Grand Unification at LHC?

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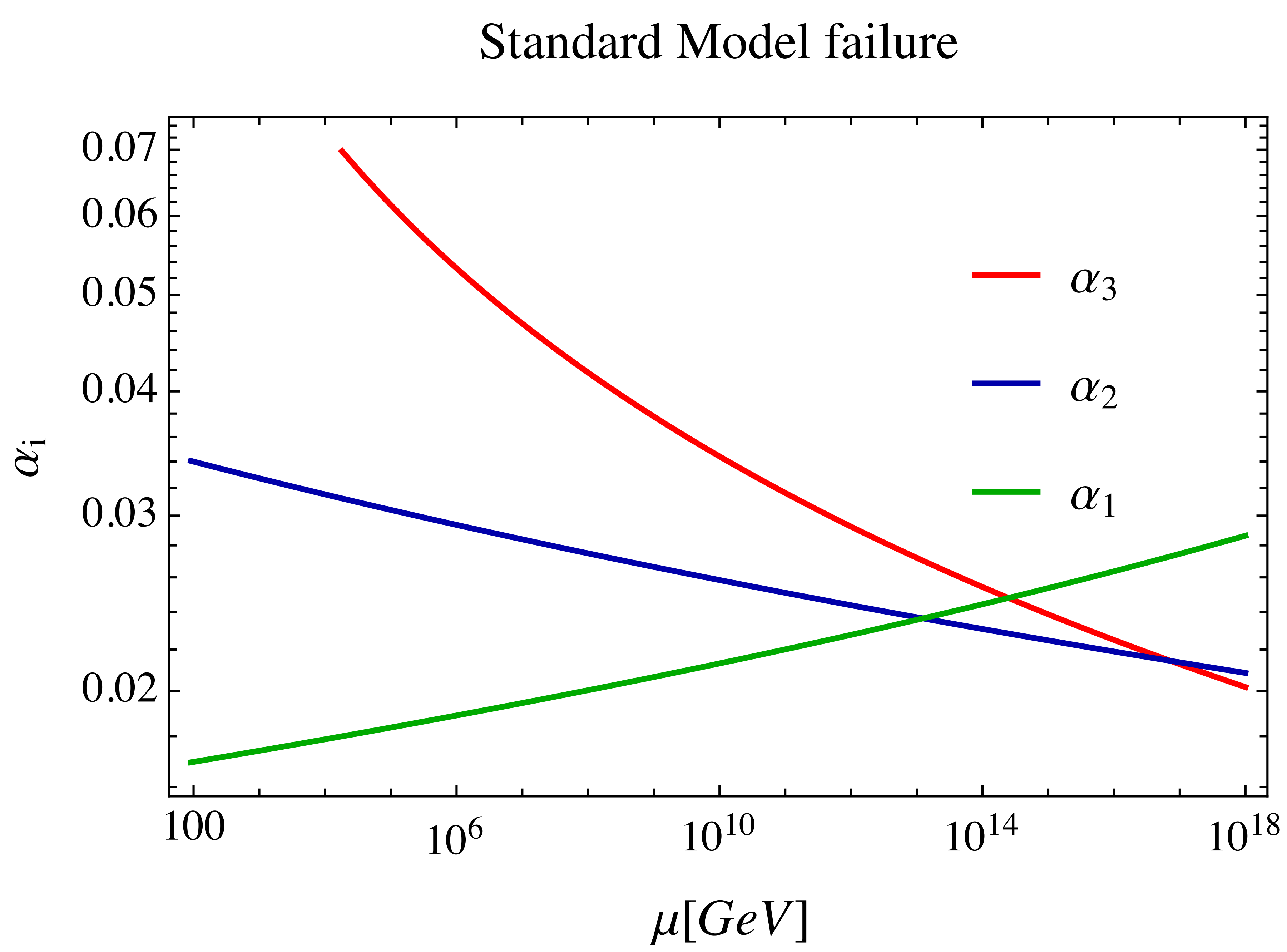
Grand unification is one of the most appealing candidates for physics beyond SM

- Charge quantization
- Proton decay
- Existence of magnetic monopoles
- Typical scales at around 10^{15}GeV $\longrightarrow$ Hopeless for low energy observer?

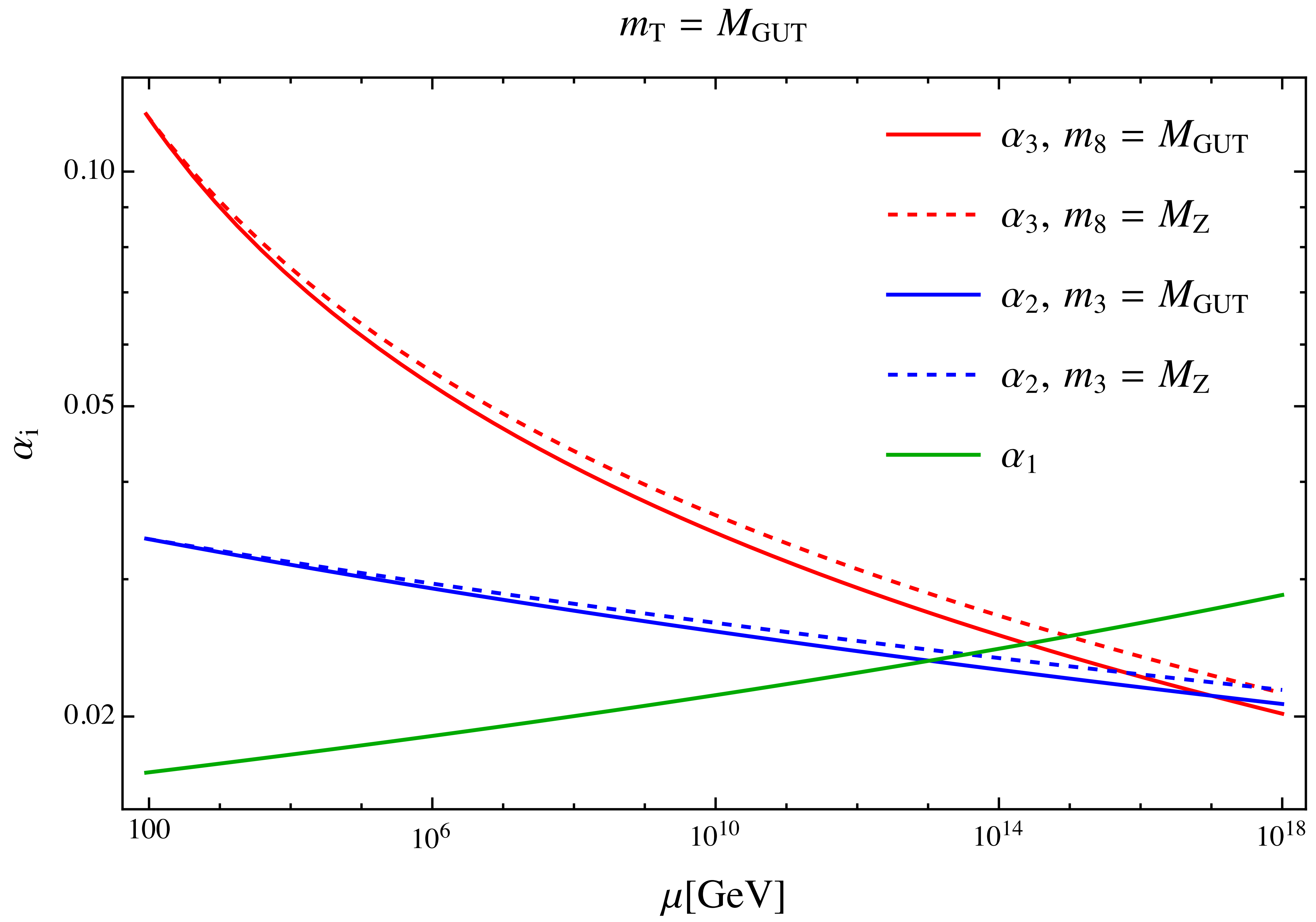
Georgi, Quinn, Weinberg 1974: Unification of gauge couplings in SM



$$\tau_p \gtrsim 10^{34}\text{yrs} \implies M_{GUT} \gtrsim 10^{15}\text{GeV}$$

However, new particle states can come to the rescue

An example: Minimal SU(5)



Georgi Glashow model is a natural candidate

$$5_H = \begin{pmatrix} T_C \\ \Phi_{SM} \end{pmatrix}, \quad 24_H = \begin{pmatrix} 8_C & X \\ \overline{X} & 3_W \end{pmatrix}$$

New massive states:
- Color triplet T_C of mass m_T
- Color octet of mass m_8
- Weak triplet of mass m_3

This states are not sufficient to ensure unification — also, neutrino is massless:

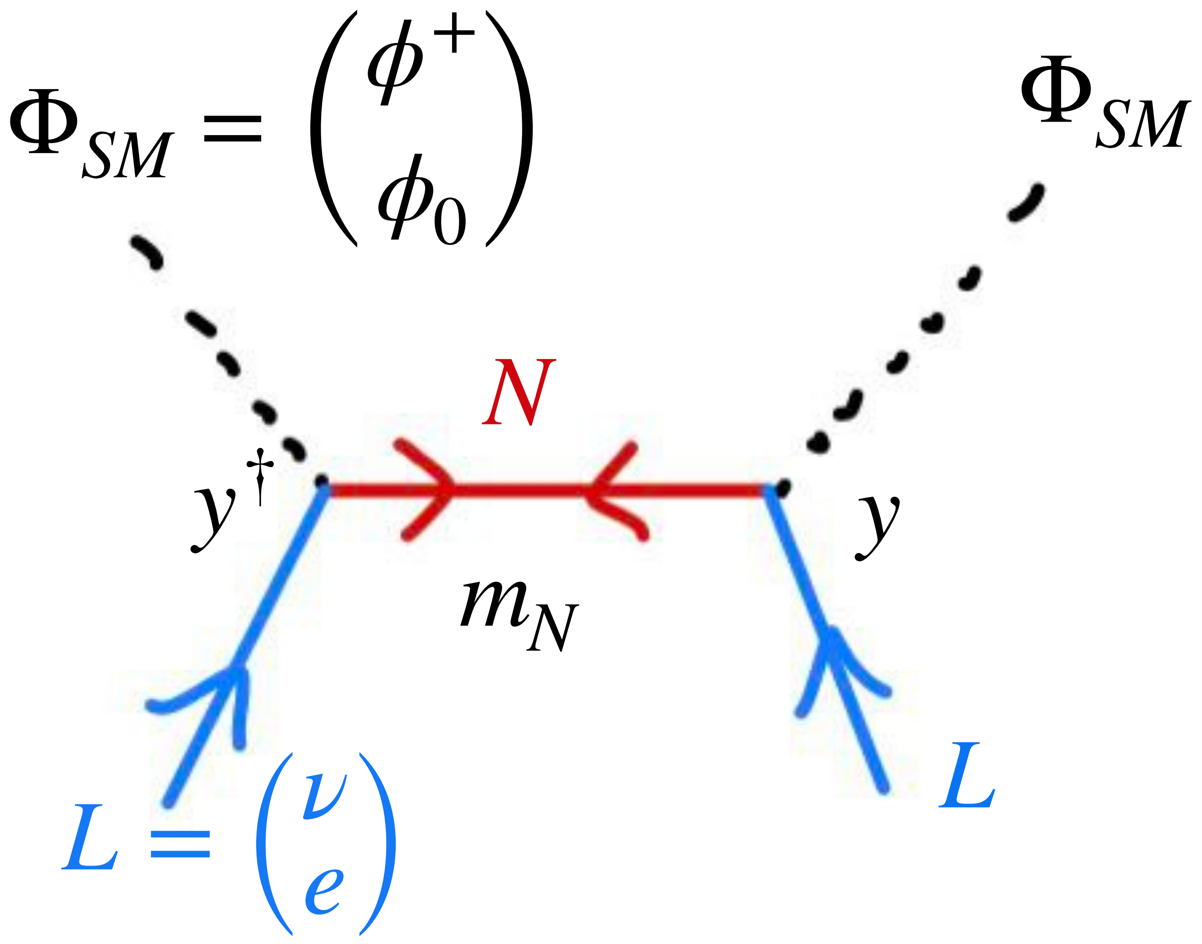
More is needed

T_C normally required heavy due to proton decay. See *Dvali '92* for the light case scenario.

How to address neutrino mass?

