Third Family Quark-Lepton Unification at the TeV Scale

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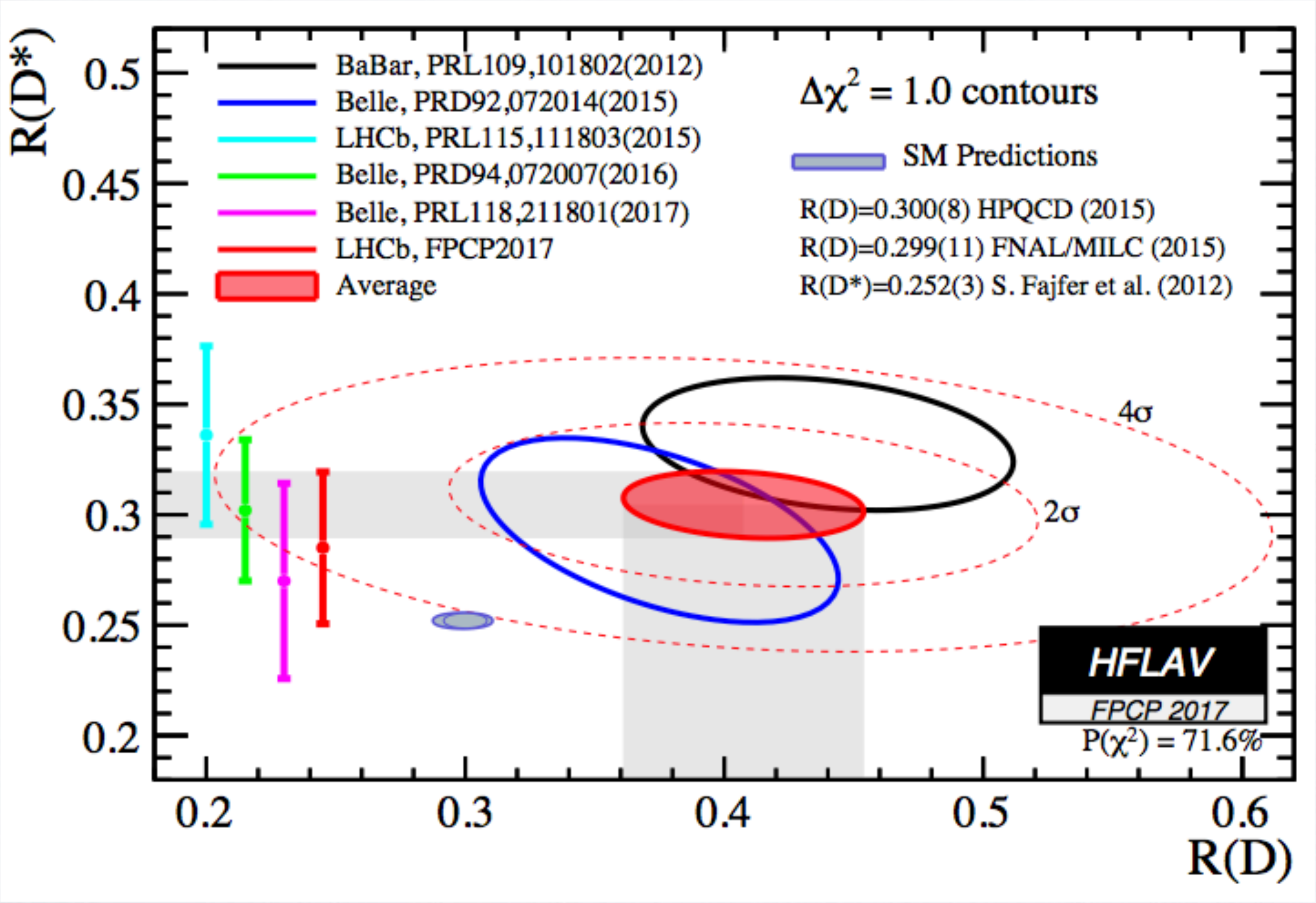
Phys. Lett. B, 2018.05.033

arXiv:1802.04274

$$b \to c\ell\bar{\nu}$$

$$R(D^{(*)}) = \frac{Br(B \to D^{(*)}\tau\nu_\tau)}{Br(B \to D^{(*)}\ell\nu_\ell)}$$

- Charged current B meson decay. Deviation from τ/ℓ universality.

