UNIVERSITY OF Southampton School of Physics and Astronomy

elusives invisiblesPlus

neutrinos, dark matter & dark energy physics

Theories of Flavour

From the Planck Scale to the Electroweak Scale

I will certainly be around for lunch, so I look forward to seeing you then.

Steve King

NExT Meeting, Southampton,

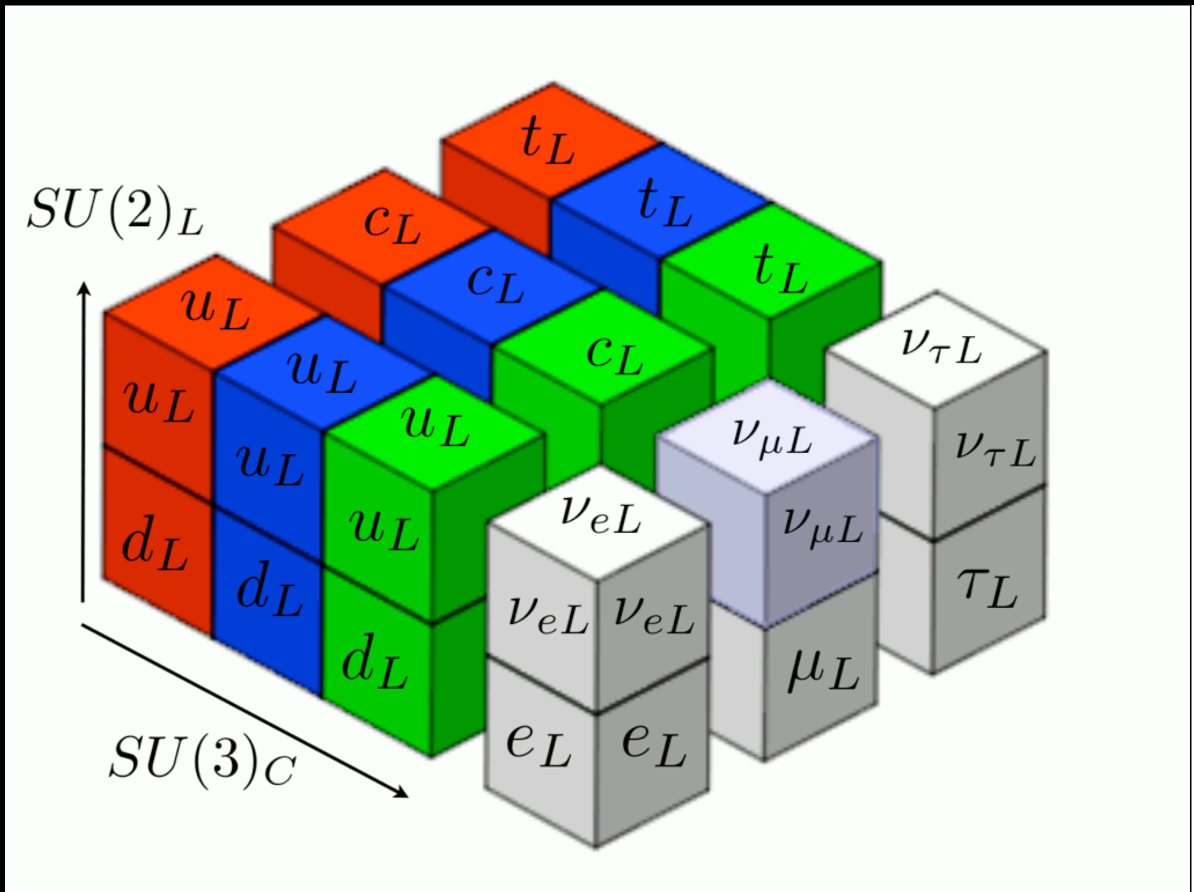
7th November, 2018

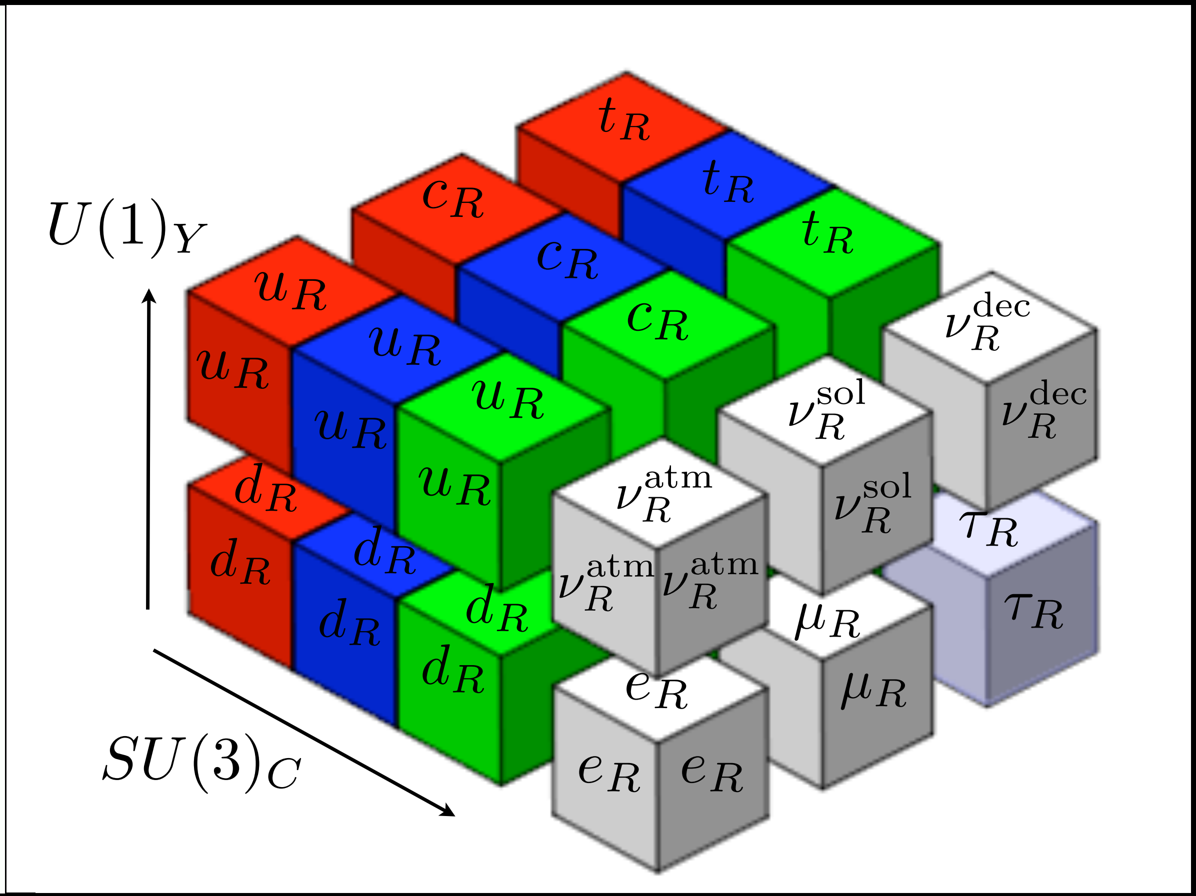
Prelude

The Flavour Problem

Theories of Flavour with effective Yukawa couplings

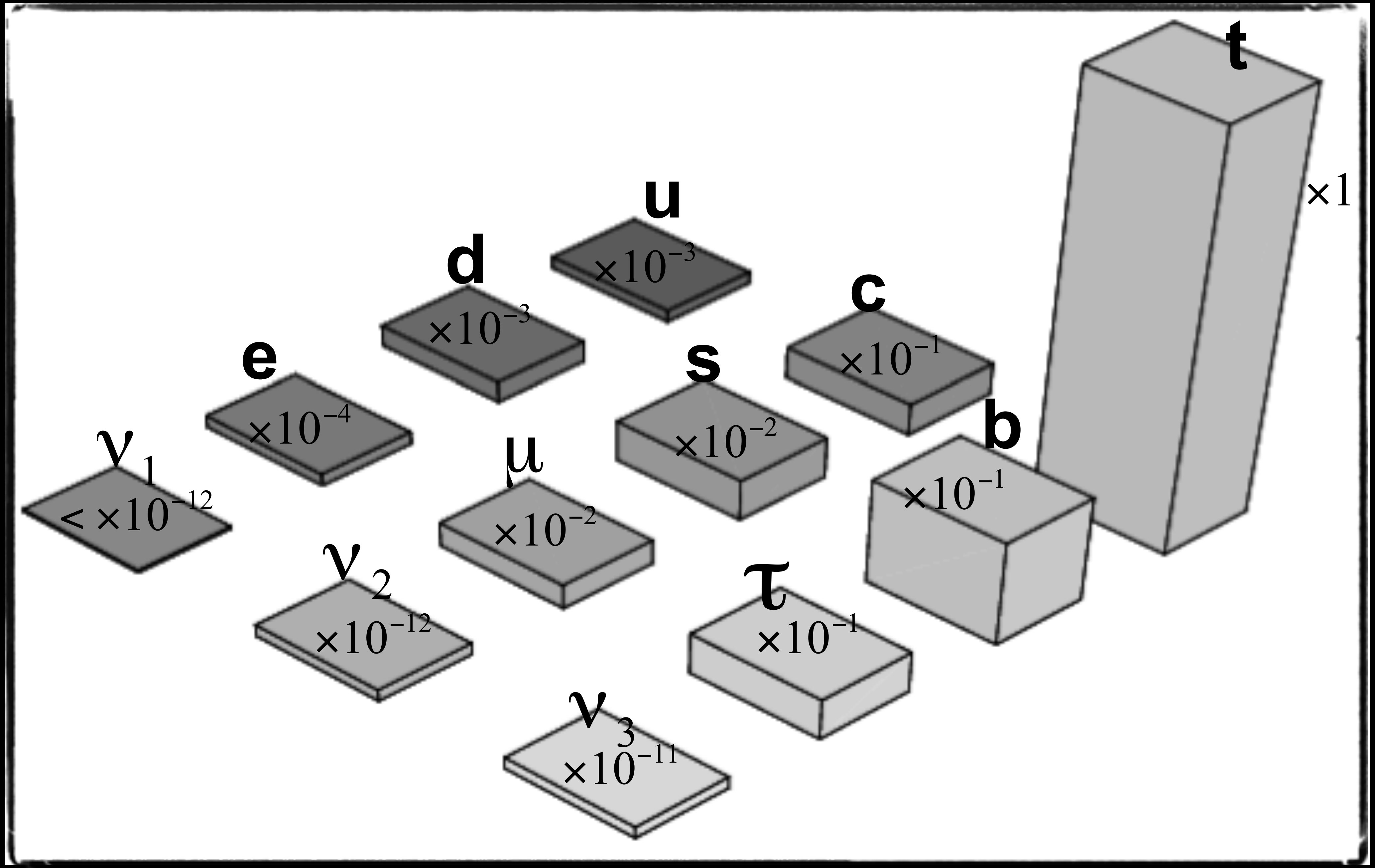
The Standard Model



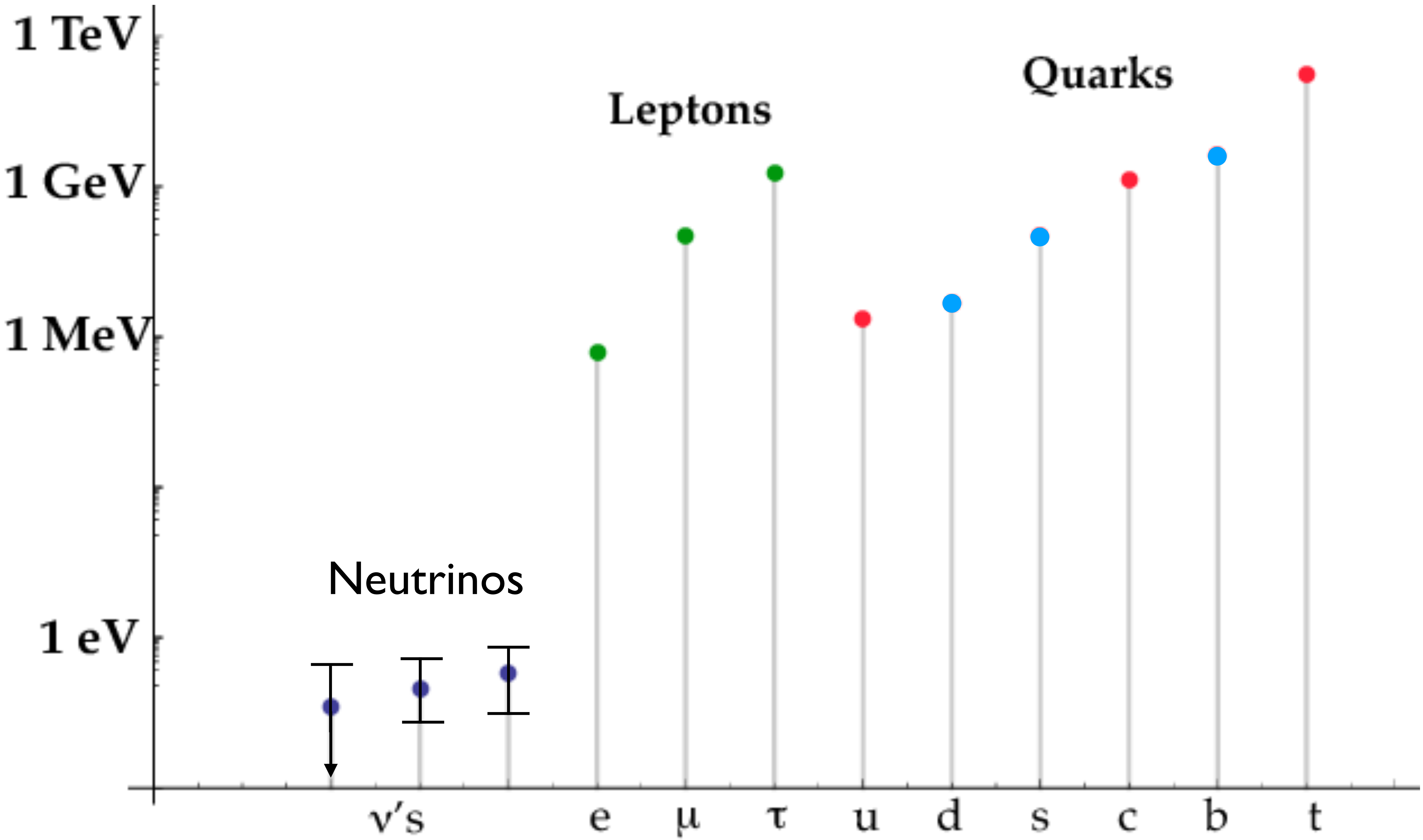


has flavour problem…

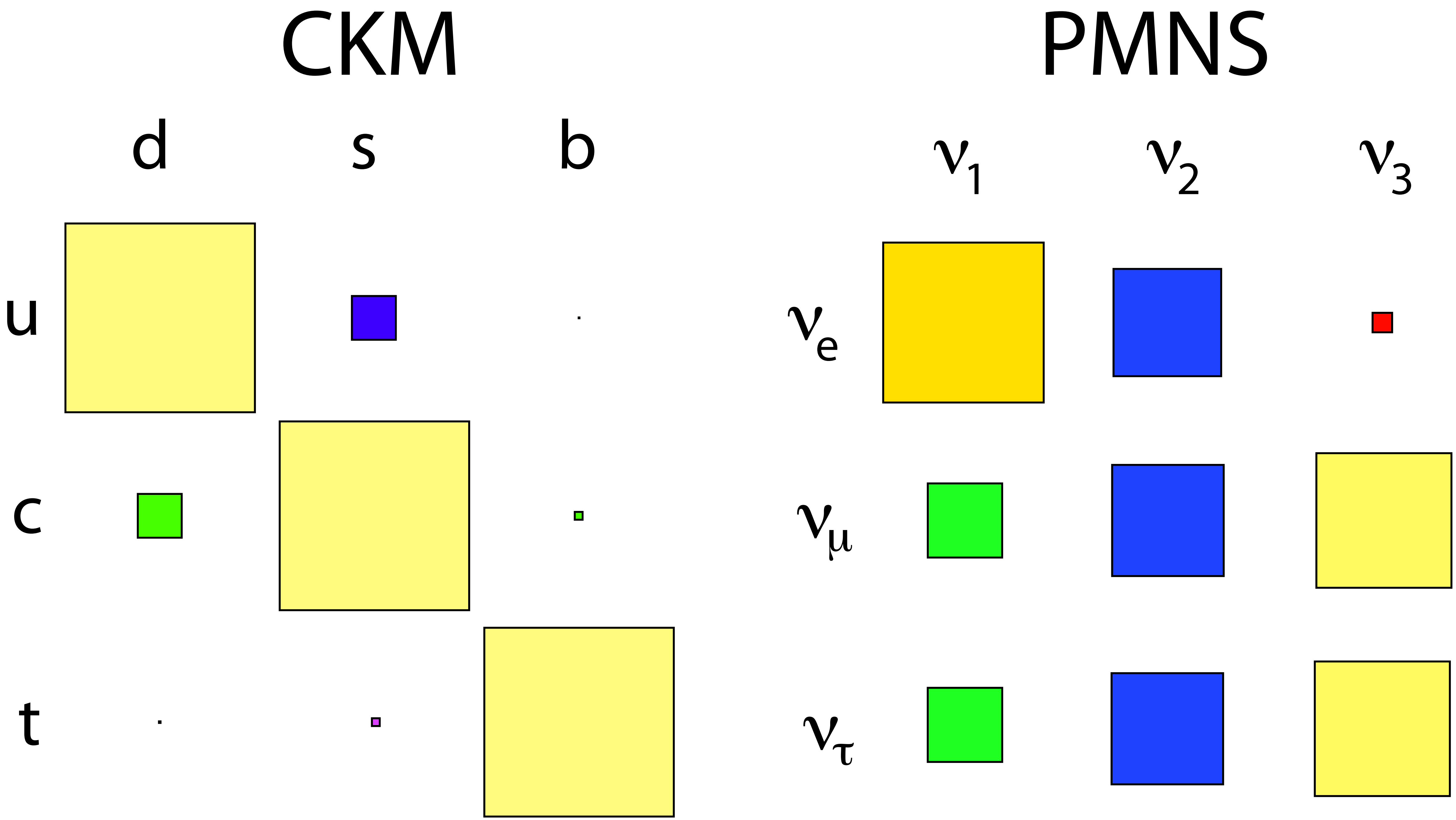
