University of Zurich[UZH]

Flavor hierarchies and B-anomalies from 5D

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Based on work with G. Isidori, J. Fuentes Martín, N. Selimović and B. A. Stefanek

[2203.01952]

Planck - 2022

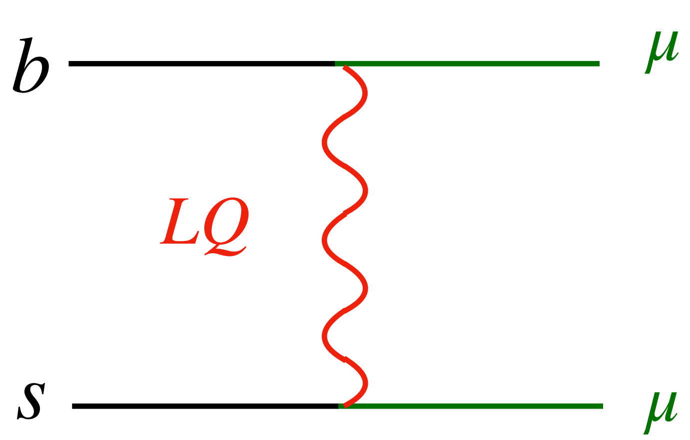
B-anomalies

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

Gino's talk

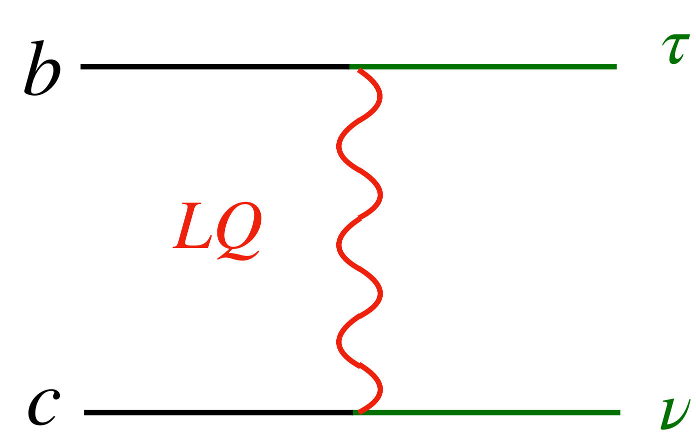
$b \to sll$

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



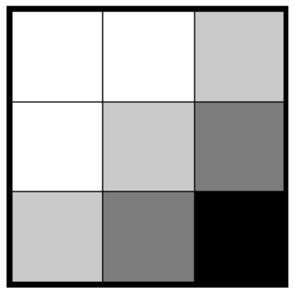
$b \to c\tau\nu$

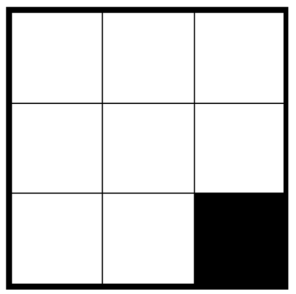
- Non universality in $\tau/\mu, e$, $\sim 3\sigma$



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

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

$\beta_L^{ql} \sim$ 

$\beta_R^{ql} \sim$ 

4321 model

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

4321 completion

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

$U(1)_Y$

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

$SU(3)_c$

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

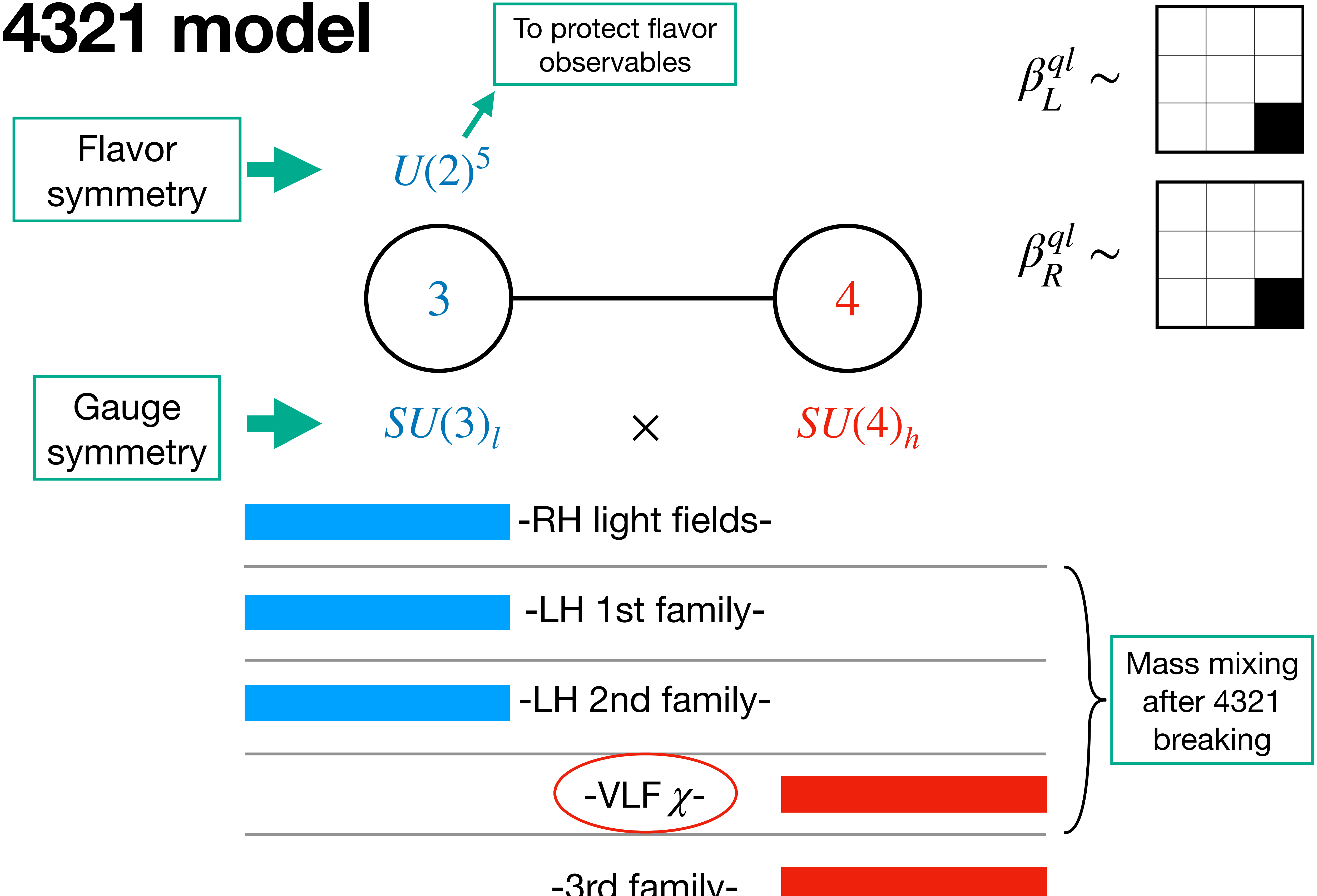
3rd family Pati-Salam unification

$$\Psi^{(3)}_{L/R} = \begin{pmatrix} Q^1_{L,R} \\ Q^2_{L,R} \\ Q^3_{L,R} \\ L_{L,R} \end{pmatrix}$$

