06/07/2018

PASCOS 2018

Higgs mass, strong CP problem, GUT

Keisuke Harigaya (UC Berkeley, LBNL)

with Lawrence Hall

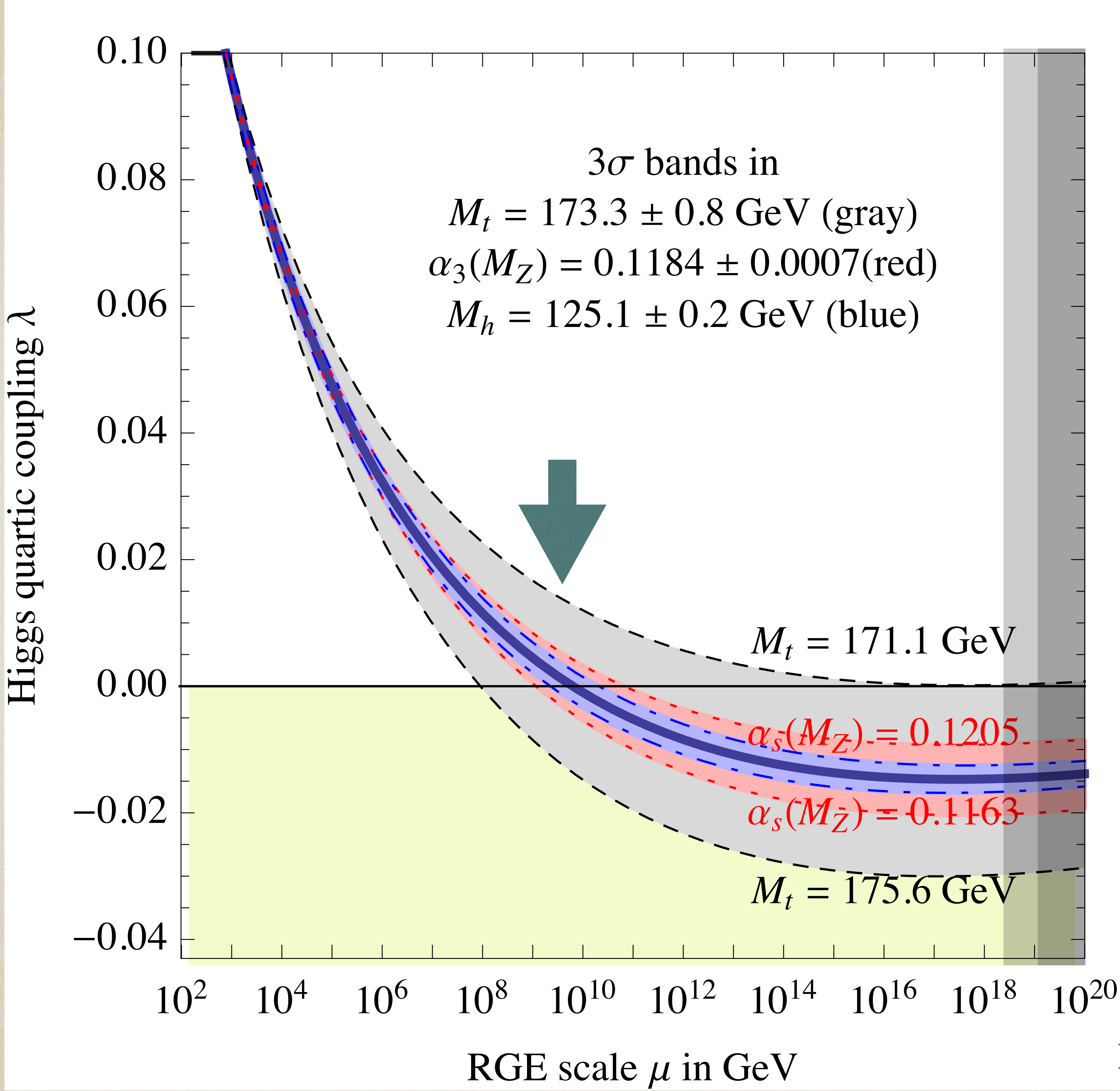
1803.08119

$$V = \lambda_{\mathrm{SM}} |H|^4 - m_H^2 |H|^2$$

$$V = \lambda_{\rm SM}|H|^4 - m_H^2|H|^2$$

Today's topic

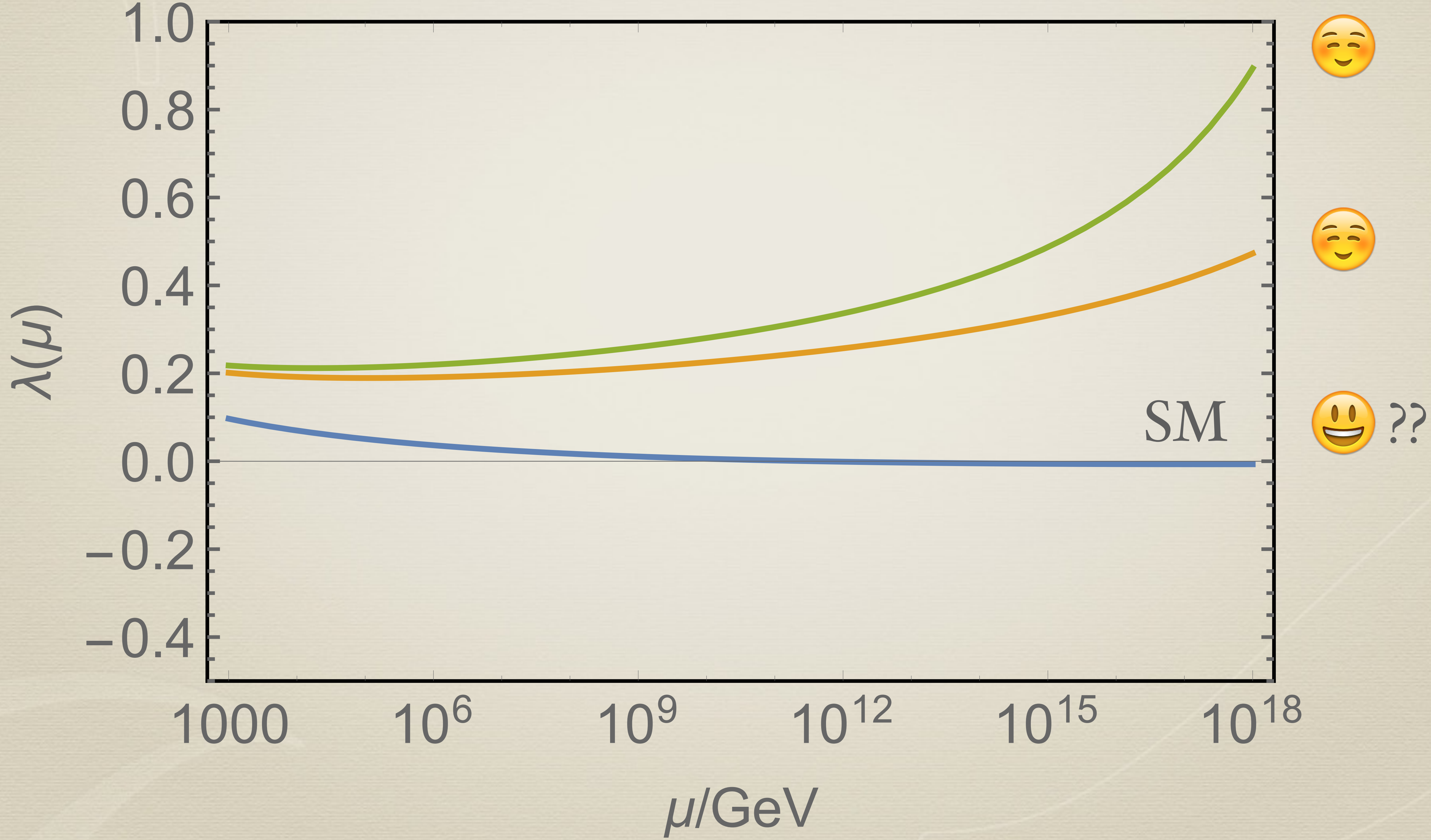
Assume that the SM is valid up to high energy scale



