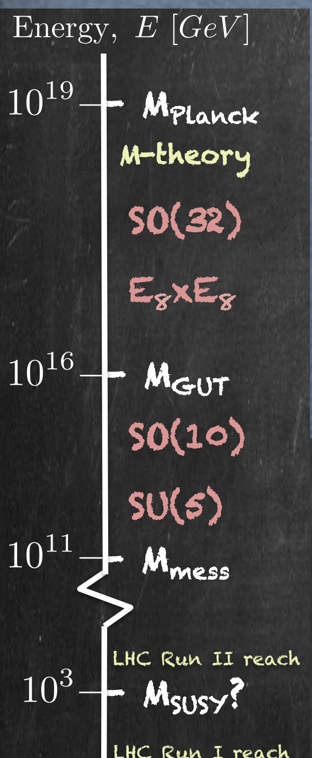

University of Southampton School of Physics and Astronomy

invisibles — neutrinos, dark matter & dark energy physics

GRADnet — South East Physics Network

SUSY GUTs & Flavour

Steve King, University of Kent,

Canterbury, 11-12th January 2016

SUPERSYMMETRY: from M-theory to the LHC

University of Hertfordshire · University of Kent · The Open University · University of Portsmouth · Queen Mary University of London

University of Reading · Royal Holloway University of London · University of Southampton · University of Surrey · University of Sussex

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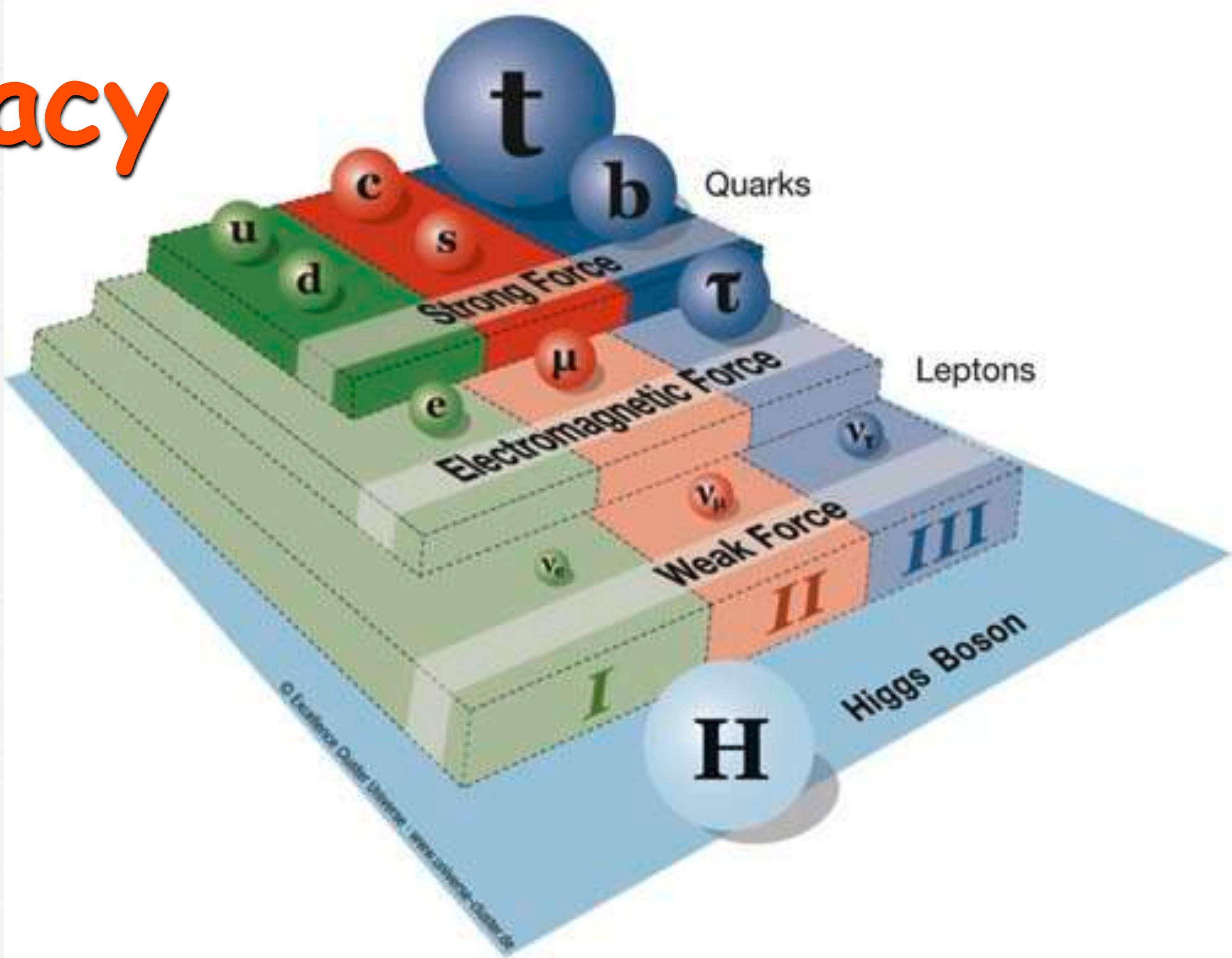
The Standard Model and its Legacy



Standard Model Puzzles

1. The origin of neutrino mass - and its relation to the weak scale, and the solution to the hierarchy problem

2. The quest for unification - the question of whether the three known forces of the standard model may be related into a grand unified theory, and whether such a theory could also include a unification with gravity.

3. The problem of flavour - the problem of the undetermined fermion (including neutrino) masses and mixing angles and CP violation, but with suppressed flavour changing neutral currents and strong CP violation.

We shall discuss all three questions
(apart from strong CP problem)

See-saw mechanism

P. Minkowski;
T. Yanagida;
M. Gell- Mann,
P. Ramond and
R. Slansky;

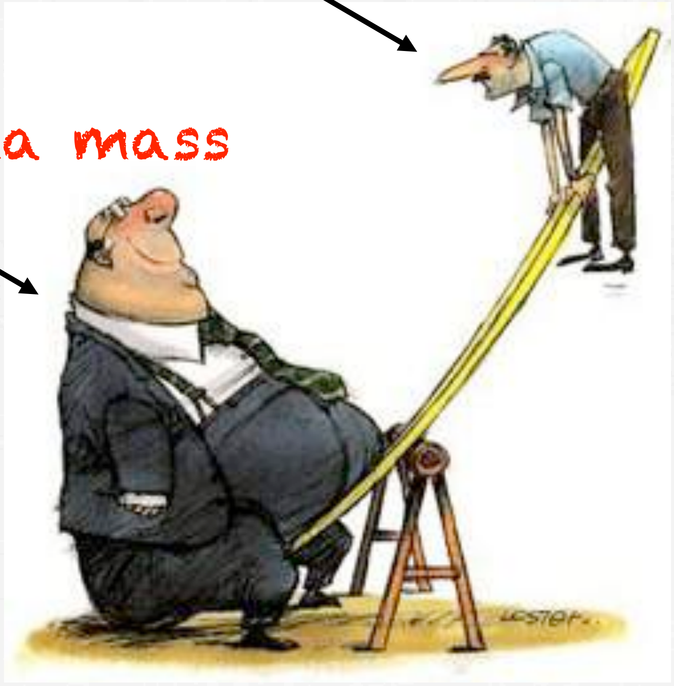
Dirac mass

$$\begin{pmatrix} \overline{\nu_L} & \overline{\nu^c_R} \end{pmatrix} \begin{pmatrix} 0 & m_{LR} \\ m^T_{LR} & M_{RR} \end{pmatrix} \begin{pmatrix} \nu^c_L \\ \nu_R \end{pmatrix}$$

Heavy Majorana mass

$$m^\nu = m_{LR}.\frac{1}{M_{RR}}.m^T_{LR}$$

Light Majorana matrix



Maybe neutrinos are so light

∵ RH neutrinos are so heavy

The minimal seesaw model is:

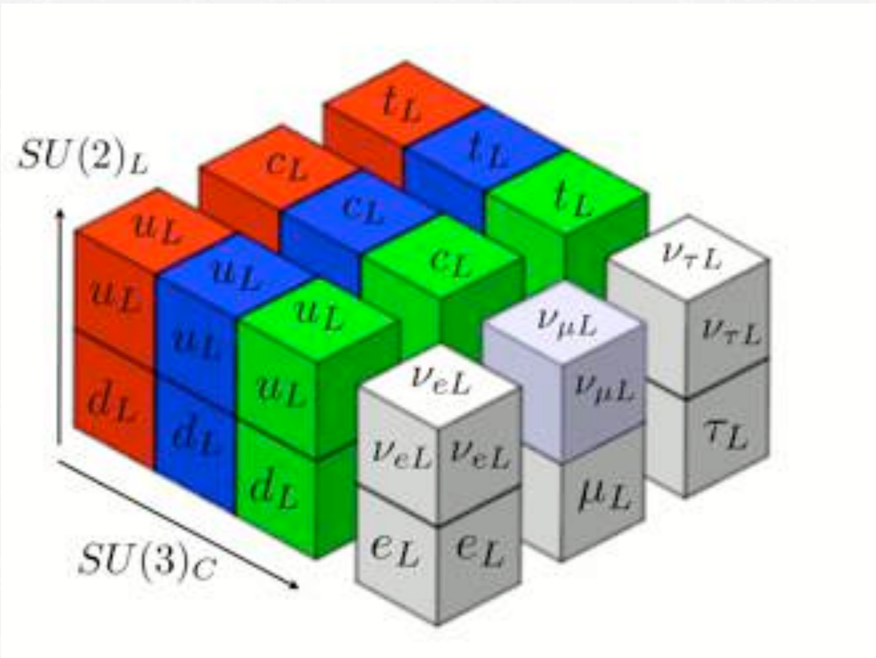
"Littlest seesaw" 1512.07531

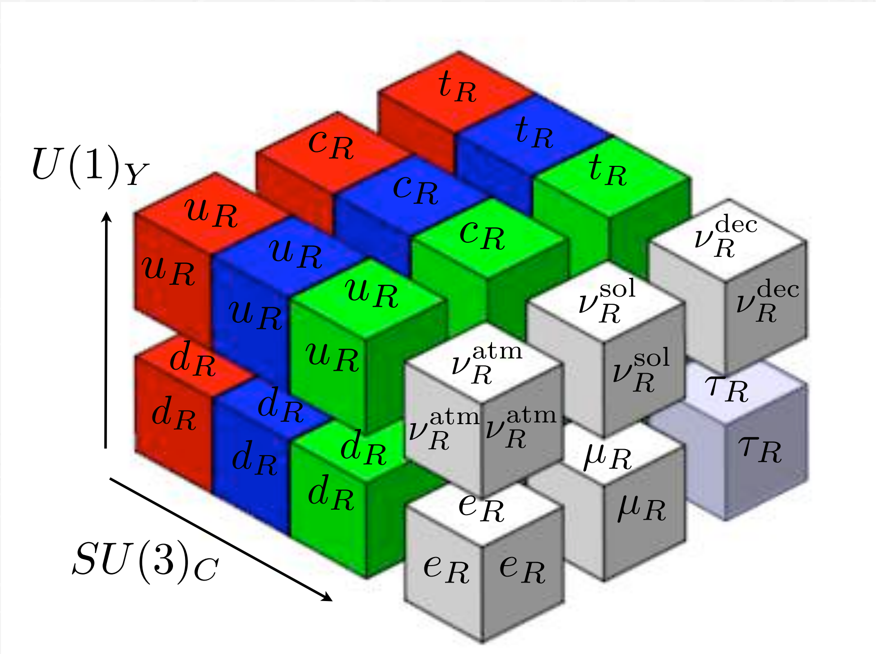
The Standard Model with 3 right-handed neutrinos

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

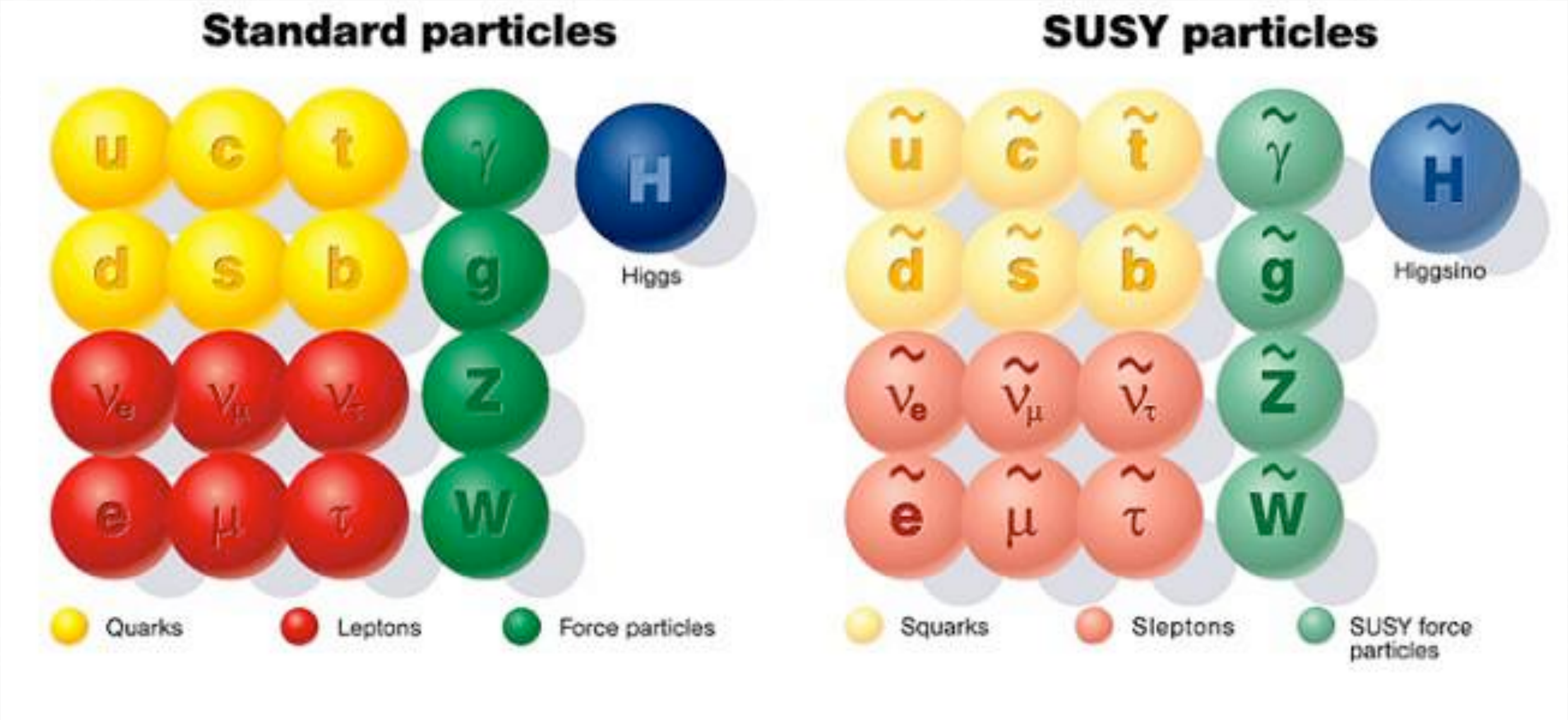
Left-handed quarks and leptons (active neutrinos)

