Quark-lepton unification of the third family at the TeV scale

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Based on work with L. Allwicher, O. L. Crosas, J. Fuentes-Martin, G. Isidori, N. Selimović and B. A. Stefanek

[2207.00018, 2203.01952, 2210.xxxxx]

Warsaw - October 2022

1. Introduction

Starting point: SM

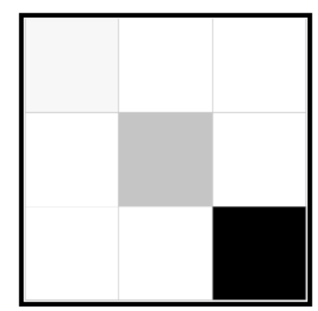
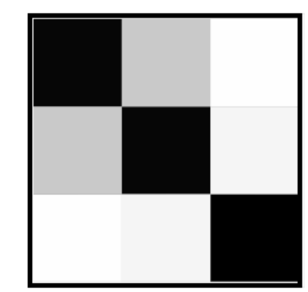
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + |D_\mu \phi|^2 - V(\phi) + \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

Flavour universal & natural

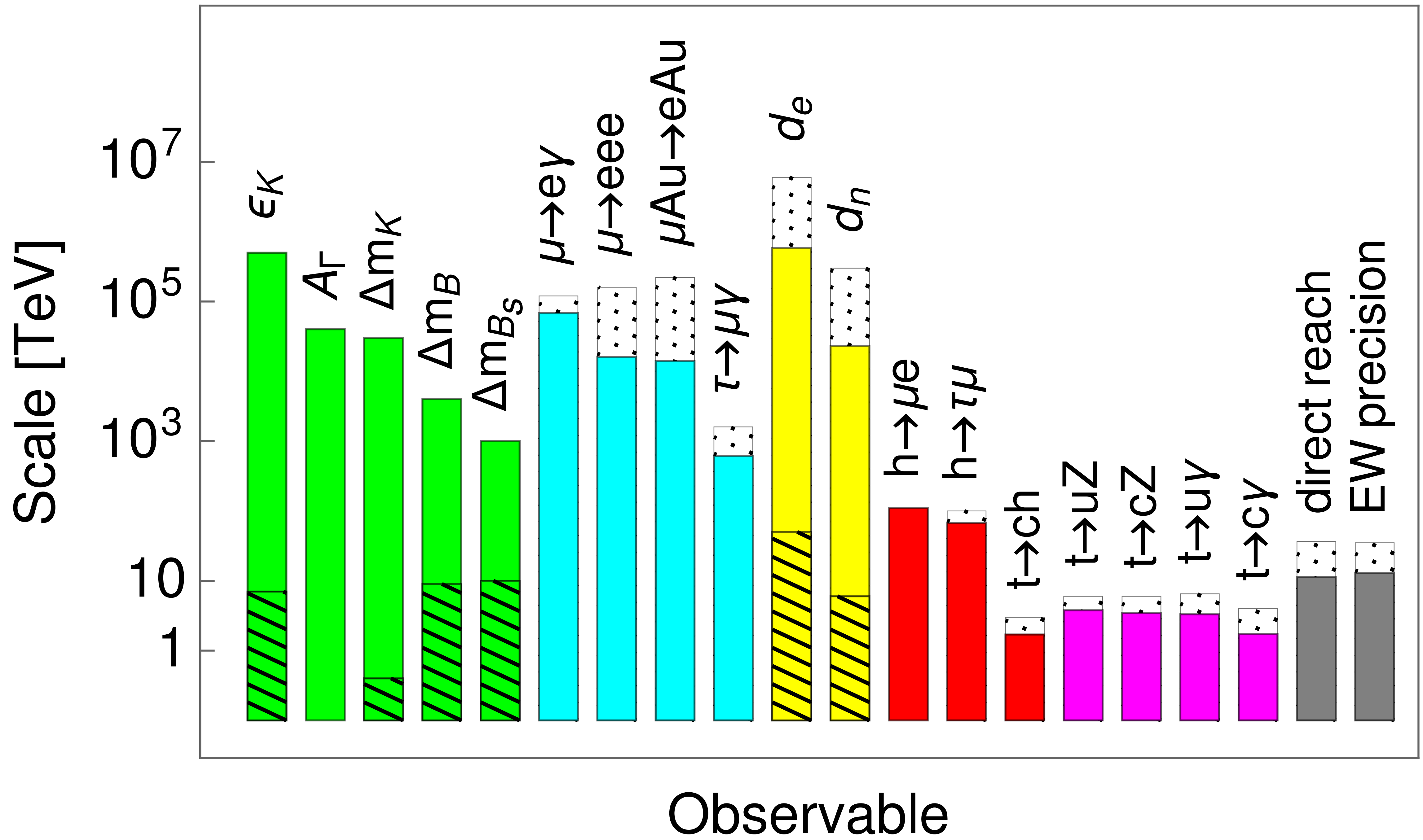
Higgs hierarchy problem

Not FU & hierarchical

- Flavor universality of SM ($U(3)^5$)
- Flavor hierarchies:

$M_{u,d,e} \sim$  $V_{\mathrm{CKM}} \sim$ 

Flavor bounds on NP

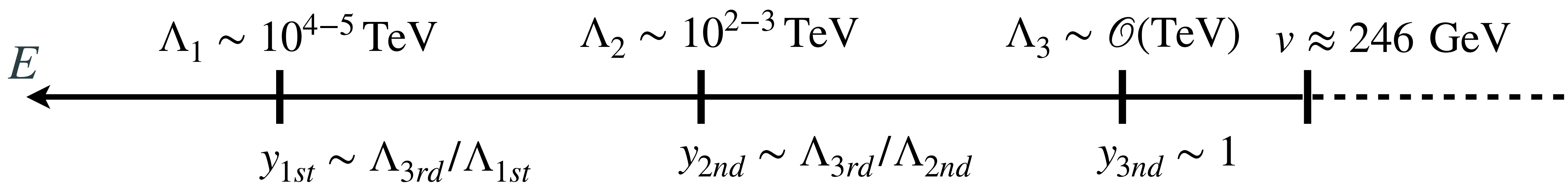


[Physics Briefing Book, 1910.11775]

Multiscale flavor

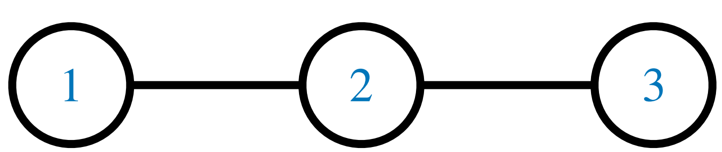
[Dvali, Shiftman, hep-ph/0001072,Panico, Pomarol, 1603.06609
Bordone, Cornella, Fuentes-Martin, Isidori, 1712.01368
Barbieri, 2103.15635]

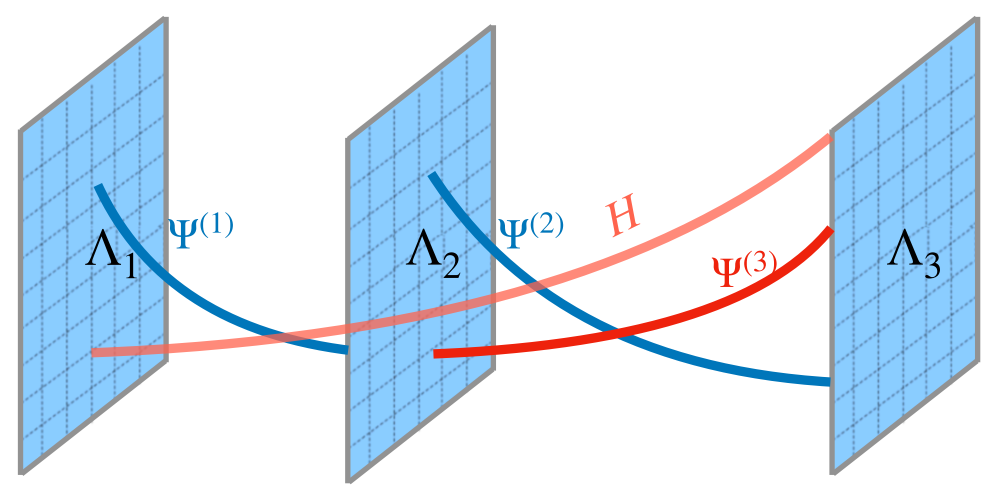
- A safe solution: multiscale origin of the flavor hierarchies.



Multi-site

Extra-dimensions ⟷ (dual) Composite dynamics

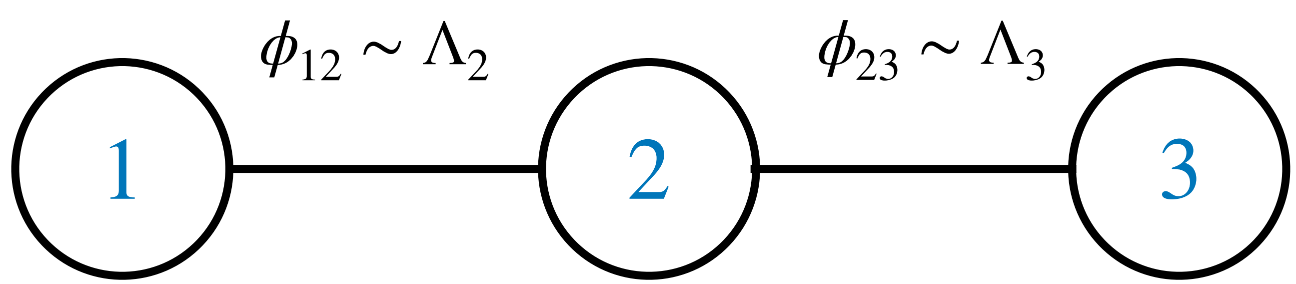




[Bordone, Cornella, Fuentes-Martin, Isidori, 1712.01368, Allwicher, Isidori, Thomsen, 2011.01946]

Deconstructing flavor

- $\mathrm{SM} = \mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \longrightarrow \mathrm{SM}^3$



$$\mathrm{SM}_1 \times \mathrm{SM}_2 \times \mathrm{SM}_3 \xrightarrow{\mathrm{TeV}} \mathrm{SM}$$

(Universal)

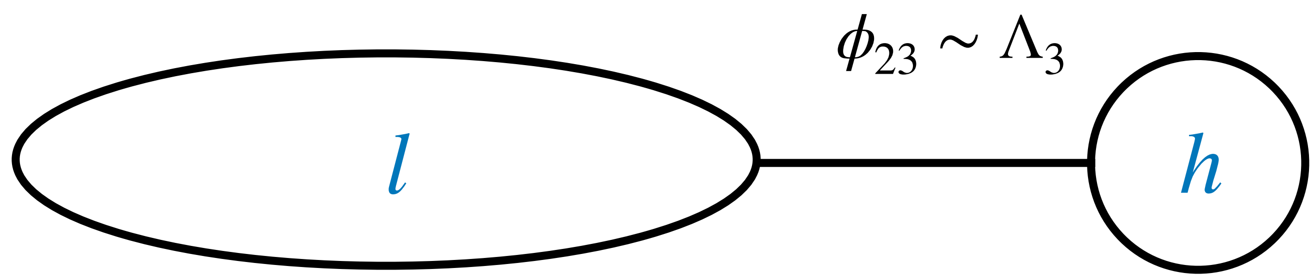
$$H_1 \qquad H_2 \qquad H_3$$

$$\mathscr{L} \supset \Lambda_{i+1} H^\dagger_{i+1} \phi_{i+1\,i} H^\dagger_i$$

$$\sim \begin{pmatrix} \Lambda_1^2 & 0 & 0 \\ 0 & \Lambda_2^2 & 0 \\ 0 & 0 & -v_{\mathrm{EW}}^2 \end{pmatrix} \longrightarrow \begin{pmatrix} \Lambda_1^2 & \Lambda_1\Lambda_2 & 0 \\ \Lambda_1\Lambda_2 & \Lambda_2^2 & \Lambda_2\Lambda_3 \\ 0 & \Lambda_2\Lambda_3 & -v_{\mathrm{EW}}^2 \end{pmatrix} \qquad \begin{pmatrix} \langle H_1 \rangle \\ \langle H_2 \rangle \\ \langle H_3 \rangle \end{pmatrix} \sim \begin{pmatrix} \Lambda_3/\Lambda_1 \\ \Lambda_3/\Lambda_2 \\ 1 \end{pmatrix} v_{\mathrm{EW}}$$

Relevant for TeV pheno…

- $\mathrm{SM} = \mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \;\longrightarrow\; \mathrm{SM}_l \times \mathrm{SM}_h$



$\mathrm{SM}_l \qquad \times \qquad \mathrm{SM}_h$

$$(\mathrm{SM}_l \times \mathrm{SM}_h \longrightarrow SU(3)_l \times SU(3)_h \times SU(2)_L \times U(1)_Y \xrightarrow{\sim \mathrm{TeV}} \mathrm{SM})$$

$$V_{\mathrm{CKM}} = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & \times \end{pmatrix} \xrightarrow{\text{After VLF mixing}} V_{\mathrm{CKM}} = \begin{pmatrix} \times & \times & \sim \epsilon' \\ \times & \times & \sim \epsilon \\ \sim \epsilon' & \sim \epsilon & \times \end{pmatrix}$$

[Chivukula, Simmons, Vignaroli, 1302.1069]

Quark-lepton unification of the third family at the TeV scale?

2. Quark-lepton unification

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

Pati-Salam model

Quark-lepton unification:

$$\Psi_{L/R} = \begin{pmatrix} Q^1_{L,R} \\ Q^2_{L,R} \\ Q^3_{L,R} \\ L_{L,R} \end{pmatrix} \qquad SU(4) \sim \left(\begin{array}{c|c} G^a & U^\alpha \\ \hline (U^\alpha)^* & Z' \end{array}\right)$$

Leptoquark ↗

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

$$Z' \sim (\mathbf{1},\mathbf{1})_0 \quad (B-L)$$

$$SU(2)_R \cup$$

$$SU(4)_c \times SU(2)_L \times U(1)_R \to SU(3)_c \times SU(2)_L \times U(1)_Y$$

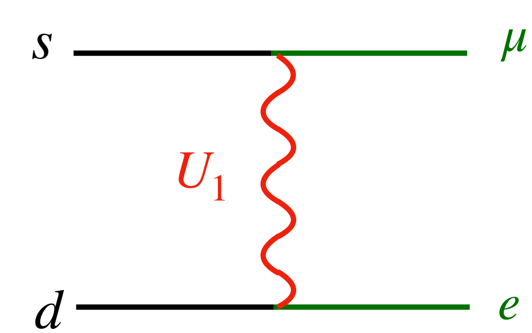
$$\cup \; U(1)_{B-L} \longrightarrow U(1)_Y \; (\downarrow \text{ from } U(1)_R)$$

$$\Psi_L \sim (\mathbf{4},\mathbf{2})_0 \to (\mathbf{3},\mathbf{2})_{1/6} + (\mathbf{1},\mathbf{2})_{-1/2}$$

$$(\mathbf{4},\mathbf{1},\mathbf{2}) \sim \Psi^R \begin{cases} \Psi^u_R \sim (\mathbf{4},\mathbf{1})_{1/2} \to (\mathbf{3},\mathbf{1})_{2/3} + (\mathbf{1},\mathbf{1})_0 \\ \Psi^d_R \sim (\mathbf{4},\mathbf{1})_{-1/2} \to (\mathbf{3},\mathbf{1})_{-1/3} + (\mathbf{1},\mathbf{1})_{-1} \end{cases}$$

Universal PS:

$$K_L \to \mu e$$



$$\Rightarrow \Lambda_{PS} > 10^3 \text{ TeV}$$

[Bordone, Cornella, Fuentes-Martin, Isidori, 1712.01368, 1805.09328;
Greljo, Stefanek, 1802.04274;
Cornella, Fuentes-Martin, Isidori 1903.11517]

4321 model

Third family quark-lepton unification:

$$SU(3)_h \rightarrow SU(3)_c$$

$$SU(3)_h \subset SU(4)_h, \quad SU(3)_l \rightarrow SU(3)_c$$

$$SU(4)_h \times SU(3)_l \times SU(2)_L \times U(1)_{R+(B-L)_l} \xrightarrow{\sim \text{TeV}} SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$SU(4)_h \supset U(1)_{(B-L)_h}, \quad U(1)_{R+(B-L)_l} \rightarrow U(1)_Y$$

$$U(1)_{(B-L)_h} \longrightarrow U(1)_Y$$

$$+U_1,\ Z',\ G'$$

$$\Lambda_U = \sqrt{2}\, m_{U_1}/g_4$$

$$g_4 \gg g_3$$

$$g_s \approx g_3$$
$$g_h^{G'} \approx g_4$$
$$g_l^{G'} \approx g_s^2/g_4$$

- Scalar sector:

$$\Omega_3 \sim (\bar{4},3,1)_{1/6},\ \Omega_1 \sim (\bar{4},1,1)_{-1/2},\ \Omega_{15} \sim (15,1,1)_0 \ \sim \text{TeV}$$

$$H \sim (1,1,2)_{1/2}$$

LHC bounds:

$$M_{G'} \gtrsim 3 - 3.5\,\text{TeV}$$

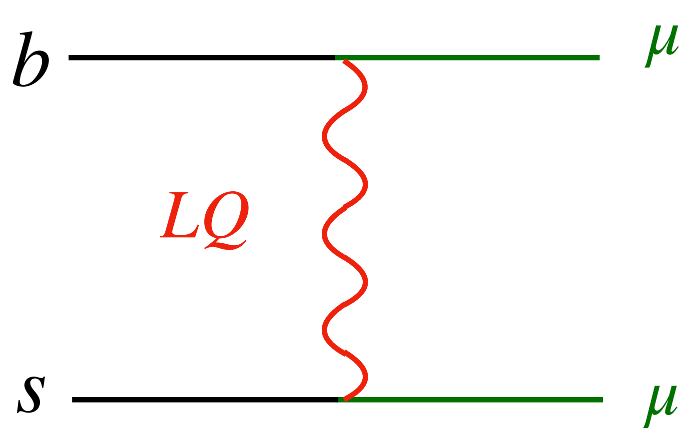
[Cornella, Faroughy, Fuentes-Martin, Isidori, Neubert, 2103.16558]

[Cornella, Fuentes-Martin, Isidori 1903.11517]
[Cornella, Faroughy, Fuentes-Martin, Isidori, Neubert, 2103.16558]

An interlude: B-anomalies

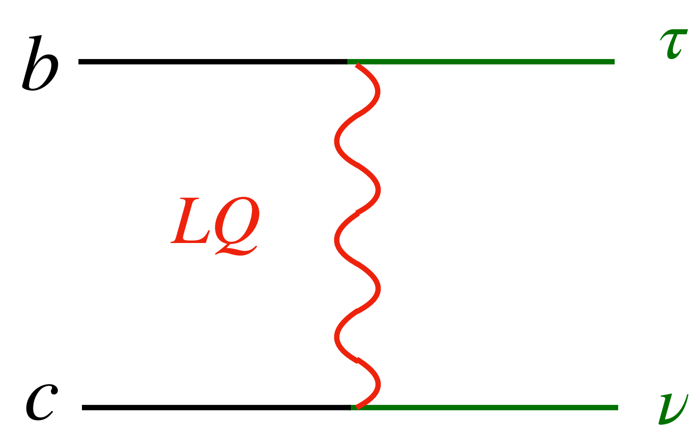
$b \to sll$

- Non-universality in $e/\mu, \ > 4\sigma$?