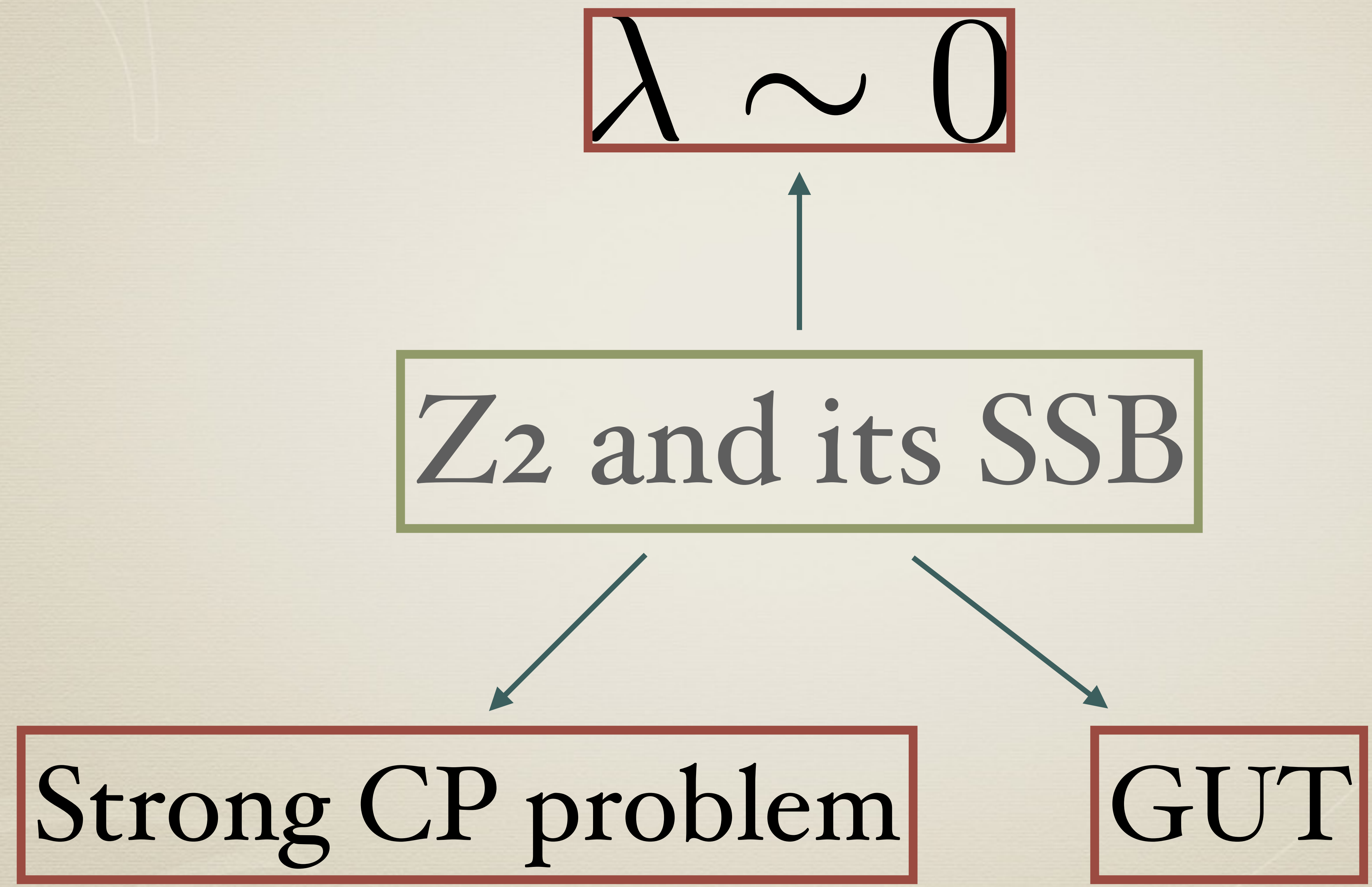
$O(0.01)$

1307.3536

Small boundary condition



Some new physics to explain $\lambda = 0$?



$\lambda \sim 0$
Z_2 and its SSB
Strong CP problem
GUT

Introduce Z_2 symmetry

$$H \leftrightarrow H'$$

$$SU(2) \leftrightarrow SU(2)'$$

$$V(H,H') = \lambda(|H|^2 + |H'|^2)^2 + \lambda'|H|^2|H'|^2 - m^2(|H|^2 + |H'|^2)$$

Let us assume $m >> v_{EW}$

$$V(H,H') = \lambda(|H|^2 + |H'|^2)^2 + \lambda'|H|^2|H'|^2 - m^2(|H|^2 + |H'|^2)$$

$$\langle H' \rangle^2 = \frac{m^2}{2\lambda} \qquad\qquad m_H^2 \simeq 0 \to \lambda' \simeq 0$$

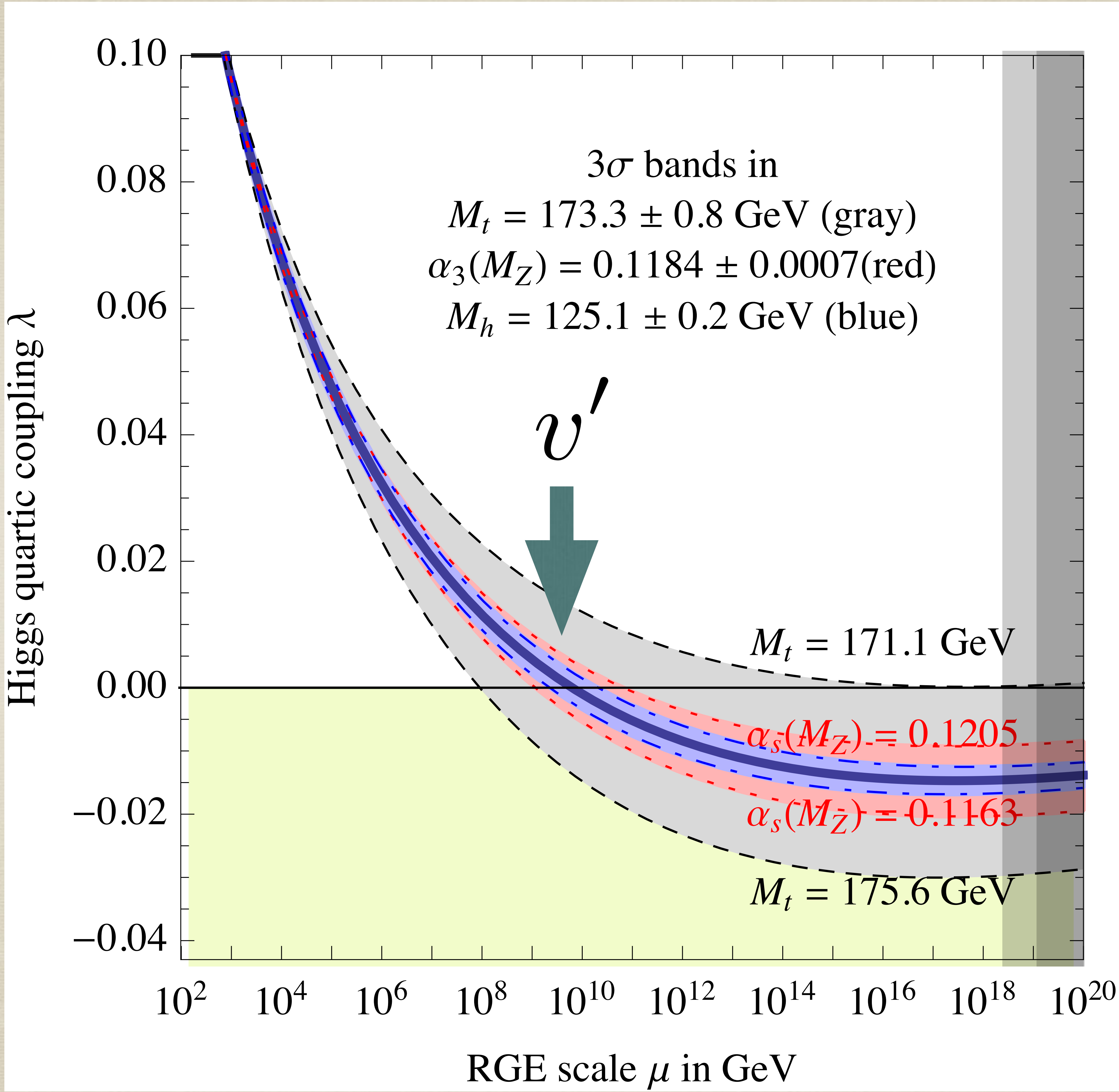
$$V(H,H') \simeq \lambda(|H|^2 + |H'|^2)^2 - m^2(|H|^2 + |H'|^2)$$

