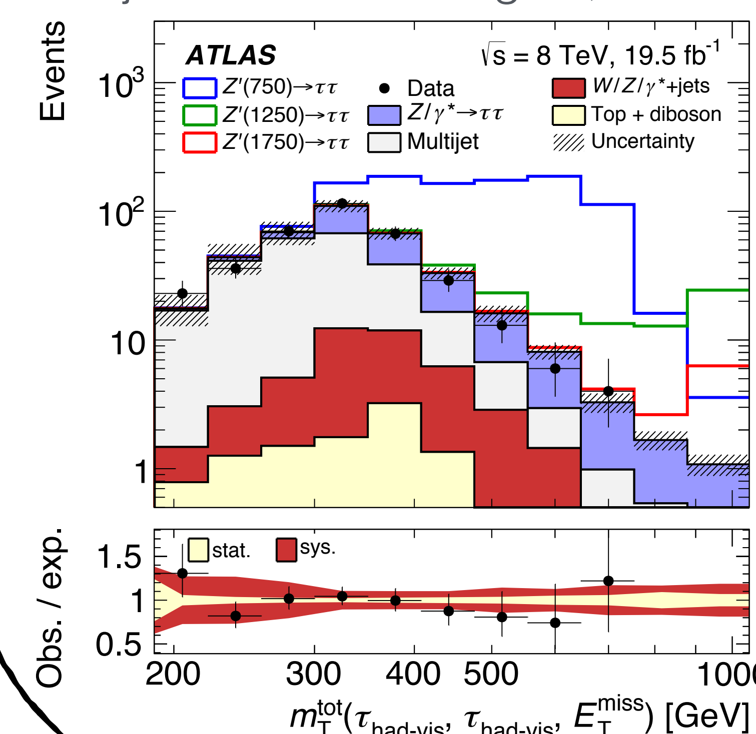
CMS: 1703.03995
ATLAS: 1508.04735





CMS: 1408.0806

Recast of ATLAS di-tau search
Inject the correct signal, set limits



ATLAS: 1502.07177

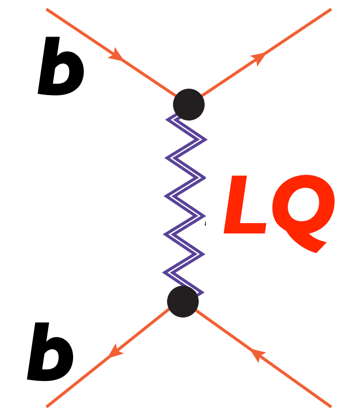
[Slides from A. Greljo]

Vector Leptoquark $U_1^\mu \equiv (\mathbf{3}, \mathbf{1}, 2/3)$

[Buttazzo, AG, Isidori, Marzocca], JHEP 1711 (2017) 044

$$\mathcal{L}_U = -\frac{1}{2}U^\dagger_{1,\mu\nu}U^{1,\mu\nu} + M_U^2 U^\dagger_{1,\mu}U_1^\mu + g_U(J_U^\mu U_{1,\mu} + \text{h.c.})$$