The Flavour Problem



Masses



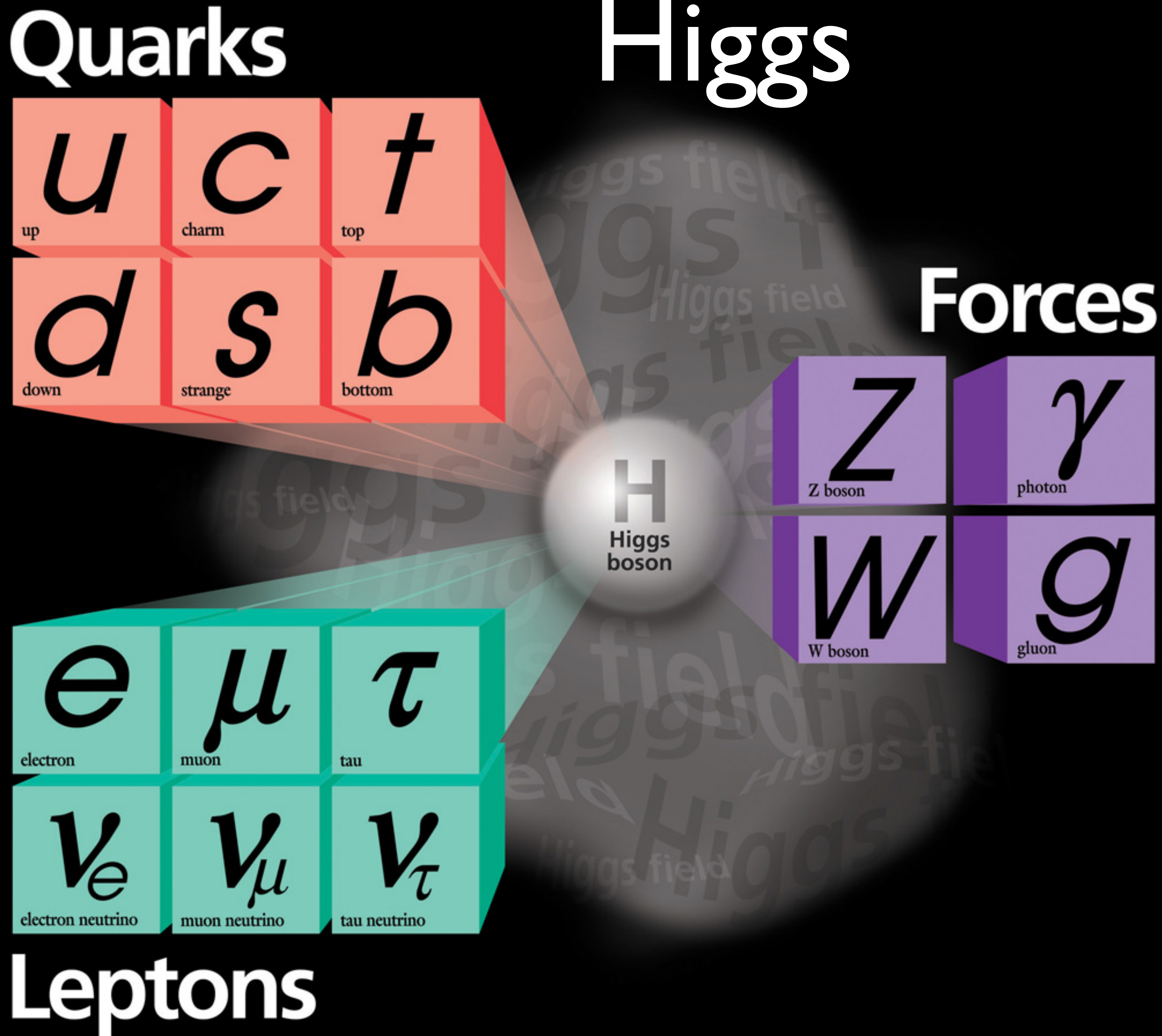
Mixing



Angles and CP

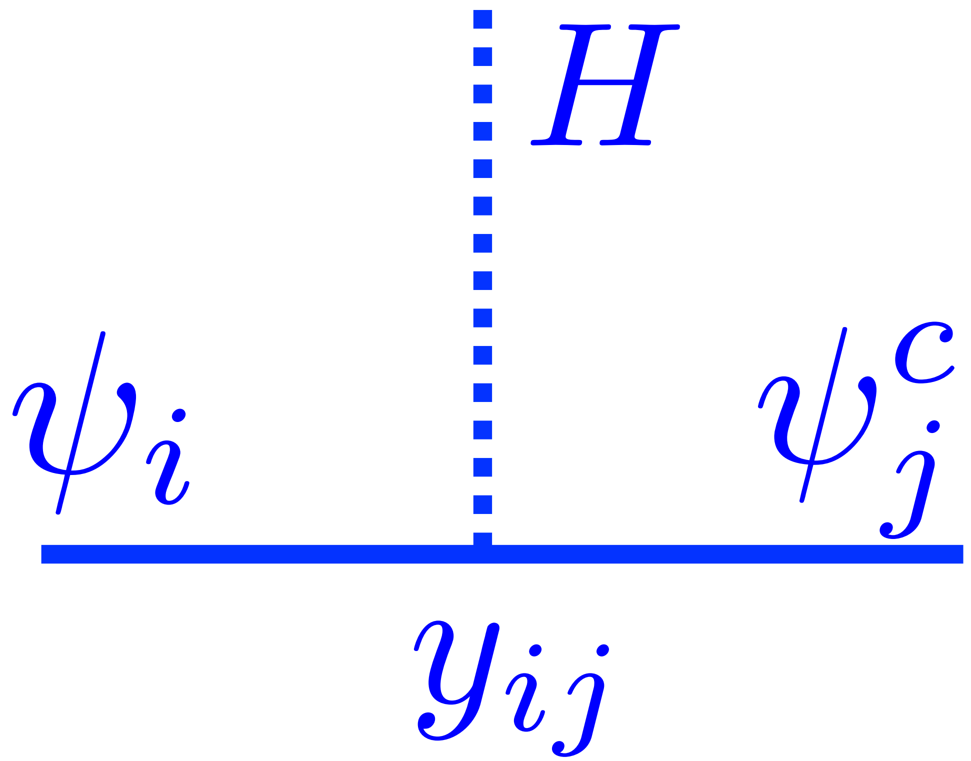
	θ_{12}	θ_{23}	θ_{13}	δ
Quarks	13° $\pm 0.1^\circ$	2.4° $\pm 0.1^\circ$	0.2° $\pm 0.05^\circ$	70° $\pm 5^\circ$
Leptons	34° $\pm 1^\circ$	45° $\pm 5^\circ$	8.5° $\pm 0.15^\circ$	-130^o $\pm 40^o$

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
Higgs field
e
electron
μ
muon
τ
tau
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
Leptons

Yukawa couplings

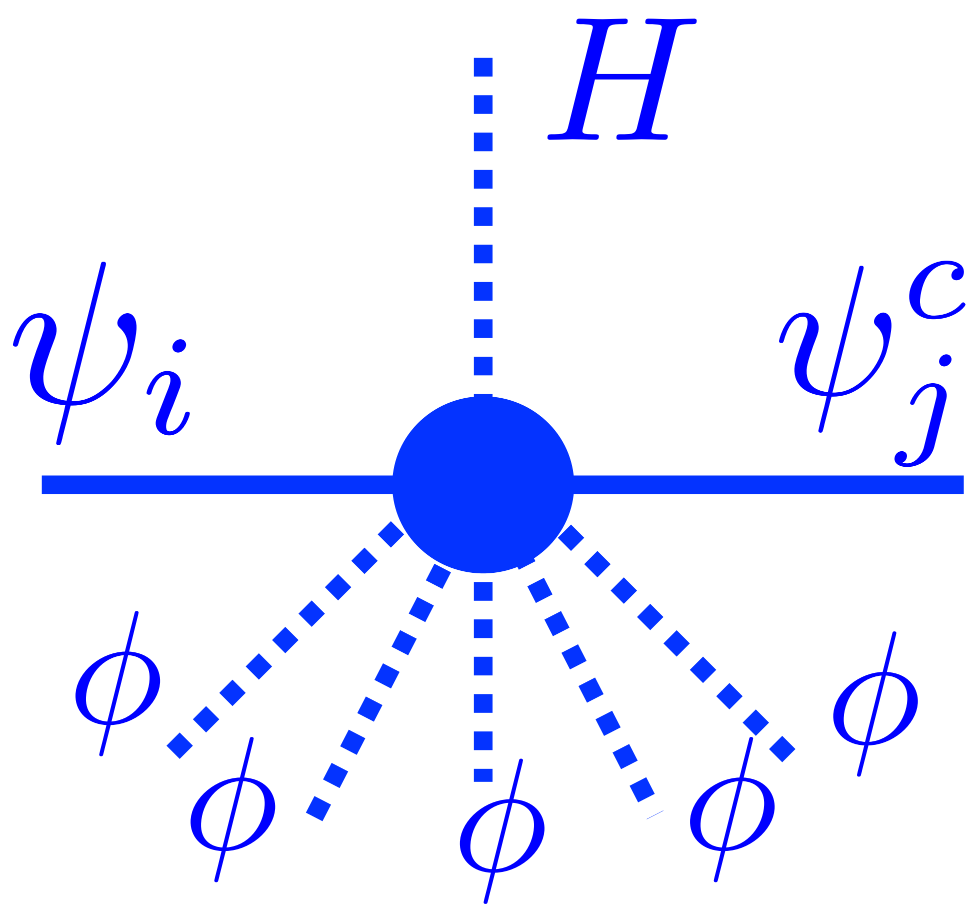
$$y_{ij} H \psi_i \psi_j^c$$



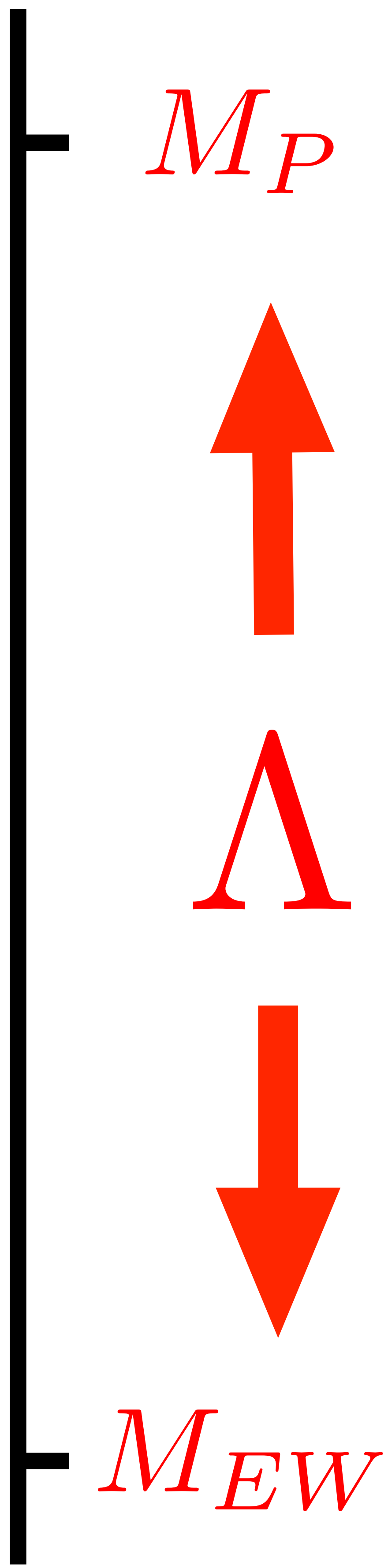
Why so small (apart from top quark)?