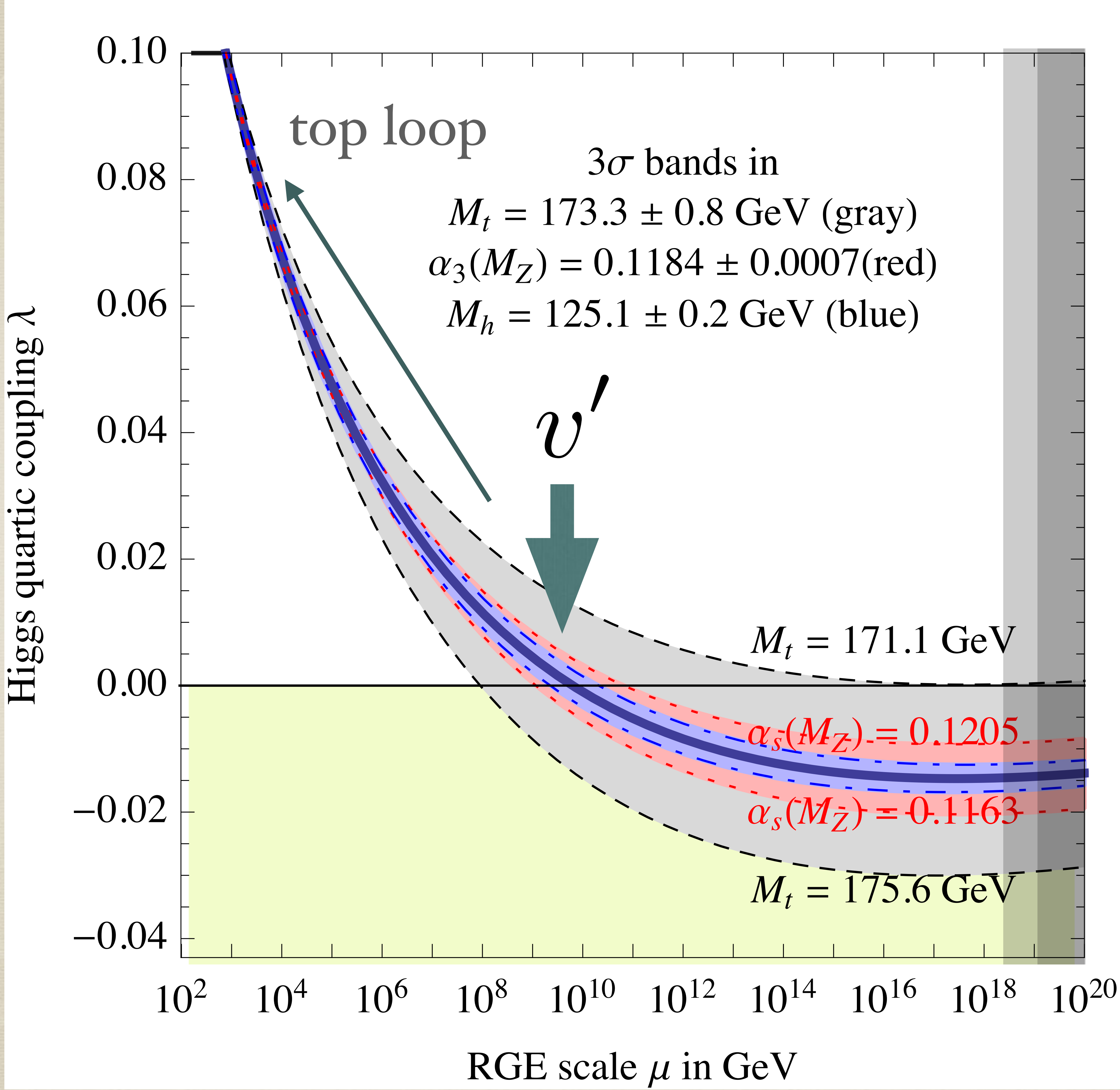
Accidentally SU(4) symmetric

SU(4) -> SU(3) by $\langle H' \rangle$

SM Higgs is a Nambu-Goldstone boson

$$\lambda_{\mathrm{SM}} = 0$$


3σ bands in
M_t = 173.3 ± 0.8 GeV (gray)
α_3(M_Z) = 0.1184 ± 0.0007(red)
M_h = 125.1 ± 0.2 GeV (blue)
v′
M_t = 171.1 GeV
α_s(M_Z) = 0.1205
α_s(M_Z) = 0.1163
M_t = 175.6 GeV
Higgs quartic coupling λ
RGE scale μ in GeV
0.10
0.08
0.06
0.04
0.02
0.00
−0.02
−0.04
10^2
10^4
10^6
10^8
10^10
10^12
10^14
10^16
10^18
10^20



top loop
3σ bands in
$M_t = 173.3 \pm 0.8$ GeV (gray)
$\alpha_3(M_Z) = 0.1184 \pm 0.0007$(red)
$M_h = 125.1 \pm 0.2$ GeV (blue)
v'
$M_t = 171.1$ GeV
$\alpha_s(M_Z) = 0.1205$
$\alpha_s(M_Z) = 0.1163$
$M_t = 175.6$ GeV
Higgs quartic coupling λ
0.10
0.08
0.06
0.04
0.02
0.00
−0.02
−0.04
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}
RGE scale μ in GeV

Fine-tuning

$$V(H,H') = \lambda(|H|^2 + |H'|^2)^2 + \lambda'|H|^2|H'|^2 - m^2(|H|^2 + |H'|^2)$$

$$\frac{v_{\rm EW}^2}{m^2} \times \frac{m^2}{\Lambda_{\rm cut}^2} \sim \frac{v_{\rm EW}^2}{\Lambda_{\rm cut}^2}$$

$\lambda' \ll 1$ $\quad$ $m^2 \ll \Lambda{\rm cut}^2$

Same as that of SM

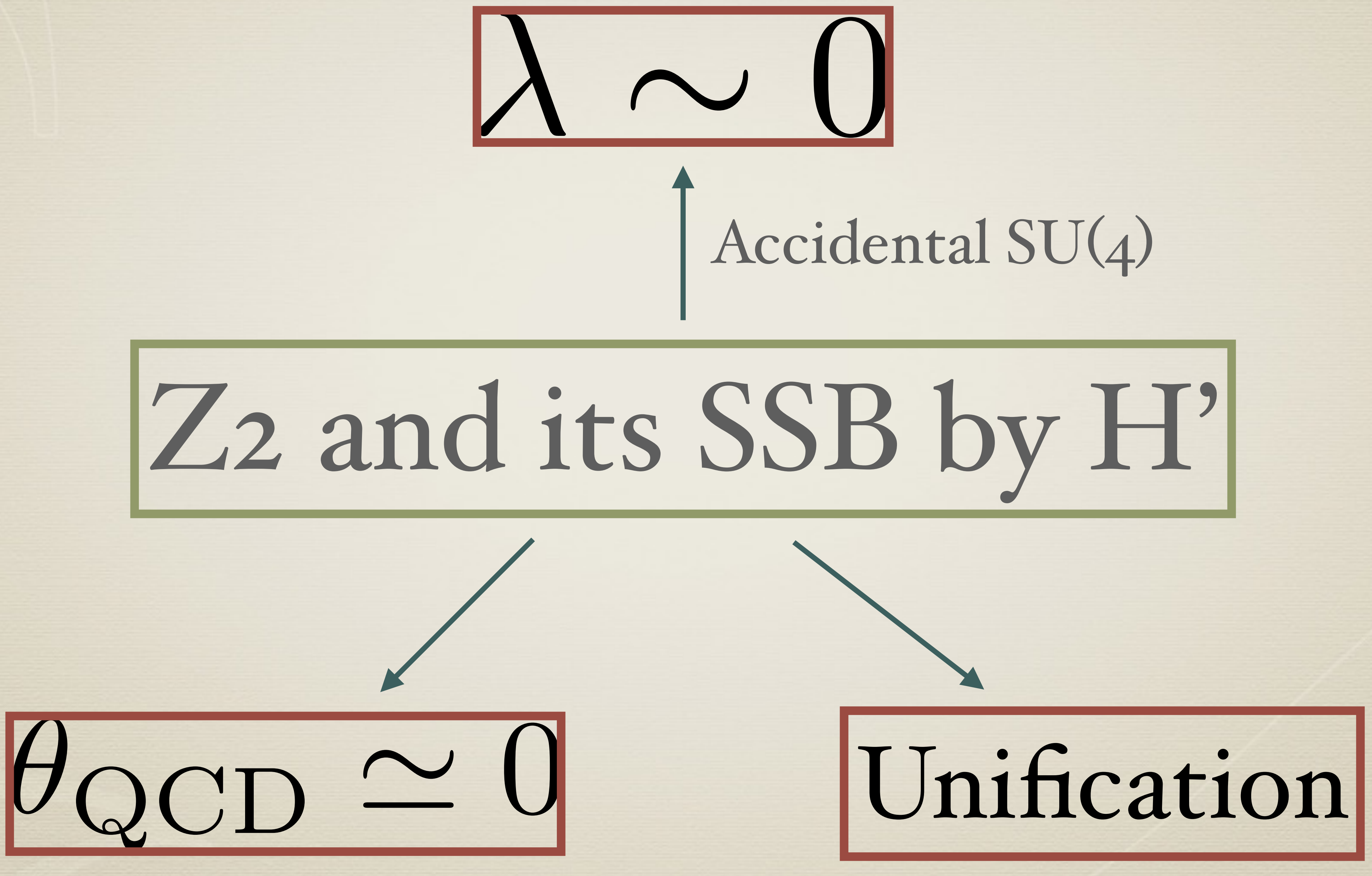
Fermions, gauge groups

$$q \leftrightarrow q' = (\bar{u}, \bar{d}),\ \ell \leftrightarrow \ell' \supset \bar{e}$$

$$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \supset SO(10)$$

$$q, \bar{u}, \bar{d}, q', \bar{u}', \bar{d}', \cdots$$

$SU(3)_c$ or $SU(3)_c \times SU(3)'_c$ $\times SU(2)_L \times SU(2)' \times$ $U(1)$ or $U(1) \times U(1)'$


