Universität Zürich[UZH]

Flavour Non-universal Pati-Salam Unification and Neutrino Masses

La Thuile, 10 Mars 2021 - Les Rencontres de Physique de la Vallée d'Aoste

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Based on

J. Fuentes-Martín, G. Isidori, J. Pagès and B. Stefanek, arXiv:2012.10492

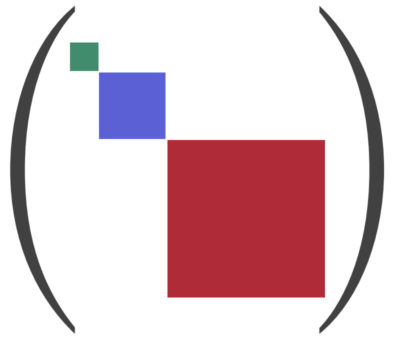
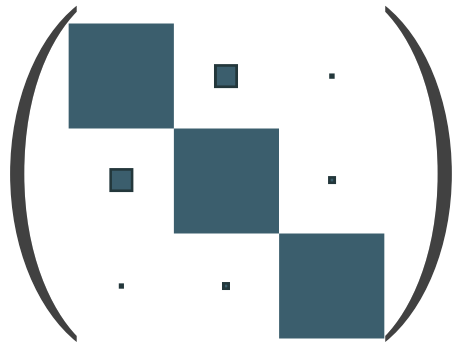
Motivation

Flavour puzzle

Structural problem of the SM:

Gauge sector is very compact
⟶ **3** parameters for all interactions

Flavour sector is more complex
⟶ **13** (+9 for neutrinos) masses and mixings spanning 5 orders of magnitude

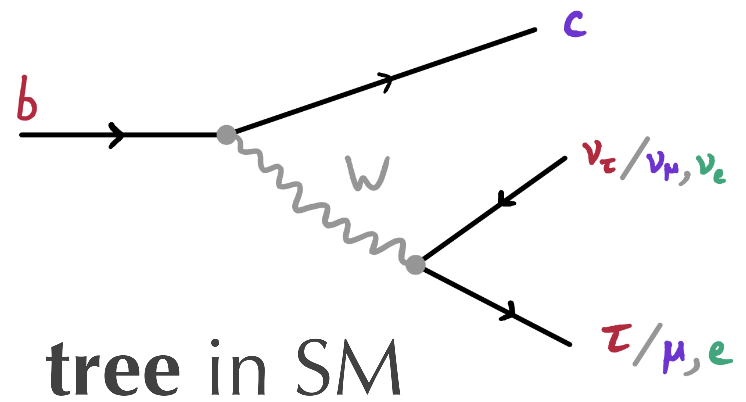
$M_{u,d,e} \sim$  $V_{\text{CKM}} \sim$ 

B anomalies

Hints of Lepton Flavour Universality Violation

⟶ $\sim 3\sigma$ in charged current

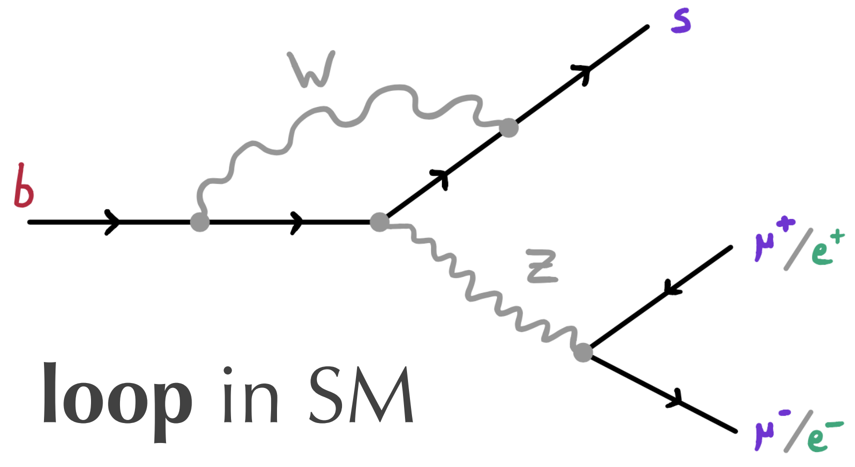
$b \to c\tau\nu$ in $\tau/\mu,e$ ratio



tree in SM

⟶ $\sim 4\sigma$ in neutral current

$b \to s\ell\ell$ in μ/e ratio



loop in SM

[See talk by Peter Stangl]

Combined explanation at TeV scale requires

NP in τ $\gg$ NP in μ/e

$U_1 \sim (3,1)_{2/3}$ vector leptoquark as best mediator

[See talk by Javier Fuentes-Martín]

Motivation

Flavour puzzle | **B anomalies**

Both exhibit approximate $U(2)^5$ flavour symmetry

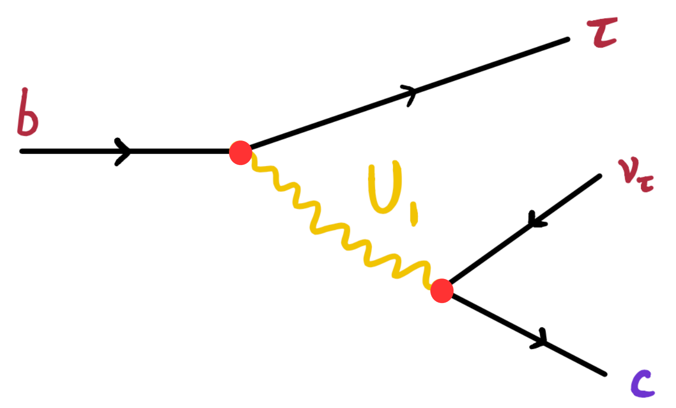
[See talk by Javier Fuentes-Martín]

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

CC $\gg$ NC

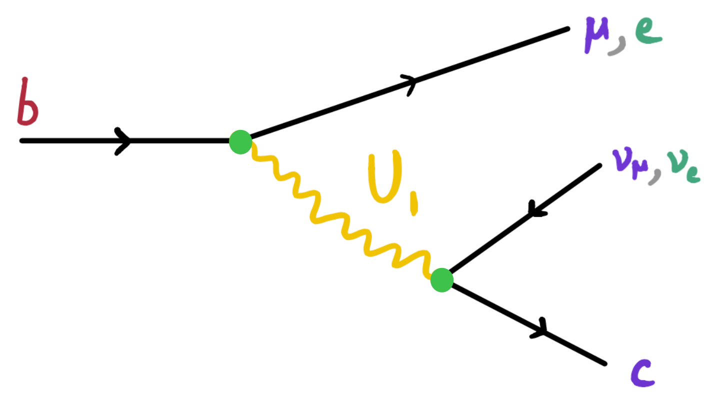
$$Y_{u,d,e} = y_{t,b,\tau} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

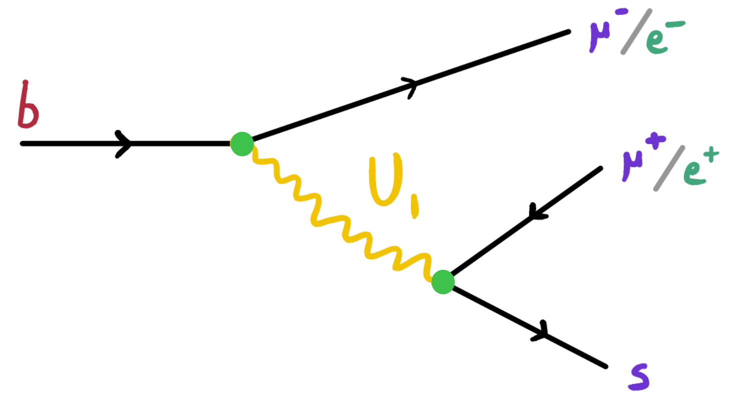
⟵ Exact $U(2)^5$ means ⟶



$$Y_{u,d,e} = y_{t,b,\tau} \begin{pmatrix} \epsilon_H & \epsilon_L \\ 0 & 1 \end{pmatrix}$$

⟵ Deviations parametrised by $U(2)^5$ spurions ⟶





$$\epsilon_L \sim 10^{-1}$$
$$\epsilon_H \sim 10^{-2}$$

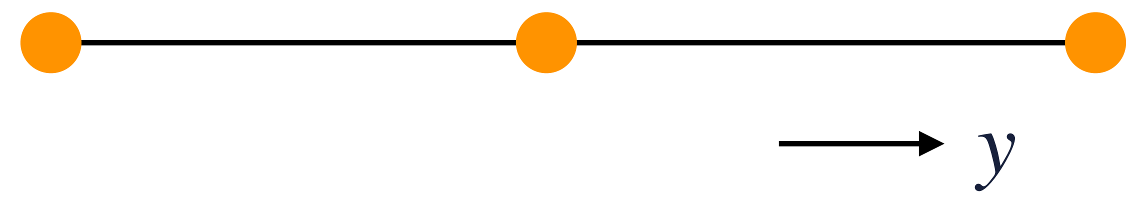
[Barbieri, Isidori, Jones-Pérez, Lodone, Straub, 1105.2296]

[Barbieri, Isidori, Pattori, Senia, 1512.01560
Buttazzo, Greljo, Isidori, Marzocca, 1706.07808
Fuentes-Martín, Isidori, JP, Yamamoto, 1909.02519]

PS^3 three-site model

UV model

Flavour non-universal: PS_1 x PS_2 x PS_3 / PS_{5D} in (x_μ, y)

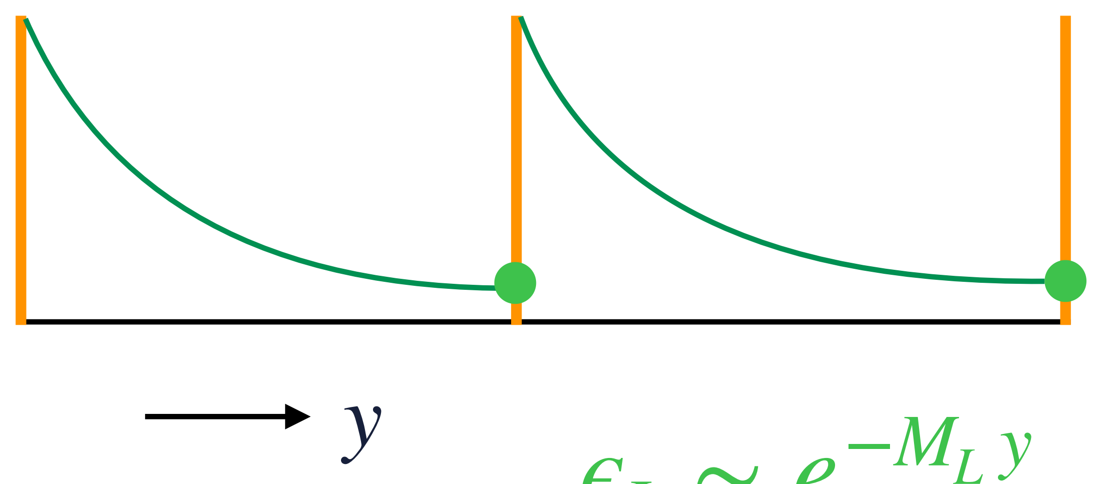


Pati-Salam Unification: $PS_i = SU(4)_i \times SU(2)_{L,i} \times SU(2)_{R,i}$ (minimal group containing U_1 leptoquark)

[Pati, Salam, PRD 10 (1974) 275-289]

