Gauge leptoquark solution to B-anomalies

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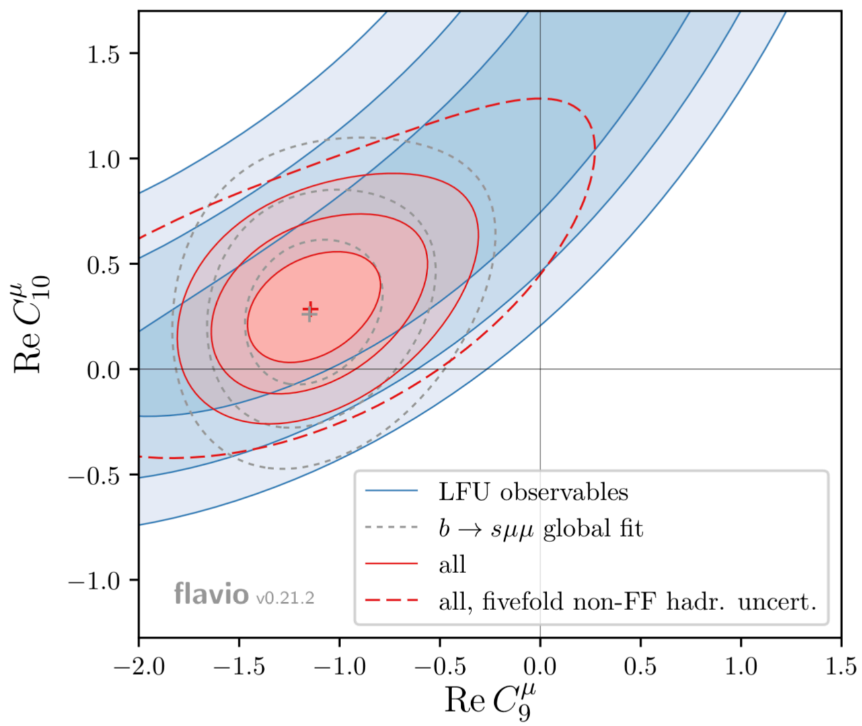
Based on **arXiv:1808.00942**, **arXiv:1712.01368, arXiv:1805.09328,** and ongoing work

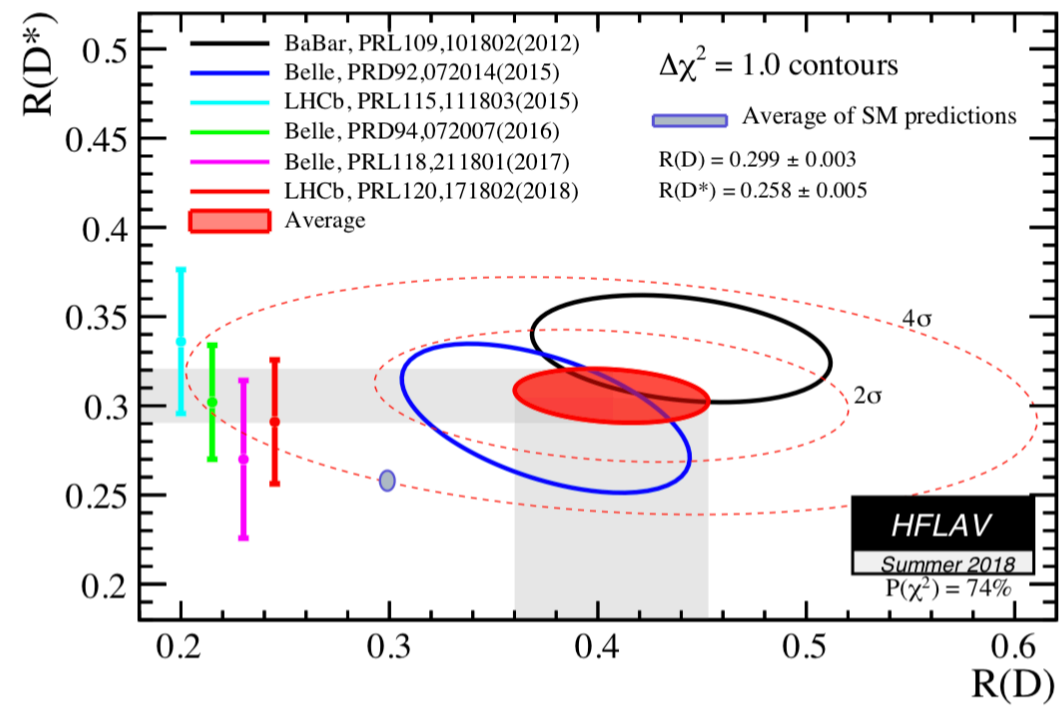
CERN-TH Institute: From flavor anomalies to direct discoveries of New Physics

You know the motivation

$b \to s\ell\ell$

$b \to c\tau\nu$





$3_Q \to 2_Q 2_L 2_L$ $\ll$ $3_Q \to 2_Q 3_L 3_L$

~25% of a SM **loop** effect

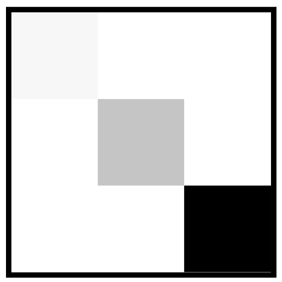
~20% of a SM **tree-level** effect

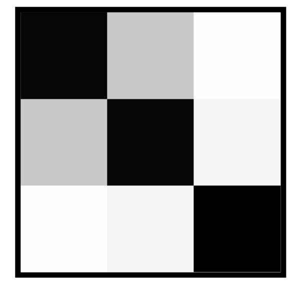
The only source of **lepton flavor universality violation** in the SM (Yukawas) follow a similar trend: $y_e \ll y_\mu \ll y_\tau$.... Are the anomalies connected to them?

U(2) flavor symmetry as a guiding principle

The SM Yukawas respect an approximate U(2) symmetry

Barbieri et al. 1105.2296

$M_{u,d} \sim$ 

$V_{\rm CKM} \sim$ 

$$\mathbf{U(2)_q \times U(2)_u \times U(2)_d}$$

$$\psi = ((\psi_1\ \psi_2)(\psi_3))$$

$$\boldsymbol{Y_{u,d}} = \left(\begin{array}{c:c} 0 & 0 \\ \hdashline 0 & 1 \end{array}\right) \longrightarrow \left(\begin{array}{c:c} 0 & \boldsymbol{V} \\ \hdashline 0 & 1 \end{array}\right) \longrightarrow \left(\begin{array}{c:c} \boldsymbol{\Delta} & \boldsymbol{V} \\ \hdashline 0 & 1 \end{array}\right)$$

$|\boldsymbol{V}| \sim |V_{ts}|$

$|\boldsymbol{\Delta}| \sim y_c$

Unbroken symmetry — Leading breaking — Final breaking

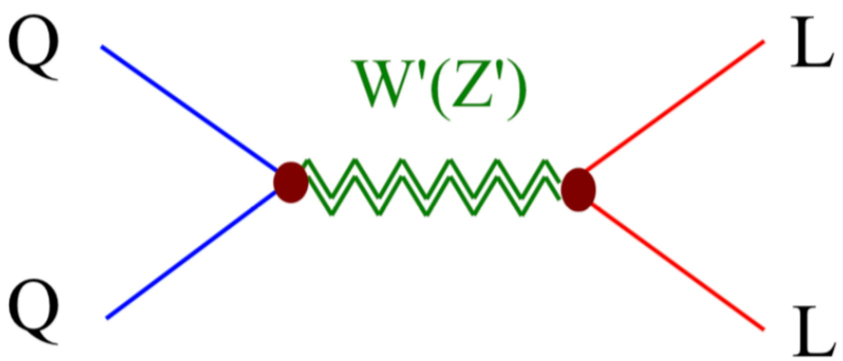
- ✓ Assuming a single leading breaking ensures an effective protection of FCNCs [**SM-like mixing among light & 3rd generations** ⟶ consistent with CKM fits]
- ✓ Large NP effects in 3rd generation, light-generation effects controlled by the breaking
- ● Compatibility between high-p_T data and $R(D^{(*)})$ require largish 32 quark couplings

Which mediator?

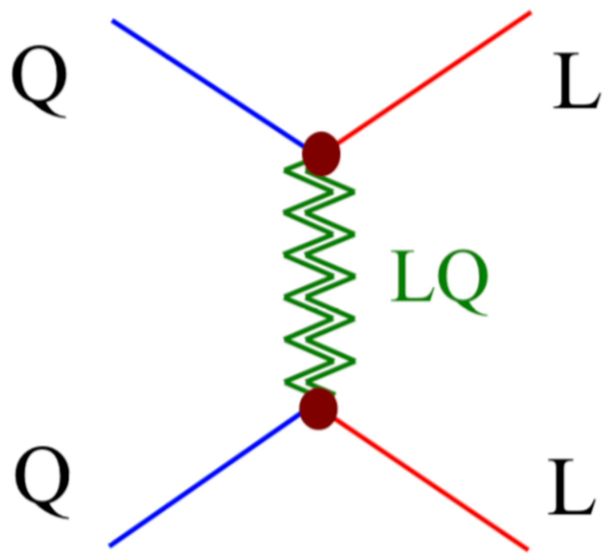
Leptoquarks have a clear advantage: they allow to **decorrelate** the semileptonic 4-fermion operators from the hadronic and leptonic ones (at tree-level)

Lepton x Lepton

(LFUV tests, LFV…)



Quark x Lepton



Quark x Quark

$(\Delta F = 2)$

Simplified dynamical models

Faroughi @ CKM18

	Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
Scalars	$S_1 = (\mathbf{3}, \mathbf{1})_{-1/3}$	✗	✓	✗
	$R_2 = (\mathbf{3}, \mathbf{2})_{7/6}$	✗	✓	✗
	$\widetilde{R}_2 = (\mathbf{3}, \mathbf{2})_{1/6}$	✗	✗	✗
	$S_3 = (\mathbf{3}, \mathbf{3})_{-1/3}$	✓	✗	✗
Vector	$U_1 = (\mathbf{3}, \mathbf{1})_{2/3}$	✓	✓	✓
	$U_3 = (\mathbf{3}, \mathbf{3})_{2/3}$	✓	✗	✗

Angelescu, Becirevic, DAF, Sumensari [1808.08179]

(*) Assuming no light ν_R (see talk by Dean Robison)

Three viable options in the market$^{(*)}$:

★ U_1 + UV completion

[di Luzio, Greljo, Nardecchia 1708.08450;
Calibbi, Crivellin, Li 1709.00692;
Bordone, Cornella, JF, Isidori 1712.01368;
Barbieri, Tesi, 1712.06844…]

★ $S_1 + S_3$

[Crivellin, Muller, Ota 1703.09226;
Buttazzo et al. 1706.07808;
Marzocca 1803.10972]

★ $S_3 + R_2$

[Bečirević et al., 1806.05689]

In this talk I will discuss different U_1 UV completions
from an extended gauge sector

Why not the Pati Salam model?