$\lambda \sim 0$
Accidental SU(4)
Z2 and its SSB by H'
$\theta_{\mathrm{QCD}} \simeq 0$
Unification

Z_2 from SO(10)

Remnant of SO(10)

$$SO(10)$$

$H, H' \subset 16$

$q, \ell, q', \ell' = 16$

$q' = (\bar{u}, \bar{d}), \ell' \supset \bar{e}$

$$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

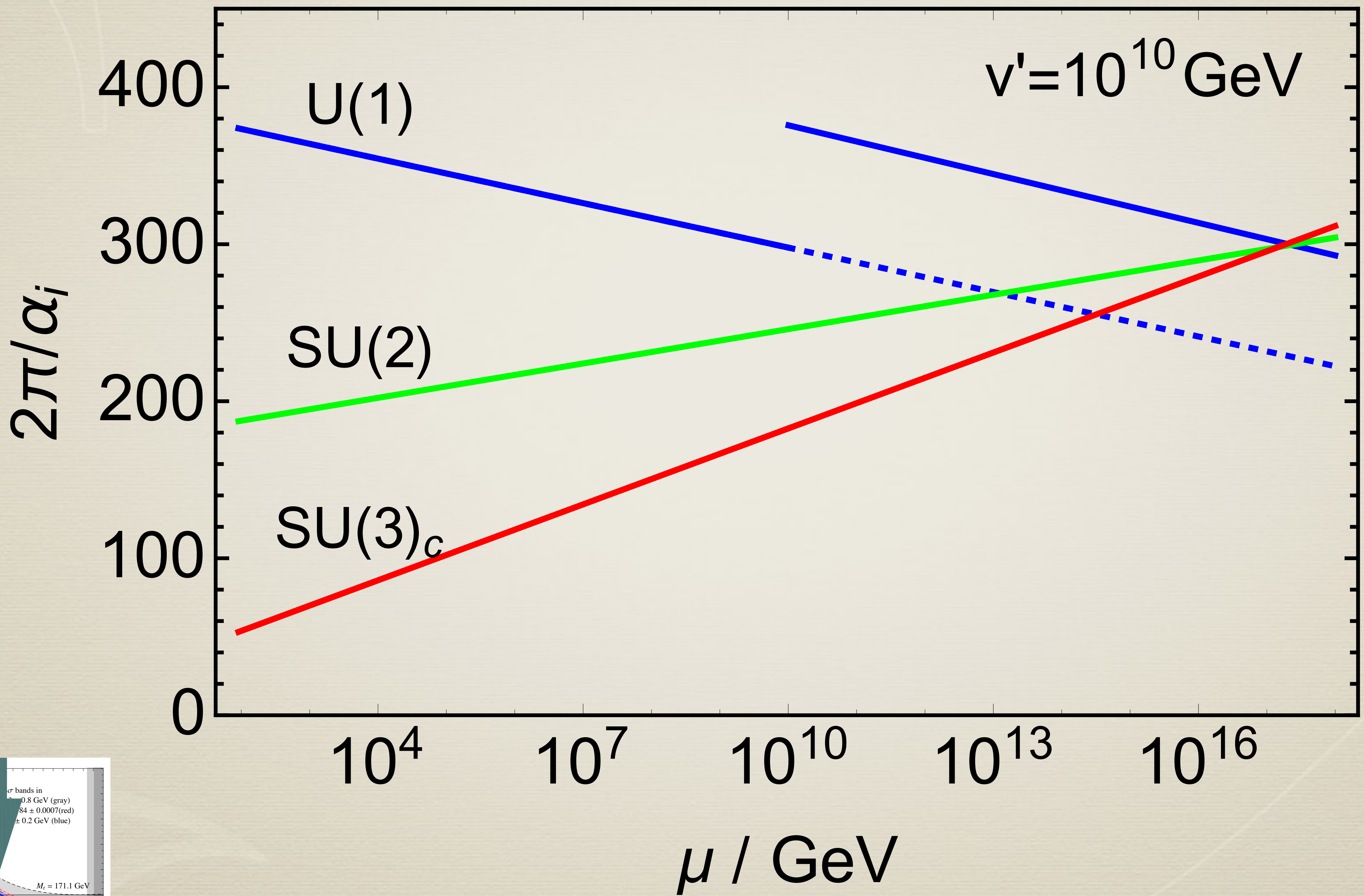
Left-right symmetry

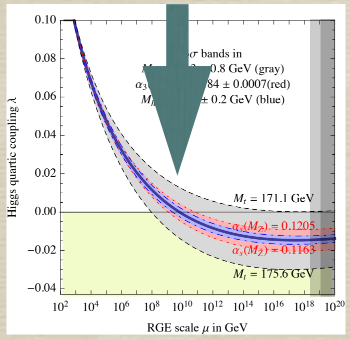
$H \leftrightarrow H'$

$\langle H' \rangle \neq 0$

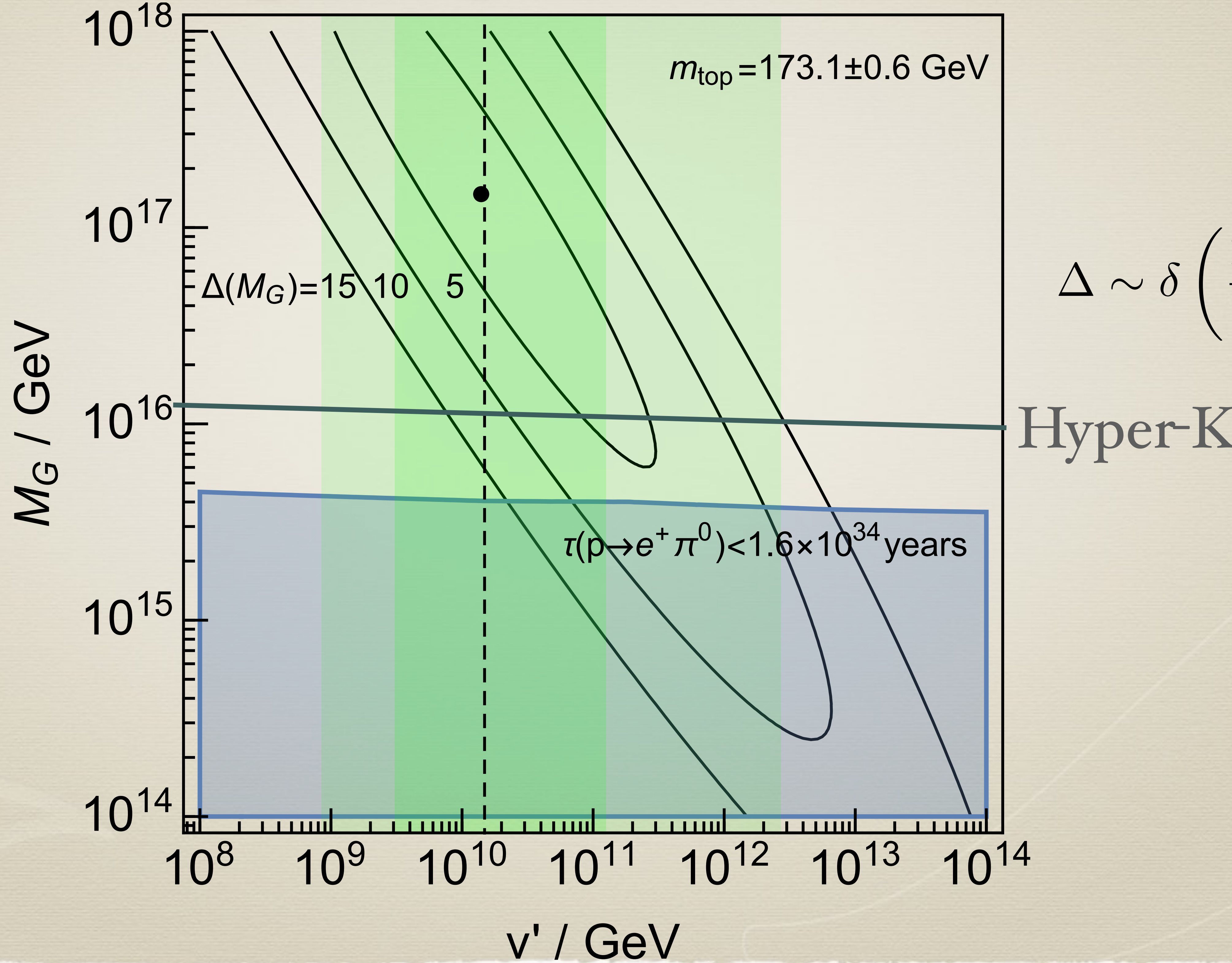
$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

Coupling unification





Coupling unification



$$\Delta \sim \delta\left(\frac{2\pi}{\alpha}\right)$$

Top-down perspective

SUSY GUT

3 parameters → 4 parameters

$g_{\rm GUT},\ M_{\rm GUT},\ m_{\rm SUSY}$ → $g_1,\ g_2,\ g_3,\ v_{\rm EW}$

GUT here

4 parameters → 5 parameters

$g_{\rm GUT},\ M_{\rm GUT},\ v',\ y_t$ → $g_1,\ g_2,\ g_3,\ y_t,\ \lambda_{\rm higgs}$

Top-down perspective

SUSY GUT

3 parameters

$g_{\rm GUT},\ M_{\rm GUT},\ m_{\rm SUSY}$

4 parameters

$g_1,\ g_2,\ g_3,\ v_{\rm EW}$

Altanative to SUSY GUT ?