Fermion families (mostly) localised on each site:

$$\Psi_L^{(i)} \sim (4,2,1)_i \qquad \Psi_R^{(i)} \sim (4,1,2)_i$$



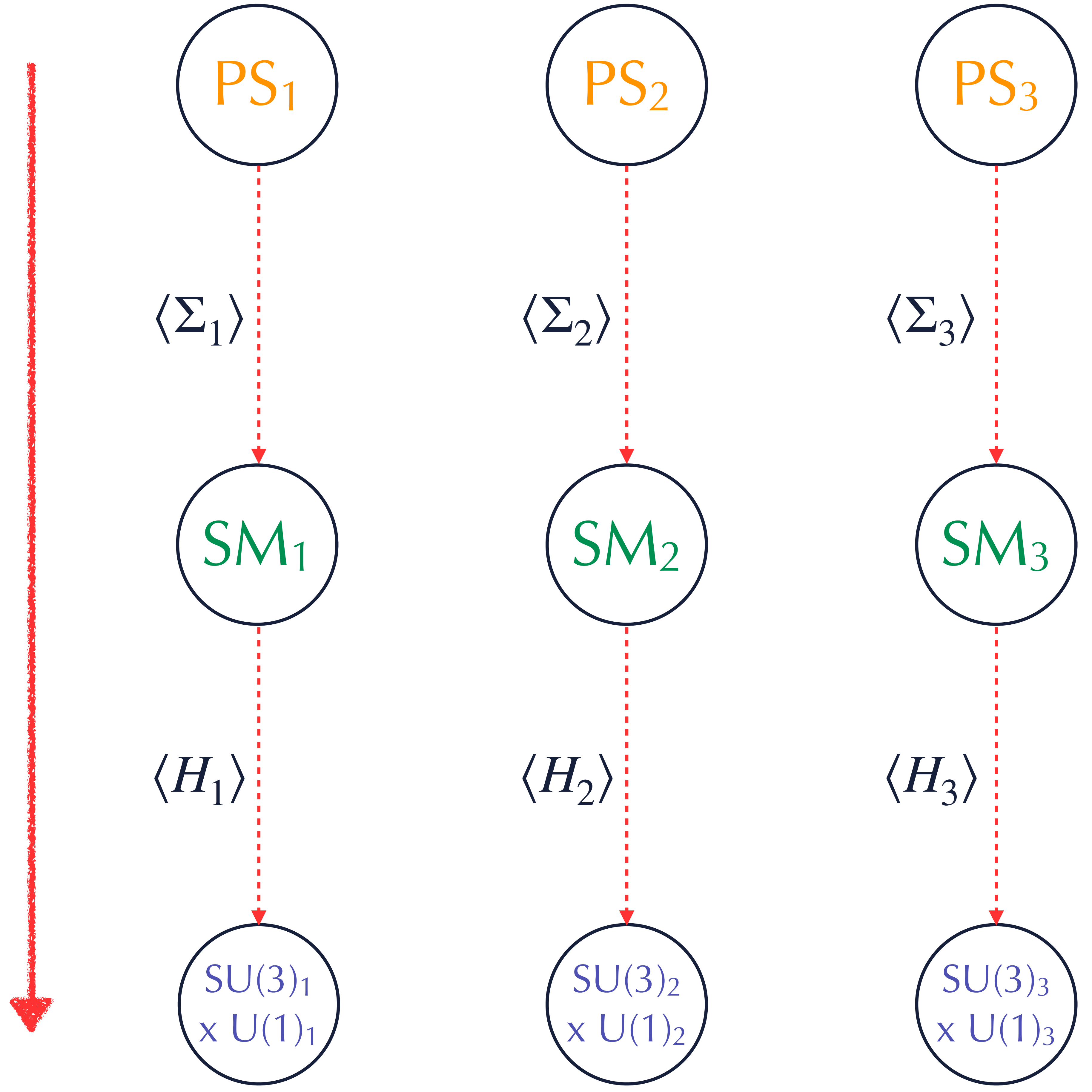
$\epsilon_L \sim e^{-M_L y}$

[Bordone, Cornella, Fuentes-Martín, Isidori, 1712.01368]

PS^3 three-site model

$PS_i = SU(4)_i \times SU(2)_{L,i} \times SU(2)_{R,i}$

Vertical breaking



Symmetry breaking scalars:

$\Sigma_i \sim (4,1,2)_i$

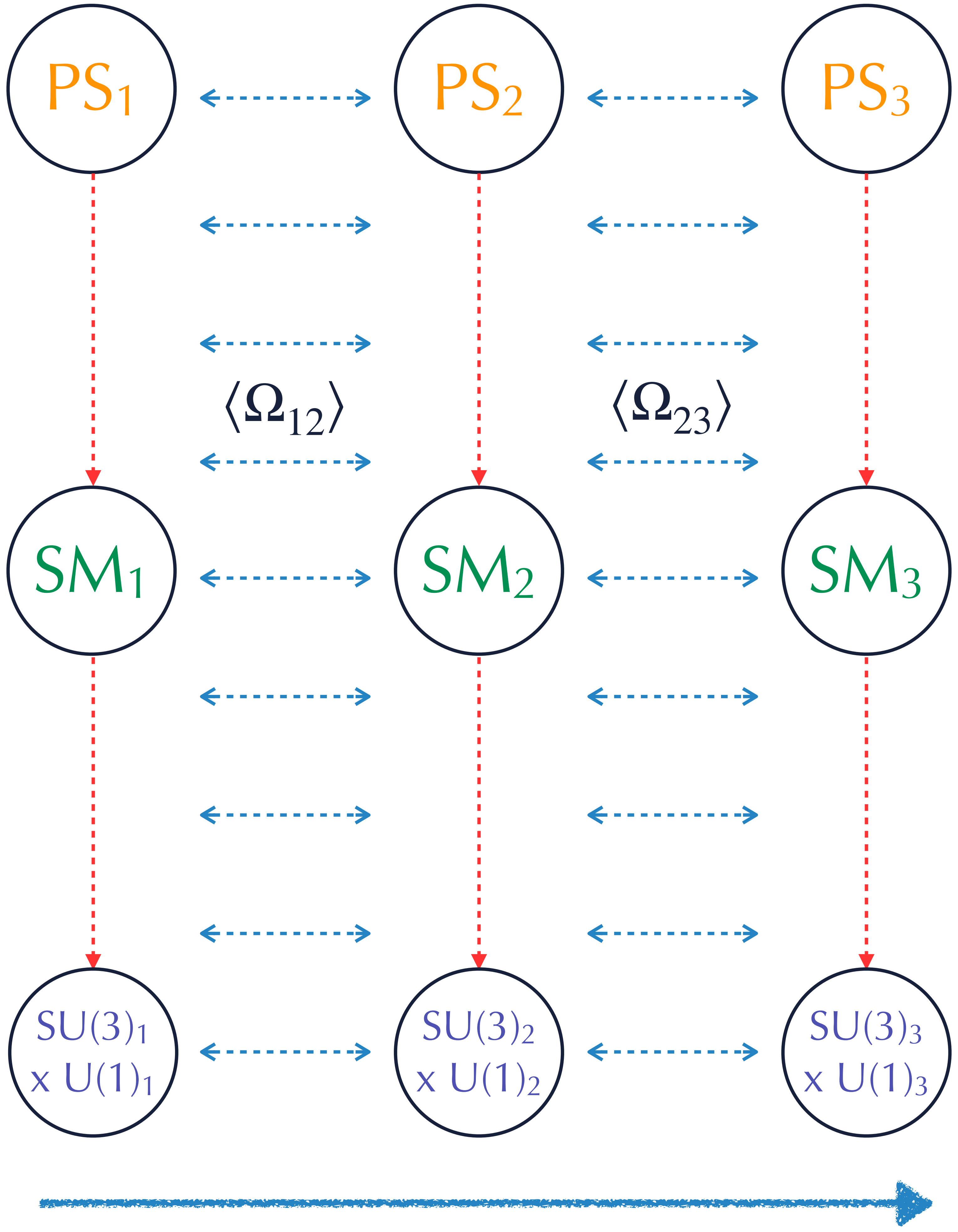
$H_i \sim (1,2,\bar{2})_i$

PS^3 three-site model

PS_i = SU(4)$_i$ x SU(2)$_{L,i}$ x SU(2)$_{R,i}$

Horizontal breaking

$G_1 \times G_2 \times G_3 \longrightarrow G_{diag}$



Non-linear link fields:

$$\Omega^4_{ij} \sim (4,1,1)_i \times (\bar{4},1,1)_j$$
$$\Omega^L_{ij} \sim (1,2,1)_i \times (1,\bar{2},1)_j$$
$$\Omega^R_{ij} \sim (1,1,2)_i \times (1,1,\bar{2})_j$$

↪ UV cut-off:

$$\Lambda \sim 4\pi f^{4,L,R}_{ij}$$ ← vevs

PS³ three-site model

UV model

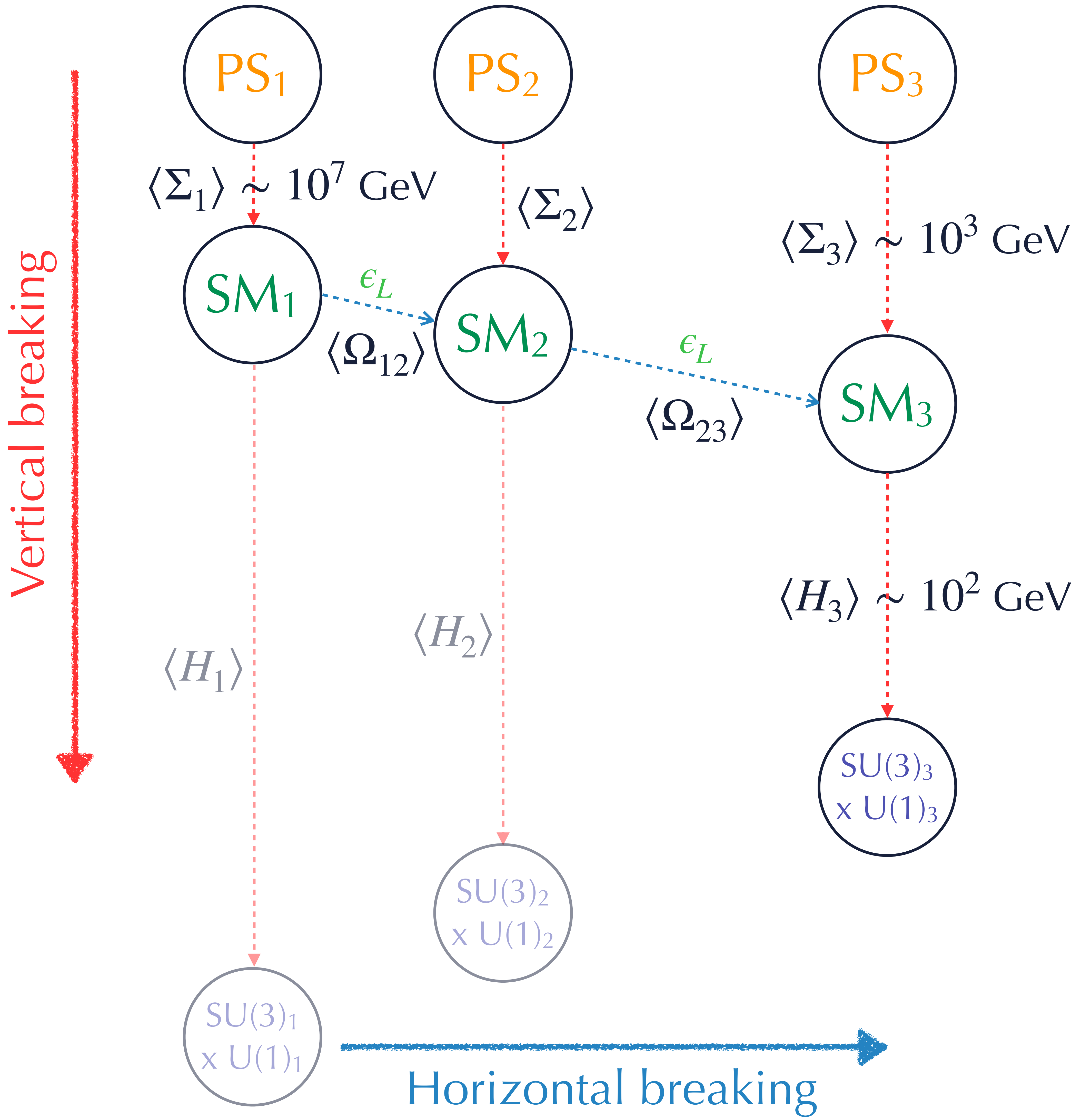
Controlling the vevs to:

