UNIVERSITY OF Southampton
School of Physics and Astronomy

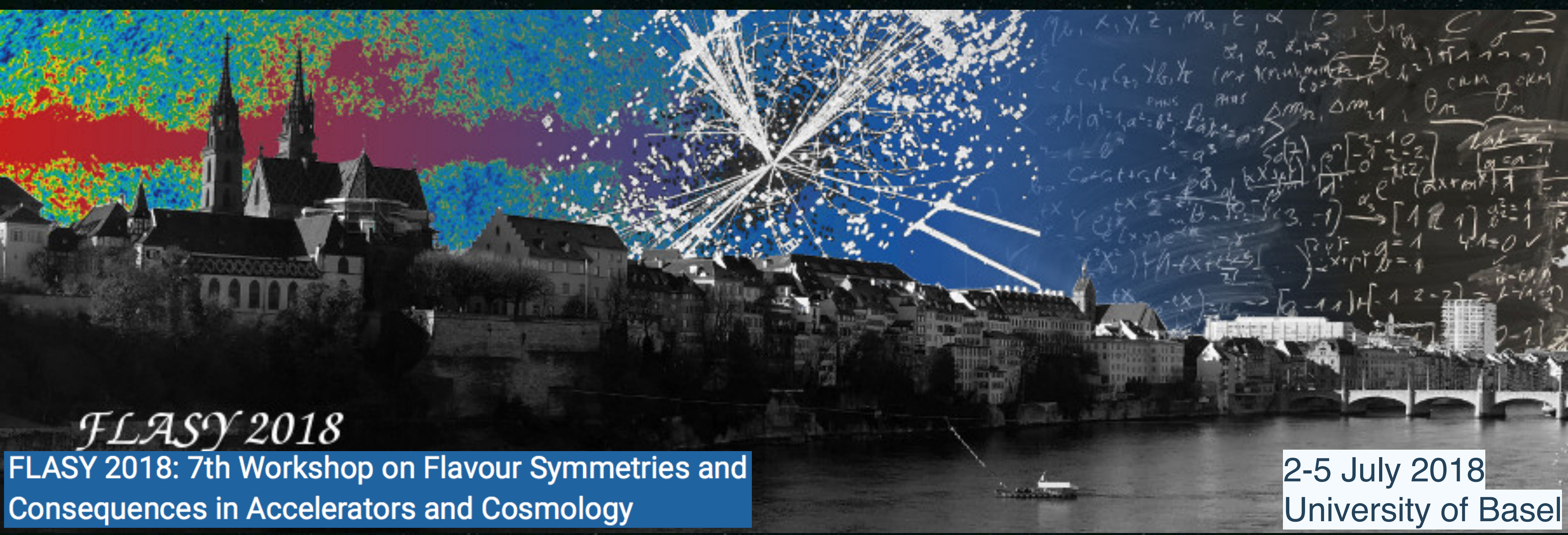
elusives
neutrinos, dark matter & dark energy physics

invisiblesPlus

Theories of Flavour

From the Planck Scale to the Electroweak Scale

Steve King



FLASY 2018: 7th Workshop on Flavour Symmetries and Consequences in Accelerators and Cosmology

