New physics flavor model

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La Thuile 2021 - Les Rencontres de Physique de la Vallée d'Aoste

The SM Lagrangian: Naturalness problems

$$\mathscr{L}_{\rm SM} = \mathscr{L}_{\rm Gauge} + \mathscr{L}_{\rm Higgs} + \mathscr{L}_{\rm Yuk}$$

3+1 parameters
(flavor universal)

[Strong CP problem]

2 parameters

[Hierarchy problem]

- Experimentally well tested
- Highly symmetric
  ($U(3)^5$ flavor symmetry)
- Natural (except for $\theta_{\rm QCD}$)

- Experimentally less tested
- One relevant parameter
  (seemingly unnatural)

The SM Lagrangian: Flavor puzzle

$$\mathscr{L}_{\rm SM} = \mathscr{L}_{\rm Gauge} + \mathscr{L}_{\rm Higgs} + \mathscr{L}_{\rm Yuk}$$

3+1 parameters
(flavor universal)

[Strong CP problem]

2 parameters

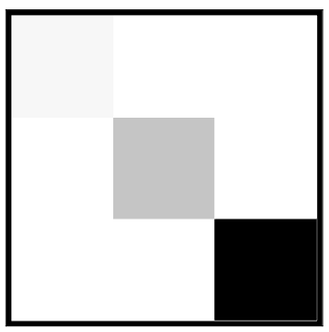
[Hierarchy problem]

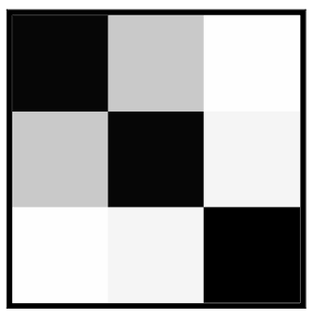
Flavor non-universal

The SM Yukawa sector is characterized by 13 parameters (for massless neutrinos)

[3 lepton masses + 6 quark masses + 3+1 CKM parameters]

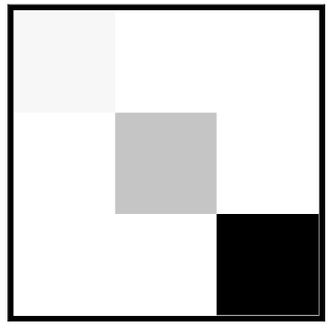
… whose values do not look at all accidental

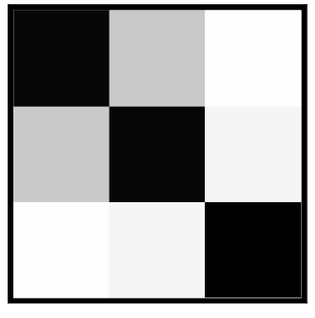
$M_{u,d,e} \sim$ 

$V_{\rm CKM} \sim$ 

The $U(2)$ flavor symmetry

The SM Yukawas do not look at all accidental

$$M_{u,d,e} \sim$$ 

$$V_{\rm CKM} \sim$$ 

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

Hints of underlying (flavor) symmetries?

They respect an approximate $U(2)^5 \equiv U(2)_q \times U(2)_\ell \times U(2)_u \times U(2)_d \times U(2)_e$ symmetry, minimally broken by 5 spurions [Barbieri et al. 1105.2296]

$$Y_{u(d)} = y_{t(b)} \begin{pmatrix} \Delta_{u(d)} & x_{t(b)} V_q \\ 0 & 1 \end{pmatrix} \qquad Y_e = y_\tau \begin{pmatrix} \Delta_e & x_\tau V_\ell \\ 0 & 1 \end{pmatrix}$$

$$|V_q| \sim |V_{ts}|$$

$$|\Delta_u| \sim y_c$$

If NP preserve this symmetry: large NP effects in 3rd generation, gradually smaller effects in the lighter generations

The SM Lagrangian: NP opportunities

$$\mathscr{L}_{\rm SM} = \mathscr{L}_{\rm Gauge} + \mathscr{L}_{\rm Higgs} + \mathscr{L}_{\rm Yuk} + \mathscr{L}_{\rm NP}\,[?]$$

3+1 parameters
(flavor universal)

[Strong CP problem]

2 parameters

[Hierarchy problem]

13 parameters
(flavor non-universal)

[Flavor puzzle]

Hints of underlying symmetries/dynamics?

Strong CP problem: PQ symmetry (axions)? PQ breaking scale should be high

Hierarchy problem: TeV scale NP (flavor structure is needed to avoid constraints)

Flavor puzzle: Flavor symmetries, e.g. $U(2)^5$
(NP coupling dominantly to the third generation, but at which scale?)

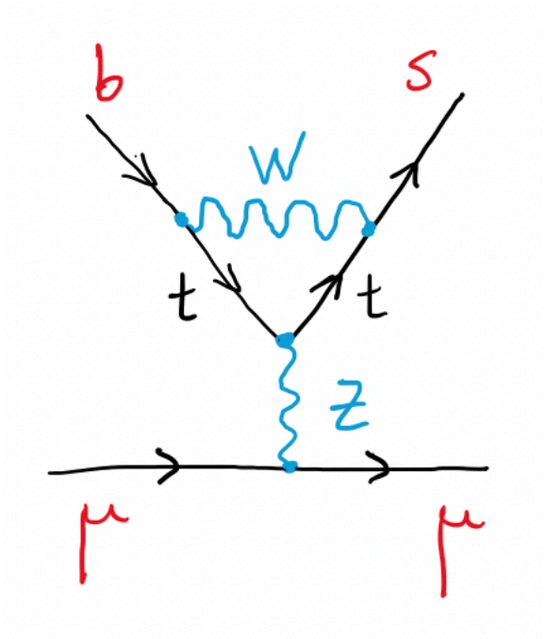
Both related to the Higgs, are these hints connected?

