4321
(or on how to make sense of the vector leptoquark solution of the B-anomalies)

High-energy implications of flavor anomalies
CERN - 23.10.2018

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[Based on:
LDL, Greljo, Nardecchia - 1708.08450
LDL, Fuentes-Martin, Greljo, Nardecchia, Renner - 1808.00942]

Outline

1. The EFT case for U ~ (3,1,2/3)

2. 4321: A renormalizable UV completion of U ~ (3,1,2/3)

   - model building challenges

   - gauge & flavour structure

   - pheno (low-energy + high-pT)

EFT [combined explanations]

- $SU(2)_L$ triplet operator as a natural starting point for explaining R(D) + R(K)*

$$-\frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\ (\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L)\right.$$

[Bhattacharya et al 1412.7164
Alonso, Grinstein, Camalich 1505.05164,
Greljo, Isidori, Marzocca 1506.01705,
Calibbi, Crivellin, Ota 1506.02661, …]

$$Q^i_L = \begin{pmatrix} (V^\dagger_{\rm CKM} u_L)^i \\ d^i_L \end{pmatrix}$$

$$L^\alpha_L = \begin{pmatrix} \nu^\alpha_L \\ e^\alpha_L \end{pmatrix}$$

*[*see talks by O. Sumensari and D. Shih for alternative approaches]*

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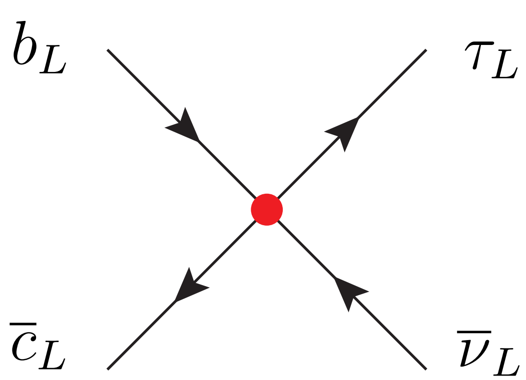

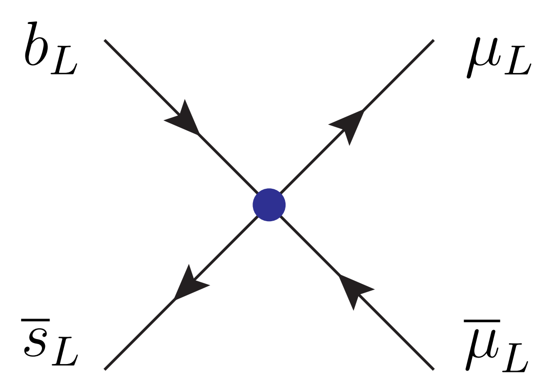

$$\Lambda_{R_D} = 3.4\ \text{TeV} \qquad \ll \qquad \Lambda_{R_K} = 31\ \text{TeV}$$

- Perturbative unitarity bound from 2 → 2 fermion scatterings (worse case scenario)

$$\sqrt{s}_{R_D} < 9.2\ \text{TeV} \qquad\qquad \sqrt{s}_{R_K} < 84\ \text{TeV}$$

→ no-loose theorem for HL/HE-LHC ? [LDL, Nardecchia 1706.01868]

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- Flavour structure:

1. large couplings in taus *[SM tree level]*
2. sizable couplings in muons *[SM one loop]*
3. negligible couplings in electrons *[well tested, not much room]*

$$\lambda^{q,\ell}_{ij}=\delta_{i3}\delta_{j3}+\text{corrections}\qquad U(2)_q\times U(2)_\ell$$ approx flavor symmetry

[Barbieri et al 1105.2296, 1512.01560]

→ link to SM Yukawa pattern ? *[see talk by R. Ziegler]*

EFT [combined explanations]

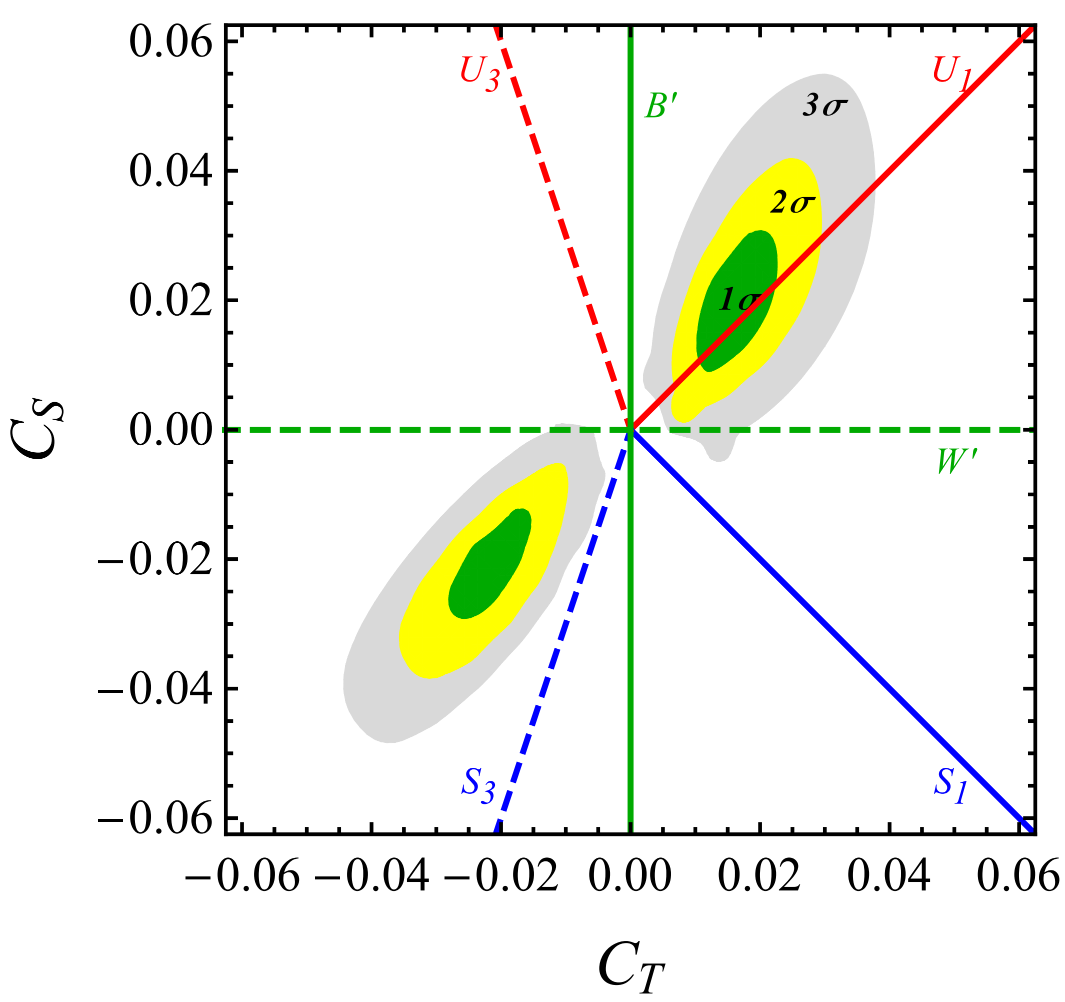
- $SU(2)_L$ triplet operator as a natural starting point for explaining R(D) + R(K)

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

- Finite list of tree-level mediators

[Zürich's guide for combined explanations, 1706.07808]

Simplified Model	Spin	SM irrep	C_S/C_T	$R_{D^{(*)}}$	$R_{K^{(*)}}$
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	✓	✓



→ *U_1 emerges as an exceptional single mediator consistent with various flavour/EW constraints*

UV completion: $U_1 \sim (3,1,2/3)$

- Massive vectors point to UV dynamics at the TeV scale

composite resonance of a new strong dynamics

gauge boson of an extended gauge sector

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- Massive vectors point to UV dynamics at the TeV scale

composite resonance of a new strong dynamics

$$\frac{G}{H} = \frac{SU(4) \times SO(5) \times U(1)_X}{SU(4) \times SO(4) \times U(1)_X}$$

[Barbieri, Isidori, Pattori, Senia 1502.01560
Barbieri, Murphy, Senia 1611.0493
Buttazzo, Greljo, Isidori, Marzocca 1706.07808
Barbieri, Tesi 1712.06844]

- pNGB Higgs + U_1 as composite state of G

🙂 conceptual link with the naturalness issue of EW scale

🙁 light LQ lowers the whole resonances' spectrum (direct searches + EWPTs)

🙁 intrinsically non-calculable (e.g. Bs-mixing quadratically divergent)

[see also talks by B. Gripaios and D. Marzocca]

UV completion: $U_1 \sim (3,1,2/3)$

- Pati-Salam (well-motivated, 44 years old)

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

$$G_{PS}/G_{SM} = U_1 + Z' + W_R$$

gauge boson of an extended gauge sector

🙂 hinted by SM chiral structure and neutrino masses + one step from SO(10)

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🙁 $M_{U_1} \gtrsim 100$ TeV from $K_L^0, B^0, B_s \to \ell\,\ell'$ *[L x R couplings both present by unitarity]*

🙁 Z' direct searches *[$M_{U_1} \sim M_{Z'} \sim$ TeV + O(g_s) Z' couplings to valence quarks]*

🙁 neutrino masses also suggest $M_{U_1} \gg$ TeV $[y_{\rm top} \sim y_{\nu_3-{\rm Dirac}}]$

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🙁 neutrino masses also suggest $M_{U_1} \gg \text{TeV}$ $[y_{\text{top}} \sim y_{\nu_3-\text{Dirac}}]$

→ LQ of minimal PS <u>cannot</u> explain B-anomalies

[Non-minimal PS options lack the beauty and simplicity of the minimal construction: Calibbi, Crivellin, Li 1709.00692, Bordone, Cornella, Fuentes-Martin, Isidori 1712.01368 + 1805.09328, Blanke, Crivellin 1801.07256, Heeck, Teresi 1808.07492 …]

