10/17/2018
Kavli IPMU

Higgs parity, strong CP problem, GUT

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with Lawrence Hall

1803.08119

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

0.1 $(100\ \mathrm{GeV})^2$

Conventional approach

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

New physics giving 100 GeV scale?

SUSY, compositeness, etc.

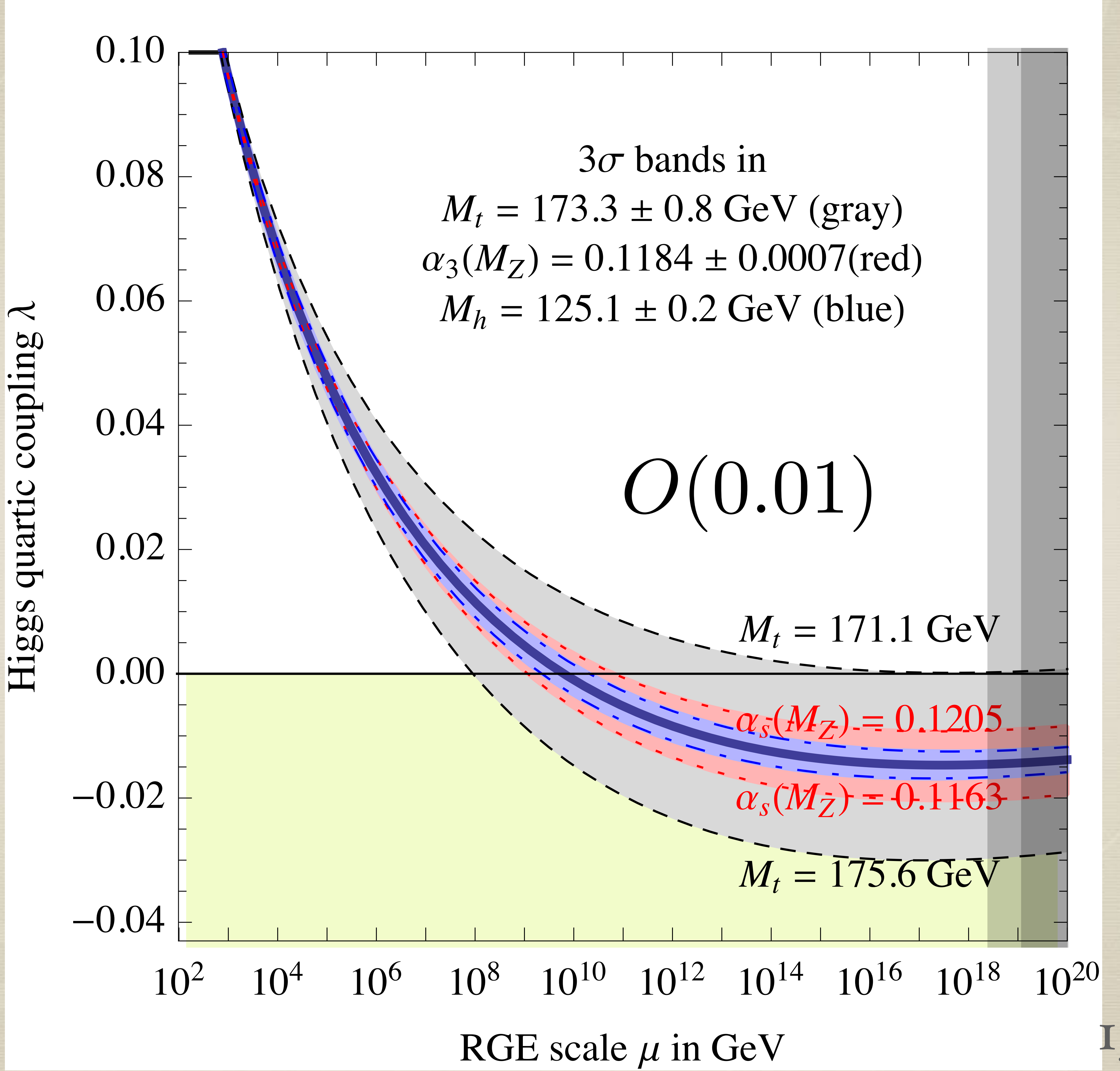
LHC has not found them so far...

Maybe other explanations.
(Anthropic principle?, though not established)

Approach today

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

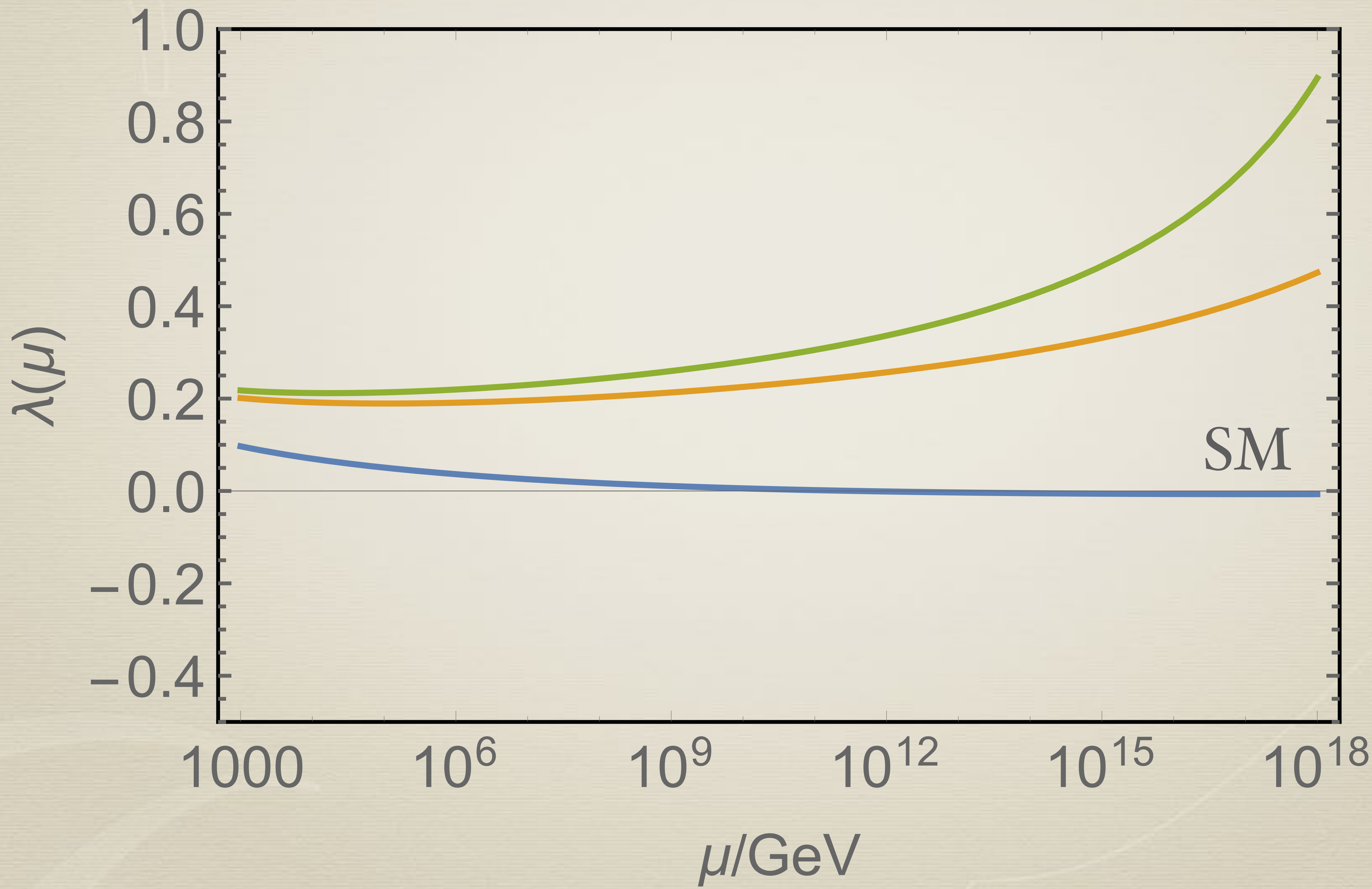
Assume that the SM is valid up to high energy scale



