JOHANNES GUTENBERG
UNIVERSITÄT MAINZ

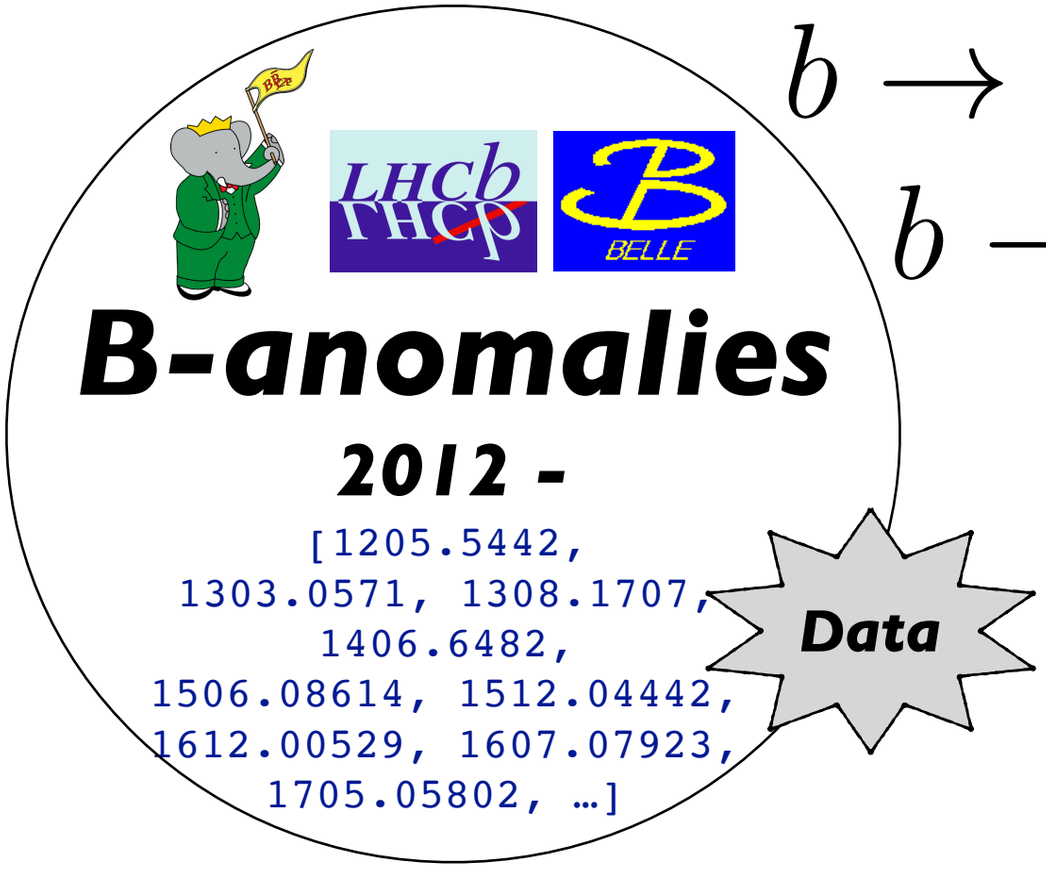
JG|U

# New directions in B-anomalies model building

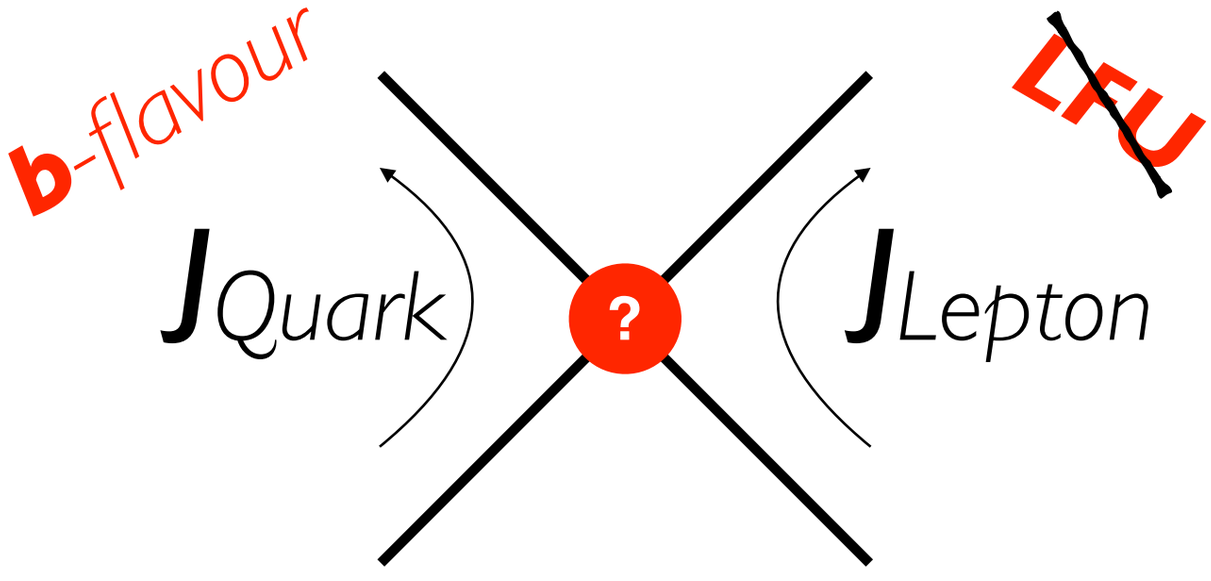
Admir Greljo

20 September 2018, CKM

To make progress we need hints…




- ***The largest coherent set of discrepancies between Theory and Experiment today***



?

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

$$b \to s\mu\bar{\mu} \qquad b \to c\tau\bar{\nu}_\tau$$

***V-A operator*** ***V-A operator***

$\mathrm{SU(2)_L}$

**Common origin?**

$$(\bar{Q}_L^i \gamma_\mu \sigma^a Q_L^j)(\bar{L}_L^\alpha \gamma^\mu \sigma^a L_L^\beta)$$

$$Q_L^i = \begin{pmatrix} V_{ji}^* u_L^j \\ d_L^i \end{pmatrix} \qquad L_L^\alpha = \begin{pmatrix} \nu_L^\alpha \\ \ell_L^\alpha \end{pmatrix}$$

# Hint I

**?**

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

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***V-A operator*** ***V-A operator***

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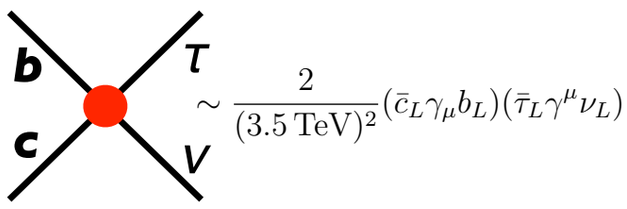
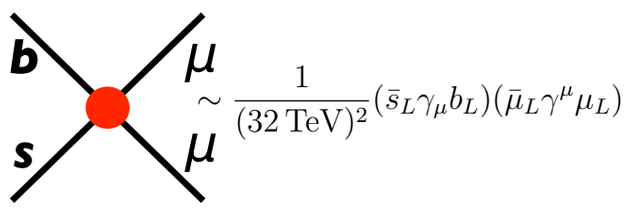
**Hint I**




$$\sim \frac{2}{(3.5\,\mathrm{TeV})^2}(\bar{c}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma^\mu \nu_L)$$




$$\sim \frac{1}{(32\,\mathrm{TeV})^2}(\bar{s}_L\gamma_\mu b_L)(\bar{\mu}_L\gamma^\mu \mu_L)$$

***Large NP in 3rd family*** ***Small NP in 2nd family***

Related to

**The SM flavour puzzle?**

**Hint II**

?

