Flavour anomalies at the LHC

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Flavour Anomalies

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

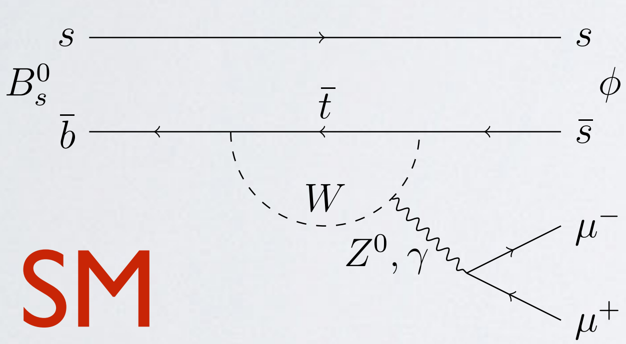
1) Angular observables in $B \to K^*\mu^+\mu^-$ $\sim 4\sigma$ (?!)

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

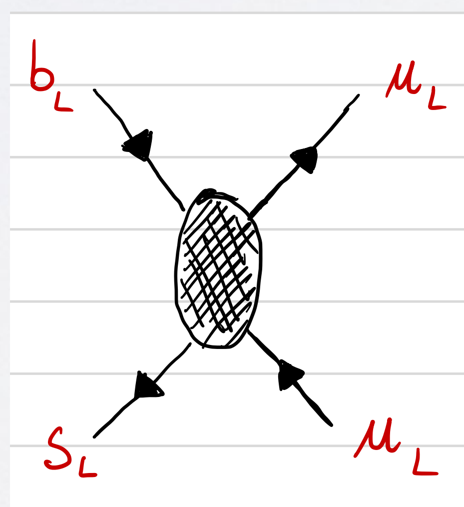
3) LFU violation in R_K 2.6σ

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

"clean" only $\approx 4\sigma$



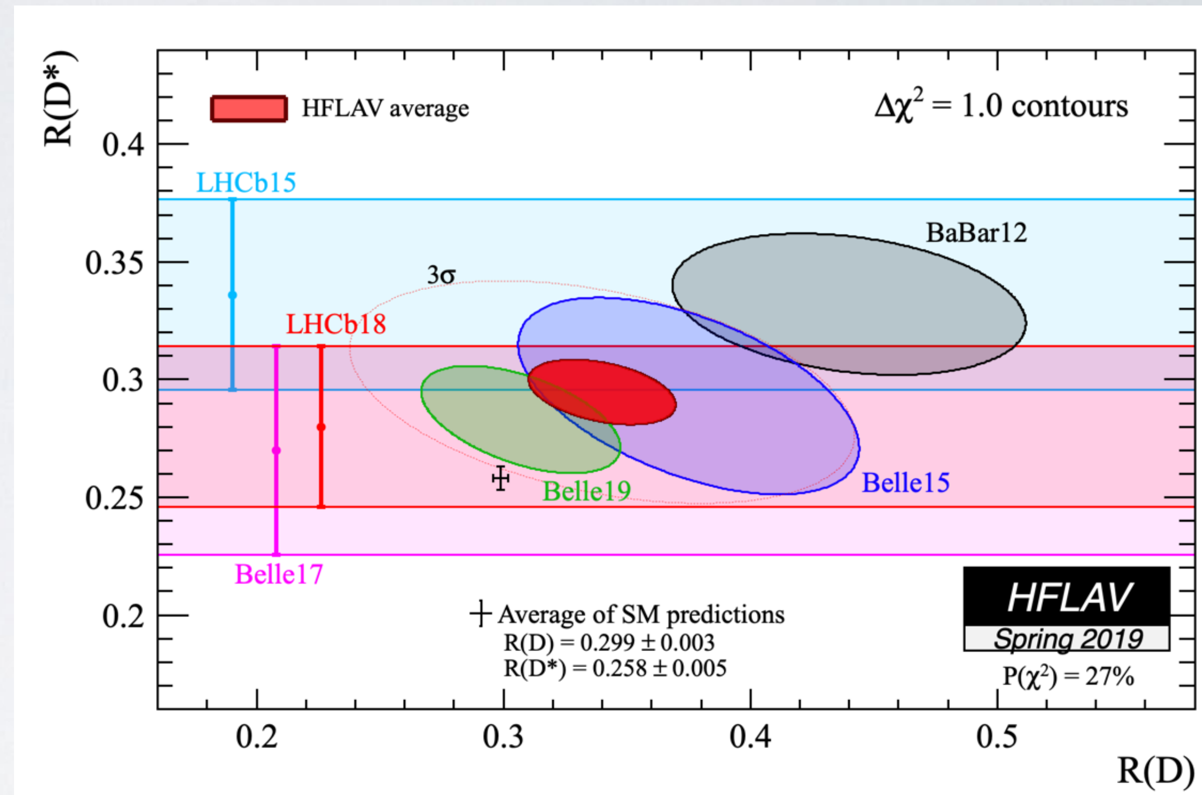
SM

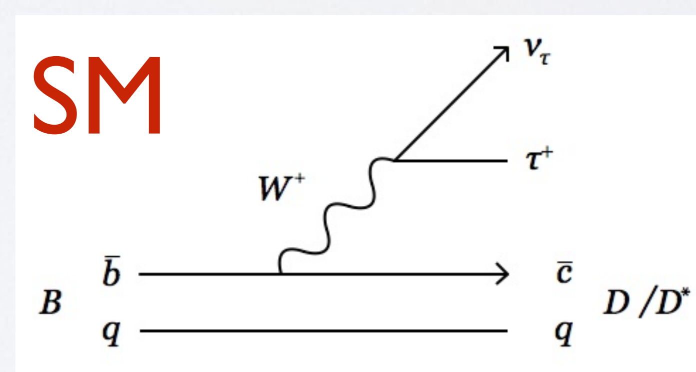


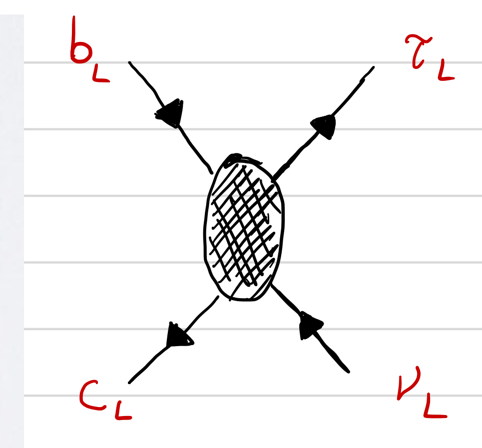
$$\mathcal{L}_{eff} = \frac{1}{\Lambda^2_{R_K}} \bar{s}_L \gamma^\mu b_L \, \bar{\mu}_L \gamma_\mu \mu_L + h.c.$$

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

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







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

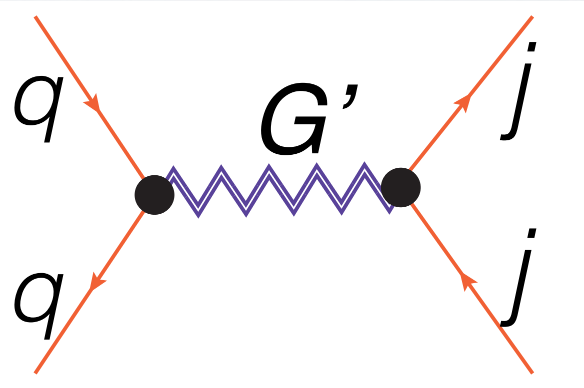
$|C_\tau^{\rm NP}| \gg |C_\mu^{\rm NP}|, |C_e^{\rm NP}|$ $\Lambda_{R_D} = 3.4$ TeV

Bottom-up path

Theoretical input / bias

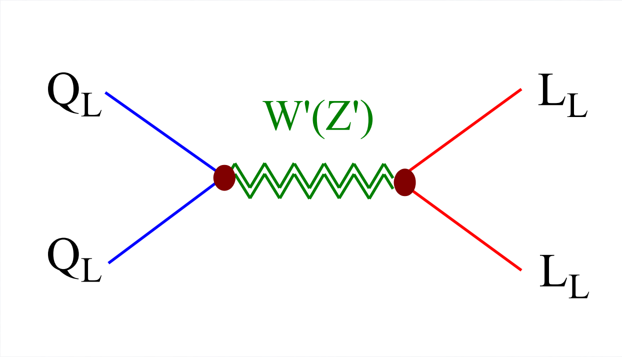
"Motivated" Models

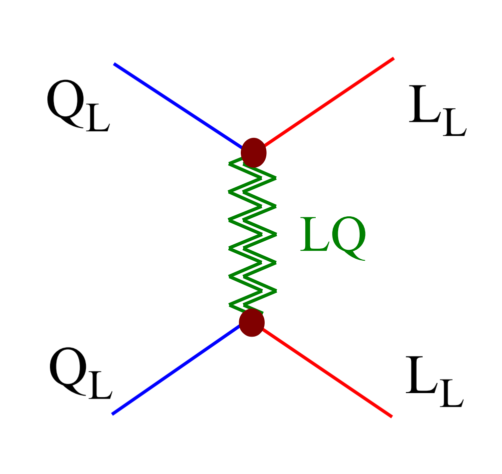
Address more questions/open problems: naturalness, origin of flavour, renormalizability/accidental symmetries.….



Simplified Models

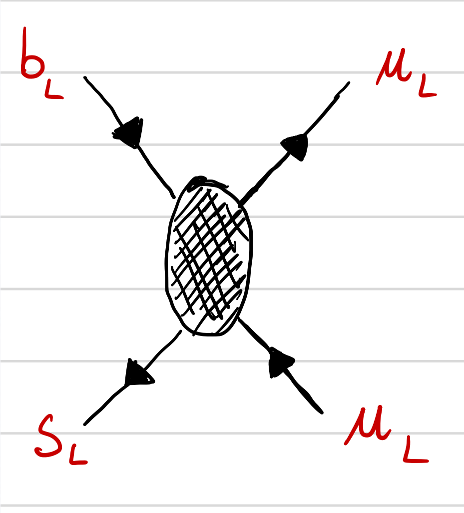
Introducing explicitly New Physics, in the simplest way as possible



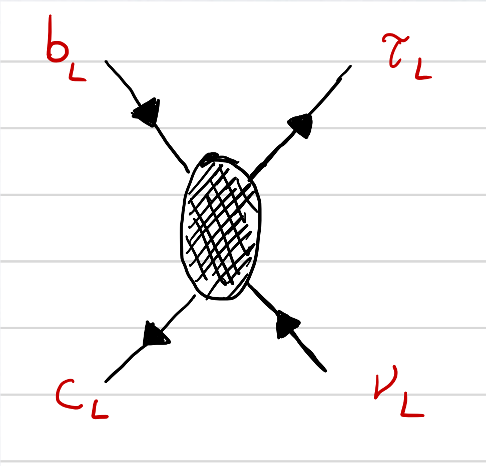


EFT

New Physics in a model independent way



$\Lambda_{R_K} = 31$ TeV



$\Lambda_{R_D} = 3.4$ TeV

Experimental input

- *What is the scale of New Physics?*

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

"Measured" Fermi constant

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

Model dependent part

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

On-shell effects @ colliders

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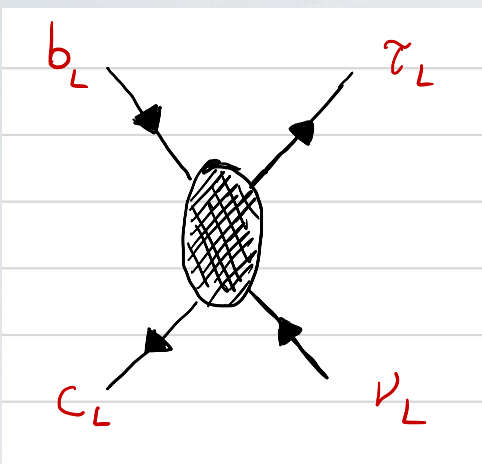
- *What do we expect?* (Worst case scenario)



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

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…

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

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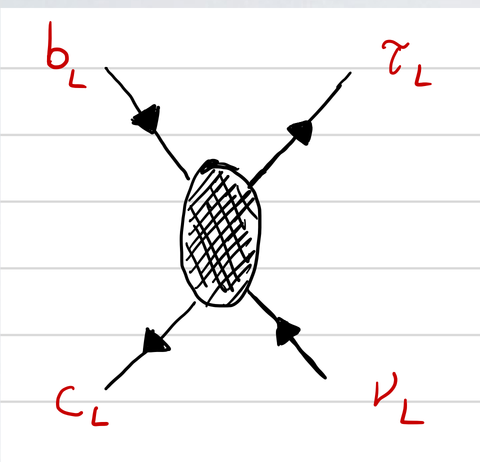

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An old lesson: VV scattering…
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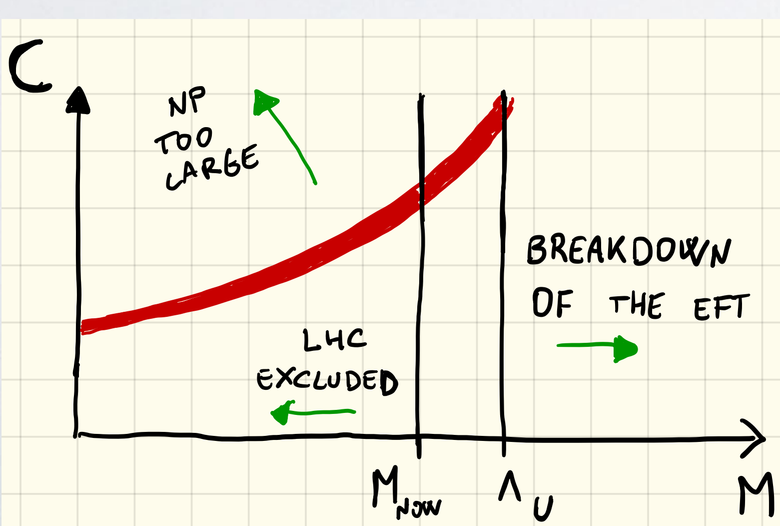
- *What do we expect?* (Warning: a simplified cartoon!)

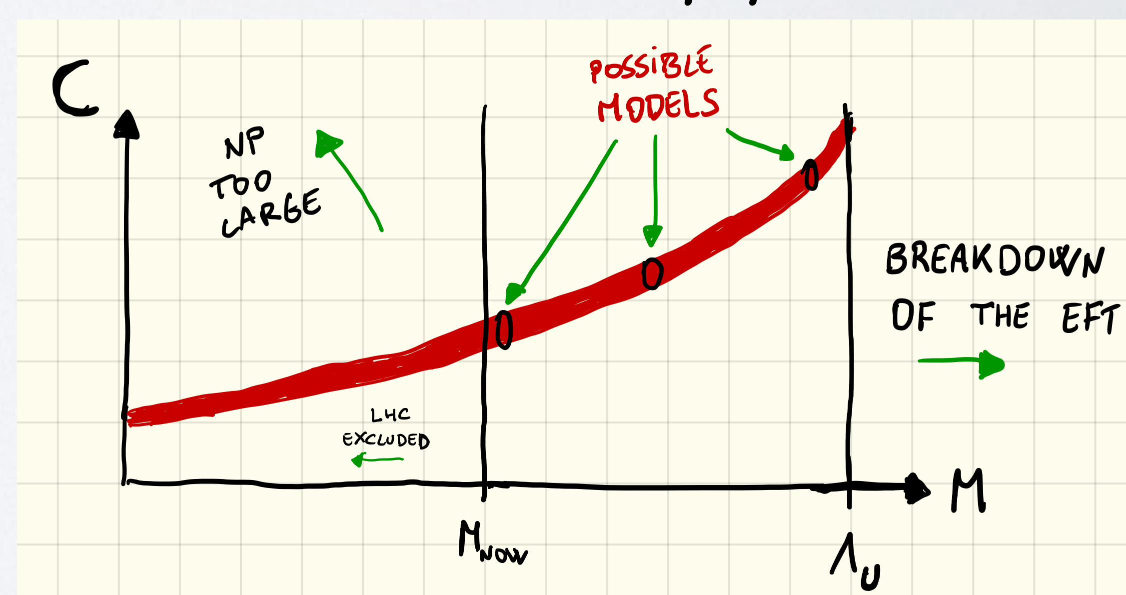
$$b \to c\tau\nu$$



Absence of New Physics at high energy

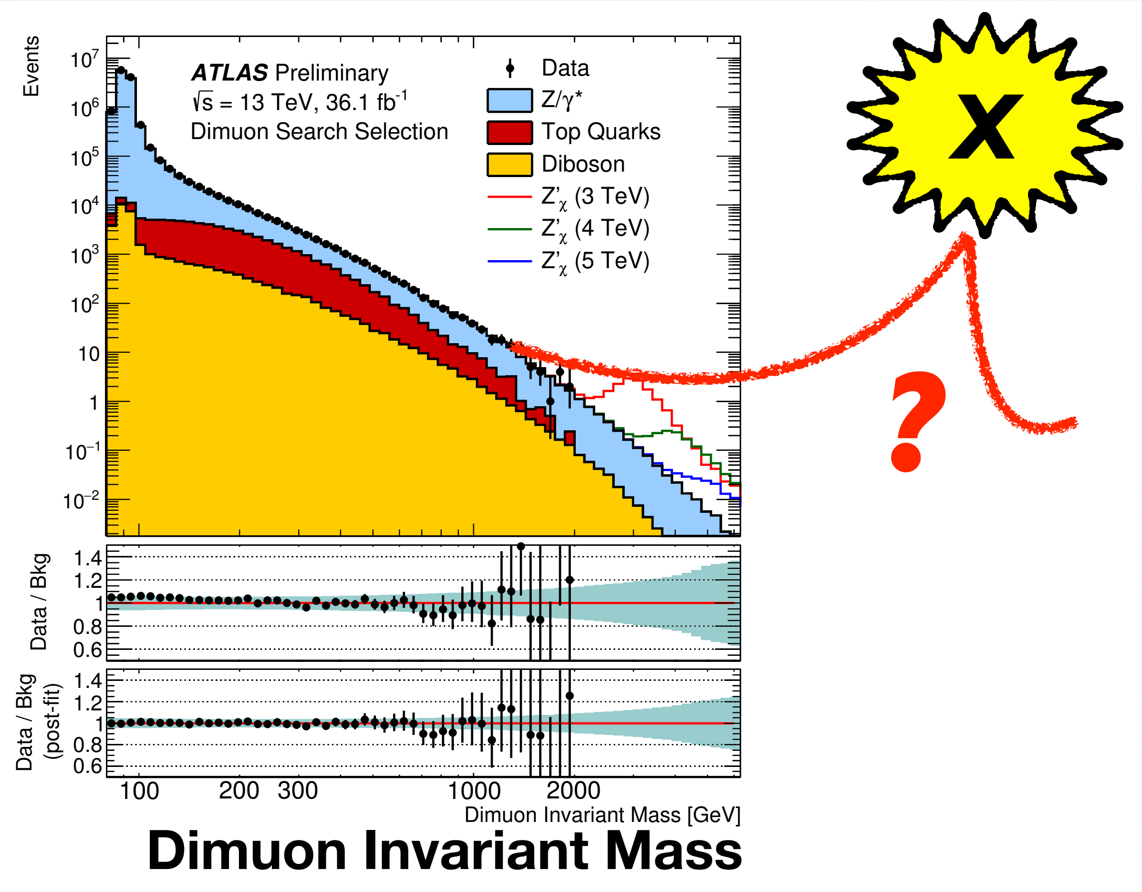
$$M_{now} \gtrsim 1 \text{ TeV}$$

$$b \to s\mu\mu$$



SM-EFT regime: tails

- If the New Physics is very heavy the strategy is to look for di-lepton pair at high-pT



