University of Zurich[UZH]

Flavour and mass hierarchies from extra dimension

Implications of LHCb measurements and future prospects
October 19-21, 2022,
CERN

Nudžeim Selimović

University of Zurich

Based on work with:

Javier Fuentes-Martin, Gino Isidori, Javier Lizana and Ben Stefanek: 2203.01952

SM

Absence of (definite) New Physics signals in data

The problems of the SM : Flavour?

Neutrino masses?

Dark matter?

Higgs hierarchy?

⋮

reasons to believe there is more!

SM

Absence of New Physics signals in data

The problems of the SM : $\boxed{\text{Flavour?}}$

Neutrino masses?

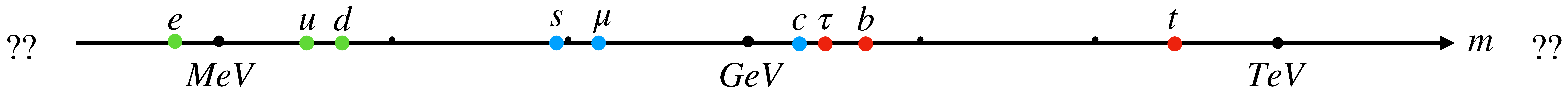
Dark matter?

Higgs hierarchy?

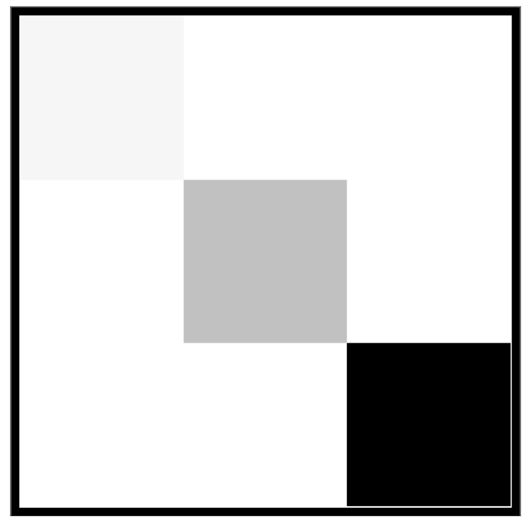
⋮

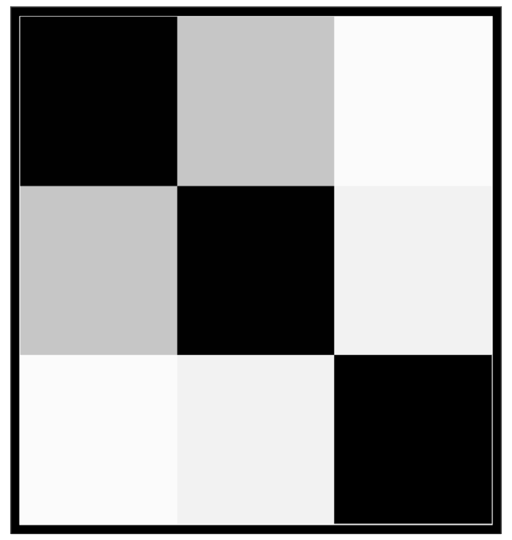
reasons to believe there is more!

The SM flavour puzzle?

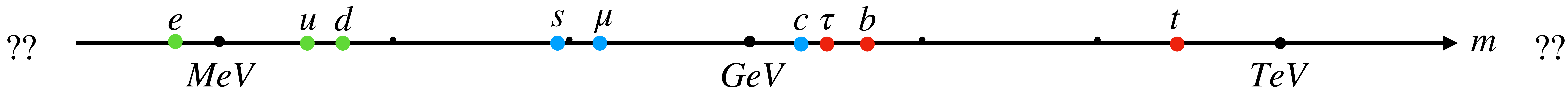


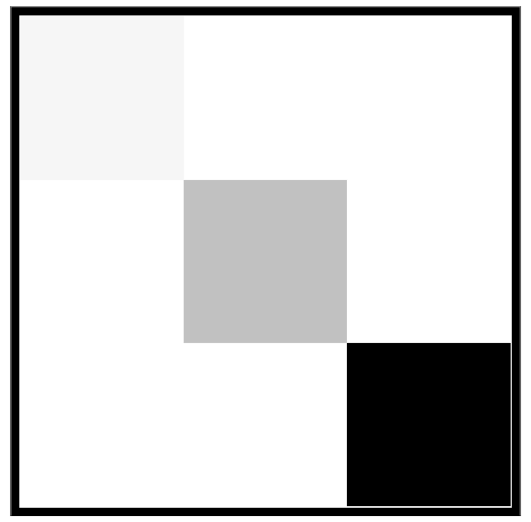
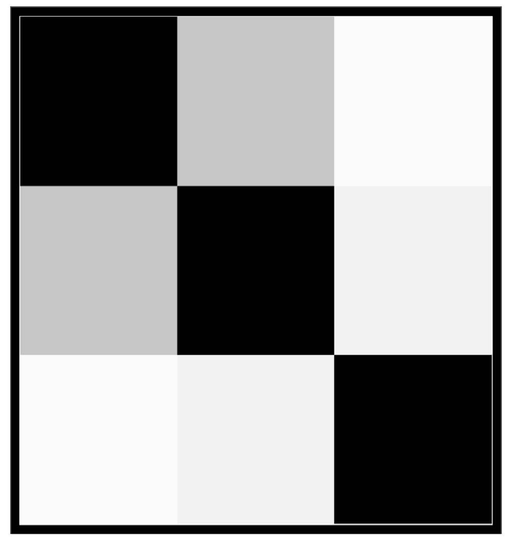
•

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

$V_{\mathrm{CKM}} \sim$ 

The SM flavour puzzle?



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

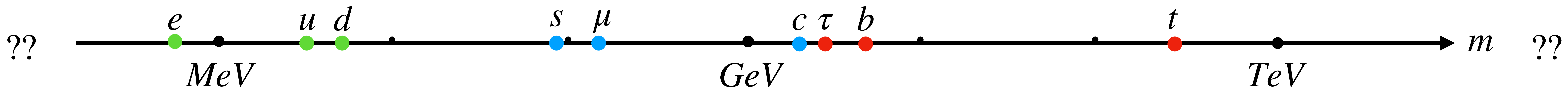
- $\mathscr{L}_Y \supset Y\bar{\psi}_L H \psi_R$ $\quad Y \sim \begin{array}{c} U(2)_{\psi_R} \\ \begin{pmatrix} \Delta & V \\ 0 & 1 \end{pmatrix} \end{array} U(2)_{\psi_L}$

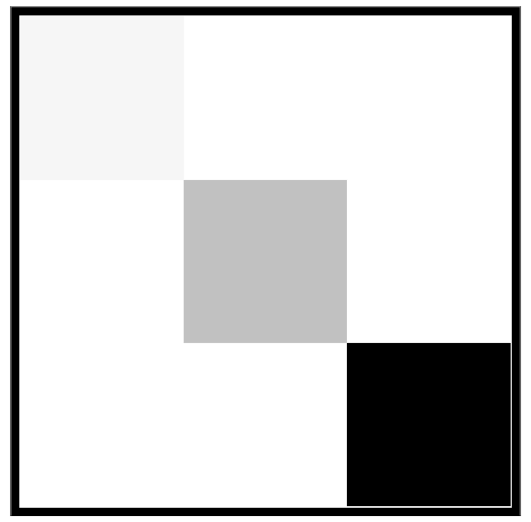
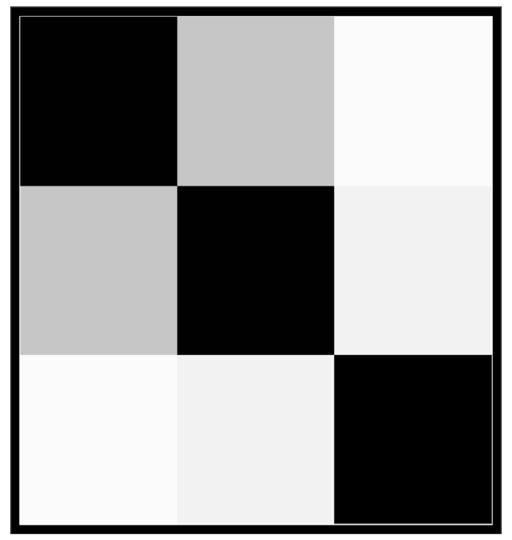
  $U(2)^5 \equiv U(2)_q \times U(2)_\ell \times U(2)_u \times U(2)_d \times U(2)_e$

  $|V_q| \sim V_{cb} \quad |\Delta_u| \sim y_c$

- Lepton Flavour Universality (LFU) is a good approximate symmetry: $y_{e,\mu,\tau} \ll g_{s,L,Y}$

The SM flavour puzzle?



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

- $\mathscr{L}_Y \supset Y \bar{\psi}_L H \psi_R \qquad Y \sim \begin{array}{cc} U(2)_{\psi_R} & \\ \begin{pmatrix} \Delta & V \\ 0 & 1 \end{pmatrix} & U(2)_{\psi_L} \end{array}$

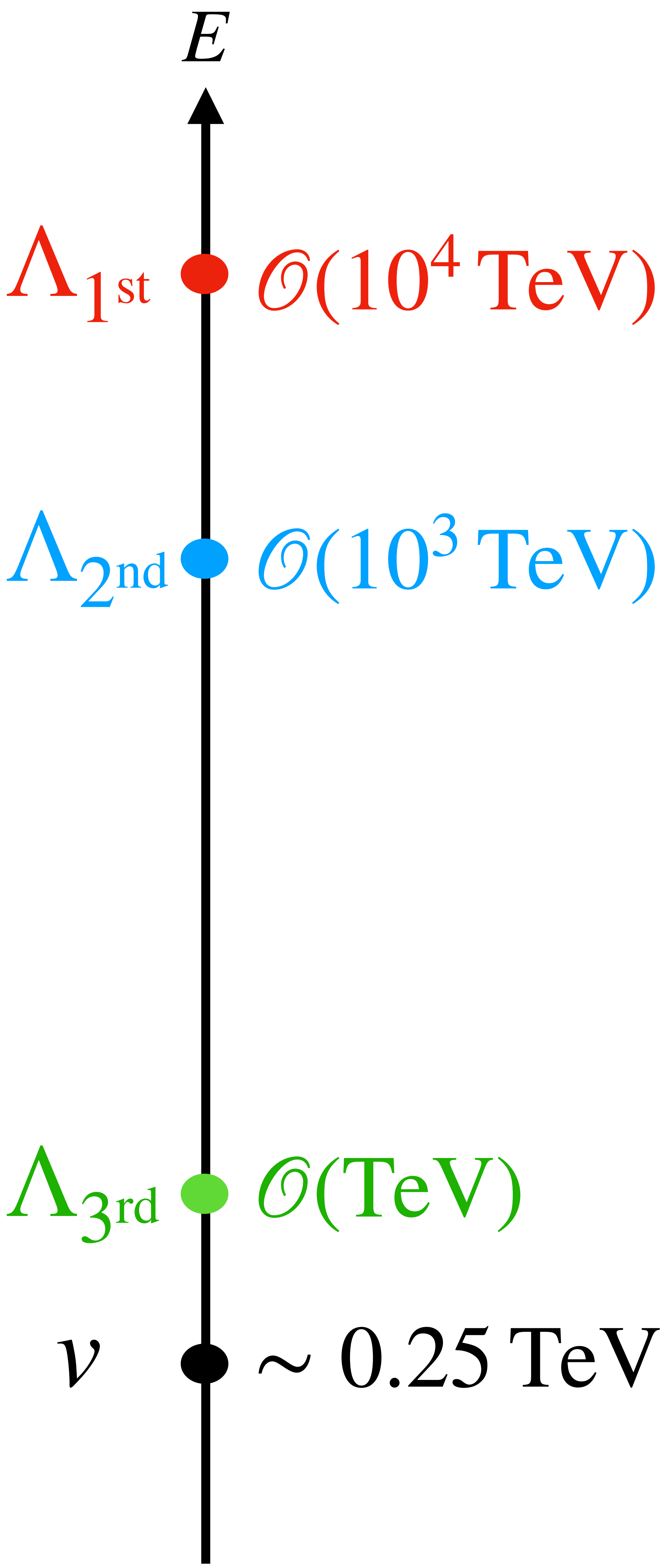
  $U(2)^5 \equiv U(2)_q \times U(2)_\ell \times U(2)_u \times U(2)_d \times U(2)_e$

  $|V_q| \sim V_{cb} \qquad |\Delta_u| \sim y_c$

- Lepton Flavour Universality (LFU) is a good approximate symmetry: $y_{e,\mu,\tau} \ll g_{s,L,Y}$

$\boxed{\textit{What is the origin of these symmetries?}}$

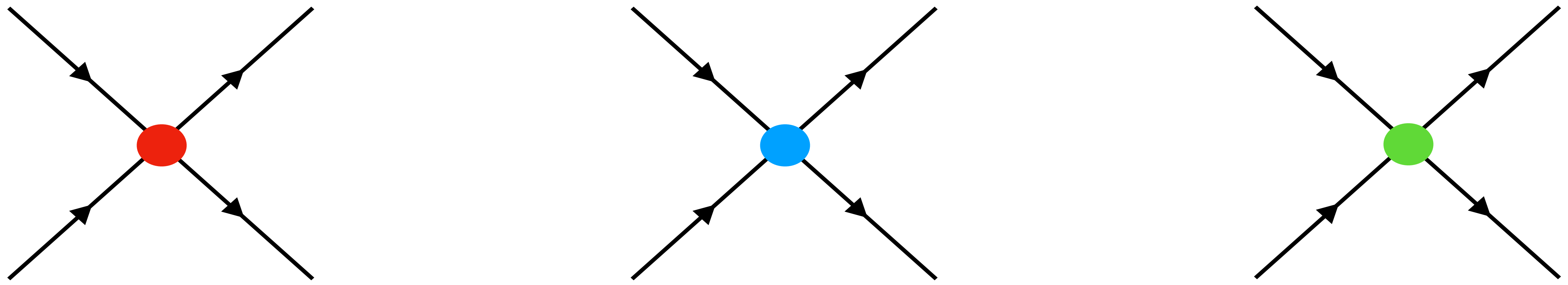
Multi-scale explanation



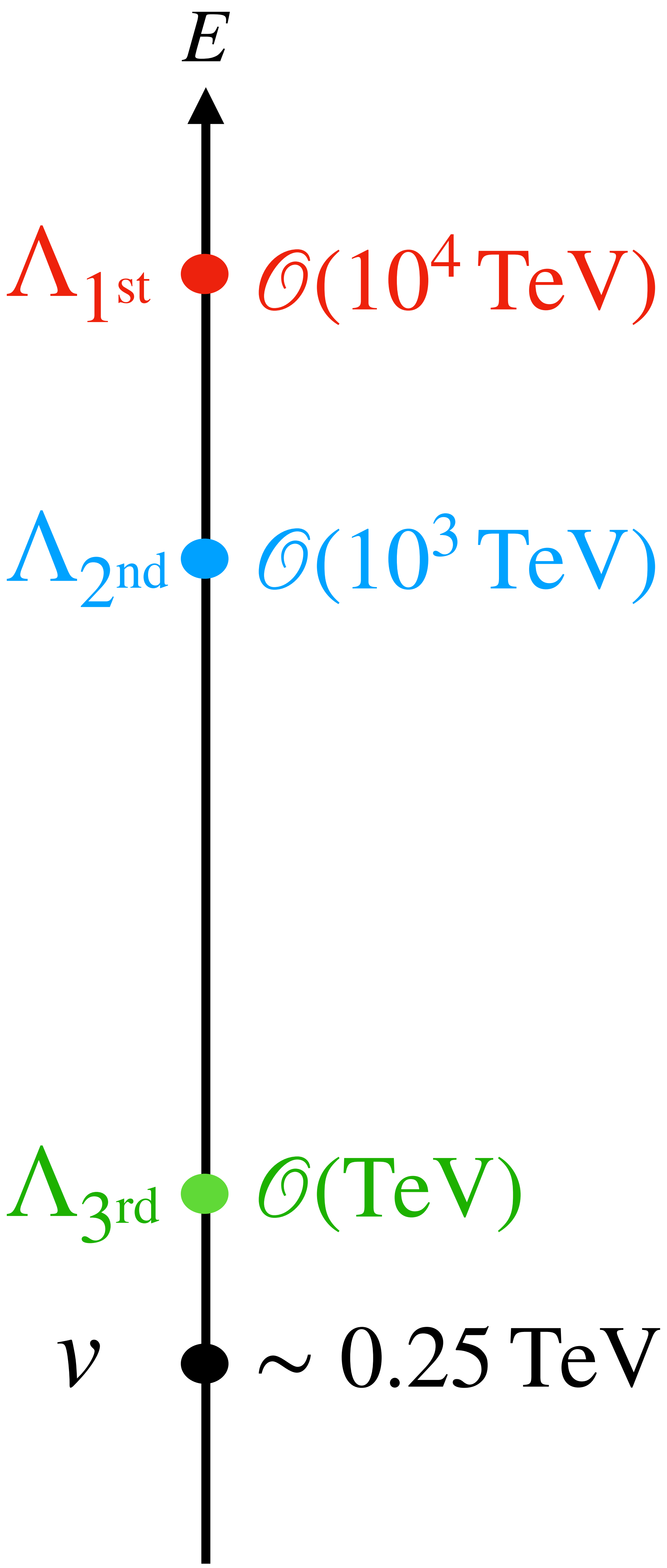
- The SM Yukawas are very hierarchical because they originate from very different scales!