Light families

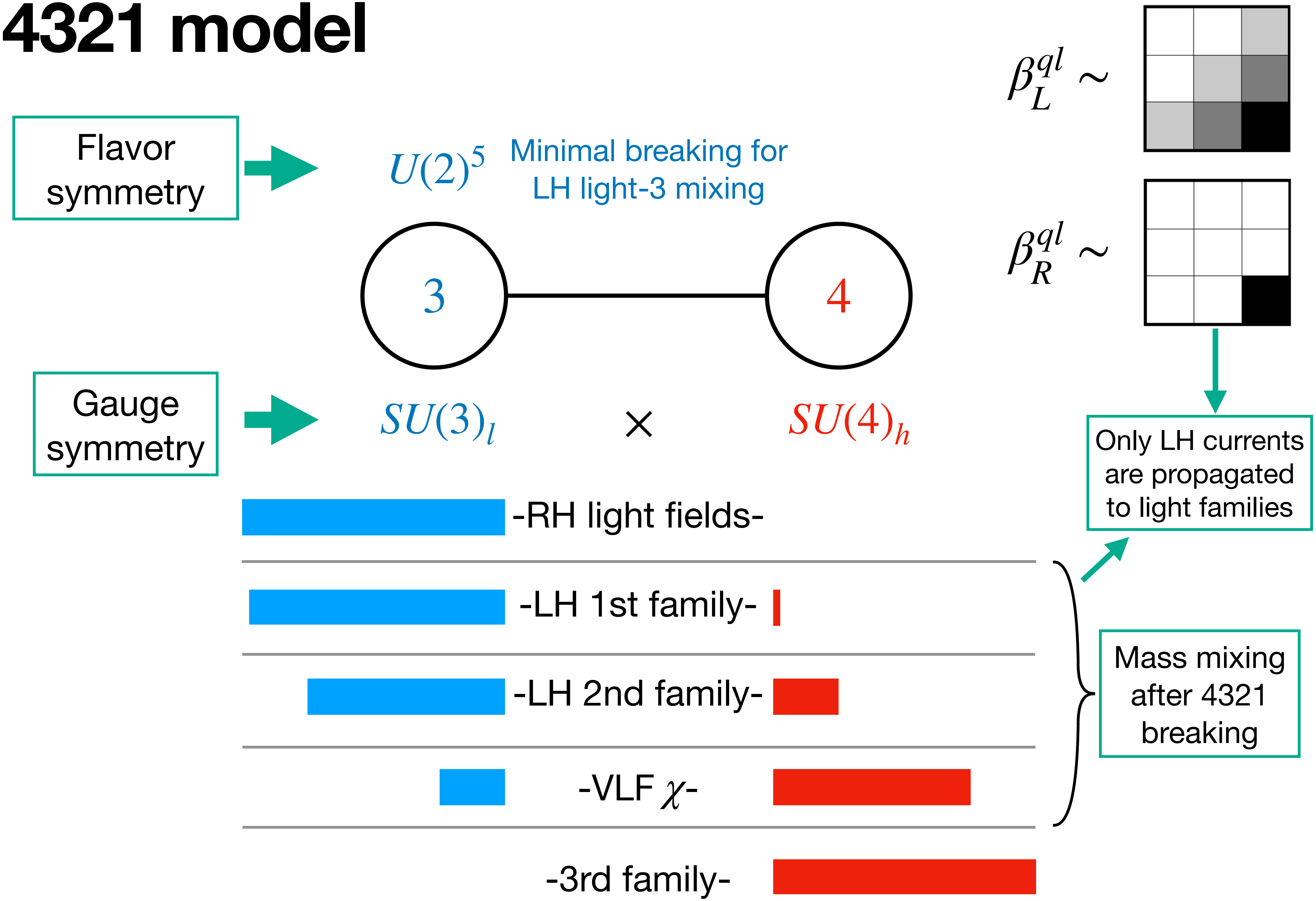
Flavor non-universal gauge theory

4321 model



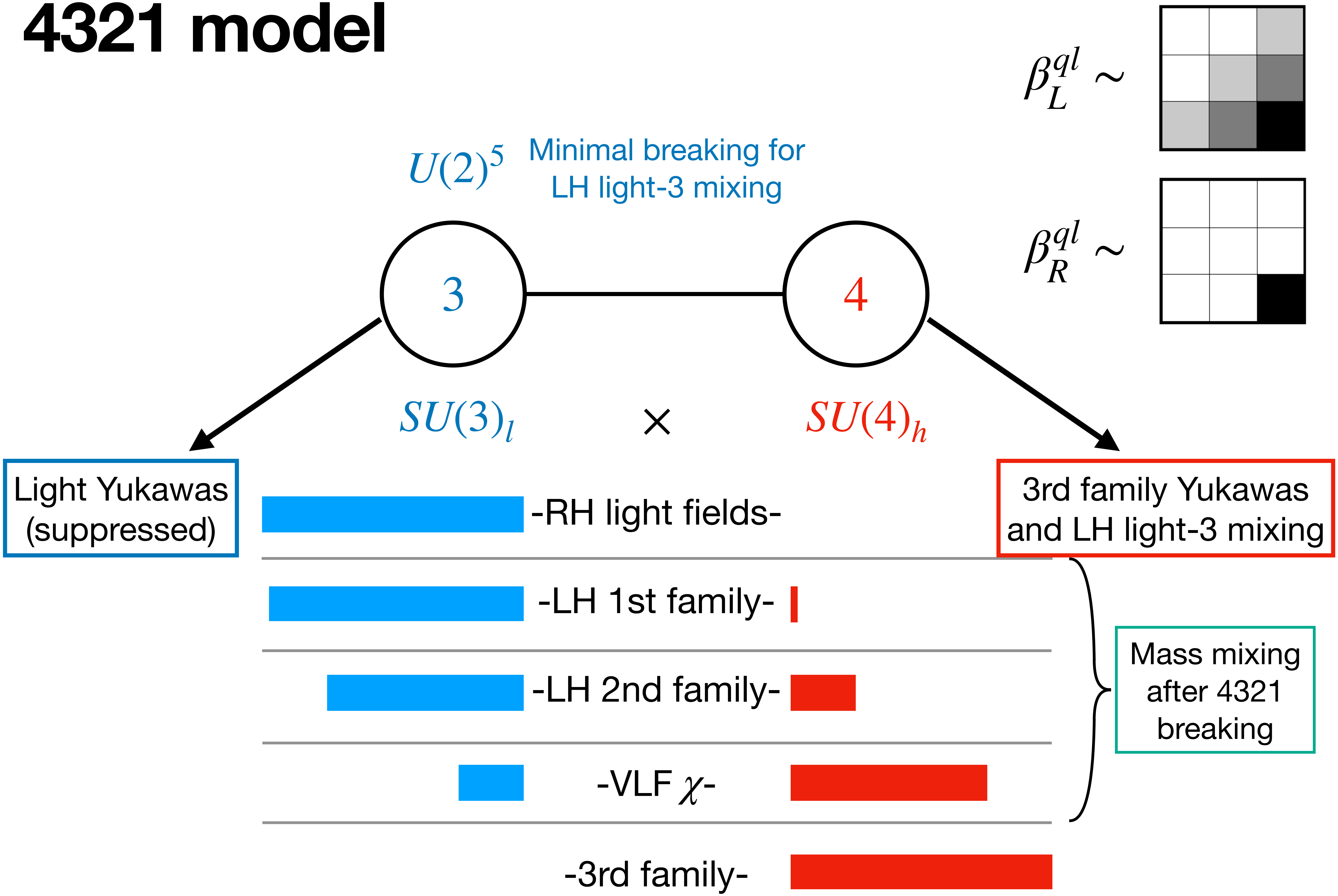
To protect flavor observables
Flavor symmetry
$U(2)^5$
Gauge symmetry
3
4
$SU(3)_l \times SU(4)_h$
$\beta_L^{ql} \sim$
$\beta_R^{ql} \sim$
-RH light fields-
-LH 1st family-
-LH 2nd family-
-VLF χ-
-3rd family-
Mass mixing after 4321 breaking

4321 model



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

4321 model

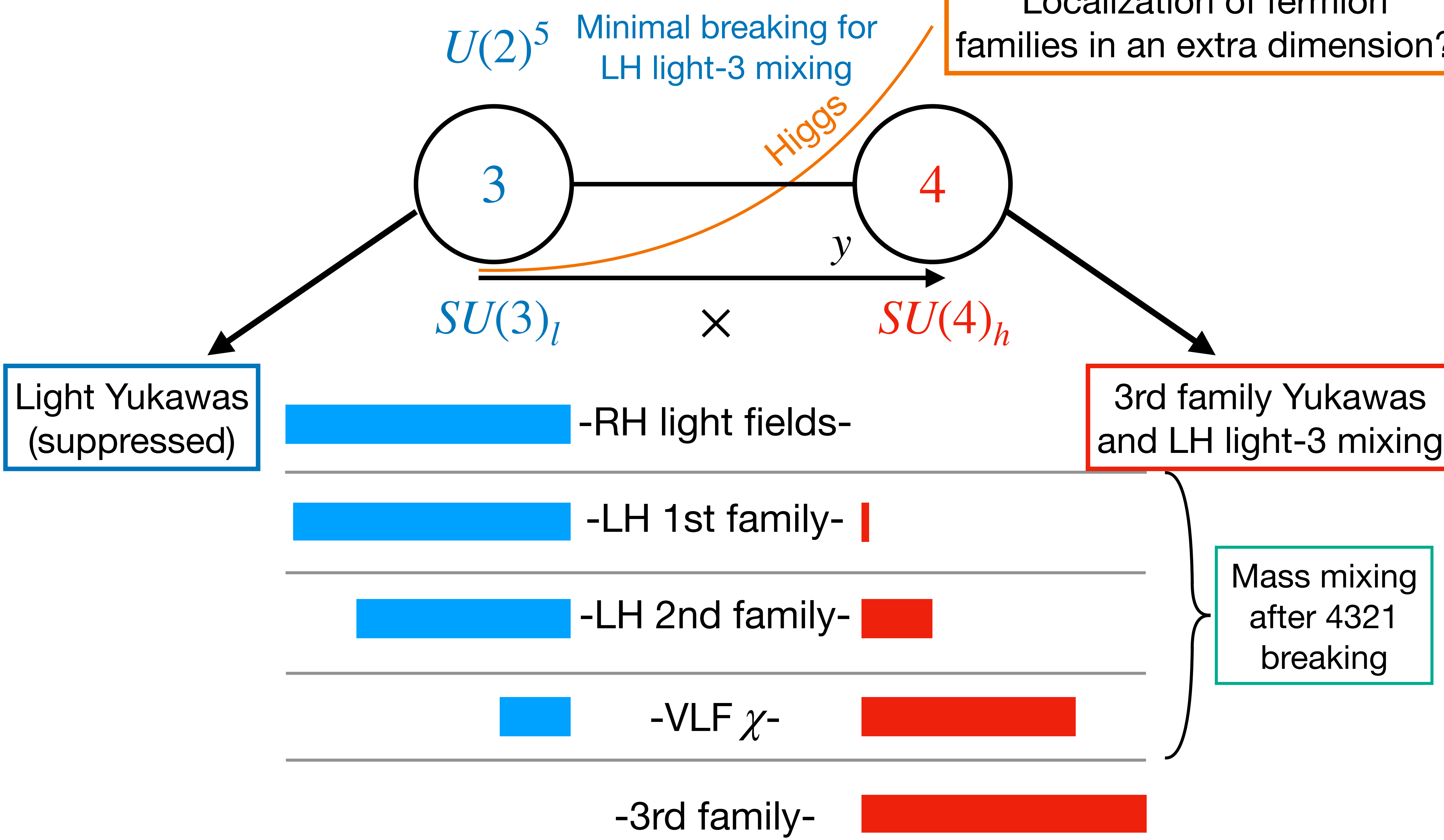


$\beta_L^{ql} \sim$
$\beta_R^{ql} \sim$
$U(2)^5$
Minimal breaking for LH light-3 mixing
3
4
$SU(3)_l \times SU(4)_h$
Light Yukawas (suppressed)
3rd family Yukawas and LH light-3 mixing
-RH light fields-
-LH 1st family-
-LH 2nd family-
-VLF χ-
-3rd family-
Mass mixing after 4321 breaking

4321 model

Connection with Higgs stabilization?

Localization of fermion families in an extra dimension?