$$\mathcal{L}^{\mathrm{SMEFT}} \supset \frac{C}{M^2}\overline{Q}\gamma^\mu Q\overline{L}\gamma_\mu L$$

$$\mathcal{A} \propto \frac{E^2}{M^2} \quad \text{valid when } E \lesssim M$$

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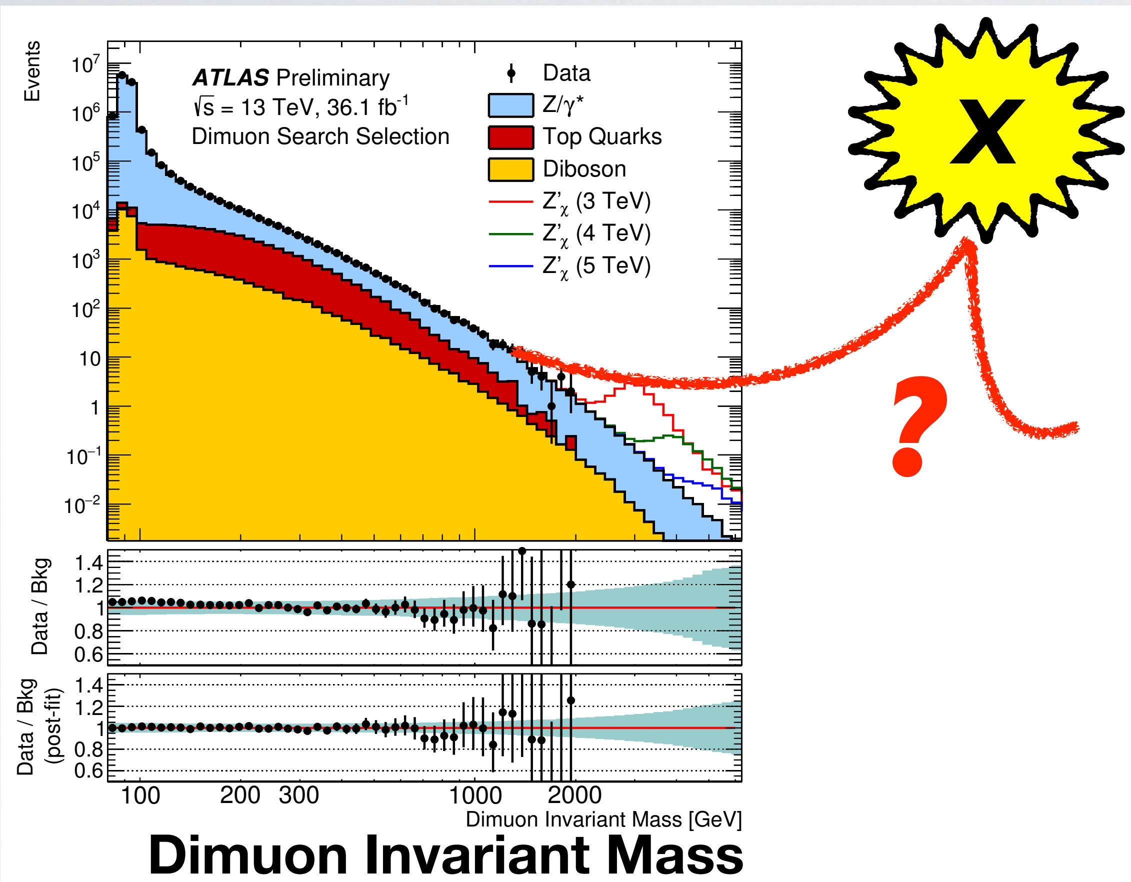

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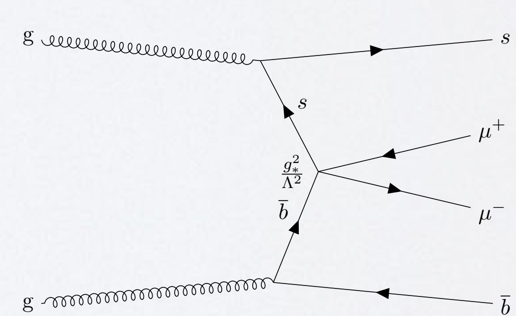
- NC anomalies [1704.09015,1805.11402]

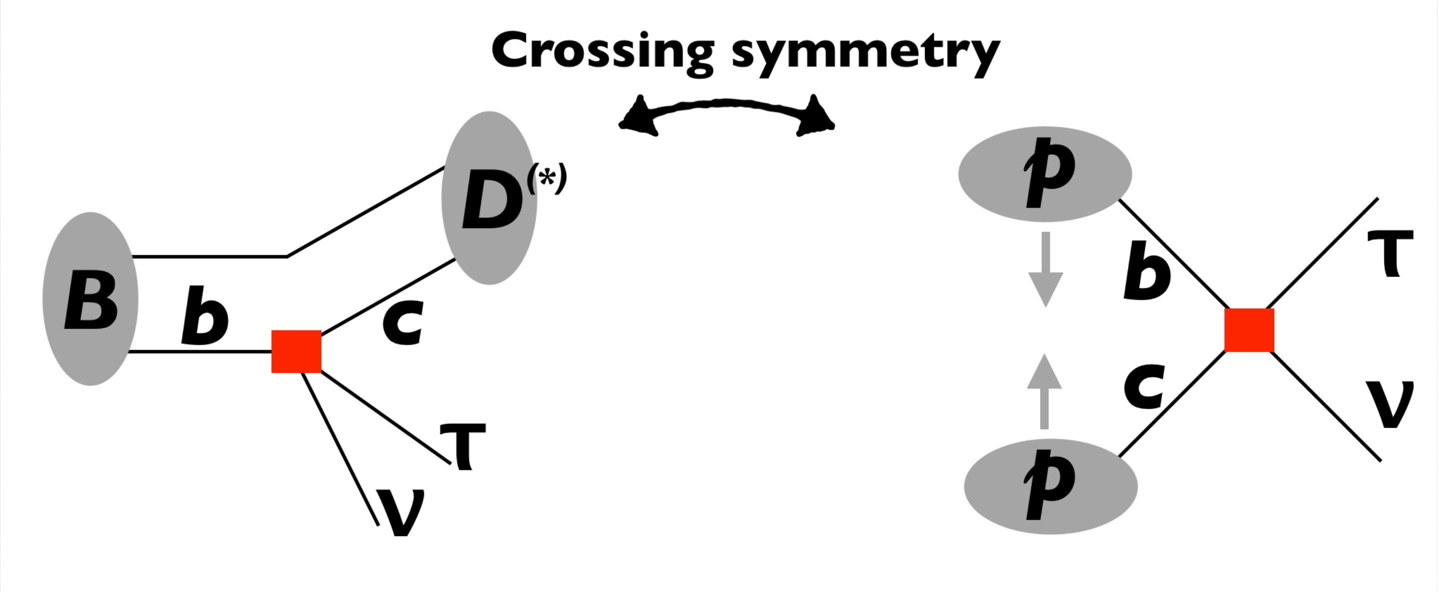
$$pp \to \mu^+\mu^-$$



No sensitivity at HL-LHC if it is present ONLY

$$\frac{1}{(30\ \text{TeV})^2} (\bar{b}\Gamma s)(\bar{\mu}\Gamma\mu)$$

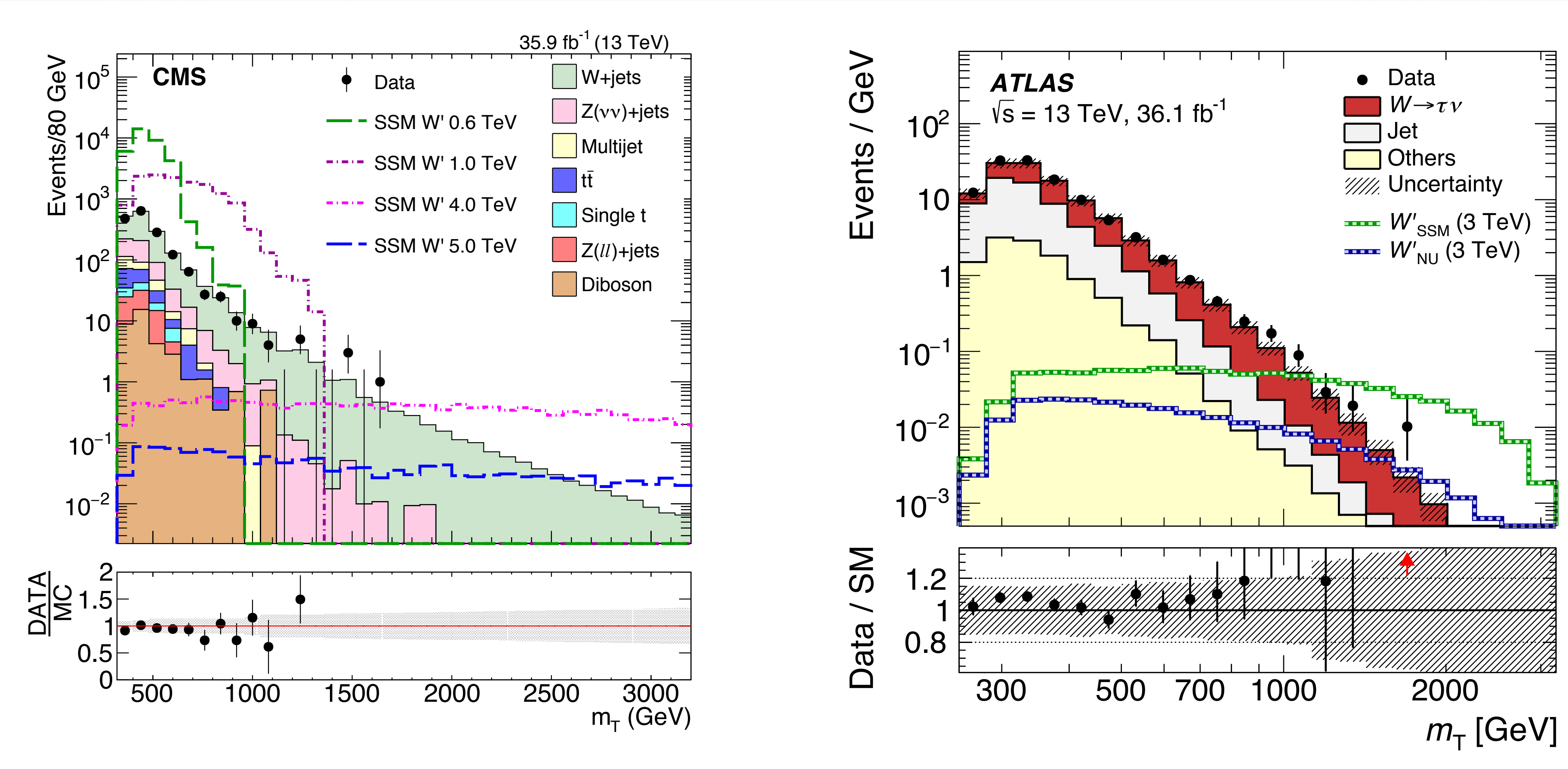
$pp \to \tau\nu$



[Greljo, Martin Camalich, Ruiz-Alvarez 1811.07920]

Phys.Rev.Lett. 122 (2019)

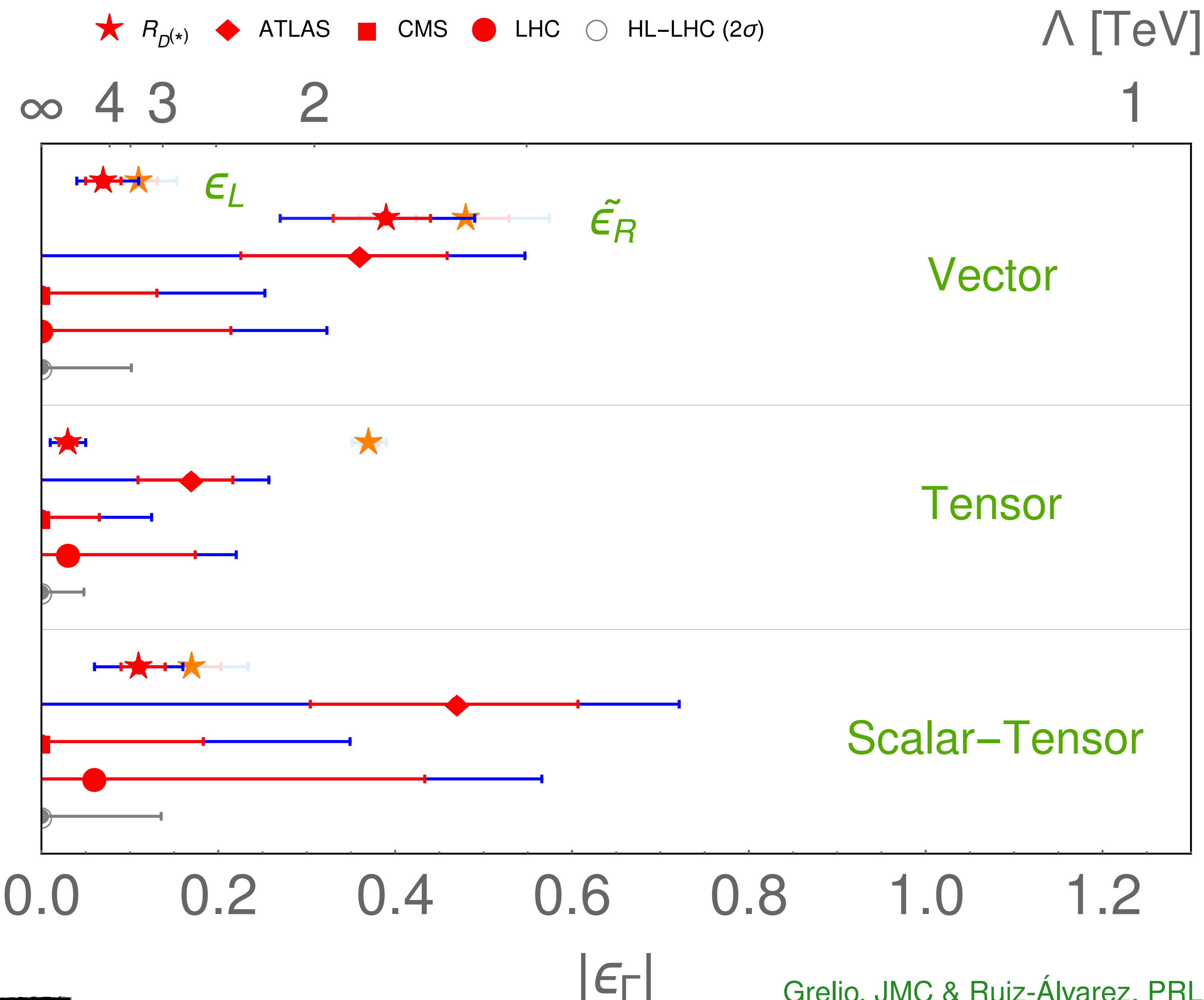
- Making use of the ATLAS and CMS mono-tau serches



$$\mathcal{L}_{\rm LEEFT} \supset -\frac{2V_{kl}}{v^2}\Big[\Big(1+\epsilon_L^{kl\tau}\Big)\bar\tau\gamma_\mu P_L\nu_\tau\cdot\bar u_k\gamma^\mu P_L d_l + \epsilon_R^{kl\tau}\bar\tau\gamma_\mu P_L\nu_\tau\cdot\bar u_k\gamma^\mu P_R d_l$$
$$+\epsilon_T^{kl\tau}\,\bar\tau\sigma_{\mu\nu}P_L\nu_\tau\cdot\bar u_k\sigma^{\mu\nu}P_L d + \epsilon_{S_L}^{kl\tau}\bar\tau P_L\nu_\tau\cdot\bar u_k P_L d_l + \epsilon_{S_R}^{kl\tau}\bar\tau P_L\nu_\tau\cdot\bar u_k P_R d_l\Big] + \text{h.c.},$$

$\Lambda = v/\sqrt{|V_{cb}||\epsilon_\Gamma|}$

* 1σ (red) and 2σ (blue) ranges on the absolute value of the WCs of semi-tauonic cb transitions at μ = mb



Greljo, JMC & Ruiz-Álvarez, PRL122, 131803 (updated)

A lot of room for improvements:

- b-tag,
- tau charge-asymetries,
- rapidity distribution,
- polarization.