- reproduce the hierarchies in the Yukawa matrices
- address the B anomalies

Suppressed nearest-neighbour interaction provides stability of the SM Higgs sector

[Allwicher, Isidori, Thomsen, 2011.01946]

short/long line = large/small vev



$\Sigma_i \sim (4,1,2)_i$

$\langle\Sigma_3\rangle = \epsilon_\Sigma \langle\Sigma_2\rangle = \epsilon_\Sigma^2 \langle\Sigma_1\rangle$

$H_i \sim (1,2,\bar{2})_i$

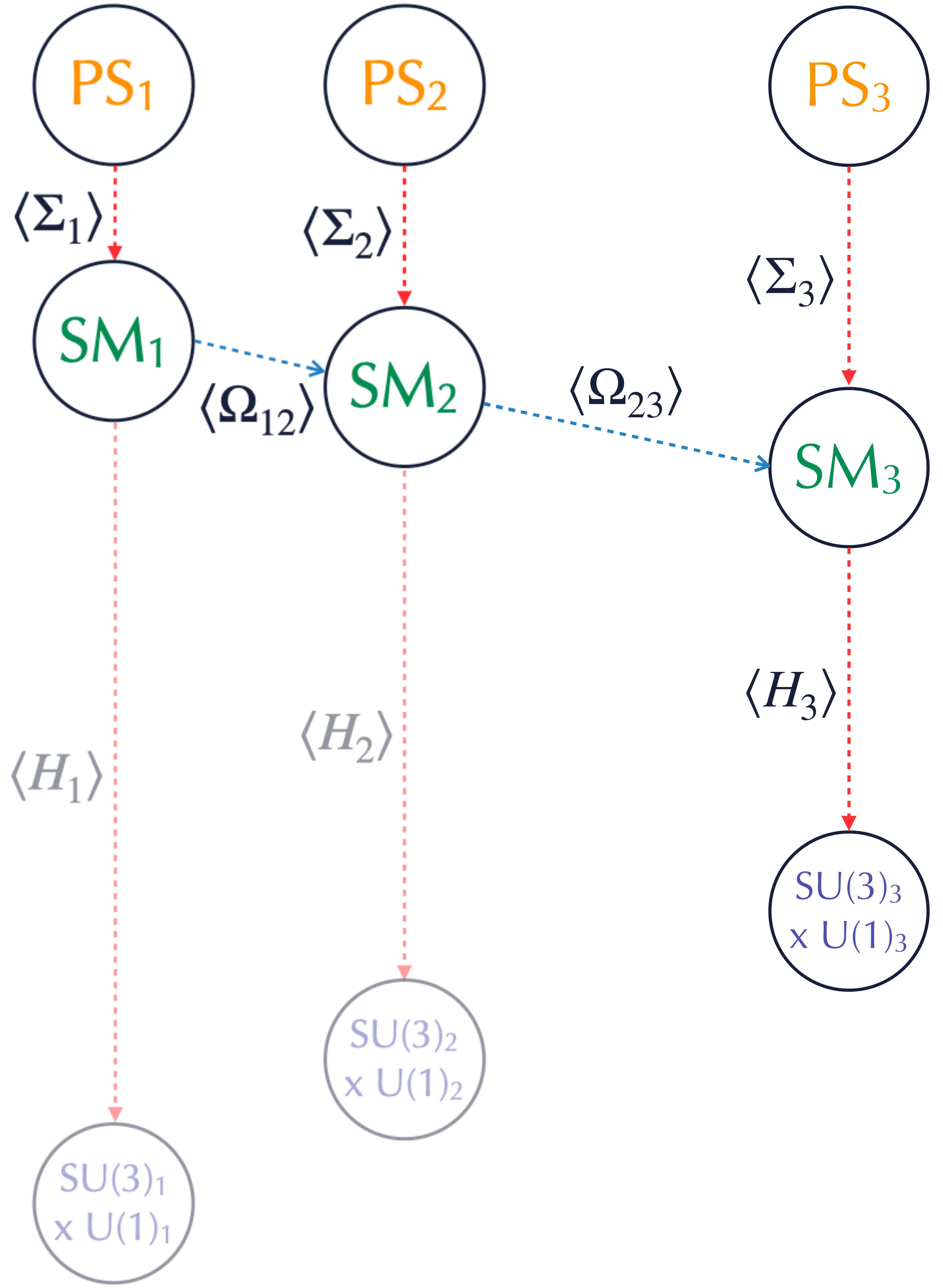
$\langle H_1\rangle = \epsilon_H \langle H_2\rangle = \epsilon_H^2 \langle H_3\rangle$

PS³ three-site model

Low-energy model

FCNC constraints fix

$$\left.\begin{aligned} PS_{1,2} &\to SM_{1,2} \\ G_1 \times G_2 &\to G_{1+2} \end{aligned}\right\} \geq 10^3 \text{ TeV}$$



PS³ three-site model

Low-energy model

Flavour structure of the SM:

- Fermion masses

$$\bar{\Psi}_L^{(i)} H_i \Psi_R^{(i)}$$

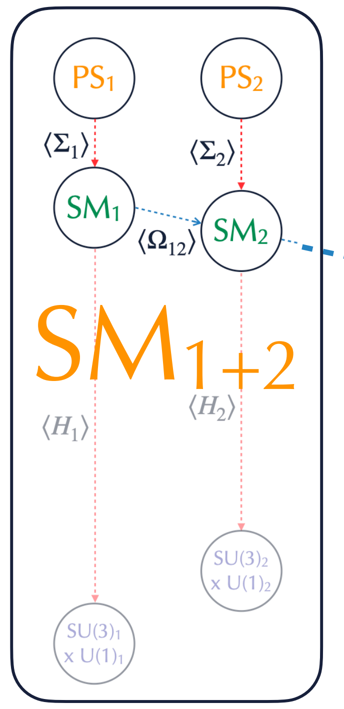
$$\langle H_1 \rangle = \epsilon_H \langle H_2 \rangle = \epsilon_H^2 \langle H_3 \rangle$$

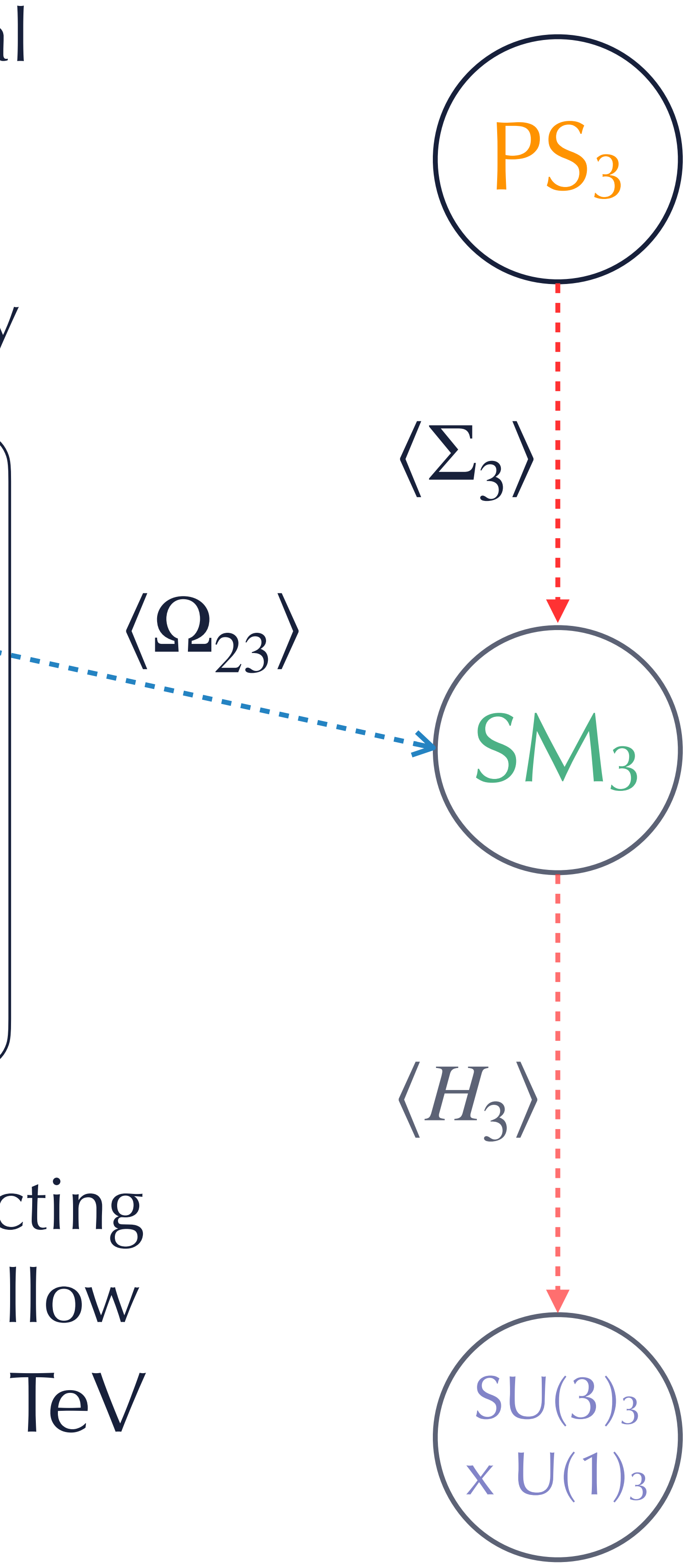
- CKM mixings

$$\epsilon_L \bar{\Psi}_L^{(2)} \frac{\Omega_4}{f_4} \frac{\Omega_L}{f_L} H_3 \Psi_R^{(3)}$$

$$\vdots$$

accidental $U(2)^5$ flavour symmetry





with ϵ_H, ϵ_L acting as spurions allow $\langle \Sigma_3 \rangle$ ~ few TeV

Contribution to B anomalies:

- PS₃ leptoquark with mass $\langle \Sigma_3 \rangle$

Flavour non-universal vector LQ $U_1 \sim (3,1)_{2/3}$

✓ couples mainly to 3rd family
✓ coupling to light families $\propto \epsilon_{ij}^L$