$$J_U^\mu \equiv \beta_{i\alpha}\,\bar{Q}_i\gamma^\mu L_\alpha$$ → **bτ + tν**

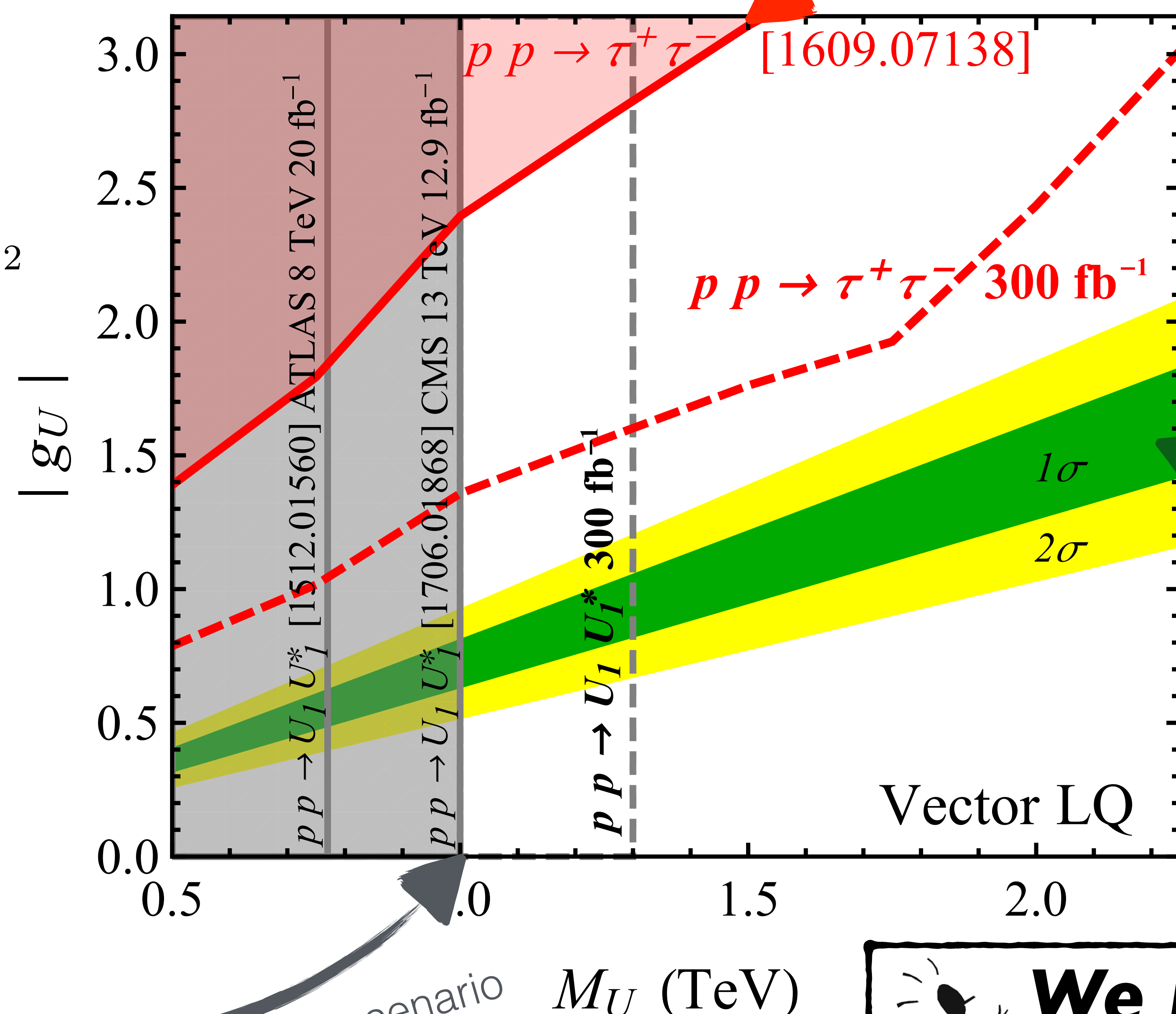


Flavour data: $\mathcal{B}(U \to t\nu) \approx \mathcal{B}(U \to b\tau) \approx 0.5$

Best fit:

$$g_U \approx 0.7\left(\frac{M_U}{1\ \text{TeV}}\right)$$

$$\frac{\Gamma_U}{M_U} \approx 1.4\% \left(\frac{M_U}{1\ \text{TeV}}\right)^2$$



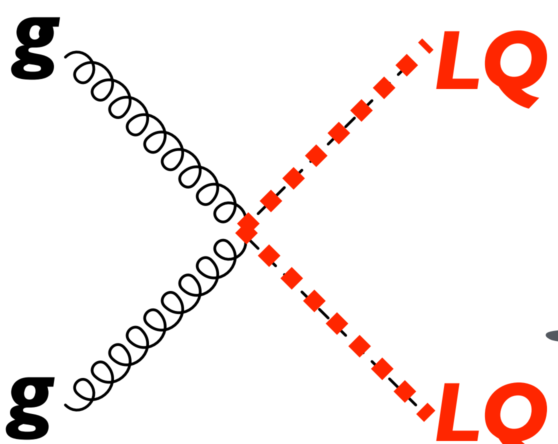
[Faroughy, AG, F. Kamenik] Phys.Lett. B764 (2017) 126-134