$b \to c\tau\nu$

- Non universality in $\tau/\mu, e, \ \sim 3\sigma$



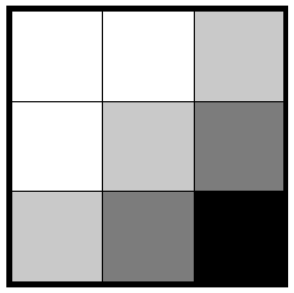
$$R_{D^{(*)}} = \frac{Br(B \to D^{(*)}\tau\nu)}{Br(B \to D^{(*)}l\nu)}$$

Single mediator: $U_{1\,\mu} \sim (\mathbf{3}, \mathbf{1}, 2/3)$

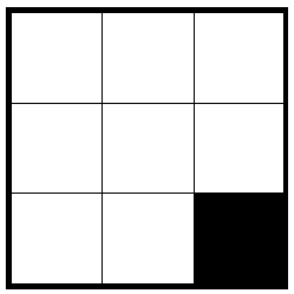
$$\mathscr{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[\beta_L^{i\alpha}\,(\bar{q}_L^i \gamma_\mu \ell_L^\alpha) + \beta_R^{i\alpha}\,(\bar{d}_R^i \gamma_\mu e_R^\alpha)\right] + \mathrm{h.c.}$$

$$\Lambda_U \sim 1\,\mathrm{TeV}$$

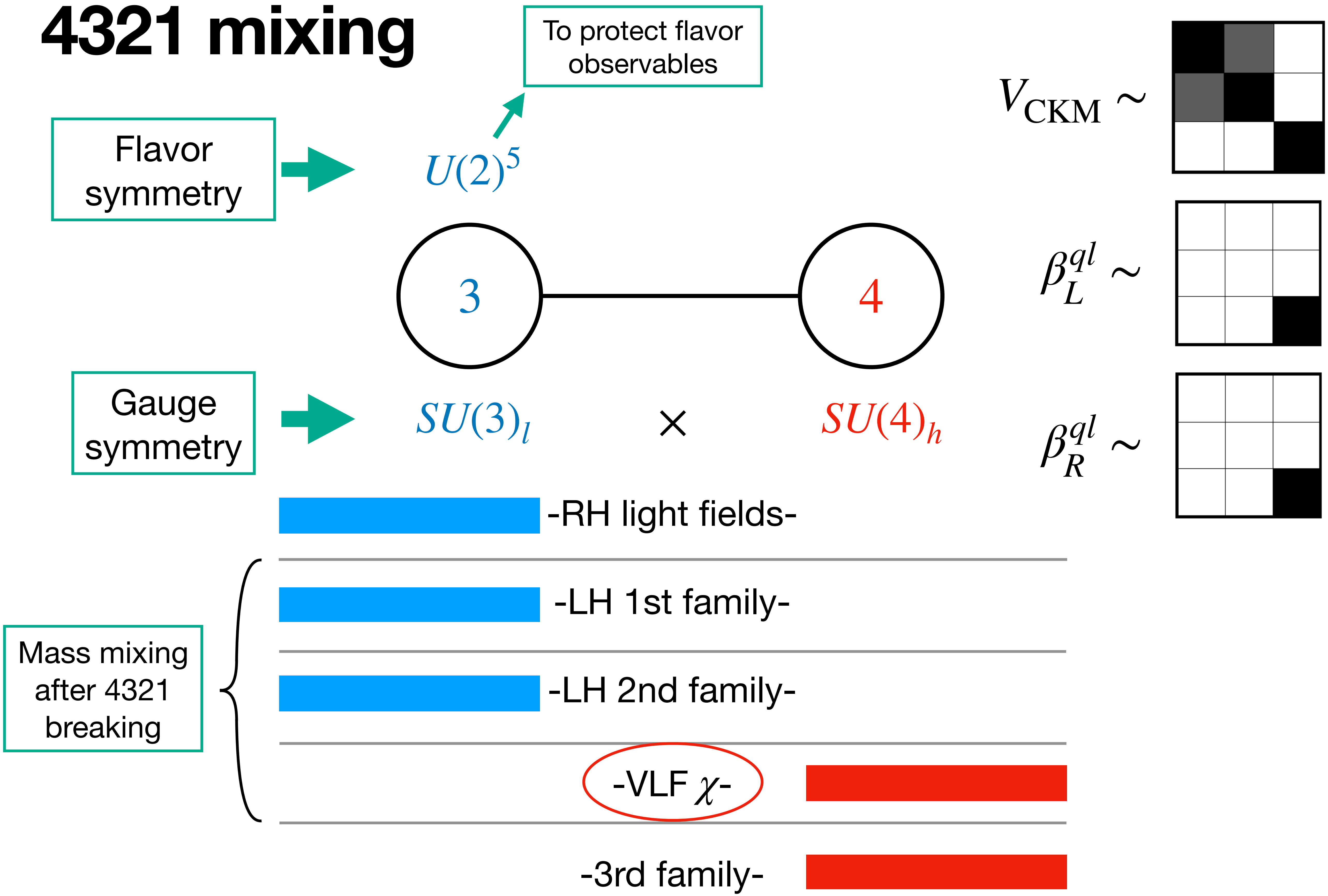
$\beta_L^{ql} \sim$



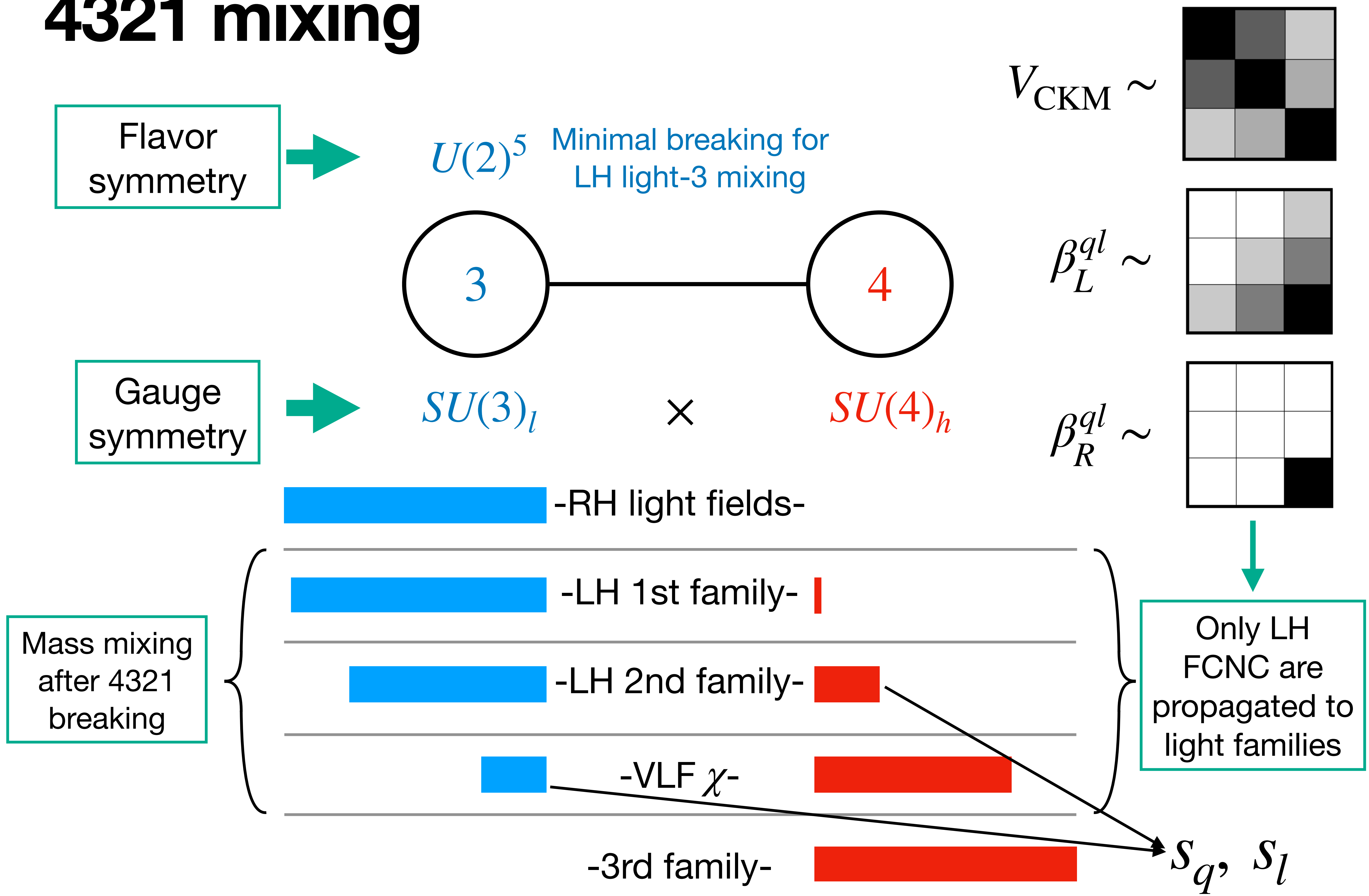
$\beta_R^{ql} \sim$



4321 mixing


To protect flavor observables
Flavor symmetry
$U(2)^5$
3
4
Gauge symmetry
$SU(3)_l$
$\times$
$SU(4)_h$
-RH light fields-
-LH 1st family-
-LH 2nd family-
-VLF χ-
-3rd family-
Mass mixing after 4321 breaking
$V_{\rm CKM} \sim$
$\beta_L^{ql} \sim$
$\beta_R^{ql} \sim$

4321 mixing



Flavor symmetry
$U(2)^5$
Minimal breaking for LH light-3 mixing
3
4
Gauge symmetry
$SU(3)_l \times SU(4)_h$
-RH light fields-
-LH 1st family-
-LH 2nd family-
-VLF χ-
-3rd family-
Mass mixing after 4321 breaking
$V_{\rm CKM} \sim$
$\beta_L^{ql} \sim$
$\beta_R^{ql} \sim$
Only LH FCNC are propagated to light families
$s_q, \; s_l$

Minimal 4321 fermion content

- Fermion sector:

1st & 2nd families	$q_L^{1,2},\ \ell_L^{1,2}$	$u_R^{1,2}$	$d_R^{1,2},\ e_R^{1,2}$
3rd family	$\psi_L \sim \begin{pmatrix} q_L^3 \\ \ell_L^3 \end{pmatrix}$	$\psi_R^+ \sim \begin{pmatrix} u_R^3 \\ \nu_R^3 \end{pmatrix}$	$\psi_R^- \sim \begin{pmatrix} d_R^3 \\ e_R^3 \end{pmatrix}$
1 VL fermion	$\chi_{L/R} = \begin{pmatrix} Q_{L/R} \\ L_{L/R} \end{pmatrix}$	1 singlet fermion	S_L

4321 breaking

$$\mathscr{L} \supset m_\chi \bar\chi_L \chi_R + \lambda_q \bar q_L^2 \Omega_3 \Psi_R + \lambda_l \bar\ell_L^2 \Omega_1 \Psi_R \longrightarrow q_L^2 \to c_q q_L^2 + s_q Q_L \quad (s_q = \lambda_q \Omega_3 / m_Q \sim 0.1)$$

$$+\lambda_S \bar S_L \Omega_1 \Psi_R \longrightarrow \nu_L^3 \to c_\nu \nu_L^3 + s_\nu S_L \quad (s_\nu = y_\nu v_{\rm EW} / \lambda_S \Omega_1 \ll 1)$$

$$+y_+ \bar\chi_L H^c t_R + y_- \bar\chi_L H b_R \longrightarrow \begin{array}{l} \mathscr{L} \supset y_- s_q\, \bar q_L^2 H b_R + y_+ s_q\, \bar q_L^2 H^c t_R \\ \mathscr{L} \not\supset \bar q_L^3 H s_R + \bar q_L^3 H^c c_R \end{array}$$

(No RH rotations)

3. Flavor & EW imprints

[Crosas, Isidori, JML, Selimović, Stefanek, 2203.01952]

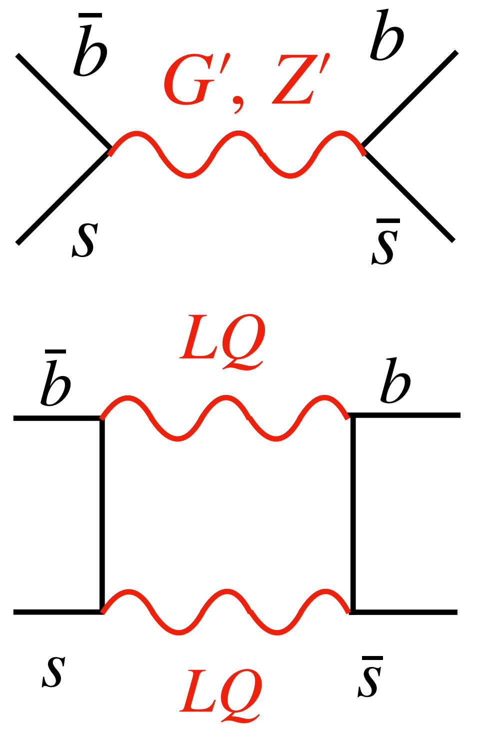
[Allwicher, Isidori, JML, Selimović, Stefanek, 2010.xxxxx]

$\Delta F = 2$ processes

$$G' \sim g_4 \begin{pmatrix} -g_3^2/g_4^2 & 0 & 0 \\ 0 & -g_3^2/g_4^2 + s_q^2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad Z' \sim g_4 \begin{pmatrix} -g_1^2/g_4^2 & 0 & 0 \\ 0 & -g_1^2/g_4^2 + s_q^2 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

After CKM rotations, LH FCNC

- $B_s - \bar{B}_s$ mixing



→ Suppressed 2-3 down rotations $y_- \to 0$

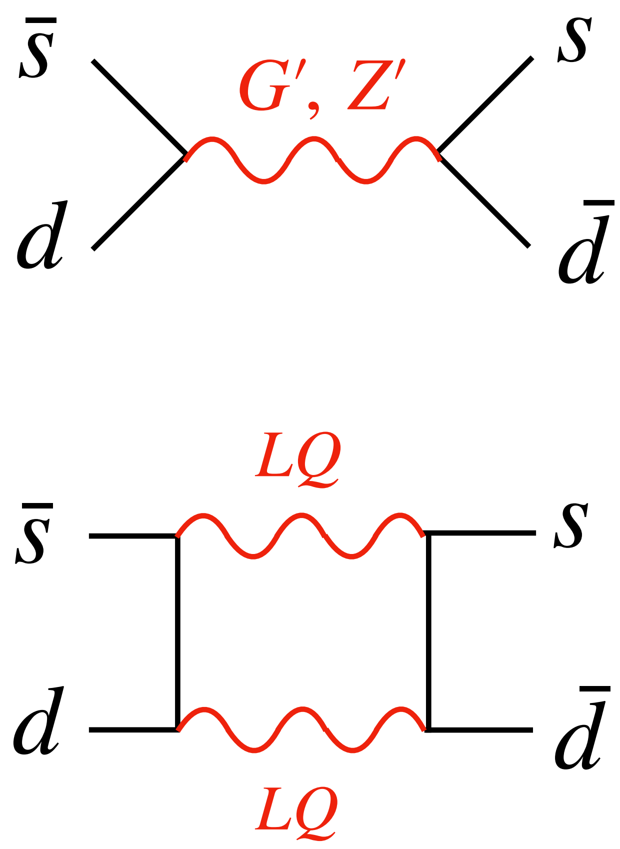
$(s_q y_+ = V_{cb} \approx 0.04)$

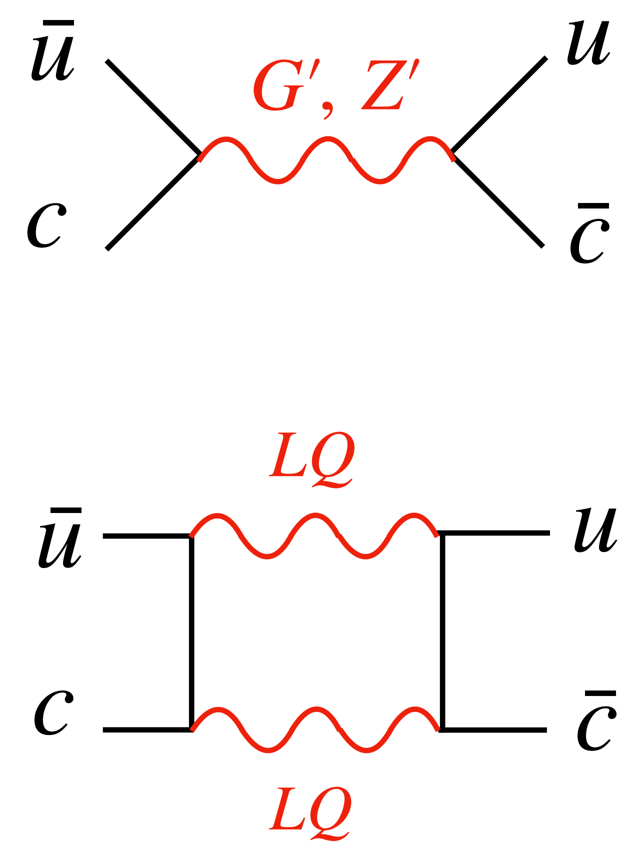
→ $m_L \lesssim 1.5\,\text{TeV}$

[Cornella, Faroughy, Fuentes-Martin, Isidori, Neubert, 2103.16558]

$\Delta F = 2$ processes: light families

$K - \bar{K}$ $\qquad$ $D - \bar{D}$





$\Delta F = 2$ processes: light families

- $\mathscr{L} \not\supset y_- s_q \bar{q}_L^1 H b_R + y_+ s_q \bar{q}_L^1 H^c t_R \Rightarrow$ No 1-3 rotation, so V_{ub}, V_{td} are generated as 1-2+2-3 rotations.