Seesaw mechanism:

Minkowski '77
Mohapatra, Senjanović '79
Yanagida '79



ν - N mass matrix

$$\begin{matrix} \nu \\ N \end{matrix} \begin{pmatrix} 0 & y^T v \\ y\, v & m_N \end{pmatrix} \longrightarrow$$

Majorana neutrino

$$m_\nu \simeq v^2 \left(y^T \frac{1}{m_N} y \right)$$

Example: Add heavy right handed neutrino to minimal $SU(5)$

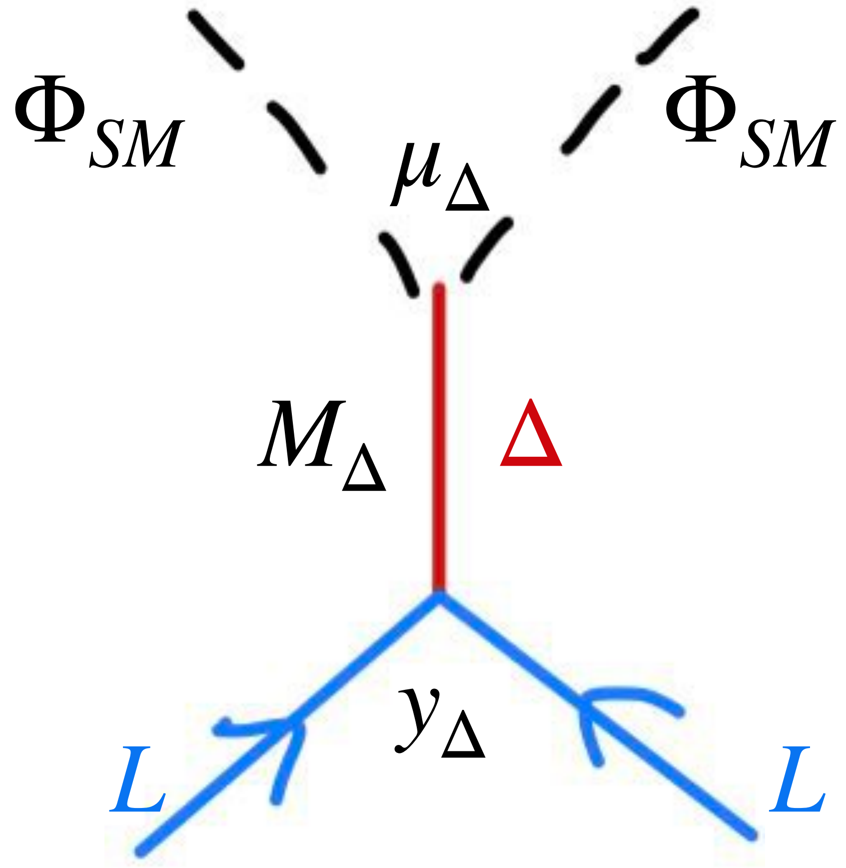
- Does not suffice to save the model as unification still fails
- It does not come with any dynamics associated with it

More is desirable

Dynamical realisations of seesaw

Minimal SU(5) + 15_H ***Doršner, Fileviez Perez '05***

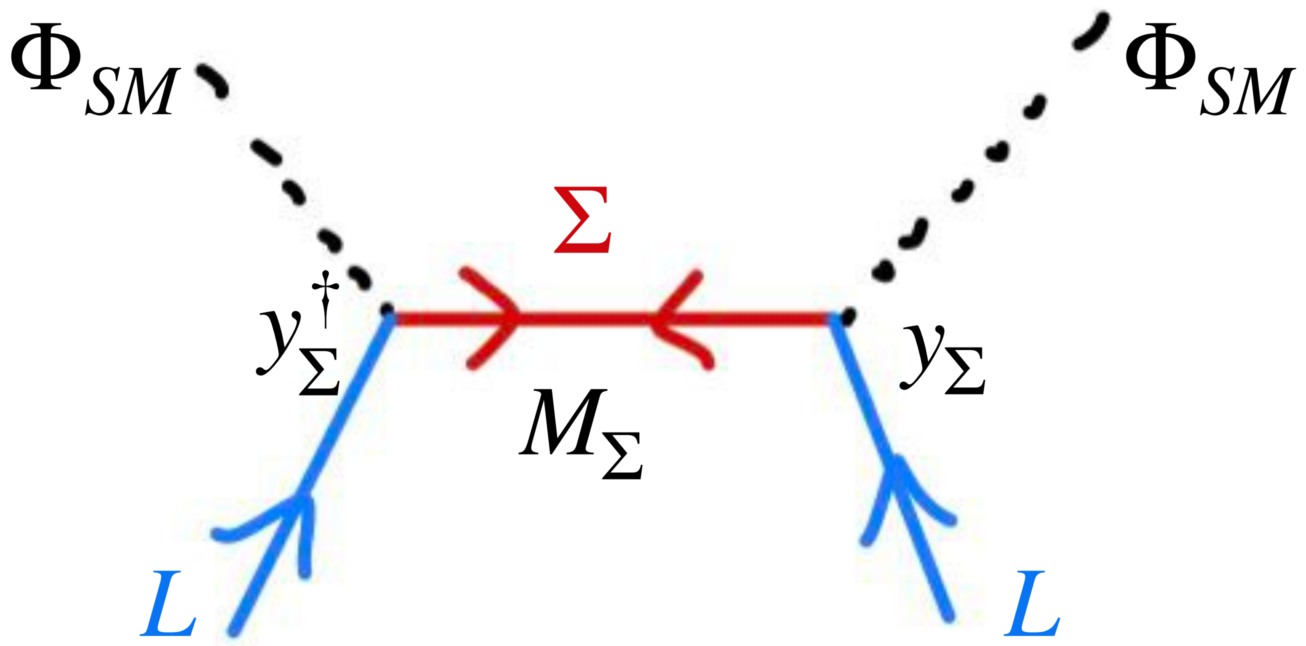
15_H contains a scalar weak triplet Δ with Y=2



$$m_\nu \simeq y_\Delta \mu_\Delta \frac{v^2}{M_\Delta^2}$$

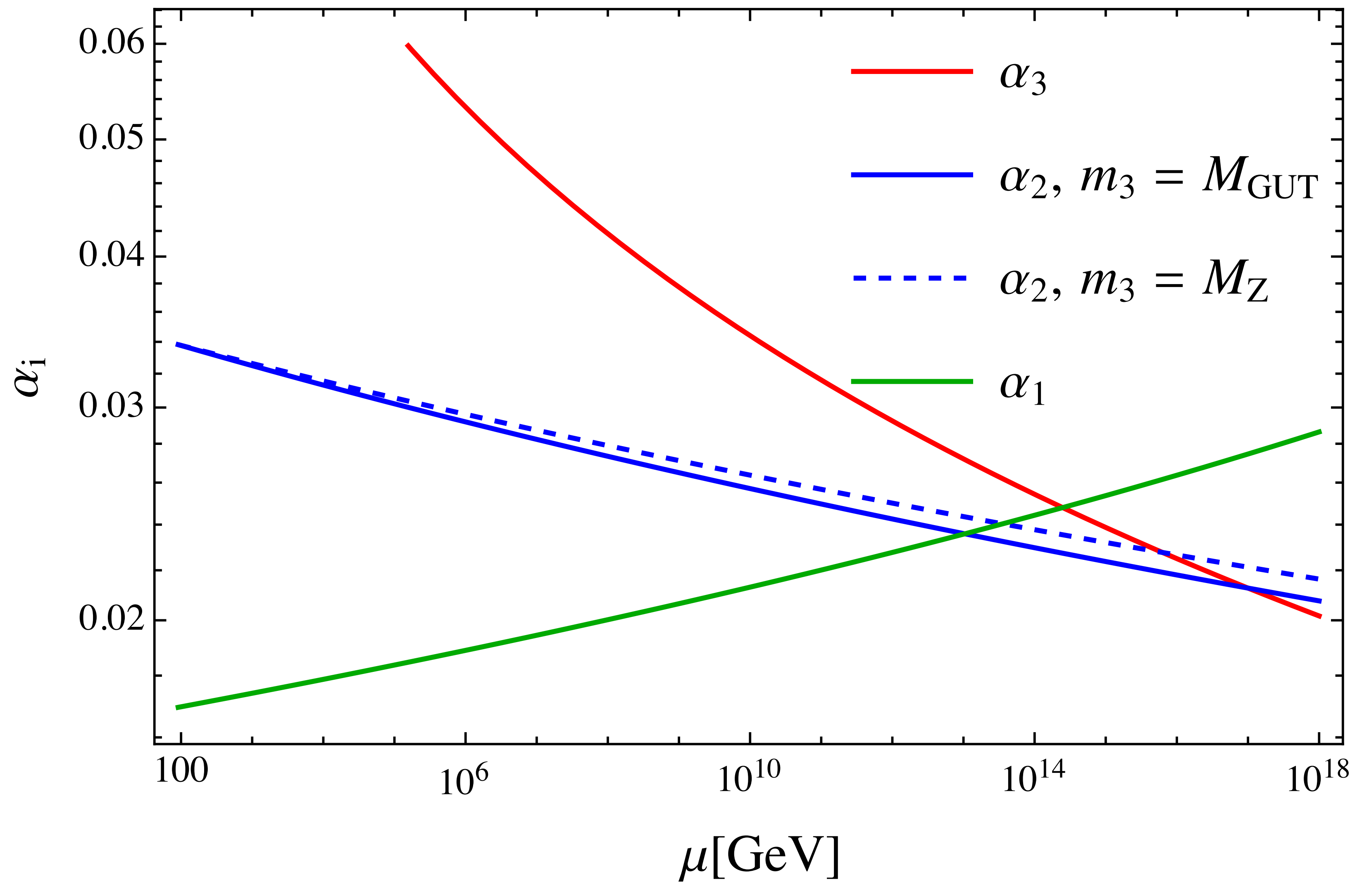
Minimal SU(5) + 24_F ***Bajc, Senjanović '07***

24_F contains a fermionic weak triplet Σ with Y=0

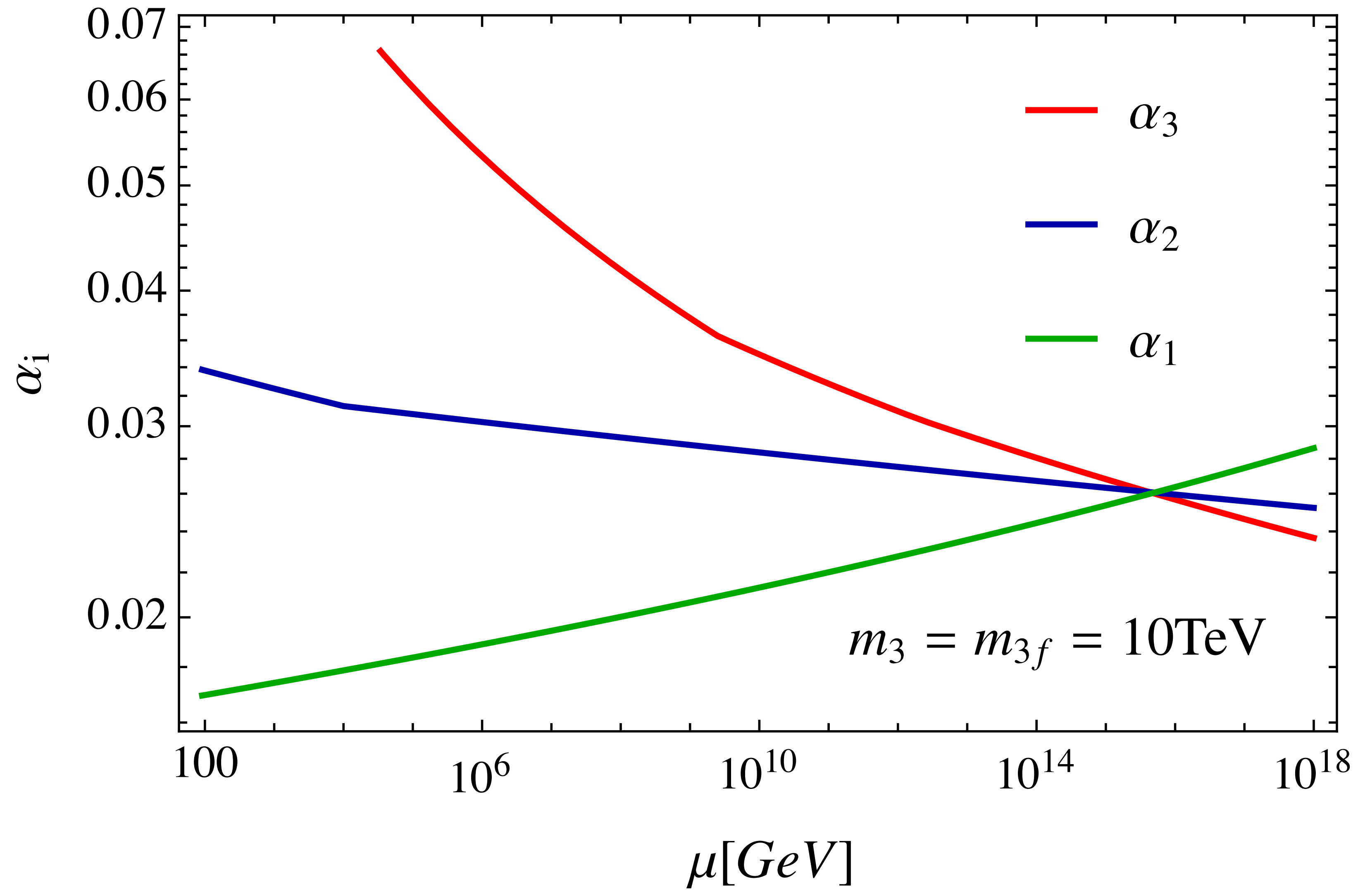


$$m_\nu \simeq v^2 \left(y_\Sigma^T \frac{1}{M_\Sigma} y_\Sigma \right)$$

Dynamical realisations of neutrino mass



BS model



Light scalar 3_W insufficient for unification:

- New particle states necessary!