- TeV-scale NP dominantly coupled to third and to a lesser extent light families.

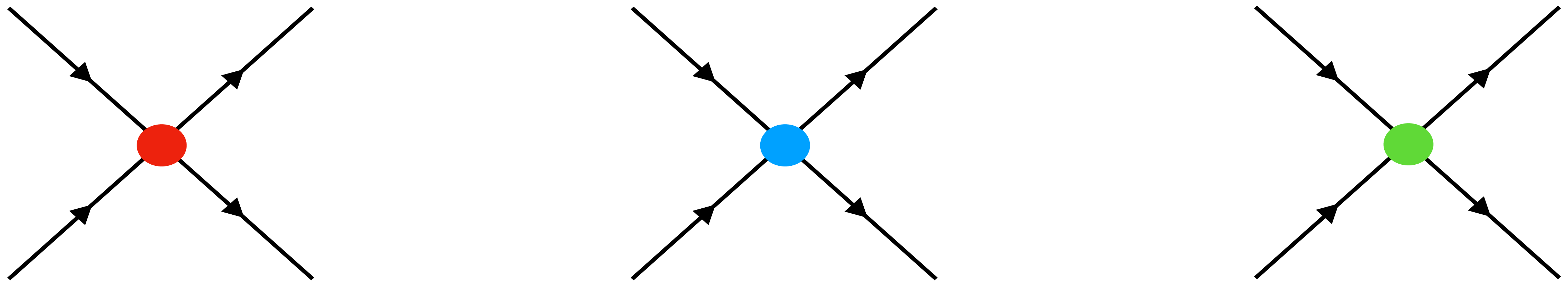
- $U(2)^5$ - like protection from flavour $\oplus$ high-p_T constraints:



$$\sim \Lambda_{1^{\text{st}}}^{-2}(\overline{\psi}_1\psi_1)^2 \qquad \sim \Lambda_{2^{\text{nd}}}^{-2}(\overline{\psi}_2\psi_2)^2 \qquad \sim \Lambda_{3^{\text{rd}}}^{-2}(\overline{\psi}_3\psi_3)^2$$



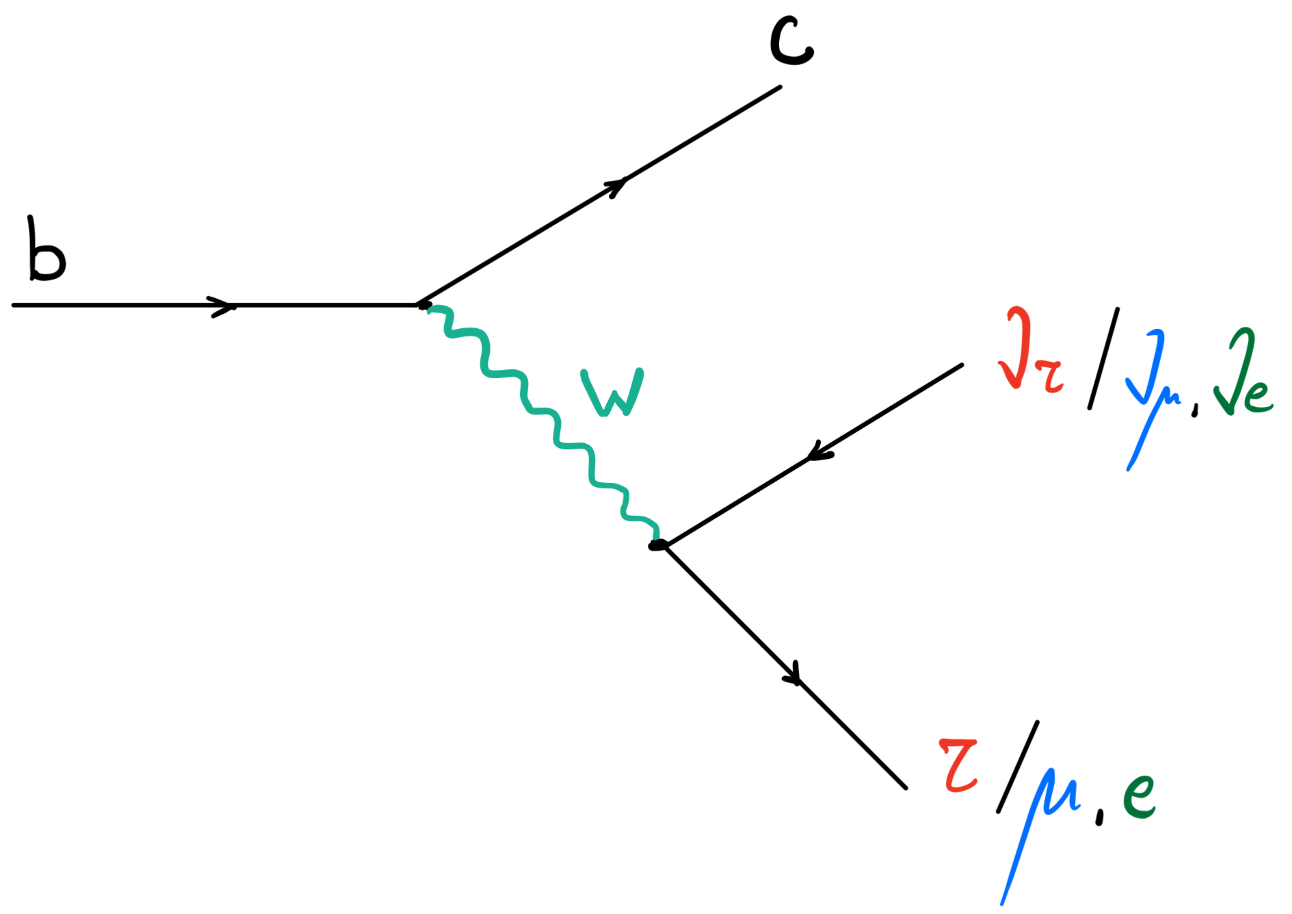
- The SM Yukawas are very hierarchical because they originate from very different scales!
- TeV-scale NP dominantly coupled to third and to a lesser extent light families.
- $U(2)^5$ - like protection from flavour $\oplus$ high-p_T constraints:



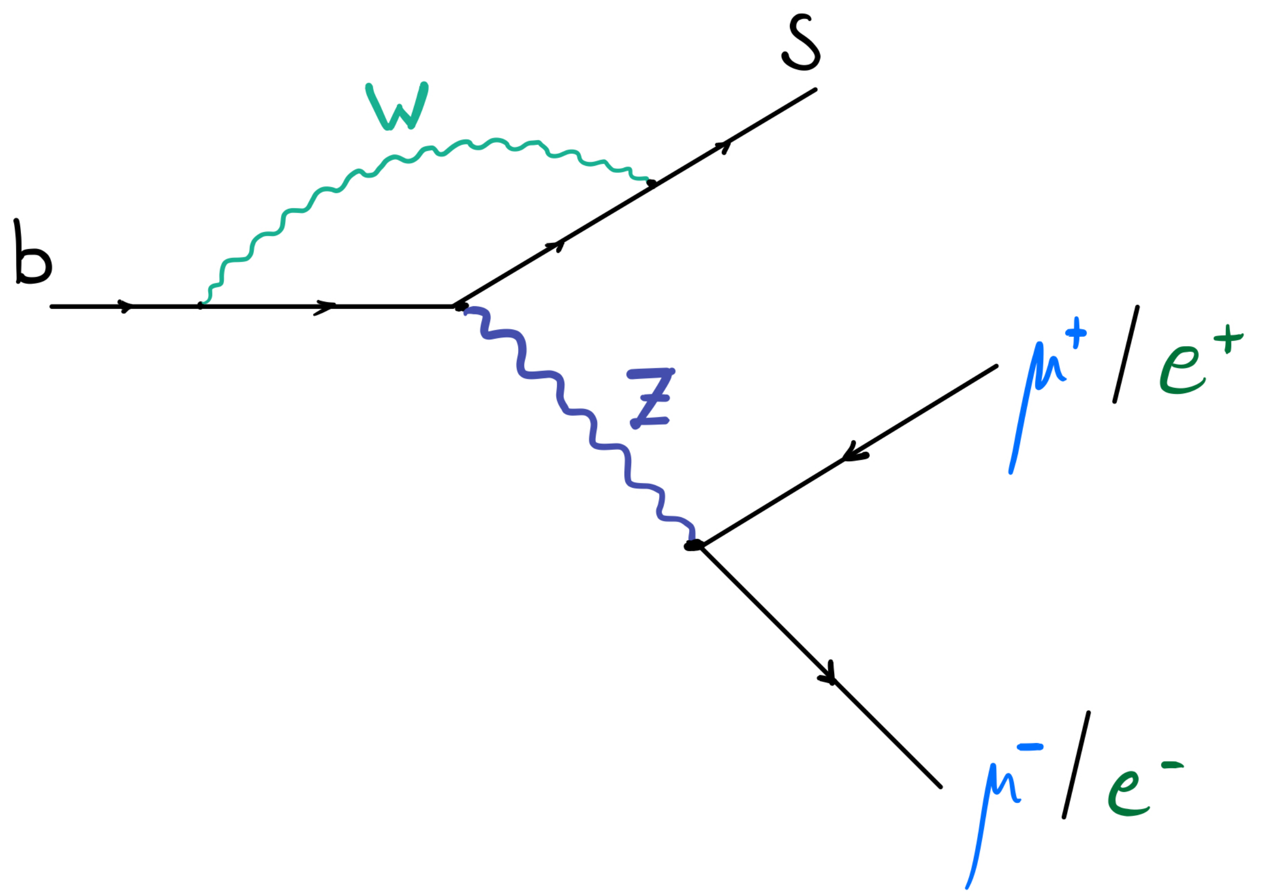
$\sim \Lambda_{1^{\rm st}}^{-2}\,(\bar{\psi}_1\psi_1)^2$ $\quad$ $\sim \Lambda_{2^{\rm nd}}^{-2}\,(\bar{\psi}_2\psi_2)^2$ $\quad$ $\sim \Lambda_{3^{\rm rd}}^{-2}\,(\bar{\psi}_3\psi_3)^2$

- *Hints in B-meson decays?*

- $\tau\,/\,\mu$ and $\tau\,/\,e$ $\sim 3\sigma$ deviation in $b \to c\tau\nu$ charged current
- $\mu\,/\,e$ $\sim 4\sigma$ deviation in $b \to s\ell\ell$ neutral current



- *Tree* level in SM



- *Loop* level in SM

Combined explanation ingredients:

1. Approximate $U(2)^5$ *flavour symmetry*

   [R. Barbieri, G. Isidori, J. Jones-Perez, P. Lodone and D. M. Straub, arXiv:1105.2296]

2. $U_1 \sim (3,1)_{2/3}$ *vector leptoquark*

   [D. Buttazzo, A. Greljo, G. Isidori and D. Marzocca, arXiv:1706.07808]

Third family quark-lepton unification at the TeV scale

$$\underset{g_4}{SU(4)_h} \times \underset{g_3}{SU(3)_l} \times SU(2)_L \times U(1)_X$$

Field	$SU(4)_h$	$SU(3)_l$	$SU(2)_L$	$U(1)_X$
$\psi_L = (q_L^3\ \ell_L^3)^T$	**4**	**1**	**2**	0
$\psi_R^+ = (u_R^3\ \nu_R^3)^T$	**4**	**1**	**1**	1/2
$\psi_R^- = (d_R^3\ e_R^3)^T$	**4**	**1**	**1**	−1/2

[L. Di Luzio, A. Greljo and M. Nardecchia, arXiv: 1708.08450]
[L. Di Luzio, J. Fuentes-Martin, A. Greljo, M. Nardecchia, S. Renner, arXiv: 1808.00942]
[M. Bordone, C. Cornella, J. Fuentes-Martin, G. Isidori, arXiv: 1712.01368, 1805.09328]
[H. Georgi, Y. Nakai, arXiv: 1606.05865] [J. Fuentes-Martın, P. Stangl, arXiv: 2004.11376]
[D. Guadagnoli, M. Reboud, P. Stangl, arXiv: 2005.10117] …

Third family quark-lepton unification at the TeV scale

$$\underset{g_4}{SU(4)_h} \times \underset{g_3}{SU(3)_l} \times SU(2)_L \times U(1)_X$$

Field	$SU(4)_h$	$SU(3)_l$	$SU(2)_L$	$U(1)_X$
$\psi_L = (q_L'^3\ \ell_L'^3)^T$	**4**	**1**	**2**	0
$\psi_R^+ = (u_R^3\ \nu_R^3)^T$	**4**	**1**	**1**	$1/2$
$\psi_R^- = (d_R^3\ e_R^3)^T$	**4**	**1**	**1**	$-1/2$
$q_L'^i$	**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

$i = 1{,}2$

$U(2)^5$: *1st ingredient*

Third family quark-lepton unification at the TeV scale

$$\underbrace{SU(4)_h}_{g_4} \times \underbrace{SU(3)_l}_{g_3} \times SU(2)_L \times U(1)_X$$

$$\longrightarrow \boxed{U_1^\mu} \; (+\, G'_\mu\,,\, Z'_\mu)$$

U_1 LQ: 2nd ingredient

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

$$\downarrow$$

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

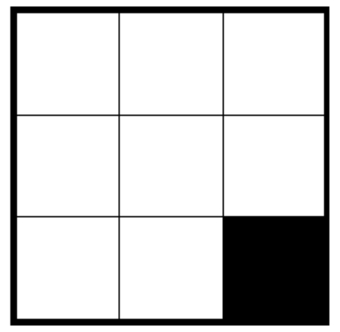
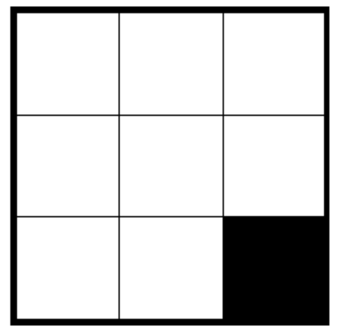
Field	$SU(4)_h$	$SU(3)_l$	$SU(2)_L$	$U(1)_X$
$\psi_L = (q_L'^3\ \ell_L'^3)^T$	**4**	**1**	**2**	0
$\psi_R^+ = (u_R^3\ \nu_R^3)^T$	**4**	**1**	**1**	$1/2$
$\psi_R^- = (d_R^3\ e_R^3)^T$	**4**	**1**	**1**	$-1/2$
$q_L'^i$	**1**	**3**	**2**	$1/6$
u_R^i	**1**	**3**	**1**	$2/3$
d_R^i	**1**	**3**	**1**	$-1/3$
$\ell_L'^i$	**1**	**1**	**2**	$-1/2$
e_R^i	**1**	**1**	**1**	-1

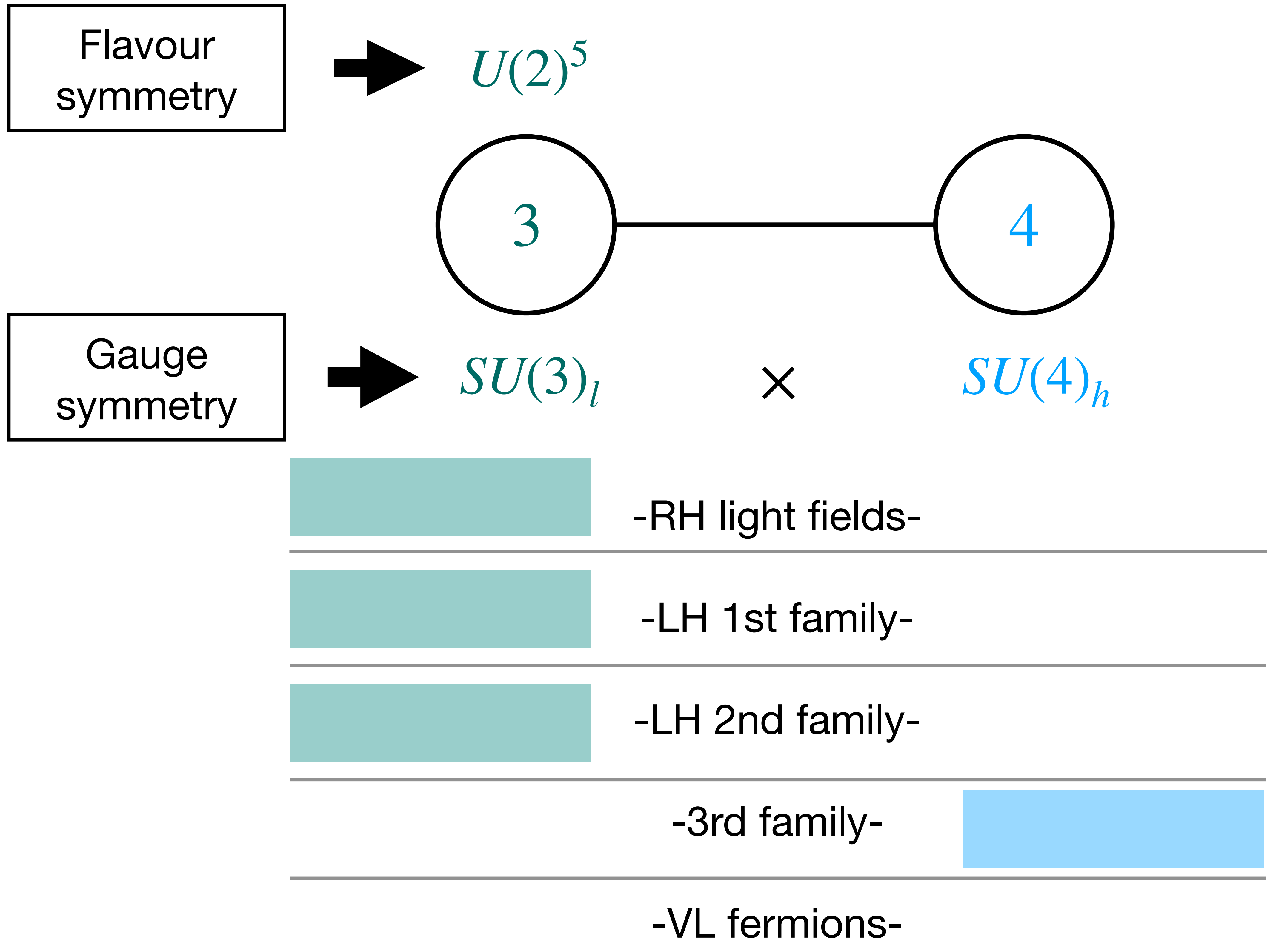
$i = 1{,}2$

$U(2)^5$: 1st ingredient

Third family quark-lepton unification at the TeV scale

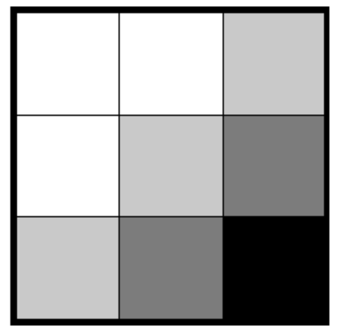
$$\mathscr{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[\beta_L^{i\alpha} (\bar{q}_L^i \gamma_\mu \ell_L^\alpha) + \beta_R^{i\alpha} (\bar{d}_R^i \gamma_\mu e_R^\alpha) \right] + \mathrm{h.c.}$$