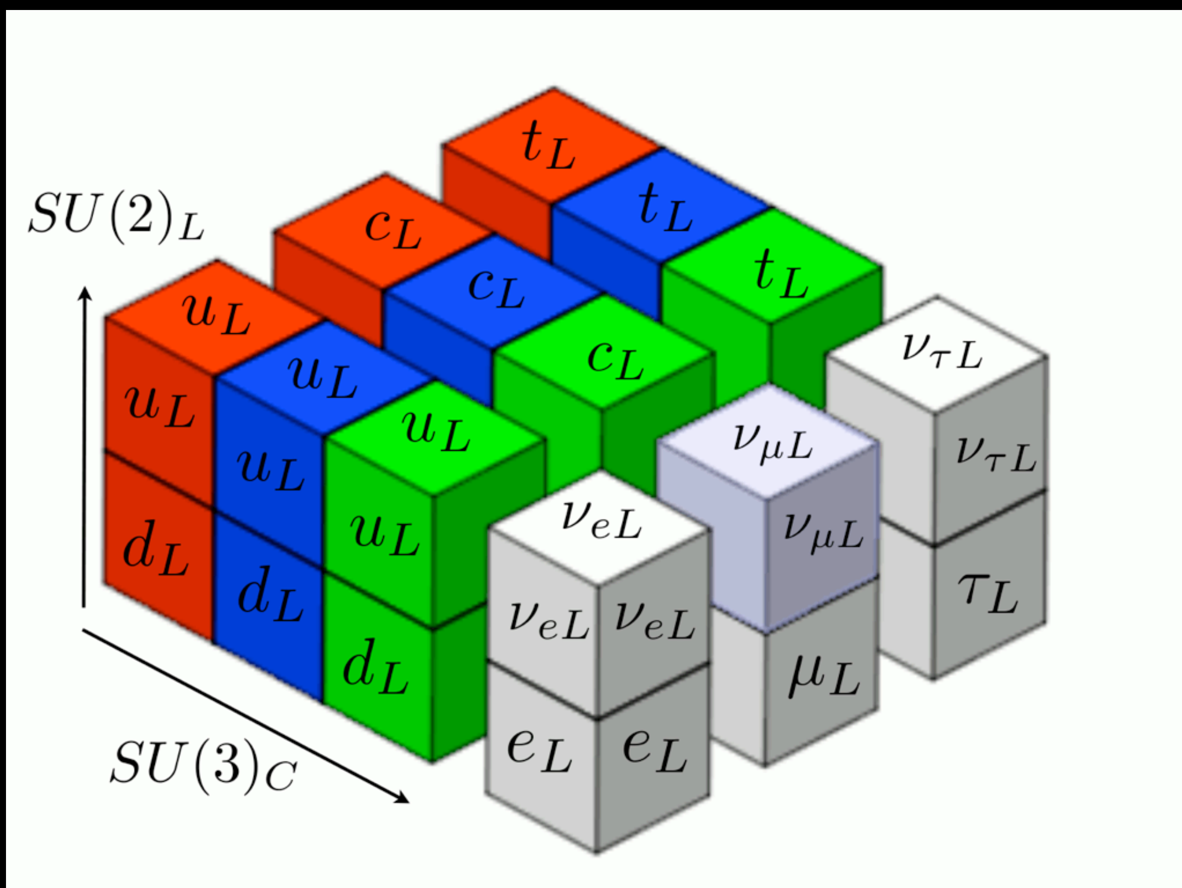
2-5 July 2018
University of Basel

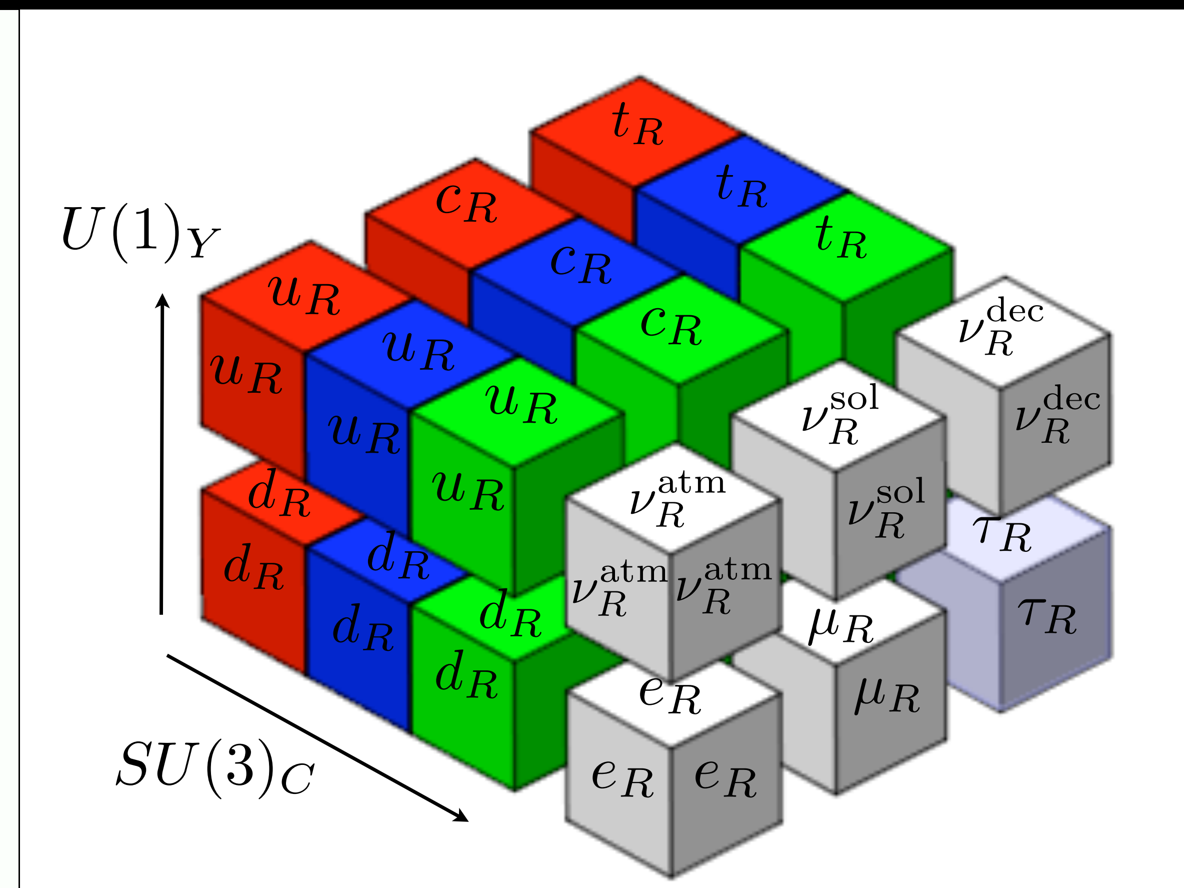
Prelude

The Flavour Puzzle

Effective Yukawa couplings

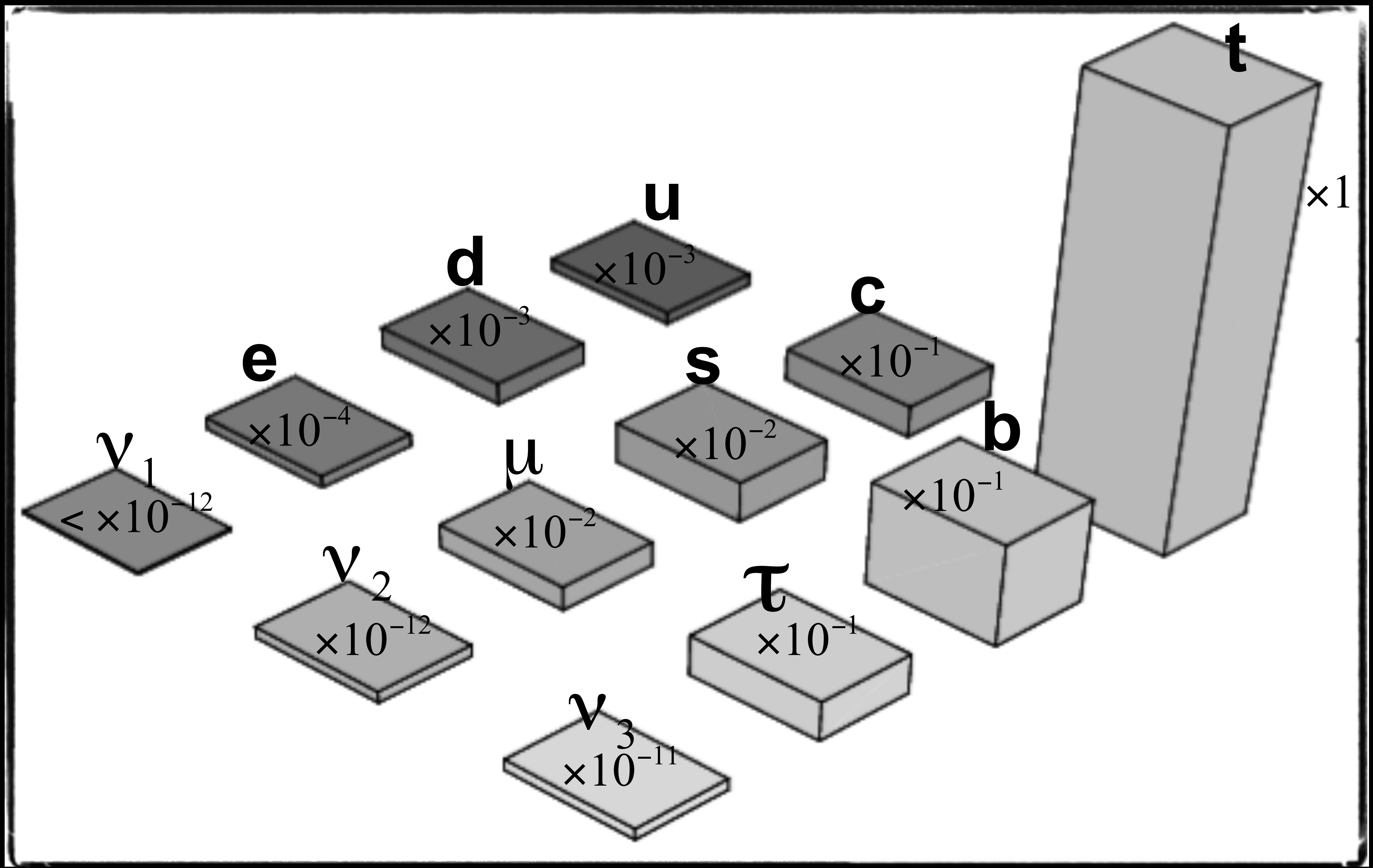
The Standard Model



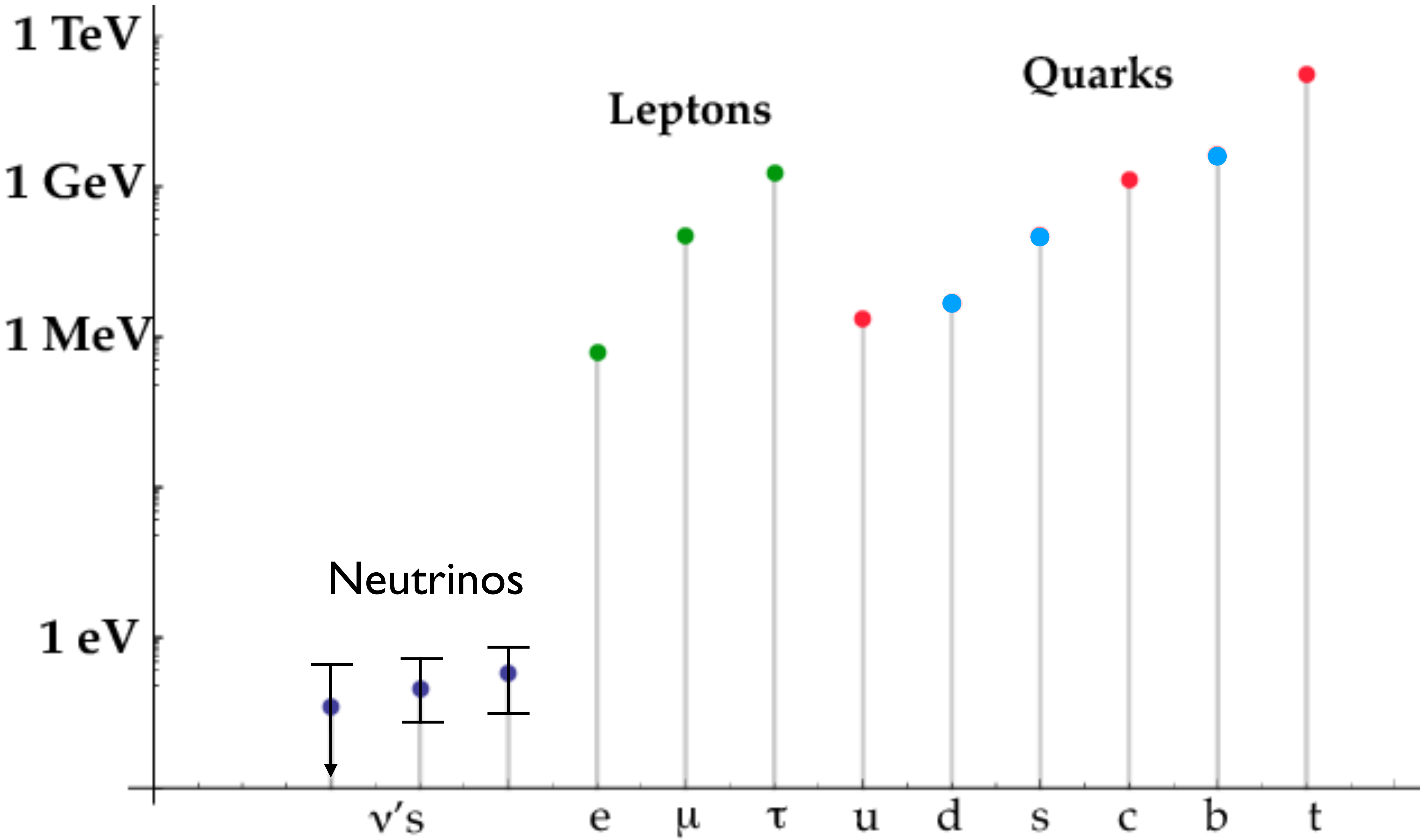


faces the flavour puzzle…

The Flavour Puzzle

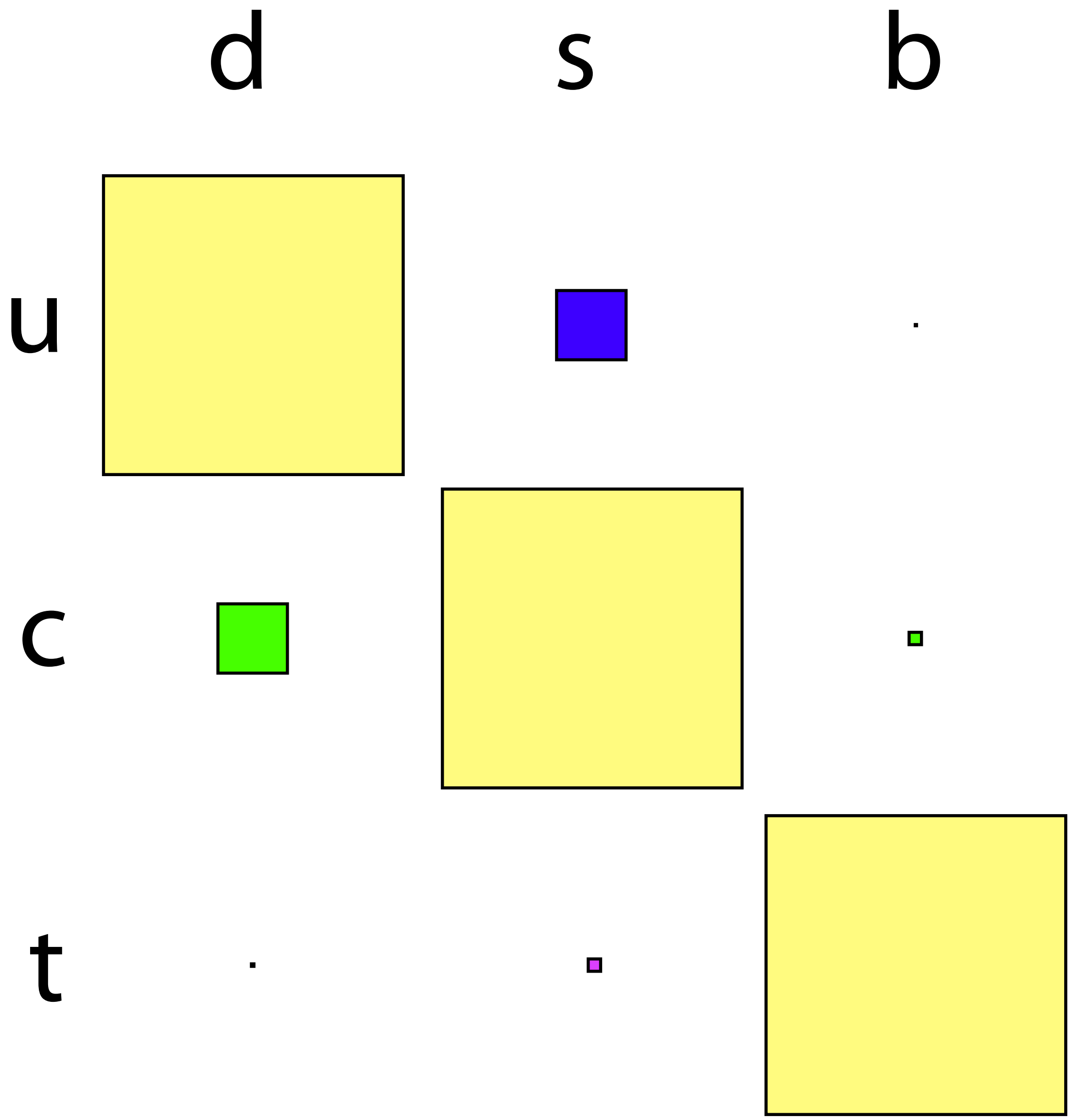


Masses

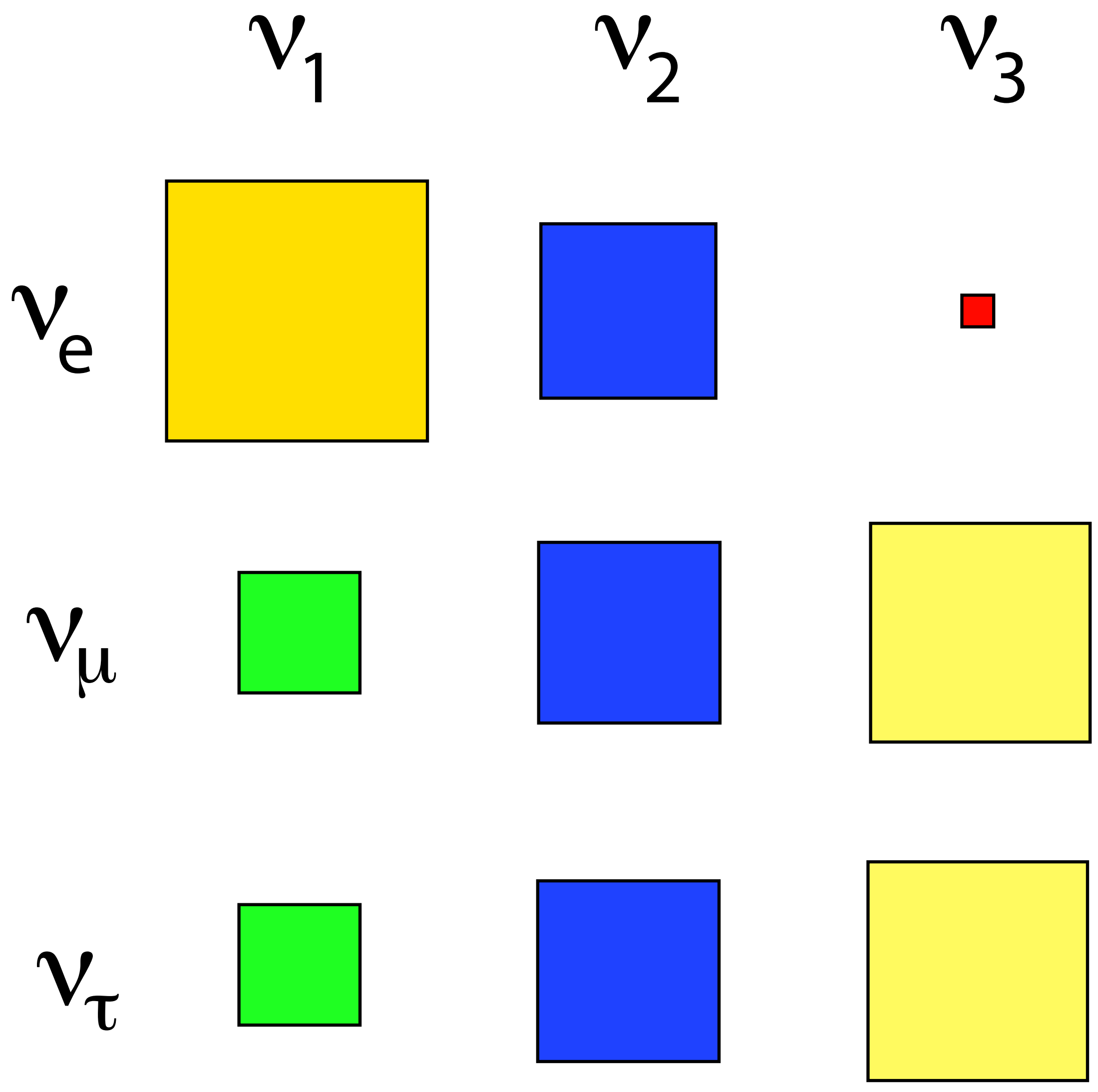


Mixing

CKM



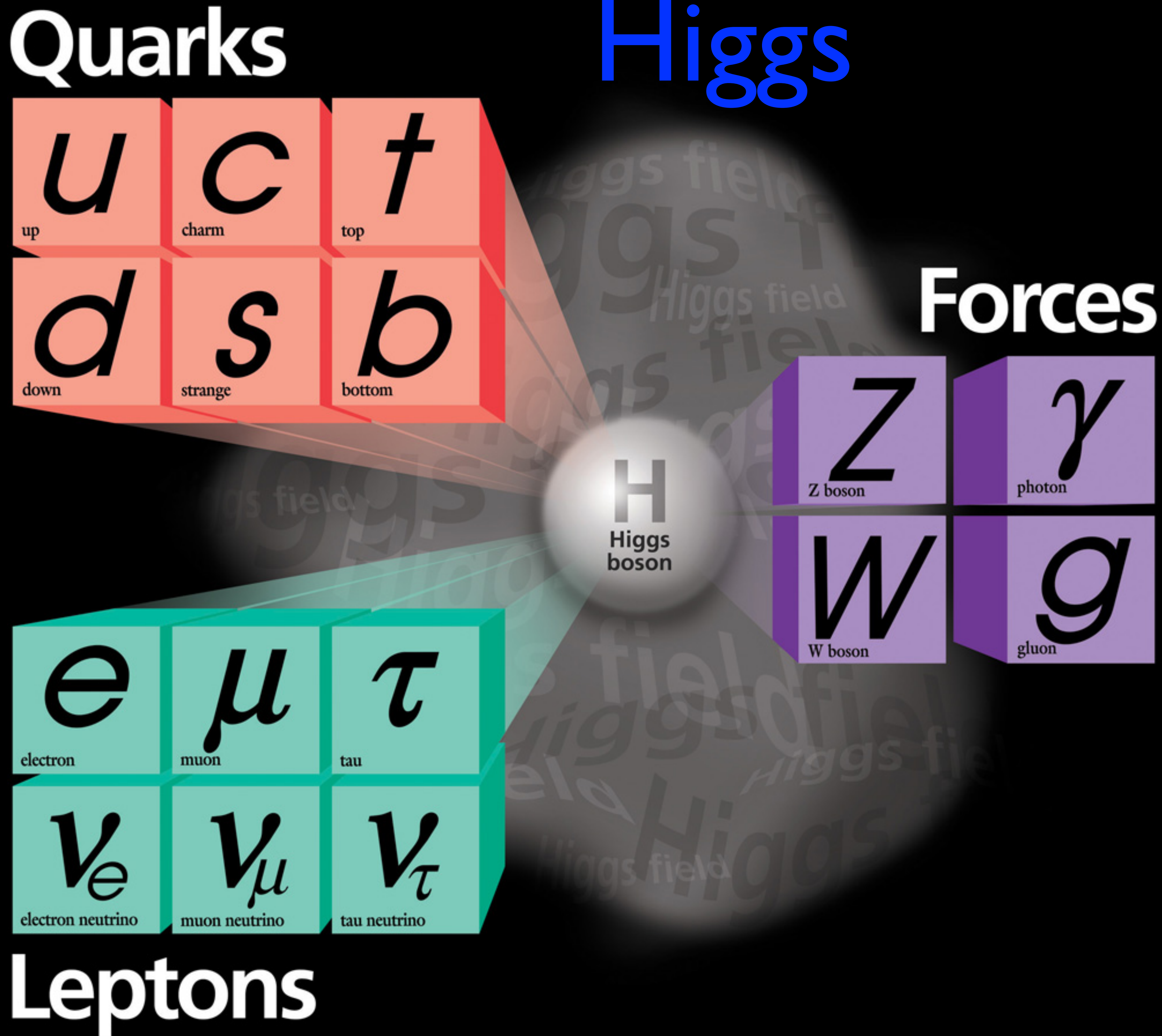
PMNS



Angles and CP

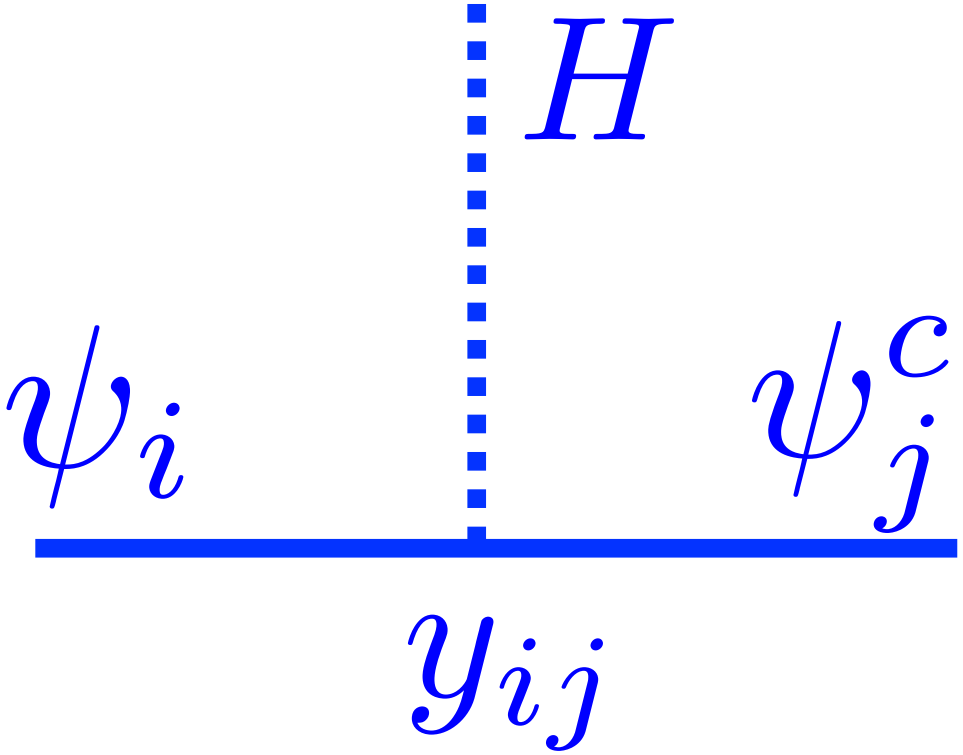
	θ_{12}	θ_{23}	θ_{13}	δ
Quarks	13° $\pm 0.1^\circ$	2.4° $\pm 0.1^\circ$	0.2° $\pm 0.05^\circ$	70° $\pm 5^\circ$
Leptons	34° $\pm 1^\circ$	45° $\pm 5^\circ$	8.5° $\pm 0.15^\circ$	-90° $\pm 50^\circ$

Higgs


Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
H
Higgs boson
e
electron
μ
muon
τ
tau
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
Leptons

Yukawa couplings

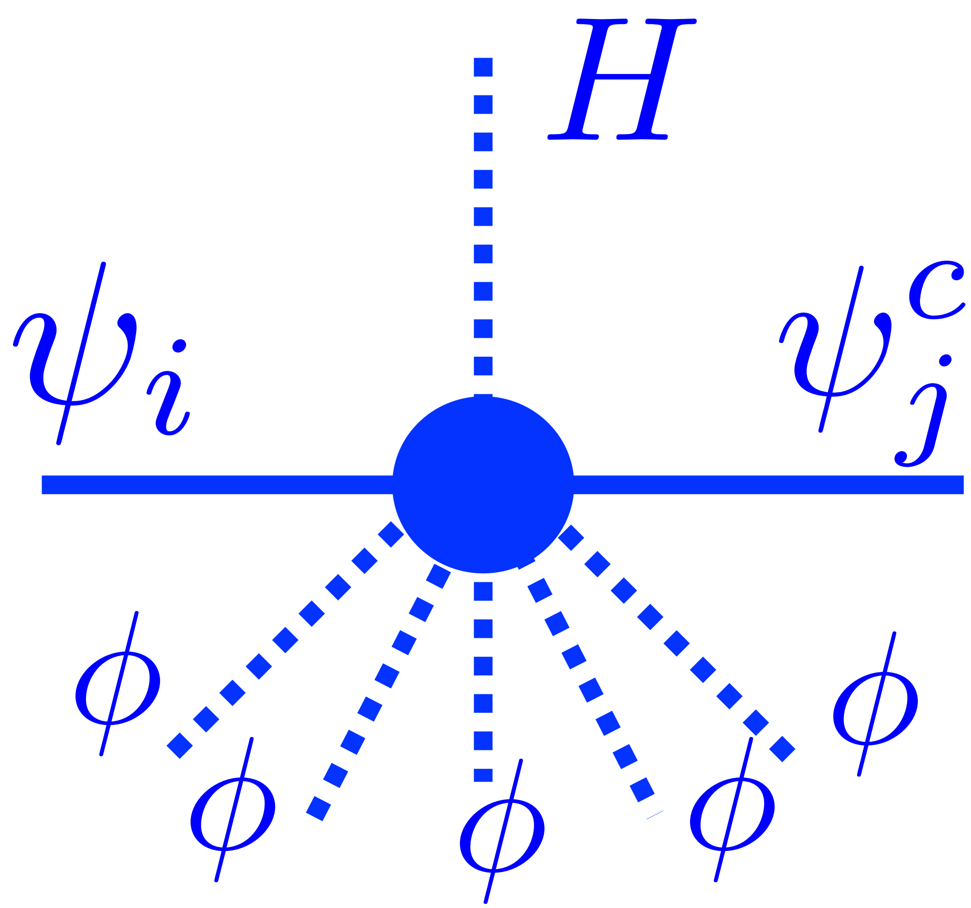
$$y_{ij} H \psi_i \psi_j^c$$



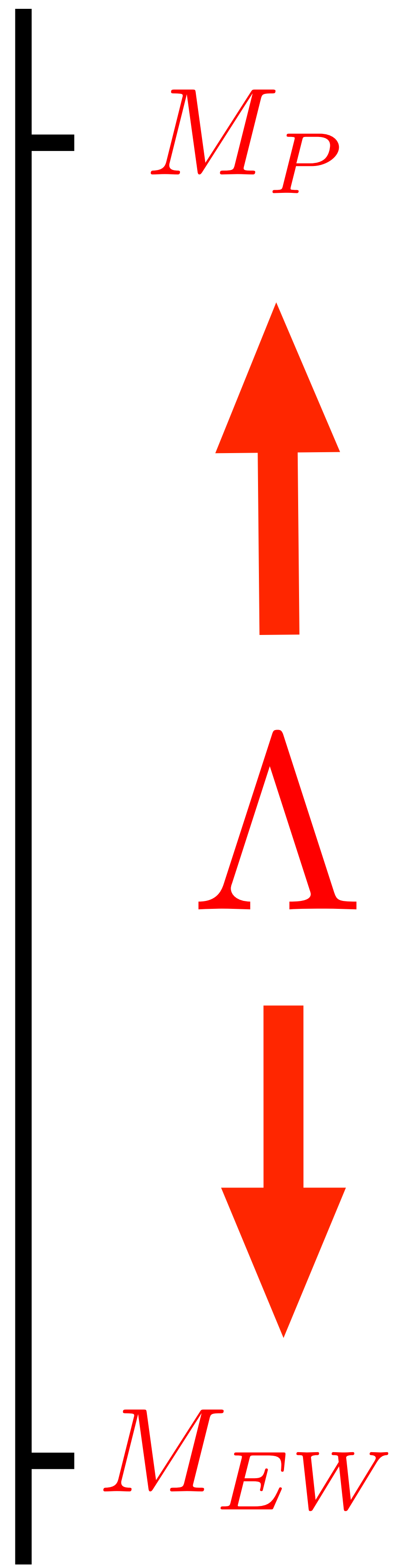
Why so small (apart from top quark)?