3σ bands in
Mt = 173.3 ± 0.8 GeV (gray)
α3(MZ) = 0.1184 ± 0.0007(red)
Mh = 125.1 ± 0.2 GeV (blue)
O(0.01)
Mt = 171.1 GeV
αs(MZ) = 0.1205
αs(MZ) = 0.1163
Mt = 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

1307.3536

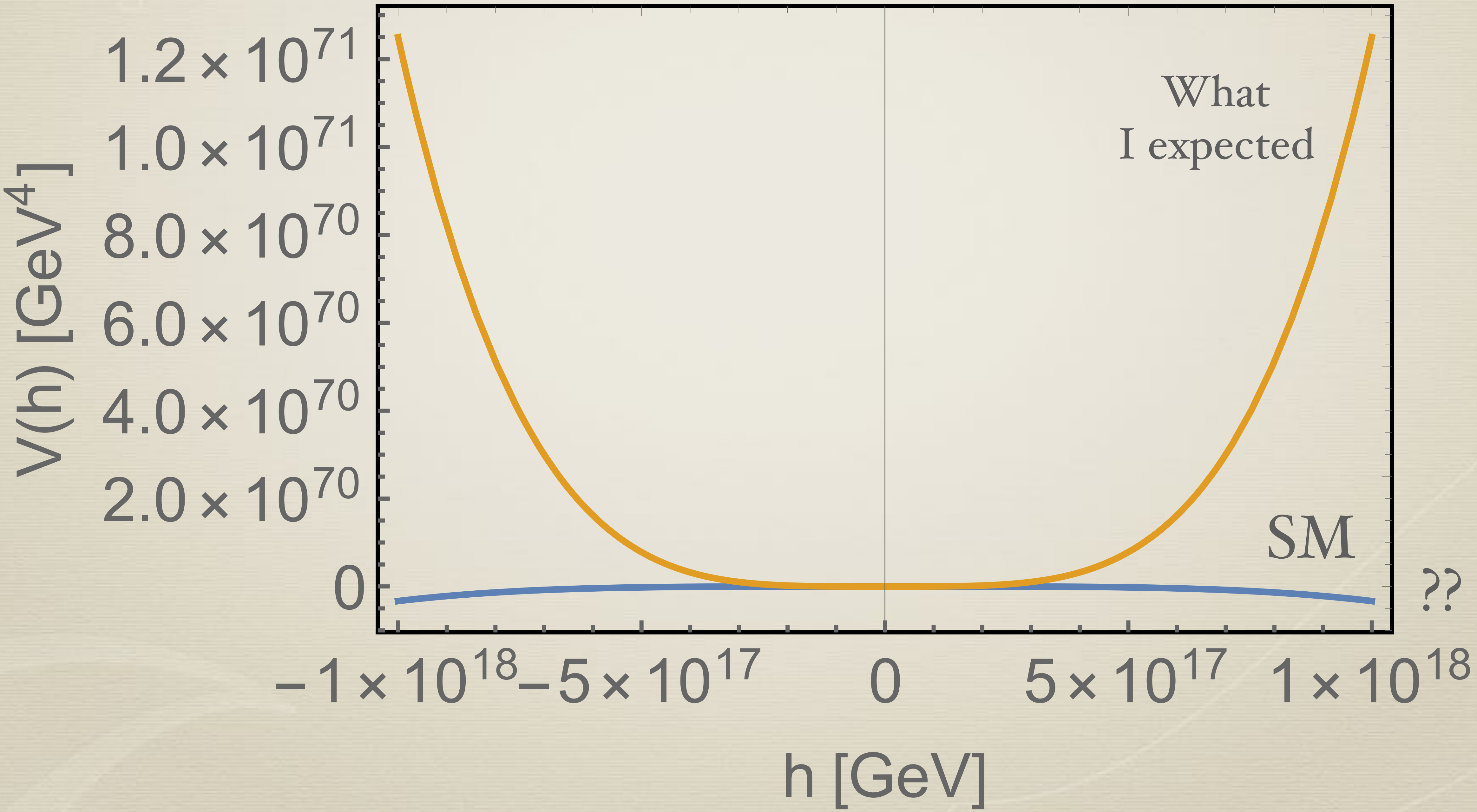
Small boundary condition



What
I expected
O(1)

??

