Universität Zürich[UZH]

A UV-complete model for B anomalies and SM flavor hierarchies

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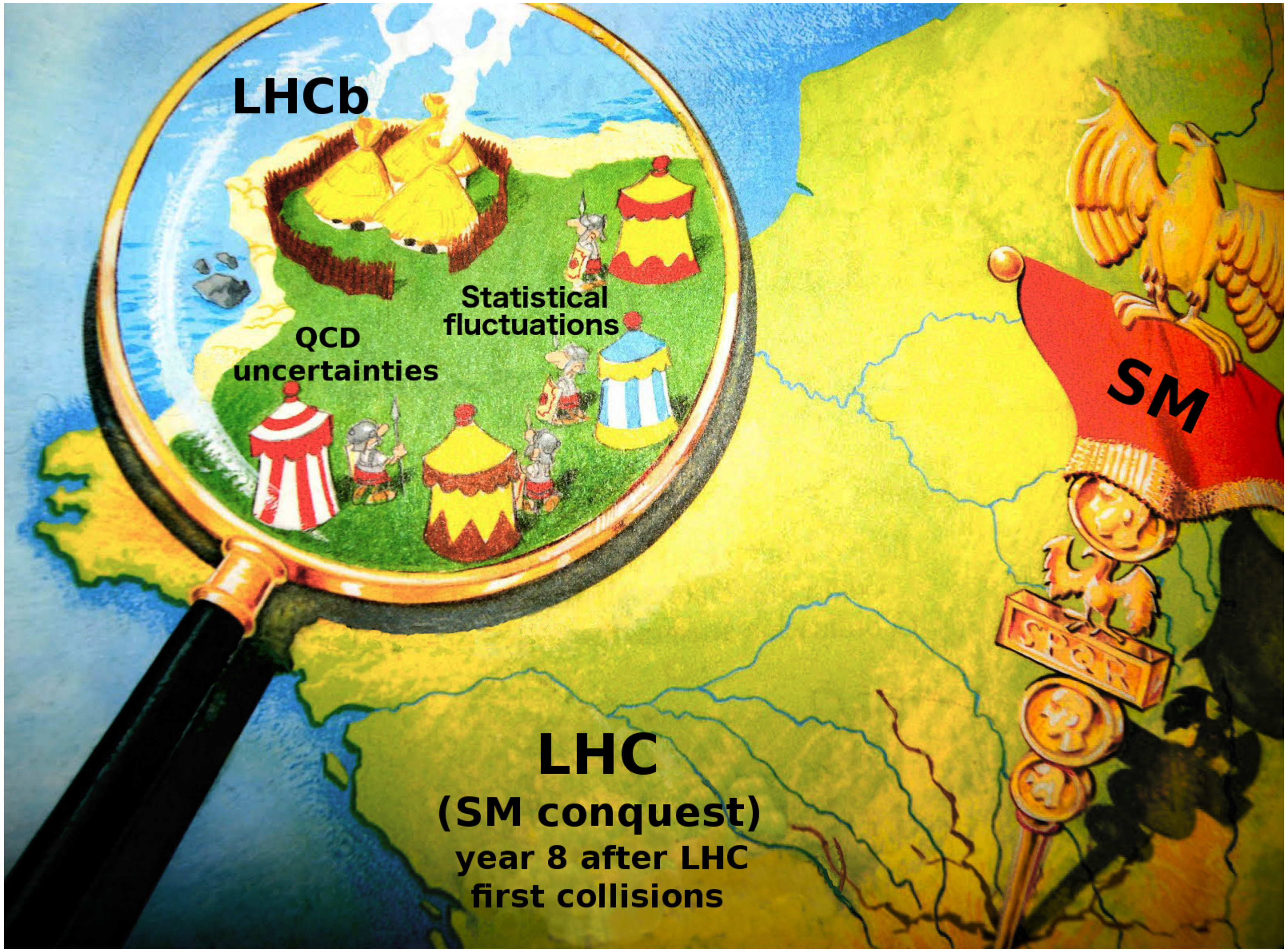
Based on **arXiv:1712.01368** and ongoing work
In collaboration with **M. Bordone, C. Cornella** and **G. Isidori**

The LHC landscape

The year is 8 after the LHC first collisions. Experimental data is entirely SM-like. Well, not entirely! The LHCb Collaboration still holds out against the SM. And life is not easy for the SM there...



The challenge: combined explanation of the anomalies

If taken together, the B anomalies are possibly the largest **coherent** set of deviations from the SM we have ever seen…

… So let me (aggressively) assume that the anomalies (both!) are genuine hints of NP. Can we make some sense out of them?

Intriguingly, they follow a very peculiar structure

$b \to s\ell\ell$ $\ll$ $b \to c\tau\nu$

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

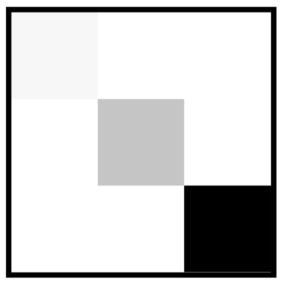
~25% of a SM **loop** effect — ~20% of a SM **tree-level** effect

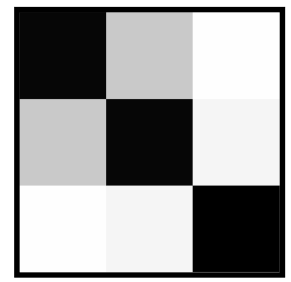
The only source of **lepton flavor universality violation** in the SM (Yukawas) follow a similar trend: $y_e \ll y_\mu \ll y_\tau$…. Are the anomalies connected to the Yukawas?

The U(2) flavor symmetry

The SM Yukawas respect an approximate U(2) symmetry

Barbieri et al. 1105.2296

$M_{u,d} \sim$ 

$V_{\rm CKM} \sim$ 

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

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

$$\boldsymbol{Y_{u,d}} = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \longrightarrow \begin{pmatrix} 0 & \boldsymbol{V} \\ 0 & 1 \end{pmatrix} \longrightarrow \begin{pmatrix} \Delta & \boldsymbol{V} \\ 0 & 1 \end{pmatrix}$$

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

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

Unbroken symmetry — Leading breaking — Final breaking

- Assuming a single leading breaking ensures an effective protection of FCNCs
  [**SM-like mixing among light & 3rd generations** $\longrightarrow$ consistent with CKM fits]
- Large NP effects in 3rd generation, light-generation effects controlled by the breaking

Lessons from the EFT

The "Zurich guide", Buttazzo et al. [1706.07808]

SM Yukawas → **U(2) symmetry**

↑

B anomalies → +

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

Vector leptoquark

[Pati Salam?]

See Admir Greljo's talk!

Analysis in terms of dynamical (simplified) models select the **vector LQ as the only single-mediator possibility**

[but of course other solutions with more mediators are available]

See Damir Bečirević talk!

Gauged vector LQ: low-scale unification?