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

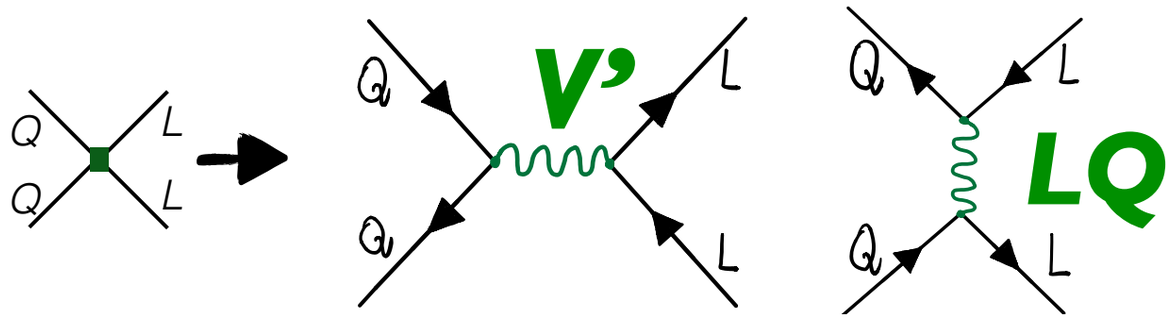
# Steps to Models

## 1 SMEFT + Flavour Symmetries

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

$$\mathrm{U}(2)_q \times \mathrm{U}(2)_\ell$$

## 2 Simplified mediator models




see e.g. [Buttazzo, AG, Isidori, Marzocca] 1706.07808

### Most notable constraints

- ✘ Other meson decays
- ✘ Neutral meson mixing
- ✘ LFU and LFV in charged leptons
- ✘ Z and W pole precision
- ✘ High-$p_T$ searches

- ✔ Mature & successful programme
- ✔ A few working solutions identified
- ✔ Complementary low and high-$p_T$ processes identified

# Challenges for Model Builders?

$B_s \leftrightarrow \bar{B}_s$

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

...

**FCNC**

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

...

**High $p_T$**

**LHC**

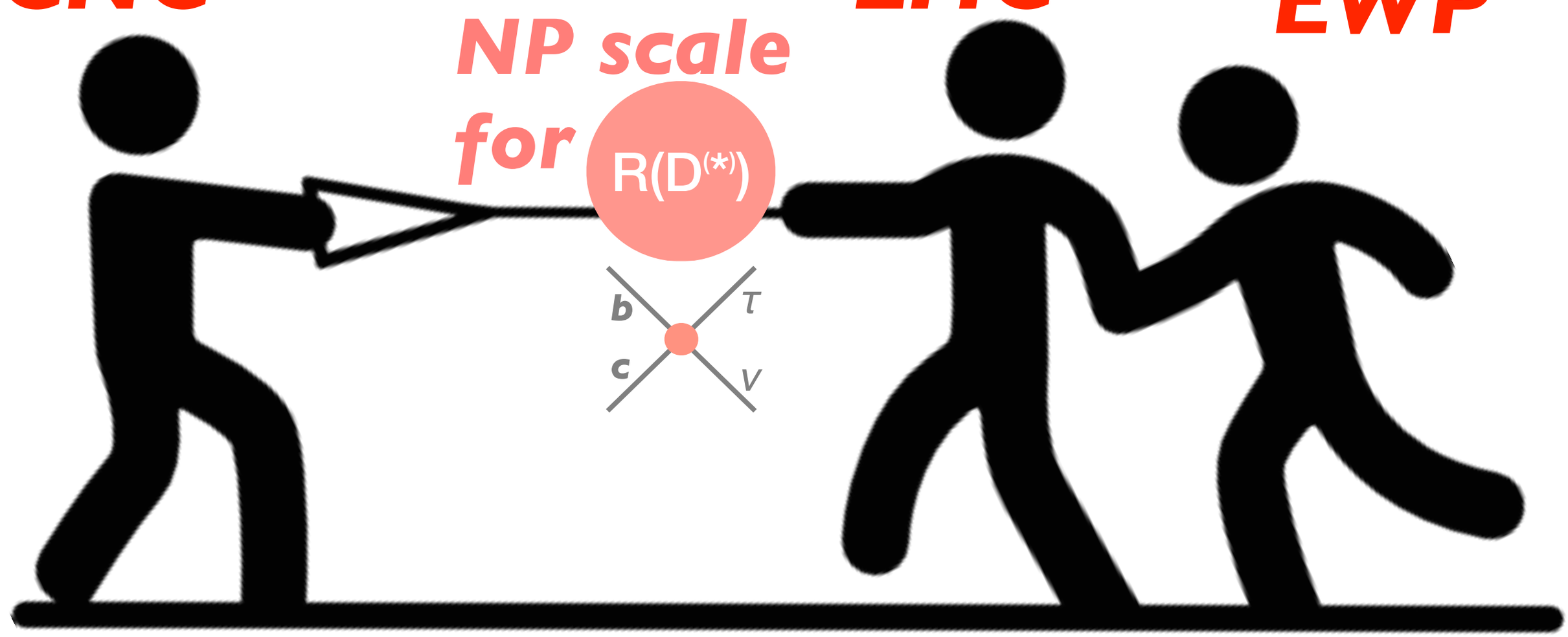
*Z decays*

*τ decays*

...

