$SO(10)$: a case for hadron colliders

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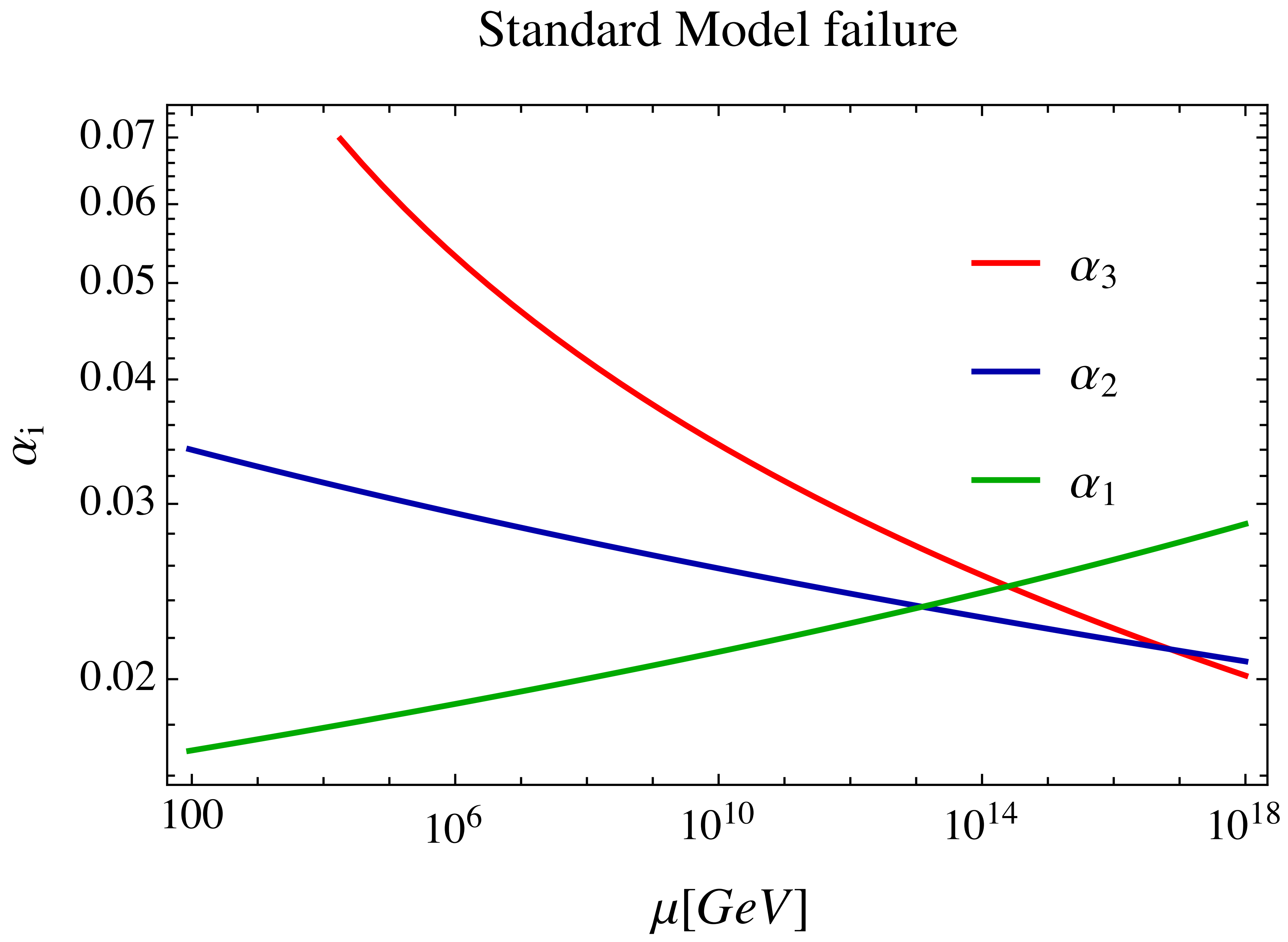
Grand unification is one of the most appealing candidates for physics beyond SM

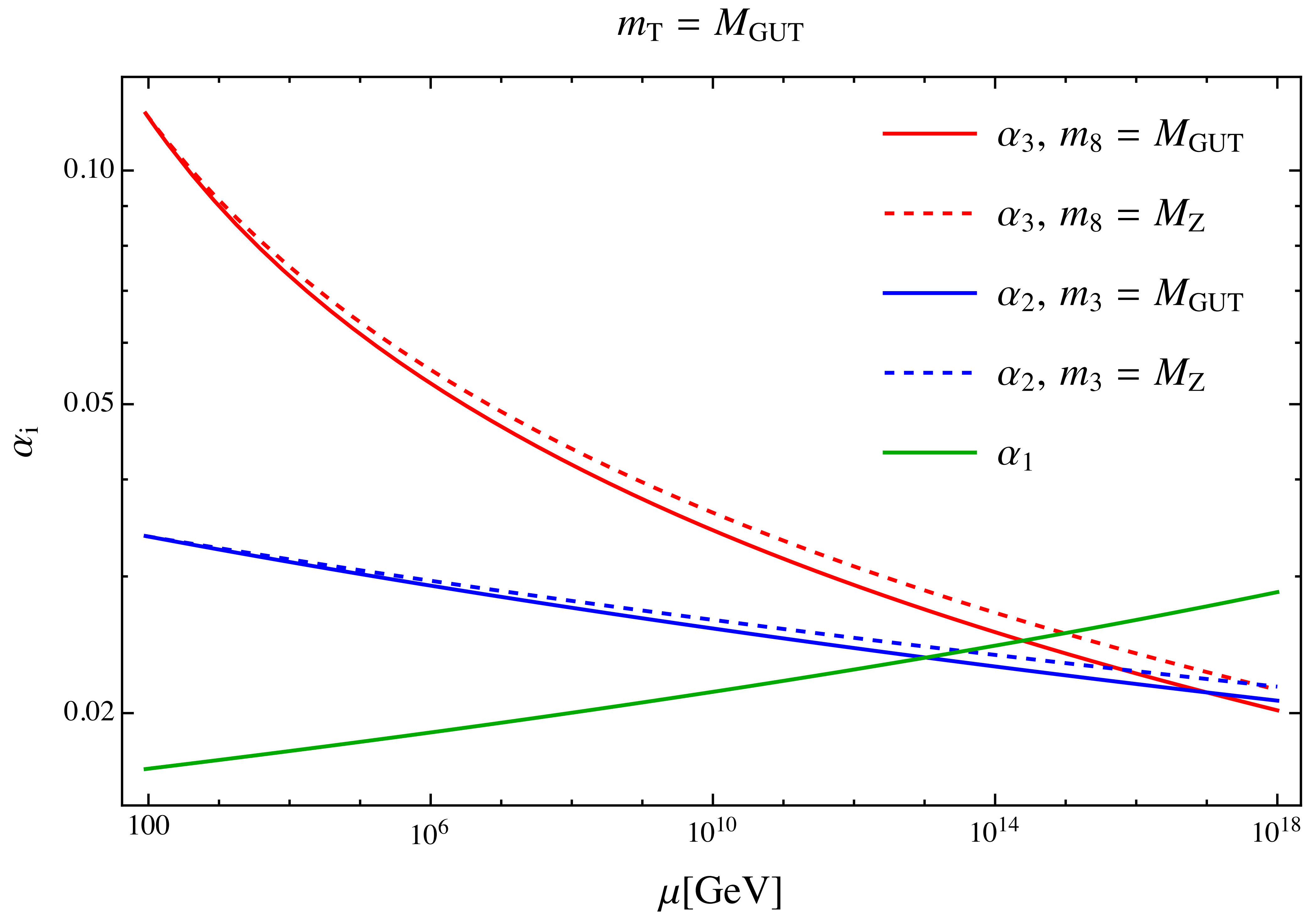
- Charge quantization
- Proton decay
- Existence of magnetic monopoles