Flat potential



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

Outline

$\boxed{\lambda \sim 0}$

Z_2 and its SSB

Strong CP problem

GUT

Higgs parity

Introduce Z_2 symmetry

$$H \leftrightarrow H'$$

Higgs parity

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

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

Let us assume $m \gg v_{EW}$

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

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

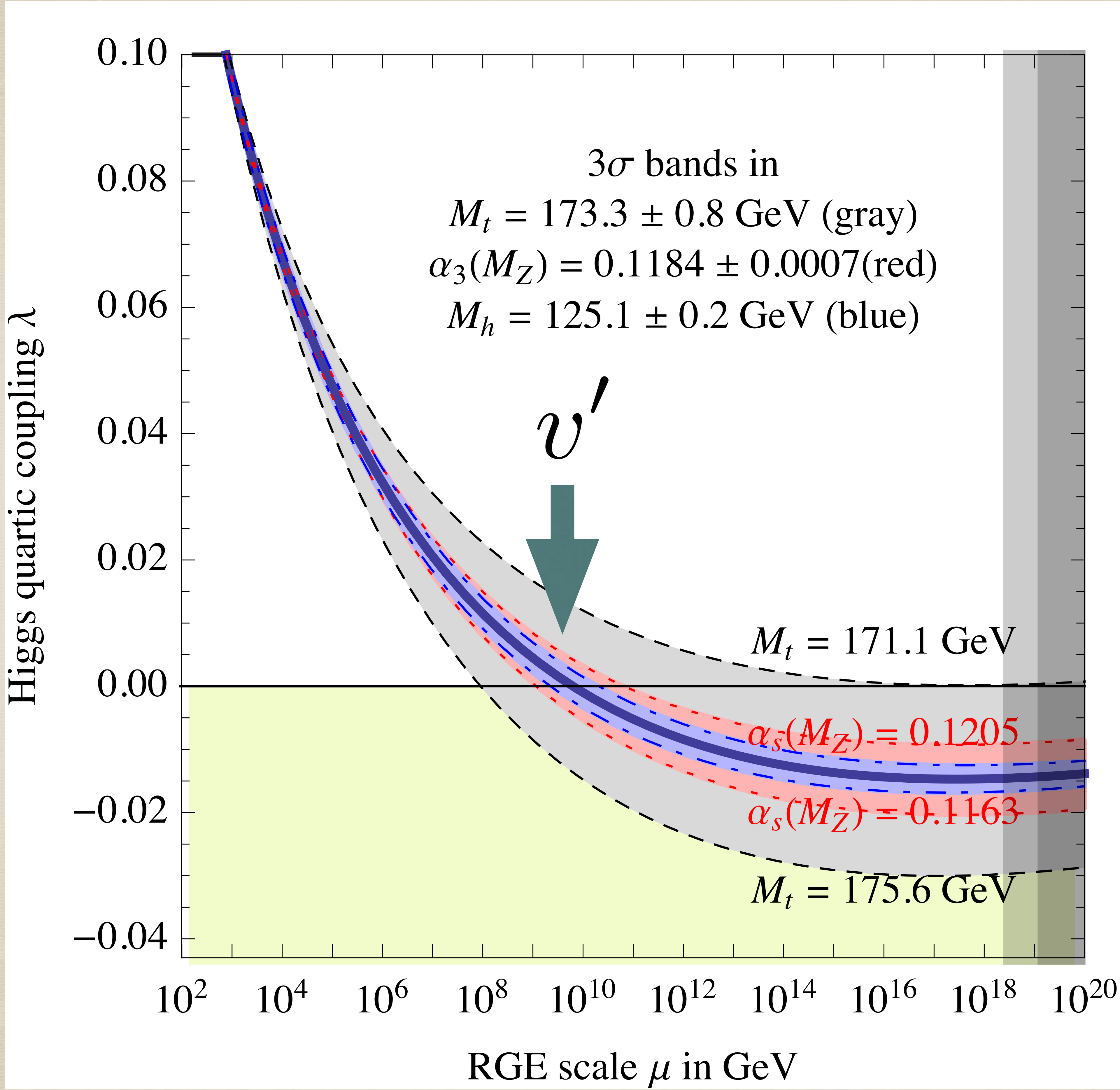
$$V(H,H') \simeq \lambda(|H|^2 + |H'|^2)^2 - m^2(|H|^2 + |H'|^2)$$

Accidentally SU(4) symmetric $\quad 4 = (H, H')$

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

SM Higgs is a Nambu-Goldstone boson

$\lambda_{\mathrm{SM}} = 0$ (up to quantum correction)



3σ bands in
M_t = 173.3 ± 0.8 GeV (gray)
$\alpha_3(M_Z)$ = 0.1184 ± 0.0007(red)
M_h = 125.1 ± 0.2 GeV (blue)
v'
M_t = 171.1 GeV
$\alpha_s(M_Z)$ = 0.1205
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Higgs quartic coupling λ
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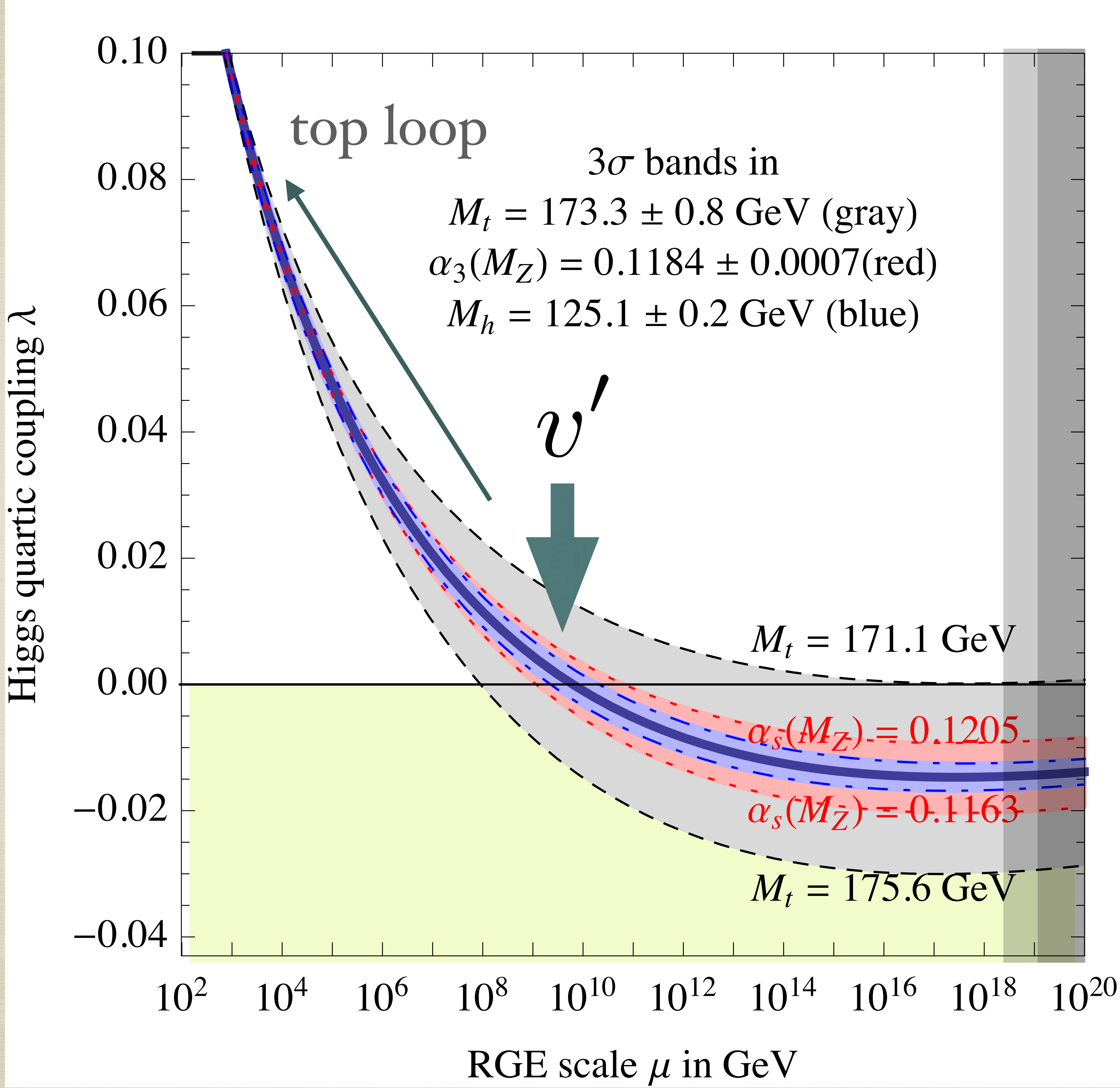
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}