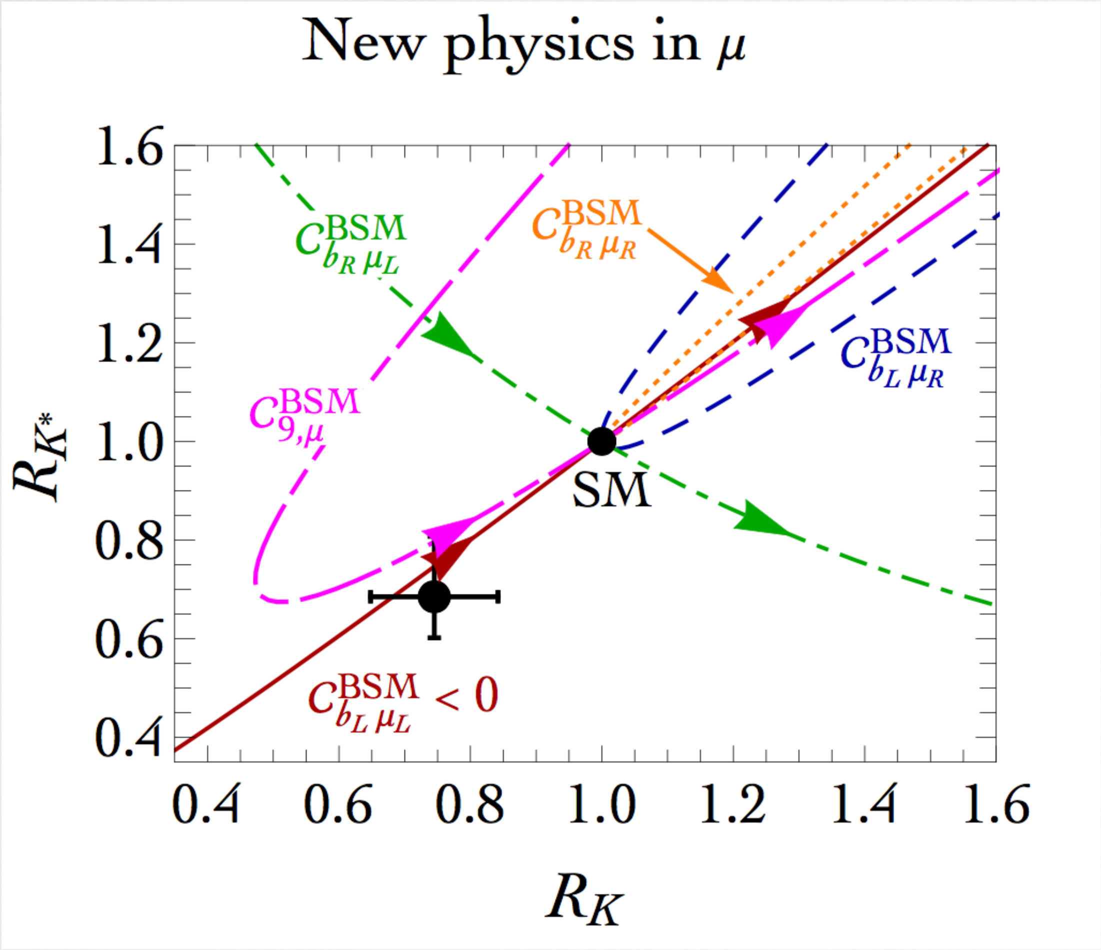


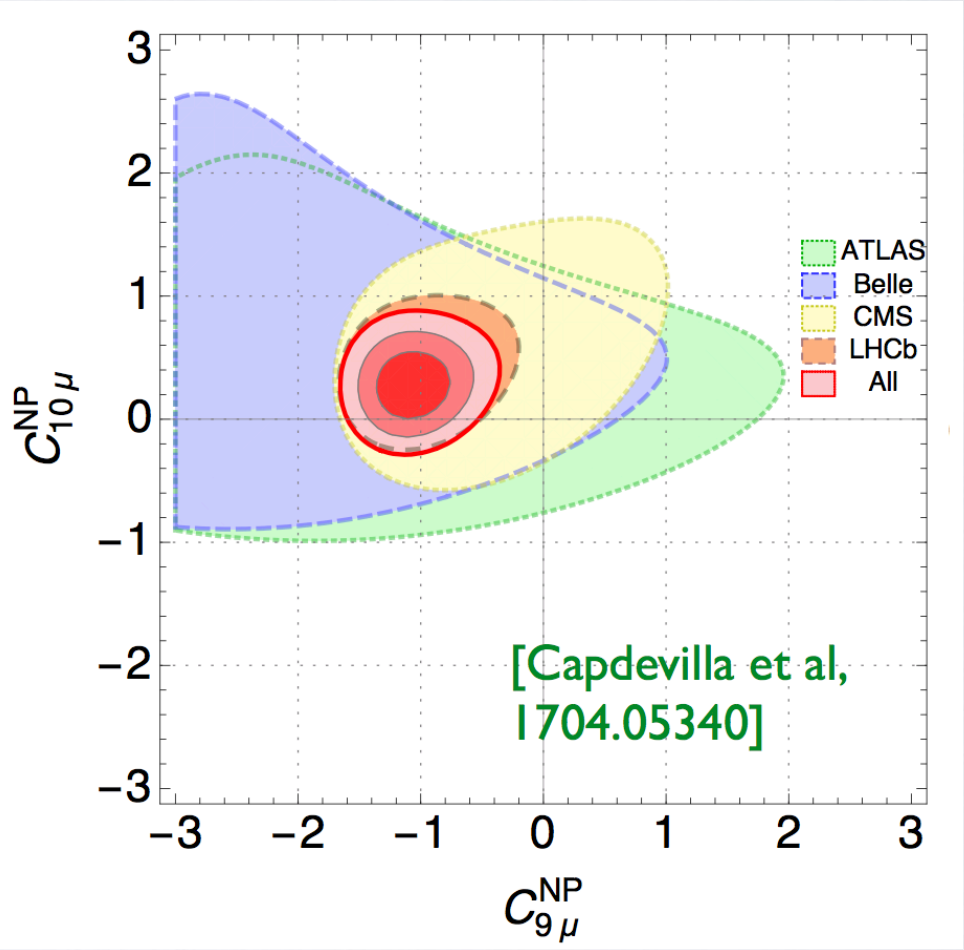
- Measurement by BaBar, Belle, and LHCb.
- Combined 4σ excess over the SM prediction.

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

$$R(K^{(*)}) = \frac{\text{Br}(B \to K^{(*)}\mu^+\mu^-)}{\text{Br}(B \to K^{(*)}e^+e^-)}$$

- Neutral current B meson decay. Deviation from μ/e universality. Measurement by LHCb, new physics fit preferred at 4σ.





$$\mathcal{O}_9^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$

$$\mathcal{O}_{10}^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

D'Amico et al, 1704.05438

Combined Explanation via New Physics?

- LFU violation in both anomalies.
- Both anomalies involve a bottom quark decaying to a 2nd generation quark.
- Data favors mainly left-handed effective interactions for both anomalies.

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

$$\lambda^q \sim \begin{pmatrix} \epsilon & \epsilon & \epsilon \\ \epsilon & V_q^2 & V_q \\ \epsilon & V_q & 1 \end{pmatrix} \qquad \lambda^\ell \sim \begin{pmatrix} \epsilon & \epsilon & \epsilon \\ \epsilon & V_\ell^2 & V_\ell \\ \epsilon & V_\ell & 1 \end{pmatrix} \qquad Q^i_L \sim \begin{pmatrix} V^*_{ki}u^k_L \\ d^i_L \end{pmatrix}$$

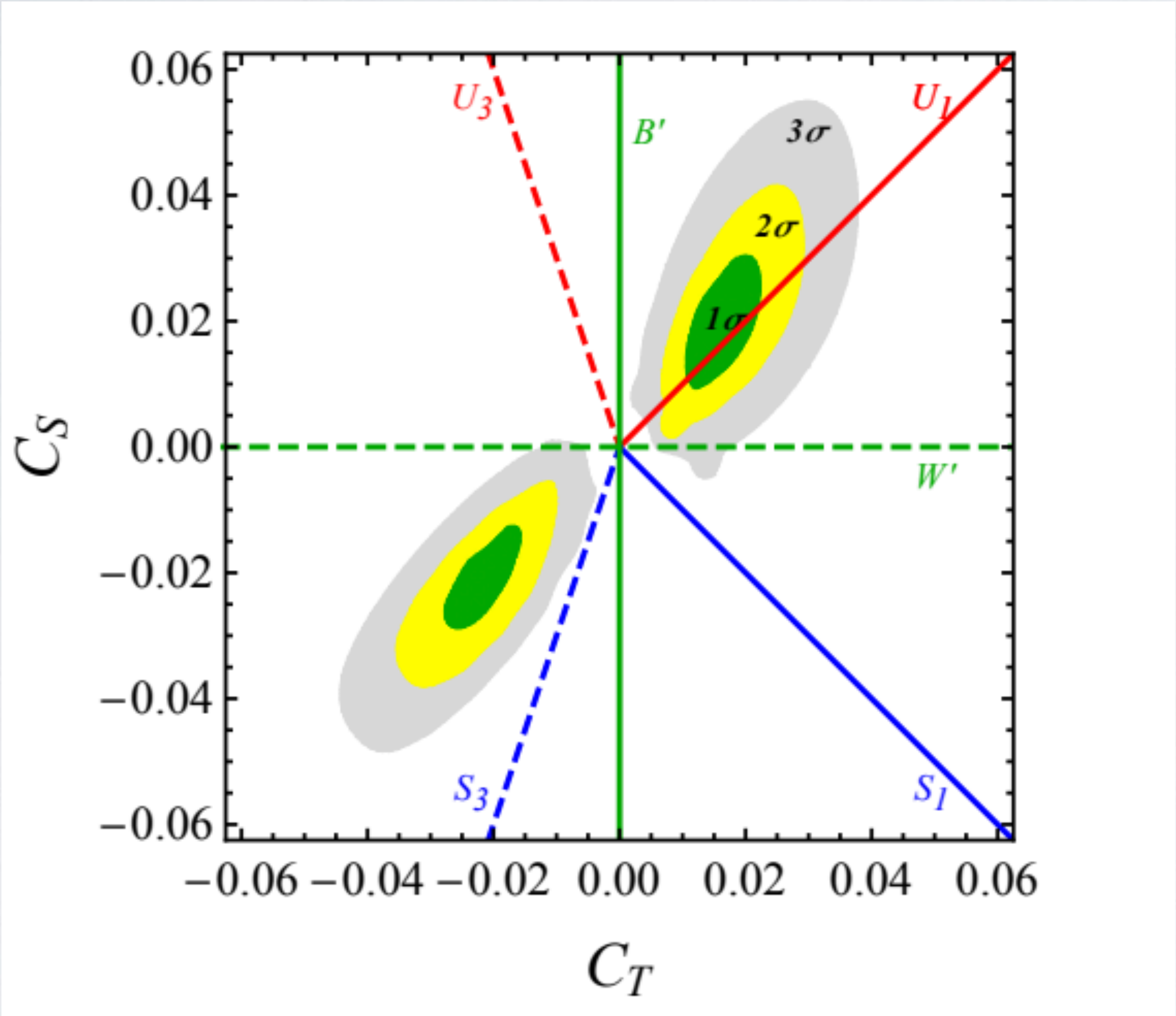
$$|V_q| \sim |V_{cb}| \qquad |V_\ell^2| \sim 10^{-2}$$

Competes with V_{cb} suppressed tree level SM process

Competes with 1-loop SM process

D. Buttazzo, A. Greljo, G. Isidori, D. Marzocca, 1706.07808

Single Median Model



Vectors

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

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

Scalar Leptoquarks

$$S_1^{\mu} = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$$

$$S_3^{\mu} = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$$

Vector Leptoquarks

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

$$U_3^{\mu} = (\mathbf{3}, \mathbf{3}, 2/3)$$

Stands out as the best option for a single mediator model.