Recast of the ATLAS di-tau search

B-anomalies

$$\begin{cases}\beta_{s\tau} = 5\,V_{cb} \\ \beta_{b\tau} = 1\end{cases}$$

CMS: 1703.03995
ATLAS: 1508.04735



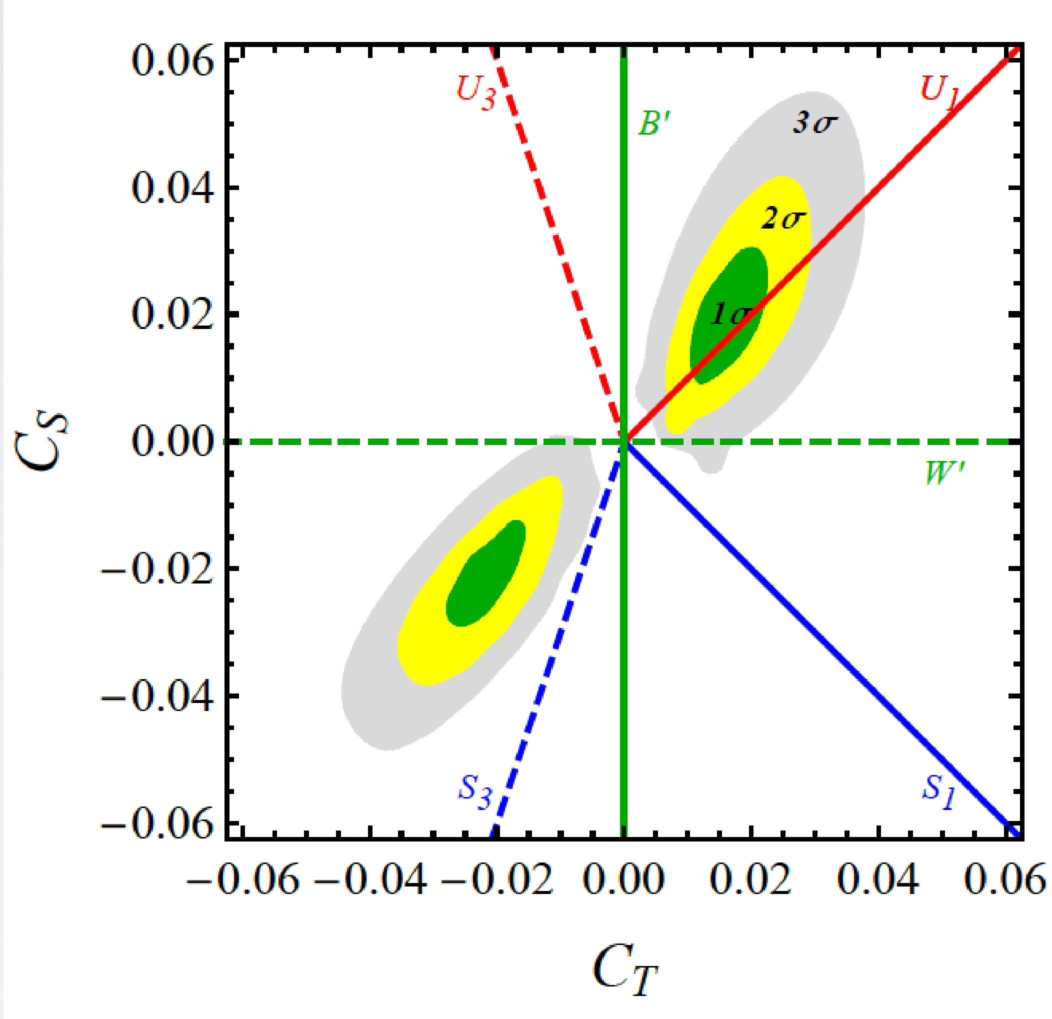
Minimal coupling scenario

[Slides from A. Greljo]

We need HL- or even HE- LHC!

The Vector Leptoquark

Simplified Model	Spin	SM irrep	c_1/c_3	$R_{D^{(*)}}$	$R_{K^{(*)}}$	No $d_i \to d_j \nu\bar{\nu}$
Z'	1	$(1,1,0)$	∞	×	✓	×
V'	1	$(1,3,0)$	0	✓	✓	×
S_1	0	$(\bar{3},1,1/3)$	-1	✓	×	×
S_3	0	$(\bar{3},3,1/3)$	3	✓	✓	×
U_1	1	$(3,1,2/3)$	1	✓	✓	✓
U_3	1	$(3,3,2/3)$	-3	✓	✓	×



[Buttazzo, Greljo, Isidori Marzocca 1706.07808]

- Remarkably there is a unique solution, if we consider a single mediator

A clear winner! $U_\mu = (3,1,2/3)$

- A spin 1 state calls for a UV completion. This is not an academic question, collider searches are dominated by the phenomenology of the extra states that emerge with the leptoquark.

Spin one particle → Composite dynamics [Barbieri, Tesi, 1712.06844]

Spin one particle → Gauge bosons [L. Di Luzio, A. Greljo, MN, 1708.08450 Bordone, Cornella, Fuentes-Martin, Isidori, 1712.01368]

[Since August:
1708.06350
1709.00692
1801.07256
1802.04274
+ in progress..]