Effective Yukawa couplings

$$\left(\frac{\langle\phi_i\rangle}{\Lambda^{\psi}_{i,n}}\right)^n \left(\frac{\langle\phi_j\rangle}{\Lambda^{\psi^c}_{j,m}}\right)^m H\psi_i\psi^c_j$$



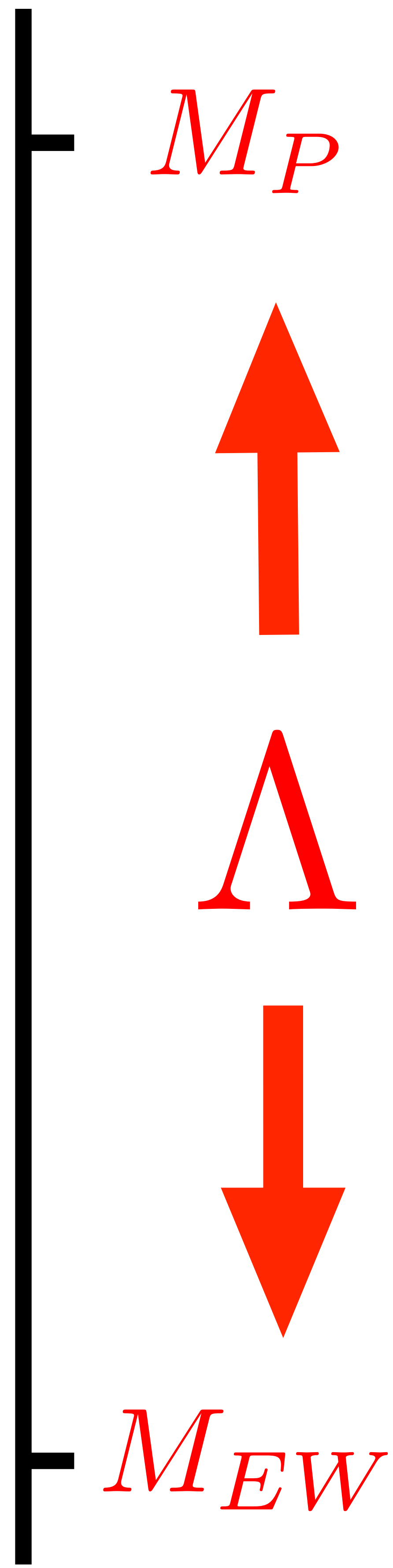
Yukawas small due to powers of ratios $\dfrac{\langle\phi\rangle}{\Lambda}$



Flavour scales can be from the Planck scale to electroweak scale

Keeping fixed ratios

$$\frac{\langle \phi \rangle}{\Lambda}$$



SUSY GUTs

suggest high scale theory of flavour

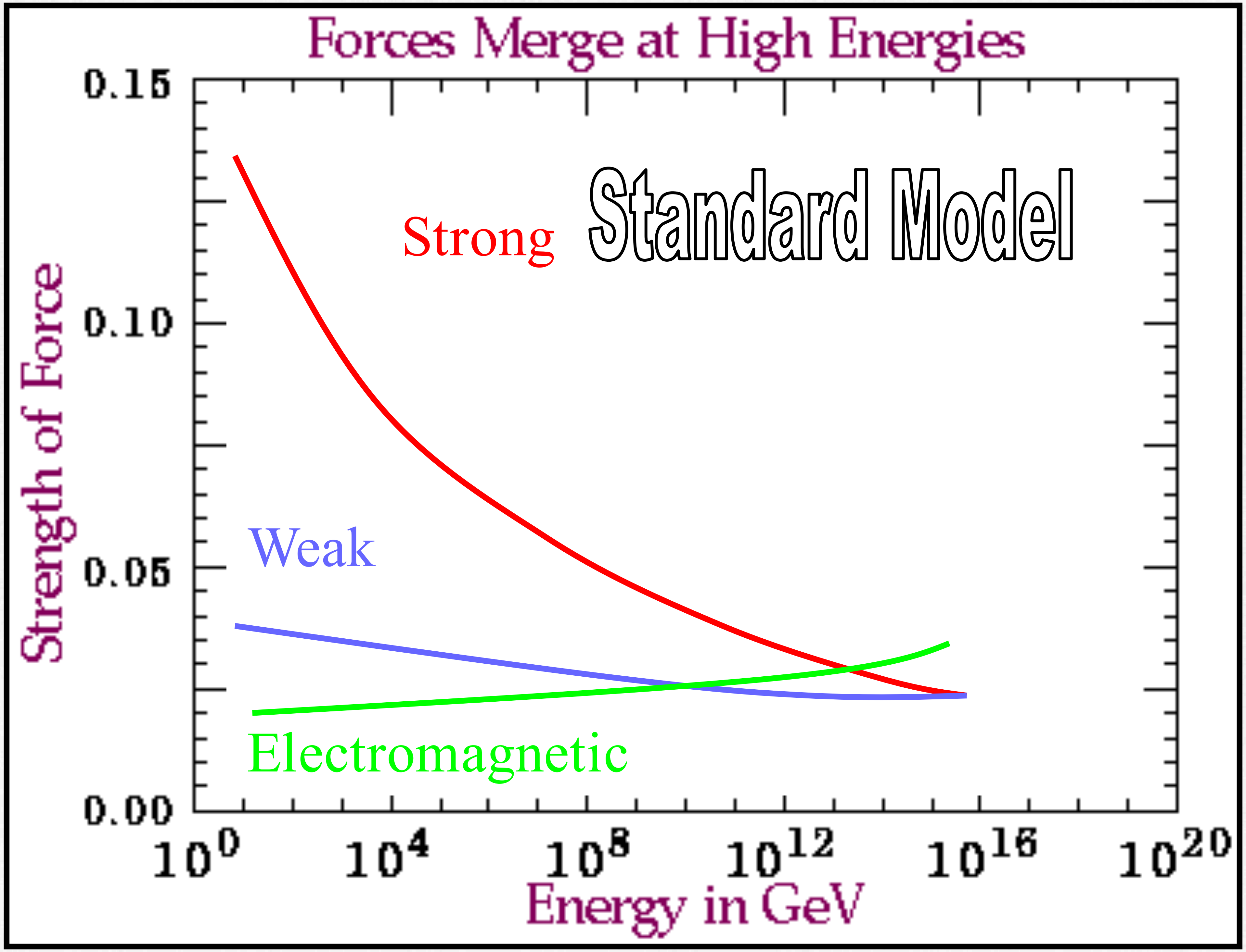
Phenomenological hints from B physics

suggest low scale theory of flavour

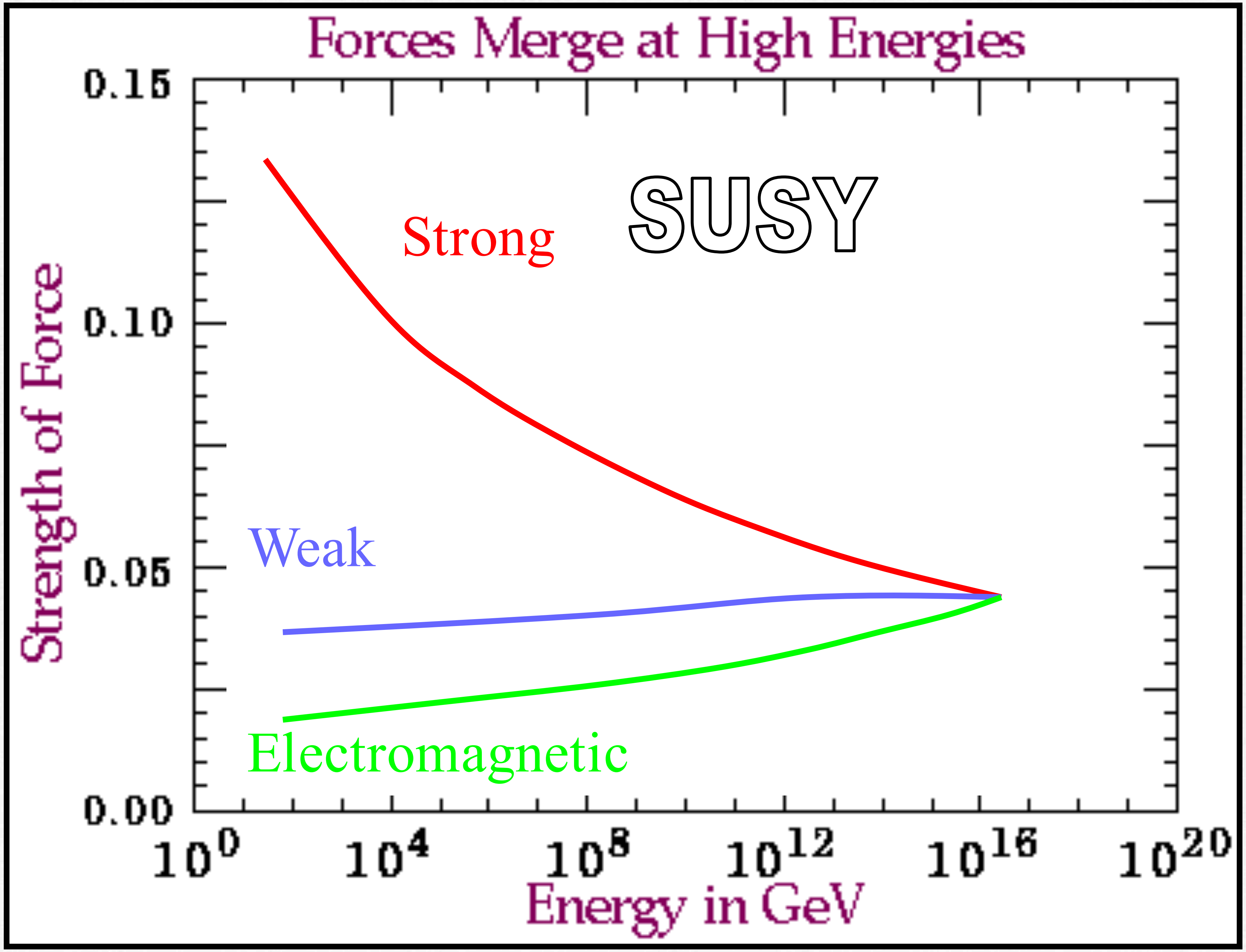
Part I

SUSY GUTs of Flavour

High scale theories of flavour



Forces Merge at High Energies
Standard Model
Strong
Weak
Electromagnetic
Strength of Force
0.15
0.10
0.05
0.00
10^0
10^4
10^8
10^{12}
10^{16}
10^{20}
Energy in GeV



Forces Merge at High Energies
SUSY
Strong
Weak
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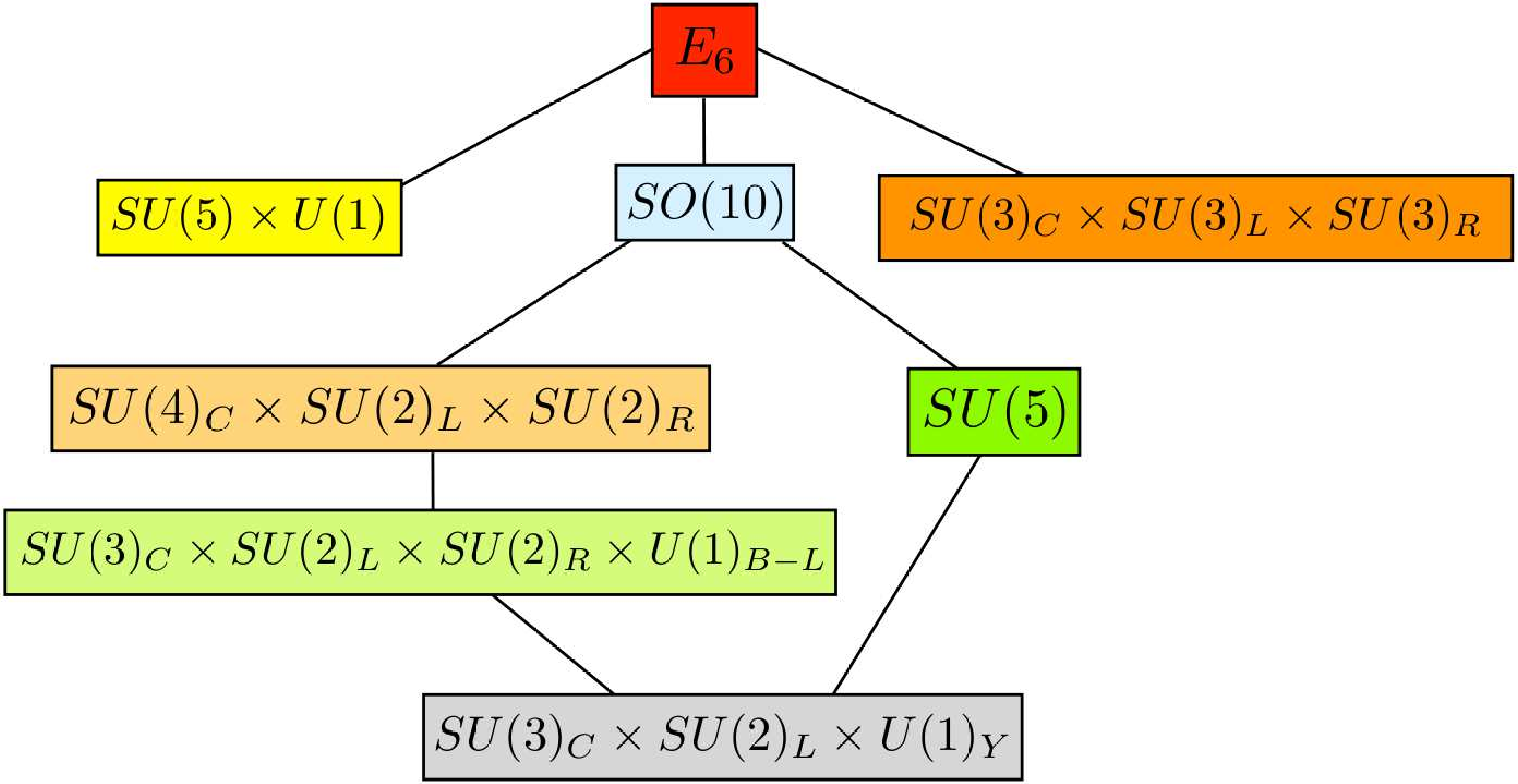
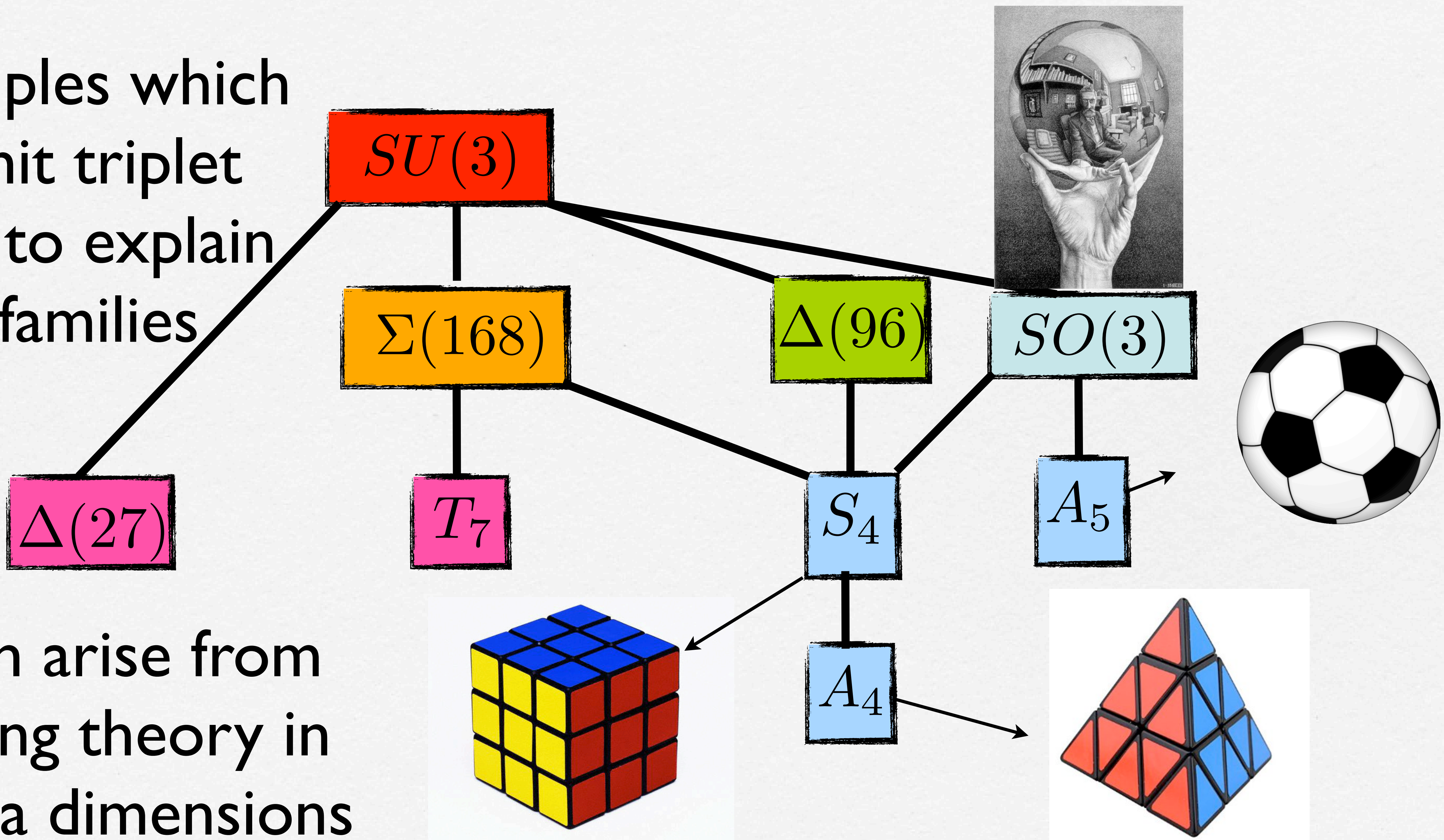
Strength of Force
0.15
0.10
0.05
0.00
10^0
10^4
10^8
10^{12}
10^{16}
10^{20}
Energy in GeV

GUTs


E_6
$SU(5) \times U(1)$
$SO(10)$
$SU(3)_C \times SU(3)_L \times SU(3)_R$
$SU(4)_C \times SU(2)_L \times SU(2)_R$
$SU(5)$
$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
$SU(3)_C \times SU(2)_L \times U(1)_Y$