D. Buttazzo, A. Greljo, G. Isidori, D. Marzocca, 1706.07808

Extended Gauge Group: The "4321" Model

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

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

~TeV

$$\langle \Omega_3 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_3 & 0 & 0 \\ 0 & v_3 & 0 \\ 0 & 0 & v_3 \\ 0 & 0 & 0 \end{pmatrix} \qquad \langle \Omega_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ 0 \\ v_1 \end{pmatrix}$$

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

$v_{\rm EW}$

Embedding

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

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

L. Di Luzio, A. Greljo, M. Nardecchia, 1708.08450

Extended Gauge Group: The "4321" Model

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

↓ ~TeV

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

15 Broken Generators

$$G' = (\mathbf{8}, \mathbf{1}, 0)$$

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

✓ $$U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$$

New SM Fermion Embedding

- 1st and 2nd family SM fermions charged under "321" and are not coupled directly to the LQ.

- 3rd family SM fermions charged under "421" and are coupled directly to the LQ.

"4321" with Family Dependent Gauge Charges

- 1st and 2nd family quarks and leptons charged under "321" but are SU(4) singlets. Here, i = 1,2.

Dominantly Light Family SM Fermions						
Gauge					Global	
Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$	$U(1)_{B'}$	$U(1)_{L'}$
$q_L'^i$	**1**	**3**	**2**	1/6	1/3	0
$u_R'^i$	**1**	**3**	**1**	2/3	1/3	0
$d_R'^i$	**1**	**3**	**1**	-1/3	1/3	0
$\ell_L'^i$	**1**	**1**	**2**	-1/2	0	1
$e_R'^i$	**1**	**1**	**1**	-1	0	1

- Third family quarks and leptons are embedded in fundamentals of SU(4).

Dominantly Third Family SM Fermions						
Gauge					Global	
Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$	$U(1)_{B'}$	$U(1)_{L'}$
ψ_L	**4**	**1**	**2**	0	1/4	1/4
ψ_R^u	**4**	**1**	**1**	1/2	1/4	1/4
ψ_R^d	**4**	**1**	**1**	-1/2	1/4	1/4

$$\psi_L = \begin{pmatrix} q_L'^3 \\ \ell_L'^3 \end{pmatrix} \qquad \psi_R^u = \begin{pmatrix} u_R'^3 \\ \nu_R'^3 \end{pmatrix} \qquad \psi_R^d = \begin{pmatrix} d_R'^3 \\ e_R'^3 \end{pmatrix}$$

Low Energy Limit of PS^3: M. Bordone, C. Cornella, J. Fuentes-Martin, G. Isidori, 1712.01368

First Attempt at a Lagrangian

- The Lagrangian for the light families looks just like the SM.

$$\mathcal{L}_{12} = -\overline{q}'_L\, Y_u\, \widetilde{H}\, u'_R - \overline{q}'_L\, Y_d\, H\, d'_R - \overline{\ell}'_L\, Y_\nu\, \widetilde{H}\, \nu'_R - \overline{\ell}'_L\, Y_e\, H\, e'_R + \mathrm{h.c.}\ ,$$

*All 1st and 2nd family Yukawas are small

→ Approximate Flavor Symmetry: $U(2)^3_q \times U(2)^3_\ell$

- The 3rd family Lagrangian contains just the following terms

$$\mathcal{L}_3 = -y^u_H \overline{\psi}_L \widetilde{H} \psi^u_R - y^d_H \overline{\psi}_L H \psi^d_R + \mathrm{h.c.}$$

✗ Predicts the same mass for the top quark and tau neutrino.

Predicts the same mass for the bottom quark and tau lepton. ✓

- Light family - 3rd family mixing not allowed without new fields.

Third Family Quark and Lepton Masses

- Can add another Higgs to split the 3rd family quark and lepton masses.

$$\langle \Phi_0^{15} \rangle \equiv v_\Phi / \sqrt{2}$$

$$y_H^u,\ y_H^d,\ y_\Phi^u,\ y_\Phi^d$$

Scalar Fields						
	Gauge				Global	
Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$	$U(1)_{B'}$	$U(1)_{L'}$
H	**1**	**1**	**2**	1/2	0	0
Φ	**15**	**1**	**2**	1/2	0	0
Ω_3	$\bar{\mathbf{4}}$	**3**	**1**	1/6	1/12	-1/4
Ω_1	$\bar{\mathbf{4}}$	**1**	**1**	-1/2	-1/4	3/4

$$v_{\rm EW}^2 = v_H^2 + v_\Phi^2$$

$$\tan\beta = v_\Phi / v_H$$

Up-type masses

$$m_t' = \frac{v_{\rm EW}}{\sqrt{2}} \left(y_H^u \cos\beta + \frac{1}{2\sqrt{6}} y_\Phi^u \sin\beta \right)$$

$$m_{\nu_\tau}' = \frac{v_{\rm EW}}{\sqrt{2}} \left(y_H^u \cos\beta - \frac{3}{2\sqrt{6}} y_\Phi^u \sin\beta \right)$$

Requires Tuning: $\frac{\rm meV}{v_{\rm EW}} \sim 10^{-14}$

Down-type masses

$$m_b' = \frac{v_{\rm EW}}{\sqrt{2}} \left(y_H^d \cos\beta + \frac{1}{2\sqrt{6}} y_\Phi^d \sin\beta \right)$$

$$m_\tau' = \frac{v_{\rm EW}}{\sqrt{2}} \left(y_H^d \cos\beta - \frac{3}{2\sqrt{6}} y_\Phi^d \sin\beta \right)$$

Bottom/Tau Splitting: $\frac{m_b}{m_\tau} \sim 2$

**Generic problem with low-scale QL-unification. Resolved in our model- later in the talk.*

Light with Third Family Mixing

- Light with 3rd family mixing is required, e.g. must generate the CKM.
- A single new vector-like fermion with the same quantum numbers as ψ_L can do the job. Contains vector-like partners to SM doublets.