The vector-leptoquark solution points to Pati-Salam unification

$$\mathbf{PS} \equiv \mathbf{SU(4)} \times \mathbf{SU(2)_L} \times \mathbf{SU(2)_R} \qquad \Psi_{L,R} = \begin{pmatrix} Q^1_{L,R} \\ Q^2_{L,R} \\ Q^3_{L,R} \\ L_{L,R} \end{pmatrix}$$

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

[**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 bound from $K_L \to \mu e$ lift the LQ mass to 100 TeV

A very interesting proposal to circumvent this problem [**Di Luzio et al.,1708.08450**] uses a (dark) $\mathrm{SU}(4)$ connected to the SM fermions through vector-like fermions

Bordone, Cornella, JF, Isidori, 1712.01368

At high energies each family is charged under an independent gauge group
(**gauge bosons carry flavor!**)

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

PS_1 ψ_1 | PS_2 ψ_2 | PS_3 ψ_3

Unification of quarks and leptons
[natural explanation for $\mathrm{U(1)_Y}$ charges]

"De-unification" of the gauge symmetry
(= flavor deconstruction)

"Flavor-friendly"
Pati-Salam

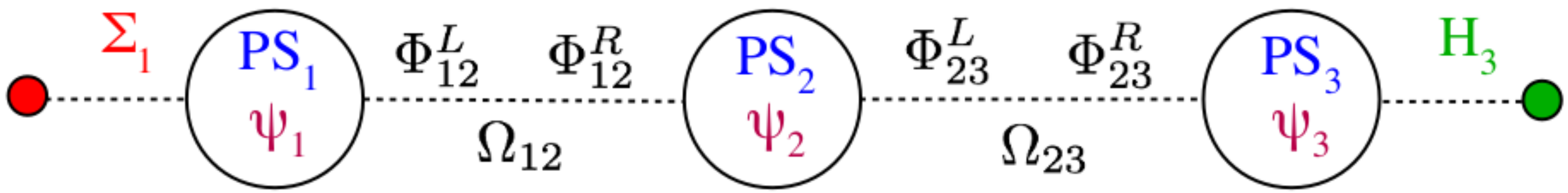
Available now at low scales!

Our proposal

Bordone, Cornella, JF, Isidori, 1712.01368

At high energies each family is charged under an independent gauge group
(**gauge bosons carry flavor!**)

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



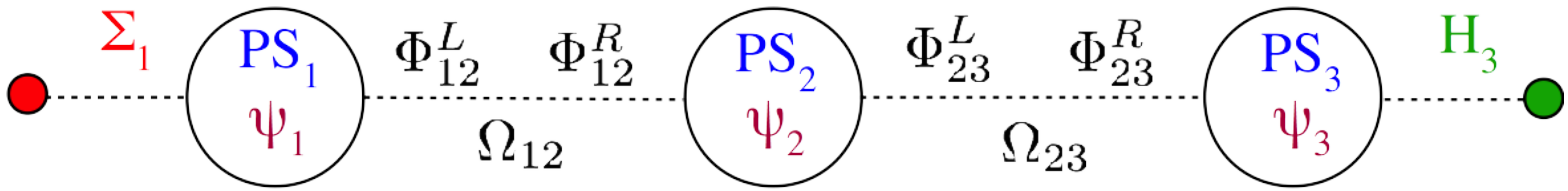
High-scale [$\sim 10^3$ TeV]
"vertical breaking":
$[\mathbf{PS_1 \to SM_1}]$

Link fields
←- - - - - - - - - - -→

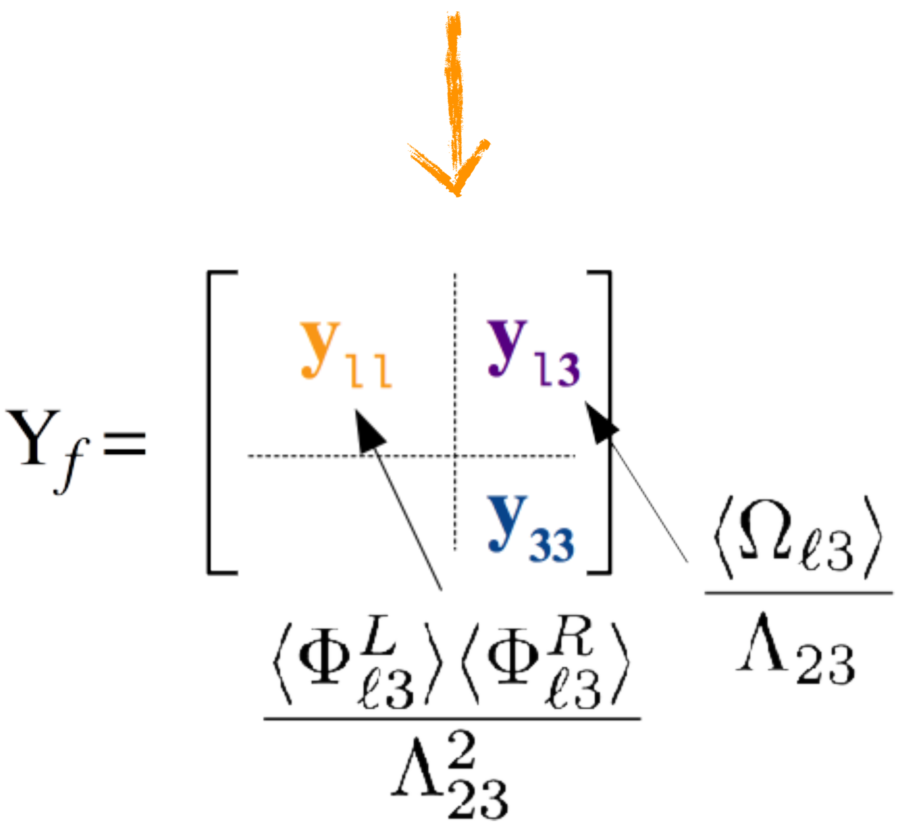
Low-scale [EW]
"vertical breaking":
$[\mathbf{SM_3 \to QED_3}]$

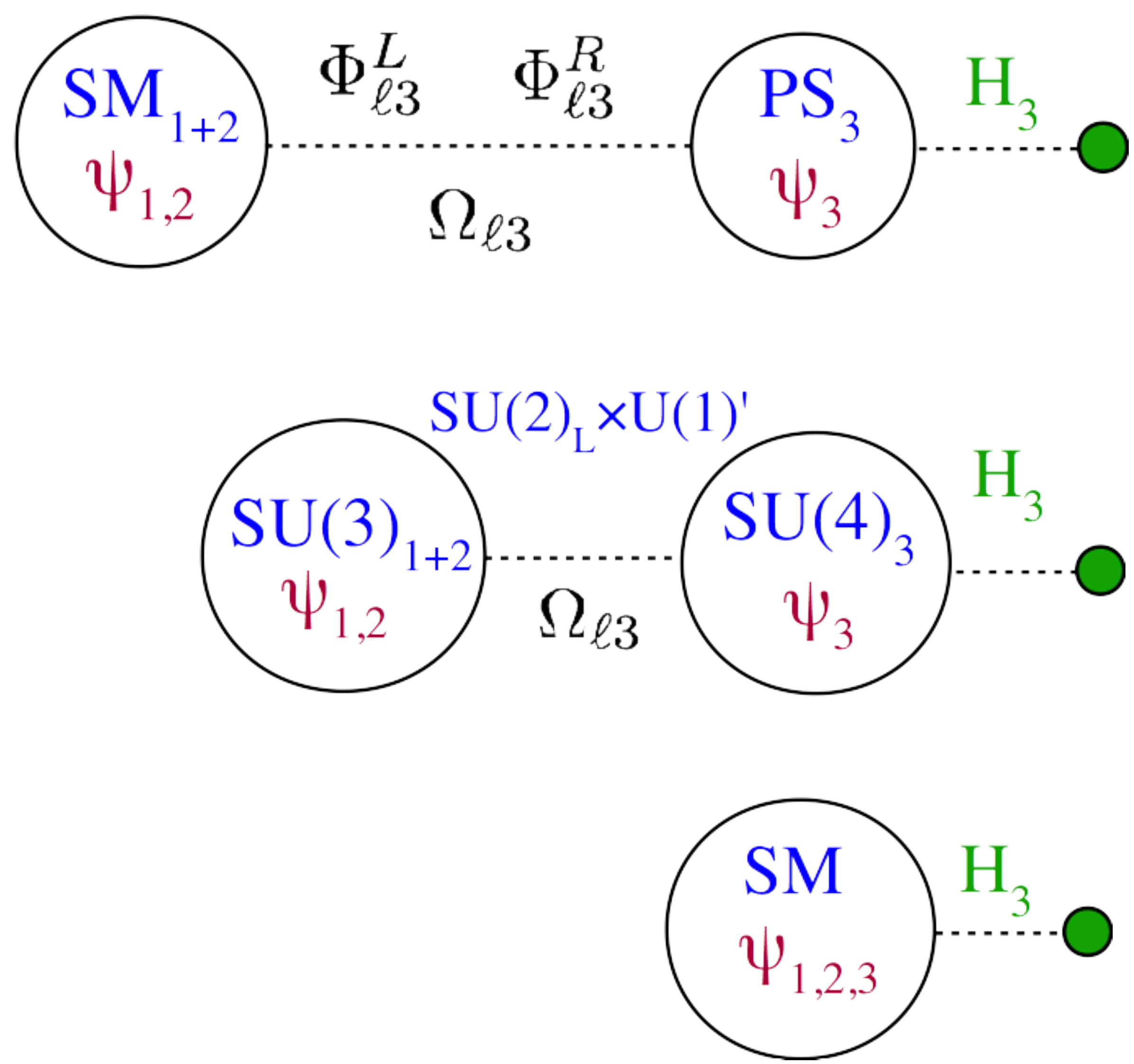
Breaking to the diagonal SM group via "link" fields $[\Omega_{ij}, \Phi^{L,R}_{ij}]$,
also responsible of the Yukawa hierarchies