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



However, new particle states can come to the rescue

An example: Minimal SU(5)



Georgi Glashow model is a natural candidate

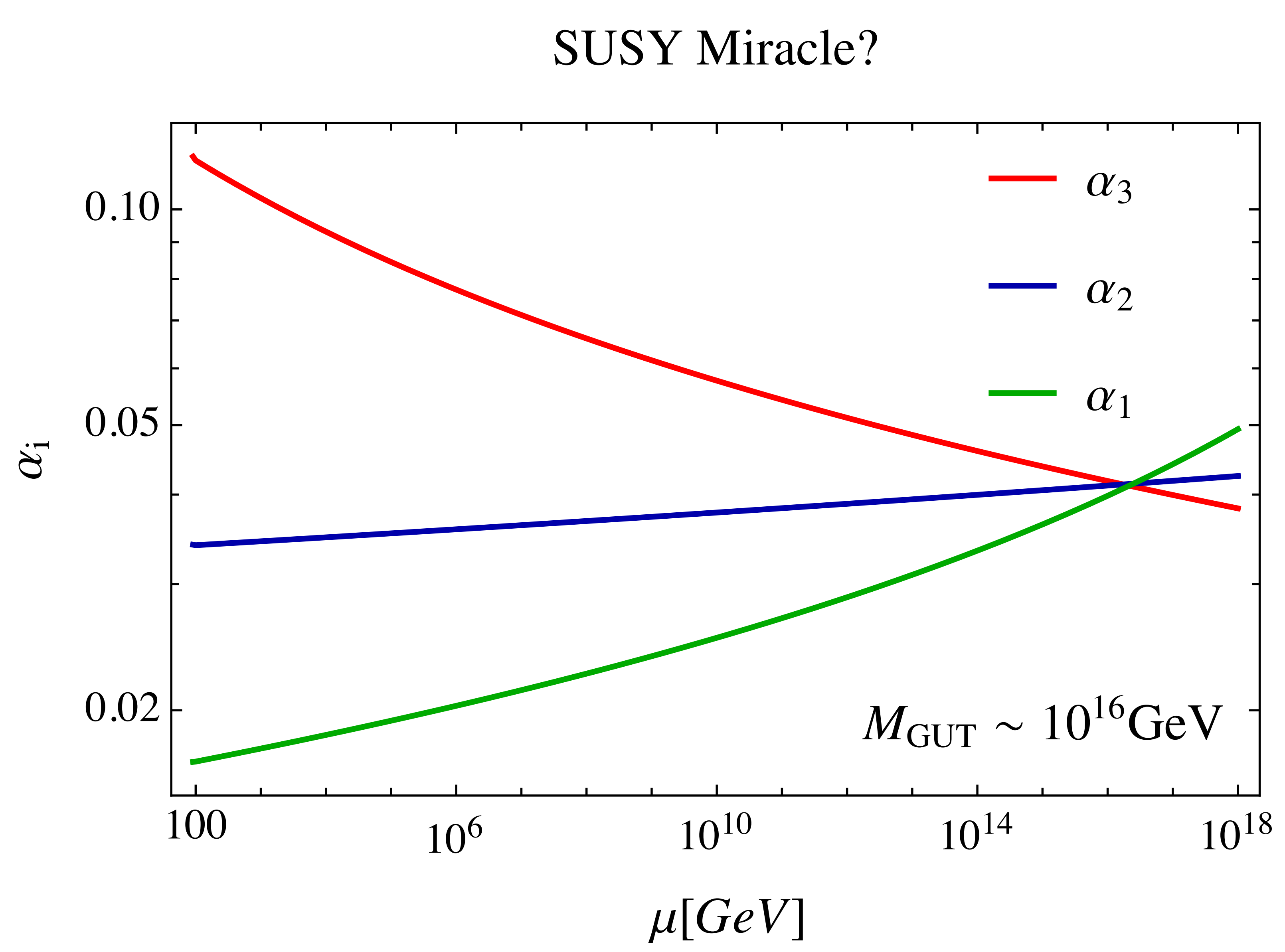
$$5_H = \begin{pmatrix} T_C \\ \Phi_{SM} \end{pmatrix}, \quad 24_H = \begin{pmatrix} 8_C & X \\ \bar{X} & 3_H \end{pmatrix}$$

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:

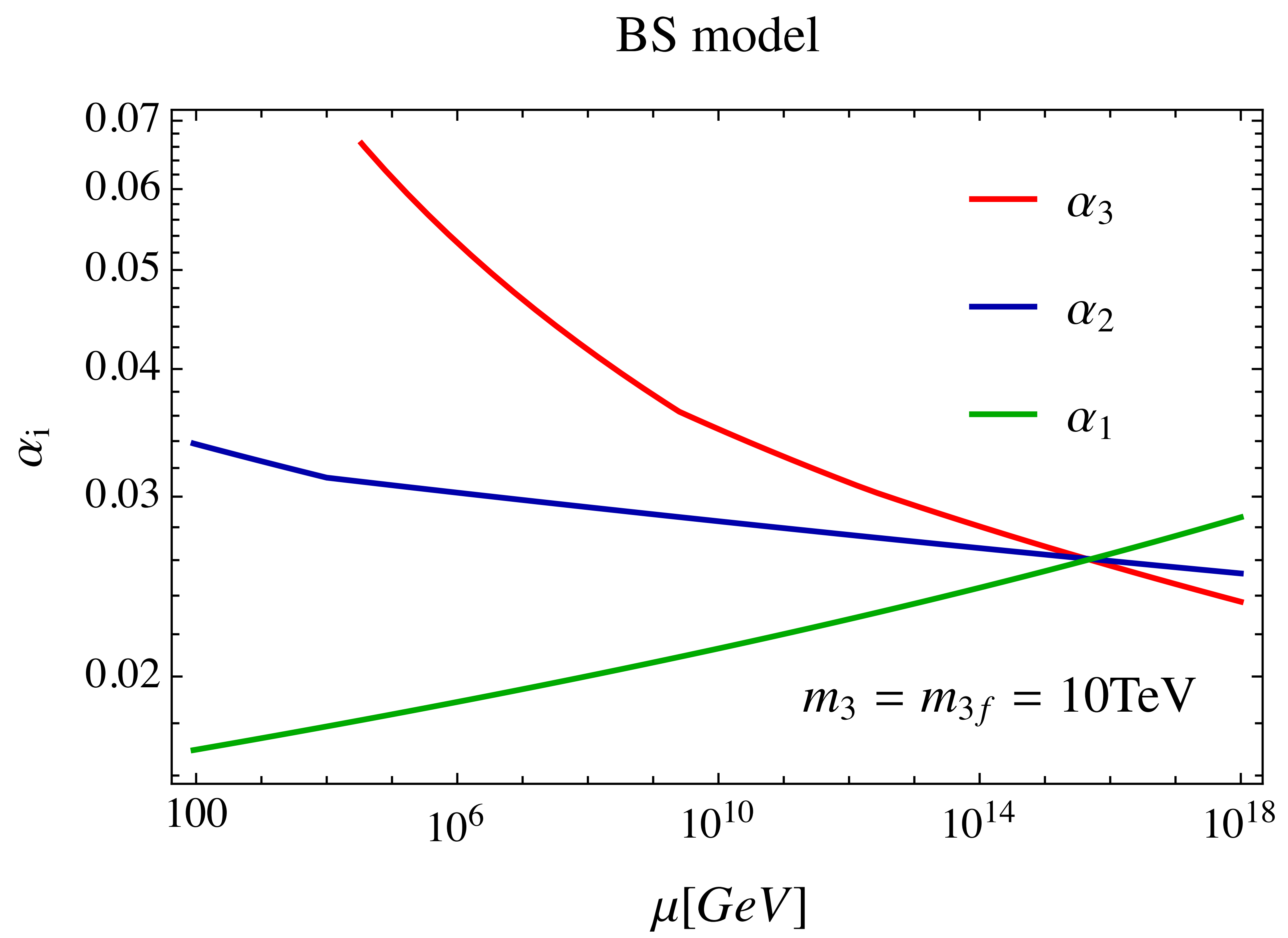
More is needed

Ways out



SM with Supersimmetry naturally unifies with (lots of) new particles at TeV

Miracle?