The vector-leptoquark solution points to Pati-Salam unification

$$\mathbf{PS} \equiv \mathbf{SU(4)} \times \mathbf{SU(2)_L} \times \mathbf{SU(2)_R}$$

Pati, Salam, Phys. Rev. D10 (1974) 275

$$\Psi_{L,R} = \begin{pmatrix} Q^1_{L,R} \\ Q^2_{L,R} \\ Q^3_{L,R} \\ L_{L,R} \end{pmatrix}$$

[Lepton number as the 4th "color"]

✓ $\mathrm{SU}(4)$ is the smallest group containing the required vector LQ [$U_1 \sim (\mathbf{3},\mathbf{1})_{2/3}$]

✓ No proton decay (protected by symmetry)

✗ The (flavor blind) Pati-Salam model cannot work

→ The bounds from $K_L \to \mu e$ and $D - \bar{D}$ lift the LQ mass to 100 TeV

✗ The associated Z' would be excessively produced at LHC

→ $M_U \sim M_{Z'} \sim \mathcal{O}(\mathrm{TeV})$ & $\mathcal{O}(g_s)$ Z' couplings to valence quarks

The 4321 model(s)

$U(1)_Y$

$$SU(4) \times SU(3) \times SU(2)_L \times U(1) \xrightarrow{SSB} SU(3)_c \times SU(2)_L \times U(1)_Y$$

$SU(3)_c$

$$SU(3)_c = (SU(4) \times SU(3))_{\rm diag}$$

$$U(1)_Y = (SU(4) \times U(1))_{\rm diag}$$

Why an additional $SU(3)$?

✘ The extra $SU(3)$ gives a g' (coloron), apart from the Z' already present in PS

✔ It allows to decorrelate the $SU(4)$ from the SM color group. In the limit $g_4 \gg g_{3,1}$, this solves the high-p_T problem

→ $\mathcal{O}(g_3/g_4)$ and $\mathcal{O}(g_1/g_4)$ g' and Z' couplings to valence quarks

The 4321 model(s)

$$\overbrace{\underbrace{SU(4)\times SU(3)}_{SU(3)_c}\times SU(2)_L\times U(1)}^{U(1)_Y} \xrightarrow{SSB} SU(3)_c\times SU(2)_L\times U(1)_Y$$

Different fermion embeddings give two distinct solutions:

- ★ The original 4321
  [di Luzio, Greljo, Nardecchia 1708.08450; Diaz, Schmaltz, Zhong 1706.05033]

- ★ PS^3 (at low energies)
  [Bordone, Cornella, JF, Isidori 1712.01368, 1805.09328; Greljo, Stefanek, 1802.04274]

The original 4321

di Luzio, Greljo, Nardecchia 1708.08450

$U(1)_Y$

$$SU(4) \times SU(3) \times SU(2)_L \times U(1) \xrightarrow{\langle \Omega_{1,3,15} \rangle} SU(3)_c \times SU(2)_L \times U(1)_Y$$

$SU(3)_c$

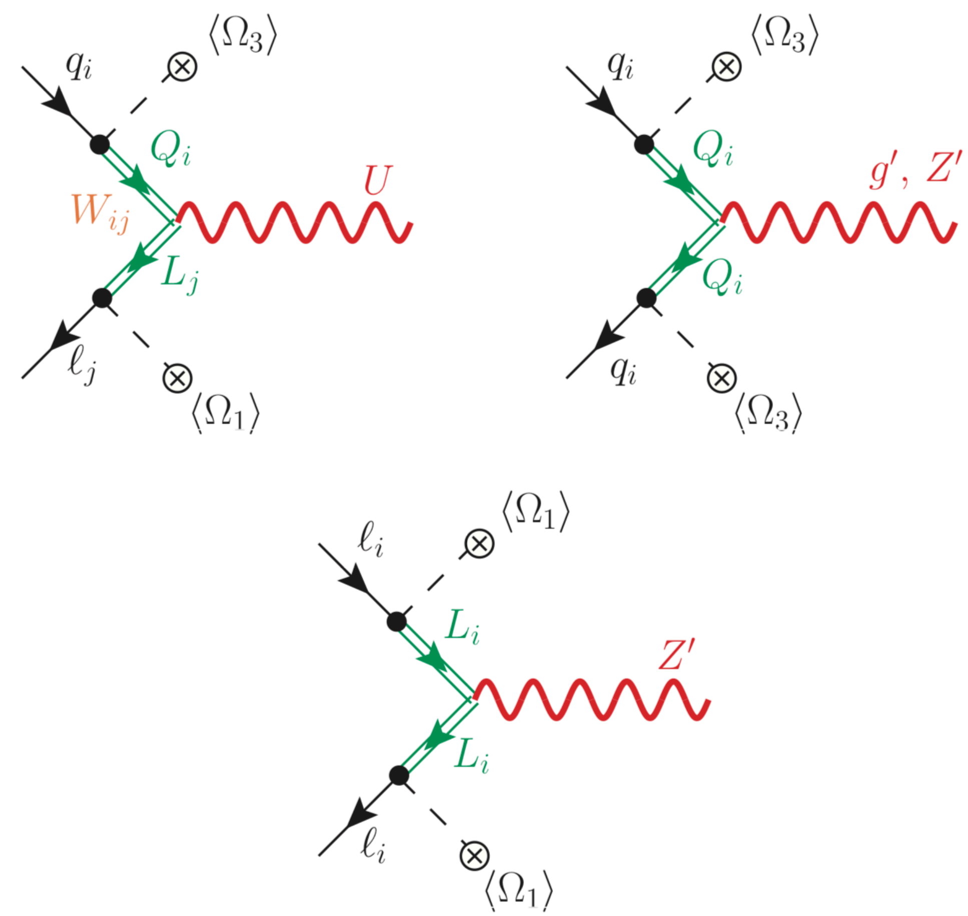
Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$
$q_L'^i$	**1**	**3**	**2**	1/6
$u_R'^i$	**1**	**3**	**1**	2/3
$d_R'^i$	**1**	**3**	**1**	−1/3
$\ell_L'^i$	**1**	**1**	**2**	−1/2
$e_R'^i$	**1**	**1**	**1**	−1
χ_L^i	**4**	**1**	**2**	0
χ_R^i	**4**	**1**	**2**	0
H	**1**	**1**	**2**	1/2
Ω_1	$\bar{\mathbf{4}}$	**1**	**1**	−1/2
Ω_3	$\bar{\mathbf{4}}$	**3**	**1**	1/6
Ω_{15}	**15**	**1**	**1**	0

$n_{\mathrm{SM-like}} = 3$

$n_{\mathrm{VL}} = 3$

Not in the "original" 4321

[di Luzio, JF, Greljo, Nardecchia, Renner 1808.00942]



Flavor structure controlled (i.e. "fixed") via SM-VL mixing

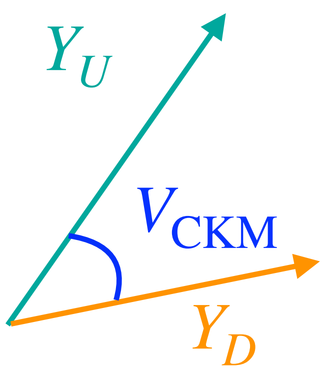
A small parenthesis: the SM flavor structure

In the SM the only source of flavor appears in the Yukawas

$$\mathscr{L}_Y \supset \boldsymbol{V^\dagger_{\mathrm{CKM}}}\, \hat{Y}_U\, \bar{q}'\, \tilde{H}\, u_R + \hat{Y}_D\, \bar{q}'\, H\, d_R$$

It presents a very interesting (nice) feature…

In the absence of one Yukawa, Y_U or Y_D, the CKM is unphysical



→ Tree-level flavor violation (via the CKM) appears <u>only in the charged currents</u>

$$q = \begin{pmatrix} \boldsymbol{V^\dagger_{\mathrm{CKM}}}\, u \\ d \end{pmatrix} \qquad \ell = \begin{pmatrix} \nu \\ \ell \end{pmatrix}$$

(down flavor basis)

Can we mimic this feature?

4321 flavor structure

As in the SM model, in 4321 the only source of flavor appears in the Yukawas…

SM Yukawas: $\mathscr{L}_Y \supset \boldsymbol{V^\dagger_{\mathrm{CKM}}}\, \hat{Y}_U\, \bar{q}'\, \tilde{H}\, u_R + \hat{Y}_D\, \bar{q}'\, H\, d_R$

Also as in the SM, Yukawa structure imposed "by hand"

SM-VL mixing: $\mathscr{L}_\Psi \supset \lambda_\ell\, \bar{\ell}'_L\, \Omega_1\, \chi_R + \lambda_q\, \bar{q}'_L\, \Omega_3\, \chi_R + \lambda_{15}\, \overline{\Psi}_L\, \Omega_{15}\, \chi_R + M\, \bar{\chi}_L\, \chi_R$

Flavor ansatz:

- $U(2)$-like quark sector ($\Delta F = 2$ obs)
- No couplings to e (or negligibly small)
- SM-VL flavor alignment$^{(*)}$
- VL masses flavor neutral

$(*)$ **Small** misalignments are possible (constrained by $\Delta F = 2$ & LFV)

4321 flavor structure

As in the SM model, the only source of flavor appears in the Yukawas…

SM Yukawas: $\mathcal{L}_Y \supset V^\dagger_{\mathrm{CKM}} \hat{Y}_U \, \bar{q}' \tilde{H} u_R + \hat{Y}_D \, \bar{q}' H d_R$

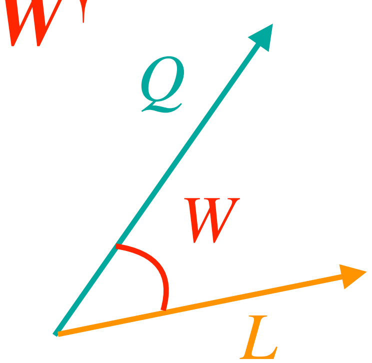
λ_{15} & $M \propto \mathbb{1}$
(flavor neutral)

SM-VL mixing: $\mathcal{L}_\Psi \supset \lambda_\ell \, \bar{\ell}'_L \Omega_1 \chi_R + \lambda_q \, \bar{q}'_L \Omega_3 \chi_R + \lambda_{15} \, \bar{\chi}_L \Omega_{15} \chi_R + M \, \bar{\chi}_L \chi_R$

Splits M_Q & M_L

$\lambda_q = \mathrm{diag}\,(\lambda_{q_{12}}, \lambda_{q_{12}}, \lambda_{q_3}) \, W^\dagger$

$\lambda_\ell = \mathrm{diag}\,(0, \lambda_\mu, \lambda_\tau) \qquad \lambda_\mu \ll \lambda_\tau$