A 5D model: a first attempt

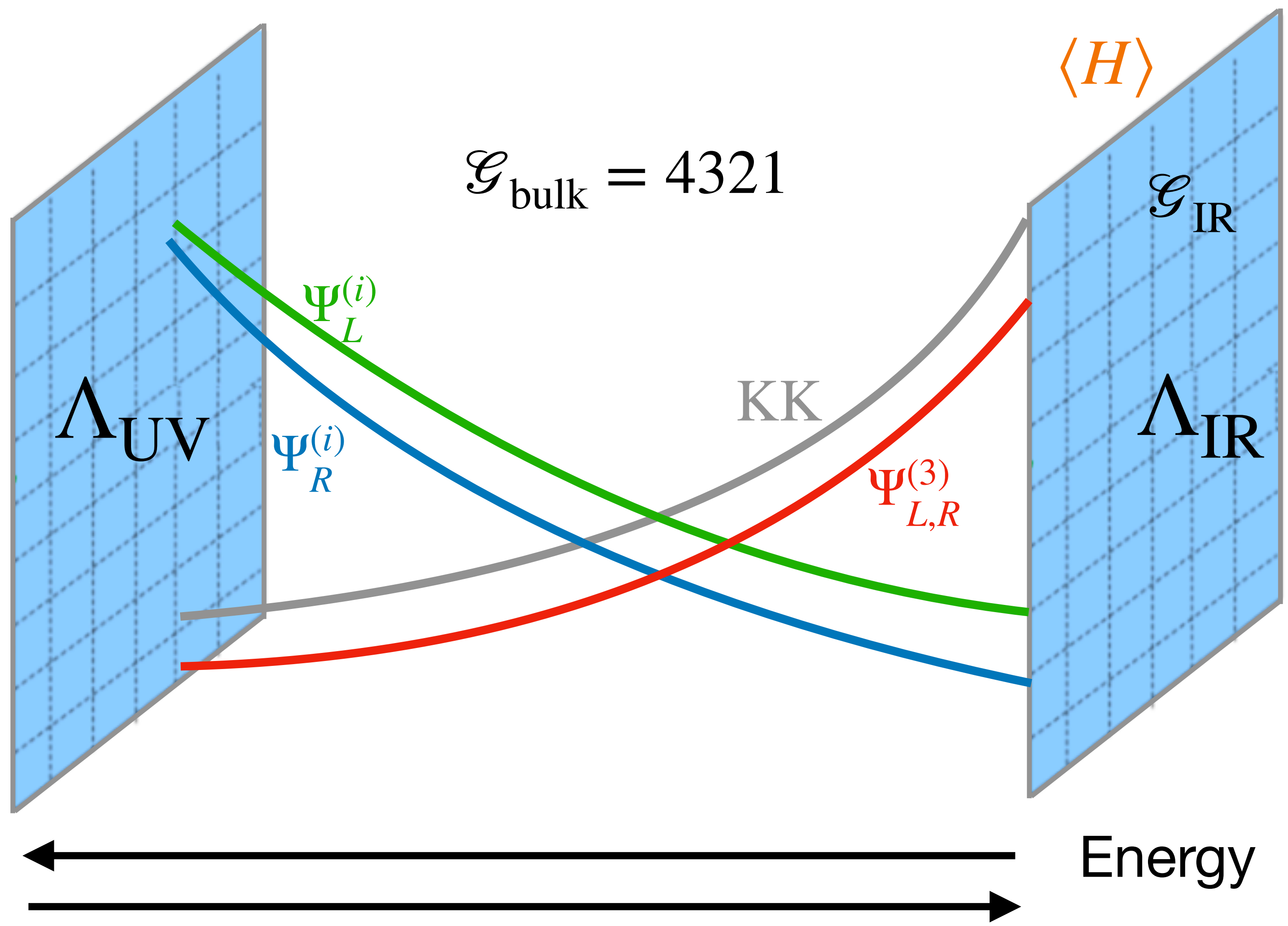
Curvature of the AdS slice

Energy scale ⇕ Position in y

- 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 $\mathcal{G}_{\rm bulk} \to \mathcal{G}_{\rm IR}$
- 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

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

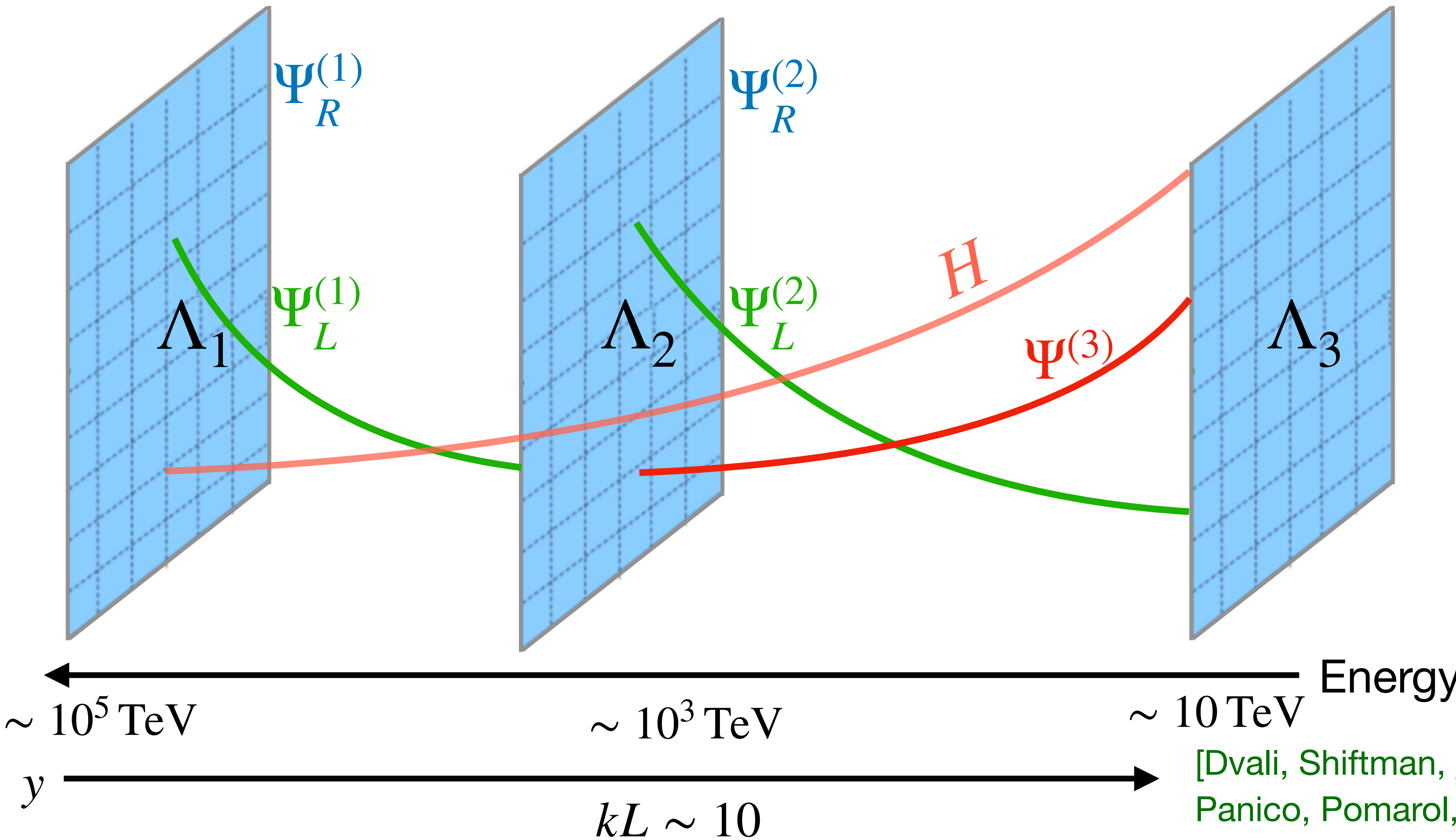


[Gherghetta, Pomarol, arXiv:hep-ph/0003129]

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

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

Λ_2 (6 broken)

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

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

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

Quark-lepton unification of light families

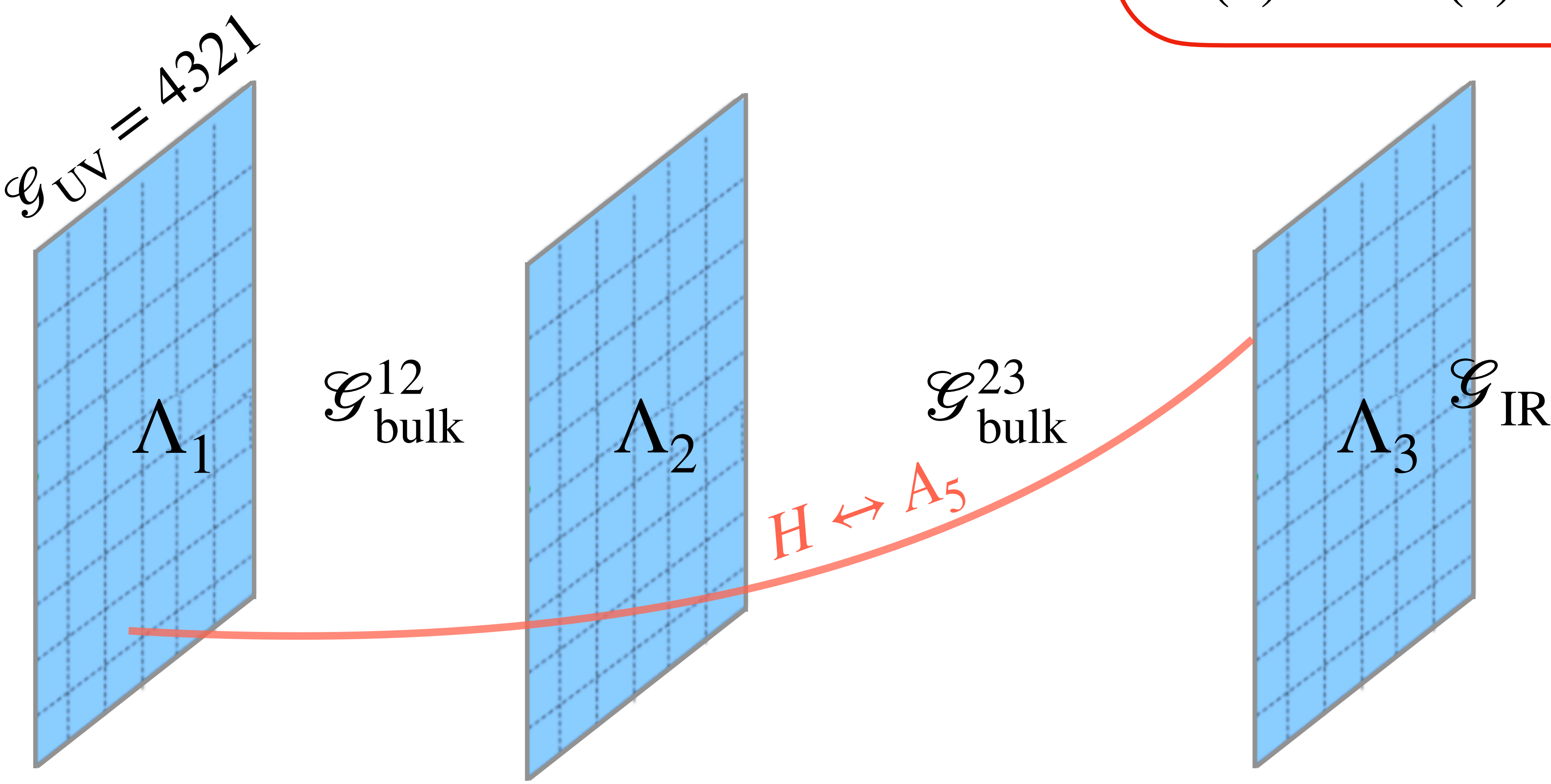
15 eaten by U_1, G', Z', $M_{4321} \sim \dfrac{M_{\text{KK}}}{\sqrt{2kL}}$