$pp \to \tau\nu$

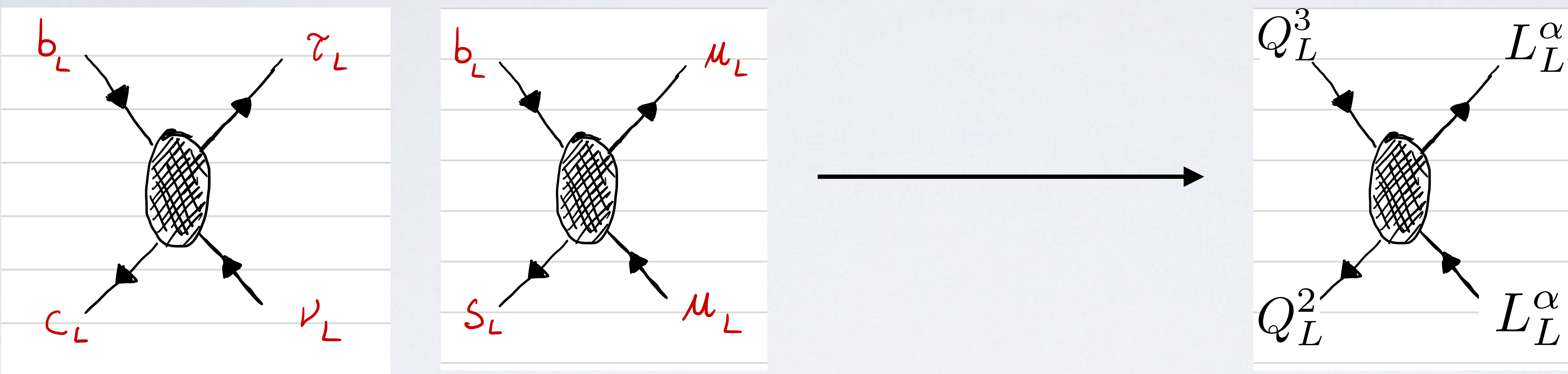
[Thanks to A. Greljo]

SIMPLIFIED MODELS

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

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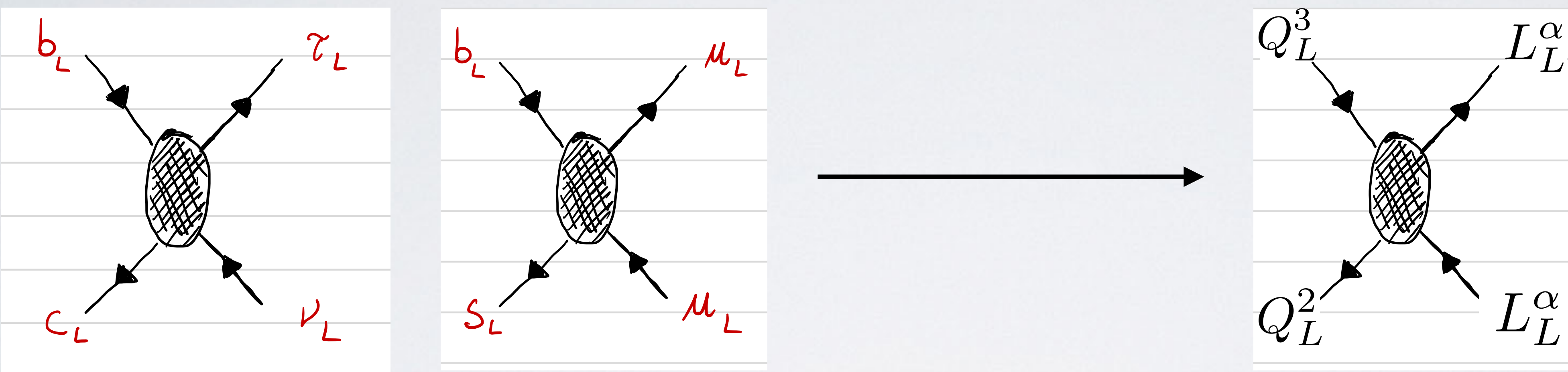
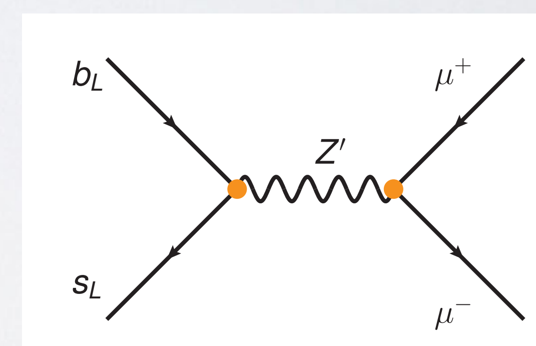
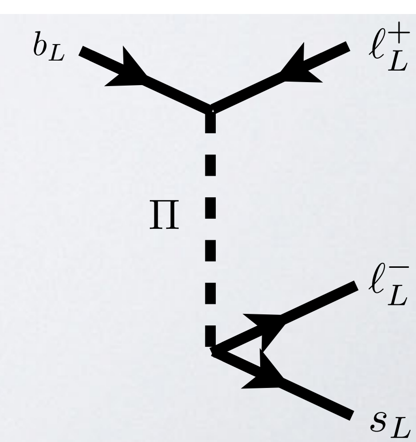


SU(2) structure induce correlations

- *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)

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(Cabibbo angle)

- *Collider implications*

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

Tree-Level Pertubative Unitarity criterium

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

Where to look

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 $Z' \to \tau\tau$)

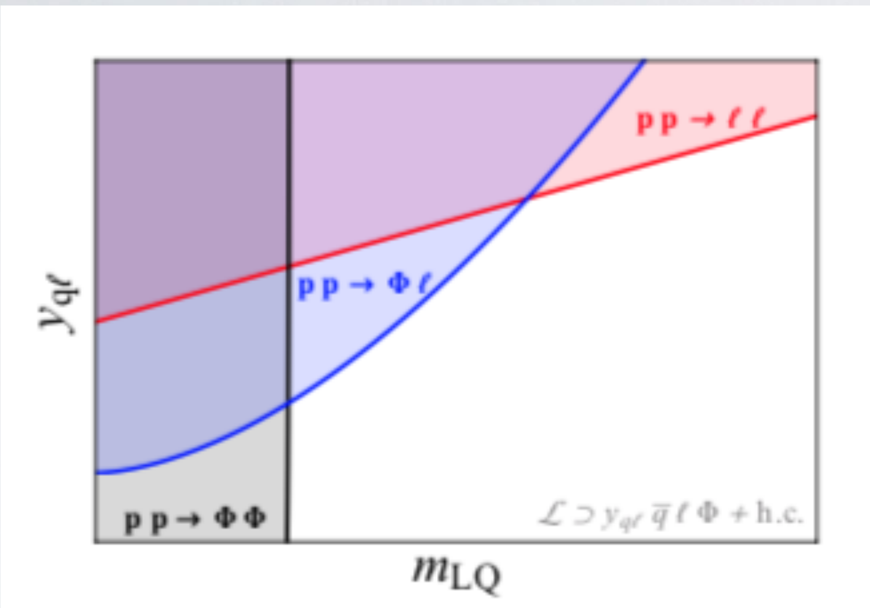
- Vector Leptoquark, U1, decaying into SM fermions of the third family
- Scalar Leptoquarks, tuning+S1+S3, decaying into SM fermions of the third family
- More complicated linear combinations (and parameter adjustments) can be thought

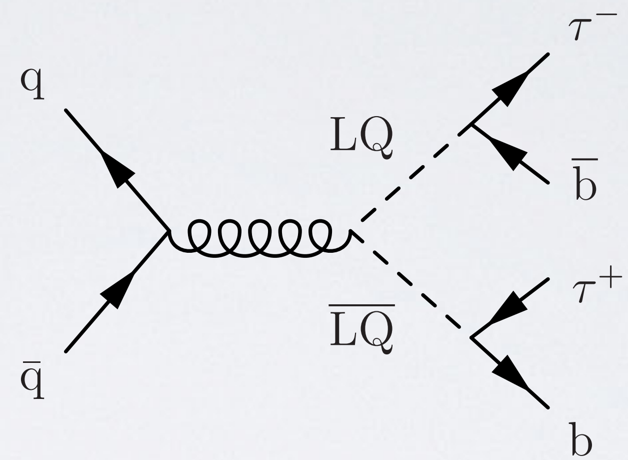
2) Resonance searches for neutral current anomalies only (and no flavour bias)

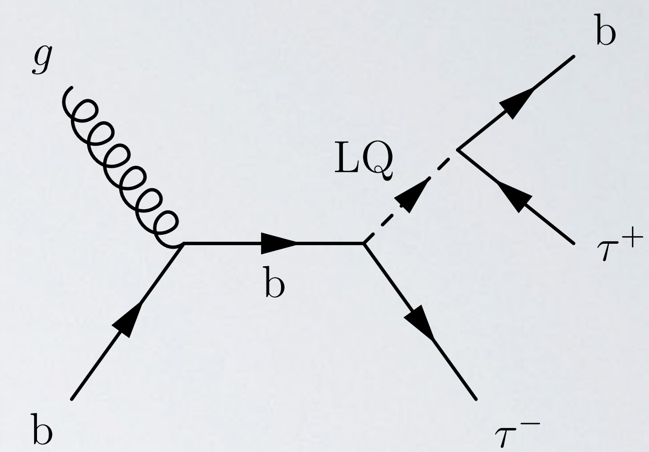
- Z' to muons
- Leptoquark in final states with muons
- One loop mediators also viable..

Leptoquarks

- Working assumption: decays into third family. Relevant parameters: LQ coupling and mass:







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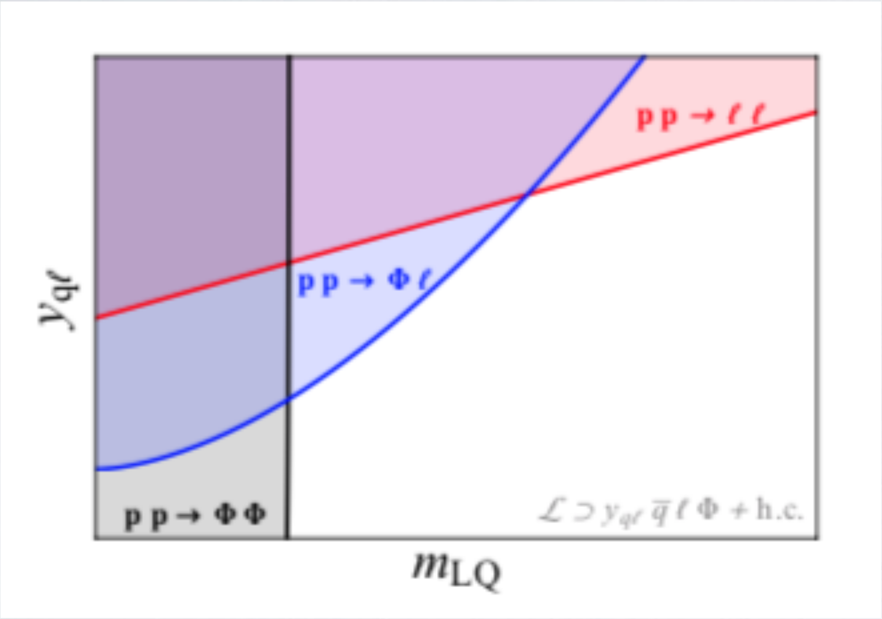
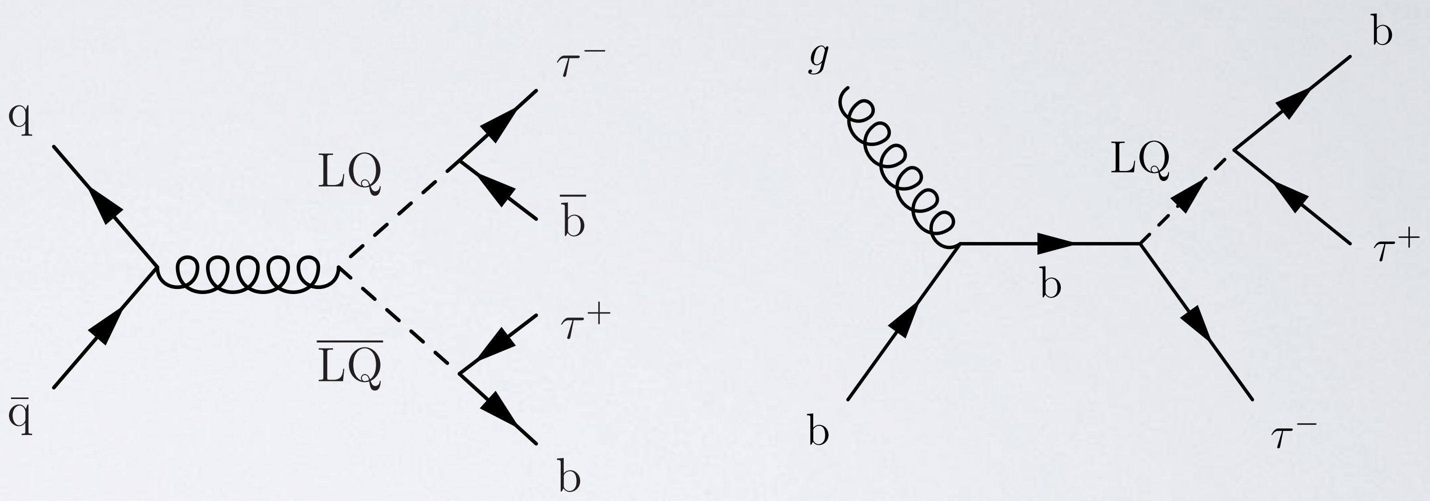
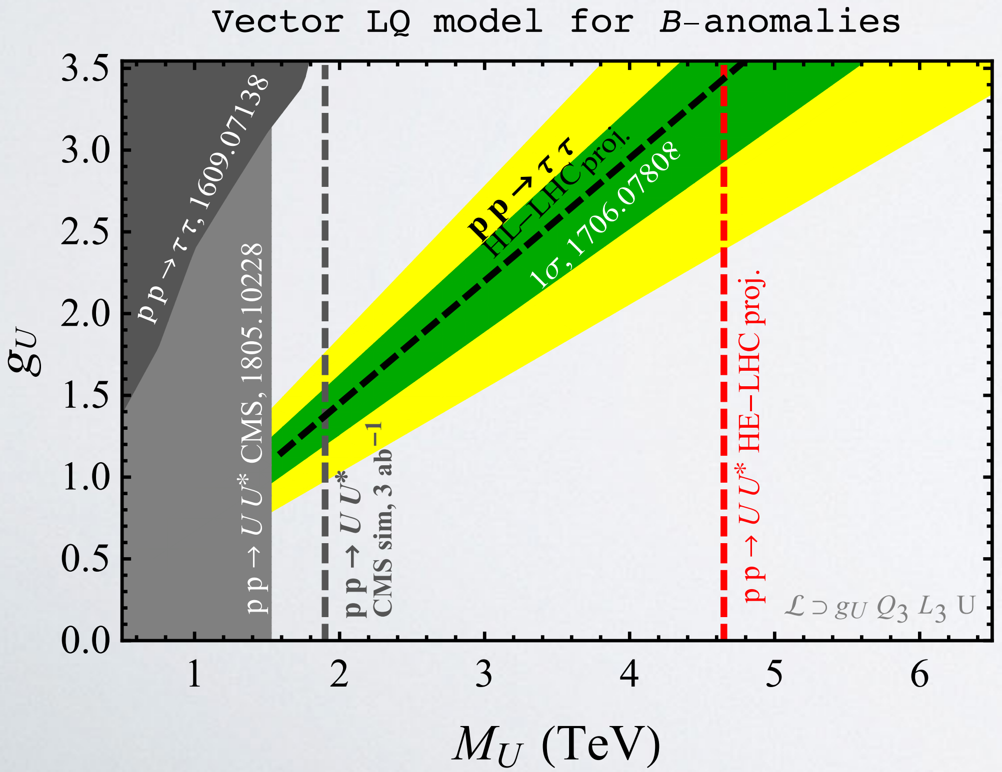






- HL-LHC and HE-LHC report [1812.07638]
- Two decay channels: bottom-tau, top-neutrino. SU(2) fix the BR to be equal
- Top-neutrino: see N.Vignaroli 1808.10309
- Message: LQ survives at the LHC and HL-LHC in large part of the parameter space…

3rd gen. Leptoquarks @ LHC

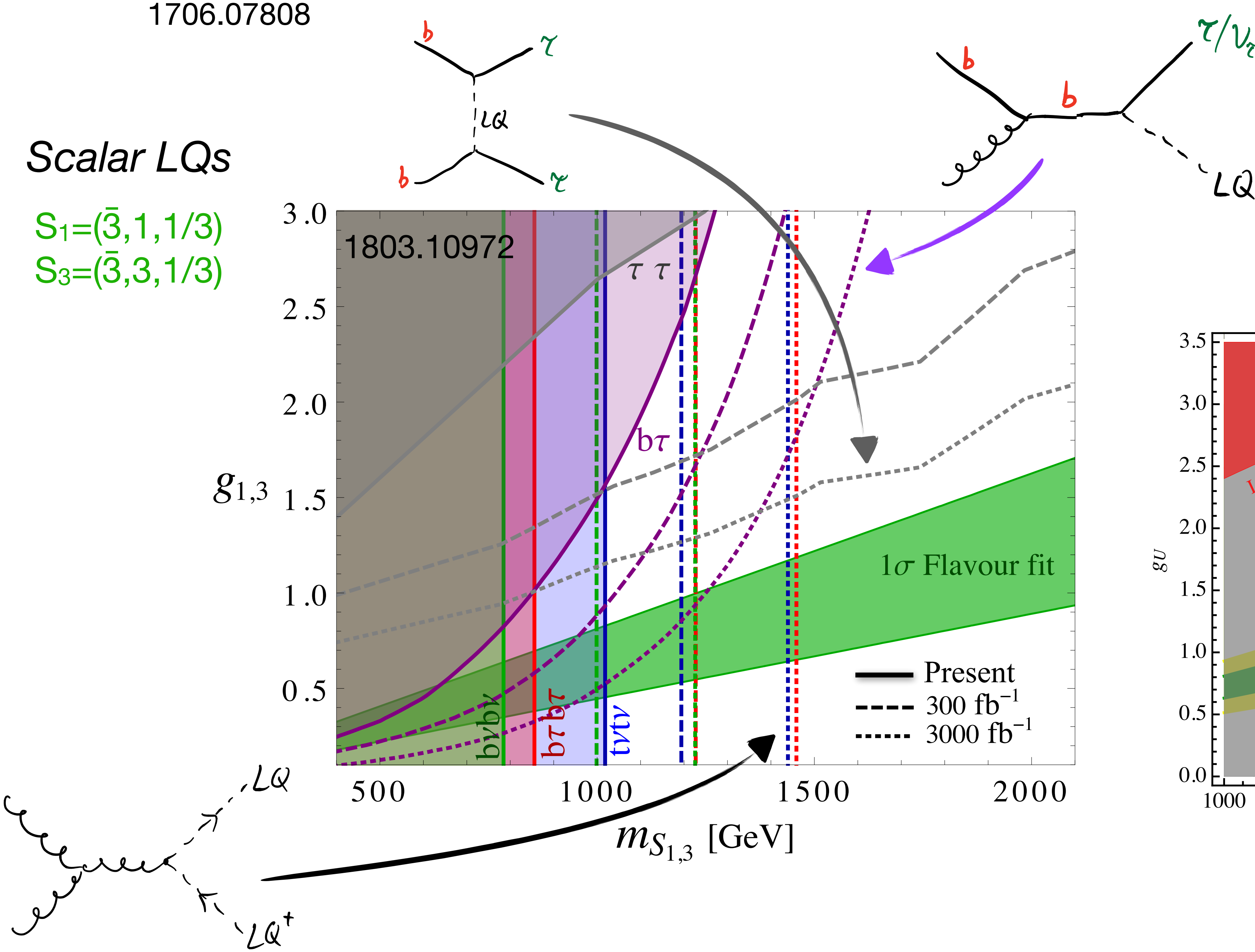
[Slide, adapted from D. Marzocca, 1803.10972]