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🙁 neutrino masses also suggest $M_{U_1} \gg$ TeV *[$y_{\text{top}} \sim y_{\nu_3-\text{Dirac}}$]*

→ <u>step 0</u>: *does a gauge UV completion of U_1 addressing these three phenomenological issues (in order to be a viable solution of B-anomalies) exist ?*

The '4321' model

[LDL, Greljo, Nardecchia 1708.08450,
See also Diaz, Schmaltz, Zhong 1706.05033]

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

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$$\underbrace{\overbrace{SU(4) \times SU(3)' \times SU(2)_L \times U(1)'}^{U(1)_Y}}_{SU(3)_C} \xrightarrow{\langle \Omega_{1,3} \rangle} G_{\rm SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$$

$g_4 \gg g_3 \gg g_1$

SM embedding:

$$SU(3)_C = (SU(3)_4 \times SU(3)')_{diag} \qquad g_s = \frac{g_4 g_3}{\sqrt{g_4^2 + g_3^2}} \simeq g_3$$

$$U(1)_Y = (U(1)_4 \times U(1)')_{diag} \qquad g_Y = \frac{g_4 g_1}{\sqrt{g_4^2 + \frac{2}{3} g_1^2}} \simeq g_1$$

The '4321' model

$$\underbrace{SU(4)}_{SU(3)_C} \times \overbrace{SU(3)' \times SU(2)_L \times U(1)'}^{U(1)_Y} \xrightarrow[\langle \Omega_{1,3} \rangle]{} G_{\rm SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$$

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SM embedding:

Massive gauge bosons: $G/G_{\rm SM} = U + Z' + g'$

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

$$M_{g'} \simeq \sqrt{2}\, M_U \qquad M_{Z'} \simeq \frac{1}{\sqrt{2}} M_U$$

→ cannot decouple g' and Z' from LQ mass scale !

[a theorem (?) that in whatever UV construction U always comes with a Z' - while the coloron is a specific consequence of the 4321 model]

The '4321' model

$U(1)_Y$

$SU(4) \times SU(3)' \times SU(2)_L \times U(1)'$ $\xrightarrow{\langle \Omega_{1,3} \rangle}$ $G_{\rm SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$

$SU(3)_C$

[LDL, Greljo, Nardecchia 1708.08450, See also Diaz, Schmaltz, Zhong 1706.05033]

Matter content:

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$
$q_L^{\prime i}$	1	3	2	$1/6$
$u_R^{\prime i}$	1	3	1	$2/3$
$d_R^{\prime i}$	1	3	1	$-1/3$
$\ell_L^{\prime i}$	1	1	2	$-1/2$
$e_R^{\prime i}$	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 fields

Vector-like fermions (Q'+L')

} mix after SSB

SSB

The '4321' model

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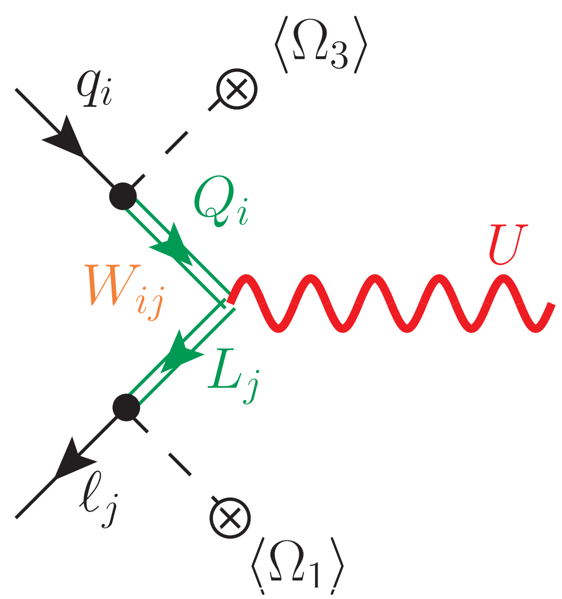
LQ dominantly couples to 3rd generation LH fields:

[matches in first approx. EFT analysis for B-anomalies + relaxes flavour bounds from chirality enhanced meson decays]



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[LDL, Greljo, Nardecchia 1708.08450,
See also Diaz, Schmaltz, Zhong 1706.05033]

$$\begin{aligned}
\mathcal{L}_L = & \frac{g_4}{\sqrt{2}} \overline{Q}'_L \gamma^\mu L'_L \, U_\mu + \text{h.c.} \\
& + g_s \left(\frac{g_4}{g_3} \overline{Q}'_L \gamma^\mu T^a Q'_L - \frac{g_3}{g_4} \, \overline{q}'_L \gamma^\mu T^a q'_L \right) g'^a_\mu \\
& + \frac{1}{6} \sqrt{\frac{3}{2}} g_Y \left(\frac{g_4}{g_1} \overline{Q}'_L \gamma^\mu Q'_L - \frac{2}{3} \frac{g_1}{g_4} \, \overline{q}'_L \gamma^\mu q'_L \right) Z'_\mu \\
& - \frac{1}{2} \sqrt{\frac{3}{2}} g_Y \left(\frac{g_4}{g_1} \overline{L}'_L \gamma^\mu L'_L - \frac{2}{3} \frac{g_1}{g_4} \, \overline{\ell}'_L \gamma^\mu \ell'_L \right) Z'_\mu
\end{aligned}$$

→ LQ dominantly couples to 3rd generation LH fields:

[matches in first approx. EFT analysis for B-anomalies + relaxes flavour bounds from chirality enhanced meson decays]

→ Suppressed Z' and g' couplings to light generations

[requires phenomenological limit $g_4 \gg g_3 \simeq g_s \gg g_1 \simeq g_Y$]

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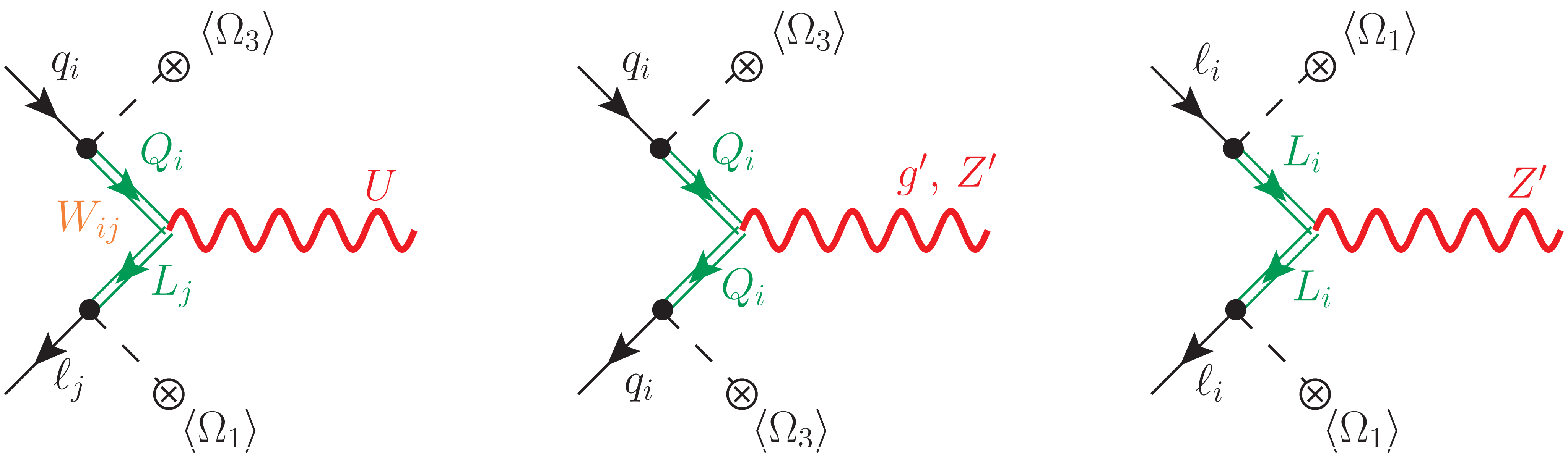
- LQ dominantly couples to 3rd generation LH fields:
  [matches in first approx. EFT analysis for B-anomalies + relaxes flavour bounds from chirality enhanced meson decays]
- Suppressed Z' and g' couplings to light generations
  [requires phenomenological limit $g_4 \gg g_3 \simeq g_s \gg g_1 \simeq g_Y$]
- B and L accidental global symmetries
  [neutrino massless as in the SM]

Key phenomenological features

1. Large quark-lepton transitions in 3-2 sector

2. Tree-level FCNC involving down quarks and leptons are absent

3. Tree-level FCNC involving up quarks are U(2) protected



[see backup slides for the discussion of the flavour structure]

[LDL, Fuentes-Martin, Greljo, Nardecchia, Renner 1808.00942]