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

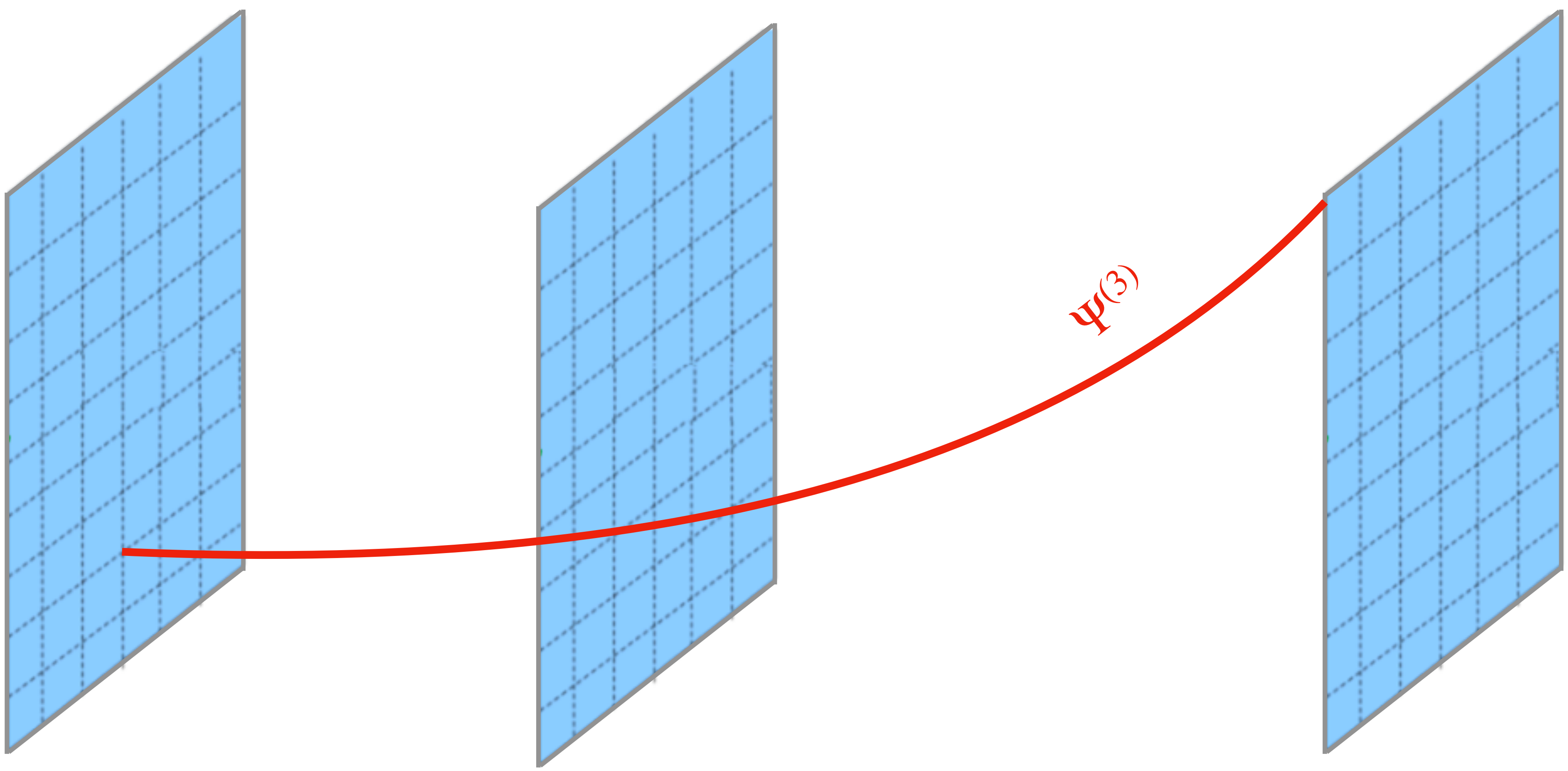
Top Yukawa

Field	$SU(4)_h$	$SU(4)_l$	$SO(5)$
Ψ^3	**4**	**1**	**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