SU(4) Pati-Salam

PRD (1975)

- Quantum numbers of the leptoquark known, easiest option: Pati-Salam

$$G_{PS} = SU(4)_{PS} \times SU(2)_L \times SU(2)_R$$

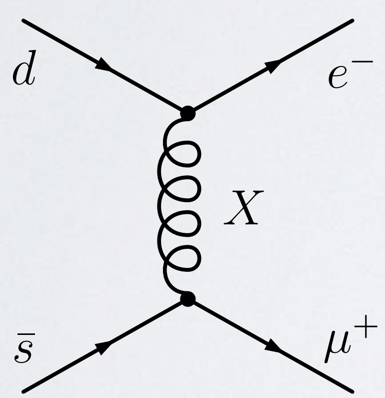
$$G_{PS} \to G_{SM}$$

$$(15 = 8 + 3 + \overline{3} + 1)$$

g U_μ Z'

$$\frac{g_s}{\sqrt{2}} U_\mu \, \beta_{ij} \, \overline{Q}^i \gamma^\mu L^j$$

- A problem: bounds from indirect searches

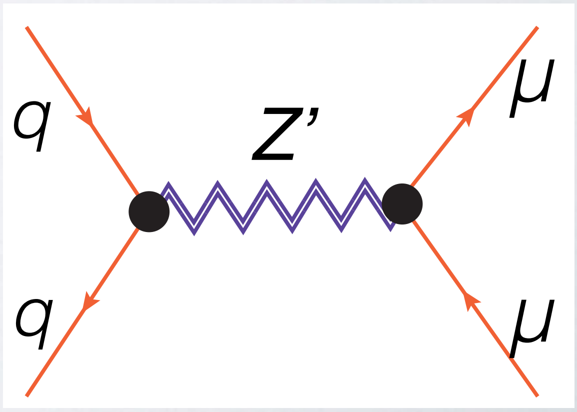


$$M_U \gtrsim 100 \text{ TeV}$$

$$M_U \lesssim 2 \text{ TeV}$$

(from the anomalies)

- Another problem: bounds from direct searches of the Z', abundantly produced by Drell-Yan processes



- After all Pati-Salam was introduced in the context of GUTs…..

The 4321 model

[L. Di Luzio, A. Greljo, MN 1708.08450]

- We need two ingredients: an enlarged gauge structure and extra matter fields

$$G = SU(4) \times SU(3)' \times SU(2)_L \times U(1)'$$

$$\downarrow \langle \Omega_3 \rangle, \langle \Omega_1 \rangle$$

$$G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$$

New states from the breaking:

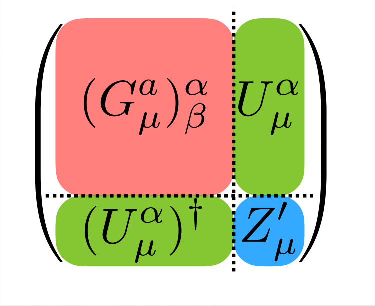
1) A leptoquark $M_U = \frac{1}{2} g_4 \sqrt{v_1^2 + v_3^2}\,,$

2) A color octet $M_{g'} = \frac{1}{\sqrt{2}} \sqrt{g_4^2 + g_3^2}\, v_3\,,$

3) A SM singlet $M_{Z'} = \frac{1}{2} \sqrt{\frac{3}{2}} \sqrt{g_4^2 + \frac{2}{3} g_1^2} \sqrt{v_1^2 + \frac{1}{3} v_3^2}\,.$

- Extra gauge bosons don't decouple, for example in some limit:

$$3 M_U^2 = M_{g'}^2 + 2 M_{Z'}^2$$



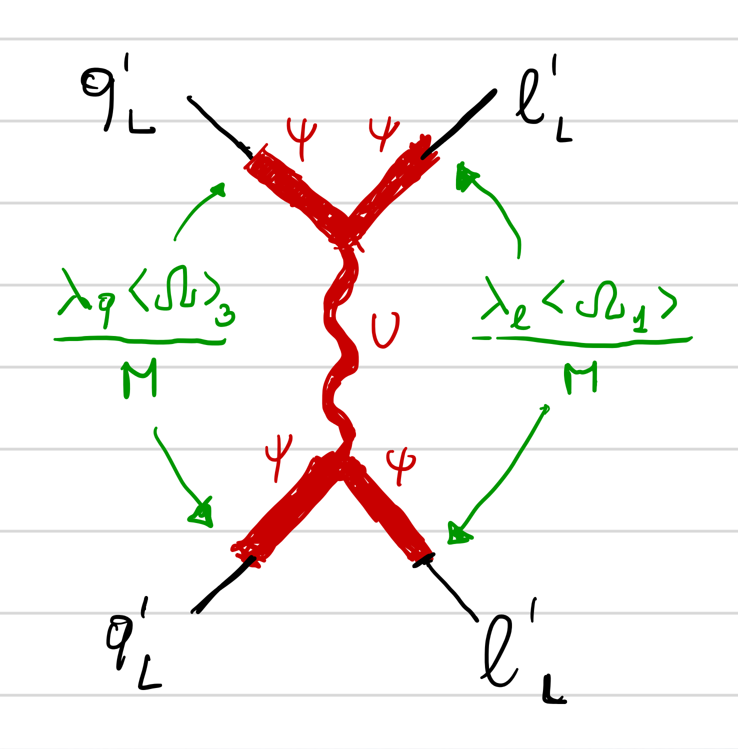
- Field content

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$
$q_L'^i$	1	3	2	1/6
$u_R'^i$	1	3	1	2/3
$d_R'^i$	1	3	1	−1/3
$\ell_L'^i$	1	1	2	−1/2
$e_R'^i$	1	1	1	−1
Ψ_L^i	4	1	2	0
Ψ_R^i	4	1	2	0
H	1	1	2	1/2
Ω_3	$\bar{4}$	3	1	1/6
Ω_1	$\bar{4}$	1	1	−1/2