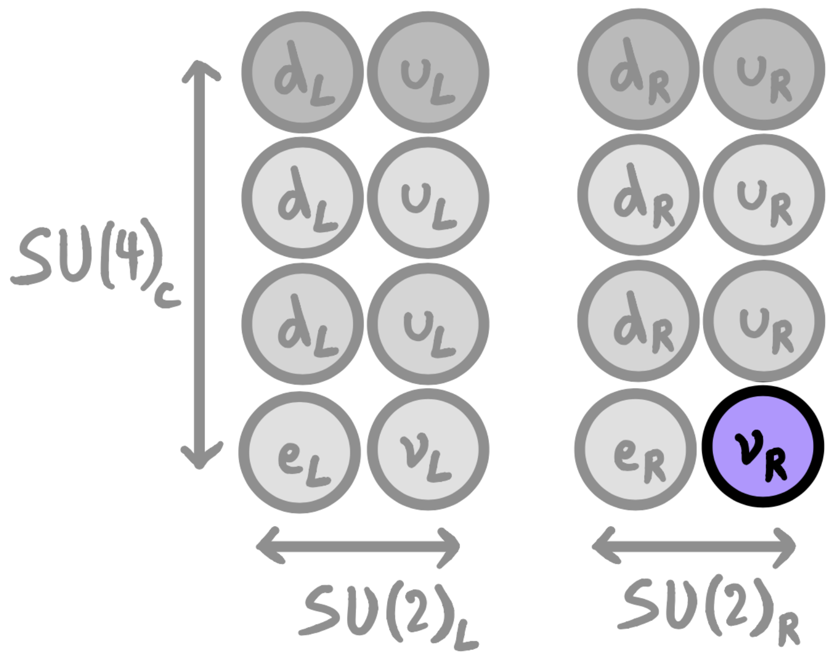
[Di Luzio, Fuentes-Martìn, Greljo, Nardecchia, Renner, 1808.00942; Cornella, Fuentes-Martìn, Isidori, 1903.11517; Fuentes-Martìn, Isidori, König, Selimovic, 1910.13474, 2006.16250. 2009.11296]

⇒ This model with nearest neighbour interactions provides a dynamical description of the flavour sector of the SM consistent with B anomalies for $\epsilon_R \approx 0$, $\epsilon_H \sim \epsilon_L^2 \sim 10^{-2}$

Neutrino Extension to PS³

Neutrino problem

PS multiplets:



Quark-lepton unification in its original form implies

$$m_e^{(i)} = m_d^{(i)} \qquad \text{and} \qquad \cancel{m_\nu^{(i)} = m_u^{(i)}}$$

Low-scale unification $\langle \Sigma_3 \rangle \sim$ TeV implies Majorana mass for ν_R is limited by $m_{\nu_R}^{(3)} \leq$ TeV

~~type-I Seesaw~~ $m_\nu \approx \dfrac{m_D^2}{m_{\nu_R}}$ (works for 1st family $\dfrac{m_u^2}{\langle \Sigma_1 \rangle} \sim 10^{-2}$ eV)

⇒ We need a new source to suppress the Dirac mass **12** orders of magnitude above the exp. bounds

$$m_\nu^{\mathrm{D}} = m_t \sim 100 \text{ GeV} \qquad m_\nu^{\exp} \leq 0.1 \text{ eV}$$

Minimal extension: add fermion singlets $S_L^{(i)}$ with (hierarchical) Majorana masses to implement inverse seesaw

[Greljo, Stefanek, 1802.04274]

Neutrino Extension to PS³

Inverse Seesaw setup

$$M_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^\intercal & 0 & m_R^\intercal \\ 0 & m_R & \mu \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \\ S_L^c \end{pmatrix}$$

Neutrino solution

$$m_\nu \approx m_D m_R^{-1} \mu (m_R^{-1})^\intercal m_D^\intercal$$

for $m_D^{(i)} \sim m_u^{(i)} \sim (10^{-2}, 1, 10^2)$ GeV

$m_R^{(i)} \sim (10^7, 10^5, 10^3)$ GeV

$\mu \sim (10^7, 10^{-1}, 10^{-9})$ GeV

$\Rightarrow 10^{-2}$ eV $\lesssim m_\nu^{(i)} \lesssim 10^{-1}$ eV

μ generated dynamically by singlet scalar Φ_i breaking spontaneously $U(1)_F$ ← fermion number

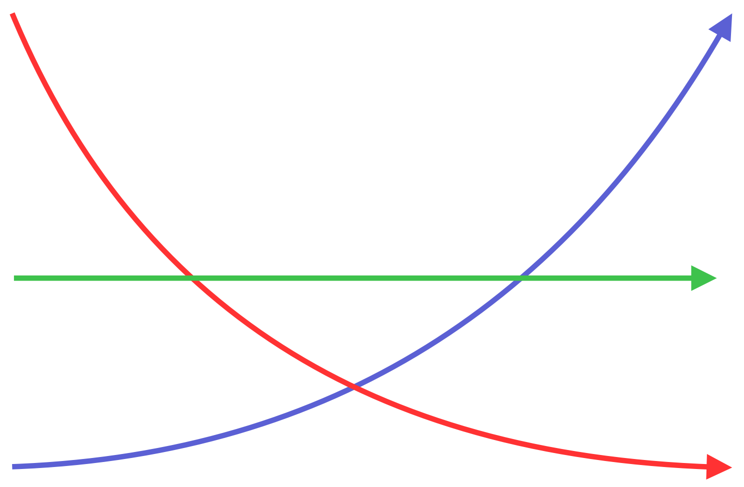
$$-\mathscr{L}_\nu \supset \underbrace{\bar{\Psi}_L^{(i)} H_i \Psi_R^{(i)}}_{\text{Dirac mass } m_D} + \underbrace{S_L^{(i)} \Sigma_i^\dagger \Psi_R^{(i)}}_{m_R \text{ matrix}} + \underbrace{(\epsilon_S \bar{S}_L^{(2)} \Sigma_1^\dagger \Psi_R^{(1)} + \cdots)}_{\text{Mixing}} + \underbrace{\bar{S}_L^{(i)} \Phi_i S_L^{(i)c}}_{\text{Majorana mass } \mu}$$

Dirac mass m_D	m_R matrix	Mixing	Majorana mass μ
$\bar{\Psi}_L^{(i)} H_i \Psi_R^{(i)}$	$S_L^{(i)} \Sigma_i^\dagger \Psi_R^{(i)}$	$(\epsilon_S \bar{S}_L^{(2)} \Sigma_1^\dagger \Psi_R^{(1)} + \cdots)$	$\bar{S}_L^{(i)} \Phi_i S_L^{(i)c}$
$\langle H_1 \rangle = \epsilon_H \langle H_2 \rangle = \epsilon_H^2 \langle H_3 \rangle$	$\langle \Sigma_3 \rangle = \epsilon_\Sigma \langle \Sigma_2 \rangle = \epsilon_\Sigma^2 \langle \Sigma_1 \rangle$	no link field needed as $U(1)_F$ global	$\langle \Phi_3 \rangle = \epsilon_\Phi \langle \Phi_2 \rangle = \epsilon_\Phi^2 \langle \Phi_1 \rangle$

Erase U(2)⁵ in the neutrino sector:

very hierarchical $\mu^{(i)} \sim \langle \Phi_i \rangle$

hierarchical ratio $\dfrac{m_D^{(i)}}{m_R^{(i)}}$



$\Rightarrow$ anarchical $m_\nu^{(i)}$

(both masses and mixing angles)

Realised for:

$\epsilon_\Phi \sim \epsilon_H^2 \, \epsilon_\Sigma^2$

$\epsilon_S \sim \epsilon_H \, \epsilon_\Sigma$

Neutrino extension

Neutrino prediction

Signature of the model: mixing between active neutrino and pseudo-Dirac neutral heavy states yields

PMNS unitarity violation

with expected pattern:

$$\eta \equiv |1 - NN^\dagger| \sim \left|\frac{m_D^{(3)}}{m_R^{(3)}}\right|^2 \begin{pmatrix} \epsilon_L^4 & \epsilon_L^3 & \epsilon_L^2 \\ \epsilon_L^3 & \epsilon_L^2 & \epsilon_L \\ \epsilon_L^2 & \epsilon_L & 1 \end{pmatrix}$$

First sign of violation in

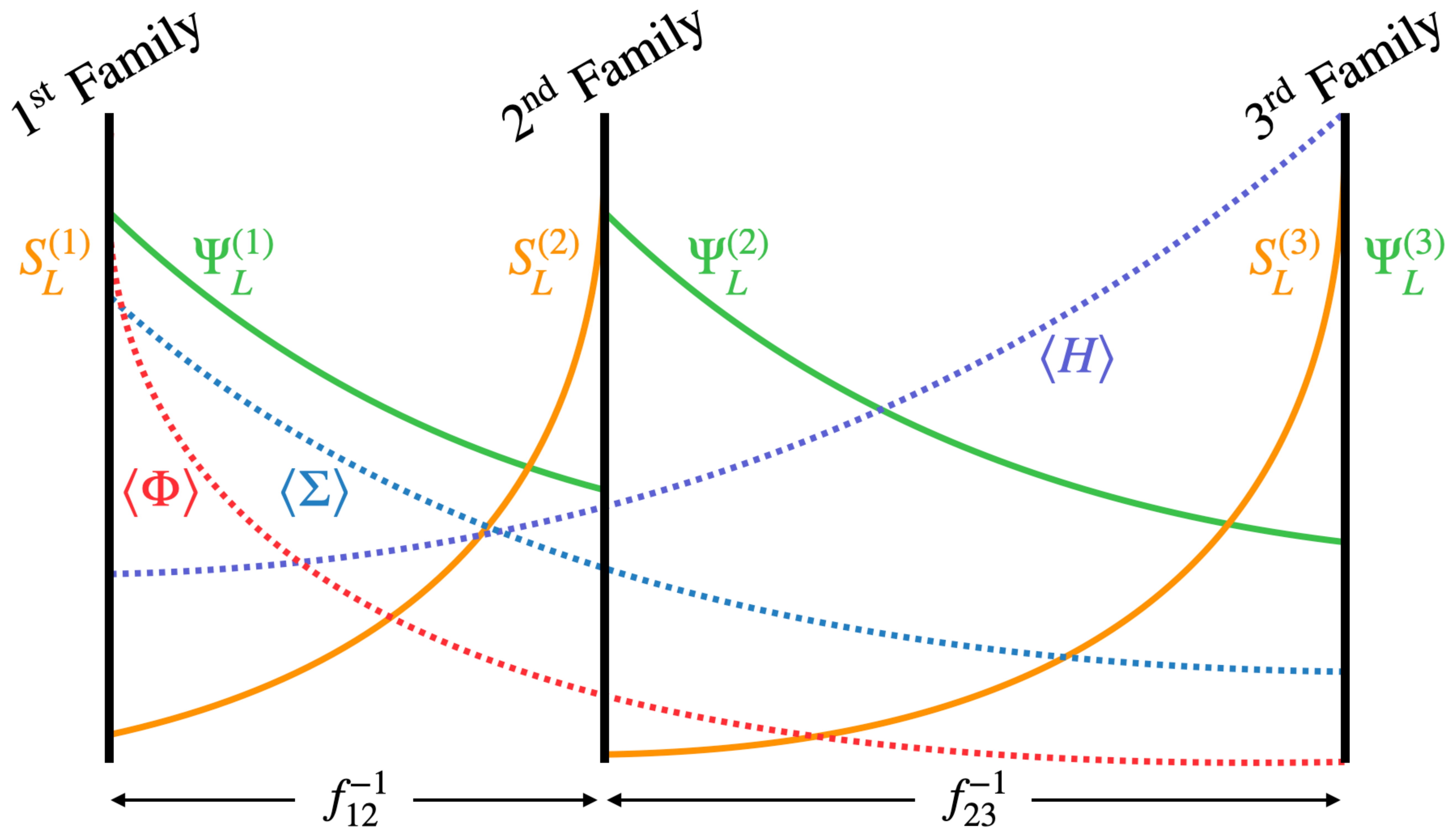
$$\eta_{33} \approx \left|\frac{m_D^{(3)}}{m_R^{(3)}}\right|^2 \sim \left|\frac{100\ \text{GeV}}{2\ \text{TeV}}\right|^2 = 2.5 \times 10^{-3}$$

$$\eta_{33}^{\text{exp}} < 5.3 \times 10^{-3} \quad (90\ \%\ \text{C.L.})$$

[Antusch, Fischer, 1407.6607]