↓

Eg., in BS the fermionic triplet below 10 TeV.*

↓

Seesaw testable at LHC

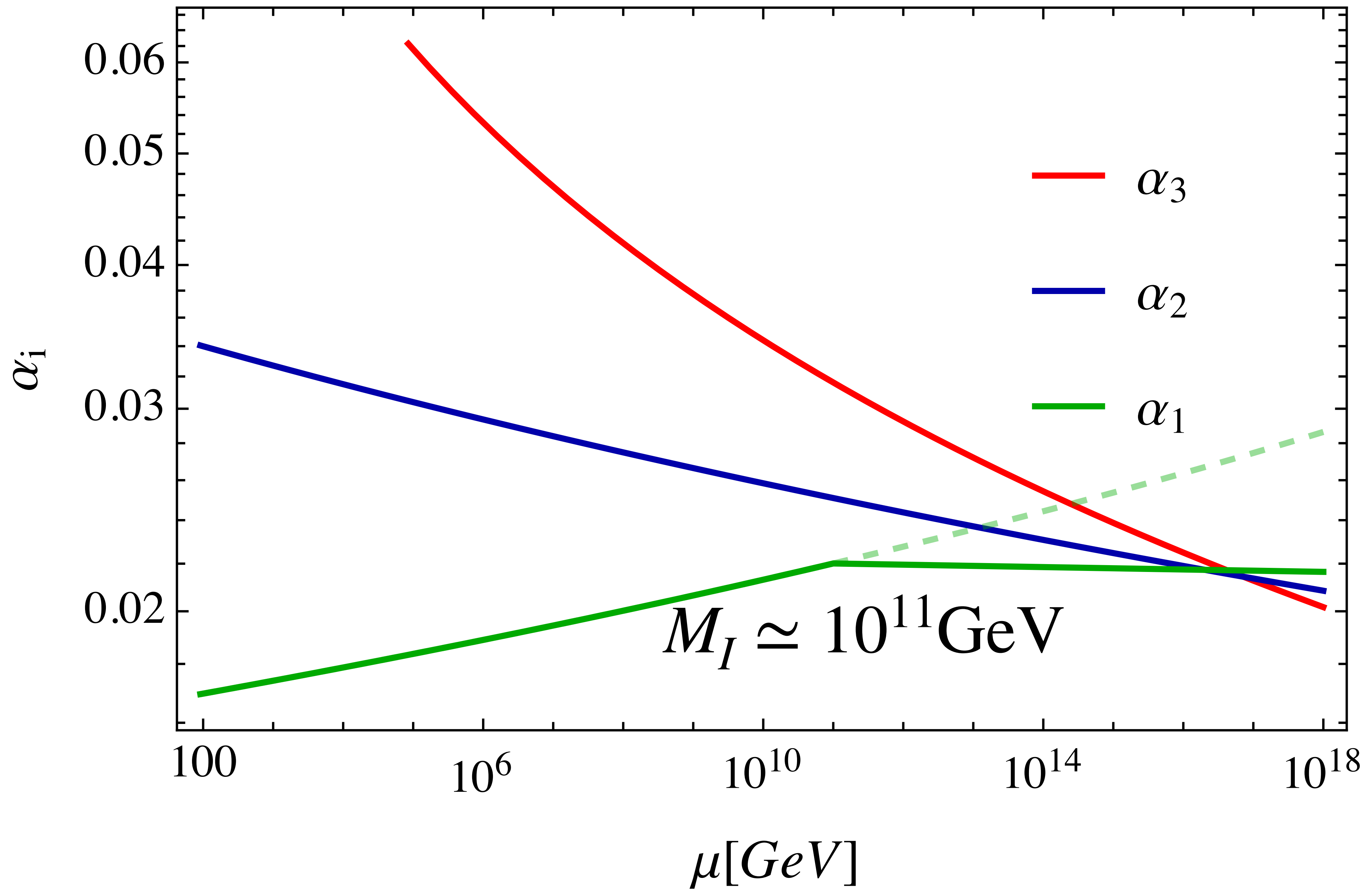
Message: small field content requires light particle states to ensure unification

*Similarly light particles in DFP

$SO(10)$: the true unification?

Georgi '74
Fritzsch, Minkowski, '74

Adding W_R *Del Aguila, Ibanez '80* *Rizzo, Senjanović '80*



$$16_F = \begin{pmatrix} u_\alpha \\ \nu \\ d_\alpha \\ e \\ e^c \\ d^c_\alpha \\ \nu^c \\ u^c_\alpha \end{pmatrix}$$

Unified generation in same multiplet

↓

Right handed neutrino already there
Charge conjugation is gauge symmetry

40 years later desert picture challenged: focus on minimal realistic theory based on small representations. Surprisingly:

- New particle states are required close to LHC scales
- P-lifetime below 10^{35}yrs within reach of experiments

A. Preda, G. Senjanović, MZ, 2201.02785

Neutrino mass plays a key-role in this

The model

$$SO(10)$$
$$\Big\downarrow \ \langle 45_H \rangle \simeq M_{GUT}$$
$$\mathcal{G}_I$$
$$\Big\downarrow \ \langle 16_H \rangle \simeq M_I$$
$$SU(3)_C \times SU(2)_L \times U(1)_Y$$
$$\Big\downarrow \ \langle 10_H \rangle \simeq M_W$$
$$SU(3)_C \times U(1)_{em}$$

Scalar sector with small representations:

Adjoint 45_H, Spinor 16_H, Fundamental 10_H

At renormalizable level, only 10_H couples to fermions

$$16_F\, 16_F \langle 10_H \rangle \implies m_d = m_e, \quad m_u = m_D \quad \textit{Neutrino Dirac mass}$$

$$\Big\downarrow$$

$$\boxed{m_{3D} = m_t}$$

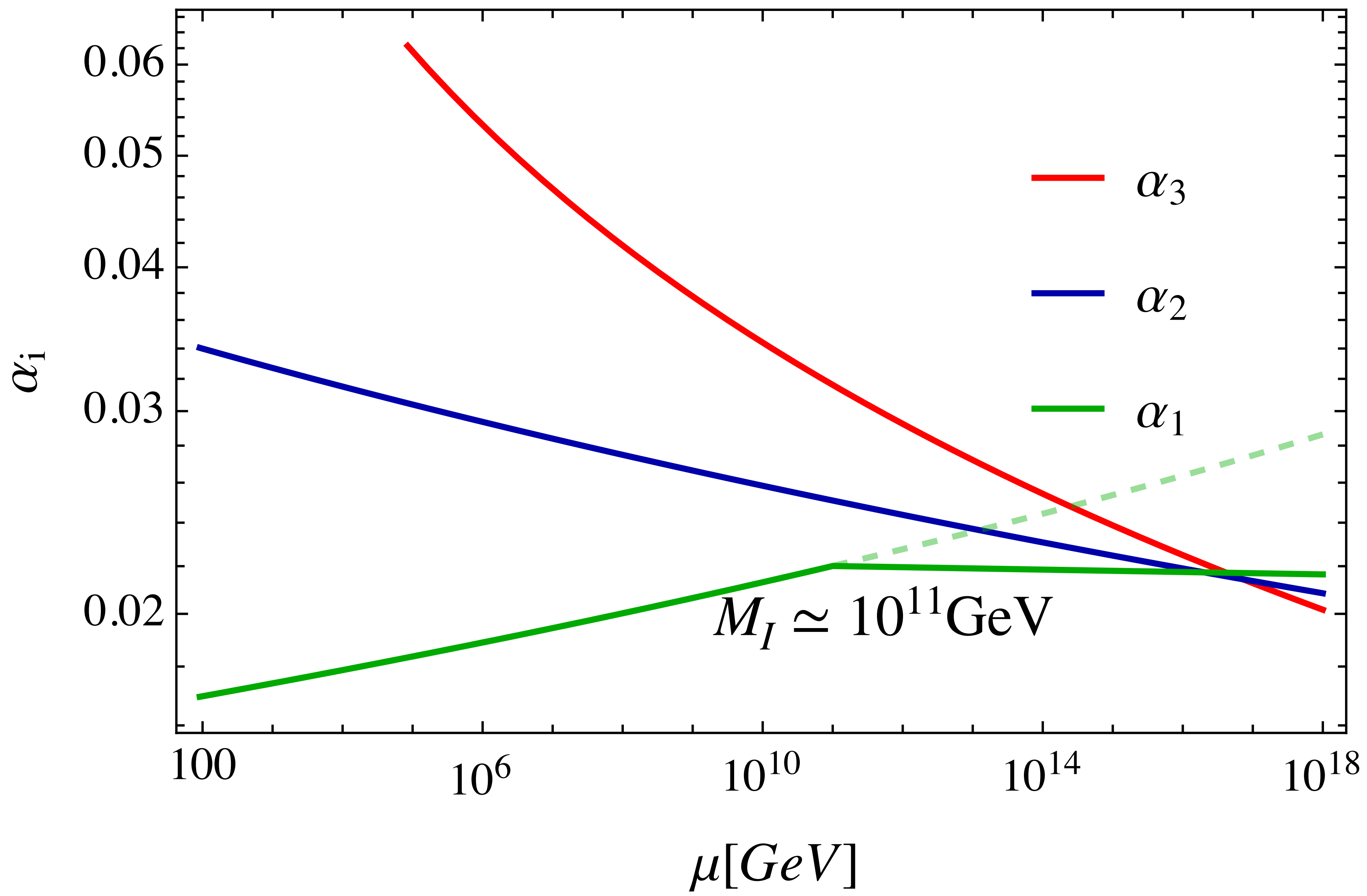
This is crux of it all!

Seesaw

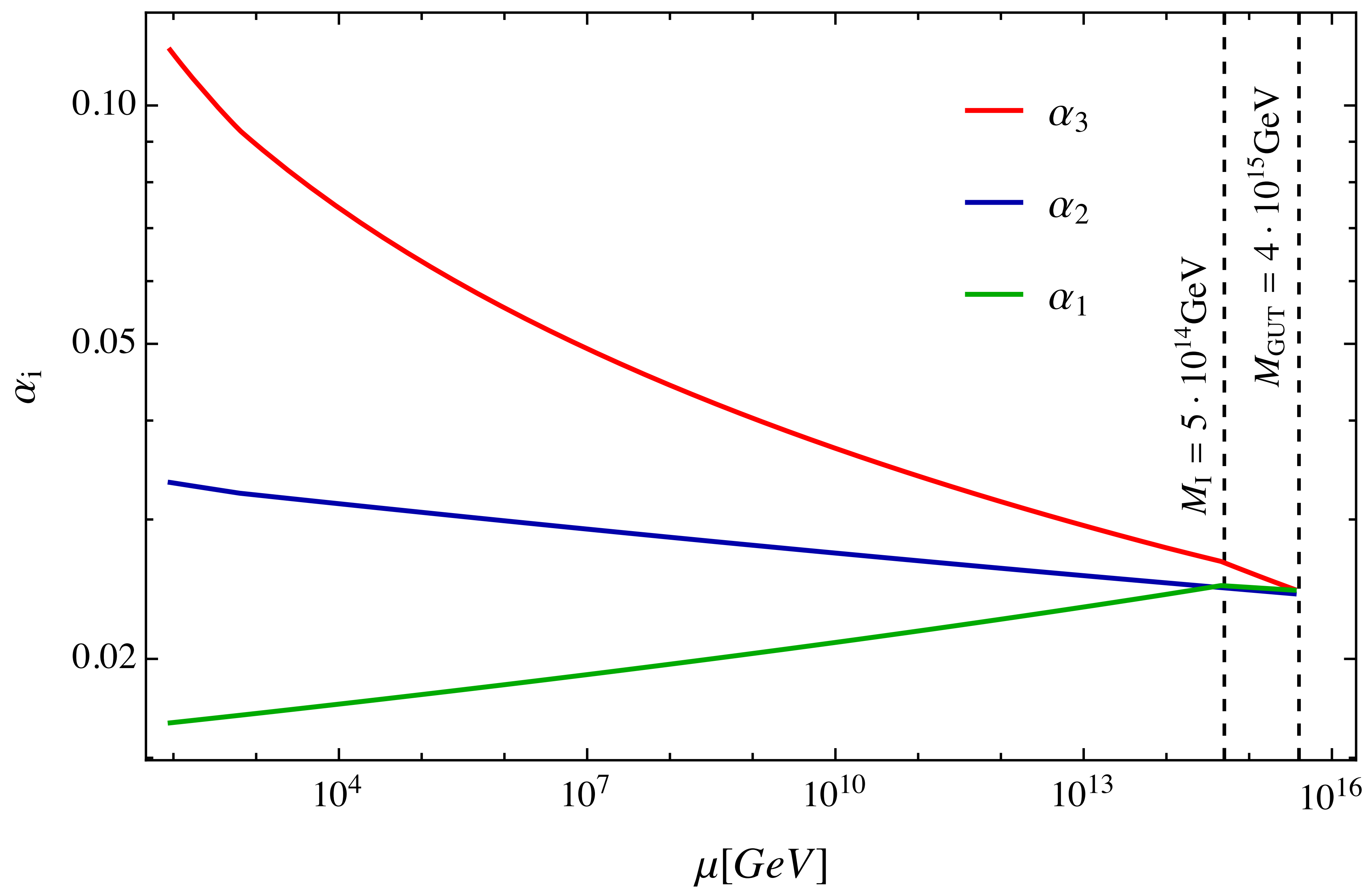
The right handed neutrino N obtains mass $m_N \sim M_I$

$$m_\nu \sim \frac{(m_{3D})^2}{m_N} \sim \frac{m_t^2}{M_I} \lesssim \text{eV} \qquad \Longrightarrow M_I \gtrsim 10^{13}\text{GeV}$$

Adding W_R



QL case



- Scalar W,Z, scalar gluon and scalar quark always lie below 10TeV to be realistic
- $M_{GUT} < 10^{16}$GeV always implying $\tau_p < 10^{35}$yrs*

A. Preda, G. Senjanović, MZ, 2201.02785

Low energy perspective of light triplet

G. Senjanović, MZ 2205.05022

$$\mu\Phi_{SM}^{\dagger} T \Phi_{SM} \longrightarrow \langle T \rangle = v_T \simeq \frac{\mu}{g^2}\left(\frac{M_W}{m_3}\right)^2$$

Buras, Ellis, Gaillard, Nanopoulos '78

Changes W-mass leaving Z-mass intact

$$\delta M_W^2 \doteq M_W^2 - (M_W^{SM})^2 \simeq \alpha_2 v_T^2, \qquad M_Z^2 = (M_Z^{SM})^2 \qquad \Longrightarrow \qquad v_T \lesssim \mathcal{O}(\text{GeV})$$