Symmetry breaking pattern

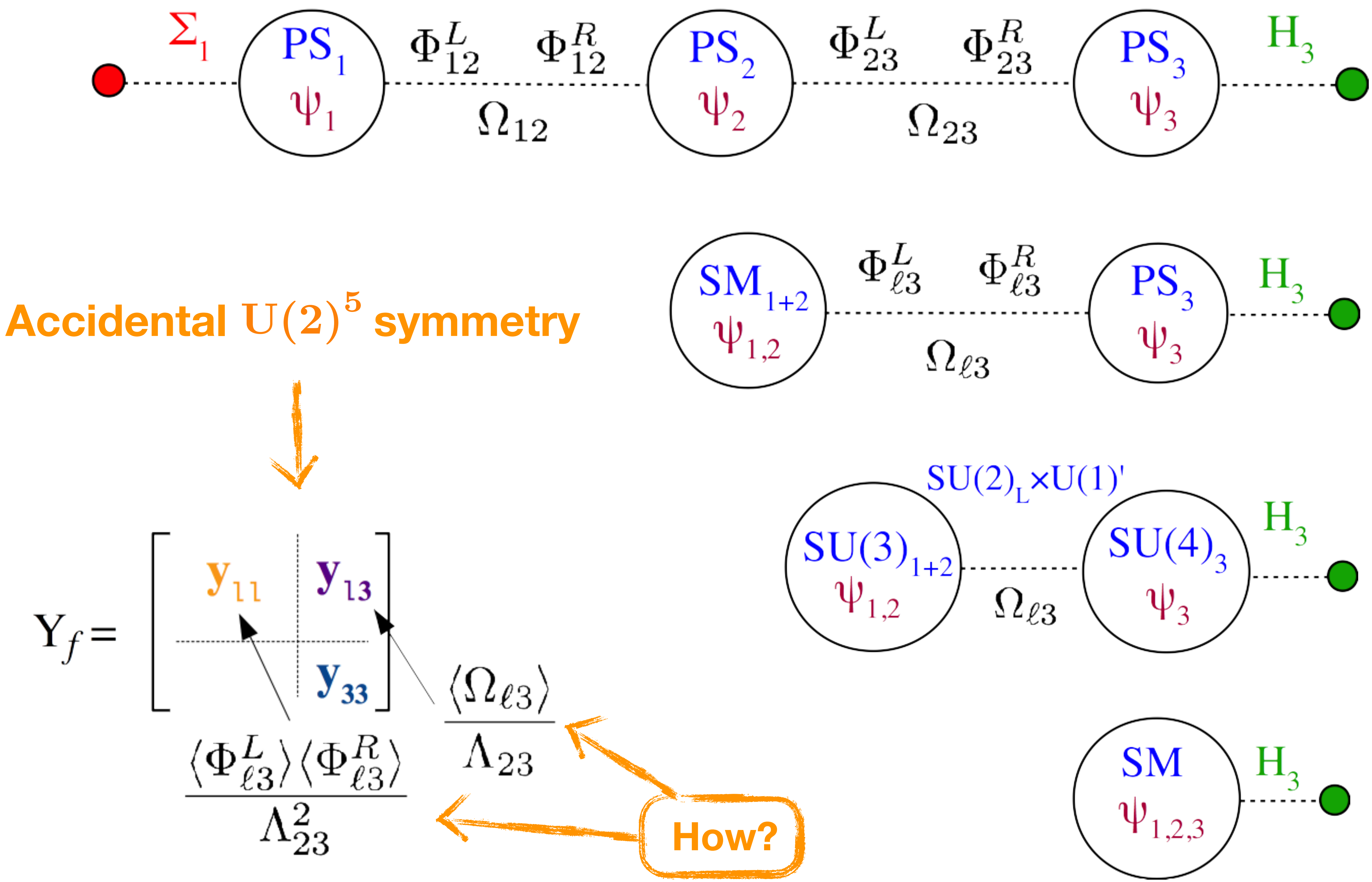


Accidental $U(2)^5$ symmetry





Symmetry breaking pattern

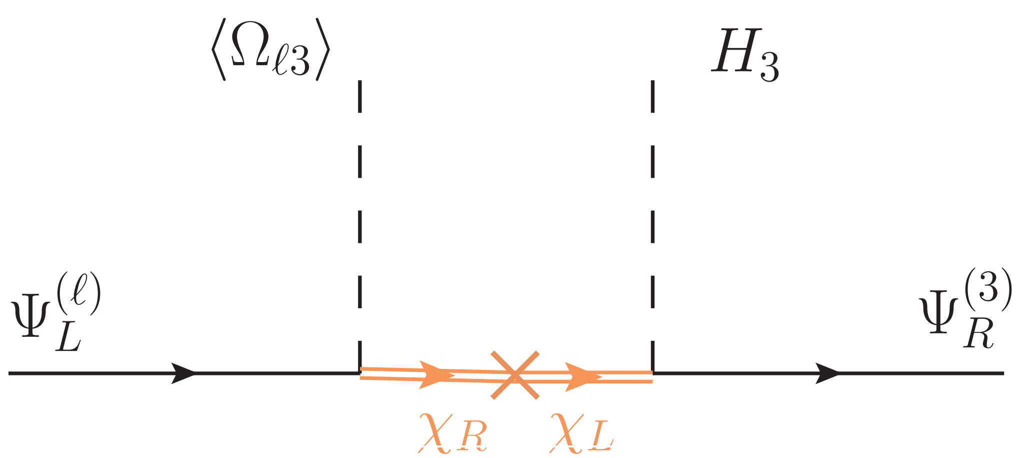


Generation of the effective Yukawas

d=5

Like in type-I seesaw

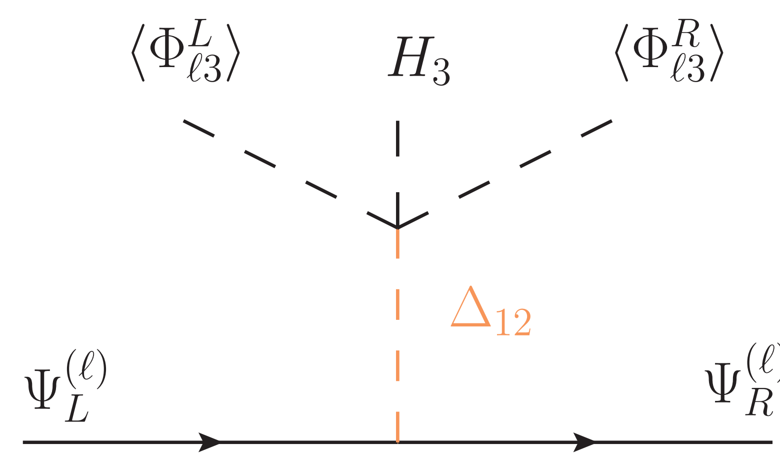
[$\boldsymbol{\chi_{L,R} \sim (4,2,1)_3}$]