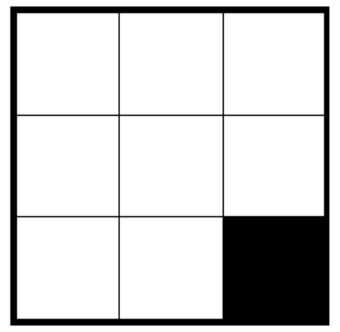
$\beta_L^{ql} \sim$  $\beta_R^{ql} \sim$ 



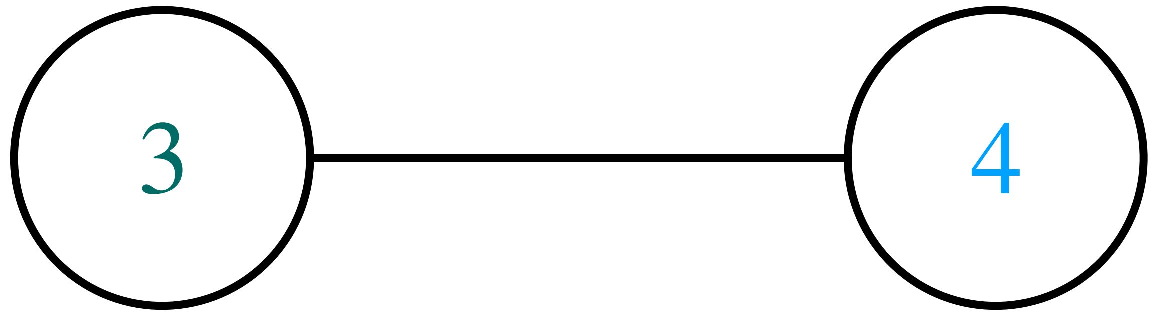
Third family quark-lepton unification at the TeV scale

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

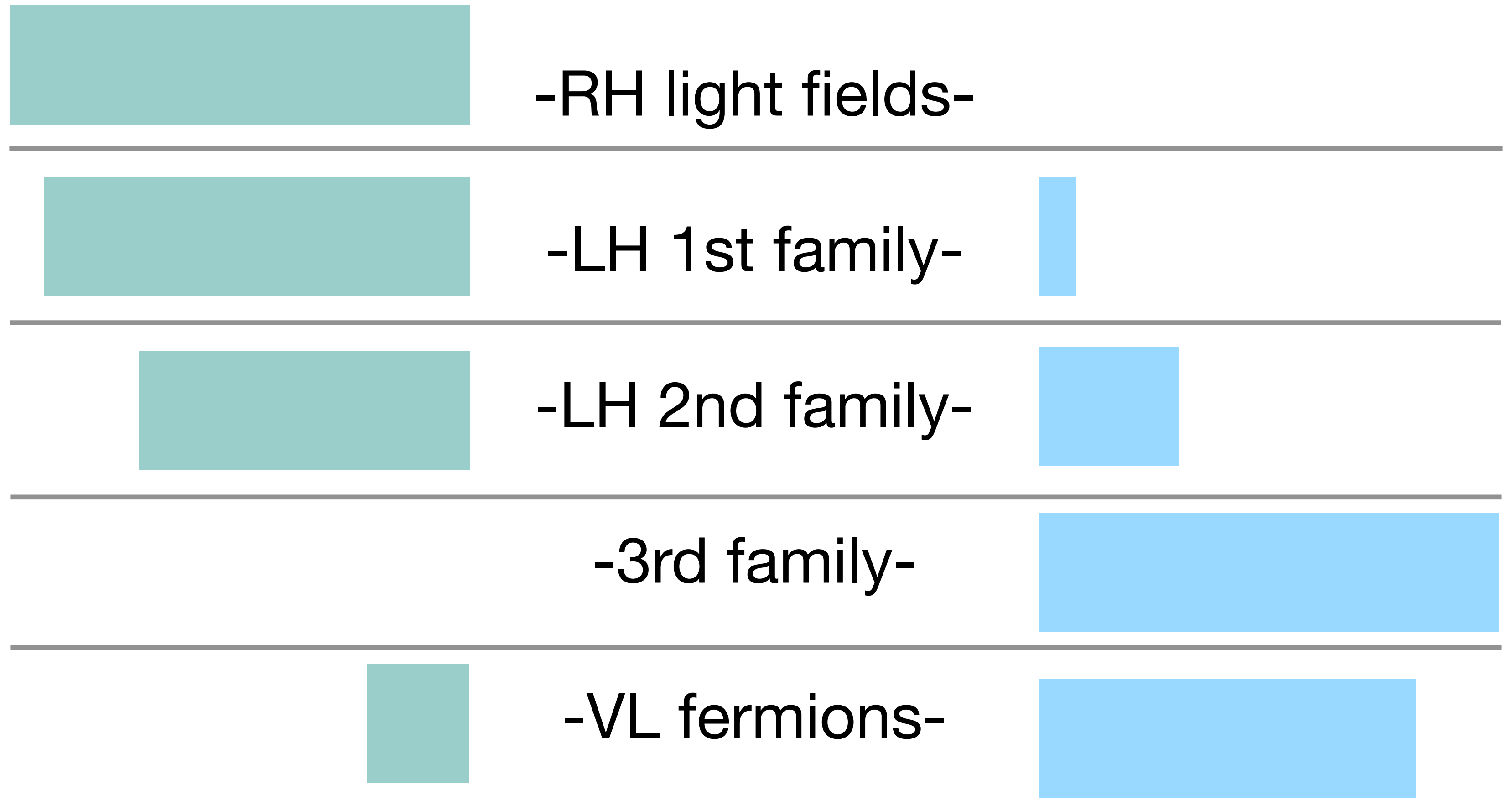
$\beta_L^{ql} \sim$ 

$\beta_R^{ql} \sim$ 

Flavour symmetry → ~~$U(2)^5$~~



Gauge symmetry → $SU(3)_l \times SU(4)_h$



Vector-like fermions: $U(2)^5$ breaking

Field	$SU(4)_h$	$SU(3)_l$	$SU(2)_L$	$U(1)_X$
$\chi_L = (Q_L' \; L_L')^T$	**4**	**1**	**2**	0
$\chi_R = (Q_R \; L_R)^T$	**4**	**1**	**2**	0

$$\mathcal{L} \supset M_q \bar{Q}_R q_L^2 + M_\ell \bar{L}_R \ell_L^2$$

Mass mixing after
$SU(4)_h \times SU(3)_l \times SU(2)_L \times U(1)_X$ breaking

A good starting point…

However, not much about:

- EW hierarchy problem (IR problem)
- Light Yukawa structure (UV problem)

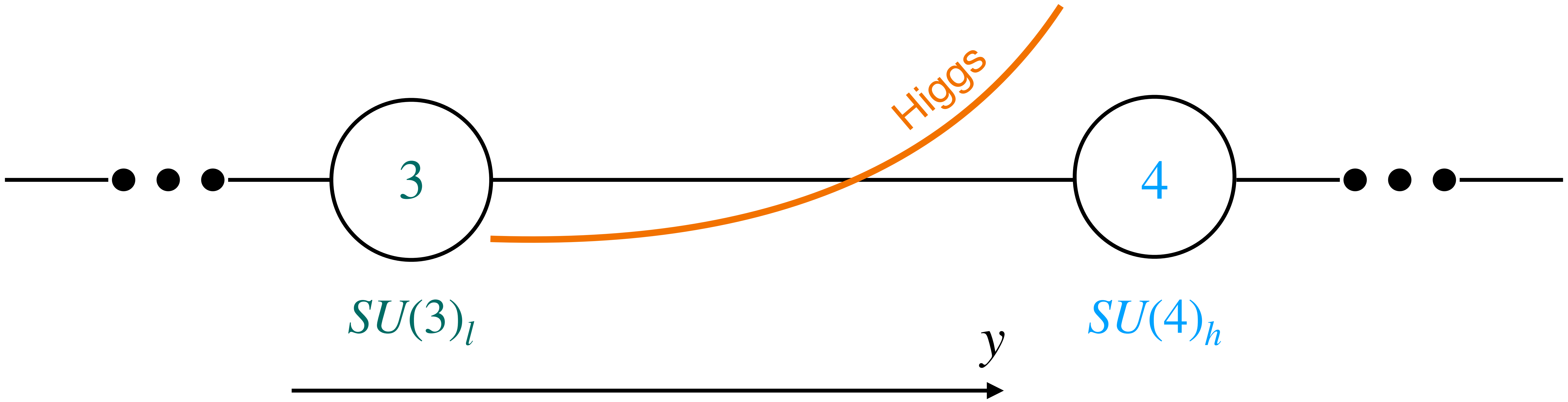
A good starting point…

However, not much about:

- EW hierarchy problem (IR problem)
- Light Yukawa structure (UV problem)

Consider a *warped 5D scenario*!

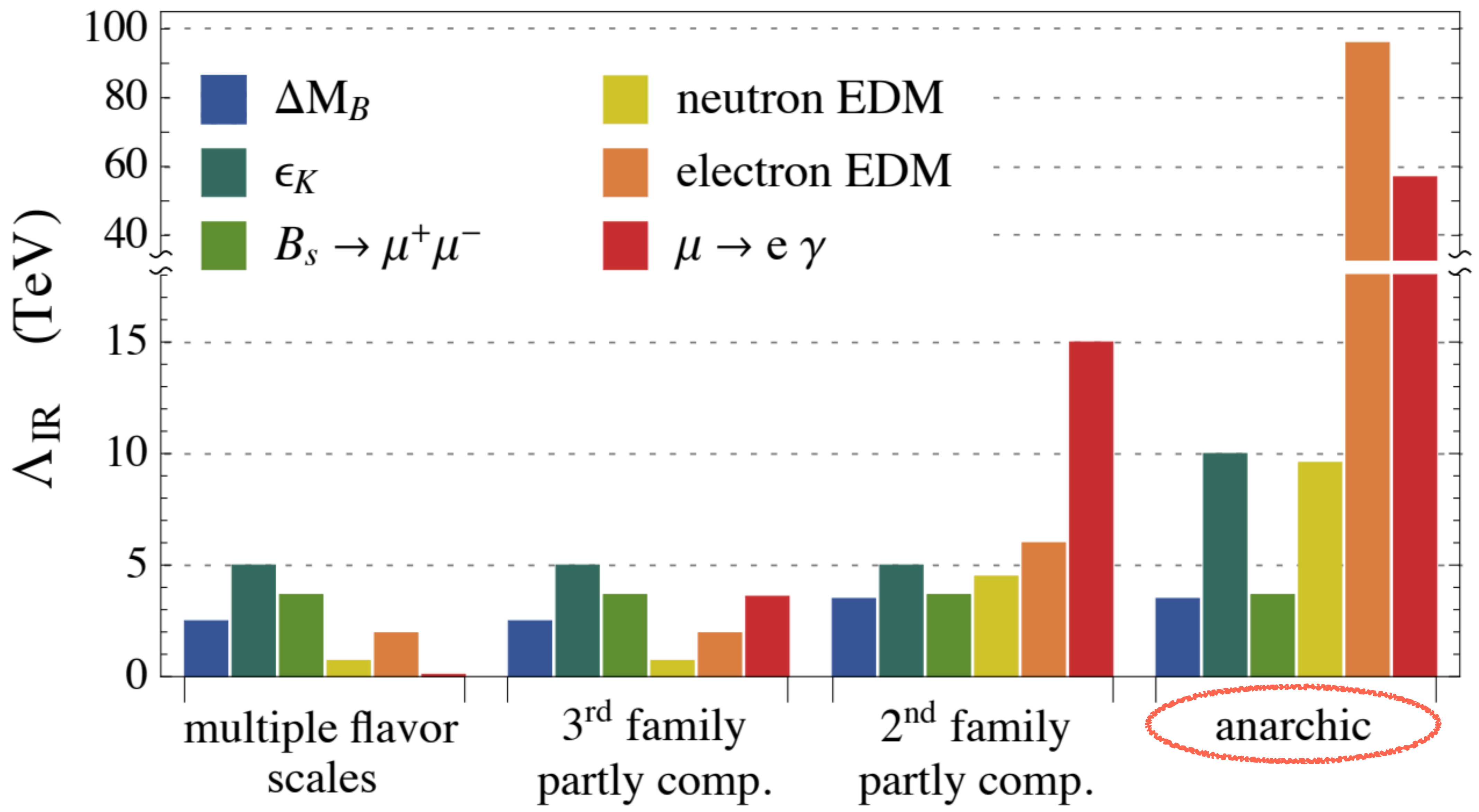
Warped geometry stabilises large scale hierarchies



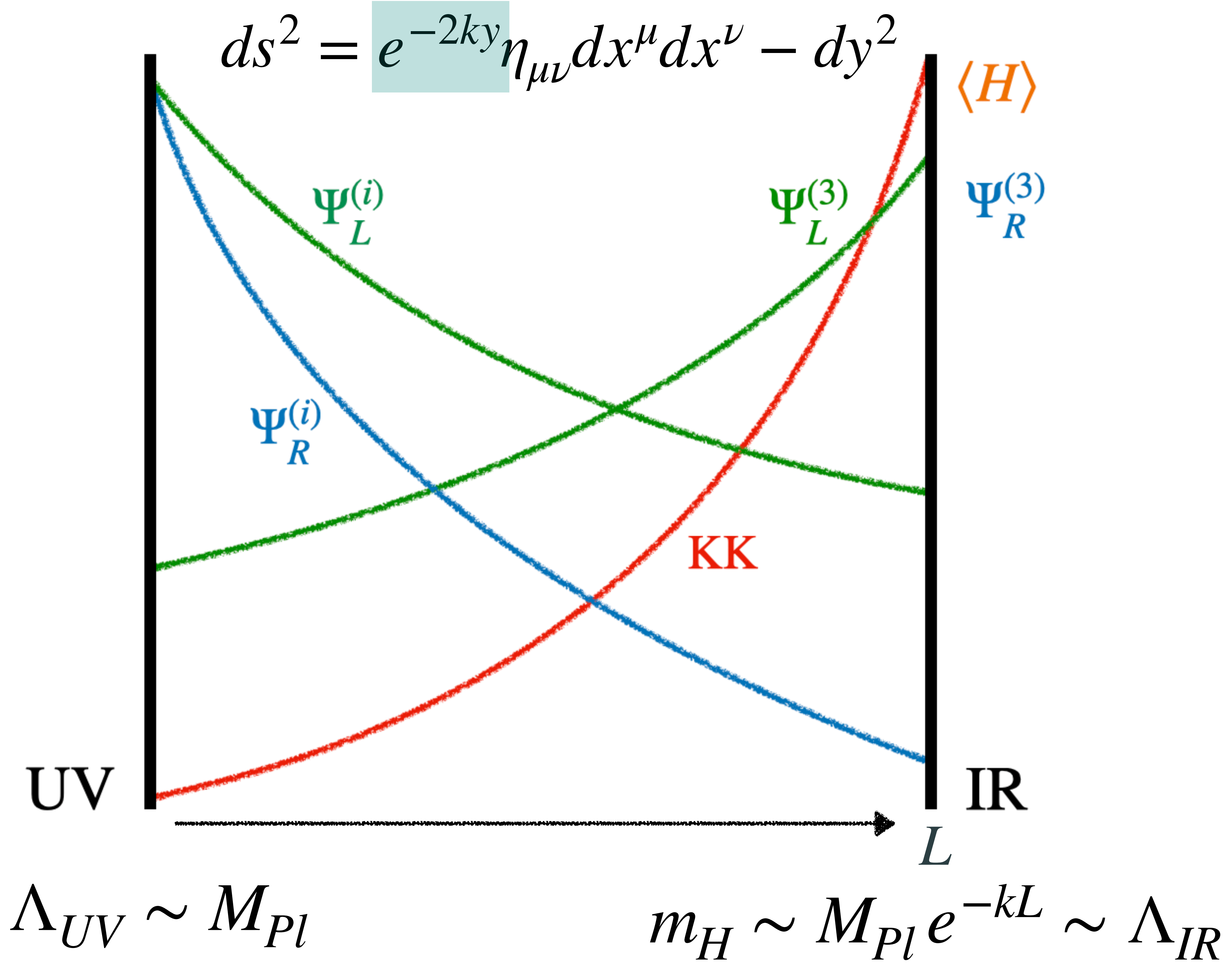
Randall-Sundrum construction

- 5D Yukawa couplings are *anarchical*, Higgs in the IR
- Light family Yukawas receive exponential suppression
- Top in the IR, light families in the UV
- RH fields must reach the IR where KK modes peak

$$g_* \sim (0,0,1) \implies U(2) \text{ flavor sym}\,.$$



[Panico, Pomarol, 1603.06609]