Effective Yukawa couplings

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

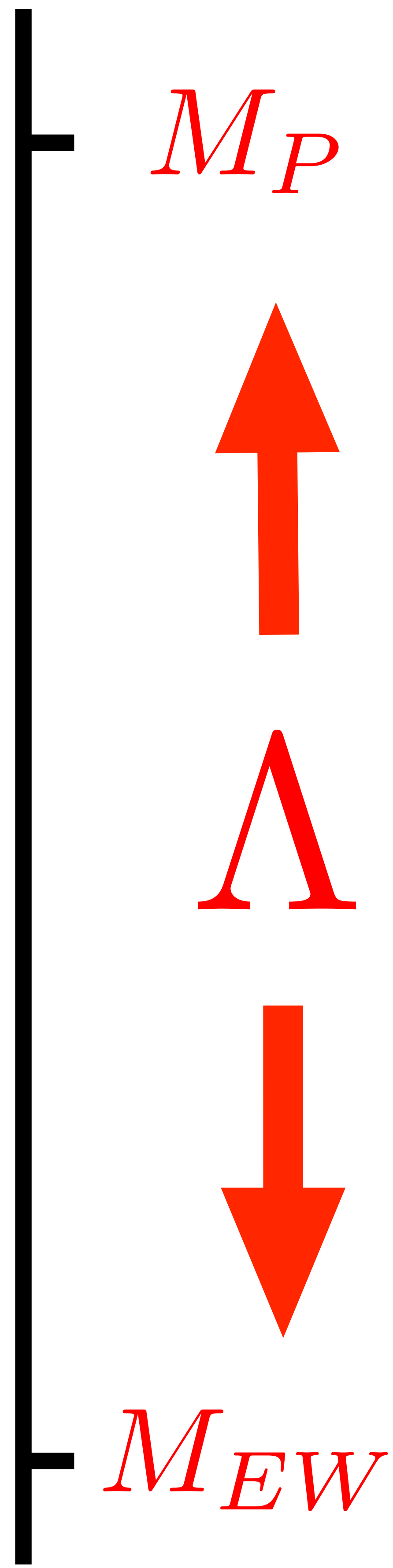


Yukawas small due to powers of ratios $\dfrac{\langle\phi\rangle}{\Lambda}$



Flavour scales can be from the Planck scale to electroweak scale

Keeping fixed ratios $\dfrac{\langle \phi \rangle}{\Lambda}$



SUSY GUTs
suggest high scale
theory of flavour

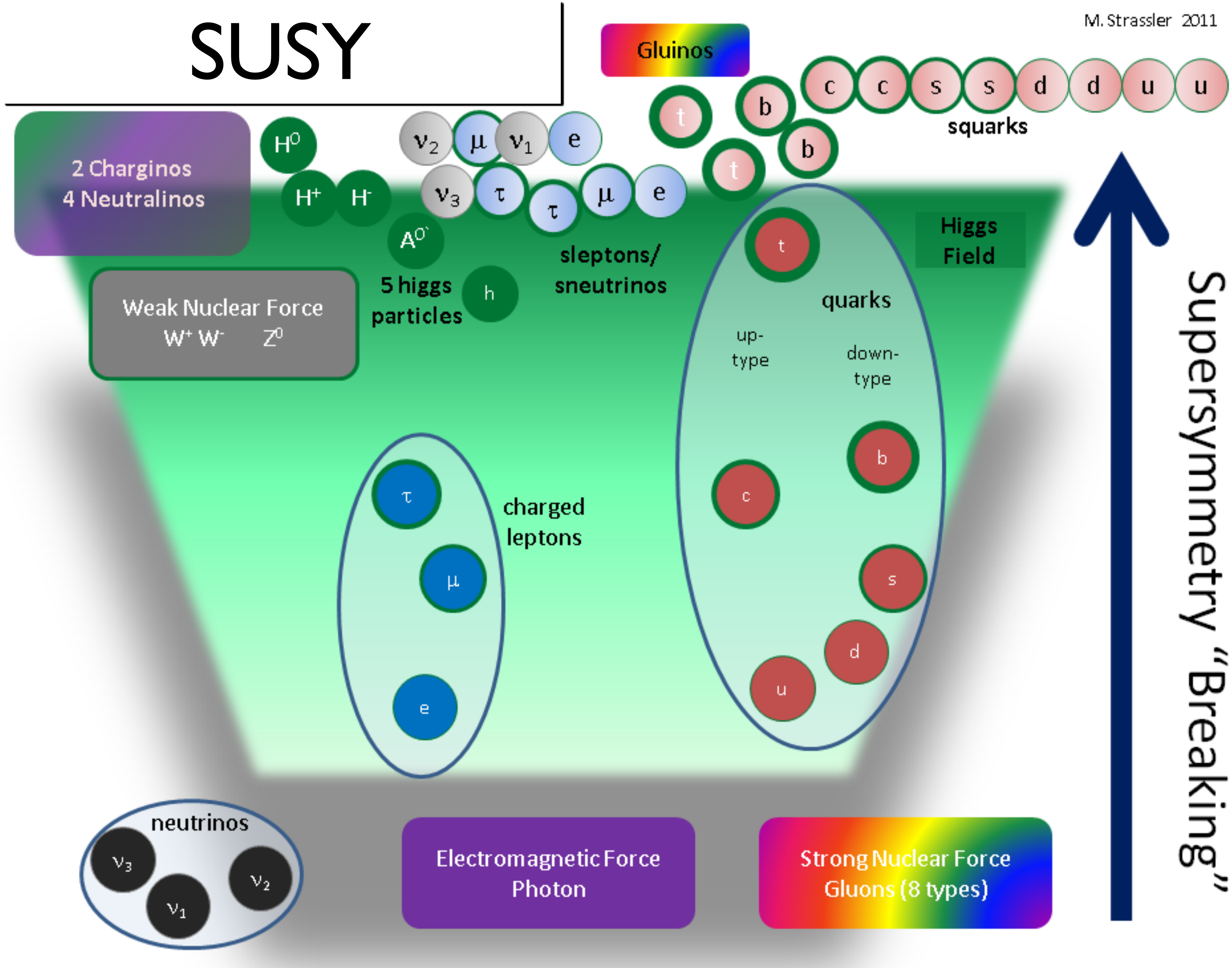
Phenomenological
hints from B physics
suggest low scale
theory of flavour

Part I

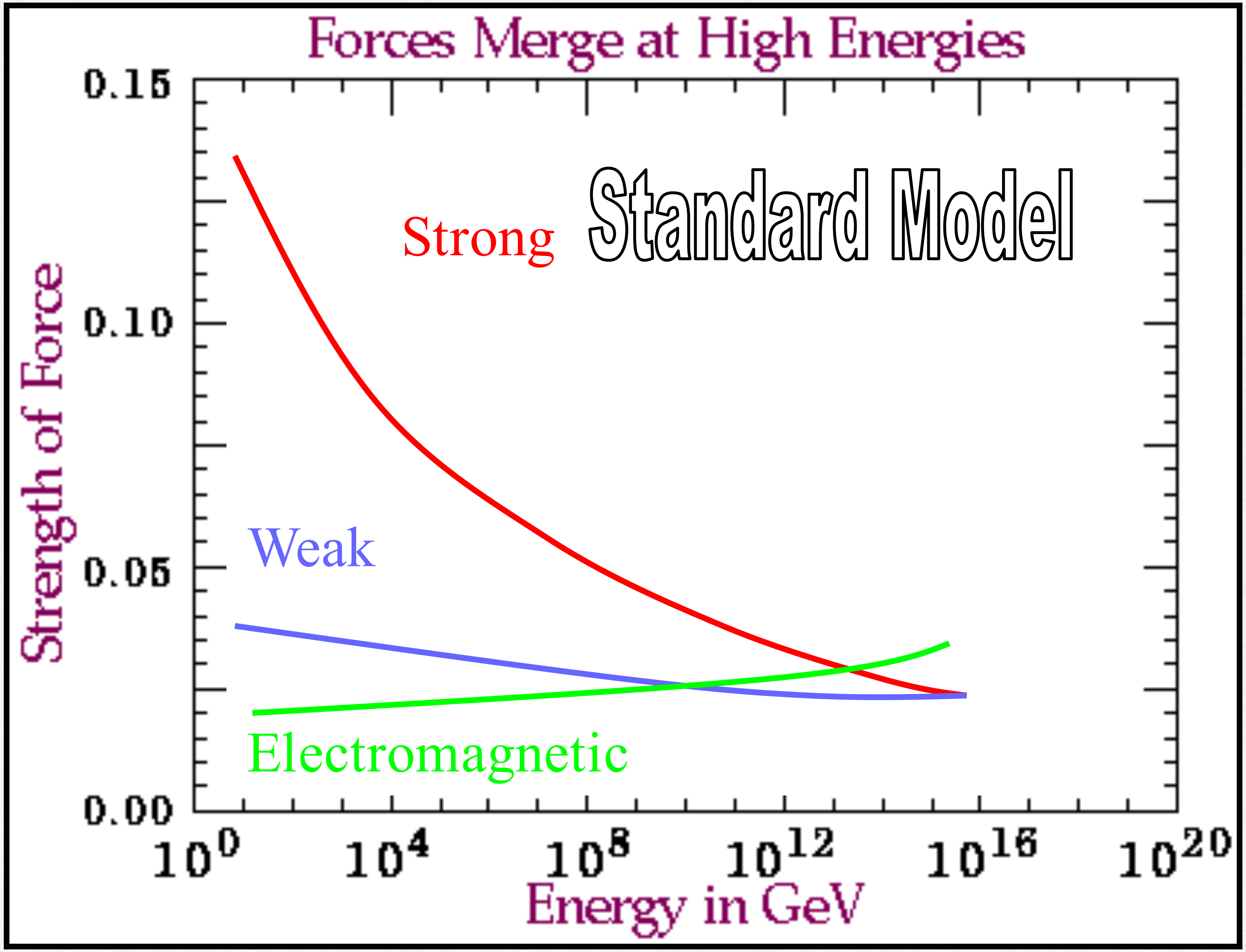
SUSY GUTs of Flavour

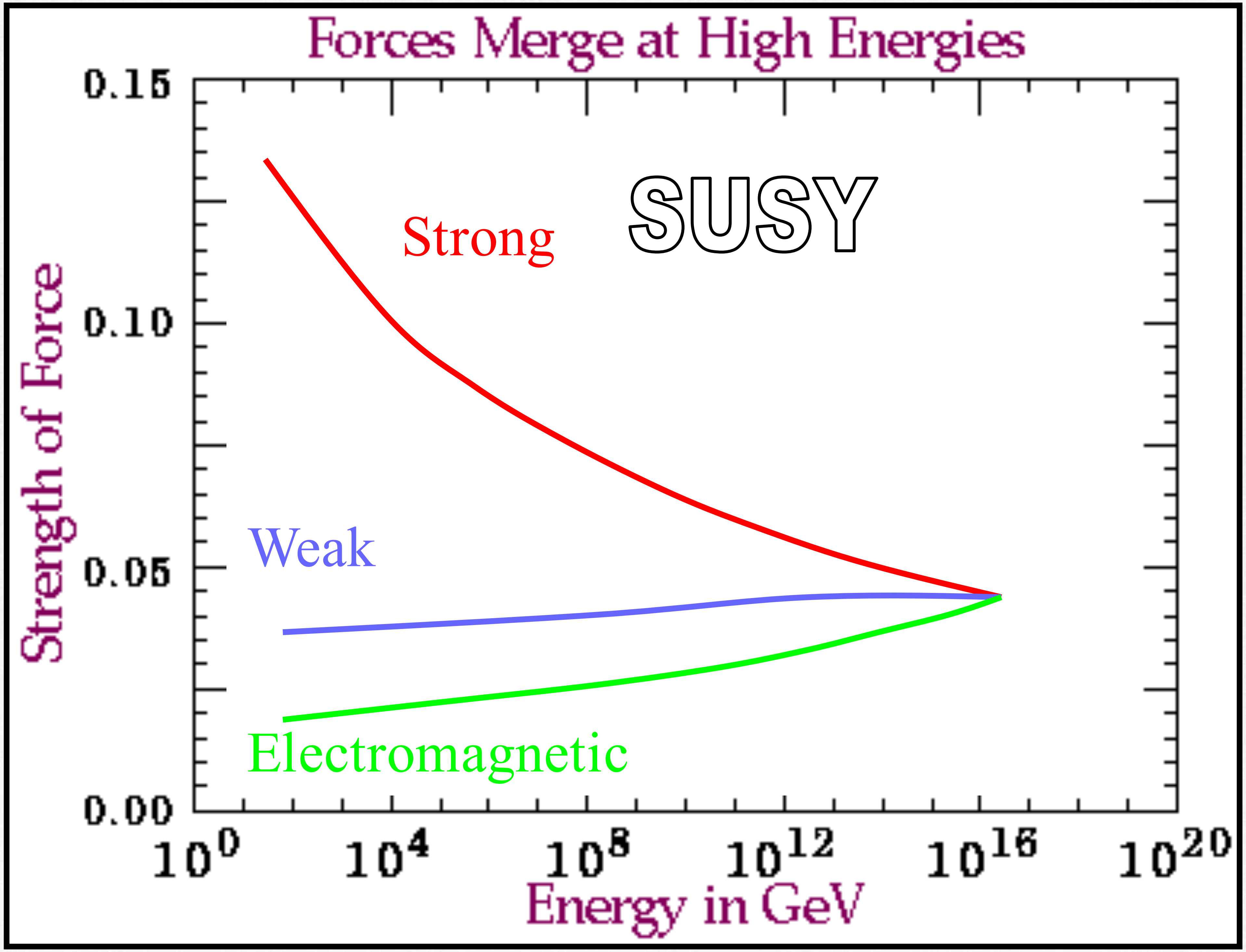
High scale theories of flavour

SUSY

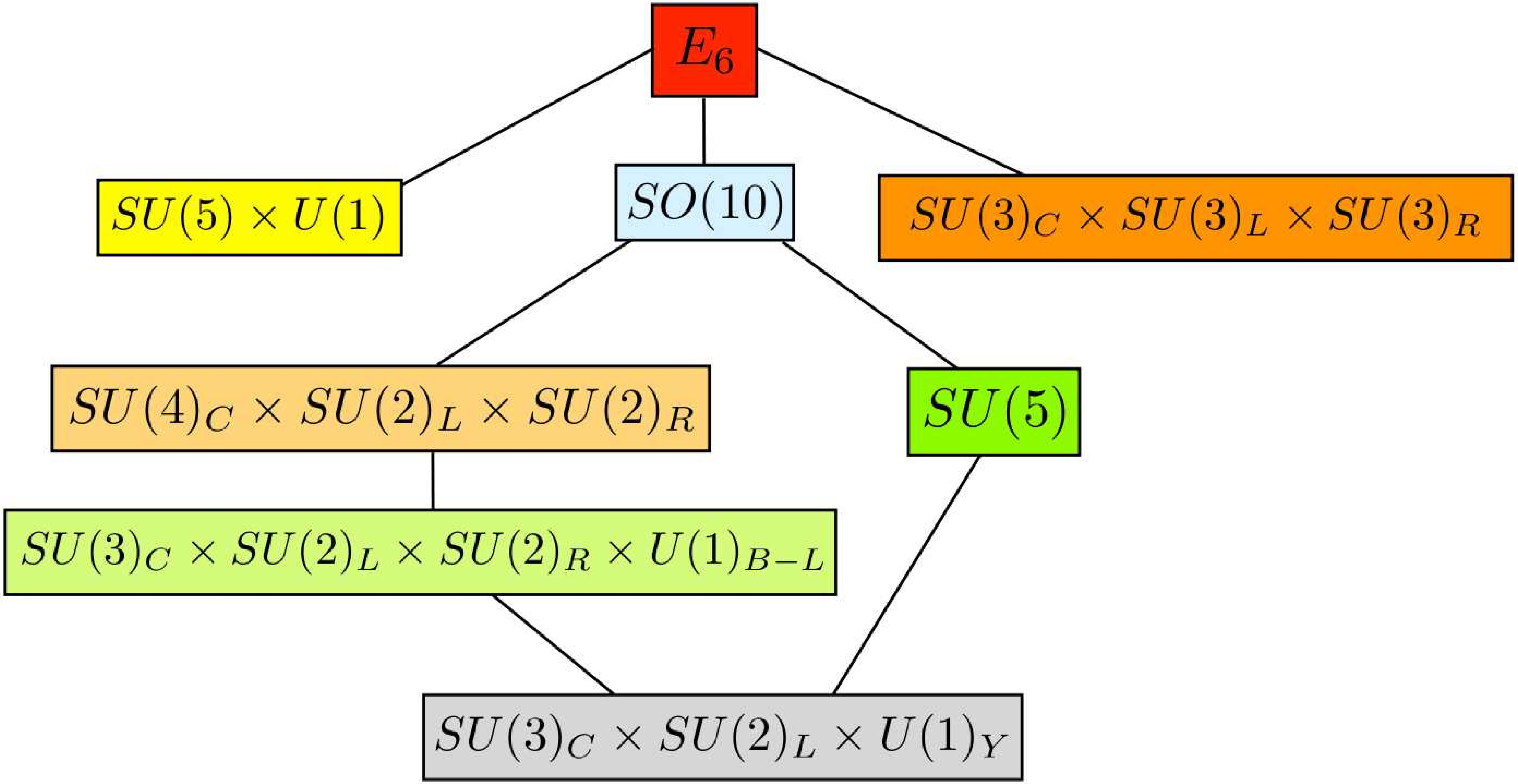


M. Strassler 2011
Gluinos
c c s s d d u u
squarks
t b b t
2 Charginos
4 Neutralinos
H0
H+ H-
A0
h
5 higgs particles
ν2 μ ν1 e
ν3 τ τ μ e
sleptons/ sneutrinos
Higgs Field
Weak Nuclear Force
W+ W- Z0
quarks
up-type
down-type
t
b
c
s
d
u
charged leptons
τ
μ
e
neutrinos
ν3
ν2
ν1
Electromagnetic Force
Photon
Strong Nuclear Force
Gluons (8 types)
Supersymmetry "Breaking"


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
Electromagnetic
Strength of Force
Energy in GeV
0.15
0.10
0.05
0.00
10^0
10^4
10^8
10^12
10^16
10^20