Right-handed quarks and leptons (sterile neutrinos)



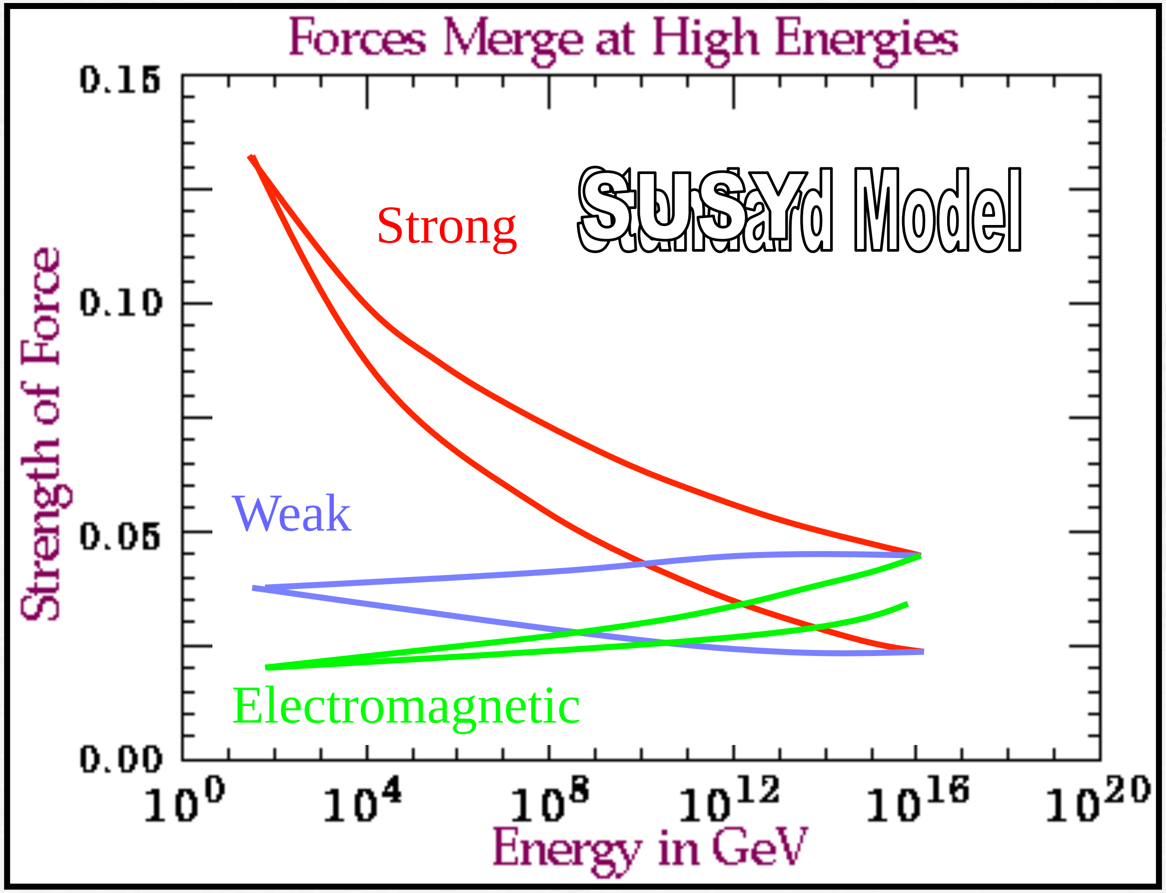


SUSY



Standard particles
u
c
t
γ
H
d
s
b
g
Higgs
ν_e
ν_μ
ν_τ
Z
e
μ
τ
W
Quarks
Leptons
Force particles
SUSY particles
$\tilde{u}$
$\tilde{c}$
$\tilde{t}$
$\tilde{\gamma}$
$\tilde{H}$
$\tilde{d}$
$\tilde{s}$
$\tilde{b}$
$\tilde{g}$
Higgsino
$\tilde{\nu}_e$
$\tilde{\nu}_\mu$
$\tilde{\nu}_\tau$
$\tilde{Z}$
$\tilde{e}$
$\tilde{\mu}$
$\tilde{\tau}$
$\tilde{W}$
Squarks
Sleptons
SUSY force particles

SUSY facilitates GUTs



Grand Unified Theories (GUTs)

Basic idea is to embed the SM gauge group into a simple gauge group G with a single coupling constant, broken at a high energy scale

$$G \to SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

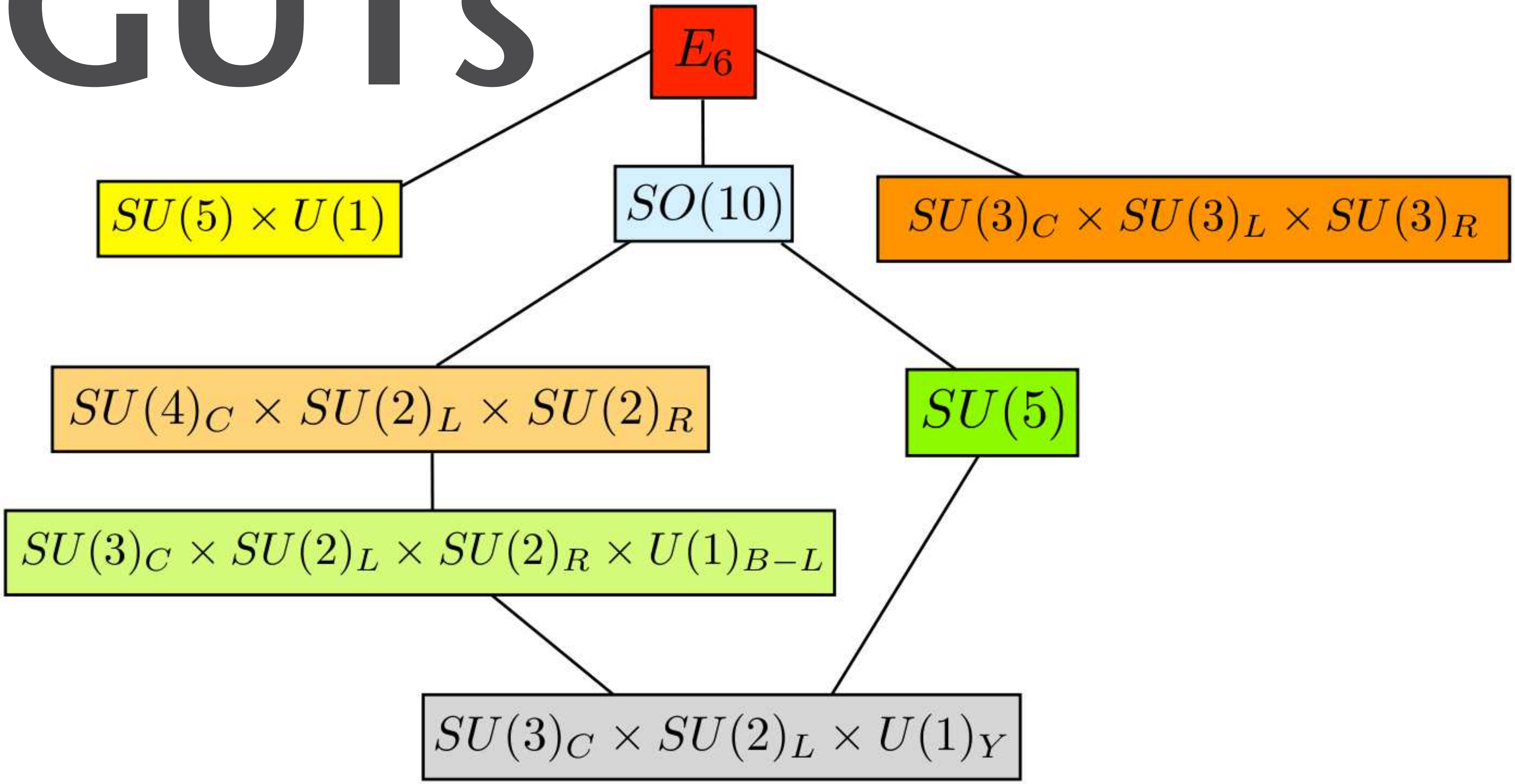
$$u_i^c = (\bar{3}, 1, -\tfrac{2}{3}), \quad d_i^c = (\bar{3}, 1, \tfrac{1}{3}), \quad e^c = (1, 1, 1),$$

$$Q^{\alpha\, i} = (u^i, d^i) = (3, 2, \tfrac{1}{6}), \qquad L^\alpha = (\nu, e) = (1, 2, -\tfrac{1}{2}),$$

Motivations

1. Continuation of process of unification of physics starting with Maxwell
2. Remarkable fit of SM multiplets into Pati-Salam, SU(5), SO(10), E_6…
3. Unification of gauge couplings at high energy scale M_{GUT}
4. Charge quantization: equality of electron and proton charges
5. High energy fermion mass relations e.g. m_b=m_τ

GUTs

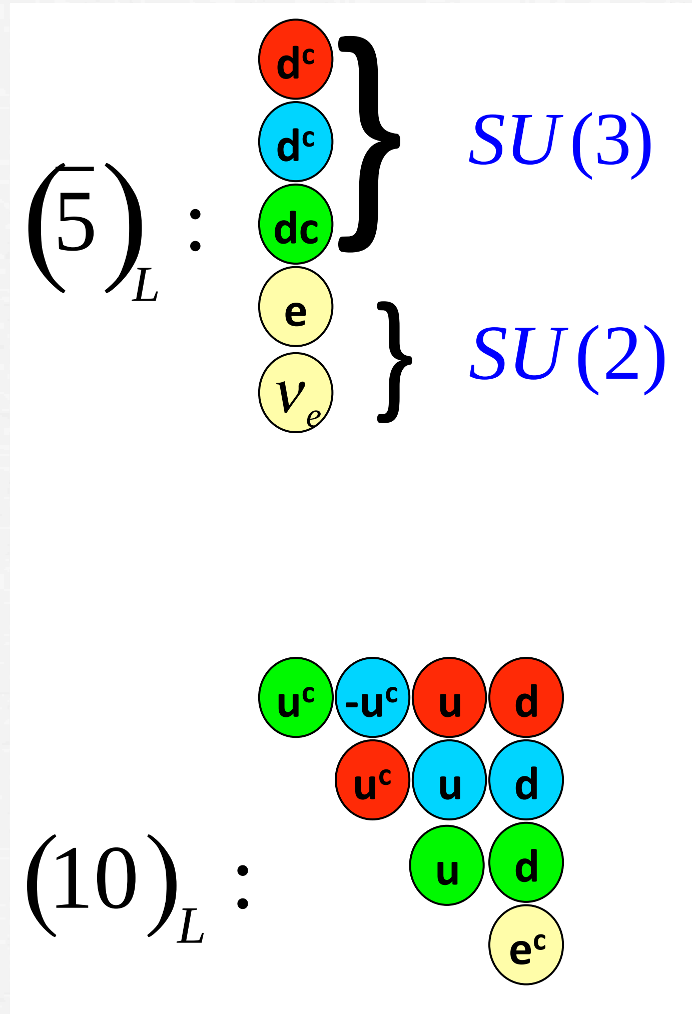


E_6
$SU(5) \times U(1)$
$SO(10)$
$SU(3)_C \times SU(3)_L \times SU(3)_R$
$SU(4)_C \times SU(2)_L \times SU(2)_R$
$SU(5)$
$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
$SU(3)_C \times SU(2)_L \times U(1)_Y$

SU(5) GUT

Right-handed neutrino is a singlet

$(1)_L : \nu^c$



SU(5) GUT

Georgi, Glashow

Each family fits nicely into the SU(5) multiplets

$$\overline{5}_i \equiv \begin{pmatrix} d_1^c \\ d_2^c \\ d_3^c \\ e^- \\ -\nu \end{pmatrix}_L \qquad 10^{[ij]} \equiv \begin{pmatrix} 0 & u_3^c & -u_2^c & u^1 & d^1 \\ . & 0 & u_1^c & u^2 & d^2 \\ . & . & 0 & u^3 & d^3 \\ . & . & . & 0 & e^c \\ . & . & . & . & 0 \end{pmatrix}_L$$

$$\overline{5} = (\overline{3}, 1, +1/3) \oplus (1, \overline{2}, -1/2) \quad \text{and} \quad 10 = (\overline{3}, 1, -2/3) \oplus (3, 2, +1/6) \oplus (1, 1, +1)$$

N.B in minimal SU(5) neutrino masses are zero.