GUT here

4 parameters

$g_{\rm GUT},\ M_{\rm GUT},\ v',\ y_t$

5 parameters

$g_1,\ g_2,\ g_3,\ y_t,\ \lambda_{\rm higgs}$

Intermediate Pati-Salam

$$SO(10)$$

$H, H' \subset 16$

$q, \ell, q', \ell' = 16$

$q' = (\bar{u}, \bar{d}), \ell' \supset \bar{e}$

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

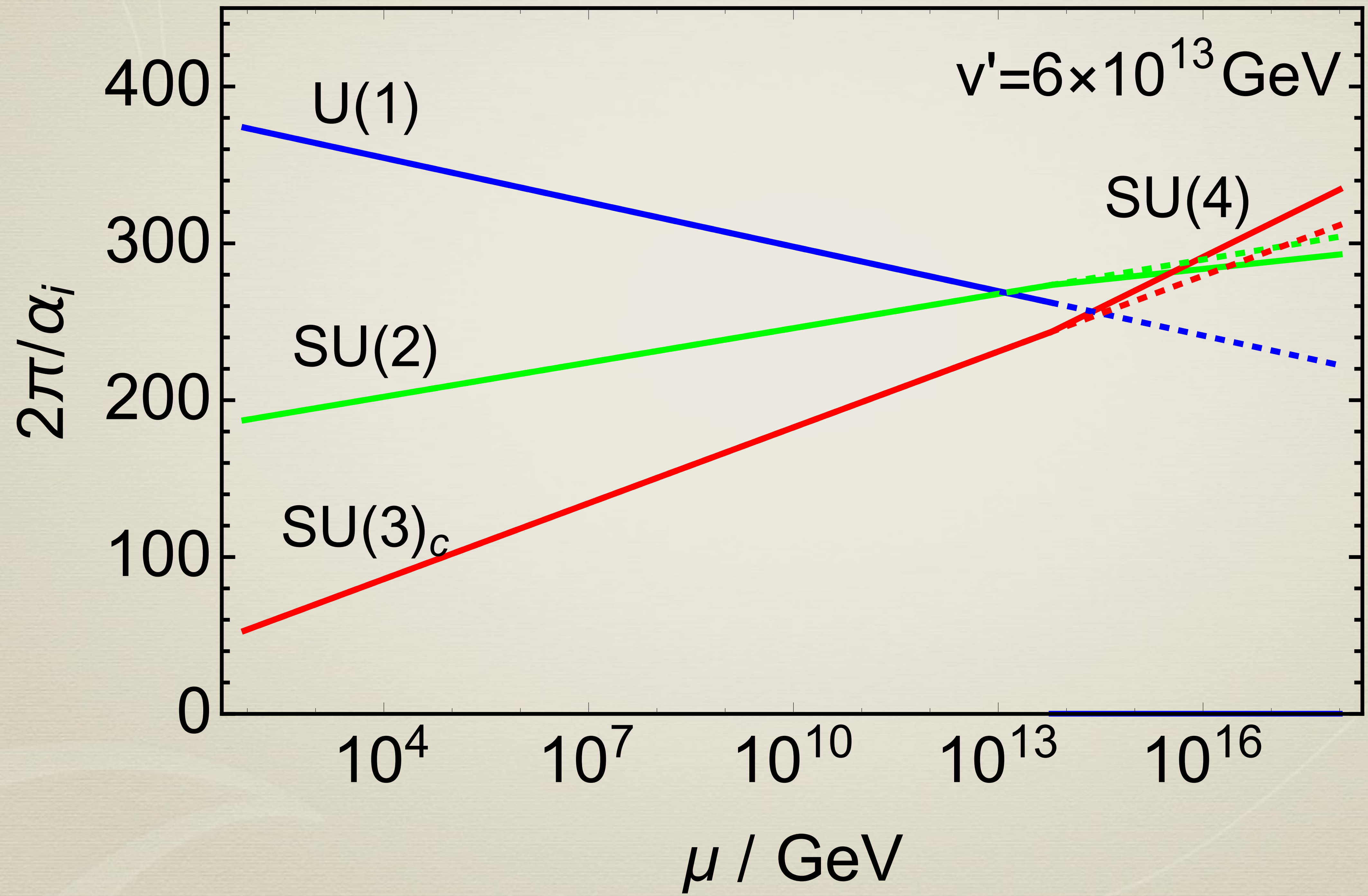
$H(\mathbf{1}, 2, 1, -\frac{1}{2}) \subset (\mathbf{4}, 2, 1)$

$H'(\mathbf{1}, 1, 2, \frac{1}{2}) \subset (\bar{\mathbf{4}}, 1, 2)$

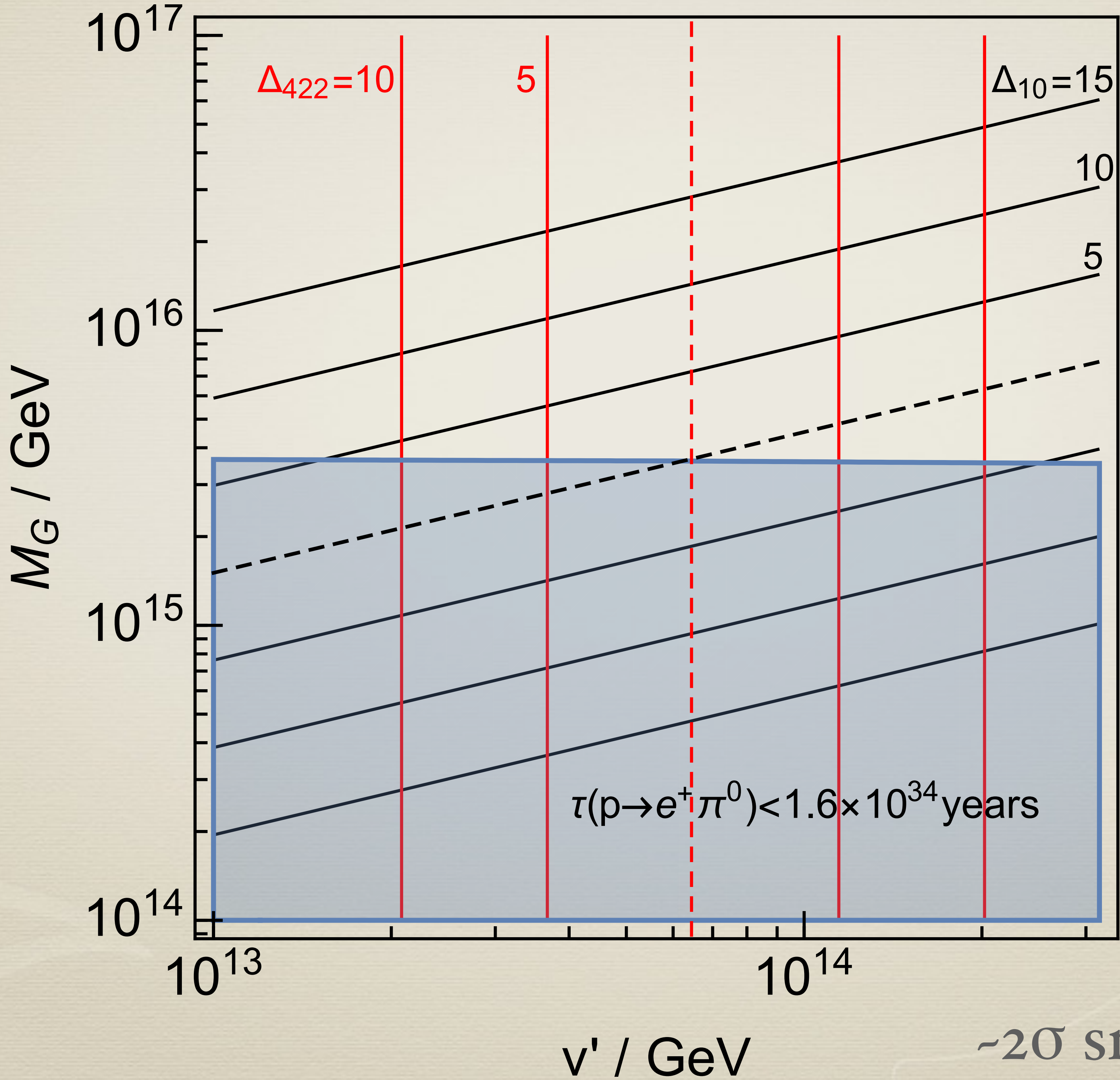
$$\langle H' \rangle = \begin{pmatrix} 0 & 0 & 0 & v' \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