GUTs



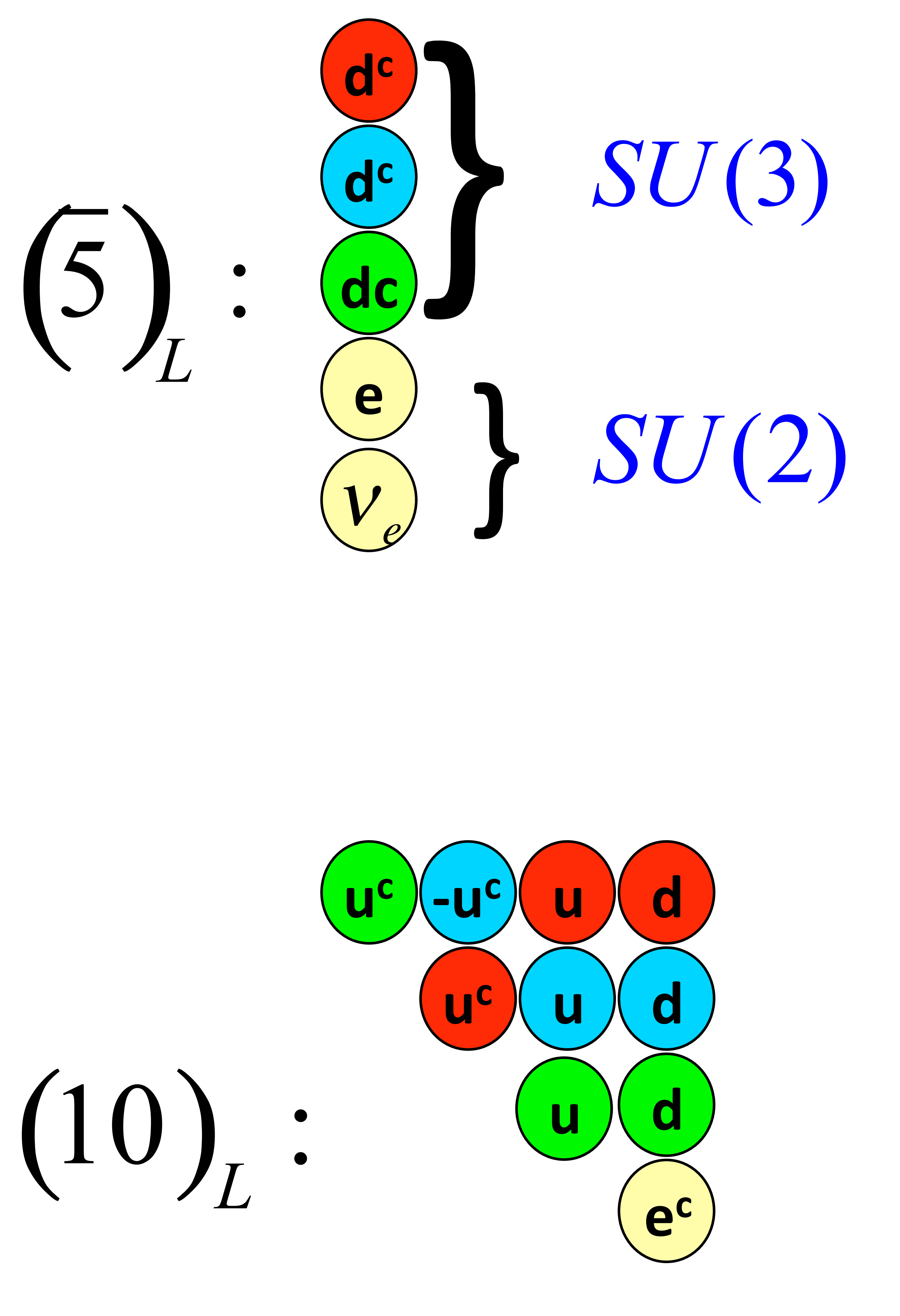
E_6
$SU(5) \times U(1)$
$SO(10)$
$SU(3)_C \times SU(3)_L \times SU(3)_R$
$SU(4)_C \times SU(2)_L \times SU(2)_R$
$SU(5)$
$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
$SU(3)_C \times SU(2)_L \times U(1)_Y$

SU(5) GUT

Georgi, Glashow 1974

Right-handed neutrino is optional singlet

ν^c



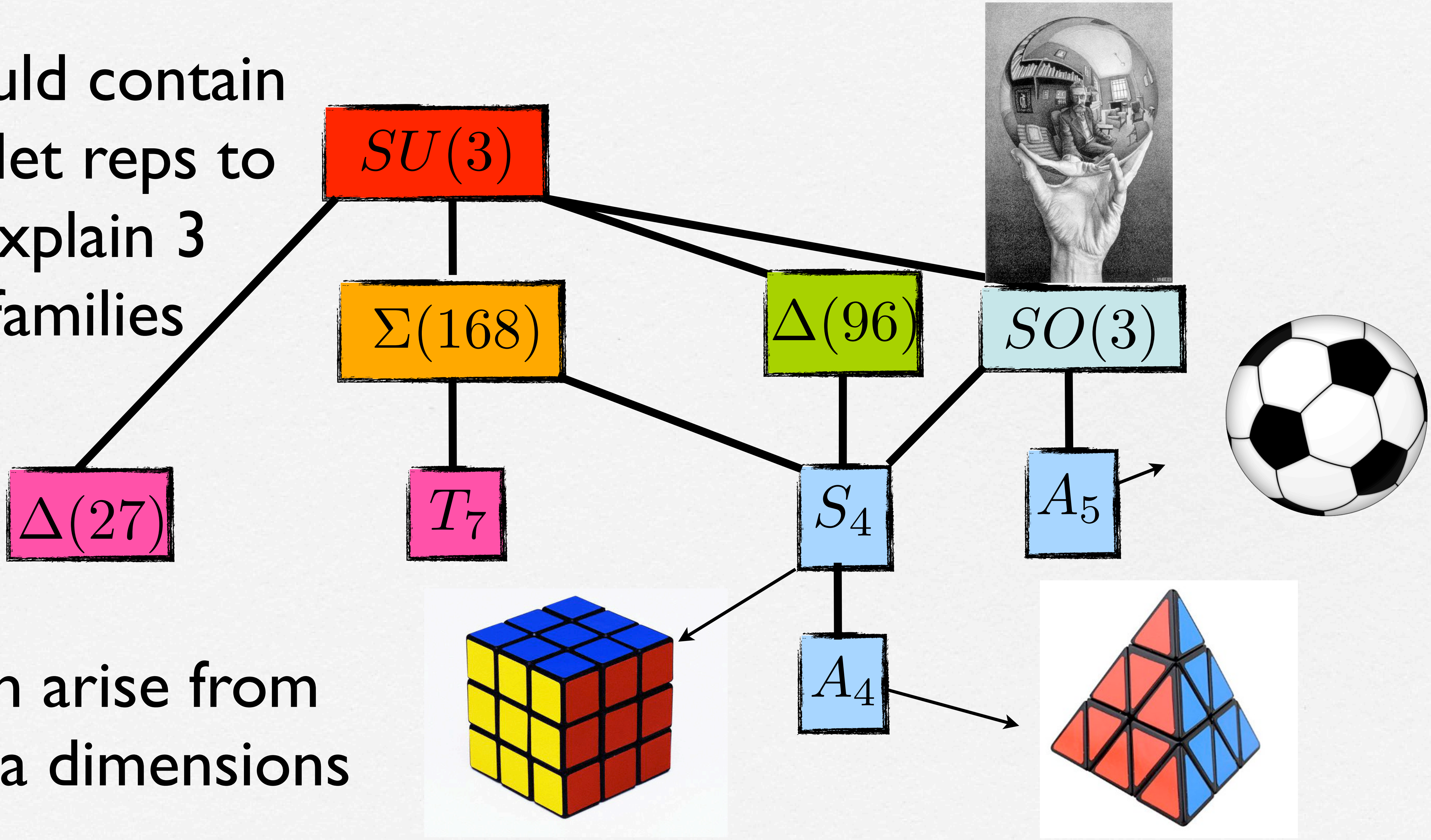
For references see review SFK 1701.04413

GUTs with flavour symmetry

G_{GUT} / G_{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]	

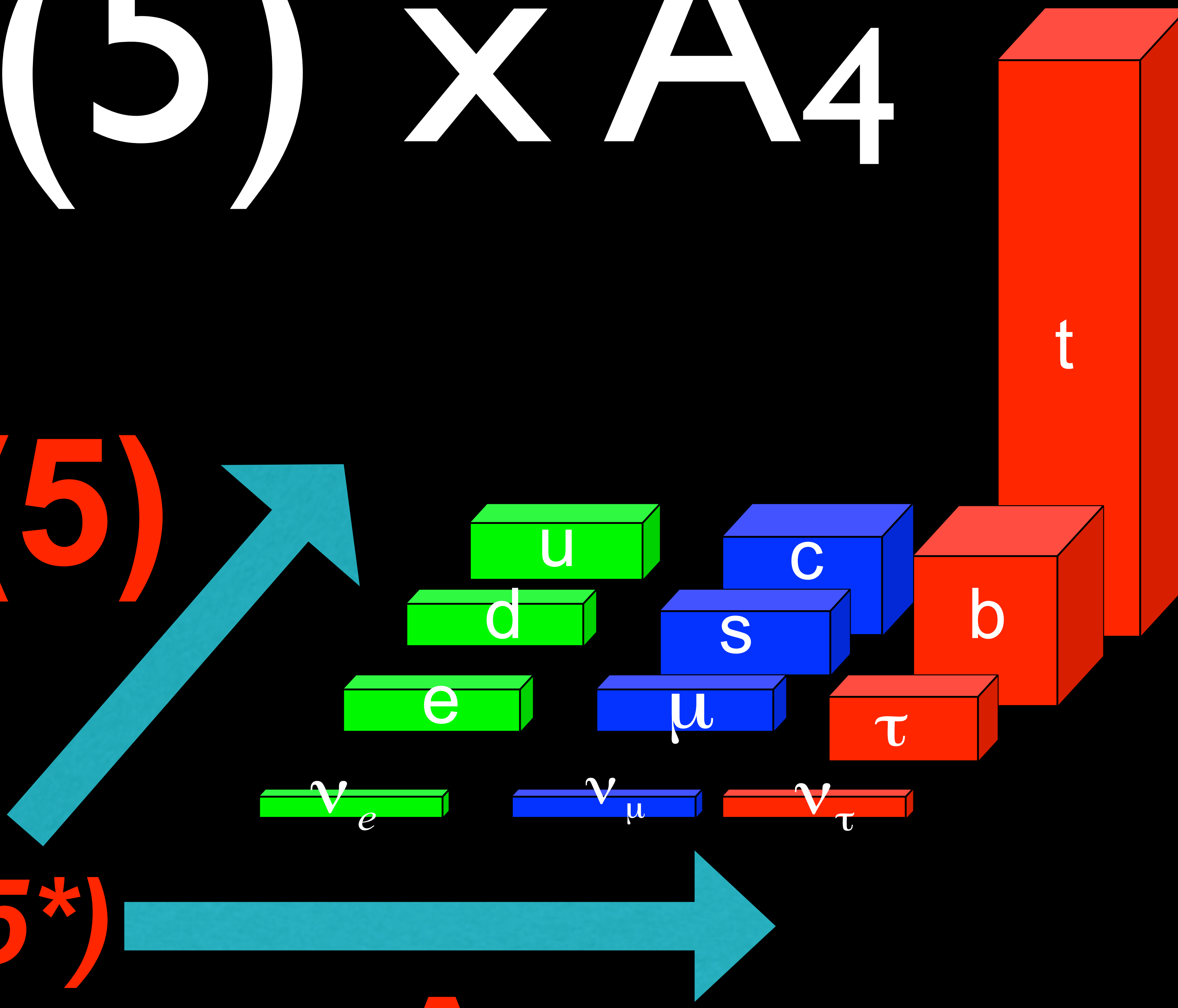
Flavour Symmetry

Should contain triplet reps to explain 3 families



Can arise from extra dimensions

SU(5) x A_4



SU(5)

***F* ~ (3,5*)**

***T_i* ~ (1,10)**

A_4

Björkeroth, de Anda, de Medeiros Varzielas, SFK
1503.03306, 1505.05504

SU(5)xA4 predicts Yukawa matrices

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

$$Y^u = \begin{pmatrix} u_{11}|\tilde{\xi}^4| & u_{12}|\tilde{\xi}^3| & u_{13}|\tilde{\xi}^2| \\ u_{12}|\tilde{\xi}^3| & u_{22}|\tilde{\xi}^2| & u_{23}|\tilde{\xi}| \\ u_{13}|\tilde{\xi}^2| & u_{23}|\tilde{\xi}| & u_{33} \end{pmatrix}$$

$$Y^d = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{1}{4} d_{11} \frac{|v_\xi v_e|}{|v_{\Lambda_{24}}|^2} & d_{12} \frac{|v_\xi v_\mu|}{|v_{\Lambda_{24}} v_{H_{24}}|} e^{i\zeta} & 0 \\ 0 & 2 d_{22} \frac{|v_{H_{24}} v_\mu|}{M^2} & 0 \\ 0 & 0 & d_{33} \frac{|v_\tau|}{M} \end{pmatrix}$$

Up matrix has small mixing and no phases

Down matrix gives Cabibbo mixing and CP phase

$$m_D = \begin{pmatrix} 0 & b \\ a & 3b \\ a & b \end{pmatrix} \quad M_R = \begin{pmatrix} M_{\rm atm} & 0 \\ 0 & M_{\rm sol} \end{pmatrix}$$

$$Y^e = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{1}{9} d_{11} \frac{|v_\xi v_e|}{|v_{\Lambda_{24}}|^2} & 0 & 0 \\ d_{12} \frac{|v_\xi v_\mu|}{|v_{\Lambda_{24}} v_{H_{24}}|} e^{i\zeta} & 9 d_{22} \frac{|v_{H_{24}} v_\mu|}{M^2} & 0 \\ 0 & 0 & d_{33} \frac{|v_\tau|}{M} \end{pmatrix}.$$

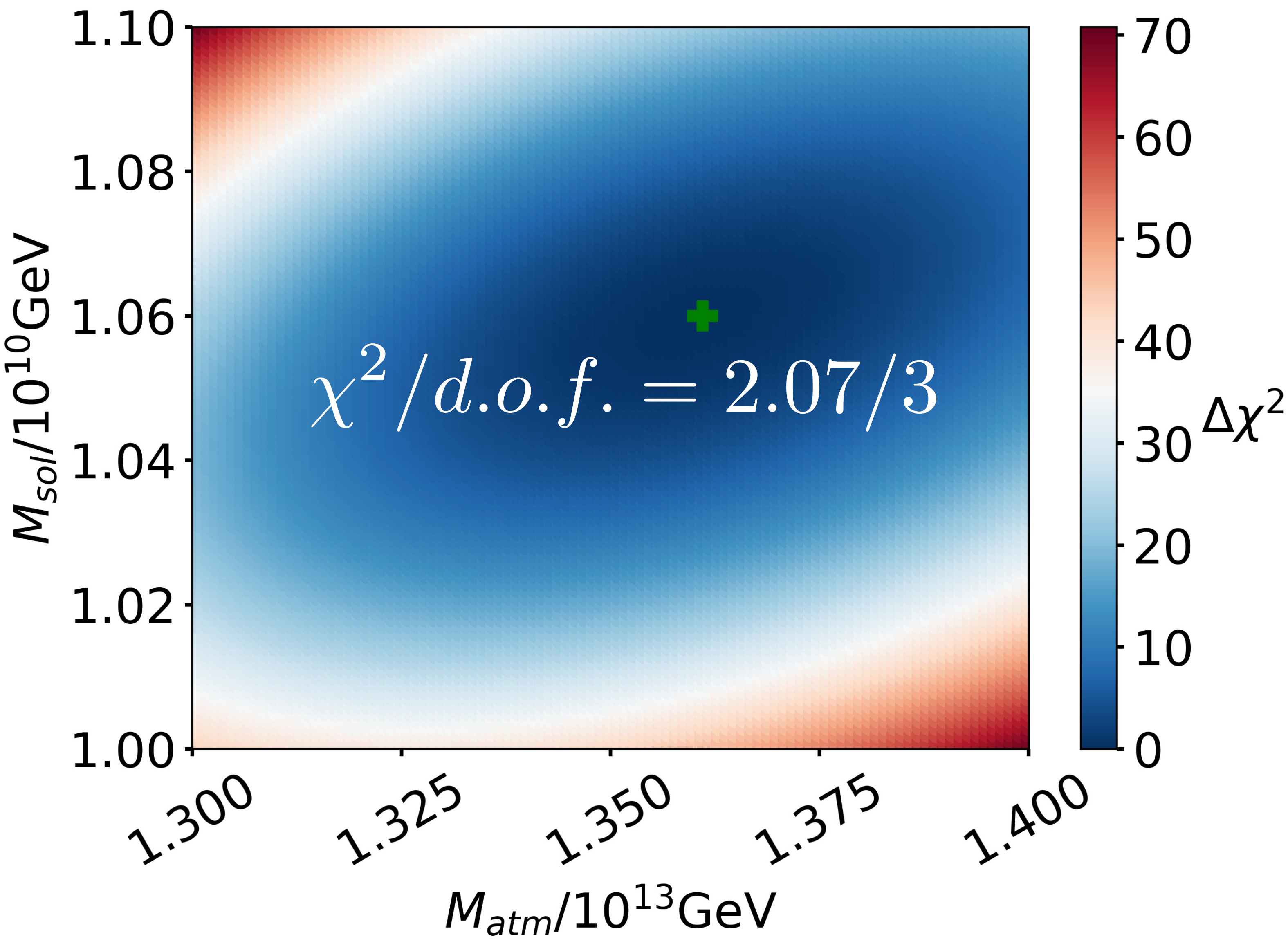
Littlest Seesaw with 4 parameters

No LH charged lepton mixing to leading order

The Fitting high-energy Littlest Seesaw parameters using low-energy neutrino data and leptogenesis