5D picture

Full model in 5D



[Fuentes-Martín, Isidori, Lizana, Selimovic, Stefanek, w.i.p]

Nearest-neighbour suppression factor:

$$\epsilon_{ij}^F = e^{-M_F/f_{ij}} \quad \text{with } f_{ij} = |y_i - y_j|^{-1}$$

Equivalence between 3-site and 5D picture

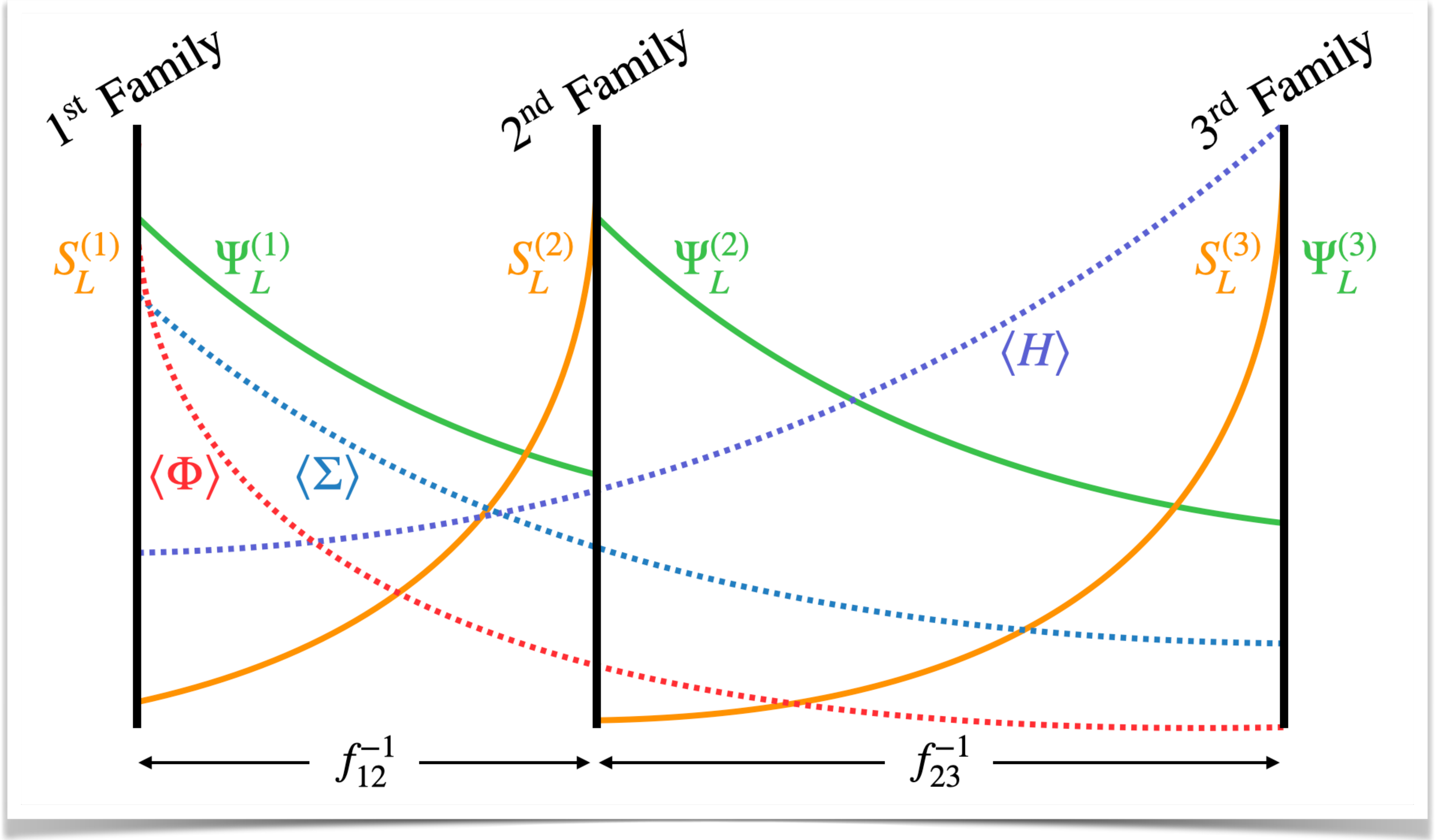
$\epsilon_R \approx 0$	$M_R \gtrsim 3\, M_L$
$\epsilon_H \sim \epsilon_L^2$	$M_H \approx 2\, M_L$
$\epsilon_\Phi \sim \epsilon_S^2$	$M_\Phi \approx 2\, M_S$
$\epsilon_S \sim \epsilon_H\, \epsilon_\Sigma$	$M_\Sigma \approx M_S - 2\, M_L$

$\hookrightarrow$ same order 5D bulk masses M_F can explain large hierarchies observed

Conclusion

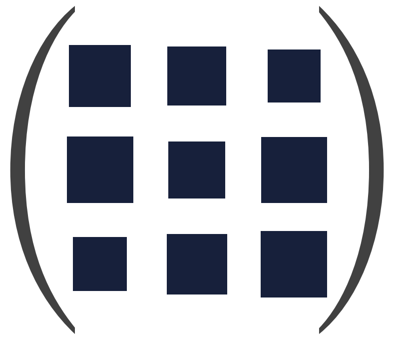
The three-site / 5D flavour non-universal Pati-Salam model:

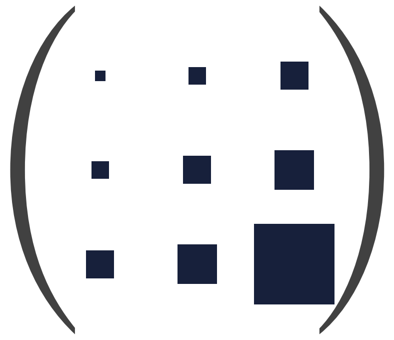
- quark-lepton unification (with quantisation of $U(1)_Y$ charges)
- natural description of the SM Yukawa couplings in terms of $\mathcal{O}(1)$ parameters and fundamental scale ratios
- explanation for the hinted B anomalies



The neutrino extension:

- minimal: addition of fermion singlets $S_L^{(i)}$ and scalar singlets Φ_i breaking $U(1)_F$
- anarchic light neutrino mass matrix despite $U(2)^5$ in the Yukawa matrices
- predicts PMNS unitarity violation with η_{33} close to experimental bounds,
- natural setup in the context of extra dimensions

$m_\nu \sim$ 

$\eta \sim$ 


*crossing fingers for next year conference to be like this picture
Thank you !*

Back-up slides

Neutrino mass matrix diagonalization

	Dirac mass m_D		m_R matrix		Mixing		Majorana mass μ
$-\mathscr{L}_\nu \supset$	$\bar{\Psi}_L^{(i)} H_i \Psi_R^{(i)}$	$+$	$\bar{S}_L^{(i)} \Sigma_i^\dagger \Psi_R^{(i)}$	$+$	$(\epsilon_S \bar{S}_L^{(2)} \Sigma_1^\dagger \Psi_R^{(1)} + \cdots)$	$+$	$\bar{S}_L^{(i)} \Phi_i S_L^{(i)c}$

$$-\mathscr{L}_\nu \supset \frac{1}{2} \bar{n}_L \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix} n_L^c + \mathrm{h.c.} \qquad \text{with } n_L = \begin{pmatrix} \nu_L \\ \nu_R^c \\ S_L \end{pmatrix}, \ M_S = \begin{pmatrix} m_D & 0 \end{pmatrix} \ \text{and} \ M_R = \begin{pmatrix} 0 & m_R^\intercal \\ m_R & \mu \end{pmatrix}$$

$m_D^{(i)} \sim (10^{-2}, 1, 10^2)$ GeV
$m_R^{(i)} \sim (10^7, 10^5, 10^3)$ GeV
$\mu \sim (10^7, 10^{-1}, 10^{-9})$ GeV

Perturbative block diagonalization: $W^\intercal \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix} W = \begin{pmatrix} (m_\nu)_{3\times 3} & 0 \\ 0 & (m_h)_{6\times 6} \end{pmatrix}$ with $W = \begin{pmatrix} \sqrt{1 - BB^\dagger} & B \\ -B^\dagger & \sqrt{1 - B^\dagger B} \end{pmatrix}$

[Schechter, Valle, PRD 25 (1982) 774]

Since $\det M_R = -\det(m_R^\intercal m_R)$, all eigenvalues $m_R^{(i)} > m_D^{(i)} \rightarrow$ expansion parameter $m_D^{(i)}/m_R^{(i)}$ independent of μ.

At lowest order: $m_\nu \approx -M_D M_R^{-1} M_D^\intercal$, $m_h \approx M_R$ and $B \approx M_D M_R^{-1}$ with $M_R^{-1} = \begin{pmatrix} -m_R^{-1} \mu (m_R^\intercal)^{-1} & m_R^{-1} \\ (m_R^\intercal)^{-1} & 0 \end{pmatrix}$

$$\Rightarrow \quad m_\nu \approx m_D m_R^{-1} \mu (m_R^\intercal)^{-1} m_D^\intercal$$

PMNS unitarity violation

PMNS:

$$N \approx (1 - BB^\dagger/2)U_\ell^\intercal U_\nu$$

where B is the mixing angle between active neutrino and sterile states.

Unitarity violation:

$$\eta \equiv |1 - NN^\dagger| \approx m_D m_R^{-1}(m_D m_R^{-1})^\dagger$$

$$\eta \sim \left|\frac{m_D^{(3)}}{m_R^{(3)}}\right| \begin{pmatrix} (\epsilon_{12}^L\epsilon_{23}^L)^2 & \epsilon_{12}^L(\epsilon_{23})^2 & \epsilon_{12}^L\epsilon_{23}^L \\ \epsilon_{12}^L(\epsilon_{23}^L)^2 & (\epsilon_{23})^2 & \epsilon_{23}^L \\ \epsilon_{12}^L\epsilon_{23}^L & \epsilon_{23} & 1 \end{pmatrix}$$

Strongest constraint:

$$\eta_{33} \approx \left|\frac{m_D^{(3)}}{m_R^{(3)}}\right| < 5.3 \times 10^{-3}$$

[Antusch, Fischer, 1407.6607]

For $m_R^{(3)} \sim 10^3$ GeV, we require $m_D^{(3)} \lesssim 0.4 m_t \approx 70$ GeV $\rightarrow$ similar to $m_\tau \approx 0.8 m_b$

↪ no fine-tuning needed but unitarity violation close to present experimental bounds.