} would-be SM states ($q_L'^i$, $u_R'^i$, $d_R'^i$, $\ell_L'^i$, $e_R'^i$)

} vector-like states (Q+L) (Ψ_L^i, Ψ_R^i)

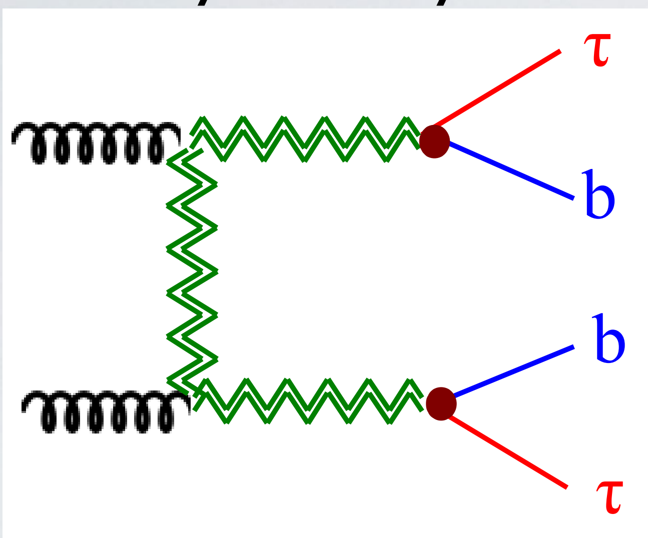
} symmetry breaking (H, Ω_3, Ω_1)



- Color octet and Z' are the most important states

Direct Searches (gauge sector)

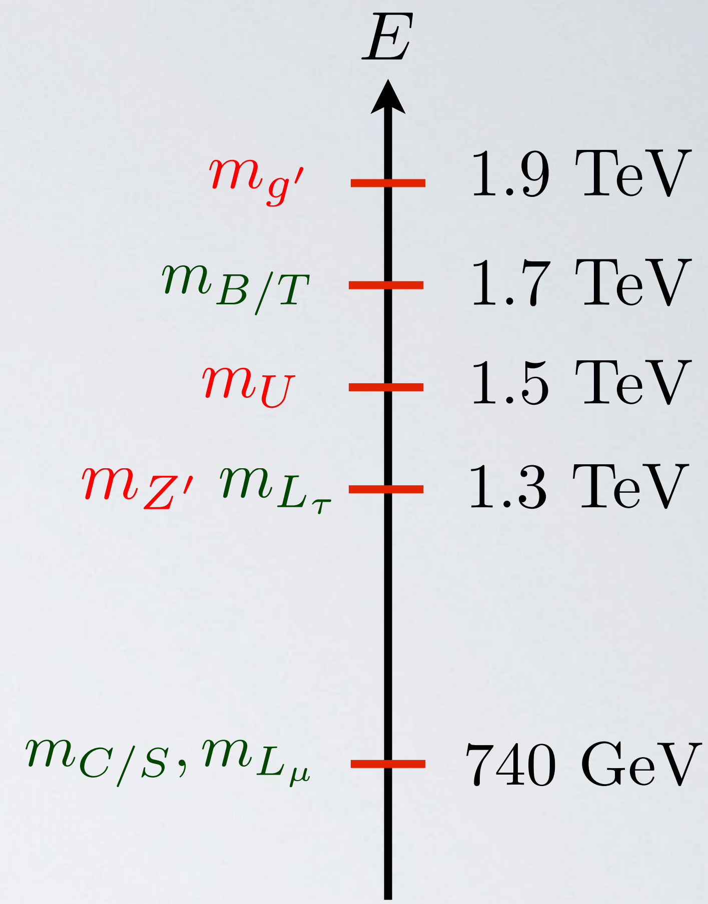
- Leptoquark, pair production by QCD interactions, decay into third family fixed by the anomaly:



$$\begin{cases} U \to b\tau^+, & \text{BR} = 50\ \% \\ U \to t\overline{\nu}, & \text{BR} = 50\ \% \end{cases}$$

(CMS search for spin-0 1703.03995)
(recast for spin-1 in 1706.01868)
(see also 1706.05033)