4 real input parameters

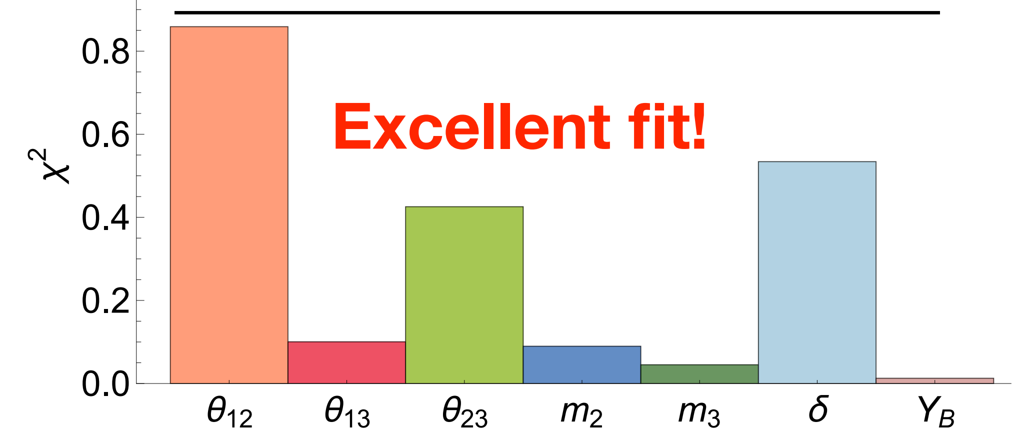
$$m_D = \begin{pmatrix} 0 & b \\ a & 3b \\ a & b \end{pmatrix} \quad M_R = \begin{pmatrix} M_{\rm atm} & 0 \\ 0 & M_{\rm sol} \end{pmatrix}$$



Predicts:

3 neutrino masses (m_1=0),
3 mixing angles,
1 Dirac CP phase,
2 Majorana phases (1 zero)
1 BAU parameter Y_B
= 10 observables
of which 7 are constrained

Predicted	$1\,\sigma$ range
$\theta_{12}/^\circ$	$34.291 \to 34.379$
$\theta_{13}/^\circ$	$8.384 \to 8.784$
$\theta_{23}/^\circ$	$44.044 \to 44.434$
$\Delta m_{12}{}^2/10^{-5}\text{eV}^2$	$7.058 \to 7.615$
$\Delta m_{31}{}^2/10^{-3}\text{eV}^2$	$2.435 \to 2.562$
$\delta/^\circ$	$-93.708 \to -92.180$
$Y_B/10^{-10}$	$0.838 \to 0.881$



Jordan Bernigaud, Bjorn Herrmann, SFK, Samuel J. Rowley (in progress)

SUSY SU(5)xA$_4$ @LHC

SUSY breaking masses at M_{GUT}

$$m_F = m_{\tilde{D}_i^c} = m_{\tilde{L}_i} = m_{H_u} = m_{H_d} ,$$
$$m_{T1} = m_{\tilde{Q}_1} = m_{\tilde{U}_1{}^c} = m_{\tilde{E}_1{}^c} ,$$
$$m_{T2} = m_{\tilde{Q}_2} = m_{\tilde{U}_2{}^c} = m_{\tilde{E}_2{}^c} ,$$
$$m_{T3} = m_{\tilde{Q}_3} = m_{\tilde{U}_3{}^c} = m_{\tilde{E}_3{}^c} .$$

Light charginos, neutralinos and RH smuons

	Parameter/Observable	Scenario 1	Scenario 2
MFV Parameters at GUT scale	m_F	5000	5000
	m_{T_1}	5000	5000
	m_{T_2}	200	233.2
	m_{T_3}	2995	2995
	a_{33}^{TT}	-940	-940
	a_{33}^{FT}	-1966	-1966
	M_1	250.0	600.0
	M_2	415.2	415.2
	M_3	2551.6	2551.6
	M_{H_u}	4242.6	4242.6
	M_{H_d}	4242.6	4242.6
	$\tan\beta$	30	30
	μ	-2163.1	-2246.8

	Parameter/Observable	Scenario 1	Scenario 2
Physical masses	m_h	126.7	127.3
	$m_{\tilde{g}}$	5570.5	5625.7
	$m_{\tilde{\mu}_L}$	4996.7	4997.5
	$m_{\tilde{\mu}_R}$	102.1	254.4
	$m_{\tilde{\chi}_1^0}$	94.6	250.4
	$m_{\tilde{\chi}_2^0}$	323.6	322.0
	$m_{\tilde{\chi}_3^0}$	2248.8	2331.1
	$m_{\tilde{\chi}_4^0}$	2248.8	2331.2
	$m_{\tilde{\chi}_1^\pm}$	323.8	322.2
	$m_{\tilde{\chi}_2^\pm}$	2249.8	2332.2
	$\Omega_{\tilde{\chi}_1^0} h^2$	0.116	0.120
	$\sigma_{SI}^{Proton}/10^{-14}pb$	2.987	1.055
	$\sigma_{SI}^{Neutron}/10^{-14}pb$	3.249	0.986

Jordan Bernigaud, Bjorn Herrmann, SFK, Samuel J. Rowley (in progress)

Flavour Violating Parameters at M_{GUT}

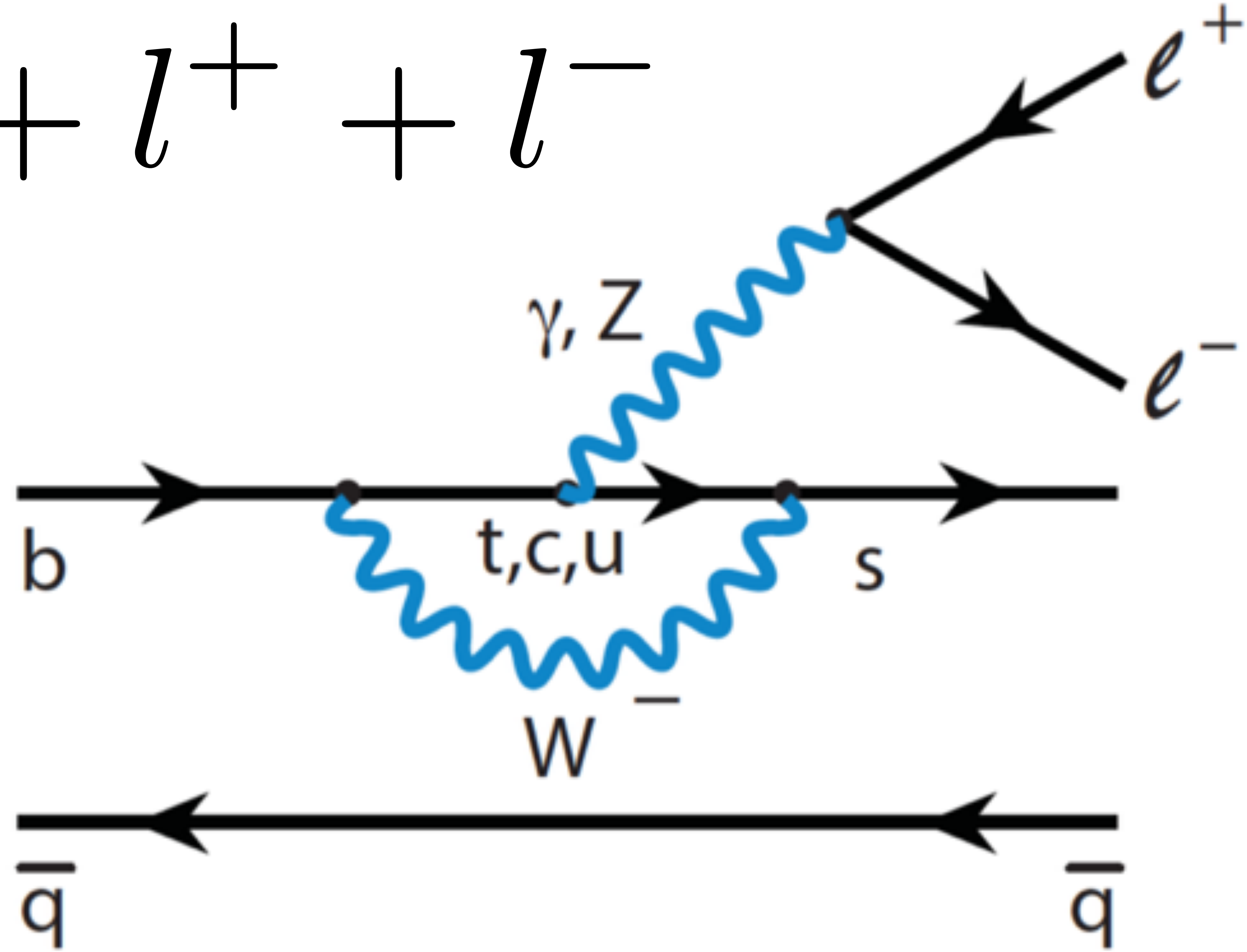
Parameters	Scenario 1	Scenario 2	Most constraining obs. 1	Most constraining obs. 2
$(\delta^T)_{12}$	[-0.015, 0.015]	[-0.12, 0.12]†	$\mu \to 3e$, $\mu \to e\gamma$, $\Omega_{\tilde{\chi}_1^0} h^2$	$\Omega_{\tilde{\chi}_1^0} h^2$, $\mu \to e\gamma$
$(\delta^T)_{13}$	]-0.06, 0.06[	[-0.3, 0.3]†	$\Omega_{\tilde{\chi}_1^0} h^2$	$\Omega_{\tilde{\chi}_1^0} h^2$
$(\delta^T)_{23}$	[0, 0]*	[-0.1, 0.1†]	$\Omega_{\tilde{\chi}_1^0} h^2$, $\mu \to 3e$, $\mu \to e\gamma$	$\Omega_{\tilde{\chi}_1^0} h^2$, $\mu \to 3e$, $\mu \to e\gamma$,
$(\delta^F)_{12}$	[-0.008, 0.008]	[-0.015, 0.015]†	$\mu \to 3e$, $\mu \to e\gamma$	$\mu \to 3e$, $\mu \to e\gamma$
$(\delta^F)_{13}$	]-0.01, 0.01[	[-0.15, 0.15]†	$\mu \to e\gamma$	$\mu \to 3e$, $\mu \to e\gamma$
$(\delta^F)_{23}$	]-0.015, 0.015[	[-0.15, 0.15]†	$\mu \to e\gamma$, $\Omega_{\tilde{\chi}_1^0} h^2$	$\Omega_{\tilde{\chi}_1^0} h^2$, $\mu \to e\gamma$, $\mu \to 3e$
$(\delta^{TT})_{12}$	[-3, 3.5] $\times 10^{-5}$	[-1, 1.5]† $\times 10^{-3}$	prior	prior, $\Omega_{\tilde{\chi}_1^0} h^2$
$(\delta^{TT})_{13}$	]-6, 7] $\times 10^{-5}$	[-4, 2.5]† $\times 10^{-3}$	prior, $\Omega_{\tilde{\chi}_1^0} h^2$	prior, $\Omega_{\tilde{\chi}_1^0} h^2$
$(\delta^{TT})_{23}$	]-0.5, 4[$\times 10^{-5}$	[-0.25, 0.2]†	prior, $\Omega_{\tilde{\chi}_1^0} h^2$	prior, $\Omega_{\tilde{\chi}_1^0} h^2$
$(\delta^{FT})_{12}$	[-0.0015, 0.0015]	[-1.2, 1.2]† $\times 10^{-4}$	$\Omega_{\tilde{\chi}_1^0} h^2$	$\mu \to 3e$, $\Omega_{\tilde{\chi}_1^0} h^2$, $\mu \to e\gamma$
$(\delta^{FT})_{13}$	]-0.002, 0.002[	[-5, 5] $\times 10^{-4}$	$\Omega_{\tilde{\chi}_1^0} h^2$	$\Omega_{\tilde{\chi}_1^0} h^2$, $\mu \to 3e$, $\mu \to e\gamma$
$(\delta^{FT})_{21}$	[0,0]*	[-1.2, 1.2]† $\times 10^{-4}$	prior	$\Omega_{\tilde{\chi}_1^0} h^2$, prior
$(\delta^{FT})_{23}$	]-0.0022, 0.0022[	[-6, 6]† $\times 10^{-4}$	$\Omega_{\tilde{\chi}_1^0} h^2$	$\mu \to 3e$, $\Omega_{\tilde{\chi}_1^0} h^2$, $\mu \to e\gamma$
$(\delta^{FT})_{31}$	]-0.0004, 0.0004[	[-2, 2]† $\times 10^{-4}$	$\Omega_{\tilde{\chi}_1^0} h^2$	$\Omega_{\tilde{\chi}_1^0} h^2$
$(\delta^{FT})_{32}$	[0,0]*	[-1.5, 1.5] $\times 10^{-4}$	prior	$\Omega_{\tilde{\chi}_1^0} h^2$

Part II

Phenomenological hints from B physics

Low scale theories of flavour

$$B \to K + l^+ + l^-$$



- $b \to sl^+l^-$ transitions are rare in the SM (no tree level contributions: GIM, CKM, in some cases helicity suppressed)
- ideally suited for indirect New Physics searches (indirectly sensitive to energy scales O(100TeV))

LFU tests with B→K(*)μμ and B→K(*)ee decays: R(K) and R(K*)

- Theoretical uncertainties on the exclusive B→K(*)ll branching fractions are **reduced to a per-mille level** in ratios *(hadronic effects cancel)*:

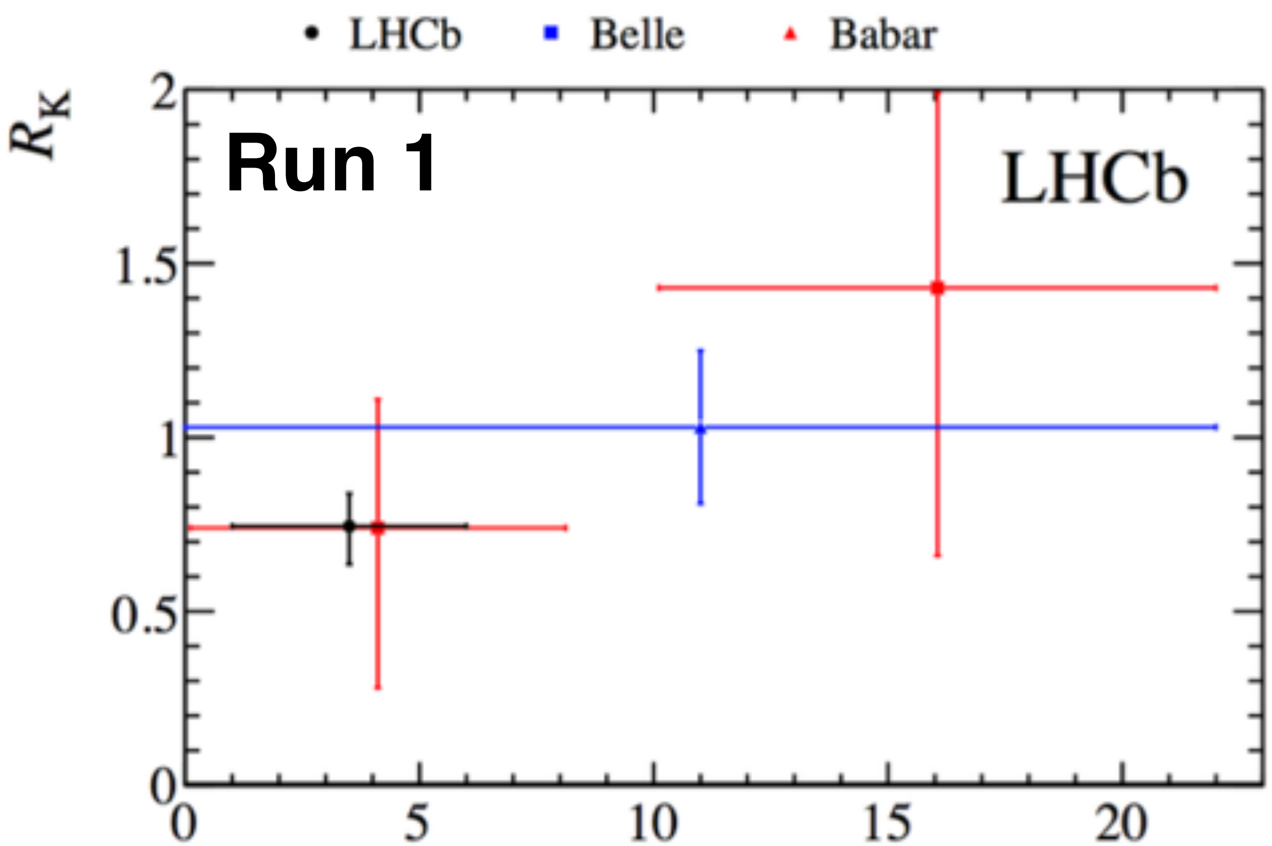
$$R(K) = \frac{B^+ \to K^+\mu^+\mu^-}{B^+ \to K^+e^+e^-} \quad R(K^*) = \frac{B^0 \to K^{*0}\mu^+\mu^-}{B^0 \to K^{*0}e^+e^-}$$

- SM, R(K) and R(K*) expected to be close to unity.
- Sensitive to new neutral and heavy gauge bosons, lepto-quarks, Z' models.