The B anomalies

Hints of Lepton Flavor Universality Violation in semileptonic B decays

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

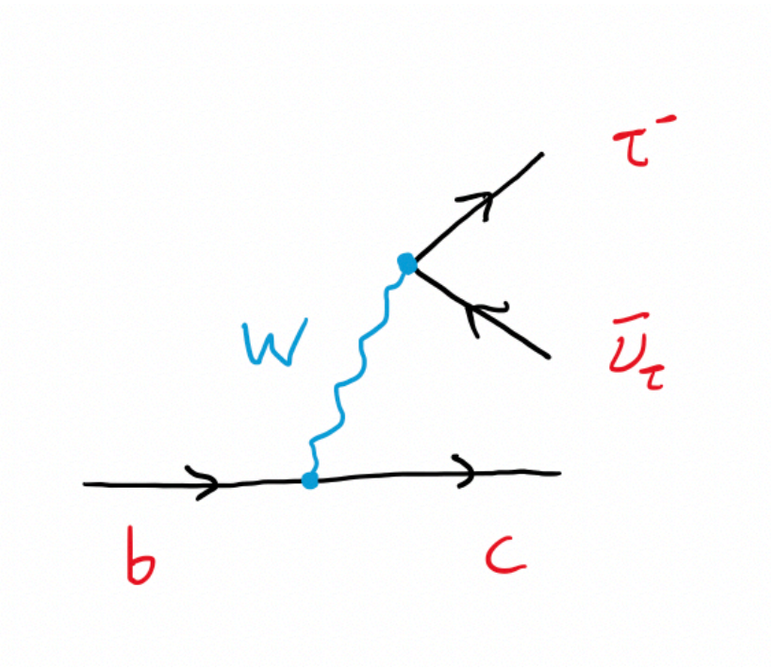
μ/e ~~universality~~



$> 4\sigma$

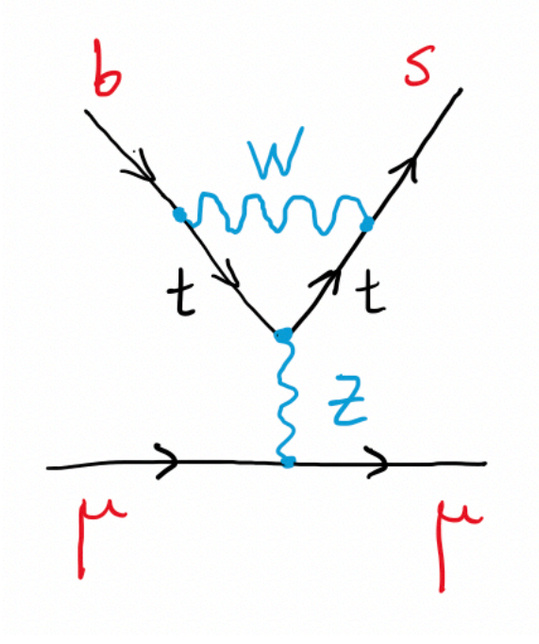
$$b \to c\tau\bar{\nu}$$

$\tau/\mu\,, e$ ~~universality~~



$\sim 3\sigma$

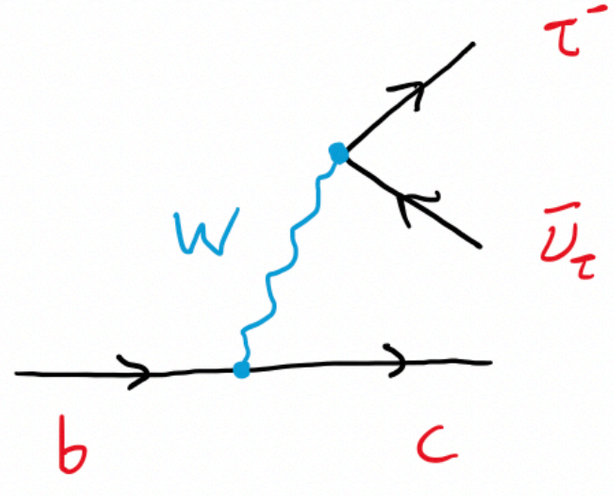
Flavor pattern of the B anomalies



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

~10% of a SM loop effect

$\ll$



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

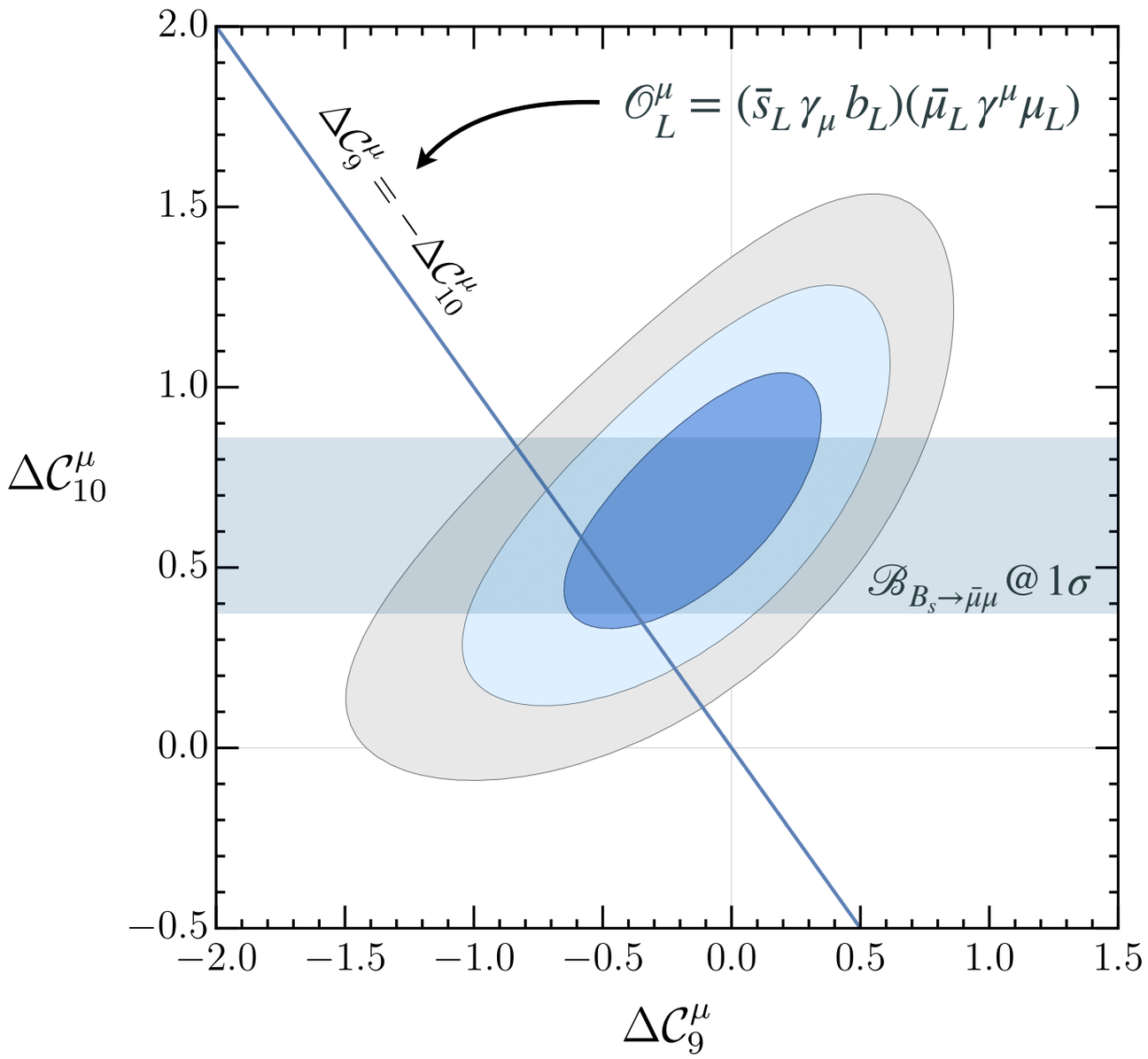
~10% of a SM tree-level effect

The only source of lepton flavor universality violation in the SM (Yukawas) follows a similar trend: $y_e \ll y_\mu \ll y_\tau \ldots$.