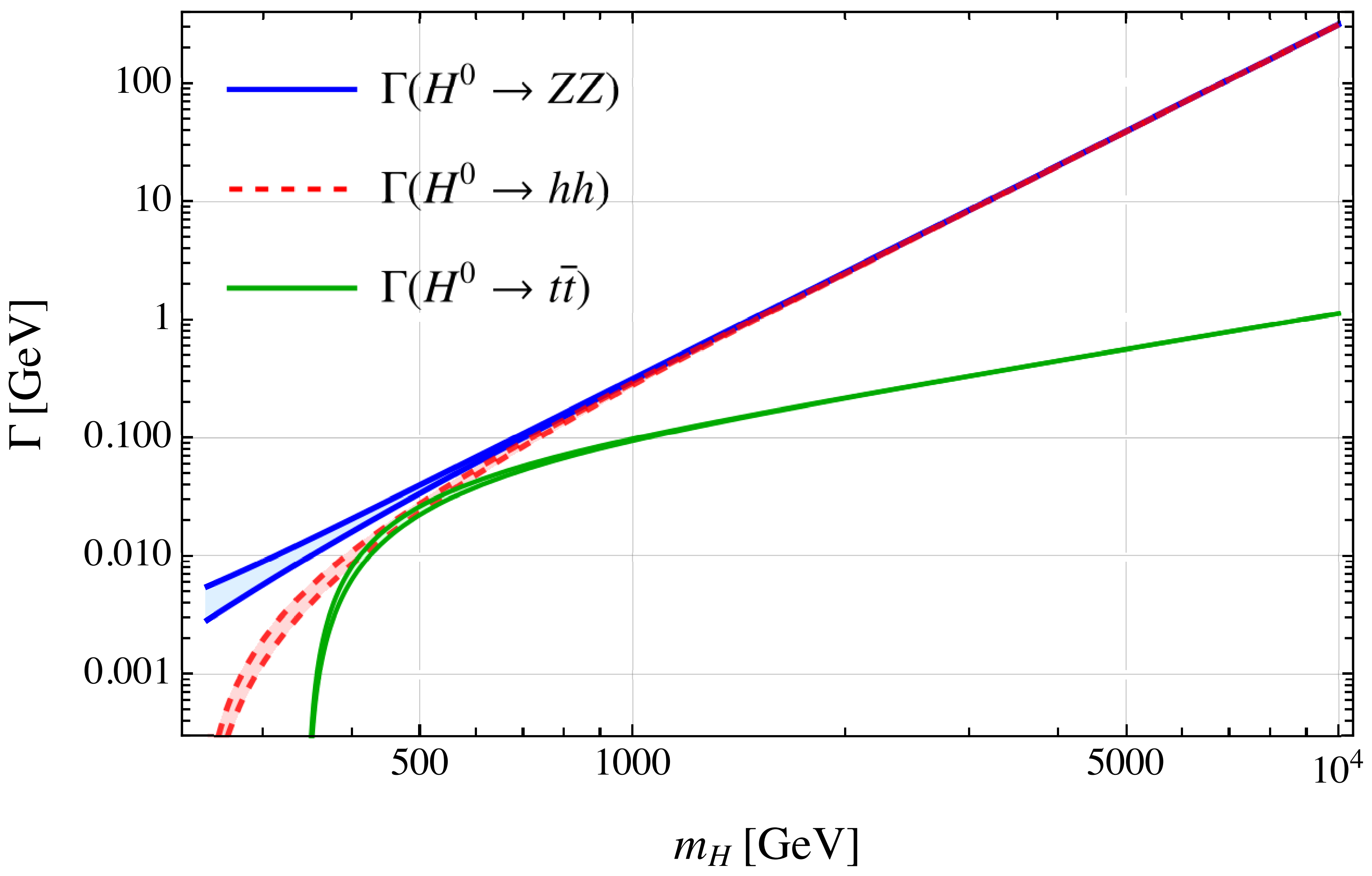
Leads to mixing θ between SM Higgs and the triplet

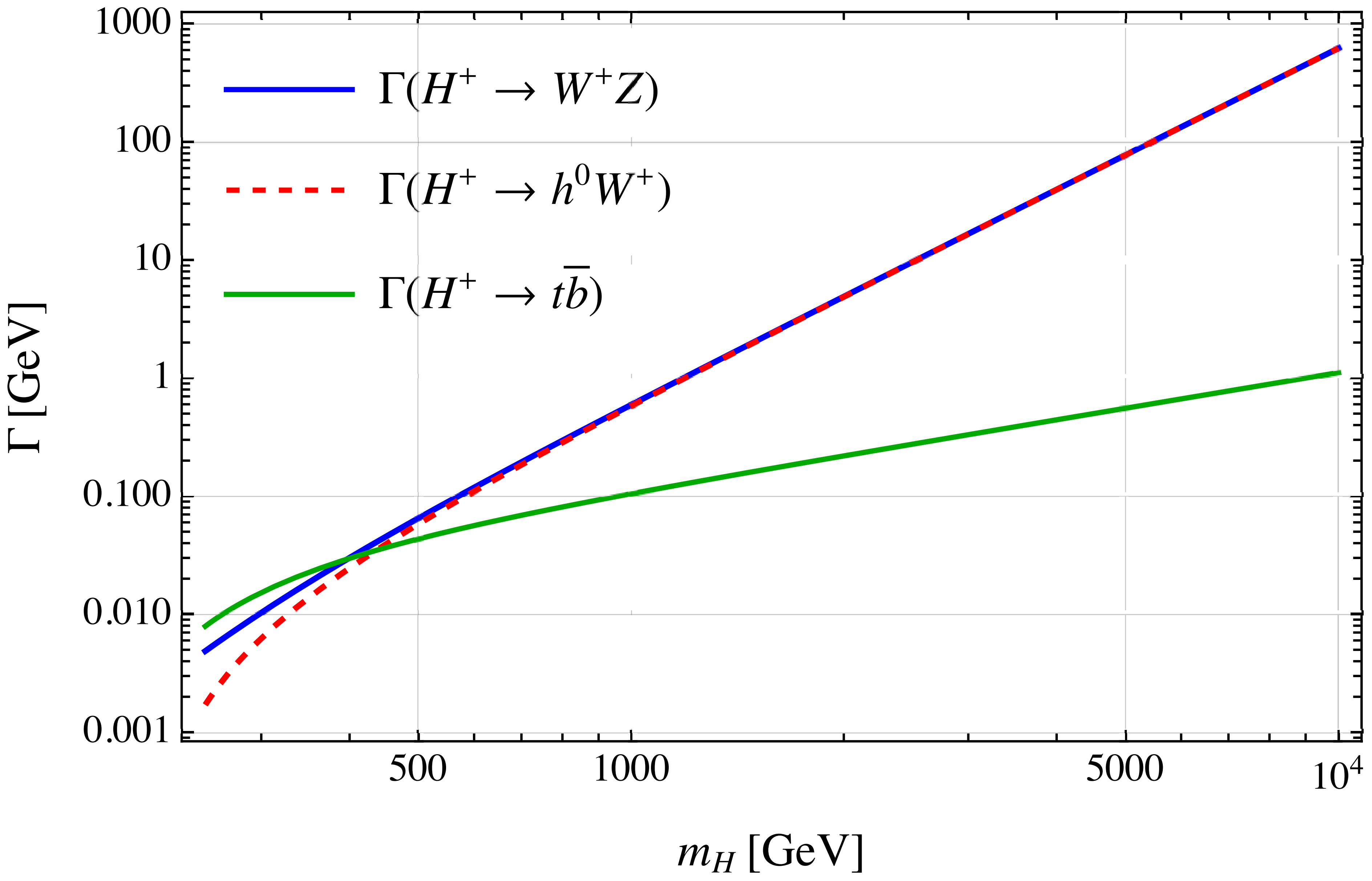
$$\theta = \theta(\delta M_W)$$

Only input needed to fix the physics of the triplet is deviation of W-mass from Standard Model value. This is a consequence of the grand unified completion of the theory.

Triplet decay rates

G. Senjanović, MZ 2205.05022





Example: CDF '22 input $\to v_T \simeq 5\,\text{GeV} \quad (\theta \sim 0.04)$

Patel, Plascencia, Fileviez Perez '22
He et al '22 …

$$\frac{1}{2}\Gamma(H^0 \to W^+W^-) \simeq \Gamma(H^0 \to ZZ) \simeq \Gamma(H^0 \to h^0h^0) \simeq \theta(\delta M_W)^2 \frac{g^2}{128\pi}\frac{m_H^3}{M_W^2}$$

$$\Gamma(H^+ \to W^+Z) \simeq \Gamma(H^+ \to W^+h^0) \simeq \Gamma(H^0 \to W^+W^-)$$

$$\Gamma(H^0 \to f\bar{f}) \simeq N_c \theta(\delta M_W)^2 \frac{g^2}{32\pi}\frac{m_f^2 m_H}{M_W^2}$$

$$\Gamma(H^+ \to t\bar{b}) \simeq \Gamma(H^0 \to t\bar{t})$$

Discussion

- Gospel of desert picture in $SO(10)$ has been challenged — minimal theory points at new particle scalar states below 10TeV:

  1. scalar weak triplet
  2. scalar quark doublet
  3. scalar gluon octet

- This comes together with a proton lifetime below 10^{35}yrs to be probed in near future

- One of the predicted light states, the weak triplet, naturally explains CDF recent $W-$mass deviation from SM value

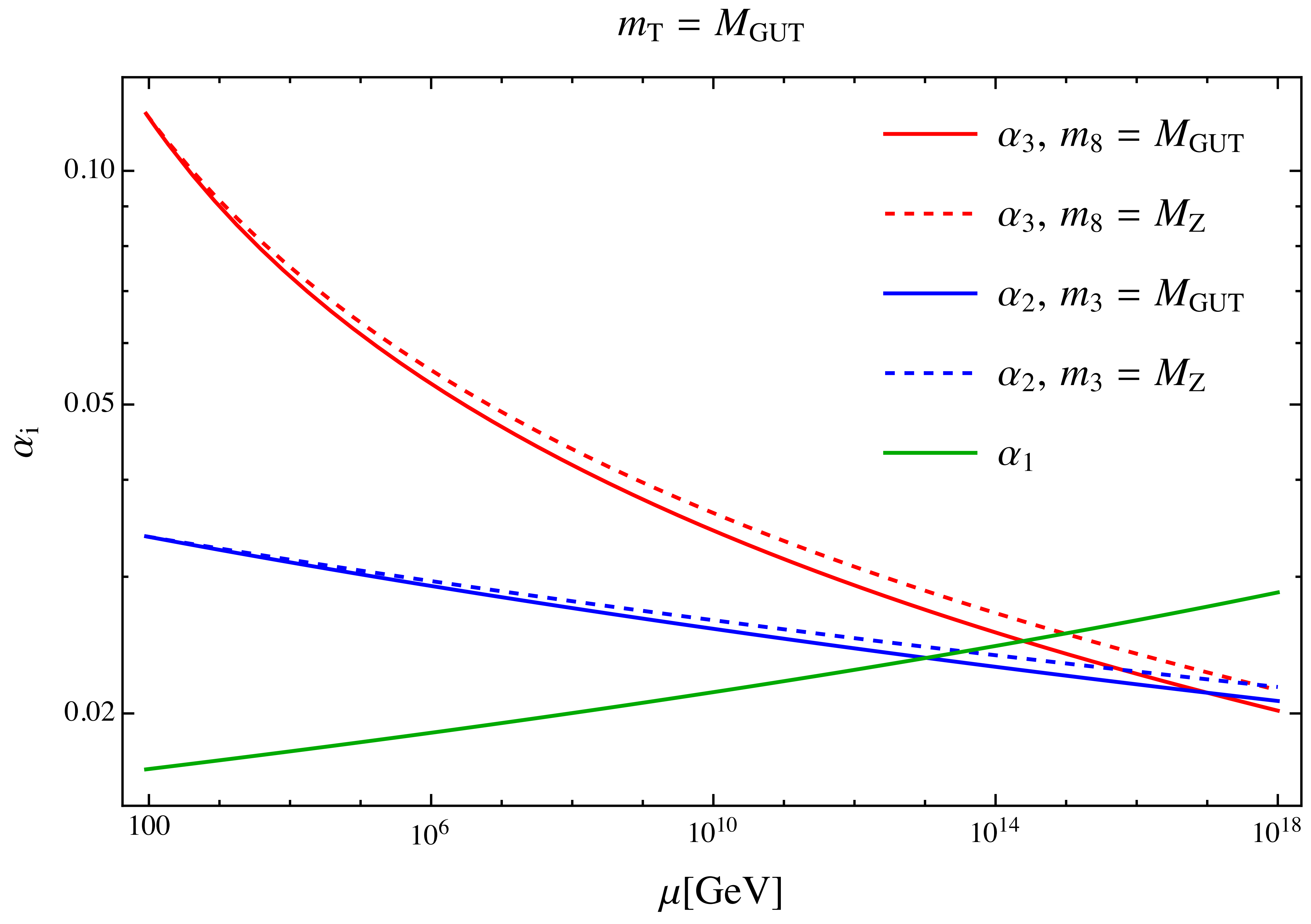
- Its decay rate into SM are fixed by its mass and $W-$mass deviation. This is consequence of Grand Unified UV completion based on small representations

- Unaware of other scenarios this predictive when addressing CDF

Thank you!