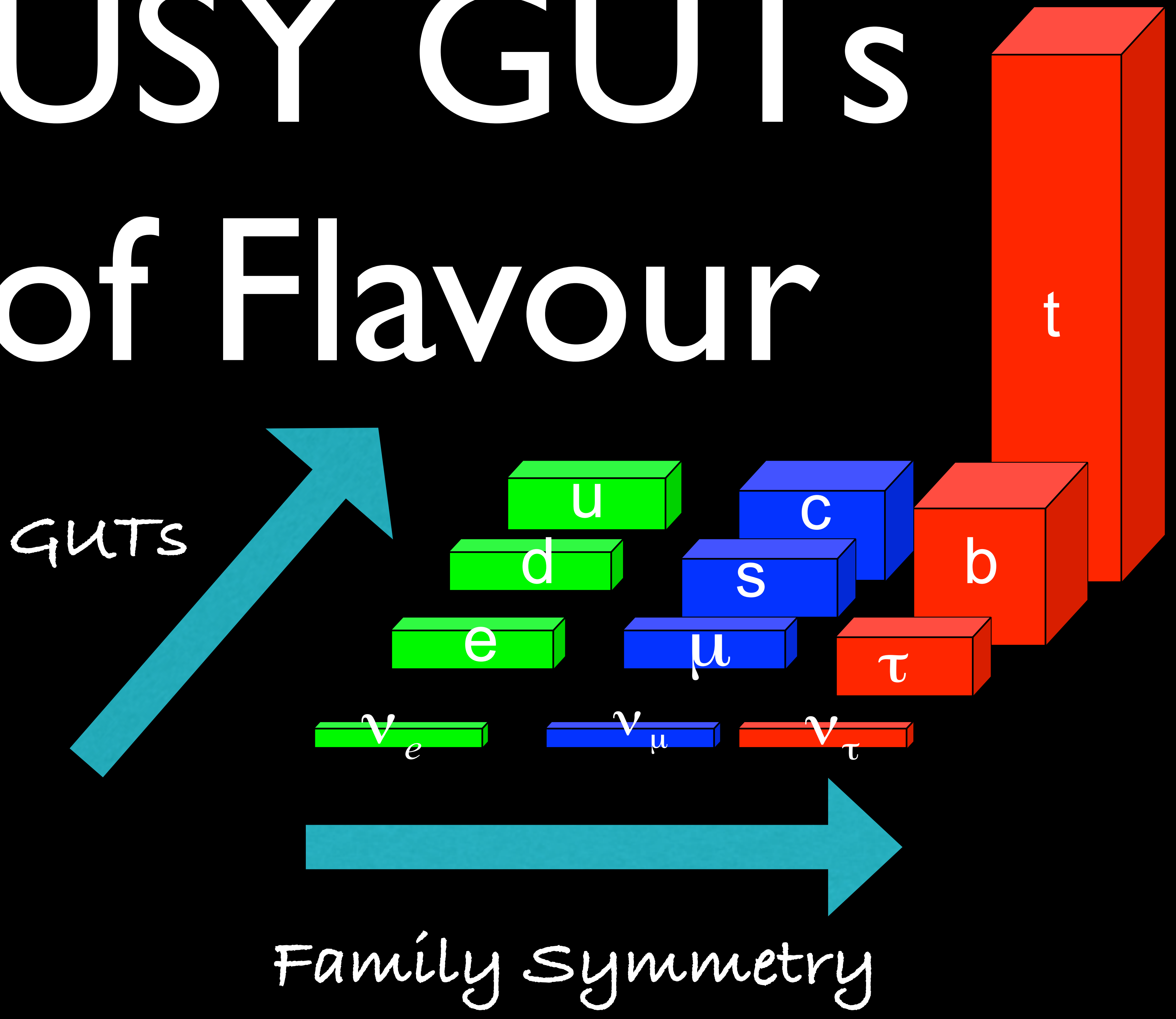
Family Symmetry

Examples which admit triplet reps to explain 3 families



Can arise from string theory in extra dimensions

SUSY GUTs of Flavour



Three families like 3 different colours green, blue, red

Grand Unified Theories of Flavour

Cárcamo Hernández Hagedorn Ma Feruglio Kaur Ding de Medeiros Varzielas Valle TANIMOTO Antusch bernigaud Nishi Romanino

$G_{\rm GUT}$ / $G_{\rm FAM}$	$SU(2)_L \times U(1)_Y$	$SU(5)$	PS	$SO(10)$
S_3	[29]			[142]
A_4	[30, 34, 51, 53, 64, 143–145]	[146–149]	[68, 150, 151]	
T'	[152]	[153]		
S_4	[31, 51, 53, 145, 155]	[156, 157]	[154]	[158]
A_5	[53, 159]	[160]		
T_7	[161, 162]			
$\Delta(27)$	[163]			[164]
$\Delta(96)$	[165, 166]	[167]		[168]
D_N	[169]			
Q_N	[170]			
other	[171]	[172]	[173]	

SU(5)xS$_4$ in 6d

de Anda, SFK 1803.04978
see also: Burrows, SFK 0909.1433,1007.2310;
Altarelli,Feruglio,Lin hep-ph/0610165

Orbifolding on a torus:

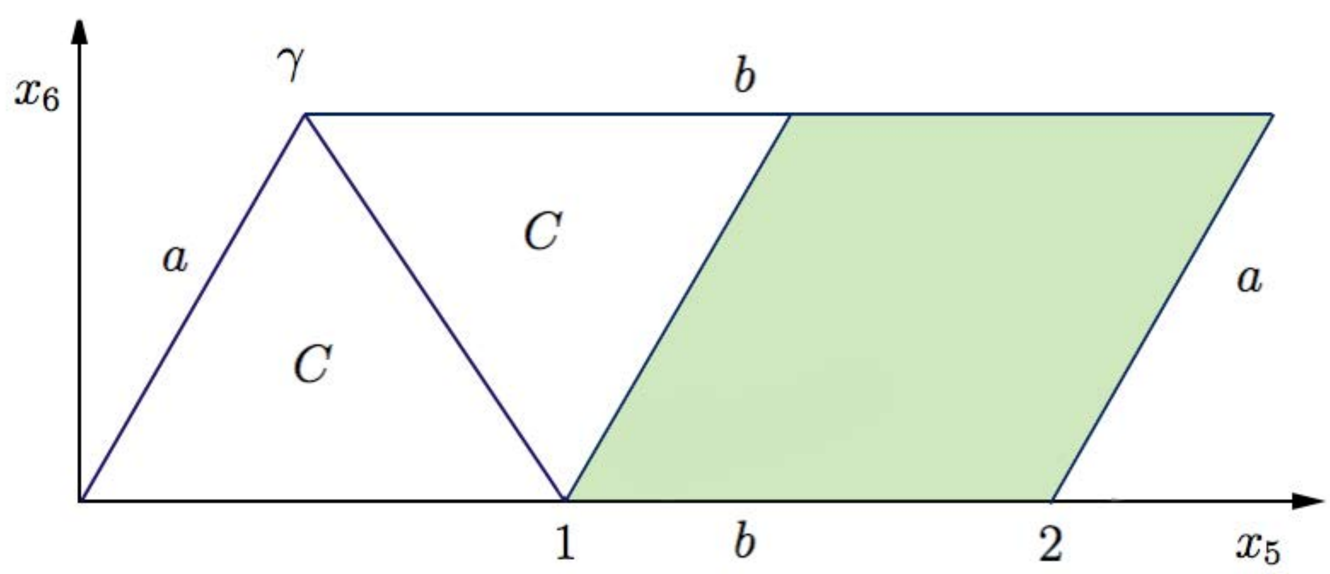
$$T^2/(\mathbb{Z}_2^{SM}\times\mathbb{Z}_2)$$

$$T^2:\begin{array}{l}(x^5,x^6)=(x^5+2\pi R_1,x^6), \quad 2\pi R_1 \Rightarrow 2\\ (x^5,x^6)=(x^5+2\pi R_2\cos\theta,x^6+2\pi R_2\sin\theta)\end{array}$$

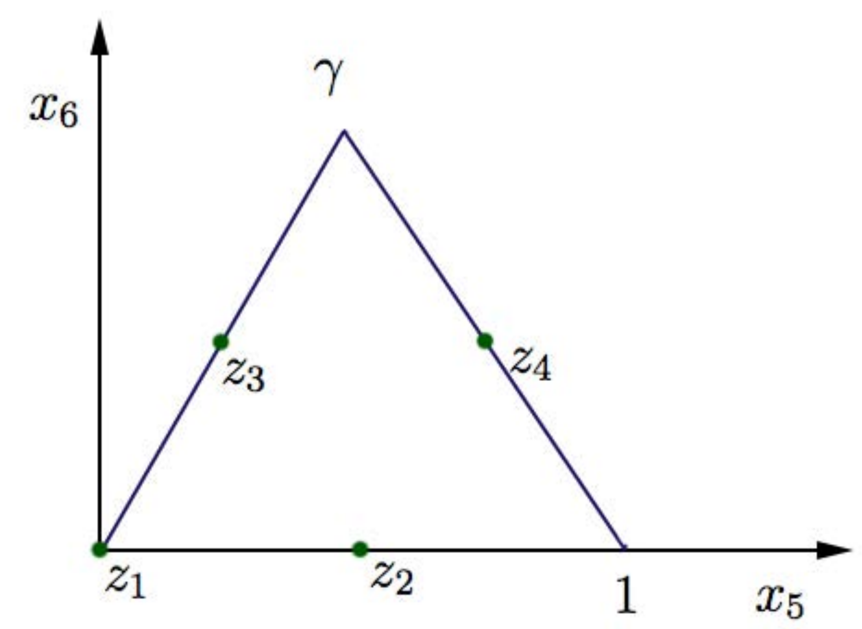
$$\theta=\pi/3 \qquad 2\pi R_2\Rightarrow 1$$

$$\mathbb{Z}_2: \quad (x^5,x^6)=(-x^5,-x^6)$$

$$\mathbb{Z}_2^{\rm SM}: \quad (x'_5,x'_6)=(-x'_5,-x'_6) \qquad (x'_5,x'_6)=(x_5+\pi R_1,x_6)$$



(a) The exta dimensional space. Identifying together sides a, b we obtain T^2. The $\mathbb{Z}_2^{SM}$ orbifolding identifies the shaded area with the non shaded. The orbifolding $\mathbb{Z}_2$ identifies both areas labeled C.



(b) The effective extra dimensional space $T^2/(\mathbb{Z}_2\times\mathbb{Z}_2^{SM})$. This is the whole bulk. The four invariant branes $z_{1,2,3,4}$ are shown.

SU(5)xS_4 in 6d

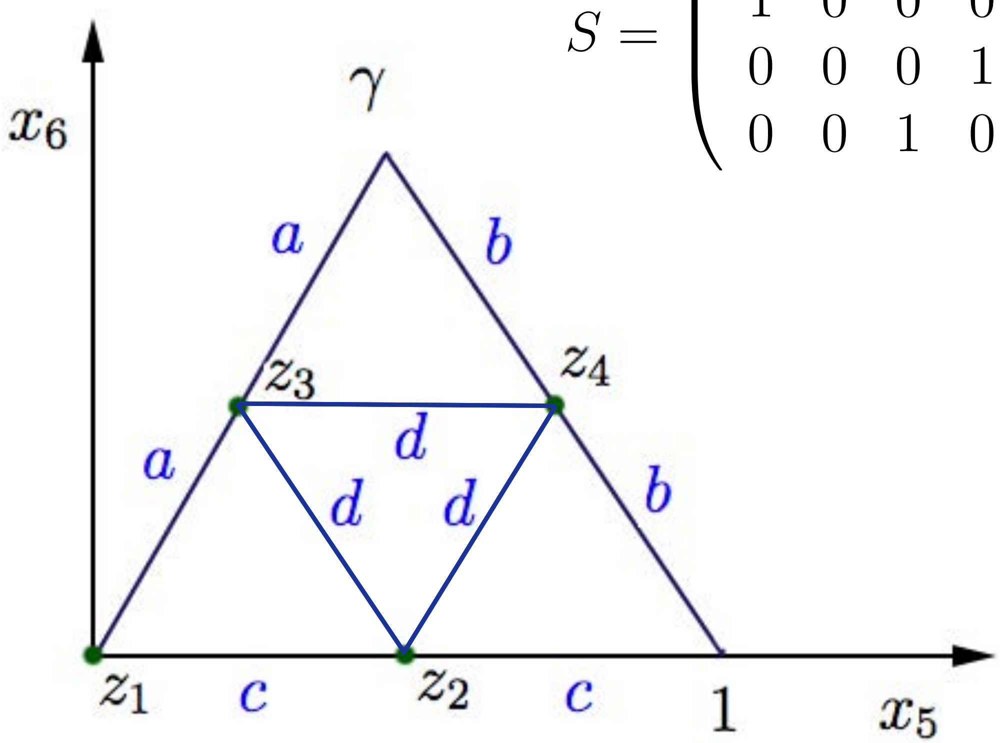
de Anda, SFK 1803.04978

$$S_1[(12)(34)],\ S_2[(13)(24)],\ R[(243)(1)],\ P[(34)(1)(2)]$$

$$S = S_1,\ T = R,\ U = P$$ symmetry of fixed points

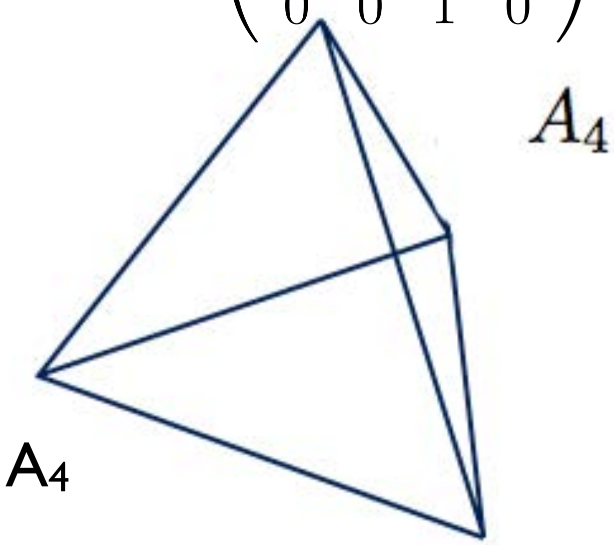
$$S^2 = T^3 = (ST)^3 = U^2 = (SU)^2 = (TU)^2 = (STU)^4 = 1$$

$$S = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}, \quad T = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 \end{pmatrix}, \quad U = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$



(c) The four branes are permuted by the symmetries S_1, S_2, R. These symmetries identify the sides a, b, c while R rotates everything by identifying sides d.

$$\mathbf{4} \to \mathbf{3} + \mathbf{1}$$



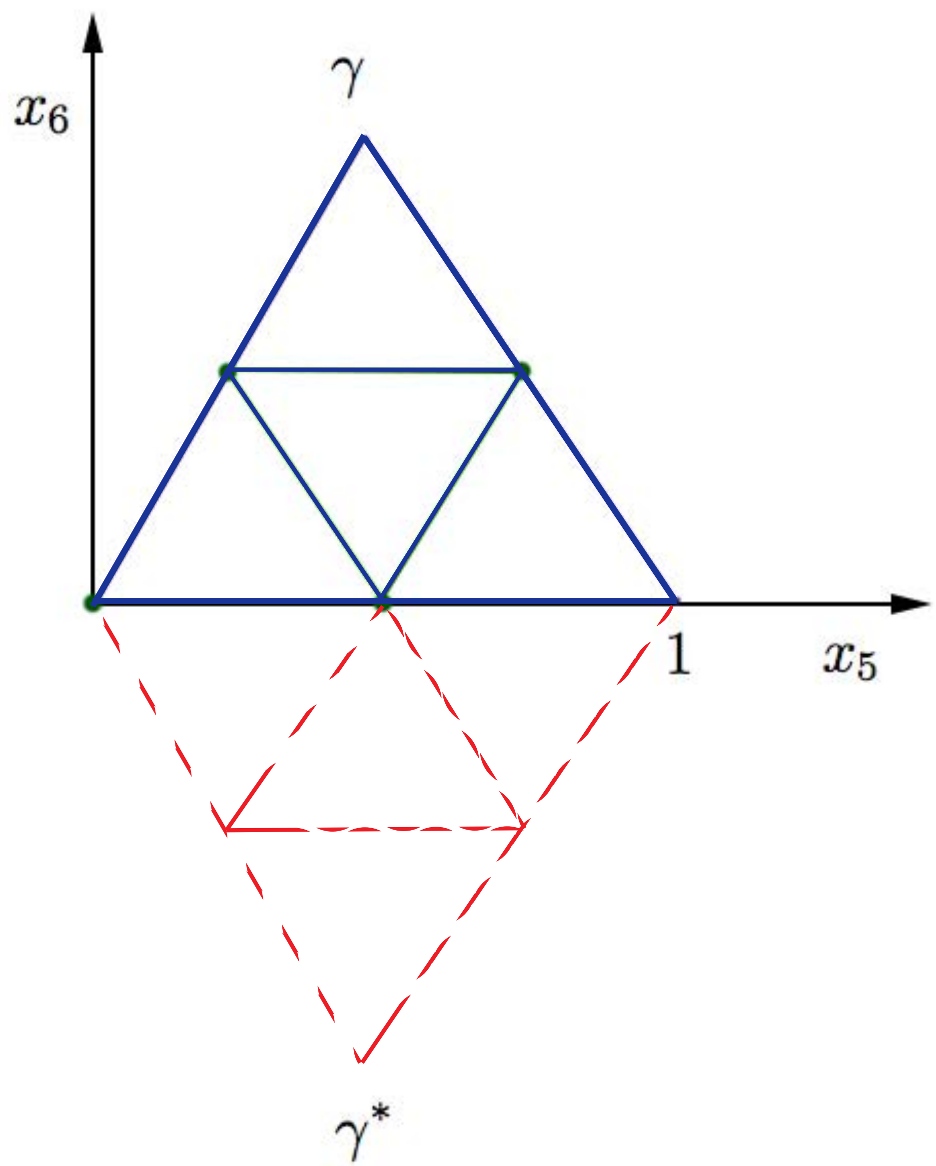
origin of A_4

(d) By actually gluing together sides a, b, c we obtain a tetrahedron, whose vertices are related by the symmetry group A_4.

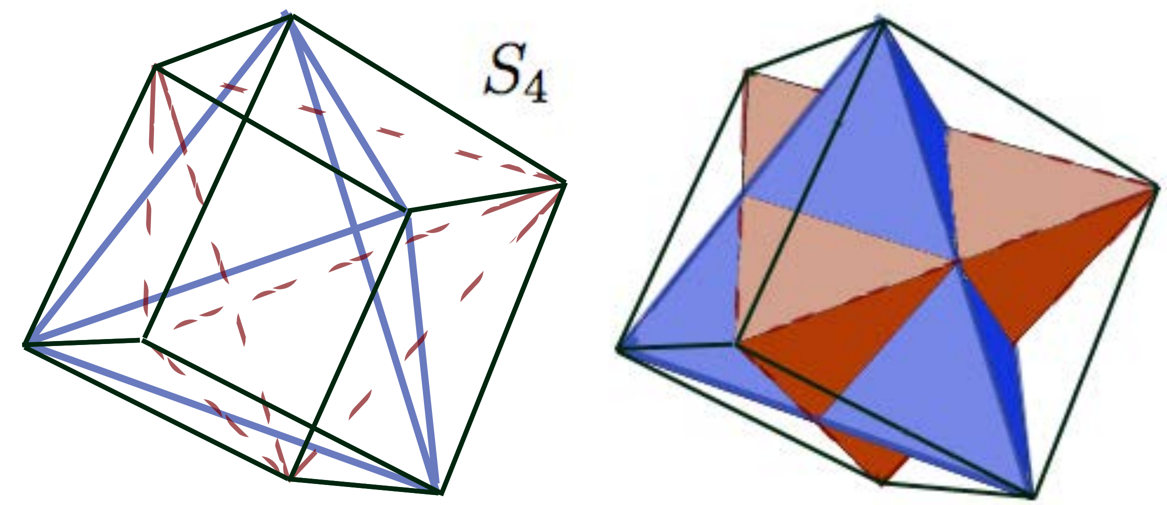
SU(5)xS_4 in 6d

de Anda, SFK 1803.04978

origin of S_4



(e) The symmetries S_1, S_2, R generate A_4. By also considering independent parities P, P' we obtain the reflected bulk space.

