JOHANNES GUTENBERG UNIVERSITÄT MAINZ

JG|U

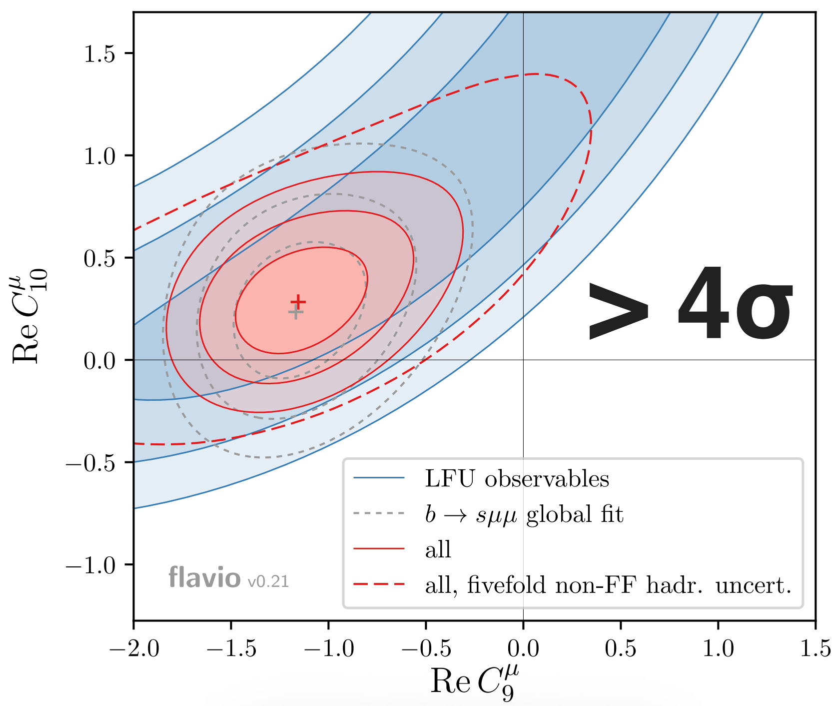
Challenges for Model Builders from semileptonic anomalies

Admir Greljo

Based on
1804.XXXXX, 1802.04274, 1801.07641,
1708.08450, 1706.07808, 1704.09015,
1609.07138, 1603.04993,
1506.01705

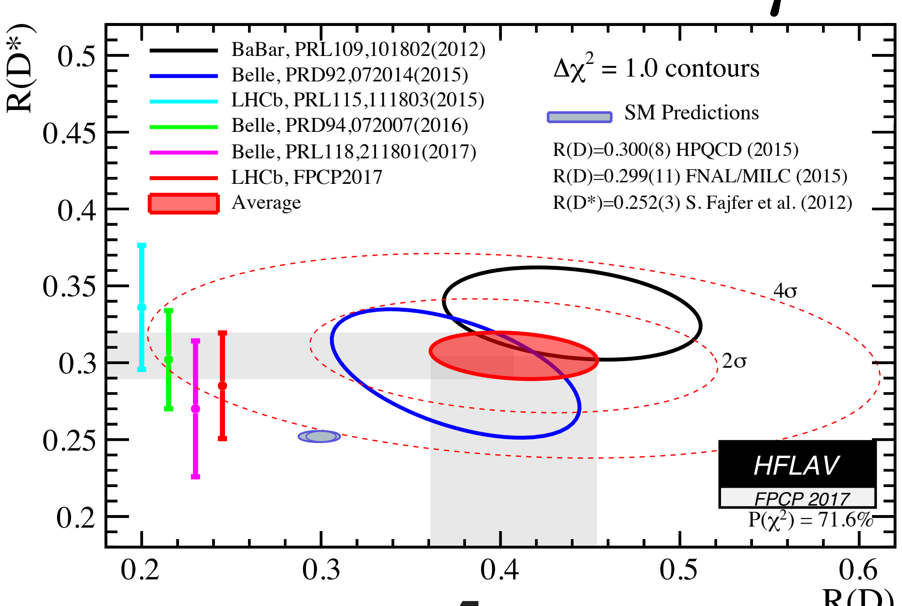
MITP workshop, 10 April 2018

$b \to s\mu\bar{\mu}$



Puzzles

$b \to c\tau\bar{\nu}_{\tau}$



~ 4σ

Today's focus

NP option?

Predictions

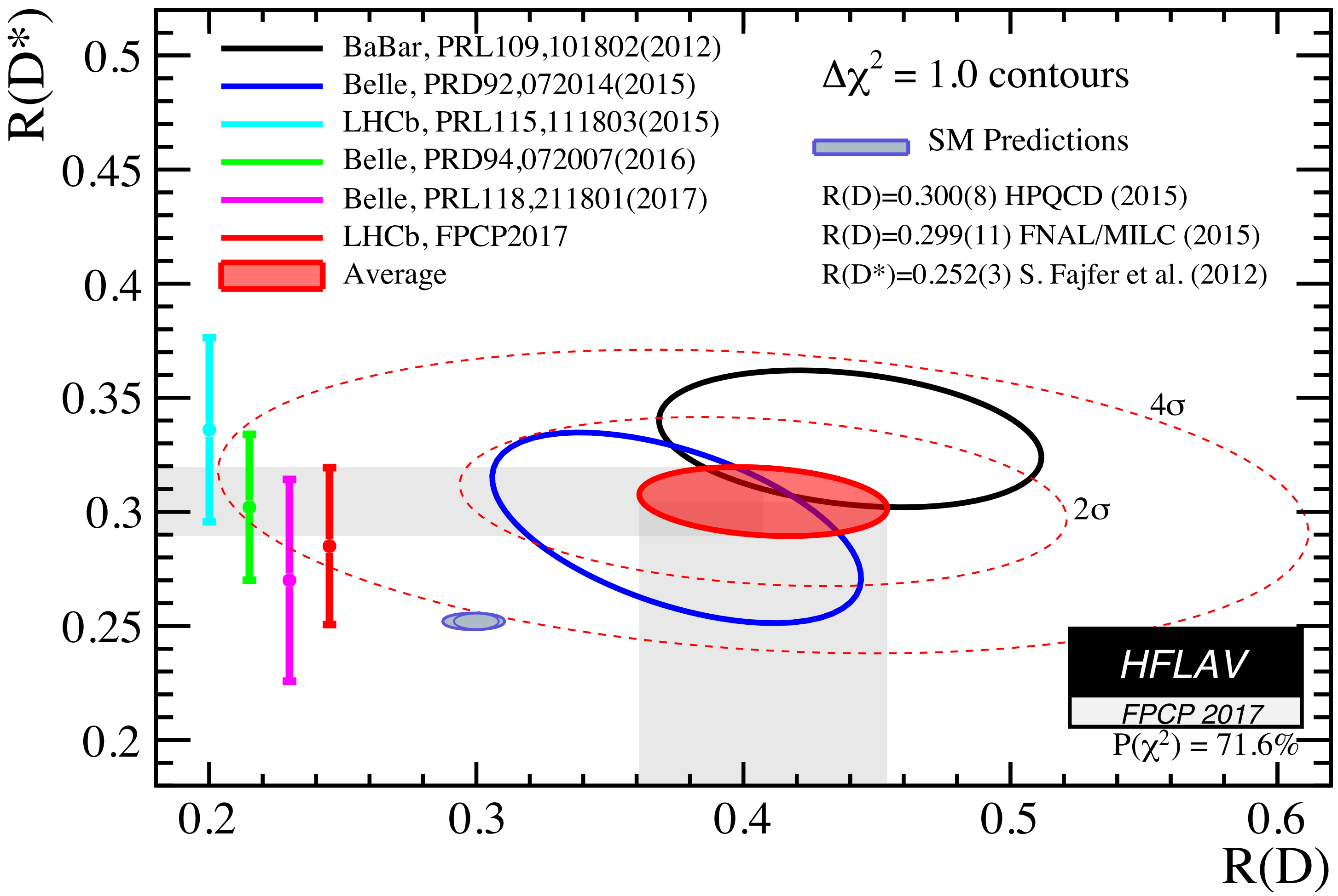
BSM theorist toolbox

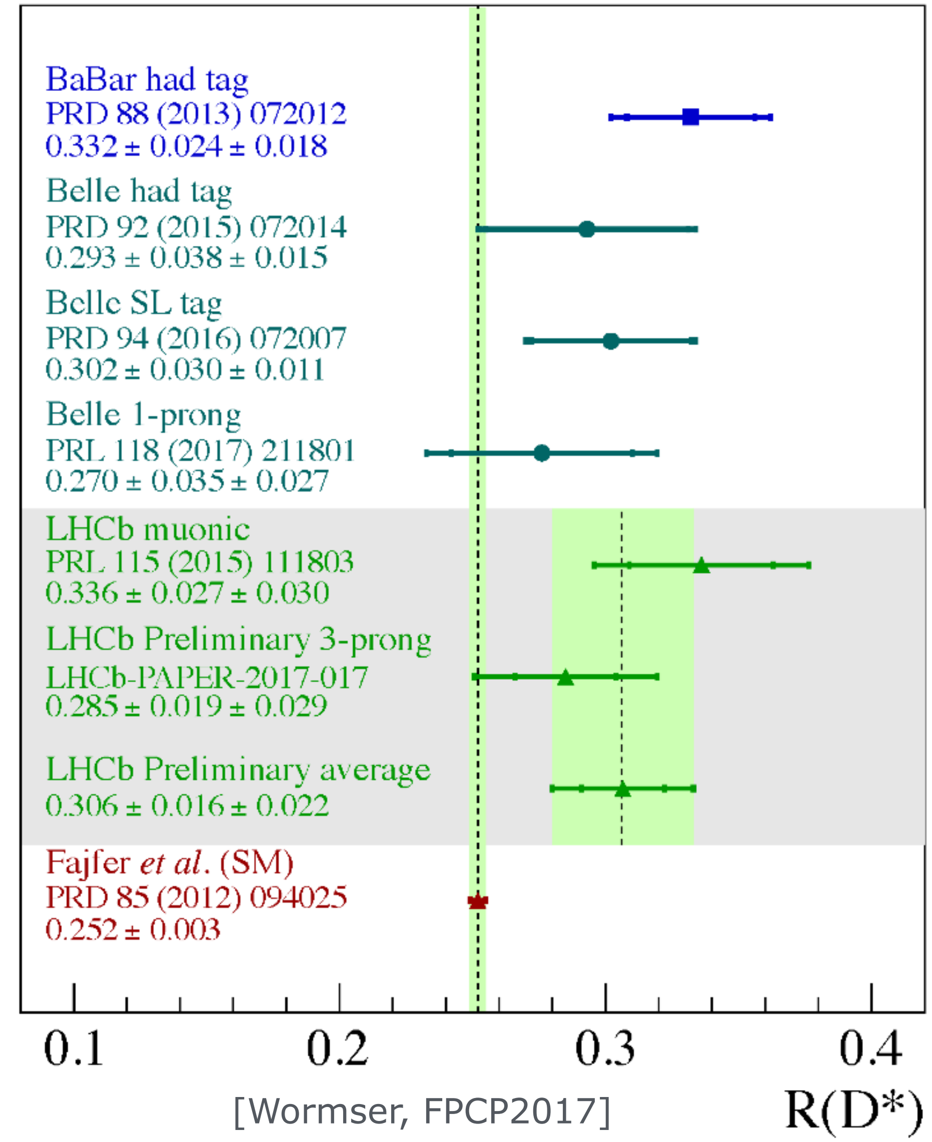
- SMEFT, Flavour symmetries
- Explicit models: Extended gauge sector, etc.

etc.

$b \to c\tau\bar{\nu}_\tau$

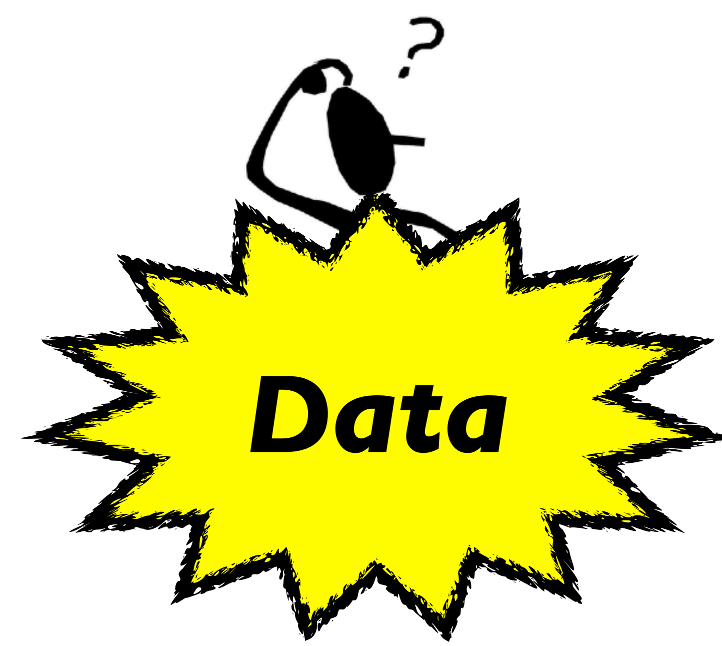
$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$





[Wormser, FPCP2017]

- **4σ excess** over the SM prediction
- Good agreement by three (very) different experiments



Outline

B-anomalies

Data

General discussion

EFT, Mediators, ...

An attempt

[AG, Isidori, Marzocca] JHEP 1507 (2015) 142

'3221'

[AG, Robinson, Shakya, Zupan] 1804.XXXXX

Working examples

'4321'

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

[Di Luzio, AG, Nardecchia] Phys.Rev. D96 (2017) 115011

[AG, Ben Stefanek] 1802.04274

Low-energy fit

$\Lambda > v$

SU(3)×SU(2)$_L$×U(1)

Linear EWSB

Dim-6 operators

SM EFT

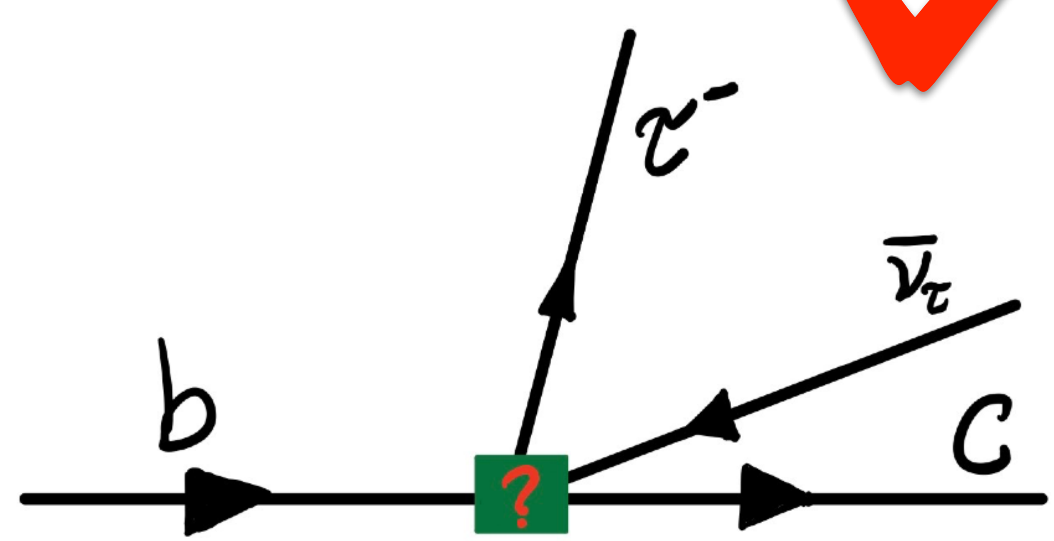
- List of all relevant operators:

$\mathcal{O}_{V_L}$ $(\bar{Q}_i \gamma_\mu \sigma^a Q_j)(\bar{L}_k \gamma^\mu \sigma_a L_l)$

$\mathcal{O}_{S_R}$ $(\bar{d}^i_R Q_j)(\bar{L}_k \ell^l_R)$

$\mathcal{O}_{S_L}$ $(\bar{Q}_i u^j_R) i\sigma^2 (\bar{L}_k \ell^l_R)$

$\mathcal{O}_T$ $(\bar{Q}\sigma_{\mu\nu} u^j_R) i\sigma^2 (\bar{L}\sigma^{\mu\nu} \ell^l_R)$



Other tree-level contributions

✗ $(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$ → *Corrections to W decays*

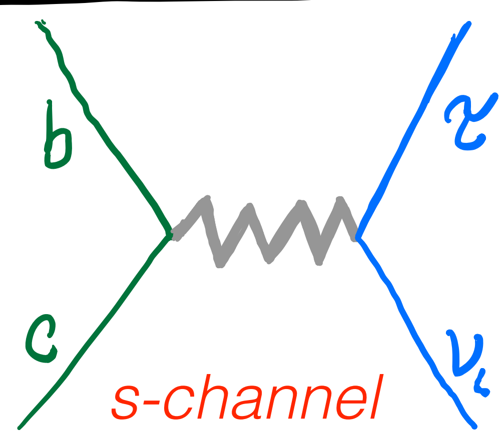
✗ $(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$ → *No LFU violation*

R(D$^{(*)}$)

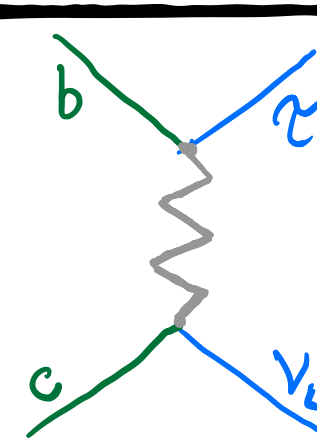
Mediators?

- Color: **1** or **3**
- Spin: **0**, **1**, ...

