Grand Unification
at
Hadron Colliders

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Bajc, Preda, Zantedeschi

Grand Unification

Unification of SM forces + charge quantisation

↓

- Magnetic monopoles
- Proton decay

SO(10) GUT, against decades long prejudice → oasis ~ TEV

Preda, GS, Zantedeschi '22

Minimal SU(5)

Georgi, Glashow '74

$$24_V = 8_C + 3_W + 1 + (3_C, 2_W) + (\bar{3}_C, 2_W)$$

SM gauge bosons   X,Y gauge bosons

$\bar{5}_F$ 10_F 24_H 5_H

Fermions   Higgs scalars

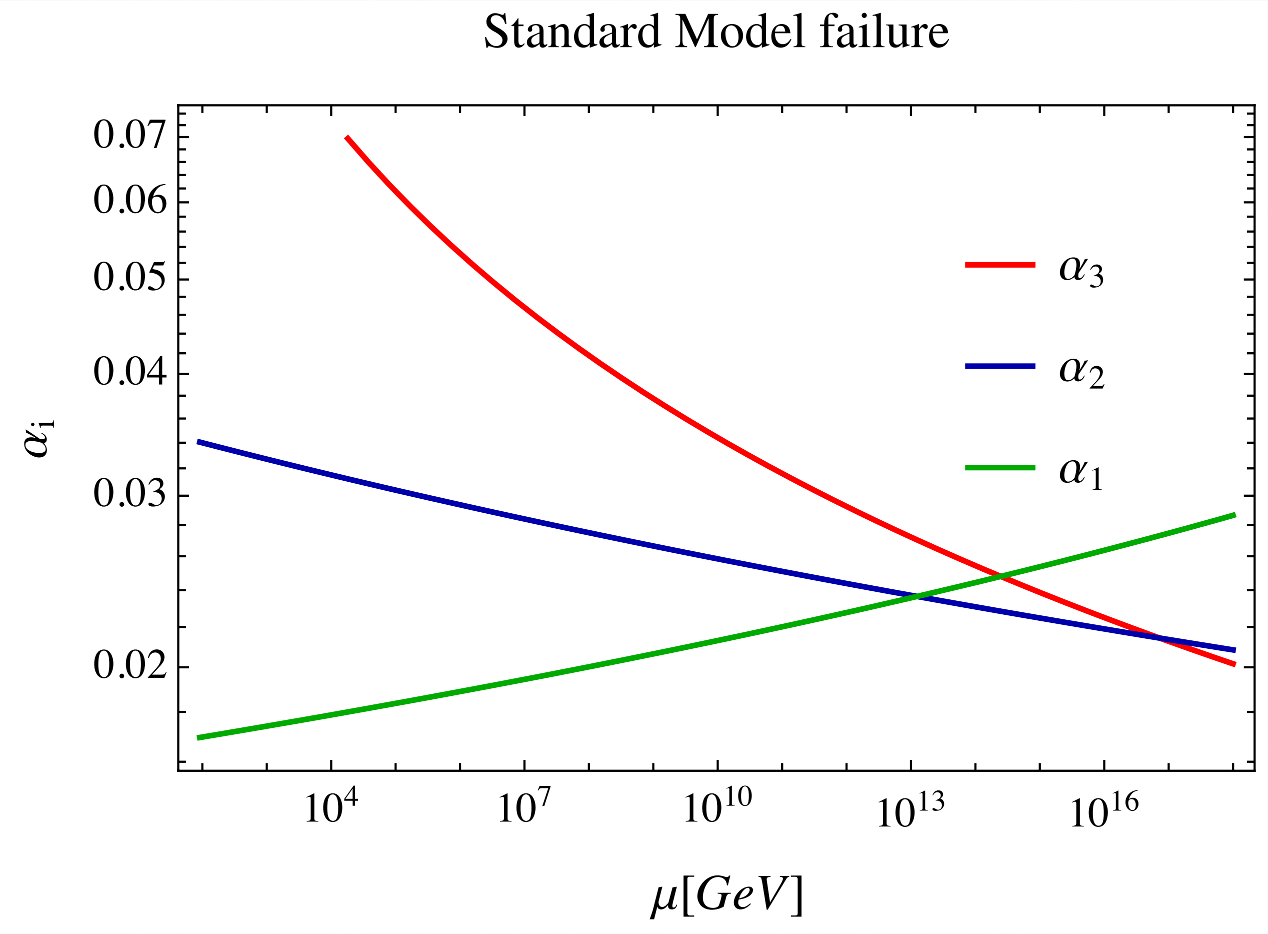
Double failure:

Gauge coupling do not unify   Neutrino massless

U1 hits SU2 too soon   No RH neutrino

Unification of gauge couplings

Low energies = SM particles



No unification:
U1 coupling hits SU2 too early

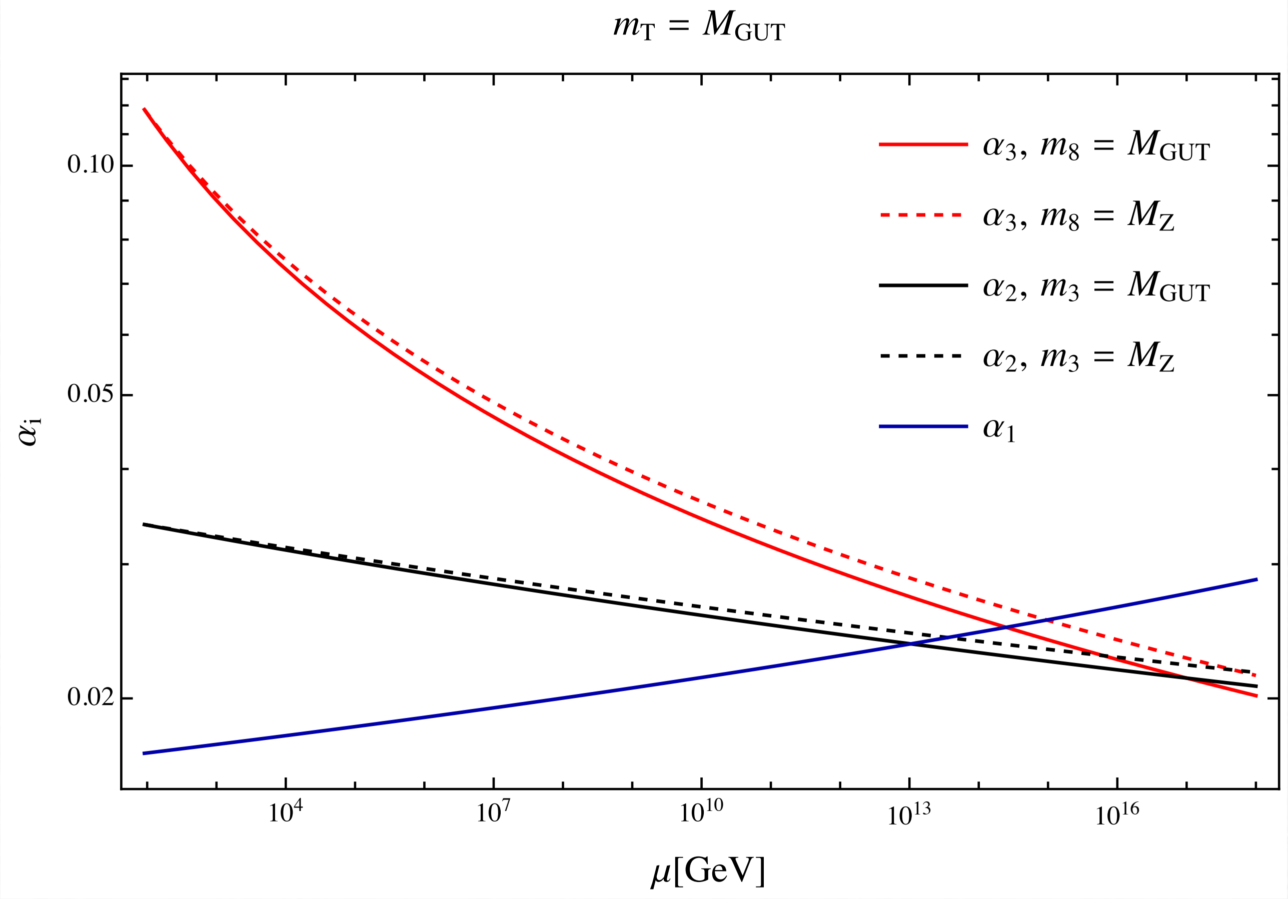
$\tau_p \gtrsim 10^{34}\, yr \quad \Rightarrow \quad M_G \gtrsim 10^{15}\, GeV$