Right-handed neutrinos may be added to give neutrino masses but they are not predicted.

Fermion Masses in SU(5)

The Yukawa superpotential for one family

$$\lambda_u H_i 10_{jk} 10_{lm} \epsilon^{ijklm} + \lambda_d \overline{H}^i 10_{ij} \overline{5}^j$$

$$\lambda_u H_u Q u^c + \lambda_d (H_d Q d^c + H_d e^c L)$$

$$\lambda_d = \lambda_e \text{ at the GUT scale}$$

Assuming this relation holds for all 3 families.

$$\underbrace{\lambda_b = \lambda_\tau,}_{\text{good}} \quad \underbrace{\lambda_s = \lambda_\mu, \quad \lambda_d = \lambda_e^T}_{\text{modify using Georgi-Jarlskog mechanism}} \text{ at } M_{GUT}$$

good

modify using Georgi-Jarlskog mechanism

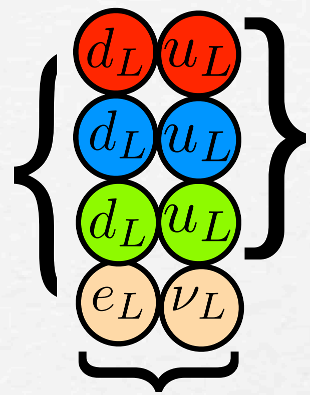
$$\lambda_b = \lambda_\tau, \quad \lambda_s = \frac{\lambda_\mu}{3}, \quad \lambda_d = 3\lambda_e$$

Pati-Salam

Talk by Patrick

$SU(4)_C \times SU(2)_L \times SU(2)_R$

$(4, 2, 1)_L : \quad SU(4)_C$

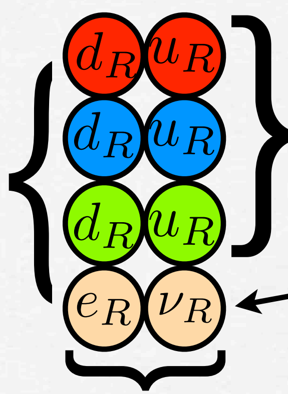


$SU(3)_C$

$SU(2)_L$

"Lepton number as the fourth colour"

$(4, 1, 2)_R : \quad SU(4)_C$



$SU(3)_C$

$SU(2)_R$

Right-handed neutrino is predicted

Pati-Salam

$$SU(4)_{PS} \times SU(2)_L \times SU(2)_R$$

$$(4,2,1) = \begin{pmatrix} u & u & u & \nu \\ d & d & d & e^- \end{pmatrix}_L \qquad (4,1,2) = \begin{pmatrix} u & u & u & \nu \\ d & d & d & e^- \end{pmatrix}_R$$

-- Predicts RH neutrinos with lepton number as the "fourth colour"

-- Allows the possibility of restoring parity if LR symmetry is imposed

-- (Quark-lepton) unification of 16 family into two LR symmetric reps

-- B-L as a gauge symmetry

-- Quantization of electric charge → $Q_e = -Q_p$

-- Pati-Salam can be unified into SO(10)

$$(4,2,1) + (4,1,2) \subset 16$$

SO(10) GUT

Georgi; Fritzsch and Minkowski

The 16 of SO(10) contains a single quark and lepton family and also predicts a single right-handed neutrino per family.

The SU(5) reps are unified into SO(10):

$$\mathbf{10} + \bar{\mathbf{5}} + \bar{\nu} \quad \subset \quad \mathbf{16}$$

The two Higgs doublets are contained in a 10 of SO(10)

$$\mathbf{5_H}, \quad \bar{\mathbf{5}}_{\mathbf{H}} \quad \subset \quad \mathbf{10_H}$$

Fermion masses arise from the coupling

$$\lambda 16.16.10_H = \lambda\left(Qh_2u^c + Qh_1d^c + Lh_1e^c + Lh_2\nu^c\right)$$

Neutrino Masses in SO(10)

$$16.16.10_H \rightarrow (\bar{\nu} \quad \bar{e})_L \begin{pmatrix} H^0 \\ H^- \end{pmatrix} \nu_R \rightarrow m_{LR} \bar{\nu}_L \nu_R$$ Dirac mass

$$16.16.126_H \rightarrow <126_H> \nu_R \nu_R$$

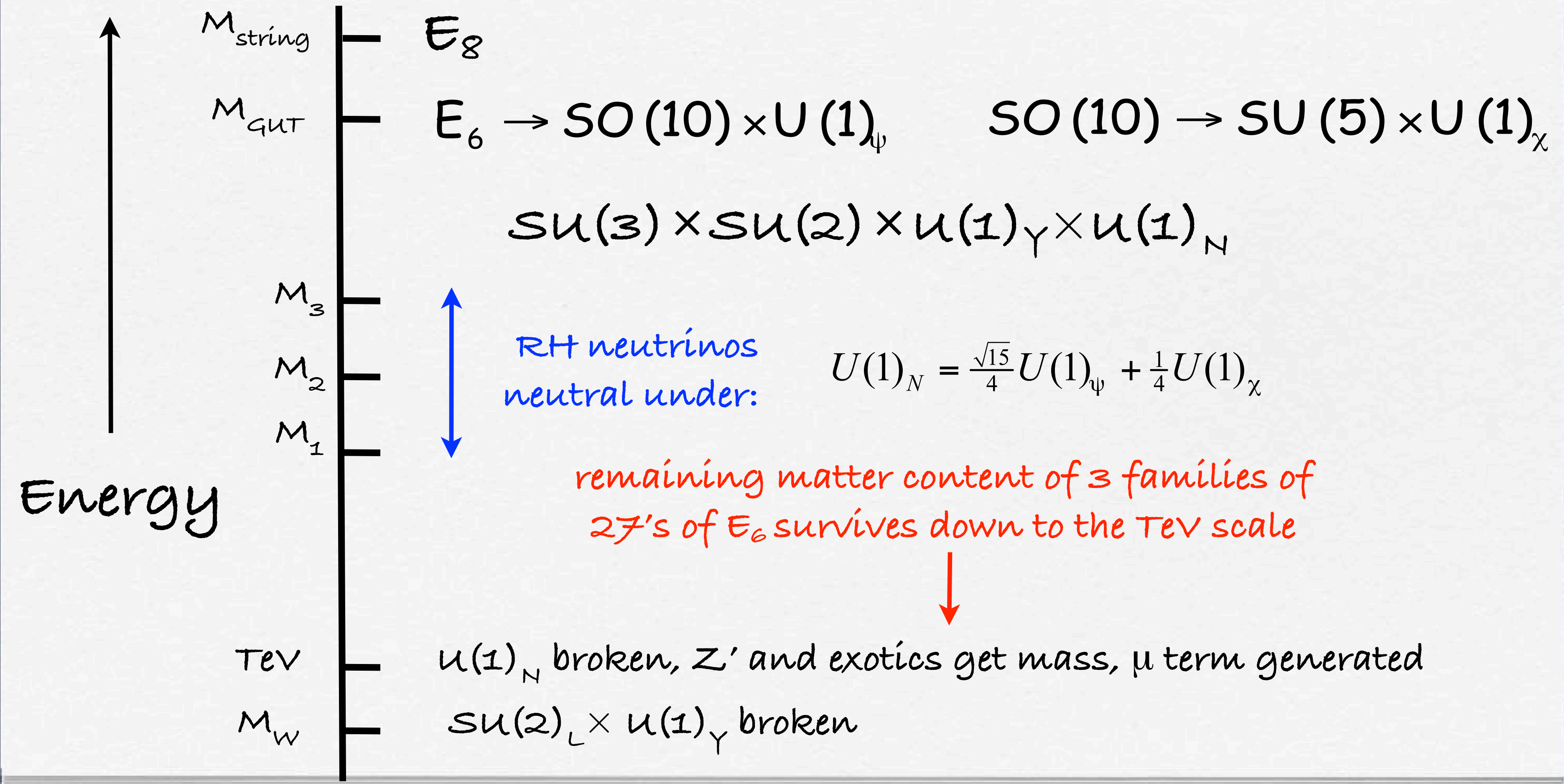
$$\frac{16.16.\overline{16}_H \overline{16}_H}{M} \rightarrow \frac{<\overline{16}_H>^2}{M} \nu_R \nu_R$$

Heavy Majorana mass

SO(10) contains all the ingredients for the see-saw mechanism

SFK, Moretti, Nevzorov

Exceptional SUSY SM (E_6SSM)



Matter Content of 27's of E_6

Miller

All the SM matter fields are contained in one 27-plet of E_6 per generation.

$$[27]_i \Rightarrow [10, 1]_i + [5^*, 2]_i + [5^*, -3]_i + [5, -2]_i + [1, 5]_i + [1, 0]_i$$

SU(5) reps. — U(1)$_N$ charge × √40

$[10, 1]_i$	$Q_i,\ u_i^c,\ e_i^c$
$[5^*, 2]_i$	$L_i,\ d_i^c$
$[5^*, -3]_i$	$H_{1\,i} = \begin{pmatrix} H^0_{1\,i} \\ H^-_{1\,i} \end{pmatrix},\ \bar{D}_i$
$[5, -2]_i$	$H_{2\,i} = \begin{pmatrix} H^+_{2\,i} \\ H^0_{2\,i} \end{pmatrix},\ D_i$
$[1, 5]_i$	S_i
$[1, 0]_i$	N_i^c

3 generations of "Higgs" ($H_{1\,i}$)

exotic quarks ($\bar{D}_i$, D_i)

singlets (S_i)

right handed neutrino (N_i^c)

Ingredients for 750 GeV Diphoton resonance - see later

E_6SSM Couplings

$S \subset S_i,$ $\quad D \subset D_i, \bar{D}_i,$

$H \subset H_i^u, H_i^d$ $\quad F \subset Q_i, L_i, U_i^c, D_i^c, E_i^c, N_i^c$

$$W = SHH + SDD + HFF + DFF$$

Singlet-Higgs-Higgs couplings includes effective μ term

Singlet-D-D couplings includes effective D mass terms

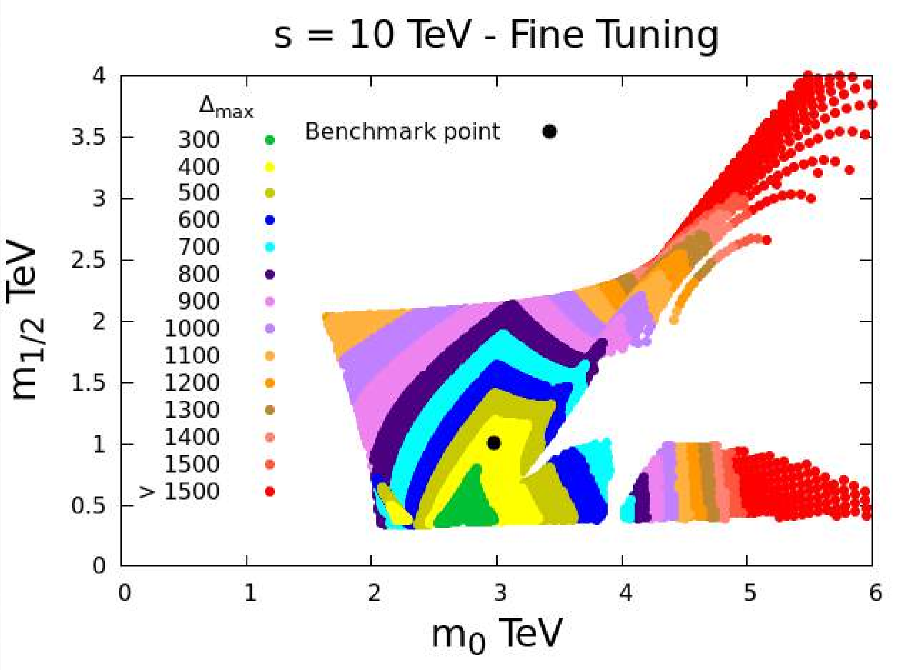
Yukawa couplings but extra Higgs give FCNCs

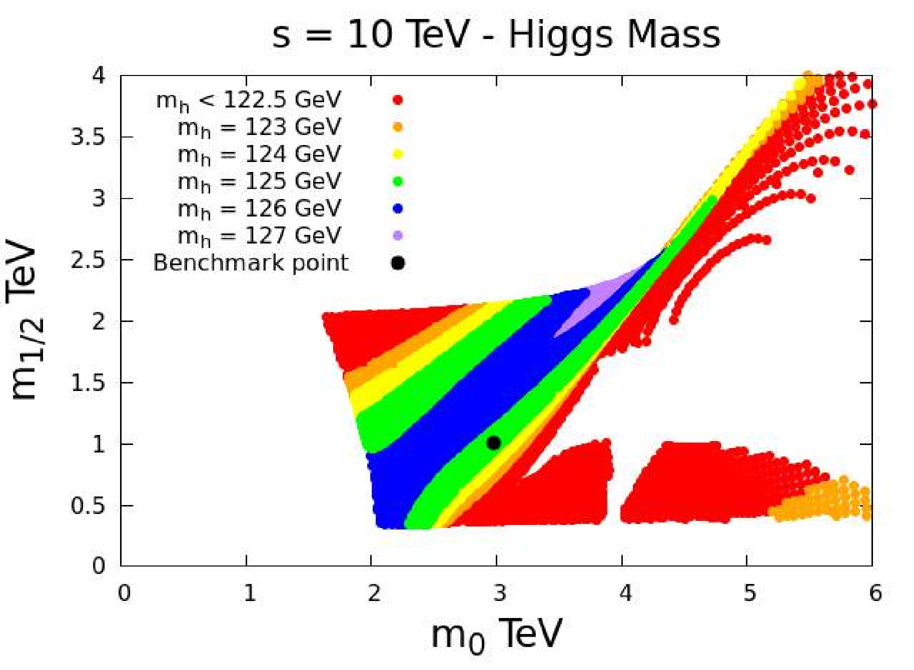
DQQ, DQL allows D decay but also proton decay. Need to:
– either forbid one of DQQ or DQL
- or allow both with Yukawas $\sim 10^{-12}$