Best candidates to address both anomalies
1706.07808

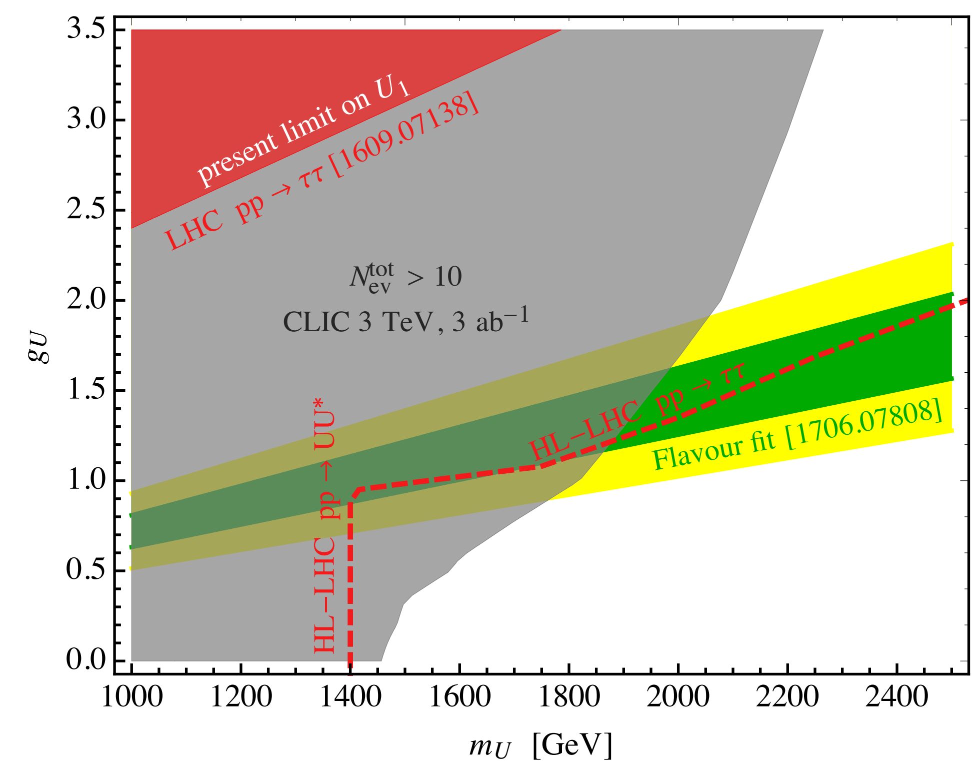
Working assumption: largest couplings to third generation fermions, couplings to lighter ones are CKM (flavour) suppressed.

Scalar LQs

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



[CLIC, Yellow report, Buttazzo, Greljo, Marzocca, Nardecchia]



CMS Collaboration, A. M. Sirunyan et al. *JHEP* **07** (2017) 121, [arXiv:1703.03995].

CMS Collaboration, A. M. Sirunyan et al. arXiv:1803.02864.

CMS Collaboration Tech. Rep. CMS-PAS-SUS-18-001, 2018.

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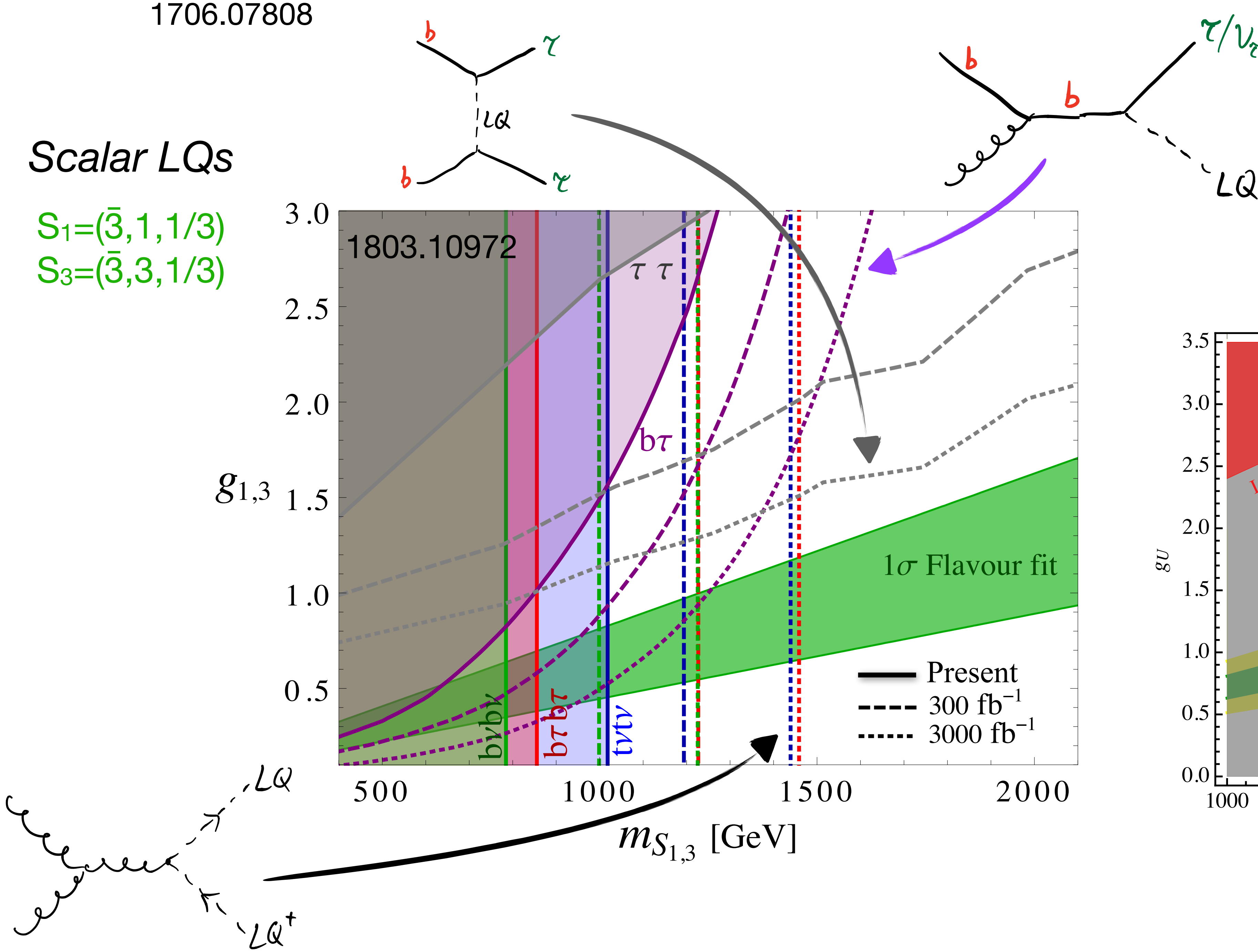
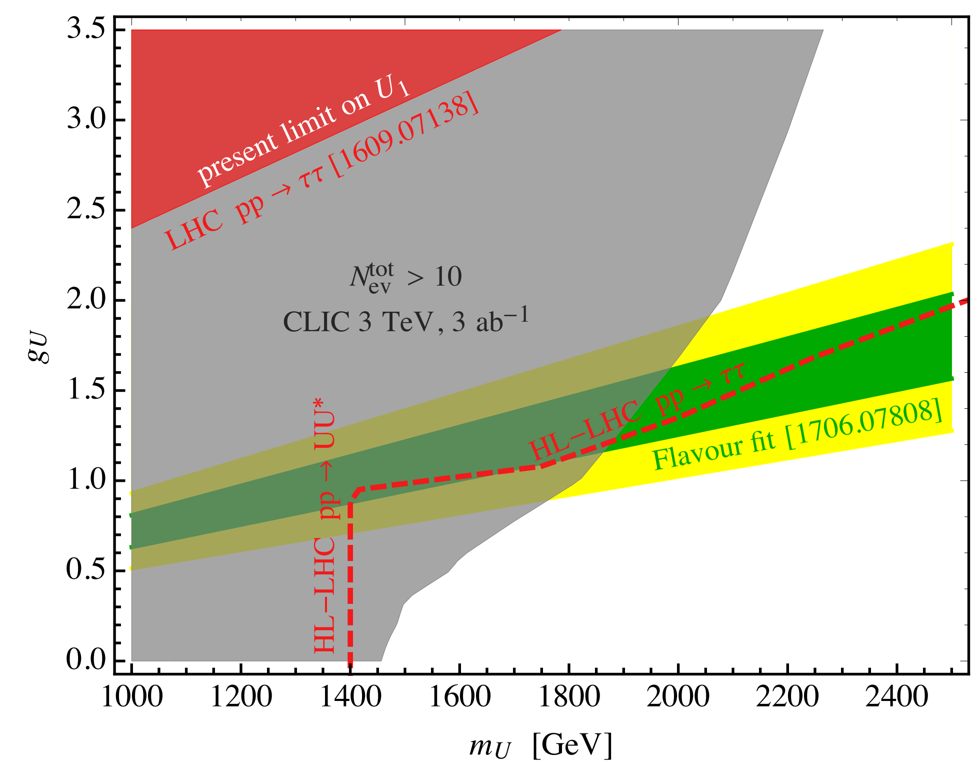


[CLIC, Yellow report, Buttazzo, Greljo, Marzocca, Nardecchia]



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CMS Collaboration Tech. Rep. CMS-PAS-EXO-17-029, 2018.

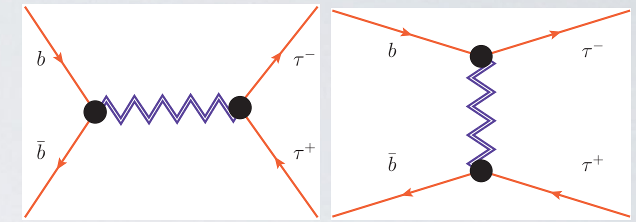
- A lot of phenomenological aspects call for full models!

Problems Beyond the naive mediator(s)

1) Direct searches.

$$\mathcal{L}_{eff} = -\frac{2}{\Lambda_{R_D}} \bar{c}_L \gamma^\mu b_L \, \bar{\tau}_L \gamma_\mu \nu_L + h.c. \rightarrow \left(\frac{1}{1\ \mathrm{TeV}}\right)^2 \bar{b}_L \gamma^\mu b_L \bar{\tau}_L \gamma^\mu \tau_L$$

$$\Lambda_{R_D} = 3.4\ \mathrm{TeV}$$

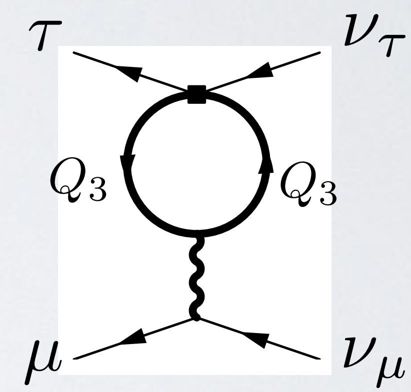


[Faroughy,Greljo,Kamenik, 1609.07138]

2) Radiative contraints

$$(\overline{Q}_L \gamma^\mu Q_L)(\overline{L}_L \gamma_\mu L_L) \rightarrow (\overline{L}_L \gamma^\mu L_L)(\overline{L}_L \gamma_\mu L_L)$$

$$\delta g^Z_{\tau_L}, \delta g^Z_{\nu_\tau}, \delta g^W_\tau, \mathcal{B}(\tau \rightarrow 3\mu)$$



[Feruglio, Paradisi, Pattori, 1606.00524,1705.00929]

3) FCNC with neutrinos.

$$\mathcal{B}(B \rightarrow K^{(*)}\nu\nu) \approx \mathcal{B}(B \rightarrow K^{(*)}\nu_\tau\nu_\tau) \gg \mathcal{B}(B \rightarrow K^{(*)}\nu\nu)_{SM}$$

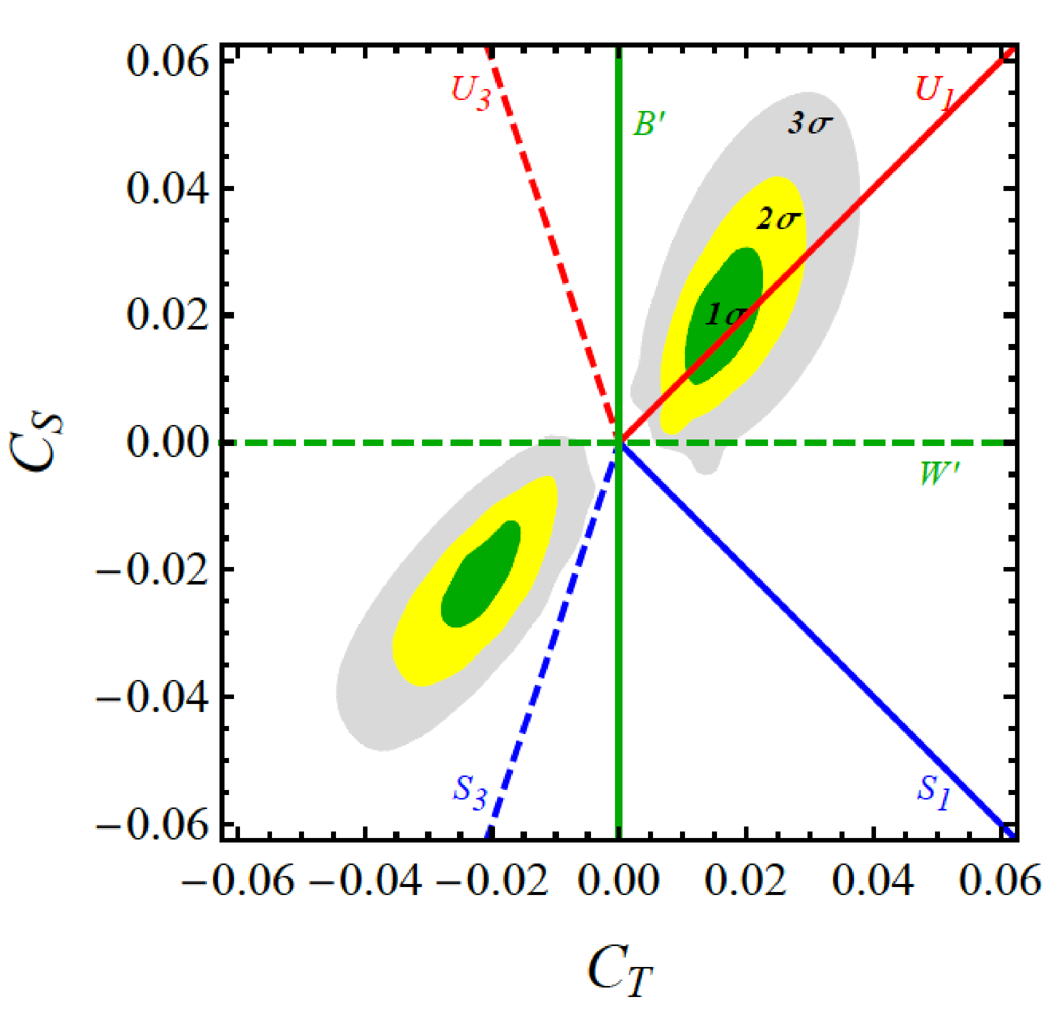
$$\frac{\mathcal{B}(B \rightarrow K^{(*)}\nu\nu)}{\mathcal{B}(B \rightarrow K^{(*)}\nu\nu)_{SM}} \lesssim 4$$

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	✓	✓	×

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

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



[Buttazzo, Greljo, Isidori Marzocca 1706.07808]