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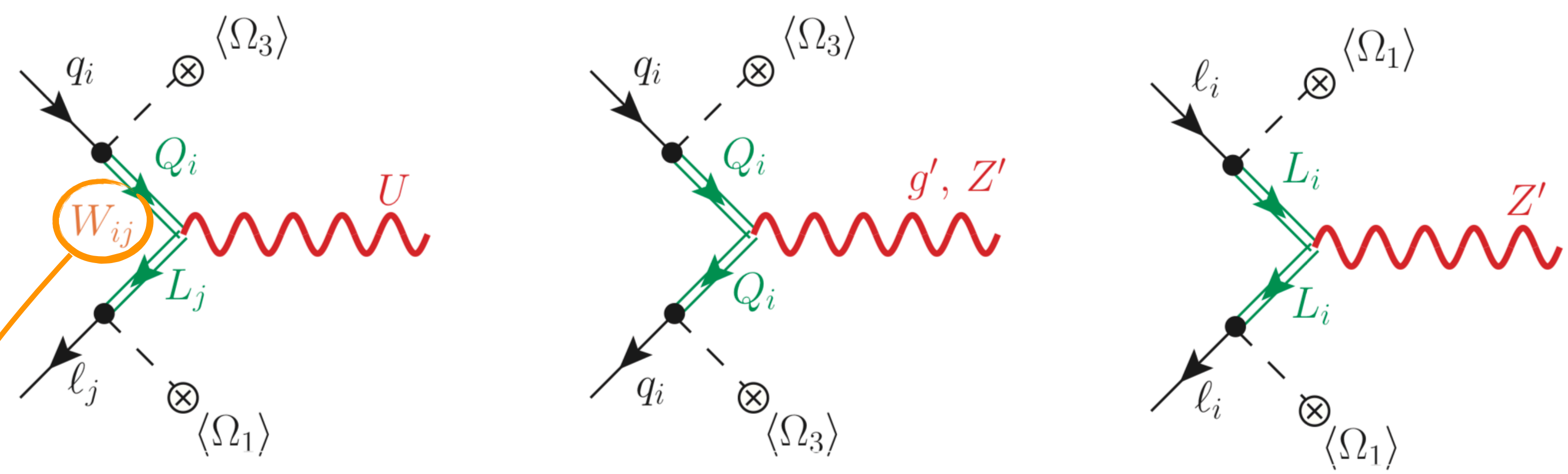
$$q = \begin{pmatrix} V^\dagger_{\mathrm{CKM}} u \\ d \end{pmatrix} \qquad \ell = \begin{pmatrix} \nu \\ \ell \end{pmatrix} \qquad \Psi = \begin{pmatrix} W^\dagger Q \\ L \end{pmatrix}$$

4321 flavor structure



Tree-level FCNCs under control

- ★ Absent in down-quark and charged lepton sectors
- ★ SM-like (i.e U(2) protected) in up-quark sector

$$W = \begin{pmatrix} 0 & 0 & 0 \\ 0 & c_{\theta_{\rm LQ}} & s_{\theta_{\rm LQ}} \\ 0 & -s_{\theta_{\rm LQ}} & c_{\theta_{\rm LQ}} \end{pmatrix}$$

Maximal 2-3 flavor violation
($\theta_{LQ} \approx \pi/4$)

$$\mathscr{L}_U \supset \frac{g_4}{\sqrt{2}} U_\mu (\beta_L^{ij}\, \bar{q}_L^i \gamma^\mu \ell_L^j + \beta_R^{ij}\, \bar{d}_R^i \gamma^\mu e_R^j) + h.c.$$

$$\beta_L \approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & c_{\theta_{LQ}} s_{q_{12}} s_{\ell_2} & s_{\theta_{LQ}} s_{q_{12}} s_{\ell_3} \\ 0 & -s_{\theta_{LQ}} s_{q_3} s_{\ell_2} s_{\ell_3} & c_{\theta_{LQ}} s_{q_3} s_{\ell_3} \end{pmatrix}$$

$$\beta_R \approx 0$$

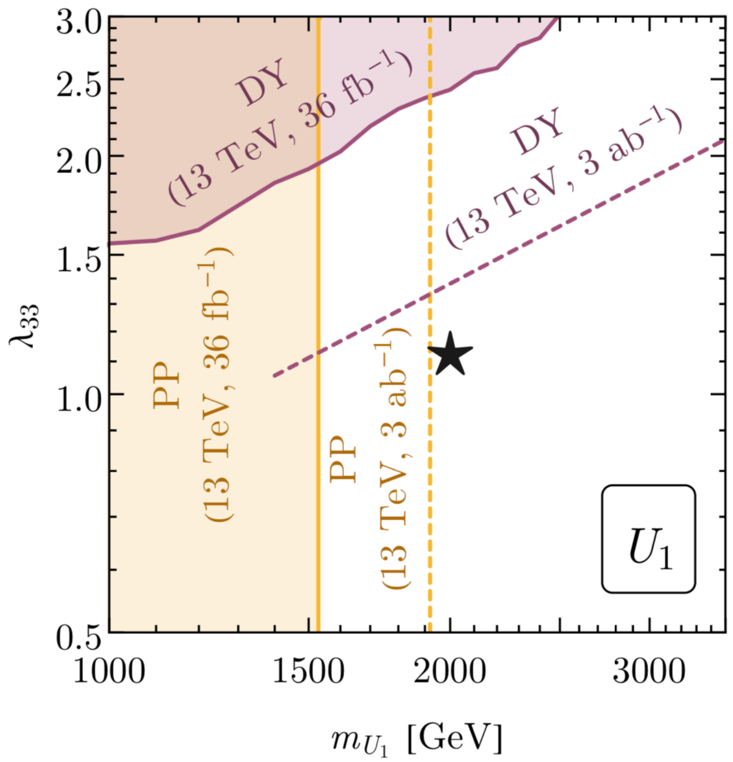
$$\Delta R_{D^{(*)}} \approx 0.2 \left(\frac{2\ \mathrm{TeV}}{M_U}\right)^2 \left(\frac{g_4}{3.5}\right)^2 \sin(2\theta_{LQ}) \left(\frac{s_{\ell_3}}{0.8}\right)^2 \left(\frac{s_{q_3}}{0.8}\right) \left(\frac{s_{q_2}}{0.3}\right)$$

Same NP contribution for $R(D)$ and $R(D^*)$

U_1 phenomelogy in 4321

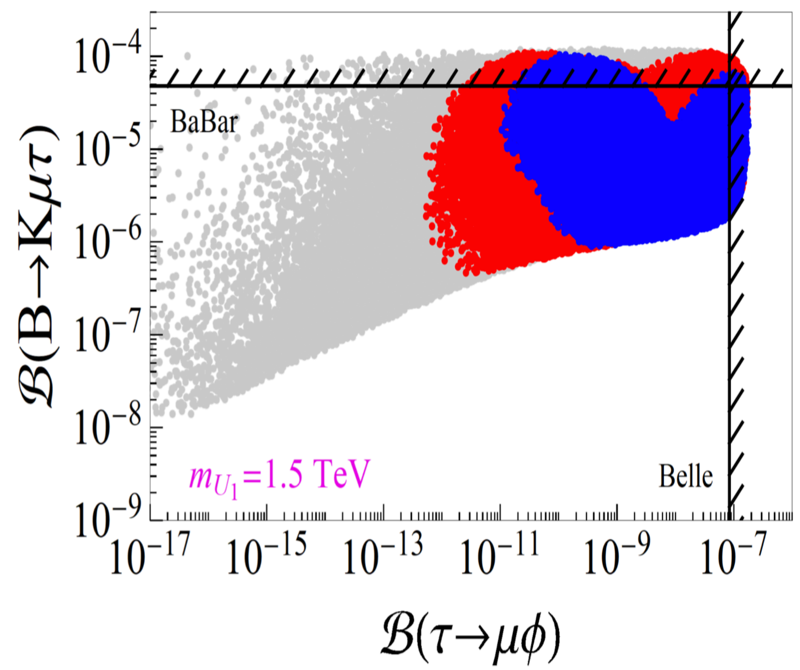
U_1 pheno closely follows the analyses based in simplified models…

High-pT is fine



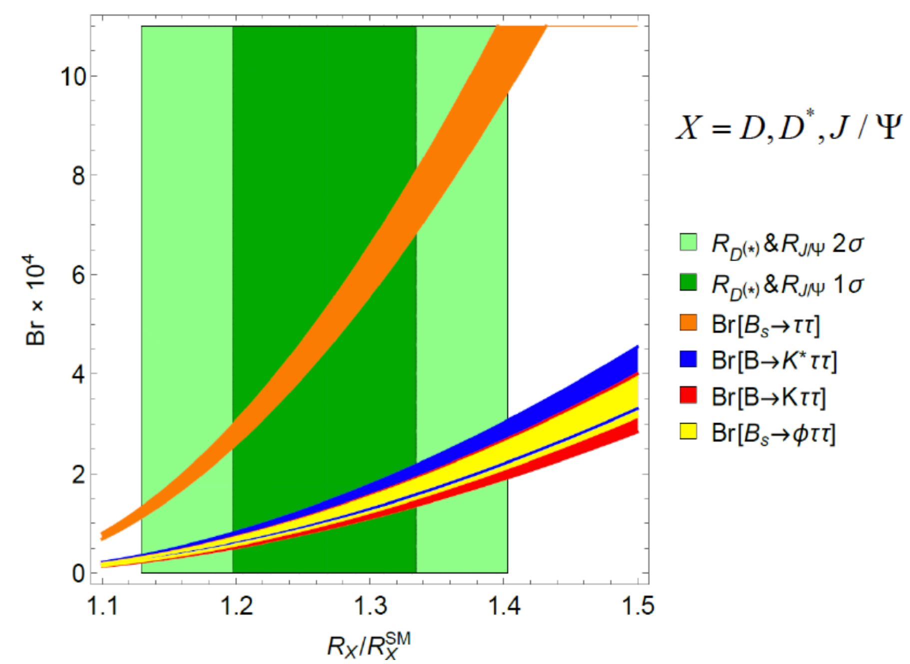
[Schmaltz, Zhong, 1810.10017]
(see also 1808.08179, 1609.07138)

LFV around the corner



[Angelescu et al., 1808.08179]