d=6

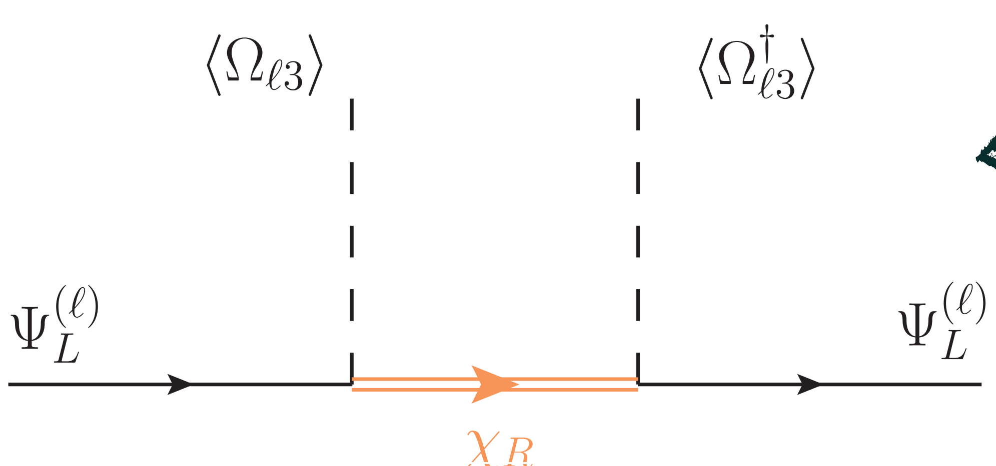
Like in type-II seesaw

[$\boldsymbol{\Delta_{12} \sim (4,2,1)_1 \times (\bar{4},1,\bar{2})_2}$]



"For free"

Leading breaking of the (accidental) U(2) symmetry

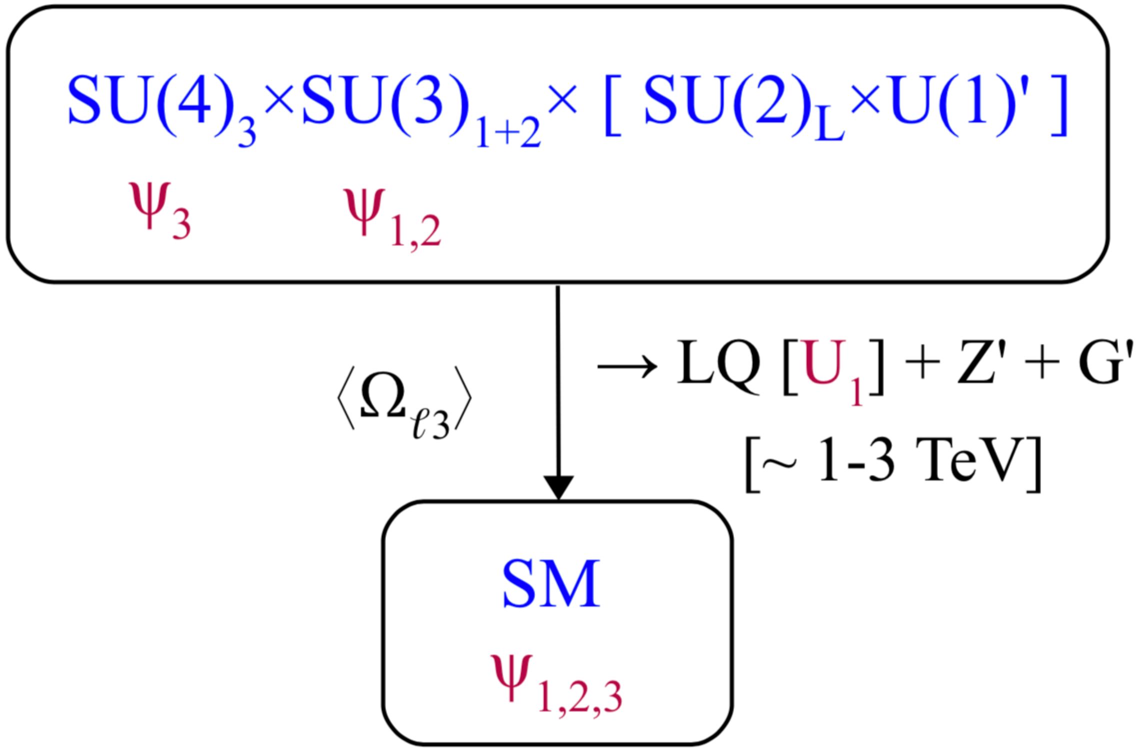


Induces a small effective coupling among the new vectors and the light fermions **(very important for $b \to s\ell\ell$!)**

Very similar setup in Greljo, Stefanek, 1802.04274

Low-energy remnants

Similar constructions in:
- Di Luzio, Greljo, Nardecchia, 1708.08450
- Diaz, Schmaltz, Zhong, 1706.05033
- Georgi, Nakai, 1606.05865



Despite the apparent complexity, the model is highly constrained at ~TeV scale

- Uninvited guests: unavoidable Z' and G', with masses close to U_1
- Key difference to other existing models

→ **unsuppressed $b_R - \tau_R$ LQ couplings**

[**Very important pheno implications!**]

Flavor structure

[$\boldsymbol{g_4 \simeq 3}$ enhances NP in $R(D^{(*)})$ and suppresses dangerous couplings]

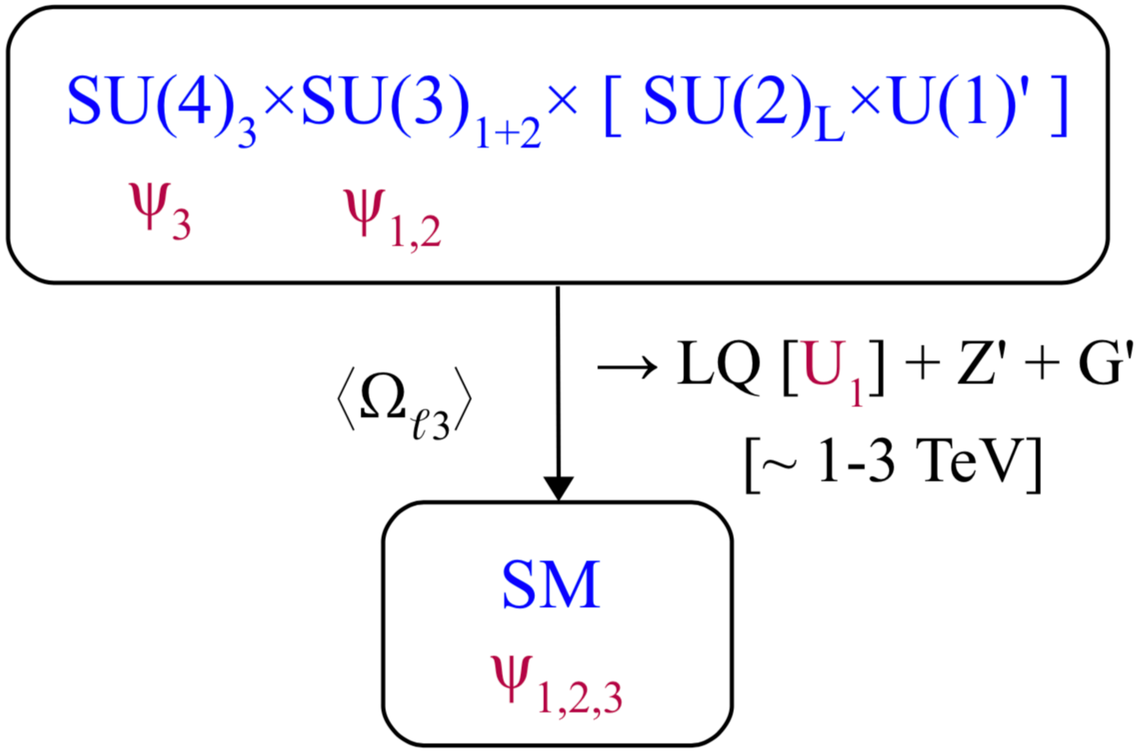
$$\boldsymbol{U_1}: \quad g_4\, \mathrm{diag}(\epsilon'_U, \epsilon_U, 1)$$ [$\epsilon_i^{(\prime)}$ from d=6 op.]