TeV-scale NP explanation consistent with $U(2)^5$ flavor symmetry with $|V_{q,\ell}| \sim 0.1$ (roughly the size inferred from the SM Yukawa $|V_q| \sim V_{cb} \approx 0.04$)

[JFM, Isidori, Pagès, Yamamoto, 1909.02519]

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



$$\mathcal{O}_9^\mu = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu} \gamma^\mu \mu)$$

$$\mathcal{O}_{10}^\mu = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu} \gamma^\mu \gamma_5 \mu)$$

$$C_9^{\rm SM} \approx -C_{10}^{\rm SM} \approx 4.2$$

Theoretically clean observables

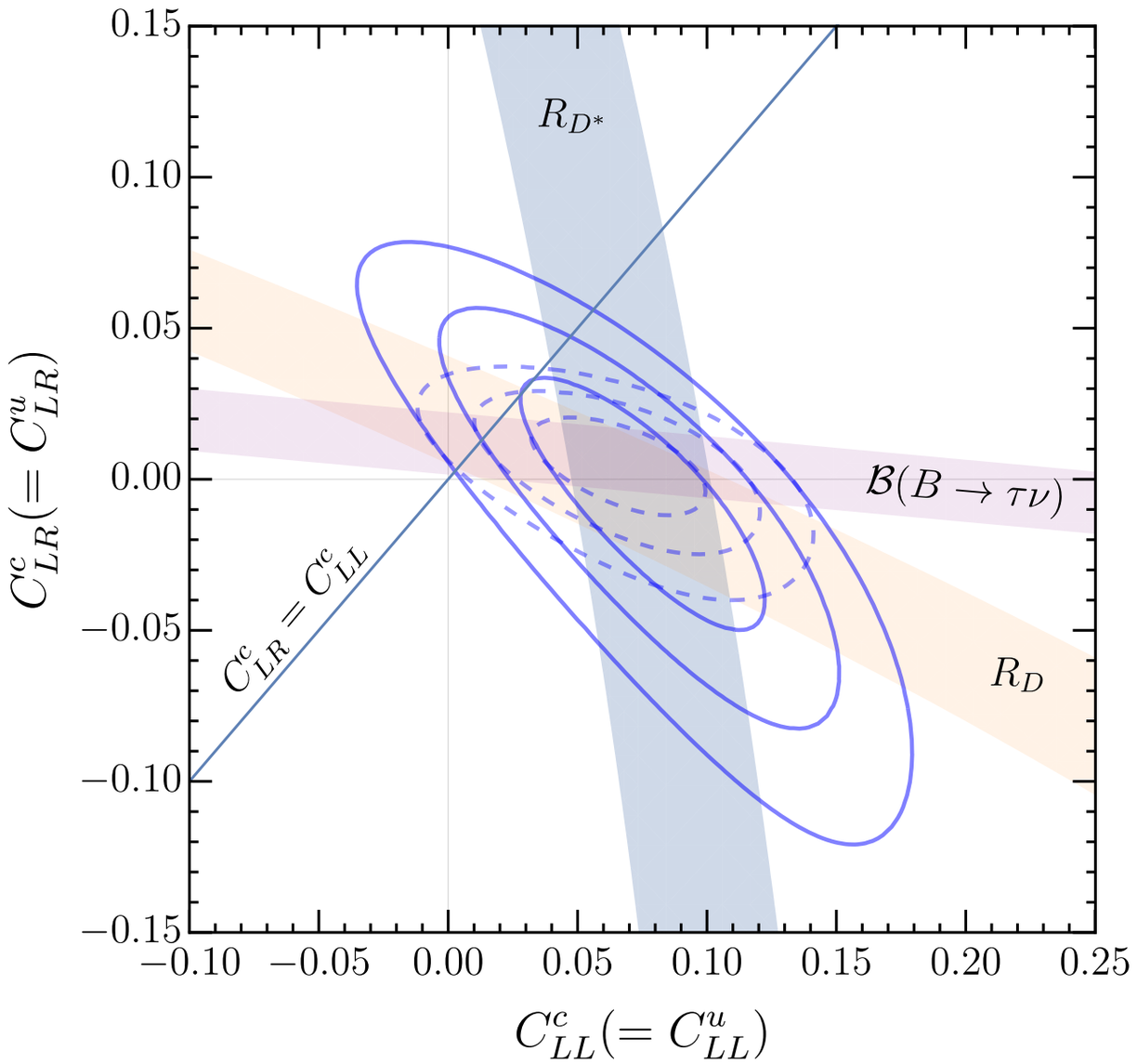
★ $R_{K^{(*)}} \equiv \dfrac{\mathcal{B}(B \to K^{(*)} \bar{\mu}\mu)}{\mathcal{B}(B \to K^{(*)} \bar{e}e)}$