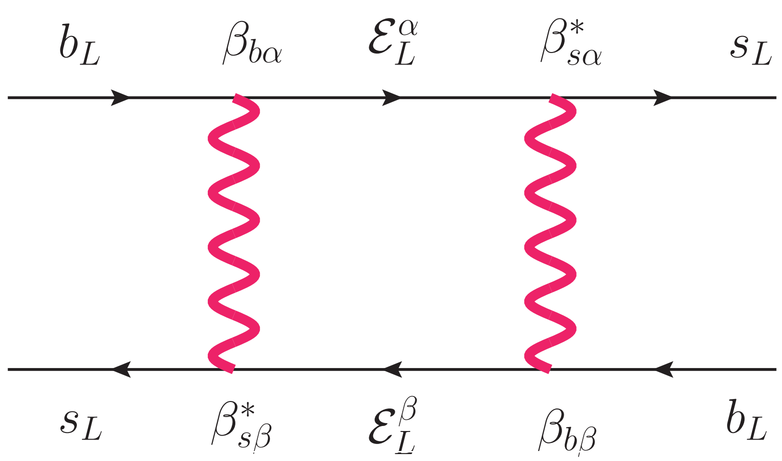
Key phenomenological features

1. Large quark-lepton transitions in 3-2 sector

2. Tree-level FCNC involving down quarks and leptons are absent

3. Tree-level FCNC involving up quarks are U(2) protected

4. FCNC @ 1-loop under control



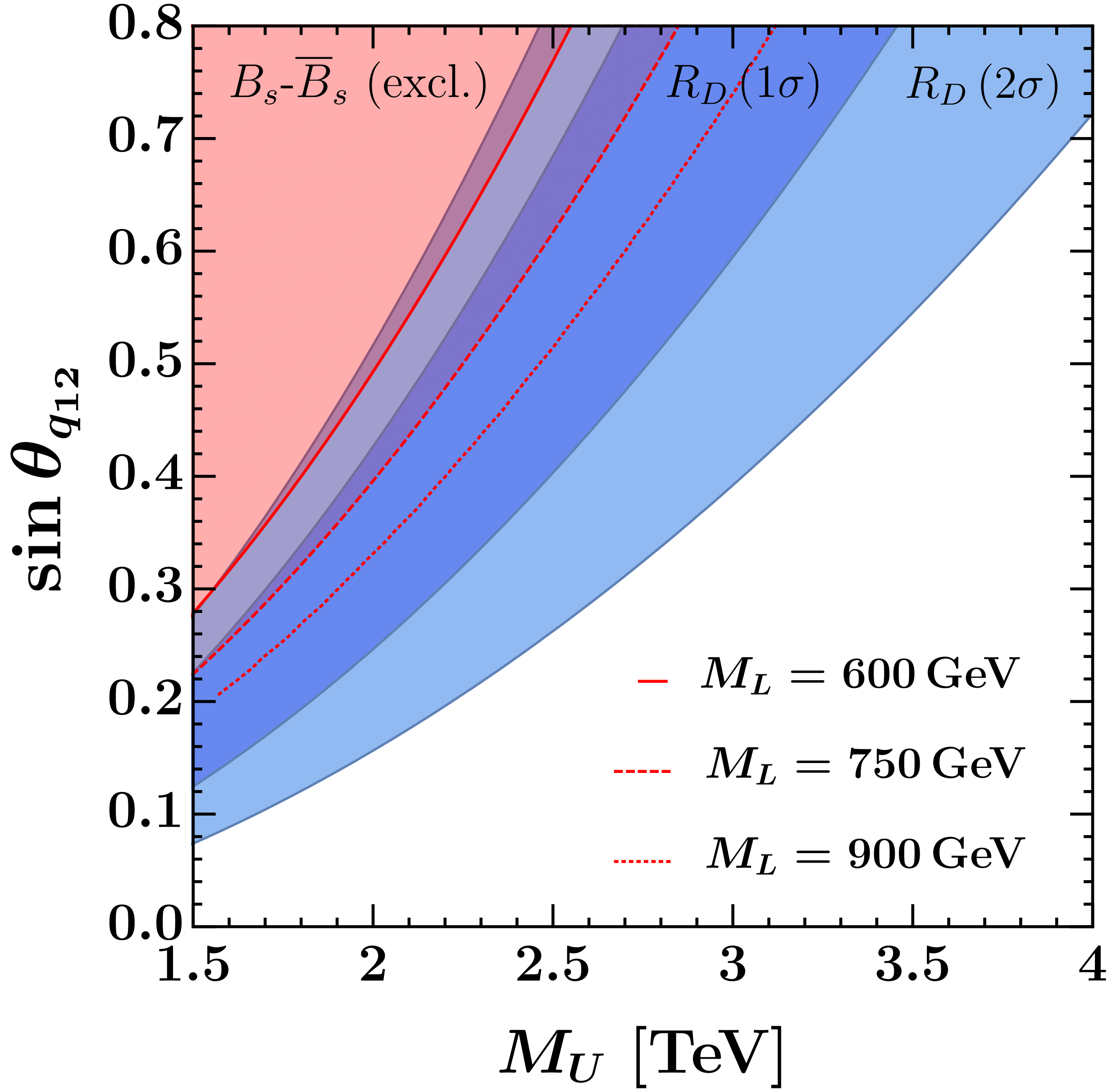
$$\mathcal{H}_{\rm eff}^{\rm NP} = -\frac{g_4^4}{128\pi^2 m_U^2} \left(\bar{b}_L \gamma^\mu s_L\right) \left(\bar{b}_L \gamma_\mu s_L\right) \sum_{\alpha,\,\beta} \lambda_\alpha \lambda_\beta F(x_\alpha, x_\beta)$$

$$\lambda_\alpha = \beta_{b\alpha}\beta^*_{s\alpha} \qquad x_\alpha = m_\alpha^2 / M_U^2 \qquad \alpha = (1, \ldots, 6)$$

$\sum_\alpha \lambda_\alpha = 0$ *[ensures cancellation of quadratic divergences]*

$F(x_\alpha, x_\beta) \simeq \cancel{1} + x_\alpha + x_\beta + \ldots$ → dynamical suppression from light lepton partners

Low-energy / high-pT interplay

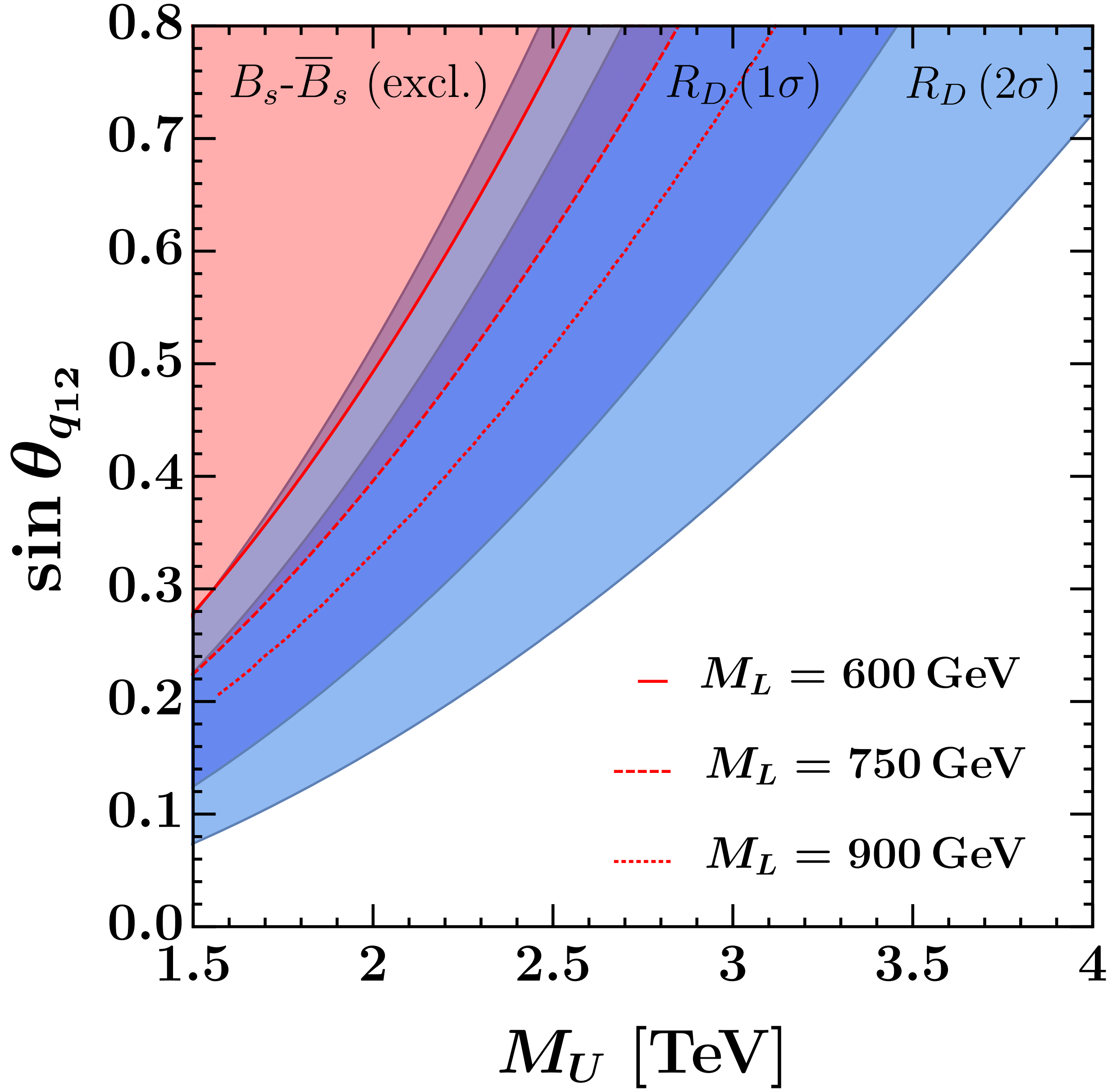


$$C_{bs}^{LL} \sim \Delta R_{D^{(*)}}^2 \, M_L^2$$

↓

vector-like leptons are predicted to be the lightest new states !