$$\boldsymbol{G'}: \quad g_c\, \mathrm{diag}\left(-\frac{g_3}{g_4} + \epsilon_q, -\frac{g_3}{g_4} + \epsilon_q, \frac{g_4}{g_3}\right)$$

+ (small) flavor rotations controlled by the U(2) symmetry

$$\boldsymbol{Z'}: \quad g_Y\, \mathrm{diag}\left(-\frac{g_1}{g_4} + \epsilon_{q,\ell'}, -\frac{g_1}{g_4} + \epsilon_{q,\ell}, \frac{g_4}{g_1}\right)$$

Low-energy phenomenology



- Uninvited guests: unavoidable Z' and G', with masses close to U_1
- Unsuppressed $b_R - \tau_R$ LQ couplings
- Flavor structure controlled by the U(2) symmetry [and d=6 ops.]

Any candidate to simultaneously explain the anomalies should "fight in two arenas":

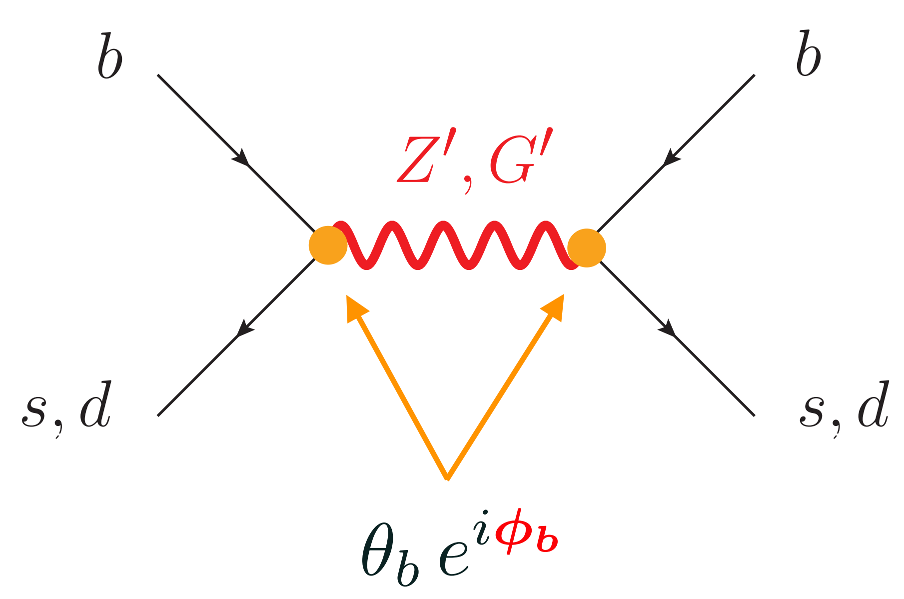
- **Other low energy data**
  - $\Delta F = 2$ transitions
  - τ decays (LFUV and LFV)
  - Other semileptonic processes
- **High-p_T searches at LHC**

and life is not easy for NP models there….

$\Delta F = 2$: 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.,1712.06572]

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

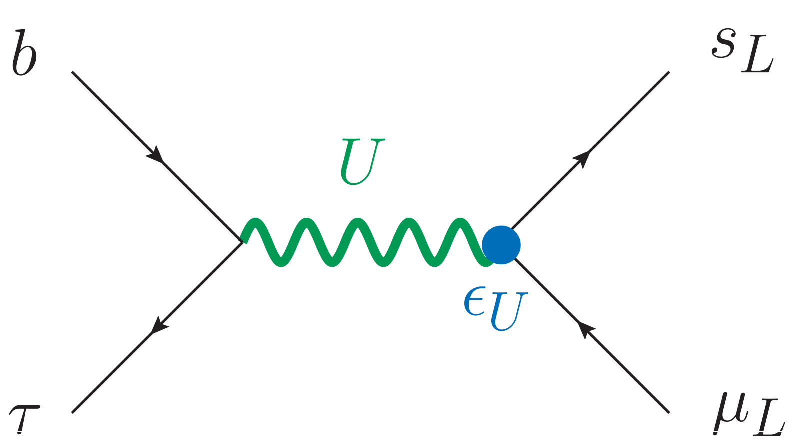
Still early to draw conclusions but it is interesting that the model can "naturally" explain the deficit

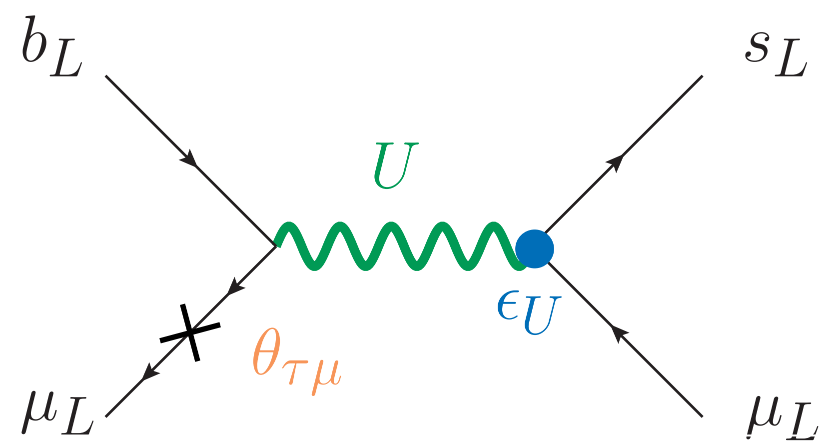
→ Possible **CP violation** effects in $b \to s, d$ transitions!
[Currently under investigation]

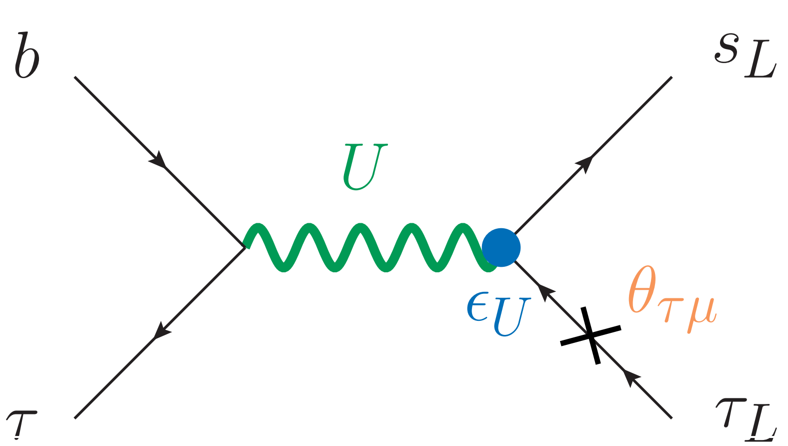
Other $\Delta F = 2$ transitions: $K - \bar{K}$, $D - \bar{D}$ also **under control**!