PMNS unitarity violation

Miminal Unitarity Violation: [Antusch, Fischer, 1407.6607]

$$\mathscr{L}_{\mathrm{MUV}} = \mathscr{L}_{RMSM} + \delta\mathscr{L}^{d=5} + \delta\mathscr{L}^{d=6}$$

$$\delta\mathscr{L}^{d=6} = c^{d=6}_{\alpha\beta}\left(\overline{L}_\alpha\tilde{\phi}\right) i\partial\left(\tilde{\phi}^\dagger L_\beta\right) \qquad \delta\mathscr{L}^{d=5} = \frac{1}{2}c^{d=5}_{\alpha\beta}\left(\overline{L}^c_\alpha\tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger L\right) + \mathrm{h.c.}$$

→ canonical normalization of the kinetic term after EWSB leads to a non-unitary leptonic mixing matrix

- Set of observables:
  - Electroweak precision observables
    - weak mixing angle
    - Z decay parameters
    - W decays
    - W boson mass
  - Low energy observables
    - Universality tests (τ, π, μ, W and K decays)
    - Rare charged leptons decays
    - Neutrino deep inelastic scattering
    - Low energy measurements of s_W^2
  - CKM unitarity

- Constraints on non-unitarity:

At 90 % C.L.

$$|NN^\dagger| = \begin{pmatrix} 0.9979 - 0.9998 & < 10^{-5} & < 2.1\times10^{-3} \\ < 10^{-5} & 0.9996 - 1.0 & < 8\times10^{-4} \\ < 2.1\times10^{-3} & < 8\times10^{-4} & 0.9947 - 1.0 \end{pmatrix}$$

- Improvements from future experiments:

FCC-ee at CERN, Mu3e at PSi, Mu2e at Fermilab, COMET at J-PARC…

$U(1)_F$ breaking

Global symmetry:

$$U(1)_{F_1} \times U(1)_{F_2} \times U(1)_{F_3} \xrightarrow[\text{neighbour interactions}]{\text{turn on nearest-}} U(1)_F$$

$U(1)_F$ spontaneously broken $\rightarrow$ Nambu-Goldstone boson:

Majoron J

with $\mathscr{L}_J \supset \frac{i}{2}\frac{J}{\langle\Phi_1\rangle}\mu_i \bar{S}_L^{(i)} S_L^{(i)c}$

Given a mass through explicit breaking at $\Lambda_F \gg \langle\Phi_1\rangle$:

$$\mathscr{L}_J \supset c_1 \frac{\Phi_1^5}{\Lambda_F} + c_2 \frac{\Phi_1^4 \Phi_1^*}{\Lambda_F} + c_3 \frac{\Phi_1^3 \Phi_2^*}{\Lambda_F} + \mathrm{h.c.}$$

$$m_J^2 \approx \frac{1}{2}(25c_1 + 9c_2 + c_3)\frac{\langle\Phi_1\rangle^3}{\Lambda_F}$$

- If $U(1)_F$ broken at Planck scale $m_J \approx 50$ GeV and decay $J \rightarrow \nu\nu$ with width controlled by $(m_\nu/\langle\Phi_1\rangle)^2$.

↪ long lived on cosmological scale and potentially lead to unacceptably large relic abundance.

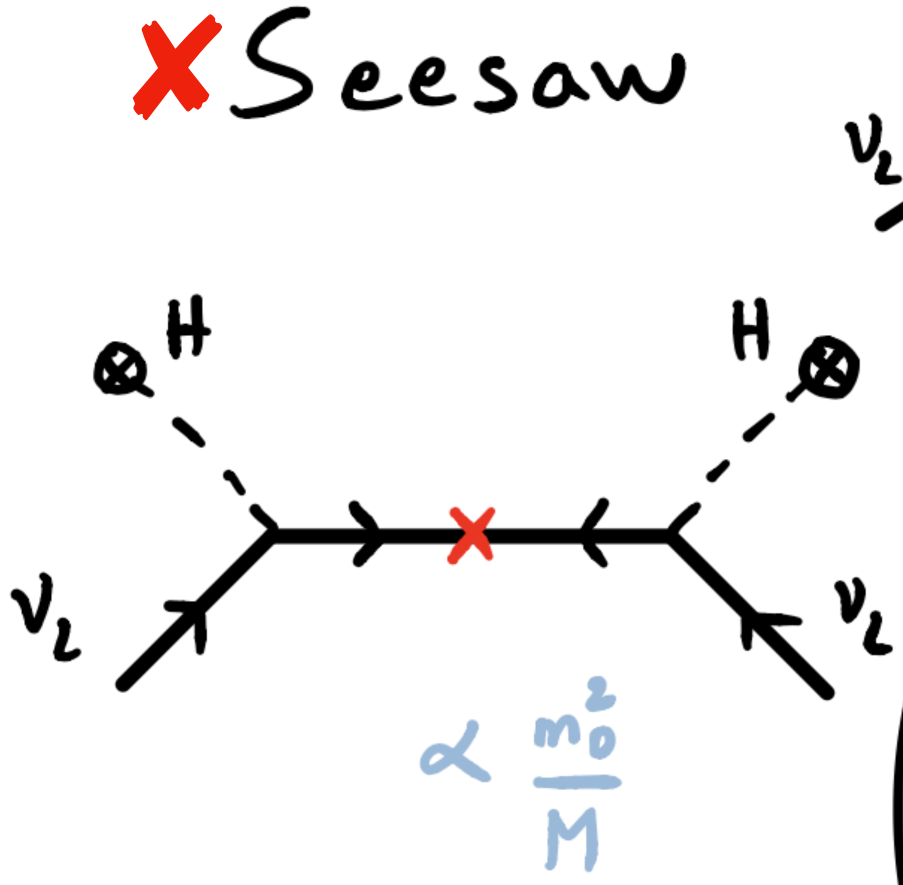
[Akhmedov, Berezhiani, Mohapatra,Senjanovic, hep-ph 9209285]

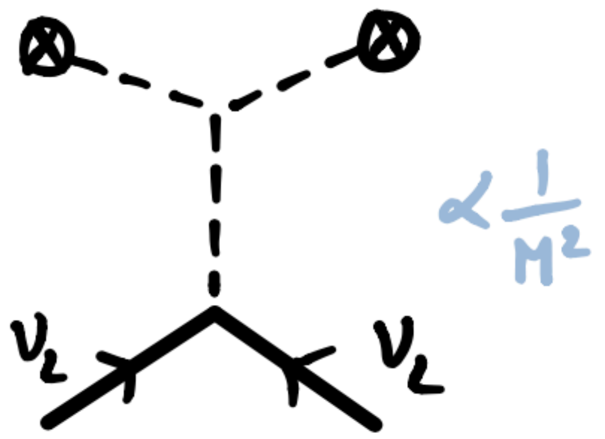
- If $\Lambda_F \lesssim 10^{12}$ GeV then $m_J \gtrsim m_R^{(2)}$ and decay $J \rightarrow \nu_R^{(2)}\nu_R^{(2)}$ open with lifetime of $\tau \sim 1$ ps.

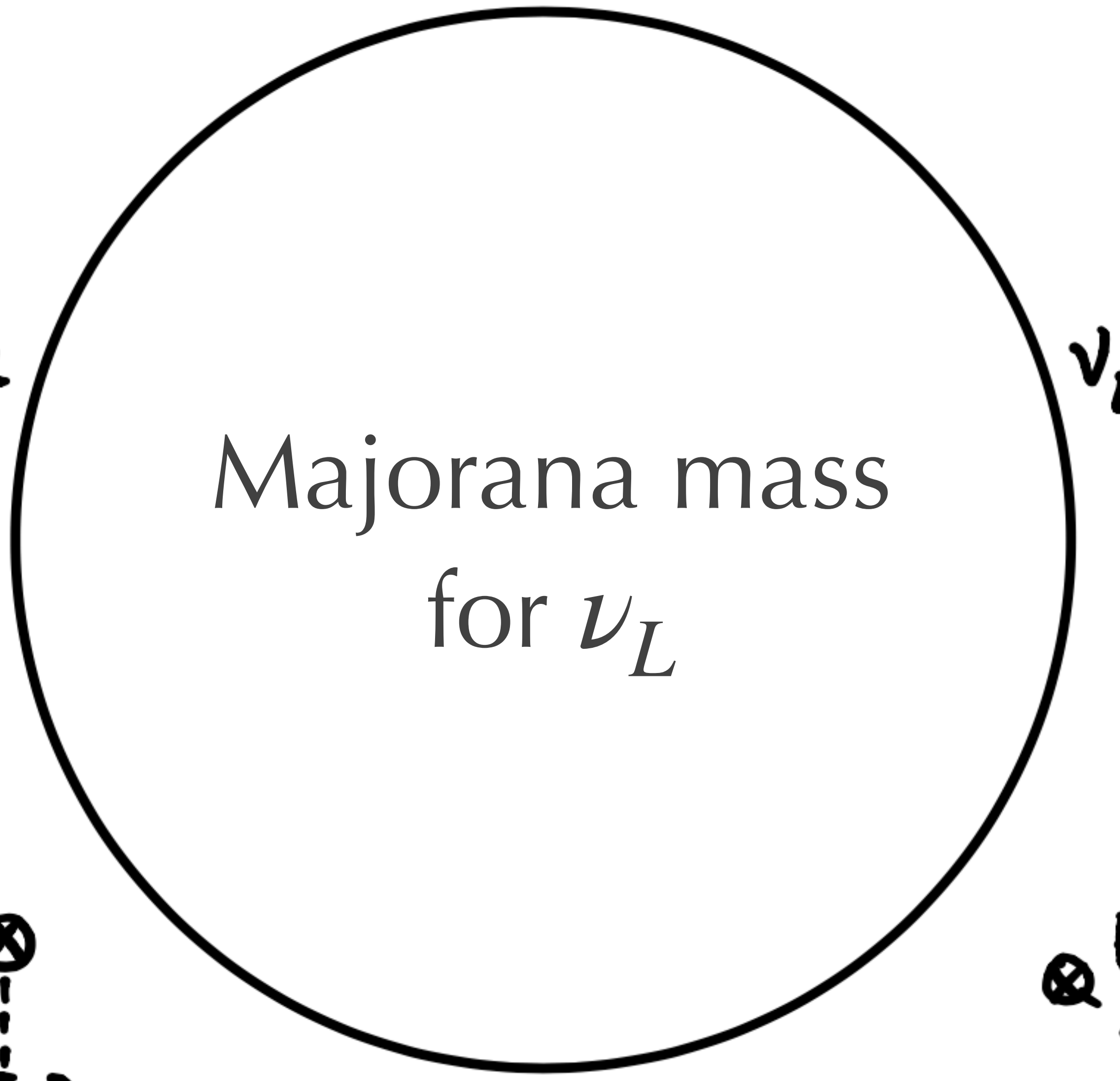
↪ no problem with relic abundances.