Either U1 or SU2 must be slowed down

Threshold effects

Eaten by X,Y gauge bosons

$$24_H = 8_C + 3_W + 1 + (3_C, 2_W) + (\bar{3}_C, 2_W)$$



Heavy:
p decay

$$5_H = 2_W + 1 + (3_C, 1_W)$$

Problem remains

SU2 must be slowed down

↓

There can be no desert in SU(5)

Saving SU(5)

Dorsner, Fileviez Perez '05

- Add 15_H

$$15_H = (3_W, 1_C, Y = 2) + \ldots$$

Type II seesaw,
Light particles

- Add 24_F

Bajc, GS '06

$$24_F = (3_W, 1_C, Y = 0) + (1_W, 1_C, Y = 0) + \ldots$$

Triplet fermion:
Type III seesaw

Singlet fermion:
type I seesaw

Unification → 3F and 3H @ TeV

Minimal SO(10)

Georgi '74

Fritzsch, Minkowski '74

$$\Psi_{16} = \begin{pmatrix} u \\ u \\ u \\ \nu \\ d \\ d \\ d \\ e \\ e^c \\ d^c \\ d^c \\ d^c \\ \nu^c \\ u^c \\ u^c \\ u^c \end{pmatrix}$$

Generation unified → (heavy) RH neutrino

↓

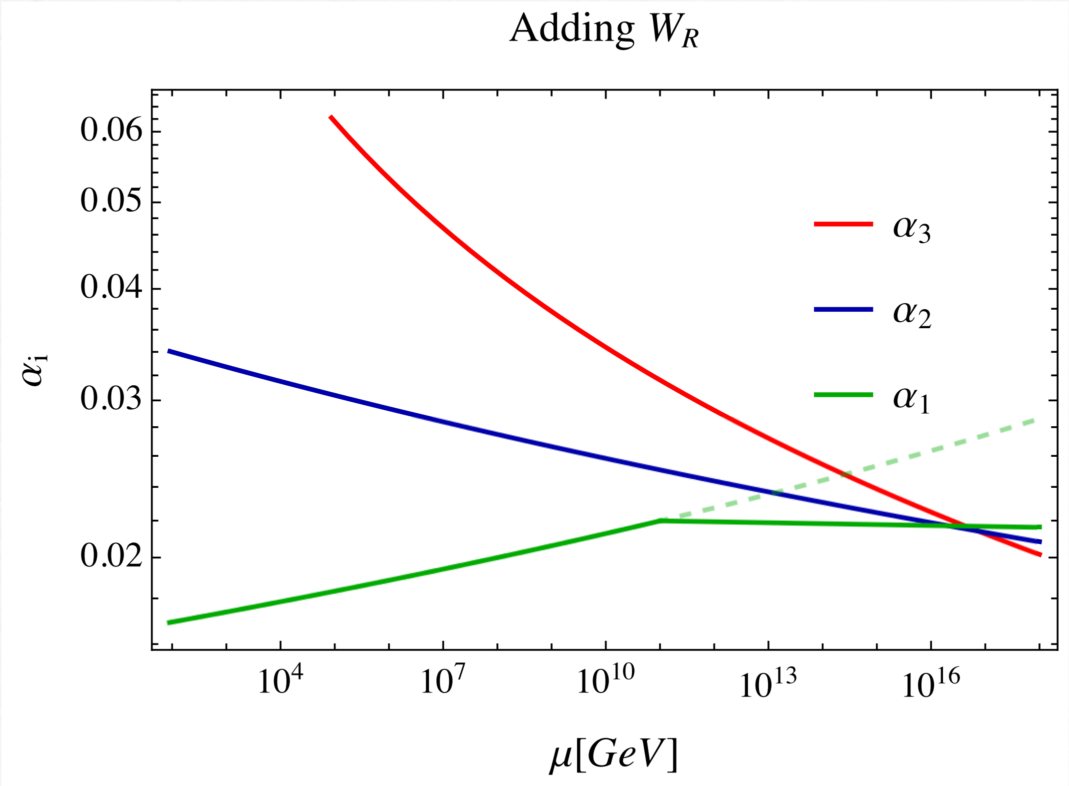
small neutrino mass through seesaw mechanism

neutrino is light,
since N is heavy

Intermediate symmetry in SO(10)