Fine-tuning in the cE6SSM

$\tan\beta = 10,\ \lambda_{12} = 0.1,\ s = 10\ \text{TeV},$

Athron, Binjonaid, SFK

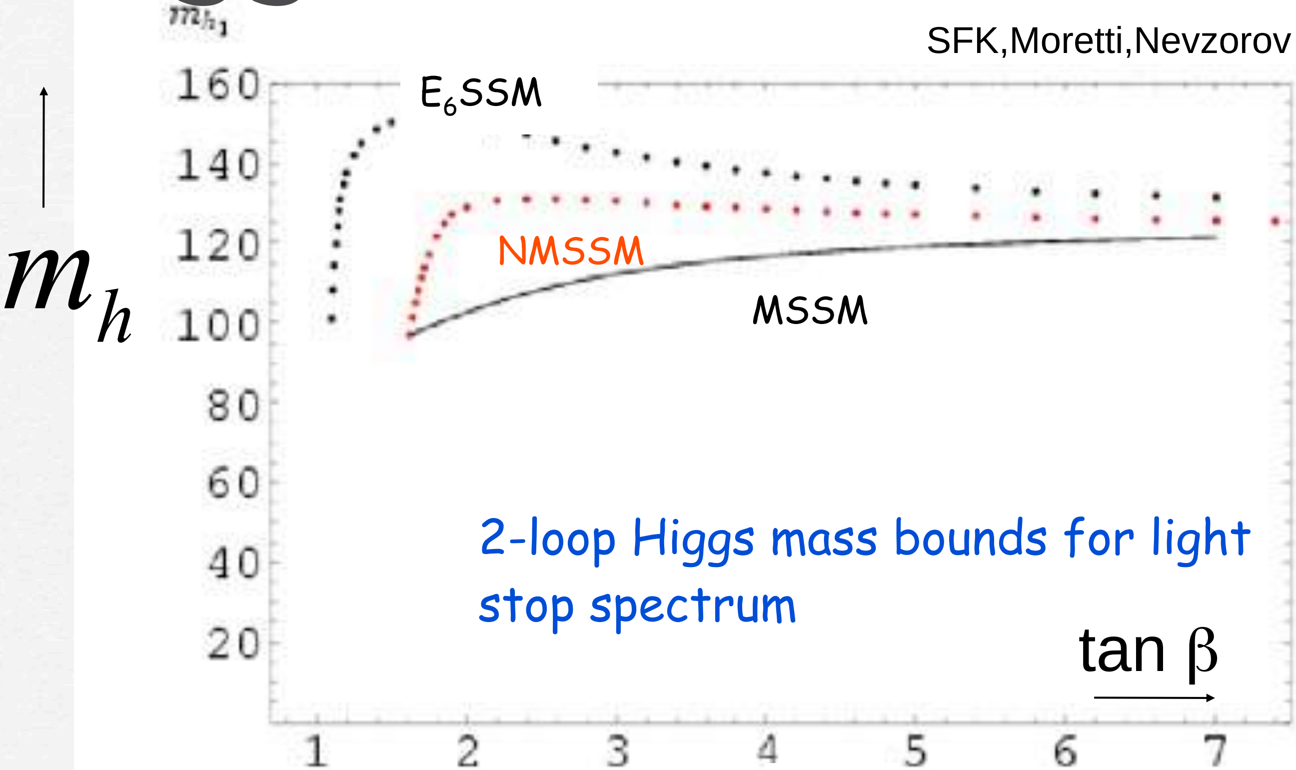




Lower fine-tuning than cMSSM

Higgs mass bounds in SSM's

SFK,Moretti,Nevzorov hep-ph/0510419



Extra terms in non-minimal models allow

$$\Delta m_h < M_Z$$

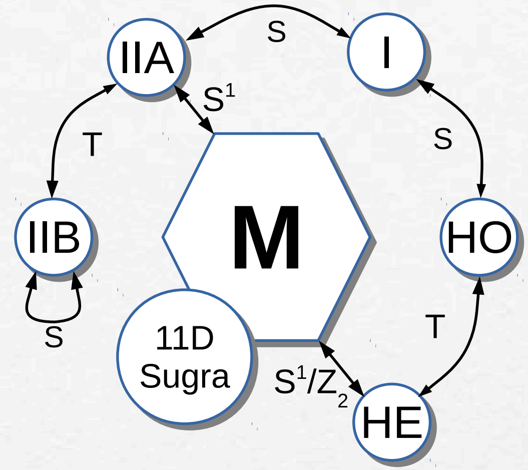
Hence allow lighter stops and lower fine-tuning

$$m_h^2 \approx \underbrace{\underbrace{\underbrace{M_Z^2 \cos^2 2\beta}_{MSSM} + \frac{\lambda^2}{2} v^2 \sin^2 2\beta}_{NMSSM} + \frac{M_Z^2}{4}\left(1+\frac{1}{4}\cos 2\beta\right)^2}_{E_6SSM} + \Delta m_h^2$$

LHC phenomenology of E_6SSM

- SUSY - typical spectrum has heavier squarks and lighter gluinos, with gluinos having longer decay chains than MSSM, due to extra neutralinos and charginos, giving less missing energy and more soft leptons and jets
- Higgs - Richer Higgs spectrum than MSSM or NMSSM, incl. inert + singlet Higgs (Diphoton)
- Exotics - Z', D-leptoquarks/diquarks (maybe long lived)

M-theory
GUTs (gravity)



Talk by Miguel Romao

- M-theory→ 11d SUGRA →4d N=1 SUGRA
- Compactified 7d → G_2 manifold

Witten, Acharya, Kane,...

- Gauge fields on dominant volume 3d submanifold
- SU(5) GUT
- SO(10) GUT
- main prediction: extra 16+16bar at TeV scale

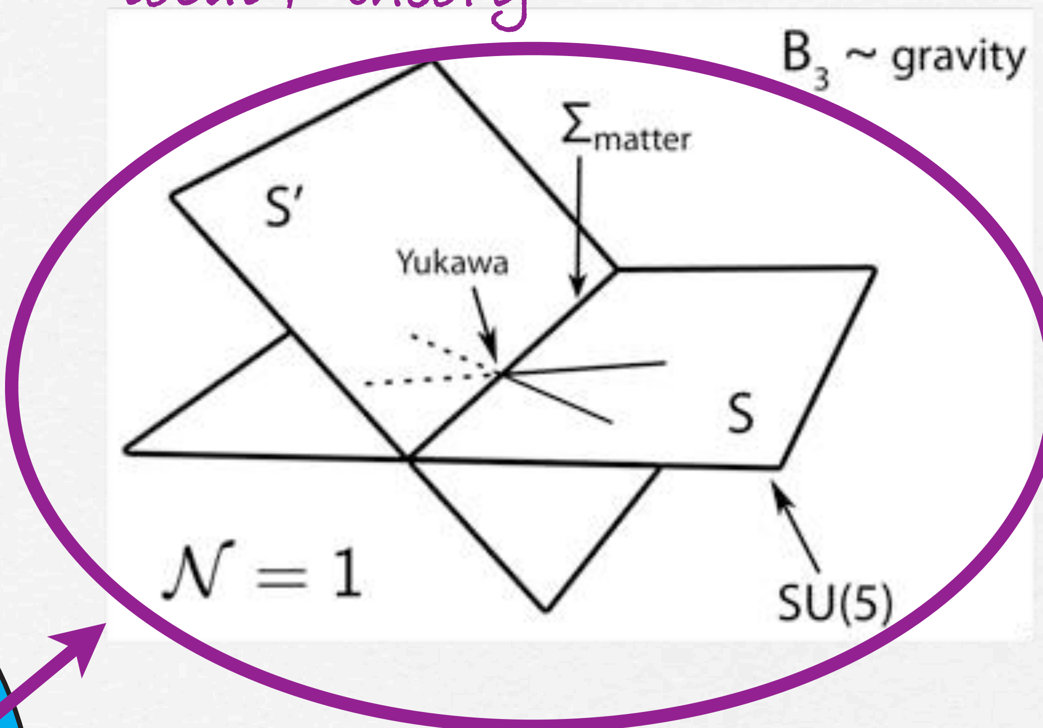
Acharya, Bozek, M.C.Romao, S.F.K. and Pongkitivanichkul 1502.01727

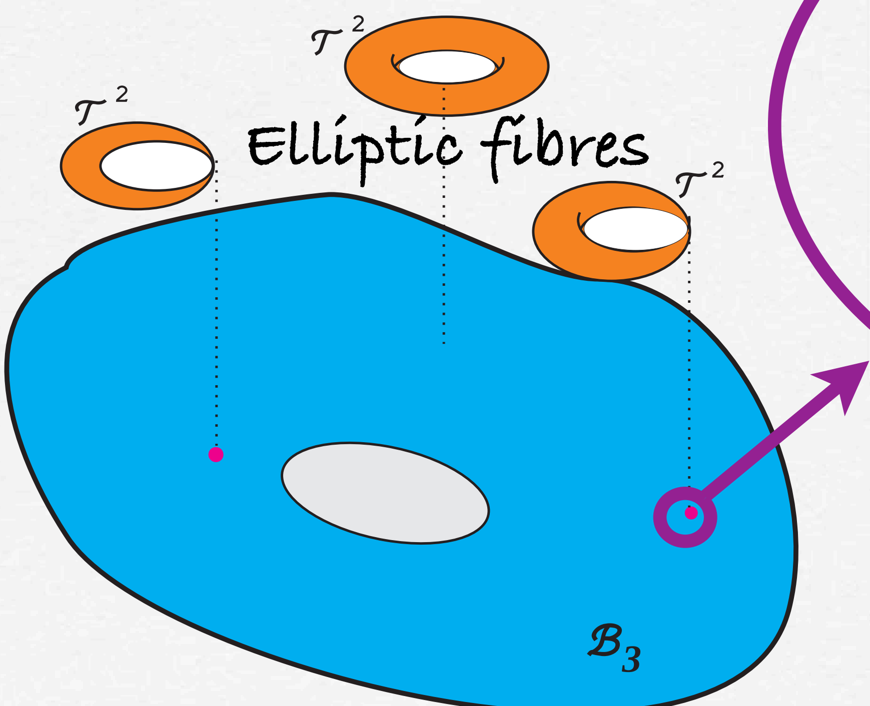
Talk by Andrew Meadowcroft

G.K. Leontaris,
``Aspects of F-Theory GUTs,''
PoS CORFU {\bf 2011} (2011) 095
[arXiv:1203.6277 [hep-th]].

F-theory GUTs

local F-theory





Type IIB string theory

dim.	internal dim.	feature
10	$6 = \dim(B_3)$	gravity
8	$4 = \dim(S)$	gauge fields
6	$2 = \dim(S \cap S')$	matter
4	$0 = \dim(S \cap S' \cap S'')$	interactions

E_6SSM from F-theory

Callaghan, SFK

E_6	$SO(10)$	$SU(5)$	Weight vector	Q_N	N_Y	$M_{U(1)}$	SM particle content	Low energy spectrum
$27_{t_1'}$	16	$\overline{5}_3$	t_1+t_5	$\frac{1}{\sqrt{10}}$	1	4	$4d^c+5L$	$3d^c+3L$
$27_{t_1'}$	16	10_M	t_1	$\frac{1}{2\sqrt{10}}$	-1	4	$4Q+5u^c+3e^c$	$3Q+3u^c+3e^c$
$27_{t_1'}$	16	θ_{15}	t_1-t_5	0	0	n_{15}	$3\nu^c$	-
$27_{t_1'}$	10	5_1	$-t_1-t_3$	$-\frac{1}{\sqrt{10}}$	-1	3	$3D+2H_u$	$3D+2H_u$
$27_{t_1'}$	10	$\overline{5}_2$	t_1+t_4	$-\frac{3}{2\sqrt{10}}$	1	3	$3\overline{D}+4H_d$	$3\overline{D}+3H_d$
$27_{t_1'}$	1	θ_{14}	t_1-t_4	$\frac{5}{2\sqrt{10}}$	0	n_{14}	θ_{14}	θ_{14}
$27_{t_3'}$	16	$\overline{5}_5$	t_3+t_5	$\frac{1}{\sqrt{10}}$	-1	-1	$\overline{d^c}+2\overline{L}$	-
$27_{t_3'}$	16	10_2	t_3	$\frac{1}{2\sqrt{10}}$	1	-1	$\overline{Q}+2\overline{u^c}$	-
$27_{t_3'}$	16	θ_{35}	t_3-t_5	0	0	n_{35}	$-$	-
$27_{t_3'}$	10	5_{H_u}	$-2t_1$	$-\frac{1}{2\sqrt{10}}$	1	0	H_u	H_u
$27_{t_3'}$	10	$\overline{5}_4$	t_3+t_4	$-\frac{3}{2\sqrt{10}}$	-1	0	$\overline{H_d}$	-
$27_{t_3'}$	1	θ_{34}	t_3-t_4	$\frac{5}{2\sqrt{10}}$	0	n_{34}	θ_{34}	θ_{34}
-	1	θ_{31}	t_3-t_1	0	0	n_{31}	θ_{31}	-
-	1	θ_{53}	t_5-t_3	0	0	n_{53}	θ_{53}	-
-	1	θ_{54}	t_5-t_4	$\frac{5}{2\sqrt{10}}$	0	n_{54}	θ_{54}	-
-	1	θ_{45}	t_4-t_5	$-\frac{5}{2\sqrt{10}}$	0	n_{45}	θ_{45}	-

$$W \sim \lambda\theta_{14}H_dH_u + \lambda_{\alpha\beta\gamma}\theta_{34}^{\alpha}H_d^{\beta}H_u^{\gamma} + \kappa_{\alpha jk}\theta_{34}^{\alpha}\overline{D}_jD_k$$