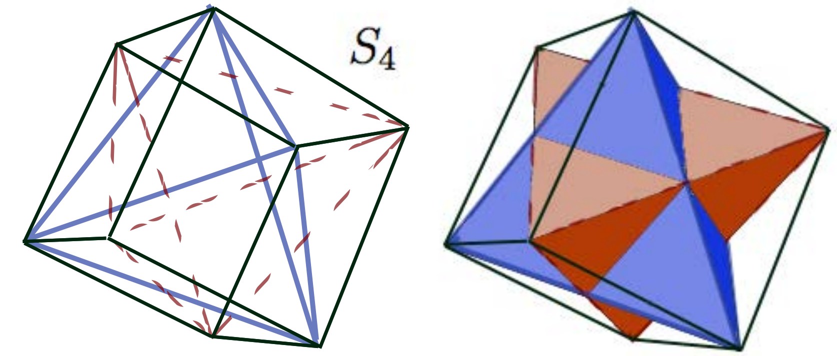


(f) Identifying sides a, b, c for each space we obtain a tetrahedron and a reflected one. The pair of tetrahedra lie inside a cube, whose vertices are related by the symmetry group S_4. The left image shows all the sides of the tetrahedra while the one on the right is solid for a better visualization.

Figure 1: Visualization on the remnant S_4 symmetry after orbifolding of the extra dimensions.

SU(5)xS4 in 6d

de Anda, SFK 1803.04978



Field	S_4	$SU(5)$	$U(1)$	P'_{SM}
	Representation			
F	3'	$\bar{5}$	$-c$	Brane
$T_1^{\pm}$	1	10	$a-4d$	±1
$T_2^{\pm}$	1	10	$a-2d$	±1
$T_3^{\pm}$	1	10	a	±1
N_s^c	1	1	$-d$	$+1$
N_a^c	1	1	$-4d$	$+1$
H_5	1	5	$-2a$	$+1$
$H_{\bar{5}}$	1	$\bar{5}$	$-2b$	$+1$
ξ	1	1	$2d$	$+1$
ρ	2	1	$-a+2b+c+d$	$+1$
ϕ_s	3'	1	$2a+c+d$	Brane
ϕ_a	3'	1	$2a+c+2d$	-1
ϕ_τ	3'	1	$-a+2b+c$	Brane
ϕ_μ	3'	1	$-a+2b+c+2d$	Brane
ϕ_e	3'	1	$-a+2b+c+4d$	$+1$
A_1	1	1	$2a-4b-2c$	$+1$
$A_{3'}$	3'	1	$-a-2b-2c-2d$	Brane
A_2	2	1	$2a-4b-2c-8d$	$+1$
A_1'	1'	1	$2a-4b-2c-4d$	Brane

Fields either distributed over the branes at fixed points or in the bulk

S_4	S	T	U
$\mathbf{1},\mathbf{1}'$	1	1	±1
$\mathbf{2}$	$\begin{pmatrix}1&0\\0&1\end{pmatrix}$	$\begin{pmatrix}\omega&0\\0&\omega^2\end{pmatrix}$	$\begin{pmatrix}0&1\\1&0\end{pmatrix}$
$\mathbf{3},\mathbf{3}'$	$\frac{1}{3}\begin{pmatrix}-1&2&2\\2&-1&2\\2&2&-1\end{pmatrix}$	$\begin{pmatrix}1&0&0\\0&\omega^2&0\\0&0&\omega\end{pmatrix}$	$\mp\begin{pmatrix}1&0&0\\0&0&1\\0&1&0\end{pmatrix}$

$$P'_{SM} = P_{SM} \otimes U$$

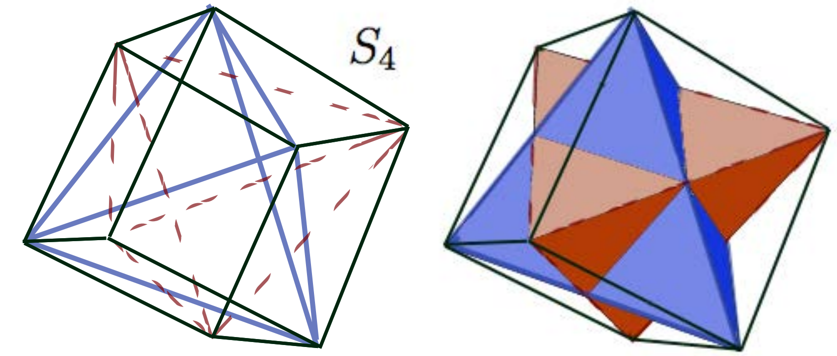
$$P_{SM} = \begin{pmatrix}+1&0&0&0&0\\0&+1&0&0&0\\0&0&-1&0&0\\0&0&0&-1&0\\0&0&0&0&-1\end{pmatrix}$$

$$SU(5) \to SM$$

Doublet-triplet splitting of H_5

SU(5)xS4 in 6d

de Anda, SFK 1803.04978



Field	Representation			
	S_4	$SU(5)$	$U(1)$	P'_{SM}
F	3'	$\bar{5}$	$-c$	Brane
$T_1^\pm$	1	10	$a-4d$	±1
$T_2^\pm$	1	10	$a-2d$	±1
$T_3^\pm$	1	10	a	±1
N_s^c	1	1	$-d$	$+1$
N_a^c	1	1	$-4d$	$+1$
H_5	1	5	$-2a$	$+1$
$H_{\bar{5}}$	1	$\bar{5}$	$-2b$	$+1$
ξ	1	1	$2d$	$+1$
ρ	2	1	$-a+2b+c+d$	$+1$
ϕ_s	3'	1	$2a+c+d$	Brane
ϕ_a	3'	1	$2a+c+2d$	-1
ϕ_τ	3'	1	$-a+2b+c$	Brane
ϕ_μ	3'	1	$-a+2b+c+2d$	Brane
ϕ_e	3'	1	$-a+2b+c+4d$	$+1$
A_1	1	1	$2a-4b-2c$	$+1$
$A_{3'}$	3'	1	$-a-2b-2c-2d$	Brane
A_2	2	1	$2a-4b-2c-8d$	$+1$
A'_1	1'	1	$2a-4b-2c-4d$	Brane

$$\langle\phi_{a,s}\rangle\,,\langle\rho\rangle\ \text{preserve}\ SU$$

$$\langle\phi_e\rangle\,,\omega\langle\phi_\mu\rangle\,,\omega^2\langle\phi_\tau\rangle\ \text{preserve}\ T$$

SFK, Luhn 1607.05276

Vacuum alignment of bulk flavons

$$P'_{SM}=P_{SM}\otimes U$$

$$\langle\rho\rangle=U\langle\rho\rangle=\begin{pmatrix}0&1\\1&0\end{pmatrix}\langle\rho\rangle\quad\rightarrow\quad\langle\rho\rangle\sim\begin{pmatrix}1\\1\end{pmatrix}$$

$$\langle\phi_a\rangle=-U\langle\phi_a\rangle=-\begin{pmatrix}1&0&0\\0&0&1\\0&1&0\end{pmatrix}\langle\phi_a\rangle\quad\rightarrow\quad\langle\phi_a\rangle\sim\begin{pmatrix}0\\1\\-1\end{pmatrix}$$

$$\langle\phi_e\rangle=-U\langle\phi_e\rangle=\begin{pmatrix}1&0&0\\0&0&1\\0&1&0\end{pmatrix}\langle\phi_e\rangle\quad\rightarrow\quad\langle\phi_e\rangle\sim\begin{pmatrix}a\\b\\b\end{pmatrix}$$

Vacuum alignment of brane flavons

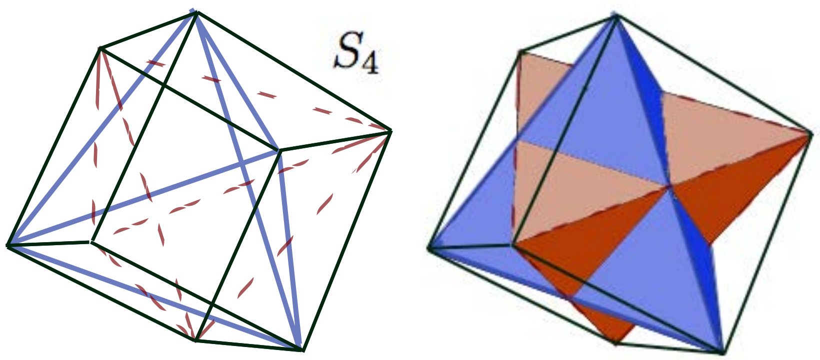
$$\mathcal{W}_A\sim A_1(\phi_\tau)^2+A_2(\phi_e)^2+A'_1(\phi_\mu\phi_\mu+\phi_e\phi_\tau)+A_3(\phi_a\phi_\tau-\rho\phi_s)$$

$$\langle\phi_s\rangle=v_s\begin{pmatrix}1\\3\\-1\end{pmatrix},\quad\langle\phi_a\rangle=v_a\begin{pmatrix}0\\1\\-1\end{pmatrix},\quad\langle\rho\rangle=v_\rho\begin{pmatrix}1\\1\end{pmatrix}$$

$$\langle\phi_e\rangle=v_e\begin{pmatrix}1\\0\\0\end{pmatrix},\quad\langle\phi_\mu\rangle=v_\mu\begin{pmatrix}0\\0\\1\end{pmatrix},\quad\langle\phi_\tau\rangle=v_\tau\begin{pmatrix}0\\1\\0\end{pmatrix}$$

SU(5)xS4 in 6d

de Anda, SFK 1803.04978



Field	S_4	$SU(5)$	$U(1)$	P'_{SM}
	Representation			
F	3'	$\bar{5}$	$-c$	Brane
$T_1^{\pm}$	1	10	$a-4d$	±1
$T_2^{\pm}$	1	10	$a-2d$	±1
$T_3^{\pm}$	1	10	a	±1
N_s^c	1	1	$-d$	$+1$
N_a^c	1	1	$-4d$	$+1$
H_5	1	5	$-2a$	$+1$
$H_{\bar{5}}$	1	$\bar{5}$	$-2b$	$+1$
ξ	1	1	$2d$	$+1$
ρ	2	1	$-a+2b+c+d$	$+1$
ϕ_s	3'	1	$2a+c+d$	Brane
ϕ_a	3'	1	$2a+c+2d$	-1
ϕ_τ	3'	1	$-a+2b+c$	Brane
ϕ_μ	3'	1	$-a+2b+c+2d$	Brane
ϕ_e	3'	1	$-a+2b+c+4d$	$+1$
A_1	1	1	$2a-4b-2c$	$+1$
$A_{3'}$	3'	1	$-a-2b-2c-2d$	Brane
A_2	2	1	$2a-4b-2c-8d$	$+1$
A_1'	1'	1	$2a-4b-2c-4d$	Brane

$$\{a,b,c,d\} = \{7,13,1,2\}$$

Yukawa operators

Up type quark masses

Down type and lepton masses

$$\mathcal{W}_Y = y^u_{ij} H_5 T_i^- T_j^+ \left(\frac{\xi}{\Lambda}\right)^{6-i-j}$$

$$+ y_{33}^{\pm} H_{\bar{5}} F \phi_\tau T_3^{\pm} \frac{1}{\Lambda} + y_{22}^{\pm} H_{\bar{5}} F \phi_\mu T_2^{\pm} \frac{1}{\Lambda} + y_{11}^{\pm} H_{\bar{5}} F \phi_e T_1^{\pm} \frac{1}{\Lambda}$$

$$+ y_{23}^{\pm} H_{\bar{5}} F \phi_\tau T_2^{\pm} \frac{\xi}{\Lambda^2} + y_{13}^{\pm} H_{\bar{5}} F \phi_\tau T_1^{\pm} \frac{\xi^2}{\Lambda^3} + y_{12}^{\pm} H_{\bar{5}} F \phi_\mu T_1^{\pm} \frac{\xi}{\Lambda^2}$$

$$+ y_a^{\nu} H_5 F \phi_a N_a^c \frac{\xi}{\Lambda^2} + y_s^{\nu} H_5 F \phi_s N_s^c \frac{1}{\Lambda} + y_s^N \frac{\xi^4}{\Lambda^3} N_a^c N_c^c + y_s^N \xi N_s^c N_s^c$$

$$+ y_H \frac{\xi^{10}}{\Lambda^9} H_5 H_{\bar{5}},$$

small mu term

Dirac masses

Majorana masses

$$M_D^{\nu} = v_u \begin{pmatrix} 0 & y_s^{\nu}\tilde{v}_s \\ -y_a^{\nu}\tilde{v}_a\tilde{\xi} & -y_s^{\nu}\tilde{v}_s \\ y_a^{\nu}\tilde{v}_a\tilde{\xi} & 3y_s^{\nu}\tilde{v}_s \end{pmatrix}, \quad M^N = \begin{pmatrix} y_a^N \tilde{\xi}^3 & 0 \\ 0 & y_s^N \end{pmatrix} \langle \xi \rangle$$

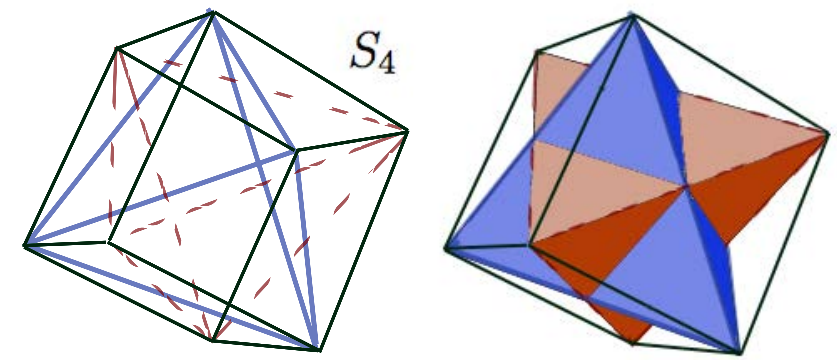
$$M^{\nu} = M_D^{\nu} (M^N)^{-1} (M^{\nu})^T$$

$$= \frac{v_u^2}{\langle\xi\rangle} \frac{(y_a^{\nu})^2 \tilde{v}_a^2}{y_a^N \tilde{\xi}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & -1 \\ 0 & -1 & 1 \end{pmatrix} + \frac{v_u^2}{\langle\xi\rangle} \frac{(y_s^{\nu})^2 \tilde{v}_s^2}{y_s^N} \begin{pmatrix} 1 & -1 & 3 \\ -1 & 1 & -3 \\ 3 & -3 & 9 \end{pmatrix}$$

Littlest seesaw

$SU(5) \times S_4$ in 6d

de Anda, SFK 1803.04978



Björkeroth, de Anda, de Medeiros Varzielas, SFK 1503.03306

Solves the strong CP problem: arg det $(M^u M^d)=0$

$$M^u = v_u \begin{pmatrix} y_{11}\ |\tilde{\xi}|^4 & y_{12}\ |\tilde{\xi}|^3 & y_{13}\ |\tilde{\xi}|^2 \\ y_{21}\ |\tilde{\xi}|^3 & y_{22}\ |\tilde{\xi}|^2 & y_{23}\ |\tilde{\xi}| \\ y_{31}\ |\tilde{\xi}|^2 & y_{32}\ |\tilde{\xi}| & y_{33} \end{pmatrix}$$

$$M^d = v_d \begin{pmatrix} y^-_{11}\ |\tilde{v}_e| & y^-_{12}\ |\tilde{v}_\mu \tilde{\xi}| e^{i\eta_\xi} & y^-_{13}\ |\tilde{v}_\tau \tilde{\xi}^2| e^{2i\eta_\xi} \\ 0 & y^-_{22}\ |\tilde{v}_\mu| & y^-_{23}\ |\tilde{v}_\tau \tilde{\xi}| e^{i\eta_\xi} \\ 0 & 0 & y^-_{33}\ |\tilde{v}_\tau| \end{pmatrix}$$

Up matrix has small mixing and no phases

Down matrix gives Cabibbo mixing and CP phase

$$M^\nu = \mu_a \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix} + \mu_s\ |\tilde{\xi}| e^{i\eta} \begin{pmatrix} 1 & 1 & 3 \\ 1 & 1 & 3 \\ 3 & 3 & 9 \end{pmatrix}$$

$$M^e = v_d \begin{pmatrix} y^+_{11}\ |\tilde{v}_e| & 0 & 0 \\ y^+_{12}\ |\tilde{v}_\mu \tilde{\xi}| e^{-i\eta_\xi} & y^+_{22}\ |\tilde{v}_\mu| & 0 \\ y^+_{13}\ |\tilde{v}_\tau \tilde{\xi}^2| e^{-2i\eta_\xi} & y^+_{23}\ |\tilde{v}_\tau \tilde{\xi}| e^{-i\eta_\xi} & y^+_{33}\ |\tilde{v}_\tau| \end{pmatrix}$$

Littlest seesaw = CSD3

SFK 1304.6264

No LH charged lepton mixing to leading order

$$\mu_{a,s} = \frac{(v_u y^\nu_{a,s})^2}{|v_\xi| y^N_{a,s}} \qquad \eta = 2\eta_s - 2\eta_a + \eta_\xi$$