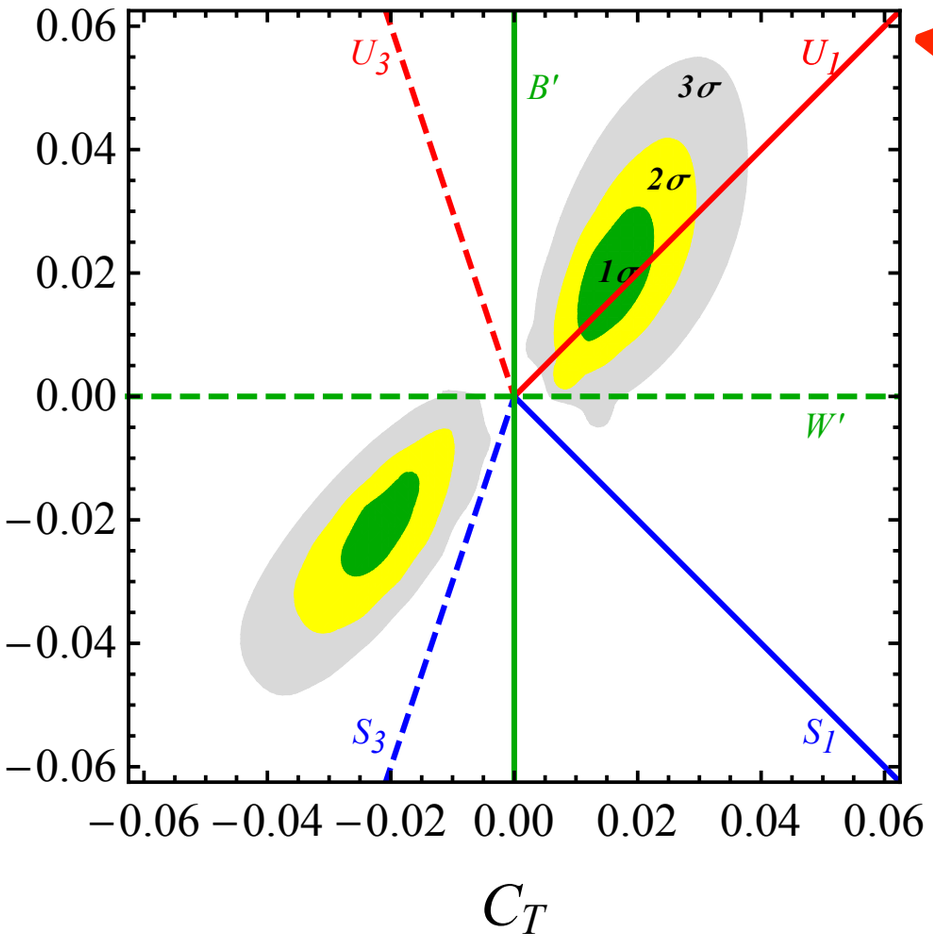
**EWP**

**NP scale for R(D(*))**



# Single mediator?

[Buttazzo, AG, Isidori, Marzocca]
1706.07808




**Vector LQ**

$$(3,1,2/3)$$

$$J^\mu_U \equiv \beta_{i\alpha}\, \bar{Q}_i \gamma^\mu L_\alpha$$

**de + uv**

*Expanding SU(2)

- ***Tree-level***

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

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

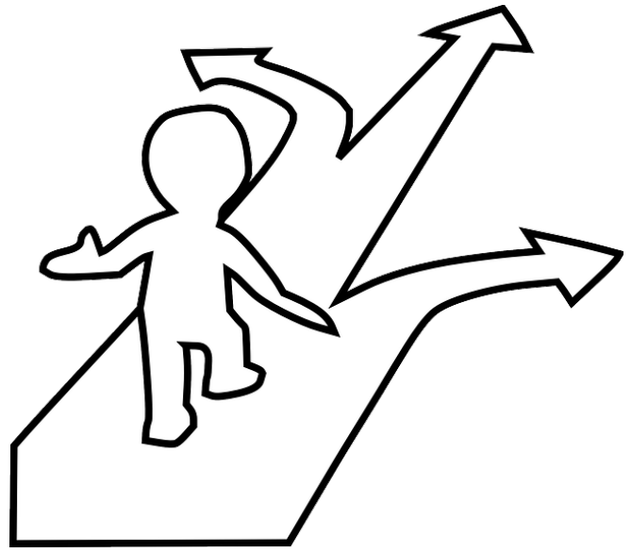
- ***Dynamical suppression:***

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

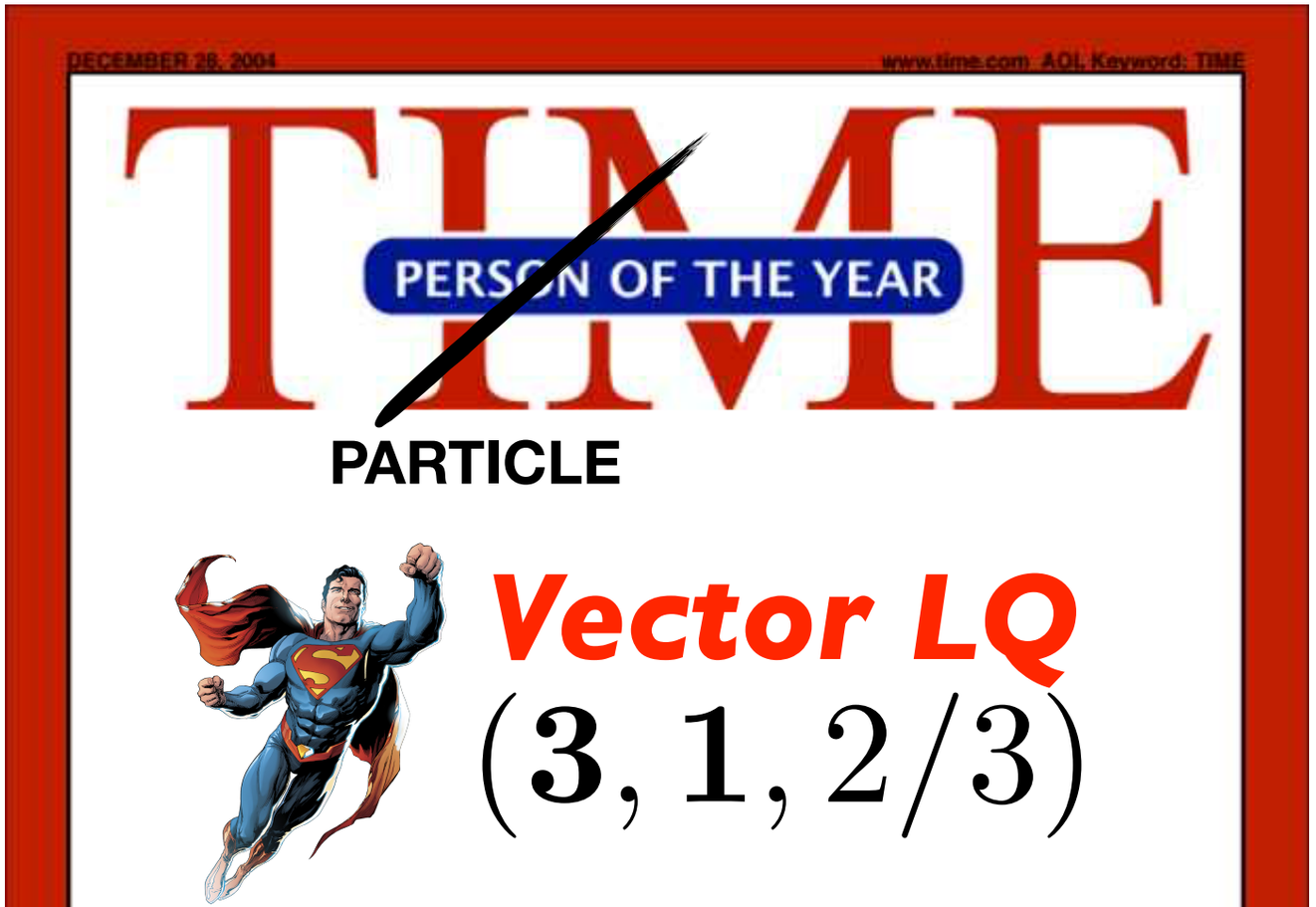
$$Z \to \tau^+\tau^-$$

[1706.07808,
1708.08450,
1709.00692,
1712.01368,
1712.06844,
1801.07256,
1802.04274,
1805.09328,
1805.03209,
1806.07403,
1807.02068,
1807.10745,
1808.00942,
1808.05511,
1808.07492,
1808.08179,
…]

Only a selection



# Direction I



A cake by [Buttazzo], 2017


'74 Pati-Salam

- *Pati-Salam quark-lepton unification*

$$\mathbf{4} = \mathbf{3}_q + \mathbf{1}_\ell$$

- *Resolves another open problem of the SM —* ***charge quantisation***
- *Low-scale Pati-Salam*
  - ✓ *No proton decay*
  - ✘ *Flavour* $\gtrsim$ *1000 TeV* [1801.02895]

A cake by [Buttazzo], 2017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Consistent model with Pati-Salam LQ at the TeV scale?

[This talk]

A cake by [Buttazzo], 2017


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Consistent model with Pati-Salam LQ at the TeV scale?