Singlets couple to the extra vector-like fermions (see later)

Bulk exotics

Theorem: flux breaking of E_6 always accompanied by bulk exotics

$$E_8 \supset E_6 \times SU(3)_\perp$$
$$248 \to (78,1) + (27,3) + (\overline{27},\overline{3}) + (1,8)$$

Bulk exotics

$$E_6 \to SO(10) \times U(1)_\psi$$
$$\to SU(5) \times U(1)_\chi \times U(1)_\psi$$
$$\to SU(3) \times SU(2) \times U(1)_Y \times U(1)_\chi \times U(1)_\psi$$

$$78 \to (1,1)_{0,0,0} + \{(1,1)_{0,0,0} + (1,1)_{0,0,0} + (8,1)_{0,0,0} + (1,3)_{0,0,0} + (3,2)_{-5,0,0} + (\overline{3},2)_{5,0,0}$$
$$+ (3,2)_{1,4,0} + (\overline{3},2)_{-1,-4,0} + (\overline{3},1)_{-4,4,0} + (3,1)_{4,-4,0} + (1,1)_{6,4,0} + (1,1)_{-6,-4,0}\}$$
$$+ \{(1,1)_{0,-5,-3} + (\overline{3},1)_{2,3,-3} + (1,2)_{-3,3,-3} + (1,1)_{6,-1,-3} + (3,2)_{1,-1,-3} + (\overline{3},1)_{-4,-1,-3}\}$$
$$+ \{(1,1)_{0,5,3} + (3,1)_{-2,-3,3} + (1,2)_{3,-3,3} + (1,1)_{-6,1,3} + (\overline{3},2)_{-1,1,3} + (3,1)_{4,1,3}\}$$

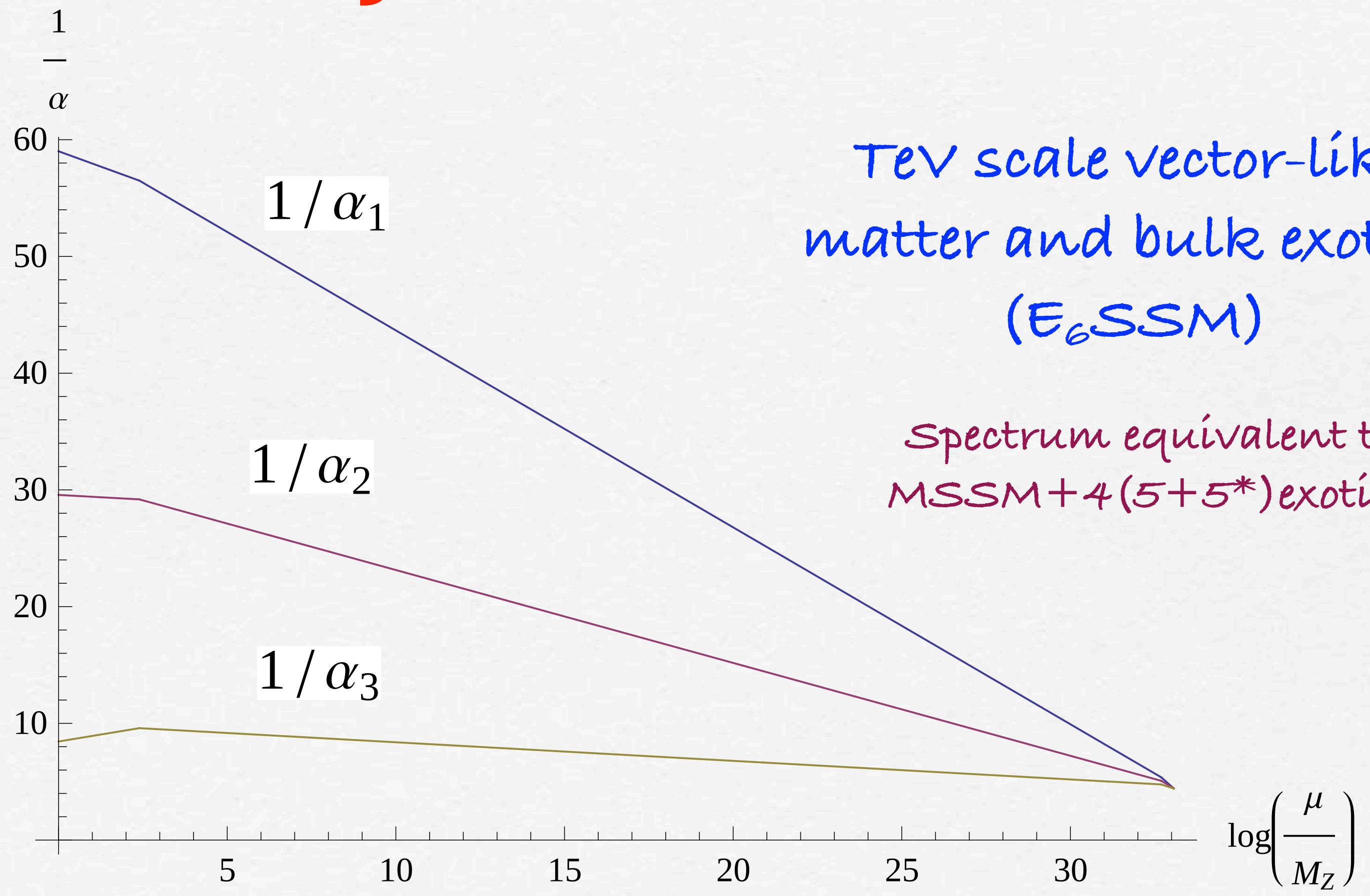
E_6 origin	$SU(5)$ origin	TeV scale spectrum	$U(1)_N$
$27_{t'_1}$	$\overline{5}$	$3d^c + 3L$	$\frac{1}{\sqrt{10}}$
$27_{t'_1}$	10	$3Q + 3u^c + 3e^c$	$\frac{1}{2\sqrt{10}}$
$27_{t'_1}$	5	$3D + 2H_u$	$-\frac{1}{\sqrt{10}}$
$27_{t'_1}$	$\overline{5}$	$3\overline{D} + 3H_d$	$-\frac{3}{2\sqrt{10}}$
$27_{t'_1}$	1	θ_{14}	$\frac{5}{2\sqrt{10}}$
$27_{t'_3}$	5	H_u	$-\frac{1}{2\sqrt{10}}$
$27_{t'_3}$	1	$2\theta_{34}$	$\frac{5}{2\sqrt{10}}$
78	$\overline{5}$	$2X_{H_d} + X_{d^c}$	$-\frac{3}{2\sqrt{10}}$
78	5	$2\overline{X}_{\overline{H}_d} + \overline{X}_{\overline{d^c}}$	$\frac{3}{2\sqrt{10}}$

Minimal allowed set of bulk exotics can restore gauge coupling unification in E_6SSM

TeV spectrum equivalent to MSSM+4(5+5*)exotics

Callaghan, SFK, Leontaris

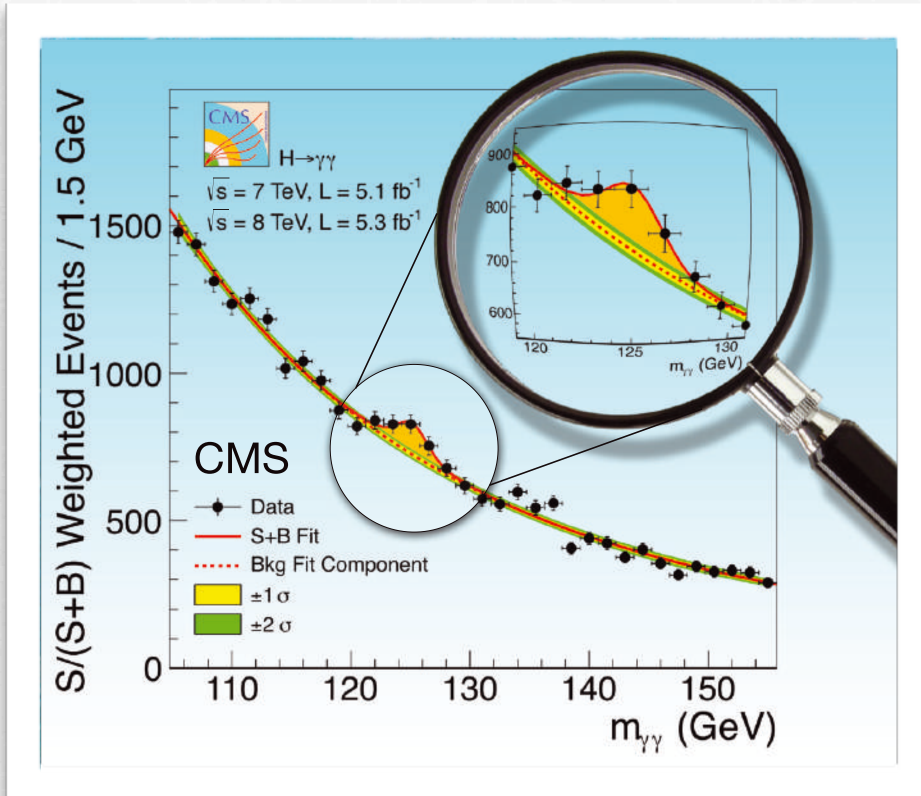
Gauge coupling unification in F-theory model with bulk exotics



TeV scale vector-like matter and bulk exotics (E_6SSM)

Spectrum equivalent to MSSM+4(5+5*)exotics

Diphoton resonance at 125 GeV



4th July, 2012

Congratulations to both Atlas and CMS Collaborations and to the builders of the LHC on a magnificent achievement!

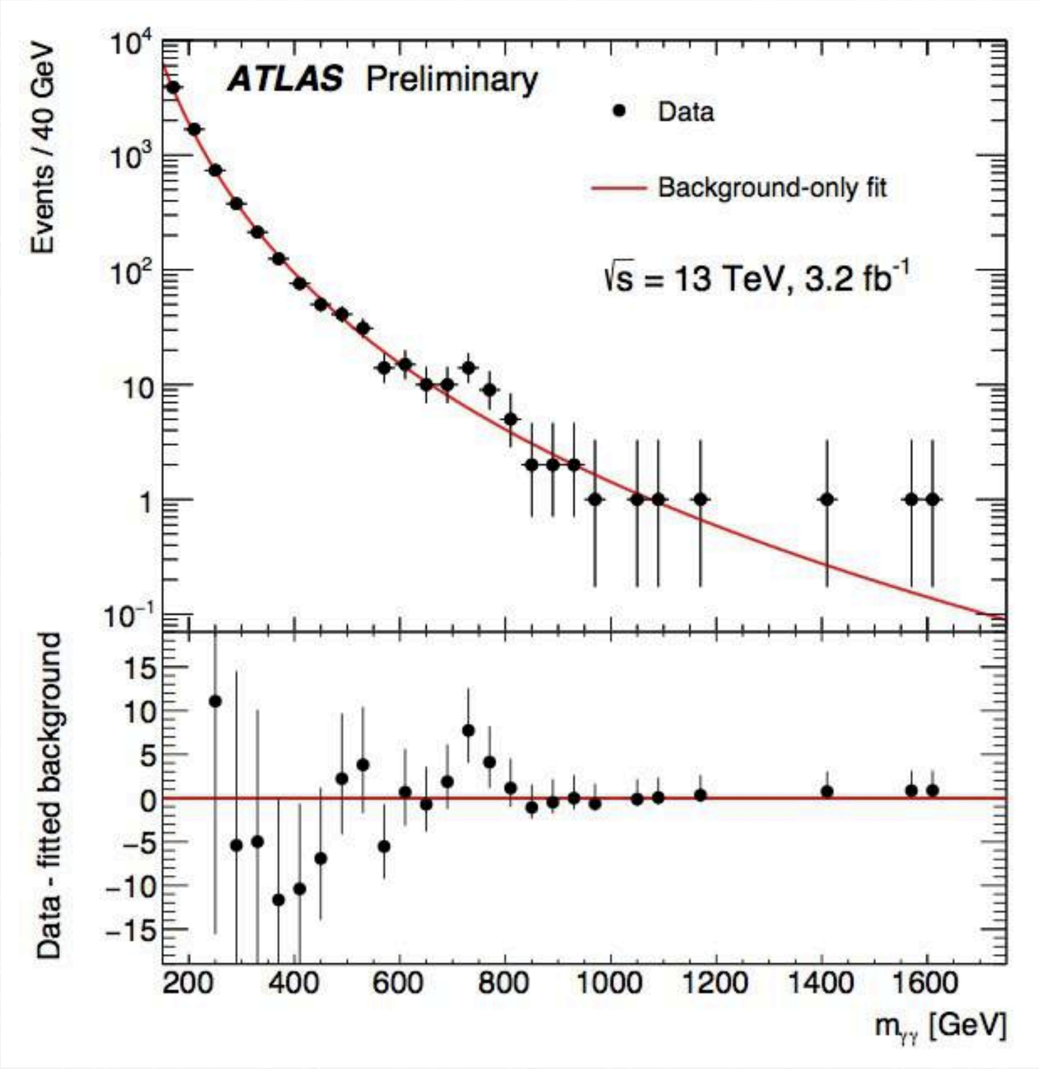
Peter Higgs

30 August 2012

" … The decay to two photons indicates that the new particle is a boson with spin different from one. The results presented here are consistent, … with expectations for a standard model Higgs boson."

