03/16/2018

Bay Area Seminar @ SFSU

Higgs mass, strong CP problem, GUT

Keisuke Harigaya (UC Berkeley, LBNL)

with Lawrence Hall

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

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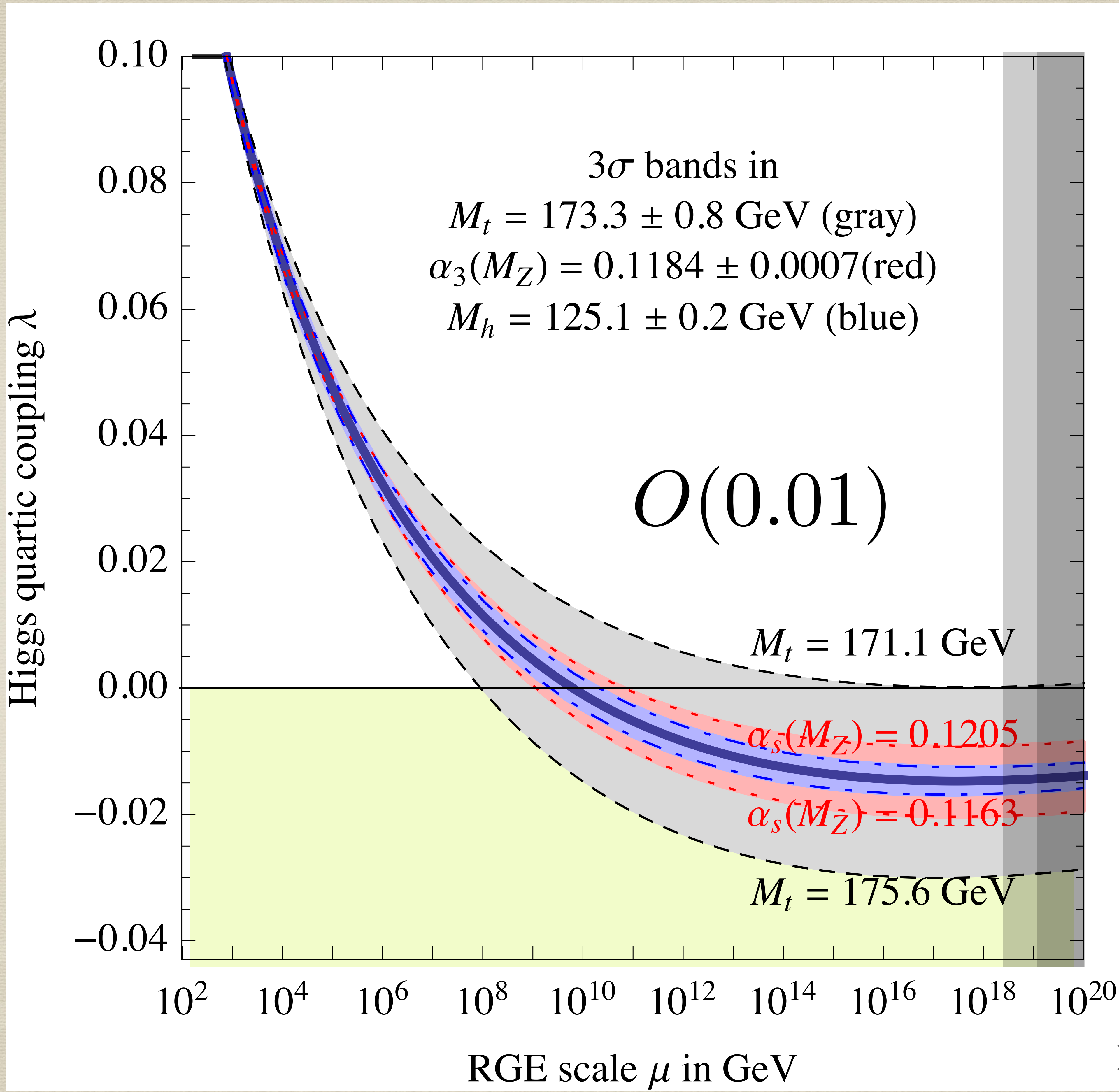
Might be requirement (anthropic principle), rather than a prediction of a theory

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

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

Today's topic

Assume that the SM is valid up to high energy scale



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)
O(0.01)
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

1307.3536

Why

$$\lambda(10^9 - M_{\rm pl}) \sim 0.01 \ll 1 \quad ?$$

Plan of the talk

* Vanishing quartic from Z_2 symmetry
* Strong CP problem
* SO(10) unification

Z_2 symmetry and Higgs potential

Introduce Z2 symmetry

$$H \leftrightarrow H'$$

$$V(H, H') = \lambda(|H|^4 + |H'|^4) + y|H|^2|H'|^2 - m^2(|H|^2 + |H'|^2)$$

Let us assume m >> v_{EW} ,
and find the vacuum $\langle H \rangle = v_{\mathrm{EW}}$