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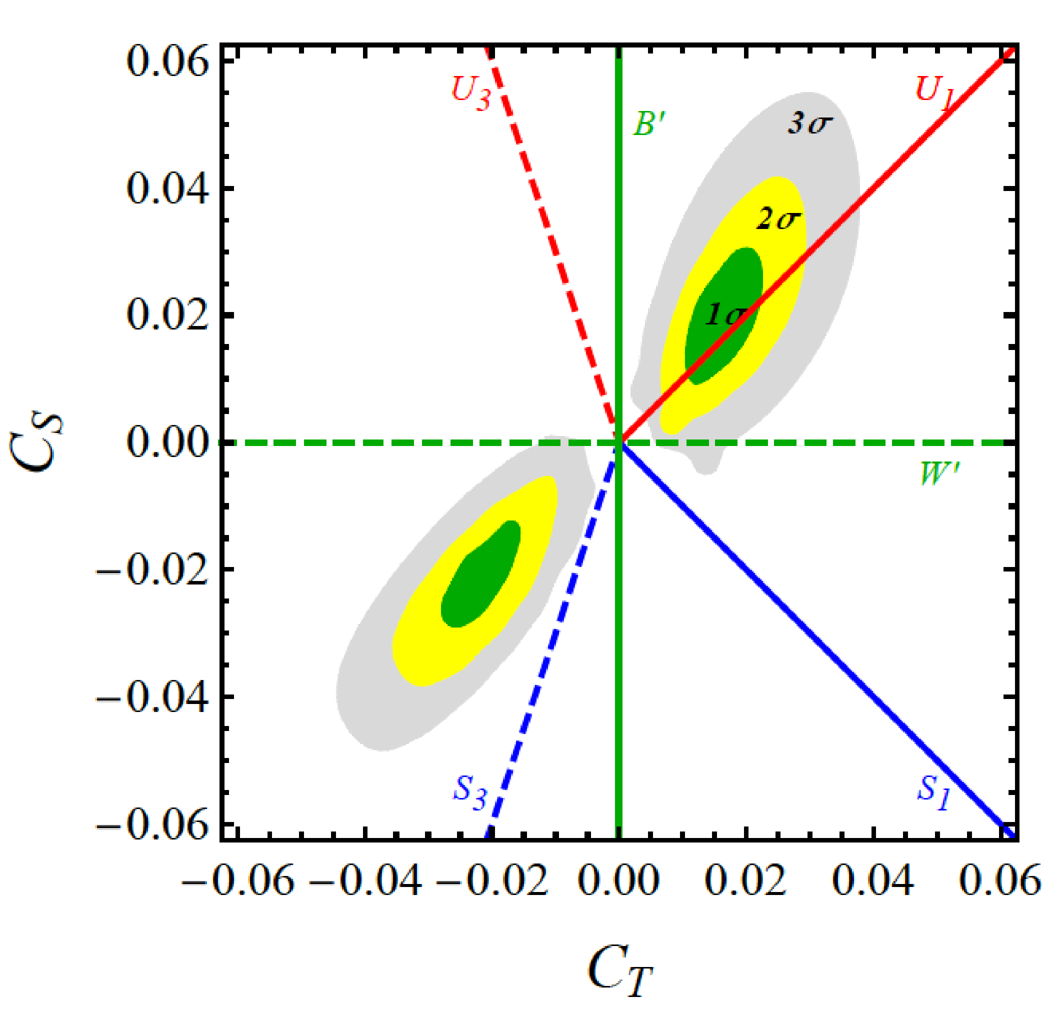

[Buttazzo, Greljo, Isidori Marzocca 1706.07808]

- 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+…]

SU(4) Pati-Salam

PRD (1975)

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

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

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

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

$8 \to g$, $3 \to U_\mu$, $1 \to Z'$

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

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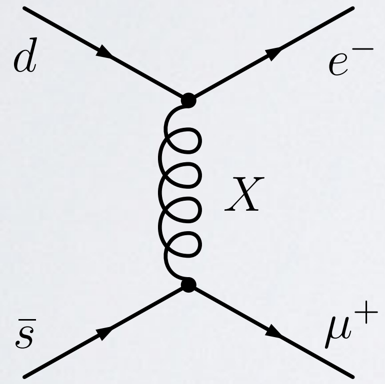
$g \quad U_\mu \quad Z'$

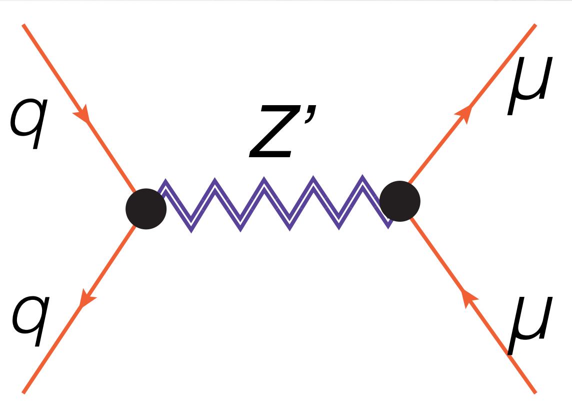
- A problem: bounds from indirect searches



$$M_U \gtrsim 100 \text{ TeV} \qquad M_U \lesssim 2 \text{ TeV}$$

(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:

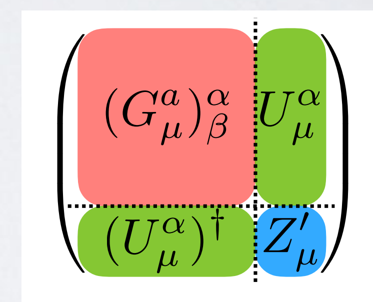
1) A leptoquark $M_U = \frac{1}{2} g_4 \sqrt{v_1^2 + v_3^2}\,,$

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:

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



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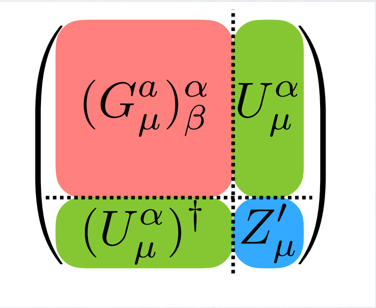


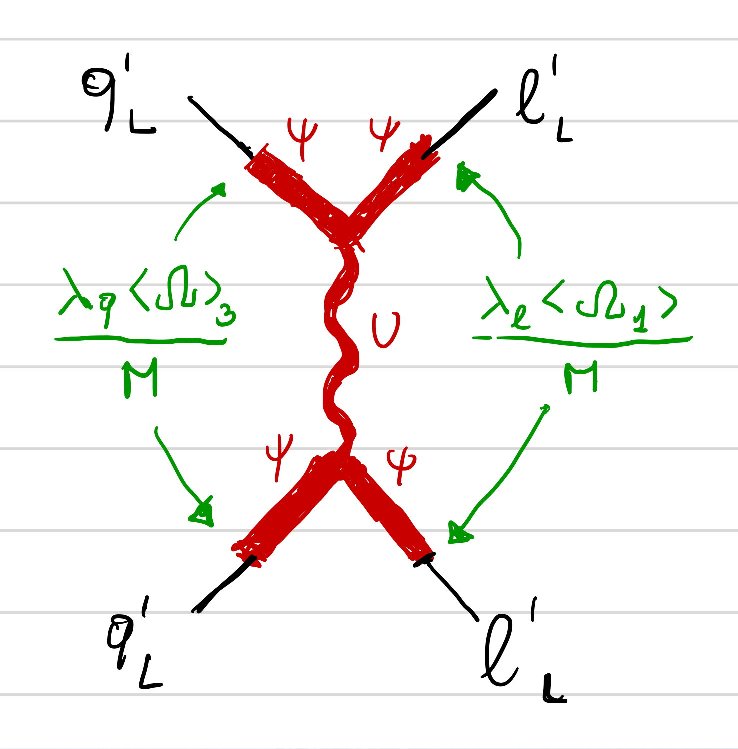
- Field content

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$
q'^i_L	1	3	2	1/6
u'^i_R	1	3	1	2/3
d'^i_R	1	3	1	−1/3
ℓ'^i_L	1	1	2	−1/2
e'^i_R	1	1	1	−1
Ψ^i_L	4	1	2	0
Ψ^i_R	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

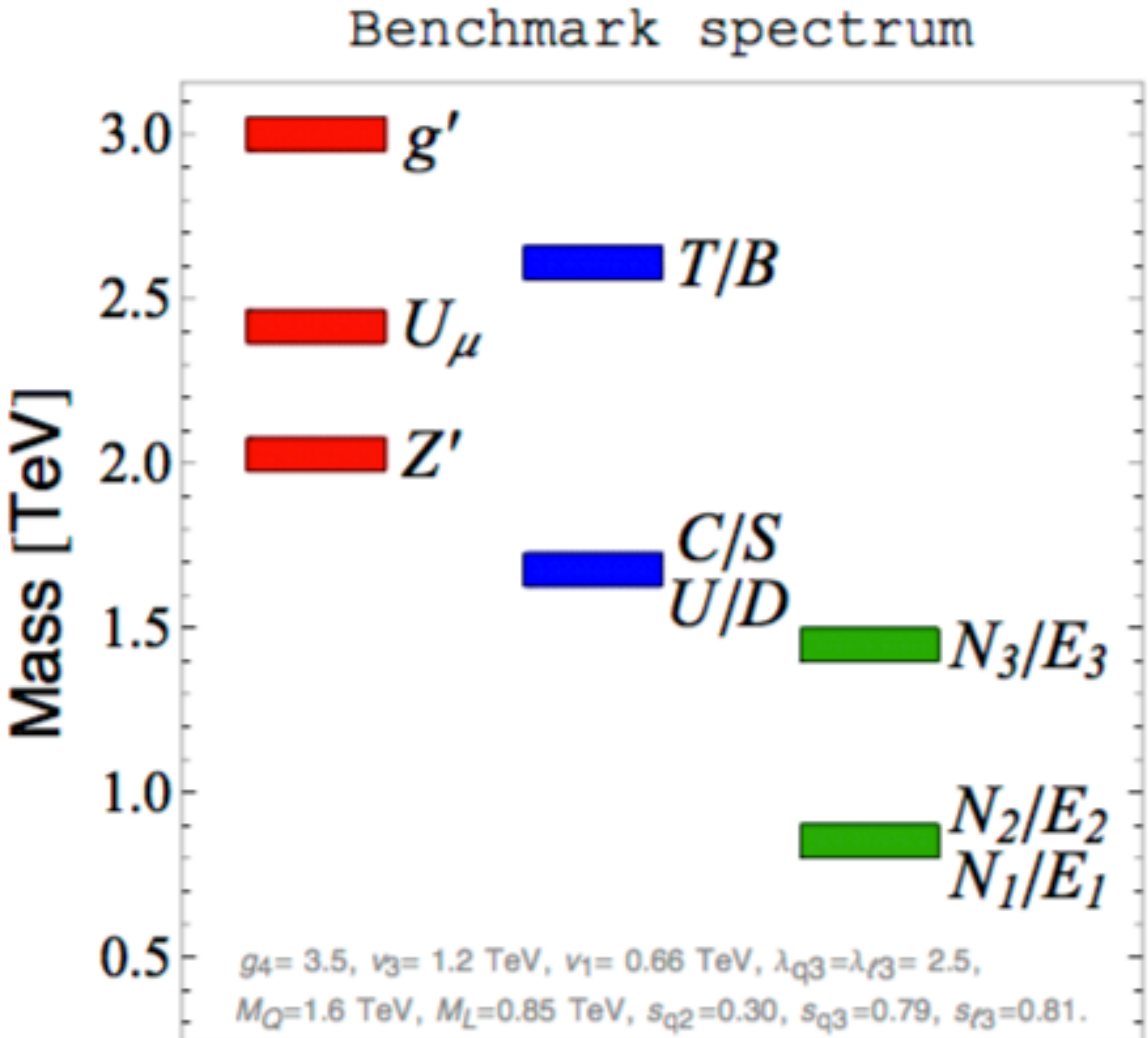
q'^i_L … e'^i_R: would-be SM states

Ψ^i_L, Ψ^i_R: vector-like states (Q+L)

H, Ω_3, Ω_1: symmetry breaking



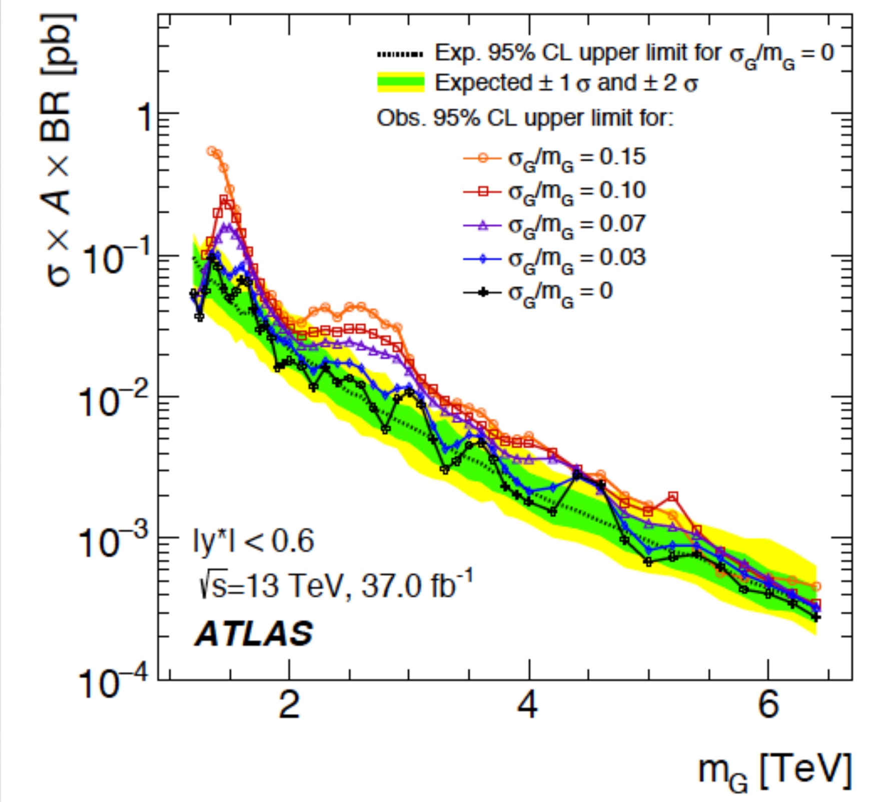
- Color octet and Z' are the most important states



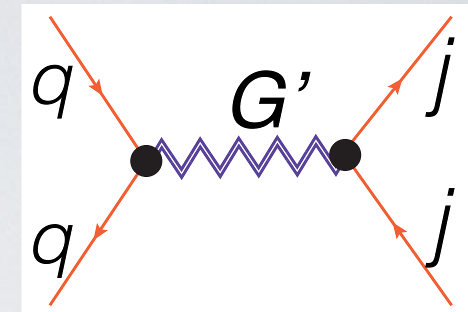
Benchmark spectrum
Mass [TeV]
3.0
2.5
2.0
1.5
1.0
0.5
g'
U_μ
Z'
T/B
C/S
U/D
N_3/E_3
N_2/E_2
N_1/E_1
g_4= 3.5, v_3= 1.2 TeV, v_1= 0.66 TeV, λ_q3=λ_ℓ3= 2.5,
M_Q=1.6 TeV, M_L=0.85 TeV, s_q2=0.30, s_q3=0.79, s_ℓ3=0.81.

Colour octet vector at the LHC

Phys.Rev. D96 (2017) no.5, 052004



- We are looking for →

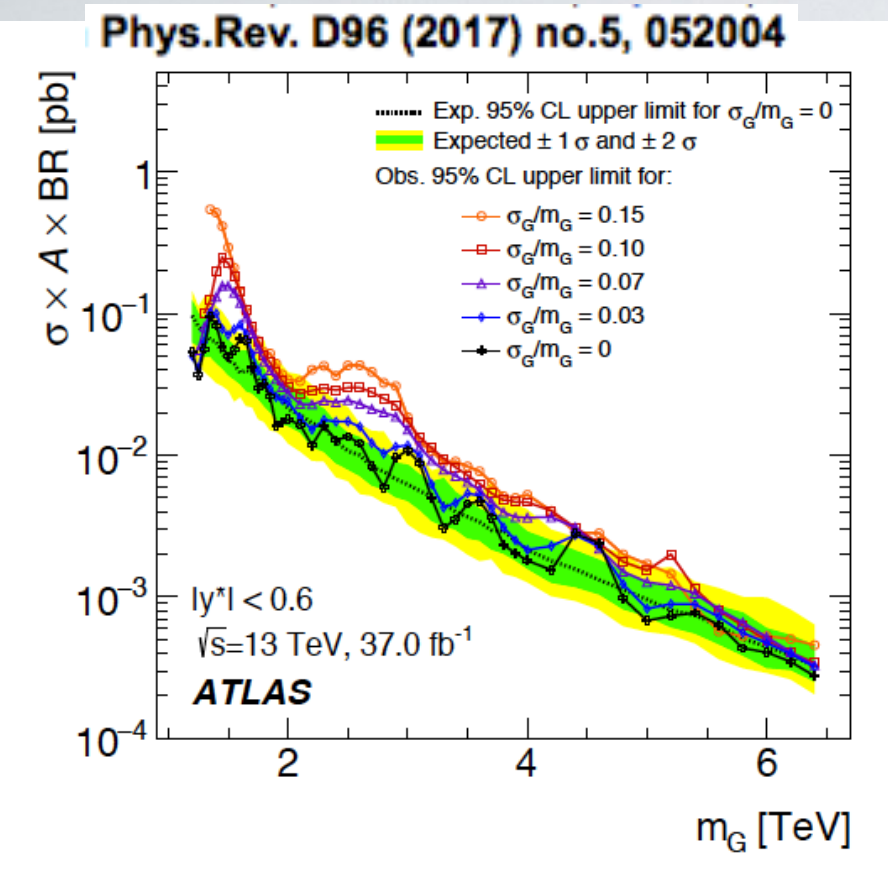


- Background fitted to data
- Exclusion limit are reported with benchmark up to

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

- In models aiming at explaining charged current anomalies, large widths are expected

Colour octet vector at the LHC



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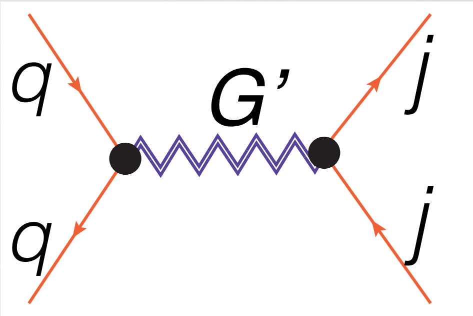