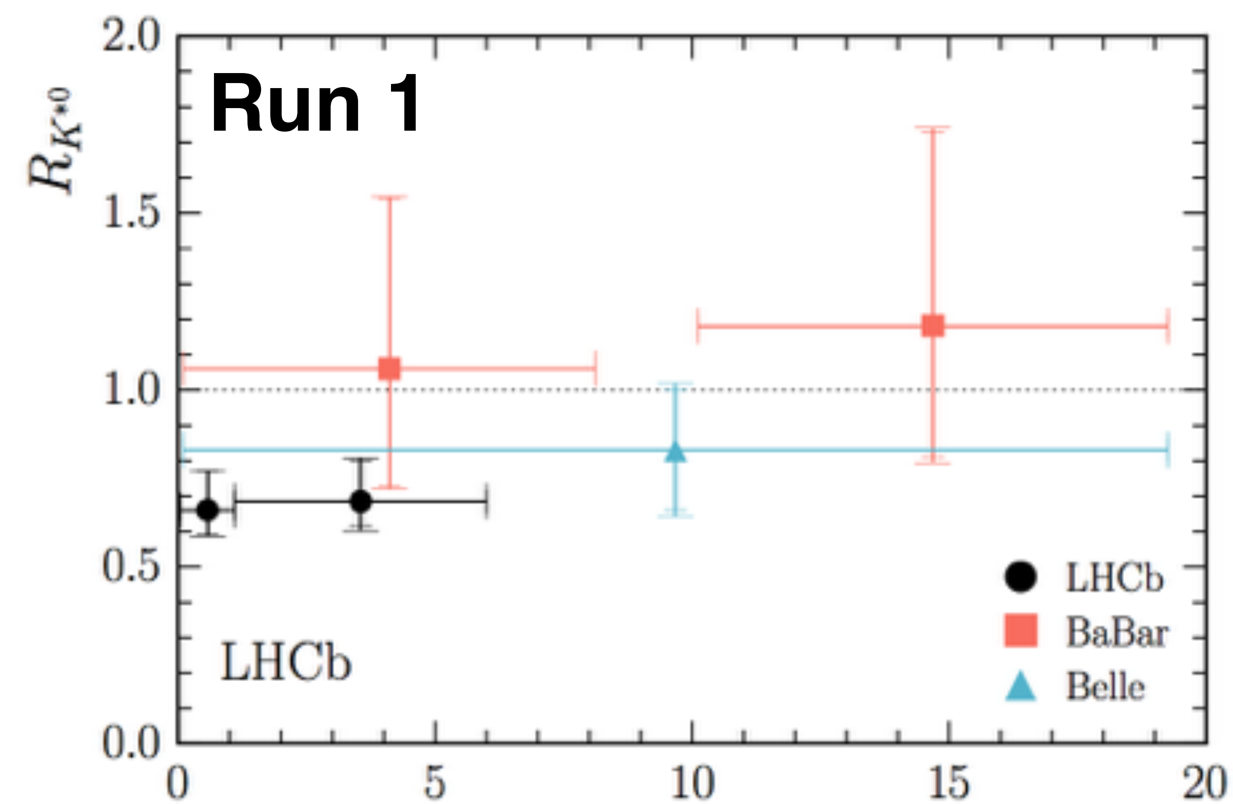
R(K) and R(K*) results

Siim Tolk

LHCb focusses on the q^2 regions with reliable theoretical predictions and small contributions from the resonant modes. Precision limited by statistics.



[PRL 113 (2014) 151601]



[JHEP 08 (2017) 055]

$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst}).$$

2.6σ Deviation from Standard Model

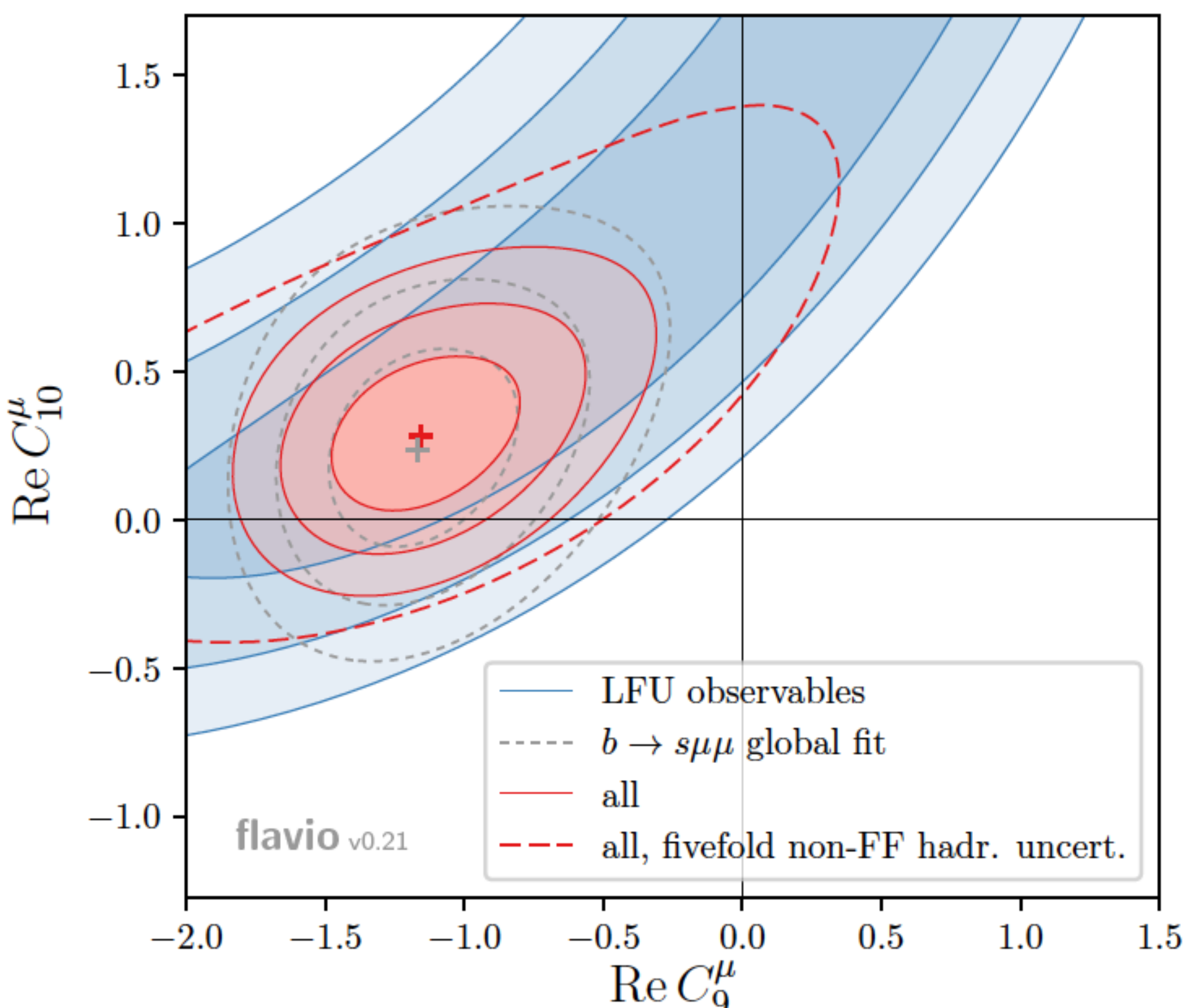
$$R_{K^{*0}} = \begin{cases} 0.66 \, ^{+}_{-} \, ^{0.11}_{0.07} \, (\text{stat}) \pm 0.03 \, (\text{syst}) & \text{for } 0.045 < q^2 < 1.1 \ \text{GeV}^2/c^4 , \\ 0.69 \, ^{+}_{-} \, ^{0.11}_{0.07} \, (\text{stat}) \pm 0.05 \, (\text{syst}) & \text{for } 1.1 \quad < q^2 < 6.0 \ \text{GeV}^2/c^4 . \end{cases}$$

2.1 - 2.4σ

Possible operators for R_K, R_{K^*}

$$\mathcal{L}^{\mathrm{NP}}_{b\to s\mu\mu} \supset \frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \left(\delta C_9^\mu O_9^\mu + \delta C_{10}^\mu O_{10}^\mu\right) + \mathrm{h.c.}$$

Altmannshofer, Stangl, Straub '17



$$O_9^\mu = \frac{\alpha}{4\pi}(\bar{s}_L\gamma_\mu b_L)(\bar{\mu}\gamma^\mu\mu)\,,$$

$$O_{10}^\mu = \frac{\alpha}{4\pi}(\bar{s}_L\gamma_\mu b_L)(\bar{\mu}\gamma^\mu\gamma_5\mu)\,.$$

Assuming LH currents and LFU observables

$$(\bar{s}_L\gamma_\mu b_L)(\bar{\mu}_L\gamma^\mu\mu_L)$$

$$\mathrm{Re}\,(\delta C_9^\mu) = -\mathrm{Re}\,(\delta C_{10}^\mu) \in [-0.81, -0.48]$$

Z' interpretation of R$_K$, R$_{K^*}$

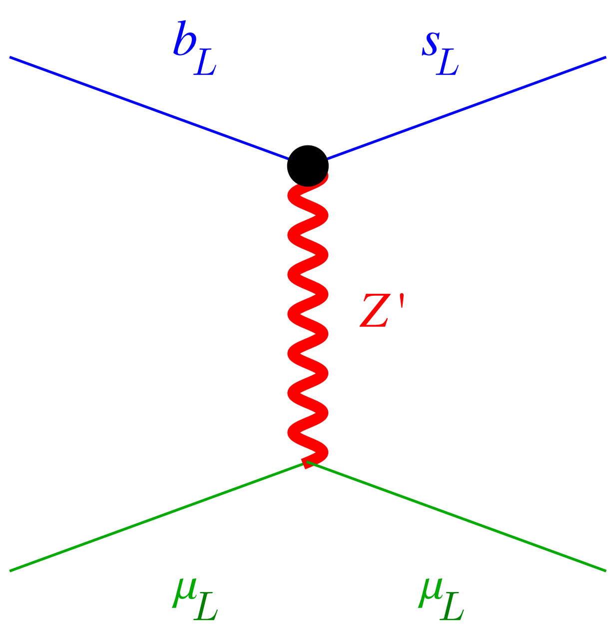
$$\Delta\mathcal{L}_{\text{eff}} \supset G_{bs\mu}(\bar{b}_L\gamma^\mu s_L)(\bar{\mu}_L\gamma_\mu\mu_L) + \text{h.c.}, \qquad G_{bs\mu} \approx \frac{1}{(31.5\ \text{TeV})^2}.$$

$G_{bs\mu} > 0$ **matches** $C_9^\mu < 0$ **and** $C_9^\mu = -C_{10}^\mu$

Could originate from massive Z' model with couplings

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

$V_{ts} \sim -0.04$



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

$$\frac{g_{bb}g_{\mu\mu}}{M_{Z'}^2} \approx \frac{1}{(6.4\ \text{TeV})^2}$$ R$_K$, R$_{K^*}$

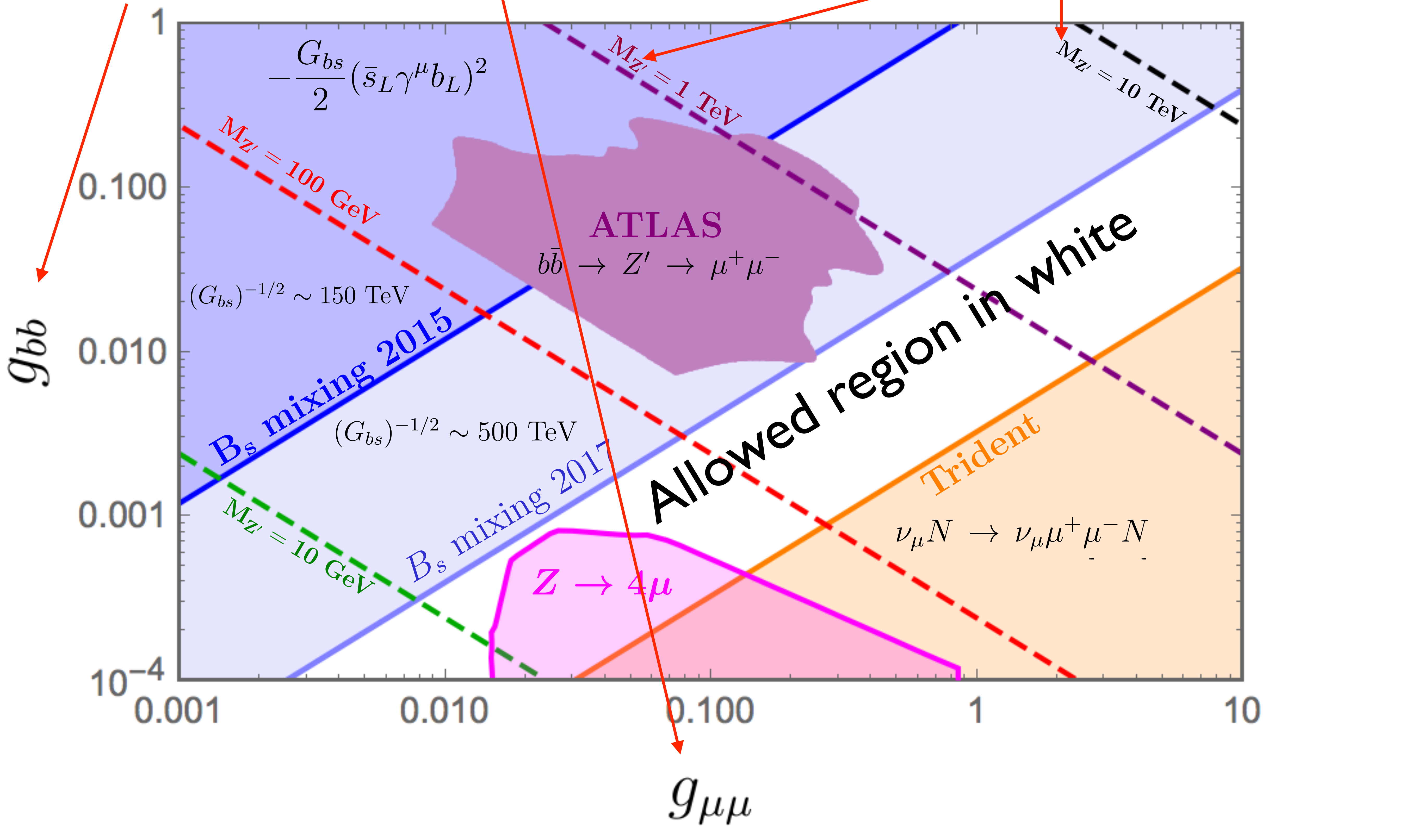
Comment on signs: $g_{bb}, g_{\mu\mu} > 0, \qquad g_{bs} = g_{bb}V_{ts} < 0$

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 $\frac{g_{bb} g_{\mu\mu}}{M_{Z'}^2} \approx \frac{1}{(6.4 \text{ TeV})^2}$