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

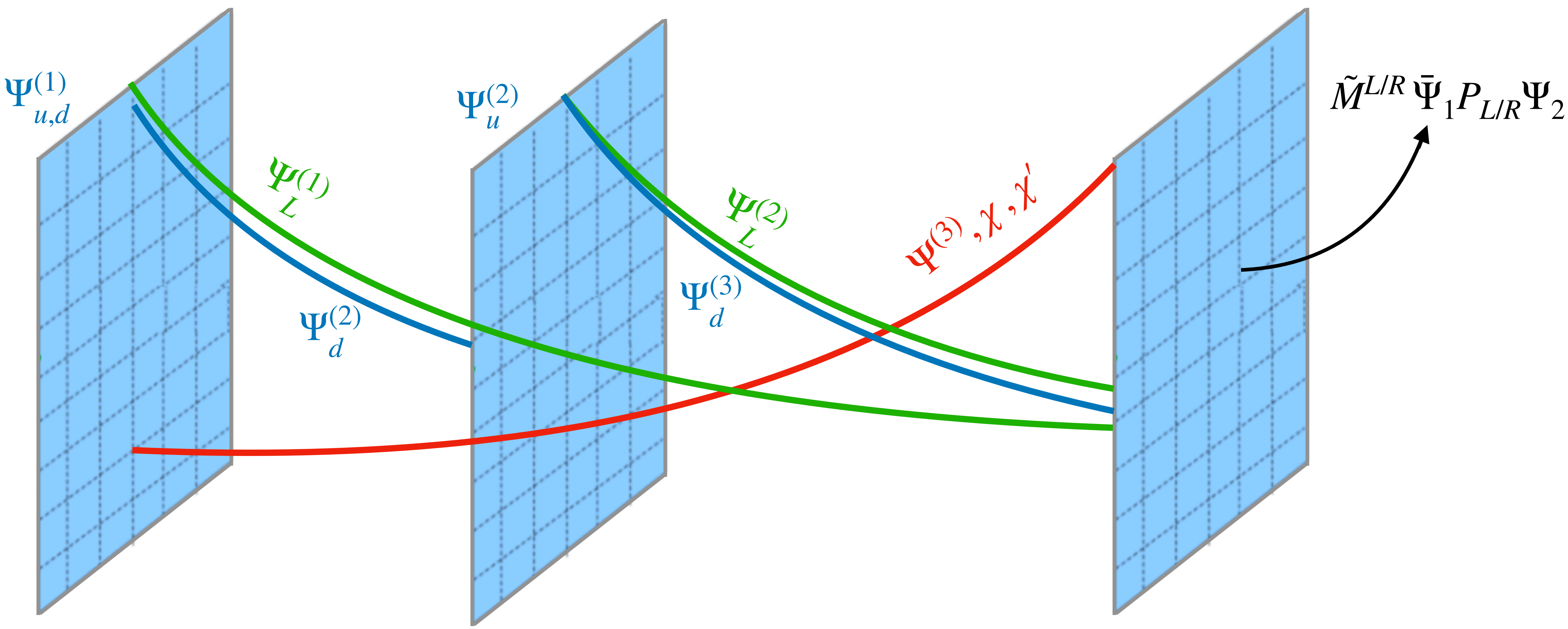


Other 3rd family Yuk. and light-heavy mixing

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

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

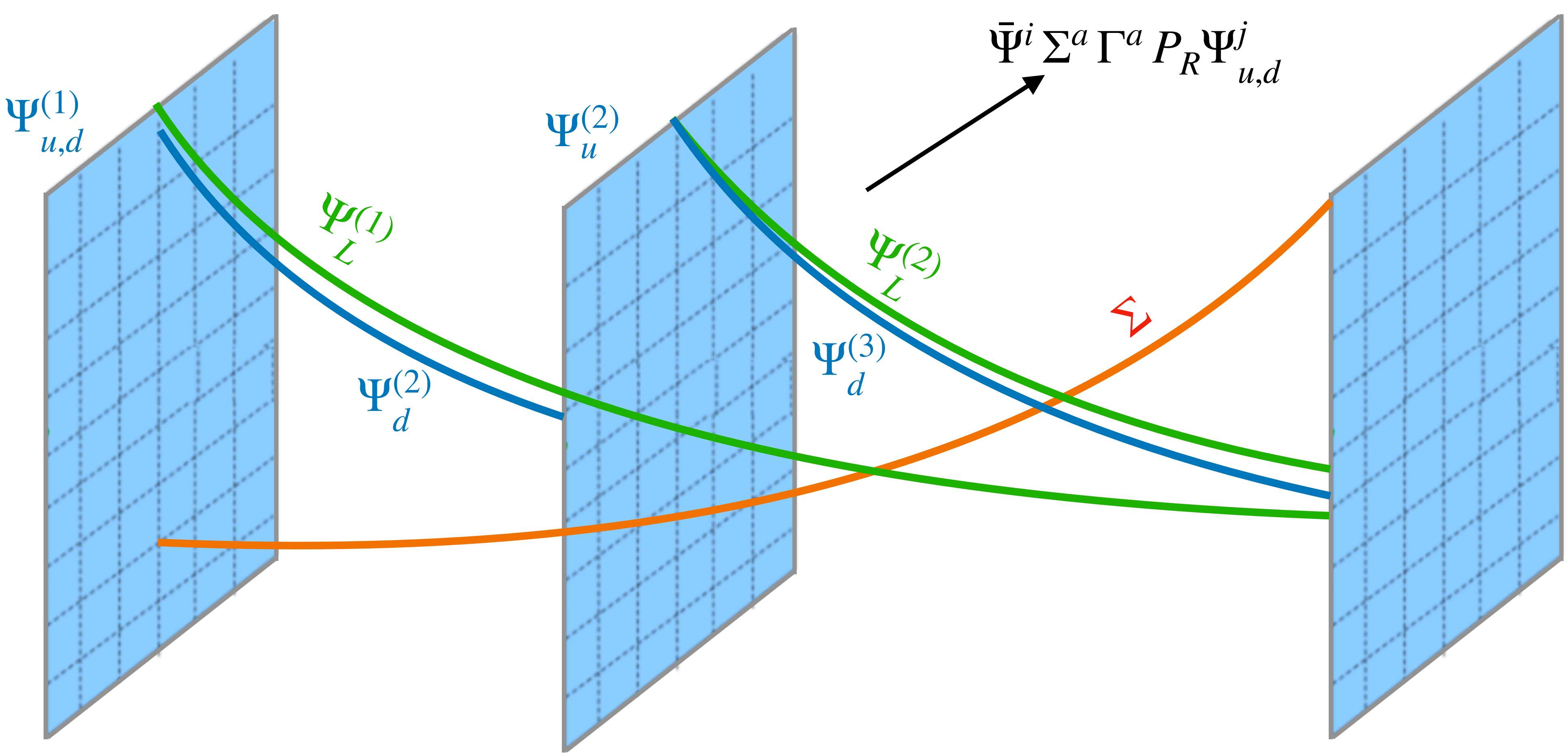


Light Yukawas

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

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

$\alpha \downarrow \Psi^3, \Omega$ $\quad$ $\beta \downarrow \Psi^3, \Sigma, W, Z$

Higgs decay constant:

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

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

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, same phenomenology as 4321 (B-anomalies)
- Main experimental limit coming from coloron direct searches:

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

[Cornella et al., 2103.16558]

Benchmark Spectrum :

E

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

First deviations from 4321

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

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

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

So high that EWPD are ok

Conclusions

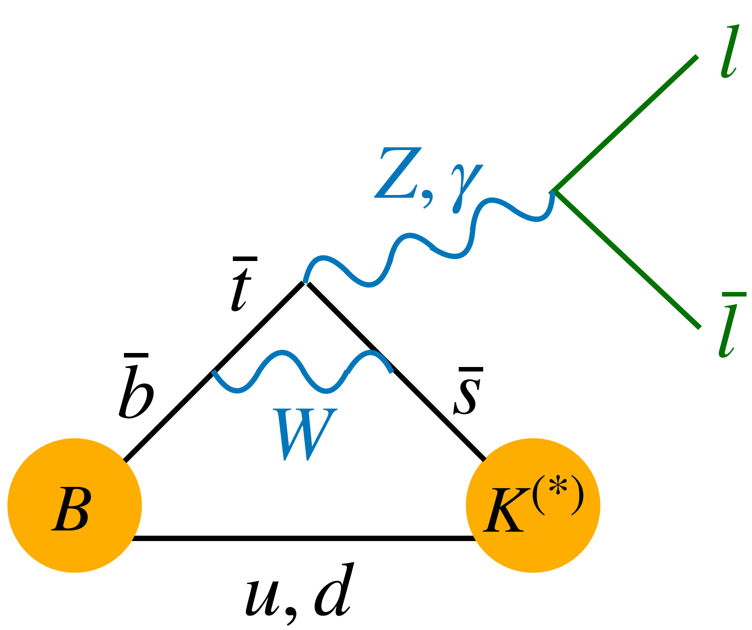
- B-anomalies hint new physics at the TeV scale.
- 4321 is a consistent UV model that can explain the B-anomalies.
- A completion of 4321 à la Randall-Sundrum points towards a multi-scale origin of the flavour hierarchies, where a $U(2)$ flavour symmetry at the TeV minimally broken can be implemented.
- We have presented a 5D model realising this idea where, in addition, the Higgs emerges as a pNGB from the same strong dynamics that breaks 4321.

Thank you!