Energy scale ↔ position along the extra dimension

Dangerous dipoles (among others) generated at the IR scale:

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

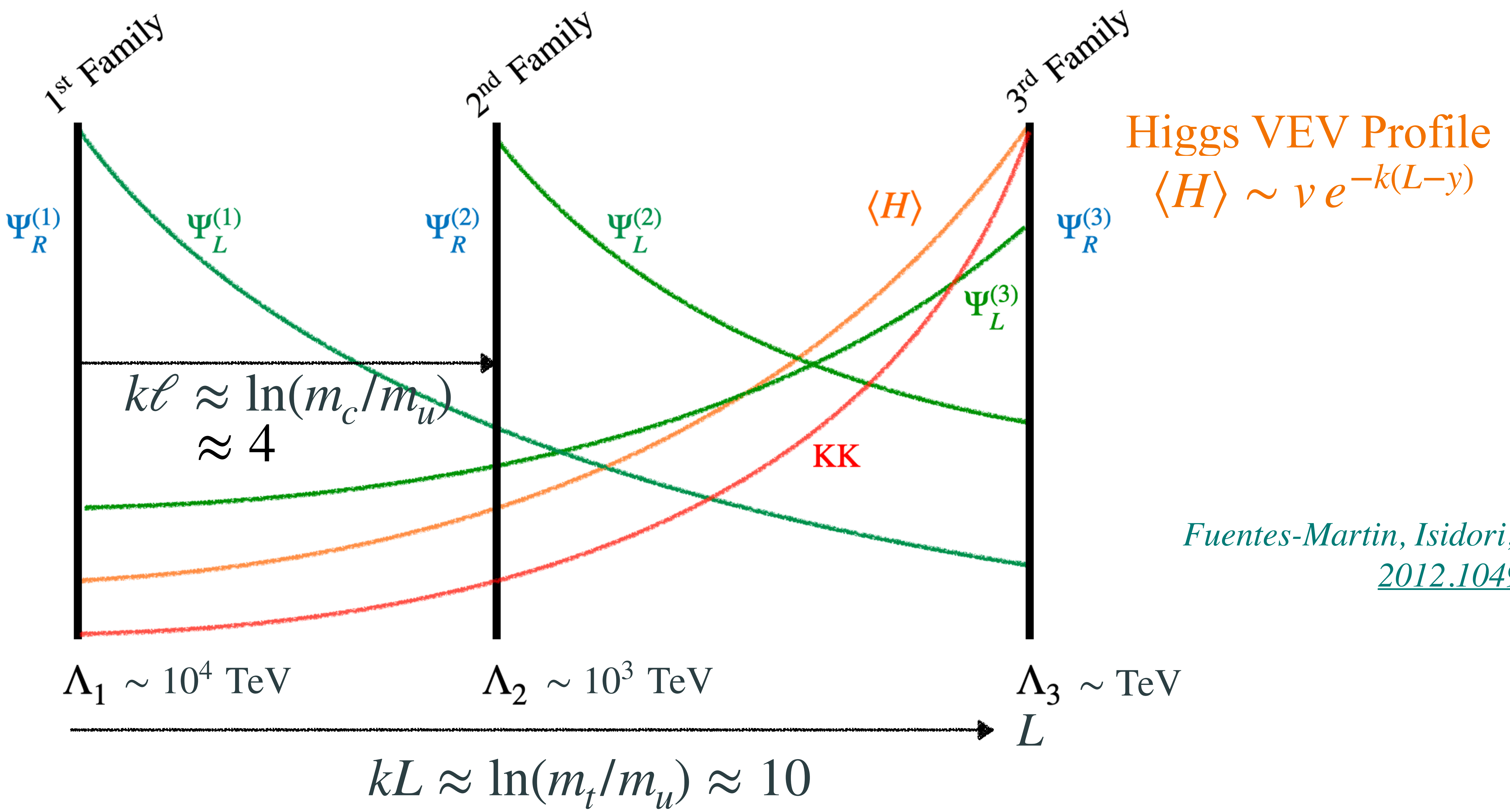
Multi-scale construction

[Dvali, Shifman, '00; Panico, Pomarol, 1603.06609]

- Higgs profile in the bulk, RH fields localised in branes
- Light family Yukawas in the UV, suppressed by the exponentially falling Higgs profile
- U(2) flavour symmetry with leading breaking in the LH sector.
- Dangerous operators involving RH fields naturally suppressed

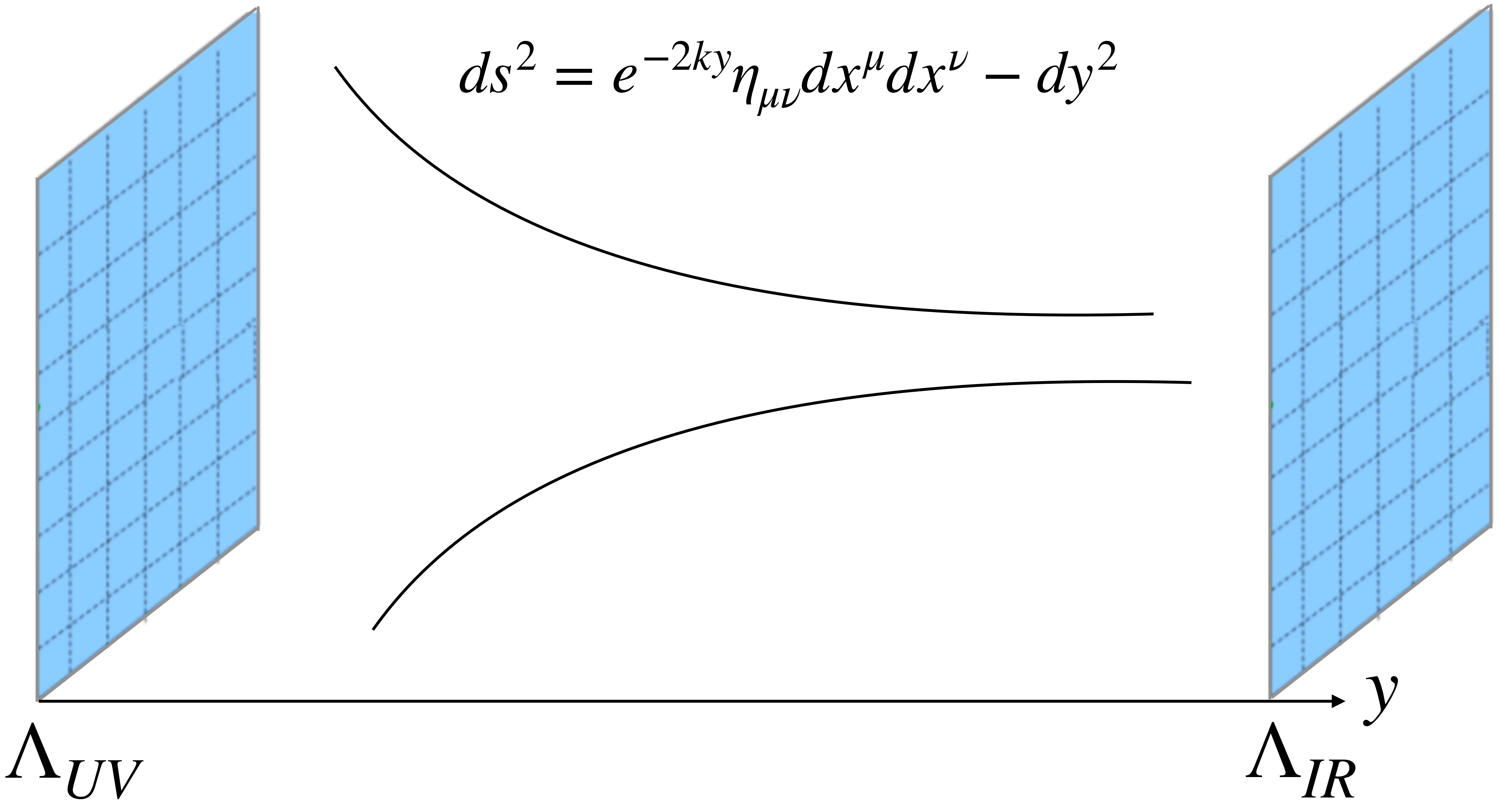
Dangerous dipoles now suppressed by the UV scales

$$\sim \frac{g_*^2}{16\pi^2}\frac{m_e}{\Lambda_1^2}\,\bar{e}_L\sigma_{\mu\nu}e_R F^{\mu\nu}$$



Fuentes-Martin, Isidori, Pagès, Stefanek, 2012.10492]

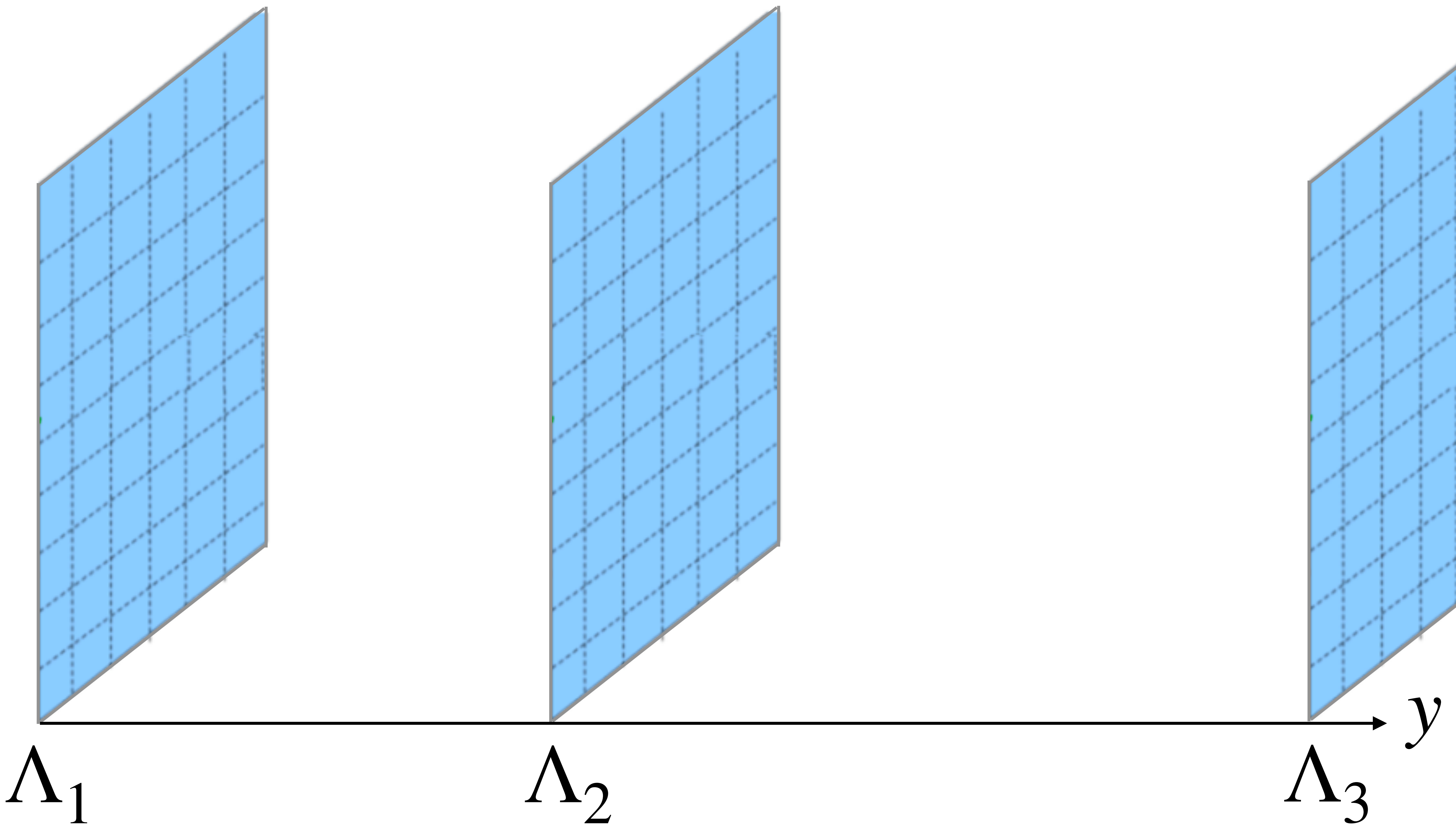
5D model realising:



5D model realising:

1.

Flavour hierarchies from *multiple scales*

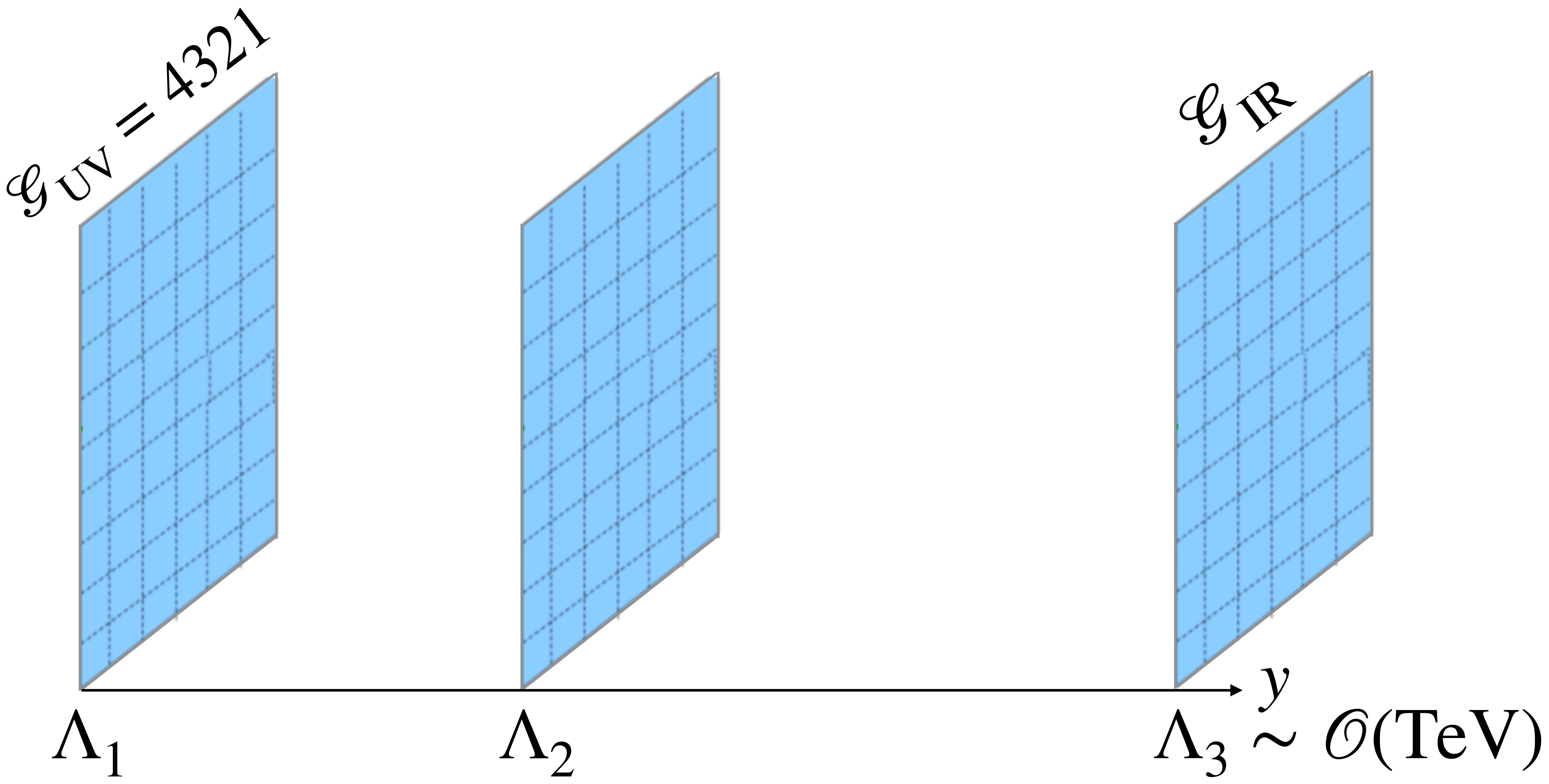


Fermion localisation at *multiple branes* along the extra dimension

5D model realising:

2.