[This talk]

## Establishing links (The big picture)

[Talk by Isidori]

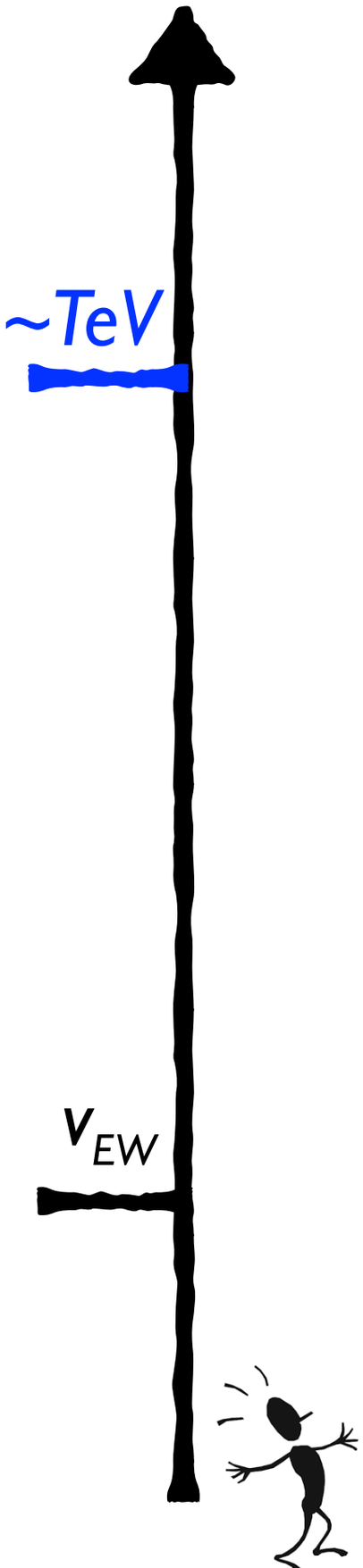
- *Hierarchy*
- *Charge quantization*
- *Flavour problem*
- *Neutrino masses*
- *B-anomalies*

- Massive vector crave an UV completion
- Simplified mediator model approach is incomplete**!**
- I want a model to be
  **Complete** (but simple),
  **Renormalizable**,
  **Calculable** (perturbatively)
- '**Proper**' low-energy model to check
  the stability of the B-anomalies solution

Consistent model with Pati-Salam LQ at the TeV scale?

[This talk]

# '4321' model




## Extended gauge symmetry

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

## Field content

| Field | $SU(4)$ | $SU(3)'$ | $SU(2)_L$ | $U(1)'$ | |
|---|---|---|---|---|---|
| Fermions | $q'^i_L$ | **1** | **3** | **2** | $1/6$ | **i=1,2,3** |
| | $u'^i_R$ | **1** | **3** | **1** | $2/3$ | |
| | $d'^i_R$ | **1** | **3** | **1** | $-1/3$ | |
| | $\ell'^i_L$ | **1** | **1** | **2** | $-1/2$ | |
| | $e'^i_R$ | **1** | **1** | **1** | $-1$ | |
| | $\Psi^i_L$ | **4** | **1** | **2** | $0$ | |
| | $\Psi^i_R$ | **4** | **1** | **2** | $0$ | |
| Scalars | $H$ | **1** | **1** | **2** | $1/2$ | |
| | $\Omega_1$ | $\overline{\mathbf{4}}$ | **1** | **1** | $-1/2$ | |
| | $\Omega_3$ | $\overline{\mathbf{4}}$ | **3** | **1** | $1/6$ | |
| | $\Omega_{15}$ | **15** | **1** | **1** | $0$ | |

4321 Model for B-anomalies
[Di Luzio, AG, Nardecchia]
1708.08450

Phenomenology
[Di Luzio, Fuentes-Martin, AG, Nardecchia, Renner]
1808.00942

Model structure from
[Georgi, Nakai], 1606.05865
[Diaz, Schmaltz, Zhong], 1706.05033

# '4321' model

~TeV

$v_{EW}$

## Extended gauge symmetry

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

SSB: $\langle \Omega_3 \rangle > \langle \Omega_1 \rangle \gg \langle \Omega_{15} \rangle \gg \langle H \rangle$

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

## 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:

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

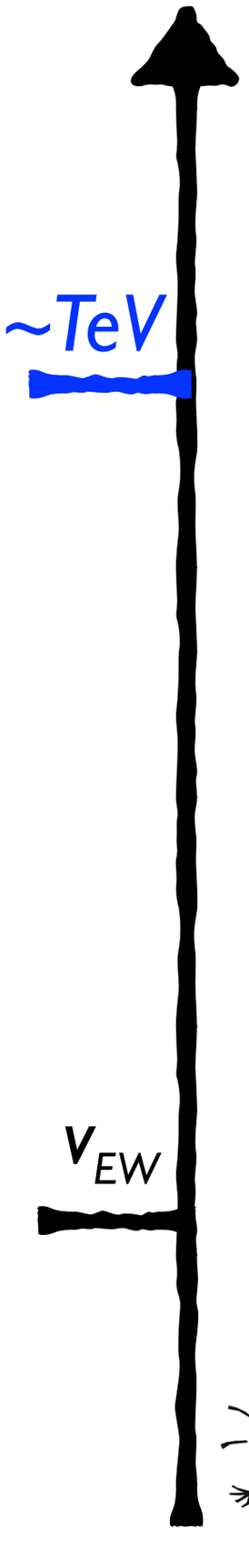
$$\langle \Omega_3 \rangle = \begin{pmatrix} \frac{v_3}{\sqrt{2}} & 0 & 0 \\ 0 & \frac{v_3}{\sqrt{2}} & 0 \\ 0 & 0 & \frac{v_3}{\sqrt{2}} \\ 0 & 0 & 0 \end{pmatrix}, \quad \langle \Omega_1 \rangle = \begin{pmatrix} 0 \\ 0 \\ 0 \\ \frac{v_1}{\sqrt{2}} \end{pmatrix}$$

## Gauge couplings:

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

*One free coupling constant

# '4321' model

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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

$(3, 1, 2/3)$
**Leptoquark**
*Complex

$(8, 1, 0)$
**G'**

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

**Close in mass to the LQ!**

# '4321' model

~TeV

$v_{EW}$

***Extended gauge symmetry***

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

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***15 broken generators***

$(3, 1, 2/3)$
***Leptoquark***
*Complex

$(8, 1, 0)$
***G'***

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

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

# '4321' model

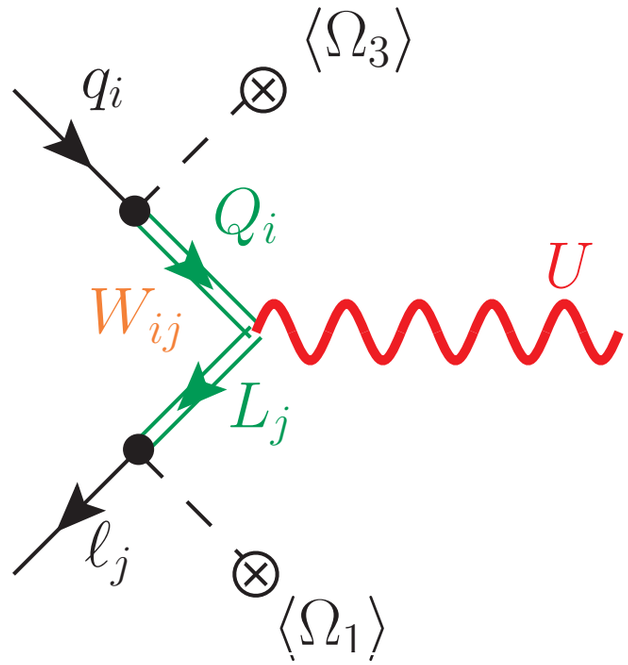
***A vector-like fermion rep.*** $(4, 1, \mathbf{2}, 0)$