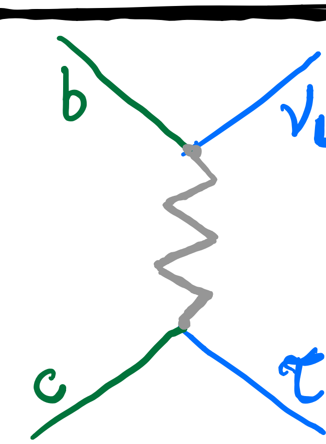
Color / Spin	1	3
0	$H' = (\mathbf{1}, \mathbf{2}, 1/2)$	$R_2 = (\mathbf{3}, \mathbf{2}, 7/6)$ $S_3 = (\overline{\mathbf{3}}, \mathbf{3}, 1/3)$ $S_1 = (\overline{\mathbf{3}}, \mathbf{1}, 1/3)$
1	$W' = (\mathbf{1}, \mathbf{3}, 0)$	$V_2 = (\overline{\mathbf{3}}, \mathbf{2}, 5/6)$ $U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$ $U_3 = (\mathbf{3}, \mathbf{3}, 2/3)$



s-channel



t-channel



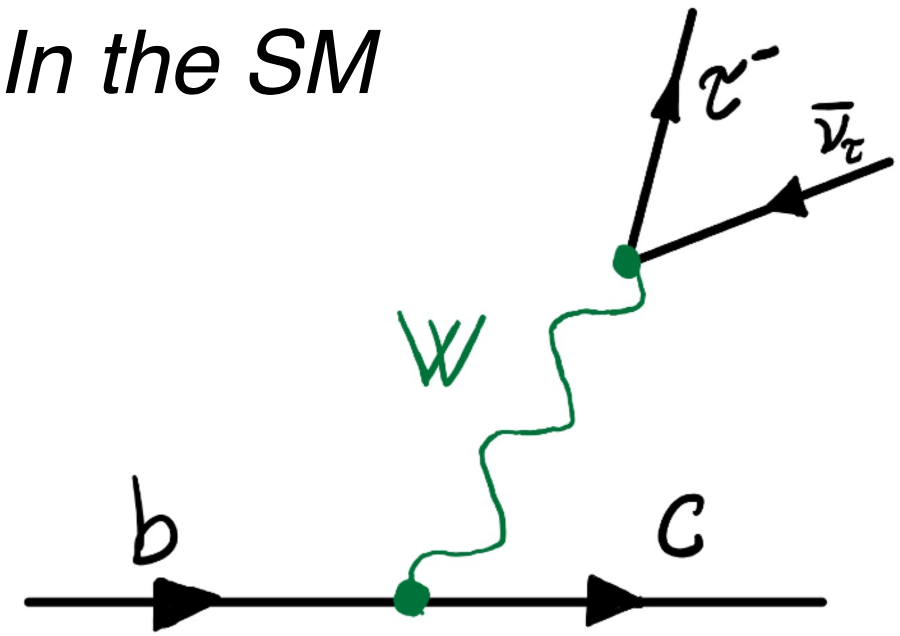
u-channel

- SU(2) weak: **1**, **2** or **3**

R(D(*))

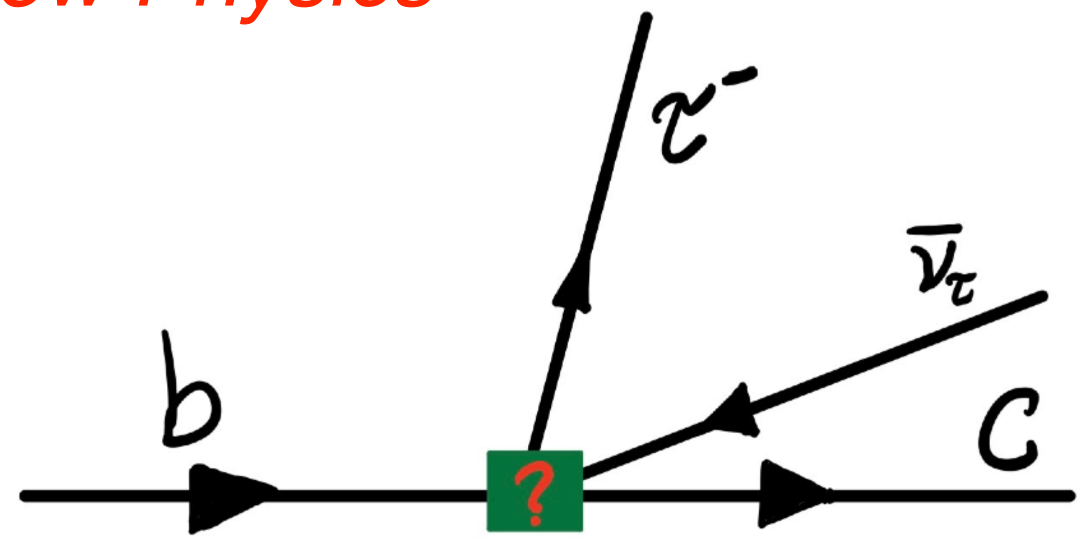
New mass scale?

In the SM



- Tree-level process
- Mild CKM suppression

New Physics



- Large NP contribution required
  [Presumably tree-level generated]

<u>Tree-level, unsuppressed</u> ($g_* \sim 1$)	<u>Tree-level, MFV</u> ($g_*^2 = V_{cb}$)
~ 3.5 TeV	**~ 0.7 TeV**

<u>Perturbative unitarity constraint</u>: NP scale $\lesssim$ 9 TeV
[Di Luzio and Nardecchia], 1706.01868

R(D$^{(*)}$)

An attempt

[AG, Isidori, Marzocca]
JHEP 1507 (2015) 142

SU(3)×SU(2)$_L$×U(1)

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

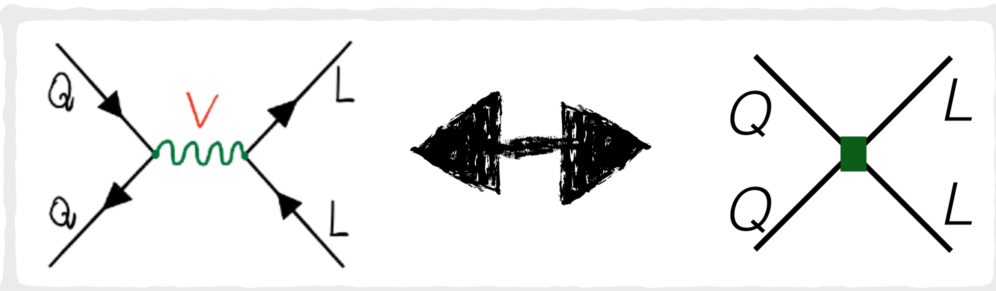
Vector triplet model

SU(3)×SU(2)$_L$×U(1)

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

$$\mathcal{L} \supset W'^{a\mu} J^a_\mu + \ldots \qquad T^a = \sigma^a/2$$

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



$$Q^i_L = \begin{pmatrix} V^*_{ji} u^j_L \\ d^i_L \end{pmatrix} \qquad L^\alpha_L = \begin{pmatrix} \nu^\alpha_L \\ \ell^\alpha_L \end{pmatrix}$$

$$\mathcal{L}^{d=6}_{\rm eff} = -\frac{1}{2m_V^2} J^a_\mu J^a_\mu \longrightarrow$$

lepton x lepton

quark x lepton

quark x quark

- Degenerate charged W'$^\pm$ and neutral Z'
- Quark FV controlled by a single matrix

[AG, Isidori, Marzocca]
JHEP 1507 (2015) 142

Fitting $R(D^{(*)})$

$$\mathcal{L}_{\rm eff} \supset -\frac{C_T}{v^2}\lambda^q_{ij}(\bar{Q}_i\gamma_\mu\sigma^a Q_j)(\bar{L}_3\gamma^\mu\sigma^a L_3)$$

$$Q^i_L = \begin{pmatrix} V^*_{ji}u^j_L \\ d^i_L \end{pmatrix}$$

$$\lambda^q_{bb} = 1$$

$$V_{cb} \approx 0.04$$

Controls FCNC in the down-quark sector

Aligned with the down-quark mass basis

Fitting $R(D^{(*)})$

$$\mathcal{L}_{\rm eff} \supset -\frac{C_T}{v^2}\lambda^q_{ij}(\bar{Q}_i\gamma_\mu\sigma^a Q_j)(\bar{L}_3\gamma^\mu\sigma^a L_3)$$

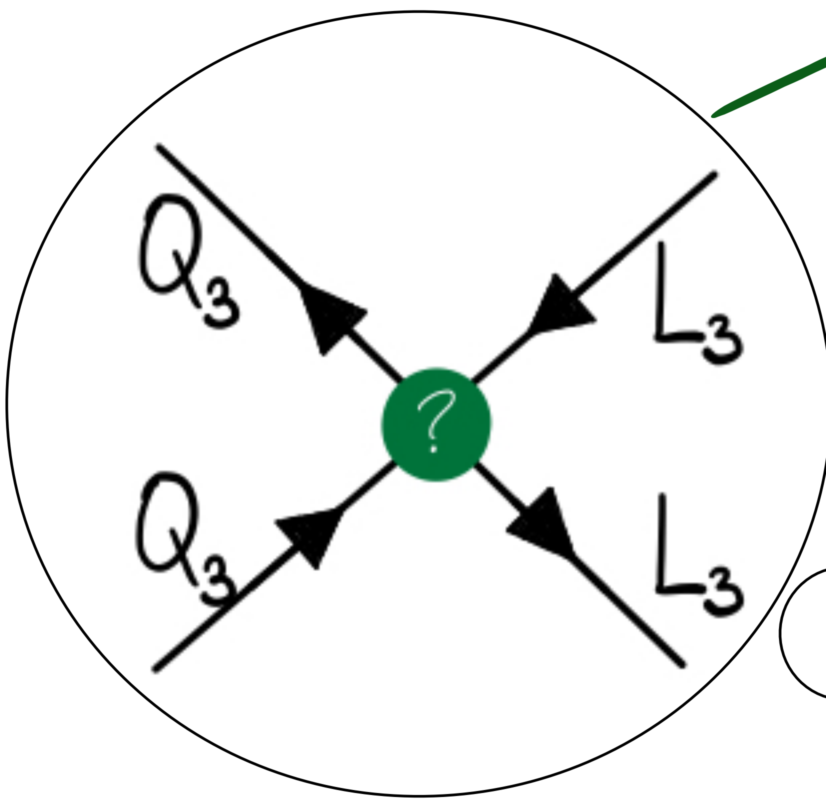
$$Q_L^i = \begin{pmatrix} V^*_{ji}u^j_L \\ d^i_L \end{pmatrix}$$

$\lambda^q_{bb} = 1$

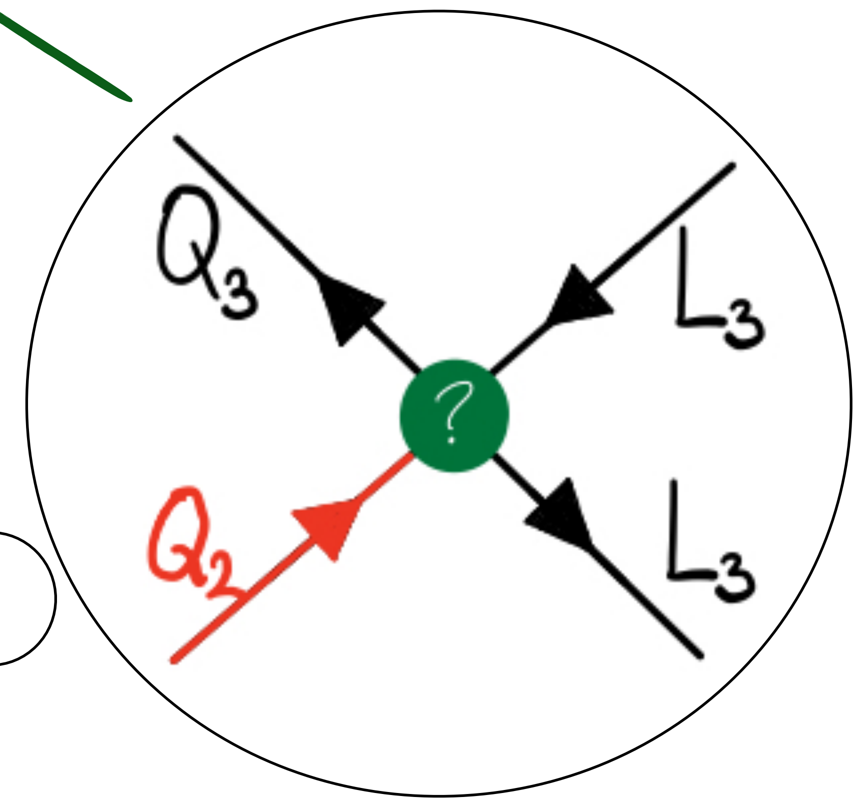
$V_{cb} \approx 0.04$

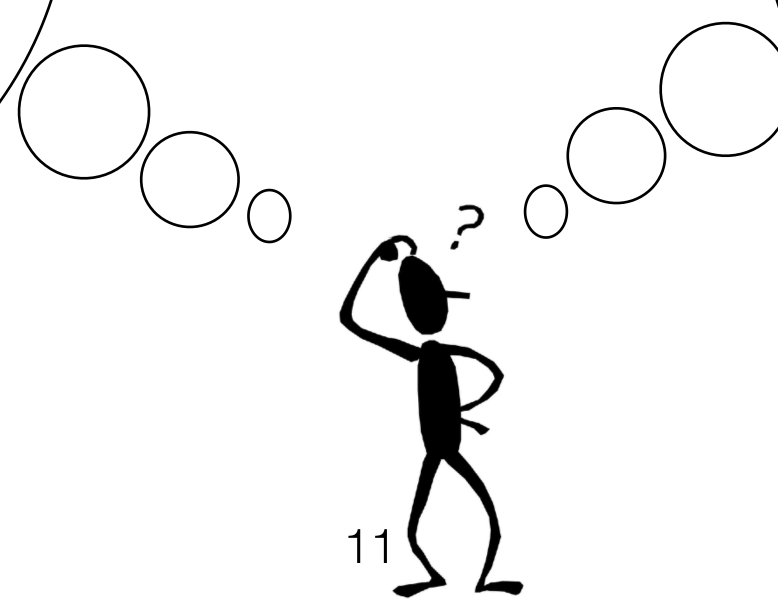
$$b \to c\tau\nu_\tau$$

$$R^{\tau\ell}_{D^{(*)}} \approx 1 + 2C_T\left(1 + \frac{\lambda^q_{sb}}{V_{cb}}\right) \approx 1.24 \pm 0.06$$



Which one dominates?





Fitting R(D(*))

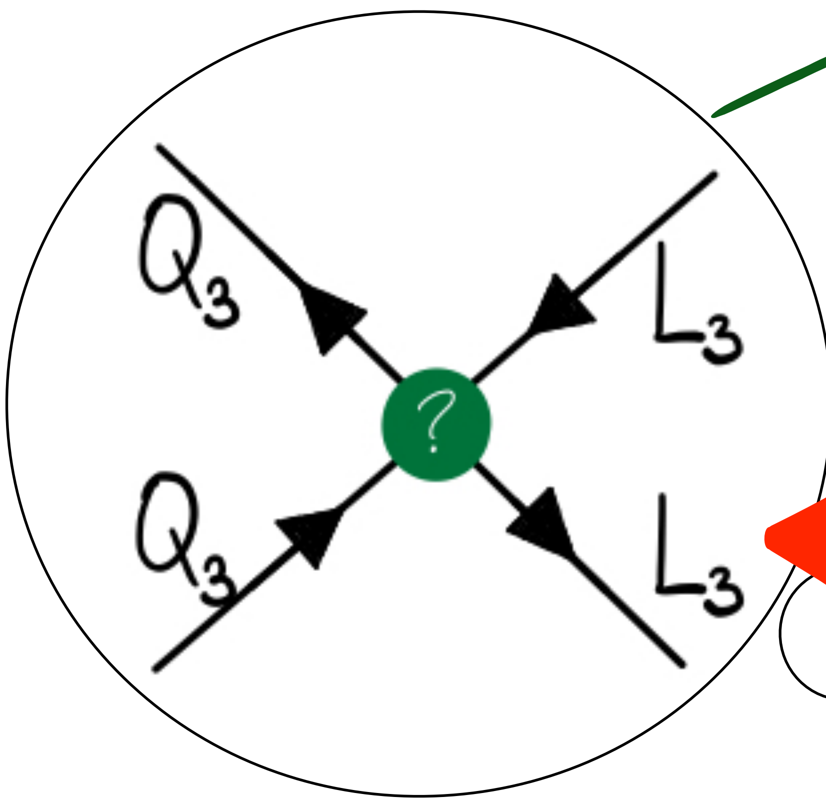
$$\mathcal{L}_{\text{eff}} \supset -\frac{C_T}{v^2}\lambda^q_{ij}(\bar{Q}_i\gamma_\mu\sigma^a Q_j$$

$$Q^i_L = \begin{pmatrix} V^*_{ji}u^j_L \\ d^i_L \end{pmatrix}$$

$\lambda^q_{bb} = 1$

$V_{cb} \approx 0.04$

$R^{\tau\ell}_{D(*)} \approx 1 +$



FCNC limits

1) $B_s \leftrightarrow \bar{B}_s$

if tree-level

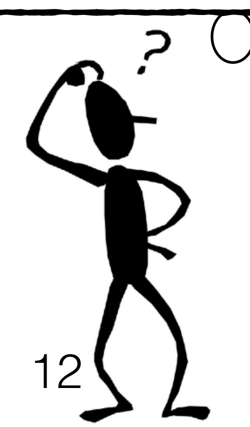
e.g. $W' = (\mathbf{1}, \mathbf{3}, 0)$ $|\lambda^q_{sb}| \lesssim 0.1 V_{cb}$