Explanation of the $b \to s\ell\ell$ anomalies

The dominant contribution to $b \to s\ell\ell$ transitions is mediated by the leptoquark







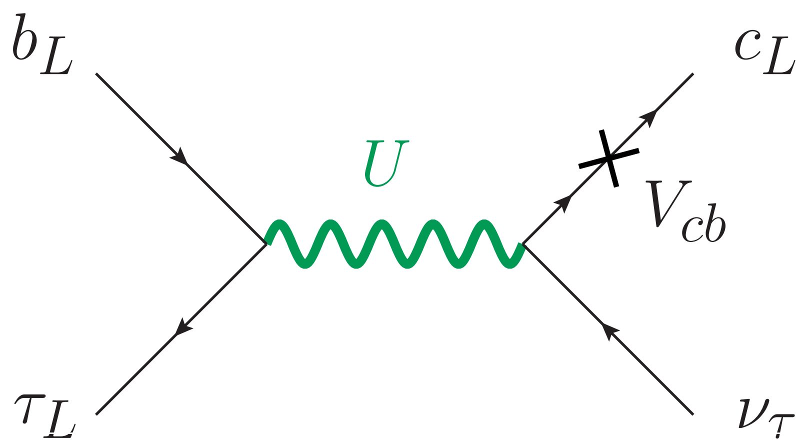
$$\boldsymbol{\theta_{\tau\mu} \sim 0.2}$$

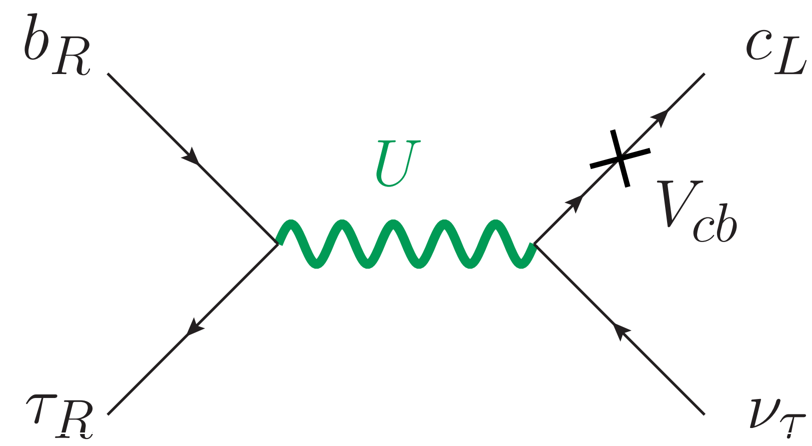
$$b \to s\tau\tau \sim b \to s\mu\mu$$

$$b \to s\tau\mu \sim \mathcal{O}(5) \times b \to s\mu\mu$$

★★ Key difference w.r.t the "standard" solutions

Explanation of the $b \to c\tau\nu$ anomalies





$\mathcal{C}^{V,LL}_{\nu edu}$ $\mathcal{C}^{S,RL}_{\nu edu}$

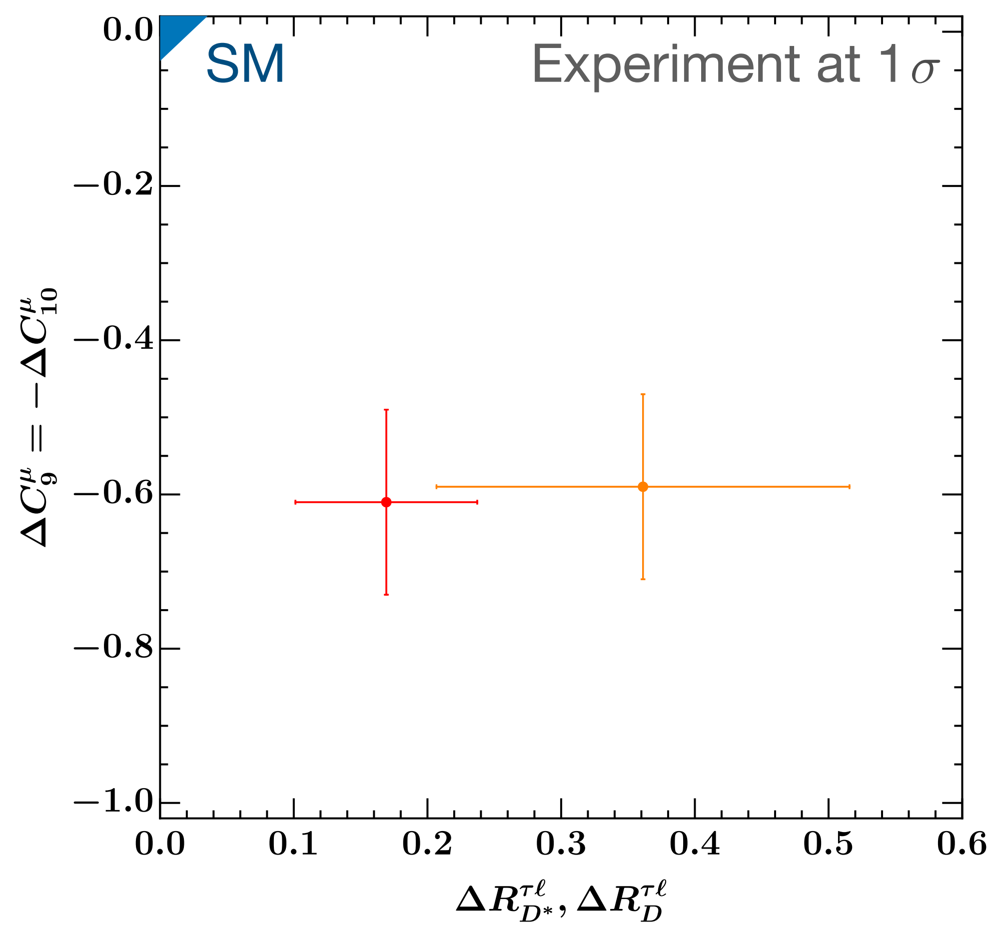
$$\Delta R_{D^*} = R_{D^*}/R_{D^*}^{\rm SM} - 1 \approx 2\,(1 + 0.17)\,C_U$$

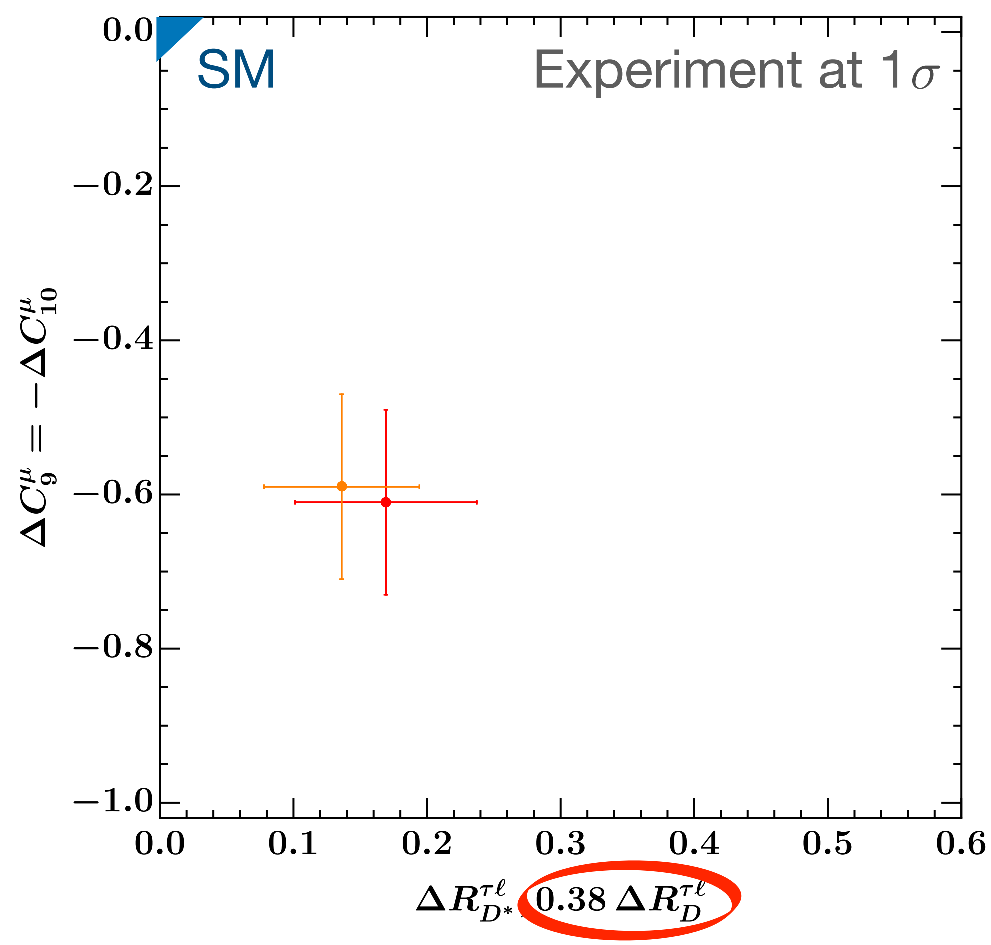
$$\Delta R_{D} = R_{D}/R_{D}^{\rm SM} - 1 \approx 2\,(1 + 2.1)\,C_U$$