Maximal subgroup: $SO(6) \times SO(4) = SU(4)_c \times SU(2)_L \times SU(2)_R$

PS 4 colors LR symmetry



↓

U1 embedded in non-Abelian

↓ $M_{LR} \simeq 10^{11}\, GeV$

slowed down

Del Aguila, Ibanez '80

Rizzo, GS '80

↓

desert all the way to intermediate scale

Minimal SO(10) theory

Higgs sector

45H = adjoint   16H = spinor   10H = vector

$\langle 45H \rangle = M_{GUT}$ GUT breaking

$\langle 16H \rangle = M_I$ B-L breaking

$\langle 10H \rangle = M_W$ SM breaking

$\mathcal{L}_Y = Y\, 16_F\, 10_H\, 16_F$

<10H> = PS singlet

$m_d = m_e\,; \quad m_u = m_D$ Neutrino Dirac mass

Needs higher dimensional operators

Minimal SO(10): revisited

Preda, GS, Zantedeschi '22

Seesaw mechanism

nu - N mass matrix

$$\begin{matrix} \nu \\ N \end{matrix} \begin{pmatrix} 0 & M_D^T \\ M_D & M_N \end{pmatrix}$$

➔

Majorana neutrino

$$M_\nu = M_D^T \frac{1}{M_N} M_D$$

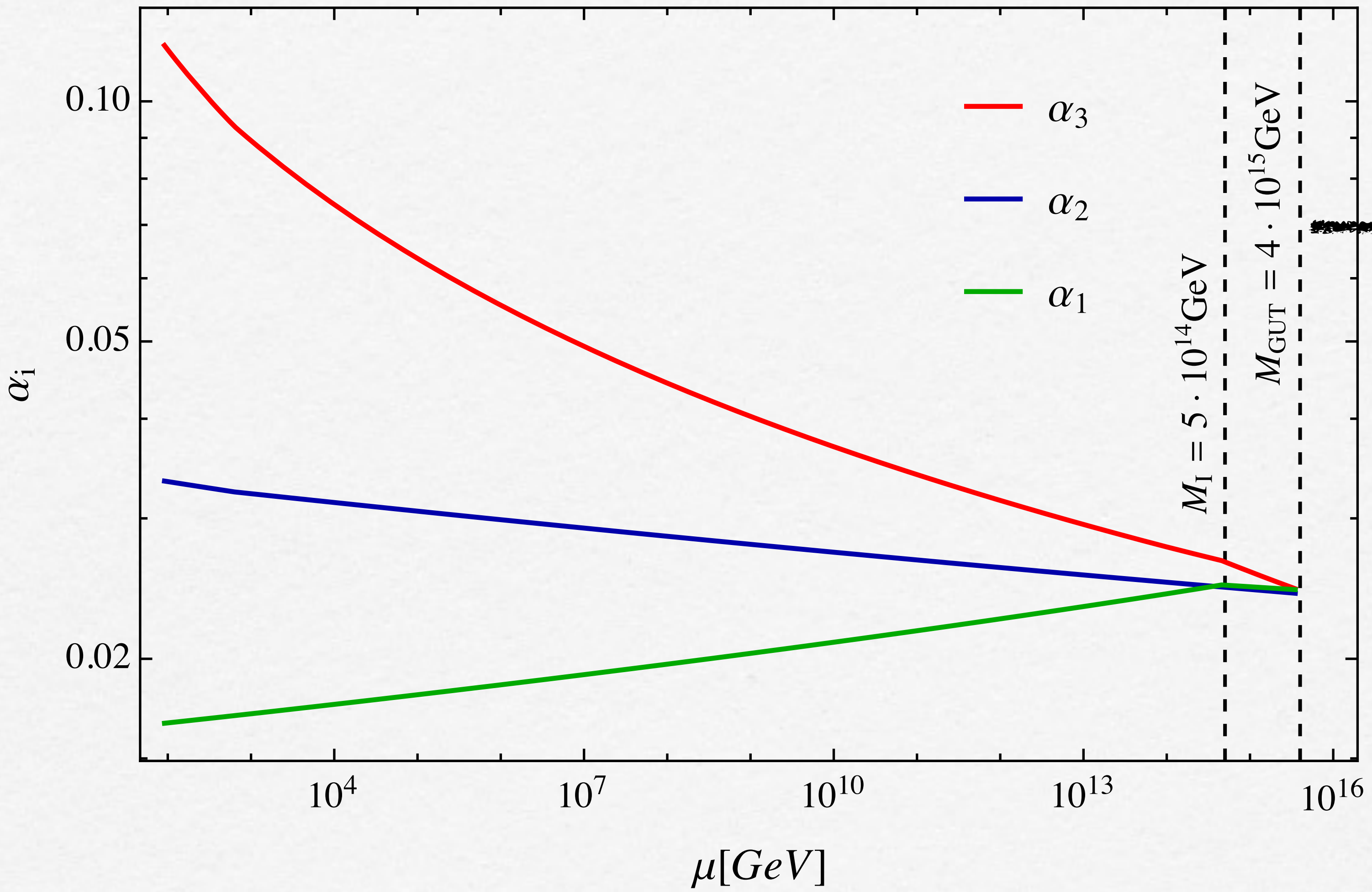
$$M_N \lesssim M_I$$

3rd generation: $m_D \simeq m_t$

$m_\nu \lesssim 1 eV$ ➔ $M_I \gtrsim 10^{13} GeV$

Needs light scalars to slow down SU2: 3_W (scalar W, Z) $(2_W, 3_C)$ (squark)

To adjust SU3: 8_C scalar gluon



$$\tau_p \simeq 10^{34}\, yr$$

$$m_3 = m_8 = m_{sq} = TeV$$

They must lie below 10 TeV

Connection with W-mass

GS, Zantedeschi '22

3_W Weak triplet, $Y = 0$ → $\mu \, \Phi_{SM}^\dagger \, 3_W \, \Phi_{SM}$ → $\langle 3_W \rangle \simeq \mu \left(\frac{M_W}{m_3} \right)^2$

Buras, Ellis, Gaillard, Nanopoulos '78

...

→ W-mass deviation,
Z intact → $\langle 3_W \rangle \ll M_W$

CDF '22

$M_W \neq M_W^{SM}$ → $\langle 3_W \rangle \simeq 5 \, GeV$

Talk by Zantedeschi

Summary

- Minimal realistic SU(5): oasis ~ TeV, in a sense expected

- SO(10) theory: decades of prejudice of a desert up to a huge M_I

  ➜ Oasis ~ TeV predicted from unification constraints

Among others, a real weak triplet scalar - tadpole vev ➜ Modifies naturally W-mass