Huge effects in $b \to s\tau\tau$

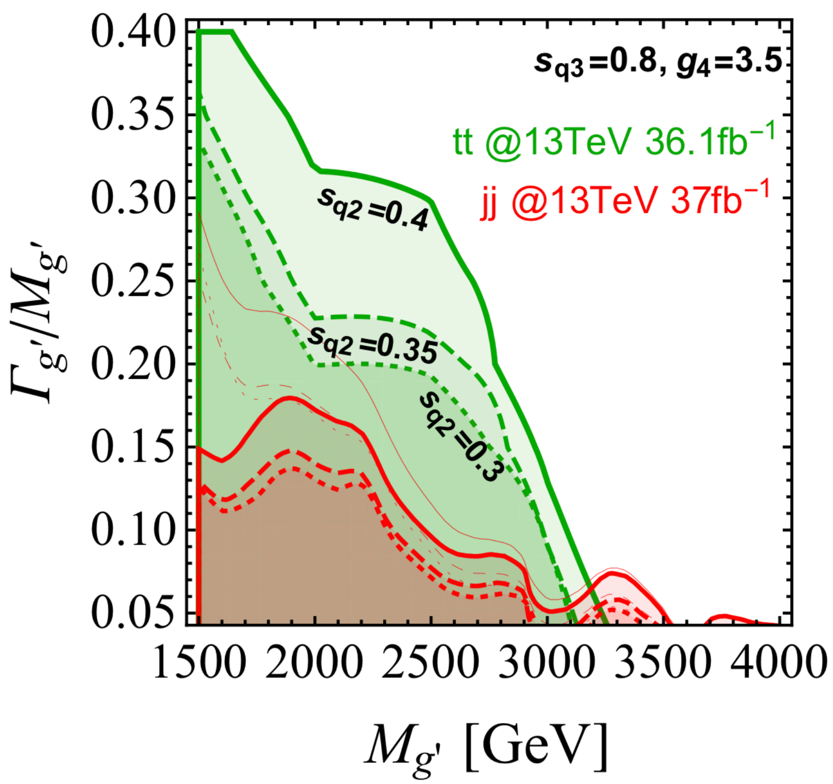


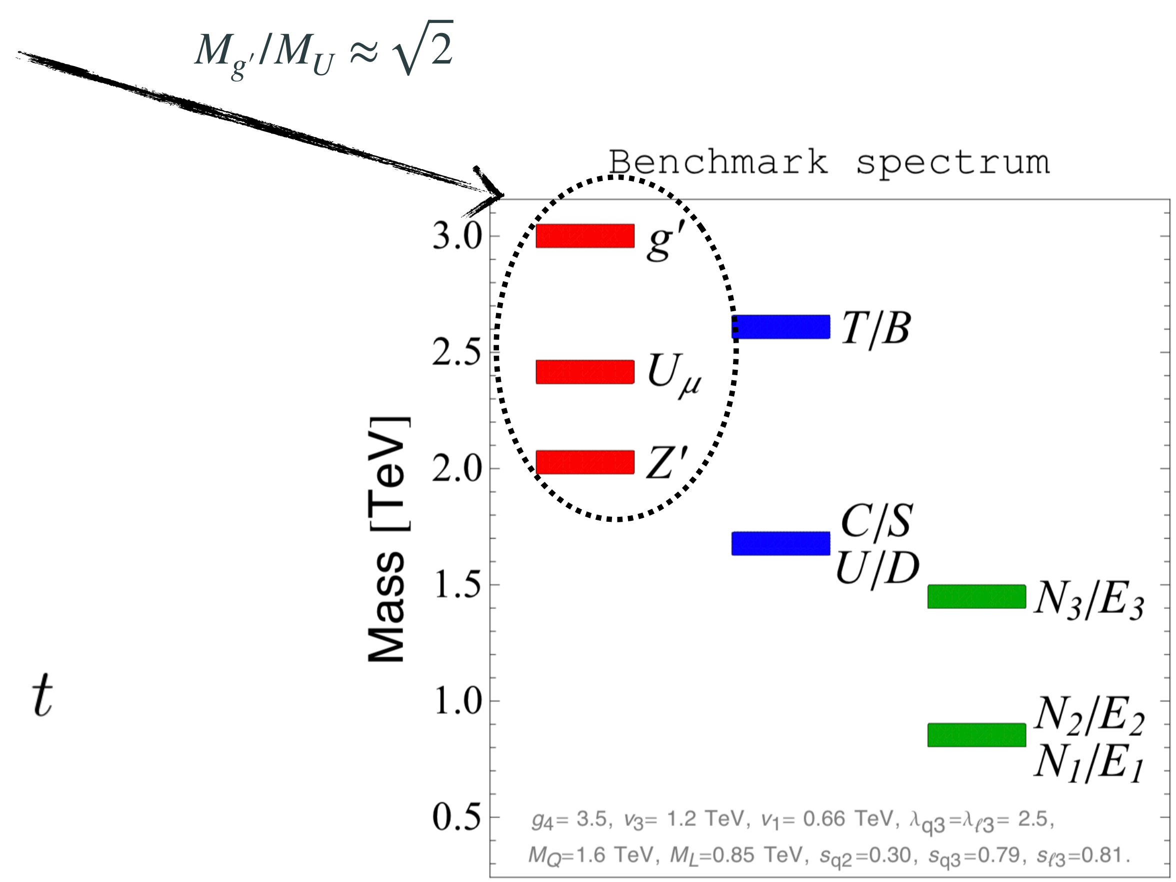
[Capdevila et al., 1712.01919]

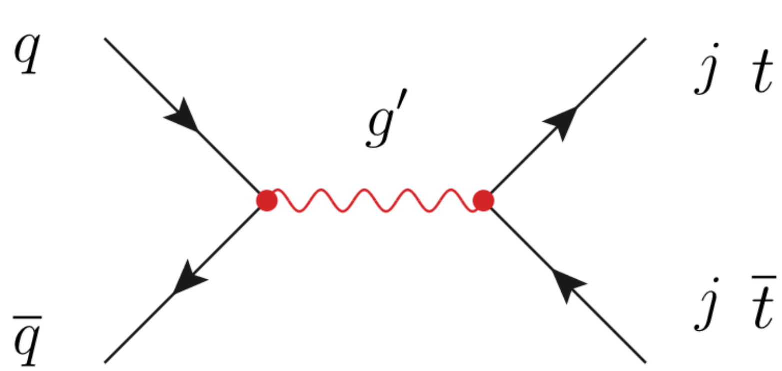
But what about the other new particles?

High-pT highlights

Coloron searches push the whole spectrum up



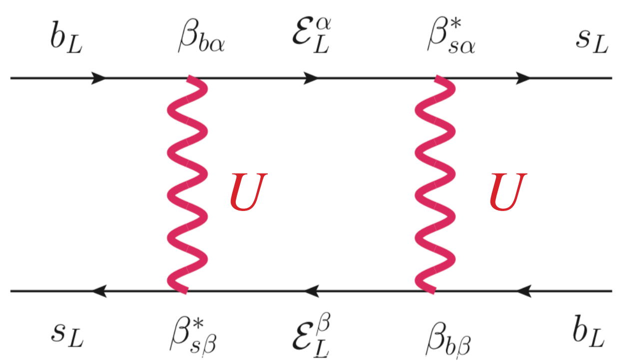




$\Delta F = 2$ observables

The assumed flavor structure ensures enough protection against tree-level FCNCs…

… but loop effects proportional to W are important (similar to the SM case with V_{CKM})



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

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

$$\sum_\alpha \lambda_\alpha = 0$$

(W unitarity)

Cancellation of divergences

$$F(x_\alpha, x_\beta) \simeq \cancel{1} + x_\alpha + x_\beta + \ldots$$

(effective suppression for light VL partners)

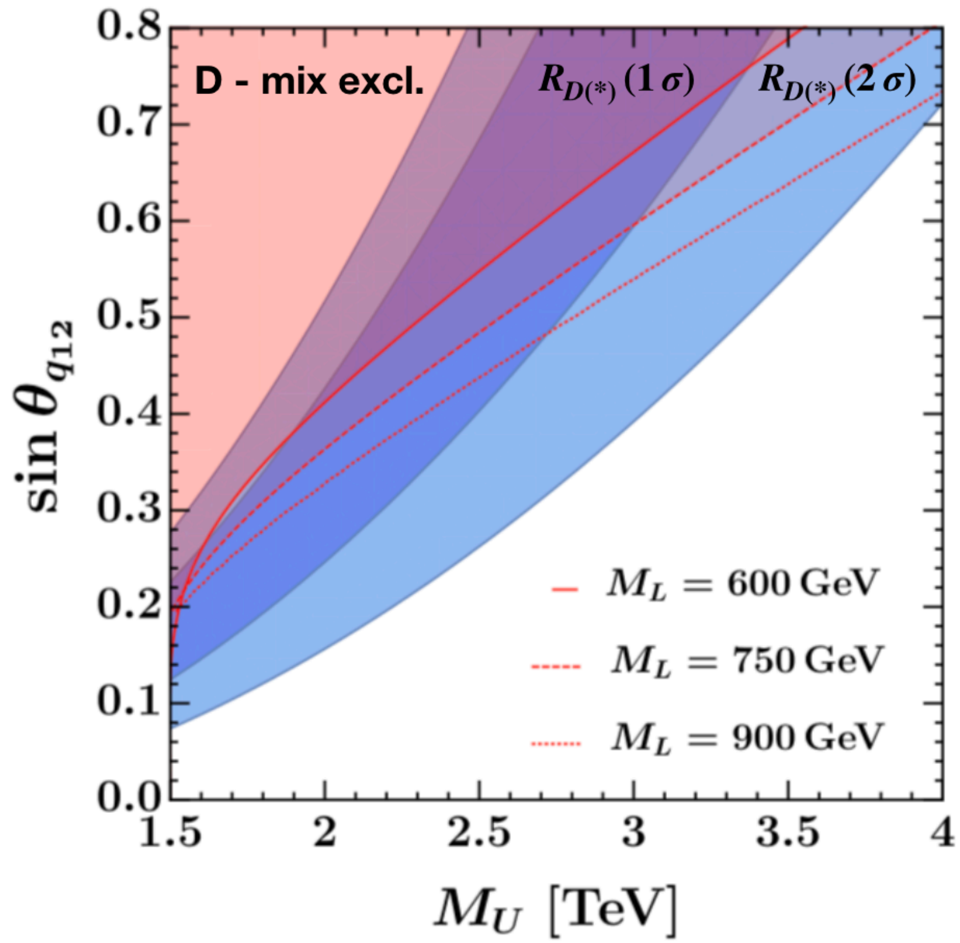
$$\boxed{C_{bs}^{LL} \sim \Delta R_{D^{(*)}} M_L^2}$$