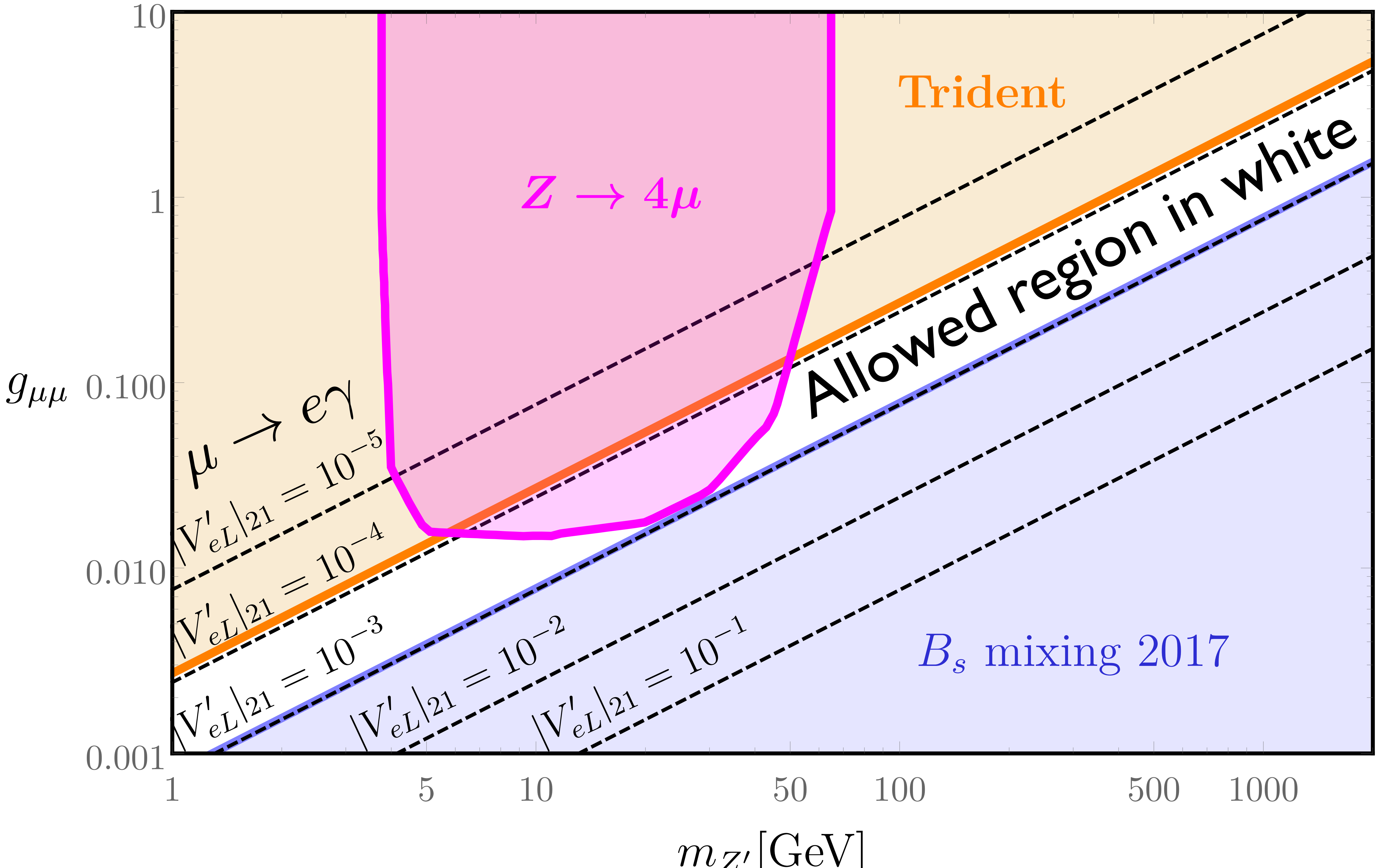


Constraints

Falkowski, SFK, Perdomo, Pierre
1803.04430

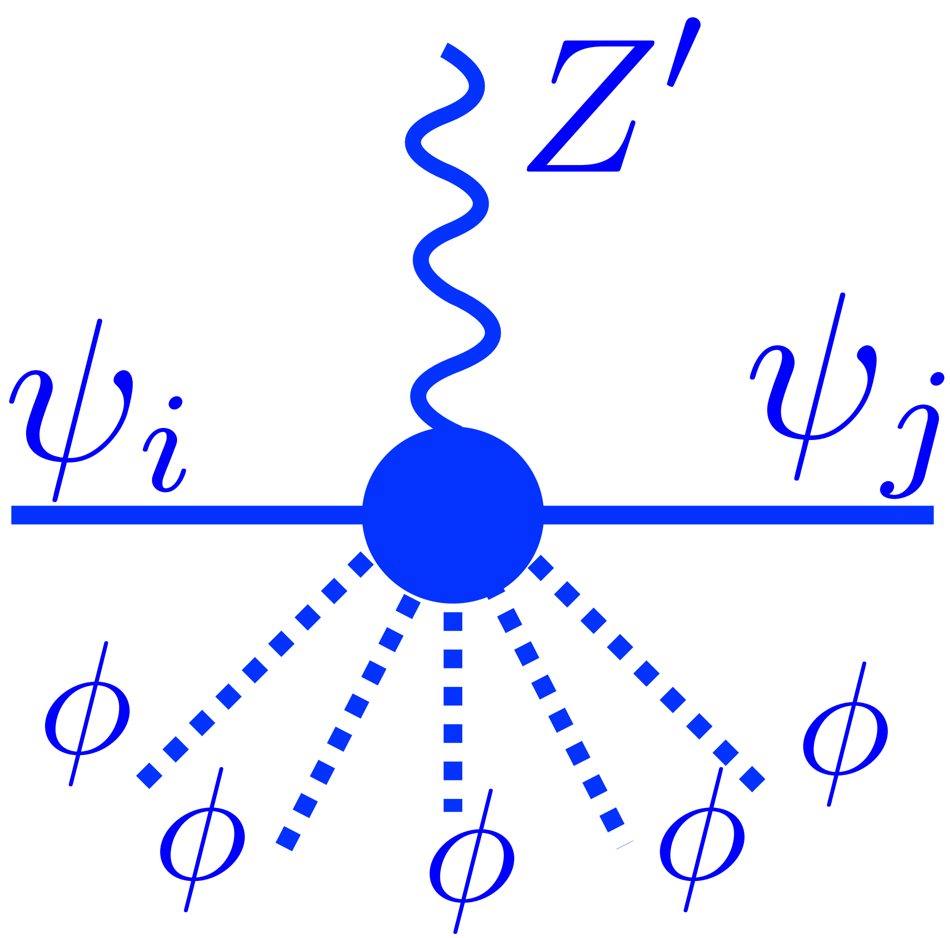
$$Z'_\mu \left(g_{bb} \bar{b}_L \gamma^\mu b_L + g_{\mu\mu} \bar{\mu}_L \gamma^\mu \mu_L \right)$$

$$\frac{g_{bb} g_{\mu\mu}}{M_{Z'}^2} \approx \frac{1}{(6.4\ \text{TeV})^2}$$



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

$\Lambda \sim TeV$

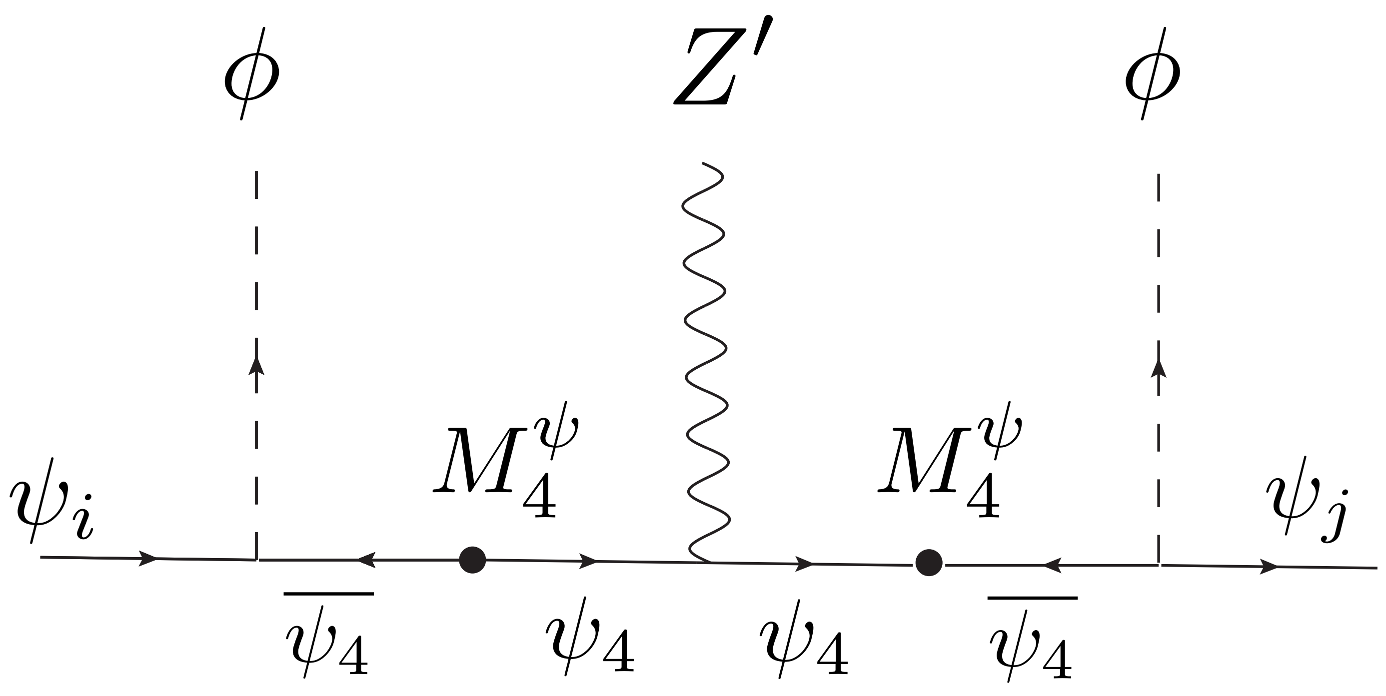
M_{EW}

SFK 1706.06100

Example of Flavourful Z' model

Introduce a vector-like fourth family which carries U(1)' charge

Usual three families do not carry U(1)' charge but couple to Z' via fourth family mixing



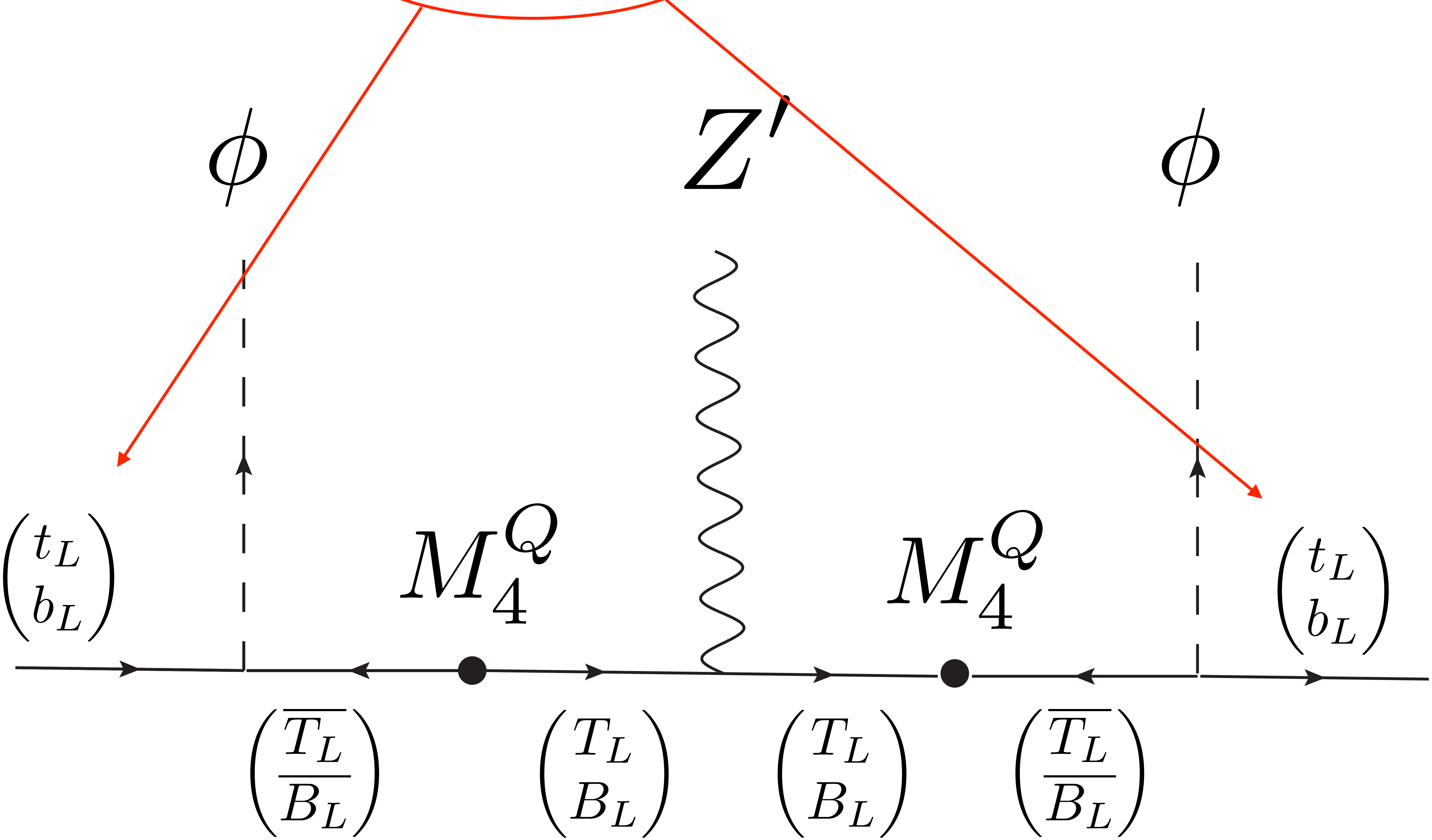
$$\frac{x_i^\psi \langle\phi\rangle}{M_4^\psi} \frac{x_j^\psi \langle\phi\rangle}{M_4^\psi} g' Z'_\mu \psi_i^\dagger \gamma^\mu \psi_j$$

"Fermiophobic model" (afraid of Z')

"Fermiophobic model"

SFK 1706.06100

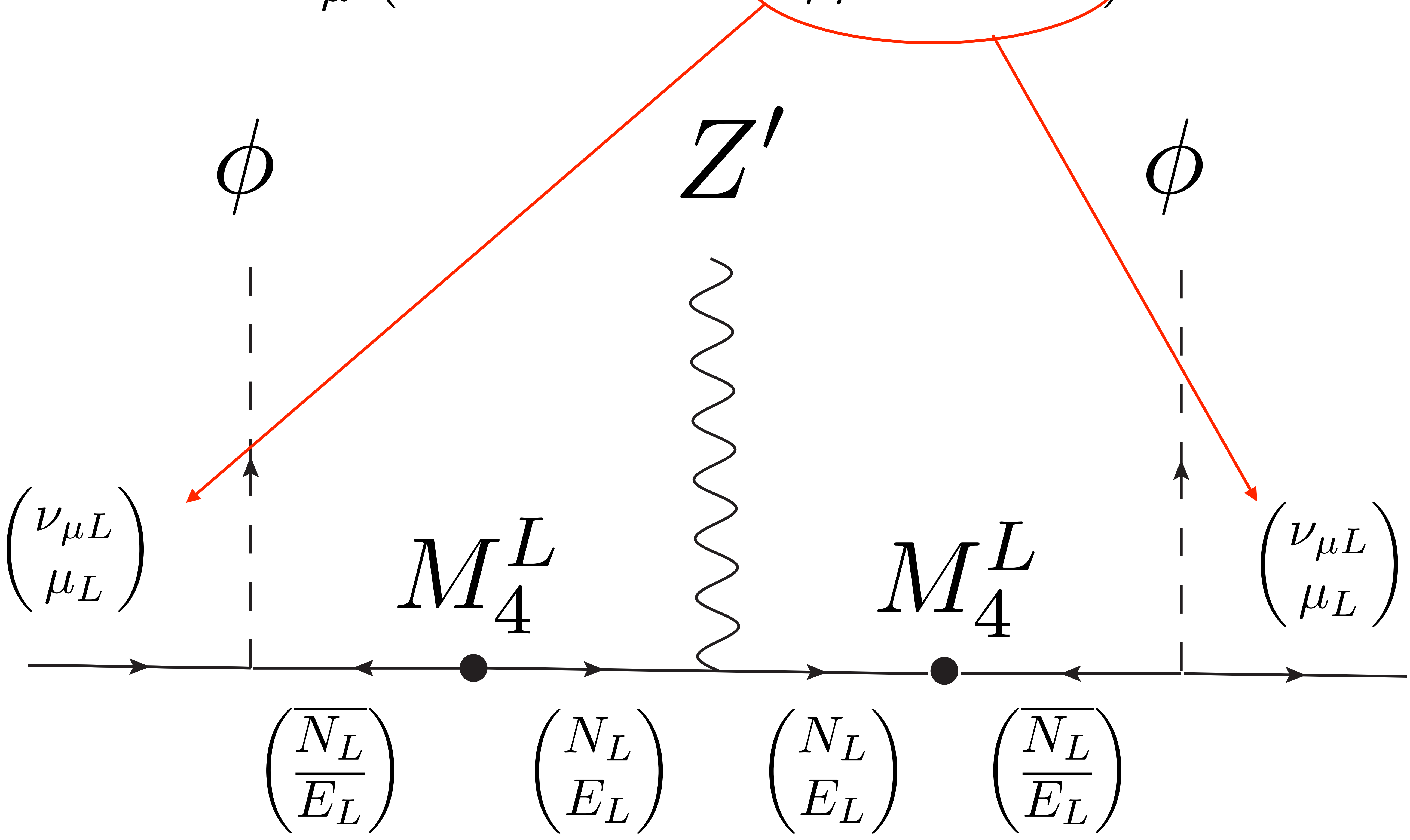
$$\mathcal{L} \supset Z'_\mu \left(g_{bb} \bar{b}_L \gamma^\mu b_L + g_{\mu\mu} \bar{\mu}_L \gamma^\mu \mu_L \right)$$