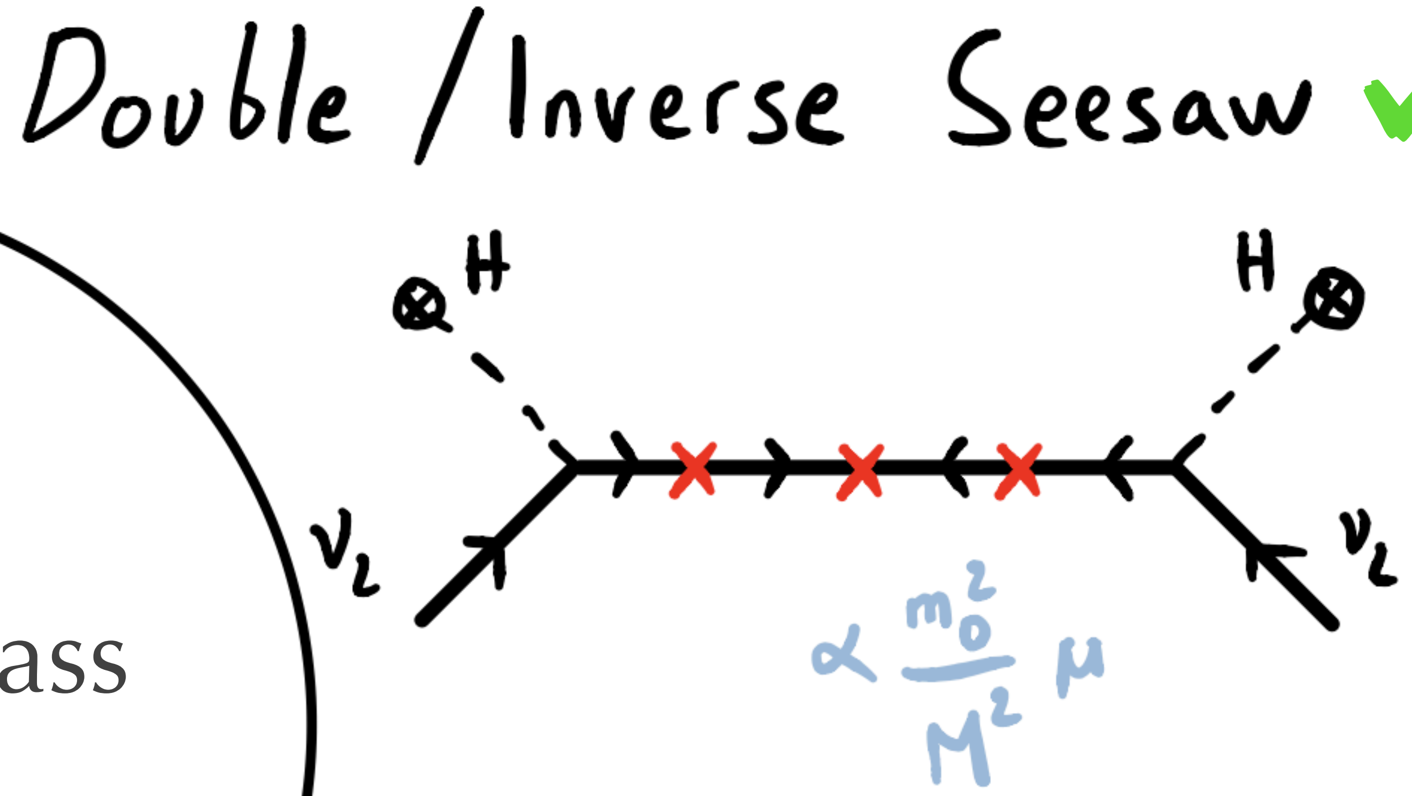
Neutrino mechanisms

From low-scale quark-lepton unification and without fine-tuning: $y_\nu \sim y_t$ and $m_{\nu_R} \lesssim 1$ TeV, hence type I Seesaw is excluded.

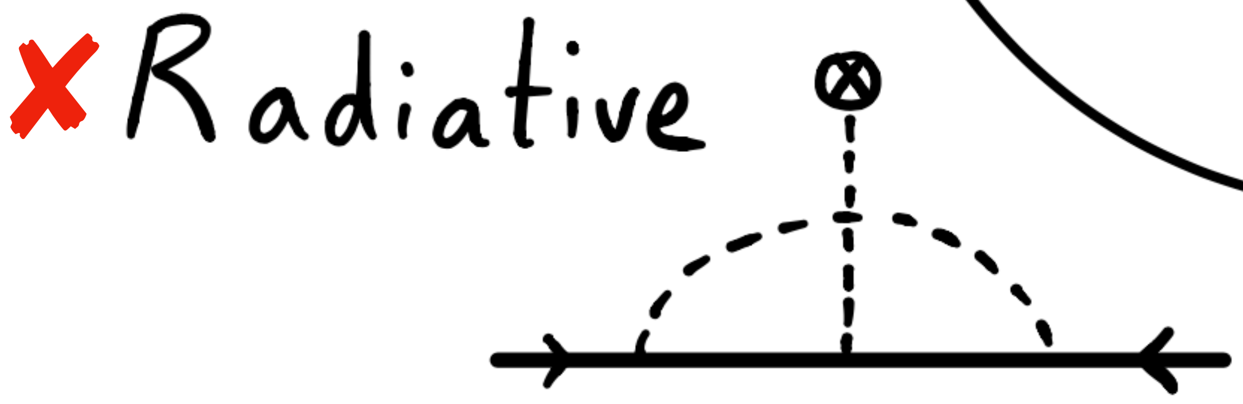






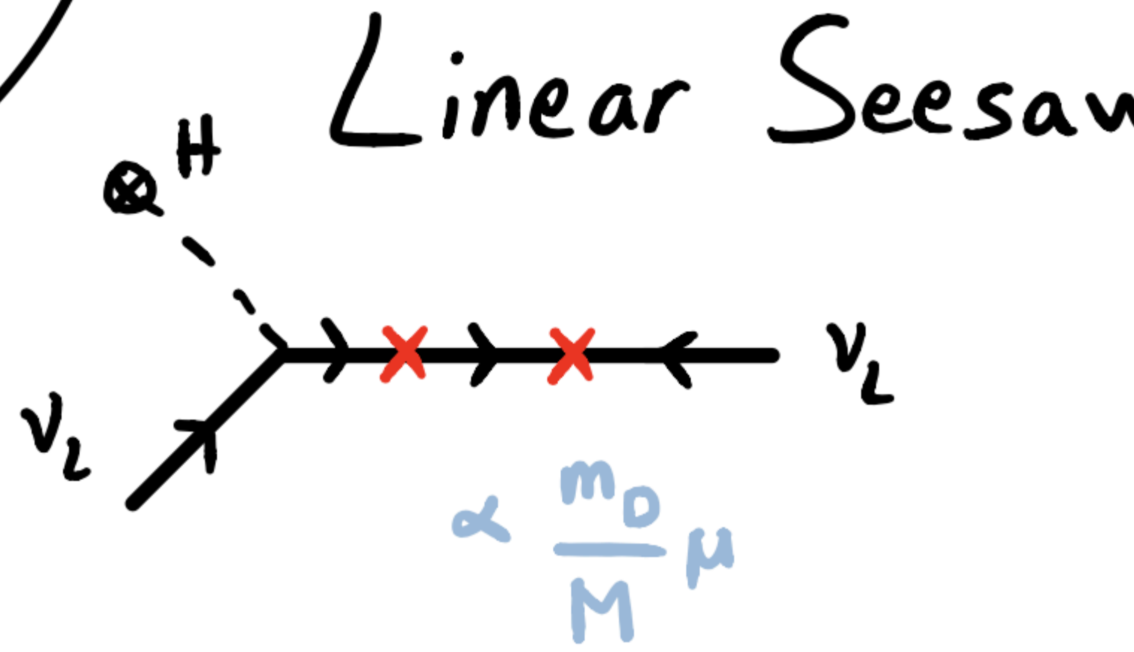


Inverse Seesaw only requires an additional fermion singlet S with a small Majorana mass μ.



A (big) Dirac mass term is already present between ν_R and ν_L, excluding type II/III Seesaw and radiative models.

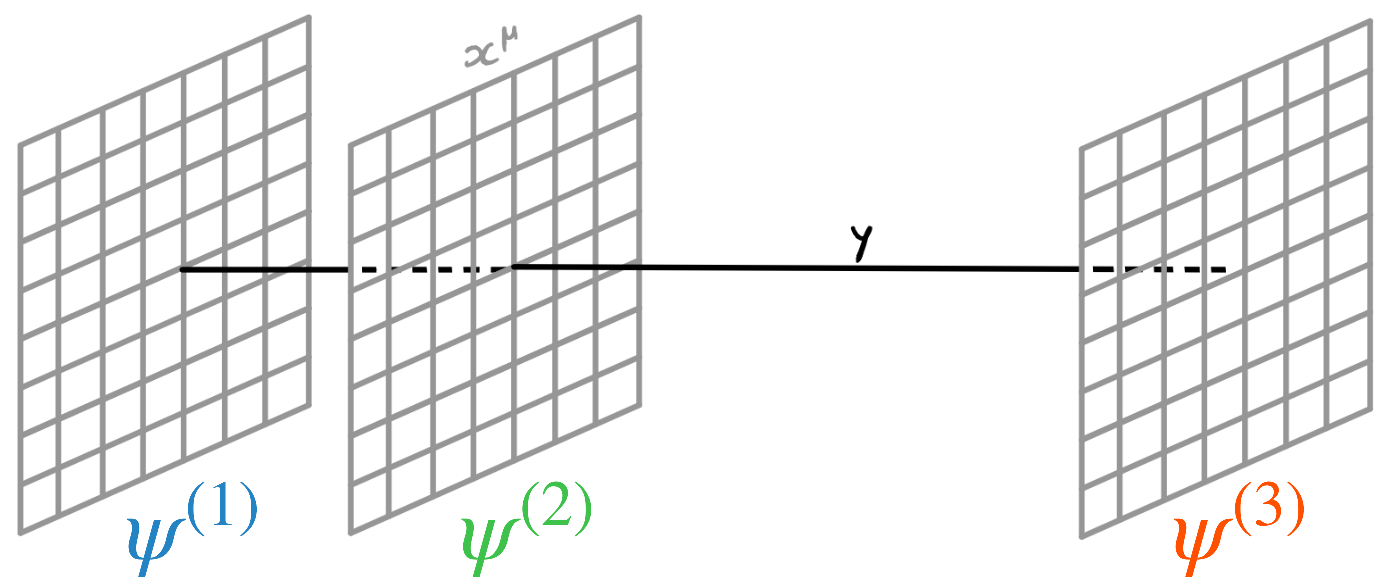
[Valle, hep-ph 0608101]



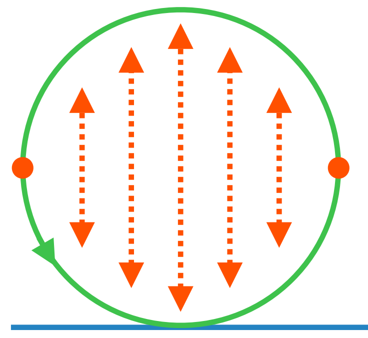
For Linear Seesaw, Ψ_L has no scalar to make a singlet with.