\- CMS Collaboration

Diphoton resonance at 750 GeV



"Who ordered that ?"

Rattazzi

ATLAS

$M \simeq 750\,\mathrm{GeV}$ $\Gamma \sim 45\,\mathrm{GeV}$ favored

~ 14 events $3.9\,\sigma$ local $2.3\,\sigma$ including LEE

CMS

$M \simeq 760\,\mathrm{GeV}$ narrow width favored

~ 10 events $2.6\,\sigma$ local $1.2\,\sigma$ including LEE

- No significant $E_{T\mathrm{miss}}$, leptons or jets in the events
- No $\gamma\gamma$ resonance at 8 TeV but small upward fluctuation

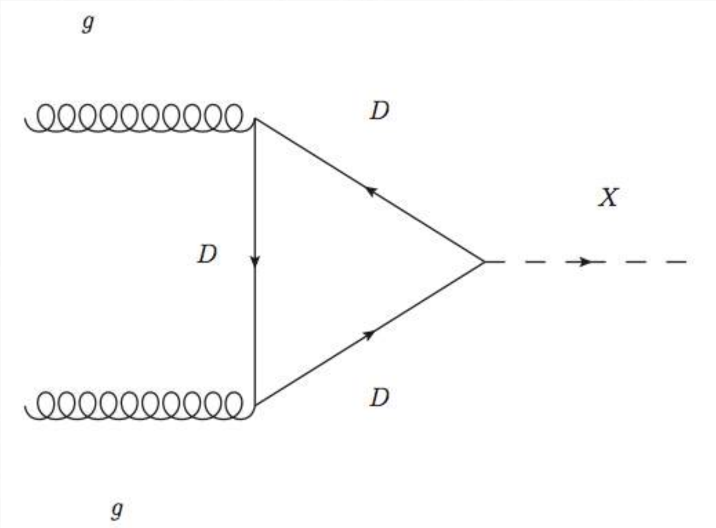
$$\sigma(pp \to \gamma\gamma) \approx \begin{cases} (0.5 \pm 0.6)\,\mathrm{fb} & \mathrm{CMS}\ [2] & \sqrt{s} = 8\,\mathrm{TeV}, \\ (0.4 \pm 0.8)\,\mathrm{fb} & \mathrm{ATLAS}\ [3] & \sqrt{s} = 8\,\mathrm{TeV}, \\ (6 \pm 3)\,\mathrm{fb} & \mathrm{CMS}\ [1] & \sqrt{s} = 13\,\mathrm{TeV}. \\ (10 \pm 3)\,\mathrm{fb} & \mathrm{ATLAS}\ [1] & \sqrt{s} = 13\,\mathrm{TeV}. \end{cases}$$

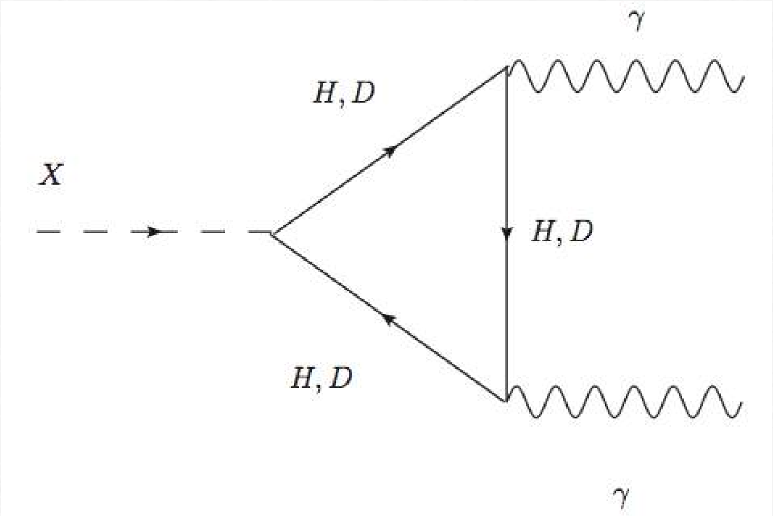
Diphoton resonance at 750 GeV

Over 100 theoretical papers with various interpretations

We propose that it is an E_6SSM F-theory singlet X coupling to vector-like Higgsino and D fermions

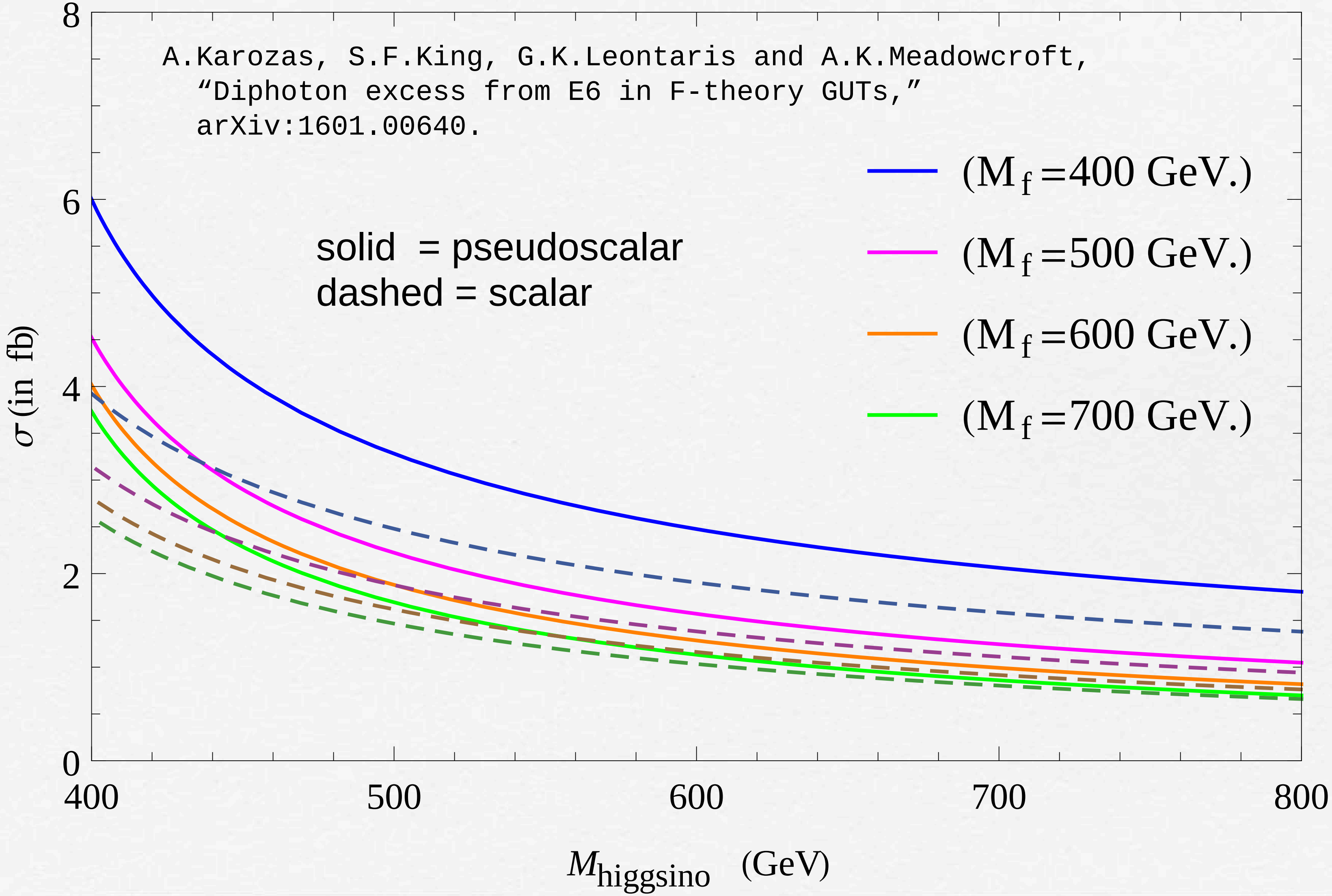
$$\mathcal{L} \sim \kappa_i X \bar{D}_i D_i + \lambda_\alpha X H_u^\alpha H_d^\alpha + M_i \bar{D}_i D_i + M_{H_\alpha} H_u^\alpha H_d^\alpha + \frac{1}{2} M^2 X^2 + \cdots$$



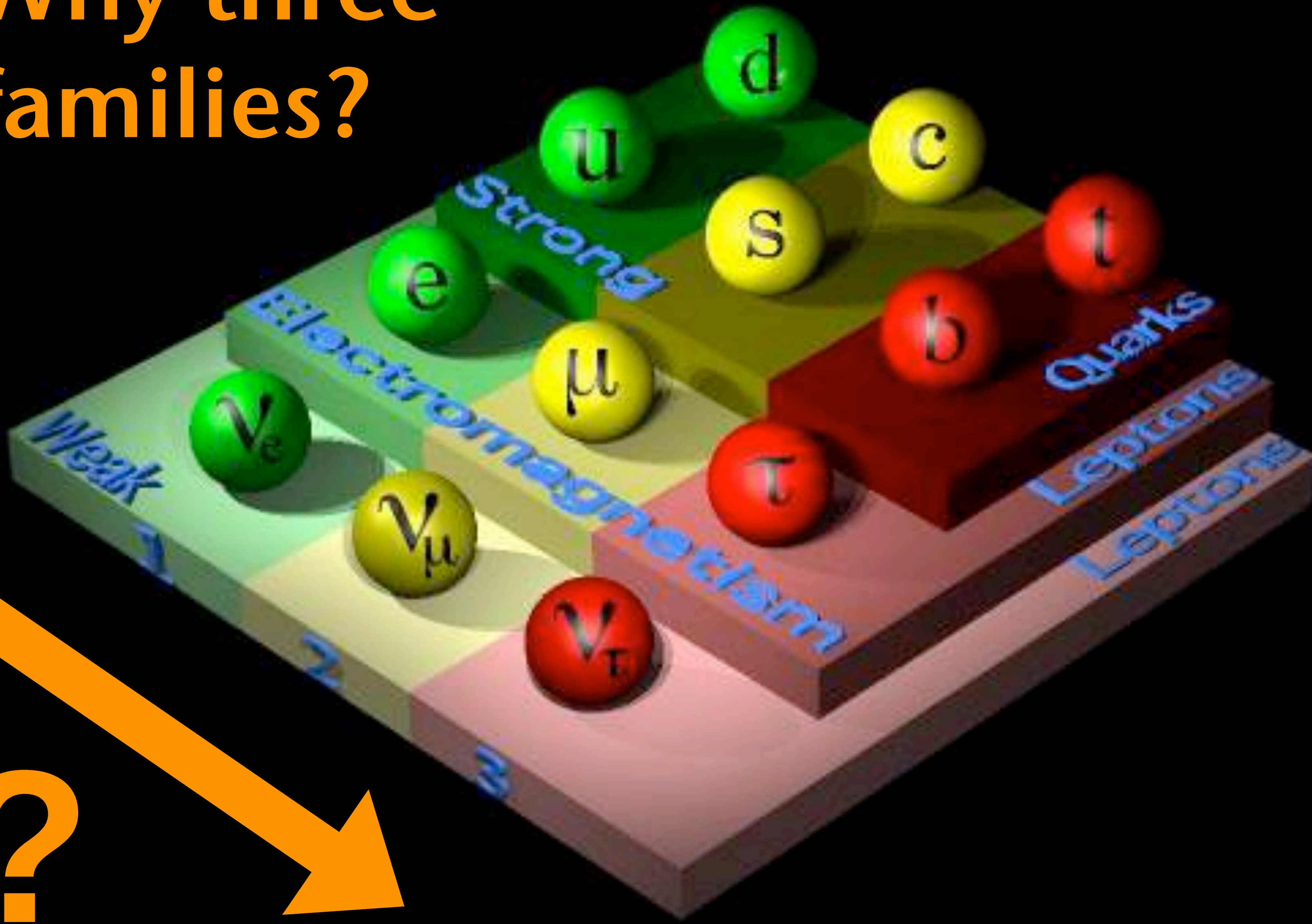


$$\sigma(pp \to X \to \gamma\gamma) = \frac{1}{M\Gamma s} C_{gg} \Gamma(X \to gg) \Gamma(X \to \gamma\gamma)$$