New Vector-like Fermions						
Gauge					Global	
Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$	$U(1)_{B'}$	$U(1)_{L'}$
$\chi_{L,R}$	**4**	**1**	**2**	0	1/4	1/4

$$\chi_{L,R} = \begin{pmatrix} Q'_{L,R} \\ L'_{L,R} \end{pmatrix}$$

$$\Psi_L \equiv \begin{pmatrix} \psi_L \\ \chi_L \end{pmatrix} \qquad \mathbf{y}_H^{u,d} \equiv \begin{pmatrix} y_H^{u,d} \\ \lambda_H^{u,d} \end{pmatrix}$$

$$\begin{aligned} \mathcal{L}_3 \to \mathcal{L}_{3\chi} = & - \overline{\Psi}_L\, \mathbf{y}_H^u \widetilde{H} \psi_R^u - \overline{\Psi}_L\, \mathbf{y}_H^d H \psi_R^d + (H \to \Phi) \\ & - \bar{q}'_L \lambda_q\, \Omega_3^T \chi_R - \bar{\ell}'_L \lambda_\ell\, \Omega_1^T \chi_R - \bar{\Psi}_L \mathbf{m}\, \chi_R + \text{h.c.} \end{aligned}$$

Higher Dimensional Operators

- When the new vector-like fermion is integrated out, the following operators are generated:

<u>Dimension-5</u> ✅ Light with 3rd family quark and lepton mixings generated.

$$\mathcal{L}_{d5} = \frac{\lambda_q}{m_\chi}\left(\lambda_H^u\, \bar{q}'_L \Omega_3^T \widetilde{H}\, \psi_R^u + \lambda_H^d\, \bar{q}'_L \Omega_3^T H\, \psi_R^d\right) + \frac{\lambda_\ell}{m_\chi}\left(\lambda_H^u\, \bar{\ell}'_L \Omega_1^T \widetilde{H}\, \psi_R^u + \lambda_H^d\, \bar{\ell}'_L \Omega_1^T H\, \psi_R^d\right) + (H \to \Phi) + \text{h.c.}$$

<u>Dimension-6</u> ✅ Suppressed leptoquark coupling to the light families generated.

$$\mathcal{L}_{\text{d6}} \supset \frac{i}{m_\chi^2} \bar{q}'_L \lambda_q\, \Omega_3^T \not{D}\, \Omega_1^*\, \lambda_\ell^\dagger\, \ell'_L \;\longrightarrow\; \frac{g_4}{\sqrt{2}}\left(\frac{v_1 v_3}{m_\chi^2}\right) \bar{q}'_L \lambda_q\, \gamma^\mu\, U_{1\mu}\, \lambda_\ell^\dagger\, \ell'_L\,,$$

Return to the Neutrino Mass Problem

Up-type Dirac masses

$$m'_t = \frac{v_{\rm EW}}{\sqrt{2}}\left(y_H^u \cos\beta + \frac{1}{2\sqrt{6}} y_\Phi^u \sin\beta\right)$$ ✓

$$m'_{\nu_\tau} = \frac{v_{\rm EW}}{\sqrt{2}}\left(y_H^u \cos\beta - \frac{3}{2\sqrt{6}} y_\Phi^u \sin\beta\right)$$ ✗ → Requires Tuning: $\frac{\rm meV}{v_{\rm EW}} \sim 10^{-14}$

Solution

- Accept a natural tau neutrino Dirac mass of order the electroweak scale.
- Add singlet fermions such that the inverse seesaw mechanism (ISS) can be implemented to obtain the correct neutrino masses.

P. Fileviez Perez and M. Wise, 1307.6213

Neutrino Lagrangian and Mass Matrix

Right Handed Singlet Fermions						
	Gauge				Global	
Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$	$U(1)_{B'}$	$U(1)_{L'}$
$\nu_R'^i$	**1**	**1**	**1**	0	0	1
S_R^a	**1**	**1**	**1**	0	0	-1

Lepton Number Conserving

Lepton Number Violating

$$\mathcal{L}_S = -\Omega_1^T\, \overline{S_R^c}\, \lambda_R \psi_R^u - \overline{S_R^c}\, M_R\, \nu_R' - \frac{1}{2}\overline{S_R^c}\, \mu_S\, S_R + \text{h.c.}$$

- After EWSB, the complete neutrino mass matrix takes the form:

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & M_\nu^D & 0 \\ (M_\nu^D)^T & 0 & \widetilde{M}_R^T \\ 0 & \widetilde{M}_R & \mu_S \end{pmatrix}$$

$$\widetilde{M}_R = (M_R \;\; \tfrac{v_1}{\sqrt{2}}\lambda_R)$$

SU(4) breaking VEV: ~ TeV

Inverse Seesaw Mechanism

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & M_\nu^D & 0 \\ (M_\nu^D)^T & 0 & \widetilde{M}_R^T \\ 0 & \widetilde{M}_R & \mu_S \end{pmatrix} \qquad M_\nu^D = \begin{pmatrix} \frac{v_H}{\sqrt{2}} U Y_\nu^{\mathrm{diag}} & -f_\nu \, \lambda_\ell \\ 0 & m'_{\nu_\tau} \end{pmatrix}$$

- ISS Hierarchy $\mu_S \ll M_\nu^D < \widetilde{M}_R$ gives 3 light Majorana neutrinos.

$$M_{\mathrm{light}} \approx M_\nu^D \widetilde{M}_R^{-1} \mu_S \, (\widetilde{M}_R^T)^{-1} (M_\nu^D)^T$$

- Parametrically, if $m_D \sim \mathrm{GeV}$, $m_R \sim \mathrm{TeV}$, works for $\mu_S \sim \mathrm{keV}$.

$$m_\nu \sim \left(\frac{m_D}{m_R} \right)^2 \mu_S$$

PMNS Non-Unitarity and B-Anomalies

- 3x3 light neutrino mixing matrix is now non-unitary:

$$N = \left[\mathbf{1} - \frac{1}{2}\Theta\,\Theta^\dagger\right] U_{\text{PMNS}}\,, \qquad \Theta \approx M_\nu^D\, \widetilde{M}_R^{-1}$$

- PMNS Non-Unitary probed by $\epsilon = \mathbf{1} - NN^\dagger \approx \Theta\,\Theta^\dagger$, so parametrically there is a contribution at least as large as:

$$\epsilon \sim \frac{m_D^2}{m_R^2} \sim \frac{m_D^2}{v_1^2|\lambda_R|^2}$$

- Meanwhile,

$$\Delta R_D^{\tau\ell} \approx 2.2\,\Delta R_{D^*}^{\tau\ell} \approx \frac{5v_{\text{EW}}^2}{v_1^2 + v_3^2}\,.$$

LHC Direct Search Coloron Bound: $v_3 \gtrsim 1\ \text{TeV}$

$$\Longrightarrow v_1 \lesssim 1\ \text{TeV}, \qquad \epsilon \sim 10^{-2}\left(\frac{m_D}{100\,\text{GeV}}\right)^2\left(\frac{1\,\text{TeV}}{v_1|\lambda_R|}\right)^2$$

Sizable effect in B-physics implies sizable PMNS unitarity violation.

Conclusions

- We present a model based on the "4321" extended gauge group with family dependent gauge charges.
- Gauge vector leptoquark U_1 = (**3**, **1**, 2/3) coupled dominantly to the 3rd family offers a single mediator explanation for B-anomalies.
- Neutrino mass problem is naturally resolved in our model by implementing the inverse seesaw mechanism.
- PMNS unitarity violation is controlled by the SU(4) breaking scale, which also controls the size of the effect in $\Delta R(D^{(*)})$.