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

$$-\overline{q}'_L \, \lambda_q \, \Omega_3^T \Psi_R - \overline{\ell}'_L \, \lambda_\ell \, \Omega_1^T \Psi_R$$

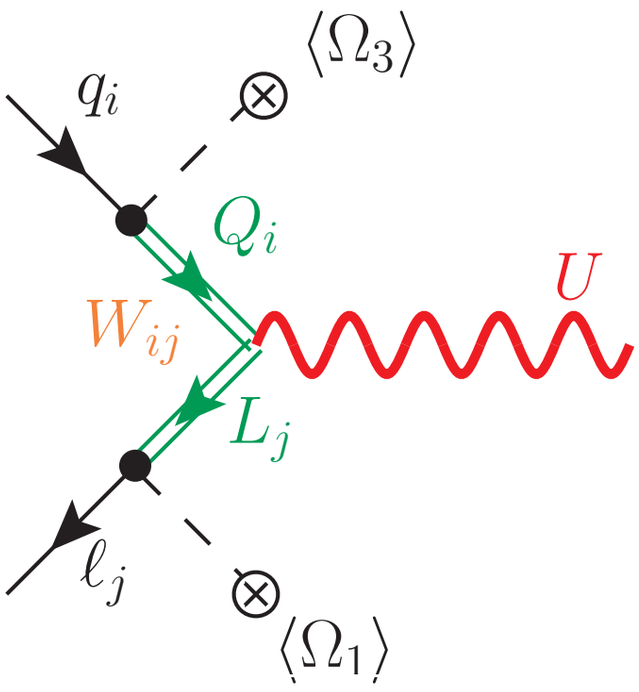
- $\langle \Omega_3 \rangle$ mixes the would-be SM state $q'_L$ with $Q'_L \subset \Psi_L$
- $\langle \Omega_1 \rangle$ mixes the would-be SM state $\ell'_L$ with $L'_L \subset \Psi_L$.

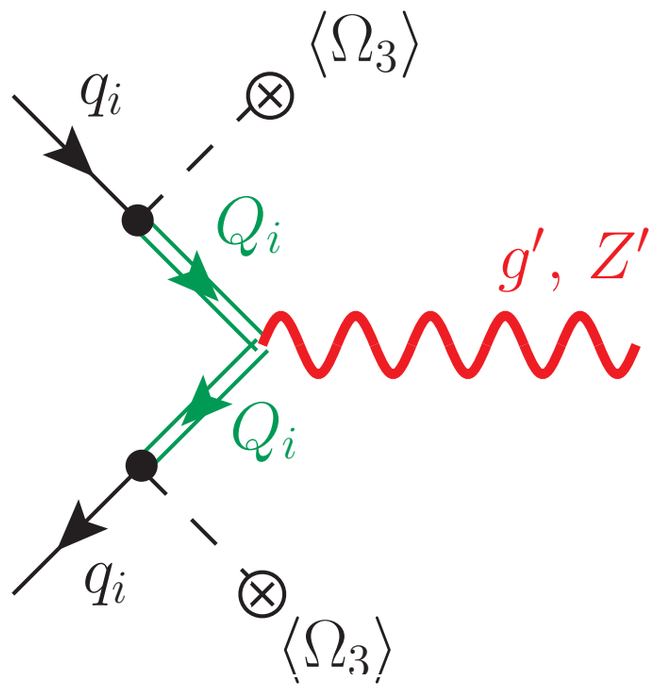
*SM fermion* ***doublets*** *mix with the vector-like partners*

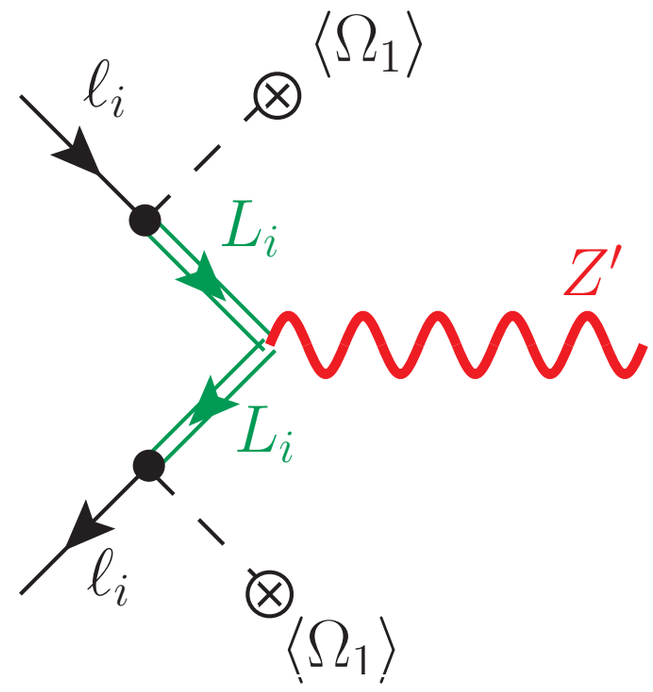



***Left-handed dominance!***

- ***How to get large flavour violation to be mediated only by the LQ?***




## ***Cabibbo mechanism for LQ***

*'4321' model*

# *Cabibbo mechanism for LQ*

Without loss of generality

$$\mathcal{L}_{\rm SM-like} = -\overline{q}'_L V^\dagger \hat{Y}_u d_R \tilde{H} - \overline{q}'_L \hat{Y}_d d_R H - \overline{\ell}'_L \hat{Y}_e e_R H + \text{h.c.}\,,$$

$$\mathcal{L}_{\rm mix} = -\overline{q}'_L \lambda_q \Psi_R \Omega_3 - \overline{\ell}'_L \lambda_\ell \Psi_R \Omega_1 - \overline{\Psi}_L (\hat{M} + \lambda_{15}\Omega_{15}) \Psi_R + \text{h.c.}$$

Assumptions

1. $\lambda_q = \hat{\lambda}_q \equiv \text{diag}\,(\lambda^q_{12}, \lambda^q_{12}, \lambda^q_3)\,,$
2. $\lambda_\ell = \hat{\lambda}_\ell\, W^\dagger \equiv \text{diag}\left(\lambda^\ell_1, \lambda^\ell_2, \lambda^\ell_3\right) \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{LQ} & -\sin\theta_{LQ} \\ 0 & \sin\theta_{LQ} & \cos\theta_{LQ} \end{pmatrix}$
3. $\lambda_{15} \propto \hat{M} \propto \mathbb{1}\,,$

*a hat means diagonal

**1**

- ***No tree-level Z', g' FCNC for down quarks***
- ***Strong suppression of tree-level FCNC for up quarks***

$$\mathcal{G}_Q \equiv U(2)_{q'+\Psi} \times U(1)_{q'_3+\Psi_3}$$
$$\lambda_\ell \to 0$$

***'4321' model***

**2** **3**

- ***Redefine***

$$\Psi_L = (Q'_L, L'_L)^T = (Q_L, W L_L)^T$$

*same for the right-handed

- ***No tree-level Z' FCNC for leptons***

$$\lambda_q \to 0 \qquad \mathcal{G}_L = U(1)_{\ell'_1+\tilde{\Psi}_1} \times U(1)_{\ell'_2+\tilde{\Psi}_2} \times U(1)_{\ell'_3+\tilde{\Psi}_3}$$