[AG, Isidori, Marzocca] JHEP 1507 (2015) 142

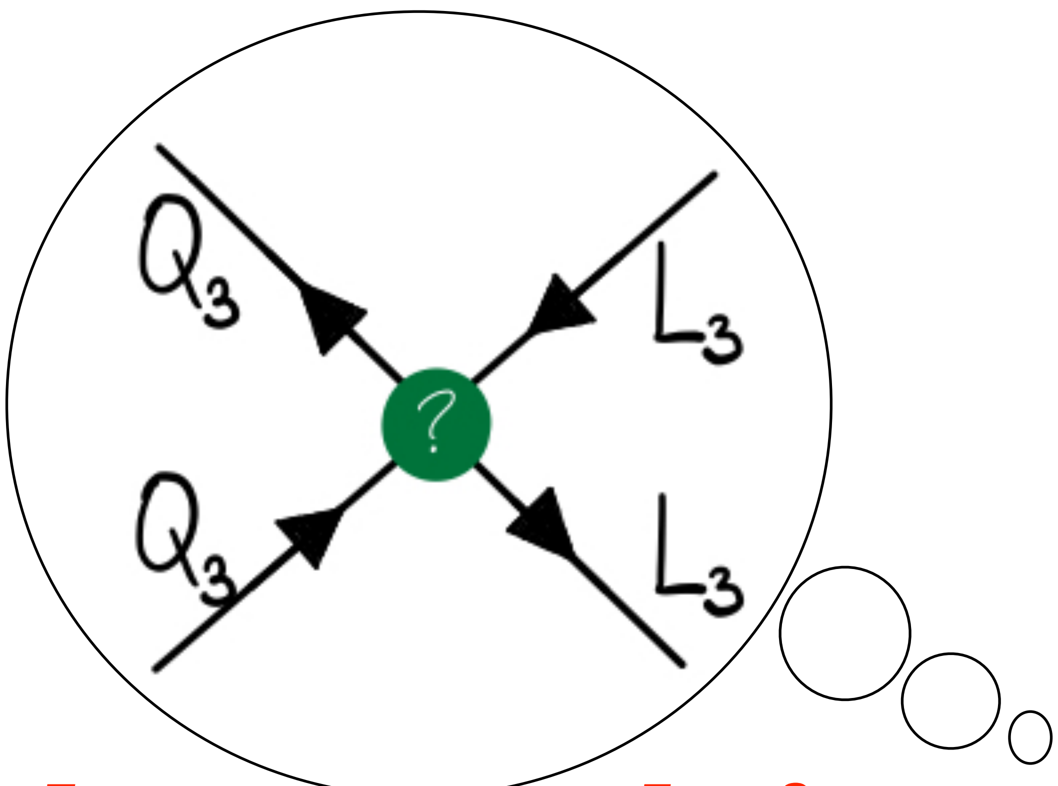
2) $B \to K^{(*)}\nu_\tau\bar{\nu}_\tau$

For triplet operator $|\lambda^q_{sb}| \lesssim 0.5 V_{cb}$

Safe road?



$$|\lambda^q_{sb}| \ll V_{cb} \ ,$$

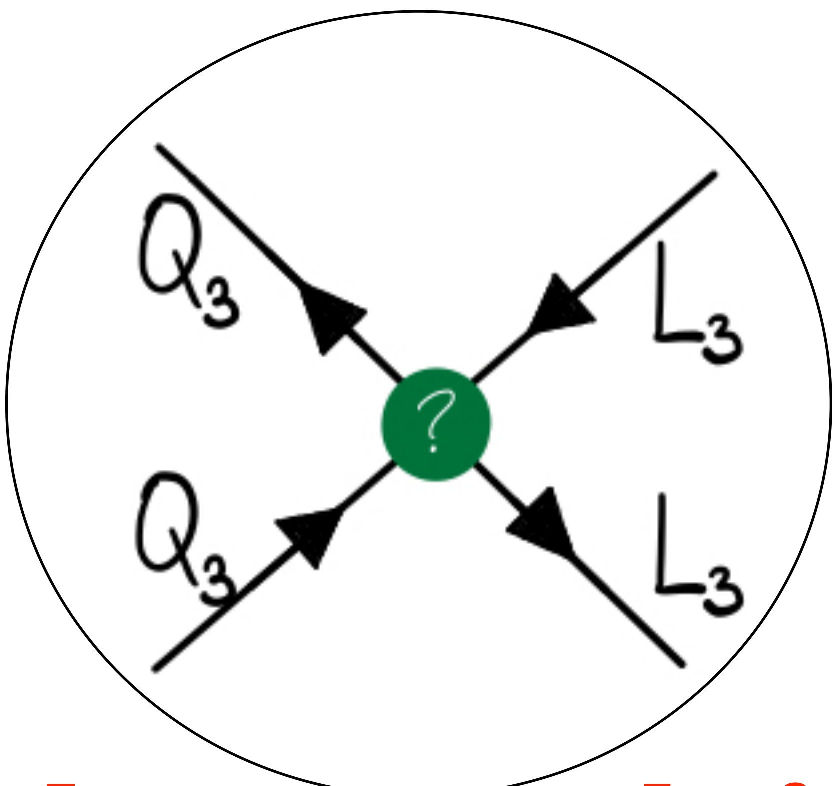


Low scale!

$$v/\sqrt{C_T} \approx 0.7 \text{ TeV}$$

*to fit R(D$^{(*)}$)

$$|\lambda^q_{sb}| \ll V_{cb} \ ,$$



Low scale!

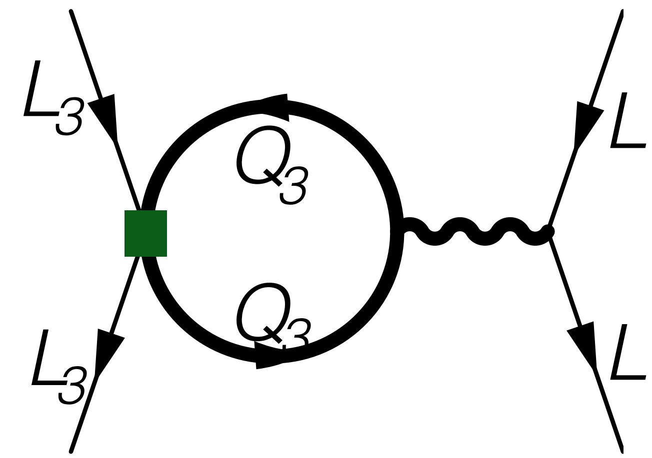
$$v/\sqrt{C_T} \approx 0.7 \text{ TeV}$$

*to fit $R(D^{(*)})$

Radiative EW effects

Tension:

Precise leptonic and EW observables

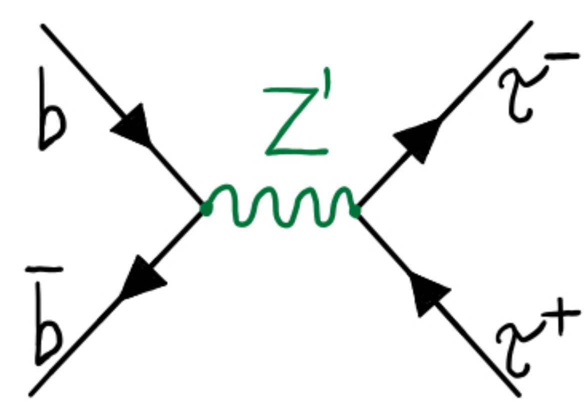


Possible fix:
Tune with a direct tree-level matching contribution

[Feruglio, Paradisi, Pattori], Phys. Rev. Lett. 118 (2017), no. 1 011801

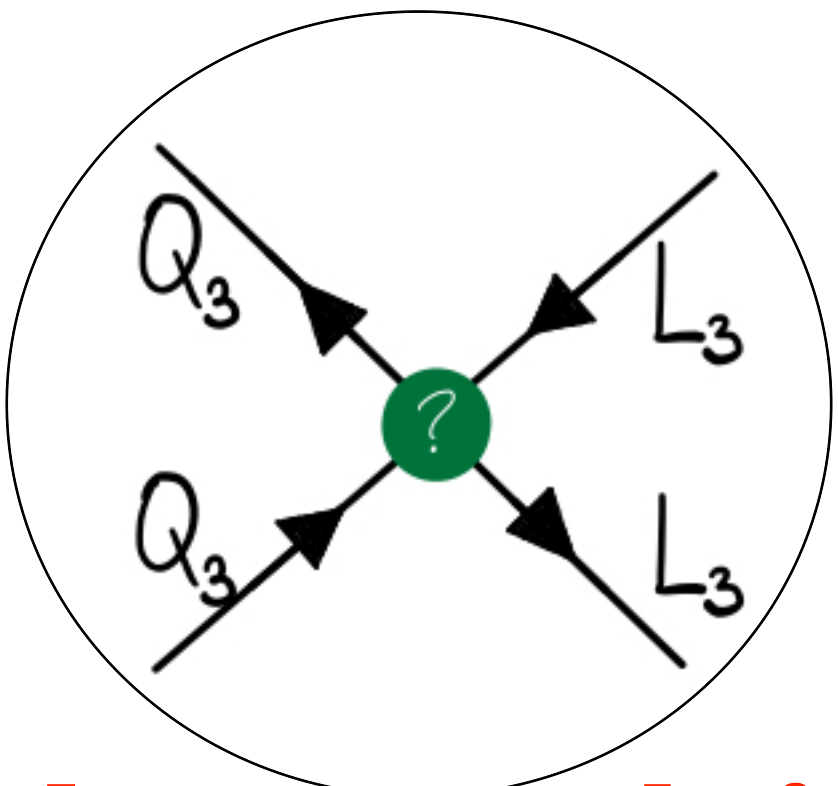
$$pp \to \tau^+\tau^-$$

Tension: ***High p_T ditau production***



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

$$|\lambda^q_{sb}| \ll V_{cb} \ ,$$



Low scale!

$$v/\sqrt{C_T} \approx 0.7 \text{ TeV}$$

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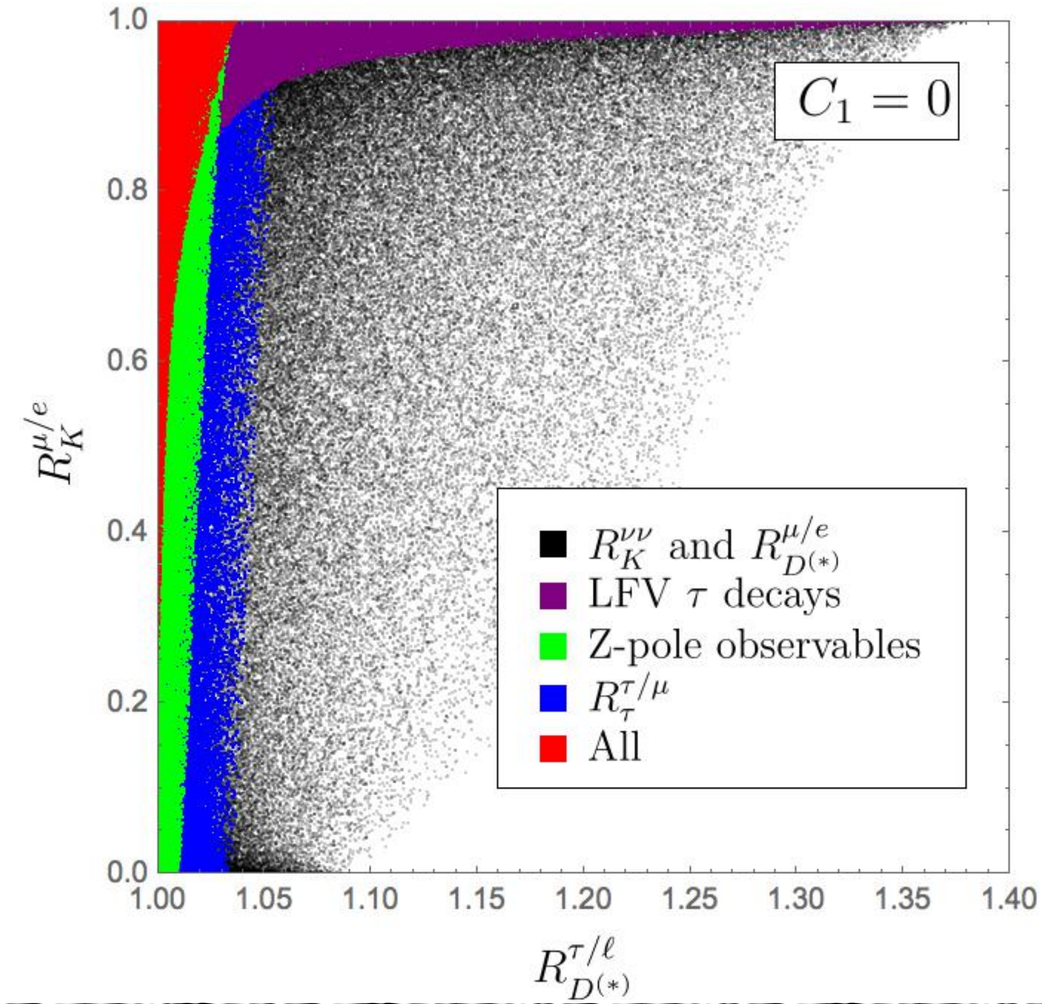
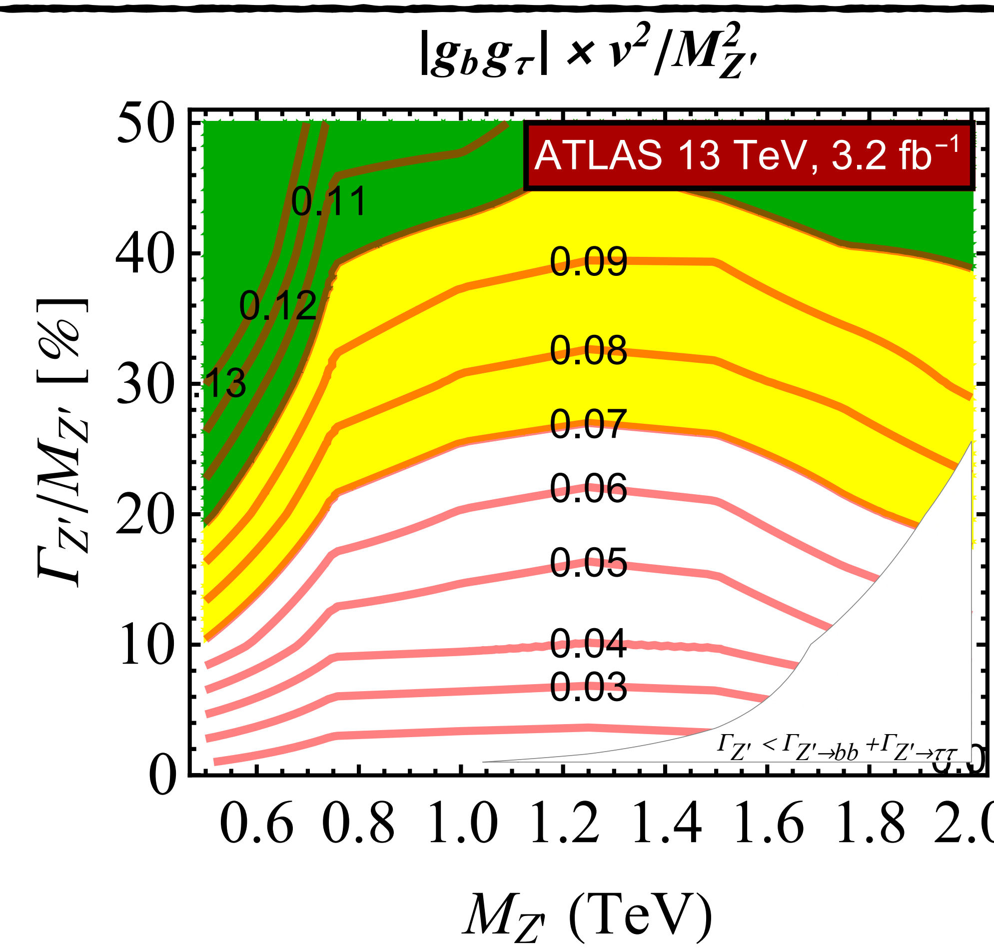




Challenges for Model Builders?

$B_s \leftrightarrow \bar{B}_s$
$B \to K^{(*)} \nu_\tau \bar{\nu}_\tau$
$\ldots$

FCNC

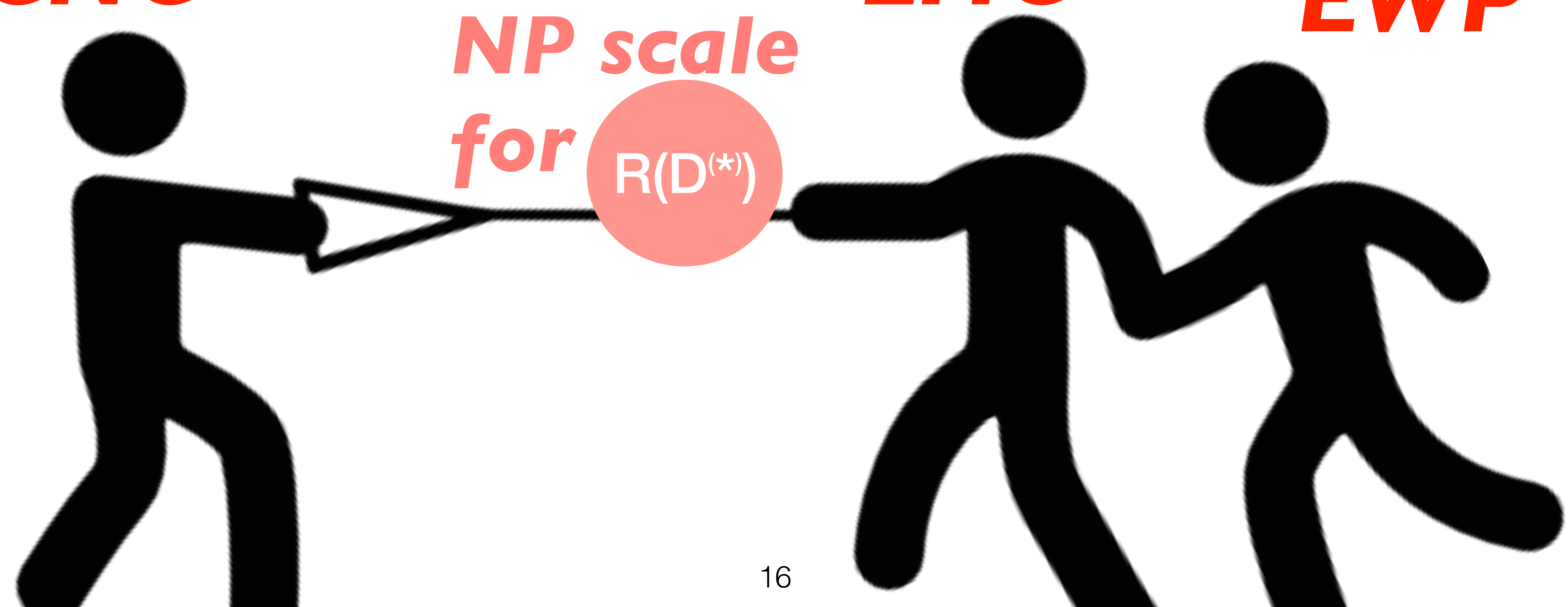
$pp \to \tau^+ \tau^-$
$\ldots$

High p_T LHC

Z decays
τ decays
$\ldots$

EWP

NP scale for



Working example I

'4321'