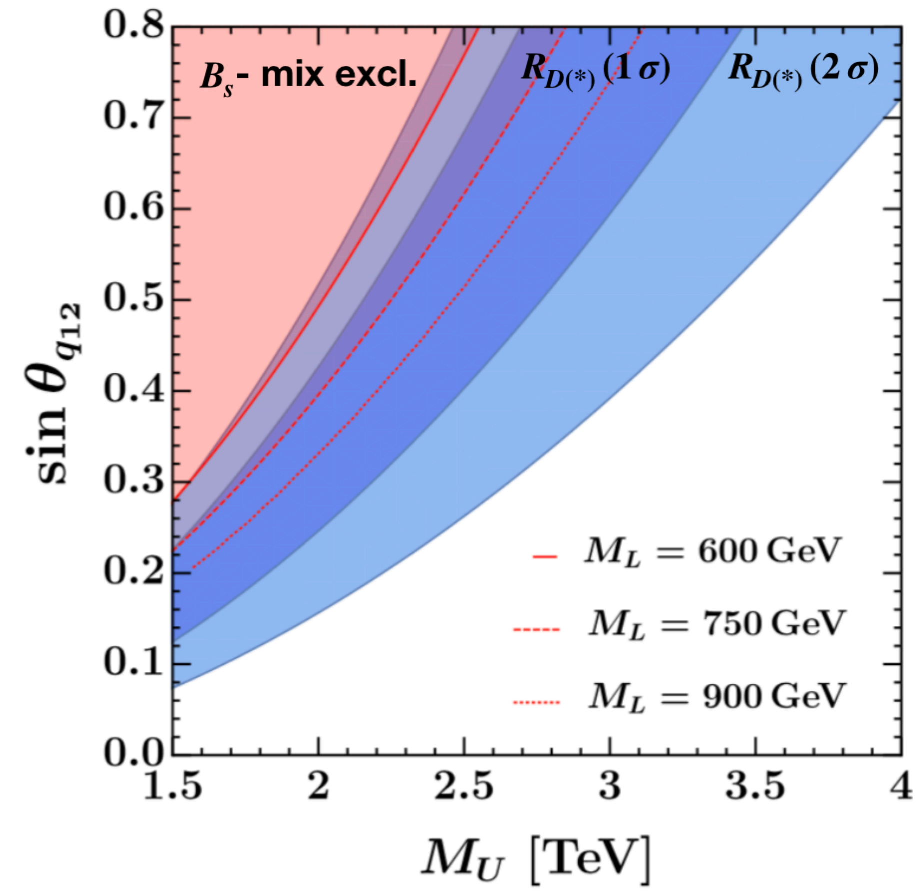
Analogous with $D - \bar{D}$ mixing, but different scaling due to different external particles

$\Delta F = 2$ observables

The assumed flavor structure ensures enough protection against tree-level FCNCs…

… but loop effects proportional to ***W*** are important (similar to the SM case with V_{CKM})

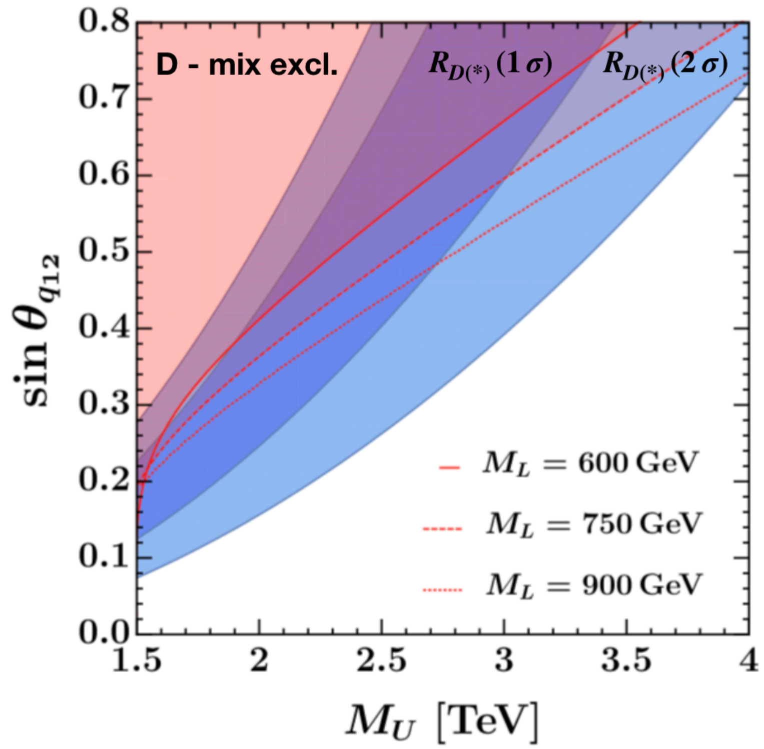




$$\boxed{C_1^D \sim s_{q_{12}}^2\, \Delta R_{D^{(*)}}^2\, M_L^2}$$

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

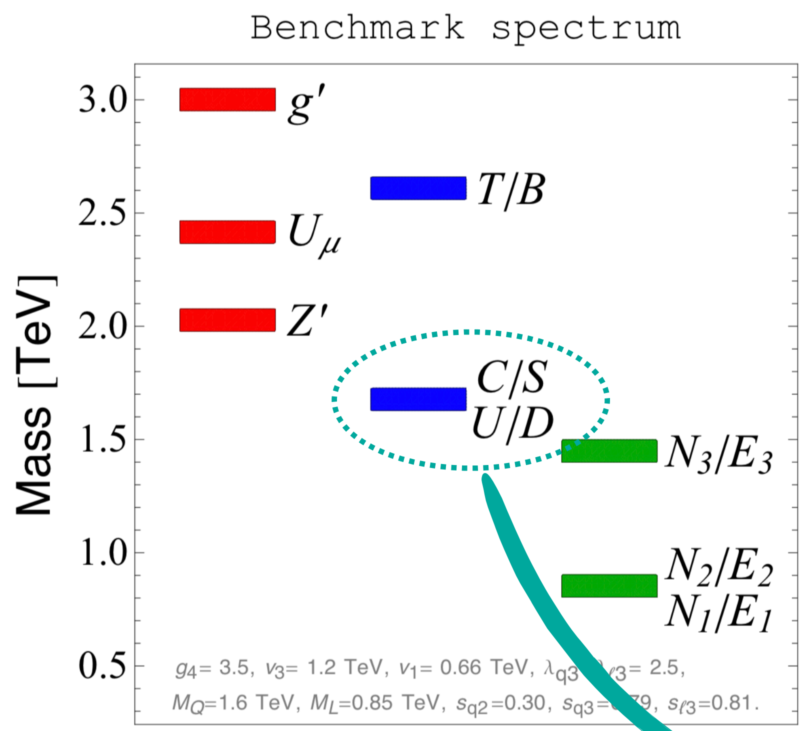
4321 exotica



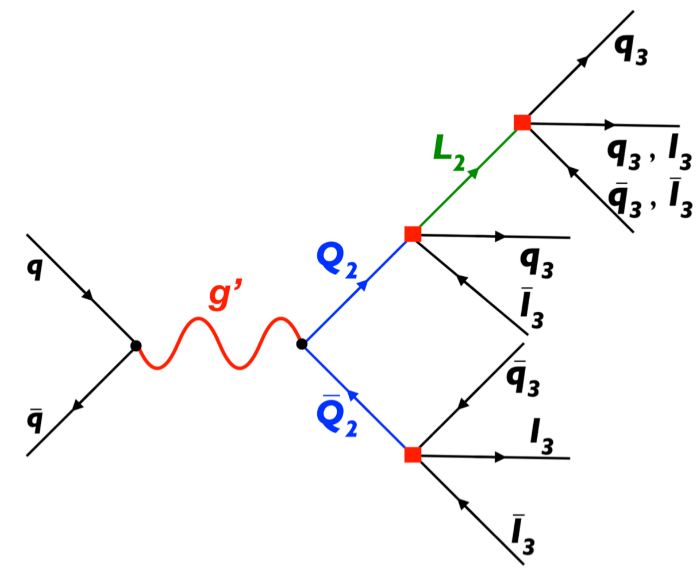
$$\boxed{C_1^D \sim s_{q_{12}}^2\, \Delta R_{D^{(*)}}^2\, M_L^2}$$

Vector-like fermions predicted to be the lightest states!