- ***Only LQ interaction feels W matrix!***

$$i\overline{\Psi}_L \gamma^\mu D_\mu \Psi_L \supset \frac{g_4}{\sqrt{2}} U_\mu\, \overline{Q}_L \gamma^\mu \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{LQ} & \sin\theta_{LQ} \\ 0 & -\sin\theta_{LQ} & \cos\theta_{LQ} \end{pmatrix} L_L\,.$$

*Calculable, so calculate!*

**Contents**

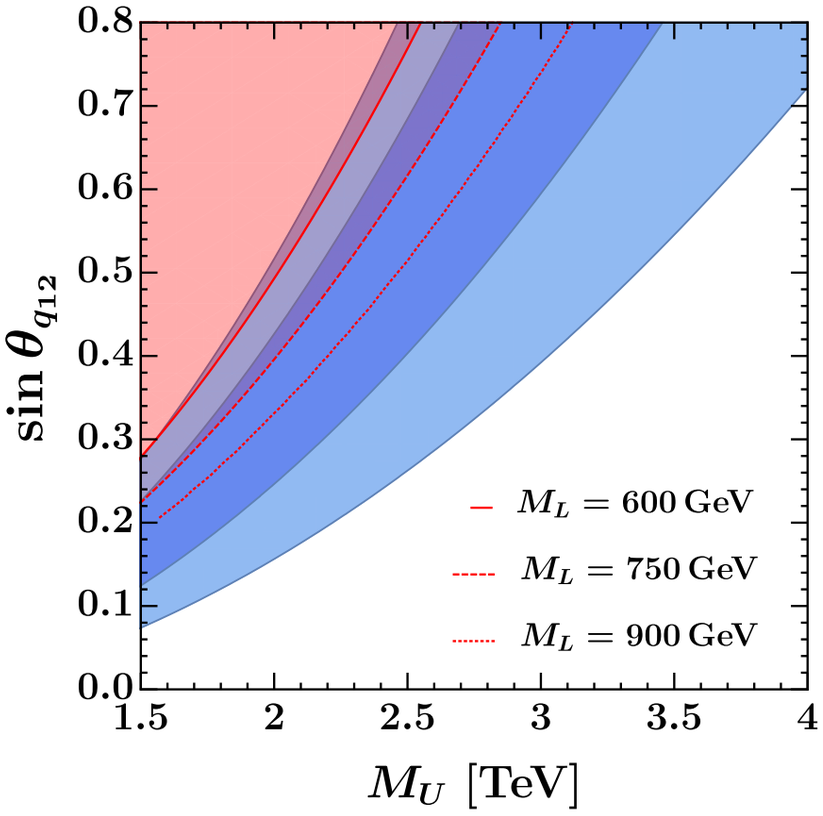


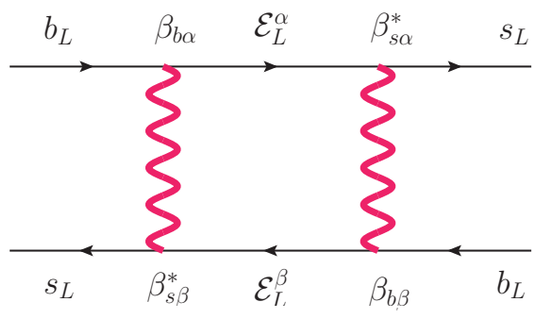
‘4321’ model

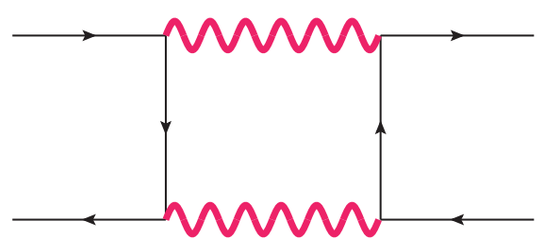
Phenomenology
[Di Luzio, Fuentes-Martin, AG, Nardecchia, Renner]
1808.00942

# '4321' model

$$B_s - \overline{B}_s$$



**GIM suppression!** $C_{bs}^{LL} \sim \Delta R^2_{D^{(*)}}\, M_L^2$

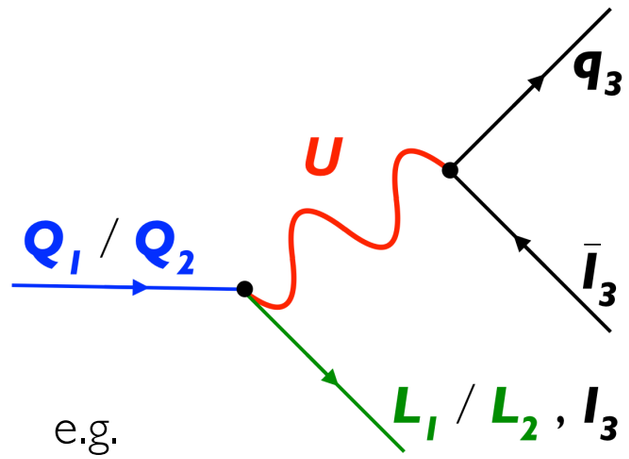
$$C_{bs}^{LL} = -\frac{g_4^2}{64\pi^2}\, C_U\, \frac{1}{(V_{tb}V_{ts}^*)^2\, R_{\rm SM}^{\rm loop}} \sum_{\alpha,\beta} \lambda_\alpha^B \lambda_\beta^B\, F(x_\alpha, x_\beta)$$

$$F(x_\alpha, x_\beta) = \frac{1}{(1-x_\alpha)(1-x_\beta)}\left(\frac{7x_\alpha x_\beta}{4} - 1\right) + \frac{x_\alpha^2 \log x_\alpha}{(x_\beta - x_\alpha)(1-x_\alpha)^2}\left(1 - 2x_\beta + \frac{x_\alpha x_\beta}{4}\right) + \frac{x_\beta^2 \log x_\beta}{(x_\alpha - x_\beta)(1-x_\beta)^2}\left(1 - 2x_\alpha + \frac{x_\alpha x_\beta}{4}\right)$$