Low-energy / high-pT interplay



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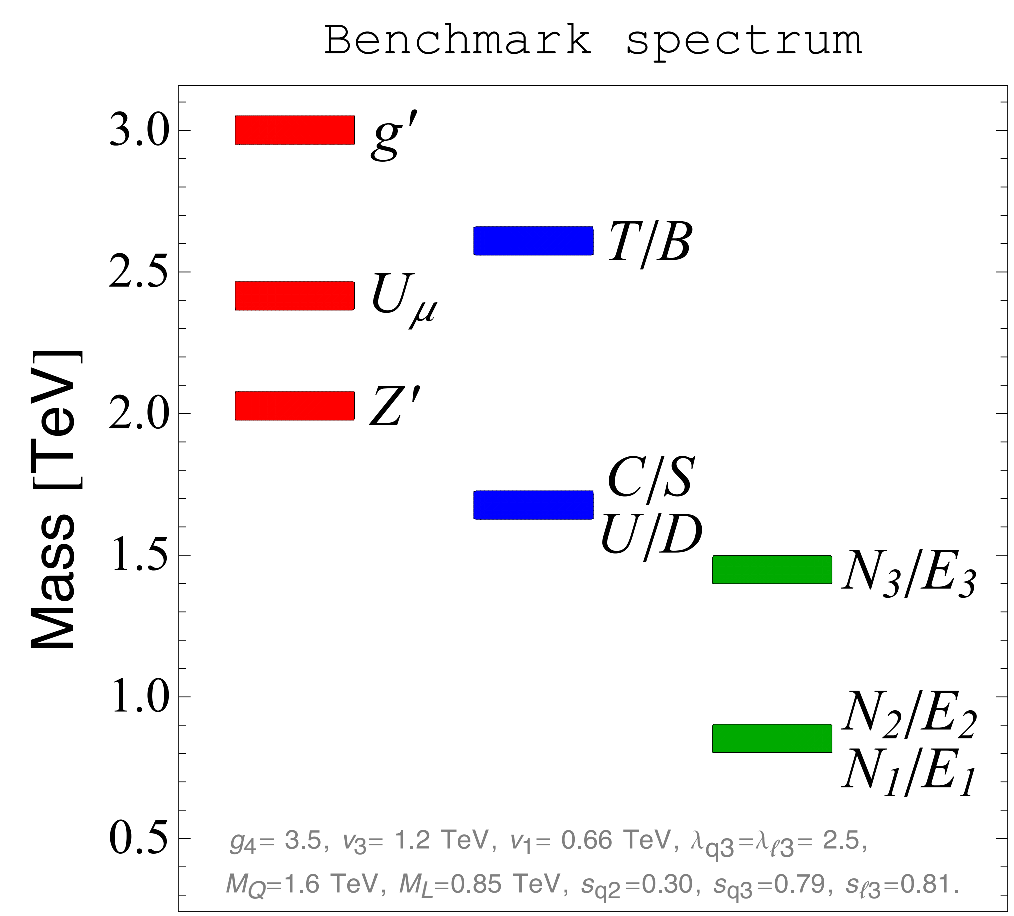
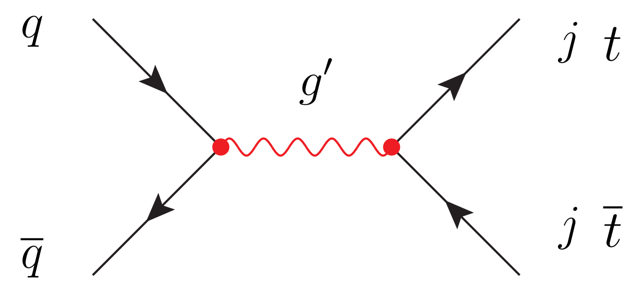
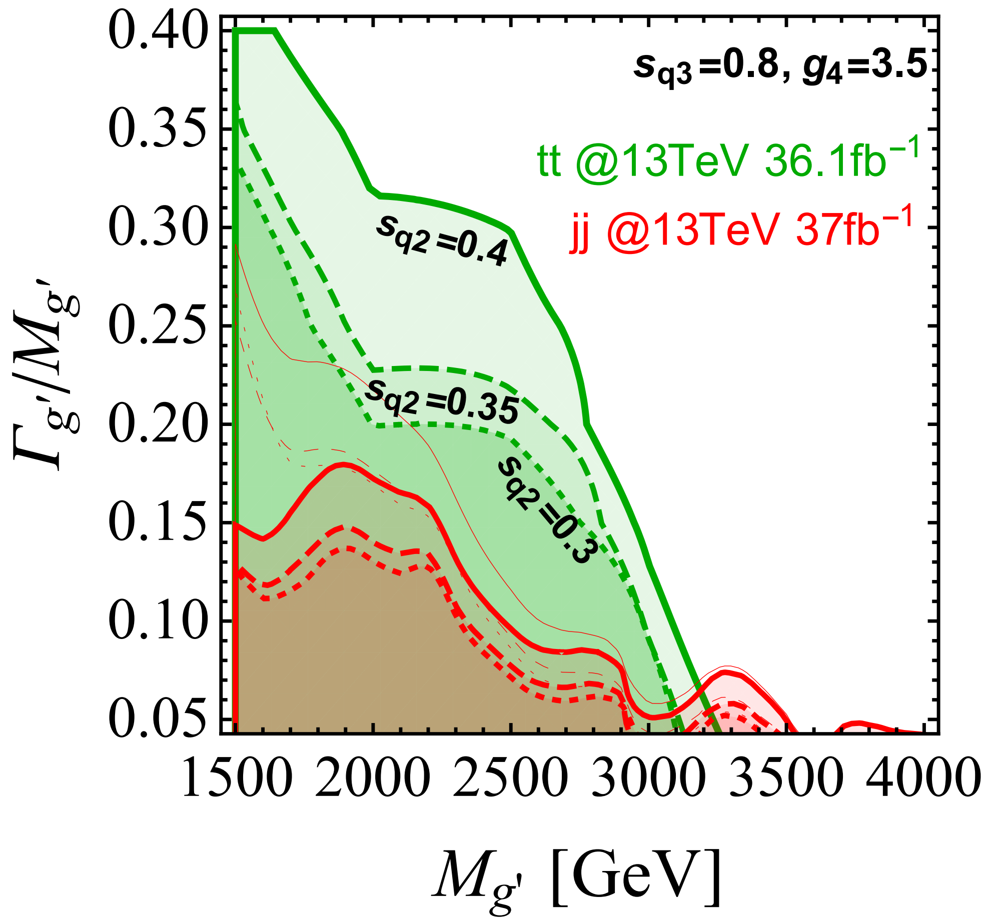
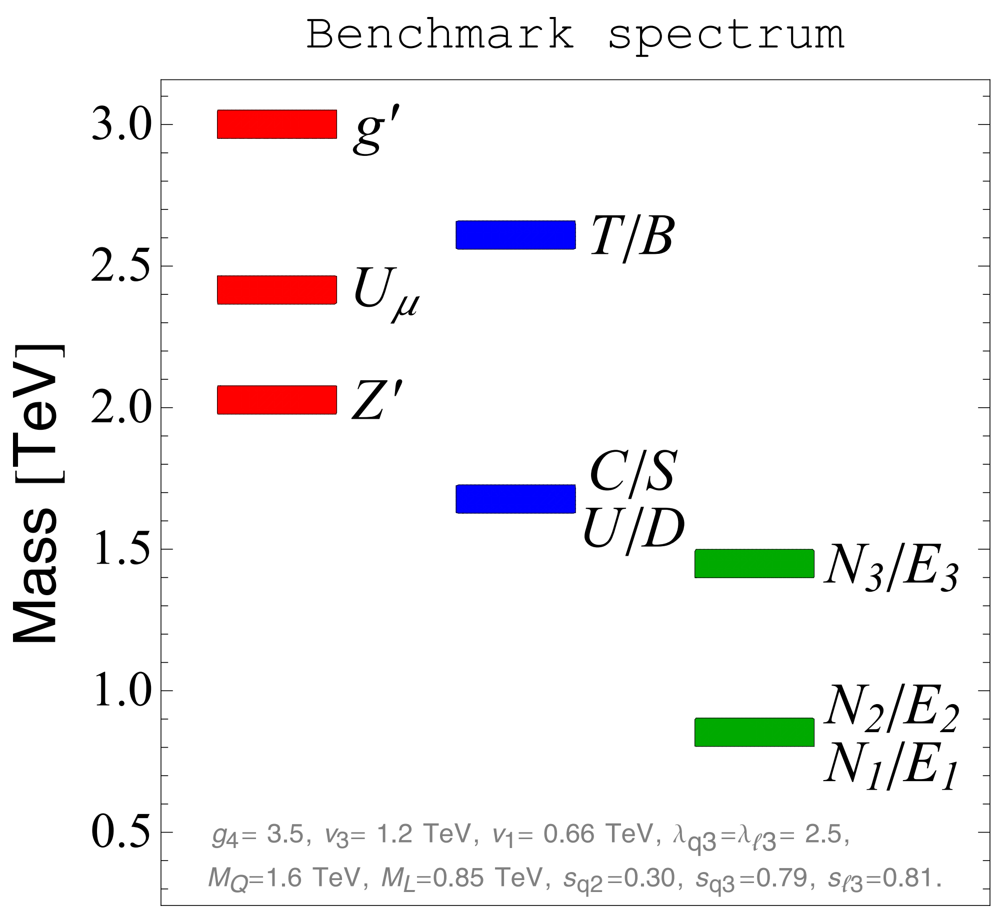