$$C_U = \frac{g_U^2 v^2}{4M_U^2}$$

Contributions from the **vector**/**scalar** operator in **green**/**blue**

The "0.38 rule" for R(D)/R(D*)



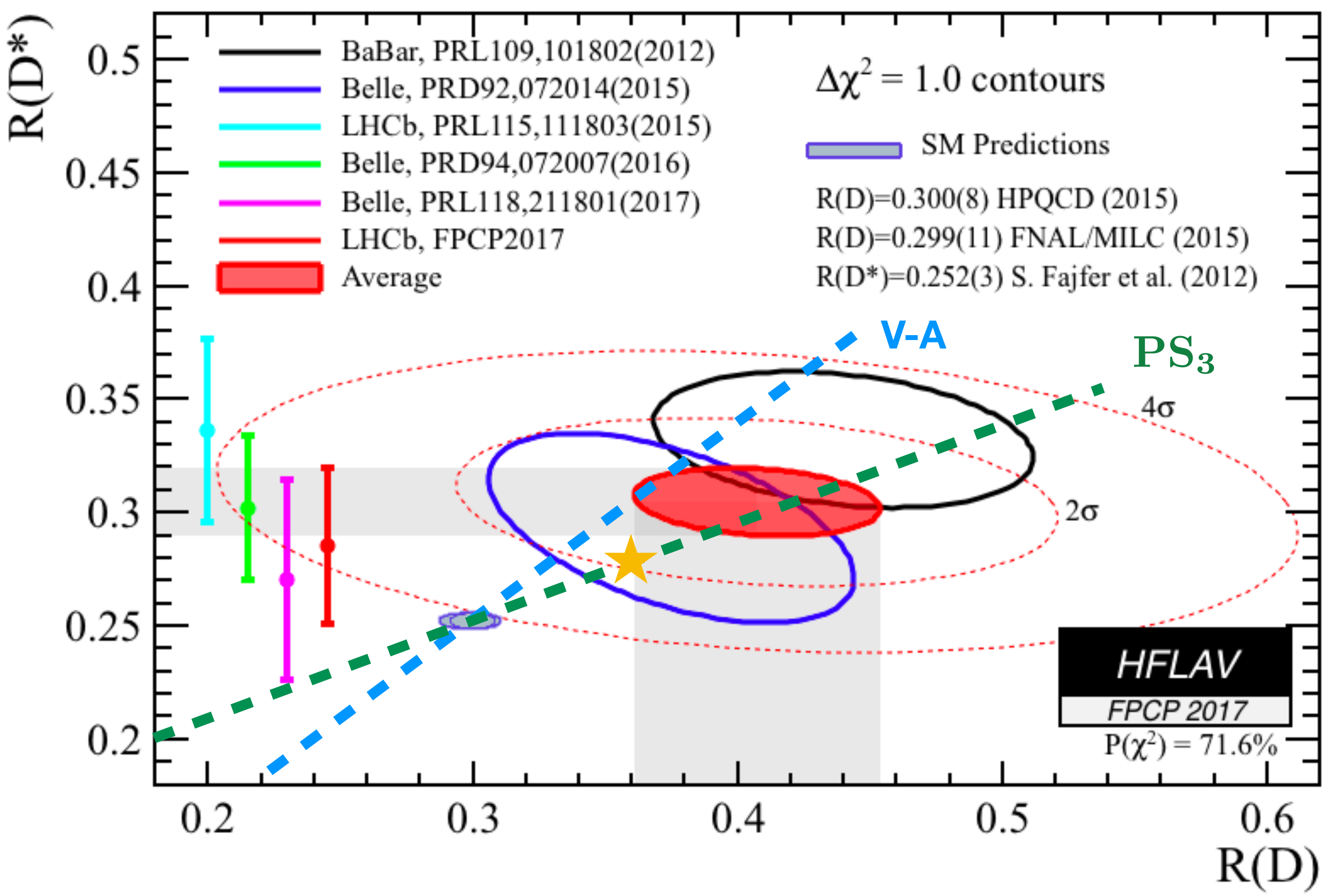


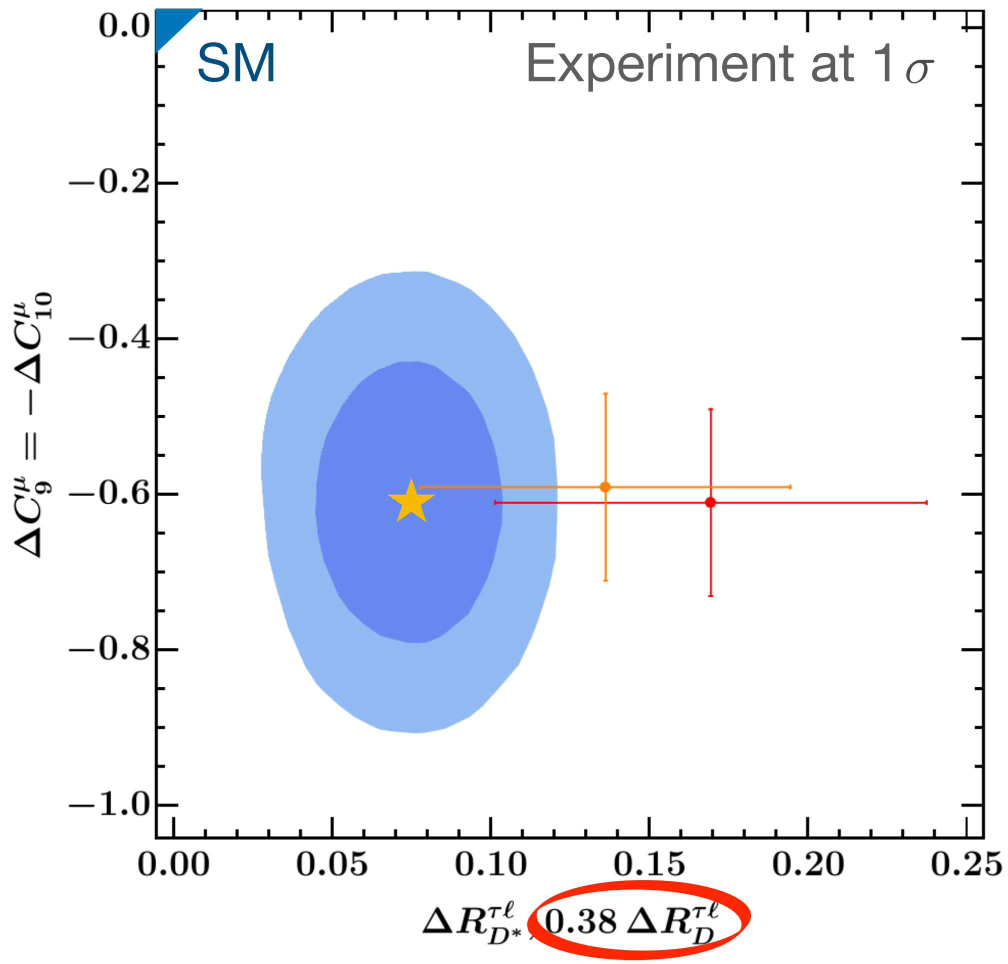
$$\left.\begin{aligned} \Delta R_{D^*} &= R_{D^*}/R_{D^*}^{\rm SM} - 1 \approx 2\,(1 + 0.17)\, C_U \\ \Delta R_D &= R_D/R_D^{\rm SM} - 1 \approx 2\,(1 + 2.1)\, C_U \end{aligned}\right\} \Longrightarrow \frac{\Delta R_{D^*}}{\Delta R_D} \simeq 0.38 \qquad C_U = \frac{g_U^2 v^2}{4 M_U^2}$$