Backup Slides

Gauge Boson Masses

$$m_{U_1} = \tfrac{1}{2} g_4 \sqrt{v_1^2 + v_3^2}\,,$$

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

$$m_{Z'} = \tfrac{1}{2}\sqrt{\tfrac{3}{2}}\sqrt{g_4^2 + \tfrac{2}{3} g_1^2}\sqrt{v_1^2 + \tfrac{1}{3} v_3^2}\,.$$

- Gauge boson spectrum cannot be split very much. To avoid direct search bounds we need $g_4 > g_3 > g_1$ and $v_3 > v_1$, then the approximate relation is

$$m_{g'} \sim \sqrt{2}\, m_{U_1} \qquad\qquad m_{Z'} \sim \frac{1}{\sqrt{2}}\, m_{U_1}$$

$$m_{Z'} \sim 1.1\,\mathrm{TeV}\,, \qquad m_{U_1} \sim 1.6\,\mathrm{TeV}\,, \qquad m_{g'} \sim 2.3\,\mathrm{TeV}$$

Gauge Boson Couplings

$$\mathbf{Q}'_L = (q'^{i}_L, q'^{3}_L, Q'_L)^T$$

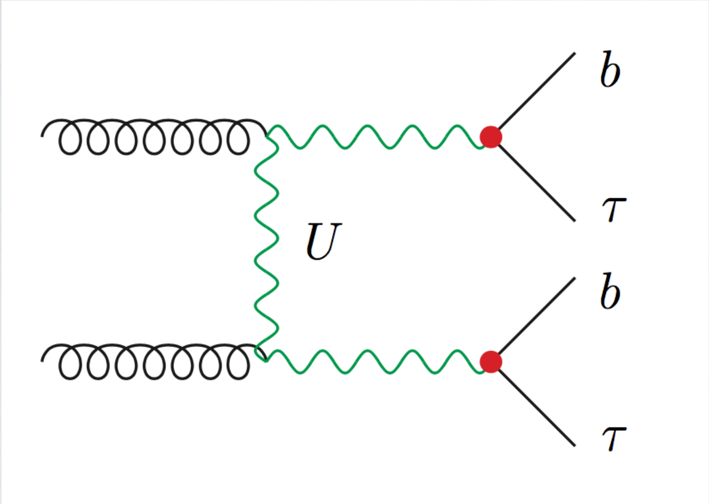
- Coloron Couplings

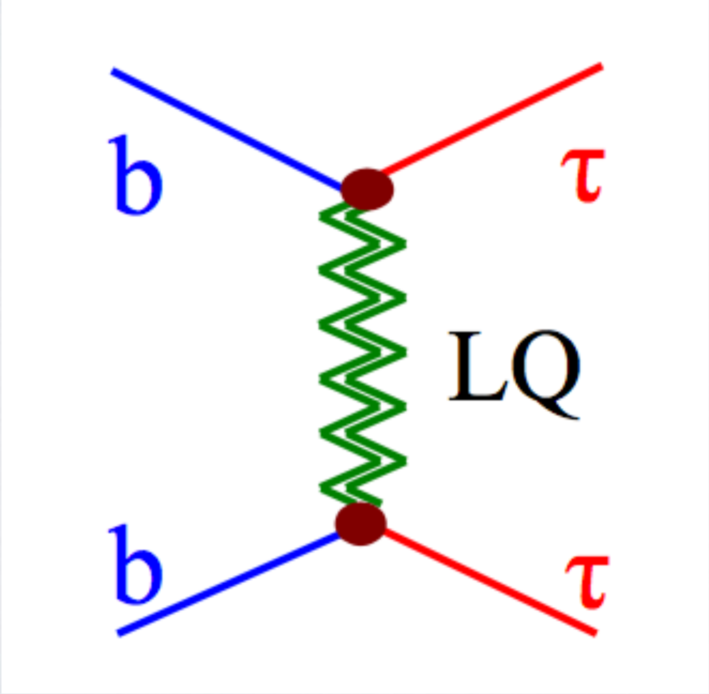
$$\mathcal{L}_{g'} \supset g_s \left(\bar{\mathbf{Q}}'_L \, C^L_{g'} \gamma^\mu T^a \mathbf{Q}'_L \right) g'^{a}_\mu \qquad C^L_{g'} = \mathrm{diag}\left(-\frac{g_3}{g_4}, -\frac{g_3}{g_4}, \frac{g_4}{g_3}, \frac{g_4}{g_3} \right)$$

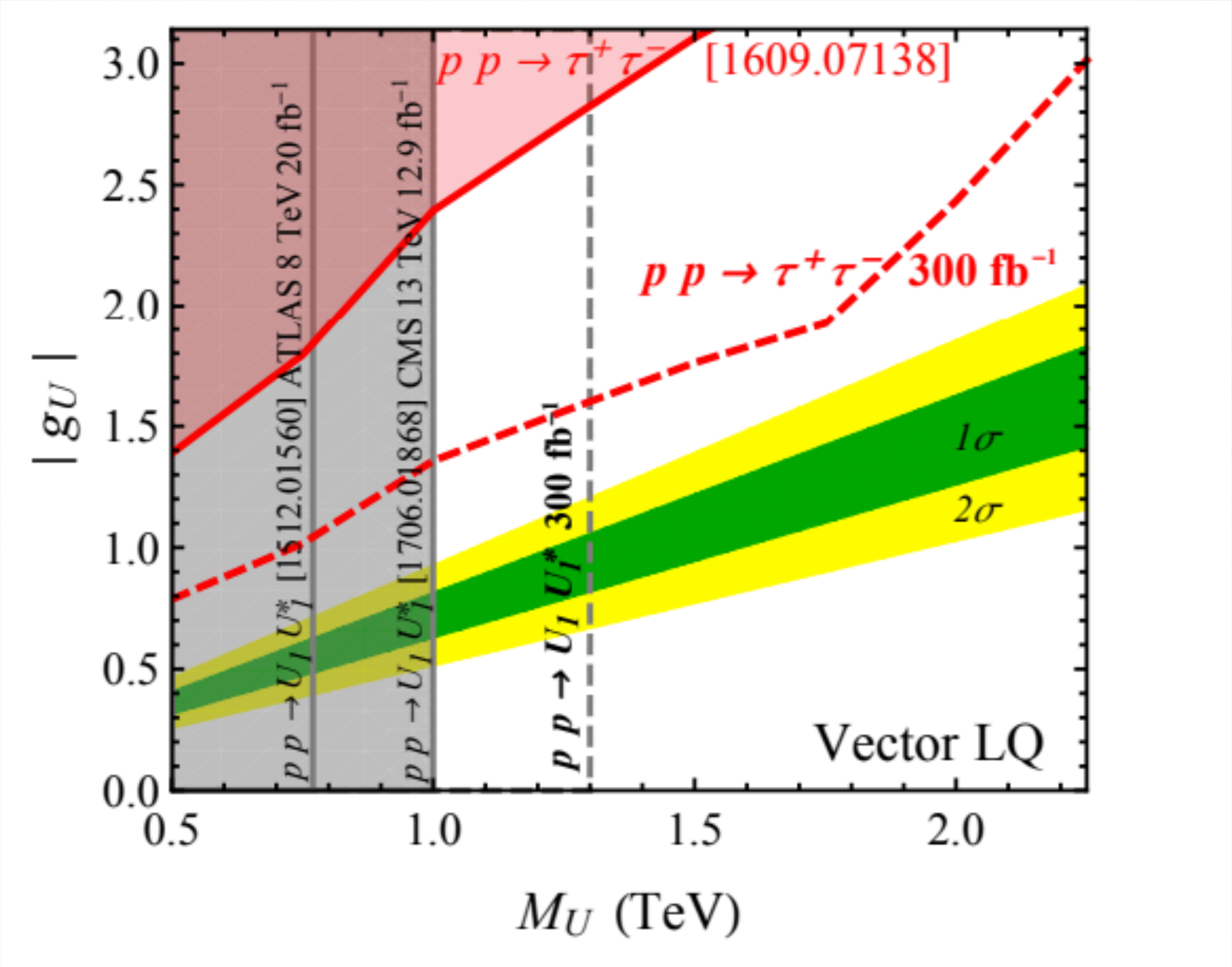
- Z' Couplings

$$\mathcal{L}_{Z'} \supset -\frac{g_Y}{2}\sqrt{\frac{3}{2}} \left(\bar{\mathbf{L}}'_L \, C^L_{Z'} \gamma^\mu \mathbf{L}'_L \right) Z'_\mu \qquad C^L_{Z'} = \mathrm{diag}\left(-\frac{2}{3}\frac{g_1}{g_4}, -\frac{2}{3}\frac{g_1}{g_4}, \frac{g_4}{g_1}, \frac{g_4}{g_1} \right)$$