$m_U > 1.3$ TeV   leptoquark mass sets the overall scale



- Z', dangerous Drell-Yann processes suppressed because coupling to the first family is reduced due to small U(1)' coupling. $\sim g_Y/g_4$

- g', coupling to the first family given by the SU(3)' factor $\sim g_s/g_4$
  resonant dijets search particularly sensitive (ATLAS 1703.09127)

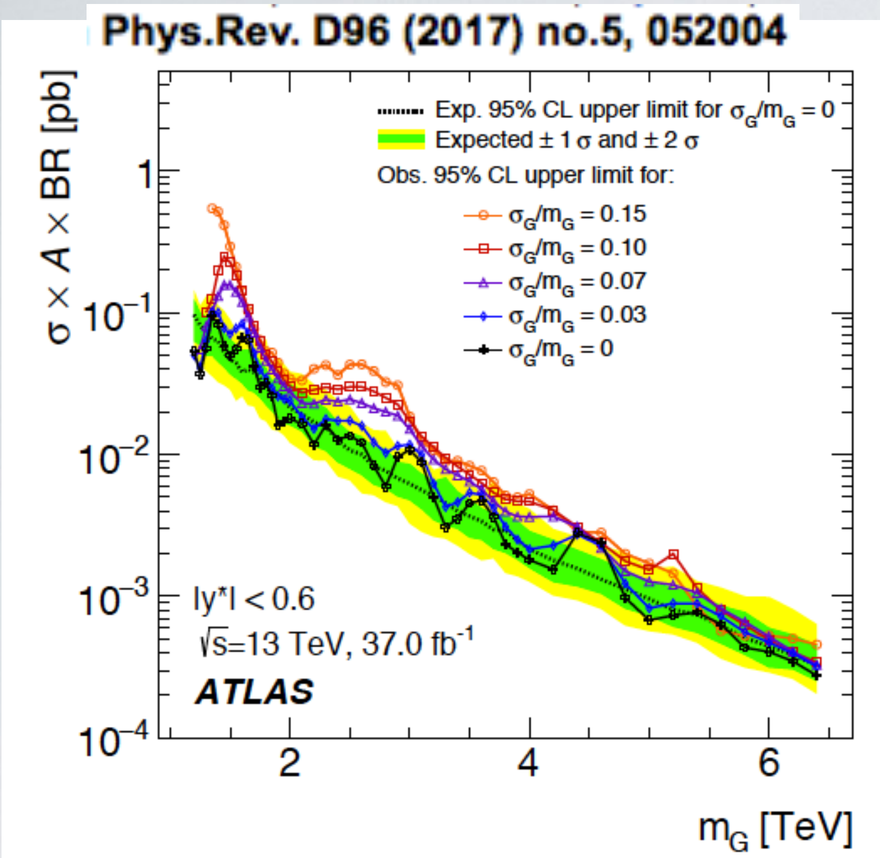
Need large g4…

$$g_4 \gtrsim 3$$

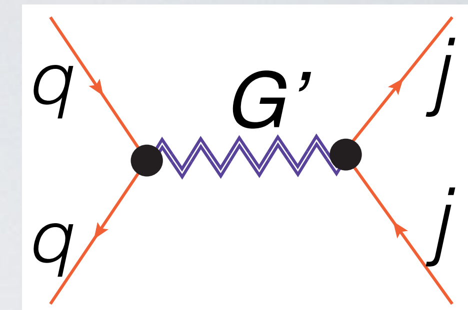
- However bump searches loose in sensitivity when the width-to-mass ratio is too large, in our case the decay width is naturally large because of the decay into heavy quarks

$\frac{\Gamma}{m} \lesssim 15\%$ from exp. analysis $\frac{\Gamma_{g'}}{m_{g'}} = 28\%$ our benchmark