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)
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$M_t = 171.1$ GeV
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10^2 10^4 10^6 10^8 10^{10} 10^{12} 10^{14} 10^{16} 10^{18} 10^{20}

Fine-tuning

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

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

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

Same as that of SM

Fermions and 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
$U(1) \times U(1)'$

Summary so far

$$\boxed{\lambda \sim 0}$$

$\uparrow$ Accidental SU(4)

$\boxed{\text{Higgs parity and its SSB}}$

$$\boxed{\lambda \sim 0}$$

Accidental SU(4)

Higgs parity and its SSB

GUT

Higgs parity from SO(10)

Remnant of SO(10)

$$SO(10)$$

$H, H' \subset 16$

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

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

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

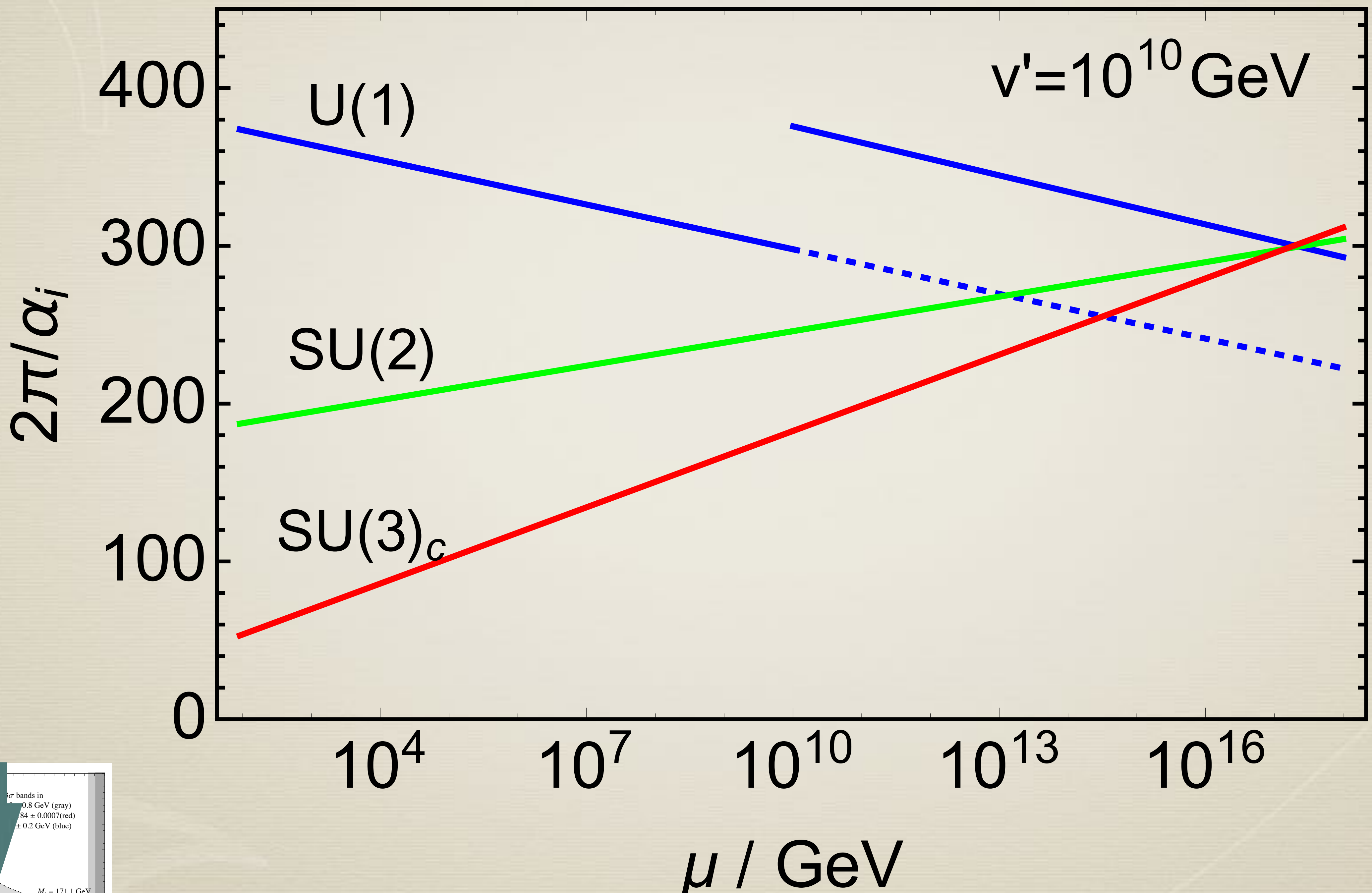
Left-right symmetry

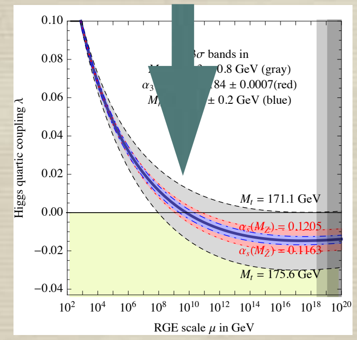
$H \leftrightarrow H'$

$\langle H' \rangle \neq 0$

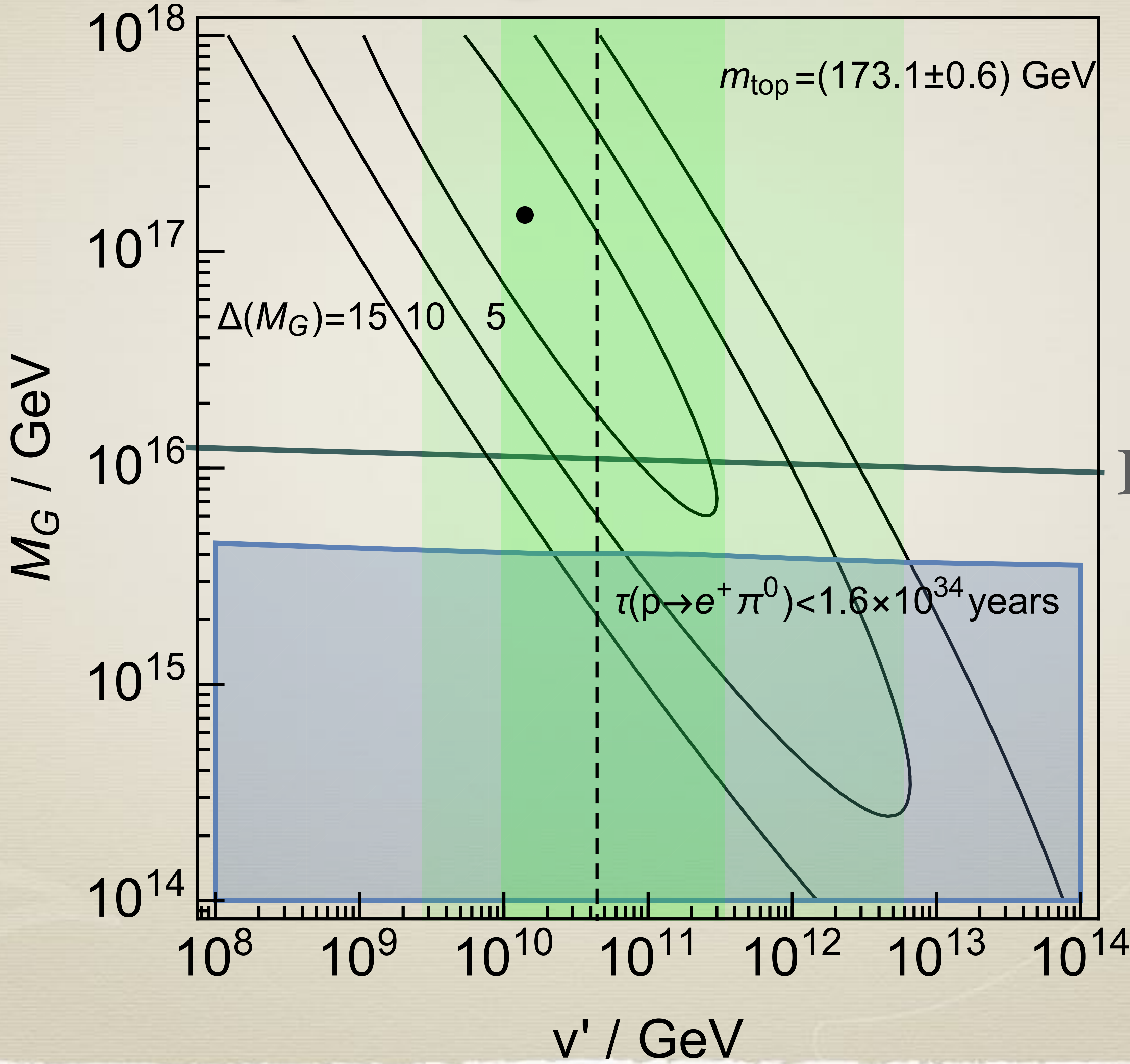
$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

Coupling unification





Coupling unification



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

Hyper-K

Top-down perspective

SUSY GUT

3 parameters → 4 parameters

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

(You can replace V_{EW} with Ω_{DM})

Higgs parity GUT

4 parameters → 5 parameters

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

Top-down perspective

SUSY GUT

3 parameters

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

→

4 parameters

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

Comparable to SUSY GUT ?