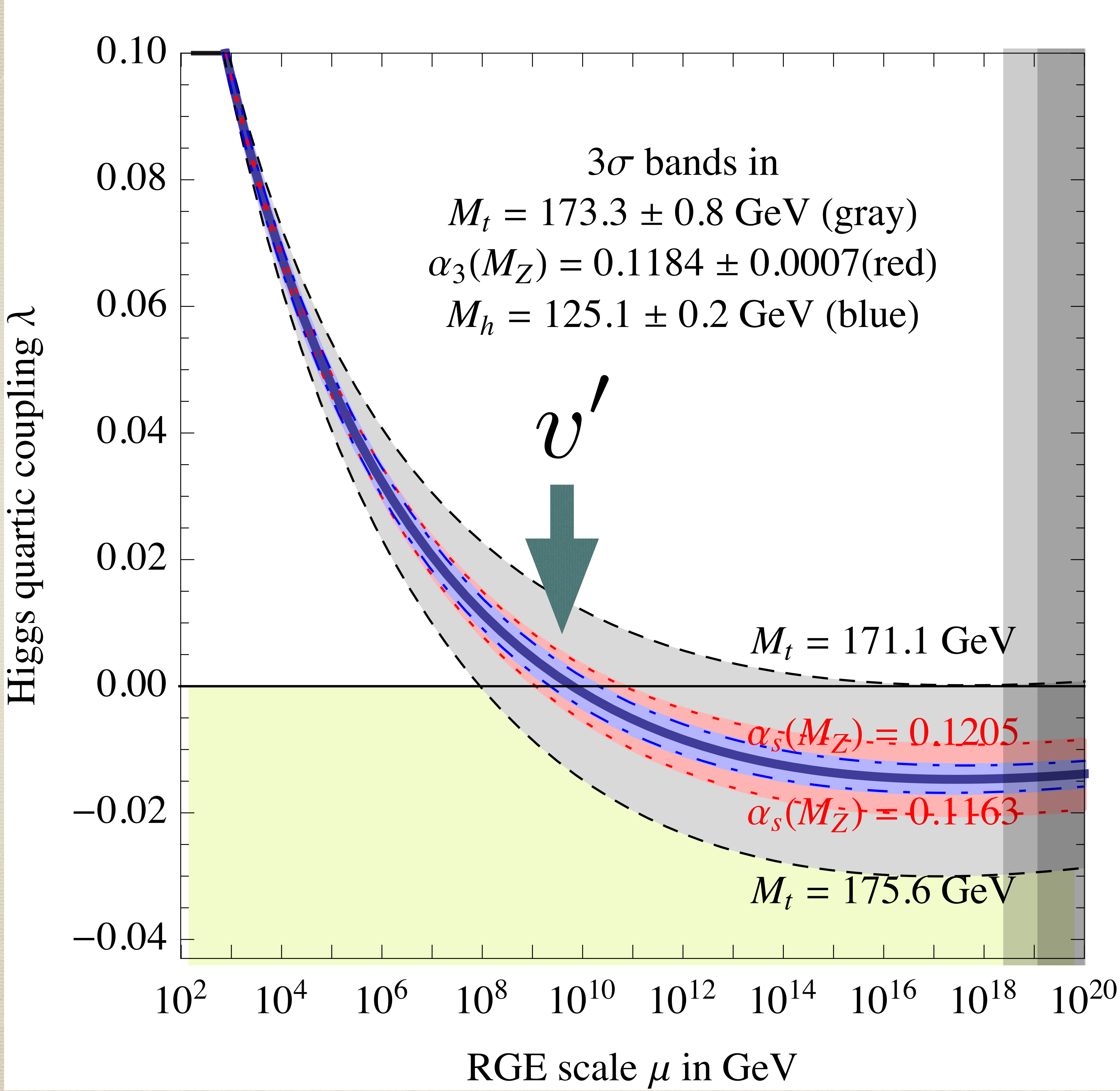
$$V(H,H') = \lambda(|H|^4 + |H'|^4) + y|H|^2|H'|^2 - m^2(|H|^2 + |H'|^2)$$

$$v'^2 \equiv \langle H' \rangle^2 = \frac{m^2}{2\lambda} \to \frac{y}{2\lambda} \simeq 1$$

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

Accidentally SU(4) symmetric

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



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v′
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$$m^2 \ll \Lambda_{\text{cut}}^2$$

More Fine-tuned than SM?

No.

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

EW Gauge group

$$v' \gg v$$

→ H' charged under additional SU(2)'

$$SU(2)_L \times SU(2)' \times U(1)$$

$$H(2,1,1/2), \quad H'(1,2,1/2)$$

$$SU(2) \times SU(2)' \times U(1) \xrightarrow{H'} SU(2)_L \times U(1)_Y$$

Fermions

Doublets have Z_2 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'	$(\mathbf{1},1,2,\frac{1}{2})$	$(\mathbf{1},1,2,\frac{1}{2})$	$(\mathbf{1},1,2,-\frac{1}{2})$	$(\mathbf{1},1,2,-\frac{1}{2})$