The required NP scale can be higher!!

★★ **Key difference w.r.t other solutions**

Low-energy fit results





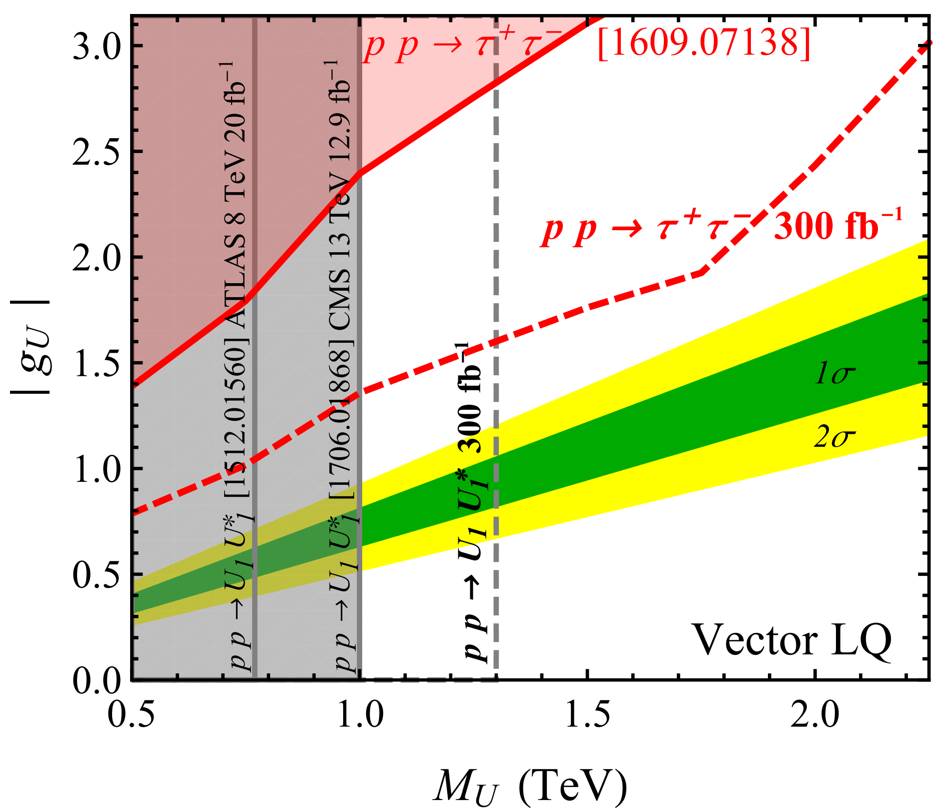
The fit to low-energy data is very good!
[**although slightly smaller NP effects in R(D)/R(D*)**]

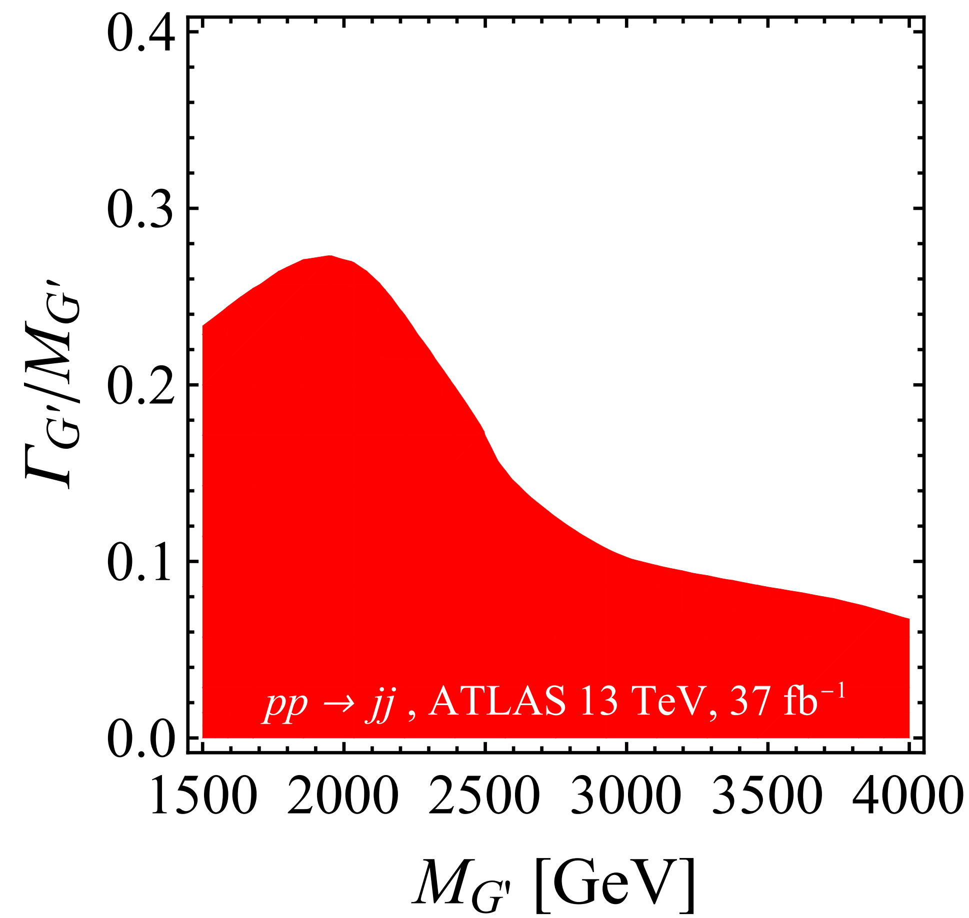
High-pT searches

General characteristics of the new exotic states:

- Flavor non-universal couplings, with much **stronger couplings to the 3rd generation**
- **Large widths** (specially for G' and Z')

Coloron exclusion for the "4321" model in [**Di Luzio et al.,1708.08450**]
(Similar conclusions apply for PS^3)





See Admir Greljo's talk!
& in Yuta's talk (coming next!)

[Di Luzio, JF, Greljo, Nardecchia, Renner, in preparation]

Conclusions

It is possible to find well-motivated combined explanations of the B anomalies, compatible with current data in both low- and high-energies

The model I presented, a **Pati-Salam deconstruction**, predicts several characteristic smoking-gun signatures that differentiate it from other solutions

- $\Delta R_{D^*}/\Delta R_D \simeq 0.38$
- NP in $b \to s\tau\tau \sim b \to s\mu\mu$ and $b \to s\tau\mu \sim \mathcal{O}(5) \times b \to s\mu\mu$
- Possibility of a deficit in $\Delta B = 2$ & CP violation involving the 3rd quark family

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

Exciting times ahead of us. Let's have fun


The end