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

Coupling Unification

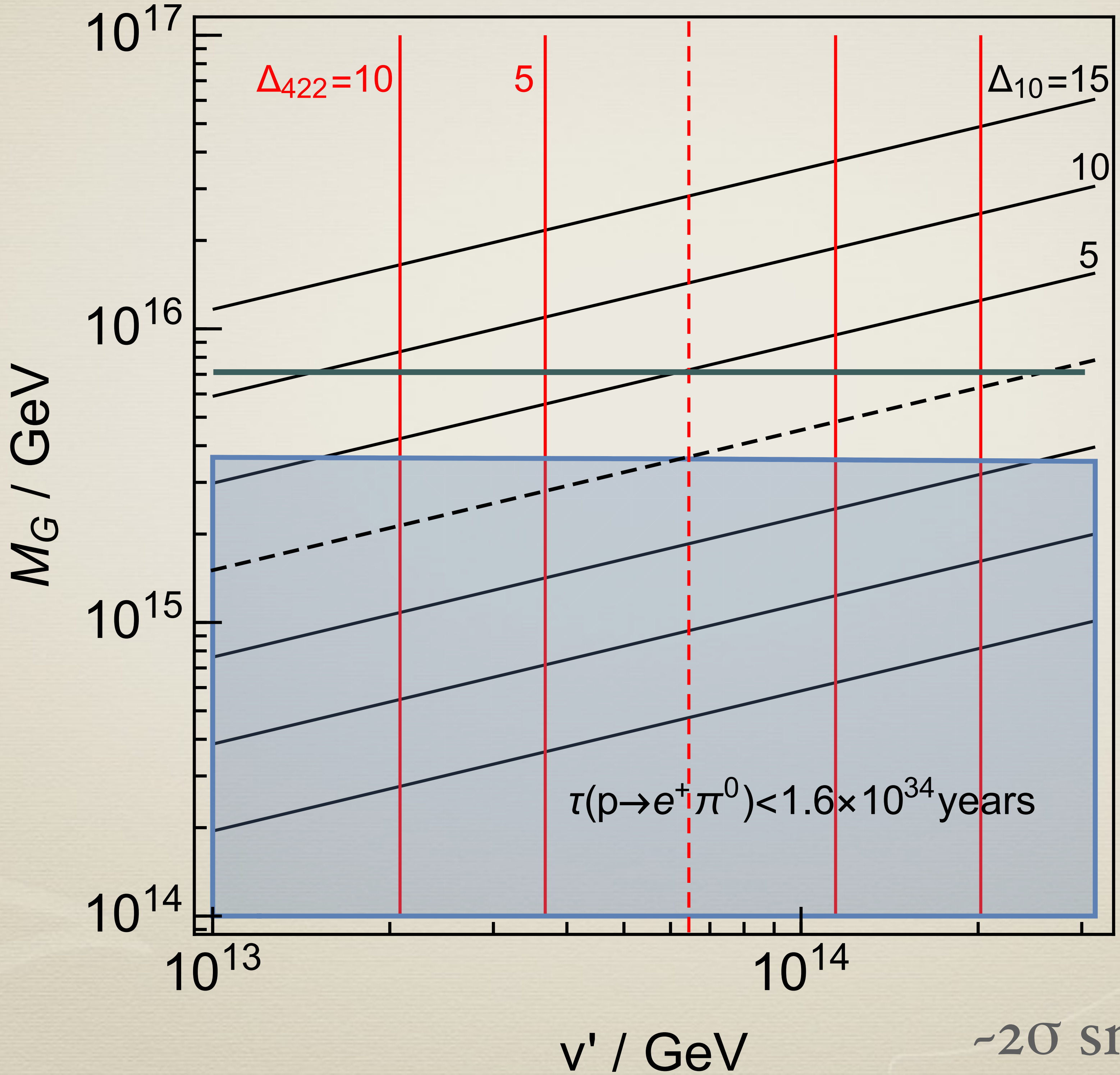


Coupling Unification



~2σ smaller top mass

Coupling Unification



Hyper-K

~2σ smaller top mass

Parity and the strong CP problem

(SO(10) is not required)

Parity

$$H(t,x) \leftrightarrow H'(t,-x)$$

$$q(t,x) \leftrightarrow i\sigma_2 q^{'*}(t,-x)$$

Assume $SU(3) \leftrightarrow SU(3)$

$$G\tilde{G} \to -G\tilde{G}$$

$$\theta_{\mathrm{QCD}} = 0$$

Yukawa coupling?

Ex. Left-Right symmetry $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

$$\frac{c_{ij}}{M} H H' q_i q'_j \qquad q(t,x) \leftrightarrow i\sigma_2 q^{'*}(t,-x)$$

$$c = c^\dagger, \arg(\det[c]) = 0$$

Also, H and H' has no physical phase dof.

Parity solutions

* 1978, Beg and Tsao, Mohapatra and Senjanovic

  Parity can solve the strong CP problem, H(2,2). Dangerous contribution from complex phase in the Higgs vev (1991, Barr, Chang and Senjanovic)

* 1989, Babu and Mohapatra

$$H(2,1) + H'(1,2)$$

with soft Z_2 breaking

Embedding into SO(10)

$$q(t,x) \leftrightarrow q'(t,x)$$

Part of SO(10)

$$q(t,x) \leftrightarrow i\sigma_2 q^*(t,-x)$$

CP

$$q(t,x) \leftrightarrow i\sigma_2 q^{'*}(t,-x)$$

$$SO(10) \times CP \xrightarrow{\phi_{45}^-} SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times P_{LR}$$

Loop correction to θ

Suppressed by loop factors, flavor mixing

$$\delta\theta \sim 10^{-11}$$

Summary

$\lambda \sim 0$

top quark mass
to determine v'

Accidental SU(4)

Z2 and its SSB by H'

Parity

Modified gauge group

$\theta_{\rm QCD} \simeq 0$

Unification

neutron EDM

Proton decay

Fermions

Doublets have Z2 partners

$$q, \ell \leftrightarrow q', \ell'$$

$$q(\mathbf{3}, 2, 1, \frac{1}{6}), \ell(\mathbf{1}, 2, 1, -\frac{1}{2}), H(\mathbf{1}, 2, 1, -\frac{1}{2})$$

	A(−, −)	B(+, −)	C(−, +)	D(+, +)
q'	$(\bar{\mathbf{3}}, 1, 2, -\frac{1}{6})$	$(\mathbf{3}, 1, 2, -\frac{1}{6})$	$(\bar{\mathbf{3}}, 1, 2, \frac{1}{6})$	$(\mathbf{3}, 1, 2, \frac{1}{6})$
ℓ', H'	$(\mathbf{1}, 1, 2, \frac{1}{2})$	$(\mathbf{1}, 1, 2, \frac{1}{2})$	$(\mathbf{1}, 1, 2, -\frac{1}{2})$	$(\mathbf{1}, 1, 2, -\frac{1}{2})$

$$q(\mathbf{3},2,1,\frac{1}{6}),\ell(\mathbf{1},2,1,-\frac{1}{2}),H(\mathbf{1},2,1,-\frac{1}{2})$$

	A(−,−)	B(+,−)	C(−,+)	D(+,+)
q'	$(\bar{\mathbf{3}},1,2,-\frac{1}{6})$	$(\mathbf{3},1,2,-\frac{1}{6})$	$(\bar{\mathbf{3}},1,2,\frac{1}{6})$	$(\mathbf{3},1,2,\frac{1}{6})$
ℓ',H'	$(\mathbf{1},1,2,\frac{1}{2})$	$(\mathbf{1},1,2,\frac{1}{2})$	$(\mathbf{1},1,2,-\frac{1}{2})$	$(\mathbf{1},1,2,-\frac{1}{2})$

A: almost vector-like and anomaly free.
q’, l’ are identified with $SU(2)_L$ singlet SM fermions

$$SU(2)'=SU(2)_R,\ U(1)\sim U(1)_{\mathrm{B-L}}$$

$$\mathcal{L}=\frac{1}{M}(q\tilde{y_u}q')H^{\dagger}H^{'\dagger}+\frac{1}{M}(q\tilde{y_d}q')HH'$$

$$q(\mathbf{3}, 2, 1, \frac{1}{6}), \ell(\mathbf{1}, 2, 1, -\frac{1}{2}), H(\mathbf{1}, 2, 1, -\frac{1}{2})$$