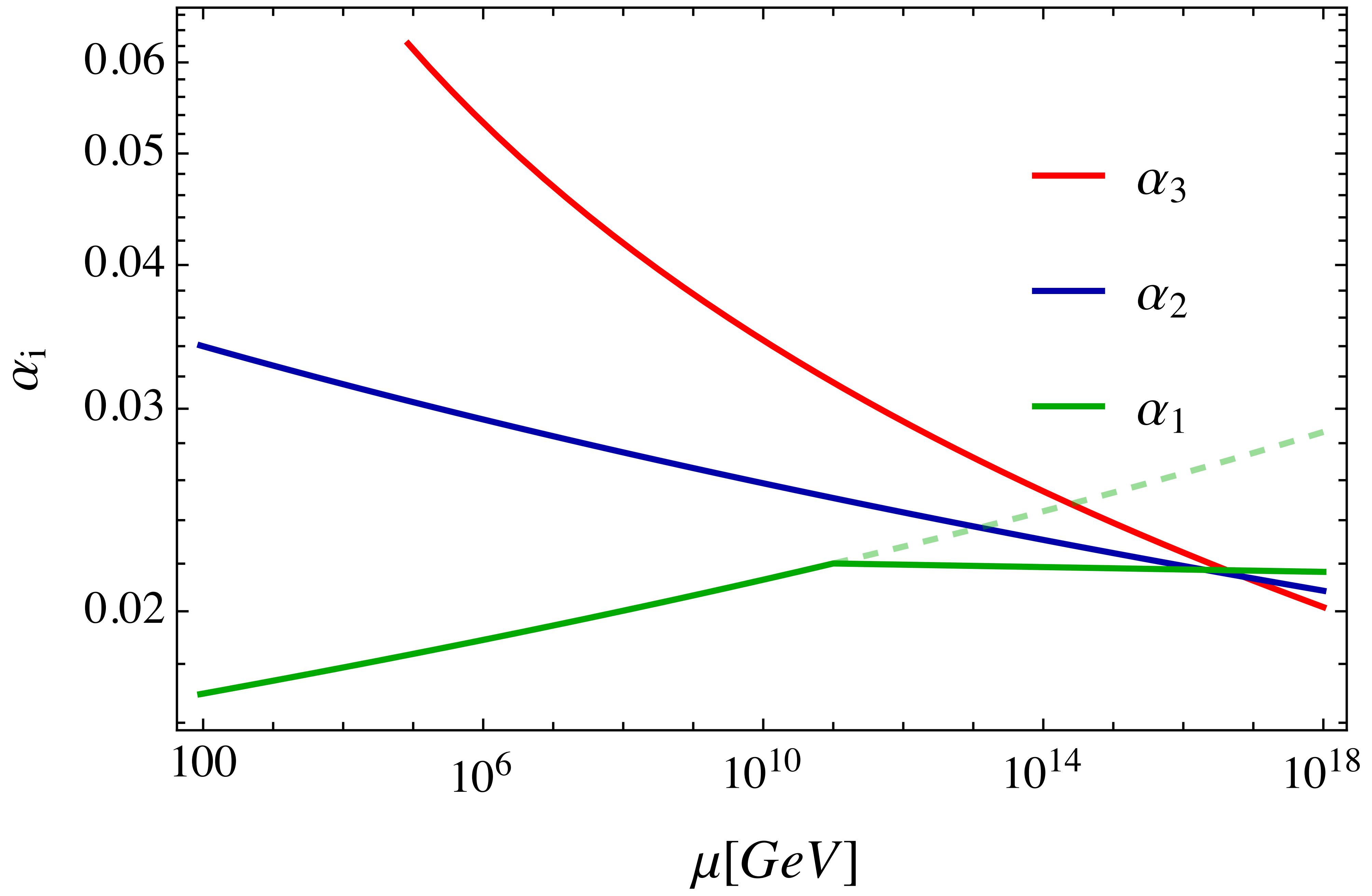
A non-SUSY solution was proposed by Bajc, Senjanović '07

- Work on small representation → spectrum more constrained
- Specifically add a 24_F : weak triplet fermion must lie within LHC energies
- Type III seesaw testable at LHC
- More on the physics of the weak triplet scalar later

Message: without intermediate scales, light particle states required to ensure unification

$SO(10)$: the real unification?

Adding W_R



- Fermions unified in 16_F — neutrino gets mass
- Unification ensured by intermediate scale $M_I \gtrsim 10^{10}$GeV
- Desert picture long-standing now for more than 40 years, no hope of probing this theory?

Same BS philosophy: study minimal viable theory based on small representations. Surprisingly:

- **New particle states are predicted at LHC scales**
- **P-lifetime below 10^{35}yrs within reach of experiments**

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

$$\Big\downarrow$$

Higher dimensional operators needed

Still…

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

This is crux of it all!

Seesaw

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

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

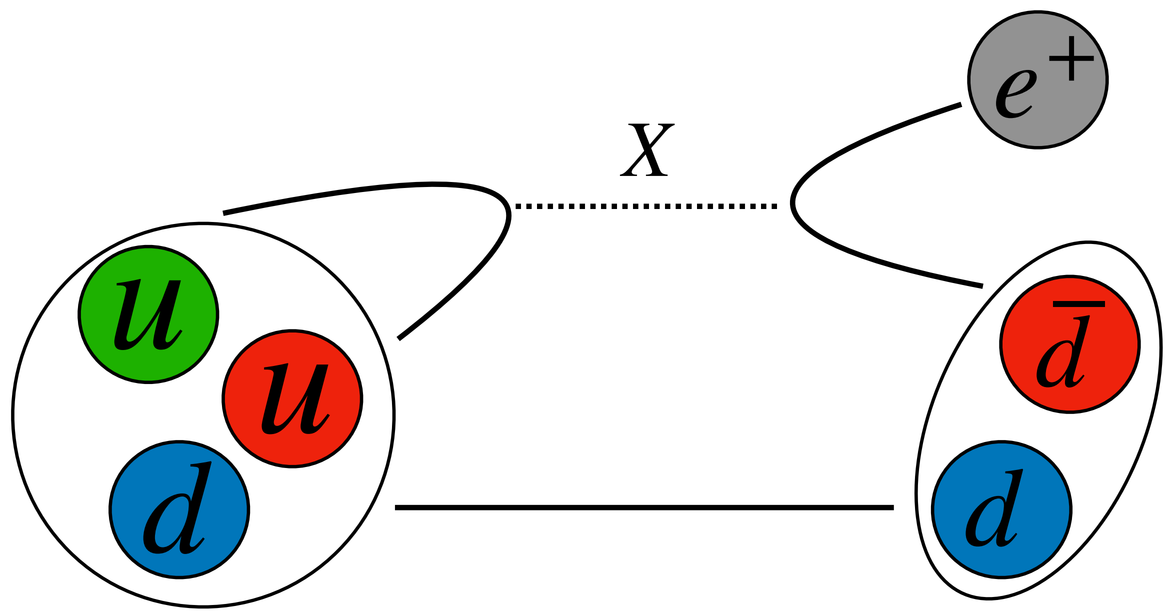
$$m_{\mathrm{N}} \simeq \frac{M_{\mathrm{I}}^2}{\Lambda}$$