Colour octet vector at the LHC



- We are looking for →

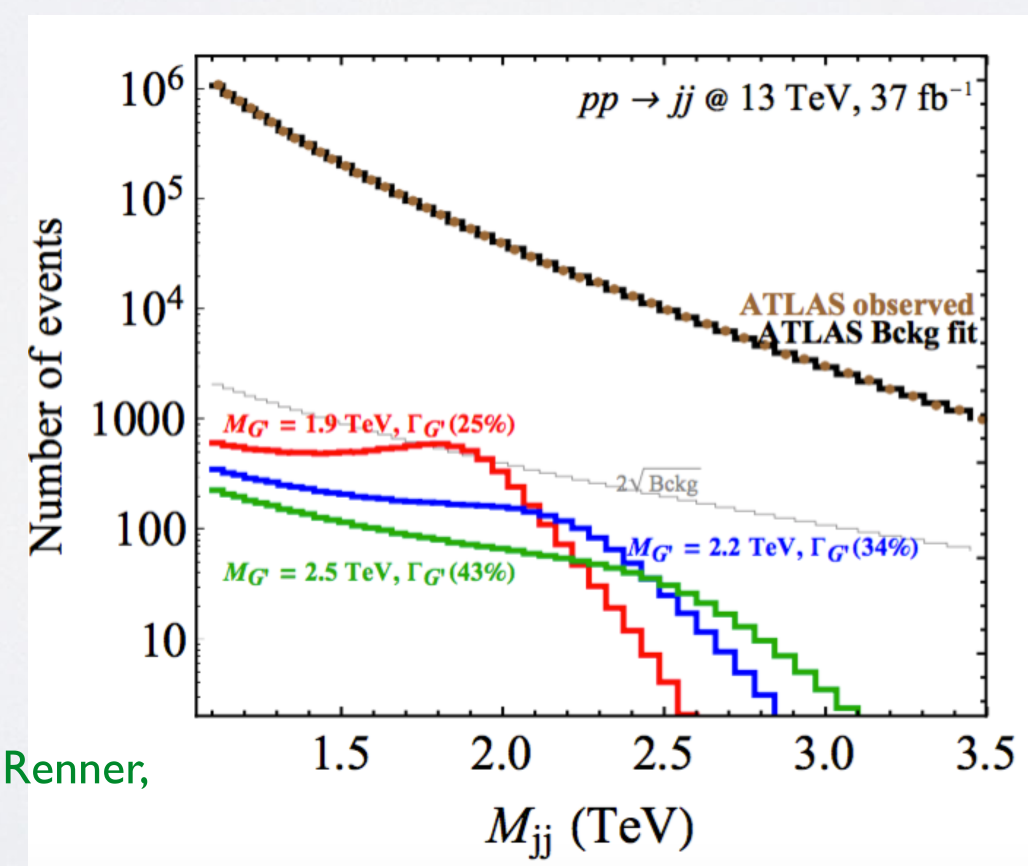


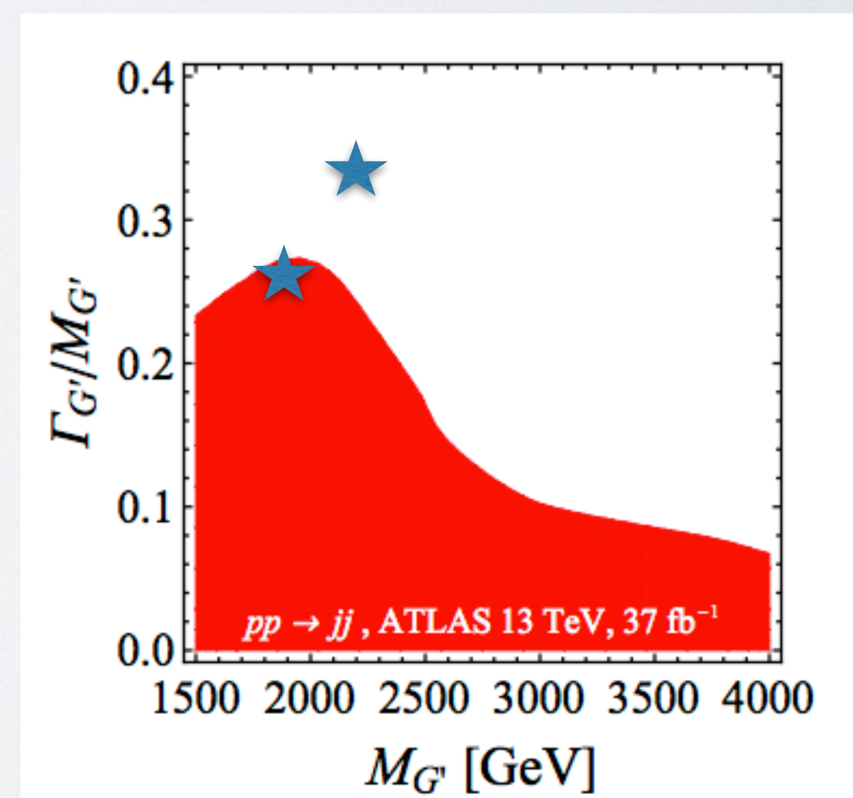
- Background fitted to data
- Exclusion limit are reported with benchmark up to

$$\frac{\Gamma}{m} \lesssim 15\%$$

- In models aiming at explaining charged current anomalies, large widths are expected, we invite the experimental collaborations to consider larger values as benchmarks

- We have interference with the background!