- 1-2 rotations fixed to reproduce $V_{\rm CKM}$.

- $K - \bar{K}$ mixing $\Rightarrow \Lambda_U > 10\,\mathrm{TeV}$.

- To reduce Λ_U, V_{ub}, V_{td} with $\mathscr{L} \supset \lambda_i\, \bar{q}_L^i \Omega_3 H^c \psi_R^+$ (dimension 5).

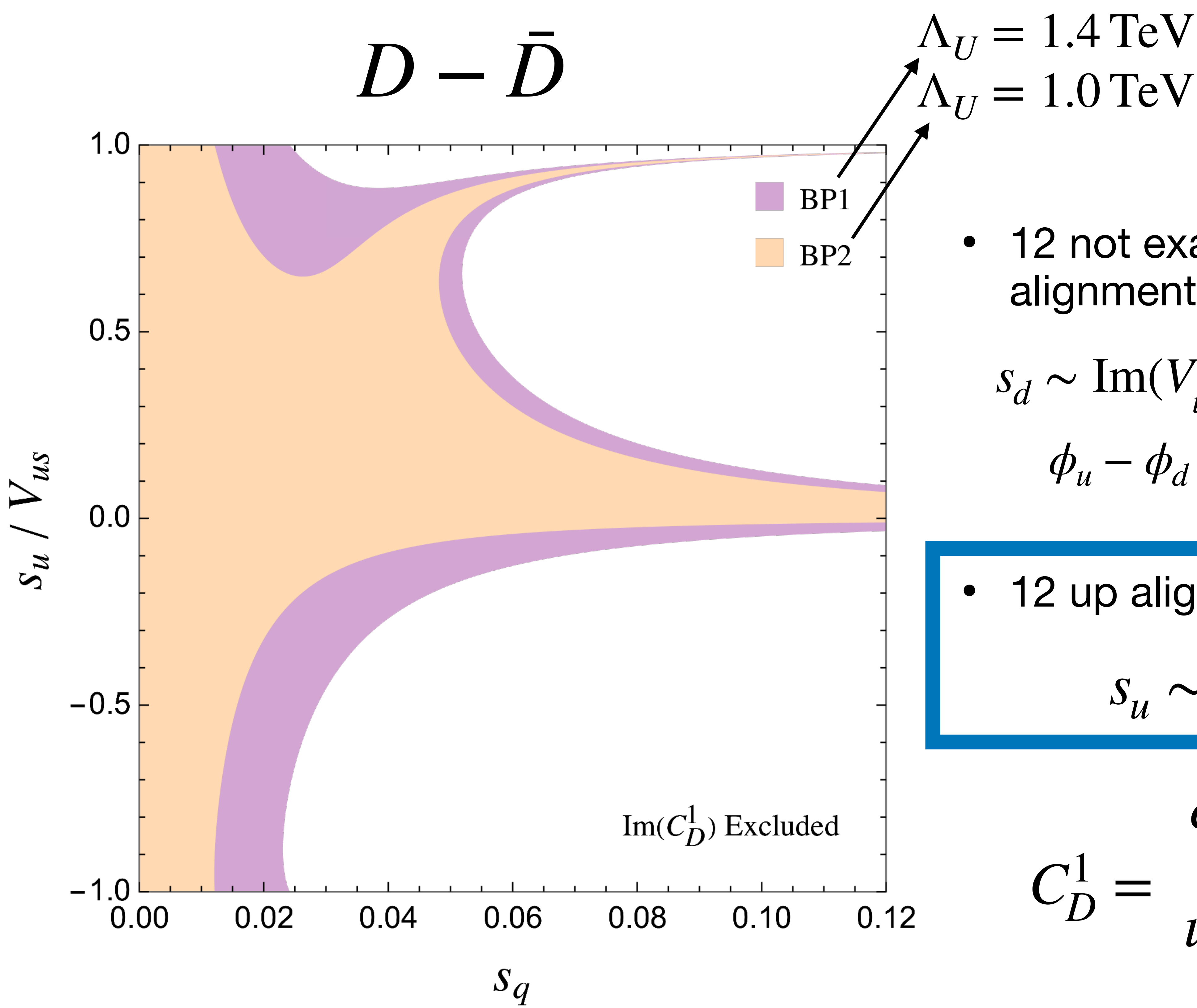
- It can be generated via a VLQ $U_{L/R} \sim (1,3,1)_{2/3}$ @ 10-100 TeV.

- Freedom in the 1-2 rotations to pass bounds from $K - \bar{K}$ and $D - \bar{D}$.

$$L_d^{12} = \begin{pmatrix} c_d & -e^{i\phi_d} s_d \\ e^{-i\phi_d} s_d & c_d \end{pmatrix} \qquad L_u^{12} = \begin{pmatrix} c_u & -e^{i\phi_u} s_u \\ e^{-i\phi_u} s_u & c_u \end{pmatrix}$$

$\Delta F = 2$ processes: light families

$D - \bar{D}$



- 12 not exact down alignment

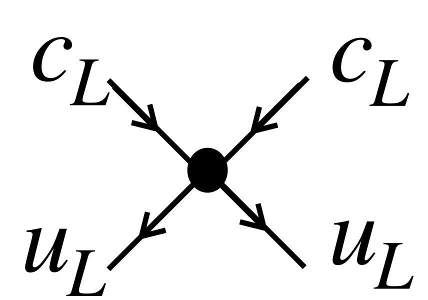
$$s_d \sim \text{Im}(V_{ub}^* V_{cb})/s_q^2$$