This leads to a neutrino mass

$$m_\nu \simeq \frac{(m_{3D})^2}{m_N} \simeq \frac{m_t^2 \Lambda}{M_I^2}$$

KATRIN experiment $m_\nu \lesssim$ eV

Proton decay



Proton lifetime from Super-Kamiokande requires

$$\tau_p \gtrsim 10^{34}\text{yrs} \rightarrow \mathrm{M_{GUT}} \gtrsim 4 \cdot 10^{15}\text{GeV}$$ [1]

When combined with neutrino constrain

$$m_\nu \simeq \frac{(m_{3D})^2}{m_N} \simeq \frac{m_t^2 \Lambda}{M_I^2} \simeq \text{eV} \left(\frac{m_t}{100\text{GeV}} \frac{6 \cdot 10^{14}\text{Gev}}{M_I} \right)^2 \left(\frac{\Lambda}{4 \cdot 10^{16}\text{GeV}} \right) \lesssim \text{eV}$$

We learn that M_I must be close to unification scale

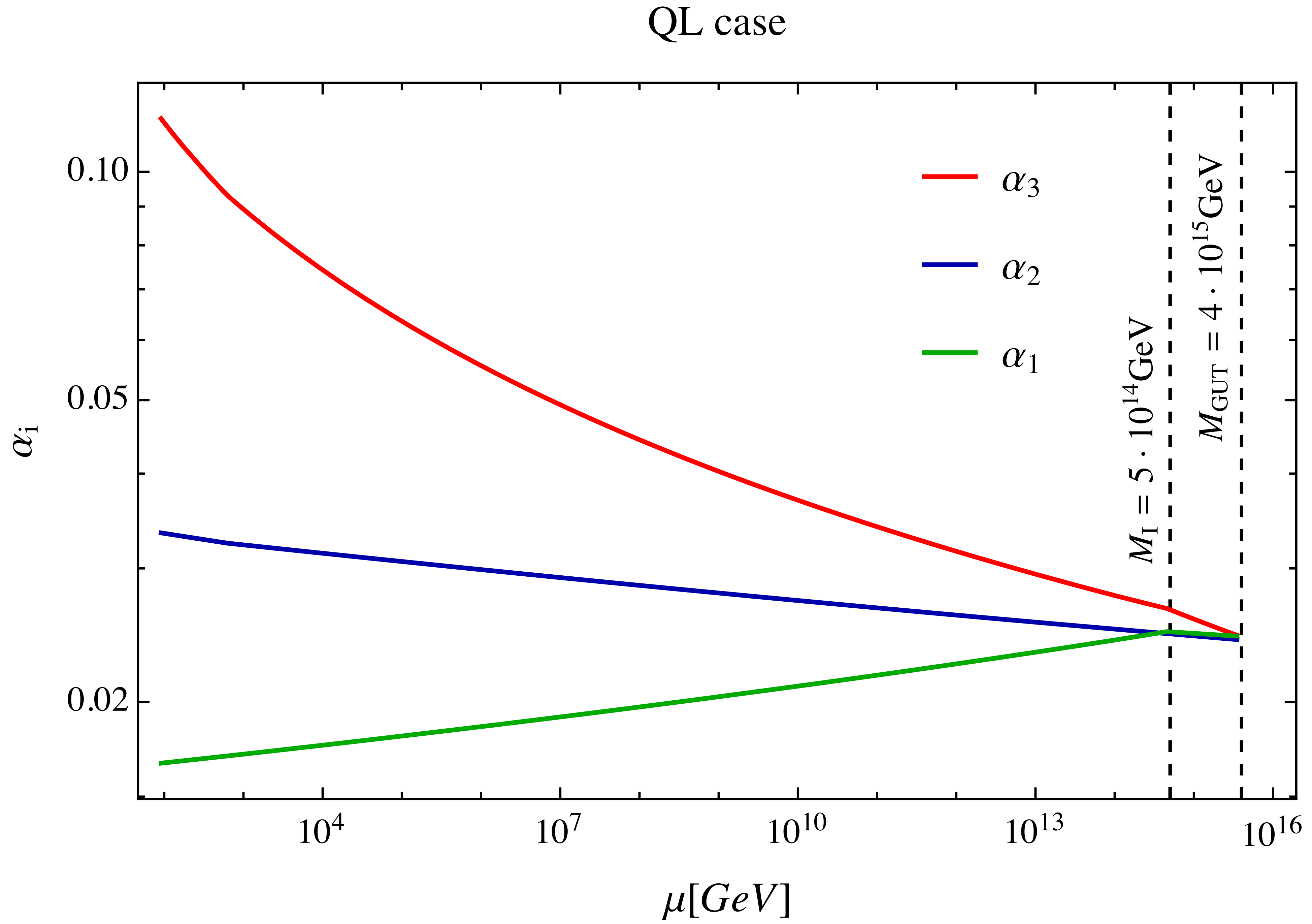
$$M_I \simeq M_{GUT}$$

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

[1] This is true in the absence of judicial cancellations in proton decay see eg., Nandi, Stern, Sudarschan '82 and Dorsner Perez '05