Leptoquark Direct Search Bounds: $m_U \gtrsim 1.5\,\mathrm{TeV}$

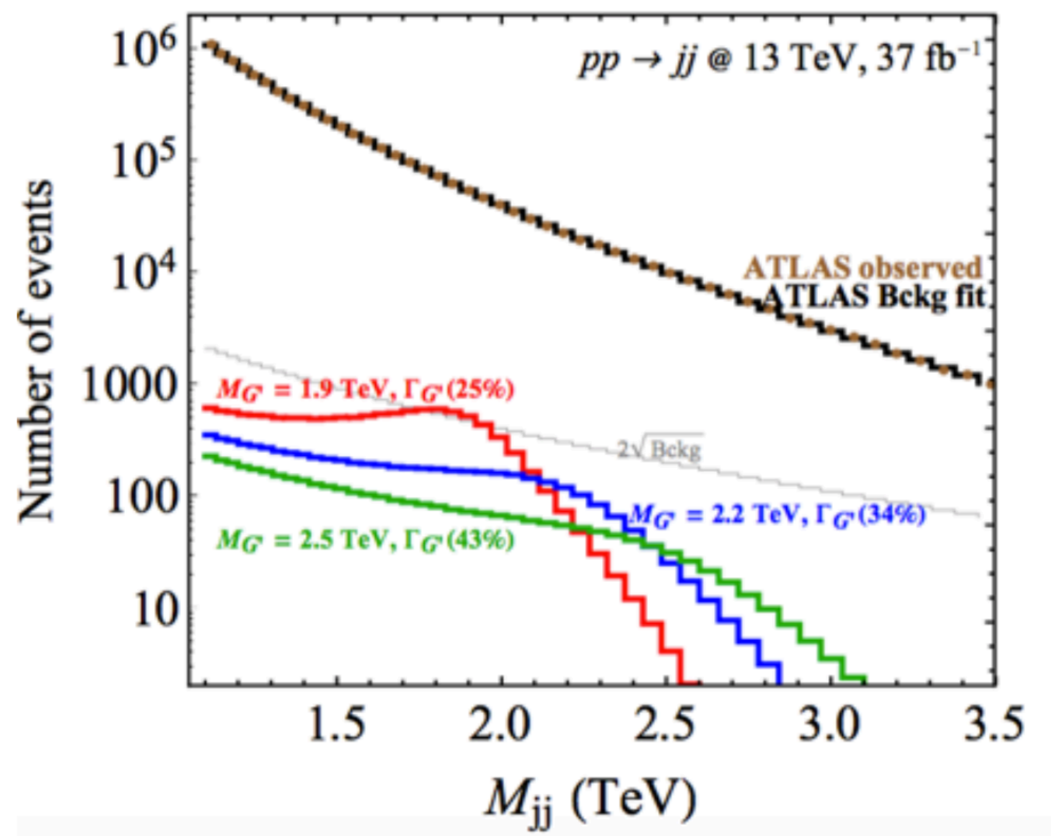


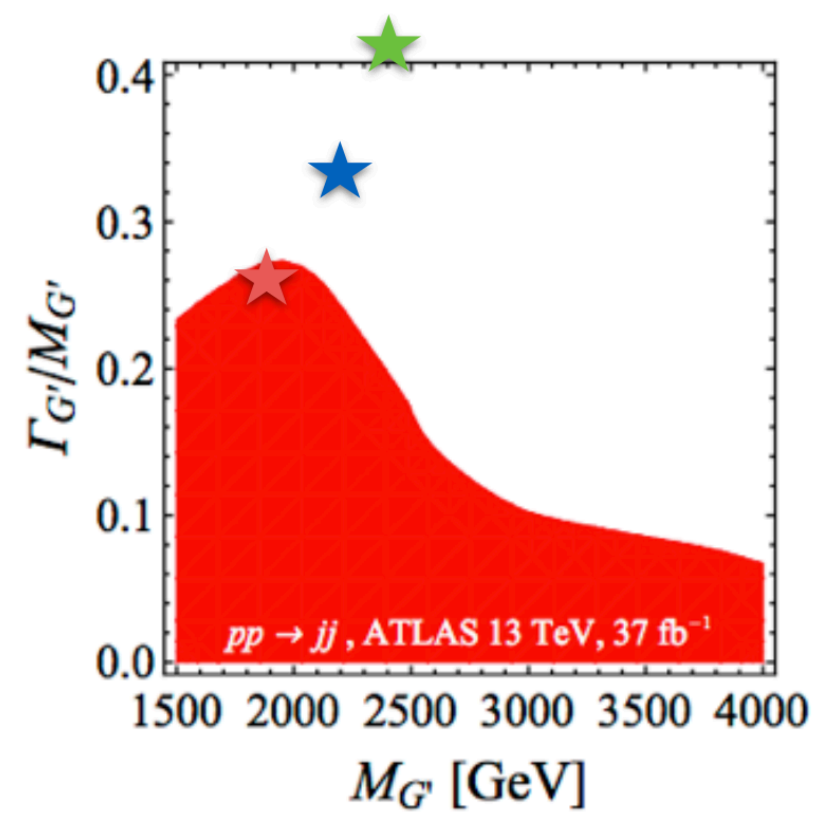




Coloron Direct Search Bounds

[LDL, Fuentes-Martin, Greljo, Nardecchia, Renner (work in progress)]





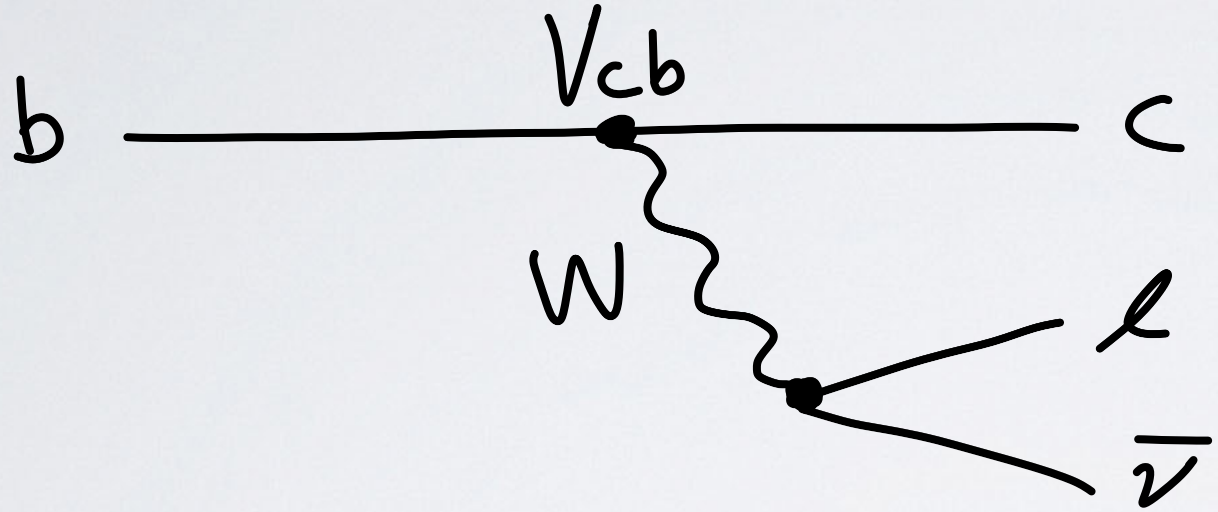
- <u>However</u>, bump-searches loose in sensitivity for large width/mass

$$\frac{\Gamma}{m} \lesssim 15\% \quad \text{(exp. analysis)}$$

$$\frac{\Gamma_{g'}}{m_{g'}} \simeq 25\%$$ (unavoidable in our scenario: large g_4 + extra channel in VLF)