CDF result: $\langle 3_W \rangle \simeq 5\, GeV$

Low energy effective theory remarkable predictive

Talk by Zantedeschi

Thank you

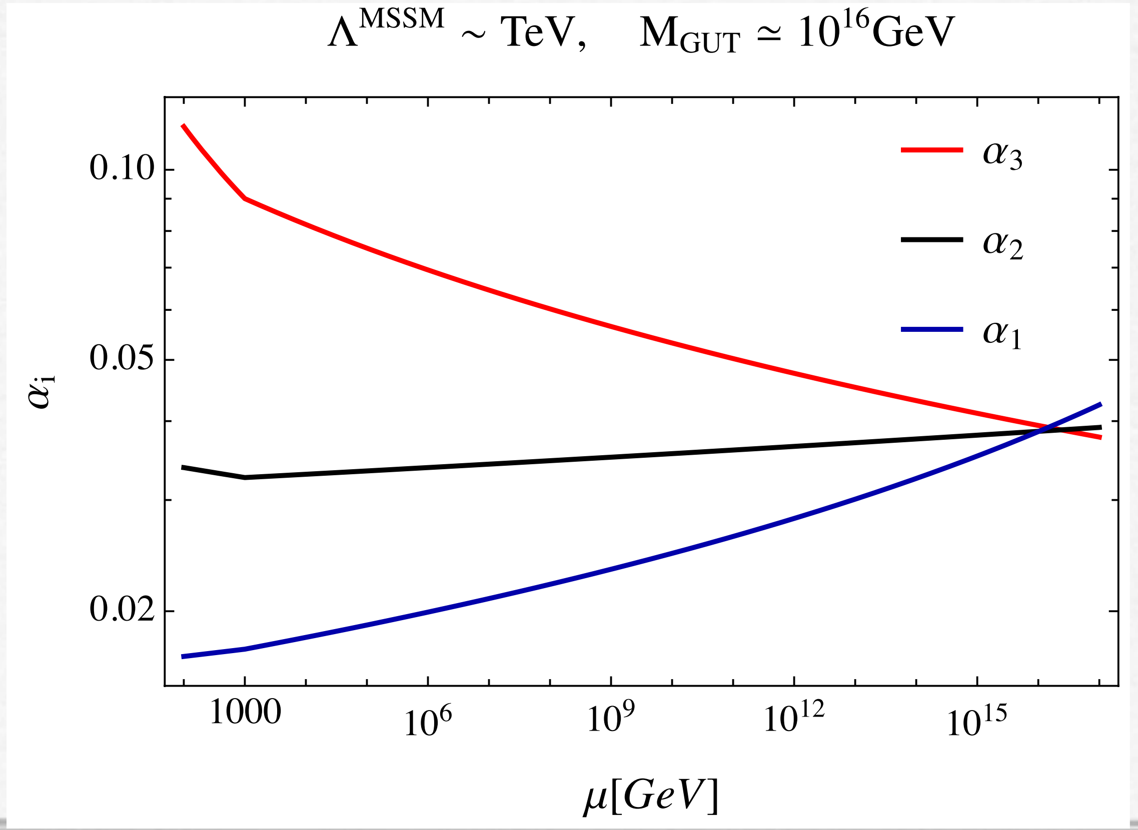
Low energy supersymmetry

Supersymmetry: particle p → sparticle $\tilde{p}$

$$m_h^2 = m_0^2 + \frac{y_t}{16\pi^2}\Lambda^2 + m_t^2 + ...$$ SM Higgs correction