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

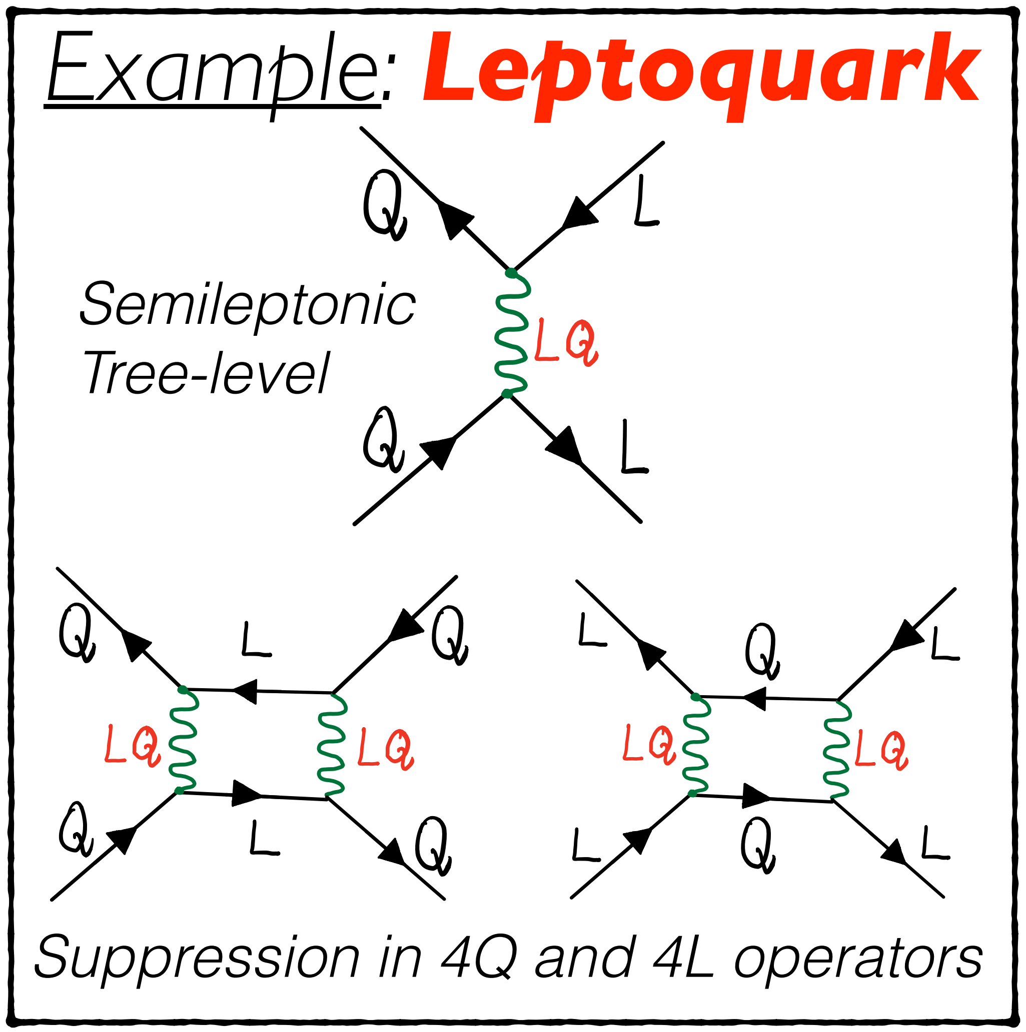
[Di Luzio, AG, Nardecchia]
Phys.Rev. D96 (2017) 115011

[AG, Ben Stefanek]
1802.04274

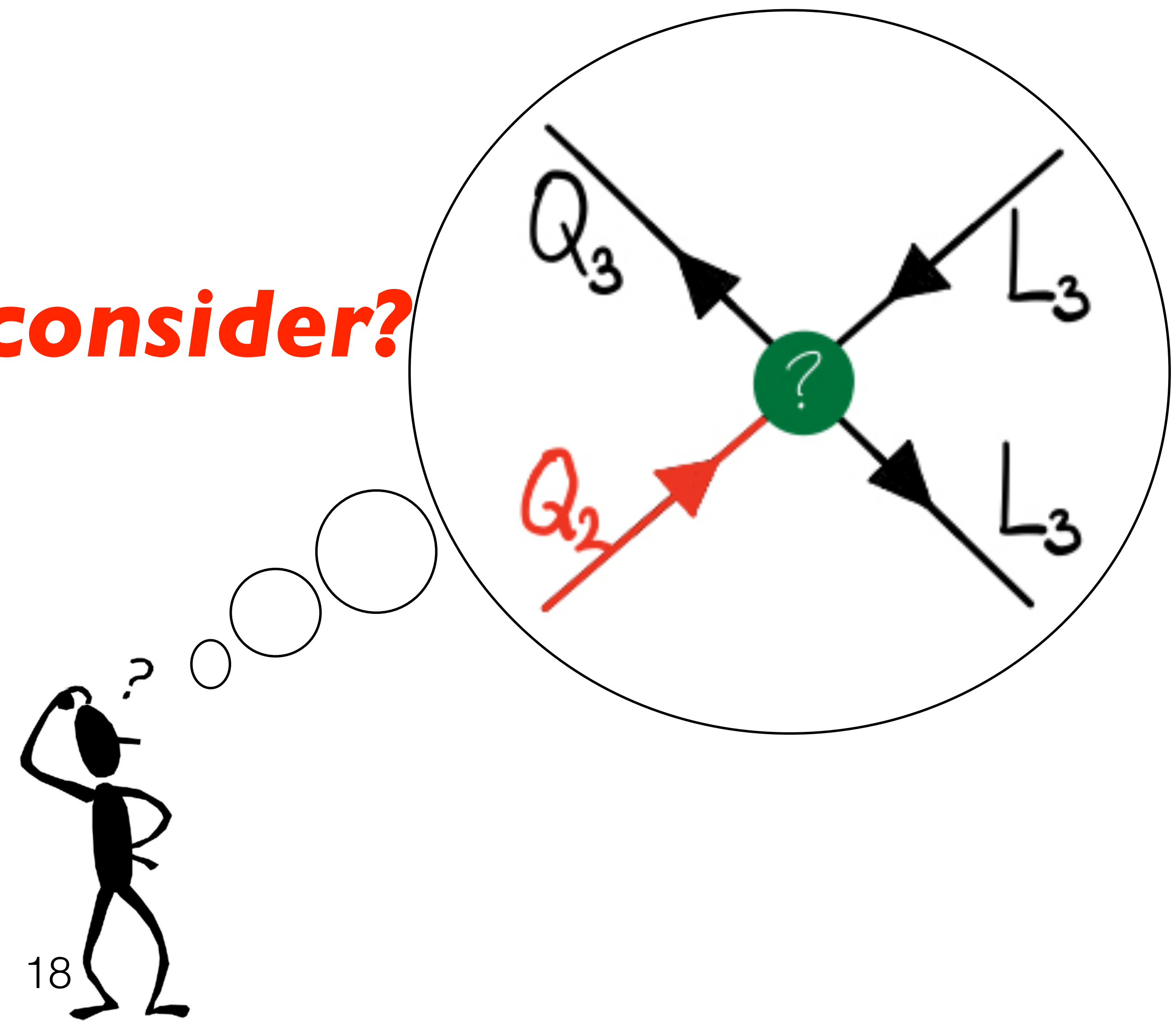
Leptoquark option?

Strategy: *Dynamical suppression in FCNC*

$$B_s \leftrightarrow \bar{B}_s \qquad\qquad B \to K^{(*)}\nu_\tau\bar{\nu}_\tau$$

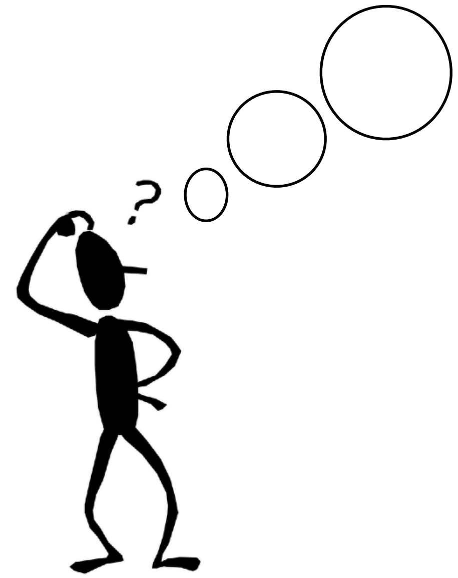


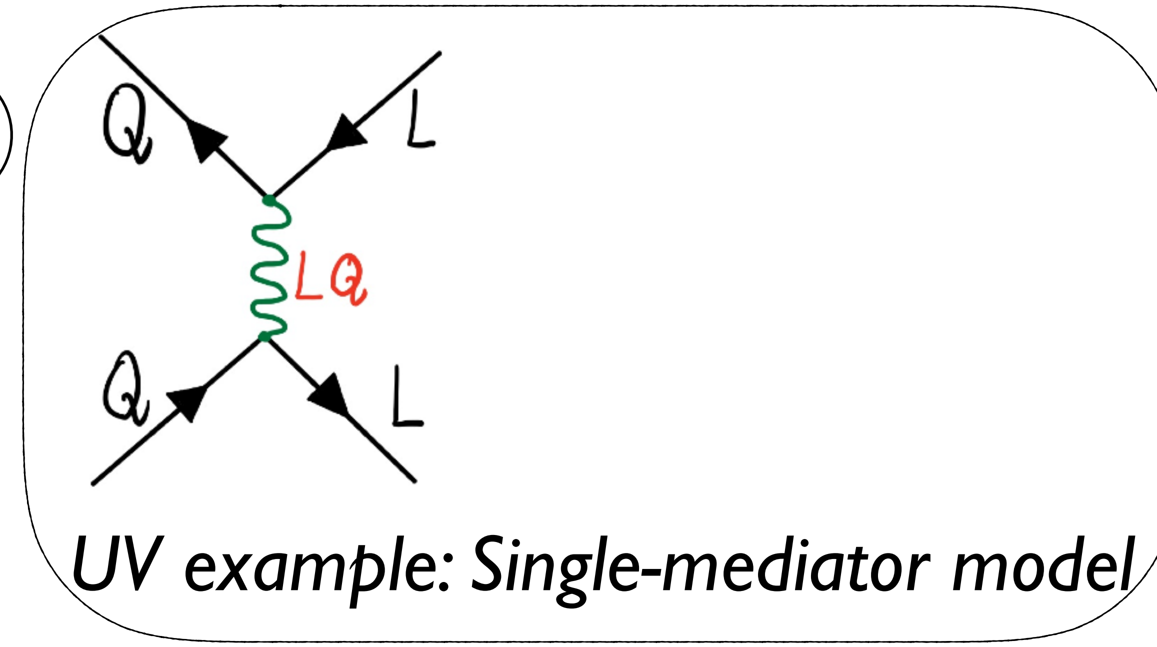
Reconsider?



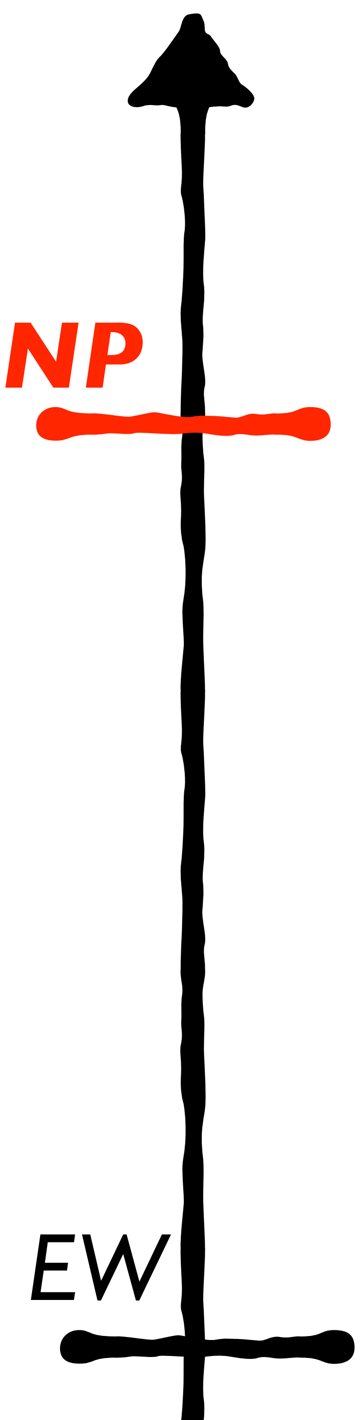
Vector LQ

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





Energy scale



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

$$J_U^\mu \equiv \beta_{i\alpha}\, \bar{Q}_i \gamma^\mu L_\alpha \longrightarrow de + u\nu \qquad \beta_{b\tau} = 1$$

*Expanding SU(2)

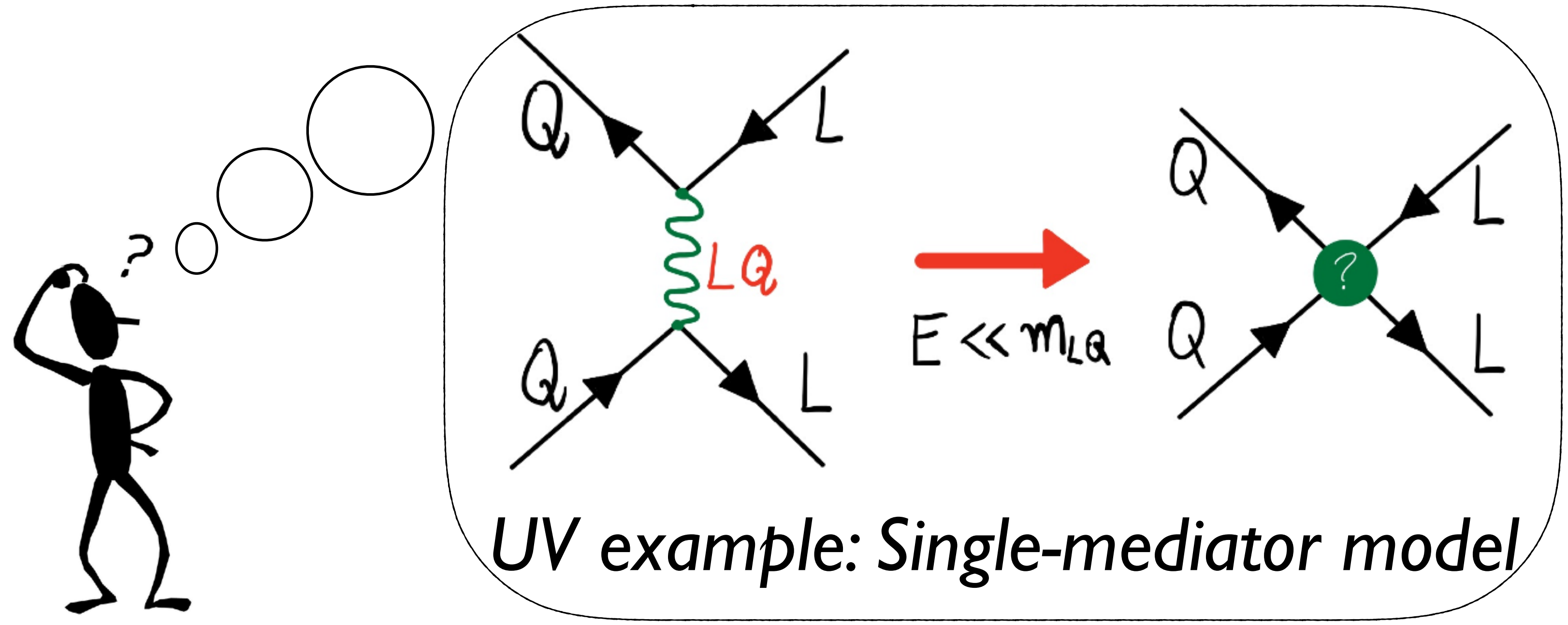
Flavour basis:

$$Q_i = (V_{ji}^* u_L^j, d_L^i)^T \quad L_i = (\nu_L^i, \ell_L^i)^T$$

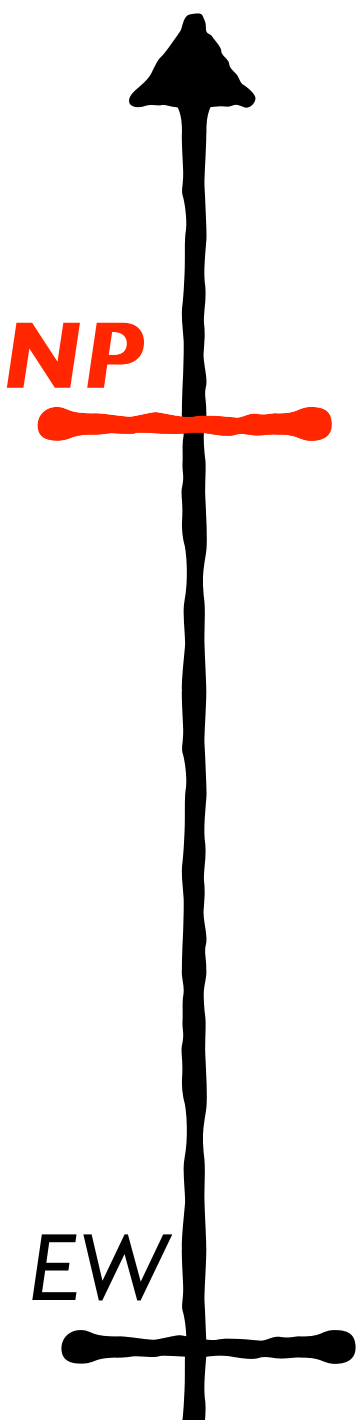
[Buttazzo, AG, Isidori, Marzocca]
JHEP 1711 (2017) 044

Vector LQ

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



Energy scale



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

$$J_U^\mu \equiv \beta_{i\alpha}\,\bar{Q}_i\gamma^\mu L_\alpha \longmapsto de + uv \qquad \beta_{b\tau} = 1$$