$\mathcal{G}_{4321} \equiv SU(4)_h \times SU(3)_l \times SU(2)_L \times U(1)_X$ gauge symmetry broken to the $\mathcal{G}_{SM}$ at the TeV scale

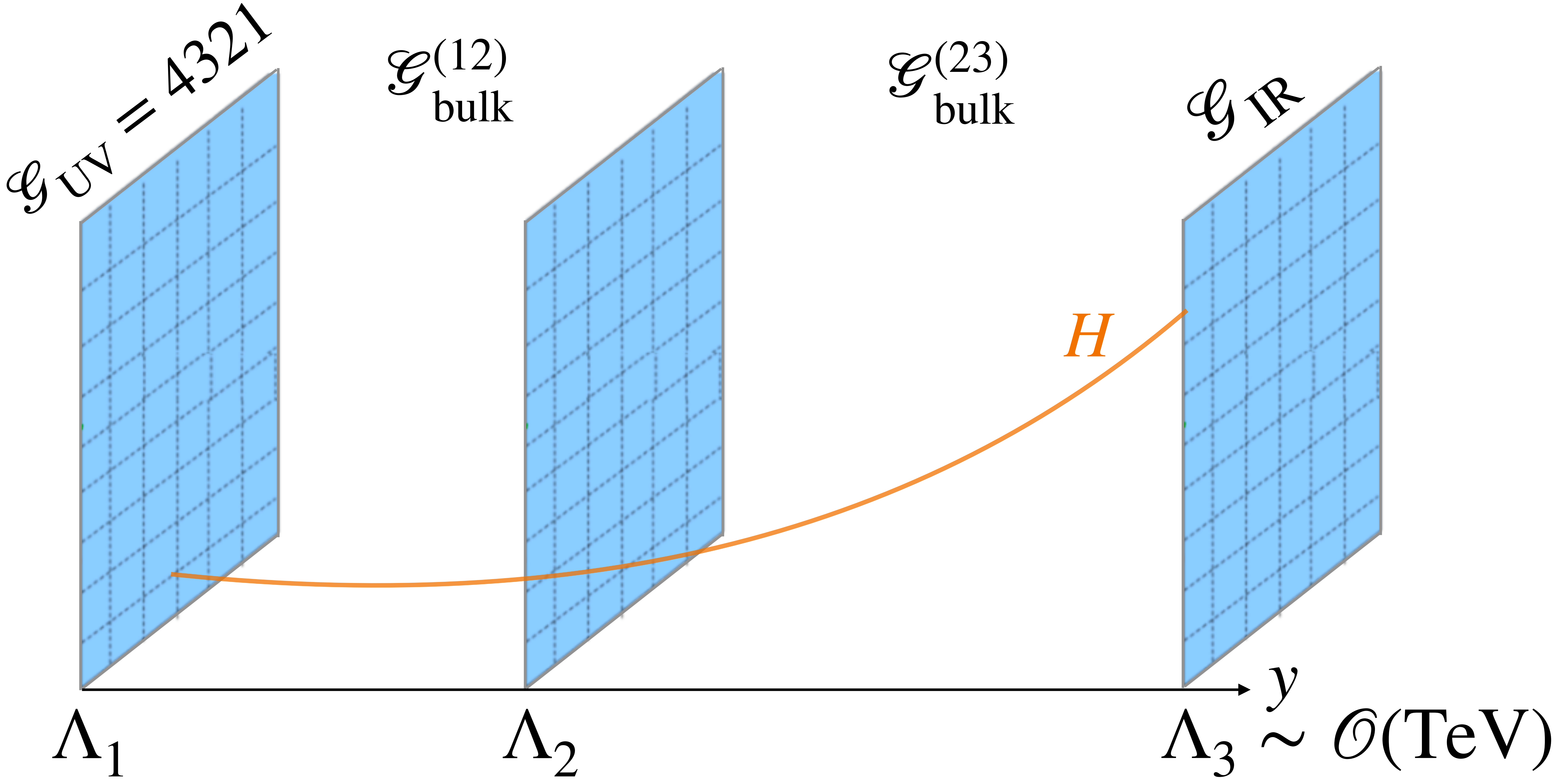


$\mathcal{G}_{UV} = \mathcal{G}_{4321}$ and $\mathcal{G}_{SM} = \mathcal{G}_{UV} \cap \mathcal{G}_{IR}$

5D model realising:

3.

Higgs as a pseudo-Goldstone of the same sector breaking $SU(4)_h \times SU(3)_l \times SU(2)_L \times U(1)_X$

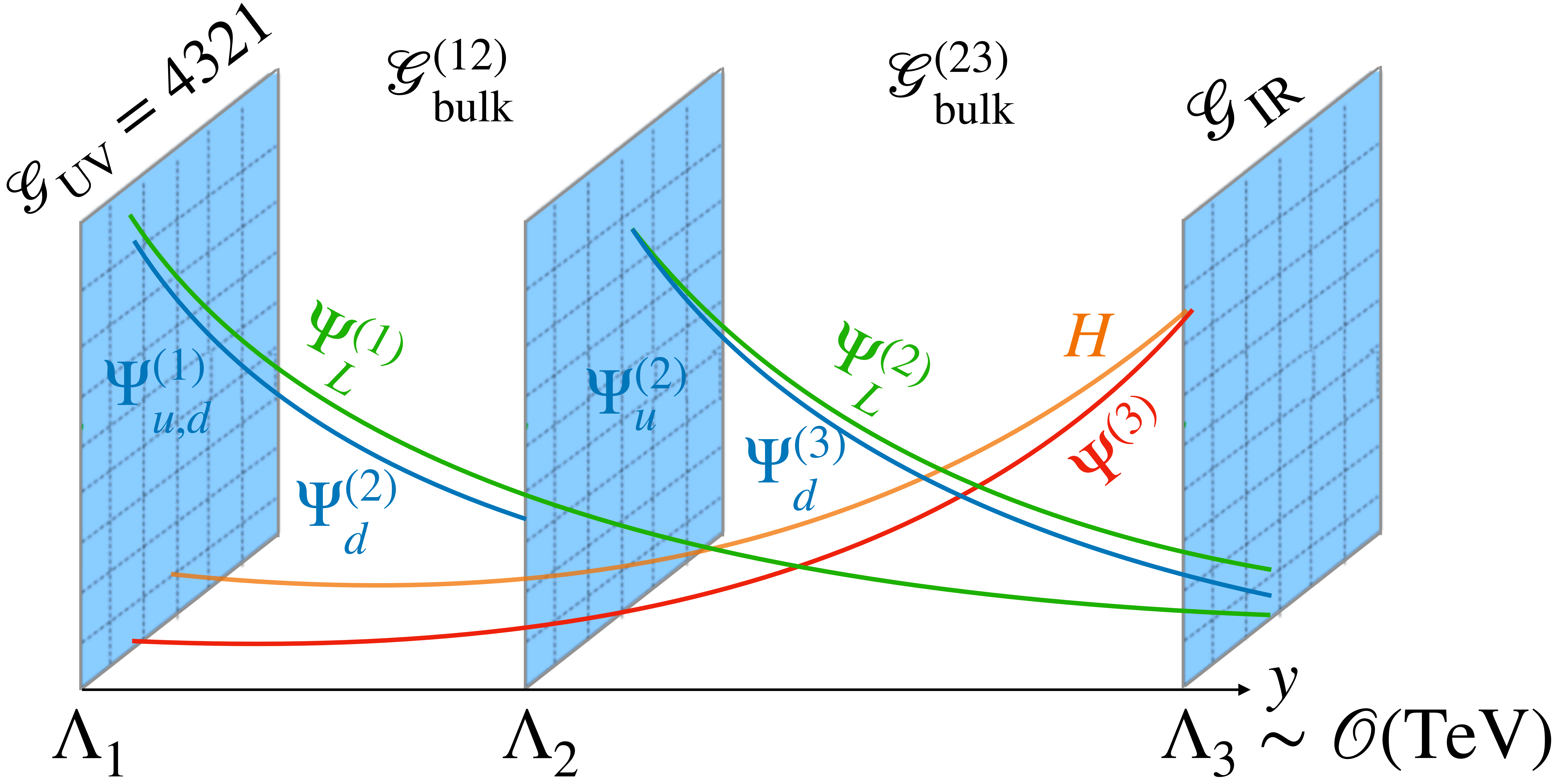


H in $\mathcal{G}^{(23)}_{\mathrm{bulk}}/\mathcal{G}_{\mathrm{IR}}$: as the 5$^{\mathrm{th}}$ component of the bulk gauge field (gauge-Higgs unification)

5D model realising:

4.

U(2) flavour symmetry with leading breaking in the LH sector.



RH fields localised in branes, with LH fields propagating to the IR brane

Gauge sector

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

Λ_2 (6 broken)

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

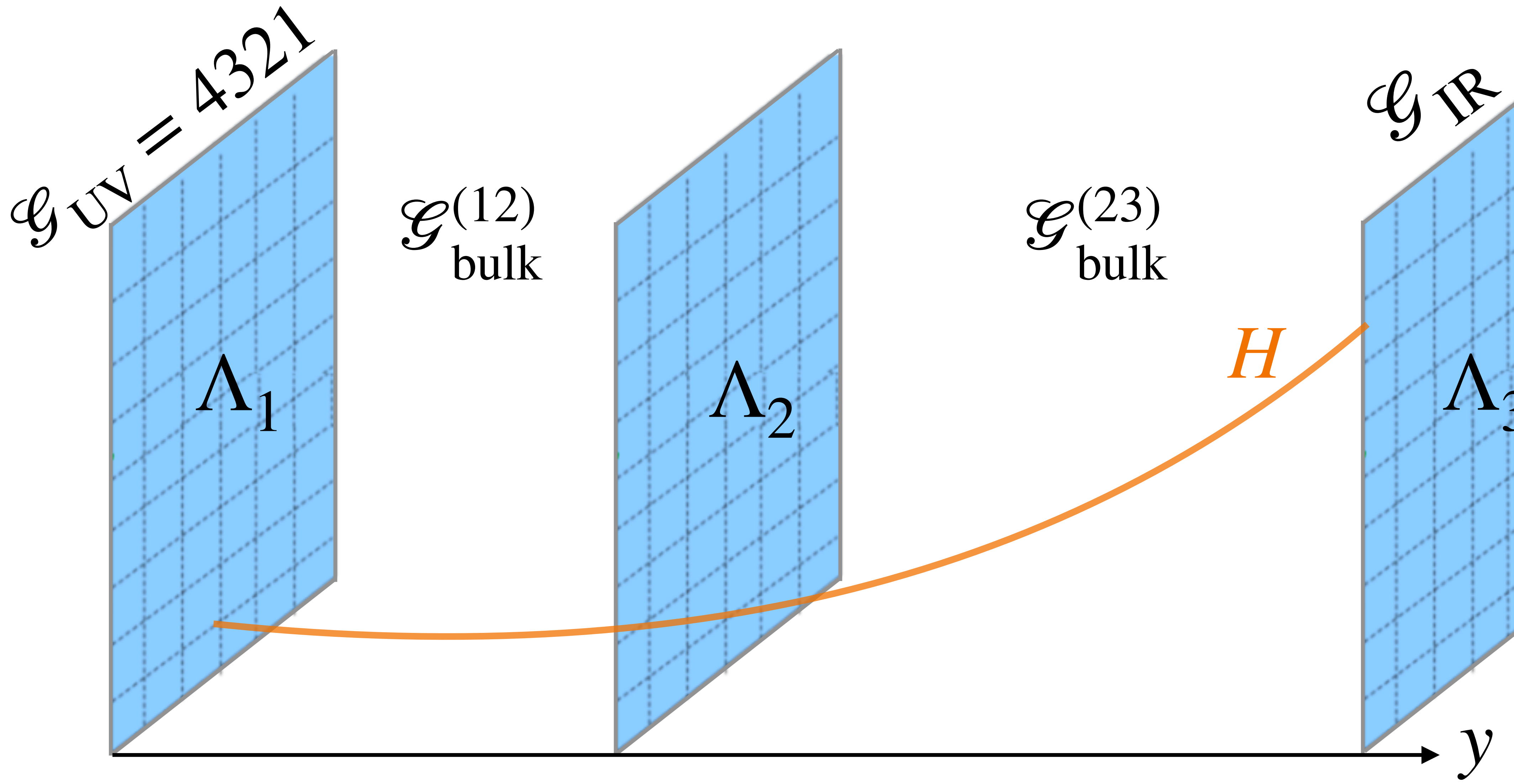
$\Lambda_3 = \Lambda_{\text{IR}}$ $(15 + 4$ broken$)$

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

Quark-lepton unification of light families

15 eaten by U_1, G', Z': $M_{4321} \sim \frac{\sqrt{2}\Lambda_3}{\sqrt{kL}} \sim \frac{M_{KK}}{\sqrt{2kL}}$

4 are pNGB Higgs: $SO(5) \to SO(4)$



Fermion and scalar sector

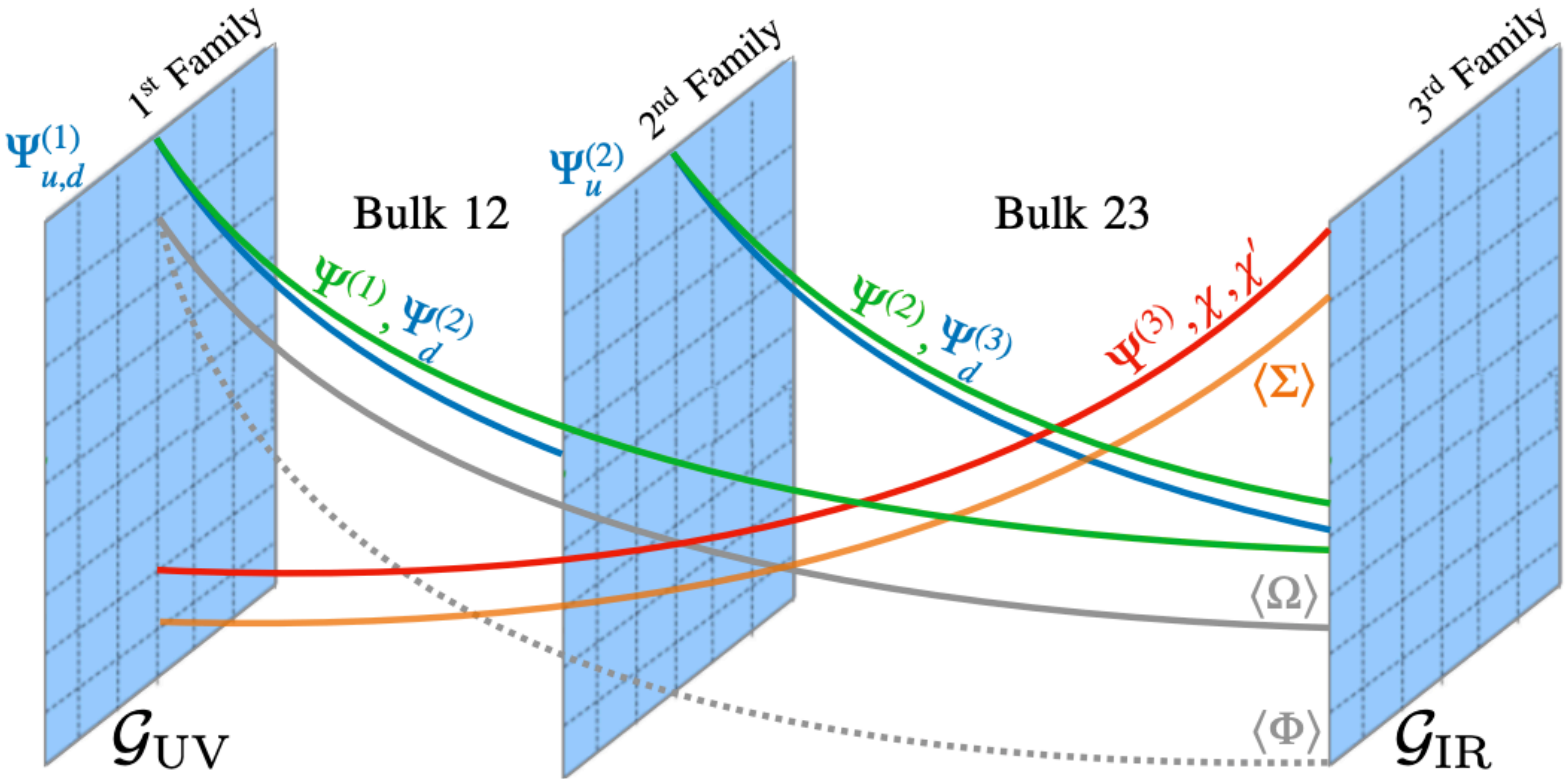
Field	Spin	$SU(4)_h$	$SU(4)_l$	$SO(5)$
$\Psi_d^{(3)}$ $\Psi^{(3)}$, $\chi^{(\prime)}$	1/2	4	1	4
$\Psi_L^{(i)}$ $\Psi_{u,d}^{(i)}$	1/2	1	4	4
Σ	0	1	1	5
$\mathcal{S}^i$ / Φ	1/2 / 0	1	1	1
Ω	0	1	4	4