★ $\mathcal{B}(B_s \to \bar{\mu}\mu)$

Other observables in $b \to s\mu\mu$ semileptonic decays also show (consistent) deviations

[See talk by Peter Stangl]

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



Vector leptoquark-inspired EFT basis

$$\mathcal{O}^i_{LL} = (\bar{u}^i_L \gamma_\mu \nu_L)(\bar{\tau}_L \gamma^\mu b_L)$$
$$= \frac{1}{2}\left(\mathcal{O}^{(1)}_{lq} + \mathcal{O}^{(3)}_{lq}\right)$$ SM operator

$$\mathcal{O}^i_{LR} = -(\bar{u}^i_L \gamma_\mu \nu_L)(\bar{\tau}_R \gamma^\mu b_R)$$
$$= 2\,(\bar{u}^i_L b_R)(\bar{\tau}_R \nu_L)$$

Theoretically clean observables

★ $R_{D^{(*)}} \equiv \dfrac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}$ $[b \to c\ell\nu]$

★ $\mathcal{B}(B \to \bar{\tau}\nu)$ $[b \to u\ell\nu]$

Assuming minimally broken $U(2)^5$ flavor symmetry:

$$C^c_{LL} = C^u_{LL} \quad \& \quad C^c_{LR} = C^u_{LR}$$

same NP effect relative to the SM
in $b \to c$ and $b \to u$ transitions

Additional constraints

There is a long list of constraints [Meson mixing, τ decays, LFV, high-p_T searches…]

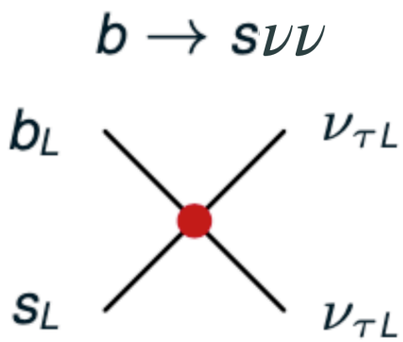
★ Crucial role of flavor symmetries/structure to suppress large NP effects on these observables

★ Other dynamical requirements are also needed

Improves the fit to $b \to s\mu\mu$ semileptonic observables!

[See talk by Peter Stangl]

[Bobeth, Haisch, arXiv:1109.1826; Crivellin et al., arXiv:1807.02068]