*Expanding SU(2)

matching

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

$$C_U = v^2|g_U|^2/(2M_U^2)$$

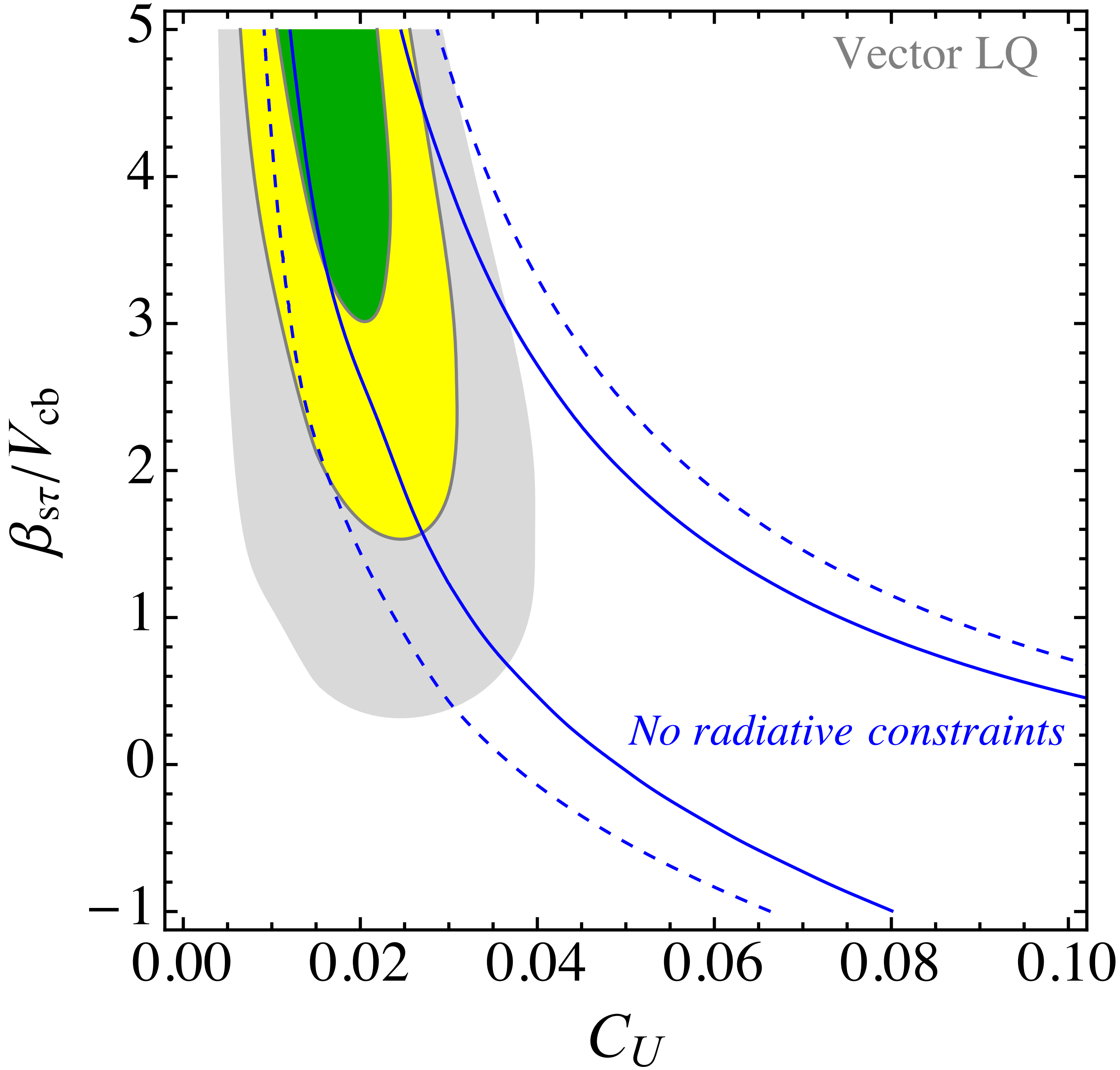
Flavour basis:

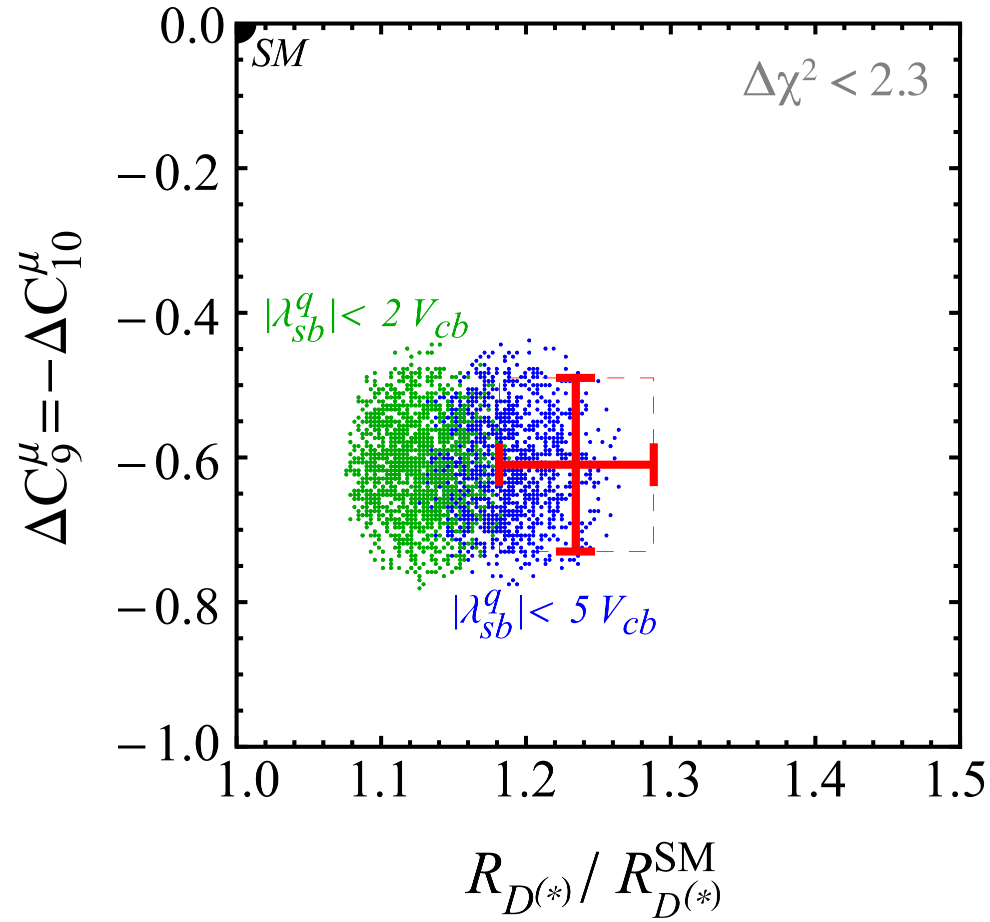
$$Q_i = (V^*_{ji}u^j_L, d^i_L)^T \quad L_i = (\nu^i_L, \ell^i_L)^T$$

Global fit to low-energy data (RGE effects included)

$$R^{\tau\ell}_{D^{(*)}} \quad \Delta C_9^\mu = -\Delta C_{10}^\mu \quad B_{K^{(*)}\nu\bar{\nu}} \quad \delta g^Z_{\tau_L} \quad \delta g^Z_{\nu_\tau} \quad |g^W_\tau/g^W_\ell|$$

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





No tree-level

$B_s \leftrightarrow \bar{B}_s$

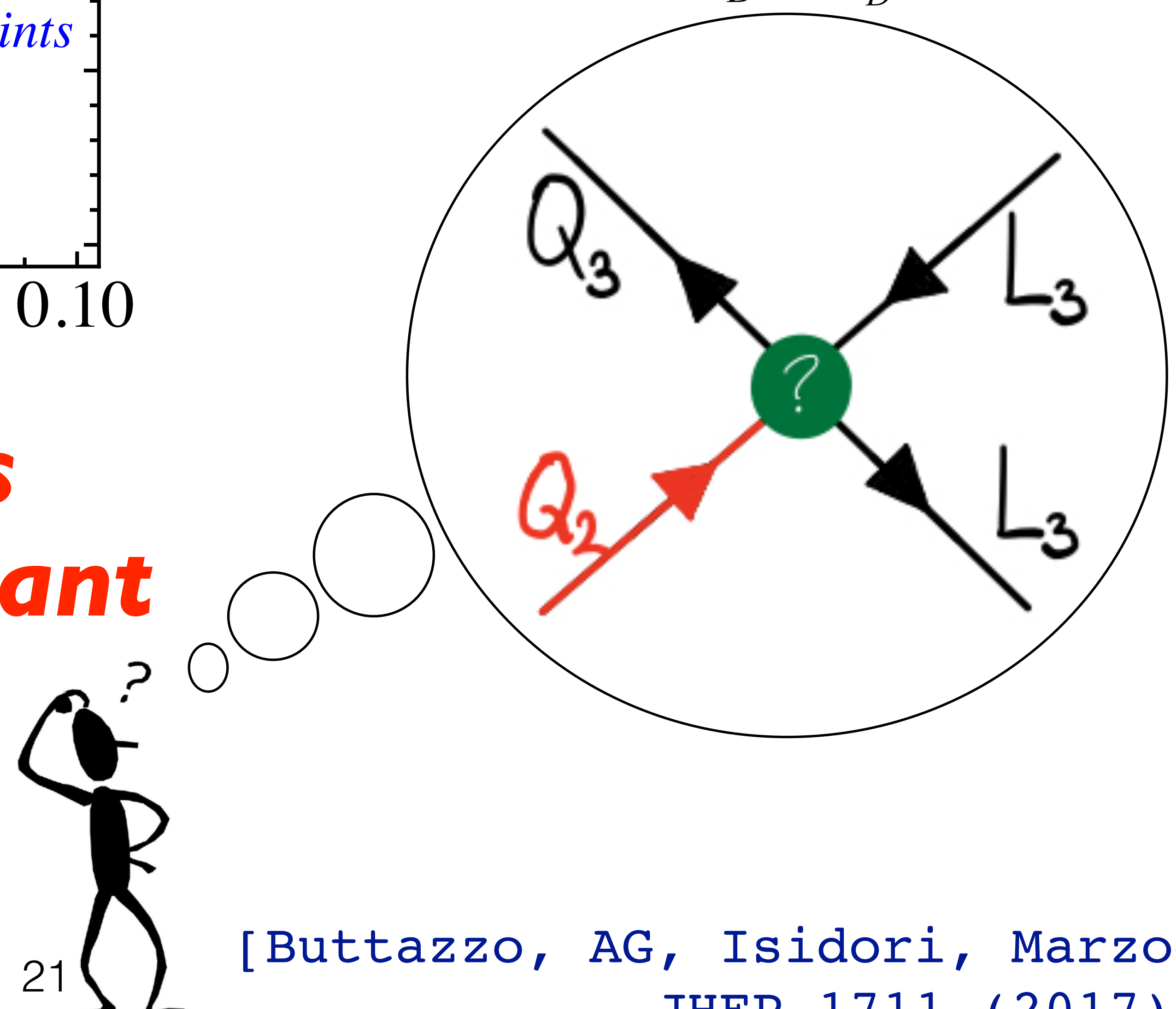
$B \to K^{(*)} \nu \bar{\nu}$

Suppressed

$Z\tau\tau$

(One-loop plus extra suppression)

It is dominant

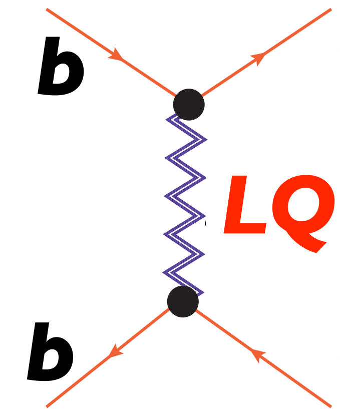


[Buttazzo, AG, Isidori, Marzocca]
JHEP 1711 (2017) 044

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

High p_T searches

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



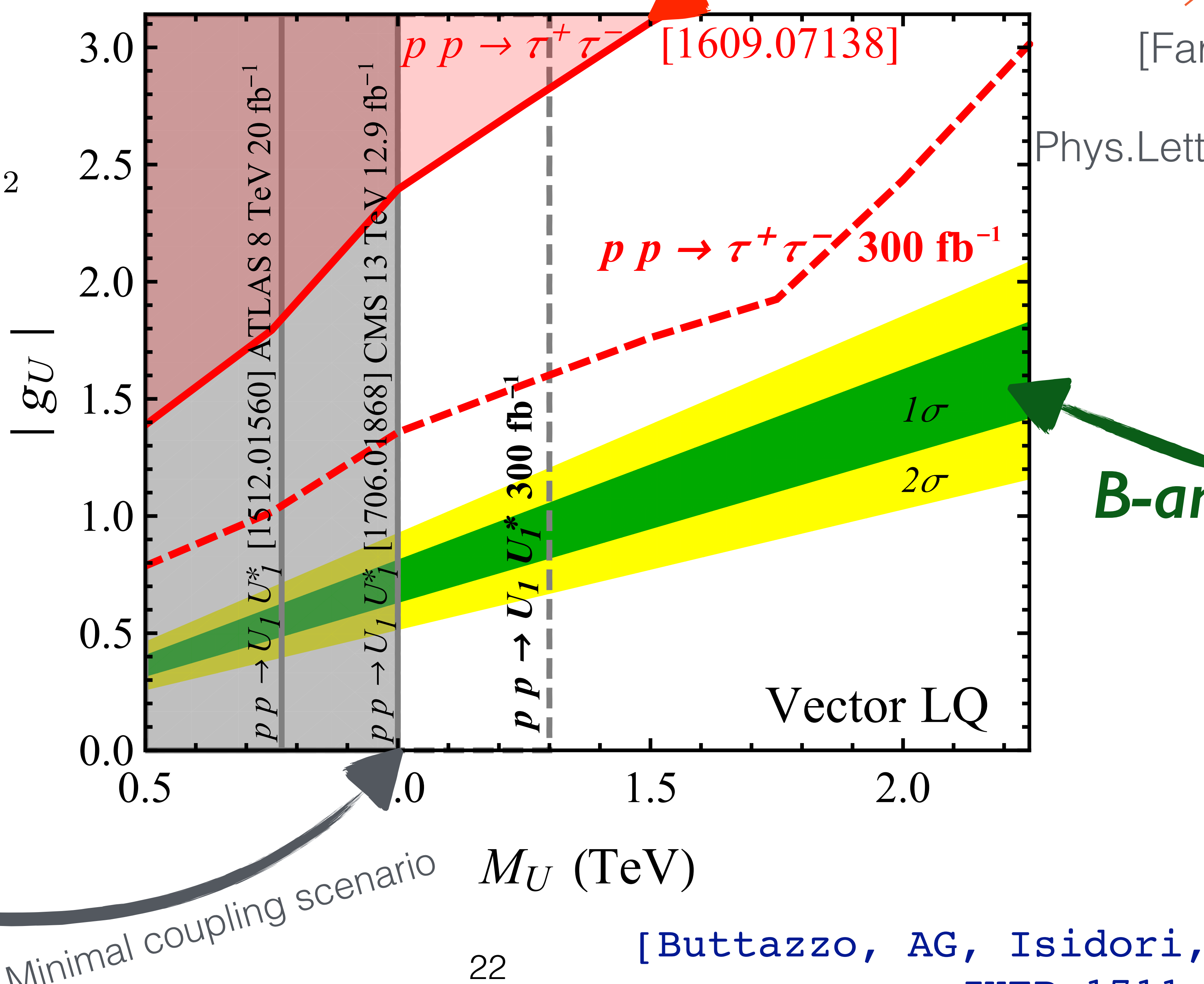
[Faroughy, AG, F. Kamenik] Phys.Lett. B764 (2017) 126-134

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

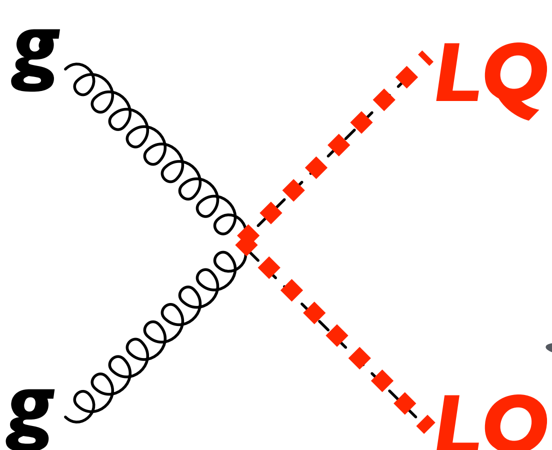
Best fit:

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

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



CMS: 1703.03995
ATLAS: 1508.04735



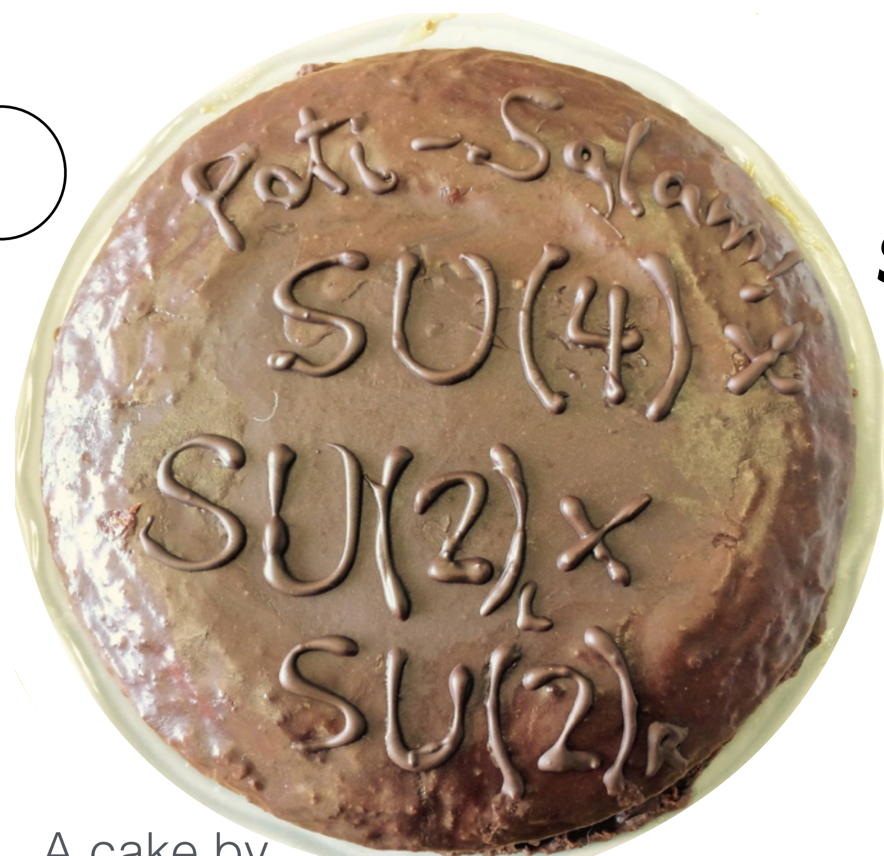
[Buttazzo, AG, Isidori, Marzocca] JHEP 1711 (2017) 044

UV completion

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

Gauge boson of an extended gauge sector

Calculable!