$$M_Q - M_L \sim \lambda_{15}\,\langle \Omega_{15} \rangle$$

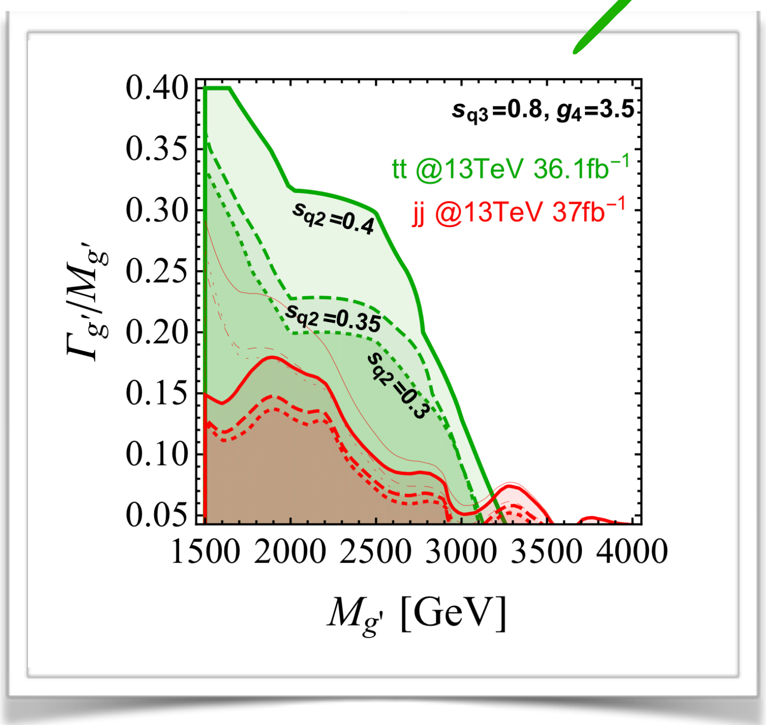


Exotic multi-jet multi-lepton signatures are predicted

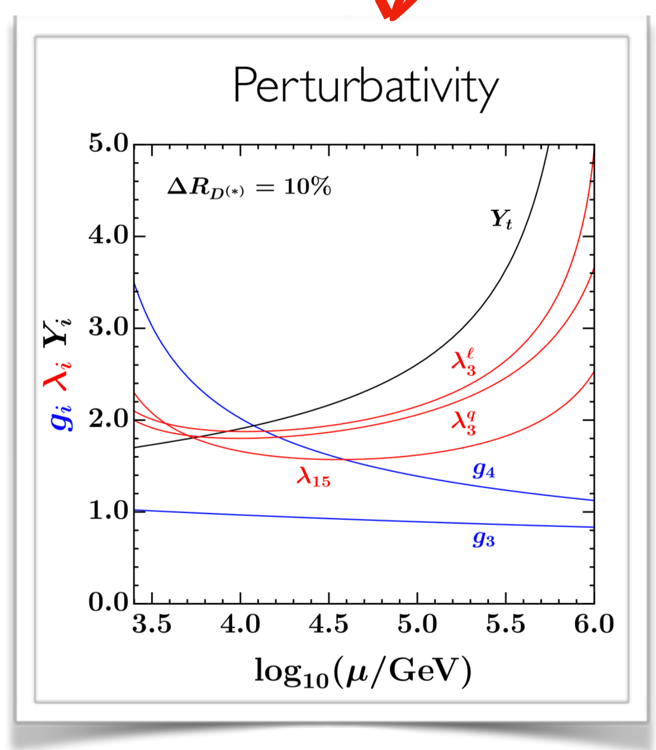


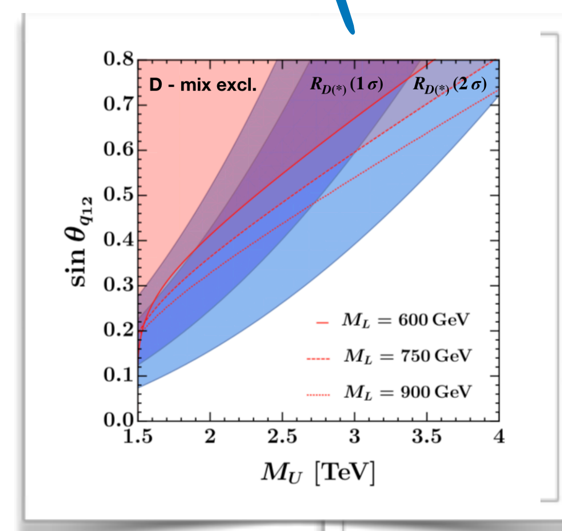
The original 4321: a snapshot

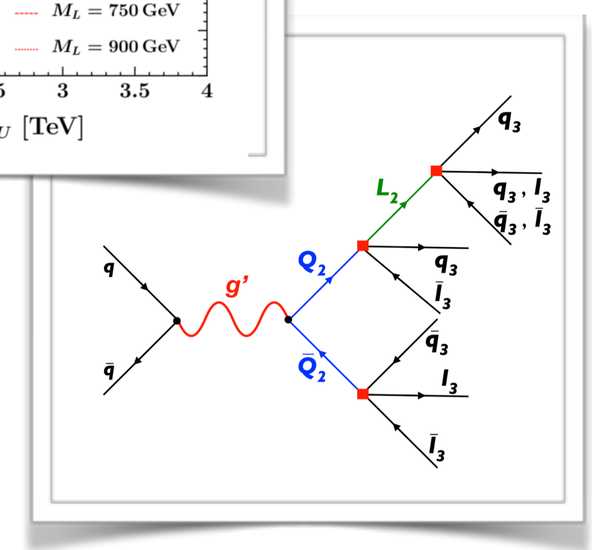
$$\Delta R_{D^{(*)}} \approx 0.2 \left(\frac{2\text{ TeV}}{M_U}\right)^2 \left(\frac{g_4}{3.5}\right)^2 \sin(2\theta_{LQ}) \left(\frac{s_{\ell_3}}{0.8}\right)^2 \left(\frac{s_{q3}}{0.8}\right) \left(\frac{s_{q2}}{0.3}\right)$$



NP scale fixed by g' searches

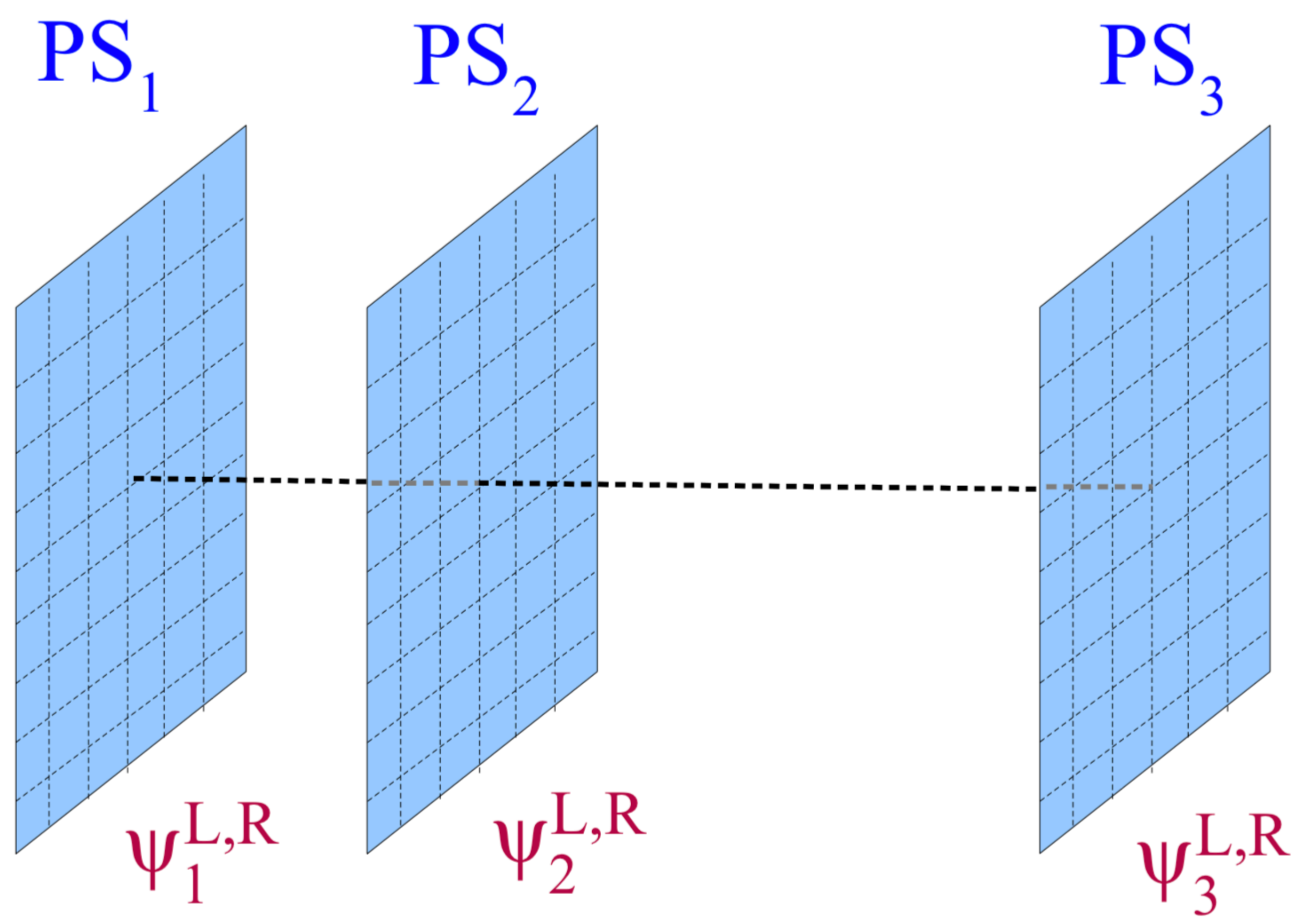






s_{q_2} limited by $D-\bar{D}$ & high-p_T signatures of vector-like leptons

$$[\ \mathrm{PS}\ ]^3 = [\ SU(4)\times SU(2)_L\times SU(2)_R\ ]^3$$



[Bordone, Cornella, JF, Isidori 1712.01368]

PS^3 at low energies… “flavored” 4321

Bordone et al. 1712.01368

$$\overbrace{\underbrace{SU(4)_3}_{SU(3)_c} \times SU(3)_{1+2} \times SU(2)_L}^{U(1)_Y} \times U(1) \xrightarrow{\langle \Omega_{1,3,15} \rangle} SU(3)_c \times SU(2)_L \times U(1)_Y$$

	Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$
	$q_L'^i$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{2}$	$1/6$
	$u_R'^i$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$2/3$
1st & 2nd families	$d_R'^i$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$
	$\ell_L'^i$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
	$e_R'^i$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	-1
3rd family	ψ_L^3	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
	$\psi_{R_{u,d}}^3$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{1}$	$\pm 1/2$
$n_{\mathrm{VL}} = 2$	χ_L^i	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
	χ_R^i	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
	$H_{1,15}$	$\mathbf{1}, \mathbf{15}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$
	Ω_1	$\bar{\mathbf{4}}$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$
	Ω_3	$\bar{\mathbf{4}}$	$\mathbf{3}$	$\mathbf{1}$	$1/6$
Not in “original” PS^3	Ω_{15}	$\mathbf{15}$	$\mathbf{1}$	$\mathbf{1}$	0

[Cornella, JF, Isidori, in preparation]

“Flavoring” of the gauge group has interesting implications

✓ U(2)-like Yukawa textures (explanation to the SM flavor hierarchies)

✓ Couplings to 3rd family naturally big (perturbativity issue fixed)

Smaller effects in 1st & 2nd families through SM-VL mixing

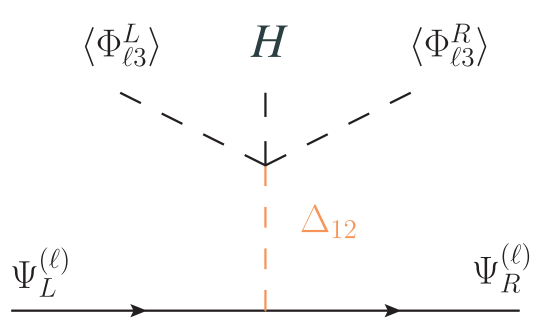
Gauge anomaly cancellation implies large **couplings also to RH fields**

PS^3 flavor structure

Yukawa hierarchies from a **flavored gauge structure** + **NP scale hierarchies**

[Bordone, Cornella, JF, Isidori 1712.01368]

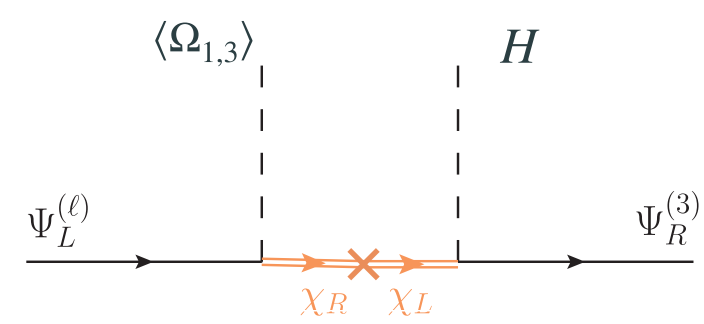
SM Yukawas: $\mathscr{L}_Y^{\text{ren}} \supset y_u\, \bar{\psi}_L^3\, \tilde{H}\, \psi_{R_u}^3 + y_d\, \bar{\psi}_L^3\, H\, \psi_{R_d}^3$



$$|\,\Delta\,| \sim \frac{\langle \Phi^L_{\ell 3} \rangle \langle \Phi^R_{\ell 3} \rangle}{\Lambda^2} \sim y_c$$

At the NP scale I'm discussing this would be $d = 4$

$$Y_f \sim \begin{bmatrix} \Delta & V \\ 0 & 1 \end{bmatrix}$$



$$|\,V\,| \sim \frac{\langle \Omega_{1,3} \rangle}{M_\chi} \sim |\,V_{ts}\,|$$

[see also Greljo, Stefanek, 1802.04274]

$y_b \approx y_\tau$ ✓

$y_t \approx y_{\nu_3}$ $\longrightarrow$ Requires low-scale seesaw

PS^3 flavor structure

Yukawa hierarchies from a **flavored gauge structure** + **NP scale hierarchies**