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

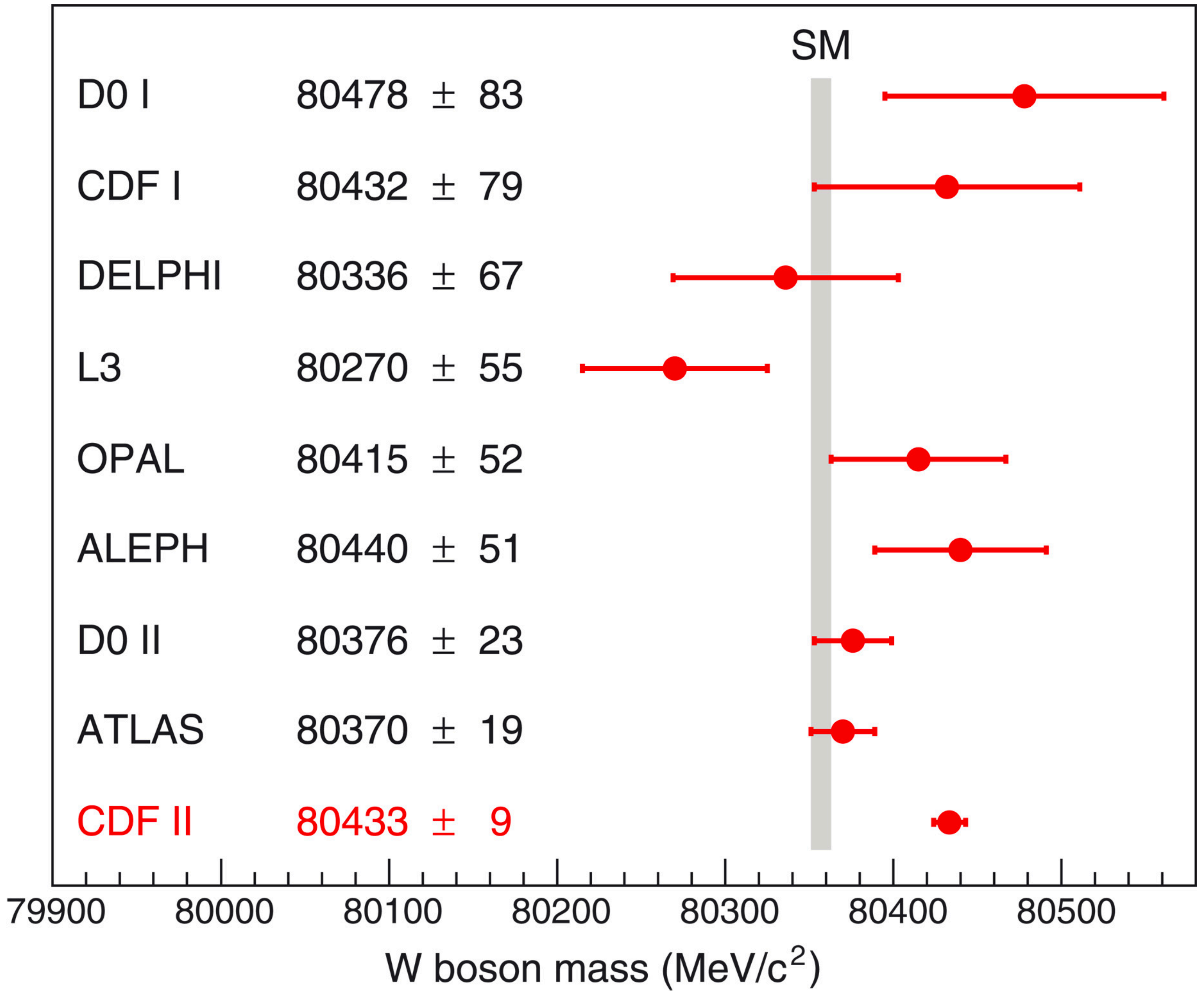
Particle	Mass range
scalar quark doublet	$m_{sq} \lesssim 10\text{TeV}$
weak triplet	$m_3 \lesssim 10\text{TeV}$
color octet	$m_8 \lesssim 10\text{TeV}$
scalar lepton doublet	$10^3\text{GeV} - M_\text{I}$
second Higgs doublet	$10^3\text{GeV} - M_\text{GUT}$
scalar down quark	$10^{12}\text{GeV} - M_\text{GUT}$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

- 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** $\tau_p < 10^{35}\text{yrs}$

Phenomenological consequences of light triplet

G. Senjanović, MZ 2205.05022

CDF Collaboration '22



Low energy effective theory contains operators of the form

$$\mu\, \Phi^\dagger_{SM}\, 3_H\, \Phi_{SM}$$

$$\downarrow$$

$$\langle 3_H \rangle = v_3 \simeq \frac{\mu}{g^2}\left(\frac{M_W}{m_3}\right)^2$$

which corrects W-mass while leaving Z-mass unchanged.

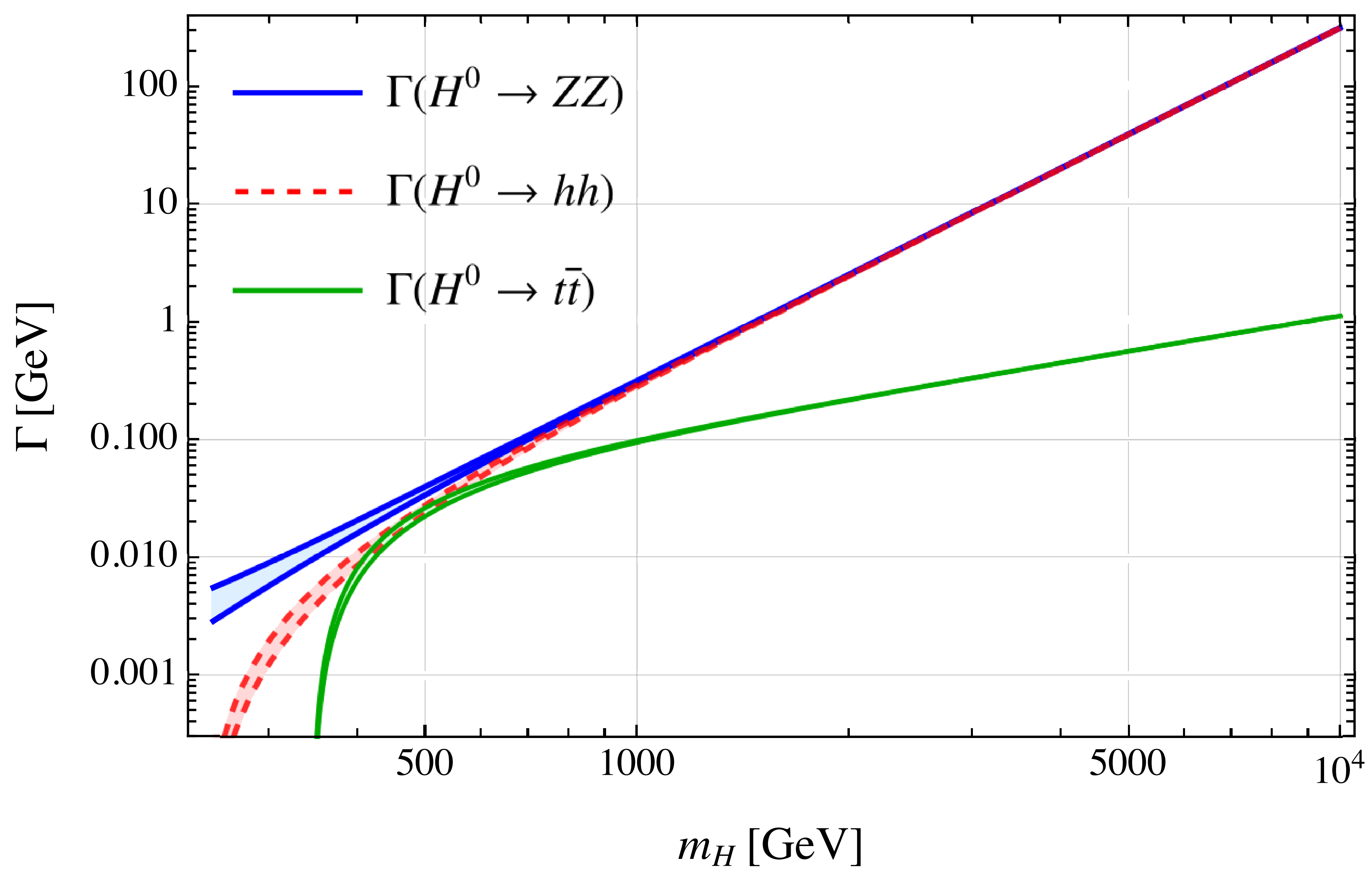
If CDF true, $v_3 \simeq \mathcal{O}(\mathrm{GeV})^*$ determines the mixing θ between 3_H and Φ_{SM}