	A(−, −)	B(+, −)	C(−, +)	D(+, +)
q'	$(\bar{\mathbf{3}}, 1, 2, -\frac{1}{6})$	$(\mathbf{3}, 1, 2, -\frac{1}{6})$	$(\bar{\mathbf{3}}, 1, 2, \frac{1}{6})$	$(\mathbf{3}, 1, 2, \frac{1}{6})$
ℓ', H'	$(\mathbf{1}, 1, 2, \frac{1}{2})$	$(\mathbf{1}, 1, 2, \frac{1}{2})$	$(\mathbf{1}, 1, 2, -\frac{1}{2})$	$(\mathbf{1}, 1, 2, -\frac{1}{2})$

B, C, D: needs extra fermion which are identified with
SU(2)$_L$ singlet SM fermions

$$\mathcal{L} = Hq\bar{u} + H'q'\bar{u}' + \cdots$$

$$\bar{u} \leftrightarrow \bar{u}'$$

Parity and the strong CP problem

$$q(t,x) \leftrightarrow i\sigma_2 q^{'*}(t,-x)$$

Model A

$$\mathcal{L} = \frac{1}{M}(q\tilde{y}_u q')H^\dagger H^{'\dagger} + \frac{1}{M}(q\tilde{y}_d q')HH' + \text{h.c.}$$

$$\tilde{y}^\dagger = \tilde{y}, \ \text{real det}\tilde{y}$$

$$\theta G\tilde{G} \ : \ \theta = 0$$

Strong CP problem is solved!

Parity and the strong CP problem

$$q(t,x) \leftrightarrow i\sigma_2 q^{'*}(t,-x)$$

Model B,C

$$\mathcal{L} = yHQ\bar{u} + y^* H'Q'\bar{u}' + y^* H^\dagger Q^\dagger \bar{u}^\dagger + yH^{'\dagger}Q^{'\dagger}\bar{u}^{'\dagger}$$

$$\det y \times \det y^* \ \text{is real}$$

Cancellation between the SM and partners

Parity and the strong CP problem

$$q(t,x) \leftrightarrow i\sigma_2 q^{'*}(t,-x)$$

Model D

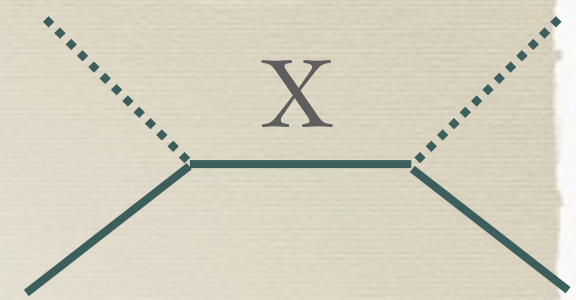
$$q(\mathbf{3},2,1,\frac{1}{6}),\ell(\mathbf{1},2,1,-\frac{1}{2}),H(\mathbf{1},2,1,-\frac{1}{2})$$

	A$(-,-)$	B$(+,-)$	C$(-,+)$	D$(+,+)$
q'	$(\bar{\mathbf{3}},1,2,-\frac{1}{6})$	$(\mathbf{3},1,2,-\frac{1}{6})$	$(\bar{\mathbf{3}},1,2,\frac{1}{6})$	$(\mathbf{3},1,2,\frac{1}{6})$
ℓ',H'	$(\mathbf{1},1,2,\frac{1}{2})$	$(\mathbf{1},1,2,\frac{1}{2})$	$(\mathbf{1},1,2,-\frac{1}{2})$	$(\mathbf{1},1,2,-\frac{1}{2})$

$$\mathcal{L} = yHq\bar{u} + y^*H'q'\bar{u}' + \lambda Hq\bar{u}' + \lambda^*H'q'\bar{u} + \text{h.c.}$$

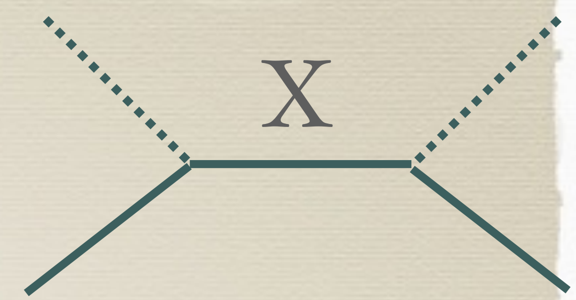
$$\det\begin{pmatrix} y & \lambda \\ \lambda^* & y^* \end{pmatrix} = \det\begin{pmatrix} \lambda & y \\ y^* & \lambda^* \end{pmatrix} = \det\begin{pmatrix} y^* & \lambda^* \\ \lambda & y \end{pmatrix} = \det\begin{pmatrix} y & \lambda \\ \lambda^* & y^* \end{pmatrix}^*$$

Yukawa couplings



	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)$	$SU(4)$	$SO(10)$	coupling
up	**3**	**1**	**1**	2/3	**15**	**45**	$\bar{X}qH^\dagger + Xq'H'^\dagger$
	3	**2**	**2**	−1/3	**6**/**10**	**45**, **54**, **210**/**210**	$\bar{X}qH'^\dagger + Xq'H^\dagger$
down	**3**	**1**	**1**	−1/3	**6**/**10**	**10**, **126**/**120**	$\bar{X}qH + Xq'H'$
	3	**2**	**2**	2/3	**15**	**120**, **126**	$\bar{X}qH' + Xq'H$
electron	**1**	**1**	**1**	−1	**10**	**120**	$\bar{X}\ell H + X\ell' H'$
	1	**2**	**2**	0	**1**/**15**	**10**, **120**/**120**, **126**	$X\ell H' + X\ell' H$
neutrino	**1**	**1**	**1**	0	**1**/**15**	**1**, **54**, **210**/**45**, **210**	$X(\ell H^\dagger + \ell' H'^\dagger)$
	1	**2**	**2**	−1	**10**	**210**	$\bar{X}\ell H'^\dagger + X\ell' H^\dagger$
	1	**3**	**1**	0	**1**	**45**	$X\ell H^\dagger$
	1	**1**	**3**	0	**1**	**45**	$X\ell' H'^\dagger$

Yukawa couplings



Small enough not to blow up the gauge coupling

	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)$	$SU(4)$	$SO(10)$	coupling
up	**3**	**1**	**1**	$2/3$	**15**	**45**	$\bar{X} q H^\dagger + X q' H'^\dagger$
	3	**2**	**2**	$-1/3$	**6/10**	**45, 54, 210/210**	$\bar{X} q H'^\dagger + X q' H^\dagger$
down	**3**	**1**	**1**	$-1/3$	**6/10**	**10, 126/120**	$\bar{X} q H + X q' H'$
	3	**2**	**2**	$2/3$	**15**	**120, 126**	$\bar{X} q H' + X q' H$
electron	**1**	**1**	**1**	-1	**10**	**120**	$\bar{X} \ell H + X \ell' H'$
	1	**2**	**2**	0	**1/15**	**10, 120/120, 126**	$X \ell H' + X \ell' H$
neutrino	**1**	**1**	**1**	0	**1/15**	**1, 54, 210/45, 210**	$X(\ell H^\dagger + \ell' H'^\dagger)$
	1	**2**	**2**	-1	**10**	**210**	$\bar{X} \ell H'^\dagger + X \ell' H^\dagger$
	1	**3**	**1**	0	**1**	**45**	$X \ell H^\dagger$
	1	**1**	**3**	0	**1**	**45**	$X \ell' H'^\dagger$

CKM phase

$$SO(10) \times CP \xrightarrow{\phi_{45}^{-}} SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times P_{LR}$$

Real yukawa without CP symmetry breaking

A simple example

$$\mathcal{L} = \left(M^{ij} + i\lambda^{ij}\phi_{45}\right) X_{10,i} X_{10,j}$$

$$m^2 \ll \Lambda_{\text{cut}}^2$$

More Fine-tuned than SM?

No.

$$\frac{v_{\text{EW}}^2}{m^2} \times \frac{m^2}{\Lambda_{\text{cut}}^2} \sim \frac{v_{\text{EW}}^2}{\Lambda_{\text{cut}}^2}$$

$y \simeq 2\lambda$ $\quad$ $m^2 \ll \Lambda\text{cut}^2$

How non-trivial?

Ex. SUSY GUT

3 parameters

$$g_{\mathrm{GUT}},\ M_{\mathrm{GUT}},\ m_{\mathrm{SUSY}}$$

↓

4 parameters

$$g_1,\ g_2,\ g_3,\ v_{\mathrm{EW}}$$

How non-trivial?