Backup

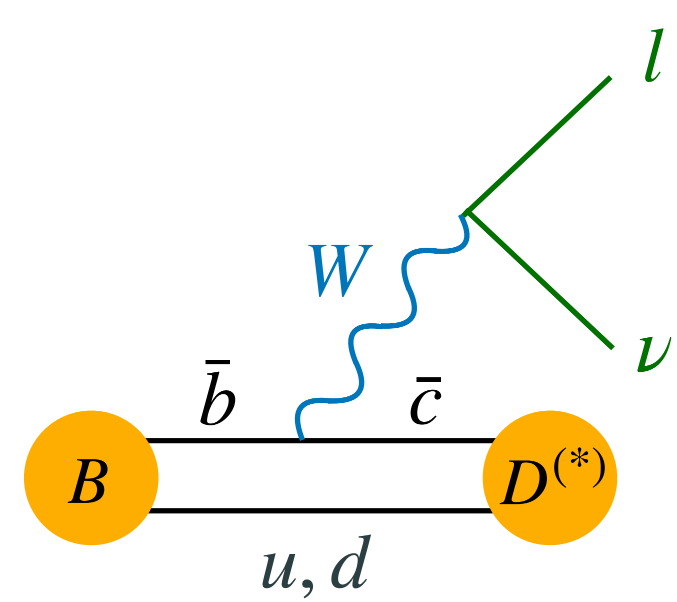
$$b \to sll$$

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



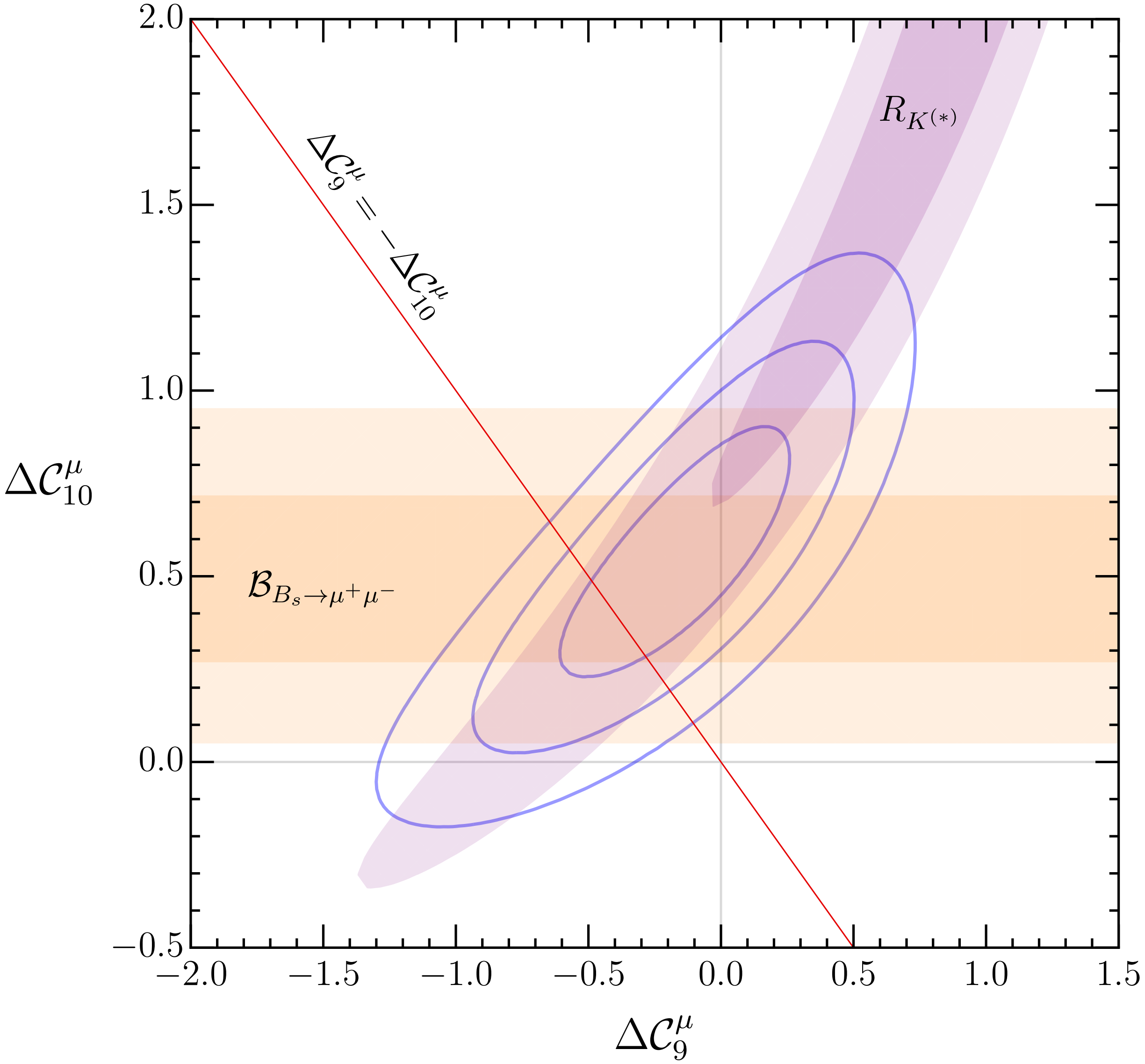
$$b \to c\tau\nu$$

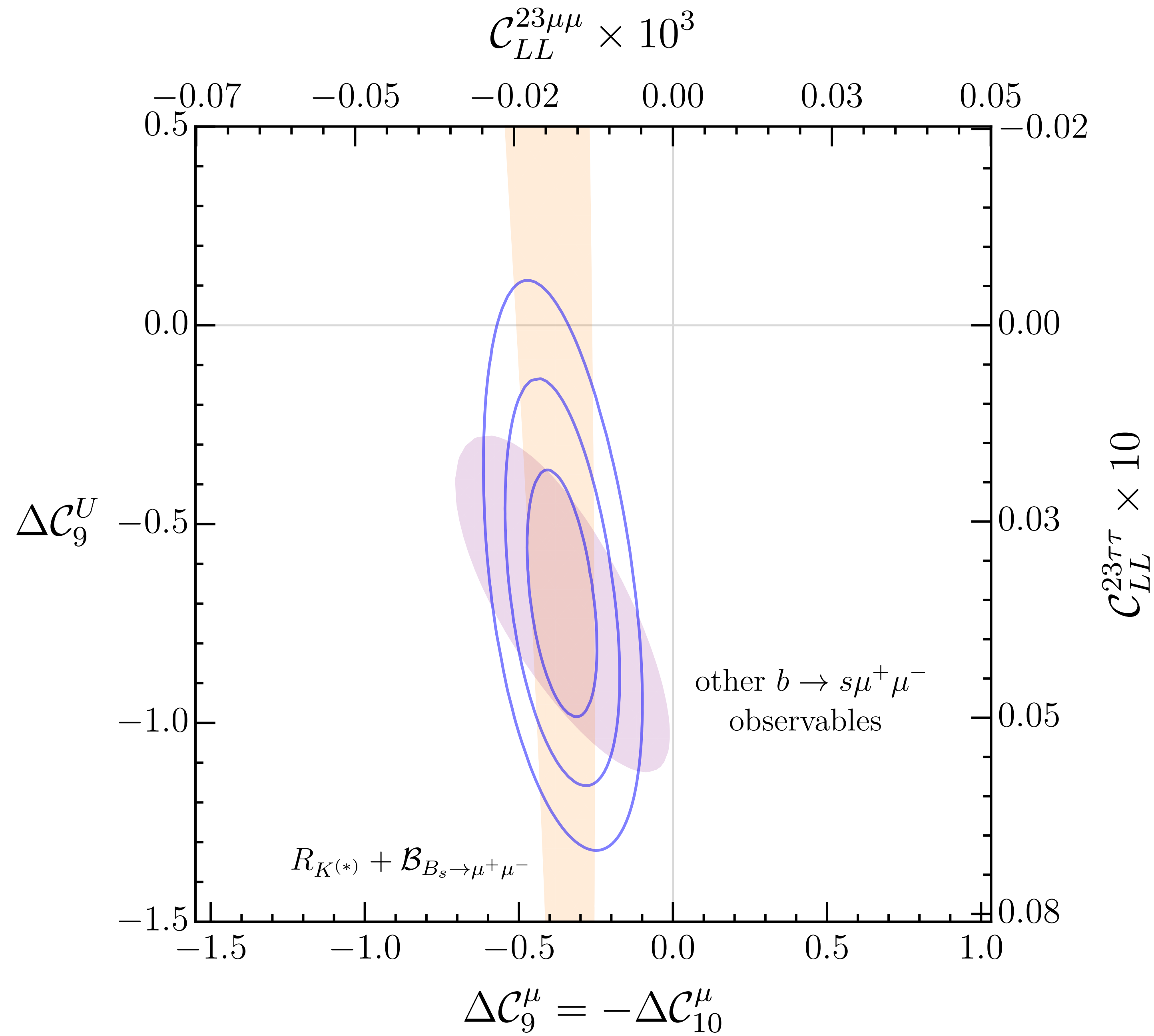
- $R_{D^{(*)}} = \dfrac{Br(B \to D^{(*)}\tau\nu)}{Br(B \to D^{(*)}l\nu)}$
- Non universality in $\tau/\mu, e, \; \sim 3\sigma$



Backup

$b \to sll$

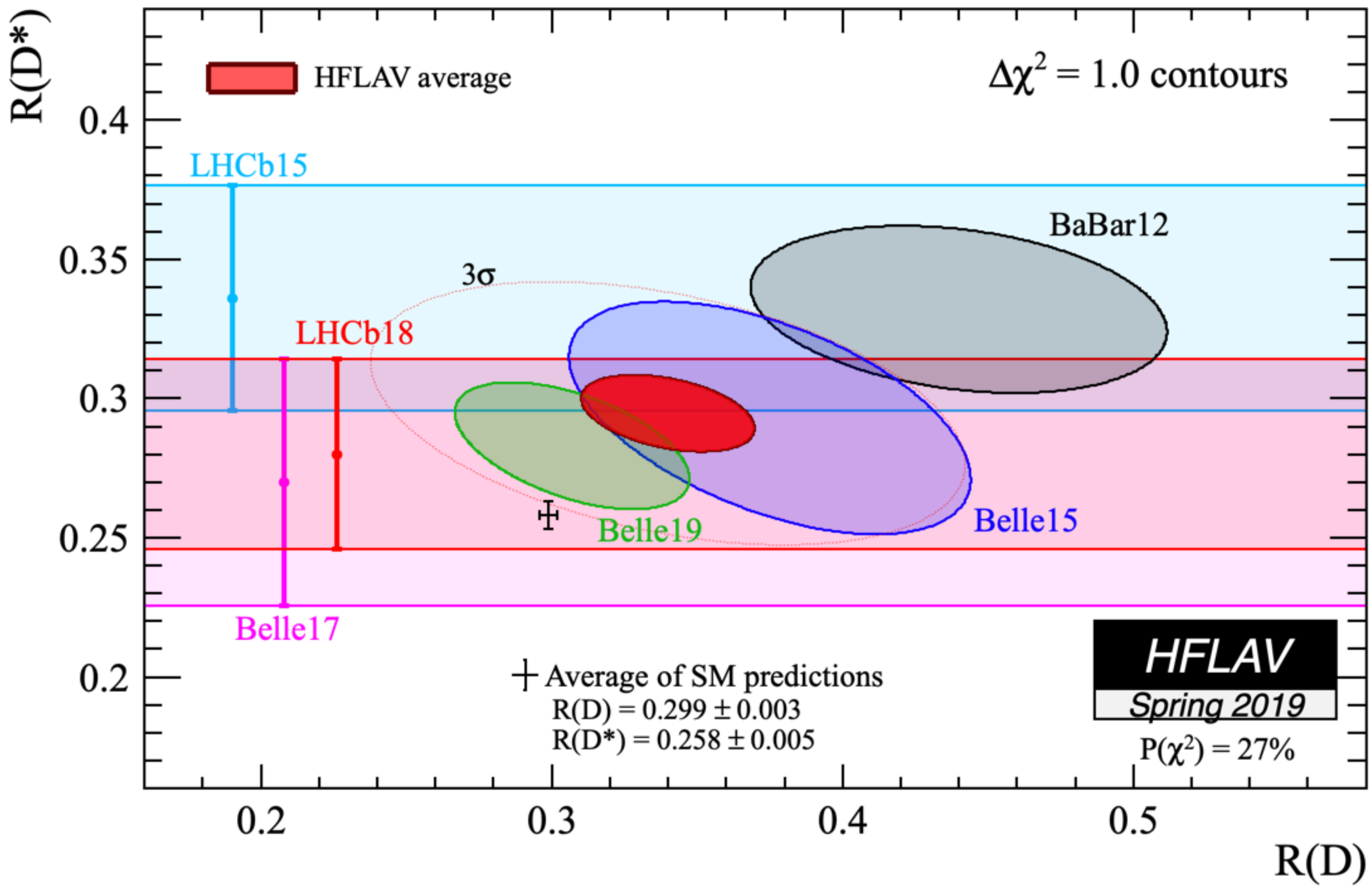




[Cornella et al., 2103.16558]