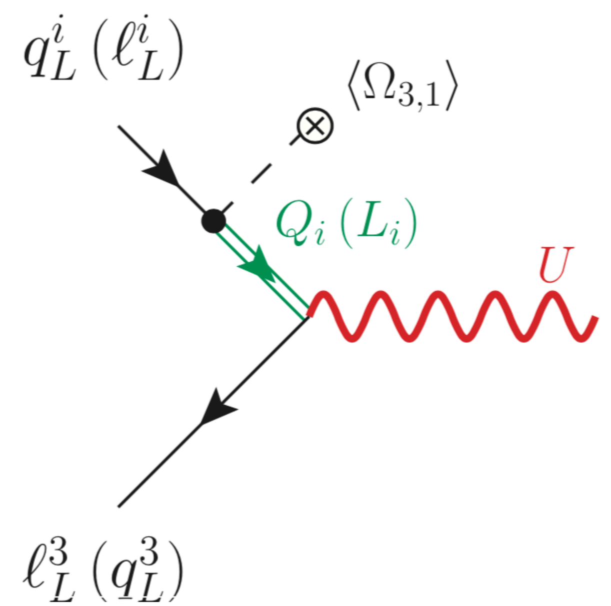
SM-VL mixing: $\mathscr{L}_\Psi \supset \lambda_\ell \, \bar{\ell}'_L \, \Omega_1 \chi_R + \lambda_q \, \bar{q}'_L \, \Omega_3 \, \chi_R + \lambda_{15} \, \bar{\chi}_L \, \Omega_{15} \, \chi_R + M \, \bar{\chi}_L \, \chi_R$

Same as before but only two families now! $\longrightarrow$ No sizable 2-3 misalignment possible from here

Ω_{15} is now a source of flavor:

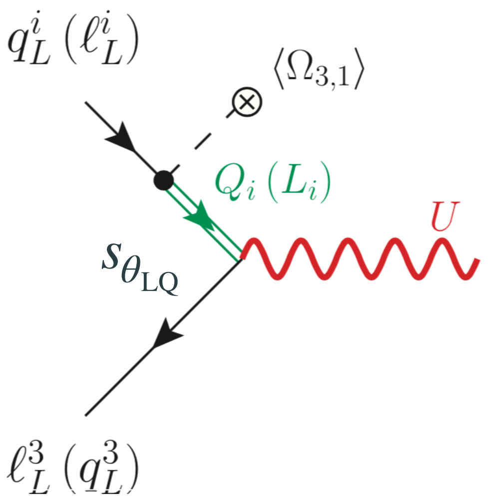
$$\lambda'_{15} \, \bar{\Psi}^3_L \, \Omega_{15} \, \chi_R$$

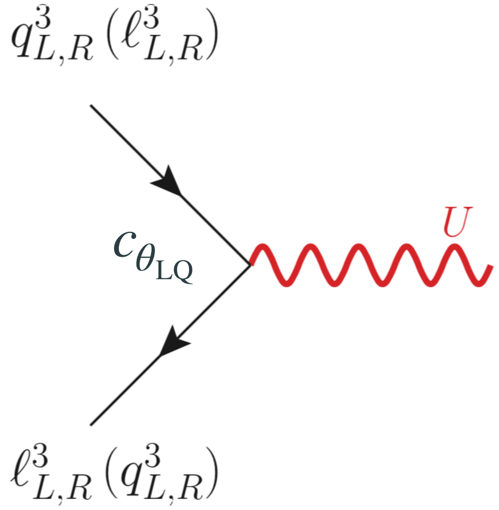
[Cornella, JF, Isidori, in preparation]



Large 2-3 misalignment
only in LQ transitions!

U_1 phenomelogy in low energy PS^3





No mixing angle suppression
($s_{q_3} = s_{\ell_3} = 1$ by construction)

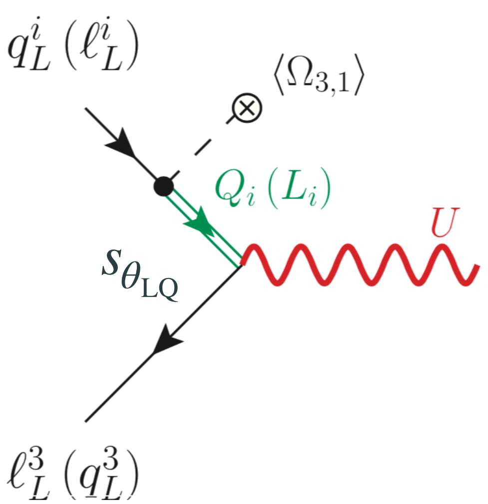
$$\mathscr{L}_U \supset \frac{g_4}{\sqrt{2}} U_\mu (\beta_L^{ij}\,\bar{q}_L^i\,\gamma^\mu\,\ell_L^j - \beta_R^{ij}\,\bar{d}_R^i\,\gamma^\mu\,e_R^j) + h.c.$$

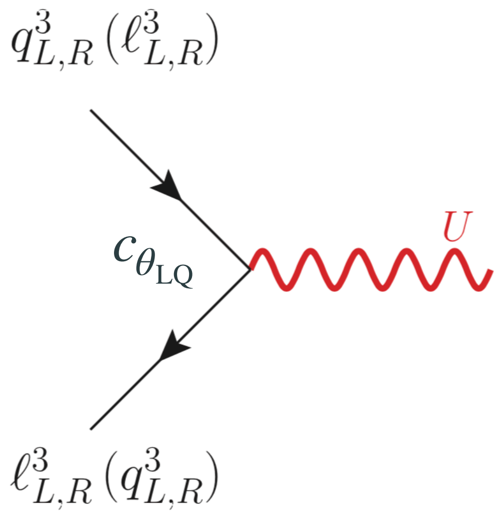
$$\beta_L \approx \begin{pmatrix} 0 & 0 & -\lambda\, s_{\theta_{LQ}}\, s_{q_{12}} \\ 0 & c_{\theta_{LQ}}\, s_{q_{12}}\, s_{\ell_2} & s_{\theta_{LQ}}\, s_{q_{12}} \\ 0 & -s_{\theta_{LQ}}\, s_{\ell_2} & c_{\theta_{LQ}} \end{pmatrix}$$

$$\beta_R \approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

n.b. $\lambda \approx 0.22$

U_1 phenomelogy in low energy PS^3





No mixing angle suppression
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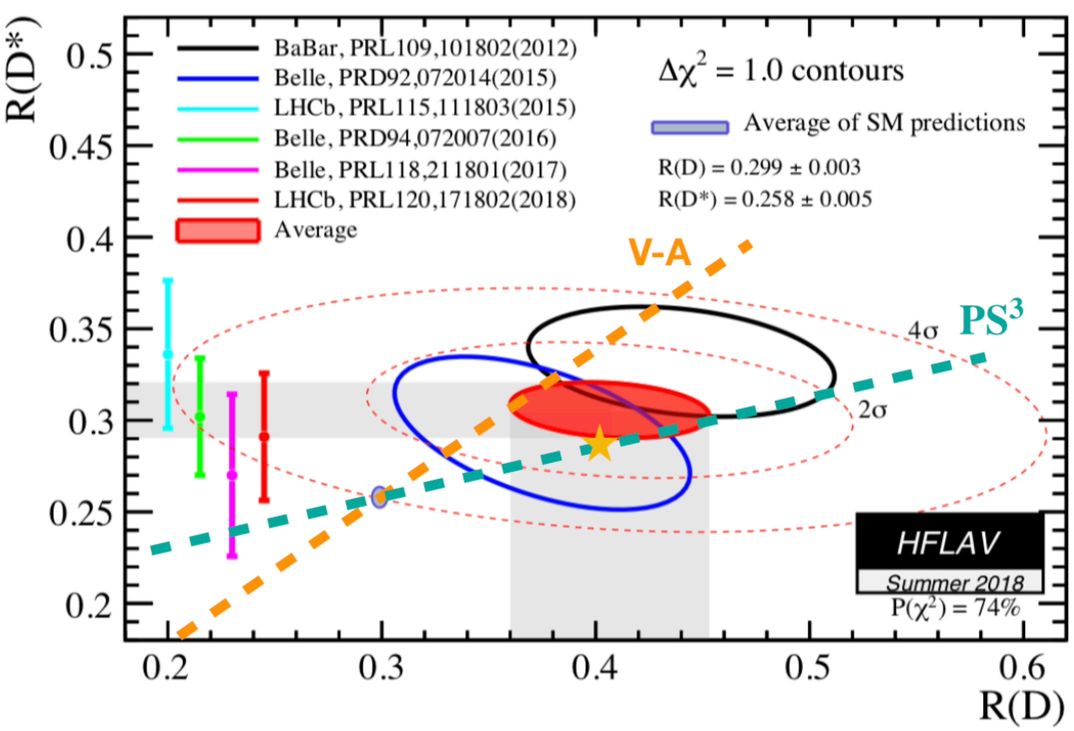
n.b. $\lambda \approx 0.22$

Fierz

$$C_{V_L} = (\bar{c}_L \gamma_\mu b_L)(\bar{\ell}_L \gamma^\mu \nu_L) \qquad C_{S_R} = (\bar{c}_L b_R)(\bar{\ell}_R \nu_L)$$

(RGE enhanced)



$$\Delta R_D \approx 0.3 \left(\frac{3\,\mathrm{TeV}}{M_U}\right)^2 \left(\frac{g_4}{3.0}\right)^2$$

$$\Delta R_{D^*} \approx 0.1 \left(\frac{3\,\mathrm{TeV}}{M_U}\right)^2 \left(\frac{g_4}{3.0}\right)^2$$

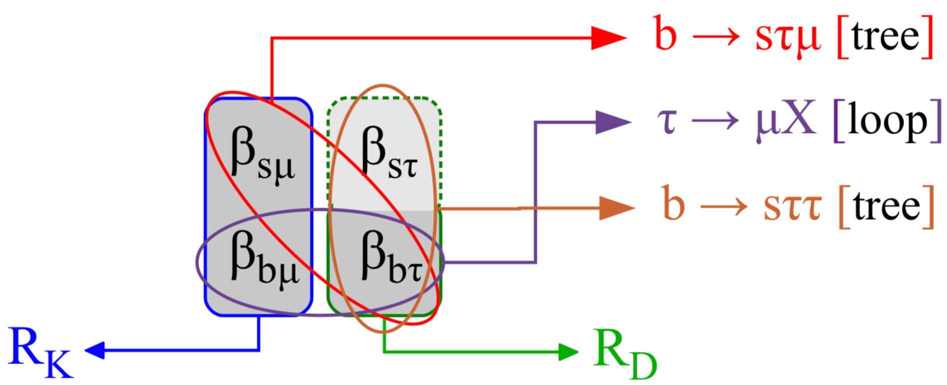
[Cornella, JF, Isidori, in preparation]

n.b. taking $\theta_{\mathrm{LQ}} = 0.5$ and $s_{q_{12}} = 0.2$

U_1 phenomelogy in low energy PS^3

$$\mathcal{L}_U \supset \frac{g_4}{\sqrt{2}} U_\mu (\beta_L^{ij}\, \bar{q}_L^i \gamma^\mu \ell_L^j + \beta_R^{ij}\, \bar{d}_R^i \gamma^\mu e_R^j) + h.c.$$

$$\beta_L \approx \begin{pmatrix} 0 & 0 & -\lambda\, s_{\theta_{LQ}} s_{q_{12}} \\ 0 & c_{\theta_{LQ}} s_{q_{12}} s_{\ell_2} & s_{\theta_{LQ}} s_{q_{12}} \\ 0 & -s_{\theta_{LQ}} s_{\ell_2} & c_{\theta_{LQ}} \end{pmatrix} \qquad \beta_R \approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