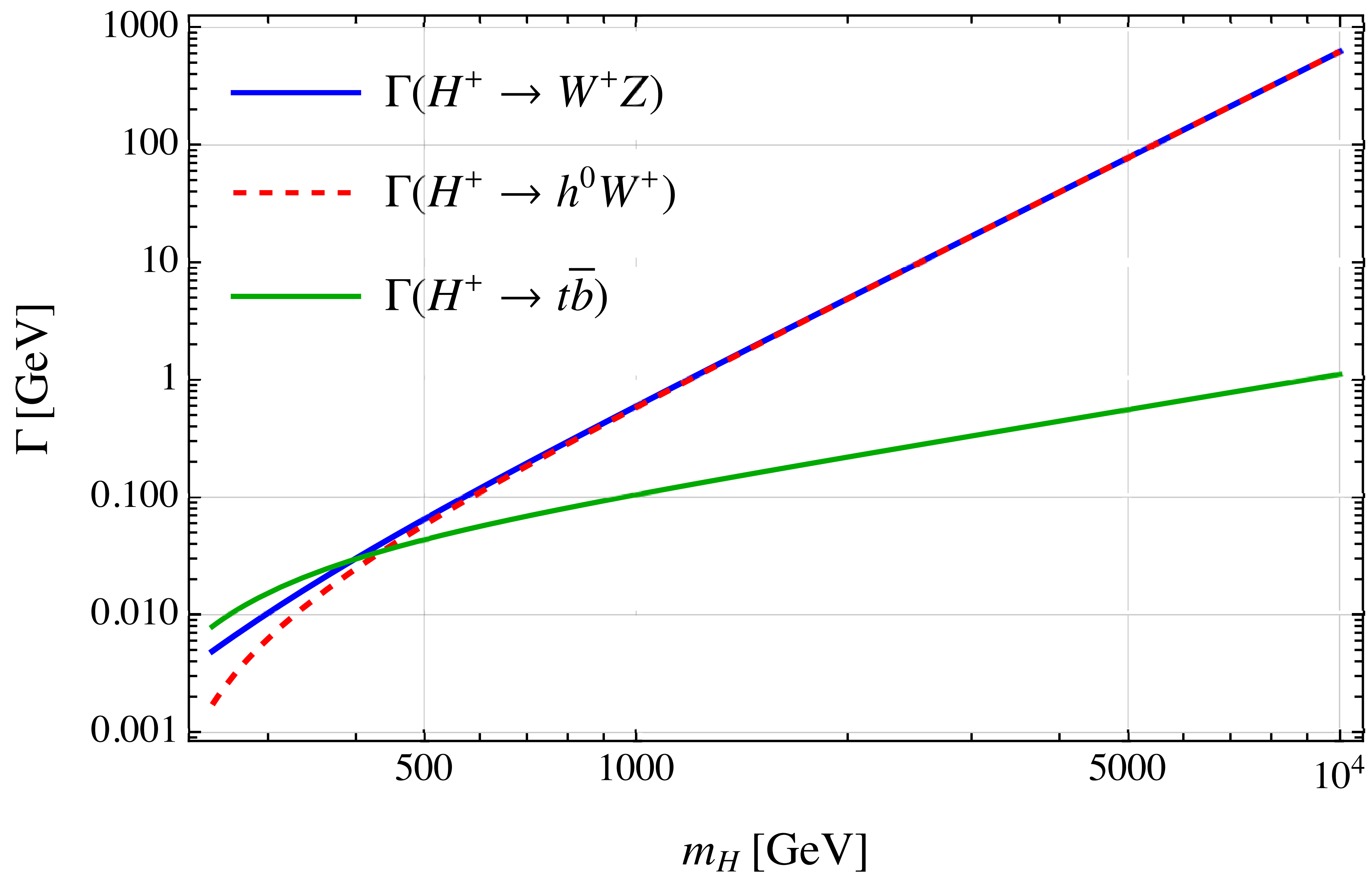
$$\downarrow$$

θ uniquely determines 3_H decay rate into SM particles

* Situation is a bit more involved if one of the new weak doublet is fine-tuned without reason at a low scale

* It is instead completely clean e.g., in BS model





Decay rates of triplet into SM are uniquely determined by its mass m_H and $W-$mass deviation θ [1]

$$\frac{1}{2}\Gamma(H^0 \to W^+W^-) \simeq \Gamma(H^0 \to ZZ)$$

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

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

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

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

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

[1] This is a consequence of working within a GUT

Discussion

- Gospel of desert picture in $SO(10)$ has been challenged — minimal theory structurally predicts 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

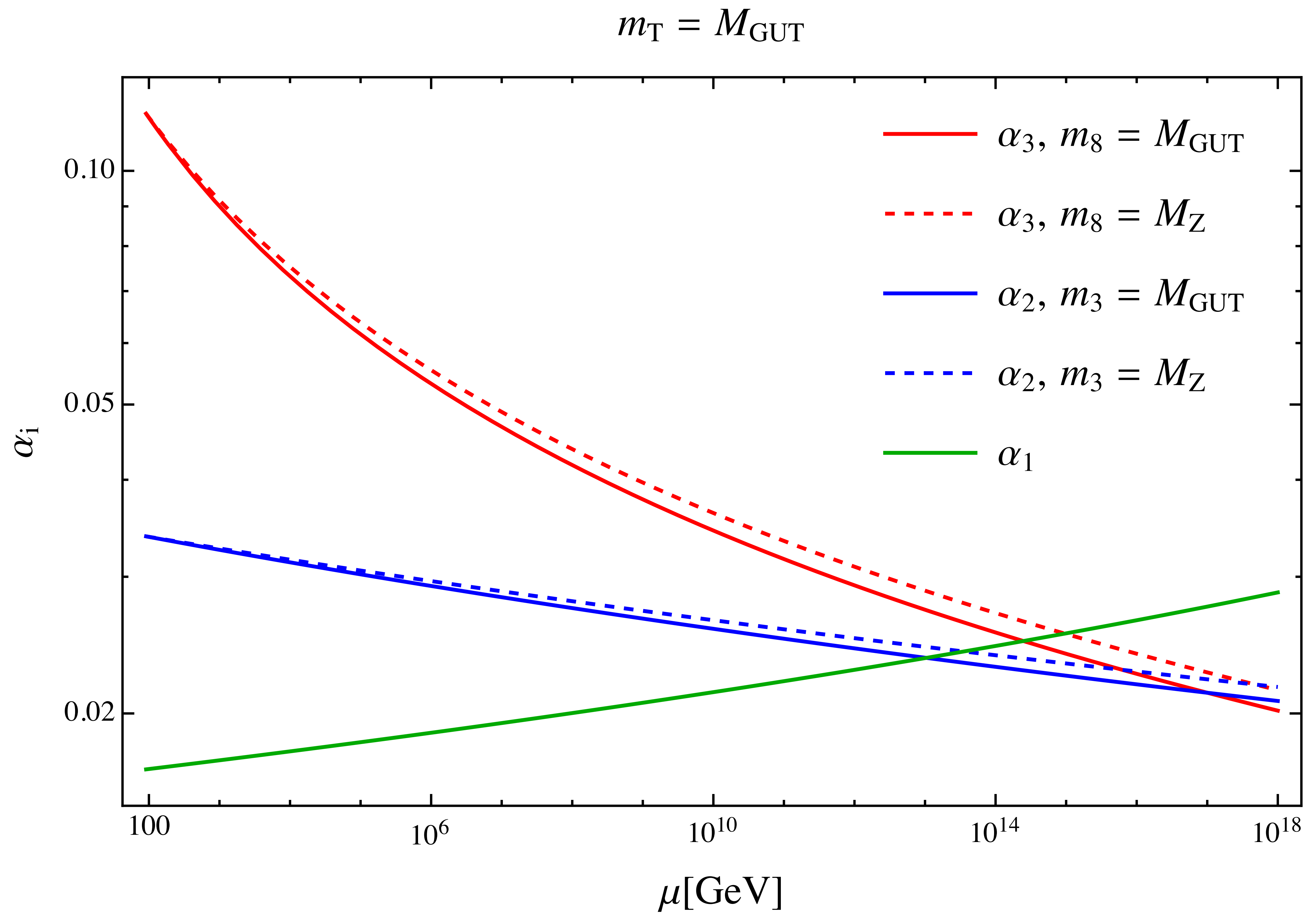
- One of the predicted light states, the weak triplet, naturally explains CDF recent $W-$mass deviation from SM value