Backup

$b \to c\tau\nu$



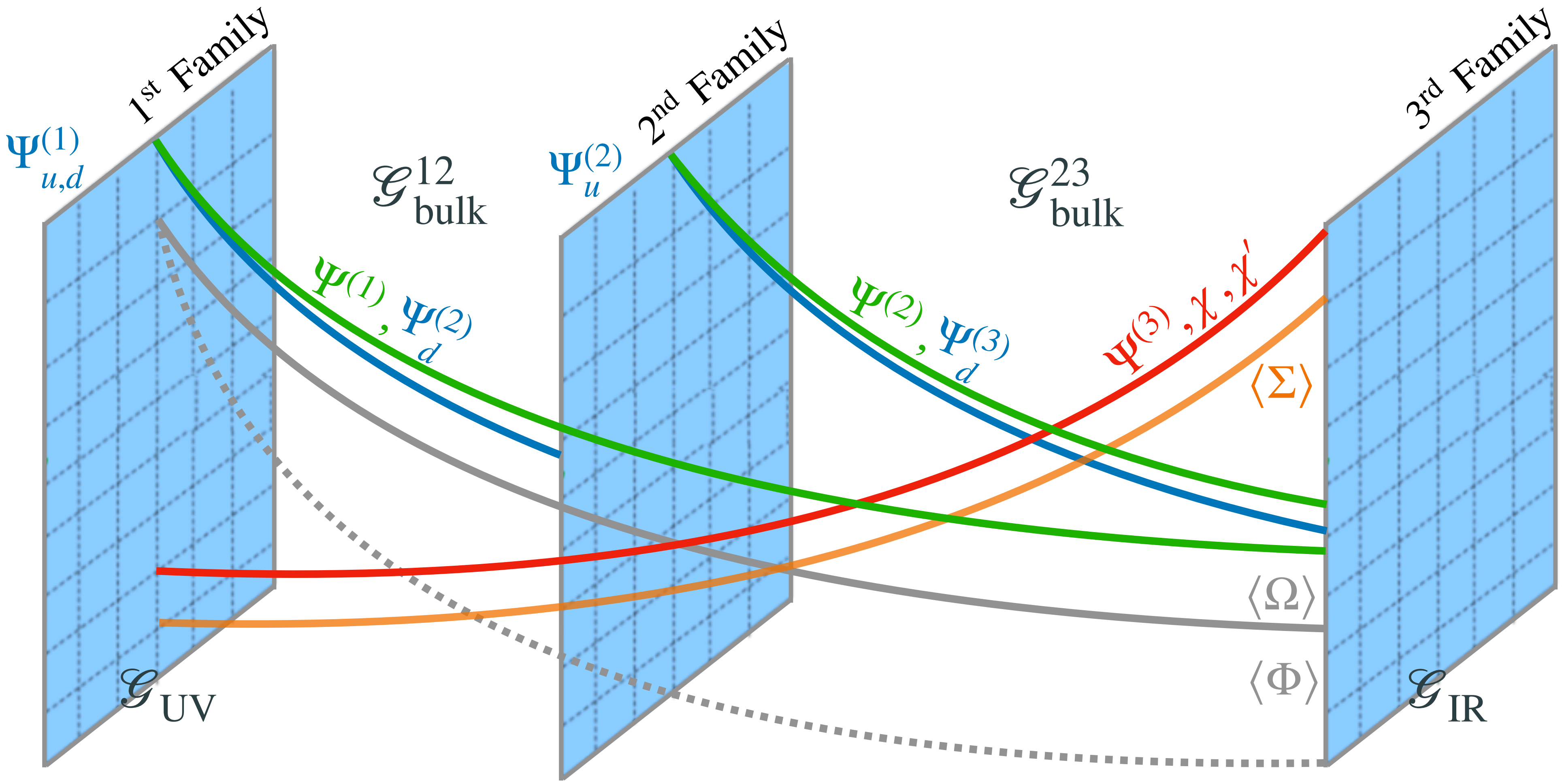
Backup

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**

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

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

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



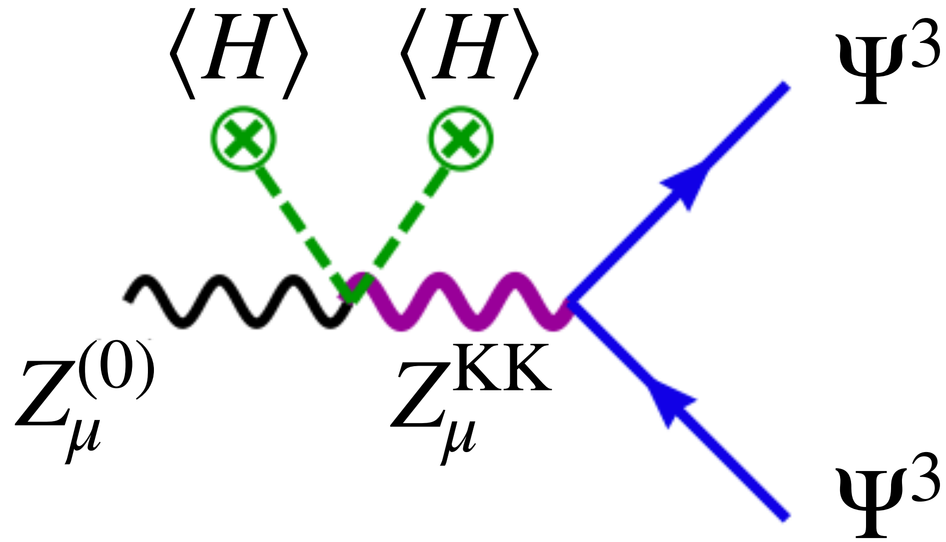
Backup

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

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

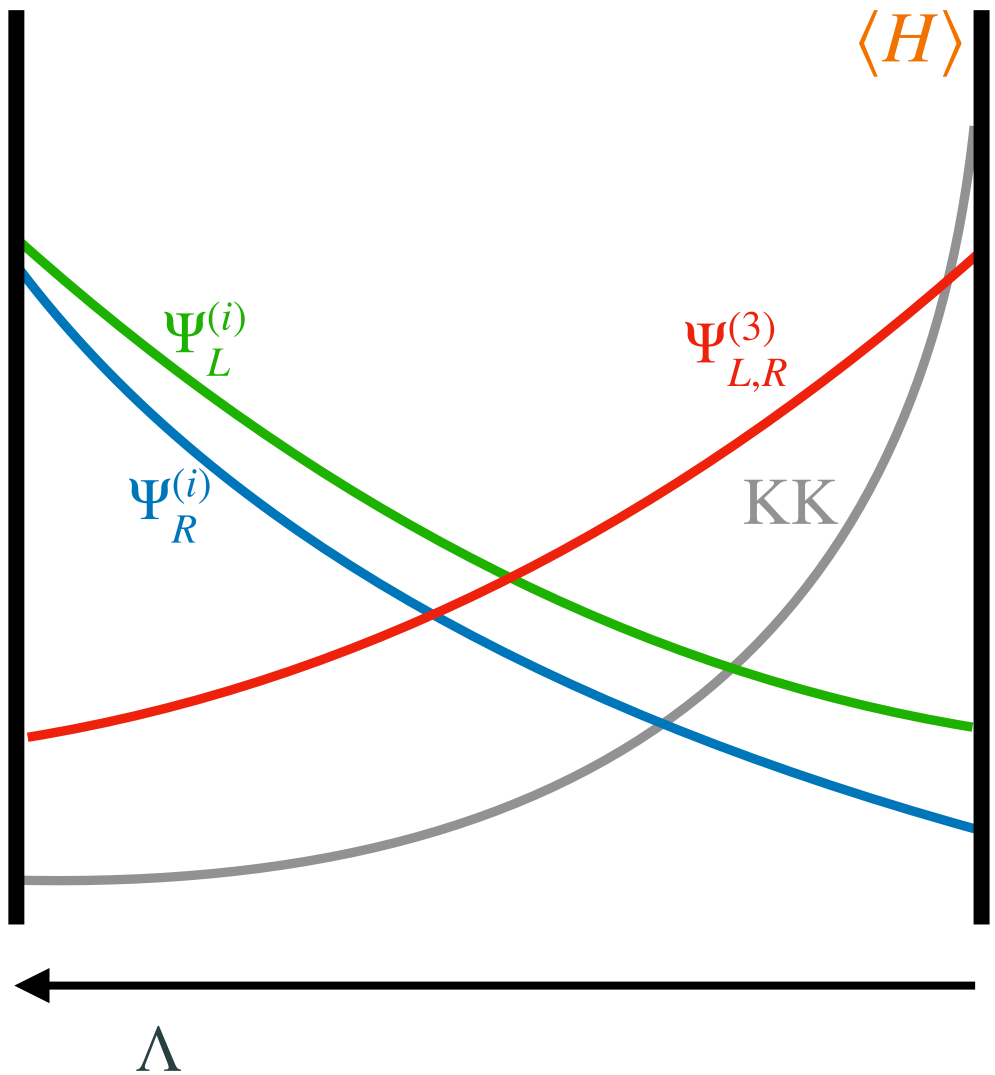
$\Downarrow$

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



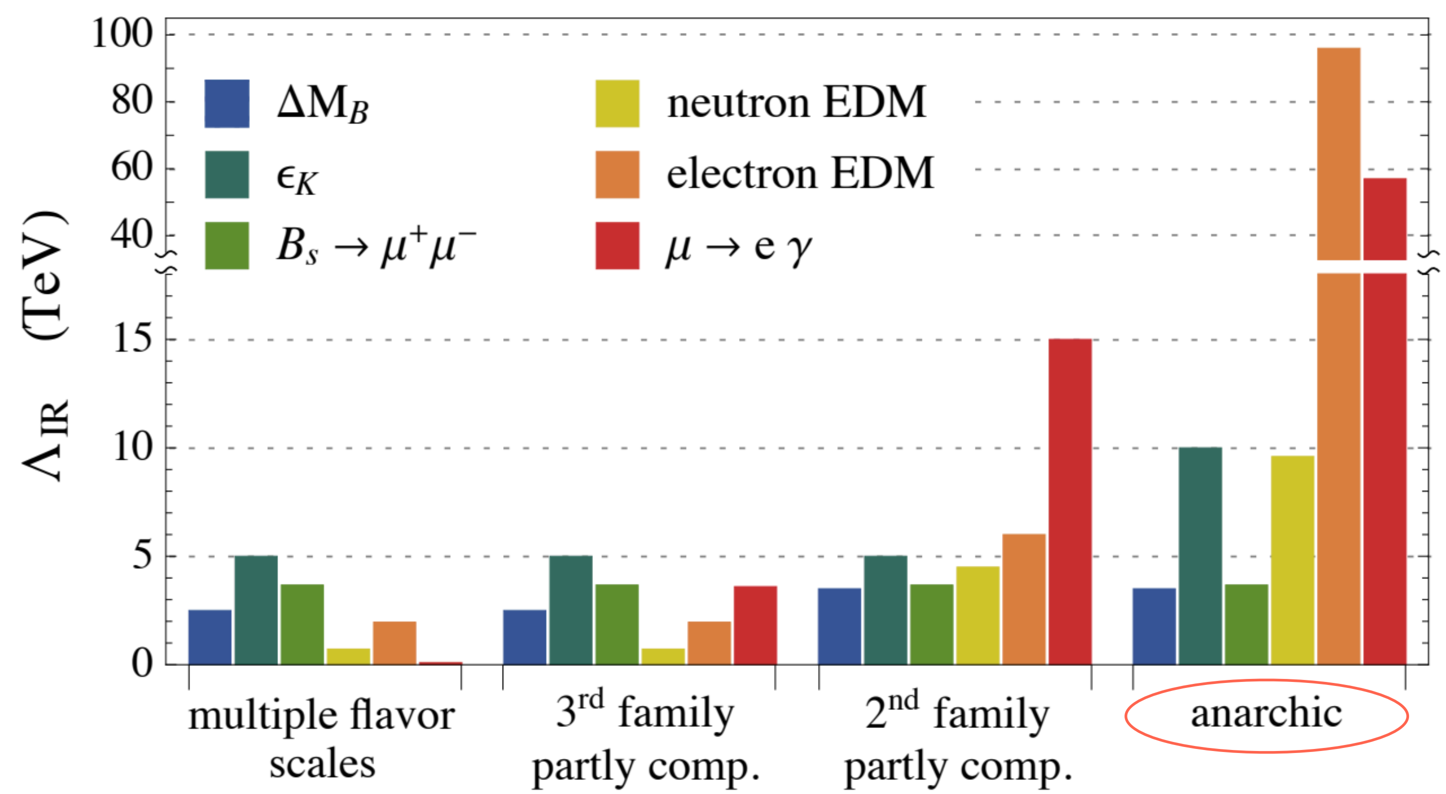
Backup

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

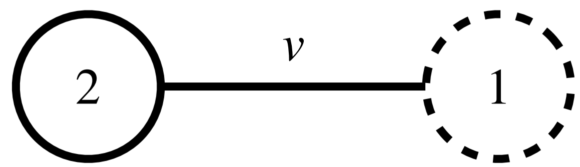
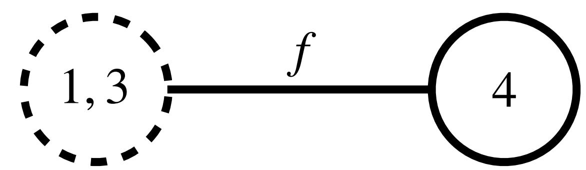
Spontaneously broken by a condensate at some IR scale

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)

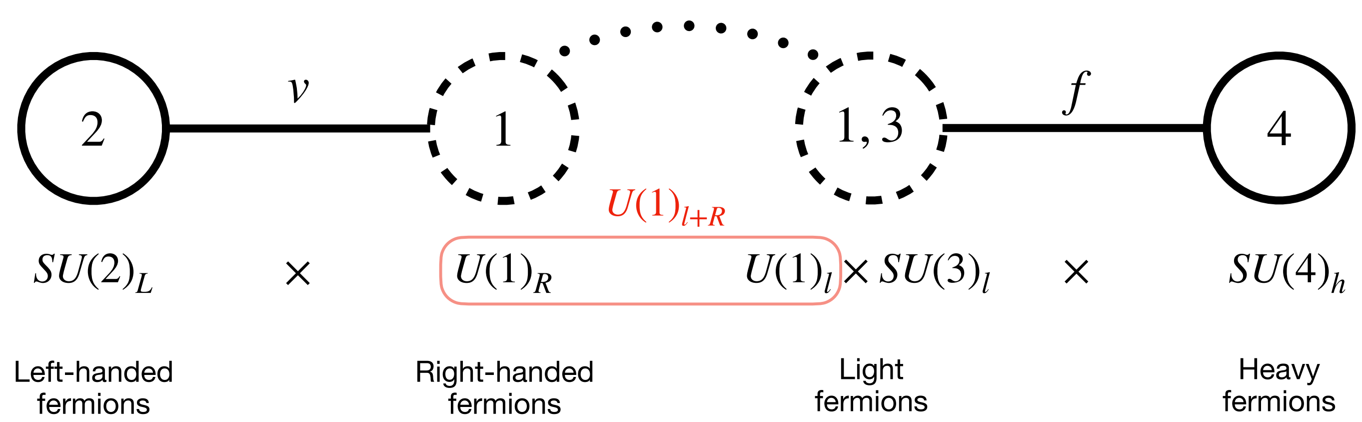
Backup

[Fuentes-Martin, Stangl 2004.11376]

The two sites are connected by the gauging

	SM Higgs Sector	4321 Models
Global symmetry	$SU(2)_L \times SU(2)_R$	$SU(4)_l \times SU(4)_h$

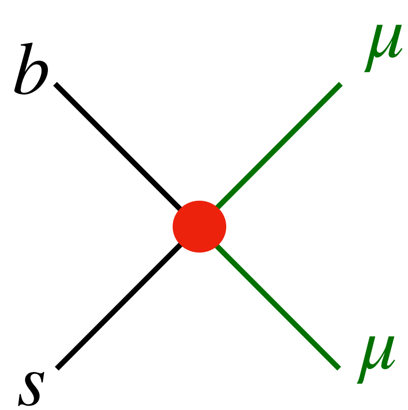
Gauge symmetry