***The lightest new states are vector-like leptons!***

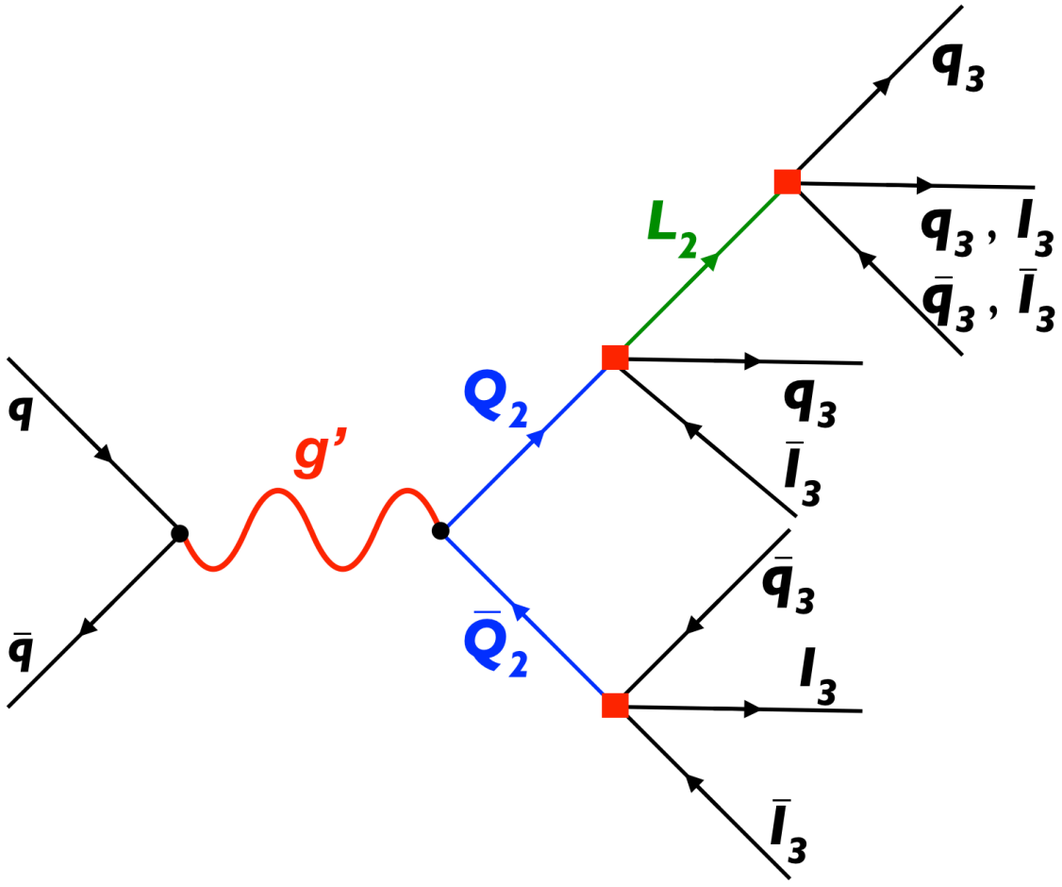
# *'4321' model*

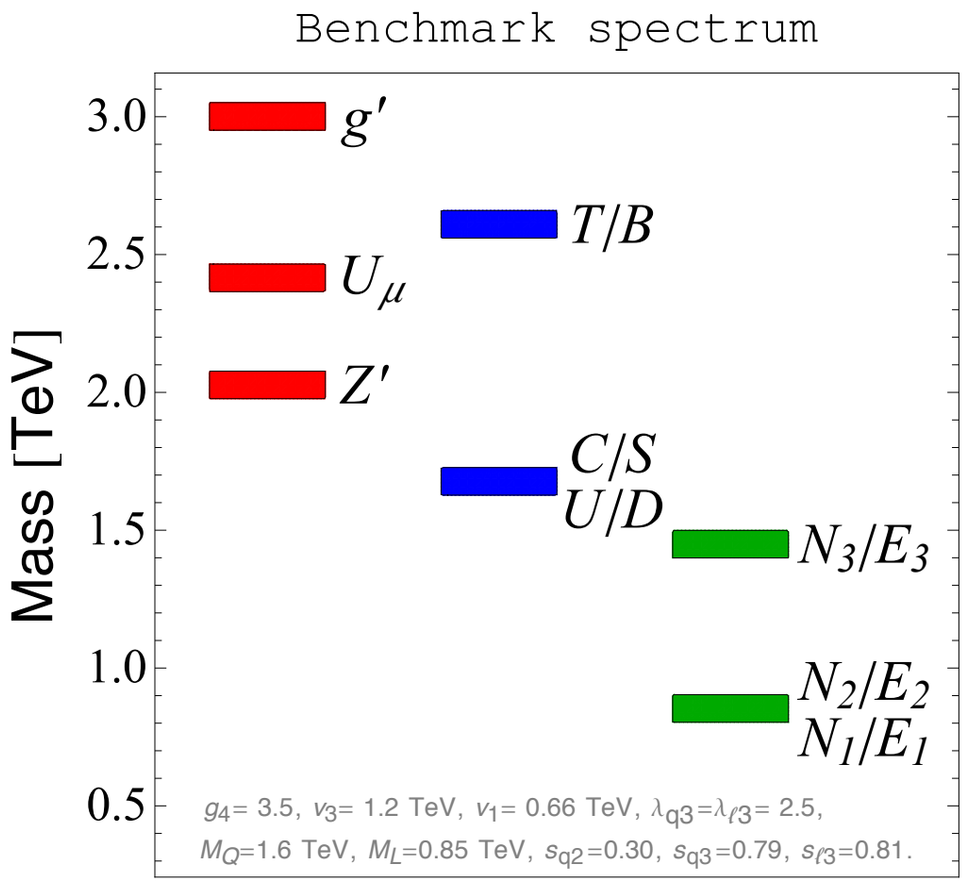
- Peculiar high-$p_T$ signatures
- Dominant decays of new fermions are $I > 3$




e.g.

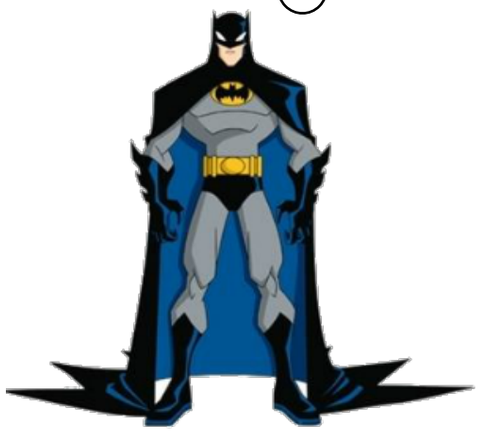
- Exotic multi-lepton & multi-jet signatures



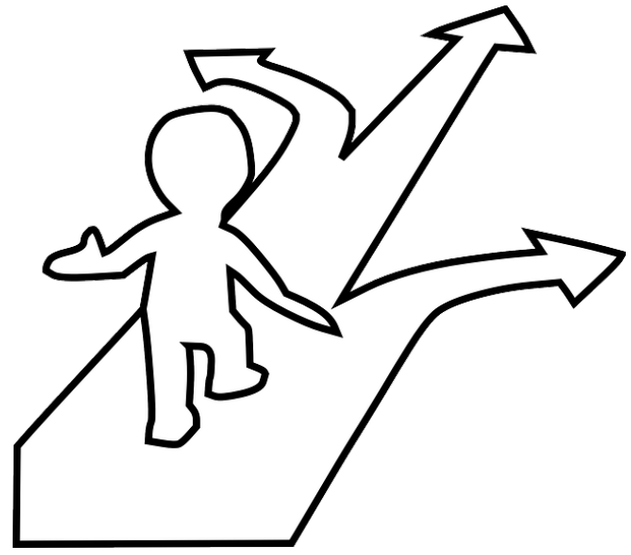



$$b \to c\tau \bar{N}_R$$

"missing"



Old idea, see e.g. [Bečirević, Fajfer, Košnik, Sumensari] 1608.08501



# Direction II

**'$SU(2)_L$ was a blessing, but also a curse'**

- Idea: **Decorrelate R(D$^{(*)}$) from FCNC limits**

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

**+ light**

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

[Asadi, Buckley, Shih] 1804.04135

[AG, Robinson, Shakya, Zupan] 1804.04642

**Recent activity**

[1804.04642,
1804.04135,
1807.04753,
1807.10745,
1809.01107,
…]

*'3221' model* [backup]

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

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

+ light

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

***Simplified mediator model***

[Marzocca et al], 1807.10745

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

$$U_1^\mu \sim (\mathbf{3}, \mathbf{1}, 2/3)$$
+ light
$$N_R = (\mathbf{1}, \mathbf{1}, 0)$$

***Simplified mediator model***

[Marzocca et al], 1807.10745

## *'4321'* Completion of the Vector LQ + RHN solution from 1807.10745

- Field content

Vector-like fermions

| Field | $SU(4)$ | $SU(3)'$ | $SU(2)_L$ | $U(1)'$ |
|---|---|---|---|---|
| $\Psi_{L,R}$ | 4 | 1 | 2 | 0 |
| $\Psi^u_{R,L}$ | 4 | 1 | 1 | 1/2 |
| $\Psi^d_{R,L}$ | 4 | 1 | 1 | -1/2 |