$$-\frac{y_t}{16\pi^2}\Lambda^2 - m_{\tilde{t}}^2 + ...$$ SSM addition

$m_{\tilde{p}} \simeq TeV$



Ibanez, Ross '81

Dimpopoulos et al '81

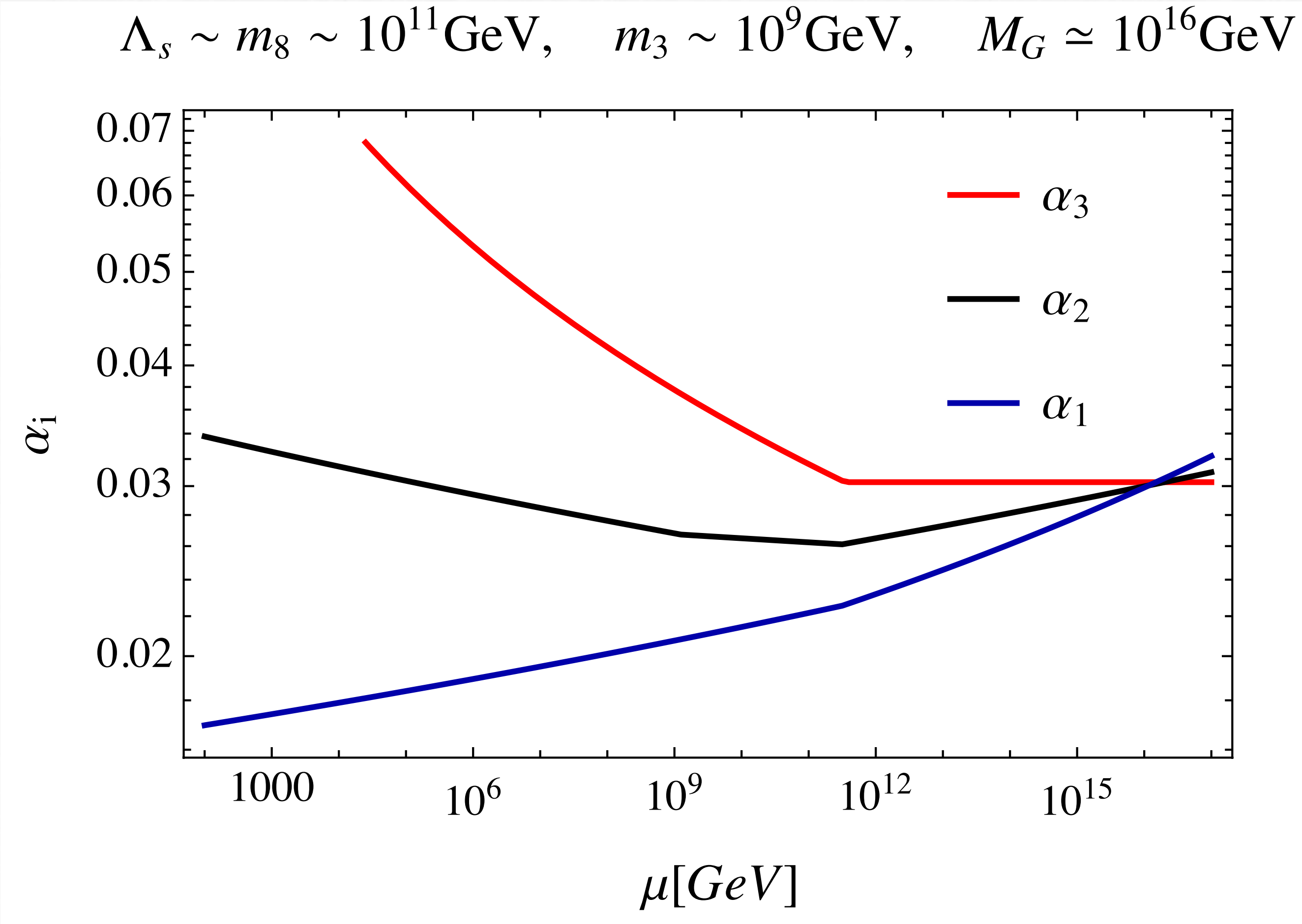
Einhorn, Jones '81

Marciano, GS '81

GS, Zantedeschi '22

Needs naturalness, otherwise:

$$\Lambda = \Lambda^{\rm MSSM}\left(\frac{M_{\rm GUT}^2}{m_3 m_8}\right)^{3/4}.$$



d=5 operators

example

$$\mathcal{L}_Y^{d=5} = 16_F\, 10_H\, \frac{\langle 45_H \rangle}{\Lambda}\, 16_F$$

Λ = cut-off

$$\Lambda \gtrsim 10\, M_{GUT}$$

And other terms ...

States

16_H

$4_C\,2_L\,2_R$	$4_C\,2_L\,1_R$	$3_c\,2_L\,2_R\,1_X$	$3_c\,2_L\,1_R\,1_X$	$3_c\,2_L\,1_Y$	5	$5'\,1_{Z'}$	$1_{Y'}$
$(4,2,1)$	$(4,2,0)$	$\left(3,2,1,+\frac{1}{6}\right)$	$\left(3,2,0,+\frac{1}{6}\right)$	$\left(3,2,+\frac{1}{6}\right)$	10	$(10,+1)$	$+\frac{1}{6}$