- Its decay rate into SM are fixed by its mass and $W-$mass deviation

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

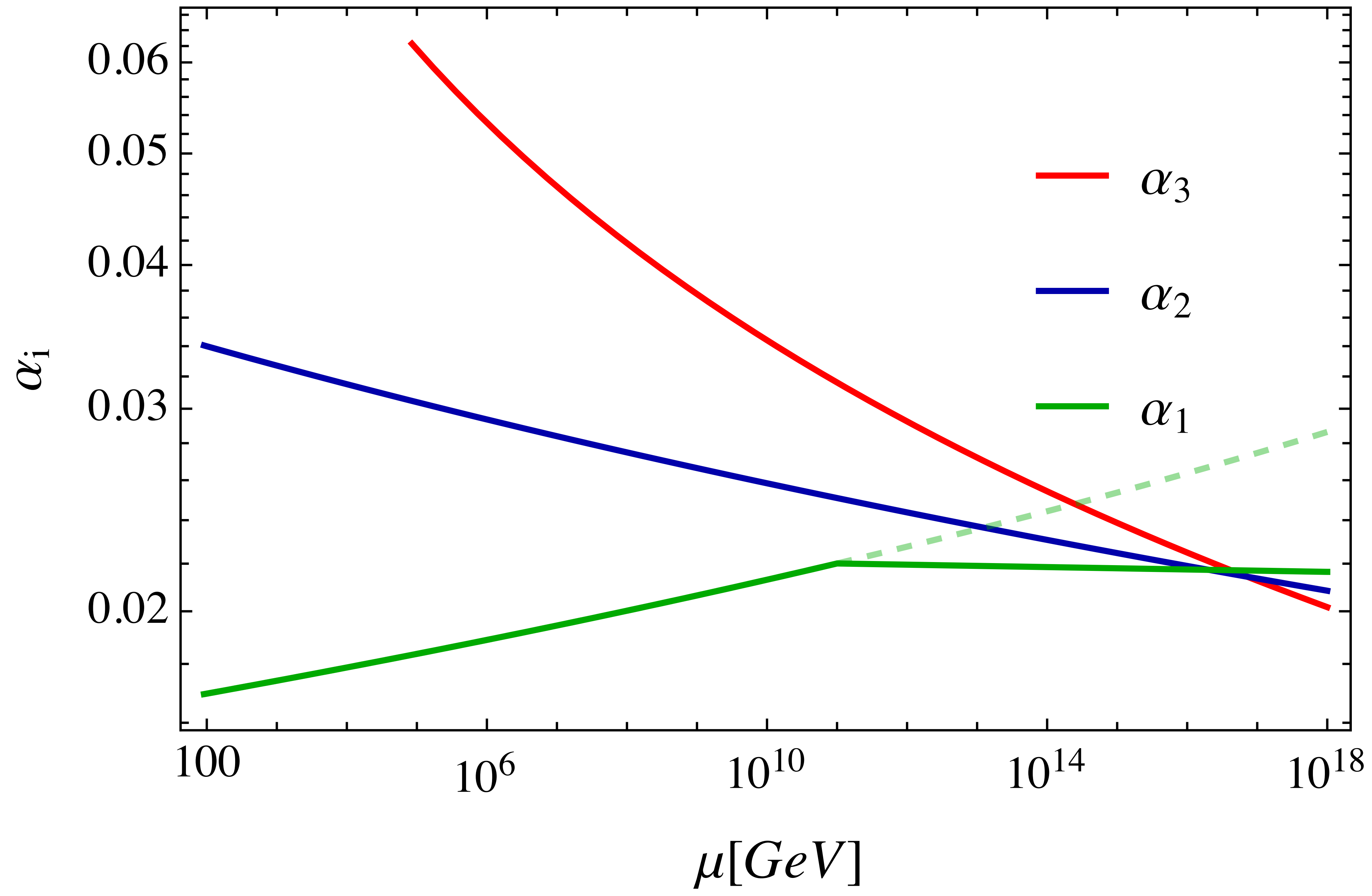
Unification around $M_{GUT} \simeq 10^{14}$GeV — in tension with proton decay lifetime $\tau_p \gtrsim 10^{34}$yrs

Moreover, neutrino is massless

Some non-renormalizable extensions developed in the years integrating new states, eg.,
Dorsner, Perez 2005 and Bajc, Senjanović 2007

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

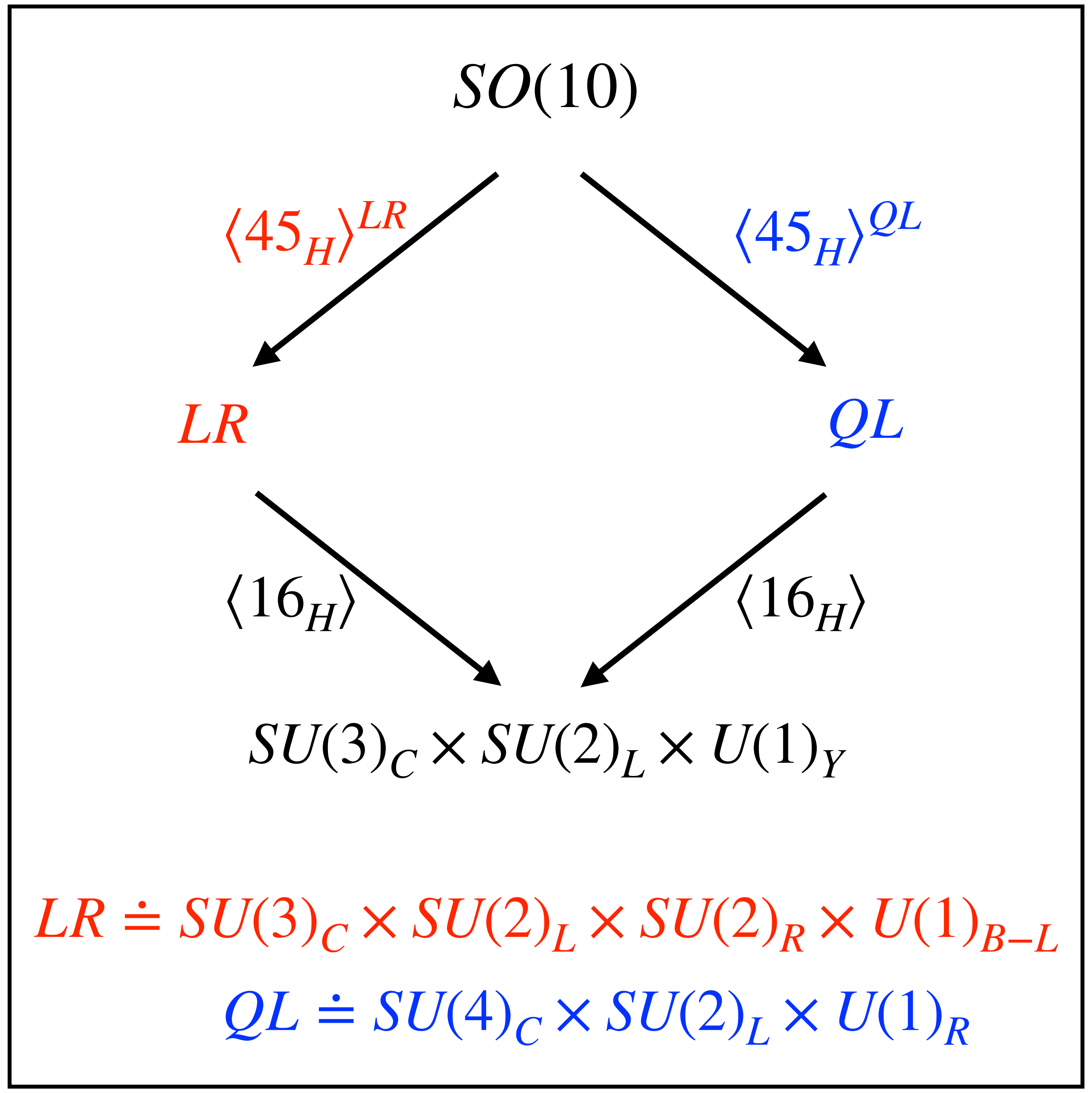
- 10_H real does not work since $m_u = m_d$ hence the need for complex 10_H
- At renormalizable level still $m_d = m_l$, so higher dimensional operators are needed for Yukawa