High-pT highlights

- Coloron searches push the whole spectrum up



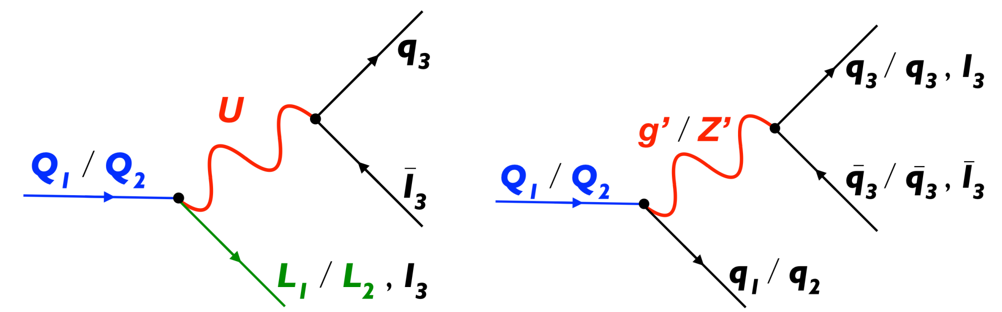


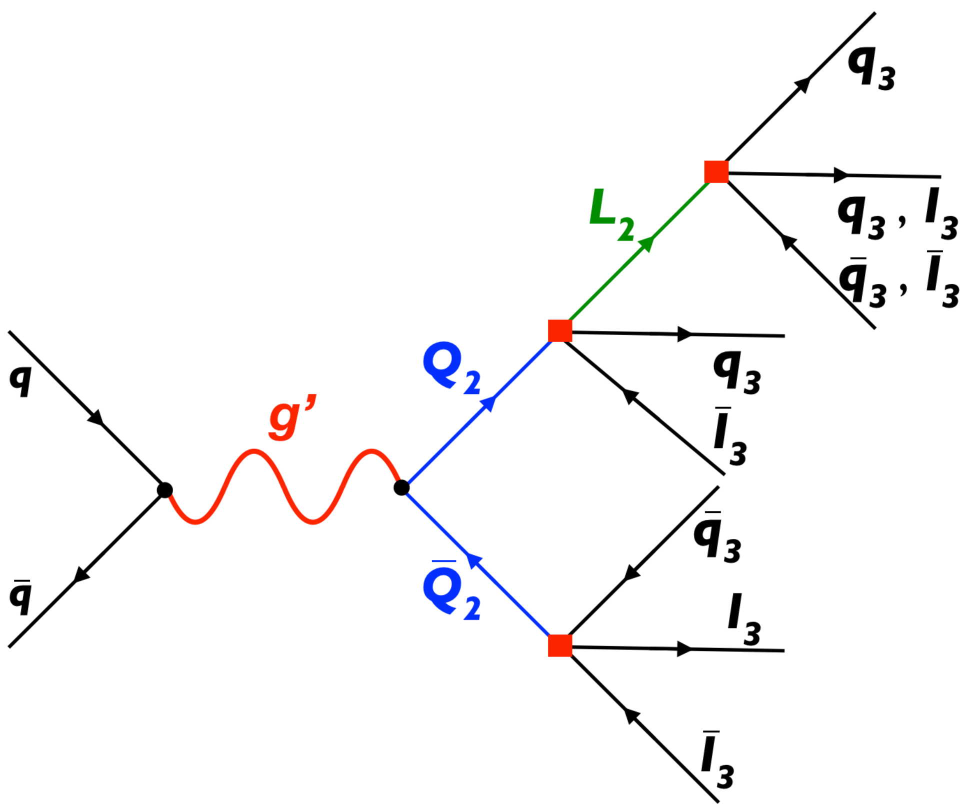


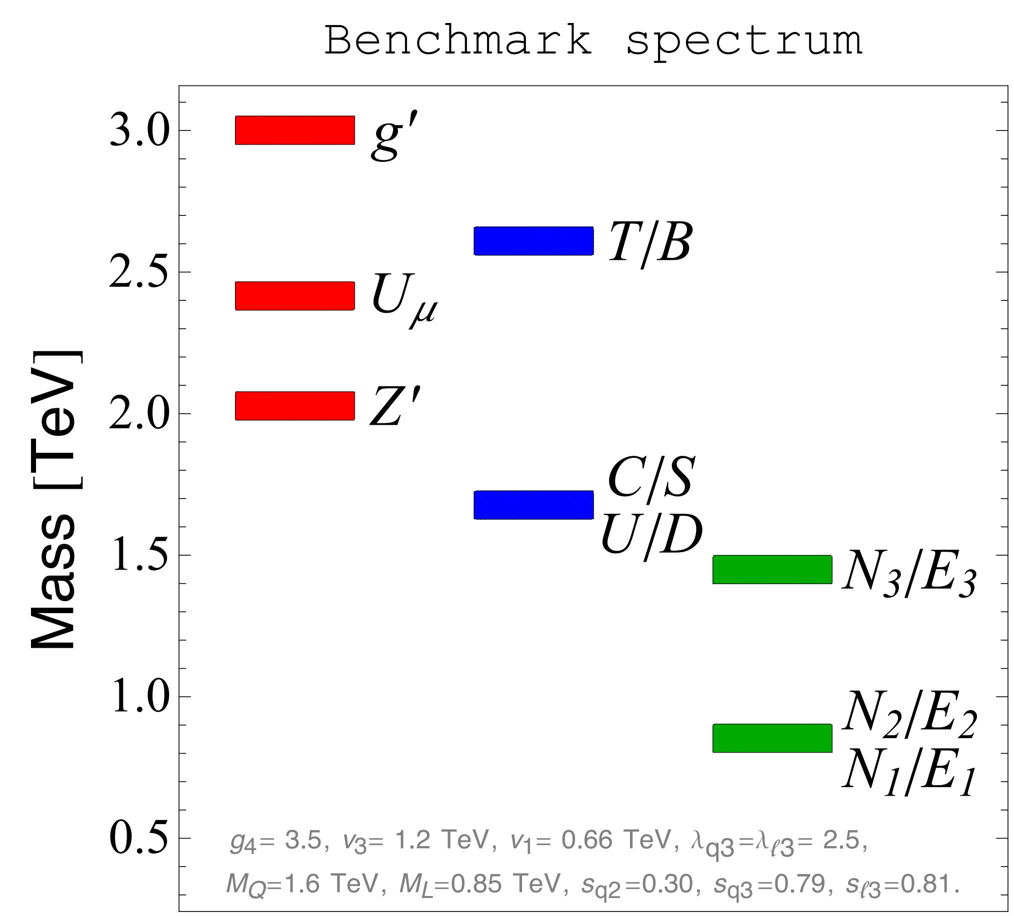
High-pT highlights

- Coloron searches push the whole spectrum up
- Exotic multi-lepton & multi-jet signatures

[Dominant decays of new fermions are 1 → 3]





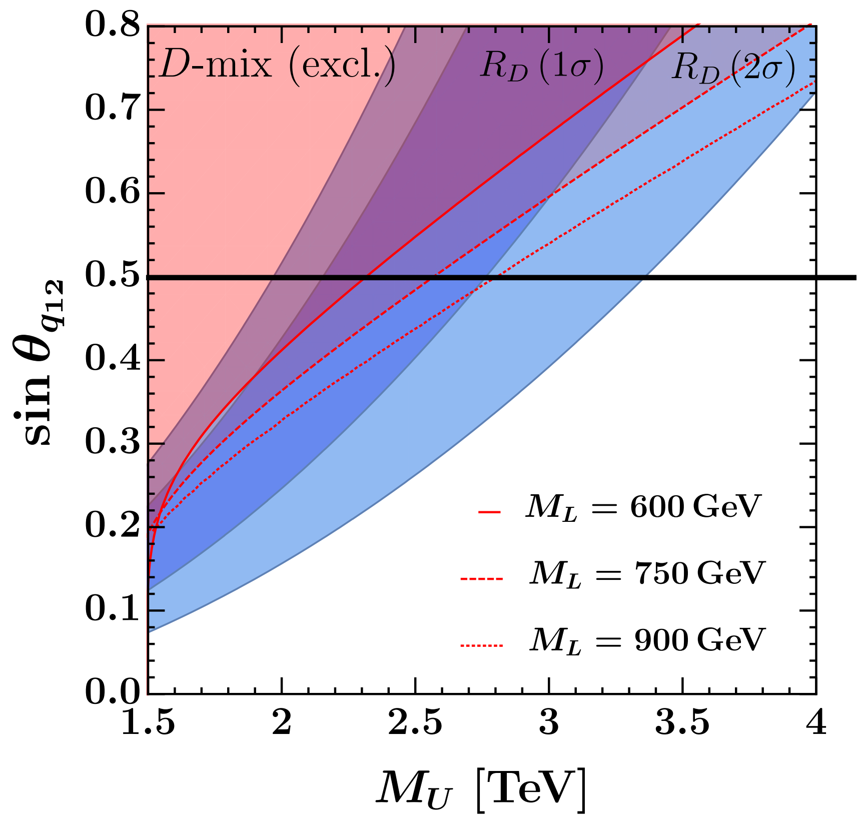


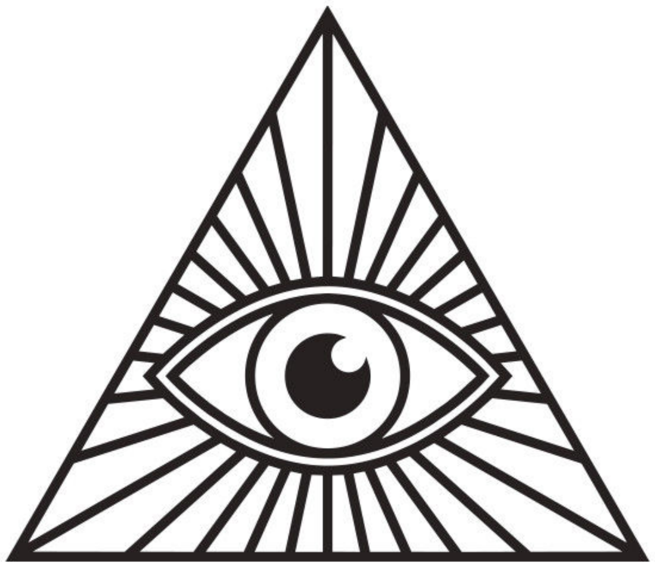
B-anomalies paradox

- NP expected to be seen yesterday ?