$$\sigma(pp \to X \to \gamma\gamma)$$

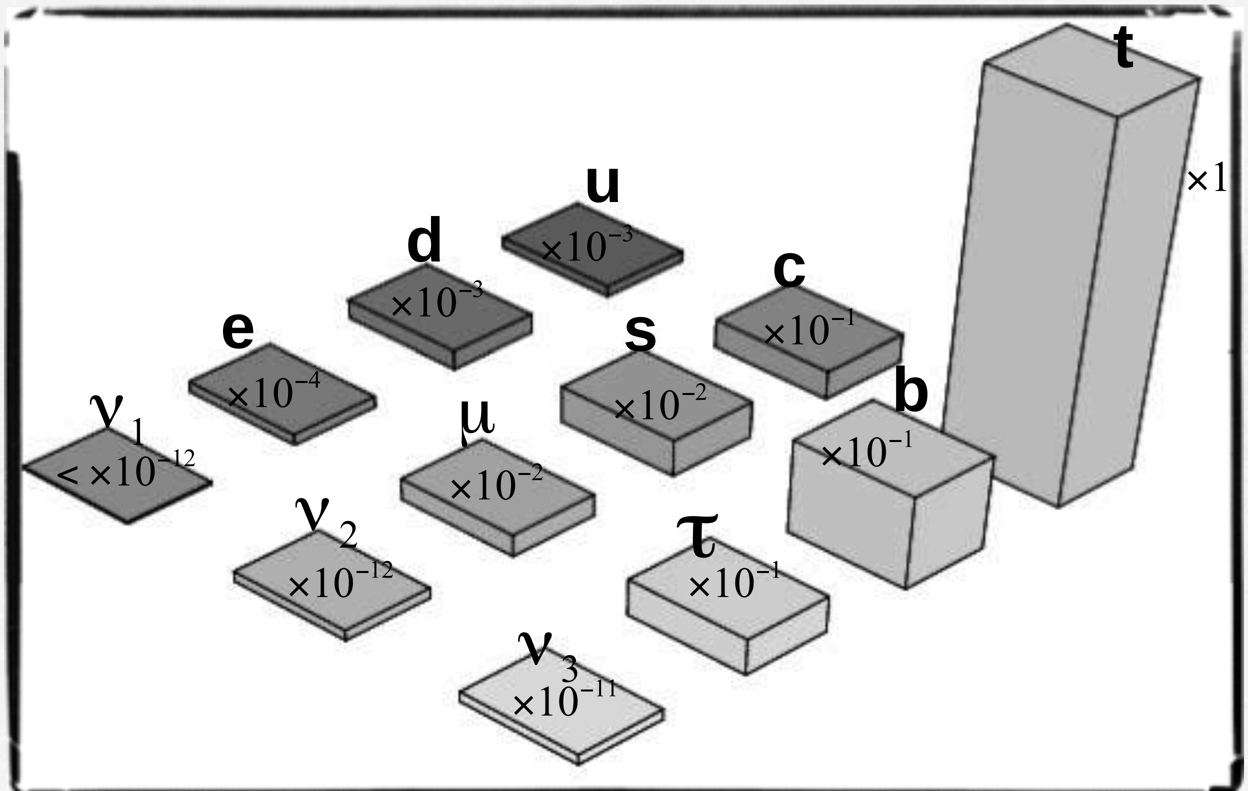


Why three families?

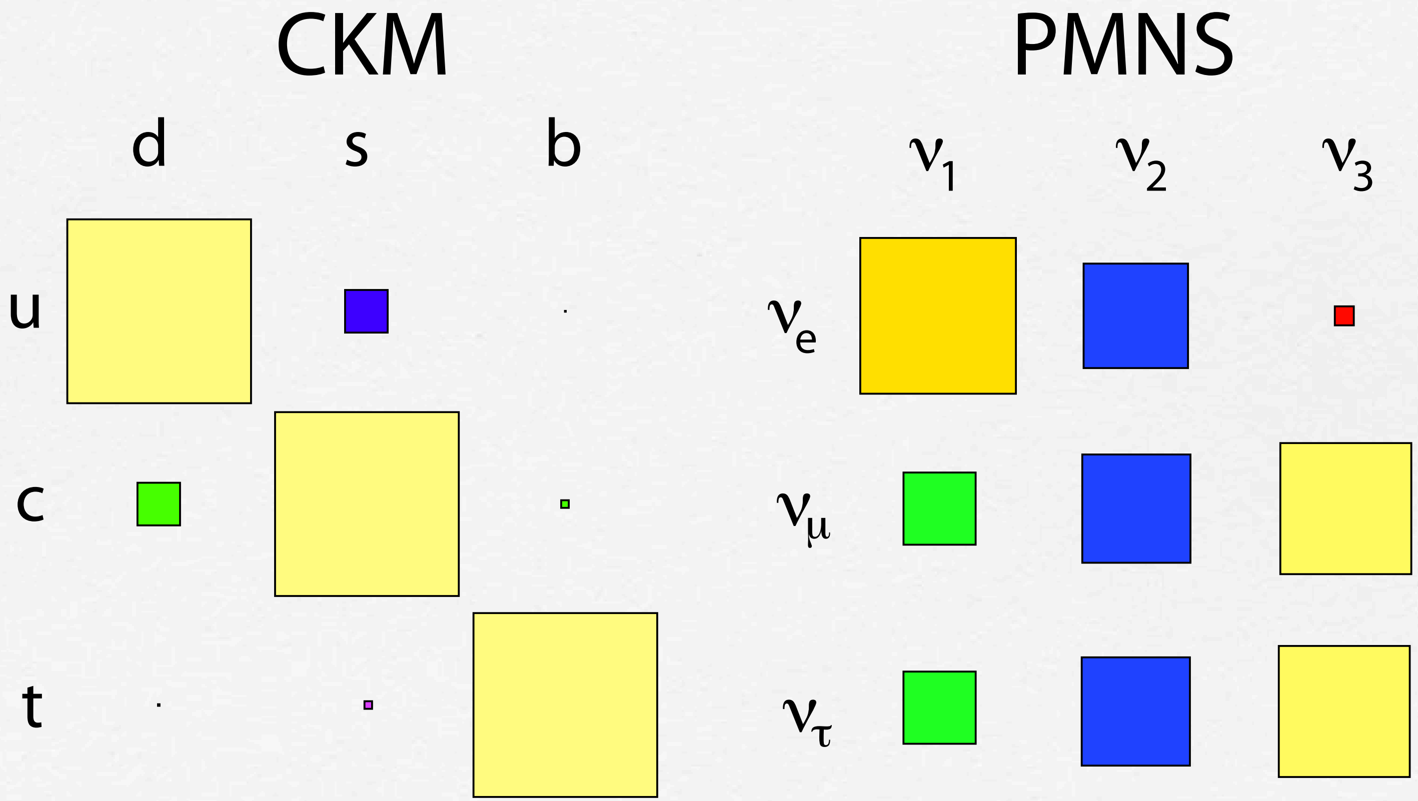


?

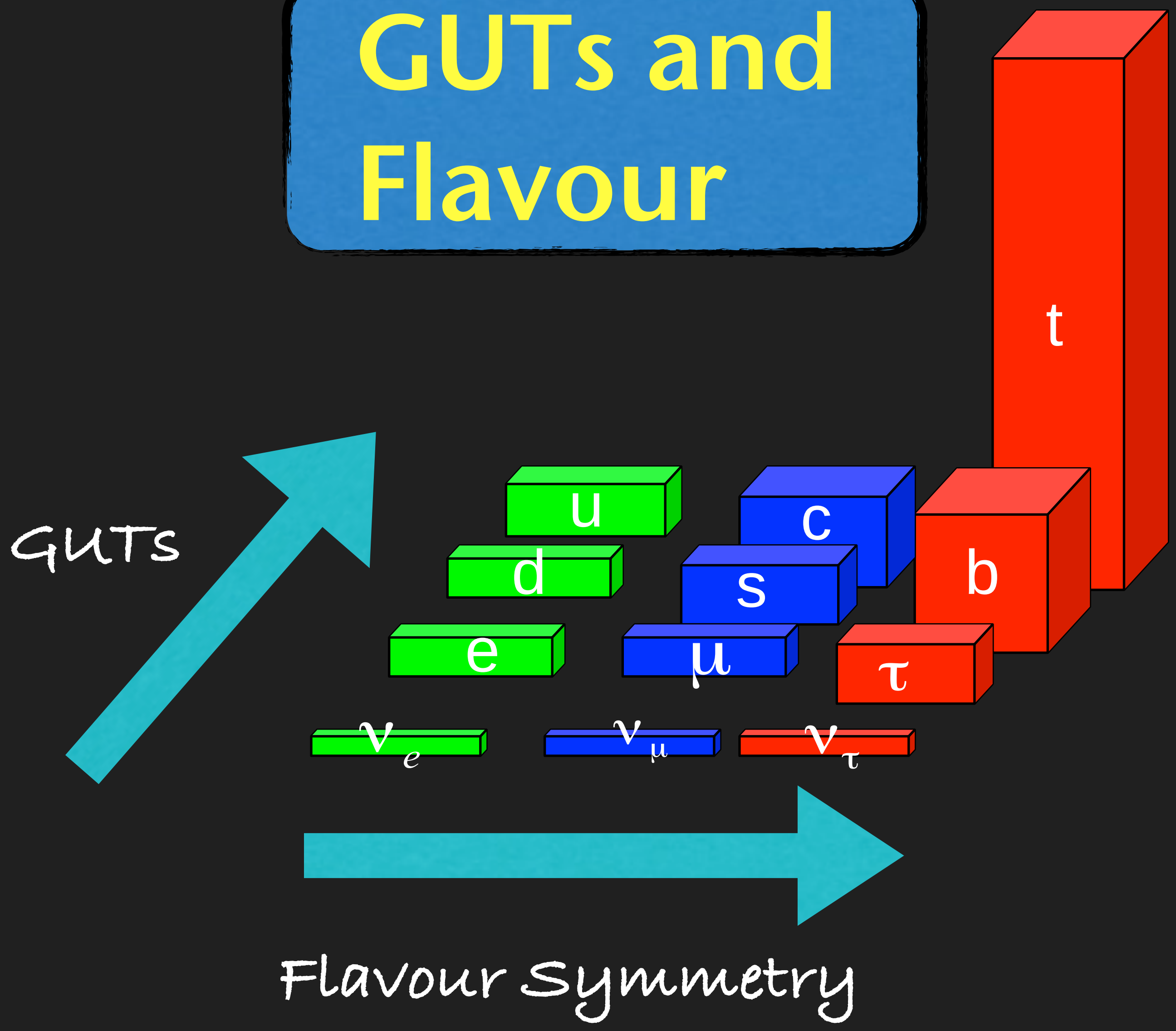
What is the origin of Quark and Lepton Masses?



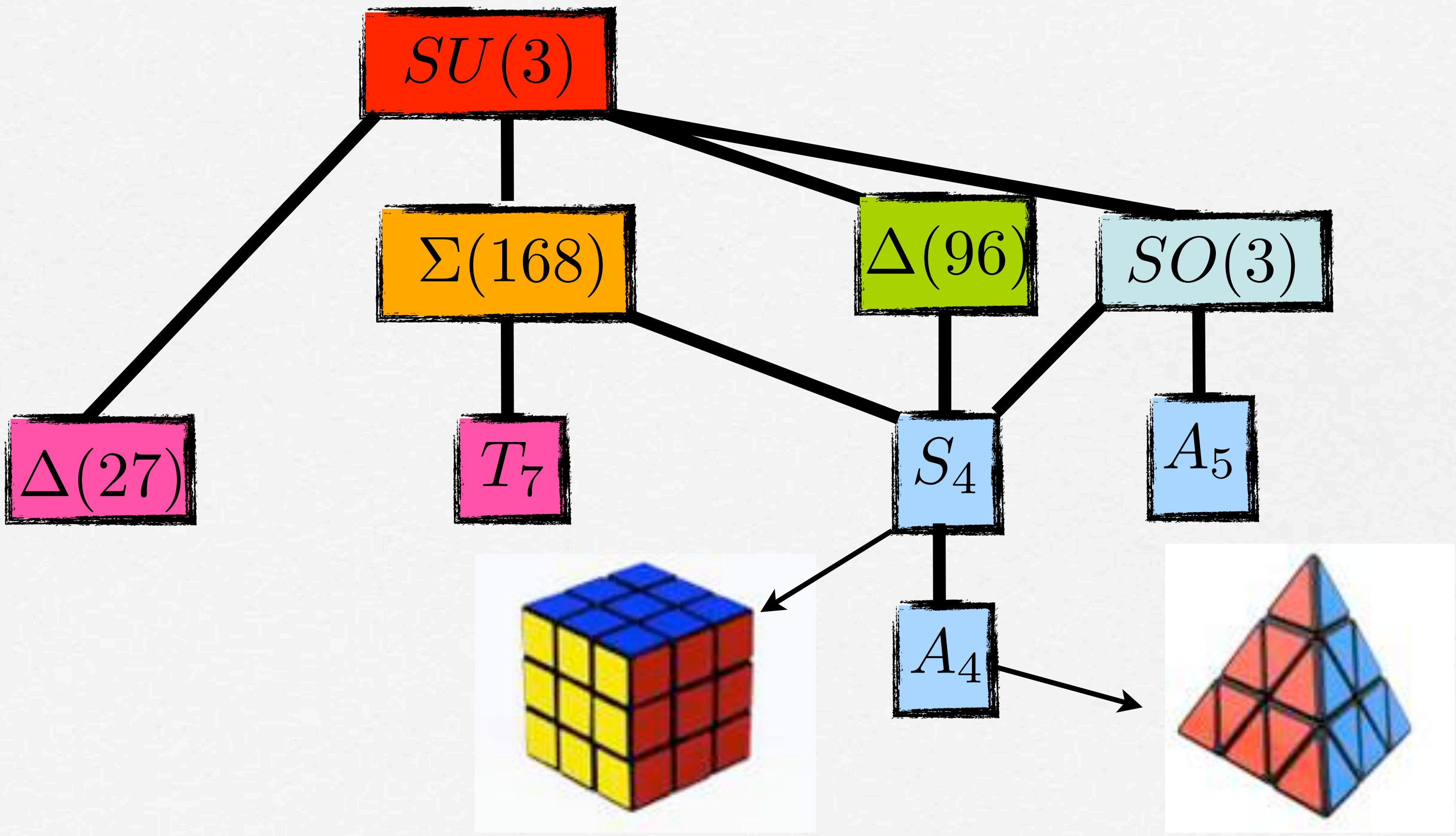
What is the origin of Quark and Lepton Mixing?