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

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

Crux: $m_{3D} = m_t$

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 $16_H\, 45_H\, 16^*_H$

	$4_C 2_L 2_R$	$3_c\, 2_L\, 1_Y$	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 $M_I \sim 10^{12\div13}\,\mathrm{GeV}$ → scalars must be light

Cutoff not so far from M_{GUT}

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

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

	$4_C\,2_L\,2_R$	$4_C\,2_L\,1_R$	$3_c\,2_L\,2_R\,1_X$	$3_c\,2_L\,1_R\,1_X$	$3_c\,2_L\,1_Y$	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

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

where $T = T^\dagger$ transforms as $T \to UTU^\dagger$, with covariant derivative $D_\mu T = \partial_\mu T + ig\left[A_\mu, T\right]$. T and Φ are decomposed as

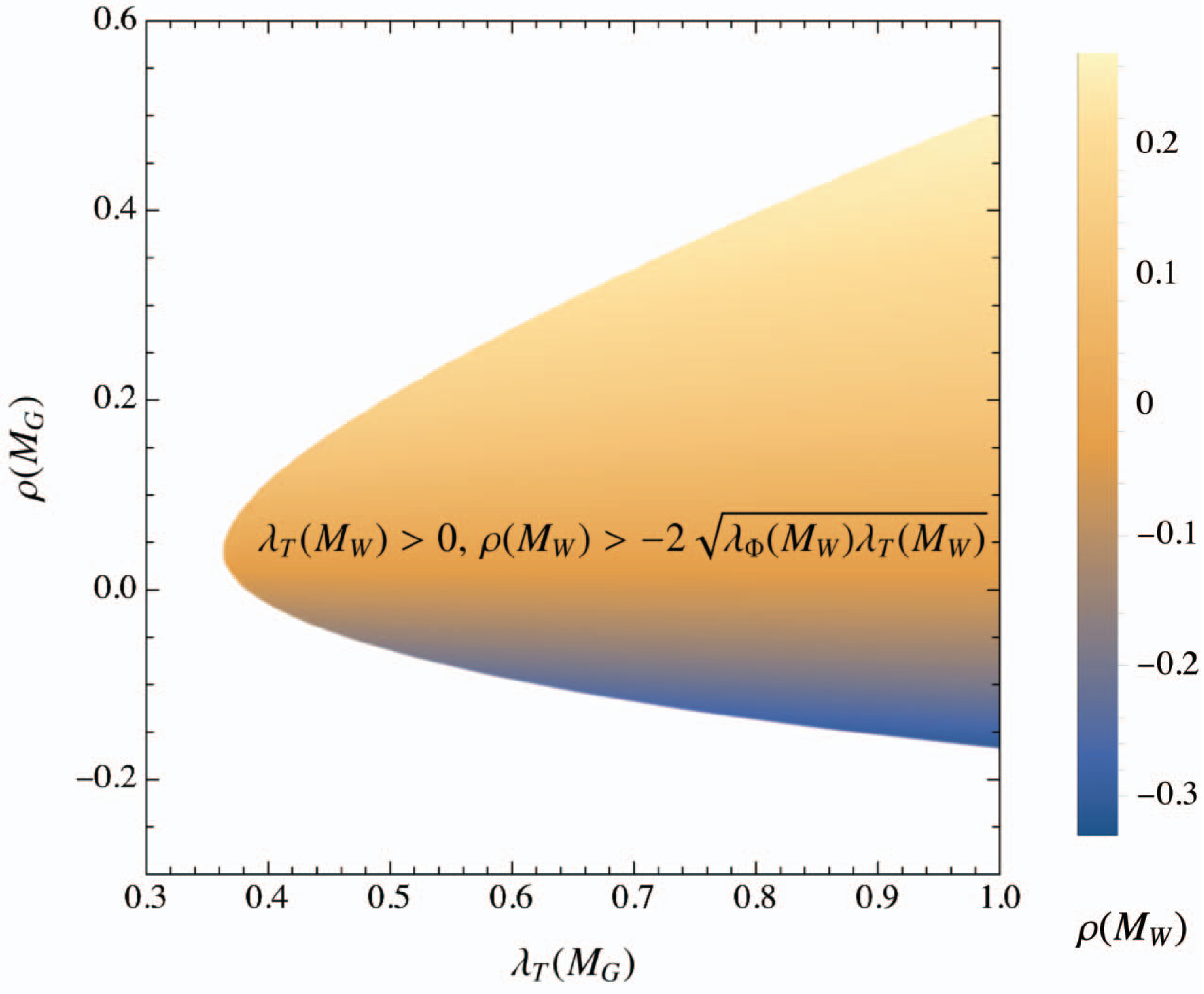
$$
\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix}\sqrt{2}\phi^+ \\ v + \phi_R^0 + i\phi_I^0\end{pmatrix}, \; T = \frac{1}{2}\begin{bmatrix} v_T + t^0 & \sqrt{2}t^+ \\ \sqrt{2}t^- & -v_T - t^0\end{bmatrix}.
$$

$$
\theta \doteq \frac{g\,v_T}{M_W}
$$

$$
\begin{aligned}
h^0 &\simeq \phi^0 + \theta\left(\frac{m_H^2}{m_H^2 - m_h^2}\right)t^0 & G^+ &\simeq \phi^+ - \theta t^+, \\
H^0 &\simeq t^0 - \theta\left(\frac{m_H^2}{m_H^2 - m_h^2}\right)\phi^0, & H^+ &\simeq t^+ + \theta\phi^+.
\end{aligned}
$$

$$
\begin{aligned}
&g\theta H^0\left(M_W WW,\, \frac{M_Z Z^2}{2c_W},\, \frac{(m_H h^0)^2}{4M_W},\, \frac{m_f\overline{f}f}{2M_W}\right), \\
&g\theta H^+\left(\frac{M_W ZW^-}{c_W},\, \frac{i}{2}\overleftrightarrow{\partial}h^0W^-,\, \frac{m_d\overline{u}_L d_R - m_u\overline{u}_R d_L}{\sqrt{2}M_W}\right).
\end{aligned}
$$

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



$$\frac{d\lambda_\Phi}{dt} \simeq \left(\frac{d\lambda_\Phi}{dt}\right)_{SM} + \frac{2}{3\pi^2}\rho^2,$$
$$\frac{d\lambda_T}{dt} \simeq \frac{1}{16\pi^2}\left(24{g_2}^4 - 24{g_2}^2\lambda_T + 11\lambda_T^2 + 16\rho^2\right),$$
$$\frac{d\rho}{dt} \simeq \frac{1}{32\pi^2}\left(12\rho y_t^2 - 3{g_1}^2\rho + 6{g_2}^4 - 33{g_2}^2\rho + 10\lambda_T\rho + 24\lambda_\Phi\rho + 16\rho^2\right),$$

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