Isidori @ TH Implications

Phenomenology of the U_1 PS^3 LQ quite different from “usual” simplified analyses:

★ Larger NP in $R(D)$ w.r.t. $R(D^*)$

★ Larger LFV effects in some obs.: $\mathcal{B}(B_s \to \tau\mu) \sim \mathcal{O}(10^{-4} - 10^{-5})$ (scalar enhanced)

★ $\mathcal{B}(B_c \to \tau\nu) \approx 5\,\%$ and $\mathcal{O}(40\%)$ NP enhancement in $\mathcal{B}(B \to \tau\nu)$

★ Very large effect in $\mathcal{B}(B_s \to \tau\tau)$ (scalar enhanced), close to current limit by LHCb

Conclusions

Current data is still inconclusive and the overall picture might change…

… it is possible to find interesting solutions to the current B anomaly data while remaining consistent with other low- and high-energy data

Connection to the SM Yukawa structure still viable

Going beyond simplified dynamical models is important

Lesson from 4321: unexpected experimental signatures (g', Z' , VL fermions,…)

If the anomalies are really pointing to NP, **new experimental indications** (both in high-p_T and at low energies) should show up soon in several observables

… However this conclusion is strongly driven by $R(D^{(*)})$

Backup slides

Z' & g' interactions

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

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

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

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

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

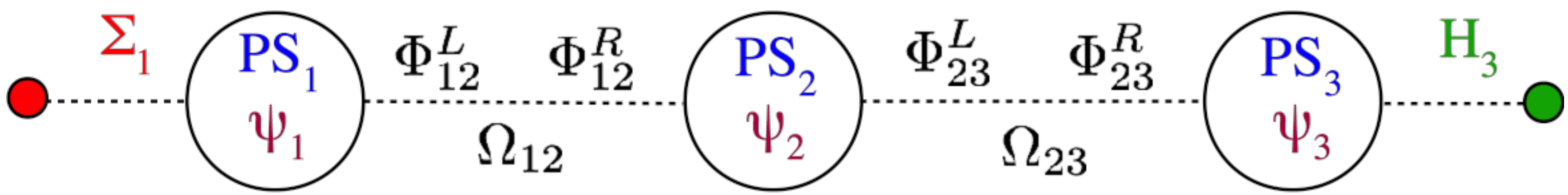
D-mixing at tree level

$$C_1^D\big|_{\rm tree} = \frac{4G_F}{\sqrt{2}}\left(C_{Z'} + \frac{C_{g'}}{3}\right)\,(V_{ub}^*\,V_{cb})^2\,\left(\sin^2\theta_{q_3} + \sin^2\theta_{q_2}\frac{V_{us}^*\,V_{cs}}{V_{ub}^*\,V_{cb}} + \sin^2\theta_{q_1}\frac{V_{ud}^*\,V_{cd}}{V_{ub}^*\,V_{cb}}\right)^2$$

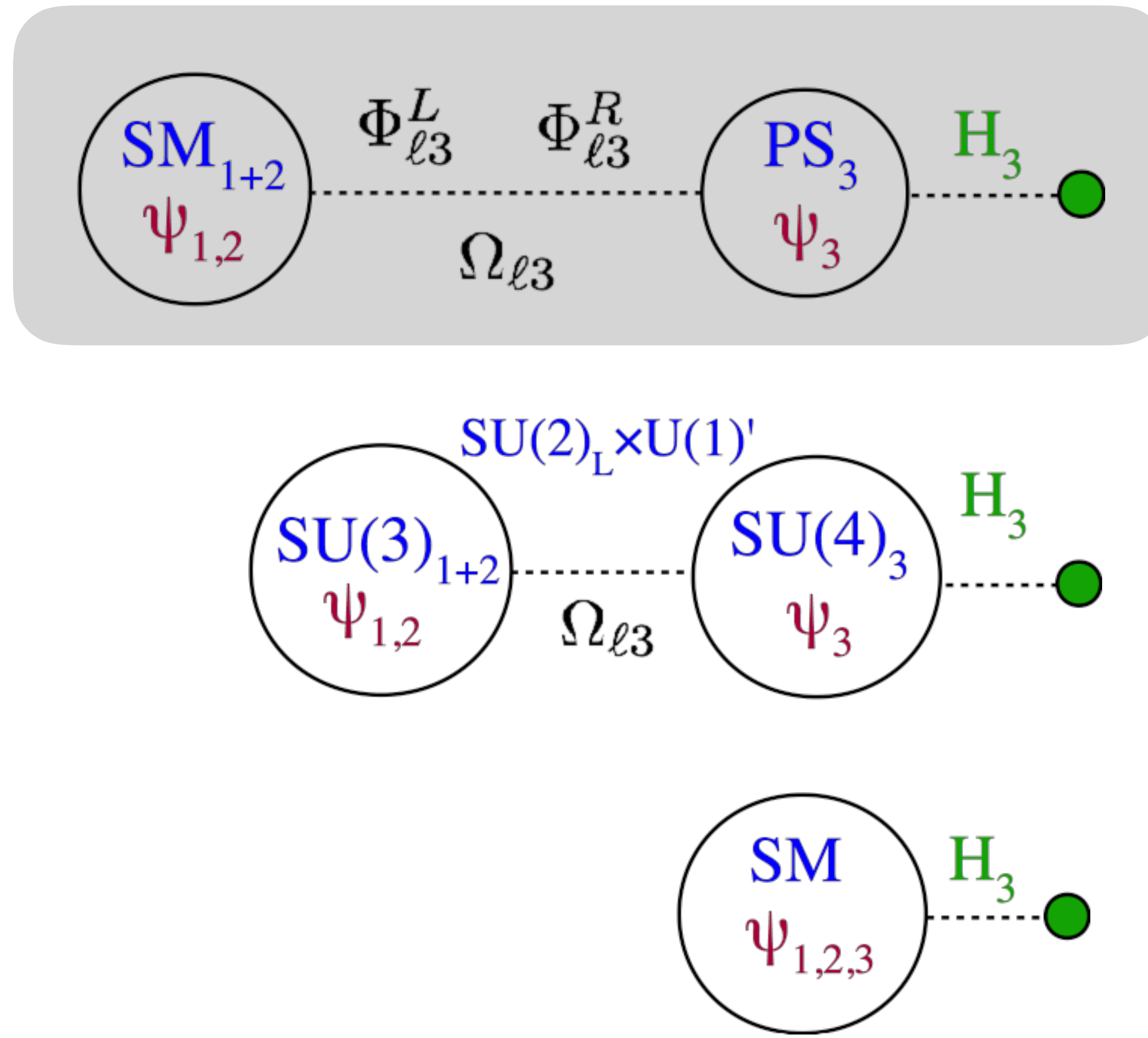
$s_{q_1} = s_{q_2}$ + **CKM unitarity**

$$C_1^D\big|_{\rm tree} = \frac{4G_F}{\sqrt{2}}\left(C_{Z'} + \frac{C_{g'}}{3}\right)\,(V_{ub}^*\,V_{cb})^2\,\left(\sin^2\theta_{q_3} - \sin^2\theta_{q_{12}}\right)^2$$

PS^3 symmetry breaking pattern



Accidental $U(2)^5$ symmetry



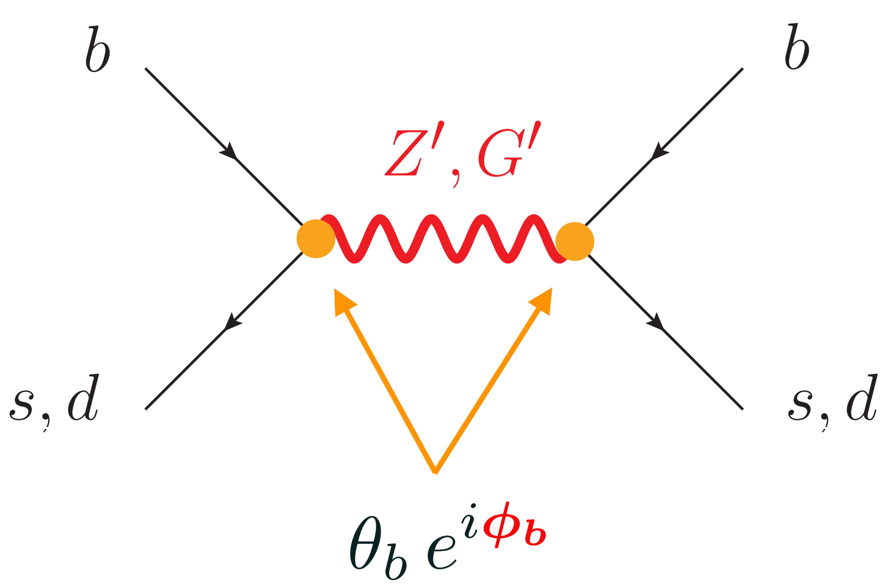
$$Y_f = \begin{bmatrix} y_{11} & y_{13} \\ & y_{33} \end{bmatrix}$$

$$\frac{\langle \Phi^L_{\ell 3}\rangle \langle \Phi^R_{\ell 3}\rangle}{\Lambda^2_{23}} \qquad \frac{\langle \Omega_{\ell 3}\rangle}{\Lambda_{23}}$$

Higher dimensional operators act as spurions (i.e. small breakings) of the U(2) symmetry

$\Delta F = 2$: one phase to save them all?

Current lattice data hint to a deficit in the experiment w.r.t. SM prediction in $B_{s,d} - \bar{B}_{s,d}$
[Fermilab/MILC 2016 [1602.03560]: SM prediction $1.8\,\sigma$ (B_d) and $1.1\,\sigma$ (B_s) **above** experiment]



CP violating NP can account for the deficit!
[Di Luzio et al., 1808.00942]

Current data	U(2) symmetry
$\boldsymbol{\phi_b} \simeq \pi/2$	$\boldsymbol{\phi_b}$ free
$\lvert\theta_b\rvert = \mathcal{O}(10\%)\,\lvert V_{ts}\rvert$	$\theta_b = \mathcal{O}(V_{ts})$

Still early to draw conclusions but it is interesting that the model can “naturally” explain the deficit

[Bordone, Cornella, JF, Isidori, 1805.09328]

Possible **CP violation** effects in $b \to s, d$ transitions!

Other $\Delta F = 2$ transitions: $K - \bar{K}$, $D - \bar{D}$ also **under control**!