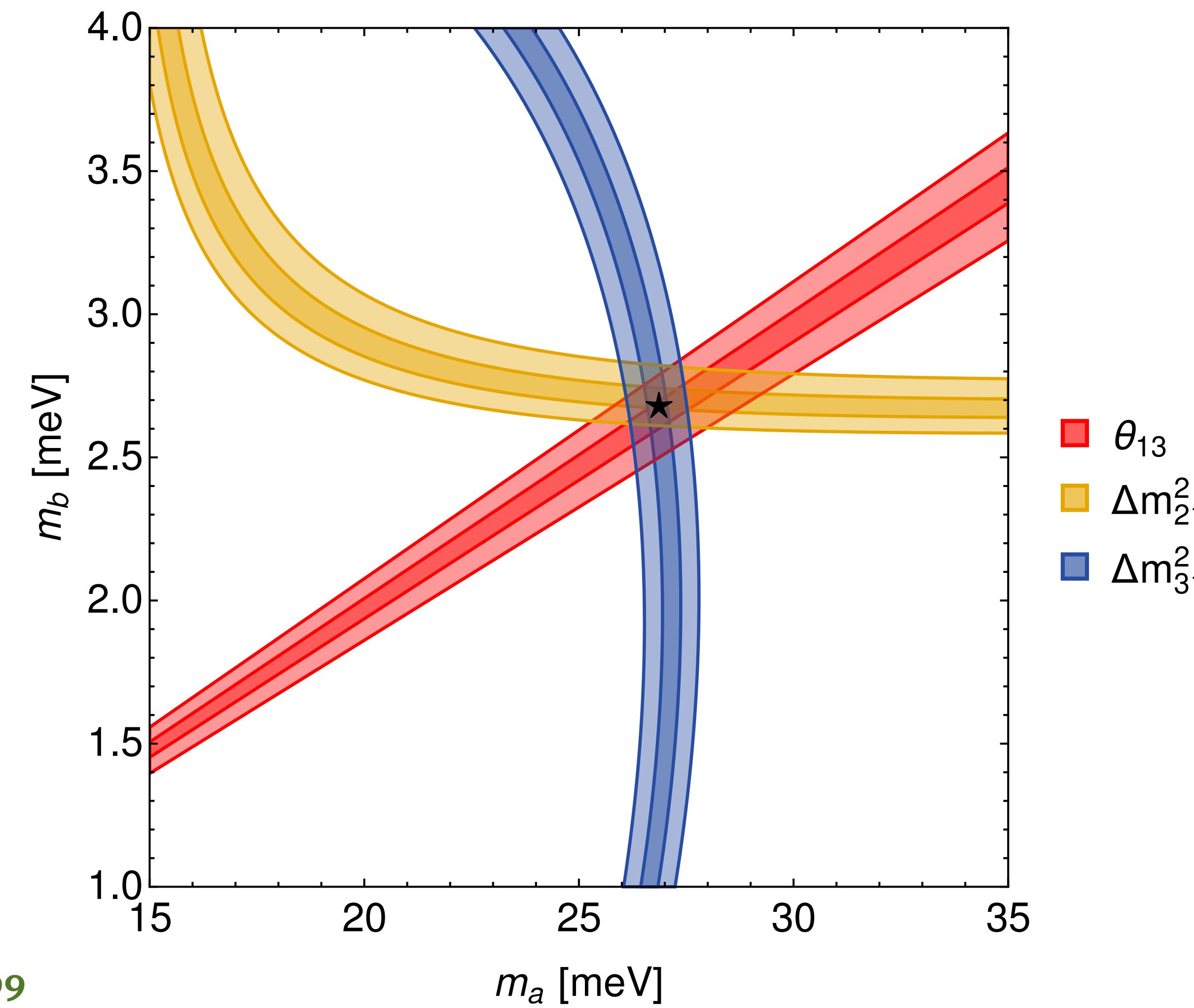
$$|\tilde{v}_e| \ll |\tilde{v}_\mu| \ll |\tilde{v}_\tau|, |\tilde{v}_a|, |\tilde{v}_s|, |\tilde{\xi}| < 1$$

SFK 1304.6264

The Littlest Seesaw

Google → 1512.07531

$$m_\nu = m_a \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix} + m_b \begin{pmatrix} 1 & 3 & 1 \\ 3 & 9 & 3 \\ 1 & 3 & 1 \end{pmatrix} e^{i2\pi/3}$$



2 input parameters

Predicts:

3 neutrino masses,
3 mixing angles,
1 Dirac CP phase,
2 Majorana phases
= 9 observables

Currently measured
5 observables

Very predictive!

e.g. max. atm & max. CPV due to approx. mu-tau sym SFK, Nishi 1807.00023

Ballett, SFK, Pascoli, Prouse, Wang 1612.01999

m_a (meV)	m_b (meV)	η (rad)	θ_{12} (°)	θ_{13} (°)	θ_{23} (°)	δ_{CP} (°)	m_1 (meV)	m_2 (meV)	m_3 (meV)
26.57	2.684	$\frac{2\pi}{3}$	34.3	8.67	45.8	-86.7	0	8.59	49.8
Value	from	[25]	$33.48^{+0.78}_{-0.75}$	$8.50^{+0.20}_{-0.21}$	$42.3^{+3.0}_{-1.6}$	-54^{+39}_{-70}	0	8.66 ± 0.10	49.57 ± 0.47

Good agreement!

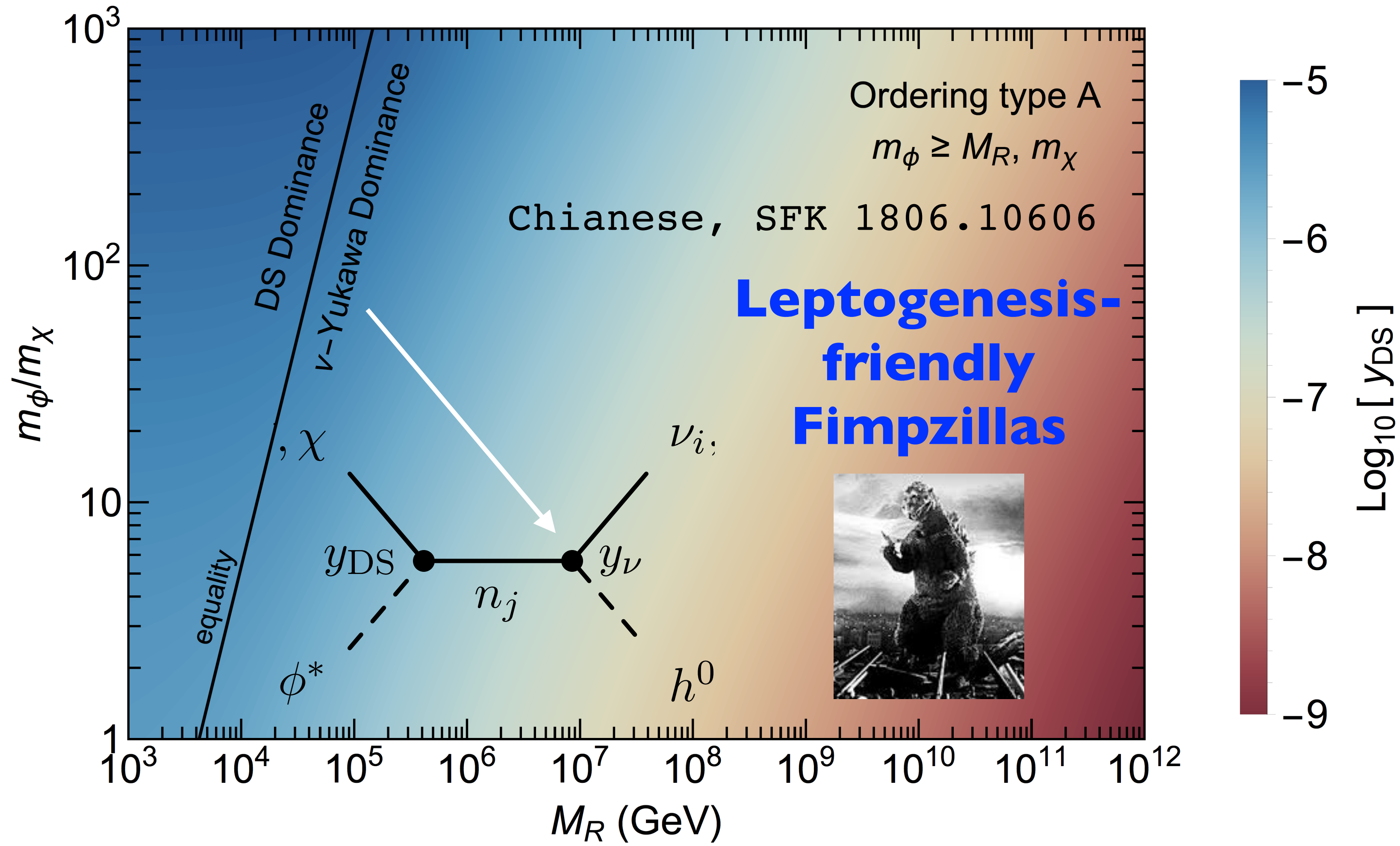
The Dark Side of the Littlest Seesaw

Chianese, SFK 1806.10606;
see also: Bhattacharya, de Medeiros Varzielas, Karmakar, SFK and Sil, 1806.00490;
Becker 1806.08579

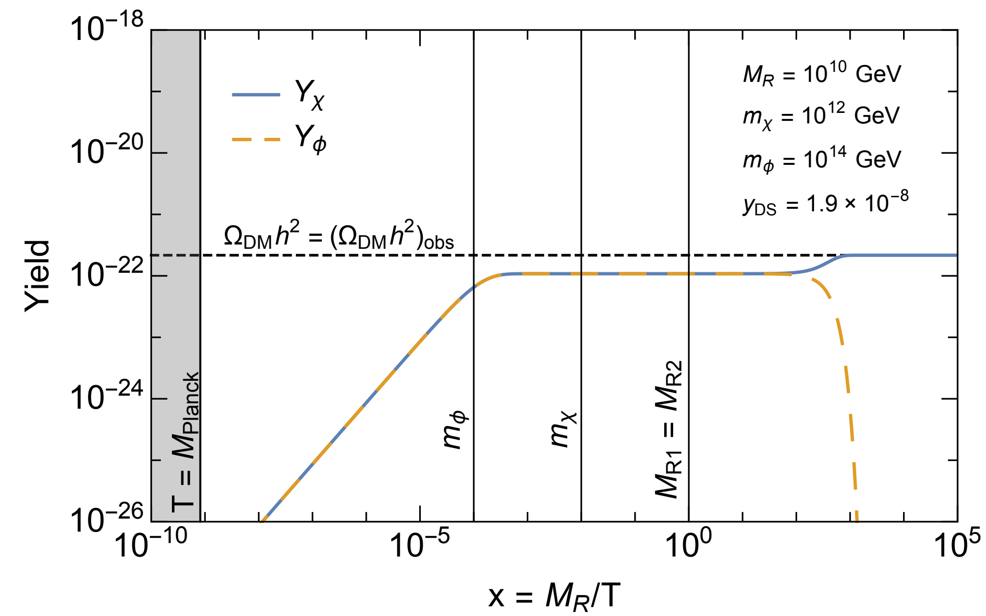
$$\mathcal{L}_{\text{Seesaw}} = -Y_{\alpha\beta}\overline{L_{L\alpha}}\tilde{H}N_{R\beta} - \frac{1}{2}M_R\overline{N_R^c}N_R + h.c.\,,$$
$$\mathcal{L}_{\text{DS}} = \overline{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi + |\partial_\mu\phi| - m_\phi^2\,|\phi|^2 + V\left(\phi\right)$$
$$\mathcal{L}_{\text{portal}} = y_{\text{DS}}\phi\,\overline{\chi}N_R + h.c\,,$$

Two RHN portal
No Higgs portal !

	N_R	ϕ	χ
$SU(2)_L$	**1**	**1**	**1**
$U(1)_Y$	0	0	0
Z_2	+	-	-



Freeze-in mechanism for fimpzillas



Chianese, SFK 1806.10606

Part II

Phenomenological hints from B physics

Low scale theories of flavour

$$R_K = \frac{\mathrm{BR}\,(B^+ \to K^+\mu^+\mu^-)}{\mathrm{BR}\,(B^+ \to K^+e^+e^-)} = 0.745 \pm 0.09_{\rm stat} \pm 0.036_{\rm syst}$$

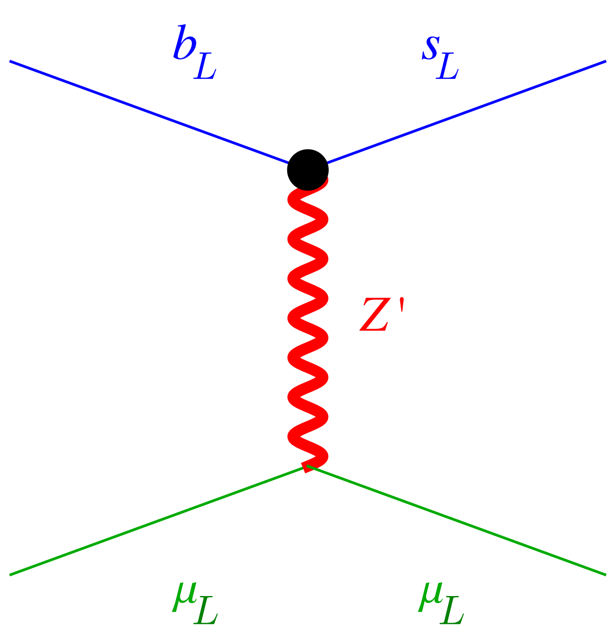
Talks by Isidori, Talbert, Hurth

Possible operator for R_K, R_{K^*}

$$\Delta\mathcal{L}_{\rm eff} \supset G_{bs\mu}(\bar{b}_L\gamma^\mu s_L)(\bar{\mu}_L\gamma_\mu\mu_L) + \mathrm{h.c.}, \qquad G_{bs\mu} \approx \frac{1}{(31.5\ \mathrm{TeV})^2}.$$

Could originate from massive Z' model with couplings

$$\mathcal{L} \supset Z'_\mu\left(g_{bb}\bar{b}_L\gamma^\mu b_L + g_{\mu\mu}\bar{\mu}_L\gamma^\mu\mu_L\right)$$



$$G_{bs\mu} = -\frac{g_{bs}g_{\mu\mu}}{M^2_{Z'}} = -\frac{V_{ts}g_{bb}g_{\mu\mu}}{M^2_{Z'}} \approx \frac{1}{(31.5\ \mathrm{TeV})^2}.$$

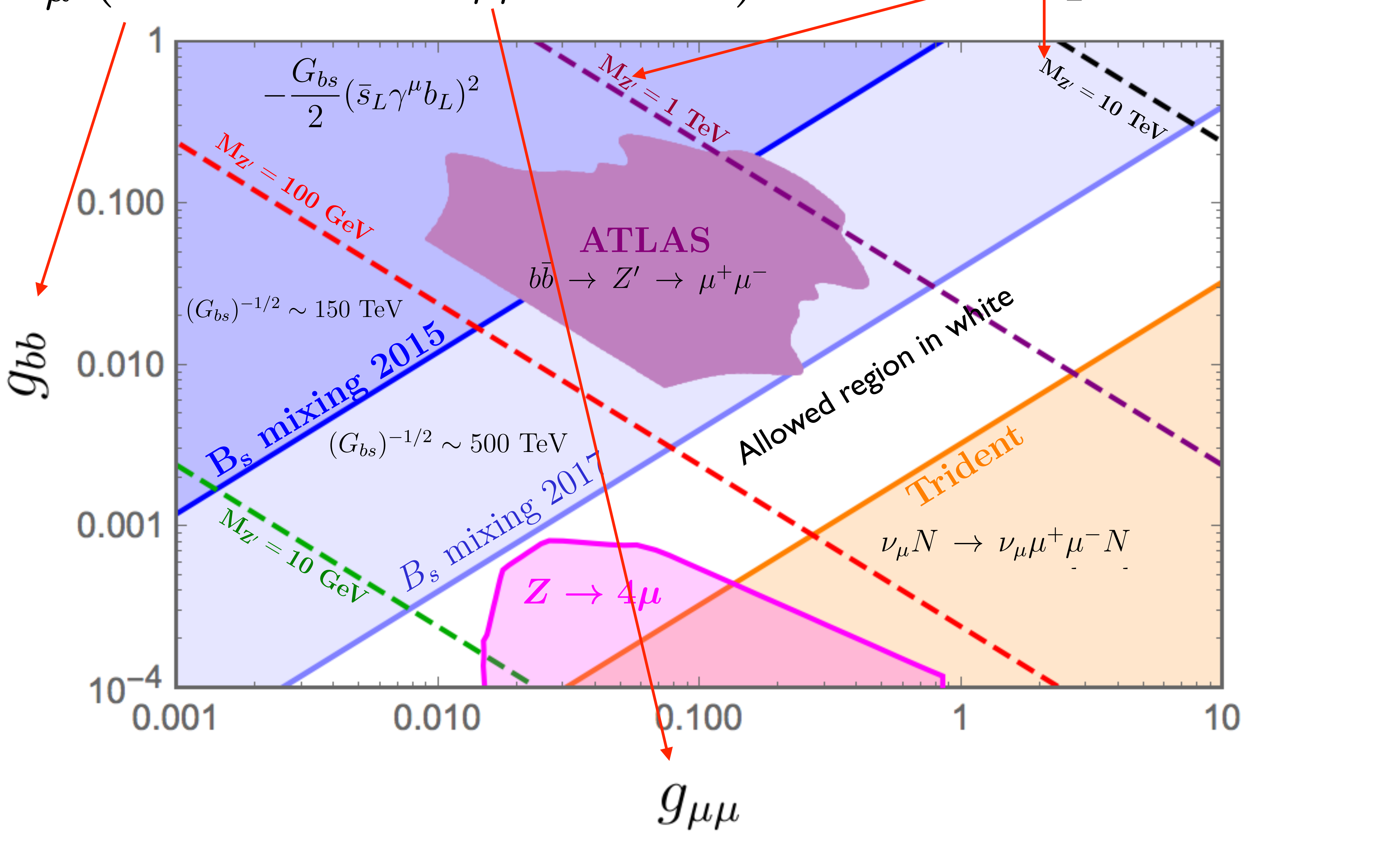
$$\frac{g_{bb}g_{\mu\mu}}{M^2_{Z'}} \approx \frac{1}{(6.4\ \mathrm{TeV})^2}$$ R_K, R_{K^*}