		$\left(1,2,1,-\frac{1}{2}\right)$	$\left(1,2,0,-\frac{1}{2}\right)$	$\left(1,2,-\frac{1}{2}\right)$	$\overline{5}$	$\left(\overline{5},-3\right)$	$-\frac{1}{2}$
$\left(\overline{4},1,2\right)$	$\left(\overline{4},1,+\frac{1}{2}\right)$	$\left(\overline{3},1,2,-\frac{1}{6}\right)$	$\left(\overline{3},1,+\frac{1}{2},-\frac{1}{6}\right)$	$\left(\overline{3},1,+\frac{1}{3}\right)$	$\overline{5}$	$(10,+1)$	$-\frac{2}{3}$
	$\left(\overline{4},1,-\frac{1}{2}\right)$		$\left(\overline{3},1,-\frac{1}{2},-\frac{1}{6}\right)$	$\left(\overline{3},1,-\frac{2}{3}\right)$	10	$\left(\overline{5},-3\right)$	$+\frac{1}{3}$
		$\left(1,1,2,+\frac{1}{2}\right)$	$\left(1,1,+\frac{1}{2},+\frac{1}{2}\right)$	$(1,1,+1)$	10	$(1,+5)$	0
			$\left(1,1,-\frac{1}{2},+\frac{1}{2}\right)$	$(1,1,0)$	1	$(10,+1)$	$+1$