Strongly constrained by

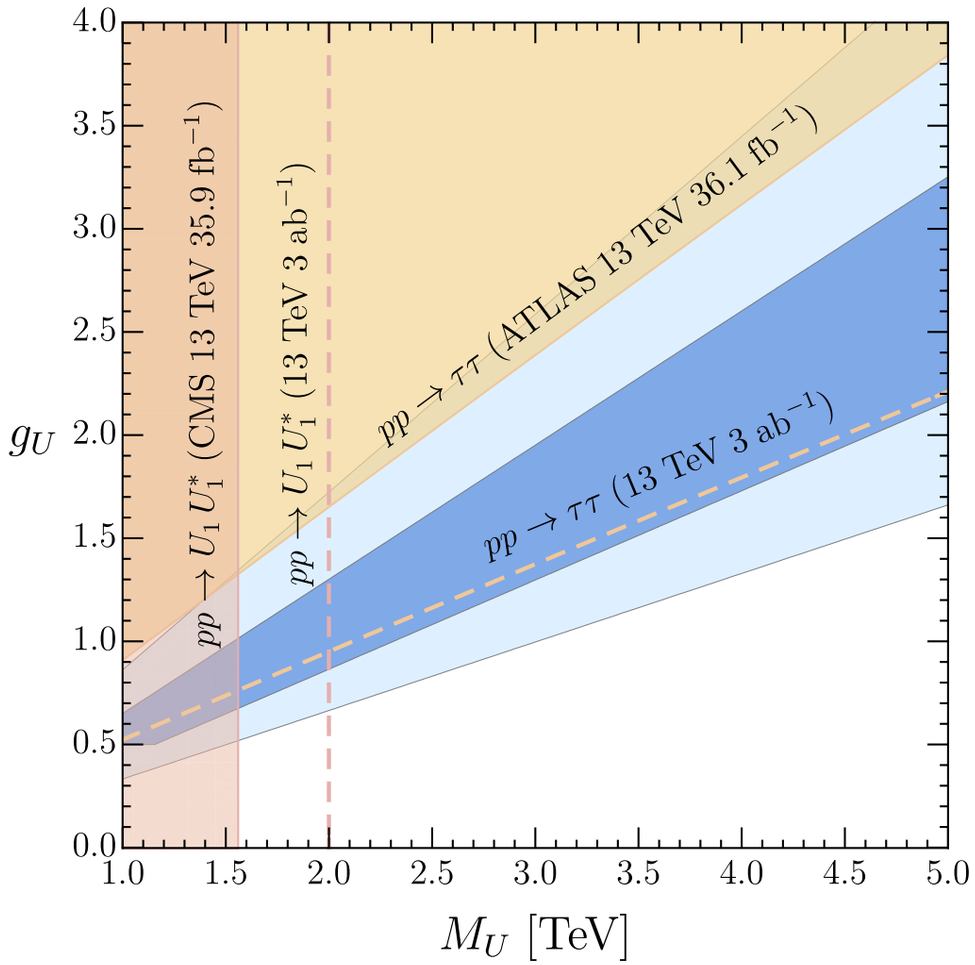
$$B \to K^{(*)}\nu\nu$$

$$([C^{(1)}_{\ell q}]_{3323} \approx [C^{(3)}_{\ell q}]_{3323})$$

Simplified U_1 leptoquark explanation

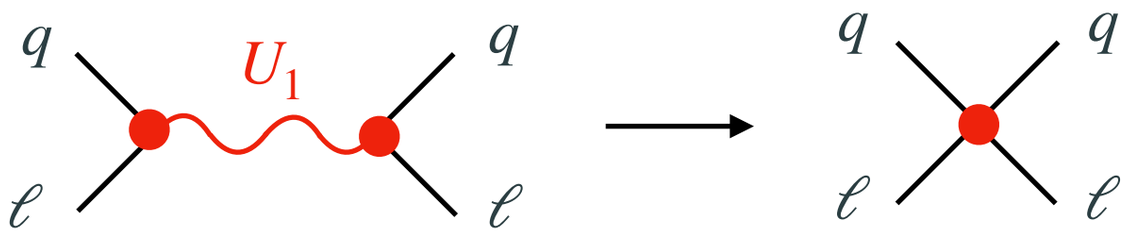
$$\mathscr{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[\beta_{i\alpha}^L (\bar{q}_L^i \gamma_\mu \ell_L^\alpha) + \beta_{i\alpha}^R (\bar{d}_R^i \gamma_\mu e_R^\alpha) \right] + \text{h . c .} \qquad U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$$

- Consistent with other low-energy and high-pT data



[Cornella, JFM, Isidori, 1903.11517;
Baker, JFM, Isidori, König, 1901.10480]

- No hadronic and leptonic operators <u>at tree level</u> (strongly constrained by data)



- The required relation $[C_{\ell q}^{(1)}]_{3323} \approx [C_{\ell q}^{(3)}]_{3323}$ is a (<u>tree-level</u>) prediction of the model

- No proton decay (protected by symmetry)

UV completion for the U_1 leptoquark

Massive spin-1 particle

- Composite resonance from strong dynamics $\sim \rho_\mu$

  [Barbieri et al. 1512.01560; Barbieri, Murphy, Senia 1611.04930; Barbieri, Tesi, 1712.06844]

- Gauge boson $\sim W_\mu$
  - π_L composite

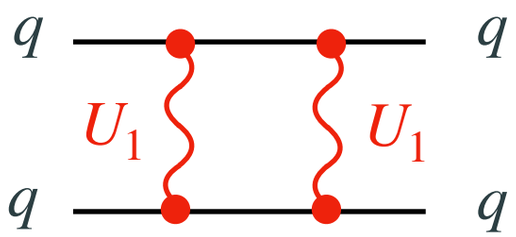
    [JFM, Stangl, 2004.11376]
  - π_L fundamental

[Di Luzio, Greljo, Nardecchia, 1708.08450; Bordone, Cornella, JFM, Isidori 1712.01368; Greljo, Stefanek, 1802.04274,…]

U_1 as a composite resonance:

✓ **Hierarchy problem:** Higgs could arise as a pNGB of the strong dynamics

✗ **Non-renormalizable:** Important loop effects can only be guessed by NDA



$$\mathscr{A}_{\Delta F=2} \propto \frac{g_U^4}{M_U^4}\frac{\Lambda^2}{16\pi^2}$$

Gauge UV completion for the U_1 leptoquark

The U_1 gauge boson UV completion points to Pati-Salam unification

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

$$\mathbf{PS} \supset SU(4) \times SU(2)_L \times U(1)_R$$

$$SU(4) \sim \begin{pmatrix} G^a & U^\alpha \\ (U^\alpha)^* & Z' \end{pmatrix}$$

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

"Leptons as the fourth color"

✓ $\mathrm{SU}(4)$ is the smallest group containing the $U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$

✗ The (flavor universal) Pati-Salam model does not work

→ The bounds from $K_L \to \mu e$ 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

4321 model(s)

[Georgi and Y. Nakai, 1606.05865; Diaz, Schmaltz, Zhong, 1706.05033; Di Luzio, Greljo, Nardecchia, 1708.08450]

$$SU(3)_c \times U(1)_Y = [SU(4) \times SU(3) \times U(1)_X]_{\text{diag}}$$

$$\underbrace{SU(4)}_{g_4} \times \underbrace{SU(3)'}_{g_3} \times SU(2)_L \times \underbrace{U(1)_X}_{g_1} \xrightarrow{SSB} SU(3)_c \times SU(2)_L \times U(1)_Y + U_1, G', Z'$$

$U(1)_Y$

$SU(3)_c$

Why an additional $SU(3)$?