Higgs parity GUT

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

$$SO(10)$$

$H, H' \subset 16$

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

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

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

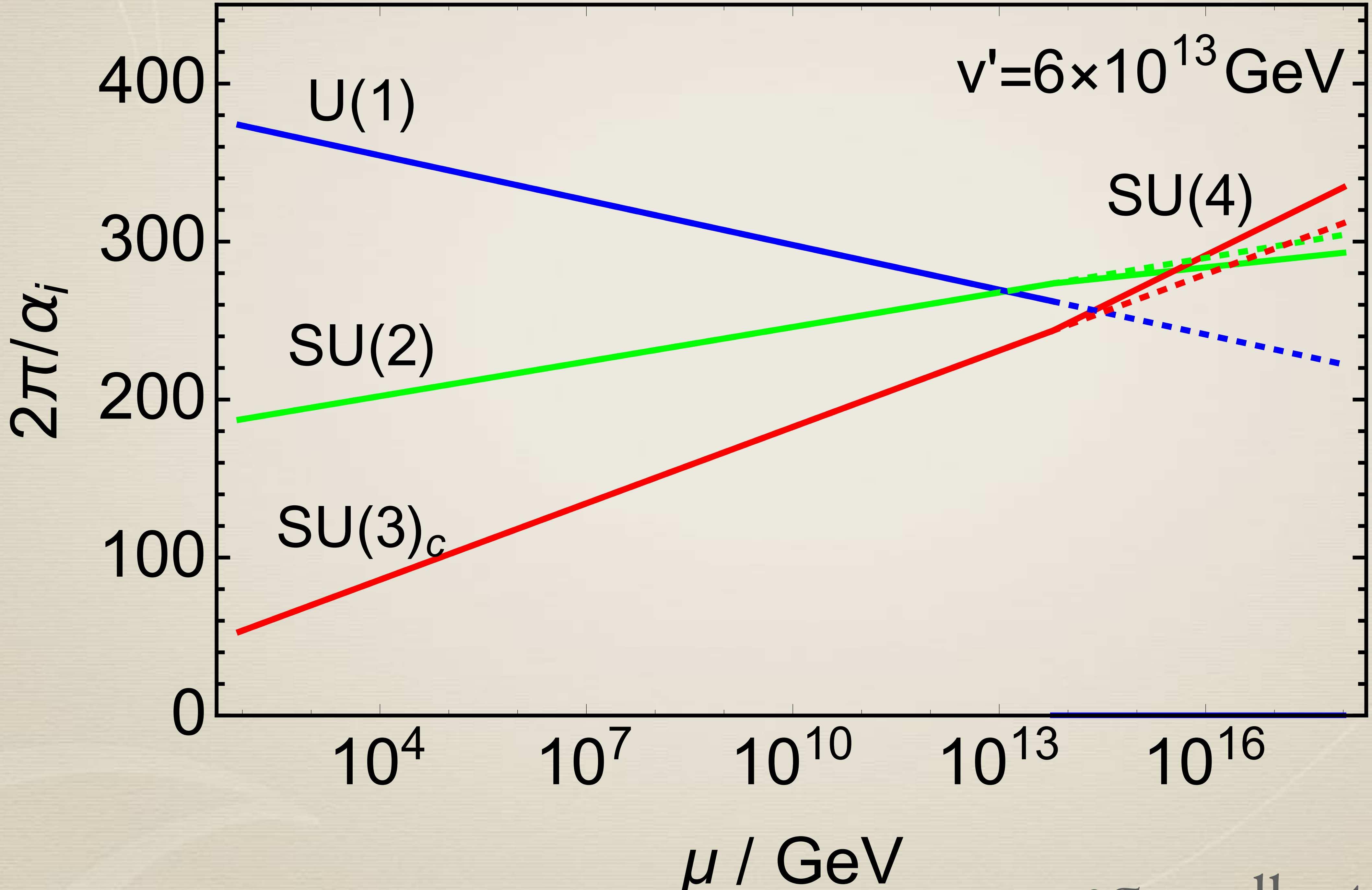
$H(\mathbf{1}, 2, 1, -\frac{1}{2}) \subset (\mathbf{4}, 2, 1)$

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

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

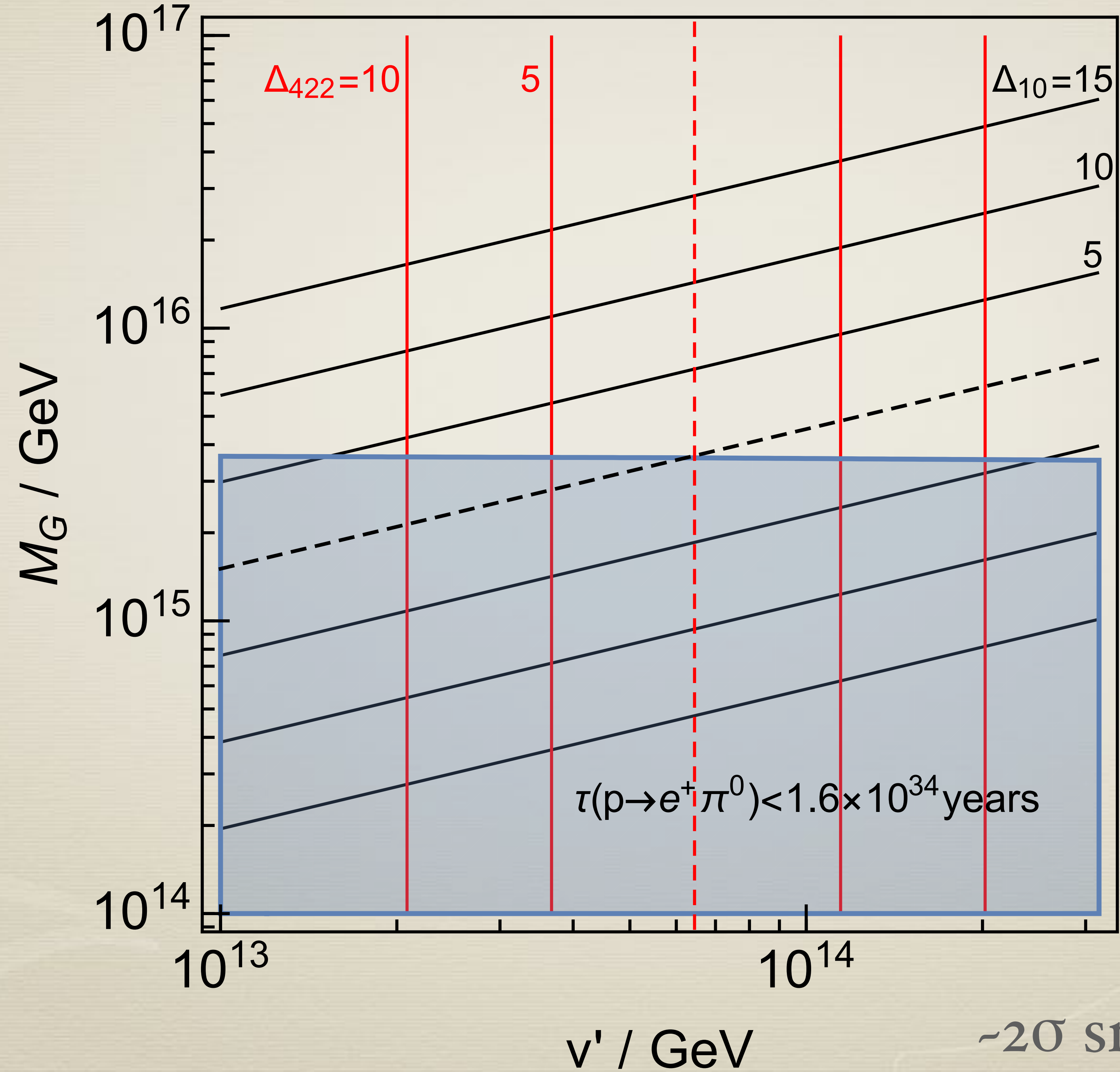
$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