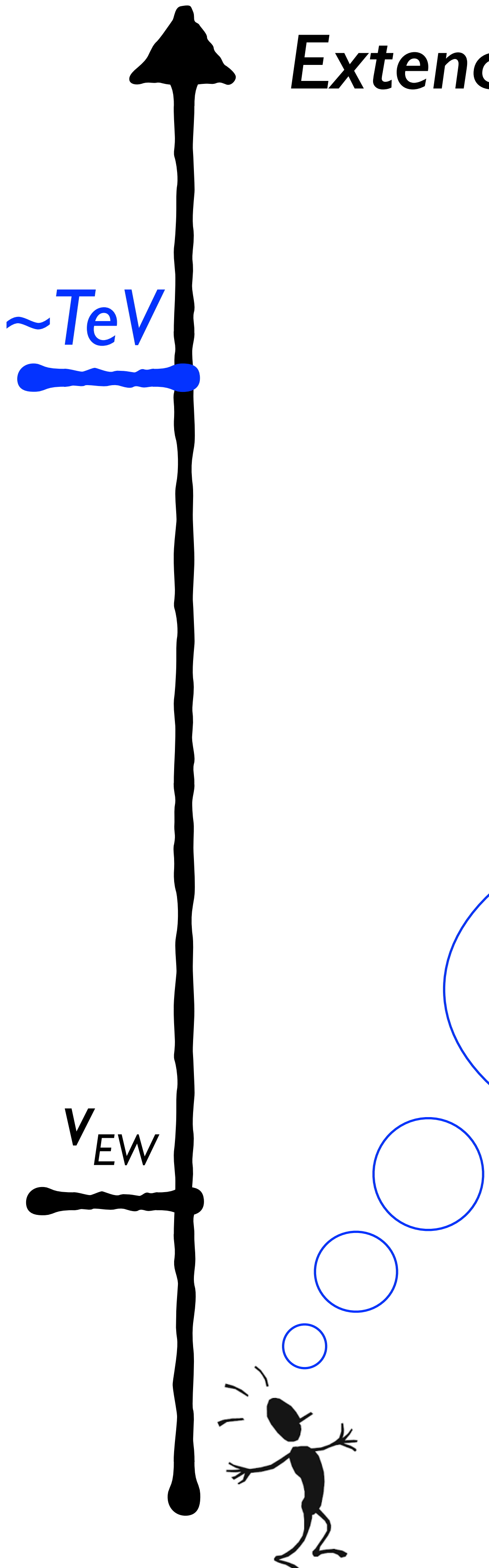
A cake by [Buttazzo], 2017

The starting point, but strong flavour bounds…

How to get TeV scale PS LQ?

‘4321’ model

[Di Luzio, AG, Nardecchia] Phys.Rev. D96 (2017) 115011



Extended gauge symmetry

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

SSB: $\langle \Omega_3 \rangle, \langle \Omega_1 \rangle$

$$G_{\rm SM} \equiv SU(3)_c \times SU(2)_L \times U(1)_Y$$

15 broken generators

$(3, 1, 2/3)$	$(8, 1, 0)$	$(1, 1, 0)$
Leptoquark *Complex	**G’**	**Z’**

- SM fermions in **321**, not coupled to LQ
  $(q'_L, \ell'_L, u'_R, d'_R, e'_R)$

See also [Georgi, Nakai], 1606.05865
[Diaz, Schmaltz, Zhong], 1706.05033

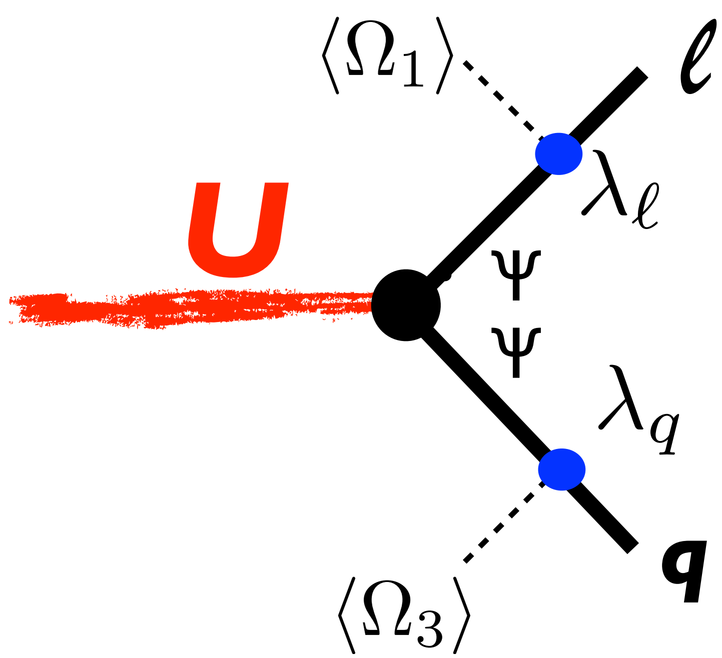
‘4321’ model

[Di Luzio, AG, Nardecchia] Phys.Rev. D96 (2017) 115011

Add a vector-like fermion $(4, 1, \mathbf{2}, 0)$

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

SM fermion ***doublets*** *mix with the vector-like partners*



Left-handed dominance!

- *B*-anomalies solved by the vector ***LQ*** alone!
- Flavour blind ***G’*** and ***Z’*** interactions possible (no FCNC) - **Non-trivial flavour structure!**
- ***G’*** at high p_T expected in ***jj***, ***tt***, ***bb*** final states

For a variation of this model see [AG, Ben Stefanek] 1802.04274

Working example II

'3221'

[AG, Robinson, Shakya, Zupan] 1804.XXXXX

$$W' = (\mathbf{1}, \mathbf{1}, +1)$$

& light

$$N_R = (\mathbf{1}, \mathbf{1}, 0)$$

$$b \to c\tau \bar{N}_R$$

'3221' model

[AG, Robinson, Shakya, Zupan]
1804.XXXXX

Extended gauge symmetry

~TeV

$$\mathcal{G} \equiv SU(3)_c \times SU(2)_L \times SU(2)_V \times U(1)'$$

SSB: $\langle H_V \rangle$

$$G_{\rm SM} \equiv SU(3)_c \times SU(2)_L \times U(1)_Y$$

3 broken generators

$(\mathbf{1}, \mathbf{1}, +1)$
W'

$(1, 1, 0)$
Z'

v_{EW}

$$\mathcal{L}_{\rm VR} = \frac{C_{ij,k}}{\Lambda^2_{\rm eff}} \left(\bar{u}^i_R \gamma^\mu d^j_R\right) \left(\bar{e}^k_R \gamma_\mu N_R\right)$$

'3221' model

Matter content

Field	$SU(3)_c$	$SU(2)_L$	$SU(2)_V$	$U(1)'$
SM-like chiral fermions				
q'^i_L	**3**	**2**	**1**	1/6
ℓ'^i_L	**1**	**2**	**1**	-1/2
u'^i_R	**3**	**1**	**1**	2/3
d'^i_R	**3**	**1**	**1**	-1/3
e'^i_R	**1**	**1**	**1**	-1
ν'^i_R	**1**	**1**	**1**	0
Extra vector-like fermions				
$Q'_{L,R}$	**3**	**1**	**2**	1/6
$L'_{L,R}$	**1**	**1**	**2**	-1/2
Scalars				
H	**1**	**2**	**1**	1/2
H_V	**1**	**1**	**2**	1/2

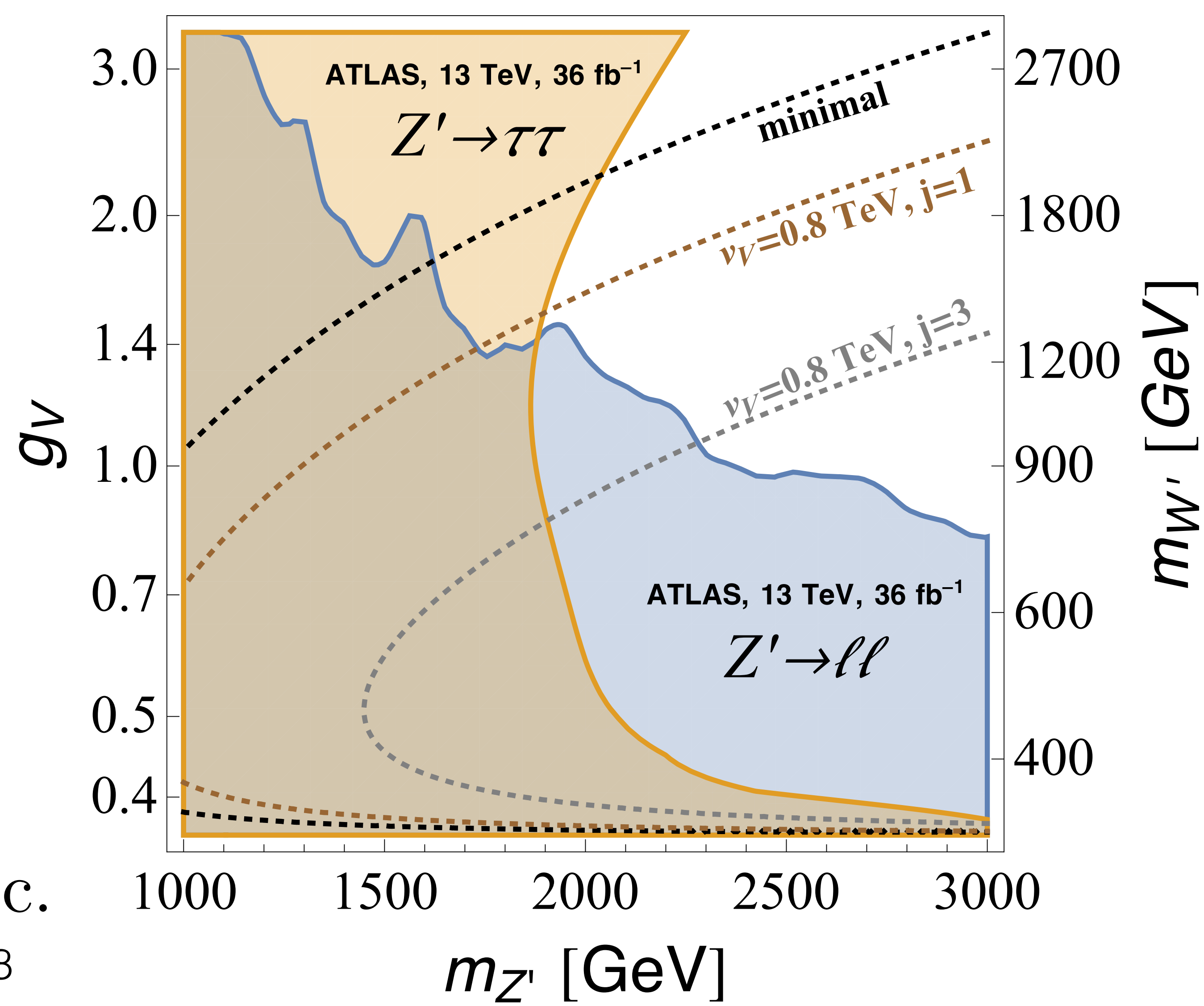
$$\mathcal{L} \supset \mathcal{L}^{\rm SM}_{\rm Yuk} - \lambda^i_d \bar{Q}'_L H_V d'^i_R - \lambda^i_u \bar{Q}'_L \tilde{H}_V u'^i_R - \lambda^i_e \bar{L}'_L H_V e'^i_R - \lambda^i_\nu \bar{L}'_L \tilde{H}_V \nu'^i_R - M_Q \bar{Q}'_L Q'_R - M_L \bar{L}'_L L'_R + \text{h.c.}$$

FL-23 case:

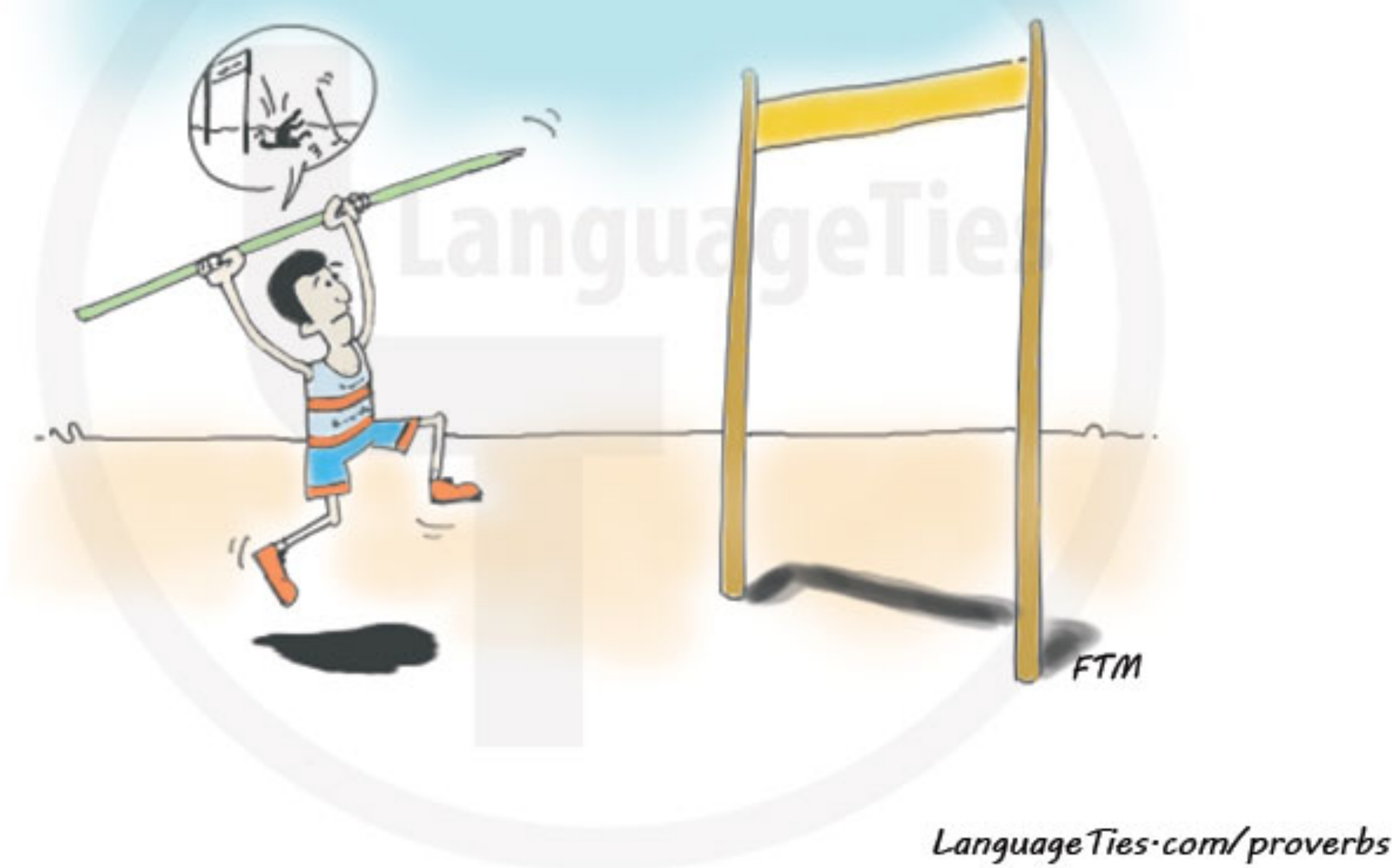
$$\lambda^i_d \sim (0,0,1) \qquad \lambda^i_u \sim (0,1,0)$$

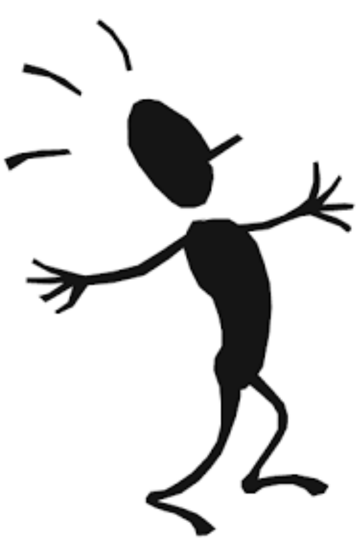
- *No FCNC* ***Z'*** *couplings predicted*
- ***Z'*** *mass can be increased independently of the W' mass*

LHC exclusions: FL-23



Hope for the best, but prepare for the worst





Backup slides

Coherent picture of B-anomalies

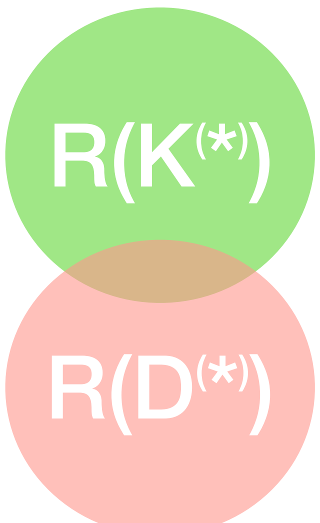
$b \to c\tau\bar{\nu}_\tau$

V-A operator

Hint I

$b \to s\mu\bar{\mu}$

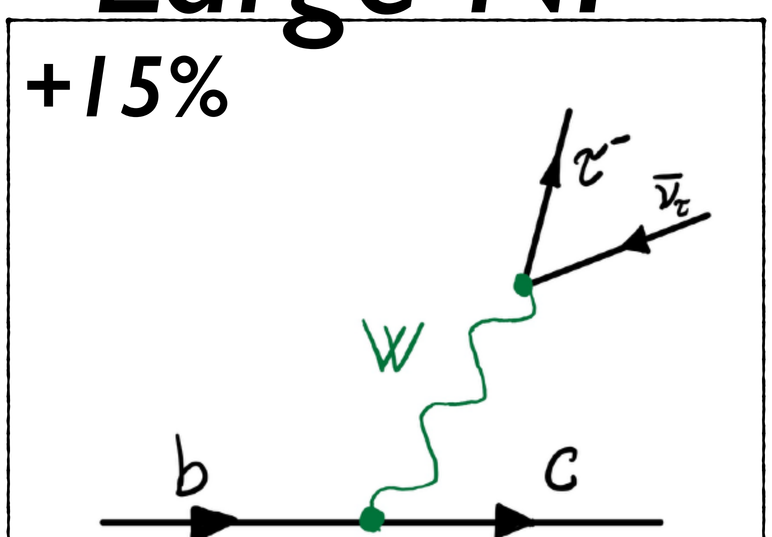
V-A operator



Common origin?