~ The extra $SU(3)$ gives a G' (color-octet), apart from the unavoidable Z'

✓ It decorrelates $SU(4)$ from the SM color group. In the limit $g_4 \gg g_{3,1}$

→ $\mathcal{O}(g_3/g_4)$ and $\mathcal{O}(g_1/g_4)$ G' and Z' couplings to valence quarks (sufficient to pass high-p_T bounds)

Third-family quark-lepton unification at the TeV scale

$$SU(4)_3 \times SU(3)_{1+2} \times SU(2)_L \times U(1)_X \xrightarrow{\langle \Omega_{1,3,15} \rangle \sim \mathcal{O}(\mathrm{TeV})} SU(3)_c \times SU(2)_L \times U(1)_Y + U_1, G', Z'$$

$U(1)_Y$

$SU(3)_c$

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

★ Accidental $U(2)^5$ symmetry in gauge sector
[direct U_1 couplings to 3rd gen. only]

★ $U(2)^5$ broken by the mixing with χ
[source of $V_{q,\ell}$ spurion: U_1 couplings + CKM]

★ Fully calculable loop contributions

Vector Leptoquarks Beyond Tree Level I, II & III
[JFM, Isidori, König, Selimovic, 1910.13474, 2006.16250, 2009.11296]

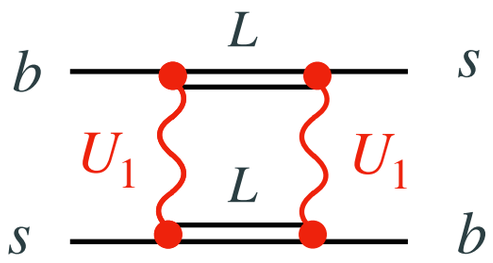
Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)_X$	
q_L^i	**1**	**3**	**2**	$1/6$	1st & 2nd families
u_R^i	**1**	**3**	**1**	$2/3$	
d_R^i	**1**	**3**	**1**	$-1/3$	
ℓ_L^i	**1**	**1**	**2**	$-1/2$	
e_R^i	**1**	**1**	**1**	-1	
ψ_L	**4**	**1**	**2**	0	3rd family
$\psi_R^\pm$	**4**	**1**	**1**	$\pm 1/2$	
χ_L^i	**4**	**1**	**2**	0	$n_{\mathrm{VL}} \geq 2$
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	

[Bordone, Cornella, JFM, Isidori 1712.01368, 1805.09328; Greljo, Stefanek, 1802.04274; Cornella, JFM, Isidori 1903.11517]

The importance of loop contributions

Important effects that appear only at one loop

I. bound on M_χ from $\Delta F = 2$
(similar to SM with charm quark)

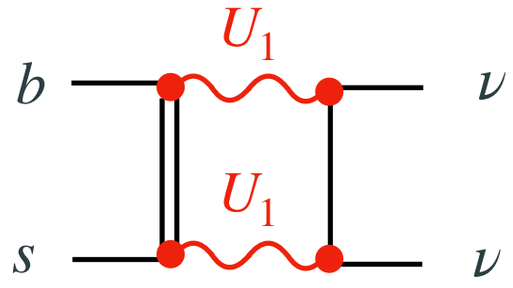


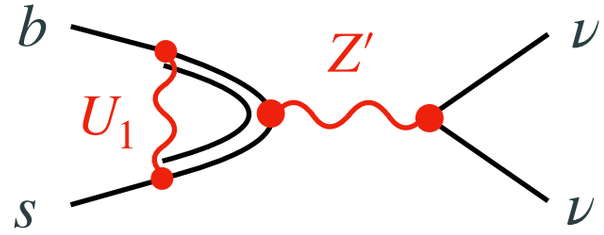
$$\sim \Delta R^2_{D^*} M_L^2 \Rightarrow M_L \sim \text{TeV}$$

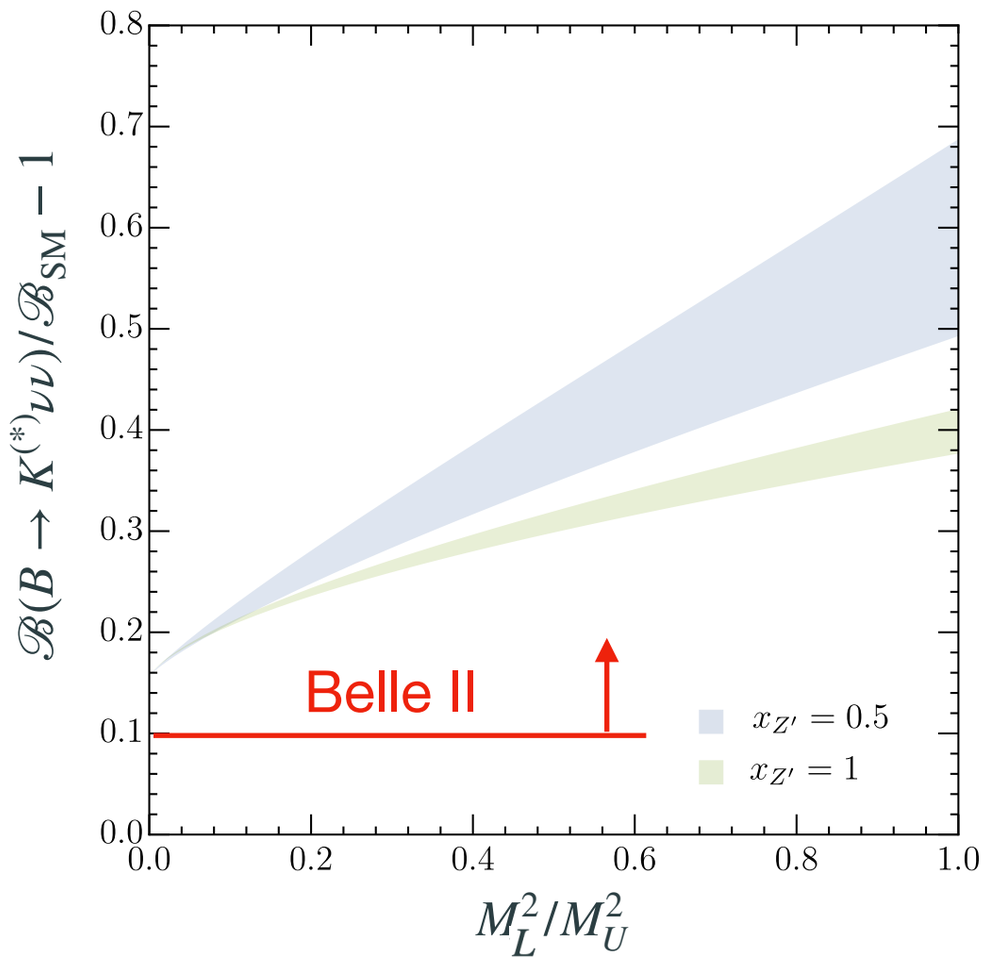
[GIM-like suppression of FCNC loops]