$$\phi_u - \phi_d \sim \pi/2$$

- 12 up alignment

$$s_u \sim 0$$

$C_D^1 =$

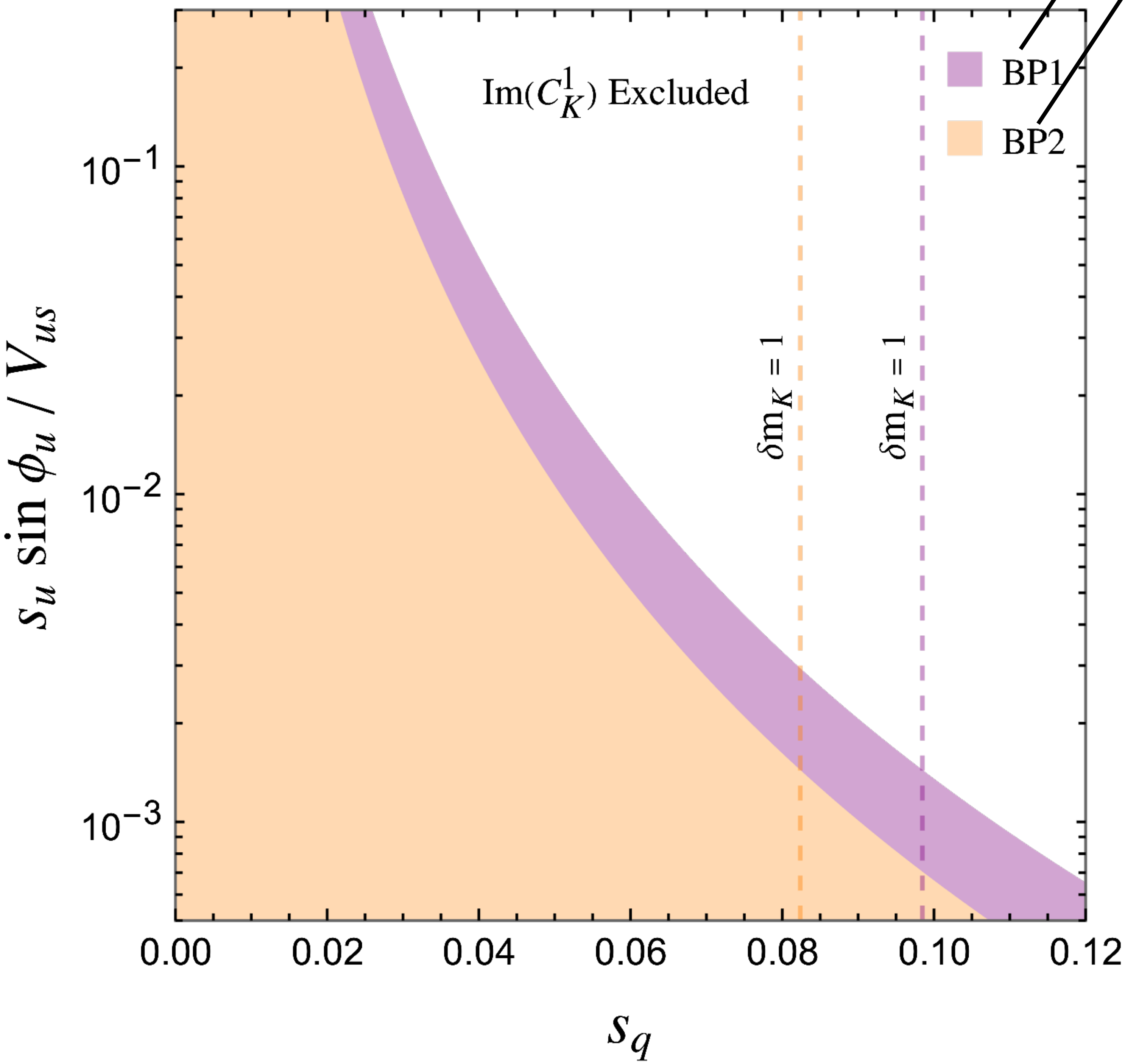


$\Delta F = 2$ processes: light families

$K - \bar{K}$

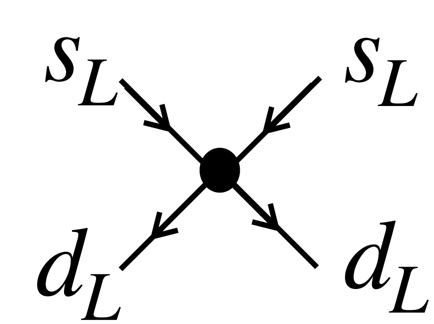
$\Lambda_U = 1.4\,\text{TeV}$

$\Lambda_U = 1.0\,\text{TeV}$

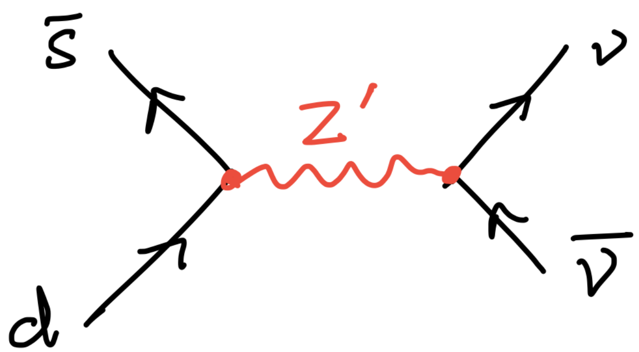


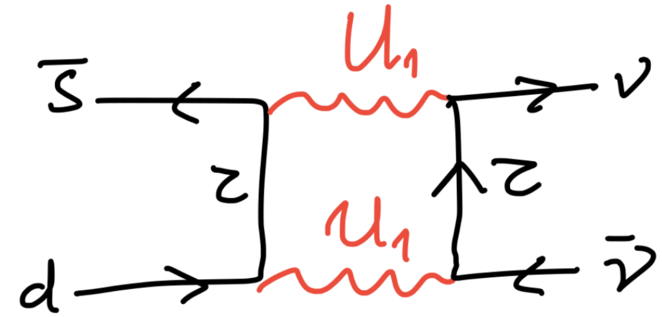
- 12 up alignment

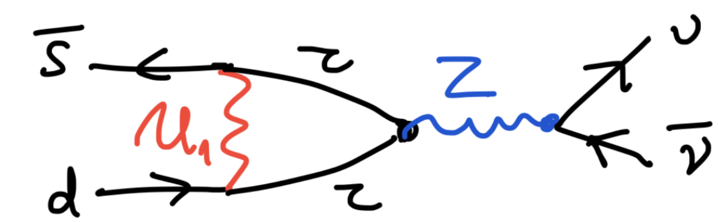
$$s_u \sim 0$$

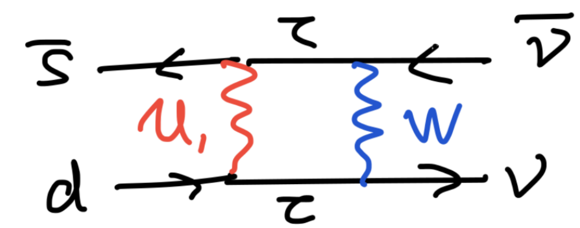
$C_K^1 =$ 

$s \to d$ transitions

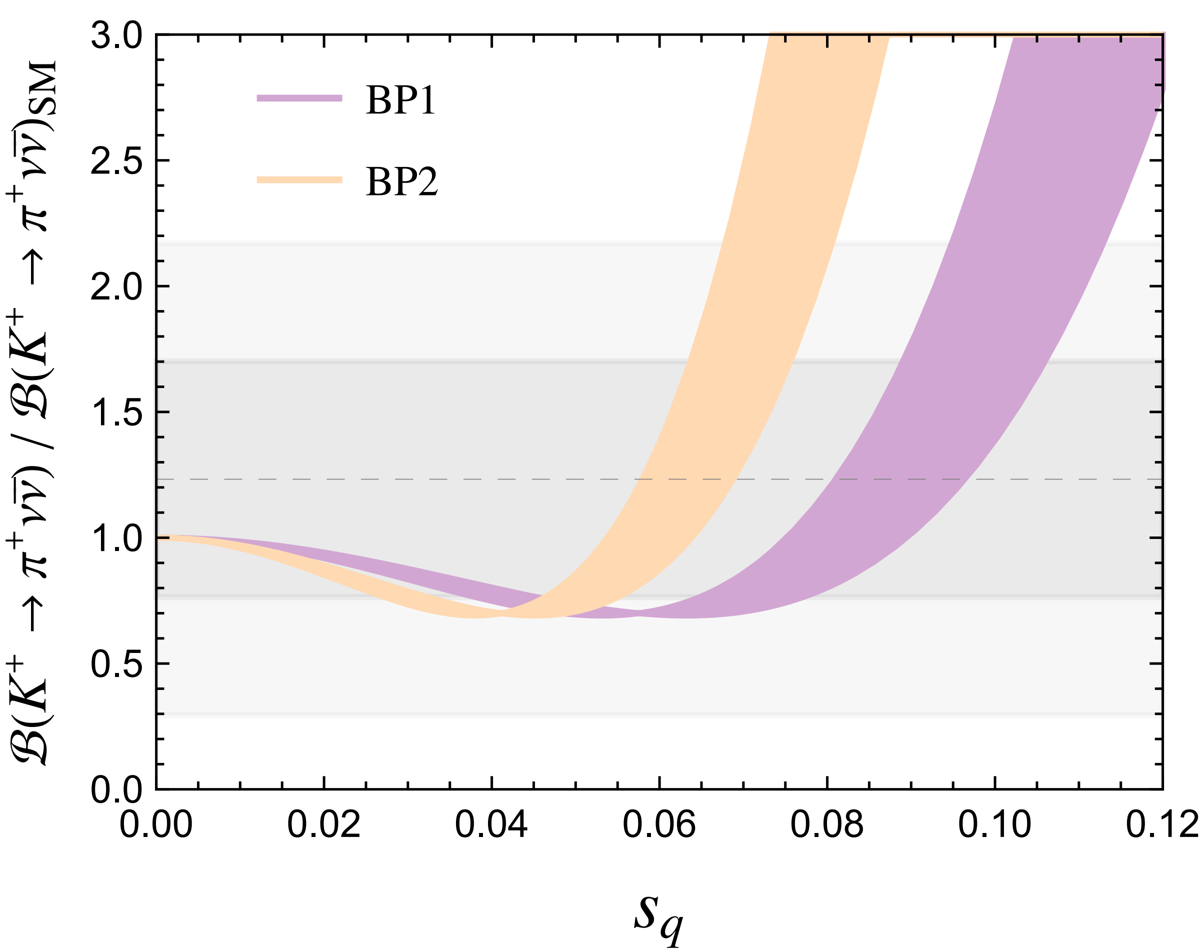


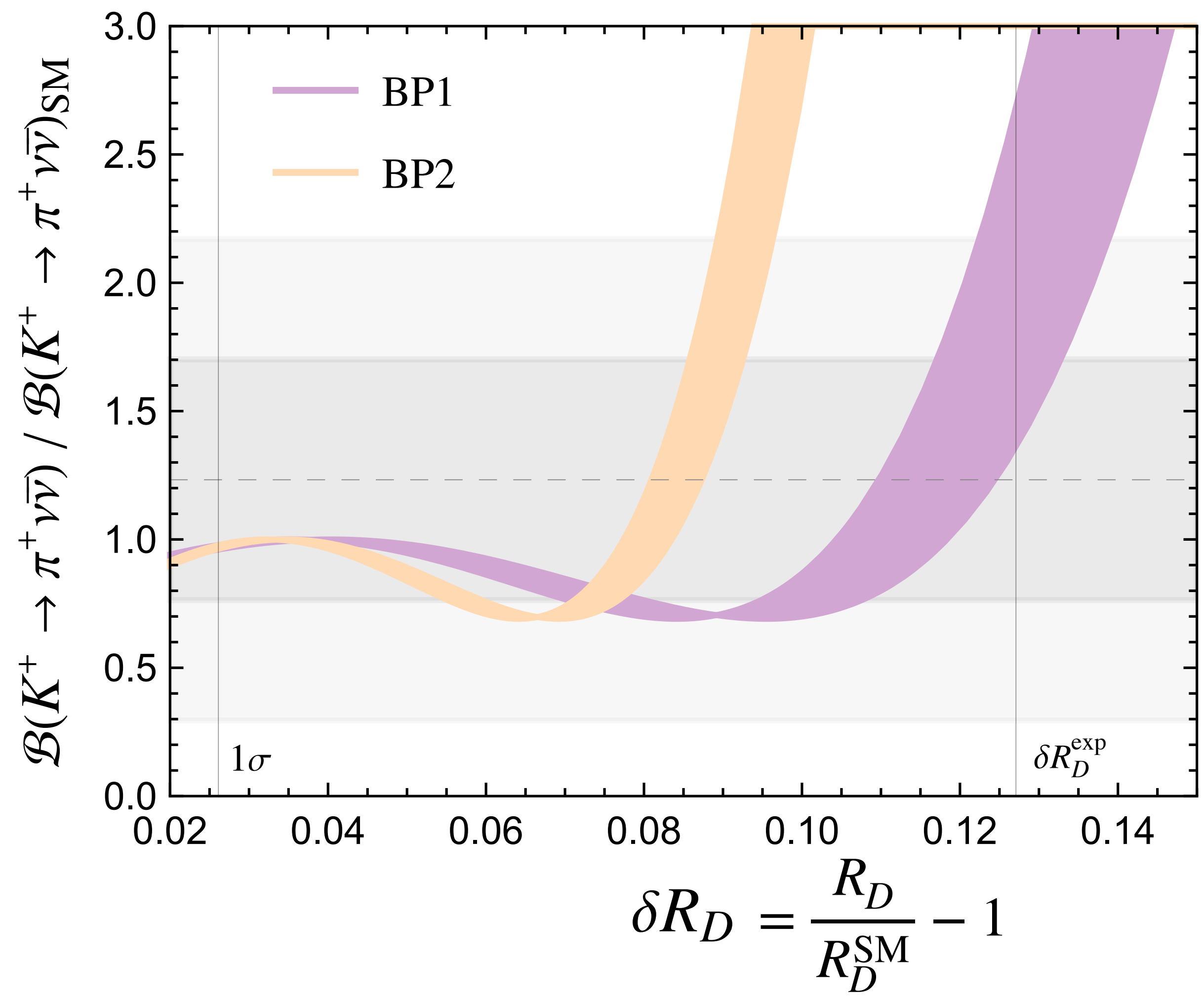






$K^+ \to \pi^+ \nu \bar{\nu}$





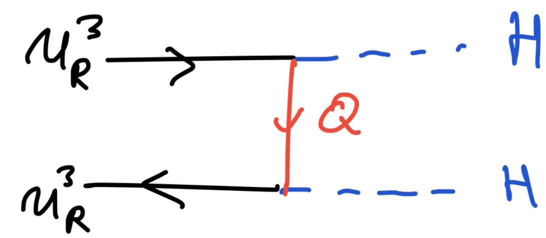
EW observables

PRELIMINARY

$(s_q y_+ = V_{cb})$

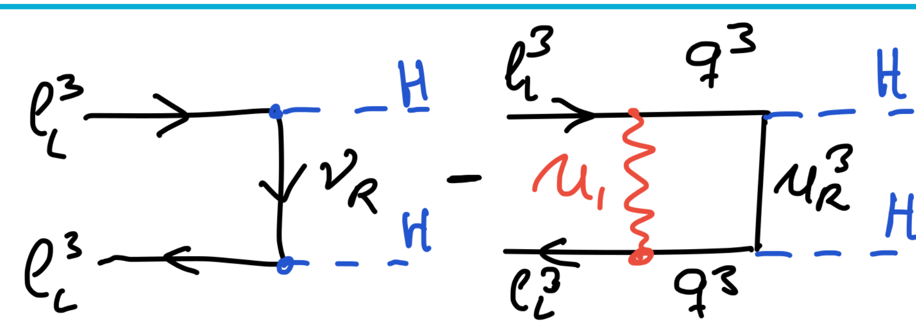
- After integrating out the 4321 states, we generate the following SMEFT operators that could affect the EW fit:

$$\mathcal{O}_{Hu}^{33} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_R^3 \gamma^\mu u_R^3)$$



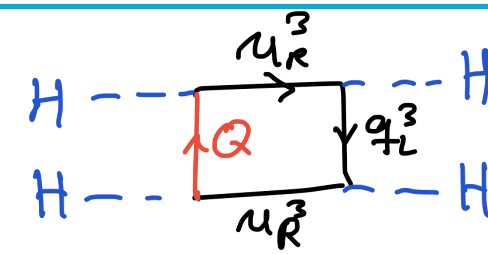
Ztt

$$\mathcal{O}_{Hl}^{(1)33} - \mathcal{O}_{Hl}^{(3)33} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{\ell}_L^3 \gamma^\mu \ell_L^3) - (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{\ell}_L^3 \tau_I \gamma^\mu \ell_L^3)$$



$Z\nu\nu,\ W\tau\nu_\tau$

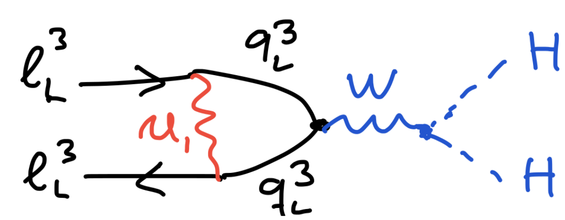
$$\mathcal{O}_{HD} = |H^\dagger D_\mu H|^2$$



$\propto y_+^2/m_Q^2$

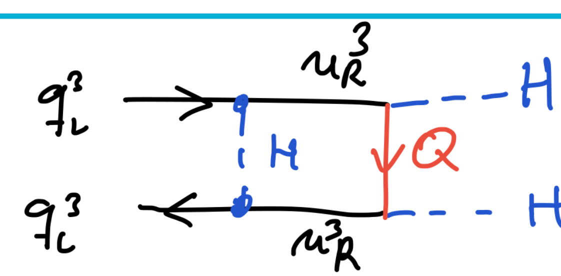
m_W

$$\mathcal{O}_{Hl}^{(3)33} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{\ell}_L^3 \tau_I \gamma^\mu \ell_L^3)$$



$Z\tau\tau$

$$\mathcal{O}_{Hq}^{(1)33} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_L^3 \gamma^\mu q_L^3)$$



Zbb

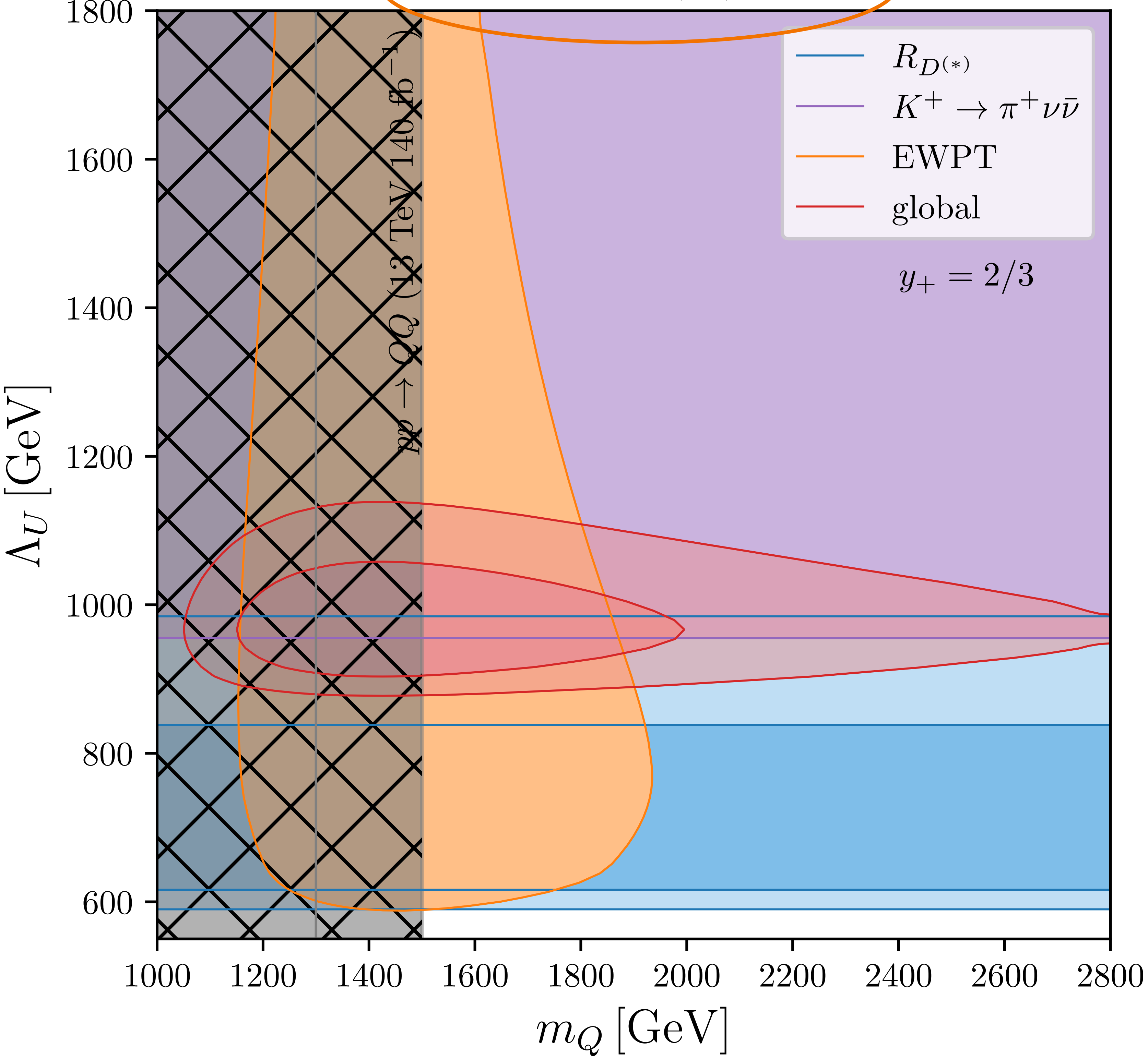
[Allwicher, Isidori, JML, Selimović, Stefanek, 2010.xxxxx]

EW observables

PRELIMINARY

$m_W = 80.410(15)$ GeV

World average, inflating errors



4. A 5D model completion

[Fuentes-Martin, Isidori, JML, Selimovic, Stefanek, 2203.01952]

A first attempt

Curvature of the AdS slice

- Warped 5D geometry (RS): $ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$
  [Randall, Sundrum, hep-ph/9905221]
- Holography ⇒ Dual to a strongly coupled sector $\mathscr{G}_{\text{bulk}} \to \mathscr{G}_{\text{IR}}$

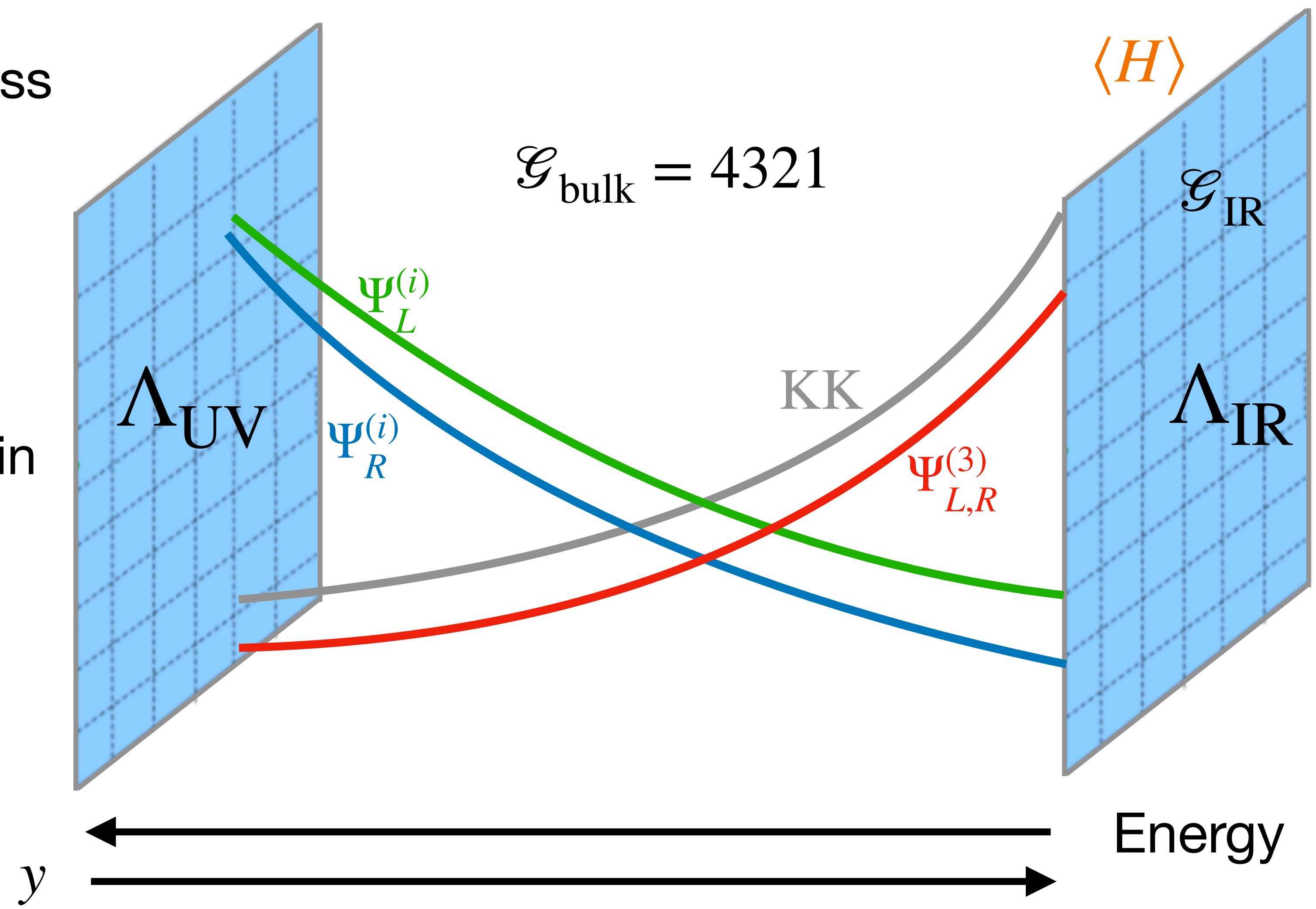
Energy scale ⬍ Position in y

- The strong dynamics can be used to break 4321 [Fuentes-Martin, Stangl 2004.11376]

- Anarchic partial compositeness paradigm in RS
- Emerging $U(2)$ symmetry at the TeV scale…
- But in principle, broken both in the LH and RH light sectors

$$\mathscr{L} \supset \bar{\Psi}_L^{(3)} H \Psi_R^{(1,2)}$$

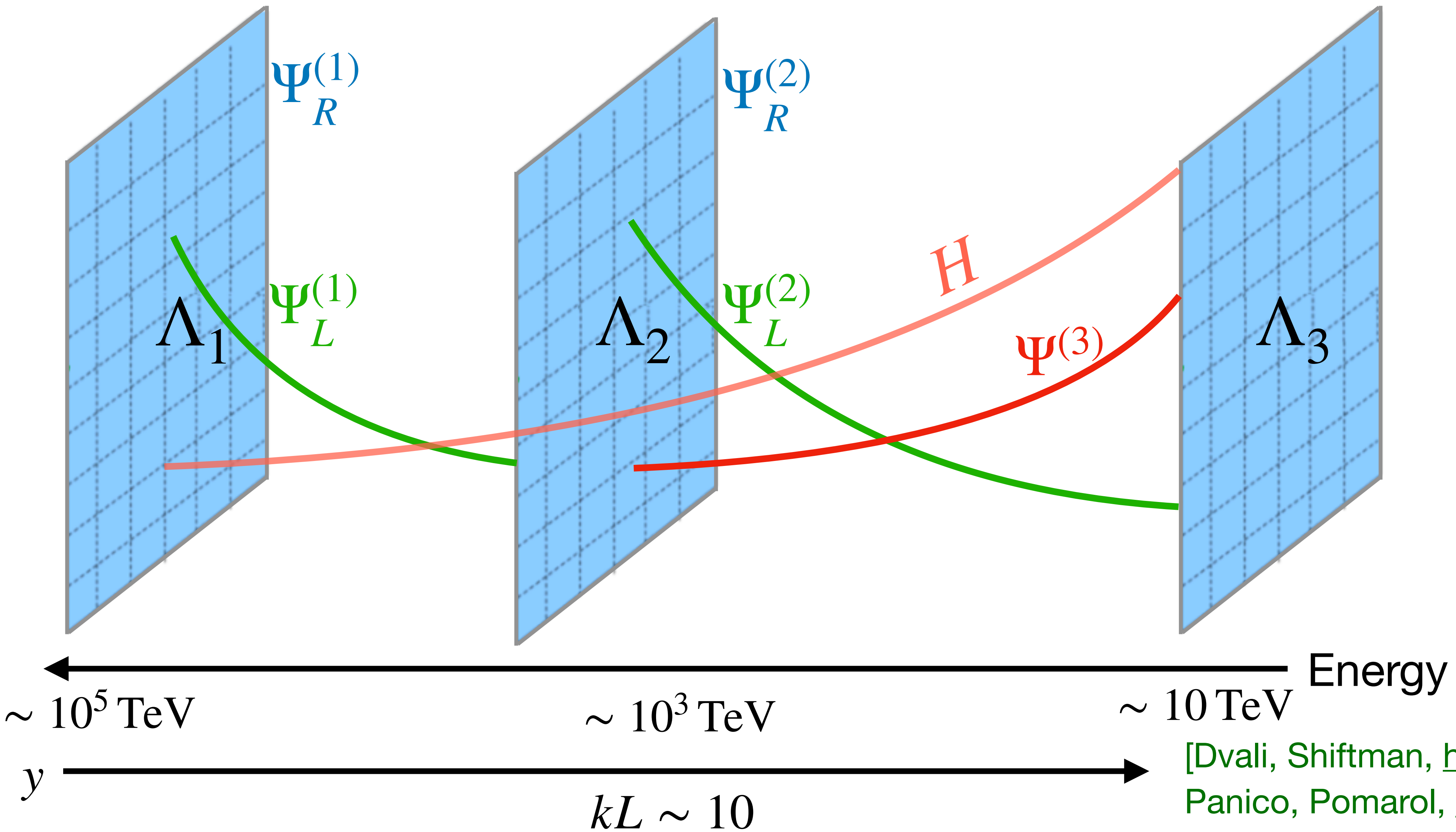
[Gherghetta, Pomarol, arXiv:hep-ph/0003129]



A multiscale 5D model

[Fuentes-Martin, Isidori, Pages, Stefanek, 2012.10492
Fuentes-Martin, Isidori, JML, Selimovic, Stefanek, 2203.01952]

- Multi-brane construction: flavor hierarchies from different scales.
- ⇒Emerging $U(2)$ symmetry minimally broken.