$\psi_L^{(i)} \sim (4,2,1)_i$ Scalars: $\Omega_{ij}^L \sim (1,2,1)_i \times (1,\bar{2},1)_j$ $H \sim (1,2,\bar{2})_3$
$\Omega_{ij}^R \sim (1,1,2)_i \times (1,1,\bar{2})_j$ $\Sigma \sim (4,1,2)_1$
$\Omega_{ij}^4 \sim (4,2,1)_i \times (\bar{4},\bar{2},1)_j$

5D construction



Basics of an additional extra-dimension: (5D, 4D)



Compactification → tower of KK modes: $\Phi(x^\mu, y) = \sum_n \phi_n(x^\mu)\, f_n(y)$

Orbifolding or boundary conditions → realise chiral fermions

Bulk mass generates fermion zero-modes of the form: $f_L^{(i)}(y) \propto e^{-M_L|y-y_i|}$

Robin boundary condition generates exponentially decaying vev from localisation site: $\langle H(y)\rangle \sim \langle H_3 \rangle e^{-M_H|y-y_3|}$

4D couplings and masses: given by integrating over y → overlap of field profiles, for example

$$m_{4D}^{ij} \propto m_{5D}^{ij} \int dy\, f_L^{(i)}(y)\, \langle H(y)\rangle\, f_R^{(j)}(y) \sim \langle H_3 \rangle e^{-M_H|y_j-y_3|} e^{-M_L|y_i-y_j|}$$

Connection to three-site model: Identify nearest-neighbour suppression factor with exponential from y profile :

$$\epsilon_{ij}^F = e^{-M_F/f_{ij}} \qquad \text{where } f_{ij} = |y_i - y_j|^{-1}$$

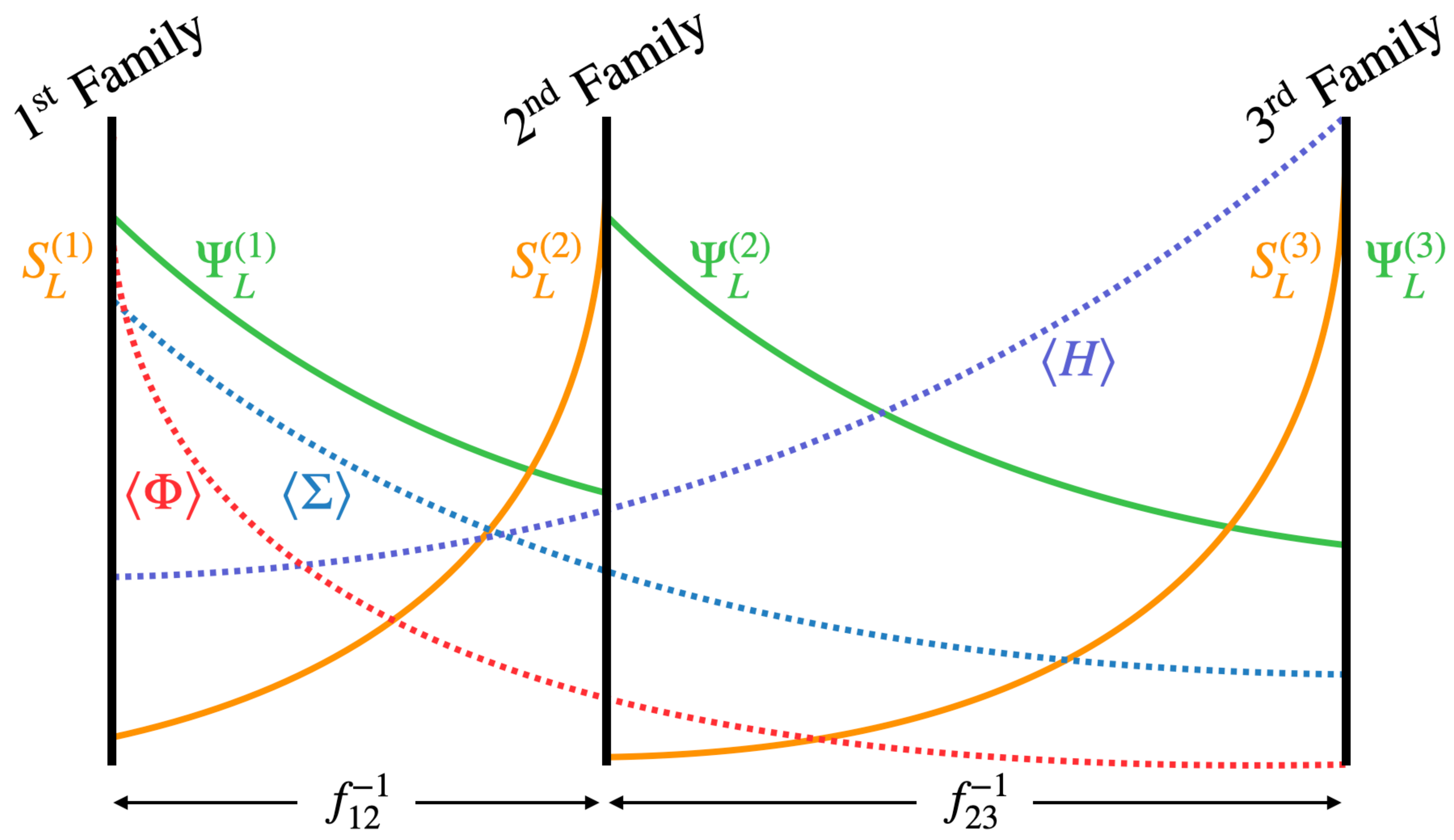
↪ same order bulk masses M_F can explain large hierarchies

5D profiles

[Dvali, Shifman, hep-ph 0001072]

5D model field content:

Fields	$SU(4)$	$SU(2)_L$	$SU(2)_R$	$U(1)_F$
Ψ_L	**4**	**2**	**1**	1
Ψ_R	**4**	**1**	**2**	1
S_L	**1**	**1**	**1**	1
Σ	**4**	**1**	**2**	0
H	**1**	**2**	$\bar{\mathbf{2}}$	0
Φ	**1**	**1**	**1**	2



Profile in the 5th dimension:

Fermions:

$f_L^{(i)}(y) \propto e^{-M_L|y-y_i|}$

$f_S^{(i)}(y) \propto e^{-M_S|y-y_i|}$

$f_R^{(i)}(y) \propto \delta(y-y_i)$

Scalars:

$\langle H(y)\rangle \sim \langle H_3\rangle e^{-M_H|y-y_3|}$

$\langle \Sigma(y)\rangle \sim \langle \Sigma_1\rangle e^{-M_\Sigma|y-y_1|}$

$\langle \Phi(y)\rangle \sim \langle \Phi_1\rangle e^{-M_\Phi|y-y_1|}$

flavour structure implies $\epsilon_{12}^L \approx 2\,\epsilon_{23}^L \Leftrightarrow \frac{f_{23}}{f_{12}} \approx \frac{2}{3}$

$\hookrightarrow$ independent on the overall 5D scale $L = f_{12}^{-1} + f_{23}^{-1}$

Gauge sector in the flat 5D

Massive vector excitations

Discrete picture

coset $\mathscr{G}_1 \times \mathscr{G}_2 \times \mathscr{G}_3 / \mathscr{G}_{\text{diag}}$ gauge bosons

eat link fields goldstones

$$m_{ij}^{\mathscr{G}} \sim g_{\mathscr{G}} \langle \Omega_{ij}^{\mathscr{G}} \rangle$$

↪ different vevs = different masses

Continuous picture

massless zero-modes gauge bosons are

supplemented by excitations tower with $m_n \sim \dfrac{n}{L}$

lowest excitation: $m_1 \sim f_{ij}$

↪ unique mass

Problems of a flat extra dimension:

1. $\langle \Omega_{ij}^4 \rangle \approx \langle \Omega_{ij}^{L,R} \rangle$ → same mass for $SU(2)_{L,R}$ and $SU(4)$ vector excitations

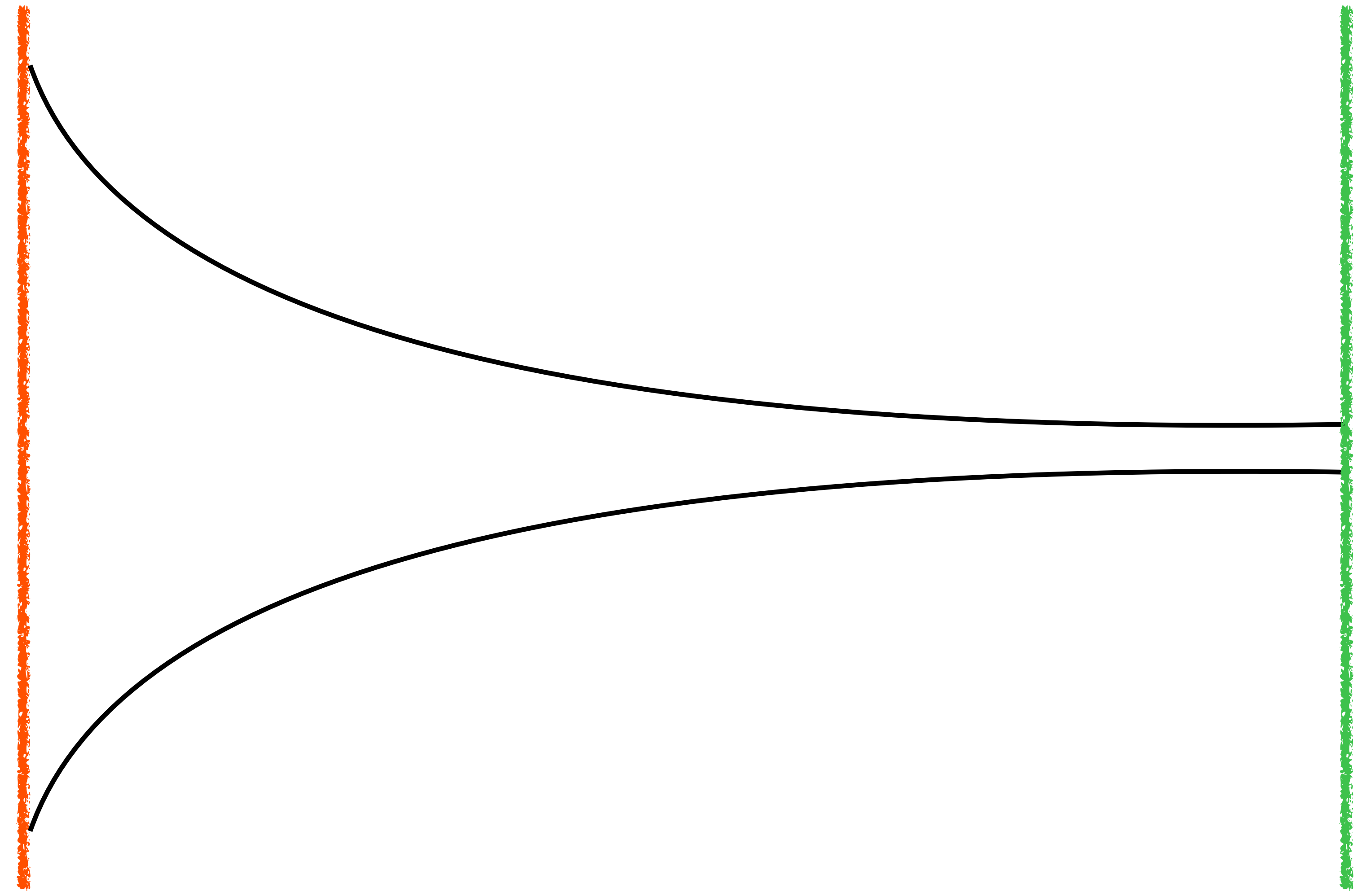
   → constraints from Z and W couplings → $\Omega_{ij}^{\mathscr{G}} \to \Omega(x_\mu, y_{\mathscr{G}})$

2. $f_{12} \sim f_{23}$ → flavour universal leptoquark → FCNC bounds → push f_{12} to 10^3 TeV or suppress 12 couplings

Warped 5D model

AdS5 geometry: $ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$

[Randall, Sundrum, hep-ph 9905221]



UV brane — $\Lambda_{\rm UV} \sim k \sim 10^4$ TeV

e^{-kL} →

IR brane — $\Lambda_{\rm IR} = v_{\rm EW}$

$kL \approx 9$

warp factor

compatible with FCNC suppression in RH currents $e^{-2kf_{23}} \sim 10^{-5}$
and realising correct fermion mass hierarchy with $\langle H(y)\rangle \propto e^{2ky}$

Features of the warped extra dimension:

→ flavour structure unchanged

→ coupling of massive vectors $\propto \left(-\frac{1}{kL}, -\frac{1}{kL}, 1\right)$

↪ emergence of $U(2)^5$ flavour symmetry

→ $SU(2)_L$ and $SU(4)$ excitations still have same mass, constraints from $Z \to \tau_L\tau_L$ incompatible with required mass for the anomalies of $m_{LQ} \leq 5$ TeV

Reasons

- PS_{5D} generators all equal on IR
- unique fundamental scale kL

Potential solutions

- brane kinetic terms
- 6D construction