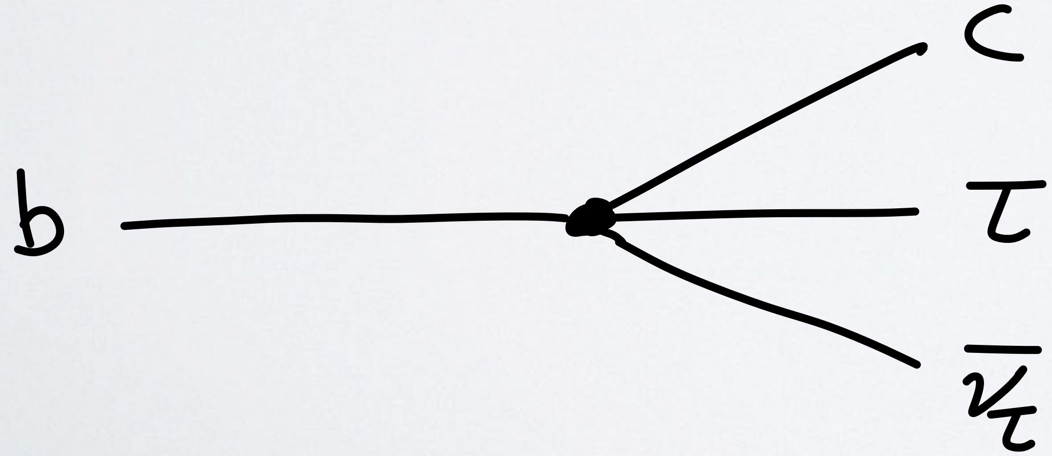
$b \to c\ell\bar{\nu}$

- Tree-level W-mediated process in SM, V_{cb} suppressed.



$$\mathcal{A}_{\rm SM} \sim \frac{g^2 V_{cb}}{m_W^2} \sim \frac{V_{cb}}{v^2}$$

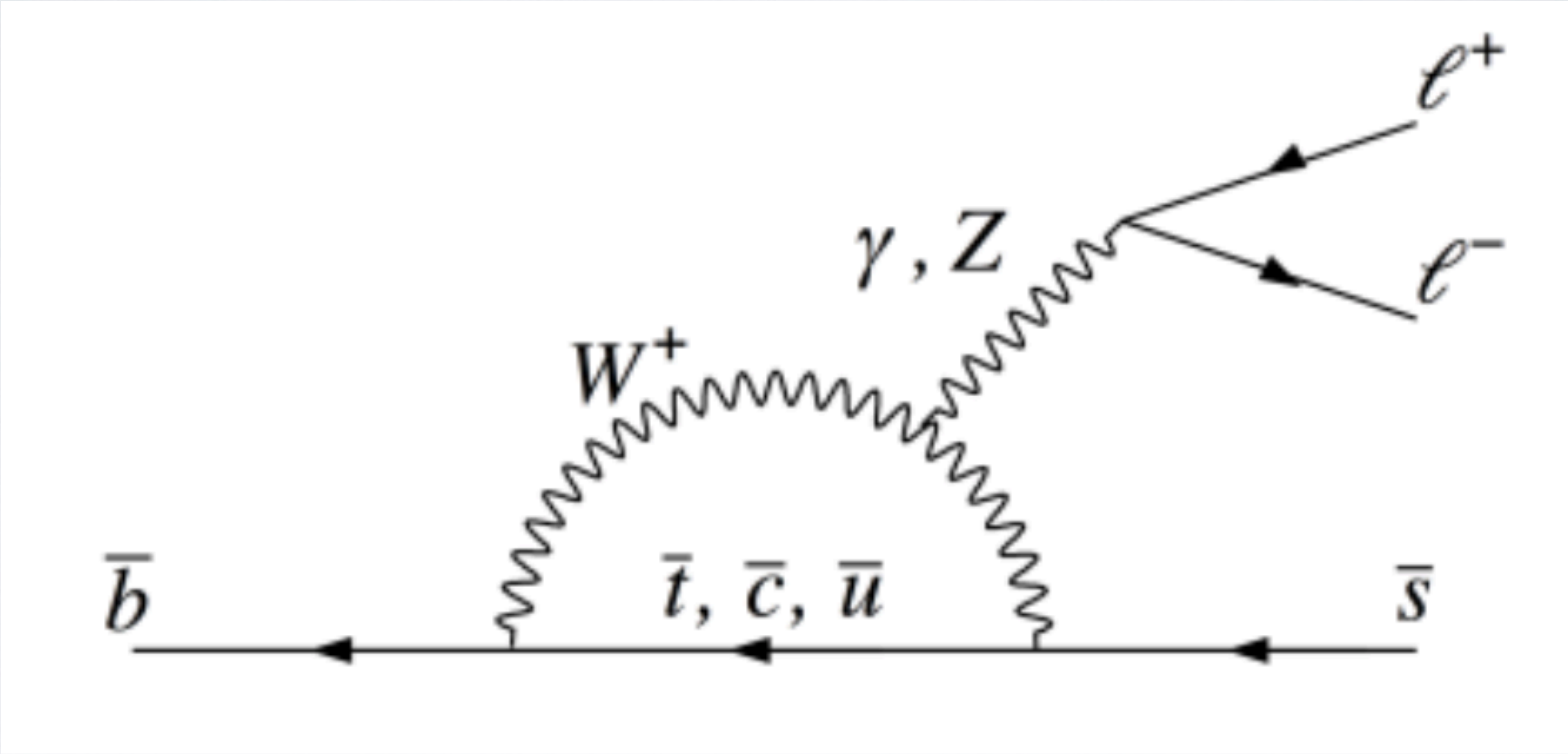
- Tree Level MFV New Physics in 3rd generation



$$\mathcal{A}_{\rm NP} \sim \frac{V_{cb}}{\Lambda^2}$$

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

- Occurs at 1-loop in the SM, additional V_{ts} ($\sim V_{cb}$) suppression.



Up-Type Leptoquark Couplings

- Up-type leptoquark coupling matrix

$$\mathcal{L} \supset \frac{g_4}{\sqrt{2}} (\overline{u}_L^i V_{ij}^u)\, \mathcal{C}_{j\alpha} \gamma^\mu U_{1\mu}\, \nu_L^\alpha$$