[Dvali, Shiftman, hep-ph/0001072
Panico, Pomarol, 1603.06609
Barbieri, 2103.15635]

A 5D model that…

- Reduces to 4321 below the KK scale
- Explains flavour hierarchies from a multi-scale origin
- Realises the Higgs as a pNGB

[Fuentes-Martin, Isidori, JML, Selimovic, Stefanek, 2203.01952]

Gauge sector

A_5 of broken generators dual to NGBs

$$\mathscr{G}^{12}_{\rm bulk} = SU(4)_h \times SU(4)_l \times SO(5)$$

Λ_2 (6 broken)

$$\mathscr{G}^{23}_{\rm bulk} = SU(4)_h \times SU(3)_l \times U(1)_l \times SO(5)$$

$\Lambda_3 = \Lambda_{\rm IR}$ (15 + 4 broken)

$$\mathscr{G}_{\rm IR} = SU(3)_c \times U(1)_{B-L} \times SO(4)$$

Quark-lepton unification of light families

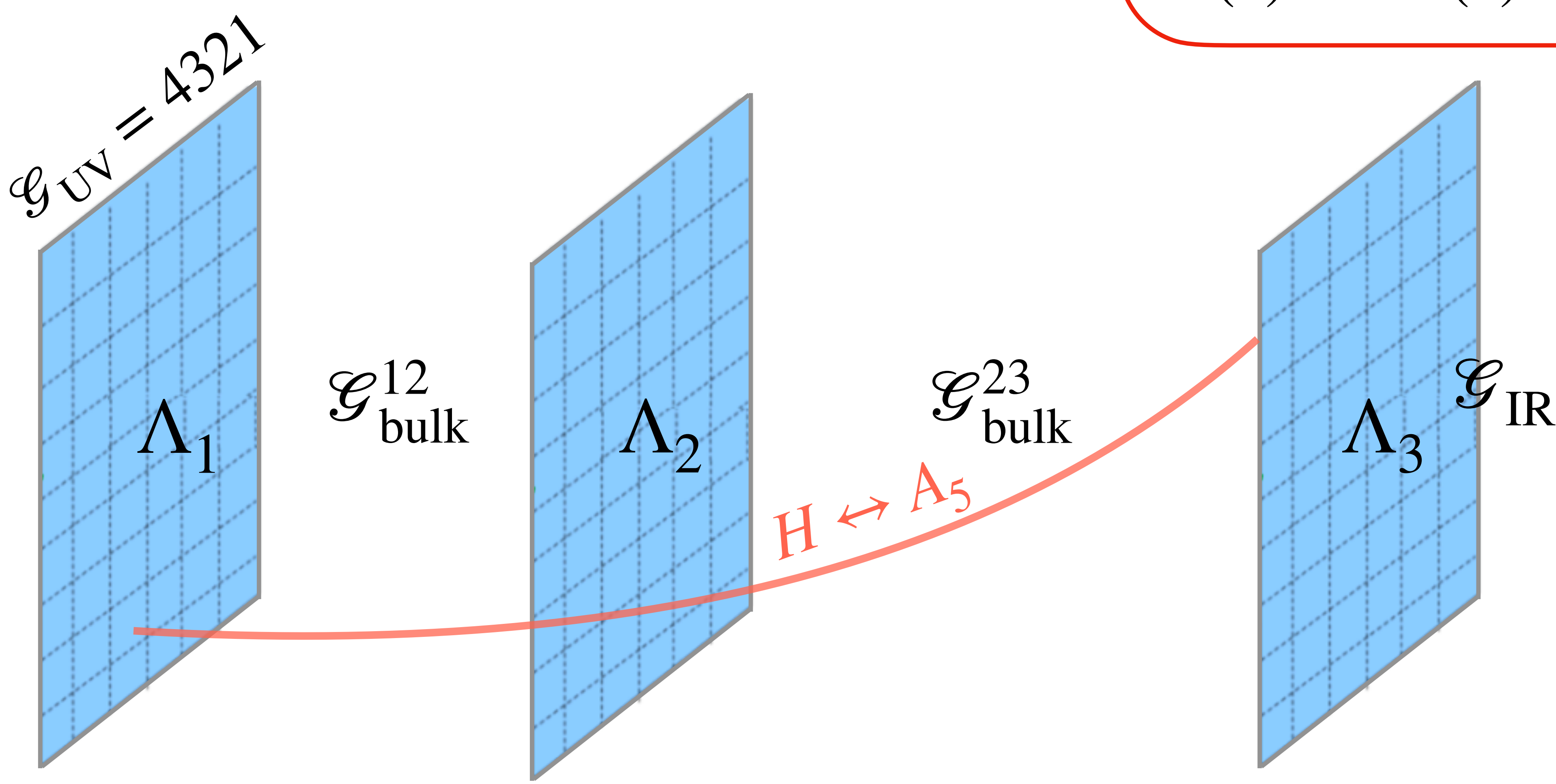
15 eaten by U_1, G', Z', $M_{4321} \sim \dfrac{M_{\rm KK}}{\sqrt{2kL}}$

4 as pNGB Higgs

$$SO(5) \to SO(4) = SU(2)_L \times SU(2)_R$$

Minimal composite Higgs (MCHM)

[Agashe, Contino, Pomarol, hep-ph/0412089]



Fermion and scalar sector

SM fermions and VLF

For neutrinos

For light Yukawas

Field	$SU(4)_h$	$SU(4)_l$	$SO(5)$
Ψ^3 Ψ^3_d $\chi^{(\prime)}$	**4**	**1**	**4**
Ψ^j $\Psi^j_{u,d}$	**1**	**4**	**4**
$\mathcal{S}^i$	**1**	**1**	**1**
Φ	**1**	**1**	**1**
Ω	**1**	**4**	**4**
Σ	**1**	**1**	**5**

Fermions

Scalars

[Fuentes-Martin, Isidori, Pages, Stefanek, 2012.10492]

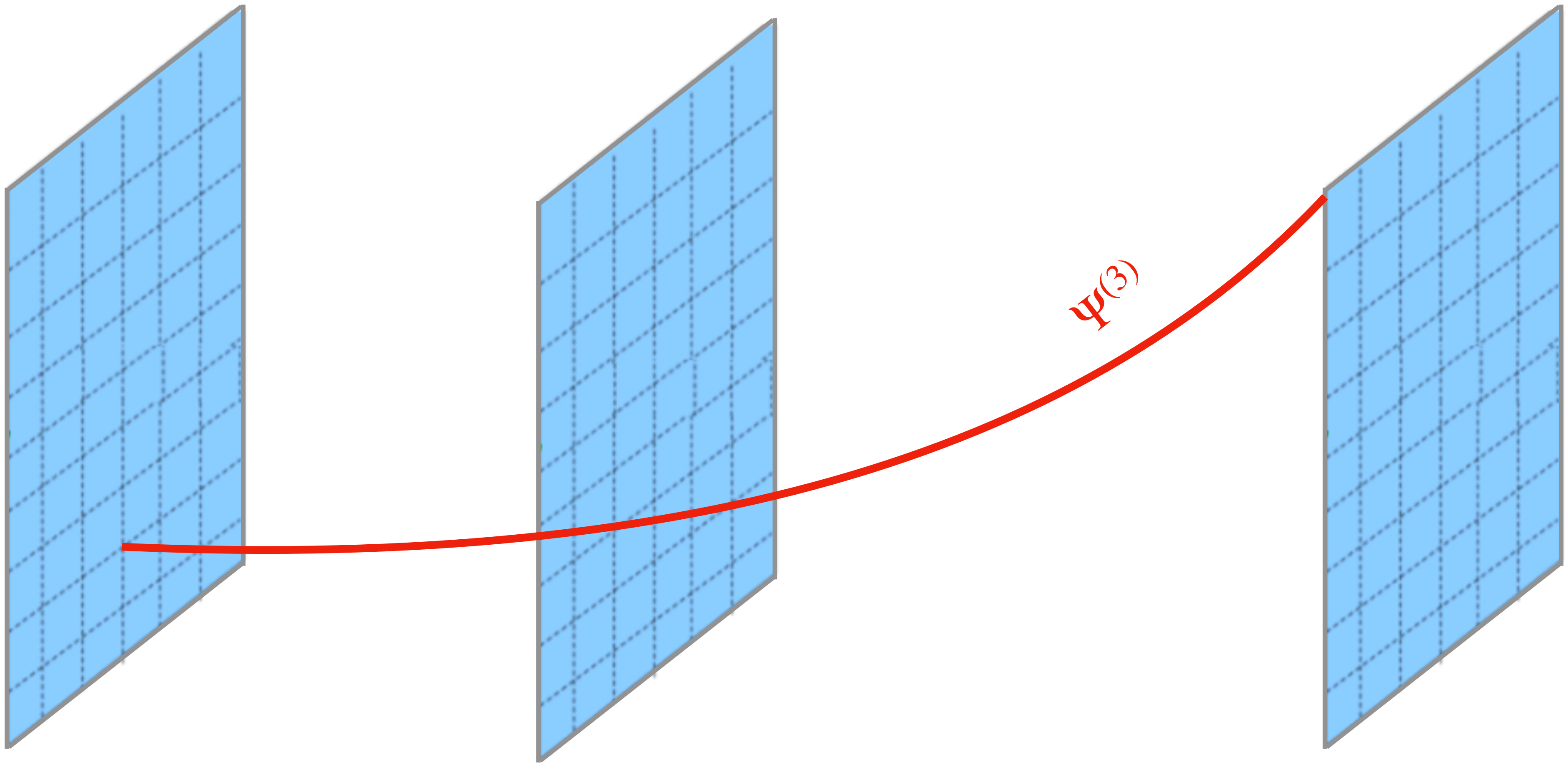
Top Yukawa

Field	$SU(4)_h$	$SU(4)_l$	$SO(5)$
Ψ^3	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{4}$

$$\Psi^3 = \begin{bmatrix} q_L \\ t_R \\ \times \end{bmatrix} \quad \begin{matrix} SU(2)_L \\ SU(2)_R \end{matrix}$$

Top Yukawa from $\bar{\Psi}^3 A_5 \Psi^3$ coupling in the bulk

$$y_t = \frac{g_*}{2\sqrt{2}} P(M_{\Psi^3}) \qquad (g_*^2 = g_5^2 k) \qquad \text{For } y_t : g_* \geq 2.2$$

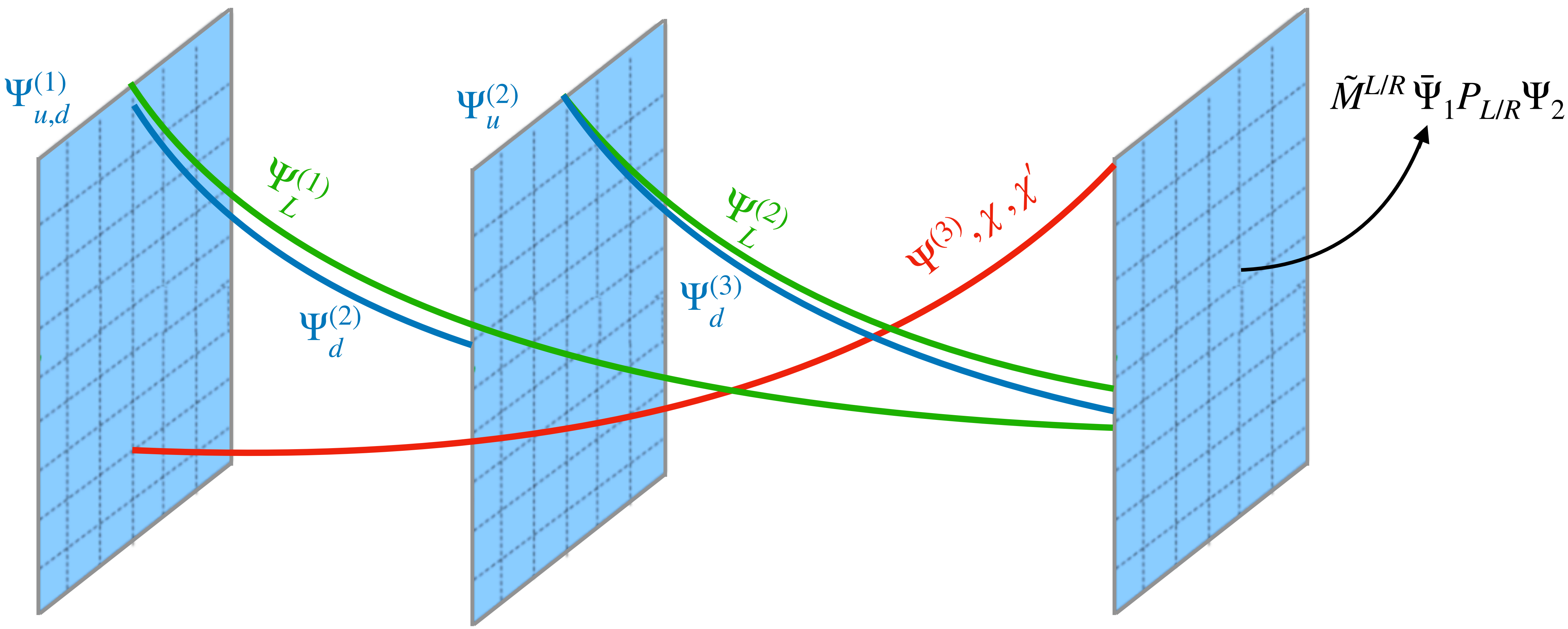


Other 3rd family Yuk. and light-heavy mixing

Field	$SU(4)_h$	$SU(4)_l$	$SO(5)$
$\Psi^3, \Psi^3_d, \mathcal{X}^{(\prime)}$	**4**	**1**	**4**
$\Psi^j, \Psi^j_{u,d}$	**1**	**4**	**4**

VLF mass, mass mixing of light families with VLF, and other 3rd family Yukawas from masses in the IR brane

$$y_{f_1 f_2} = \frac{g_*}{2\sqrt{2}}(\tilde{M}^L - \tilde{M}^R) \times \text{(profile suppression)}$$

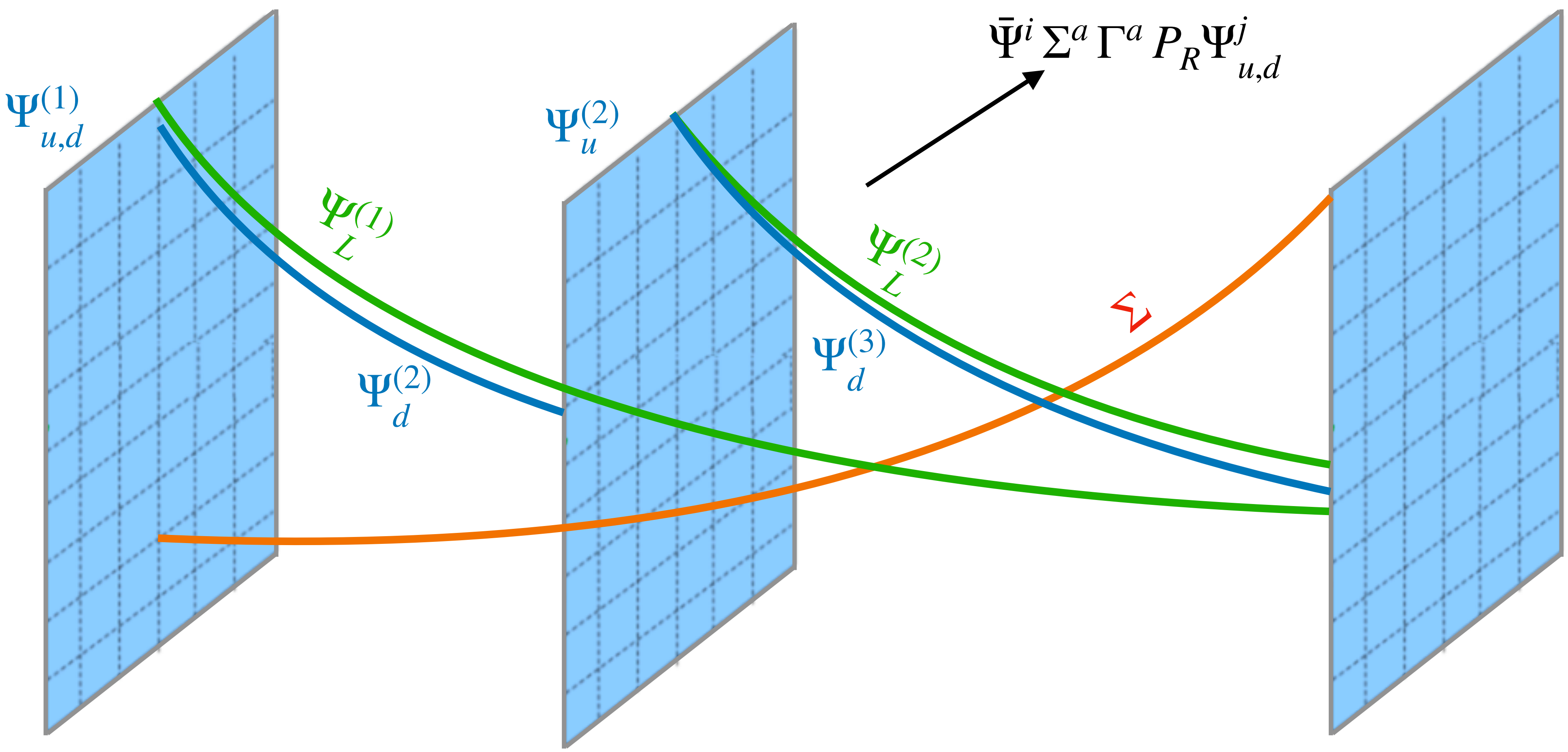


Light Yukawas

Field	$SU(4)_h$	$SU(4)_l$	$SO(5)$
$\Psi^j, \Psi^j_{u,d}$	$\mathbf{1}$	$\mathbf{4}$	$\mathbf{4}$
Σ	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{5}$