Coupling Unification



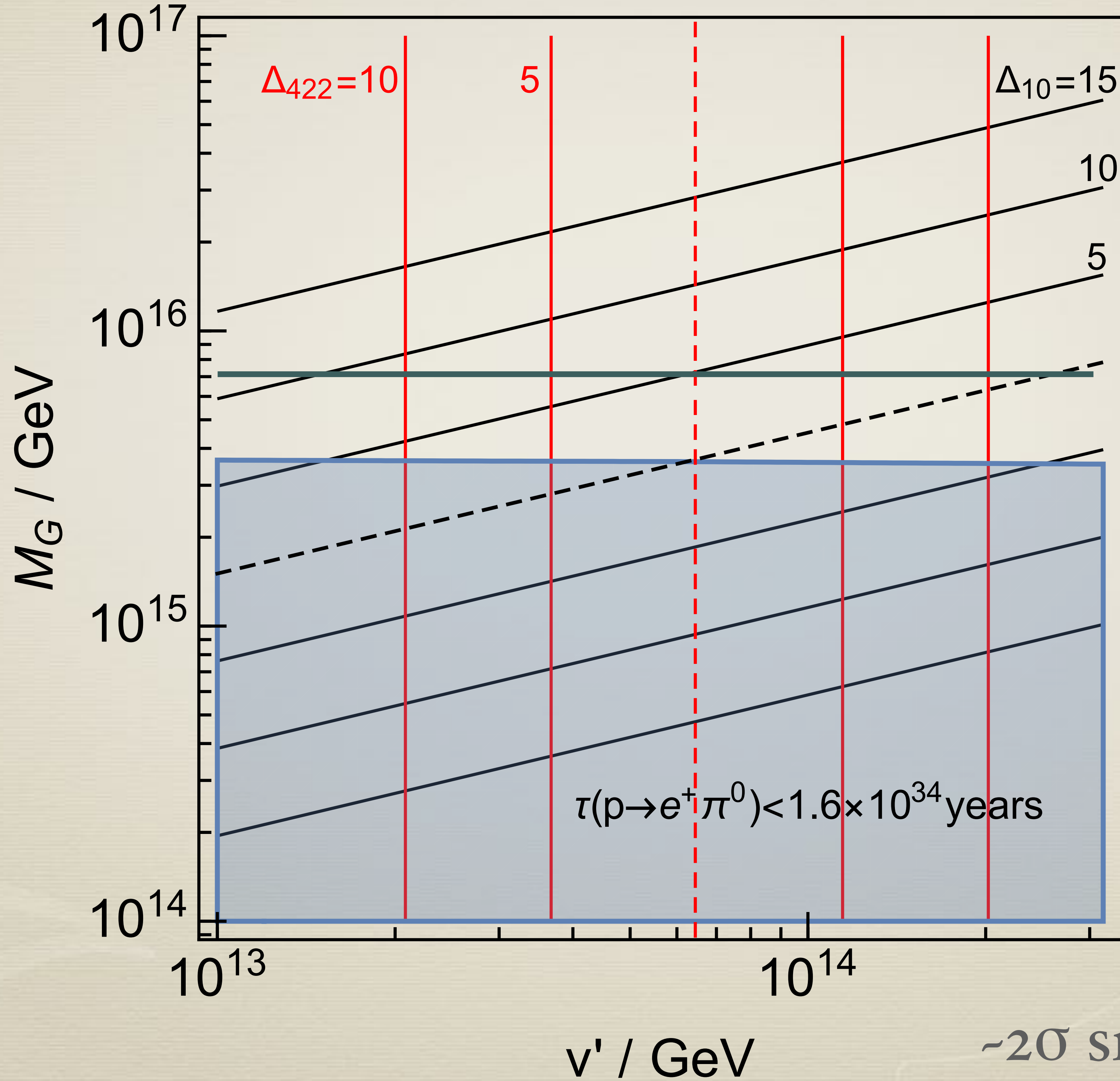
~2σ smaller top mass

Coupling Unification



~2σ smaller top mass

Coupling Unification



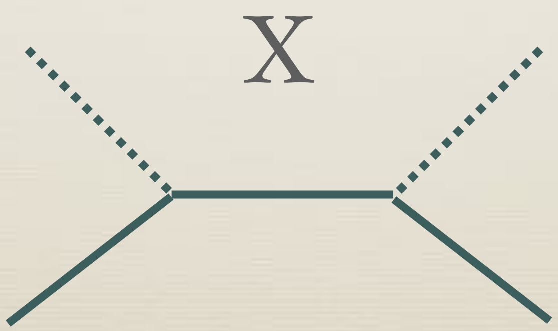
Hyper-K

~2σ smaller top mass

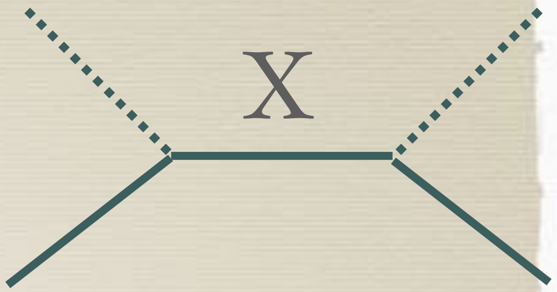
Yukawa couplings

$$H(2,1),\ \ H'(1,2),\ \ q(2,1),\ \ q'(1,2)$$

$$\frac{c_{ij}}{M} H H' q_i q'_j$$

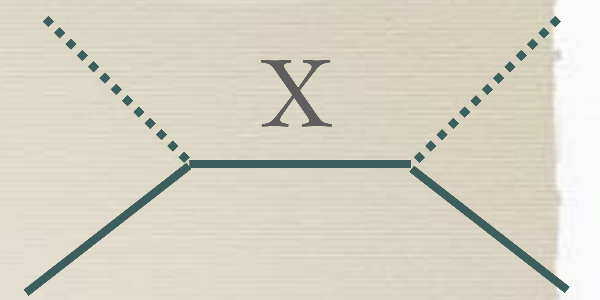


Yukawa couplings



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

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	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$2/3$	$\mathbf{15}$	$\mathbf{45}$	$\bar{X} q H^\dagger + X q' H'^\dagger$
	$\mathbf{3}$	$\mathbf{2}$	$\mathbf{2}$	$-1/3$	$\mathbf{6}/\mathbf{10}$	$\mathbf{45}, \mathbf{54}, \mathbf{210}/\mathbf{210}$	$\bar{X} q H'^\dagger + X q' H^\dagger$
down	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$-1/3$	$\mathbf{6}/\mathbf{10}$	$\mathbf{10}, \mathbf{126}/\mathbf{120}$	$\bar{X} q H + X q' H'$
	$\mathbf{3}$	$\mathbf{2}$	$\mathbf{2}$	$2/3$	$\mathbf{15}$	$\mathbf{120}, \mathbf{126}$	$\bar{X} q H' + X q' H$
electron	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	-1	$\mathbf{10}$	$\mathbf{120}$	$\bar{X} \ell H + X \ell' H'$
	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	0	$\mathbf{1}/\mathbf{15}$	$\mathbf{10}, \mathbf{120}/\mathbf{120}, \mathbf{126}$	$X \ell H' + X \ell' H$
neutrino	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}/\mathbf{15}$	$\mathbf{1}, \mathbf{54}, \mathbf{210}/\mathbf{45}, \mathbf{210}$	$X(\ell H^\dagger + \ell' H'^\dagger)$
	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	-1	$\mathbf{10}$	$\mathbf{210}$	$\bar{X} \ell H'^\dagger + X \ell' H^\dagger$
	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{45}$	$X \ell H^\dagger$
	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	0	$\mathbf{1}$	$\mathbf{45}$	$X \ell' H'^\dagger$

Summary so far

$$\boxed{\lambda \sim 0}$$

$$\boxed{\text{Higgs parity and its SSB}}$$

$$\boxed{\text{GUT}}$$

$\lambda \sim 0$

Higgs parity and its SSB

Strong CP problem

GUT

Higgs Parity and the strong CP problem

SO(10) is not required in this story

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

Space Parity

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

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

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

$$G\tilde{G} \rightarrow -G\tilde{G}$$

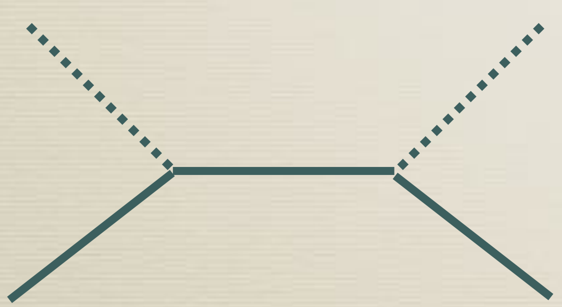
$$\theta_{\mathrm{QCD}} = 0$$