Backup

More on failure of minimal SU(5)



Georgi Glashow model is a natural candidate

New massive scalars from 24_H:
A color octet of mass m_8
A weak triplet of mass m_3

Higher-dimensional operators necessary to correct wrong Yukawa relations

Gauge coupling unification is not helped by operators such as

$$\frac{1}{\Lambda} F\, 24_H\, F$$

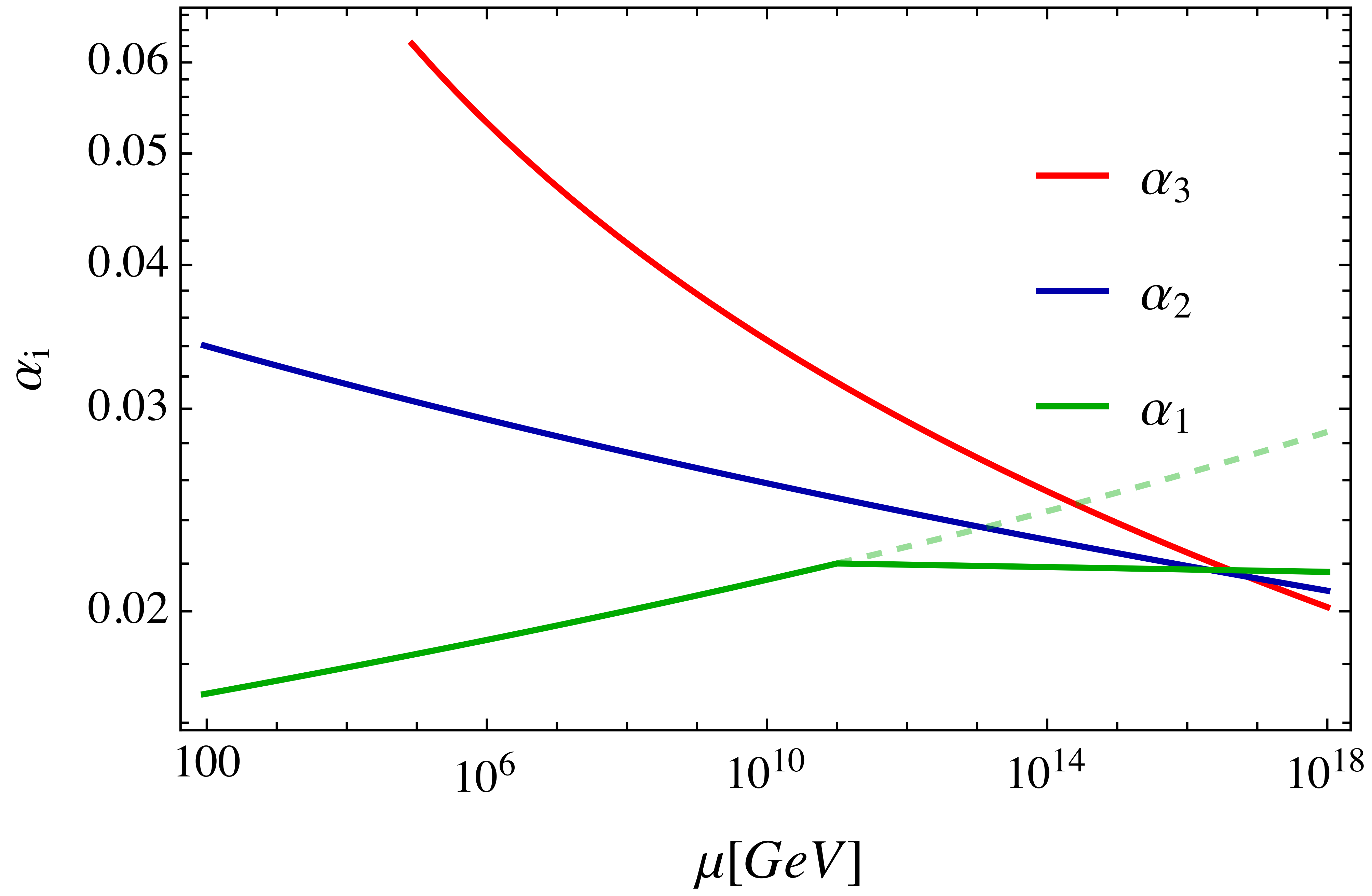
Shafi, Wetterich '84

Unification around $M_{GUT} \simeq 10^{14}$GeV — in tension with proton decay lifetime $\tau_p \gtrsim 10^{34}$yrs

Moreover, neutrino is massless

More on $SO(10)$?

Adding W_R



- Unification ensured by intermediate scale M_I
- Right-handed neutrino gets a mass — fermions unified in 16_F
- Can realize seesaw mechanism

Higgs sector:

$45_H; \quad 16_H; \quad 10_H$

SM undergoes usual breaking with 10_H

- 10_H real does not work since $m_u = m_d$ hence the need for complex 10_H
- At renormalizable level still $m_d = m_e$, so higher dimensional operators are needed for Yukawa

In what follows, for validity of perturbativity, we will require cutoff

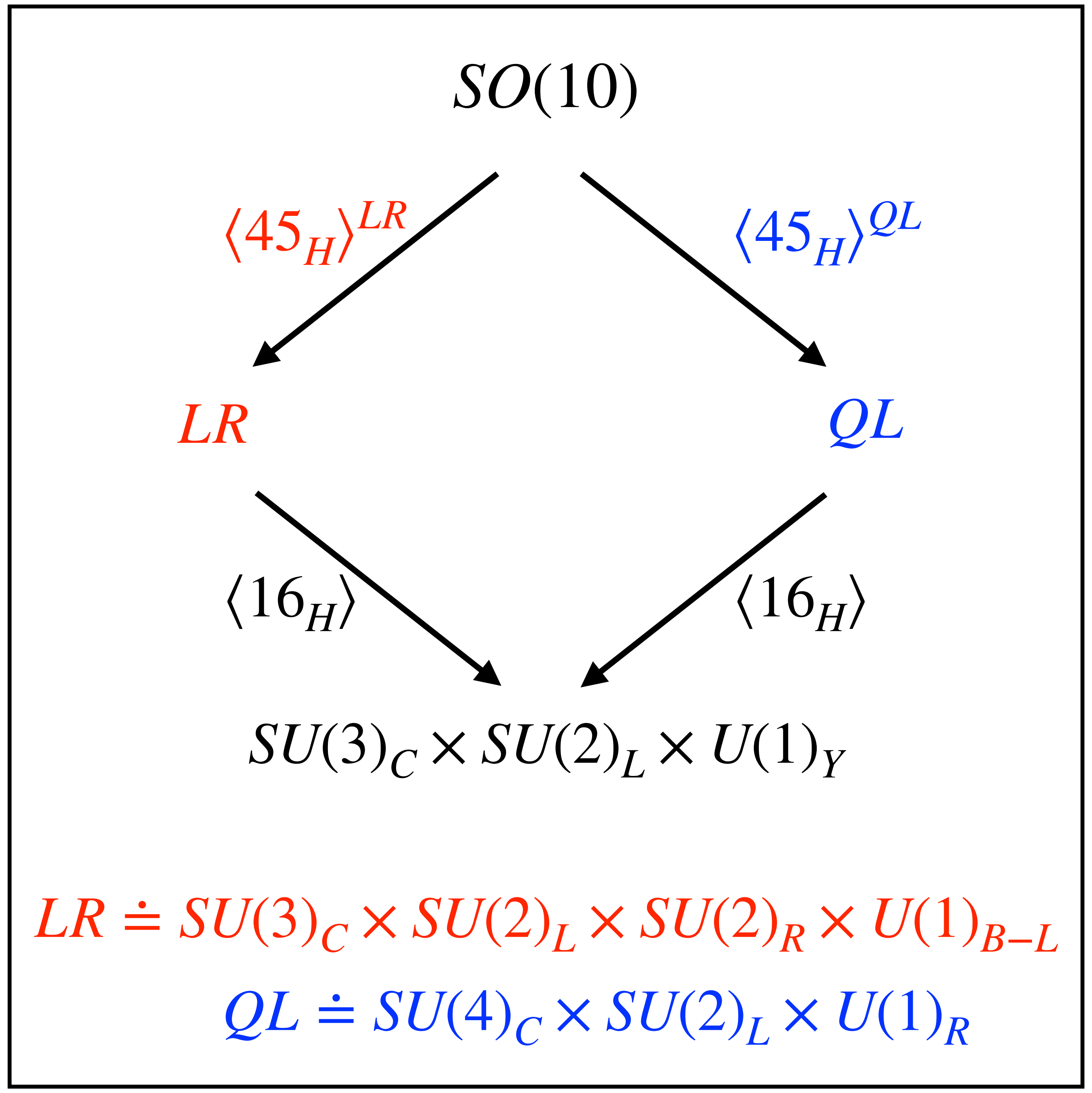
$$\Lambda \gtrsim 10\, M_{GUT}$$

Crux: $m_{3D} = m_t$

	$4_C\,2_L\,2_R$	$4_C\,2_L\,1_R$	$3_c\,2_L\,2_R\,1_X$	$3_c\,2_L\,1_R\,1_X$	$3_c\,2_L\,1_Y$	5	$5'\,1_{Z'}$	$1_{Y'}$
16_H	$(4,2,1)$	$(4,2,0)$	$\left(3,2,1,+\frac{1}{6}\right)$	$\left(3,2,0,+\frac{1}{6}\right)$	$\left(3,2,+\frac{1}{6}\right)$	10	$(10,+1)$	$+\frac{1}{6}$
			$\left(1,2,1,-\frac{1}{2}\right)$	$\left(1,2,0,-\frac{1}{2}\right)$	$\left(1,2,-\frac{1}{2}\right)$	$\overline{5}$	$(\overline{5},-3)$	$-\frac{1}{2}$
	$(\overline{4},1,2)$	$\left(\overline{4},1,+\frac{1}{2}\right)$	$\left(\overline{3},1,2,-\frac{1}{6}\right)$	$\left(\overline{3},1,+\frac{1}{2},-\frac{1}{6}\right)$	$\left(\overline{3},1,+\frac{1}{3}\right)$	$\overline{5}$	$(10,+1)$	$-\frac{2}{3}$
		$\left(\overline{4},1,-\frac{1}{2}\right)$		$\left(\overline{3},1,-\frac{1}{2},-\frac{1}{6}\right)$	$\left(\overline{3},1,-\frac{2}{3}\right)$	10	$(\overline{5},-3)$	$+\frac{1}{3}$
			$\left(1,1,2,+\frac{1}{2}\right)$	$\left(1,1,+\frac{1}{2},+\frac{1}{2}\right)$	$(1,1,+1)$	10	$(1,+5)$	0
				$\left(1,1,-\frac{1}{2},+\frac{1}{2}\right)$	$(1,1,0)$	1	$(10,+1)$	$+1$

	$4_C\,2_L\,2_R$	$4_C\,2_L\,1_R$	$3_c\,2_L\,2_R\,1_X$	$3_c\,2_L\,1_R\,1_X$	$3_c\,2_L\,1_Y$	5	$5'\,1_{Z'}$	$1_{Y'}$
45_H	$(1,1,3)$	$(1,1,+1)$	$(1,1,3,0)$	$(1,1,+1,0)$	$(1,1,+1)$	10	$(10,-4)$	$+1$
		$(1,1,0)$		$(1,1,0,0)$	$(1,1,0)$	1	$(1,0)$	0
		$(1,1,-1)$		$(1,1,-1,0)$	$(1,1,-1)$	$\overline{10}$	$(\overline{10},+4)$	-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	$(\overline{10},+4)$	$-\frac{1}{6}$
				$\left(\overline{3},2,-\frac{1}{2},+\frac{1}{3}\right)$	$\left(\overline{3},2,-\frac{1}{6}\right)$	$\overline{10}$	$(24,0)$	$+\frac{5}{6}$
	$(15,1,1)$	$(15,1,0)$	$(1,1,1,0)$	$(1,1,0,0)$	$(1,1,0)$	24	$(24,0)$	0
			$\left(3,1,1,+\frac{2}{3}\right)$	$\left(3,1,0,+\frac{2}{3}\right)$	$\left(3,1,+\frac{2}{3}\right)$	$\overline{10}$	$(\overline{10},+4)$	$+\frac{2}{3}$
			$\left(\overline{3},1,1,-\frac{2}{3}\right)$	$\left(\overline{3},1,0,-\frac{2}{3}\right)$	$\left(\overline{3},1,-\frac{2}{3}\right)$	10	$(10,-4)$	$-\frac{2}{3}$
			$(8,1,1,0)$	$(8,1,0,0)$	$(8,1,0)$	24	$(24,0)$	0

More on the breaking Pattern



Content

At tree level only one VEV allowed for

$$\langle 45_H \rangle^{SU(5)} = v_{GUT}\, \sigma_2 \otimes \mathrm{diag}(1,1,1,\pm 1,\pm 1),$$