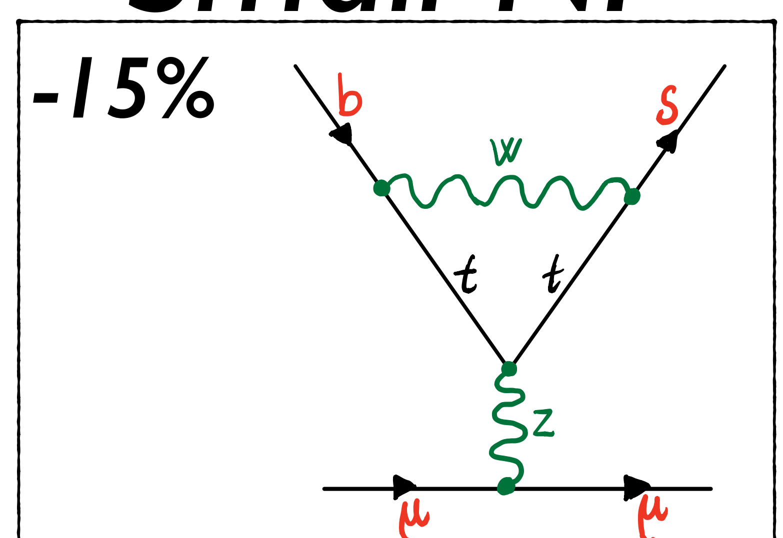
$$(\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L)$$

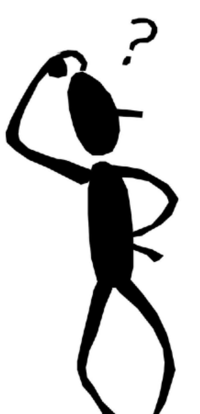
Large NP



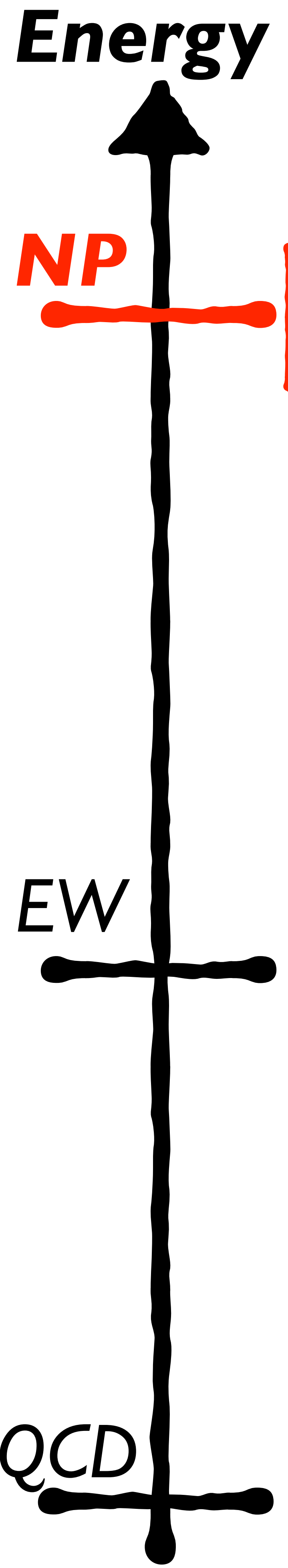
Hint II

Small NP





Flavour puzzle?



Benchmark picture

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

Flavour basis:

$$Q_i = (V^*_{ji}u^j_L, d^i_L)^T \quad L_i = (\nu^i_L, \ell^i_L)^T$$

Fit parameters:

$C_T,\ C_S,\ \lambda^q_{sb},\ \text{and}\ \lambda^\ell_{\mu\mu}$

$\lambda^q_{bb} = \lambda^\ell_{\tau\tau} = 1$

- ***Global fit to low-energy data*** *(RGE effects included)*

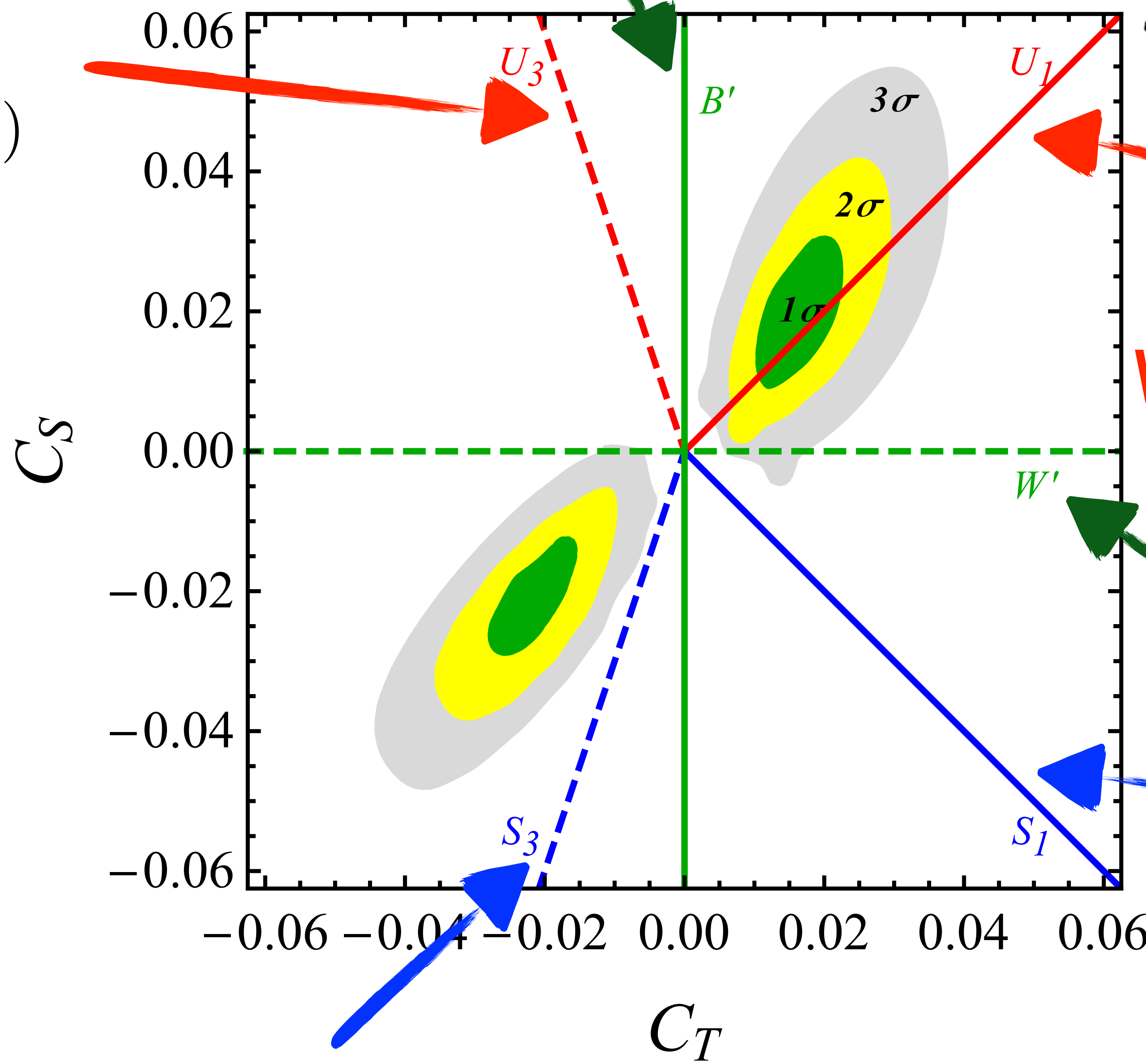
Observable	Experimental bound	Linearised expression
$R^{\tau\ell}_{D^{(*)}}$	1.237 ± 0.053	$1 + 2C_T(1-\lambda^q_{sb}V^*_{tb}/V^*_{ts})(1-\lambda^\ell_{\mu\mu}/2)$
$\Delta C^\mu_9 = -\Delta C^\mu_{10}$	-0.61 ± 0.12 [36]	$-\frac{\pi}{\alpha_{\rm em}V_{tb}V^*_{ts}}\lambda^\ell_{\mu\mu}\lambda^q_{sb}(C_T + C_S)$
$R^{\mu e}_{b\to c} - 1$	0.00 ± 0.02	$2C_T(1-\lambda^q_{sb}V^*_{tb}/V^*_{ts})\lambda^\ell_{\mu\mu}$
$B_{K^{(*)}\nu\bar\nu}$	0.0 ± 2.6	$1 + \frac{2}{3}\frac{\pi}{\alpha_{\rm em}V_{tb}V^*_{ts}C^{\rm SM}_\nu}(C_T - C_S)\lambda^q_{sb}(1+\lambda^\ell_{\mu\mu})$
$\delta g^Z_{\tau_L}$	-0.0002 ± 0.0006	$0.033C_T - 0.043C_S$
$\delta g^Z_{\nu_\tau}$	-0.0040 ± 0.0021	$-0.033C_T - 0.043C_S$
$\lvert g^W_\tau/g^W_\ell\rvert$	1.00097 ± 0.00098	$1 - 0.084C_T$
$\mathcal{B}(\tau\to 3\mu)$	$(0.0 \pm 0.6)\times 10^{-8}$	$2.5\times 10^{-4}(C_S - C_T)^2(\lambda^\ell_{\tau\mu})^2$

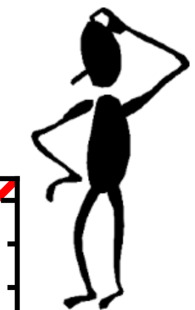
[Buttazzo, AG, Isidori, Marzocca],
JHEP 1711 (2017) 044

Single-mediator models

Z' $(\mathbf{1},\mathbf{1},0)$

Vector LQ triplet
$(\mathbf{3},\mathbf{3},2/3)$





U_1 works well
Combinations are possible (e.g. $S_1 + S_3$)

Vector LQ singlet
$(\mathbf{3},\mathbf{1},2/3)$

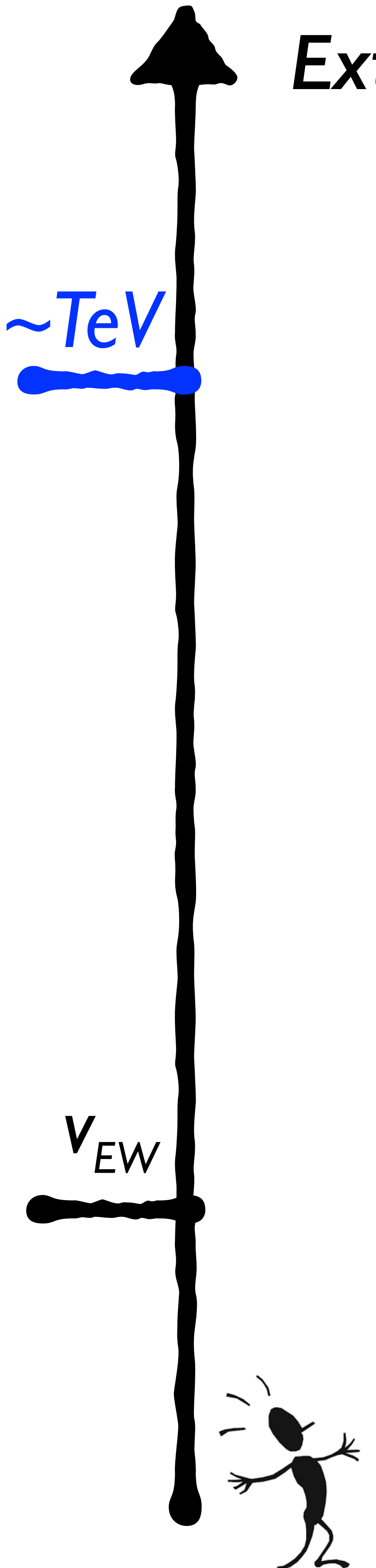
W' $(\mathbf{1},\mathbf{3},0)$

Scalar LQ singlet
$(\bar{\mathbf{3}},\mathbf{1},1/3)$

Scalar LQ triplet
$(\bar{\mathbf{3}},\mathbf{3},1/3)$

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

'4321' model



Extended gauge symmetry

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

SSB: $\langle \Omega_3 \rangle, \langle \Omega_1 \rangle$

$$G_{\rm SM} \equiv SU(3)_c \times SU(2)_L \times U(1)_Y$$

Embedding:

$$SU(3)_4 \times U(1)_4 \subset SU(4)$$

and

$$SU(3)_c = (SU(3)_4 \times SU(3)')_{\rm diag}$$
$$U(1)_Y = (U(1)_4 \times U(1)')_{\rm diag}$$

Scalars:

$$\Omega_1 = (\bar{4}, 1, 1, -1/2)$$
$$\Omega_3 = (\bar{4}, 3, 1, 1/6)$$

$$\langle \Omega_3 \rangle = \begin{pmatrix} \frac{v_3}{\sqrt{2}} & 0 & 0 \\ 0 & \frac{v_3}{\sqrt{2}} & 0 \\ 0 & 0 & \frac{v_3}{\sqrt{2}} \\ 0 & 0 & 0 \end{pmatrix}, \quad \langle \Omega_1 \rangle = \begin{pmatrix} 0 \\ 0 \\ 0 \\ \frac{v_1}{\sqrt{2}} \end{pmatrix}$$

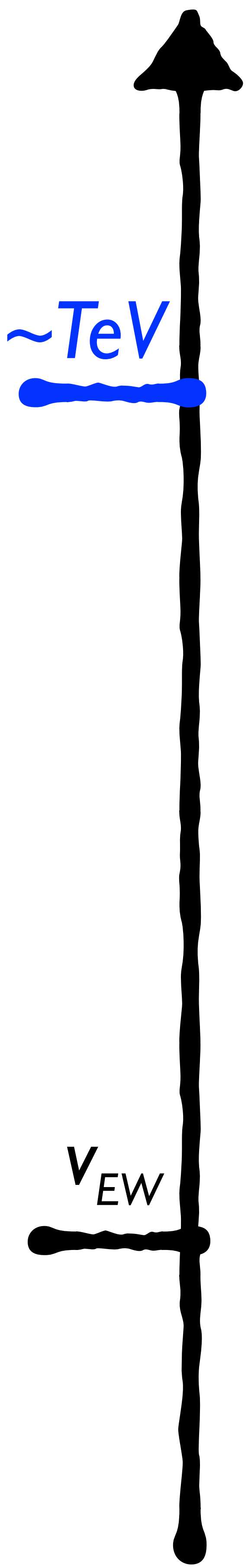
Gauge couplings:

$$g_s = \frac{g_4 g_3}{\sqrt{g_4^2 + g_3^2}} \qquad g_Y = \frac{g_4 g_1}{\sqrt{g_4^2 + \frac{2}{3} g_1^2}}$$

[Georgi, Nakai], 1606.05865
[Diaz, Schmaltz, Zhong], 1706.05033

'4321' model

[Di Luzio, AG, Nardecchia], Phys.Rev. D96 (2017) 115011



Extended gauge symmetry

$$\overset{\alpha\,=\,1,\dots,15}{H^{\alpha}_{\mu}} \qquad \overset{a\,=\,1,\dots,8}{G'^{a}_{\mu}} \qquad \overset{i\,=\,1,2,3}{W^{i}_{\mu}} \qquad B'_{\mu}$$

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

SSB: $\langle \Omega_3 \rangle, \langle \Omega_1 \rangle$

$$\Omega_3 = (\bar{4}, 3, 1, 1/6)$$
$$\Omega_1 = (\bar{4}, 1, 1, -1/2)$$

$$G_{\rm SM} \equiv SU(3)_c \times SU(2)_L \times U(1)_Y$$

Embedding:

$$SU(3)_c = (SU(3)_4 \times SU(3)')_{\rm diag}$$
$$U(1)_Y = (U(1)_4 \times U(1)')_{\rm diag}$$

where

$$SU(3)_4 \times U(1)_4 \subset SU(4)$$

$$g_s = \frac{g_4 g_3}{\sqrt{g_4^2 + g_3^2}} \qquad g_Y = \frac{g_4 g_1}{\sqrt{g_4^2 + \frac{2}{3} g_1^2}}$$

Massive gauge boson spectrum: $G/G_{\rm SM}$

Leptoquark $(3, 1, 2/3)$ $\quad M_U = \frac{1}{2} g_4 \sqrt{v_1^2 + v_3^2}$

$$U^{1,2,3}_{\mu} = \frac{1}{\sqrt{2}} \left(H^{9,11,13}_{\mu} - i H^{10,12,14}_{\mu} \right)$$

Color octet: $(8, 1, 0)$

$$g'^{a}_{\mu} = \frac{g_4 H^a_{\mu} - g_3 G'^a_{\mu}}{\sqrt{g_4^2 + g_3^2}}$$

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

Orthogonal field: **Gluon**

Z': $(1, 1, 0)$

$$Z'_{\mu} = \frac{g_4 H^{15}_{\mu} - \sqrt{\frac{2}{3}} g_1 B'_{\mu}}{\sqrt{g_4^2 + \frac{2}{3} g_1^2}}$$

$$M_{Z'} = \frac{1}{2} \sqrt{\frac{3}{2}} \sqrt{g_4^2 + \frac{2}{3} g_1^2} \sqrt{v_1^2 + \frac{1}{3} v_3^2}$$