Yukawa coupling?

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

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

$$\frac{c_{ij}}{M} H H' q_i q_j'$$



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

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

Yukawa coupling?

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

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

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

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

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)

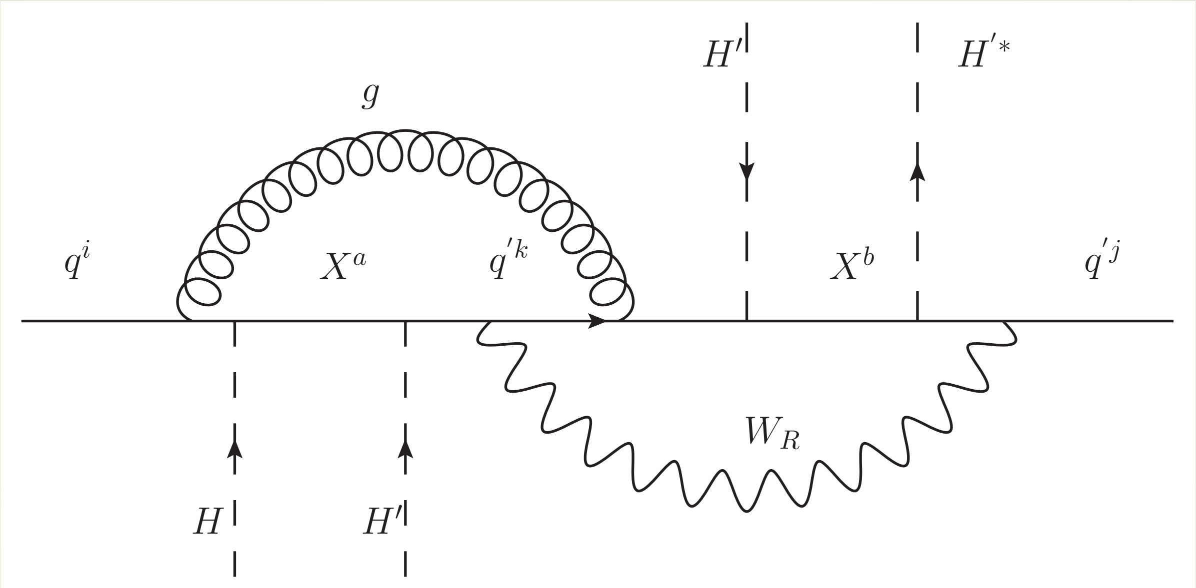
- 1989, Babu and Mohapatra

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

with explicit soft Z_2 breaking

Loop correction to θ

For $q' = (\bar{u}, \bar{d})$



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

Suppressed by loop factors, flavor mixing

Embedding into SO(10)

SO(10) with 16 fermion is chiral.
How can we obtain Parity?

Start from SO(10) + CP

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

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

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

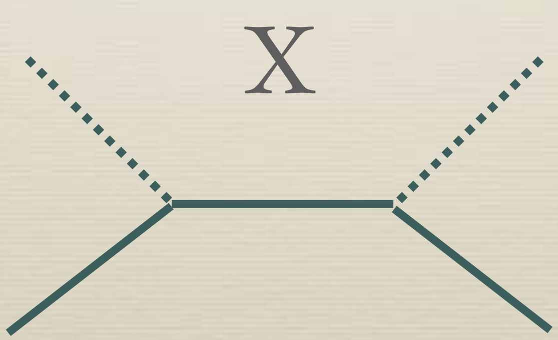
CKM phase

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

Real yukawas, without CP symmetry breaking...

A simple renormalizable example to obtain CP phases

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



Summary

$\boxed{\lambda \sim 0}$

top quark mass
to determine v'

Accidental SU(4)

Higgs parity and its SSB

Parity

Extra gauge group

Strong CP problem

GUT

neutron EDM?

Proton decay

Backup

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

Might be requirement for us to emerge,
rather than a prediction of a theory

e.g. Agrawal, Barr, Donoghue and Seckel (1998)
Hall, Pinner, Ruderman (2014)

Not established nor denied

The electroweak scale may not be a guiding principle

Correction to the gauge coupling unification by high dimensional operator

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

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

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

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

Correction to the gauge coupling unification by high dimensional operator

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

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

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

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