[di Luzio, JFM, Greljo, Nardecchia, Renner 1808.00942;
Cornella, JFM, Isidori 1903.11517;
JFM, Isidori, König, Selimovic, 2009.11296]

II. $B \to K^{(*)}\nu\nu$ [JFM, Isidori, König, Selimovic, 2009.11296]

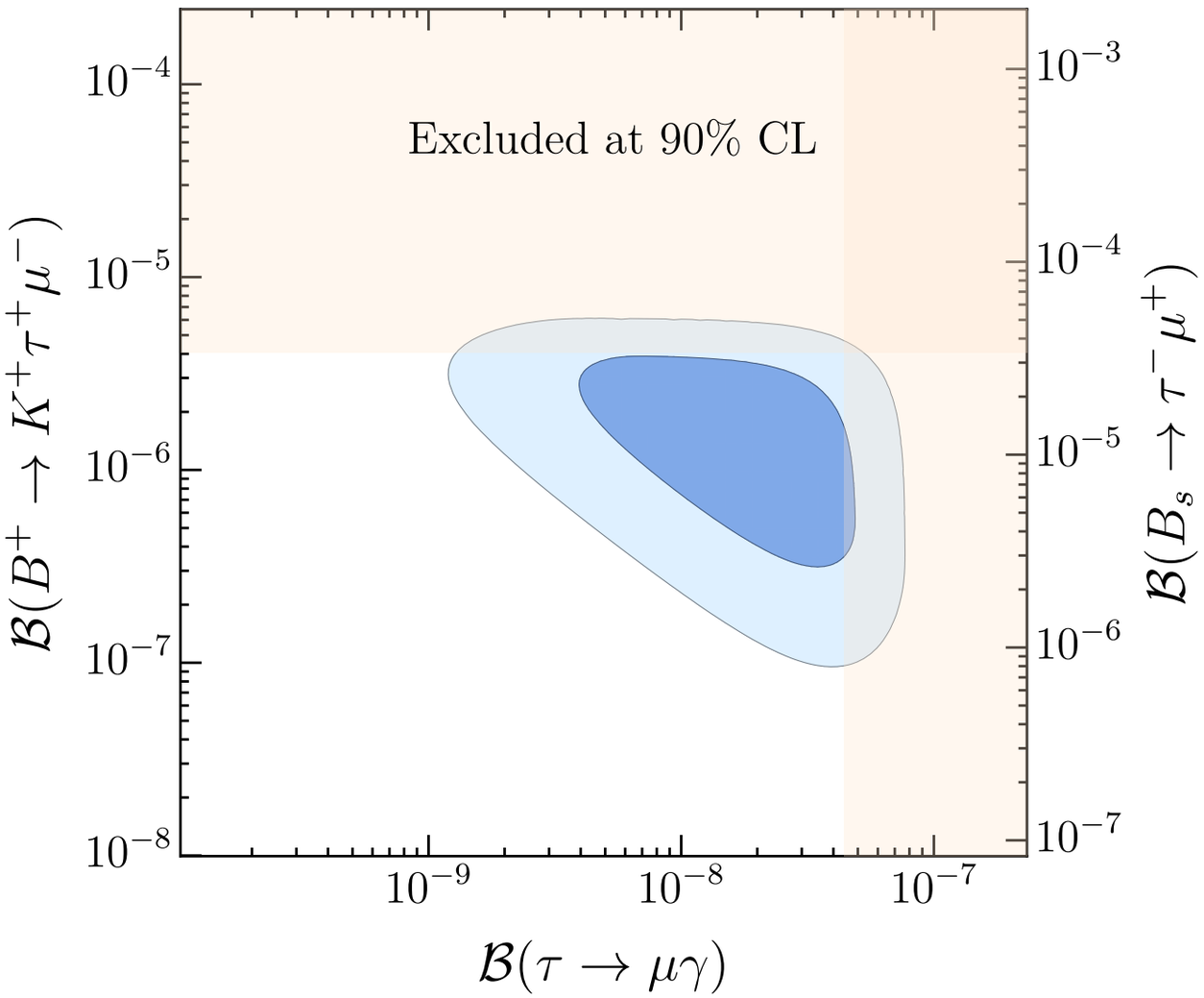






Other predictions: LFV and neutrino masses

I. LFV in B and τ decays



[Cornella, JFM, Isidori 1903.11517]