$\Sigma^T \sim (H' \; \phi)$ takes a VEV along the singlet direction and propagates the breaking of $SO(5)$ into the bulk

$$y^{ij}_{u,d} = \frac{g_*}{2\sqrt{2}} \tilde{Y}^{ij}_{u,d} \frac{\langle \Sigma_{\rm IR} \rangle}{\Lambda_{\rm IR}} \times \text{(profile suppression)}$$



Higgs potential

Higgs potential fully calculable

Contributions:

- **Tree level** from scalars with a VEV in the bulk breaking $SO(5)$: Σ, Ω
- **One loop** from top and gauge fields

$$V(h) \approx \alpha \cos\left(\frac{h}{f_h}\right) - \beta \sin^2\left(\frac{h}{f_h}\right)$$

$\alpha \rightarrow \Psi^3, \Omega$

$\beta \rightarrow \Psi^3, \Sigma, W, Z$

Higgs decay constant:

$$f_h = \frac{2\Lambda_{\rm IR}}{g_*}$$

$$\cos\left(\frac{\langle h\rangle}{f_h}\right) = -\frac{\alpha}{2\beta} \qquad m_h^2 = \frac{2\beta\langle h\rangle^2}{f_h^4}$$

All contributions of the correct order, up to some little-hierarchy tuning

β of the right size for $g_* \approx 2.5$, compatible with the top Yukawa

Low-energy phenomenology

- Below KK scale, similar phenomenology as 4321 (B-anomalies)
- Main experimental limit coming from coloron direct searches:

$$M_{4321} \gtrsim 3.5\,\mathrm{TeV}$$

[Cornella, Faroughy, Fuentes-Martin, Isidori, Neubert, 2103.16558]

Benchmark Spectrum :

E

$$M_{\mathrm{KK}} \approx 2\Lambda_{\mathrm{IR}} = 16\,\mathrm{TeV}$$

First deviations from 4321

$$\Lambda_{\mathrm{IR}} = 8\,\mathrm{TeV}$$

$$f_h \approx \frac{M_{\mathrm{KK}}}{g_*} \approx 6.4\,\mathrm{TeV}$$

$$M_{4321} \approx \frac{g_* f_h}{\sqrt{2kL}} \approx 3.6\,\mathrm{TeV}$$

So high that EWPD are ok

Conclusions

- A multi-scale origin of the flavor hierarchies open the possibility to have quark-lepton unification of the third family à la Pati-Salam at the TeV scale.
- The minimal realization of this idea establishes interesting connections between different observables, as $R_D^{(*)}$, $K \to \pi\nu\nu$, and EW observables.
- We have also presented a 5D model that UV-completes 4321, where the flavor hierarchies have a multi-scale origin, and in addition, the Higgs emerges as a pNGB from the same strong dynamics that breaks 4321.

Thank you!

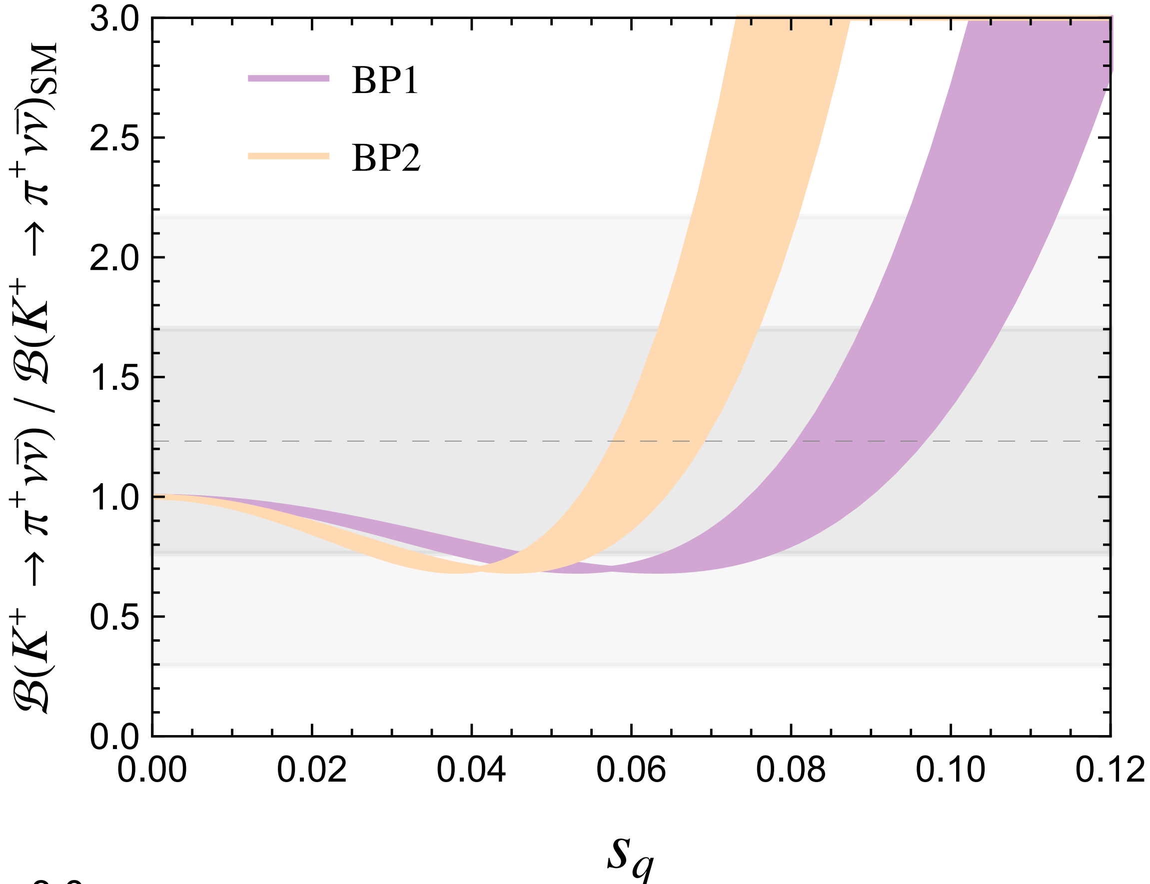
Backup

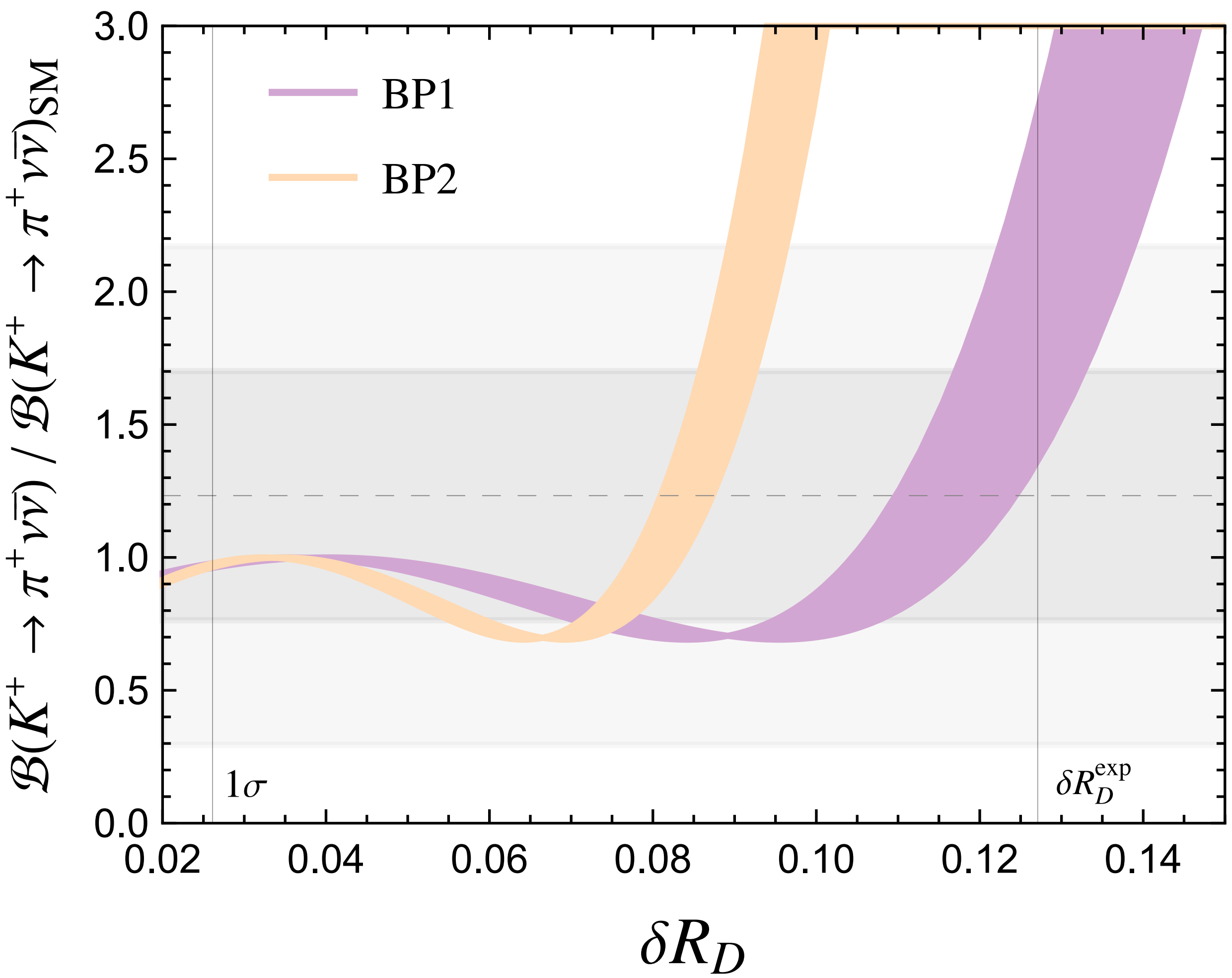
Field	$SU(4)_h$	$SU(3)_l$	$SU(2)_L$	$U(1)_{l+R}$	
q_L^i	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{2}$	$1/6$	1st & 2nd families
u_R^i	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$2/3$	
d_R^i	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	
ℓ_L^i	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	
e_R^i	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	-1	
ψ_L	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0	3rd family
$\psi_R^\pm$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{1}$	$\pm 1/2$	
$\chi_{L,R}$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0	VL fermion
H	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$	
Ω_1	$\bar{\mathbf{4}}$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$	4321 SSB scalars
Ω_3	$\bar{\mathbf{4}}$	$\mathbf{3}$	$\mathbf{1}$	$1/6$	
Ω_{15}	$\mathbf{15}$	$\mathbf{1}$	$\mathbf{1}$	0	
S_L	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	0	Neutrinos

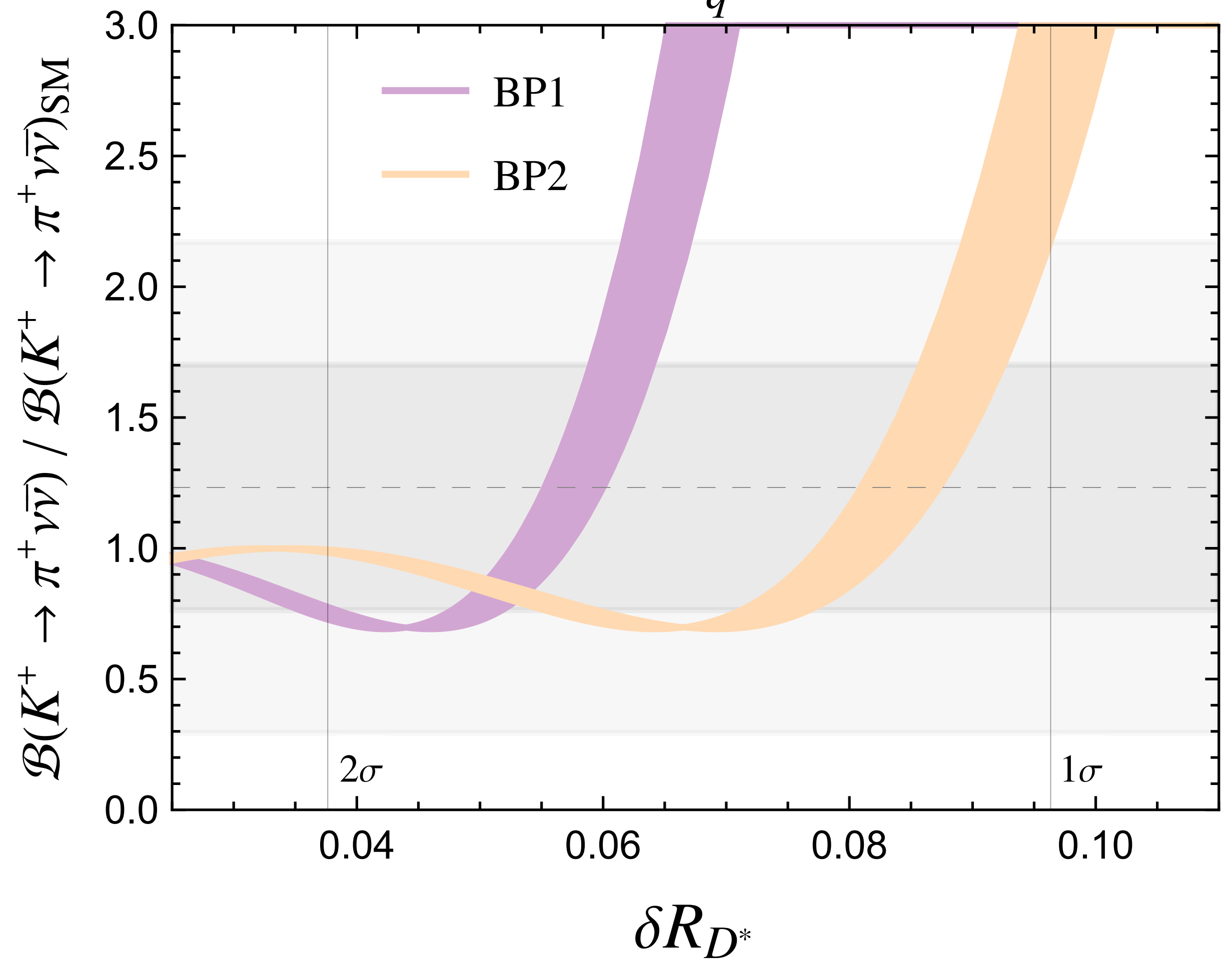
Backup

BP1 : $\Lambda_U = 1.4\,\text{TeV},\ \text{Re}(\beta_R) = -0.3$

BP2 : $\Lambda_U = 1.0\,\text{TeV},\ \text{Re}(\beta_R) = 0$



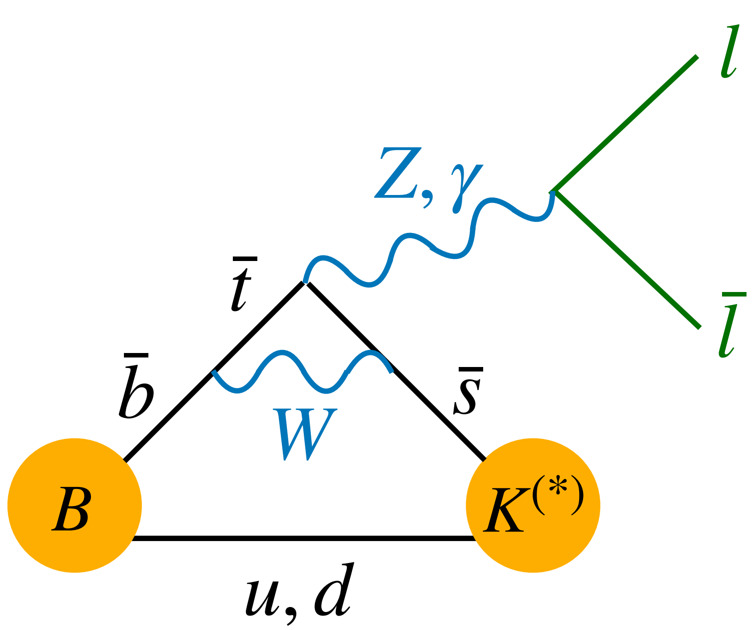




Backup

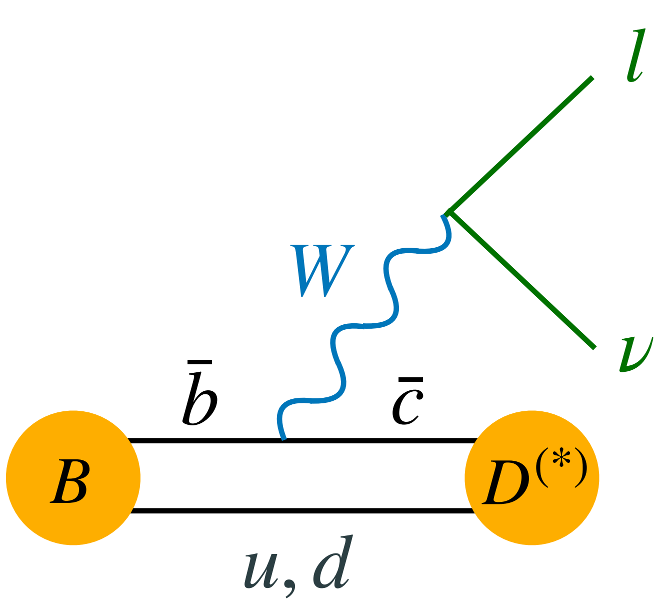
$b \to sll$

- $R_{K^{(*)}} = \dfrac{Br(B \to K^{(*)}\mu\mu)}{Br(B \to K^{(*)}ee)}$
- $B_s \to \mu\mu$
- $B \to Kll$, angular distributions, etc…
- Non-universality in e/μ, $> 4\sigma$