4 parameters

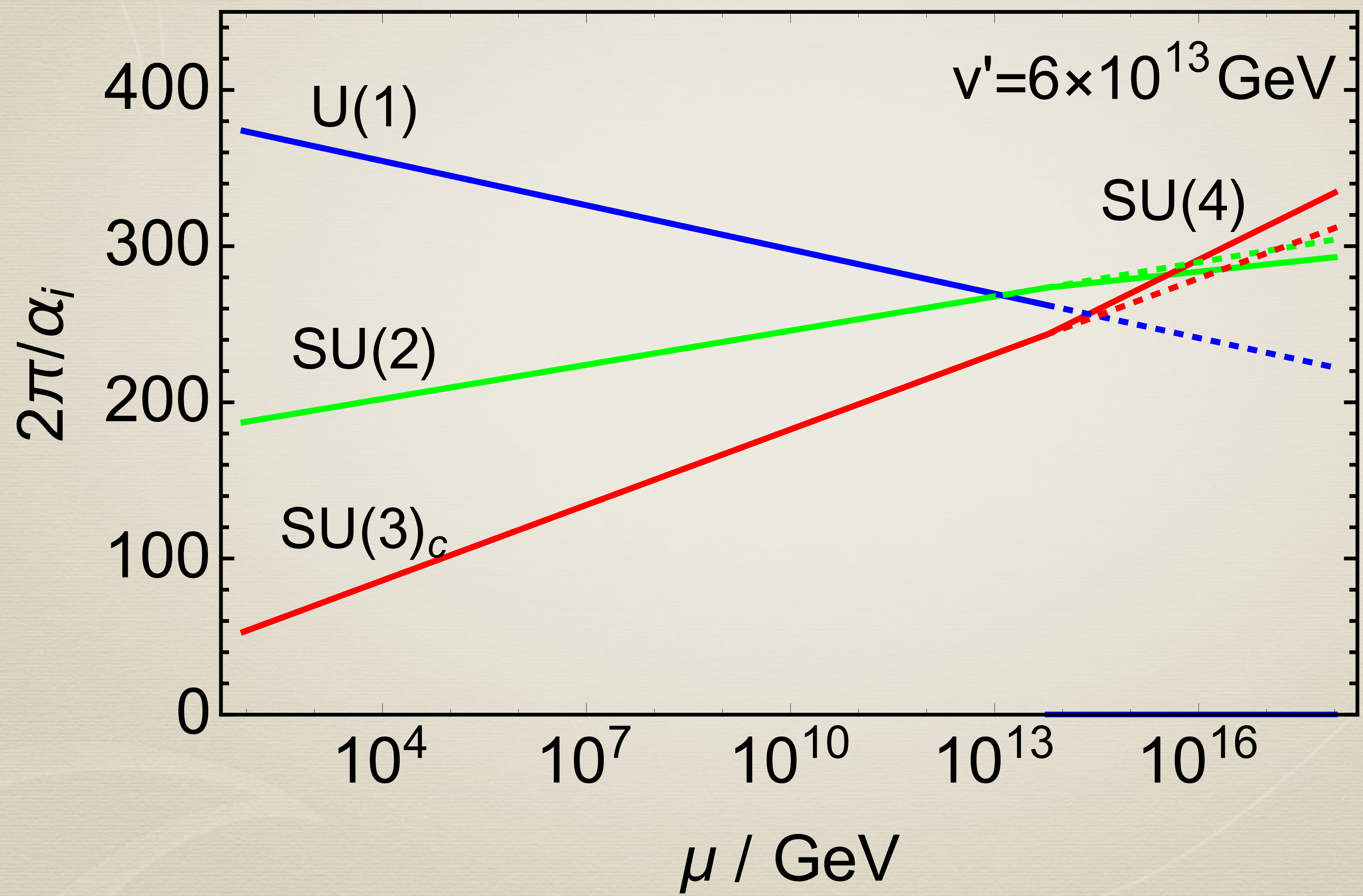
$$g_{\mathrm{GUT}},\ M_{\mathrm{GUT}},\ v',\ y_t$$

5 parameters

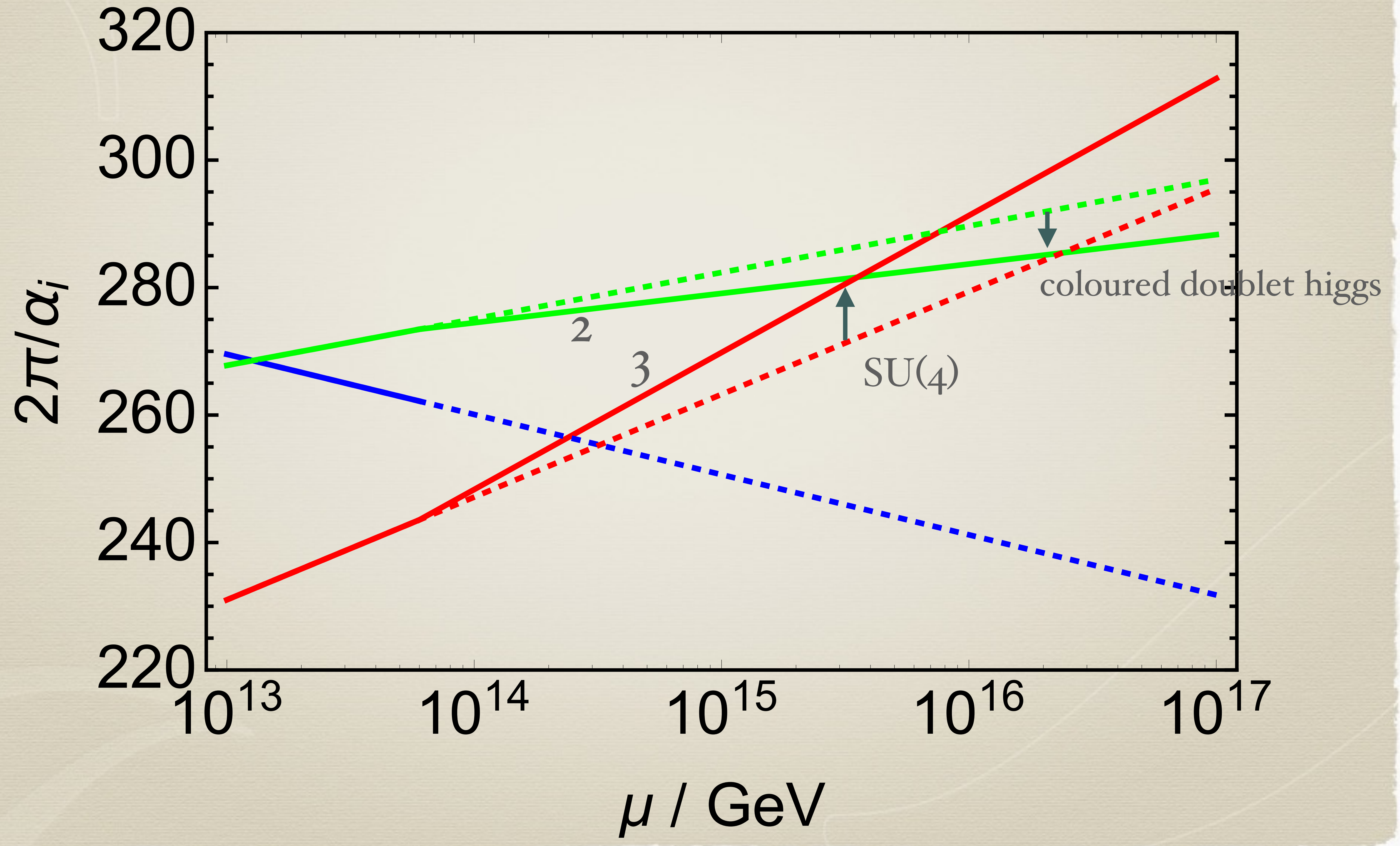
$$g_1,\ g_2,\ g_3,\ y_t,\ \lambda_{\mathrm{higgs}}$$

Altanative to SUSY GUT ?

Coupling Unification



Coupling Unification



Correction to the gauge coupling unification by high dimensional operator

$$SO(10) \stackrel{\phi_{210}}{\longrightarrow} SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times C_{LR}$$

$$\frac{210^{abcd}}{M_*} F_{10}^{ab} F_{10}^{cd} \qquad \Delta\left(\frac{2\pi}{\alpha}\right) \lesssim 10$$

$$SO(10) \times CP \stackrel{\phi_{45}}{\longrightarrow} SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times P_{LR}$$

$$\frac{45^{ac}}{M_*} \frac{45^{bd}}{M_*} F_{10}^{ab} F_{10}^{cd} \qquad \Delta\left(\frac{2\pi}{\alpha}\right) \lesssim 1$$

Correction to the gauge coupling unification by high dimensional operator

$$SO(10) \xrightarrow{\phi_{54}} SU(4) \times SU(2)_L \times SU(2)_R \times C_{LR}$$

$$\frac{54^{ab}}{M_*} F_{10}^{ac} F_{10}^{bc} \qquad \Delta\left(\frac{2\pi}{\alpha}\right) \lesssim 1$$

$$SO(10) \times CP \xrightarrow{\phi_{210}} SU(4) \times SU(2)_L \times SU(2)_R \times P_{LR}$$

$$\frac{210}{M_*} \frac{210}{M_*} F_{10} F_{10} \qquad \Delta\left(\frac{2\pi}{\alpha}\right) \ll 1$$