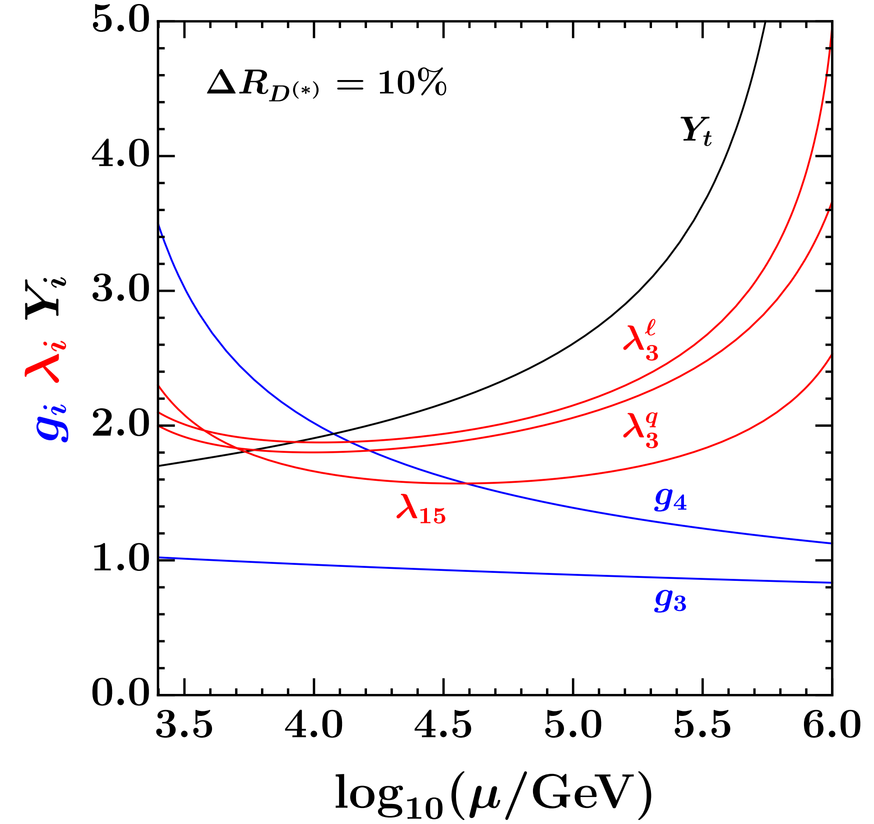
$$\Delta R_{D^{(*)}} \approx 0.2 \left(\frac{2\text{ TeV}}{M_U}\right)^2 \left(\frac{g_4}{3.5}\right)^2 \sin(2\theta_{LQ}) \left(\frac{s_{\ell_3}}{0.8}\right)^2 \left(\frac{s_{q3}}{0.8}\right) \left(\frac{s_{q2}}{0.3}\right)$$

ΔF = 2 + direct searches





Perturbativity



Conclusions

1. Early <u>speculations</u> point to TeV-scale vector leptoquark (R(D)+R(K) explanation)

   - who ordered that ?

   - connection to EW naturalness and SM flavour ?

2. In the meanwhile, lesson from 4321 [UV complete / calculable model]

   → <u>unexpected</u> experimental signatures (coloron, vector-like leptons, …)
   + playground to compute correlations

3. Situation is tough, but not impossible *[e.g. if deviation in $R(D^{(*)})$ gets reduced]*

Backup slides

Flavour structure

- Pick-up a basis exploiting U(3)[7] symmetry of kinetic term

$$\mathcal{L}_{\rm SM-like} = -\bar{q}'_L \hat{Y}_d \, d'_R \, H - \bar{q}'_L V^\dagger \hat{Y}_u \, u'_R \, \tilde{H} - \bar{\ell}'_L \hat{Y}_e \, e'_R \, H$$

$$\mathcal{L}_{\rm mix} = -\bar{q}'_L \lambda_q \Psi_R \, \Omega_3 - \bar{\ell}'_L \lambda_\ell \Psi_R \, \Omega_1 - \bar{\Psi}_L \hat{M} \Psi_R$$

**hat denotes a diagonal matrix*

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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	$-1/2$

$$\Psi = \begin{pmatrix} Q' \\ L' \end{pmatrix}$$

Flavour structure

- $\mathcal{L}_{\text{mix}} \to 0$

$$\mathcal{L}_{\text{SM-like}} = -\overline{q}'_L \hat{Y}_d \, d'_R \, H - \overline{q}'_L V^\dagger \hat{Y}_u \, u'_R \, \tilde{H} - \overline{\ell}'_L \hat{Y}_e \, e'_R \, H$$

- A well-known story:

- $Y_u \to 0: \; U(1)_d \times U(1)_s \times U(1)_b$

- $Y_d \to 0: \; U(1)_u \times U(1)_c \times U(1)_t$

Flavour structure

- $\mathcal{L}_{\rm mix} \to 0$

$$\mathcal{L}_{\rm SM-like} = -\overline{q}'_L \hat{Y}_d \, d'_R \, H - \overline{q}'_L V^\dagger \hat{Y}_u \, u'_R \, \tilde{H} - \overline{\ell}'_L \hat{Y}_e \, e'_R \, H$$

- A well-known story:

- $Y_u \to 0: \;\; U(1)_d \times U(1)_s \times U(1)_b$
- $Y_d \to 0: \;\; U(1)_u \times U(1)_c \times U(1)_t$

$$\xrightarrow{SU(2)_L} \; U(1)_{d+u} \times U(1)_{s+c} \times U(1)_{b+t} \xrightarrow{V} U(1)_B$$

- Collective breaking in the SM ensures:

1. No FCNC in either up or down sector [forbidden by the two $U(1)^3$ in isolation]
2. FCCC from up/down misalignement [due to CKM $\neq$ 1]

Flavour structure

- Let us assume:

$$\mathcal{L}_{\rm mix} = -\overline{q}'_L \lambda_q \Psi_R \Omega_3 - \overline{\ell}'_L \lambda_\ell \Psi_R \Omega_1 - \overline{\Psi}_L \hat{M} \Psi_R$$

$$\mathcal{L}_{\rm SM-like} = -\overline{q}'_L \hat{Y}_d d'_R H - \overline{q}'_L V^\dagger \hat{Y}_u u'_R \tilde{H} - \overline{\ell}'_L \hat{Y}_e e'_R H$$

$$\lambda_q = {\rm diag}\,(\lambda^q_{12}, \lambda^q_{12}, \lambda^q_3)$$

$$\lambda_\ell = {\rm diag}\left(\lambda^\ell_1, \lambda^\ell_2, \lambda^\ell_3\right) W \qquad W = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{LQ} & \sin\theta_{LQ} \\ 0 & -\sin\theta_{LQ} & \cos\theta_{LQ} \end{pmatrix} \qquad \hat{M} \propto \mathbb{1}$$

Flavour structure

- Let us assume:

$$\mathcal{L}_{\rm mix} = -\overline{q}'_L \lambda_q \Psi_R \Omega_3 - \overline{\ell}'_L \lambda_\ell \Psi_R \Omega_1 - \overline{\Psi}_L \hat{M} \Psi_R$$

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- $\lambda_\ell \to 0$

$\mathcal{G}_Q = U(2)_{q'+\Psi} \times U(1)_{q'_3+\Psi_3}$ *[promoting approximate $U(2)_{q'}$ of SM to NP]*

1. No tree-level FCNC in the down sector (λ_q and Y_d diagonal in the same basis)

2. CKM-induced tree-level FCNC in the up sector (D-mixing) protected by $U(2)_{q'}$

$$C^D_1 \propto (V_{cb} V^*_{ub})^2 \sim 10^{-8}$$

Flavour structure

- Let us assume:

$$\mathcal{L}_{\rm mix} = -\overline{q}'_L \lambda_q \Psi_R \Omega_3 - \overline{\ell}'_L \lambda_\ell \Psi_R \Omega_1 - \overline{\Psi}_L \hat{M} \Psi_R$$

$$\mathcal{L}_{\rm SM-like} = -\overline{q}'_L \hat{Y}_d d'_R H - \overline{q}'_L V^\dagger \hat{Y}_u u'_R \tilde{H} - \overline{\ell}'_L \hat{Y}_e e'_R H$$

$$\lambda_q = {\rm diag}\,(\lambda^q_{12}, \lambda^q_{12}, \lambda^q_3)$$

$$\lambda_\ell = {\rm diag}\left(\lambda^\ell_1, \lambda^\ell_2, \lambda^\ell_3\right) W \qquad W = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{LQ} & \sin\theta_{LQ} \\ 0 & -\sin\theta_{LQ} & \cos\theta_{LQ} \end{pmatrix} \qquad \hat{M} \propto \mathbb{1}$$

- $\lambda_q \to 0$

$$\mathcal{G}_L = U(1)_{\ell'_1 + \tilde{\Psi}_1} \times U(1)_{\ell'_2 + \tilde{\Psi}_2} \times U(1)_{\ell'_3 + \tilde{\Psi}_3} \qquad \left[\, \tilde{\Psi} = W \Psi \,\right]$$

1. No tree-level FCNC in the lepton sector (λ_ℓ and Y_e diagonal in the same basis)

2. W is unphysical

Flavour structure

- Let us assume:

$$\mathcal{L}_{\text{mix}} = -\overline{q}'_L \lambda_q \Psi_R \Omega_3 - \overline{\ell}'_L \lambda_\ell \Psi_R \Omega_1 - \overline{\Psi}_L \hat{M} \Psi_R$$

$$\mathcal{L}_{\text{SM-like}} = -\overline{q}'_L \hat{Y}_d d'_R H - \overline{q}'_L V^\dagger \hat{Y}_u u'_R \tilde{H} - \overline{\ell}'_L \hat{Y}_e e'_R H$$

$$\lambda_q = \text{diag}\,(\lambda^q_{12}, \lambda^q_{12}, \lambda^q_3)$$

$$\lambda_\ell = \text{diag}\left(\lambda^\ell_1, \lambda^\ell_2, \lambda^\ell_3\right) W \qquad W = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{LQ} & \sin\theta_{LQ} \\ 0 & -\sin\theta_{LQ} & \cos\theta_{LQ} \end{pmatrix} \qquad \hat{M} \propto \mathbb{1}$$