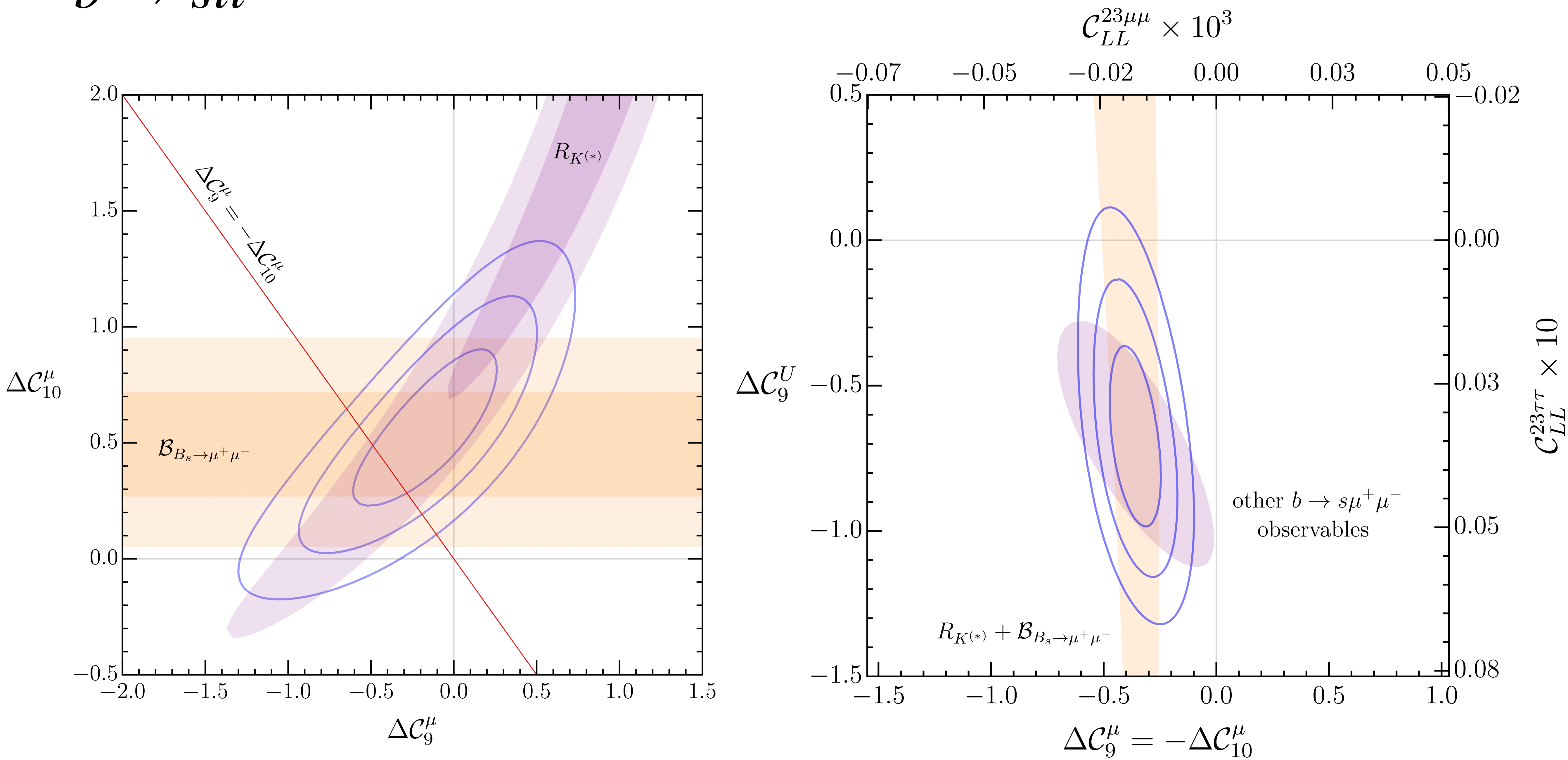
$b \to c\tau\nu$

- $R_{D^{(*)}} = \dfrac{Br(B \to D^{(*)}\tau\nu)}{Br(B \to D^{(*)}l\nu)}$
- Non universality in $\tau/\mu, e$, $\sim 3\sigma$



Backup

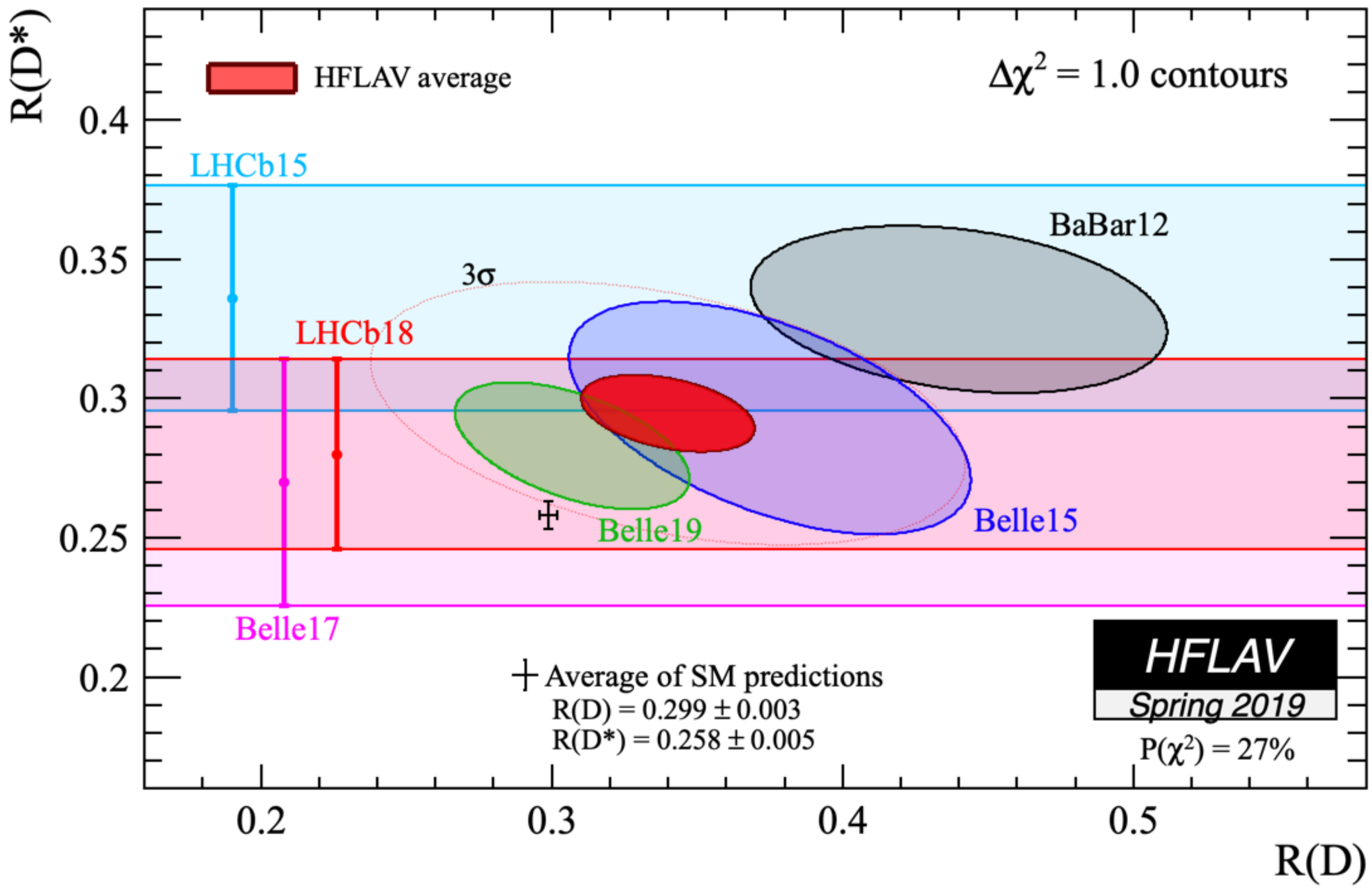
$b \to sll$



[Cornella et al., 2103.16558]

Backup

$b \to c\tau\nu$



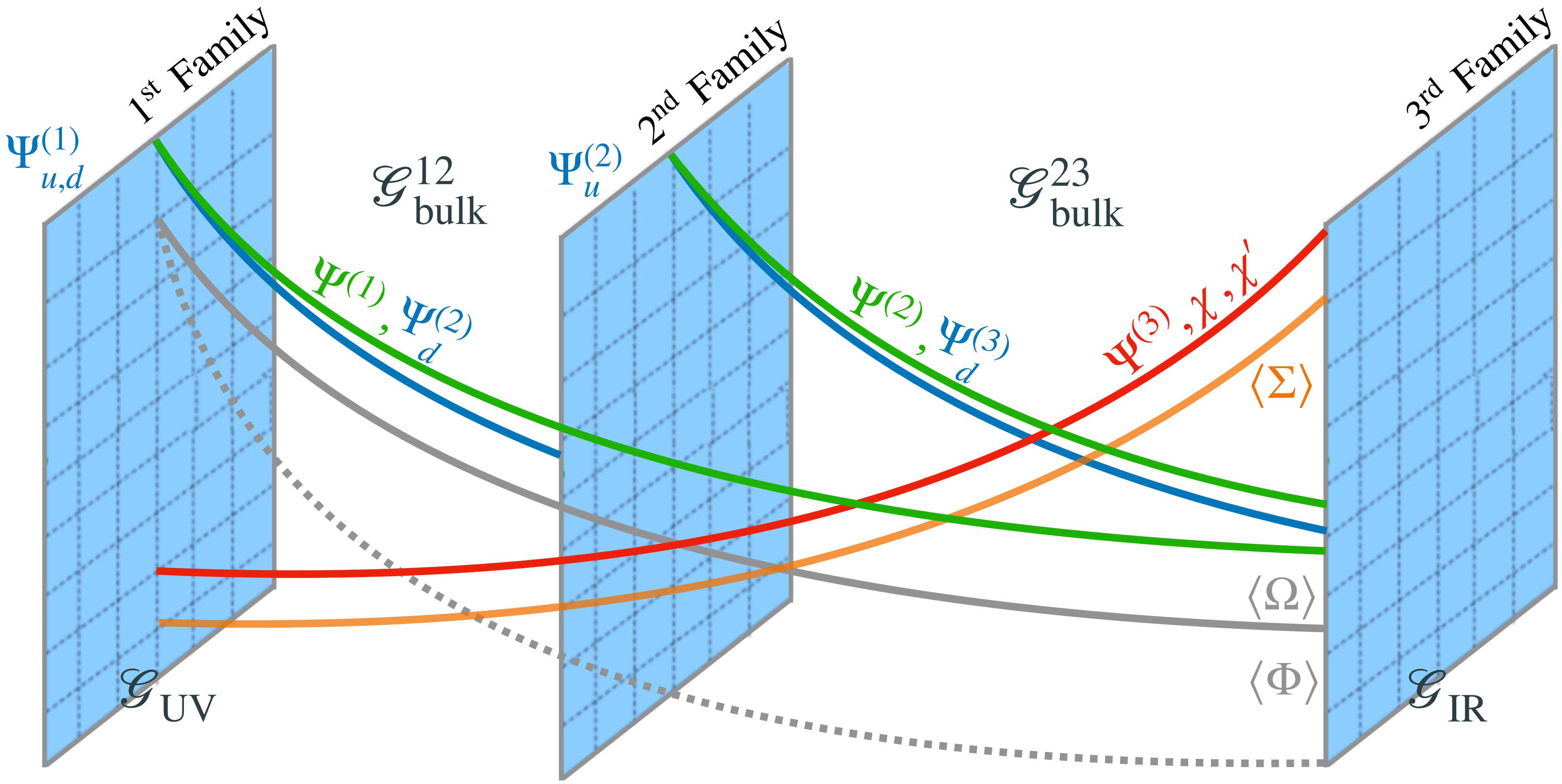
Backup

Field	$SU(4)_h$	$SU(4)_l$	$SO(5)$
$\Psi^3, \Psi^3_d, \mathcal{X}^{(\prime)}$	**4**	**1**	**4**
$\Psi^j, \Psi^j_{u,d}$	**1**	**4**	**4**
$\mathcal{S}^i$	**1**	**1**	**1**
Σ	**1**	**1**	**5**
Ω	**1**	**4**	**4**
Φ	**1**	**1**	**1**

$$\Psi^3 = \begin{bmatrix} \psi^3\,(+,+) \\ \psi^3_u\,(-,-) \\ \tilde{\psi}^3_d\,(+,-) \end{bmatrix}, \qquad \Psi^3_d = \begin{bmatrix} \tilde{\psi}^3\,(+,-) \\ \tilde{\psi}^3_u\,(+,-) \\ \psi^3_d\,(-,-) \end{bmatrix},$$

$$\mathcal{X}^{(\prime)} = \begin{bmatrix} \chi^{(\prime)}(\pm,\pm) \\ \chi^{(\prime)}_u\,(\mp,\pm) \\ \chi^{(\prime)}_d\,(\mp,\pm) \end{bmatrix}, \qquad \Psi^j = \begin{bmatrix} \psi^j\,(+,+) \\ \tilde{\psi}^j_u\,(-,+) \\ \tilde{\psi}^j_d\,(-,+) \end{bmatrix},$$

$$\Psi^j_u = \begin{bmatrix} \tilde{\psi}^j\,(+,-) \\ \psi^j_u\,(-,-) \\ \hat{\psi}^j_d\,(+,-) \end{bmatrix}, \qquad \Psi^j_d = \begin{bmatrix} \hat{\psi}^j\,(+,-) \\ \hat{\psi}^j_u\,(+,-) \\ \psi^j_d\,(-,-) \end{bmatrix},$$



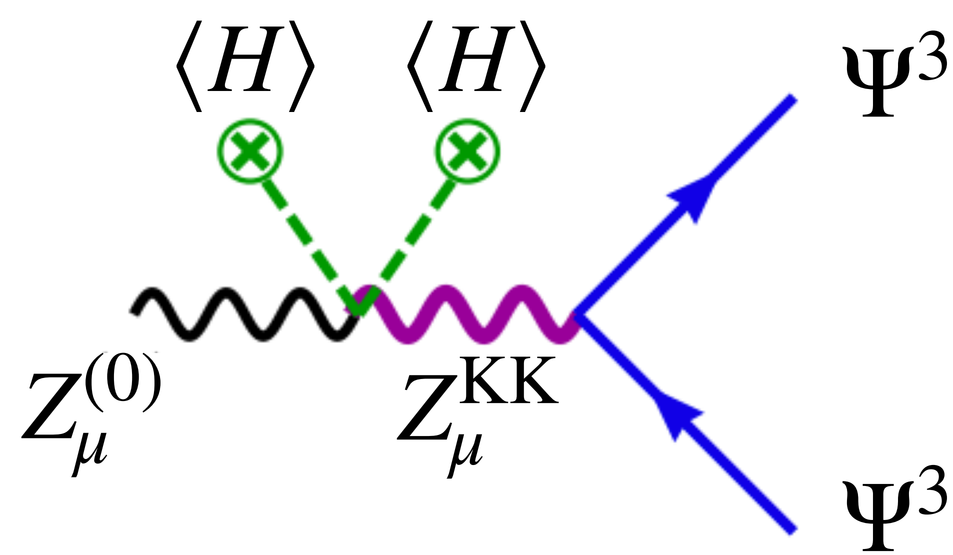
Backup

- The most constraining EW observable in 5D is $Z \to \bar{\tau}\tau$, affected by the mixing of Z and Z^{KK}:

$$\frac{\delta g_{Z\Psi^3\Psi^3}}{g_{Z\Psi^3\Psi^3}} \approx -0.3 \frac{m_Z^2}{M_{\rm KK}^2}\frac{g_*^2}{g_L^2} \approx -\frac{0.3}{4c_W^2}\frac{\langle h\rangle^2}{f^2} \lesssim 10^{-3}$$