- Background fitted to data
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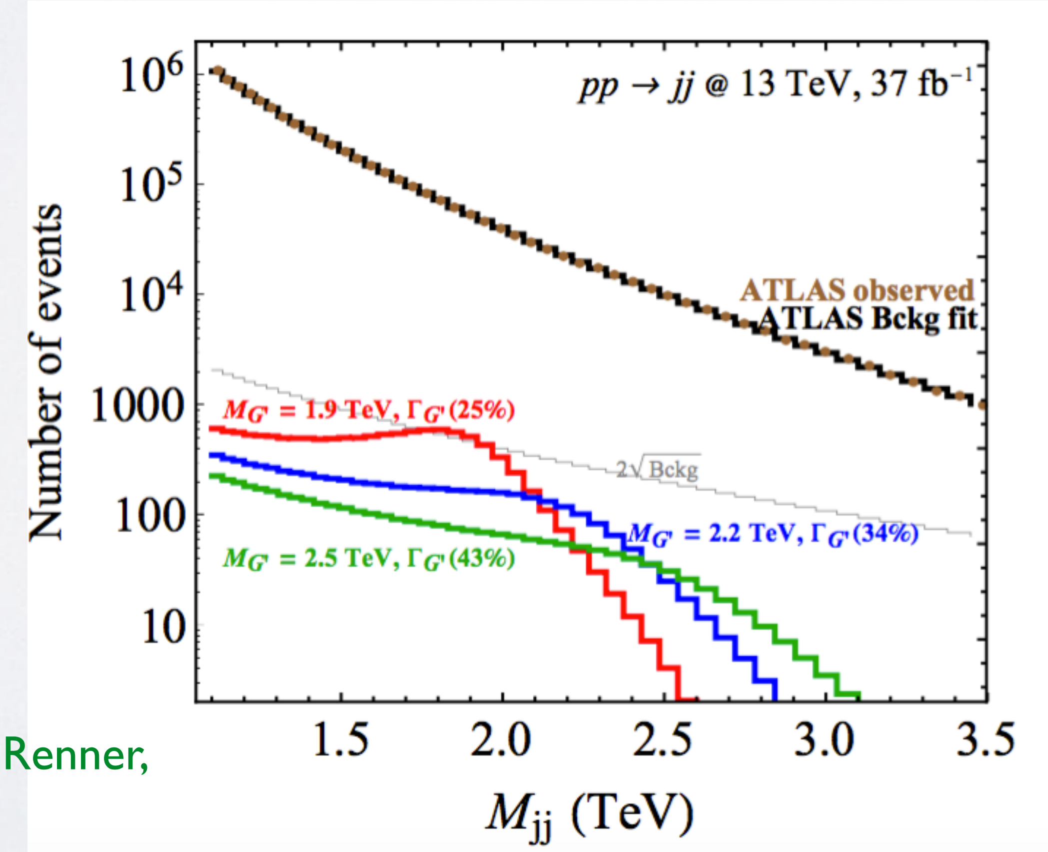
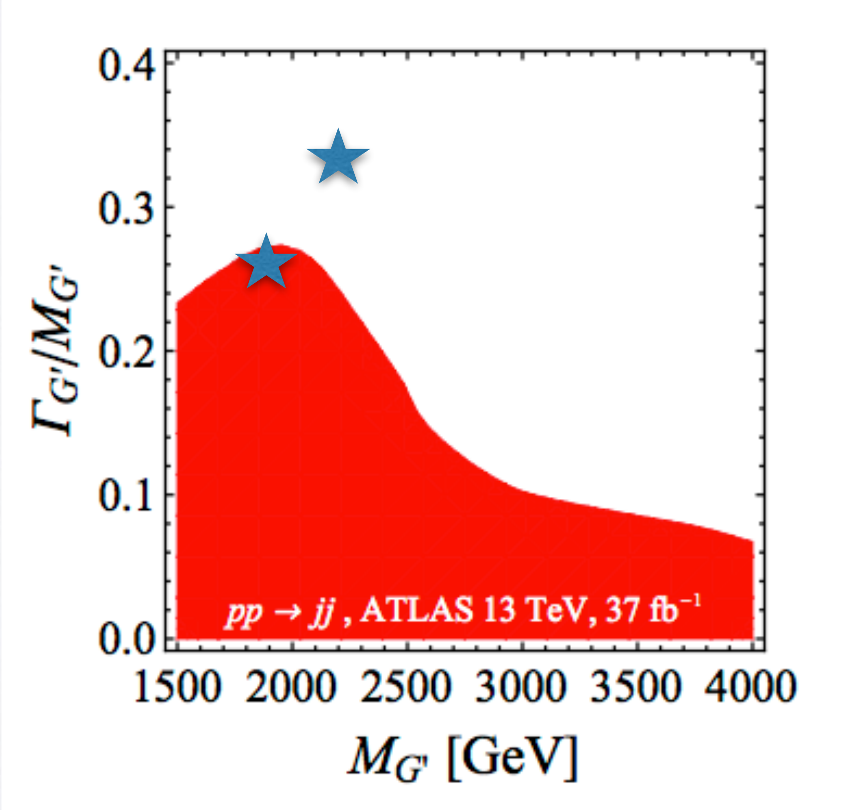
$$\frac{\Gamma}{m} \lesssim 15\%$$

- In models aiming at explaining charged current anomalies,large widths are expected

- Very strong bounds





[Greljo,Di Luzio, Fuentes-Martin, MN, Renner, 1808.00942]

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.

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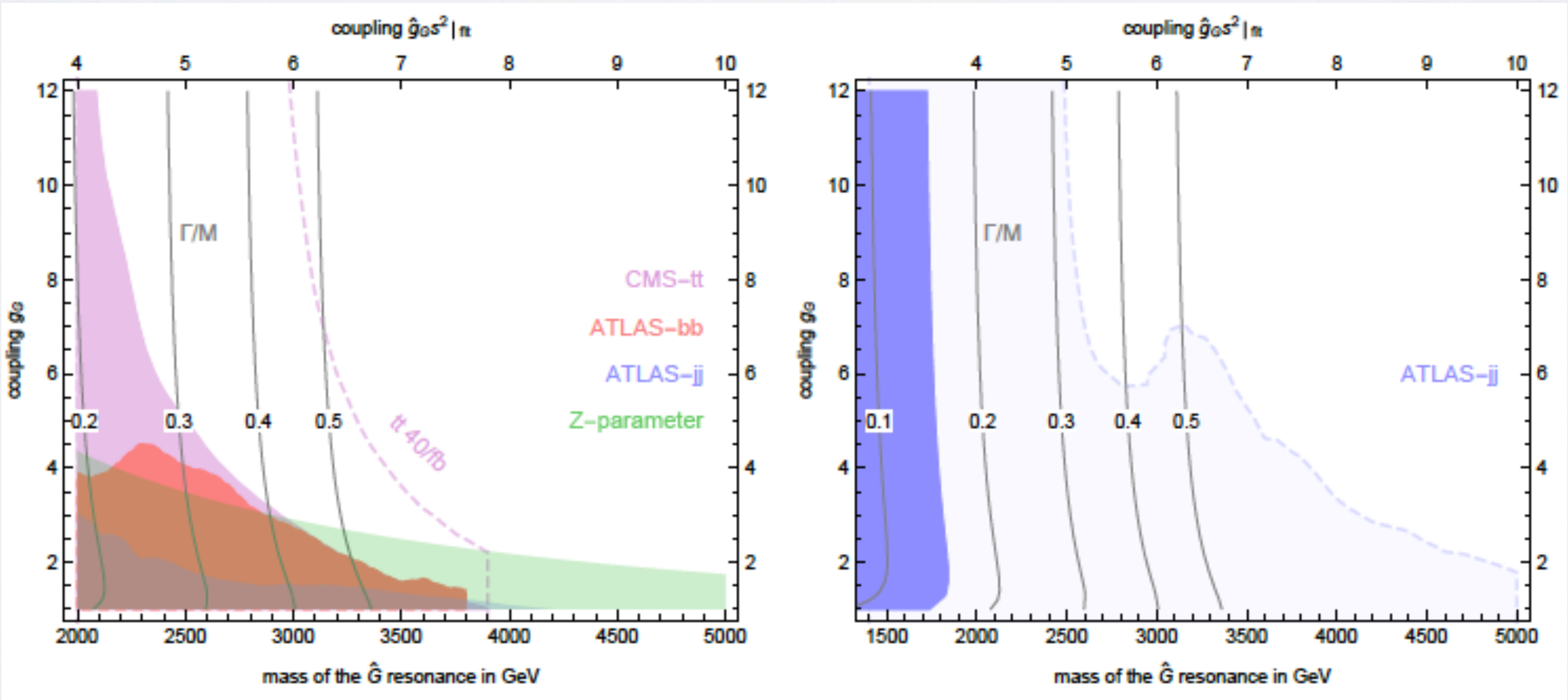
Final states containing quarks and leptons of the third family: a correlation with the flavour structure hinted by the anomalies. Top is present because of SU(2) gauge structure.

- 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)

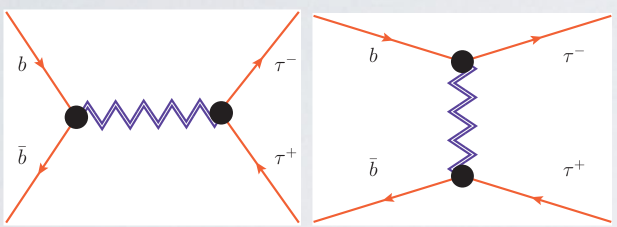
NEUTRAL CURRENT (ONLY)

Why Neutral Current only?

- A couple of (personal) prejudices…

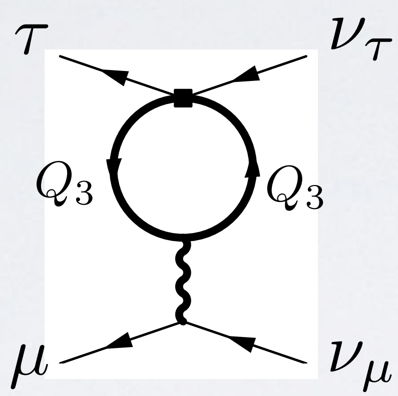
1) The very low NP scale hinted by the anomalies in charged currents is problematic

Direct searches



[Faroughy,Greljo,Kamenik, 1609.07138]

Radiative contraints



[Feruglio, Paradisi, Pattori, 1606.00524,1705.00929]

Other indirect probes

$$\begin{cases} B \to K^{(*)}\overline{\nu}\nu \\ B_s, K, D \text{ mixing} \\ \ldots \end{cases}$$

- However, models can be constructed… separately, bounds can be satisfied. The interplay of various constraints is very important (some models, seems naively ok but…)
- Even if allowed, large couplings are required (calculability is lost?)

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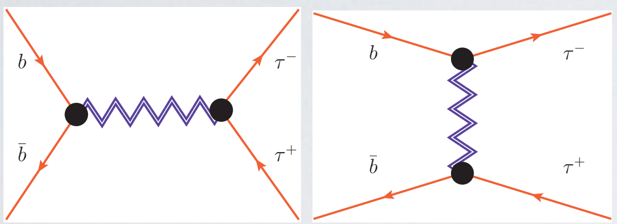

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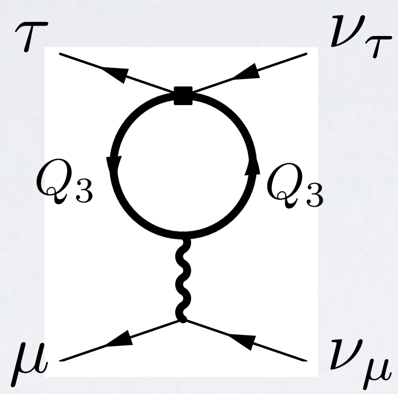

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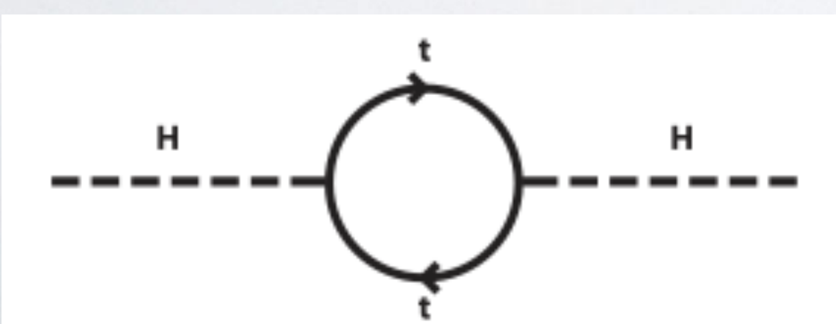
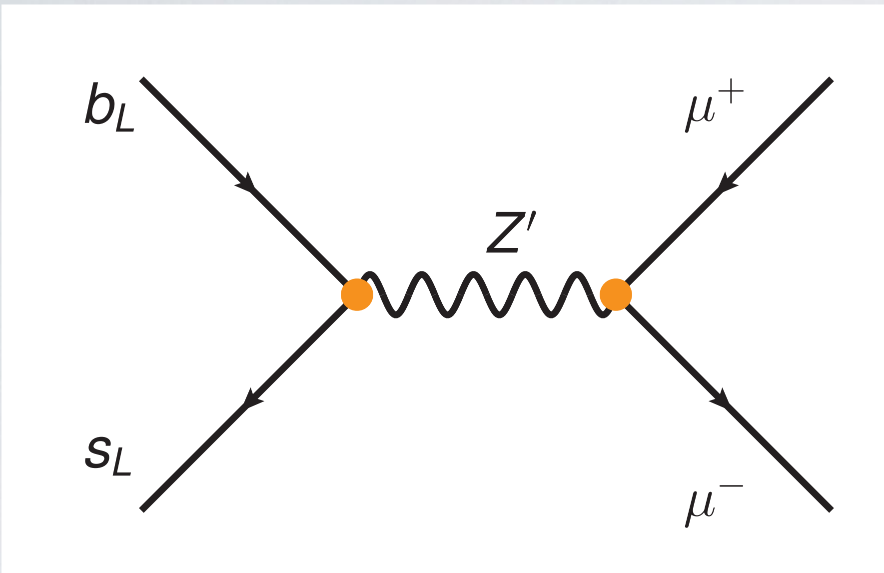
- However, models can be constructed… separately, bounds can be satisfied. The interplay of various constraints is very important (some models, seems naively ok but…)
- Even if allowed, large couplings are required (calculability is lost?)

2) Models addressing the anomalies (in CC) do not fit well in frameworks that address the issue of the naturalness problem of the EW scale

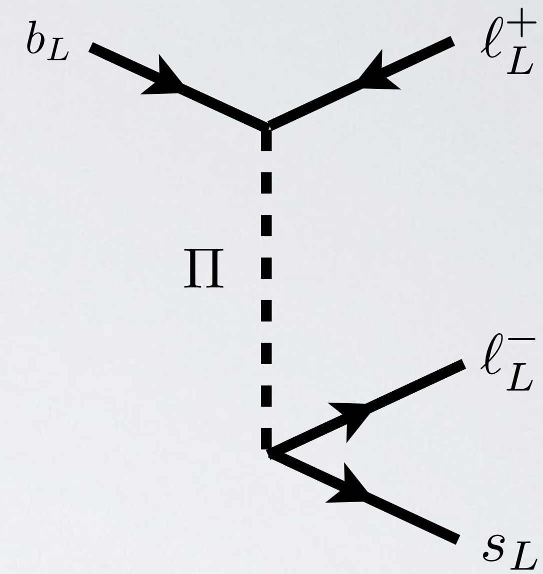


Viable attempts in particular in the context of the composite Higgs framework (SUSY is more problematic)

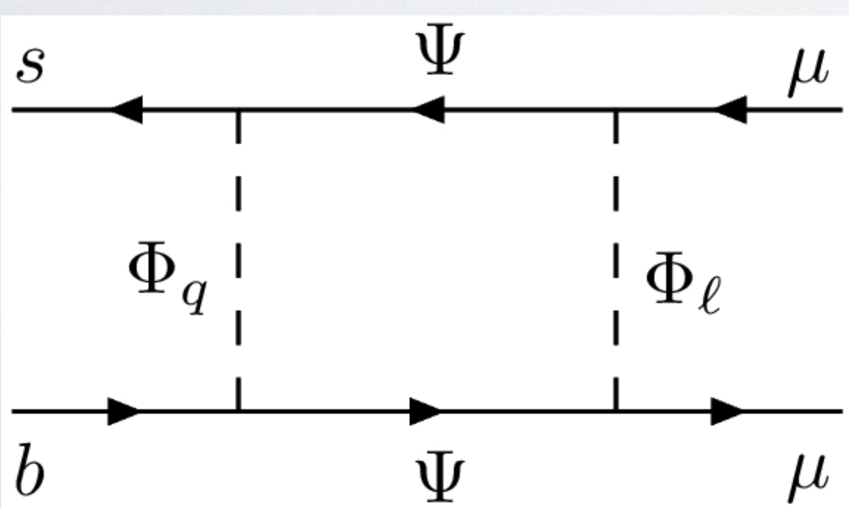
Models for NC anomalies $b \to s\mu\mu$

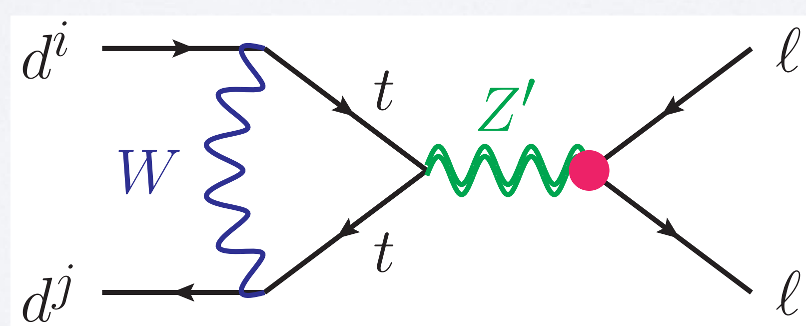


$$\frac{\Delta_{bs}\Delta_{\mu\mu}}{m_{Z'}^2} \approx \frac{1}{(30\mathrm{TeV})^2}$$



$$\frac{\lambda_{b\mu}\lambda_{s\mu}}{m_\Pi^2} \approx \frac{1}{(30\,\mathrm{TeV})^2}$$





$$\frac{y^4}{16\pi^2}\frac{1}{m_{NP}^2} \approx \frac{1}{(30\ \mathrm{TeV})^2}$$

Z' at HL/HE-LHC [Allanach, Gripaios, You 1609.07138]

- Assumption 1: Left currents $(\bar{b}_L \gamma^\mu s_L)(\overline{\mu}\gamma_\mu \mu_L)$
- Assumption 2: Narrow Width (fair coverage of weakly coupled realisations) $\Gamma_{Z'}/M_{Z'} < 10\%$
- Assumption 3: "Pessimism" (making few assumptions as possible)

$$\mathcal{L}_{Z'}^{\text{min.}} \supset \left(g_L^{sb} Z'_\rho \bar{s}\gamma^\rho P_L b + \text{h.c.} \right) + g_L^{\mu\mu} Z'_\rho \bar{\mu}\gamma^\rho P_L \mu$$

$$\mathcal{L}_{[33\mu\mu]} = Z'_\rho \left(g_L^q \, \overline{Q}_3 \gamma^\rho Q_3 + g_L^{\mu\mu} \, \overline{L}_\mu \gamma^\rho L_\mu \right)$$