3rd family and VL fermions ← $\Psi_d^{(3)}$ $\Psi^{(3)}$, $\chi^{(\prime)}$

Light families $i = 1,2$ ← $\Psi_L^{(i)}$ $\Psi_{u,d}^{(i)}$

For light Yukawa ← Σ

$\mathcal{S}^i$, Φ, Ω → For neutrinos



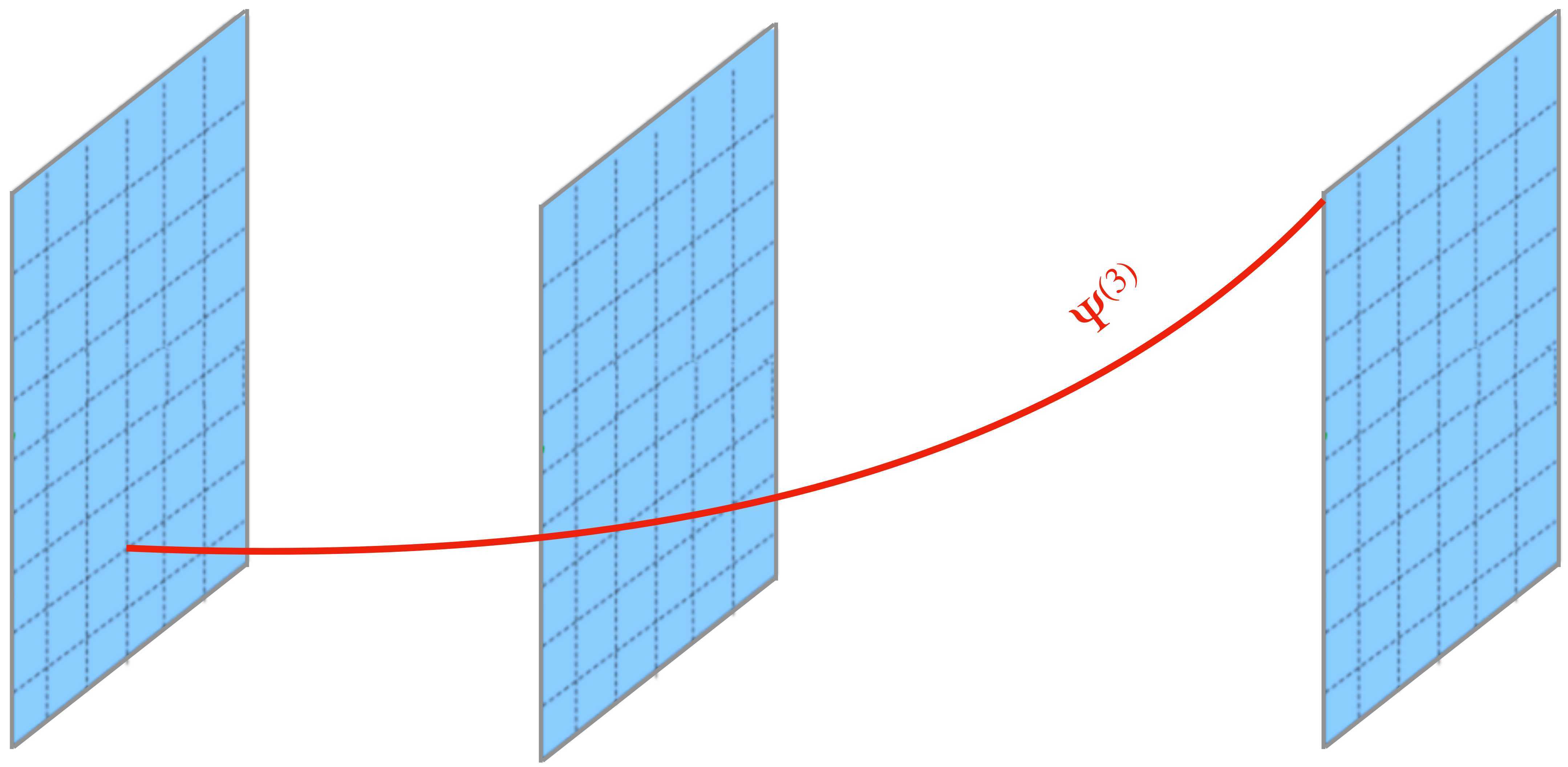
Top Yukawa

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

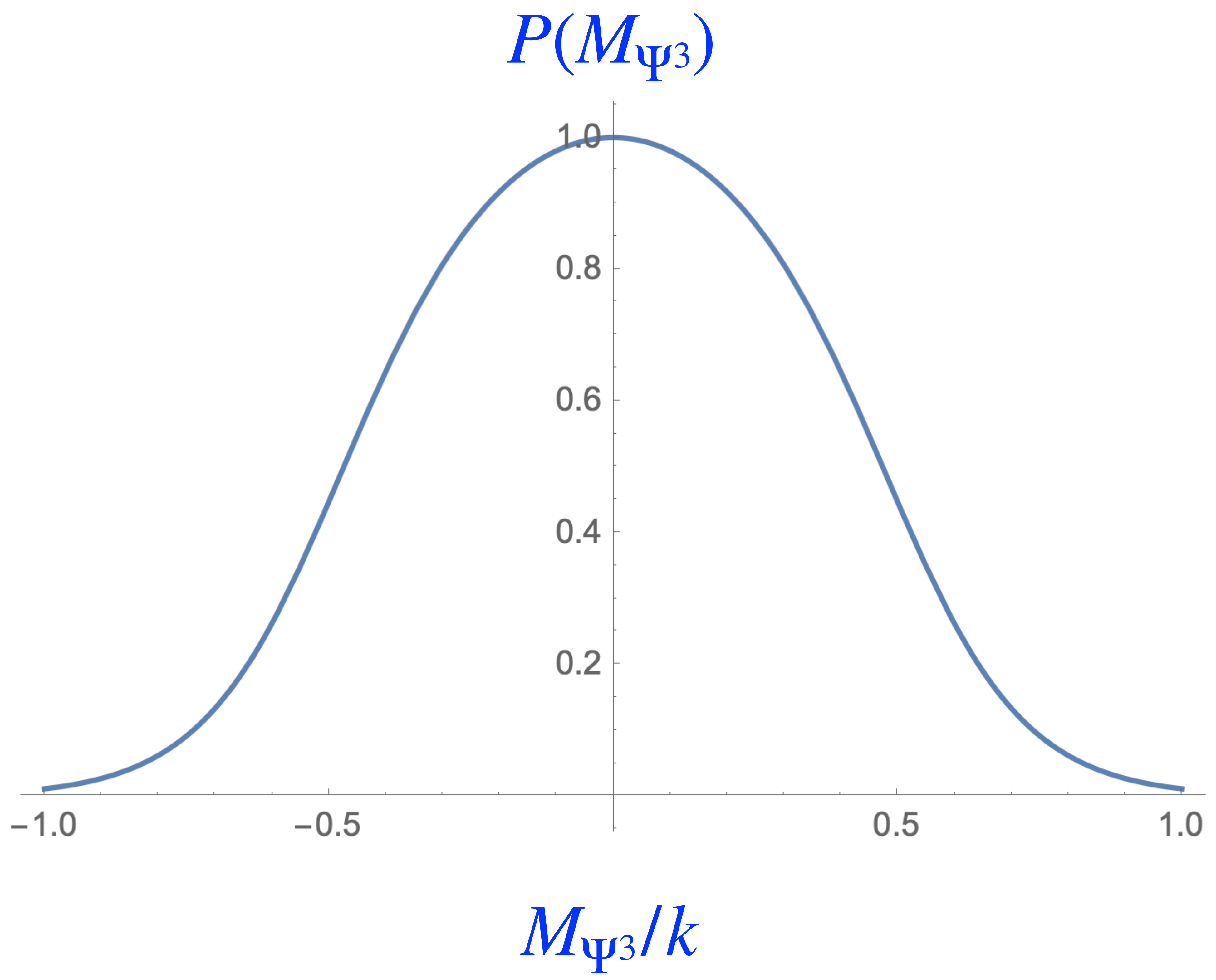
$$\Psi^3 = \begin{bmatrix} q_L \\ t_R \\ \times \end{bmatrix} \begin{array}{l} SU(2)_L \\ \left.\begin{array}{l} \\ \\ \end{array}\right\} SU(2)_R \end{array}$$

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

$$y_t = \frac{g_*}{2\sqrt{2}} P(M_{\Psi^3}) \quad , \quad g_*^2 = g_5^2 k$$



y_t for : $g_* \geq 2.2$



Bottom Yukawa + light-heavy mixing

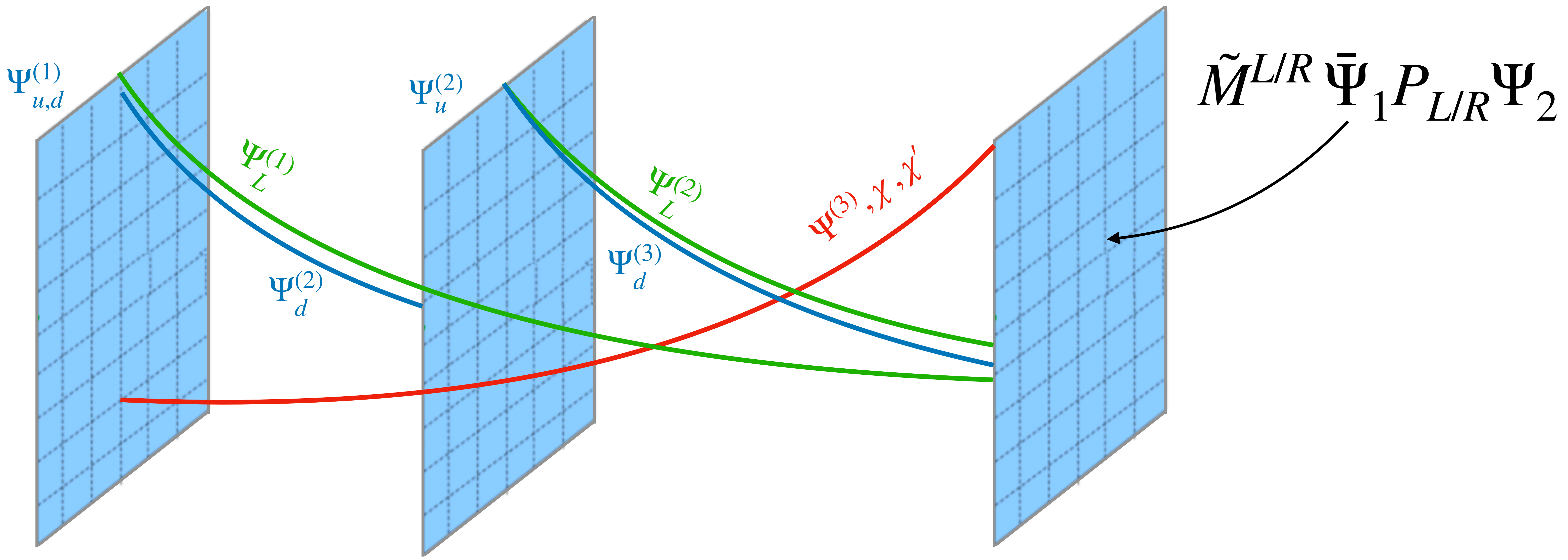
Field	$SU(4)_h$	$SU(4)_l$	$SO(5)$
$\Psi_d^{(3)}$ $\Psi^{(3)}$, $\chi^{(\prime)}$	4	1	4
$\Psi_L^{(i)}$ $\Psi_{u,d}^{(i)}$	1	4	4

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

$$y_{f_1 f_2} = \frac{g_*}{2\sqrt{2}}(\tilde{M}^L - \tilde{M}^R) \times P\left(M_{\Psi^j}, M_{\Psi^3}\right)$$

e.g. $P\left(M_{\Psi^j}, M_{\Psi^3}\right) \sim e^{-k(L-\ell_j)/2} \approx V_{j3}$ for

$$M_{\Psi_L^{(j)}} = k$$
$$M^{(1)}_{\Psi_d^{(3)}} = 0$$
$$M^{(2)}_{\Psi_d^{(3)}} = -k$$



Light Yukawas

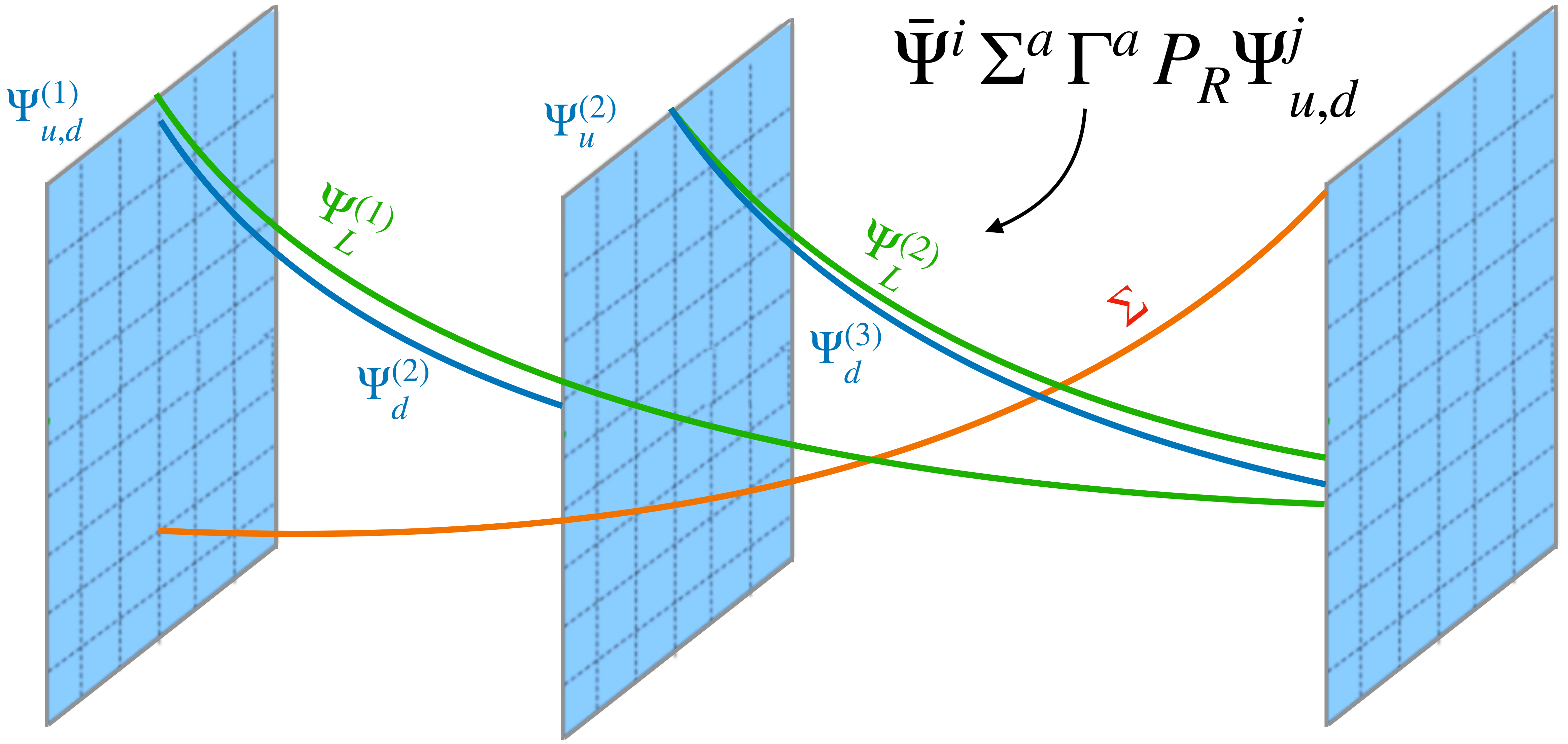
Field	$SU(4)_h$	$SU(4)_l$	$SO(5)$
$\Psi_L^{(i)}$ $\Psi_{u,d}^{(i)}$	1	4	4
Σ	1	1	5

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

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

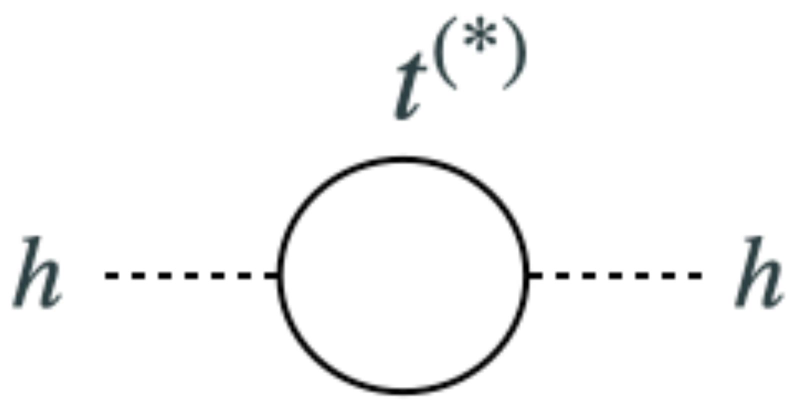
e.g. $e^{-k(L-\ell_j)} \, e^{-k(c_i^{(1)}-\frac{1}{2})|y_i-\ell_j|} \, e^{k(c_j^{(1)}+\frac{1}{2})|y_j-\ell_j|}$

$(c = M/k)$

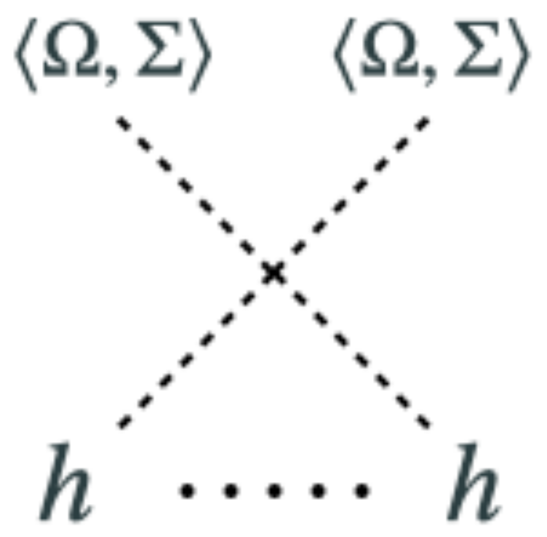


Higgs potential

One-loop contribution from top and EW gauge bosons



Field	$SU(4)_h$	$SU(4)_l$	$SO(5)$
$\Psi^{(3)}$	4	1	4
Σ	1	1	5
Ω	1	4	4



Tree level from VEVs in the bulk breaking $SO(5)$

Fully calculable!

$$V(h) \approx \underset{\Psi^3,\,\Omega}{\underset{\downarrow}{\alpha}} \cos\left(\frac{h}{f}\right) - \underset{\Psi^3,\,\Sigma,\,W,Z}{\underset{\downarrow}{\beta}} \sin^2\left(\frac{h}{f}\right)$$

Decay constant and mass:

$$f = \frac{2\Lambda_{\mathrm{IR}}}{g_*}\ ,\ (M_{\mathrm{KK}} = g_* f)\ ,\ m_h^2 = \frac{2\beta\langle h\rangle^2}{f^4}$$

$\lambda = \beta/f^4$ of the right size for $g_* \approx 2.5$, compatible with the top Yukawa

All contributions of the correct order, up to some "little-hierarchy" tuning connected to 4321 breaking

Low-energy pheno

- 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

High enough: EWPD ok! ⟵ $M_{\text{KK}} \approx 2\Lambda_{\text{IR}} = 16\,\text{TeV}$

⟶ First deviations from 4321

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

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

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

- Fine tuning $\sim v^2/f^2 \sim 10^{-3}$ (preferring light 4321 states?)