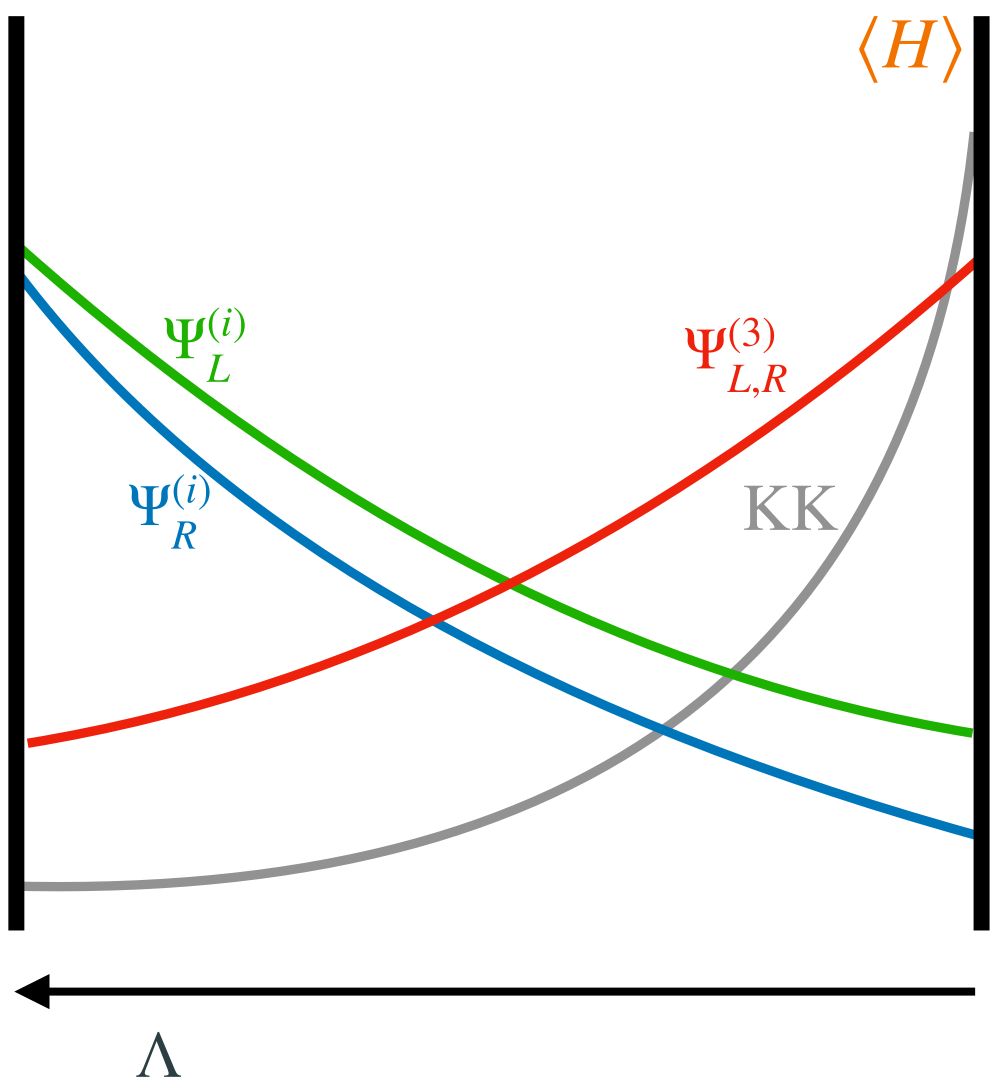
↓

$$f > 2.5\,\text{TeV},\;\; M_{\rm KK} > 6\,\text{TeV}$$



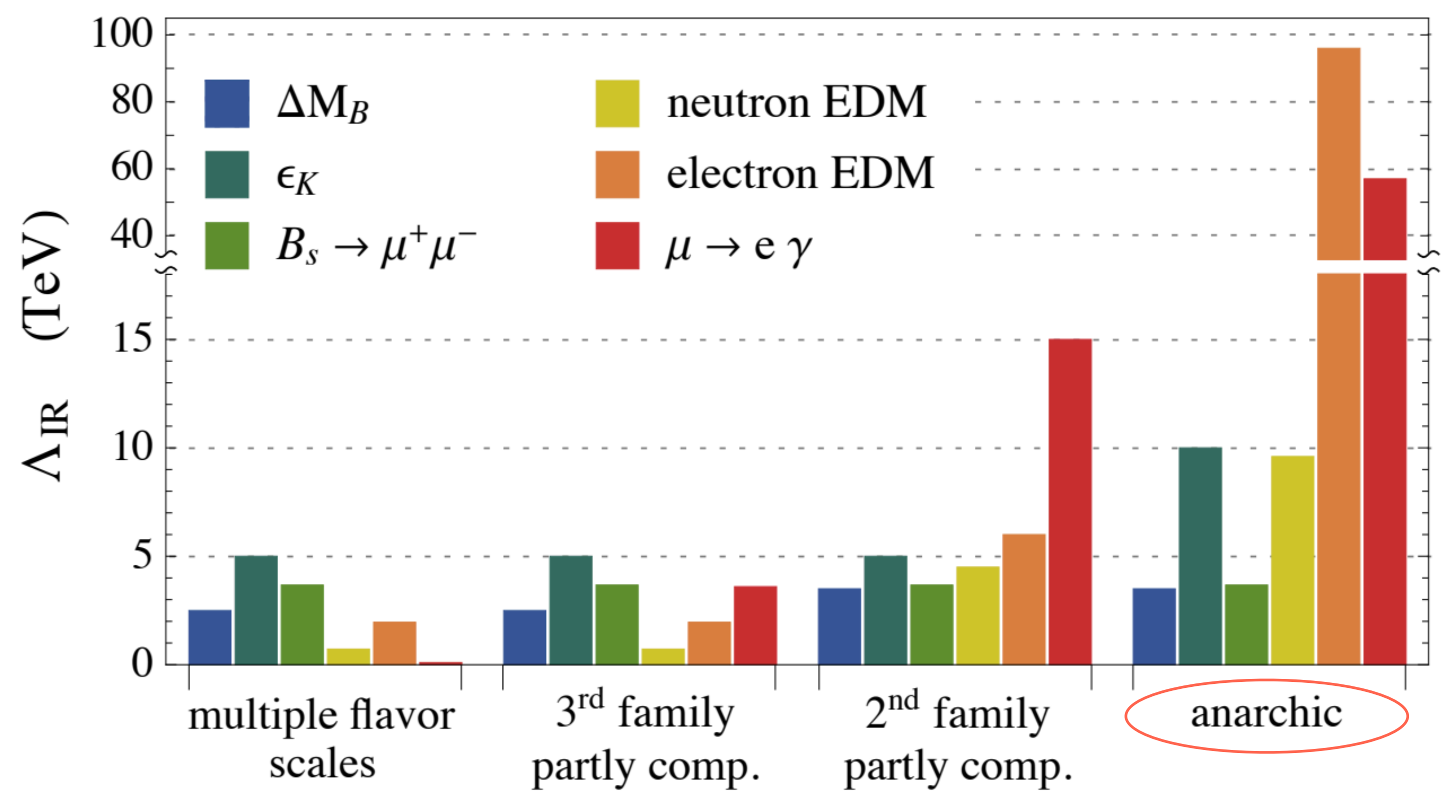
Backup

- Anarchic partial compositeness paradigm in RS



Dangerous dipoles (among others) generated at the IR scale

$$\sim \frac{g_*^2}{16\pi^2}\frac{m_e}{\Lambda_{\rm IR}^2}\,\bar{e}_L\sigma_{\mu\nu}e_R F^{\mu\nu}$$



[Panico, Pomarol, 1603.06609]

Backup

Minimal composite Higgs (MCHM)

[Agashe, Contino, Pomarol, hep-ph/0412089]

- Breaking by a composite sector [Fuentes-Martin, Stangl 2004.11376]

Global symmetry	$\mathcal{G}_{\text{global}} = SU(4)_h \times SU(4)_l \times SO(5)$
Gauge symmetry	$\mathcal{G}_{\text{global}} = SU(4)_h \times SU(3)_l \times SU(2)_L \times U(1)_{l+R}$

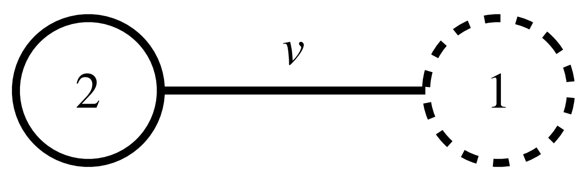
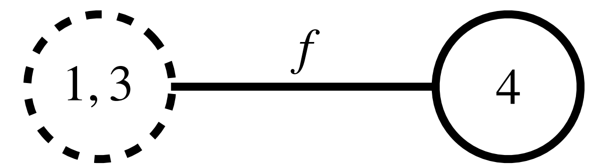
Spontaneously broken by a condensate at some IR scale

Global SBB	$\mathcal{G}_{\text{IR}} = SU(4)_D \times SU(2)_L \times SU(2)_R$
Gauge SSB	$\mathcal{G}_0 = \mathcal{G}_{\text{IR}} \cap \mathcal{G}_{\text{gauge}} = SU(3)_c \times SU(2)_L \times U(1)_Y$
Goldstones	15 (eaten by U_1, G', Z') + 4 (NGB Higgs)

SM Higgs emerges as a Nambu-Goldstone boson of the same (strong) dynamics breaking 4321 gauge symmetry

Backup

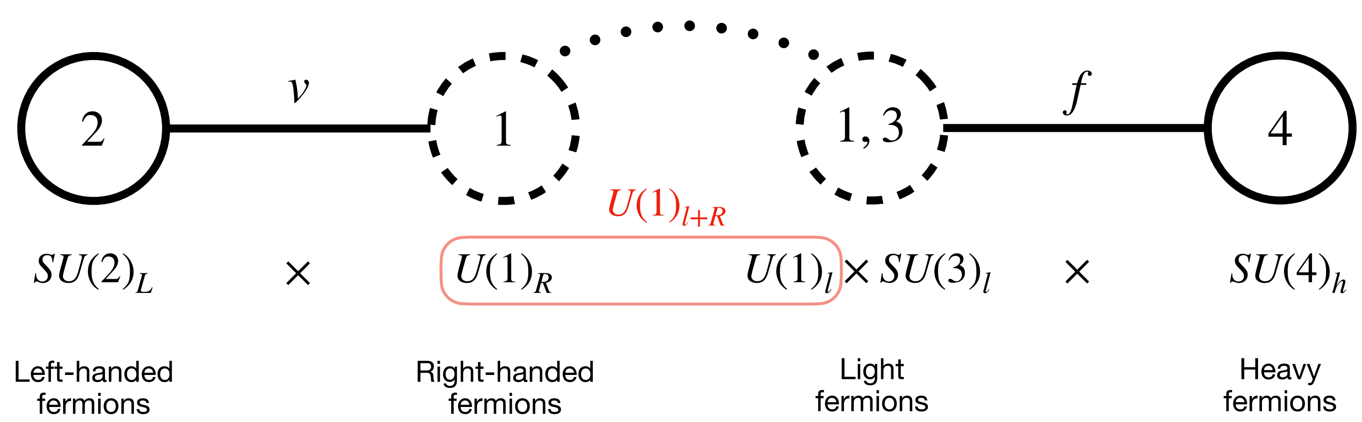
[Fuentes-Martin, Stangl 2004.11376]

	SM Higgs Sector	4321 Models
Global symmetry	$SU(2)_L \times SU(2)_R$	$SU(4)_l \times SU(4)_h$
Gauge symmetry	 $SU(2)_L \times U(1)_R$ Left-handed fermions × Right-handed fermions	 $U(1)_l \times SU(3)_l \times SU(4)_h$ Light fermions × Heavy fermions
Global SSB	$SU(2)_V$	$SU(4)_D$
Gauge SSB	$U(1)_V$	$U(1)_{B-L} \times SU(3)_c$
Goldstones	3 (3 eaten)	15 (15 eaten)

Backup

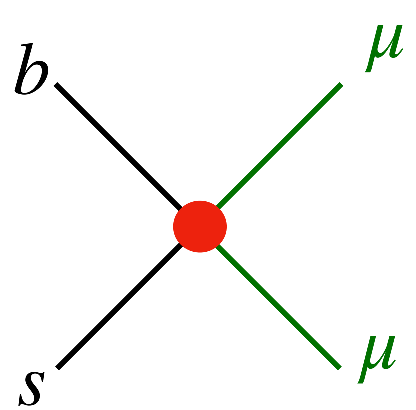
[Fuentes-Martin, Stangl 2004.11376]

The two sites are connected by the gauging

	SM Higgs Sector	4321 Models
Global symmetry	$SU(2)_L \times SU(2)_R$	$SU(4)_l \times SU(4)_h$
Gauge symmetry		
Global SSB	$SU(2)_V$	$SU(4)_D$
Gauge SSB	$U(1)_{\text{em}} \times SU(3)_c$	
Goldstones	$3\ (W, Z)$	$15\ (U_1, G', Z')$

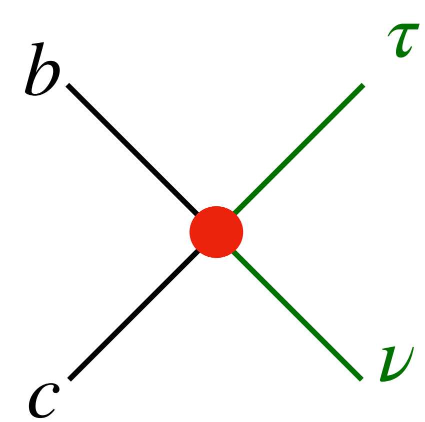
B-anomalies

$$b \to sll$$



$\ll$

$$b \to c\tau\nu$$



- Non-universality in e/μ, $> 4\sigma$

$$c \sim (40\ \mathrm{TeV})^{-2}$$

$$3_q \to 2_q 2_l 2_l$$

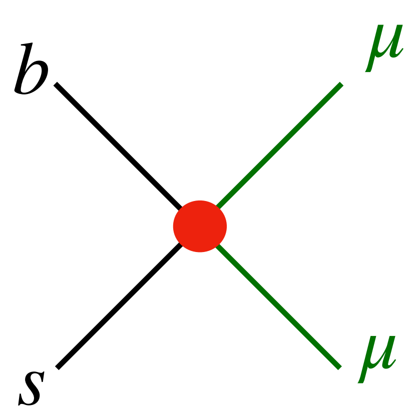
- Non universality in $\tau/\mu, e$, $\sim 3\sigma$

$$c \sim (3\ \mathrm{TeV})^{-2}$$

$$3_q \to 2_q 3_l 3_l$$

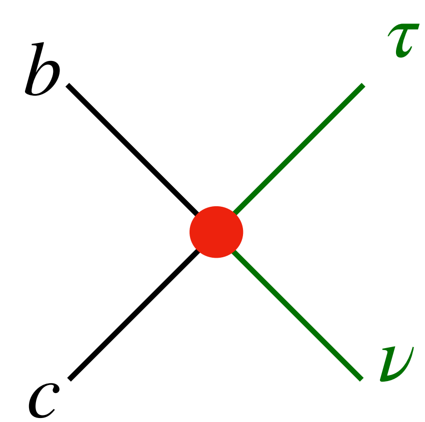
B-anomalies

$b \to sll$



$\ll$

$b \to c\tau\nu$



- Non-universality in e/μ, $> 4\sigma$
- Non universality in $\tau/\mu, e$, $\sim 3\sigma$

$$c \sim \epsilon_q \epsilon_l^2 \ \mathrm{TeV}^{-2}$$

$$3_q \to 2_q 2_l 2_l$$

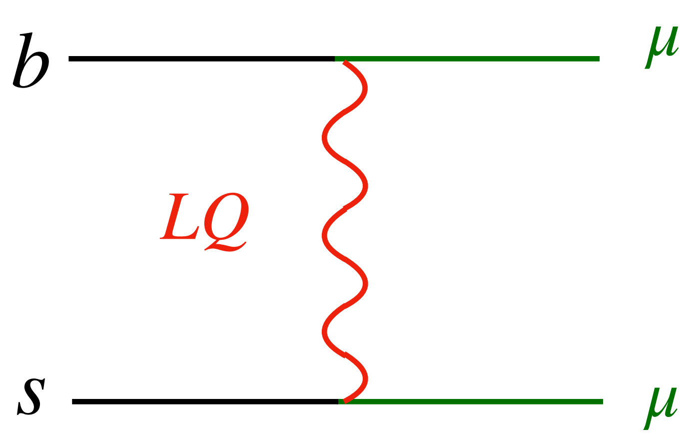
$$\epsilon_q, \epsilon_l \sim 0.1$$

$$c \sim \epsilon_q \ \mathrm{TeV}^{-2}$$

$$3_q \to 2_q 3_l 3_l$$

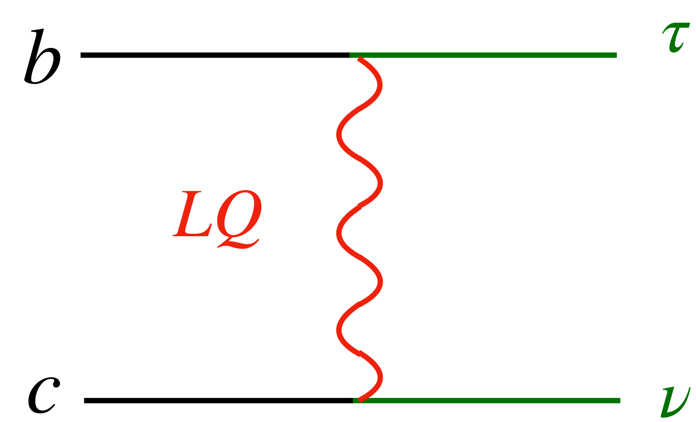
B-anomalies

$b \to sll$



$\ll$

$b \to c\tau\nu$



- Non-universality in e/μ, $> 4\sigma$
- Non universality in $\tau/\mu, e$, $\sim 3\sigma$

$$c \sim \epsilon_q \epsilon_l^2 \ \mathrm{TeV}^{-2}$$

$$3_q \to 2_q 2_l 2_l$$

$\epsilon_q, \epsilon_l \sim 0.1$

$$c \sim \epsilon_q \ \mathrm{TeV}^{-2}$$

$$3_q \to 2_q 3_l 3_l$$

LQ mostly coupled to the third family ➡ $U(2)^5$ in light families to protect flavour observables