"Fermiophobic model"

SFK 1706.06100

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



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

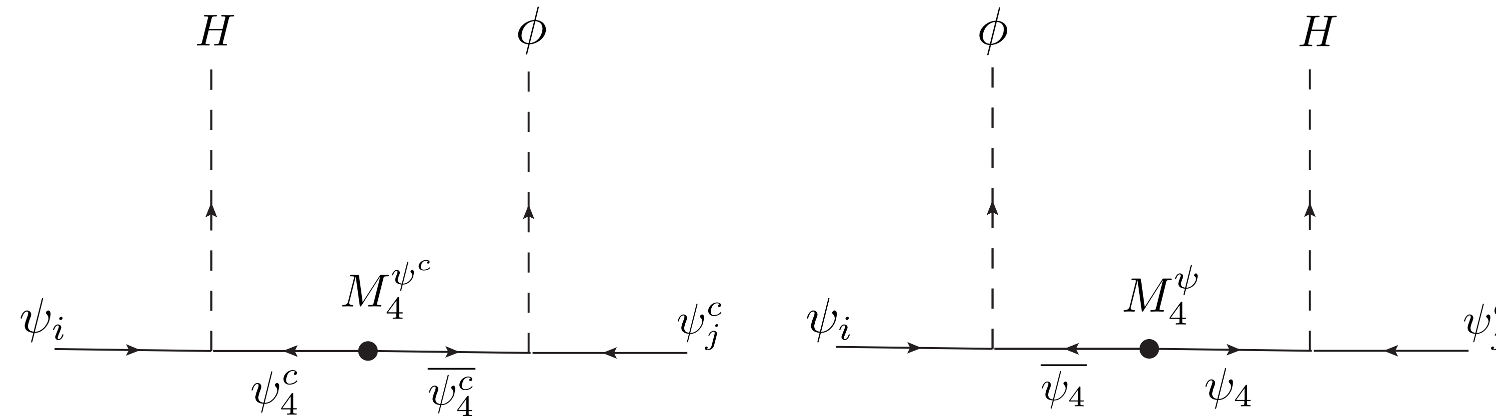
SFK 1806.06780

"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

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L_i	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	0
e_i^c	$\mathbf{1}$	$\mathbf{1}$	1	0
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d_4^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$1/3$	1
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$\overline{Q_4}$	$\overline{\mathbf{3}}$	$\overline{\mathbf{2}}$	$-1/6$	-1
$\overline{u_4^c}$	$\mathbf{3}$	$\mathbf{1}$	$2/3$	-1
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$\overline{L_4}$	$\mathbf{1}$	$\overline{\mathbf{2}}$	$1/2$	-1
$\overline{e_4^c}$	$\mathbf{1}$	$\mathbf{1}$	-1	-1
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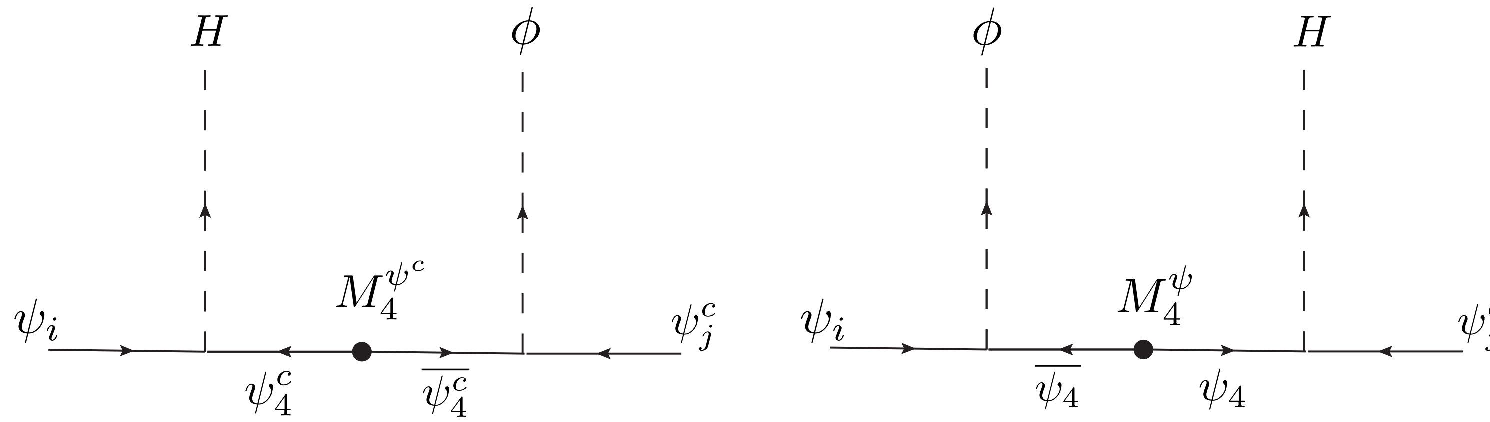
H_d	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	-1

Yukawas generated via mixing with fourth family

Ferretti, SFK, Romanino hep-ph/0609047

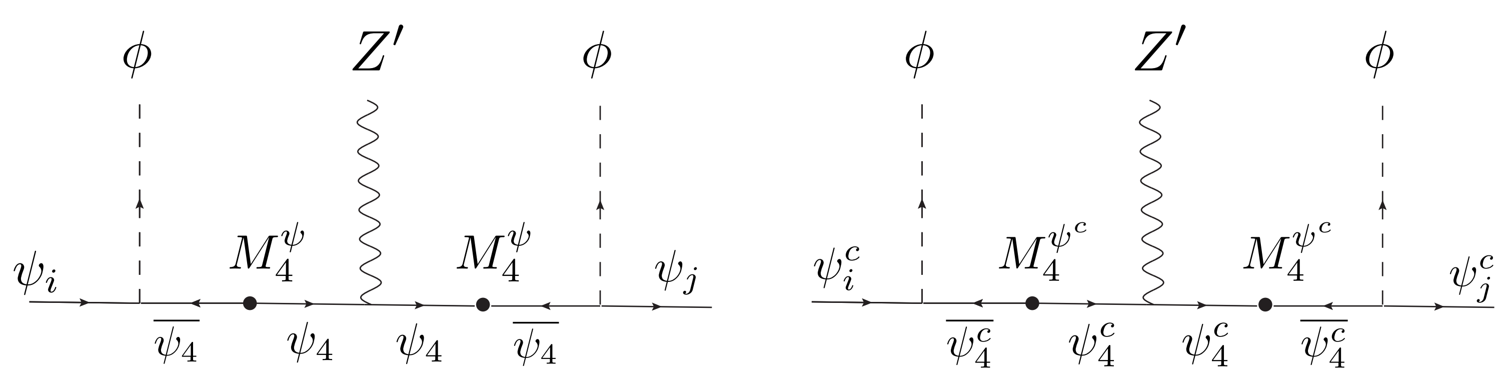


Yukawas

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

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"

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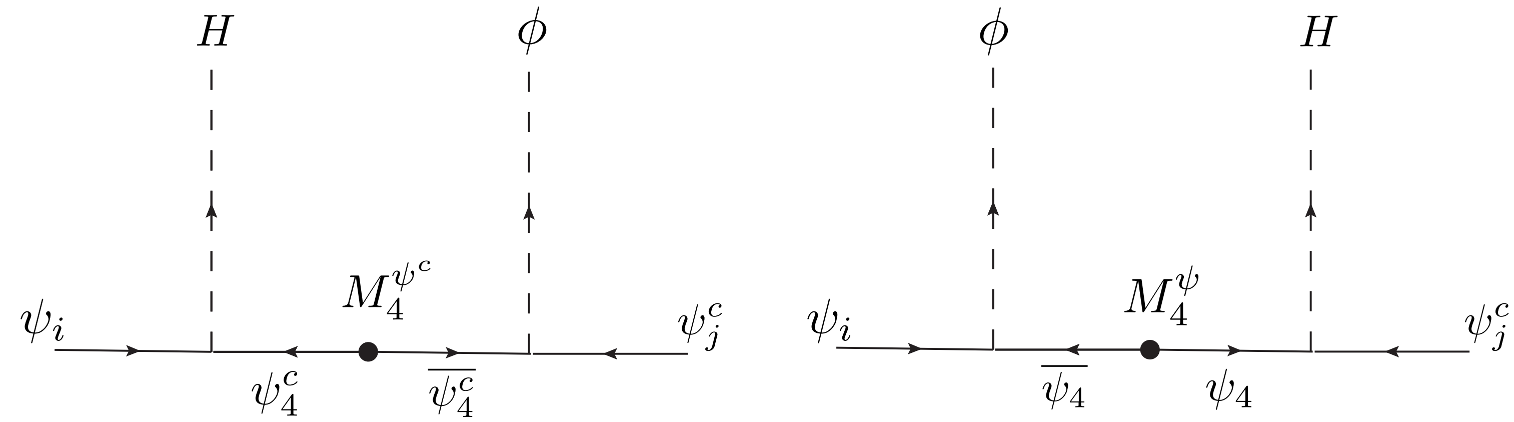
d_i^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$1/3$	0
L_i	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	0
e_i^c	$\mathbf{1}$	$\mathbf{1}$	1	0
ν_i^c	$\mathbf{1}$	$\mathbf{1}$	0	0
Q_4	$\mathbf{3}$	$\mathbf{2}$	$1/6$	1
u_4^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	1
d_4^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$1/3$	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

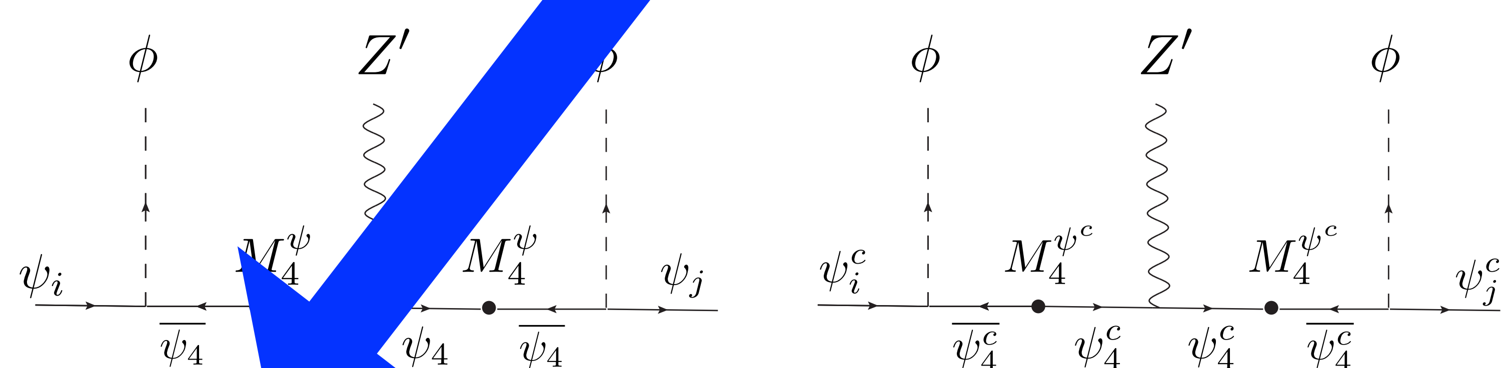
SFK 1806.06780



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"

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ν_i^c	$\mathbf{1}$	$\mathbf{1}$	0	0
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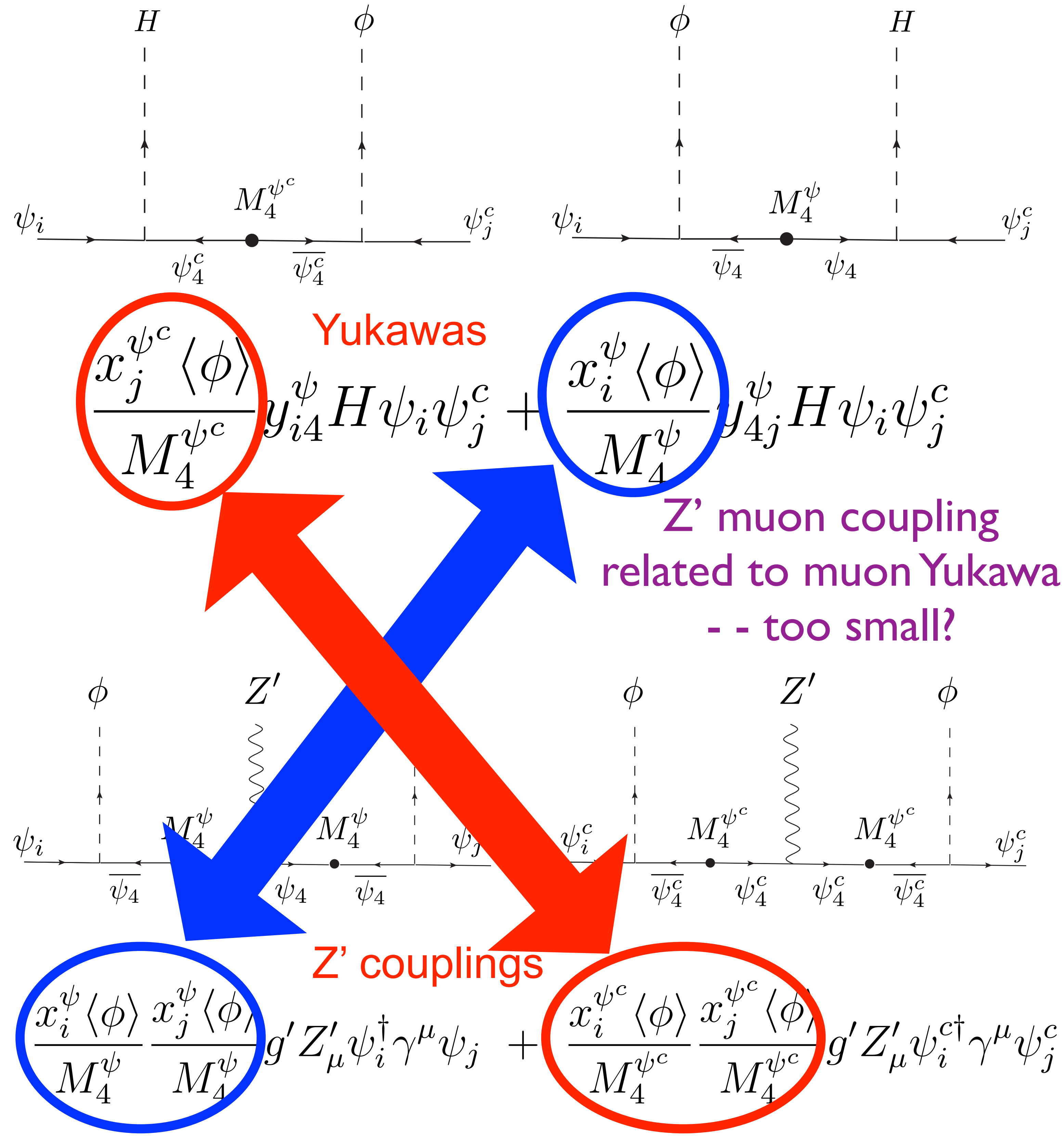
Yukawa and Z' couplings are related

SFK 1806.06780



Finale

The Flavour Problem

- 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 orbifolding
- 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