Constraints

Falkowski, SFK, Perdomo, Pierre
1803.04430

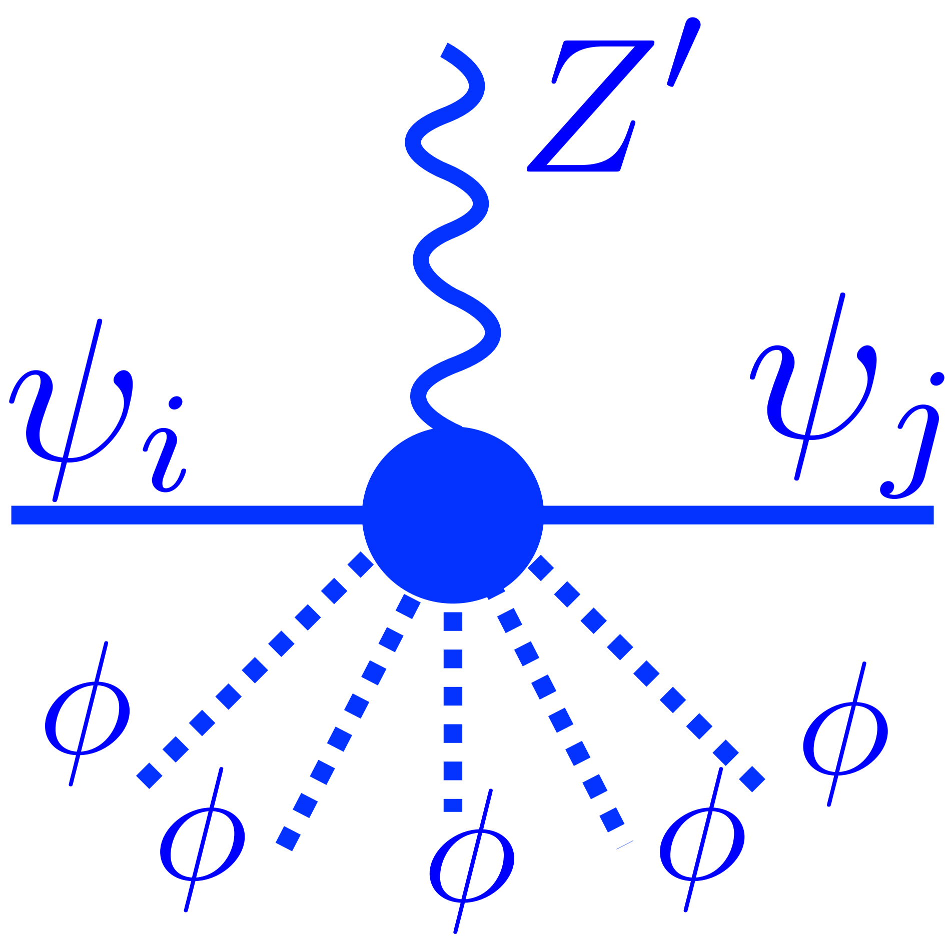
$$Z'_\mu \left(g_{bb} \bar{b}_L \gamma^\mu b_L + g_{\mu\mu} \bar{\mu}_L \gamma^\mu \mu_L \right)$$

R_K, R_{K^*} fixes $\frac{g_{bb} g_{\mu\mu}}{M_{Z'}^2} \approx \frac{1}{(6.4\ \mathrm{TeV})^2}$



Effective Z' couplings

$$\left(\frac{\langle \phi_i^\dagger \rangle}{\Lambda'^{\psi}_{i,n}}\right)^n \left(\frac{\langle \phi_j \rangle}{\Lambda'^{\psi}_{j,m}}\right)^m g' Z'_\mu \psi_i^\dagger \gamma^\mu \psi_j$$



Z' couplings small due to powers of ratios $\dfrac{\langle \phi \rangle}{\Lambda}$

M_P

Now the scale is fixed

$$M_{Z'} \sim g' \langle \phi_i \rangle$$

$$\sim TeV$$

Phenomenological hints from B physics suggest low scale theory of flavour

$\Lambda \sim TeV$

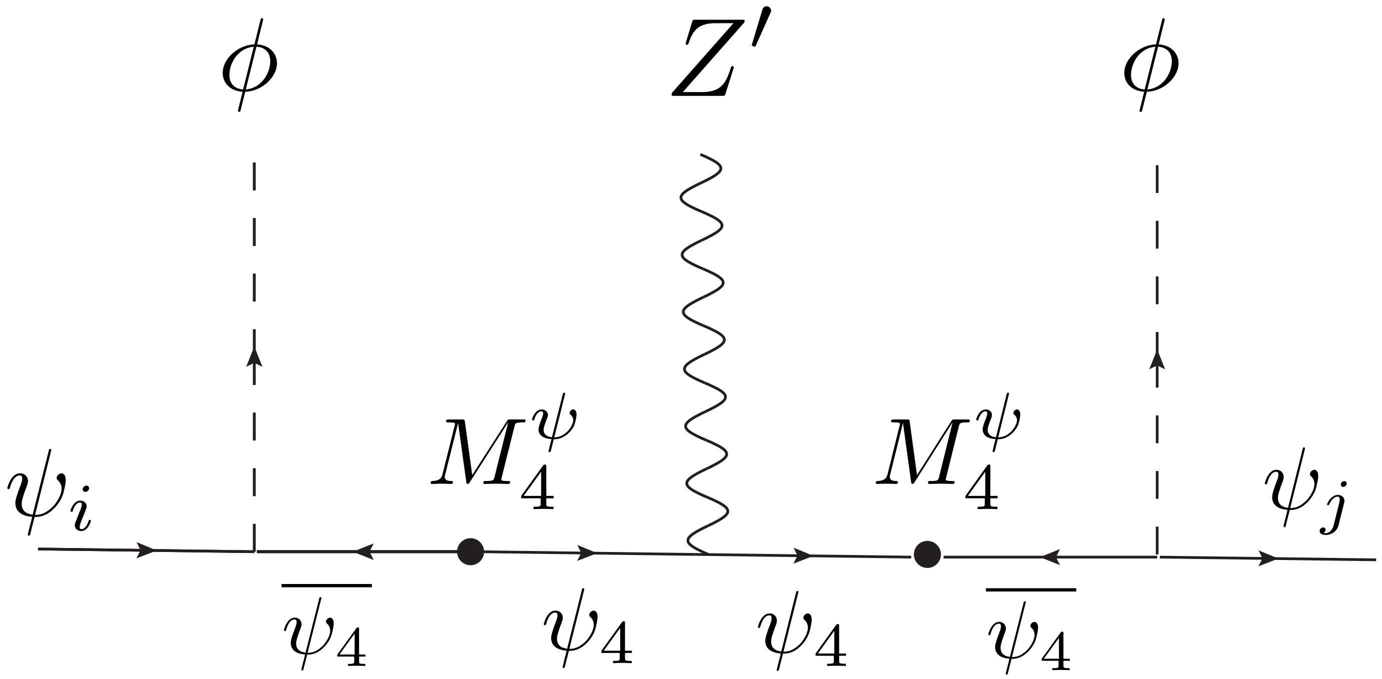
M_{EW}

SFK 1706.06100; Crispim Romao, SFK, Leontaris 1710.02349; Antusch, Hohl, SFK, Susic 1712.05366; Raby,Trautner 1712.09360; Cárcamo Hernández, SFK 1803.07367

Flavourful Z' models

Introduce a vector-like fourth family which carries U(1)' charges (anomaly free)

Non-universality induced by fourth family mixing

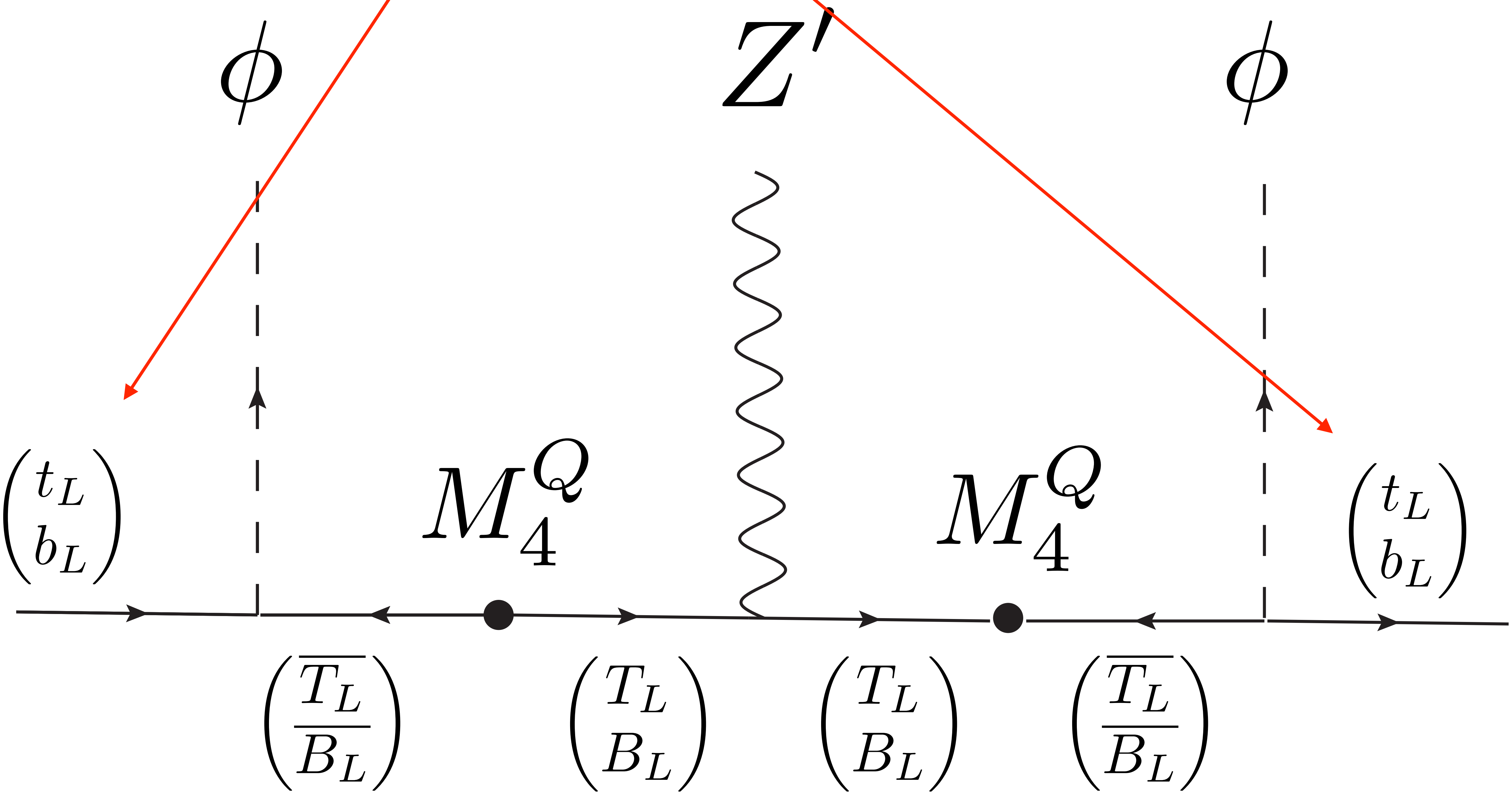


“Fermiophobic model”

SFK 1706.06100; Falkowski, SFK, Perdomo, Pierre 1803.04430
Raby,Trautner 1712.09360
(see following talk by Trautner)

$$\mathcal{L} \supset Z'_\mu \left(g_{bb} \bar{b}_L \gamma^\mu b_L + g_{\mu\mu} \bar{\mu}_L \gamma^\mu \mu_L \right)$$

Z’ couplings generated entirely via mixing with fourth family



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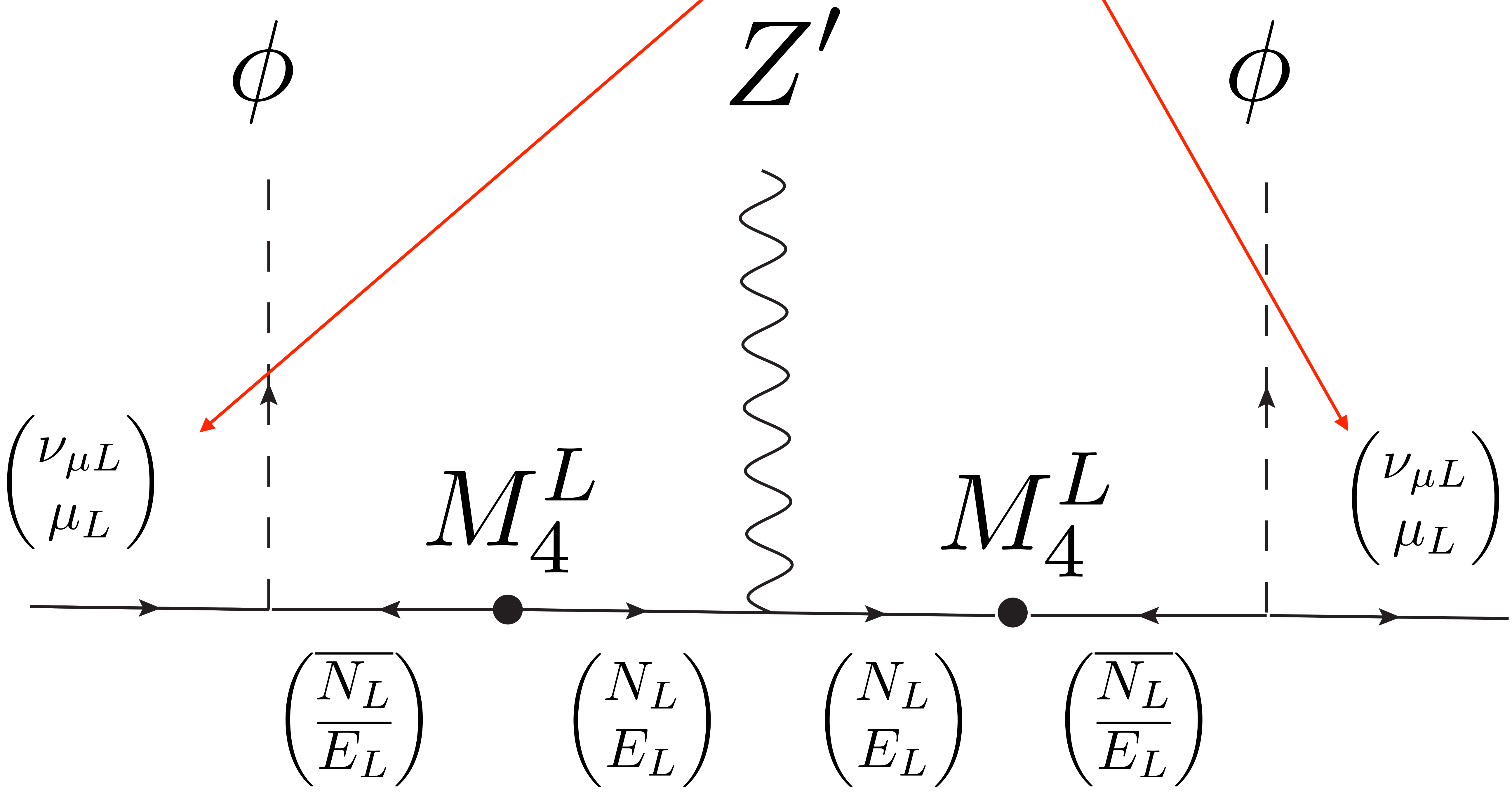


$R_{K^{(*)}}$ and the origin of Yukawa couplings

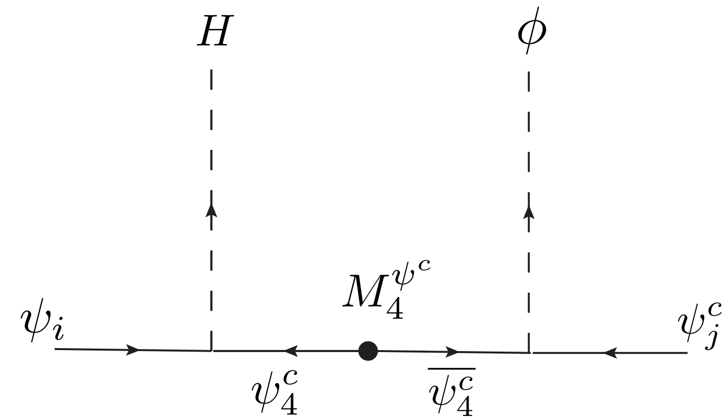
SFK 1806.06780

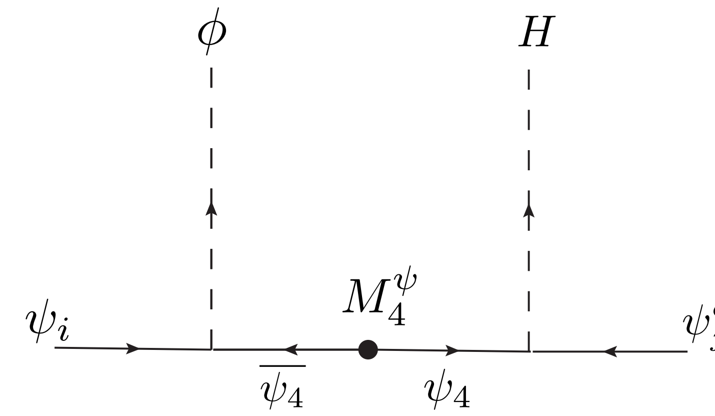
"Fermiophobic model"

Field	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
Q_i	$\mathbf{3}$	$\mathbf{2}$	$1/6$	0
u_i^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	0
d_i^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$1/3$	0
L_i	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	0
e_i^c	$\mathbf{1}$	$\mathbf{1}$	1	0
ν_i^c	$\mathbf{1}$	$\mathbf{1}$	0	0
Q_4	$\mathbf{3}$	$\mathbf{2}$	$1/6$	1
u_4^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	1
d_4^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$1/3$	1
L_4	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	1
e_4^c	$\mathbf{1}$	$\mathbf{1}$	1	1
ν_4^c	$\mathbf{1}$	$\mathbf{1}$	0	1
$\overline{Q_4}$	$\overline{\mathbf{3}}$	$\overline{\mathbf{2}}$	$-1/6$	-1
$\overline{u_4^c}$	$\mathbf{3}$	$\mathbf{1}$	$2/3$	-1
$\overline{d_4^c}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	-1
$\overline{L_4}$	$\mathbf{1}$	$\overline{\mathbf{2}}$	$1/2$	-1
$\overline{e_4^c}$	$\mathbf{1}$	$\mathbf{1}$	-1	-1
$\overline{\nu_4^c}$	$\mathbf{1}$	$\mathbf{1}$	0	-1
ϕ	$\mathbf{1}$	$\mathbf{1}$	0	1
H_u	$\mathbf{1}$	$\mathbf{2}$	$1/2$	-1
H_d	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	-1

Yukawas generated via mixing with fourth family

Ferretti, SFK, Romanino hep-ph/0609047





Yukawas

$$\frac{x_j^{\psi^c}\langle\phi\rangle}{M_4^{\psi^c}} y_{i4}^{\psi} H \psi_i \psi_j^c + \frac{x_i^{\psi}\langle\phi\rangle}{M_4^{\psi}} y_{4j}^{\psi} H \psi_i \psi_j^c$$