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- Extrapolate current 13 TeV di-muon searches

$$\mathcal{L}^{\text{min.}}_{Z'} \supset \left(g_L^{sb} Z'_\rho \bar{s}\gamma^\rho P_L b + \text{h.c.}\right) + g_L^{\mu\mu} Z'_\rho \bar{\mu}\gamma^\rho P_L \mu$$

[ATLAS 1607.03669]

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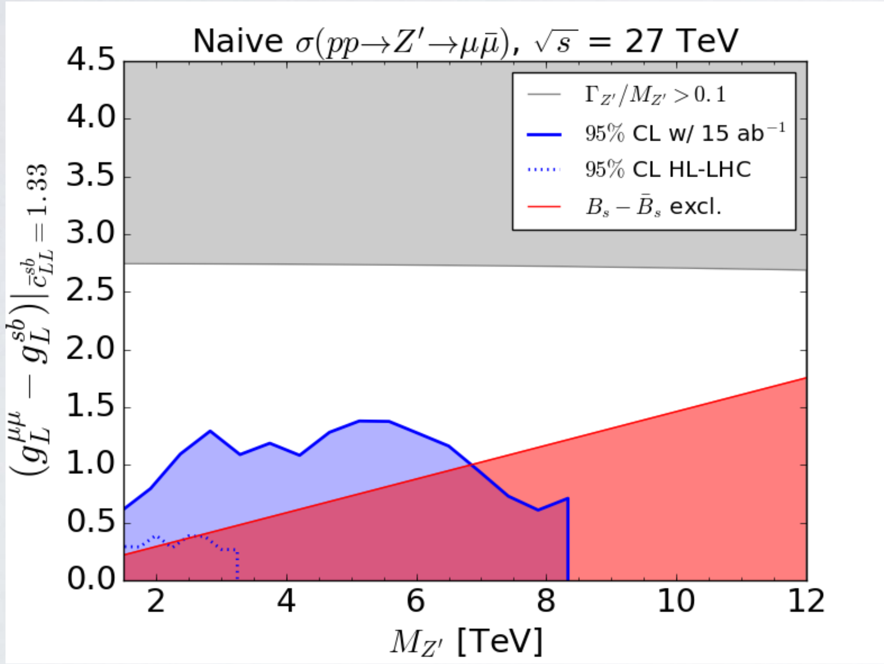
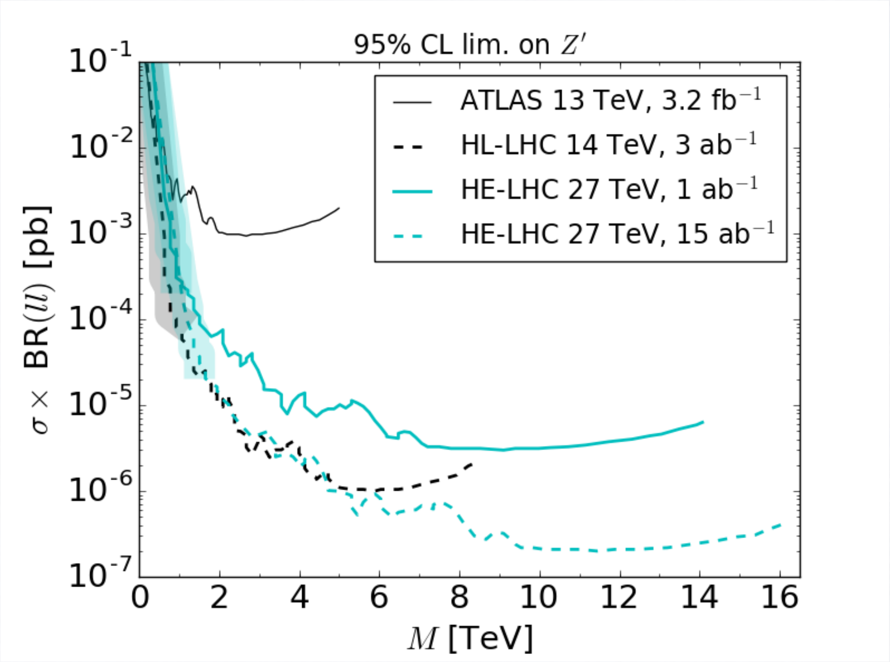
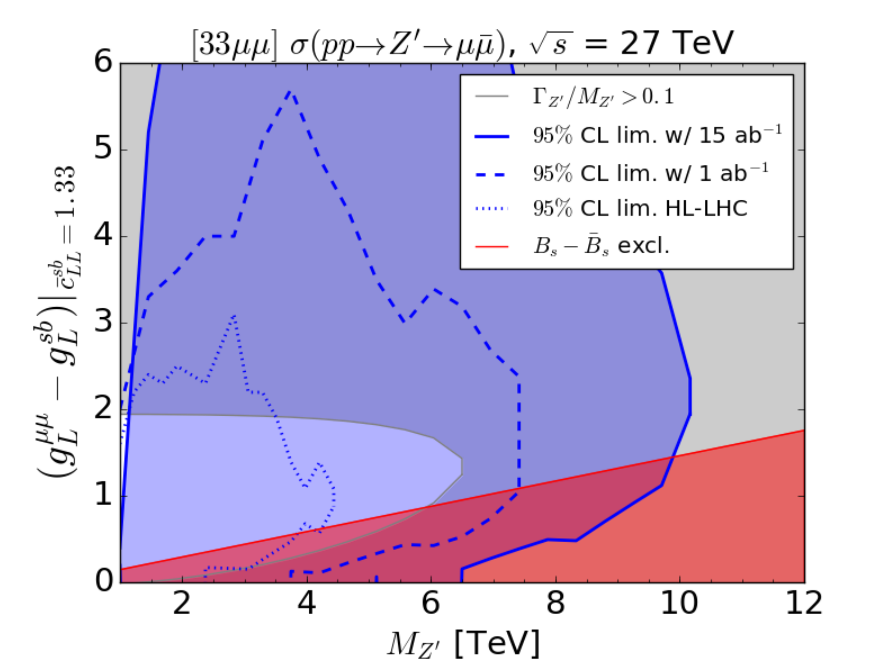
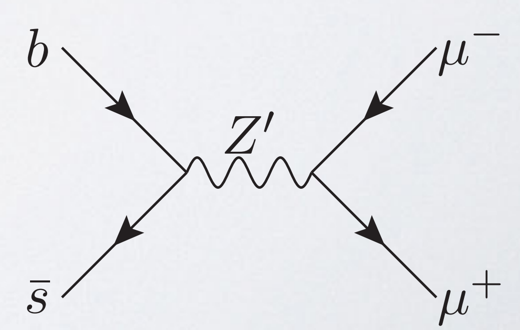






- Room left after HL-HE for the naive model
- Full coverage of the "motivated" [33mumu] model!
- Remember that these are just 2 (useful) benchmarks.



Leptoquarks for NC anomalies

[Allanach, Gripaios, You 1609.07138]

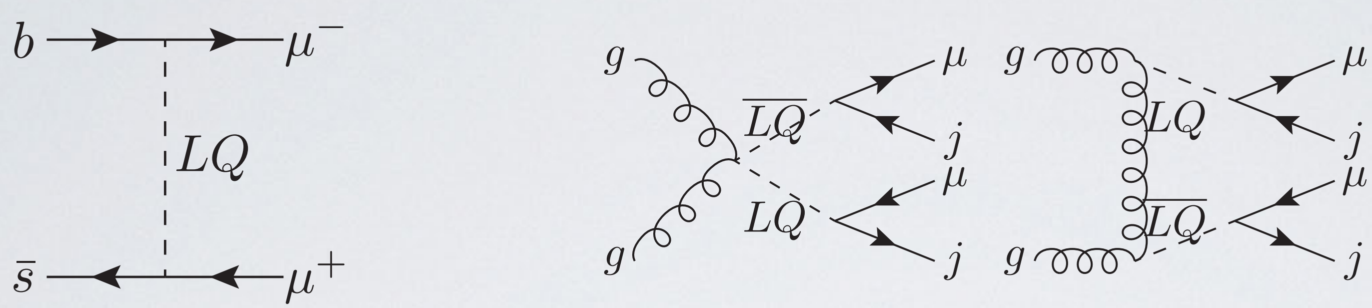
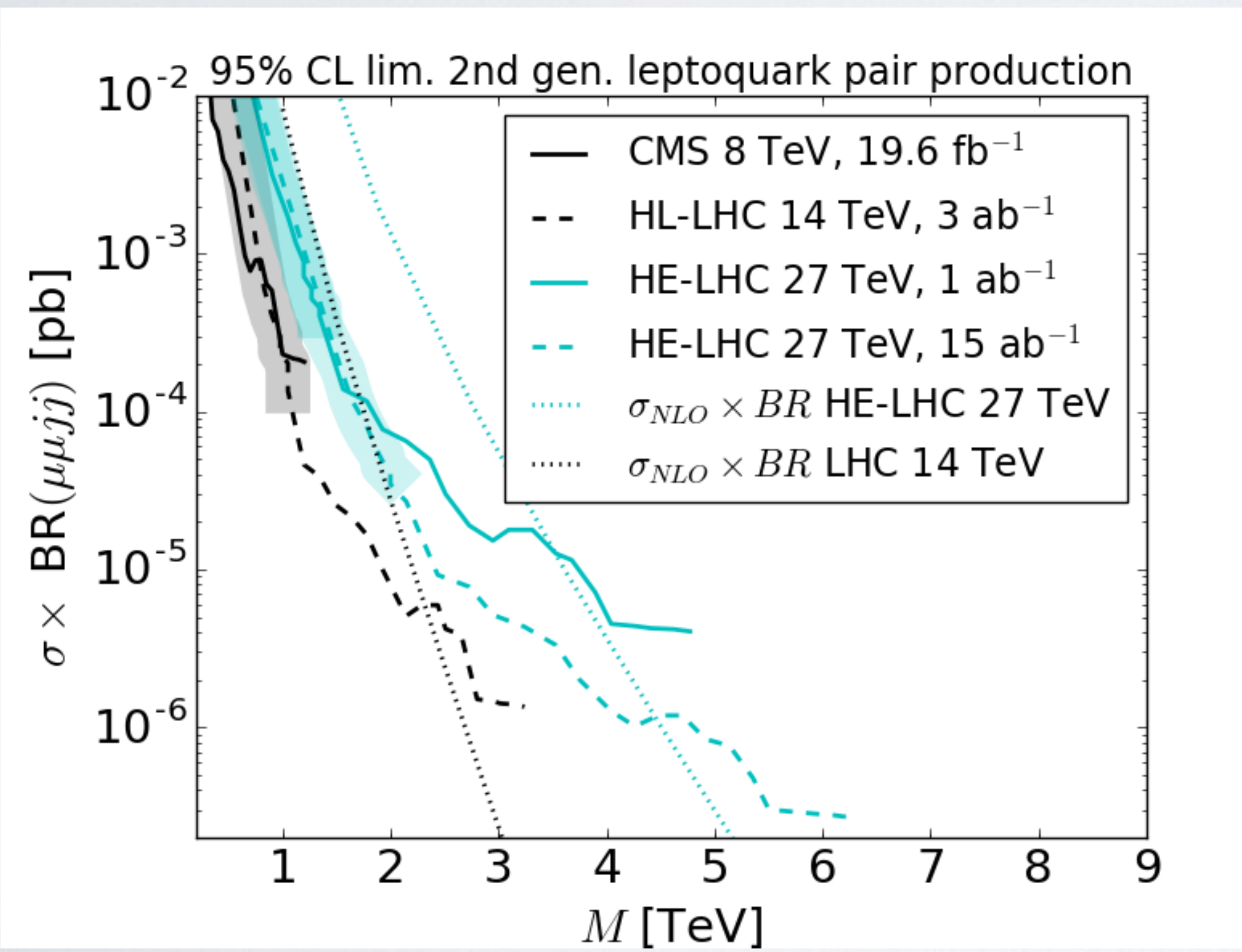
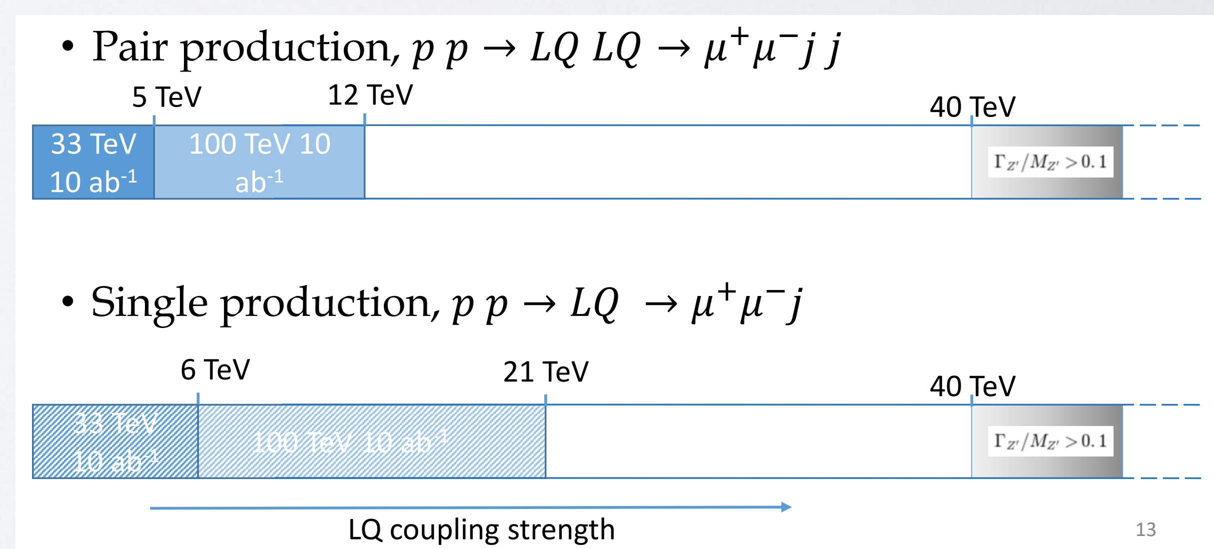


Figure 6. Example Feynman diagrams of LQ production at a hadron collider followed by subsequent decay of each into μj.

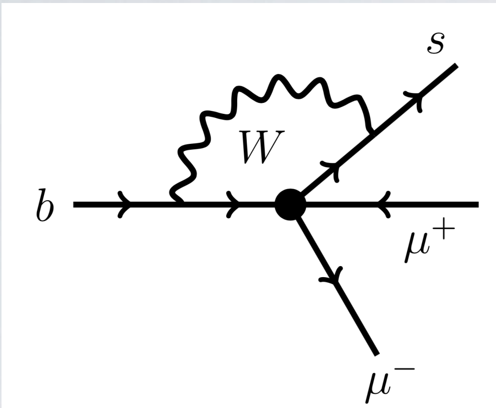


- Extrapolation from [CMS-PAS-EXO-12-041]
- Same hypothesis as before
- Take home message:

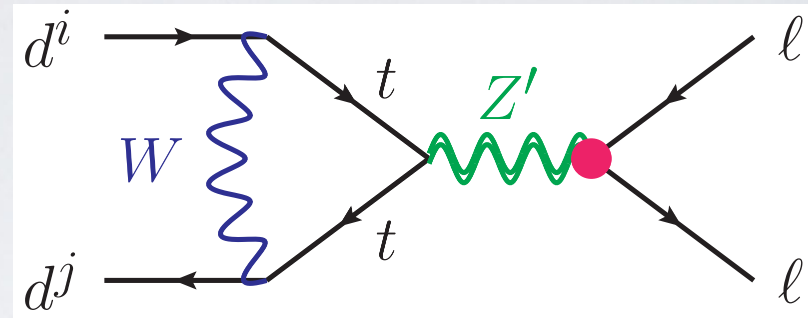


Loop induced anomalies

[An example from
Camargo-Molina, Celis, Faroughy,
1805.04917]

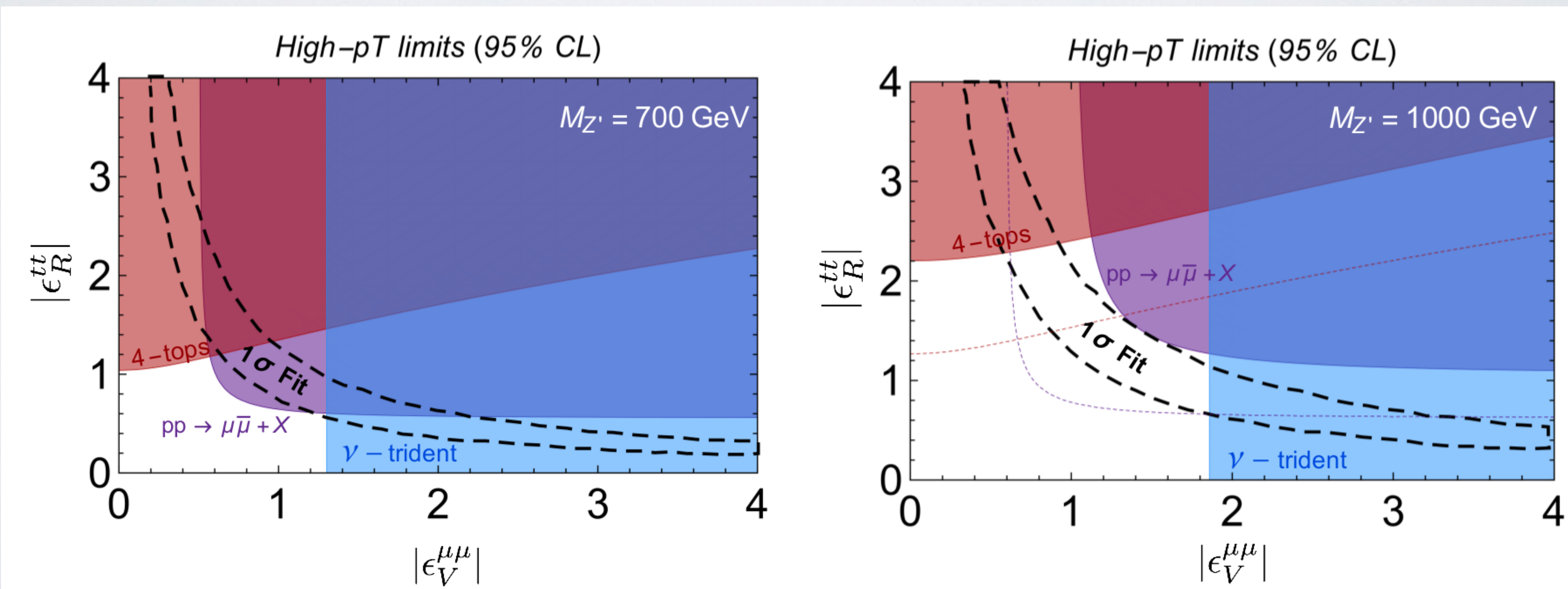


$=$



$$\frac{y^4}{16\pi^2}\frac{1}{m_{NP}^2} \approx \frac{1}{(30\ \mathrm{TeV})^2}$$

$$\mathcal{L} = Z'_\alpha \left[\bar{\mu}\gamma^\alpha(\epsilon_L^{\mu\mu} P_L + \epsilon_R^{\mu\mu} P_R)\mu + \epsilon_R^{tt}\,\bar{t}\gamma^\alpha P_R t\right]$$



- Loop induced models: in general quite good discovery prospects at HL-HE LHC

(No) Conclusions

- We are waiting for the confirmation/disproval of the flavor anomalies. By the start of HL-LHC the situation will be clarified.