Non viable for unification

Including higher dimensional operators, new directions are possible

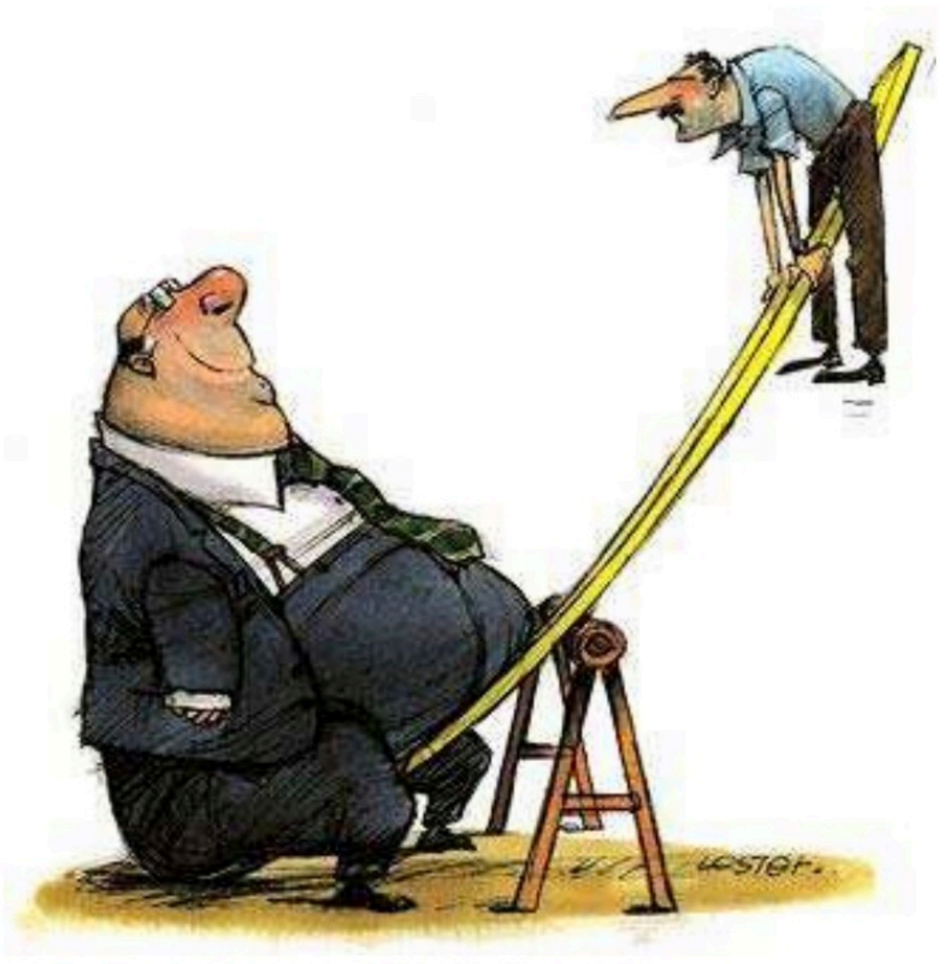
$$\langle 45_H \rangle^{LR} = v_{GUT}\, \sigma_2 \otimes \mathrm{diag}(1,1,1,0,0),$$
$$\langle 45_H \rangle^{QL} = v_{GUT}\, \sigma_2 \otimes \mathrm{diag}(0,0,0,1,1)$$

→ Breaking pattern possible also at tree-level via inclusion of radiative corrections (see Bertolini, Di Luzio, Malinsky 0912.1796)

→ Higher-dimensional operators give more freedom in the spectrum

$\langle 16_H \rangle \simeq M_I$ realizes tadpole for vanishing component when acquiring VEV via $16_H\, 45_H\, 16^*_H$

Seesaw



The right handed neutrino N obtains mass from $d=5$ operator

$$16_F 16_F 16^*_H 16^*_H / \Lambda$$

$$m_{\mathrm{N}} \simeq \frac{M_{\mathrm{I}}^2}{\Lambda}$$

$$\downarrow \qquad \begin{pmatrix} 0 & m_D^T \\ m_D & m_N \end{pmatrix} \begin{matrix} \nu \\ N \end{matrix}$$

$$m_\nu \simeq \frac{(m_{3D})^2}{m_N} \simeq \frac{m_t^2 \Lambda}{M_I^2} \simeq \mathrm{eV} \left(\frac{m_t}{100\mathrm{GeV}} \frac{4 \cdot 10^{14}\mathrm{Gev}}{M_I} \right)^2 \left(\frac{\Lambda}{4 \cdot 10^{16}\mathrm{GeV}} \right) \lesssim \mathrm{eV}$$

$$\Longrightarrow \; M_I \gtrsim 0.1\, M_{GUT}$$

But in the absence of an intermediate scale, we learnt from $SU(5)$ that new light states are necessary

Scalar weak triplet 3_W, a squark $(2_W, 3_C)$ and an octet scalar gluon 8_C

	$4_C 2_L 2_R$	$3_c\, 2_L\, 1_Y$	m_i
16_H	$(4,2,1)$	$(3,2,+\frac{1}{6})$	m_{sq}
		$(1,2,-\frac{1}{2})$	
	$(\overline{4},1,2)$	$(\overline{3},1,+\frac{1}{3})$	m_{sd}
		$(\overline{3},1,-\frac{2}{3})$	m_{sup}
		$(1,1,+1)$	m_{sel}
		$(1,1,0)$	

	$4_C 2_L 2_R$	$3_C 2_L 1_Y$	m_i
45_H	$(1,1,3)$	$(1,1,+1)$	m_{sel}
		$(1,1,0)$	
		$(1,1,-1)$	
	$(1,3,1)$	$(1,3,0)$	m_3
	$(6,2,2)$	$(3,2,\frac{1}{6})$	m_{sq}
		$(3,2,-\frac{5}{6})$	
		$(\overline{3},2,+\frac{5}{6})$	
		$(\overline{3},2,-\frac{1}{6})$	
	$(15,1,1)$	$(1,1,0)$	
		$(3,1,+\frac{2}{3})$	
		$(\overline{3},1,-\frac{2}{3})$	m_{sup}
		$(8,1,0)$	m_8

10_H contains 2 doublets (one of which is SM one). Also, it contains 2 coloured triplets mediating p-decay → heavy or decoupled *Dvali '92*

One-loop RG leads to

$$\frac{M_{GUT}}{M_Z} \simeq \exp\left\{\frac{\pi}{10}\left(5\alpha_1^{-1} - 3\alpha_2^{-1} - 2\alpha_3^{-1}\right)_{M_Z}\right\}\left[\left(\frac{M_Z}{M_I}\right)^{22}\left(\frac{M_Z^2 m_{sel} m_{sup}}{m_3 m_8 m_{sq}^2}\right)\right]^{\frac{1}{20}}$$

- p-decay → $M_{GUT} \gtrsim 4 \cdot 10^{15}\,\mathrm{GeV}$
- ν mass → $M_I \gtrsim 10^{14}\,\mathrm{GeV}$ and $\Lambda \sim 10\, M_{GUT}$

Typically $M_I \sim 10^{12}\,\mathrm{GeV}$ → scalars must be light

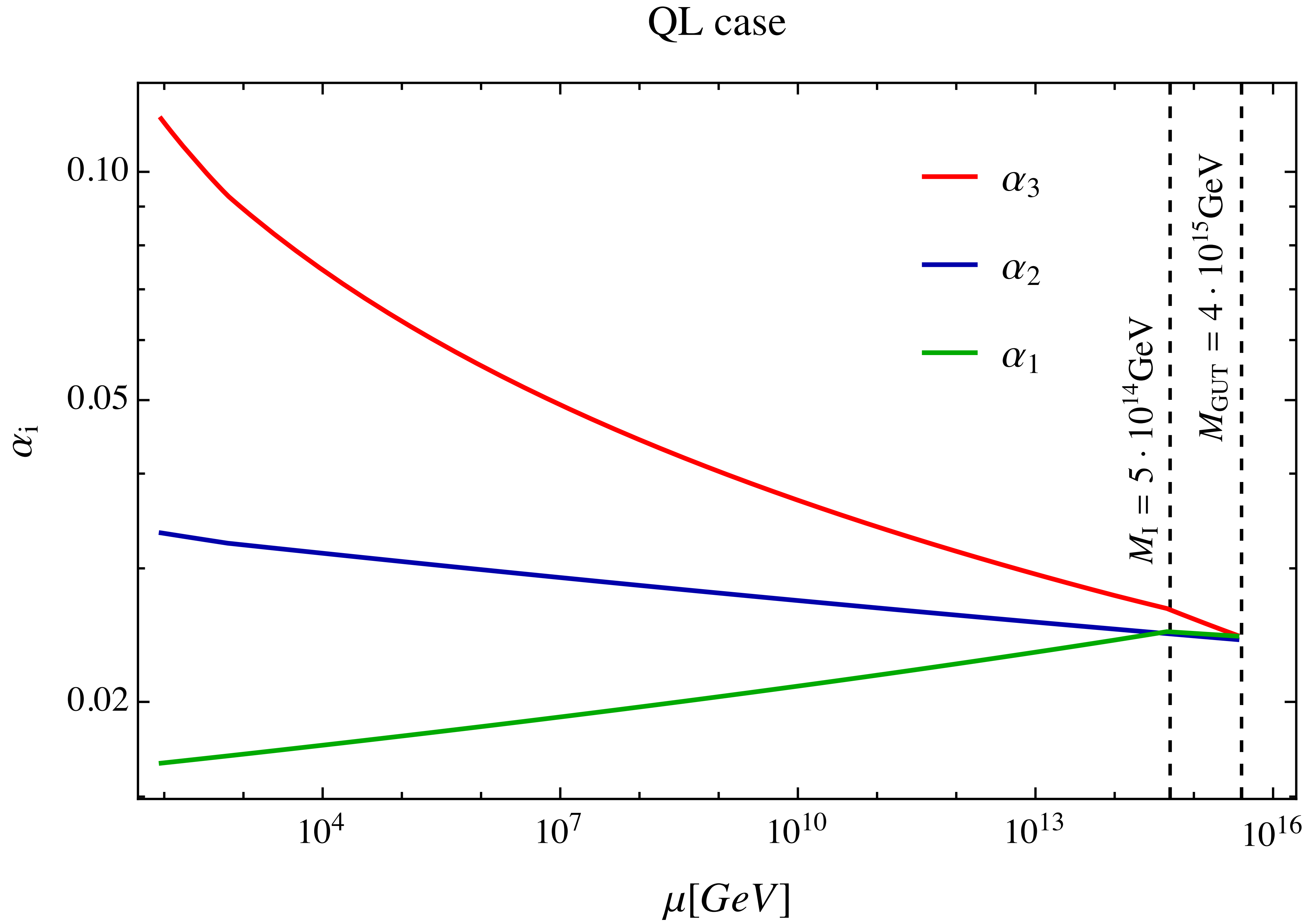
Cutoff not so far from M_{GUT}

$$\frac{1}{\Lambda^2} F F\, 45_H^2$$

$$\delta\alpha_1^{\mathrm{LR}} = \delta\alpha_1^{\mathrm{QL}} = \left(\frac{M_{GUT}}{\Lambda}\right)^2 ; \quad \delta\alpha_3^{\mathrm{LR}} = \frac{5}{2}\left(\frac{M_{GUT}}{\Lambda}\right)^2 ; \quad \delta\alpha_2^{\mathrm{QL}} = \frac{5}{3}\left(\frac{M_{GUT}}{\Lambda}\right)^2$$

2-loops RG analysis

We varied all particle masses and took into account the effects of higher dimensional operators



Example of realization:
$m_3 = m_8 = m_{sq} = \text{TeV}$

Spectrum

Particle	Mass range
scalar quark doublet	$m_{sq} \lesssim 10\text{TeV}$
weak triplet	$m_3 \lesssim 10\text{TeV}$
color octet	$m_8 \lesssim 10\text{TeV}$
scalar lepton doublet	$10^3\text{GeV} - M_I$
second Higgs doublet	$10^3\text{GeV} - M_{GUT}$
scalar down quark	$10^{12}\text{GeV} - M_{GUT}$
color triplet Higgs partners	$10^{12}\text{GeV} - M_{GUT}$
scalar up quark	$10^{14}\text{GeV} - M_{GUT}$
scalar electron	$10^{14}\text{GeV} - M_{GUT}$

- m_3, m_{sq}, m_8 **always lie below** 10TeV **to ensure unification, p-lifetime and neutrino mass**
- $M_{GUT} < 10^{16}\text{GeV}$ **always implying** $\tau_p < 10^{35}\text{yrs}$

Low energy perspective

G. Senjanović, MZ 2205.05022

This results in the low energy theory for a scalar weak doublet Φ and a weak triplet T

$$\mathscr{L} = |D_\mu \Phi|^2 + \mathrm{Tr}(D_\mu T)^2 + m_\Phi^2 \Phi^\dagger \Phi - m_T^2 \mathrm{Tr}\, T^2 - \lambda_T \left(\mathrm{Tr}\, \mathrm{T}^2\right)^2 - \lambda_\Phi (\Phi^\dagger \Phi)^2 - \rho \Phi^\dagger \Phi \mathrm{Tr}\, T^2 - \mu \Phi^\dagger T \Phi$$

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi^+ \\ v + \phi_R^0 + i\phi_I^0 \end{pmatrix}, \qquad T = \frac{1}{2} \begin{bmatrix} v_T + t^0 & \sqrt{2} t^+ \\ \sqrt{2} t^- & -v_T - t^0 \end{bmatrix}.$$

Tadpole induced for triplet $v_T \simeq \frac{\mu}{g^2} \left(\frac{M_W}{m_T} \right)^2$ $\longrightarrow$ Changes W-mass while leaving Z-mass intact

Buras et al '77

High precision of Standard Model $\implies v_T \lesssim \mathcal{O}(\mathrm{GeV}) \implies m_T^2 \simeq m_{t^\pm}^2 = m_{t^0}^2 + \mathcal{O}(v_T^2)$

Electroweak vacuum stability $\implies m_T, \mu \lesssim v^2 / v_T$

If $v_T \sim$ GeV $\implies m_T \lesssim 10$ TeV $\longleftrightarrow$ Light also to ensure coupling unification

Low energy perspective

G. Senjanović, MZ 2205.05022

Mixing between doublet and triplet $\theta \doteq \dfrac{g\, v_T}{M_W}$

SM Higgs $\longrightarrow$ $h^0 \simeq \phi^0 + \theta \left(\dfrac{m_H^2}{m_H^2 - m_h^2} \right) t^0$

New triplet $\longrightarrow$ $H^0 \simeq t^0 - \theta \left(\dfrac{m_H^2}{m_H^2 - m_h^2} \right) \phi^0,$

$$G^+ \simeq \phi^+ - \theta t^+,$$
$$H^+ \simeq t^+ + \theta \phi^+ .$$

There was another coupling leading to mixing in the starting Lagrangian

$$V \supset \lambda_T \left(\mathrm{Tr}\, \mathrm{T}^2\right)^2 + \lambda_\Phi (\Phi^\dagger \Phi)^2 + \rho \Phi^\dagger \Phi \mathrm{Tr}\, T^2 + \mu \Phi^\dagger T \Phi$$

ρ is negligible due to compatibility with Grand Unified UV completion i.e., it affects only slightly the neutral mixing.