II. Neutrino masses: Third-family quark-lepton unification at the TeV scale yields

[See talk by Julie Pagès]

$$\psi_R^- = \begin{pmatrix} b_R \\ \tau_R \end{pmatrix} \qquad \psi_R^+ = \begin{pmatrix} t_R \\ \nu_R \end{pmatrix}$$

$$y_b(M_U) \approx y_\tau(M_U) \checkmark$$

$$y_t(\Lambda) \approx y_\nu(\Lambda)$$

Inverse see-saw mechanism

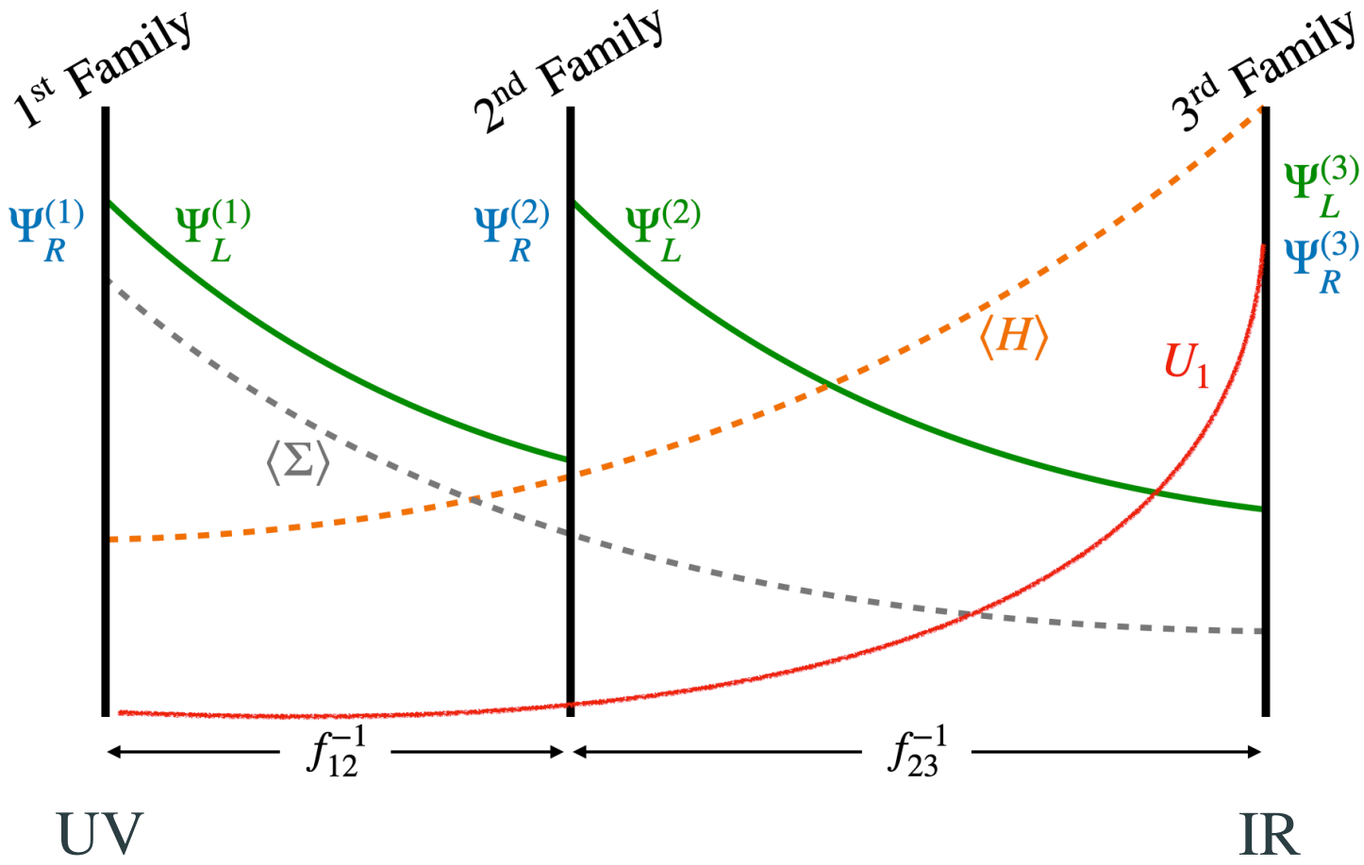
[Measurable PMNS unitarity violation in the 33 entry]

[Greljo, Stefanek, 1802.04274;
JFM, Isidori, Pagès, Stefanek,2012.10492]

Back to Pati-Salam unification… but in 5D!

Warped (compact) extra dimension with three 4D branes

$$\mathrm{PS}_{5D} \equiv SU(4) \times SU(2)_L \times SU(2)_R$$



[JFM, Isidori, Pagès, Stefanek,2012.10492
JFM, Isidori, Lizana, Selimovic, Stefanek, w.i.p]

Flavor $\longleftrightarrow$ fermion quasi-localization in each of the branes (fermion mixing from different profile overlaps)

[Dvali, Shifman, hep-ph/0001072]

$$f_i(y) \sim e^{-c_i y}$$

Higgs IR quasi-localization $\longleftrightarrow$ stabilization of the mass hierarchies (as in Randall-Sundrum)

[Randall, Sundrum hep-ph/9905221]

$SU(4)$ symmetry broken in the UV $\longleftrightarrow$ U_1 LQ as SU(4) KK mode(s) (dominantly coupled to 3rd family)

Conclusions

- Current data is still not conclusive, but the recent **LFU anomalies** in $b \to c\tau\nu$ and $b \to s\ell\ell$ transitions provide one of the strongest hints of physics beyond the SM

- The two anomalies are well consistent among each other (and with other low-energy and high-p_T observables) and, when taken together, clearly point to new **TeV scale dynamics** with a very precise **flavor structure** that resembles the structure observed in the SM Yukawa couplings

- These two indications suggest a possible connection with a solution to the **SM flavor puzzle** and maybe even to the **Higgs hierarchy problem** [several attempts in this direction in the context of composite and extra dimensional models]

- The U_1 vector leptoquark is an excellent mediator to explain the anomalies, hinting to the possibility of **low-scale quark-lepton unification**

- Many experimental predictions (B-decays, LFV, high-p_T signatures…) and upcoming measurements

Thank you!