[Greljo, Di Luzio, Fuentes-Martin, MN, Renner, in preparation]

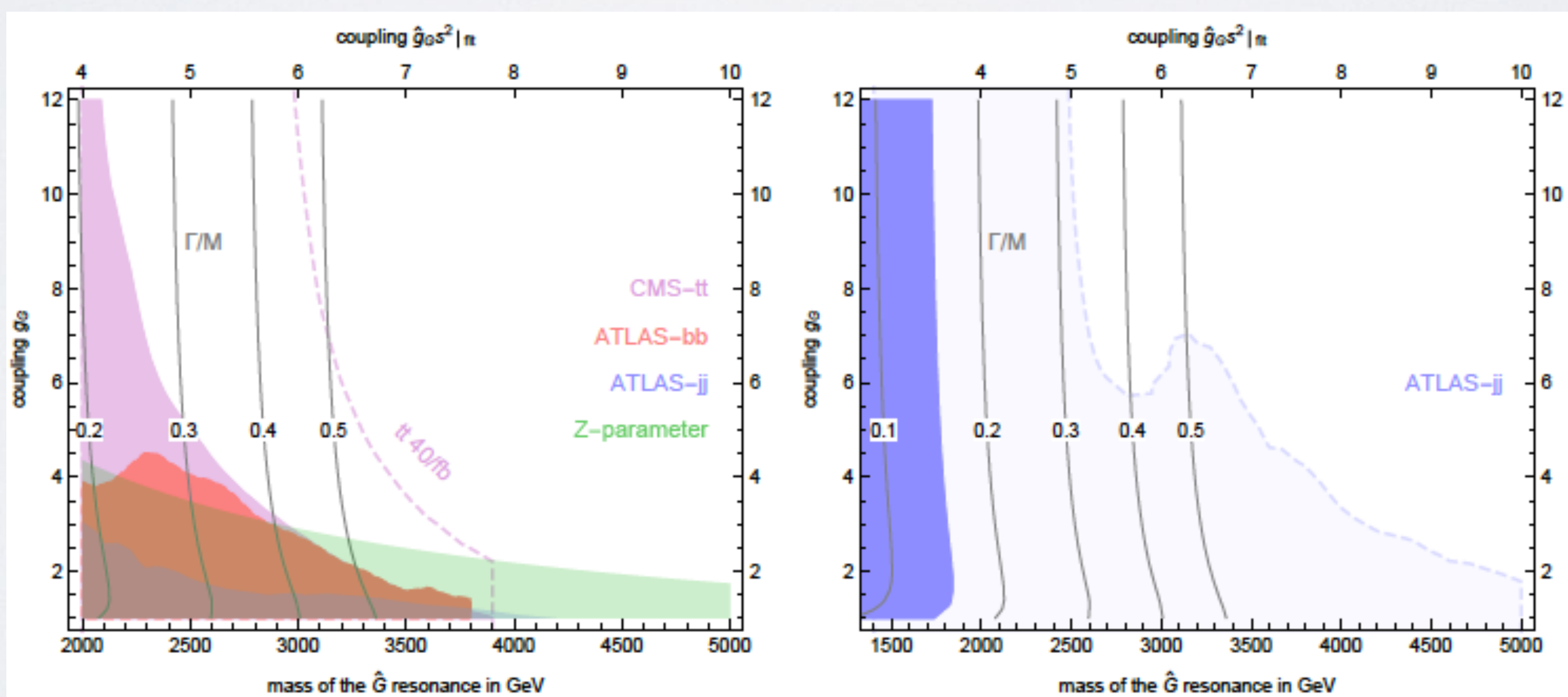
Other channels of interest

- Depending on the value of the parameters/models, it is important to consider also:

$$\begin{cases} g' \to t\bar{t} \\ g' \to b\bar{b} \\ Z' \to t\bar{t} \\ Z' \to b\bar{b} \\ Z' \to \tau\tau \end{cases}$$

Final states containing quarks and leptons of the third family: a correlation with the flavour structure hinted by the anomalies. Top is present because of SU(2) gauge structure.

- This holds also in strongly coupled models. As before states don't decouple and large widths are expected. $M_U = M_{g'} = M_{Z'}$



[Barbieri, Tesi, 1712.06844]

- Fair to say that all the models are under pressure by various simultaneous constraints (EW and FCNC observables, direct searches)

Conclusions

- Flavour anomalies are surviving in a coherent way in both charged current (2012) and neutral current (2013).
- There is a physics program ongoing from LHCb: we are waiting for run 2 results, as well as new measurements $\Delta P_5', R(\phi), R(\Lambda), R(D_s), R(\Lambda_c), R(\Lambda_c^*), + \ldots$
- Current anomalies in B decays have a simple and consistent interpretation at the effective field theory level.
- The NP scale inferred from the charged current anomalies is within the reach of present or near future colliders.
- Leptoquarks stands out as preferred mediators to be searched at colliders.
- In UV "complete" models with vector leptoquarks main signal in direct searches could arise from neutral states decaying into SM fermions of the third family. Typically we expect large decay widths.
- If charged current anomalies disappears, NP could be at much higher energy.