Therefore, mixing is fixed uniquely by tadpole and triplet mass.

High energy perspective Input

G. Senjanović, MZ 2205.05022

$$\frac{d\lambda_\Phi}{dt} \simeq \left(\frac{d\lambda_\Phi}{dt}\right)_{SM} + \frac{2}{3\pi^2}\rho^2,$$

$$\frac{d\lambda_T}{dt} \simeq \frac{1}{16\pi^2}\left(24{g_2}^4 - 24{g_2}^2\lambda_T + 11\lambda_T^2 + 16\rho^2\right),$$

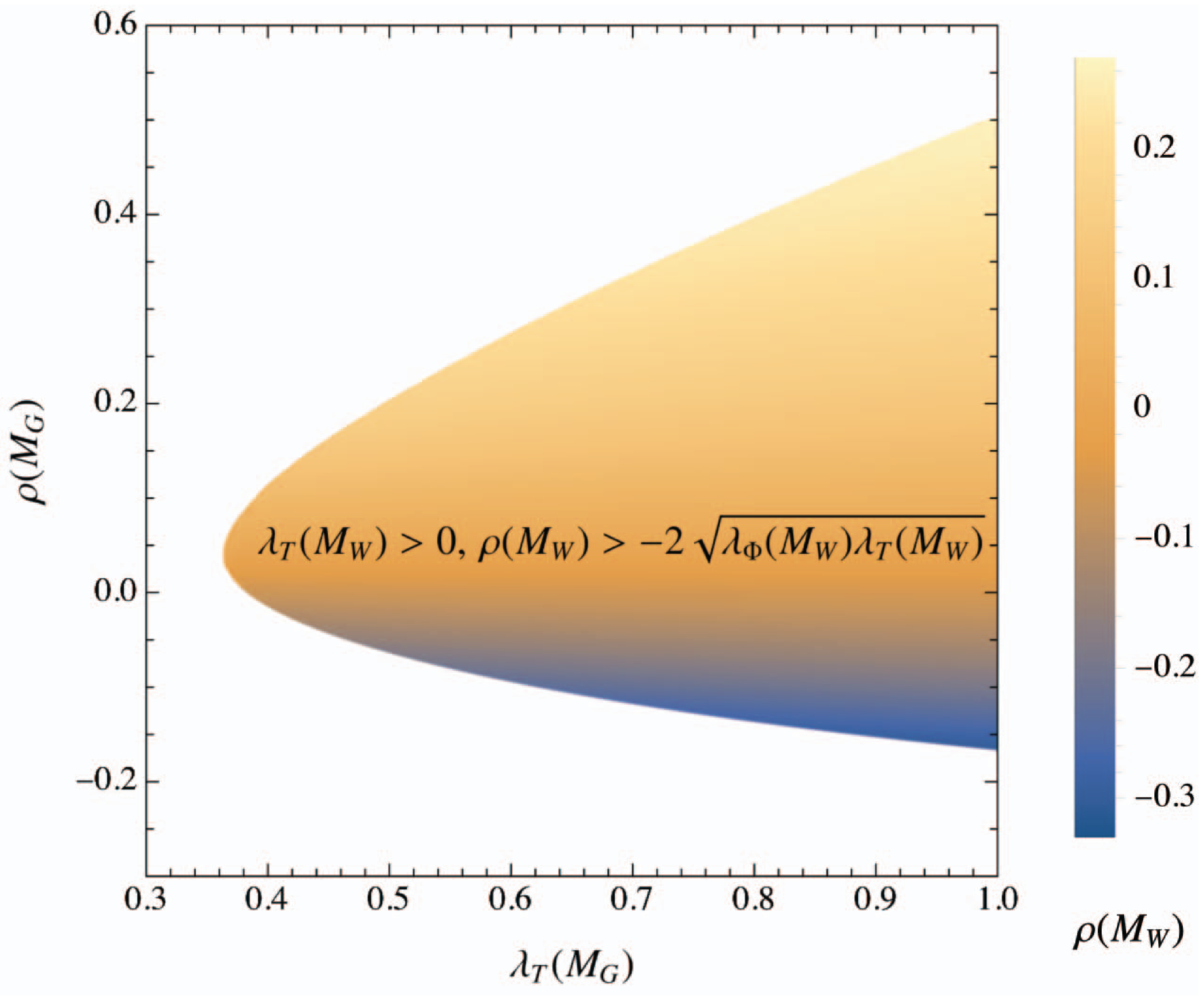
$$\frac{d\rho}{dt} \simeq \frac{1}{32\pi^2}\left(12\rho y_t^2 - 3{g_1}^2\rho + 6{g_2}^4 - 33{g_2}^2\rho + 10\lambda_T\rho + 24\lambda_\Phi\rho + 16\rho^2\right)$$

Requiring perturbativity of couplings at M_{GUT} together with vacuum stability leads to

$|\rho(M_W)| \lesssim 0.3$

ρ is negligible (more later).

Same μ coupling determines mixing and W-mass deviation.



Phenomenological consequences of light triplet

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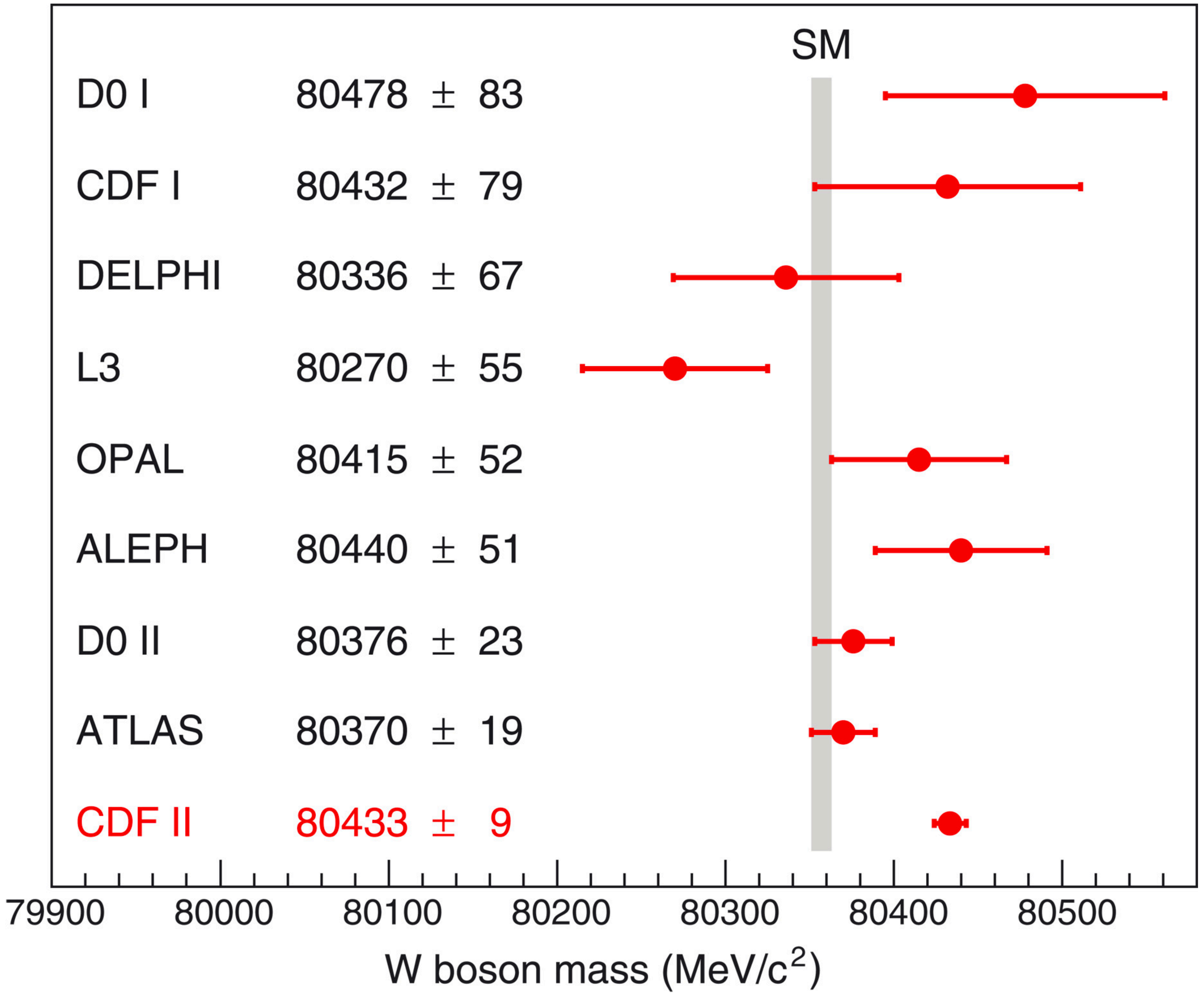
CDF Collaboration '22