Conclusions

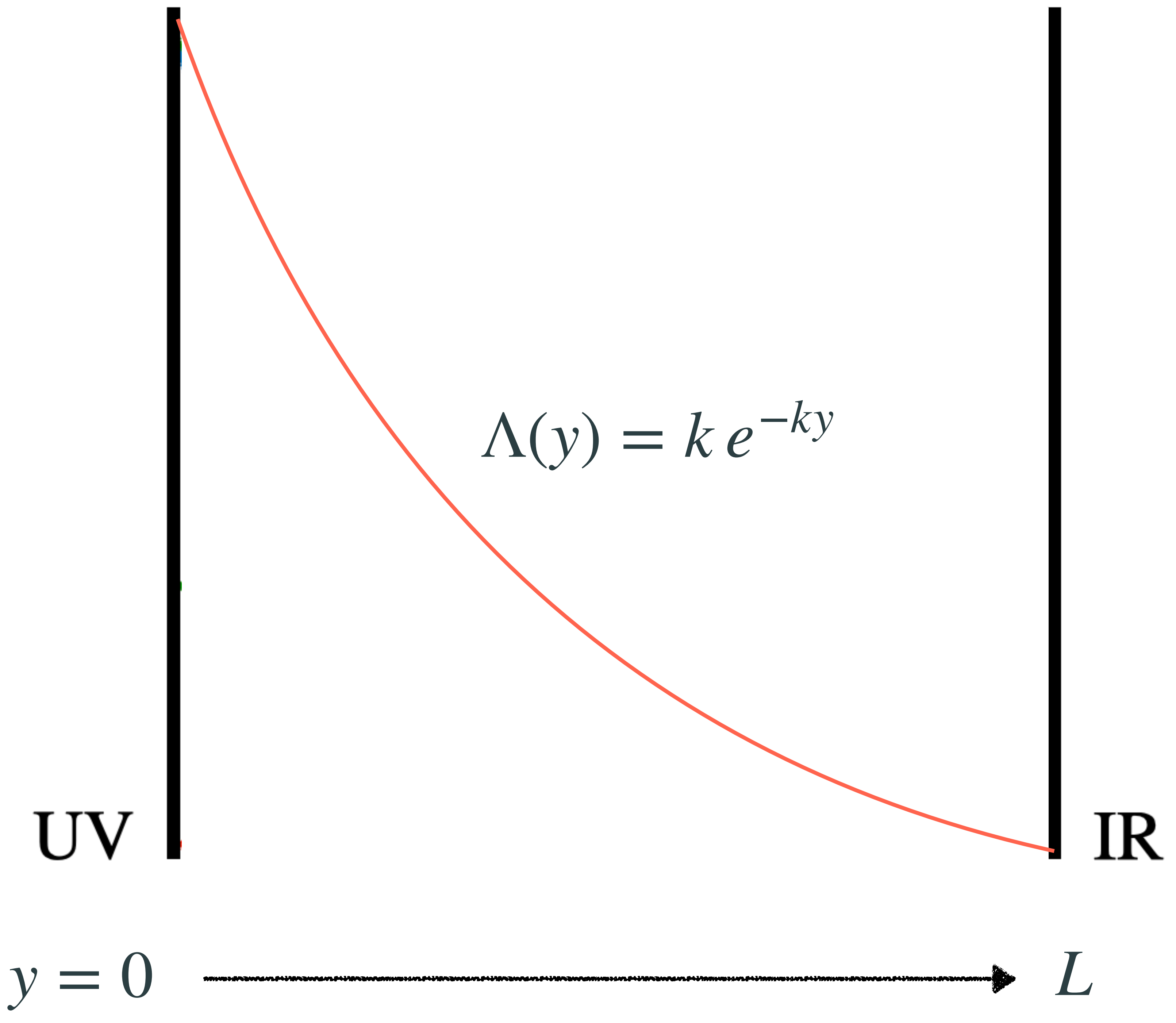
- A model with *flavour hierarchies* naturally emerging from a *3-brane structure* in a warped extra dimension: each SM family is quasi-localised on a different brane.
- $U(2)^5$ flavour symmetry with leading breaking in the left-handed sector.
- A model reduces to the *4321* model, good explanation of the B-meson anomalies.
- *Higgs* as a pseudo-Nambu-Goldstone boson from the same strong dynamics breaking 4321 gauge symmetry.

Backup

5D Basics: Warping and Fermion Zero Modes

Warped Geometry (AdS_5)

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$



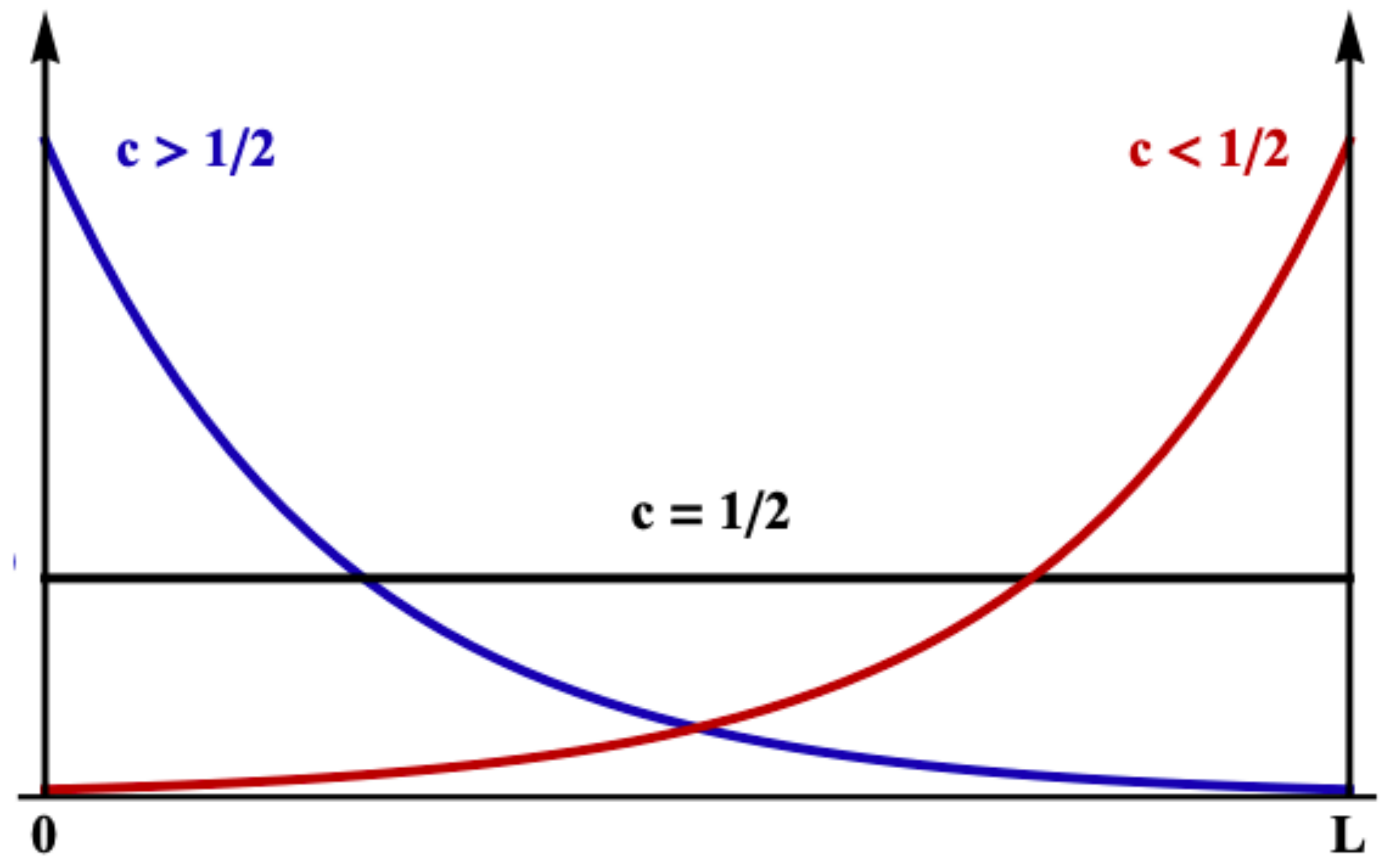
$* \ \Lambda_{\mathrm{IR}}/\Lambda_{\mathrm{UV}} = e^{-kL}$ *Planck hierarchy solved for* $kL \approx 37$

KK Decomposition

$$X_{5\mathrm{D}}(x^\mu, y) = \frac{1}{\sqrt{L}}\sum_{n=0}^{\infty} f_n(y)\,X_n(x^\mu)$$

For fermion zero modes:

$$f_{(0)}^{\Psi_{L,R}}(y) = N_{L,R}\exp\left[\left(\frac{1}{2} \mp c_{L,R}\right)ky\right], \quad c_{L,R} = \frac{M_{L,R}}{k}$$



*4D couplings determined by profile function overlap

Holography

A_5 in the bulk + boundary conditions $\Phi_0 \;\leftrightarrow\;$ vanishing A_5 + boundary conditions $\Phi'_0 = e^{-i\theta(x)}\Phi_0$

$$W(x) = e^{-i\theta(x)}\,, \qquad \theta(x) = g_5 \int_0^L dy\, A_5(x,y) = g_5 T^{\hat{a}} h^{\hat{a}} \frac{e^{kL}}{\sqrt{2k}} = g_5\sqrt{k} T^{\hat{a}} h^{\hat{a}} \frac{1}{\sqrt{2}\Lambda_{IR}} = T^{\hat{a}} h^{\hat{a}} \frac{g_*}{\sqrt{2}\Lambda_{IR}}$$

$$\theta(x) = \frac{\sqrt{2} T^{\hat{a}} h^{\hat{a}}}{f} \longrightarrow f = \frac{2\Lambda_{IR}}{g_*}$$

$$W(x) = \begin{pmatrix} \cos\frac{h}{2f} & \sin\frac{h}{2f}\,\hat{\sigma} \\ -\sin\frac{h}{2f}\,\hat{\sigma}^\dagger & \cos\frac{h}{2f} \end{pmatrix} \qquad \sigma = \frac{\sigma^{\hat{a}} h^{\hat{a}}}{h} \qquad \sigma^{\hat{a}} = \{\vec{\sigma}, -i1\} \quad h \equiv \sqrt{(h^{\hat{a}})^2}$$

e.g. $\quad \mathcal{L}^{\text{holo}} = \frac{1}{2}\left(\Pi^{ij}_{L(R)} + \Pi^{ji}_{L(R)}\right) \overline{\hat{\psi}}^{i}_{q_L} \Sigma\, P_{12(34)}\, \Sigma^\dagger \frac{\not{p}}{p} \hat{\psi}^{j}_{qL}$

e.g. matching to W mass: $g_L = g_* / \sqrt{kL(1 + r_{UV}^2 + r_{IR}^2)}$

IR masses

$$\Psi^3 = \begin{bmatrix} \psi^3\,(+,+) \\ \psi^3_u\,(-,-) \\ \tilde{\psi}^3_d\,(+,-) \end{bmatrix}, \quad \Psi^3_d = \begin{bmatrix} \tilde{\psi}^3\,(+,-) \\ \tilde{\psi}^3_u\,(+,-) \\ \psi^3_d\,(-,-) \end{bmatrix}, \quad \mathcal{X}^{(\prime)} = \begin{bmatrix} \chi^{(\prime)}(\pm,\pm) \\ \chi^{(\prime)}_u\,(\mp,\pm) \\ \chi^{(\prime)}_d\,(\mp,\pm) \end{bmatrix},$$

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

$$\mathcal{L}_{\mathrm{IR}} \supset \left(\bar{\mathcal{X}}_L \tilde{M}_\chi + \bar{\Psi}^3_L \tilde{M}_\Psi + \bar{\Psi}^j_L \tilde{m}^j_\psi\right) \mathcal{P}_L \mathcal{X}'_R \,,$$

$$\mathcal{L}_{\mathrm{IR}} \supset \bar{\Psi}^3_L \tilde{M}^L_{\Psi d} \mathcal{P}_L \Psi^3_{dR} + \bar{\Psi}^j_L \tilde{m}^R_{\Psi j} \mathcal{P}_R \Psi^3_R + \bar{\mathcal{X}}_L \tilde{M}^R_{\chi u} \mathcal{P}_R \Psi^3_R$$
$$+ \bar{\Psi}^j_L (\tilde{m}^L_{dj} \mathcal{P}_L + \tilde{m}^R_{dj} \mathcal{P}_R) \Psi^3_{dR} + \bar{\mathcal{X}}_L (\tilde{M}^L_{\chi d} \mathcal{P}_L + \tilde{M}^R_{\chi d} \mathcal{P}_R) \Psi^3_{dR} \,.$$

Effective 4D "Holographic" Lagrangian

$$\mathcal{L}_{\rm IR} \supset \left(\bar{\mathcal{X}}_L \tilde{M}_\chi + \bar{\Psi}^3_L \tilde{M}_\Psi + \bar{\Psi}^j_L \tilde{m}^j_\psi\right) \mathcal{P}_L \mathcal{X}'_R\,,$$

$$\begin{aligned}\mathcal{L}_{\rm IR} \supset\ & \bar{\Psi}^3_L \tilde{M}^L_{\Psi d} \mathcal{P}_L \Psi^3_{dR} + \bar{\Psi}^j_L \tilde{m}^R_{\Psi j} \mathcal{P}_R \Psi^3_R + \bar{\mathcal{X}}_L \tilde{M}^R_{\chi u} \mathcal{P}_R \Psi^3_R \\ & + \bar{\Psi}^j_L (\tilde{m}^L_{dj} \mathcal{P}_L + \tilde{m}^R_{dj} \mathcal{P}_R) \Psi^3_{dR} + \bar{\mathcal{X}}_L (\tilde{M}^L_{\chi d} \mathcal{P}_L + \tilde{M}^R_{\chi d} \mathcal{P}_R) \Psi^3_{dR}\,.\end{aligned}$$

$$\Downarrow$$

$$\begin{aligned}-\mathcal{L}_{\rm 4D} \supset\ & \frac{g_*}{2\sqrt{2}} \left[\bar{\psi}^3_L - \bar{\chi}_L \tilde{M}^R_{\chi u} - c_j\, e^{-\frac{k z_j}{2}} \bar{\psi}^j_L \tilde{m}^R_{\Psi j}\right] \tilde{H} \psi^3_{uR} + y^{ij}_u \bar{\psi}^i_L \tilde{H} \psi^j_{uR} + + y^{ij}_d \bar{\psi}^i_L H \psi^j_{dR} \\ & + \frac{g_*}{2\sqrt{2}}\, c_2\, e^{-\frac{k z_2}{2}} \left[\bar{\psi}^3_L \tilde{M}^L_{\Psi d} + \bar{\chi}_L (\tilde{M}^L_{\chi d} - \tilde{M}^R_{\chi d}) + c_j\, e^{-\frac{k z_j}{2}}\ \bar{\psi}^j_L (\tilde{m}^L_{dj} - \tilde{m}^R_{dj})\right] H \psi^3_{dR} \\ & + \frac{\Lambda_{\rm IR}}{\sqrt{kL}} \left[\bar{\psi}^3_L \tilde{M}_\Psi + \bar{\chi}_L \tilde{M}_\chi + c_j\, e^{-\frac{k z_j}{2}}\ \bar{\psi}^j_L \tilde{m}^j_\psi\right] \chi'_R + \text{h.c.}\end{aligned}$$