- Collective breaking (Q and L locked by SU(4) gauge symmetry)

$$\mathcal{G}_Q \cap \mathcal{G}_L \xrightarrow{SU(4)+W} U(1)_{q'_1+\ell'_1+\Psi_1} \times U(1)_{q'+\ell'+\Psi}$$

1. no FV involving down and electrons

2. only LQ feels W matrix

$$\Psi_L = (Q'_L, L'_L)^T = (Q_L, W L_L)^T \quad \longrightarrow \quad i\overline{\Psi}_L \gamma^\mu D_\mu \Psi_L \supset \frac{g_4}{\sqrt{2}} U_\mu \overline{Q}_L \gamma^\mu W L_L$$

A suggestive analogy*

321	4321
θ_C	θ_{LQ}
V	W
W^μ	U^μ
$q_L = \begin{pmatrix} u_L \\ V d_L \end{pmatrix}$	$\Psi_L = \begin{pmatrix} Q_L \\ W L_L \end{pmatrix}$
$Y_u,\ Y_d$	$\lambda_q,\ \lambda_\ell$
$SU(2)_L$	$SU(4)$
$U(1)_u \times U(1)_c \times U(1)_t$	$U(2)_{q'+\Psi} \times U(1)_{q'_3+\Psi_3}$
$U(1)_d \times U(1)_s \times U(1)_b$	$U(1)_{\ell'_1+\tilde{\Psi}_1} \times U(1)_{\ell'_2+\tilde{\Psi}_2} \times U(1)_{\ell'_3+\tilde{\Psi}_3}$
$U(1)_B$	$U(1)_{q'_1+\ell'_1+\Psi_1} \times U(1)_{q'+\ell'+\Psi}$
$u \to d$ tree level	$Q \to L$ tree level
$u_i \to u_j$ loop level	$Q_i \to Q_j$ loop level
$d_i \to d_j$ loop level	$L_i \to L_j$ loop level

* symmetries in 321 accidental, in 4321 imposed (still, helpful for understanding pheno)

Fermion mass basis

$$\mathcal{M}_u = \begin{pmatrix} V^\dagger \hat{Y}_u \frac{v}{\sqrt{2}} & \hat{\lambda}_q \frac{v_3}{\sqrt{2}} \\ 0 & \hat{M}_Q \end{pmatrix}, \qquad \mathcal{M}_d = \begin{pmatrix} \hat{Y}_d \frac{v}{\sqrt{2}} & \hat{\lambda}_q \frac{v_3}{\sqrt{2}} \\ 0 & \hat{M}_Q \end{pmatrix},$$

$$\mathcal{M}_N = \begin{pmatrix} 0 & \hat{\lambda}_\ell \frac{v_1}{\sqrt{2}} \\ 0 & \hat{M}_L \end{pmatrix}, \qquad \mathcal{M}_e = \begin{pmatrix} \hat{Y}_e \frac{v}{\sqrt{2}} & \hat{\lambda}_\ell W^\dagger \frac{v_1}{\sqrt{2}} \\ 0 & \hat{M}_L \end{pmatrix},$$

$$M_{L_i} = \sqrt{\frac{|\lambda_i^\ell|^2 v_1^2}{2} + \hat{M}_L^2}, \qquad M_{Q_i} = \sqrt{\frac{|\lambda_i^q|^2 v_3^2}{2} + \hat{M}_Q^2},$$

$$m_{f_i} \approx |\hat{Y}_f^i| \cos\theta_{f_i} \frac{v}{\sqrt{2}} \qquad (f = u, d, e)\,.$$

$$\sin\theta_{q_i} = \frac{\lambda_i^q v_3}{\sqrt{|\lambda_i^q|^2 v_3^2 + 2\,\hat{M}_Q^2}},$$

$$\sin\theta_{\ell_i} = \frac{\lambda_i^\ell v_1}{\sqrt{|\lambda_i^\ell|^2 v_1^2 + 2\,\hat{M}_L^2}},$$

LQ interactions

1. Large quark-lepton transitions in 3-2 sector

$$\mathcal{L}_U \supset \frac{g_4}{\sqrt{2}} \beta_{ij}\, \overline{q}^i_L \gamma^\mu \ell^j_L U_\mu$$

$$\beta = \textbf{diag}(s_{q_{12}}, s_{q_{12}}, s_{q_3})\, W\, \textbf{diag}(0, s_{\ell_2}, s_{\ell_3}) = \begin{pmatrix} 0 & 0 & 0 \\ 0 & c_{\theta_{LQ}} s_{q_{12}} s_{\ell_2} & s_{\theta_{LQ}} s_{q_{12}} s_{\ell_3} \\ 0 & -s_{\theta_{LQ}} s_{q_3} s_{\ell_2} & c_{\theta_{LQ}} s_{q_3} s_{\ell_3} \end{pmatrix}$$

$$\Delta R_{D^{(*)}} = \frac{g_4^2 v^2}{2\, M_U^2}\, \beta_{b\tau} \left(\beta_{b\tau} + \beta_{s\tau} \frac{V_{tb}^*}{V_{ts}^*} \right)$$

$\beta_{s\tau} > V_{ts} \sim 0.04$ → allows to raise the LQ mass scale

we need: $\theta_{LQ} \sim \pi/4$ $\theta_{\ell_3} \sim \pi/2$ $\theta_{q_3} \sim \pi/2$ $\theta_{q_{12}} \sim \mathcal{O}(1)$

Z' / g' interactions

$$\mathcal{L}_{g'} \supset g_s \frac{g_4}{g_3} g'^a_\mu \left[\kappa_q^{ij}\, \overline{q}^i \gamma^\mu T^a q^j + \kappa_u^{ij}\, \overline{u}^i_R \gamma^\mu T^a u^j_R + \kappa_d^{ij}\, \overline{d}^i_R \gamma^\mu T^a d^j_R\right]$$

$$\mathcal{L}_{Z'} \supset \frac{g_Y}{2\sqrt{6}} \frac{g_4}{g_1} Z'_\mu \left[\xi_q^{ij}\, \overline{q}^i \gamma^\mu q^j + \xi_u^{ij}\, \overline{u}^i_R \gamma^\mu u^j_R + \xi_d^{ij}\, \overline{d}^i_R \gamma^\mu d^j_R - 3\,\xi_\ell^{ij}\, \overline{\ell}^i \gamma^\mu \ell^j - 3\,\xi_e^{ij}\, \overline{e}^i_R \gamma^\mu e^j_R\right]$$

$$\kappa_q \approx \begin{pmatrix} s^2_{q_1} & 0 & 0 \\ 0 & s^2_{q_2} & 0 \\ 0 & 0 & s^2_{q_3} \end{pmatrix} - \frac{g_3^2}{g_4^2} \mathbb{1}\,, \qquad \kappa_u \approx \kappa_d \approx -\frac{g_3^2}{g_4^2} \mathbb{1}\,,$$

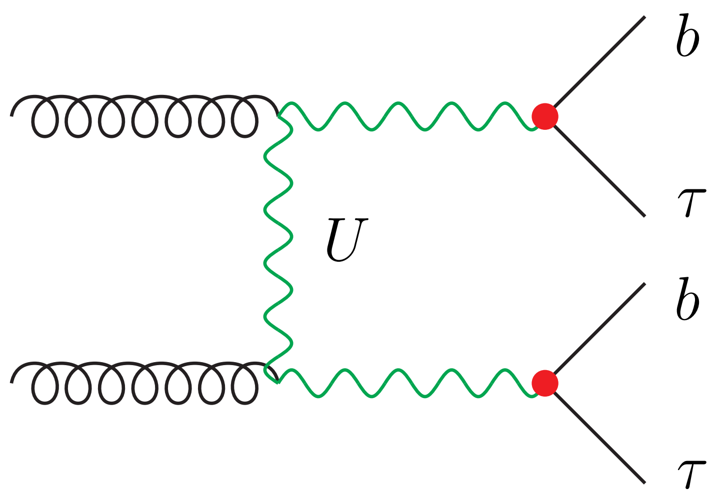
$$\xi_q \approx \begin{pmatrix} s^2_{q_1} & 0 & 0 \\ 0 & s^2_{q_2} & 0 \\ 0 & 0 & s^2_{q_3} \end{pmatrix} - \frac{2\,g_1^2}{3\,g_4^2} \mathbb{1}\,, \qquad \xi_u \approx \xi_d \approx -\frac{2\,g_1^2}{3\,g_4^2} \mathbb{1}\,,$$

$$\xi_\ell \approx \begin{pmatrix} s^2_{\ell_1} & 0 & 0 \\ 0 & s^2_{\ell_2} & 0 \\ 0 & 0 & s^2_{\ell_3} \end{pmatrix} - \frac{2\,g_1^2}{3\,g_4^2} \mathbb{1}\,, \qquad \xi_e \approx -\frac{2\,g_1^2}{3\,g_4^2} \mathbb{1}\,.$$

High-p_T searches

- LQ pair production via QCD

  - 3rd generation final states (fixed by anomaly and $SU(2)_L$ invariance)



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

[CMS search for spin-0, 1703.03995
recast for spin-1 1706.01868 (see also 1706.05033) + Moriond EW update]

$m_U \gtrsim 1.5$ TeV → LQ mass sets the overall scale: $M_{g'} \simeq \sqrt{2}\, M_U \quad M_{Z'} \simeq \frac{1}{\sqrt{2}} M_U$