Effect of triplet VEV on W-mass

$$M_W^2 \simeq (M_W^{SM})^2(1+\theta^2), \quad M_Z^2 = (M_Z^{SM})^2$$

$$\text{CDF} \ \rightarrow M_W = 80.433 \pm 0.009$$

$$M_W^{SM} = 80.357 \pm 0.006 \text{GeV}$$

$$\theta \simeq 0.04 \ (v_T \sim 5\,\text{GeV})$$

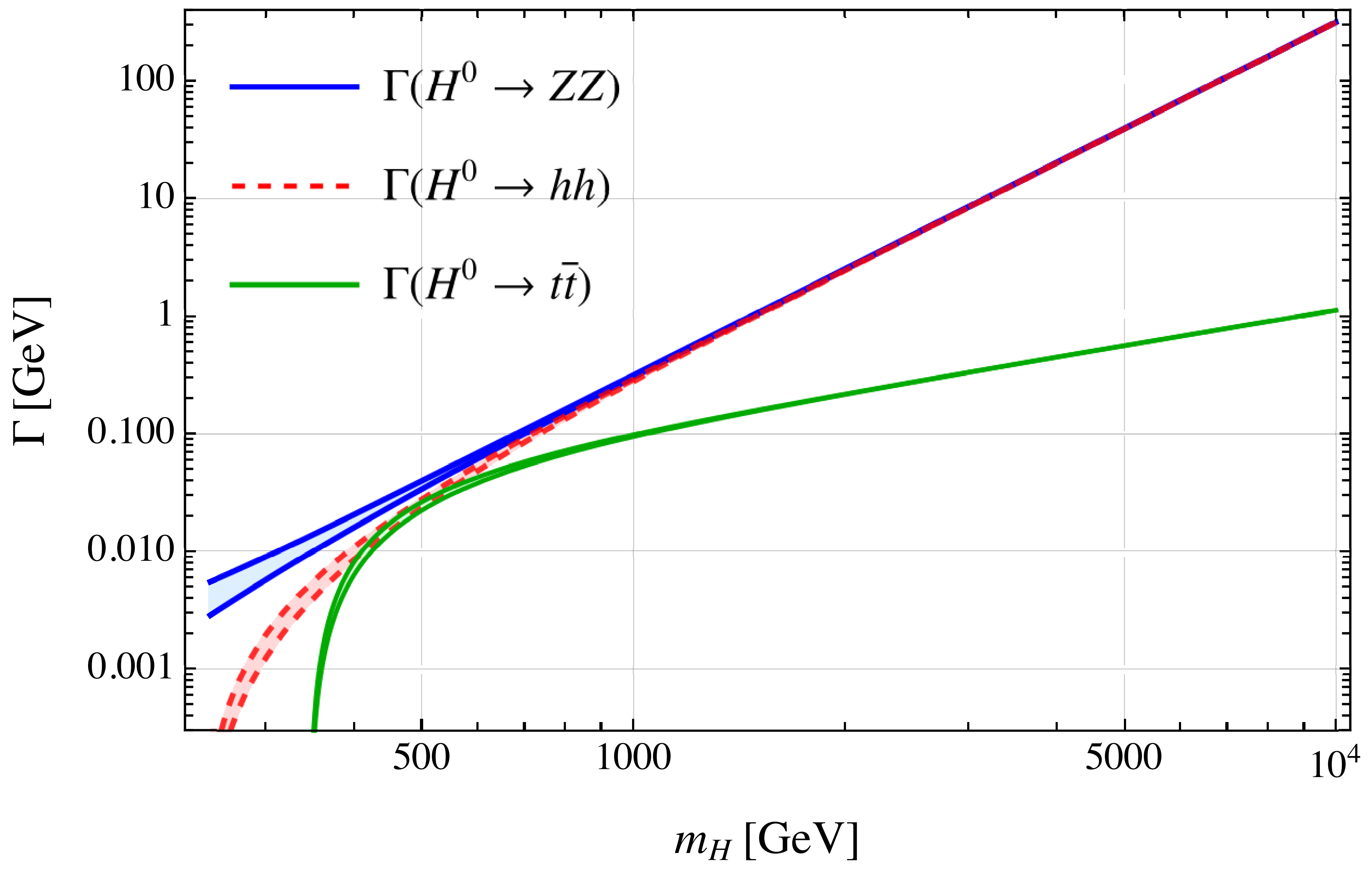
Patel, Plascencia, Fileviez Perez '22

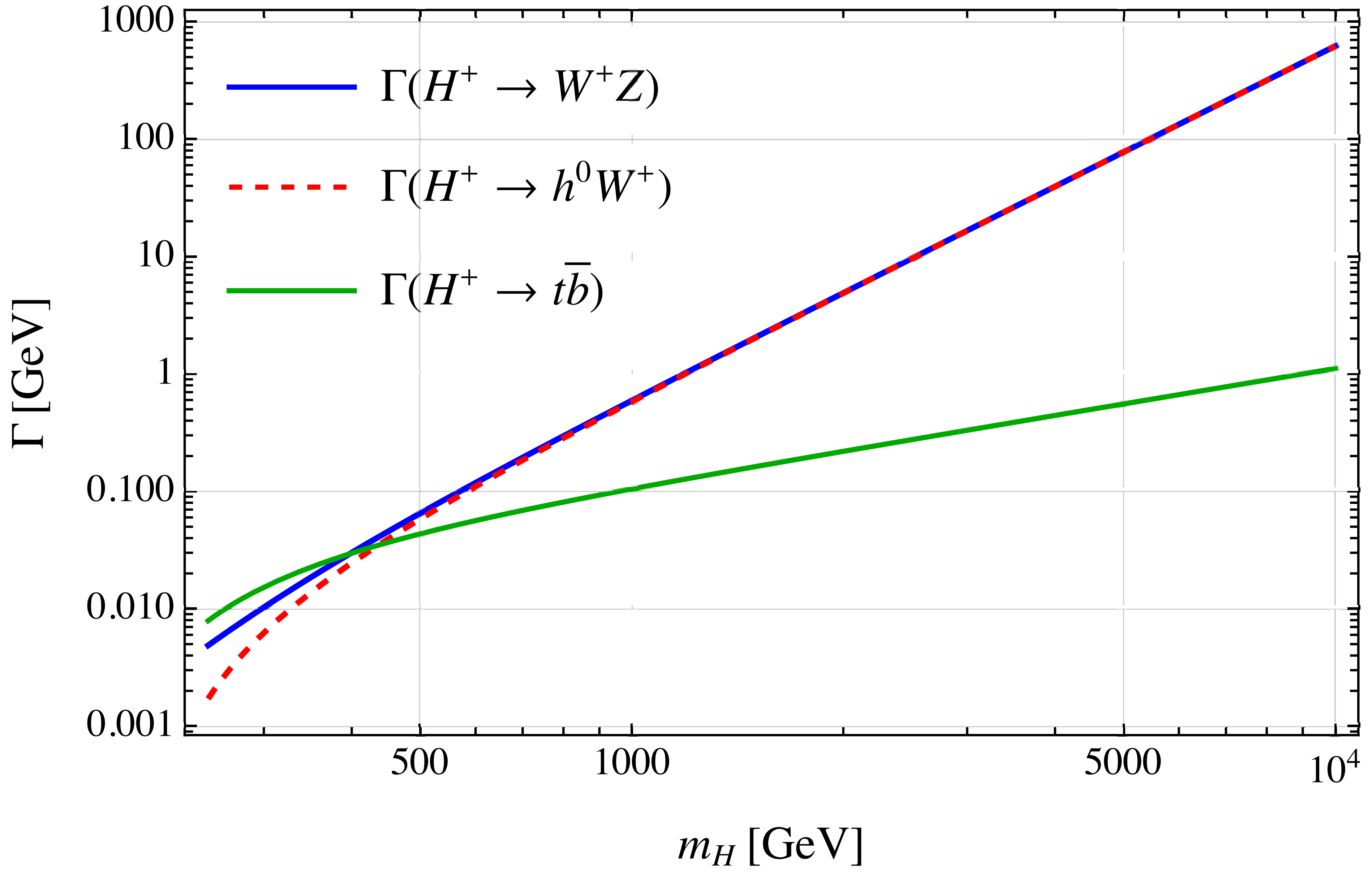
Mixing leads to the following couplings of triplet to SM

$$g\theta H^0: \quad M_W WW, \frac{M_Z Z^2}{2c_W}, \frac{(m_H h^0)^2}{4M_W}, \frac{m_f \bar{f} f}{2M_W},$$

$$g\theta H^+: \quad \frac{M_W Z W^-}{c_W}, \frac{i}{2}\overleftrightarrow{\partial} h^0 W^-, \frac{m_d \bar{u}_L d_R - m_u \bar{u}_R d_L}{\sqrt{2} M_W}.$$

Only experimental input needed is W-mass deviation





Decay rates of triplet into SM are uniquely determined by its mass m_H and $W-$mass deviation θ

$$\frac{1}{2}\Gamma(H^0 \to W^+W^-) \simeq \Gamma(H^0 \to ZZ) \simeq \Gamma(H^0 \to h^0h^0) \simeq \theta^2 \frac{g^2}{128\pi}\frac{m_H^3}{M_W^2}$$

$$\Gamma(H^+ \to W^+Z) \simeq \Gamma(H^+ \to W^+h^0) \simeq \Gamma(H^0 \to W^+W^-)$$

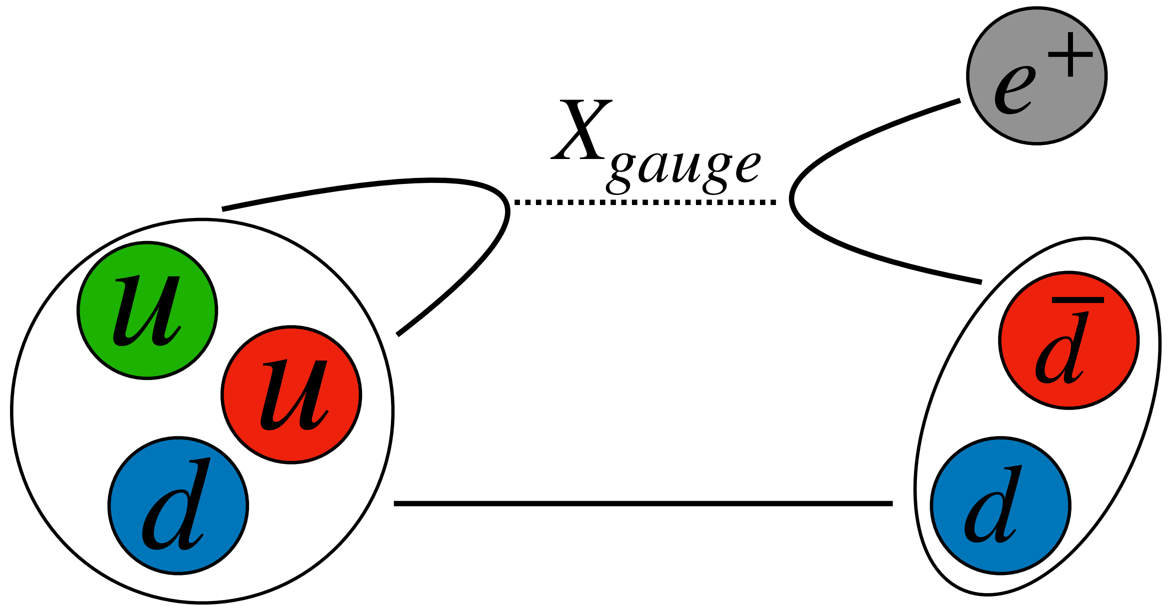
$$\Gamma(H^0 \to f\bar{f}) \simeq N_c\theta^2 \frac{g^2}{32\pi}\frac{m_f^2 m_H}{M_W^2}$$

$$\Gamma(H^+ \to t\bar{b}) \simeq \Gamma(H^0 \to t\bar{t})$$

$m_H \gtrsim 250\,\text{GeV}$ collider bound *M. Ramsey-Musolf '20*

$m_H \lesssim \dfrac{M_W^2}{v_T} \sim 10\,\text{TeV}$ from EW vacuum stability and running

The problem of proton decay and GUT scale



Proton lifetime from Super-Kamiokande requires

$$\tau_p = \simeq C \frac{M_{\rm GUT}^4}{\alpha_{\rm GUT}^2} m_{\rm p}^{-5} \gtrsim 10^{34}{\rm yrs} \rightarrow {\rm M_{GUT}} \gtrsim 4 \cdot 10^{15}{\rm GeV}$$

Channel	Lifetime (10^{30}yrs)
$N \to e^+ \pi$	5300 (n), 16000 (p)
$N \to \mu^+ \pi$	3500 (n), 7700 (p)
$N \to \nu \pi$	1100 (n), 390 (p)
$N \to e^+ K$	17 (n), 1000 (p)
$N \to \mu^+ K$	26 (n), 1600 (p)
$N \to \nu K$	86 (n), 5900 (p)

The constant C is not uniquely determined - it depends on the rotation of fermions to mass basis

$$\left(\overline{u^c}\, U_c^\dagger U\, u\right)\left(\overline{e^c}\, E_c^\dagger D\, d + \overline{d^c}\, D_c^\dagger E\, e\right)$$
$$+\left(\overline{u^c}\, U_c^\dagger D\, d\right)\left(\overline{e^c}\, E_c^\dagger U\, u + \overline{d^c}\, D_c^\dagger N\, \nu\right)$$

Full rotation of proton decay, i.e., $\tau_p = \infty$ incompatible with $\theta_{13} \neq 0$ [1]

$M_{\rm GUT} \gtrsim 6.5 \cdot 10^{13}$ GeV *Senjanović , MZ (discussion) in progress*

[1] See eg., Nandi, Stern, Sudarschan '82 and Doršner, Fileviez Perez '05

The problem of scale in supersymmetry

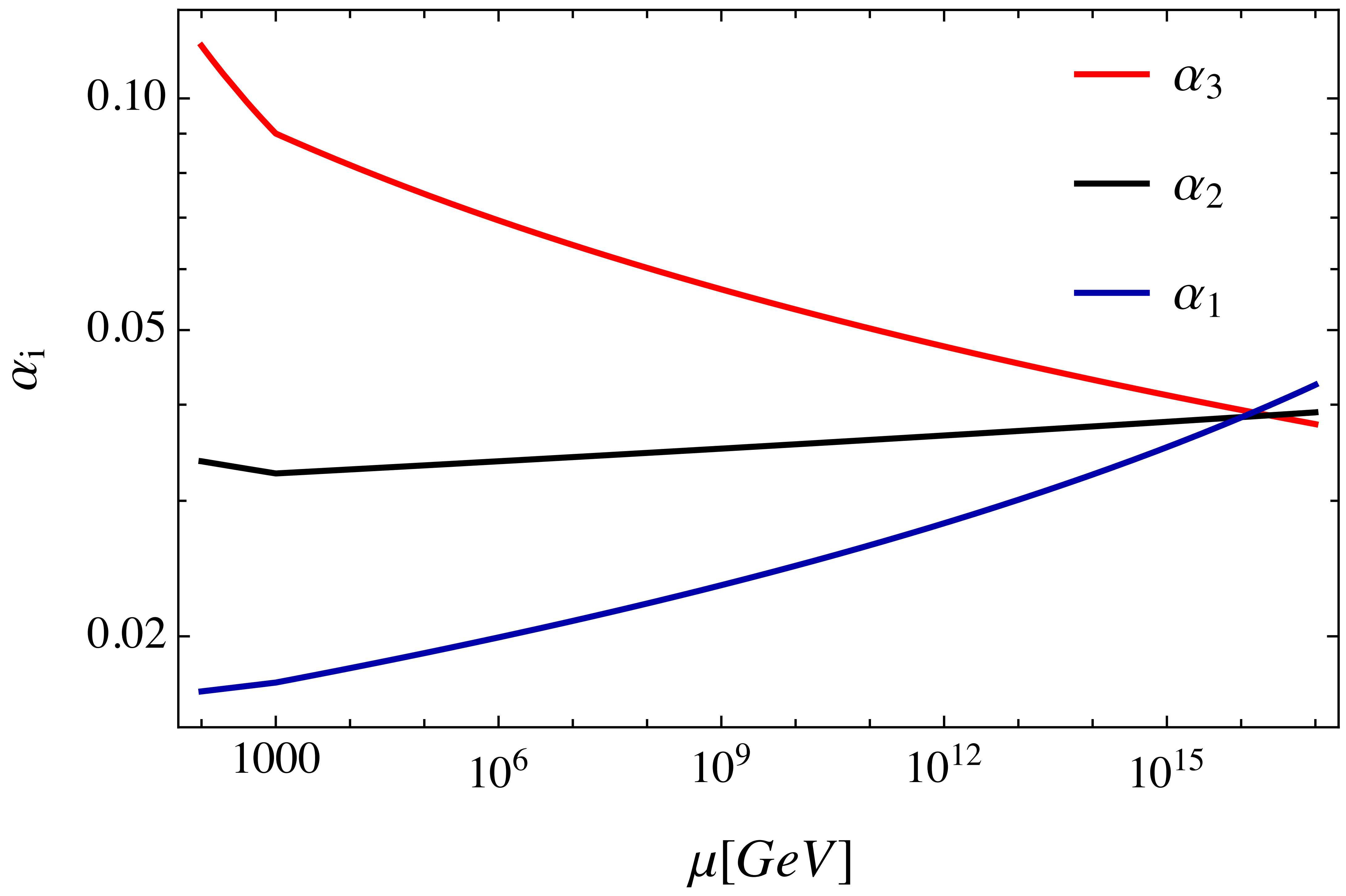
Supersymmetry: particle p $\longrightarrow$ sparticle $\tilde{p}$

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

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

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

$\Lambda^{\text{MSSM}} \sim \text{TeV}, \quad \text{M}_{\text{GUT}} \simeq 10^{16}\text{GeV}$



The problem of scale in supersymmetry

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

For more, tune in to G. Senjanović closing talk on Friday

Senjanović, MZ (discussion) in progress

$$\Lambda_s \sim m_8 \sim 10^{11}\mathrm{GeV}, \quad m_3 \sim 10^9\mathrm{GeV}, \quad M_G \simeq 10^{16}\mathrm{GeV}$$