1 family

Decomposition under the SM:

$$\Psi_{L,R} = \begin{pmatrix} Q'_{L,R} \\ L'_{L,R} \end{pmatrix} \quad \Psi^u_{L,R} = \begin{pmatrix} U'_{L,R} \\ N'_{L,R} \end{pmatrix}$$

$$\Psi^d_{L,R} = \begin{pmatrix} D'_{L,R} \\ E'_{L,R} \end{pmatrix}$$

*Full 'Pati-Salam' family

$i=1,2,3$ SM-like fermions

| Field | $SU(4)$ | $SU(3)'$ | $SU(2)_L$ | $U(1)'$ |
|---|---|---|---|---|
| $q_L^i$ | 1 | 3 | 2 | 1/6 |
| $u_R^i$ | 1 | 3 | 1 | 2/3 |
| $d_R^i$ | 1 | 3 | 1 | -1/3 |
| $\ell_L^i$ | 1 | 1 | 2 | -1/2 |
| $e_R^i$ | 1 | 1 | 1 | -1 |
| $\nu_R^i$ | 1 | 1 | 1 | 0 |

light-sterile neutrino

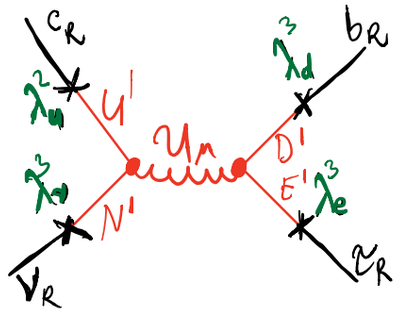
- 4321 > 321 breaking from 1708.08450
- Yukawa

$$\mathcal{L}_Y \supset -\bar{q}'_L\, Y_d\, H d'_R - \bar{q}'_L\, Y_u\, \tilde{H} u'_R - \bar{\ell}'_L\, Y_e\, H e'_R \quad (9)$$
$$- \bar{q}'_L\, \lambda_q\, \Omega_3^T \Psi_R - \bar{\ell}'_L\, \lambda_\ell\, \Omega_1^T \Psi_R - \bar{\Psi}_L\, M\, \Psi_R + \text{h.c.}\,,$$

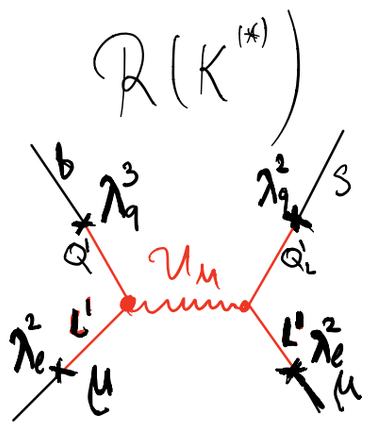
$$-\bar{\Psi}^u_L \lambda_u \Omega_3^* u'_R - \bar{\Psi}^u_L \lambda_\nu \Omega_1^* \nu'_R - \bar{\Psi}^u_L M^u \Psi^u_R$$
$$-\bar{\Psi}^d_L \lambda_d \Omega_3^* d'_R - \bar{\Psi}^d_L \lambda_e \Omega_1^* e'_R - \bar{\Psi}^d_L M^d \Psi^d_R + \text{h.c.}$$

- Anomalies

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




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






[AG, Marzocca], TBD

[LHCb please stop this madness]

# Backup slides

# '3221' model

[Asadi, Buckley, Shih] 1804.04135
[AG, Robinson, Shakya, Zupan] 1804.04642

~TeV

***Extended gauge symmetry***

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

SSB: $\langle H_V \rangle$

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

***3 broken generators***

$(1,1,+1)$
***W'***

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

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

$v_{EW}$

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

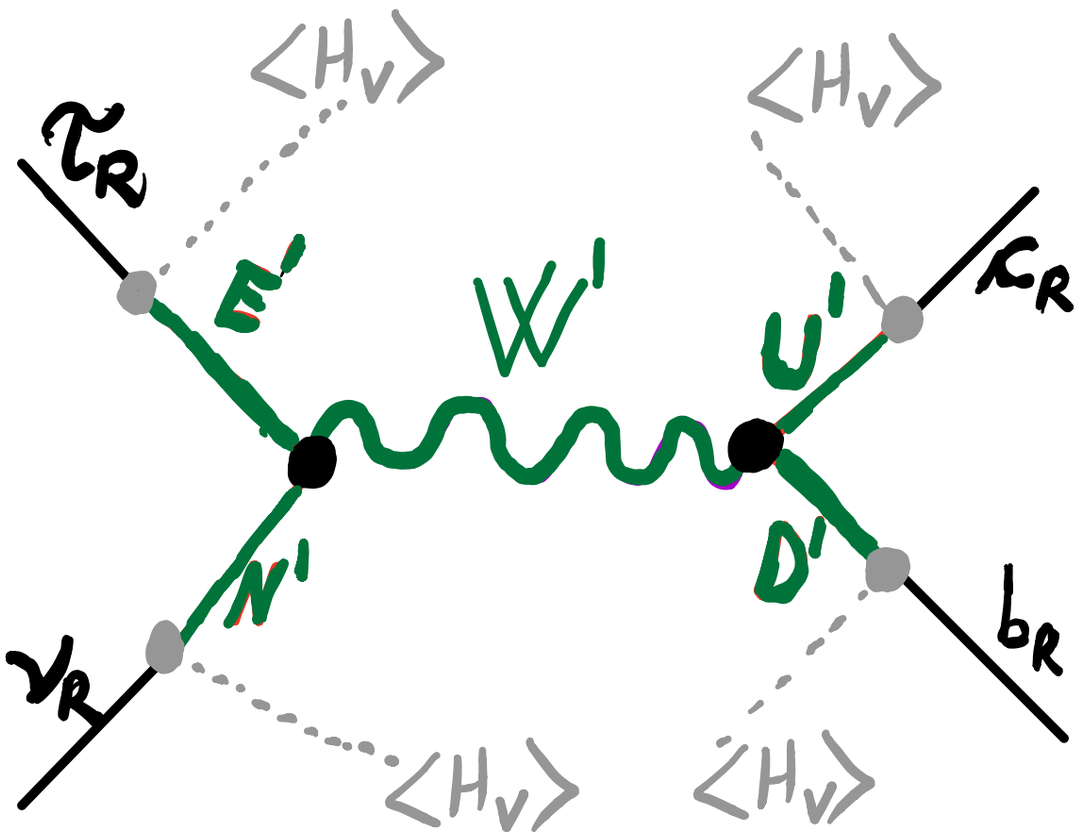
# '3221' model

[AG, Robinson, Shakya, Zupan]
1804.04642

## 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 |
| $\ell'^i_L$ | **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 |
| $\nu'^i_R$ | **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:**

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

**: ) FV Z' couplings uncorrelated!**

# '4321' model

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

~TeV

$v_{EW}$

## Extended gauge symmetry

$$H_\mu^\alpha \quad (\alpha = 1,\dots,15) \qquad G'^a_\mu \quad (a = 1,\dots,8) \qquad W_\mu^i \quad (i = 1,2,3) \qquad B'_\mu$$

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

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

$\Omega_3 = (\overline{4}, 3, 1, 1/6)$

$\Omega_1 = (\overline{4}, 1, 1, -1/2)$

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

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

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

*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