High-p_T searches

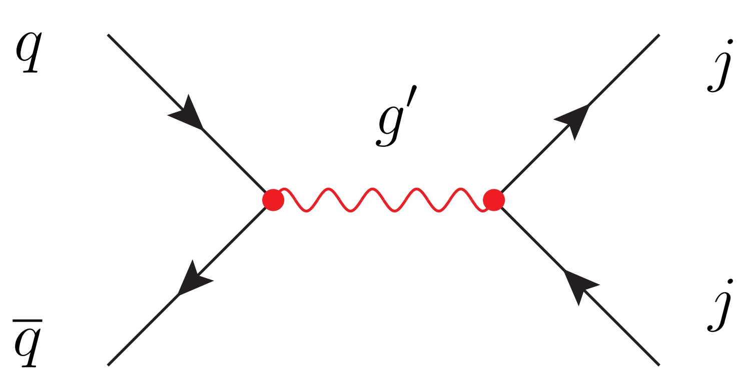
- LQ pair production via QCD

- Z' Drell-Yan production naturally suppressed

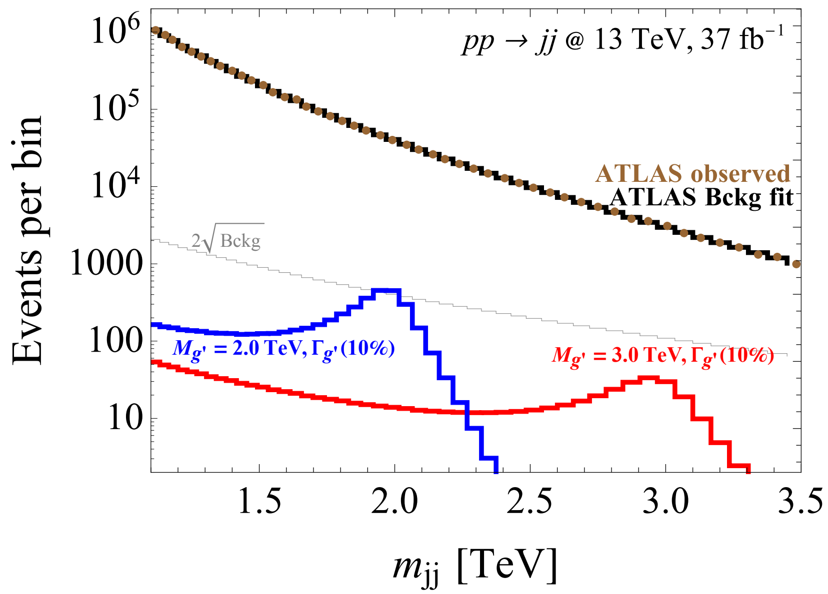
$$\sin\theta_{Z'} = \sqrt{\frac{3}{2}}\frac{g_Y}{g_4} \simeq 0.09$$ → requires $g_4 \gtrsim 3$

- g' resonant di-jet searches [ATLAS, 1703.09127]

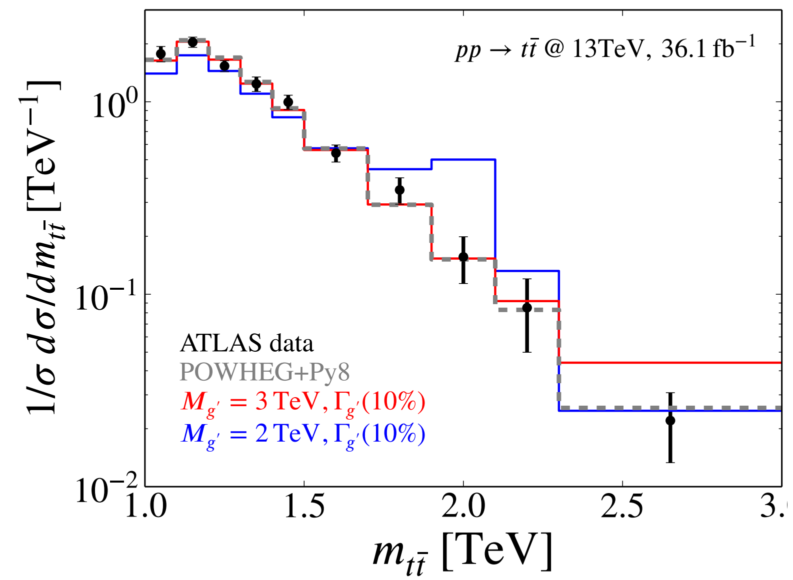
$$\sin\theta_{g'} = \frac{g_s}{g_4} \simeq 0.3$$ → 2 TeV coloron naively excluded



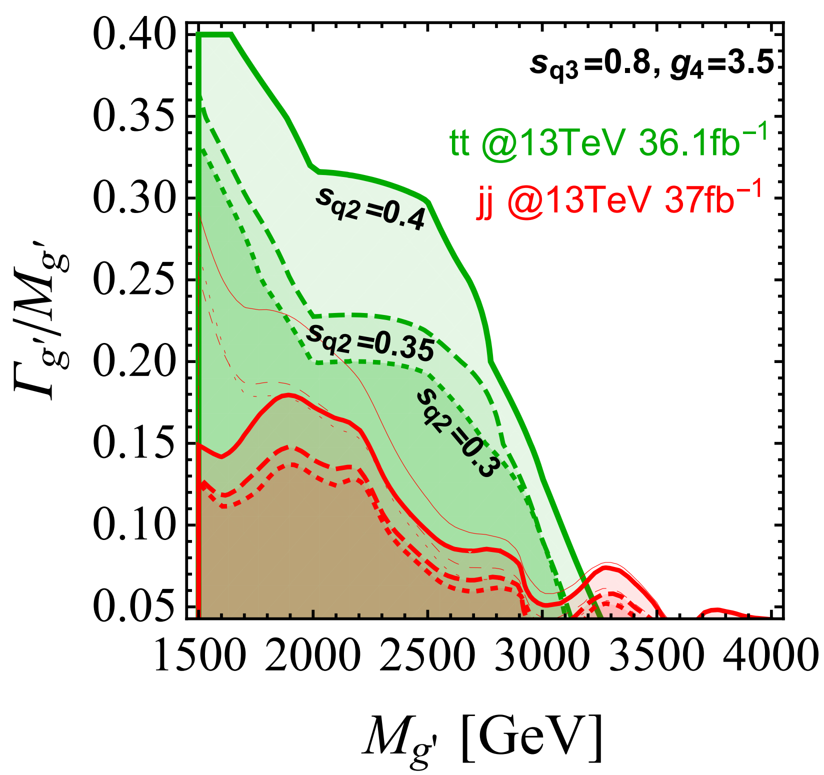
Coloron



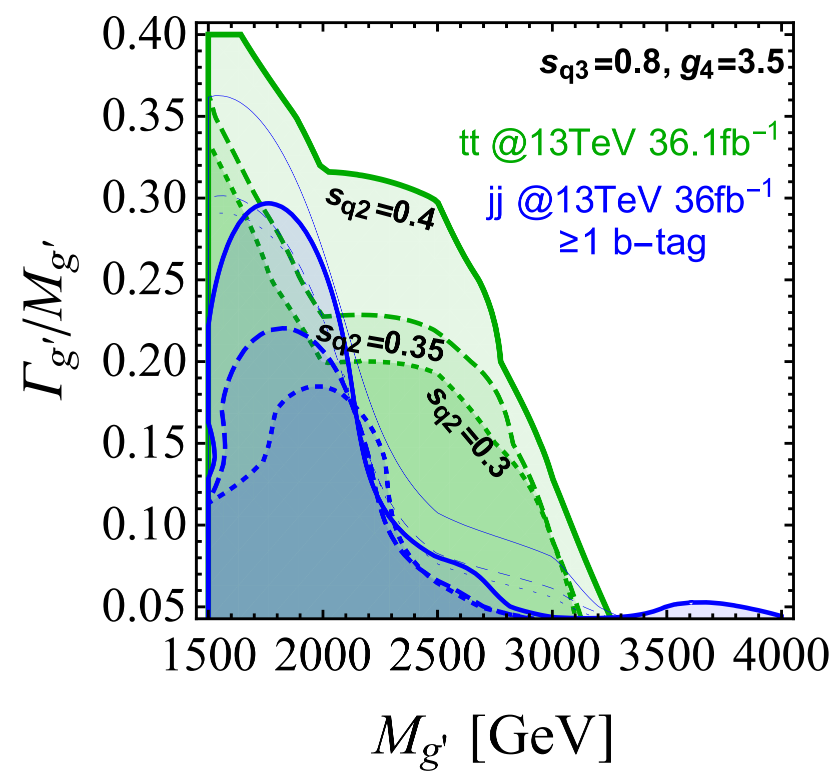
$pp \to jj$ @ 13 TeV, 37 fb^{-1}
ATLAS observed
ATLAS Bckg fit
$2\sqrt{\text{Bckg}}$
$M_{g'}$ = 2.0 TeV, $\Gamma_{g'}$(10%)
$M_{g'}$ = 3.0 TeV, $\Gamma_{g'}$(10%)
Events per bin
m_{jj} [TeV]



$pp \to t\bar{t}$ @ 13TeV, 36.1 fb^{-1}
ATLAS data
POWHEG+Py8
$M_{g'}$ = 3 TeV, $\Gamma_{g'}$(10%)
$M_{g'}$ = 2 TeV, $\Gamma_{g'}$(10%)
$1/\sigma\, d\sigma/dm_{t\bar{t}}$ [TeV^{-1}]
$m_{t\bar{t}}$ [TeV]



s_{q3}=0.8, g_4=3.5
tt @13TeV 36.1fb^{-1}
jj @13TeV 37fb^{-1}
s_{q2}=0.4
s_{q2}=0.35
s_{q2}=0.3
$\Gamma_{g'}/M_{g'}$
$M_{g'}$ [GeV]



s_{q3}=0.8, g_4=3.5
tt @13TeV 36.1fb^{-1}
jj @13TeV 36fb^{-1}
≥1 b−tag
s_{q2}=0.4
s_{q2}=0.35
s_{q2}=0.3
$\Gamma_{g'}/M_{g'}$
$M_{g'}$ [GeV]