Orthogonal field: **Hypercharge**

[Georgi, Nakai], 1606.05865
[Diaz, Schmaltz, Zhong], 1706.05033

'4321' model

[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

'4321' model for B-anomalies

[Di Luzio, AG, Nardecchia], Phys.Rev. D96 (2017) 115011

Yukawa sector

$$\mathcal{L}_Y \supset -\overline{q}'_L\, Y_d\, H d'_R - \overline{q}'_L\, Y_u\, \tilde{H} u'_R - \overline{\ell}'_L\, Y_e\, H e'_R$$
$$- \overline{q}'_L\, \lambda_q\, \Omega_3^T \Psi_R - \overline{\ell}'_L\, \lambda_\ell\, \Omega_1^T \Psi_R - \overline{\Psi}_L\, M\, \Psi_R + \text{h.c.}$$

Flavour symmetry (ignoring Yukawa)

$$U(3)_{q'} \times U(3)_{u'} \times U(3)_{d'} \times U(3)_{\ell'} \times U(3)_{e'} \times U(n_\Psi)_{\Psi_L} \times U(n_\Psi)_{\Psi_R}$$

$n_\Psi \geq 2$
To fit B-anomalies (FPP bound)

Down-quark alignment (I)

$$\mathcal{M}_d = \begin{pmatrix} \frac{v}{\sqrt{2}} Y_d^{\text{diag}} & \frac{v_3}{\sqrt{2}} \lambda_q \\ 0 & M^{\text{diag}} \end{pmatrix}$$

$$\lambda_q = \begin{pmatrix} 0 & 0 \\ \lambda_q^s & 0 \\ 0 & \lambda_q^b \end{pmatrix} \qquad |\lambda_q^s| \ll |\lambda_q^b|$$

In the interaction basis

Down-quark alignment (II)

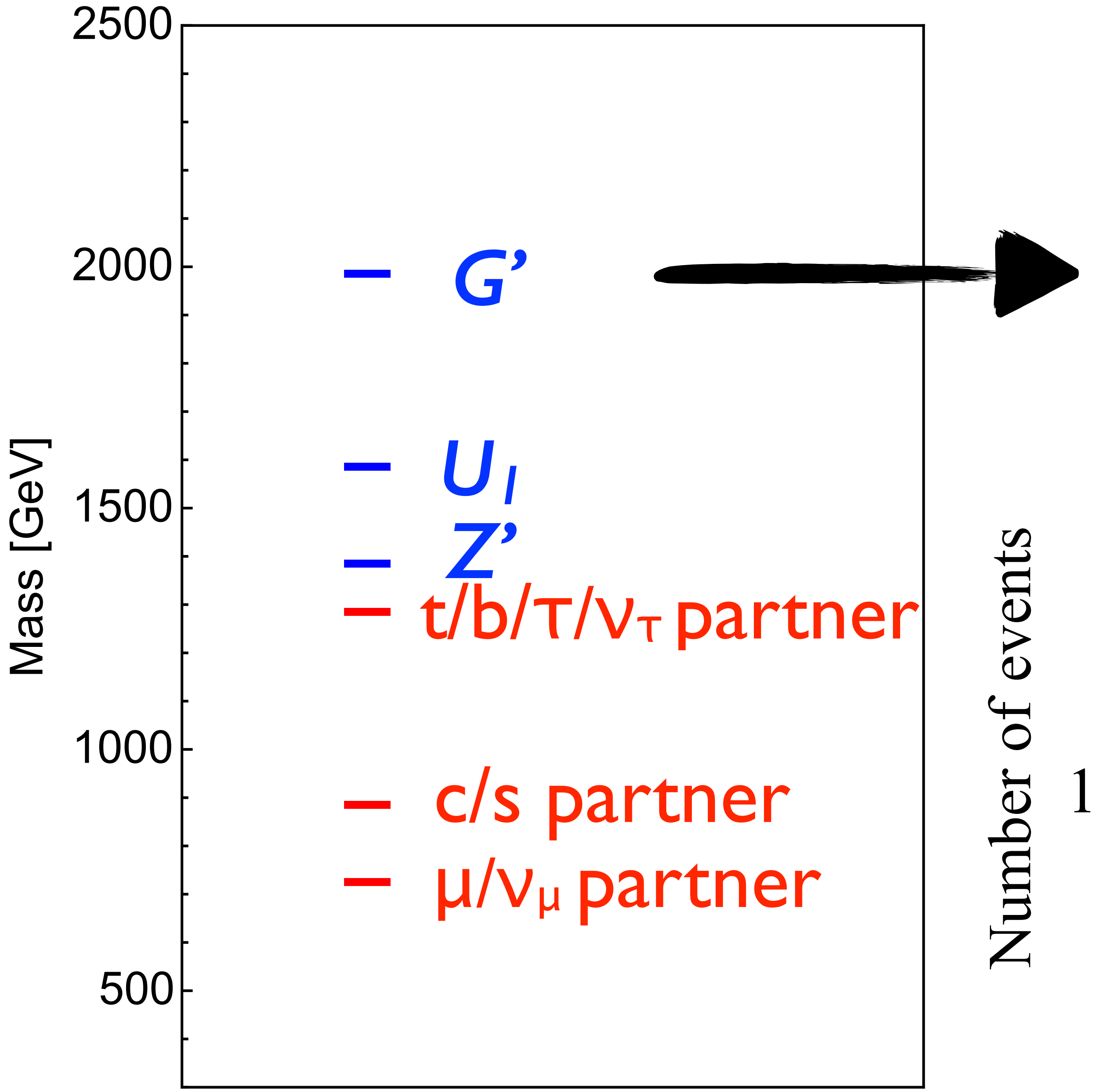
$$U(3)_{d'} \equiv U(3)_{\Psi_L} \equiv U(3)_{\Psi_R}$$

One spurion $Y_d \propto \lambda_q$

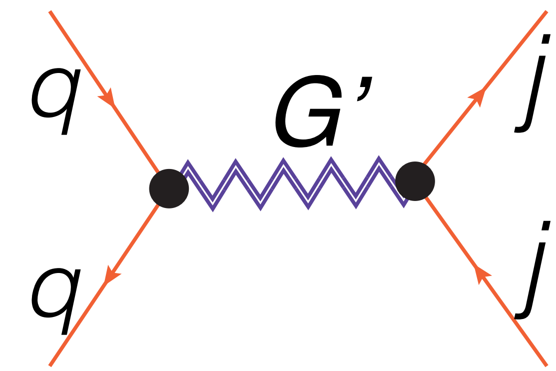
Absence of tree-level FCNC in the down-sector due to Z' and G'

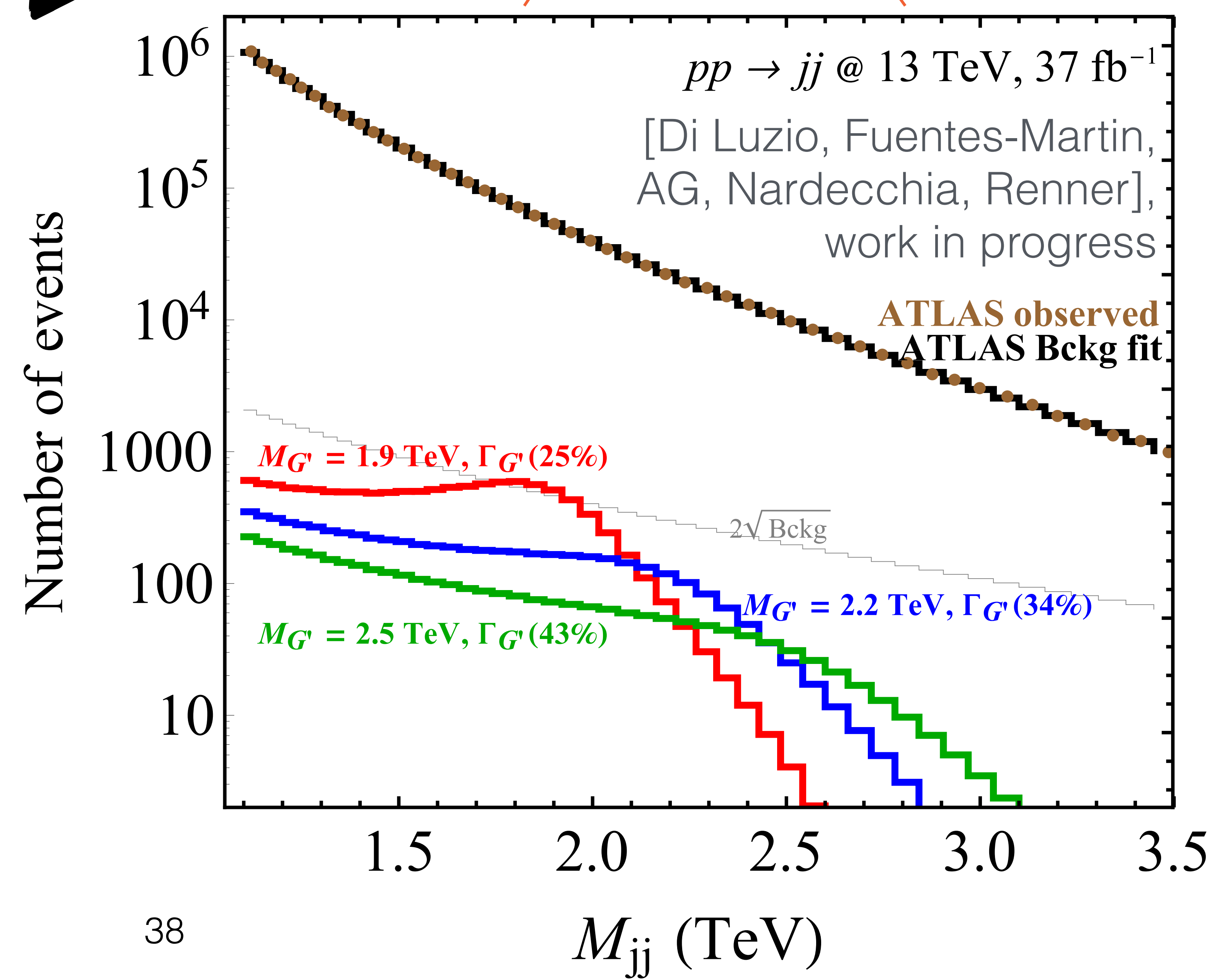
'4321': High p_T phenomenology

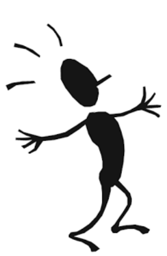
Benchmark: Spectrum



Colour octet vector



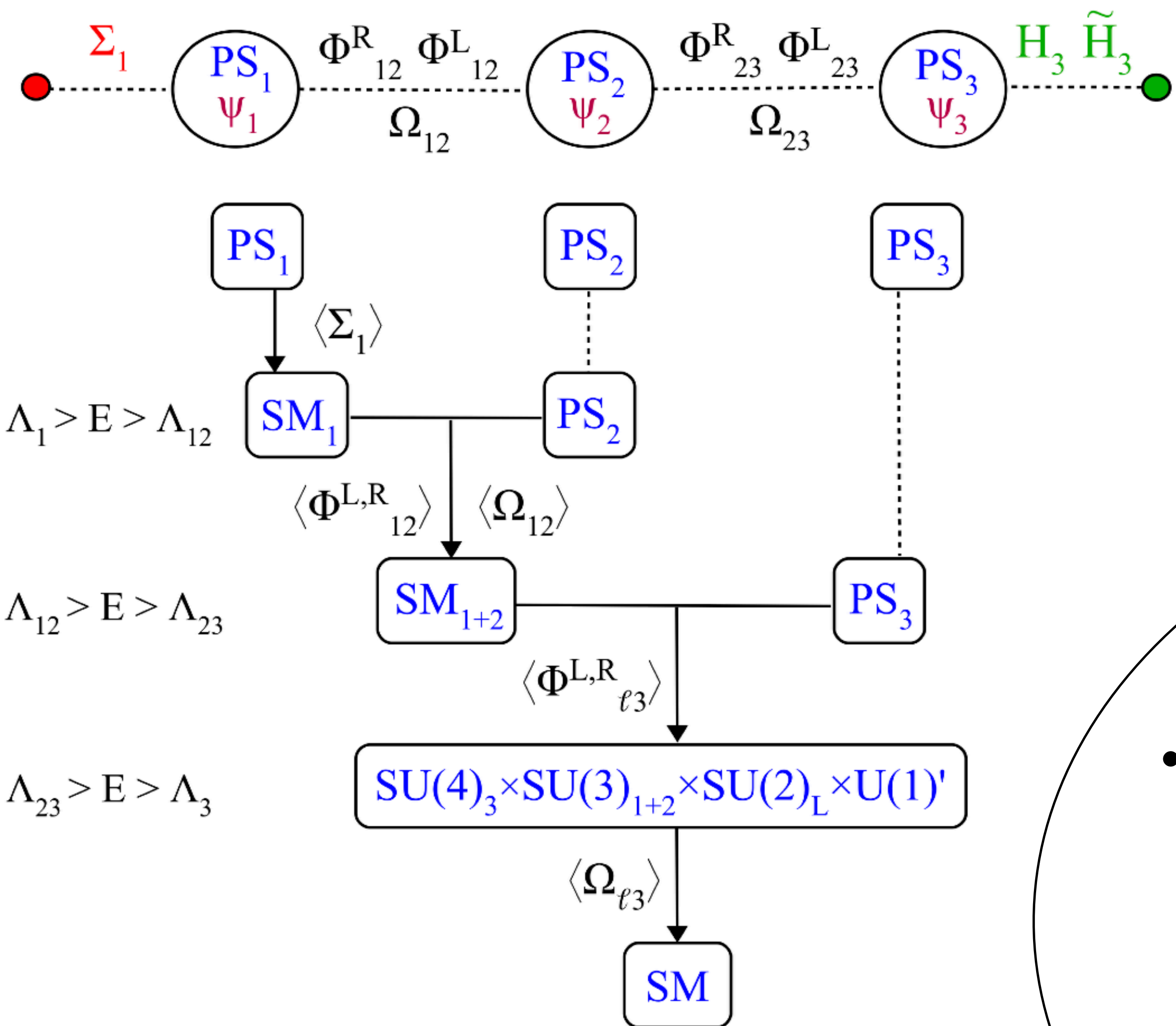




Around corner?

Flavour anomalies & hierarchies in one shot?

[Bordone, Cornella, Fuentes-Martin, Isidori], 1712.01368

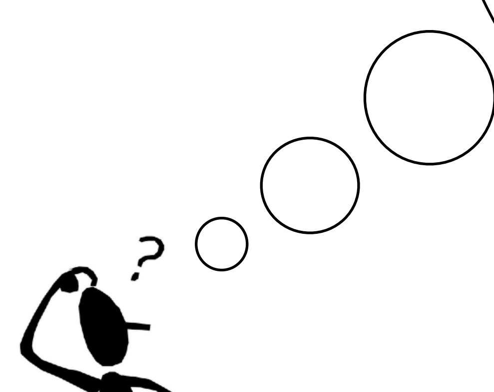


- One PS group for each family
- SM Yukawa from hierarchical VEVs of the link fields
- '4321'-like at low-energies

Lessons

- Family non-universality literally understood
- Resurrection of right-handed currents in R(D$^{(*)}$)

$$\Delta R_D^{\tau\ell} \approx 5/2 \times \Delta R_{D^*}^{\tau\ell}$$



Alternative 4321

[AG, Ben Stefanek], 1802.04274

- Toy model to study low-energy phenomenology of PS^3

Gauge symmetry and breaking as in [Di Luzio, AG, Nardecchia]

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

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

$$G_{\rm SM} \equiv SU(3)_c \times SU(2)_L \times U(1)_Y$$

Slightly different fermion content

1st & 2nd family	**3rd family**
Chiral	Chiral
$(q'_L, \ell'_L, u'_R, d'_R, e'_R)$	(**4**,1,**2**,0) $(\Psi_L)^T = (Q'^3_L \;\; L'^3_L)$
SM-like **321** charges	(**4**,1,1,1/2) $(\Psi^u_R)^T = (u'^3_R \;\; \nu'^3_R)$
	(**4**,1,1,-1/2) $(\Psi^d_R)^T = (d'^3_R \;\; e'^3_R)$

Dynamical fields of PS^3 at the TeV-scale

Vector-like fermion

$\chi_{L,R} \quad (4, 1, 2, 0)$

Gauge singlets

Right-chiral $\quad \mathcal{S}^a_R$

Extra matter

Alternative 4321

[AG, Ben Stefanek], 1802.04274

- Toy model to study low-energy phenomenology of PS^3

CKM structure [without link fields]

SM-like Yukawa terms for light and 3rd family separately

$$\mathcal{L}_\chi \supset -\overline{q}'_L \,\lambda_q\, \Omega_3^T \chi_R - \overline{\ell}'_L \,\lambda_\ell\, \Omega_1^T \chi_R - \overline{\chi}_L \, M\, \chi_R - \lambda_u \overline{\chi}_L \widetilde{H} \Psi_R^u - \lambda_d \overline{\chi}_L H \Psi_R^d$$

$\rightarrow$ $-\frac{c^u}{\Lambda}\overline{q'}_L \Omega_3 \widetilde{H}\, \Psi_R^u$ etc.

1-3 and 2-3 mixing!

Neutrino mass problem EW Higgses: H=(1,1,**2**,1/2) Φ=(**15**,1,**2**,1/2)

$$\mathcal{L}_3 = -y_H^u \overline{\Psi}_L \widetilde{H} \Psi_R^u - y_H^d \overline{\Psi}_L H \Psi_R^d - y_\Phi^u \overline{\Psi}_L \widetilde{\Phi}^\alpha T^\alpha \Psi_R^u - y_\Phi^d \overline{\Psi}_L \Phi^\alpha T^\alpha \Psi_R^d$$

- Top quark and tau neutrino masses of the same order?

$\rightarrow$ Elegant solution

Inverse see-saw

$$\mathcal{L}_\nu = -\frac{1}{2}\mu_{\mathcal{S}}^{ab}\, \overline{\mathcal{S}_a^c}\, \mathcal{S}_b - \frac{1}{2}\kappa_{\mathcal{S}\Psi}^a\, \Omega_1\, \overline{\mathcal{S}_a^c}\, \Psi_R^u - \frac{1}{2} M_{\mathcal{S}\nu}^{ai}\, \overline{\mathcal{S}_a^c}\, \nu_R'^i$$

PMNS non-unitarity <> B-anomalies