$$\mathcal{K}_{i\alpha}^u \equiv V_{ij}^u\, \mathcal{C}_{j\alpha}$$

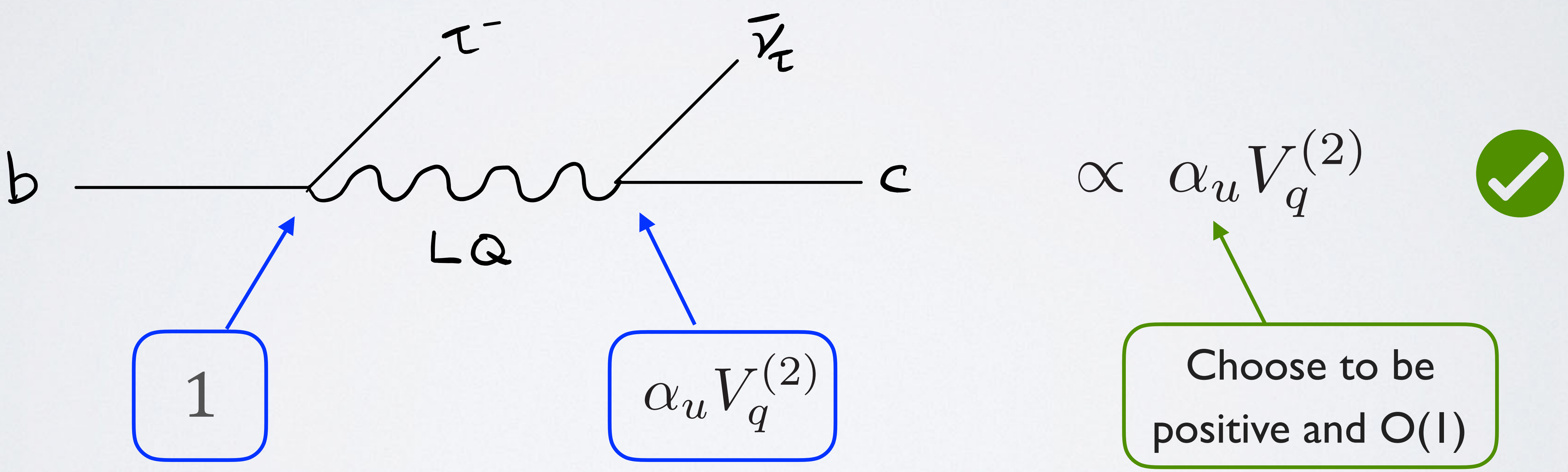
$$\mathcal{K}^u = \begin{pmatrix} V_\ell^{*(1)}(V_{ud}V_q^{(1)} + V_{us}V_q^{(2)}) & V_\ell^{*(2)}(V_{ud}V_q^{(1)} + V_{us}V_q^{(2)}) & \alpha_u\,(V_{ud}V_q^{(1)} + V_{us}V_q^{(2)}) \\ V_\ell^{*(1)}(V_{cd}V_q^{(1)} + V_{cs}V_q^{(2)}) & V_\ell^{*(2)}(V_{cd}V_q^{(1)} + V_{cs}V_q^{(2)}) & \alpha_u\,(V_{cd}V_q^{(1)} + V_{cs}V_q^{(2)}) \\ -\alpha_u^*\, V_\ell^{*(1)}|V_q|^2 & -\alpha_u^*\, V_\ell^{*(2)}|V_q|^2 & 1 \end{pmatrix}$$

$$V_\ell^{(i)} = \frac{v_1}{m_\chi} \lambda_\ell^{(i)} \qquad\qquad V_q^{(i)} = \frac{v_3}{m_\chi} \lambda_q^{(i)}$$

Leptoquark Contribution: $b \to c\ell\bar{\nu}$

$$\mathcal{K}^u_{23} = \alpha_u \left(V_{cd} V_q^{(1)} + V_{cs} V_q^{(2)}\right) \approx \alpha_u V_q^{(2)}$$

- Take couplings to be real, need $V_q \sim V_{cb}$



Down-Type Leptoquark Couplings

- Down-type leptoquark coupling matrix

$$\mathcal{L} \supset \frac{g_4}{\sqrt{2}} (\bar{d}_L^i V_{ij}^d) \, \mathcal{C}_{j\alpha} \gamma^\mu \, U_{1\mu} \, (V_{\alpha\beta}^e e_L^\beta)$$

$$\mathcal{K}_{i\beta}^d \equiv V_{ij}^d \, \mathcal{C}_{j\alpha} V_{\alpha\beta}^e$$

$$\mathcal{K}^d = \begin{pmatrix} V_q^{(1)} V_\ell^{*(1)} & V_q^{(1)} V_\ell^{*(2)} & \alpha_d \, V_q^{(1)} \\ V_q^{(2)} V_\ell^{*(1)} & V_q^{(2)} V_\ell^{*(2)} & \alpha_d \, V_q^{(2)} \\ \alpha_e^* \, V_\ell^{*(1)} & \alpha_e^* \, V_\ell^{*(2)} & 1 \end{pmatrix}$$

$$V_\ell^{(i)} = \frac{v_1}{m_\chi} \lambda_\ell^{(i)} \qquad\qquad V_q^{(i)} = \frac{v_3}{m_\chi} \lambda_q^{(i)}$$

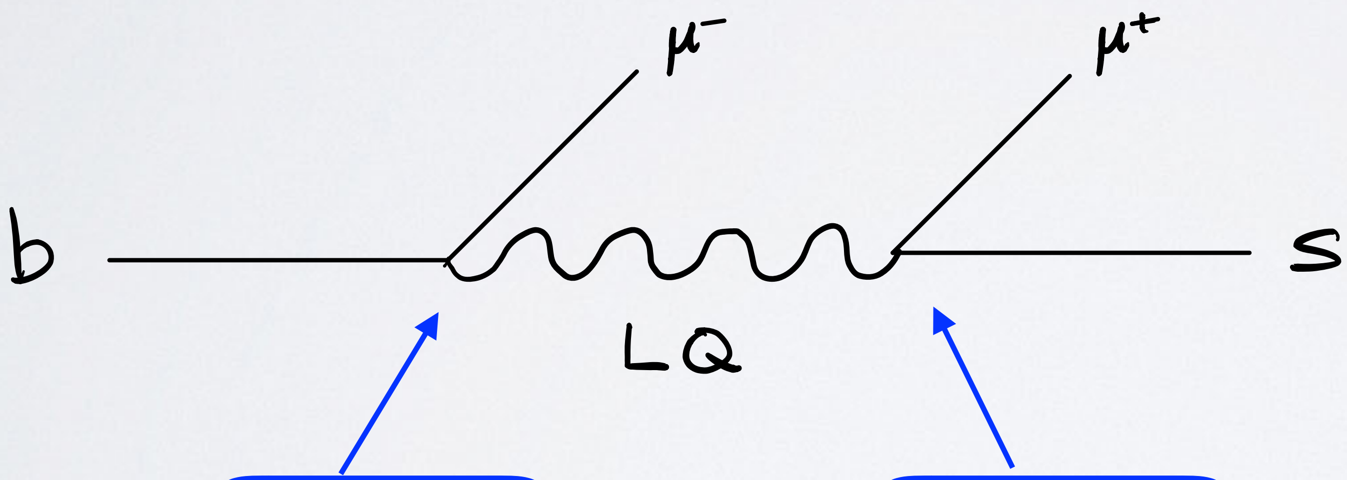
Leptoquark Contribution: $b \to s\bar{\ell}\ell$

$$\mathcal{K}^d = \begin{pmatrix} V_q^{(1)} V_\ell^{*(1)} & V_q^{(1)} V_\ell^{*(2)} & \alpha_d\, V_q^{(1)} \\ V_q^{(2)} V_\ell^{*(1)} & V_q^{(2)} V_\ell^{*(2)} & \alpha_d\, V_q^{(2)} \\ \alpha_e^*\, V_\ell^{*(1)} & \alpha_e^*\, V_\ell^{*(2)} & 1 \end{pmatrix}$$

$$V_q^{(i)} = \frac{v_3}{m_\chi} \lambda_q^{(i)}$$

$$V_\ell^{(i)} = \frac{v_1}{m_\chi} \lambda_\ell^{(i)}$$

- Take couplings to be real, need destructive -15% effect:



$\alpha_e\, V_\ell^{(2)}$

$V_q^{(2)} V_\ell^{(2)}$

$$\propto\ \alpha_e\, V_q^{(2)} (V_\ell^{(2)})^2$$

Choose to be negative and O(1)

B_s Mixing and $B \to K\nu\nu$

- FCNC generated only at 1-loop with a LQ mediator.
- Vanishes due to dynamics for U_1 vector LQ.

$$\mathcal{B}(B \to K^*\nu\nu) \propto (C_T - C_S)$$