$R_{K^{(*)}}$ and the origin of Yukawa couplings

SFK 1806.06780

"Fermiophobic model"

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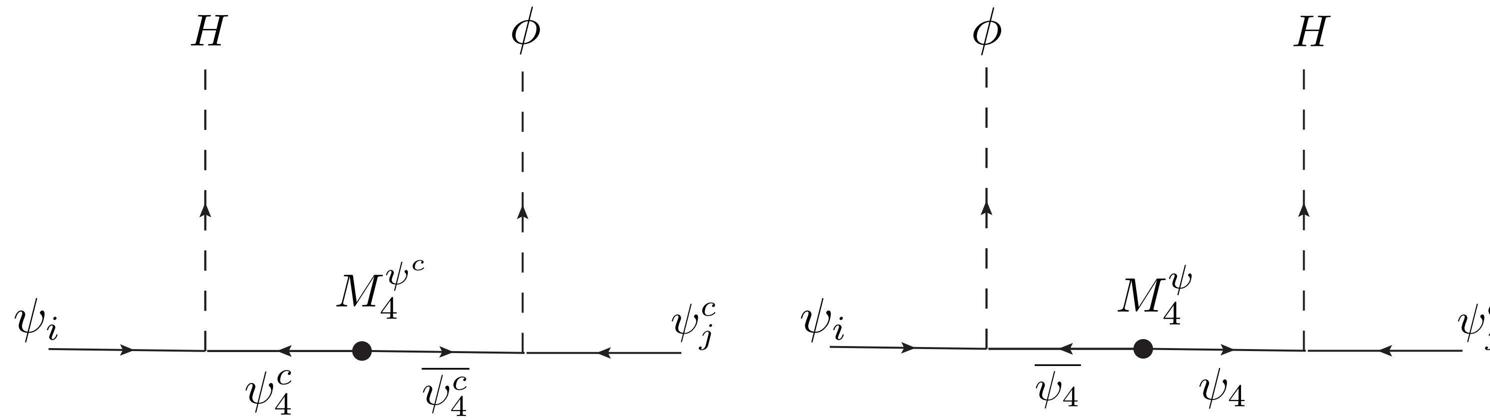
u_i^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	0
d_i^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$1/3$	0
L_i	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	0
e_i^c	$\mathbf{1}$	$\mathbf{1}$	1	0
ν_i^c	$\mathbf{1}$	$\mathbf{1}$	0	0
Q_4	$\mathbf{3}$	$\mathbf{2}$	$1/6$	1
u_4^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	1
d_4^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$1/3$	1
L_4	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	1
e_4^c	$\mathbf{1}$	$\mathbf{1}$	1	1
ν_4^c	$\mathbf{1}$	$\mathbf{1}$	0	1
$\overline{Q_4}$	$\overline{\mathbf{3}}$	$\overline{\mathbf{2}}$	$-1/6$	-1
$\overline{u_4^c}$	$\mathbf{3}$	$\mathbf{1}$	$2/3$	-1
$\overline{d_4^c}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	-1
$\overline{L_4}$	$\mathbf{1}$	$\overline{\mathbf{2}}$	$1/2$	-1
$\overline{e_4^c}$	$\mathbf{1}$	$\mathbf{1}$	-1	-1
$\overline{\nu_4^c}$	$\mathbf{1}$	$\mathbf{1}$	0	-1
ϕ	$\mathbf{1}$	$\mathbf{1}$	0	1
H_u	$\mathbf{1}$	$\mathbf{2}$	$1/2$	-1
H_d	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	-1

Yukawas generated via mixing with fourth family

Ferretti, SFK, Romanino hep-ph/0609047

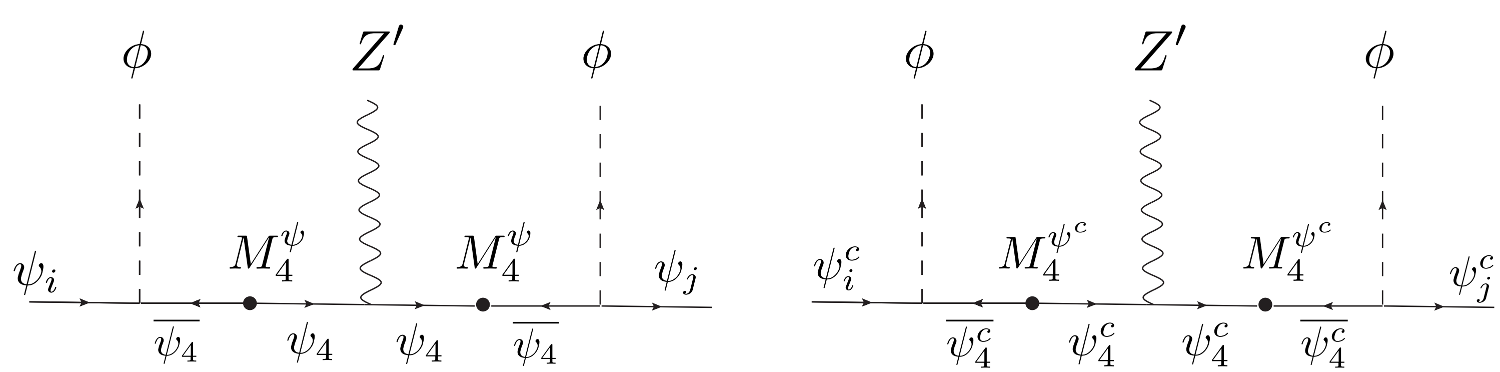


Yukawas

$$\frac{x_j^{\psi^c}\langle\phi\rangle}{M_4^{\psi^c}} y_{i4}^{\psi} H\psi_i\psi_j^c + \frac{x_i^{\psi}\langle\phi\rangle}{M_4^{\psi}} y_{4j}^{\psi} H\psi_i\psi_j^c$$

Z' couplings generated via mixing with fourth family

SFK 1706.06100



Z' couplings

$$\frac{x_i^{\psi}\langle\phi\rangle}{M_4^{\psi}}\frac{x_j^{\psi}\langle\phi\rangle}{M_4^{\psi}} g' Z'_{\mu}\psi_i^{\dagger}\gamma^{\mu}\psi_j + \frac{x_i^{\psi^c}\langle\phi\rangle}{M_4^{\psi^c}}\frac{x_j^{\psi^c}\langle\phi\rangle}{M_4^{\psi^c}} g' Z'_{\mu}\psi_i^{c\dagger}\gamma^{\mu}\psi_j^c$$

$R_{K^{(*)}}$ and the origin of Yukawa couplings

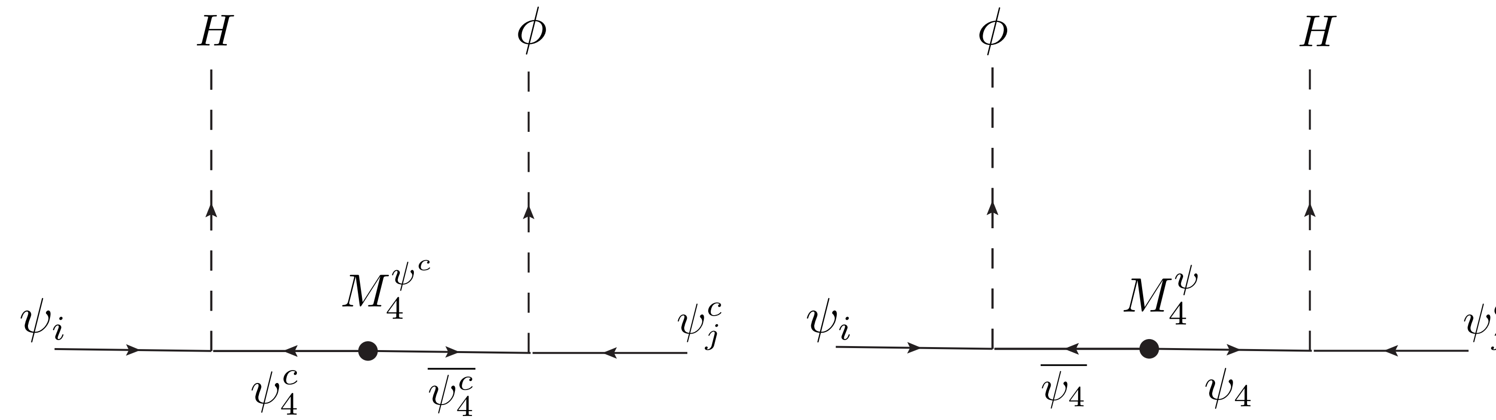
SFK 1806.06780

"Fermiophobic model"

Field	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
Q_i	$\mathbf{3}$	$\mathbf{2}$	$1/6$	0
u_i^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	0
d_i^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$1/3$	0
L_i	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	0
e_i^c	$\mathbf{1}$	$\mathbf{1}$	1	0
ν_i^c	$\mathbf{1}$	$\mathbf{1}$	0	0
Q_4	$\mathbf{3}$	$\mathbf{2}$	$1/6$	1
u_4^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	1
d_4^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$1/3$	1
L_4	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	1
e_4^c	$\mathbf{1}$	$\mathbf{1}$	1	1
ν_4^c	$\mathbf{1}$	$\mathbf{1}$	0	1
$\overline{Q_4}$	$\overline{\mathbf{3}}$	$\overline{\mathbf{2}}$	$-1/6$	-1
$\overline{u_4^c}$	$\mathbf{3}$	$\mathbf{1}$	$2/3$	-1
$\overline{d_4^c}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	-1
$\overline{L_4}$	$\mathbf{1}$	$\overline{\mathbf{2}}$	$1/2$	-1
$\overline{e_4^c}$	$\mathbf{1}$	$\mathbf{1}$	-1	-1
$\overline{\nu_4^c}$	$\mathbf{1}$	$\mathbf{1}$	0	-1
ϕ	$\mathbf{1}$	$\mathbf{1}$	0	1
H_u	$\mathbf{1}$	$\mathbf{2}$	$1/2$	-1
H_d	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	-1

Yukawa and Z' couplings are related

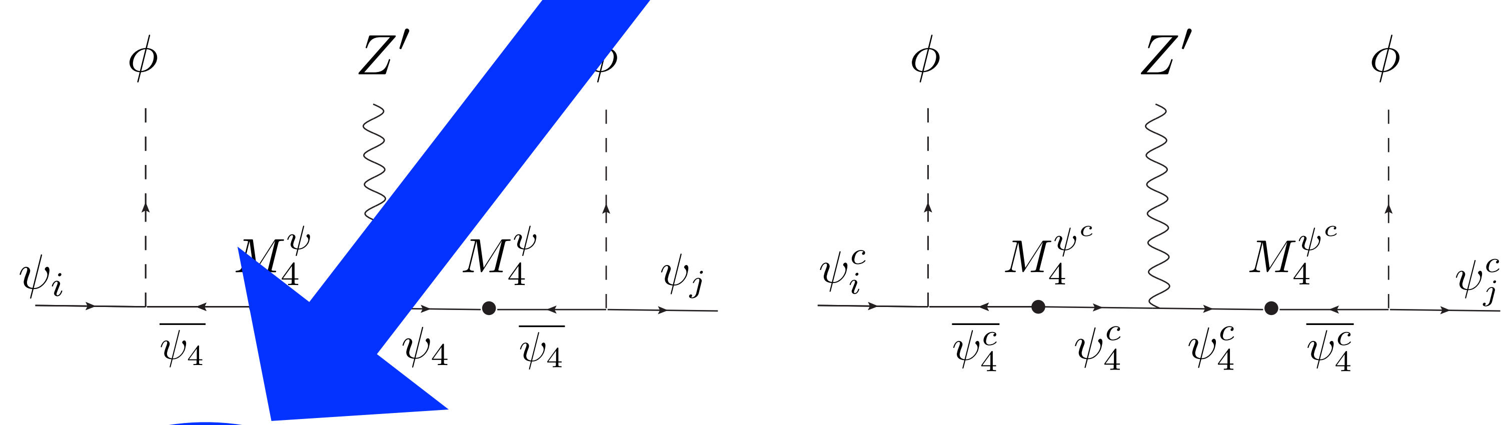
SFK 1806.06780



Yukawas

$$\frac{x_j^{\psi^c}\langle\phi\rangle}{M_4^{\psi^c}} y_{i4}^{\psi} H\psi_i\psi_j^c + \frac{x_i^{\psi}\langle\phi\rangle}{M_4^{\psi}} y_{4j}^{\psi} H\psi_i\psi_j^c$$

Z' muon coupling related to muon Yukawa - - too small?



Z' couplings

$$\frac{x_i^{\psi}\langle\phi\rangle}{M_4^{\psi}}\frac{x_j^{\psi}\langle\phi\rangle}{M_4^{\psi}} g' Z'_\mu \psi_i^\dagger\gamma^\mu\psi_j + \frac{x_i^{\psi^c}\langle\phi\rangle}{M_4^{\psi^c}}\frac{x_j^{\psi^c}\langle\phi\rangle}{M_4^{\psi^c}} g' Z'_\mu \psi_i^{c\dagger}\gamma^\mu\psi_j^c$$

$R_{K^{(*)}}$ and the origin of Yukawa couplings

SFK 1806.06780

"Fermiophobic model"

Field	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
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d^c_i	$\overline{\mathbf{3}}$	$\mathbf{1}$	$1/3$	0
L_i	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	0
e^c_i	$\mathbf{1}$	$\mathbf{1}$	1	0
ν^c_i	$\mathbf{1}$	$\mathbf{1}$	0	0
Q_4	$\mathbf{3}$	$\mathbf{2}$	$1/6$	1
u^c_4	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	1
d^c_4	$\overline{\mathbf{3}}$	$\mathbf{1}$	$1/3$	1
L_4	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	1
e^c_4	$\mathbf{1}$	$\mathbf{1}$	1	1
ν^c_4	$\mathbf{1}$	$\mathbf{1}$	0	1
$\overline{Q_4}$	$\overline{\mathbf{3}}$	$\overline{\mathbf{2}}$	$-1/6$	-1
$\overline{u^c_4}$	$\mathbf{3}$	$\mathbf{1}$	$2/3$	-1
$\overline{d^c_4}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	-1
$\overline{L_4}$	$\mathbf{1}$	$\overline{\mathbf{2}}$	$1/2$	-1
$\overline{e^c_4}$	$\mathbf{1}$	$\mathbf{1}$	-1	-1
$\overline{\nu^c_4}$	$\mathbf{1}$	$\mathbf{1}$	0	-1
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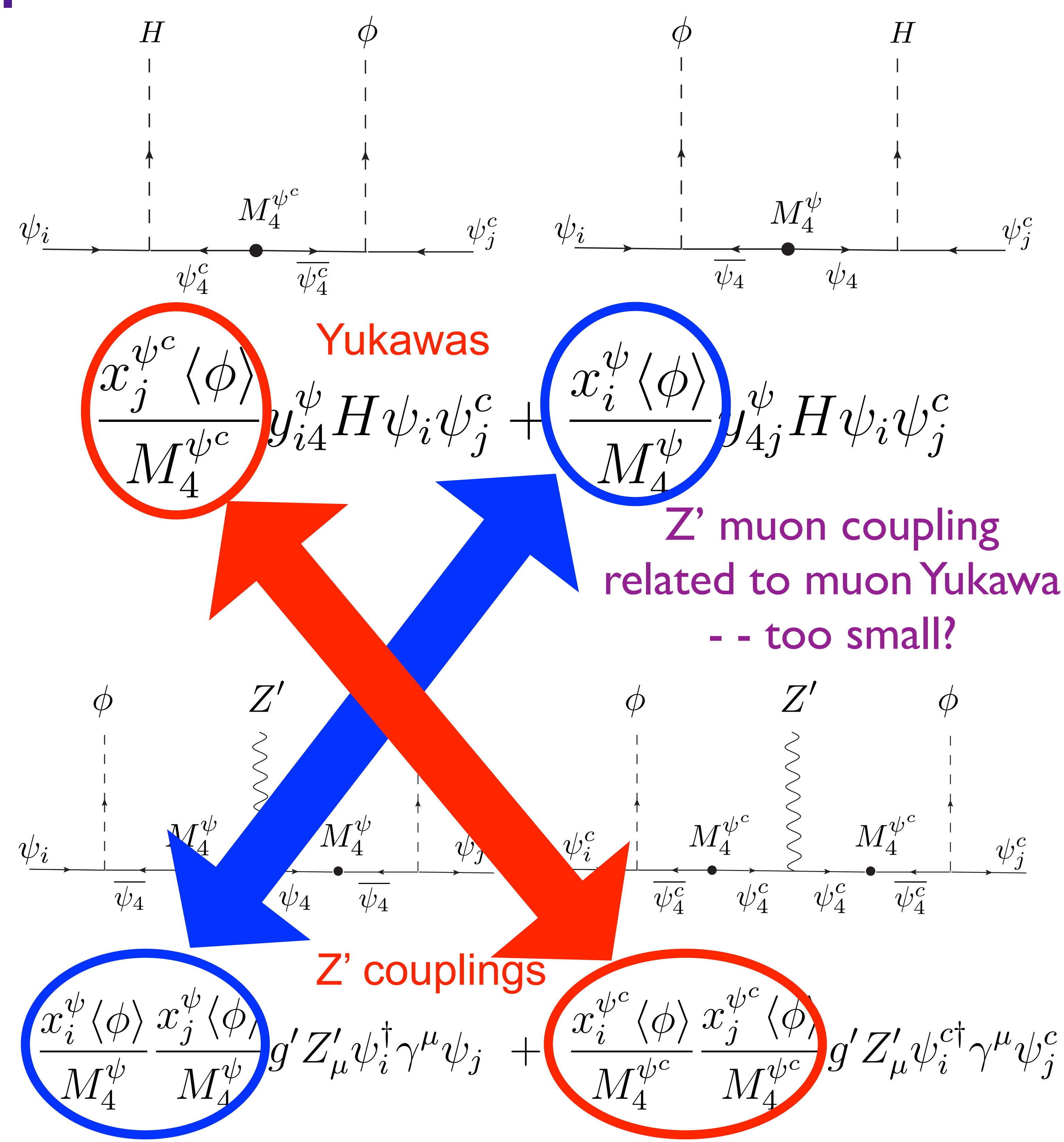
Yukawa and Z' couplings are related

SFK 1806.06780



Finale

The Flavour Puzzle

- Not going away - biggest problem of SM ?
- More interesting since neutrino mass & mixing

Theories of Flavour near Planck Scale

- Well motivated by SUSY GUTs
- Include discrete family symmetry from string theory
- Many possibilities - hard to test (but Littlest Seesaw)
- Need to discover SUSY!

Theories of Flavour near Electroweak scale

- Motivated by anomalies in B physics
- Many phenomenological constraints
- Models under construction