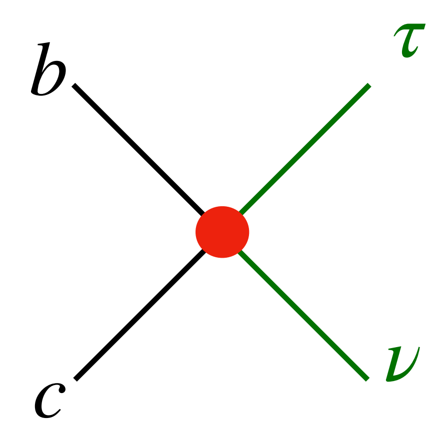
	SM Higgs Sector	4321 Models
Global SSB	$SU(2)_V$	$SU(4)_D$
Gauge SSB	$U(1)_{\text{em}} \times SU(3)_c$	
Goldstones	$3\ (W, Z)$	$15\ (U_1, G', Z')$

B-anomalies

$b \to sll$ | $b \to c\tau\nu$



$\ll$



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

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

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

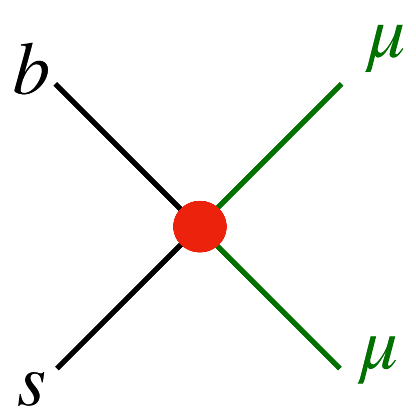
$$c \sim (3\ \text{TeV})^{-2}$$

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

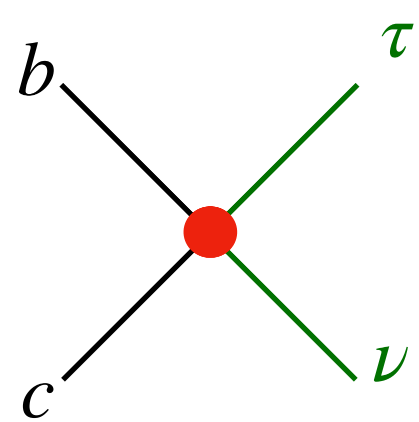
B-anomalies

$b \to sll$

$b \to c\tau\nu$



$\ll$



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

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

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

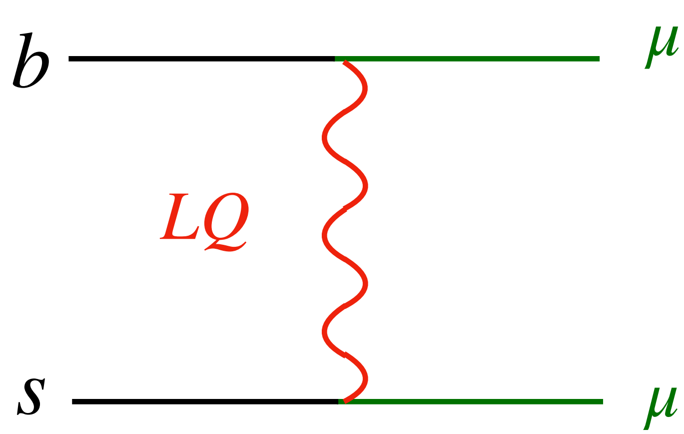
$$\boxed{\epsilon_q, \epsilon_l \sim 0.1}$$

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

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

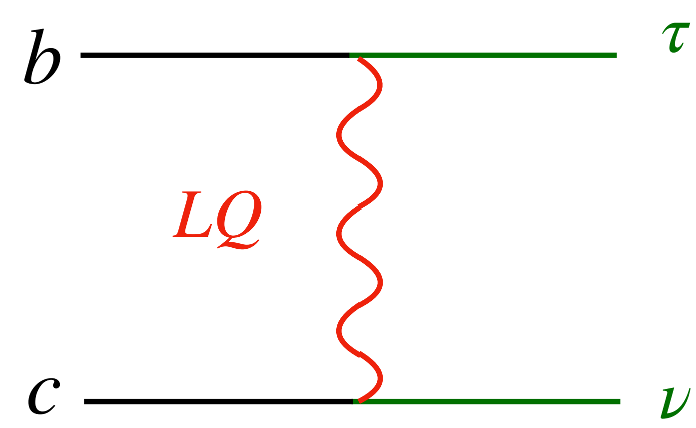
B-anomalies

$b \to sll$



$\ll$

$b \to c\tau\nu$



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