GUTs and Flavour



Flavour Symmetry



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S4xSU(5)xU(1)

$$m_\nu^{\rm eff} \approx \frac{y_D^2 v_u^2}{\lambda^4 M}\left[\begin{pmatrix} b^\nu + c^\nu - a^\nu & a^\nu & a^\nu \\ a^\nu & b^\nu & c^\nu \\ a^\nu & c^\nu & b^\nu \end{pmatrix} e^{-i\theta_A} + \begin{pmatrix} 0 & 0 & d^\nu \\ 0 & d^\nu & 0 \\ d^\nu & 0 & 0 \end{pmatrix} \lambda\, e^{i(\theta_D - 2\theta_A)}\right]$$

	Matter fields				Higgs fields			Flavon fields								
	T_3	T	F	ν^c	H_5	$H_{\bar{5}}$	$H_{\overline{45}}$	ϕ_2^u	$\tilde{\phi}_2^u$	ϕ_3^d	$\tilde{\phi}_3^d$	ϕ_2^d	$\phi_{3'}^\nu$	ϕ_2^ν	ϕ_1^ν	η
$SU(5)$	**10**	**10**	$\bar{\mathbf{5}}$	**1**	**5**	$\bar{\mathbf{5}}$	$\overline{\mathbf{45}}$	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
S_4	**1**	**2**	**3**	**3**	**1**	**1**	**1**	**2**	**2**	**3**	**3**	**2**	$\mathbf{3'}$	**2**	**1**	**1**
$U(1)$	0	5	4	−4	0	0	1	−10	0	−4	−11	1	8	8	8	7

Yukawa couplings

$\lambda \approx 0.22$

$$Y^u = \begin{pmatrix} y_1^u\lambda^8 & 0 & 0 \\ 0 & y_2^u\lambda^4 & 0 \\ 0 & 0 & y_3^u \end{pmatrix},\qquad \frac{A^u}{A_0} = \begin{pmatrix} a_1^u\lambda^8 & 0 & 0 \\ 0 & a_2^u\lambda^4 & 0 \\ 0 & 0 & a_3^u \end{pmatrix},$$

Soft SUSY breaking trilinears

$$Y^d = \begin{pmatrix} 0 & y_3^d\lambda^5 & -y_3^d\lambda^5 \\ -y_3^d\lambda^5 & y_1^d\lambda^4 & (y_3^d - yd_1)\lambda^4 \\ 0 & 0 & y_2^d\lambda^2 \end{pmatrix},\qquad \frac{A^d}{A_0} = \begin{pmatrix} 0 & a_3^d\lambda^5 & -a_3^d\lambda^5 \\ -a_3^d\lambda^5 & a_1^d\lambda^4 & (a_3^d - a_1^d)\lambda^4 \\ 0 & 0 & a_2^d\lambda^2 \end{pmatrix}$$

$$Y^e = \begin{pmatrix} 0 & -y_3^e\lambda^5 & 0 \\ y_3^e\lambda^5 & -3y_1^e\lambda^4 & 0 \\ -y_3^e\lambda^5 & (3y_1^e + y_3^e)\lambda^4 & y_2^e\lambda^2 \end{pmatrix},\qquad \frac{A^e}{A_0} = \begin{pmatrix} 0 & -a_3^e\lambda^5 & 0 \\ a_3^e\lambda^5 & -3a_1^e\lambda^4 & 0 \\ -a_3^e\lambda^5 & (3a_1^e + a_3^e)\lambda^4 & a_2^e\lambda^2 \end{pmatrix},$$

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Mass insertion parameters

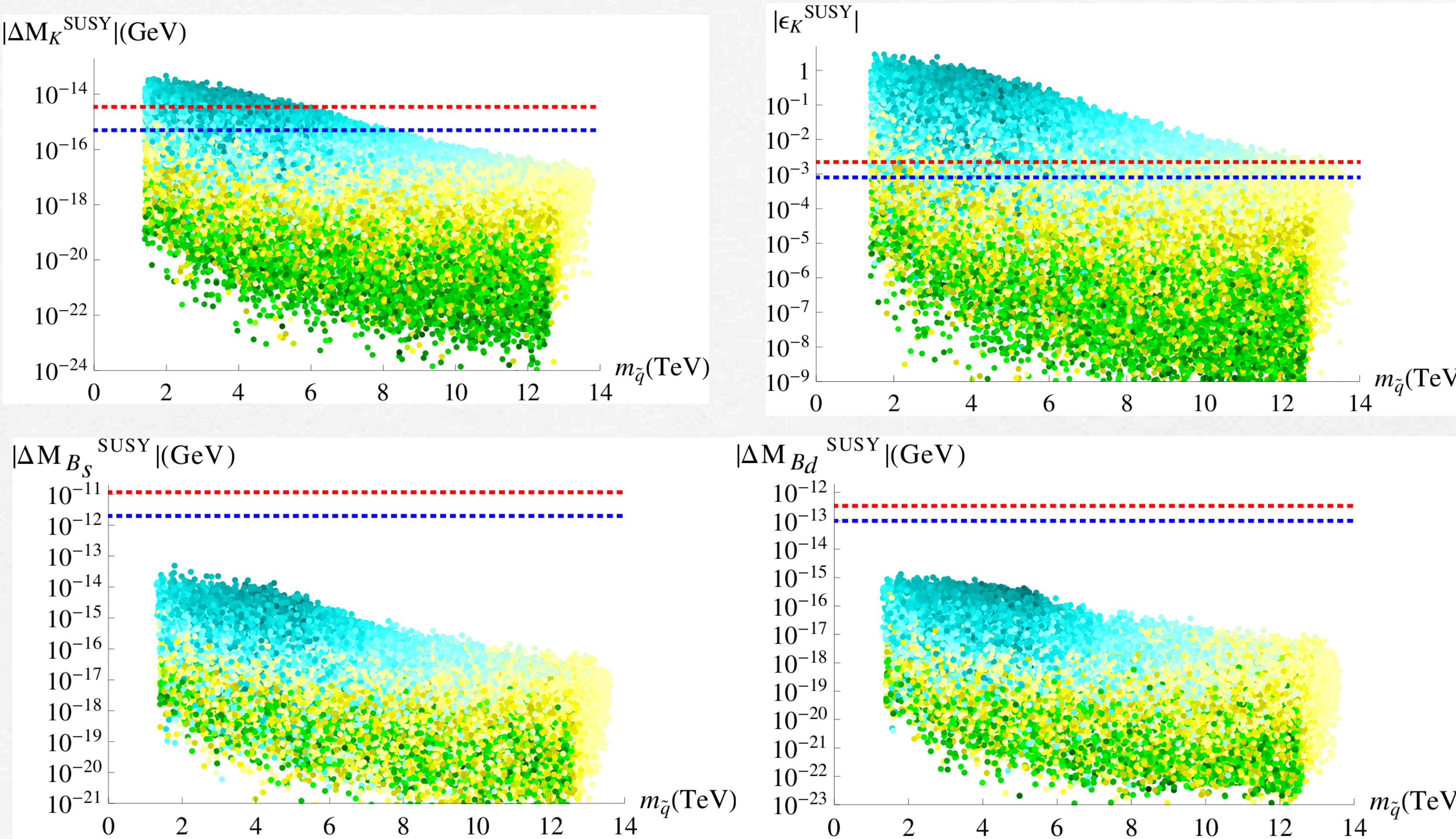
Closely resemble Minimal Flavour Violation $\lambda \approx 0.22$

$$\delta^u_{LL} \sim \begin{pmatrix} 1 & \lambda^4 & \lambda^6 \\ \cdot & 1 & \lambda^5 \\ \cdot & \cdot & 1 \end{pmatrix}, \quad \delta^u_{RR} \sim \begin{pmatrix} 1 & \lambda^4 & \lambda^6 \\ \cdot & 1 & \lambda^5 \\ \cdot & \cdot & 1 \end{pmatrix}, \quad \delta^u_{LR} \sim \begin{pmatrix} \lambda^8 & 0 & \lambda^7 \\ 0 & \lambda^4 & \lambda^6 \\ 0 & \lambda^7 & 1 \end{pmatrix},$$

$$\delta^d_{LL} \sim \begin{pmatrix} 1 & \lambda^3 & \lambda^4 \\ \cdot & 1 & \lambda^2 \\ \cdot & \cdot & 1 \end{pmatrix}, \quad \delta^d_{RR} \sim \begin{pmatrix} 1 & \lambda^4 & \lambda^4 \\ \cdot & 1 & \lambda^4 \\ \cdot & \cdot & 1 \end{pmatrix}, \quad \delta^d_{LR} \sim \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^5 \\ \lambda^5 & \lambda^4 & \lambda^4 \\ \lambda^6 & \lambda^6 & \lambda^2 \end{pmatrix},$$

$$\delta^e_{LL} \sim \begin{pmatrix} 1 & \lambda^4 & \lambda^4 \\ \cdot & 1 & \lambda^4 \\ \cdot & \cdot & 1 \end{pmatrix}, \quad \delta^e_{RR} \sim \begin{pmatrix} 1 & \lambda^3 & \lambda^4 \\ \cdot & 1 & \lambda^2 \\ \cdot & \cdot & 1 \end{pmatrix}, \quad \delta^e_{LR} \sim \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^6 \\ \lambda^5 & \lambda^4 & \lambda^6 \\ \lambda^5 & \lambda^4 & \lambda^2 \end{pmatrix}.$$

Poster by Maria Dimou



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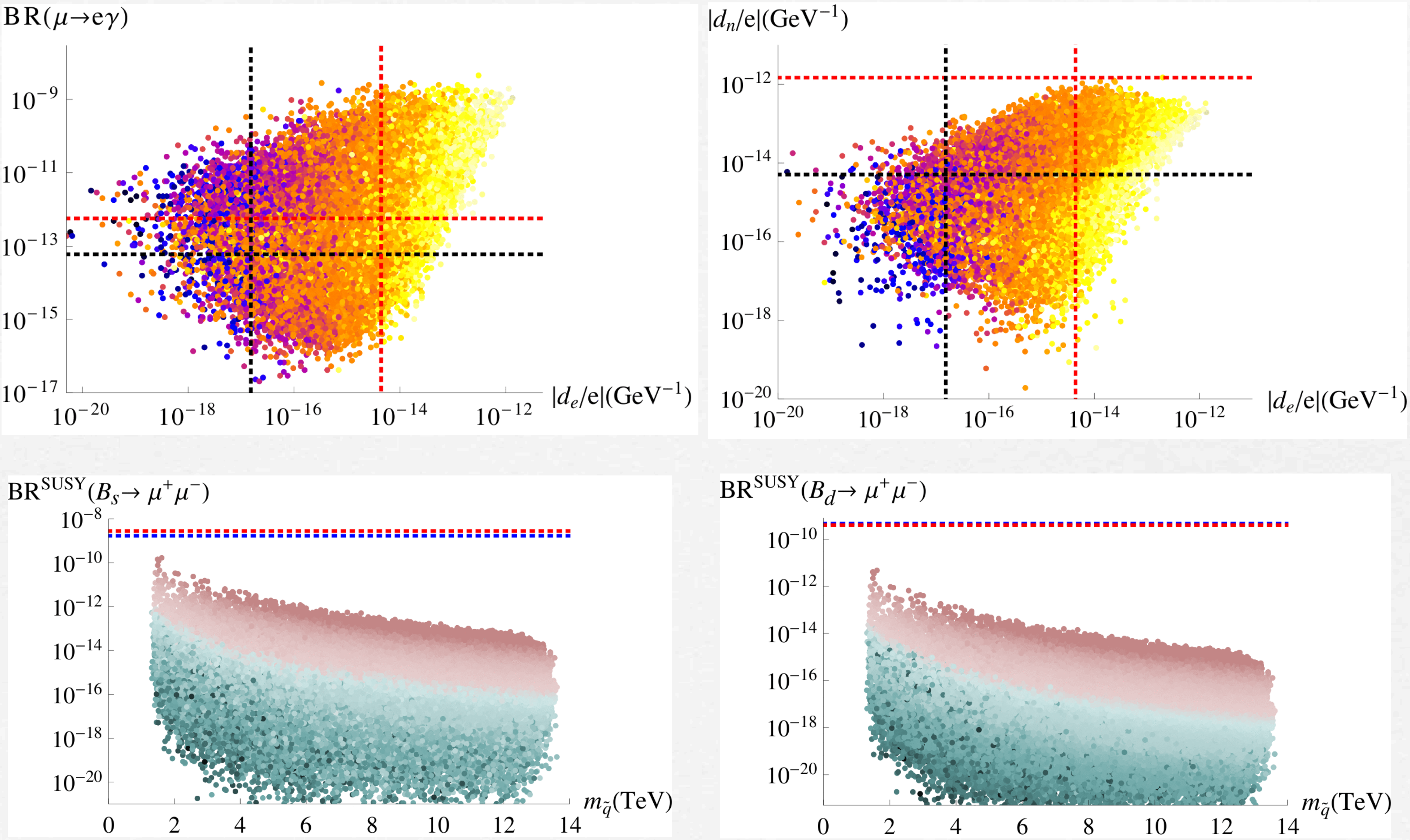

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Conclusion

- The Standard Model is highly successful but leaves three questions: nu mass, unification, flavour
- Nu mass motivates RH neutrinos
- SUSY facilitates unification: SU(5), SO(10), E_6
- E_6SSM allows seesaw, predicts singlet+extra matter
- We discussed E_6SSM from F-theory to the LHC
- It has all the ingredients for 750 GeV Diphotons
- Flavour problem necessitates flavour symmetry
- We discussed S_4xSU(5)xU(1) with flavour predictions