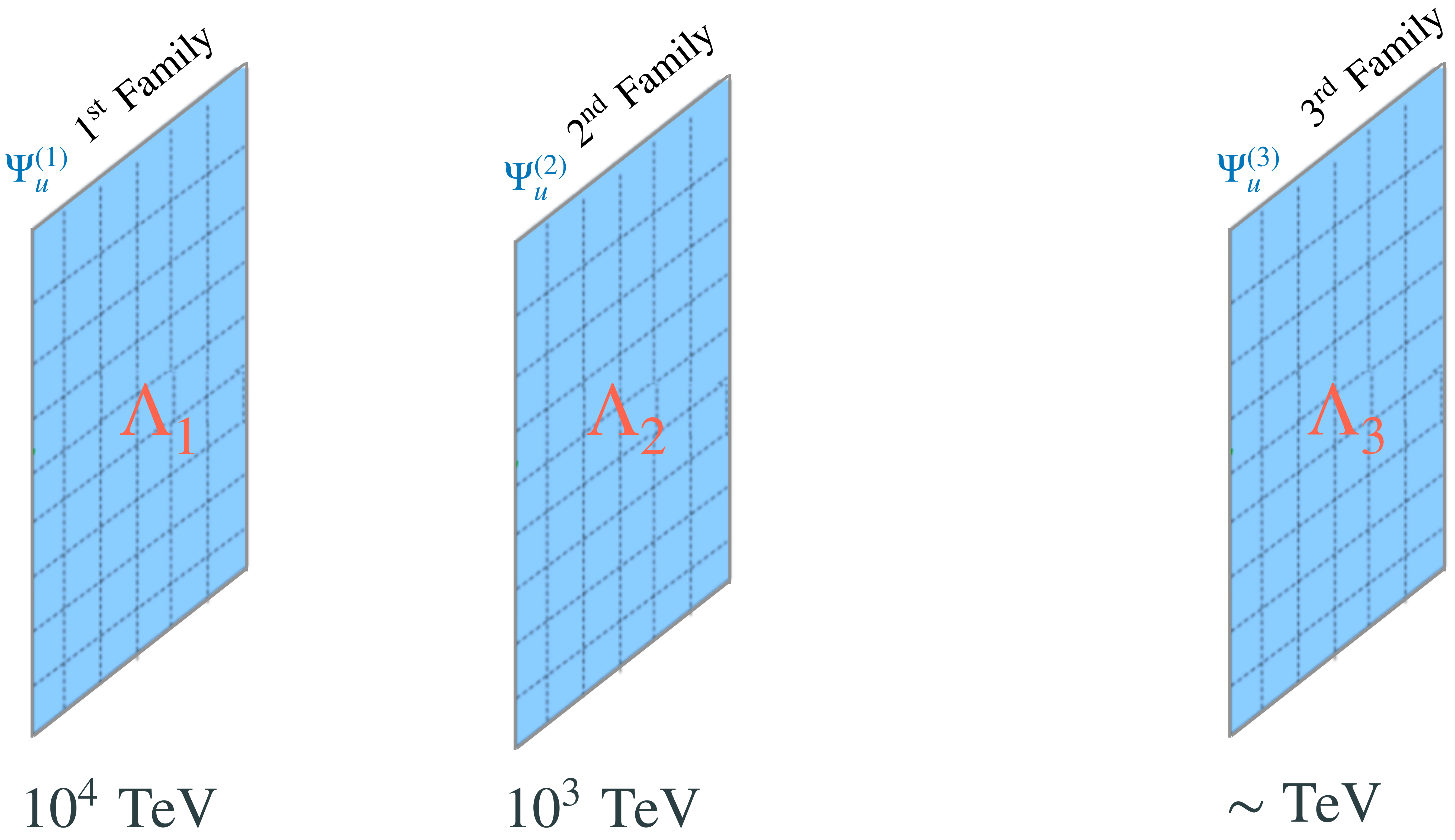
Matching to 4321: $M_\chi = \tilde{M}_\chi \Lambda_{\rm IR}/\sqrt{kL} \approx 2$ TeV, $\quad y_t = g_*/2\sqrt{2}, \quad y_+ = y_t \tilde{M}^R_{\chi u}, \quad$ etc.

Neutrino masses: Type I seesaw?

- Type 1 Seesaw would give:

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**

$$\Psi_u \sim \begin{pmatrix} u_R \\ \nu_R \end{pmatrix}, \qquad m_\nu^i \sim \frac{(M_u^i)^2}{M_R^i} \rightarrow \frac{(M_u^i)^2}{\Lambda_i}$$



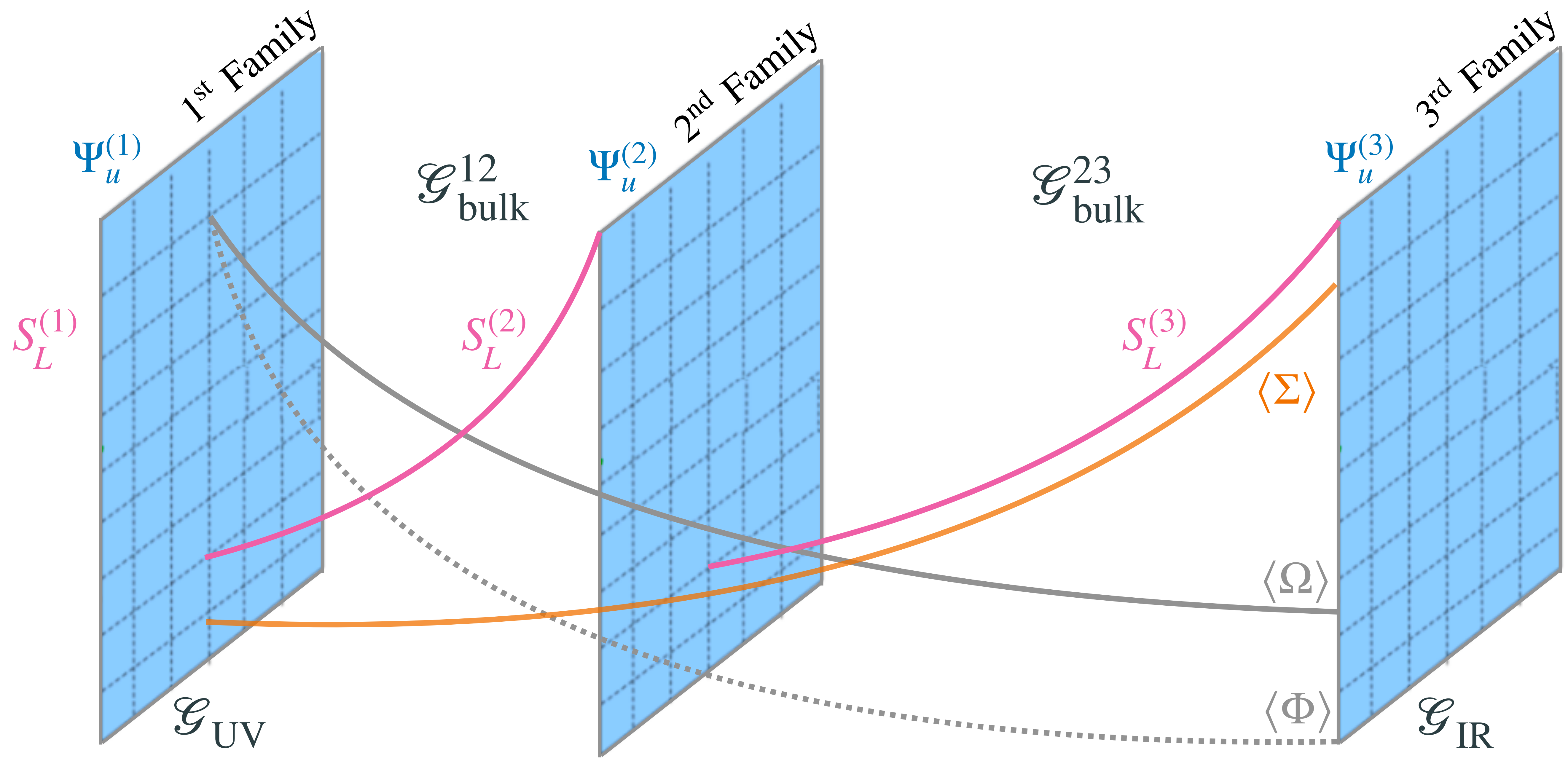
Neutrino masses: ISS

ISS

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**
Ω	**1**	**4**	**4**
Φ	**1**	**1**	**1**

- Anarchic neutrino masses for:

$$m_\nu^i = \left(\frac{M_u^i}{M_R^i}\right)^2 \mu_i \;\to\; \left(\frac{\langle\Sigma_i\rangle}{\langle\Omega_i\rangle}\right)^2 \langle\Phi_i\rangle \approx \text{const}\,.$$

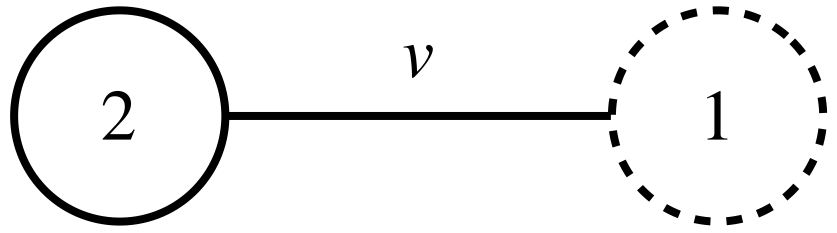
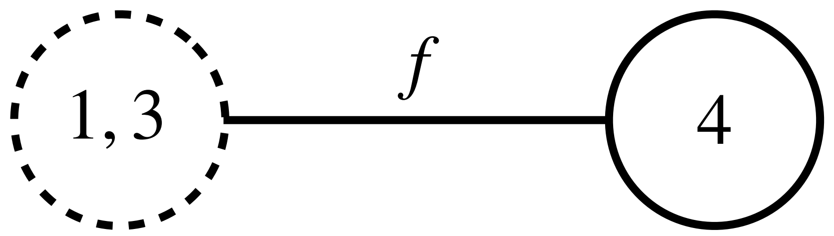


4321 symmetry breaking and EWSB: Parallels

[Fuentes-Martin, Stangl 2004.11376]

$$\overbrace{\underbrace{SU(4)_h \times SU(3)_l}_{SU(3)_c} \times SU(2)_L \times U(1)_{l+R}}^{U(1)_Y} \xrightarrow{\langle \Omega_{1,3,15} \rangle \sim \mathcal{O}(\mathrm{TeV})} SU(3)_c \times SU(2)_L \times U(1)_Y$$

In the limit of vanishing gauge and Yukawa couplings:

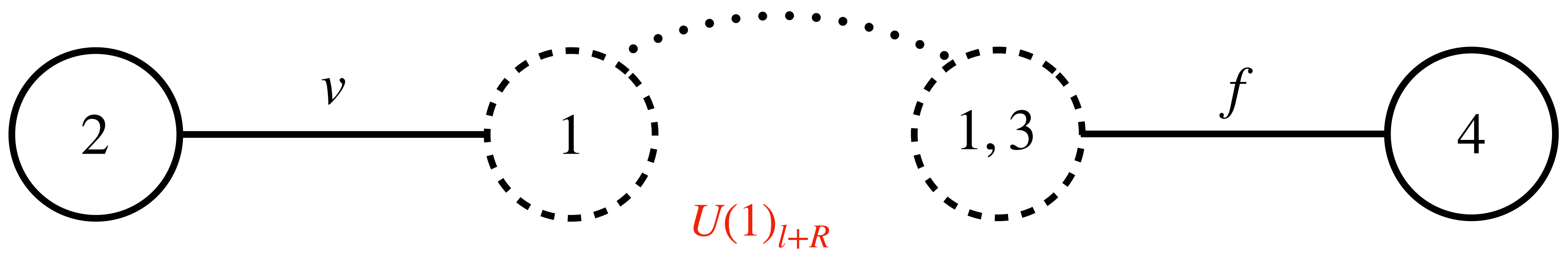
	SM Higgs Sector	4321 Models
Global symmetry	$SU(2)_L \times SU(2)_R$	$SU(4)_l \times SU(4)_h$
Gauge symmetry	 $SU(2)_L$ $\times$ $U(1)_R$ Left-handed fermions Right-handed fermions	 $U(1)_l \times SU(3)_l$ $\times$ $SU(4)_h$ Light fermions Heavy fermions
Global SSB	$SU(2)_V$	$SU(4)_D$
Gauge SSB	$U(1)_V$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

4321 symmetry breaking and EWSB: Parallels

[Fuentes-Martin, Stangl 2004.11376]

$$\overbrace{\underbrace{SU(4)_h \times SU(3)_l}_{SU(3)_c} \times SU(2)_L \times U(1)_{l+R}}^{U(1)_Y} \xrightarrow{\langle \Omega_{1,3,15} \rangle \sim \mathcal{O}(\mathrm{TeV})} SU(3)_c \times SU(2)_L \times U(1)_Y$$

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	 $SU(2)_L \times \boxed{U(1)_R \quad U(1)_l} \times SU(3)_l \times SU(4)_h$ Left-handed fermions · Right-handed fermions · Light fermions · Heavy fermions	
Global SSB	$SU(2)_V$	$SU(4)_D$
Gauge SSB	$U(1)_{\mathrm{em}} \times SU(3)_c$	
Goldstones	$3\ (W, Z)$	$15\ (U_1, G', Z')$

Higgs Potential

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

$\alpha \downarrow$ Ψ^3, Ω

$\beta \downarrow$ Ψ^3, Σ, W, Z

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

Higgs Mass :

$$m_h^2 \equiv 2\lambda \langle h \rangle^2 \approx \frac{2\beta \langle h \rangle^2}{f^4}$$

Higgs VEV $(\alpha \approx -2\beta)$:

$$\cos(\langle h \rangle / f) = -\frac{\alpha}{2\beta}$$

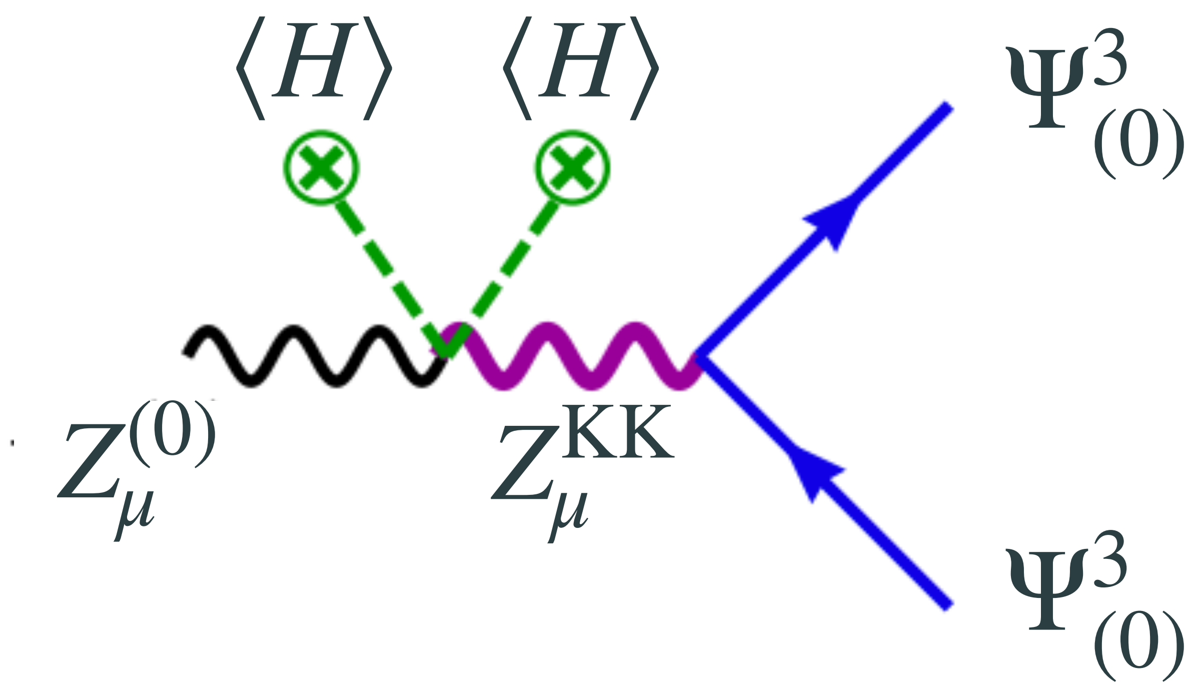
$$\lambda \approx \frac{1}{16\pi^2}\left[N_c\, y_t^4 \log\frac{\Lambda_{\mathrm{IR}}^2}{m_t^2} - \frac{9}{32}\zeta(3) g_*^2 \left(3g_L^2 + g_Y^2\right) + \frac{\pi^2 g_*^4}{2(kL)^2}\frac{\langle \Sigma_{\mathrm{IR}} \rangle^2}{\Lambda_{\mathrm{IR}}^2}(\tilde{M}_{H'} - \tilde{M}_S)\right]$$

top loop | EW gauge loop | Σ tree

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

Low-energy phenomenology, deviations from 4321

- Low energy pheno is the same as in the non-universal 4321 model.
- Strongest bound on the overall scale comes from coloron direct searches.
- Leading deviation in 3rd family EW vertex corrections from KK $\leftrightarrow$ SM mixing.



Leading effect in $Z \to \tau_L \tau_L$

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

Benchmark Spectrum :

E

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

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

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

$$M_{15} \approx \frac{g_* f}{\sqrt{2kL}} \approx 3.6\,\mathrm{TeV}$$

$[f > 2.5\,\mathrm{TeV} \;\; (M_{\mathrm{KK}} > 6\,\mathrm{TeV})]$

Extension to Planck and Cosmological Signatures