- Current anomalies in B decays have a simple, coherent and consistent interpretation at the effective field theory level.

- Charged current and neutral current anomalies point (naively) to different New Physics scale. No no-lose theorem at the LHC can be formulated using perturbative unitarity arguments

- Charged Currents: leptoquarks seem to be preferred as mediators. Full models are needed, first signal at high pT could arise from other sectors

- [Fair to say that models addressing the CC anomalies are under pressure by various simultaneous constraints (EW and FCNC observables, direct searches)]

- Neutral Currents @ tree level: more options are viable, simplified models under minimal assumptions can be constructed. Z' and leptoquarks represents good physics cases for HL/HE.

- Neutral Currents @ 1-loop: an open possibility, New Physics has to be light and with large couplings to SM fermion. High pT aspects are more model dependent.

Backup

'4321': Field content

[Di Luzio, AG, Nardecchia], 1708.08450

	Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$
Fermions	$q_L'^i$	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
Scalars	H	1	1	2	1/2
	Ω_3	$\overline{4}$	3	1	1/6
	Ω_1	$\overline{4}$	1	1	−1/2

- *Would-be SM fermions in the absence of mixing with Ψ*
- *Three copies*

- *Three (min. two) copies of vector-like fermions*

$$\Psi_{L,R} = (Q'_{L,R}, L'_{L,R})^T$$

Large left-handed mixing matrix
[Explains the dominance of left-handed interactions at low energies]

In the interaction basis

$$\mathcal{L}_L \supset \frac{g_4}{\sqrt{2}} \overline{Q}'_L \gamma^\mu L'_L U_\mu + \text{h.c.}$$

$$+ \frac{g_4 g_s}{g_3}\left(\overline{Q}'_L \gamma^\mu T^a Q'_L - \frac{g_3^2}{g_4^2}\overline{q}'_L \gamma^\mu T^a q'_L\right) g'^a_\mu$$

$$+ \frac{1}{6}\frac{\sqrt{3}\, g_4 g_Y}{\sqrt{2}\, g_1}\left(\overline{Q}'_L \gamma^\mu Q'_L - \frac{2g_1^2}{3g_4^2}\overline{q}'_L \gamma^\mu q'_L\right) Z'_\mu$$

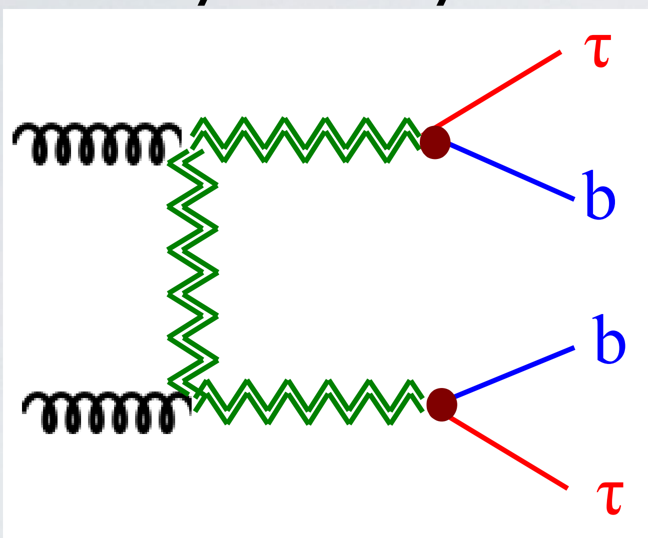
$$- \frac{1}{2}\frac{\sqrt{3}\, g_4 g_Y}{\sqrt{2}\, g_1}\left(\overline{L}'_L \gamma^\mu L'_L - \frac{2g_1^2}{3g_4^2}\overline{\ell}'_L \gamma^\mu \ell'_L\right) Z'_\mu$$

Suppressed couplings to light generations in the limit $g_4 >> g_1, g_3$

For such construction but in different context: [Diaz, Schmaltz, Zhong], 1706.05033

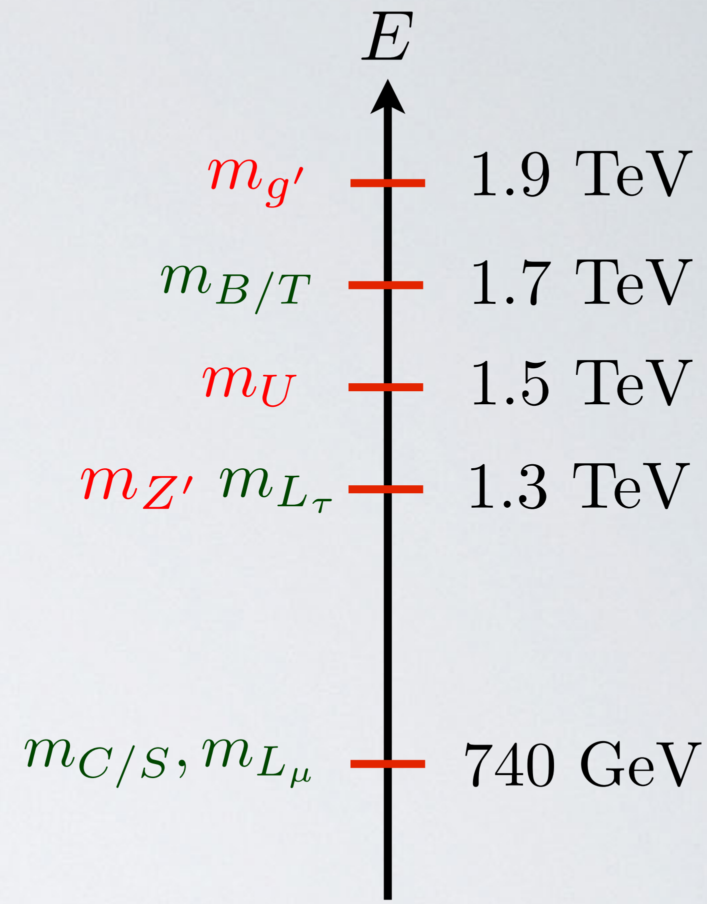
Direct Searches (gauge sector)

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



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

(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)

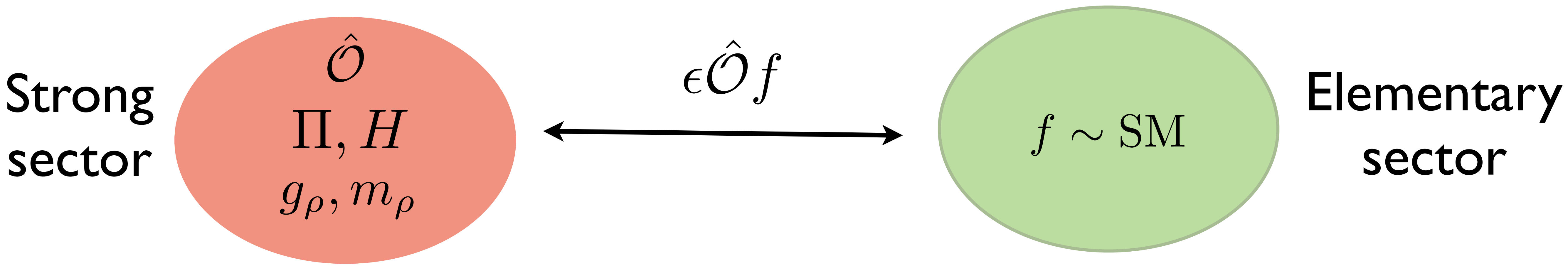
Need large g4…

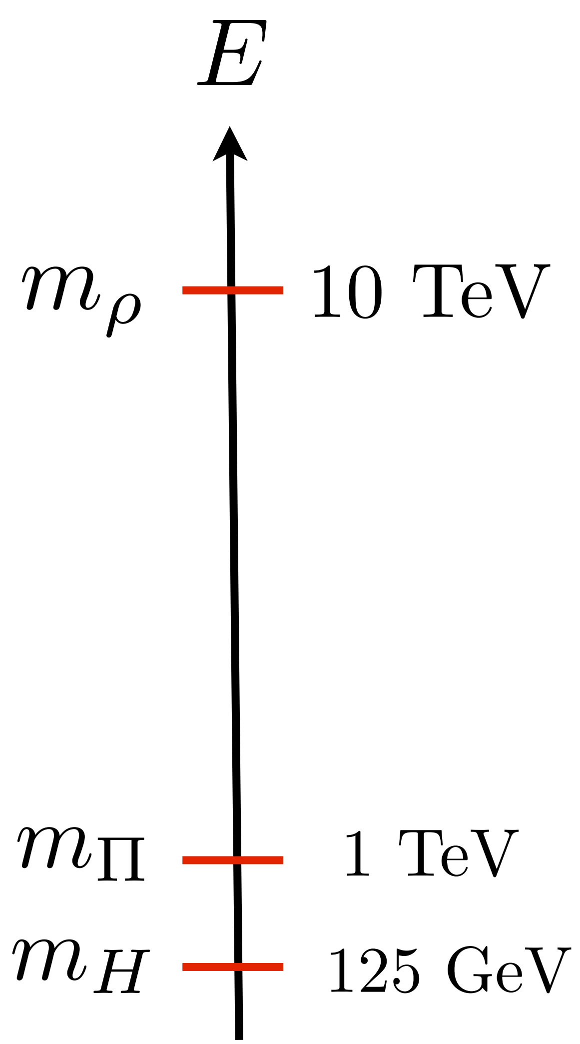
$g_4 \gtrsim 3$

- 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

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

Composite Higgs Framework





- Being PGB, Higgs and Leptoquarks are lighter than the other resonances coming from the strong sector

- SM fermion masses are generated by the mechanism of partial compositeness

$$|SM\rangle = \cos\epsilon |f\rangle + \sin\epsilon |\mathcal{O}\rangle$$

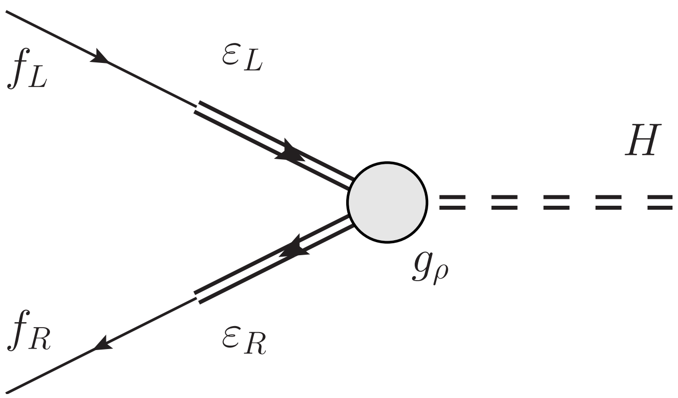
- BSM Flavour violation regulated by the same mechanism

- Naturalness (…)

Based on 1412.5942, JHEP,
Ben Gripaios and Sophie Renner

Partial Compositeness in CH models

- Yukawa sector:



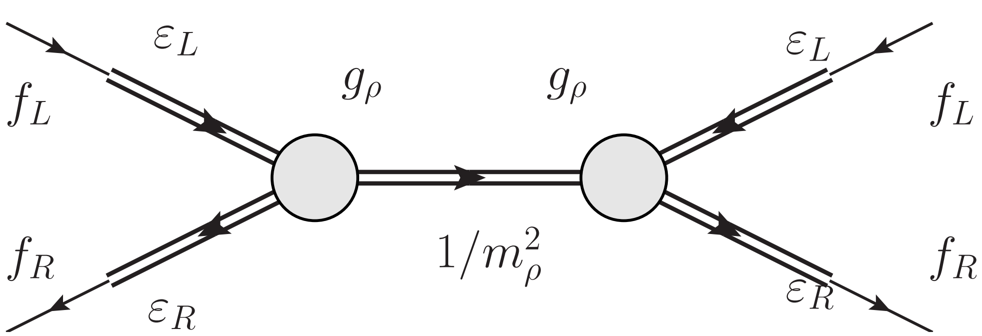
$$\mathcal{L}_{\rm elem} = i\overline{f}\gamma^\mu D_\mu f$$

$$\mathcal{L}_{\rm comp} = \mathcal{L}_{\rm comp}(g_\rho, m_\rho, H)$$

$$\mathcal{L}_{\rm mix} = \epsilon_L\, f_L \mathcal{O}_L + \epsilon_L\, f_R \mathcal{O}_R + h.c.$$

$$Y^{ij} = c_{ij}\,\epsilon_L^i \epsilon_R^j\, g_\rho \longrightarrow Y^{ij} \sim \epsilon_L^i \epsilon_R^j g_\rho$$

- Flavor violation beyond the CKM one is generated:



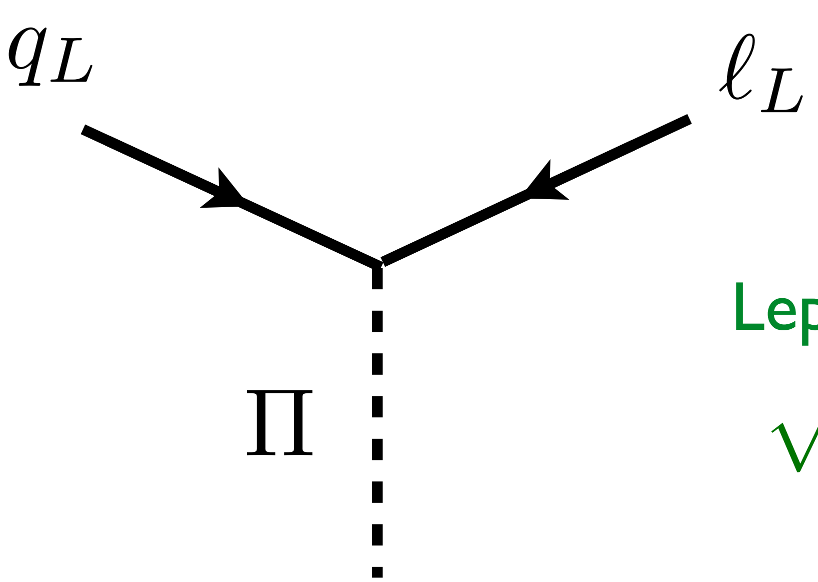
$$\sim \frac{g_\rho^2}{m_\rho^2}\epsilon_L^i \epsilon_R^i \epsilon_L^j \epsilon_R^j$$

FV related to the SM one but not in a Minimal FV way

Flavour Violation & Leptoquarks

- Comment later about the flavour physics associated with m_ρ
- Relevant Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + (D^\mu \Pi)^\dagger D_\mu \Pi - M^2 \Pi^\dagger \Pi + \lambda_{ij}\, \overline{q}^c_{Lj} i\tau_2 \tau_a \ell_{Li}\, \Pi + \text{ h.c.}$$



Quarks →

Leptons $\sqrt{Y_\ell}$ ↓

$\lambda_{ij}/(c_{ij} g_\rho^{1/2} \epsilon_3^q)$	$j=1$	$j=2$	$j=3$
$i=1$	1.92×10^{-5}	8.53×10^{-5}	1.67×10^{-3}
$i=2$	2.80×10^{-4}	1.24×10^{-3}	2.43×10^{-2}
$i=3$	1.16×10^{-3}	5.16×10^{-3}	0.101

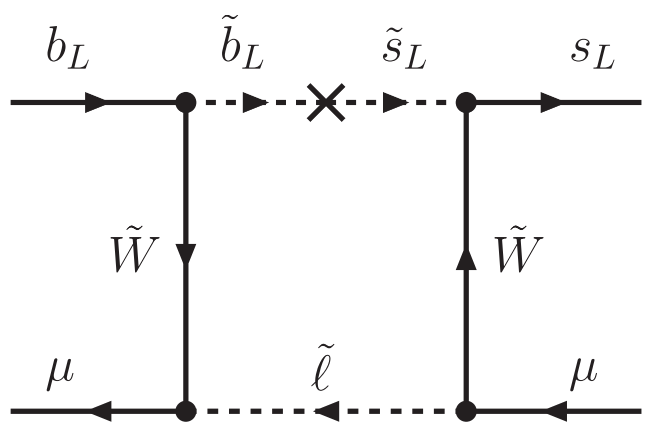
- c are O(1) parameters
- Only 3 fundamental parameters reduced to a single combination in all the flavour observable!

$$(g_\rho, \epsilon_3^q, M) \longrightarrow \sqrt{g_\rho}\,\epsilon_3^q / M$$

MSSM (ask me)

- LFU in the MSSM without R-Parity Violation: loop level

Altmannshofer, Straub, 1411.3161
D'Amico et al, 1704.05438



- Lepton universality is broken by slepton masses $m_{\tilde{e}} \gg m_{\tilde{\mu}}$
- Box diagrams are numerically small, very light particles in the loop
- No free parameter on the Feynman vertices: EW couplings
- Direct searches (LHC+LEP) give strong constraints, probably no holes left (but a careful analysis is required)

- MSSM wit R-Parity Violation: basically SM + some specific leptoquark

The LHCb results with large effect in muons suggest an extensions of the MSSM