45_H

$4_C\,2_L\,2_R$	$4_C\,2_L\,1_R$	$3_c\,2_L\,2_R\,1_X$	$3_c\,2_L\,1_R\,1_X$	$3_c\,2_L\,1_Y$	5	$5'\,1_{Z'}$	$1_{Y'}$
$(1,1,3)$	$(1,1,+1)$	$(1,1,3,0)$	$(1,1,+1,0)$	$(1,1,+1)$	10	$(10,-4)$	$+1$
	$(1,1,0)$		$(1,1,0,0)$	$(1,1,0)$	1	$(1,0)$	0
	$(1,1,-1)$		$(1,1,-1,0)$	$(1,1,-1)$	$\overline{10}$	$\left(\overline{10},+4\right)$	-1
$(1,3,1)$	$(1,3,0)$	$(1,3,1,0)$	$(1,3,0,0)$	$(1,3,0)$	24	$(24,0)$	0
$(6,2,2)$	$\left(6,2,+\frac{1}{2}\right)$	$\left(3,2,2,-\frac{1}{3}\right)$	$\left(3,2,+\frac{1}{2},-\frac{1}{3}\right)$	$\left(3,2,\frac{1}{6}\right)$	10	$(24,0)$	$-\frac{5}{6}$
	$\left(6,2,-\frac{1}{2}\right)$		$\left(3,2,-\frac{1}{2},-\frac{1}{3}\right)$	$\left(3,2,-\frac{5}{6}\right)$	24	$(10,-4)$	$+\frac{1}{6}$
		$\left(\overline{3},2,2,+\frac{1}{3}\right)$	$\left(\overline{3},2,+\frac{1}{2},+\frac{1}{3}\right)$	$\left(\overline{3},2,+\frac{5}{6}\right)$	24	$\left(\overline{10},+4\right)$	$-\frac{1}{6}$
			$\left(\overline{3},2,-\frac{1}{2},+\frac{1}{3}\right)$	$\left(\overline{3},2,-\frac{1}{6}\right)$	$\overline{10}$	$(24,0)$	$+\frac{5}{6}$
$(15,1,1)$	$(15,1,0)$	$(1,1,1,0)$	$(1,1,0,0)$	$(1,1,0)$	24	$(24,0)$	0
		$\left(3,1,1,+\frac{2}{3}\right)$	$\left(3,1,0,+\frac{2}{3}\right)$	$\left(3,1,+\frac{2}{3}\right)$	$\overline{10}$	$\left(\overline{10},+4\right)$	$+\frac{2}{3}$
		$\left(\overline{3},1,1,-\frac{2}{3}\right)$	$\left(\overline{3},1,0,-\frac{2}{3}\right)$	$\left(\overline{3},1,-\frac{2}{3}\right)$	10	$(10,-4)$	$-\frac{2}{3}$
		$(8,1,1,0)$	$(8,1,0,0)$	$(8,1,0)$	24	$(24,0)$	0

Large representations

Survival principle

del Agiola, Ibanez '81

Mohapatra, GS '82

Assume scalars masses: largest value consistent with symmetries

$$m_p = \lambda M \quad \rightarrow \quad m_p \simeq M$$

Fails completely in minimal SO10

Higgs sector

45H = adjoint   126H = spinor   10H = vector

M_I - arbitrary: TeV -> $\sim M_{GUT}$

Preda, GS, Zantedeschi '22