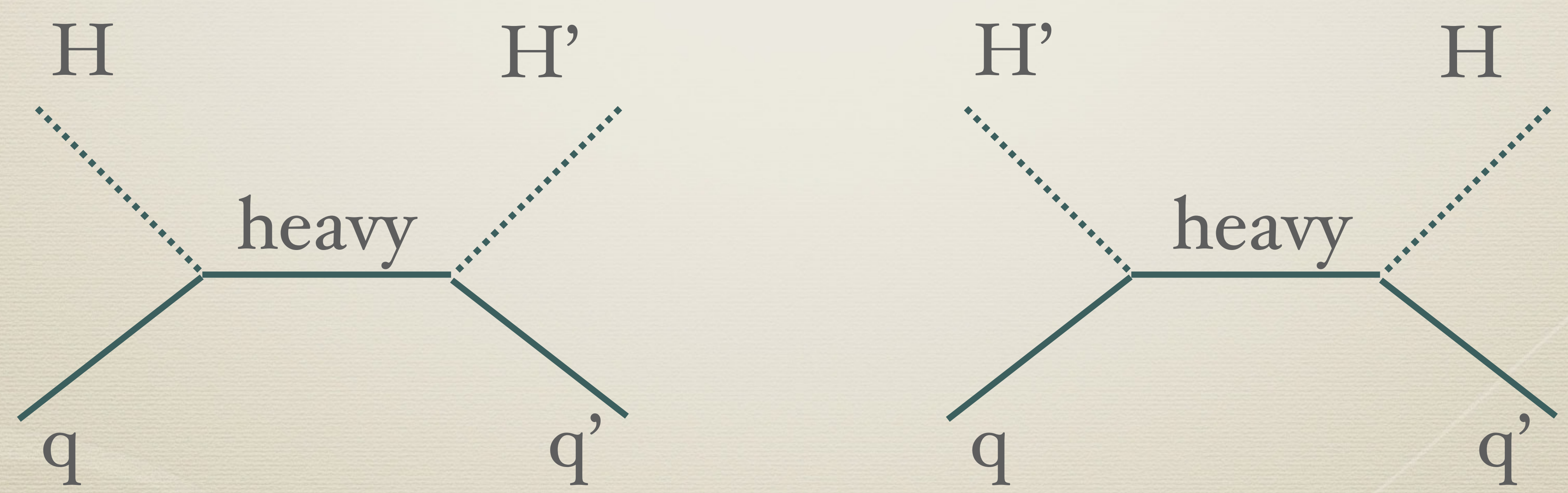
A: almost vector-like and anomaly free.
q', l' are identified with $SU(2)_L$ singlet SM fermions

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

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

Yukawa coupling

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



Z_2 symmetry and the strong CP problem

Action of Z_2 symmetry

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

1. Simple exchange C_{LR}

$$q \leftrightarrow q'$$

2. Involving space-time Parity P_{LR}

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

Action of Z_2 symmetry

$$q(\mathbf{3}, 2, 1, \frac{1}{6}), \ell(\mathbf{1}, 2, 1, -\frac{1}{2}),$$
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1. Simple exchange C_{LR}

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2. Involving space-time Parity P_{LR}

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

Parity

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

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

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

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

Strong CP problem is solved!

(Also for Models B, C and D)

SSB of Parity by H'

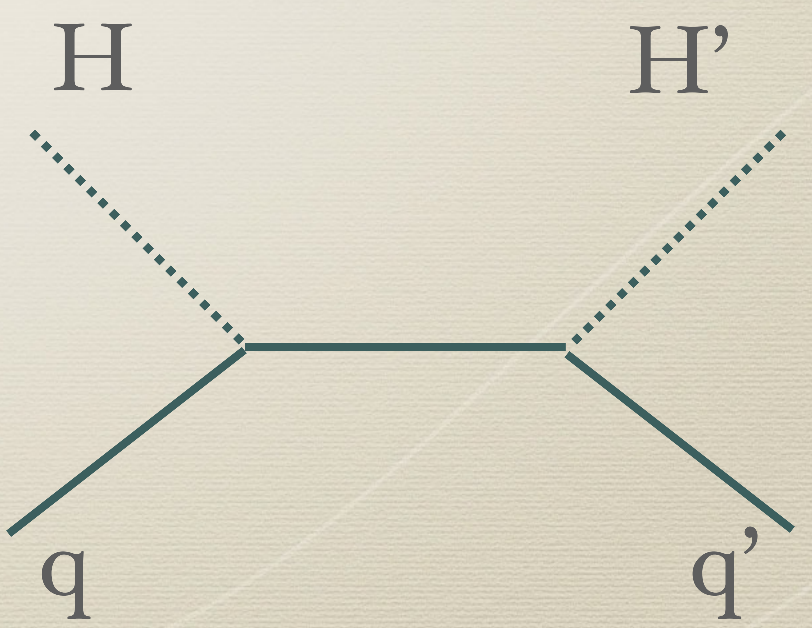
Parity solutions

* 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 potential (1991, Barr, Chang and Senjanovic)

* 1989, Babu and Mohapatra

  Model A with soft Z2 breaking



SO(10) GUT

Matter unification

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

$$q, \ell, q', \ell' = \mathbf{16}$$

$$H, H' \subset \mathbf{16}$$

Symmetry breaking chain

$$SO(10)$$

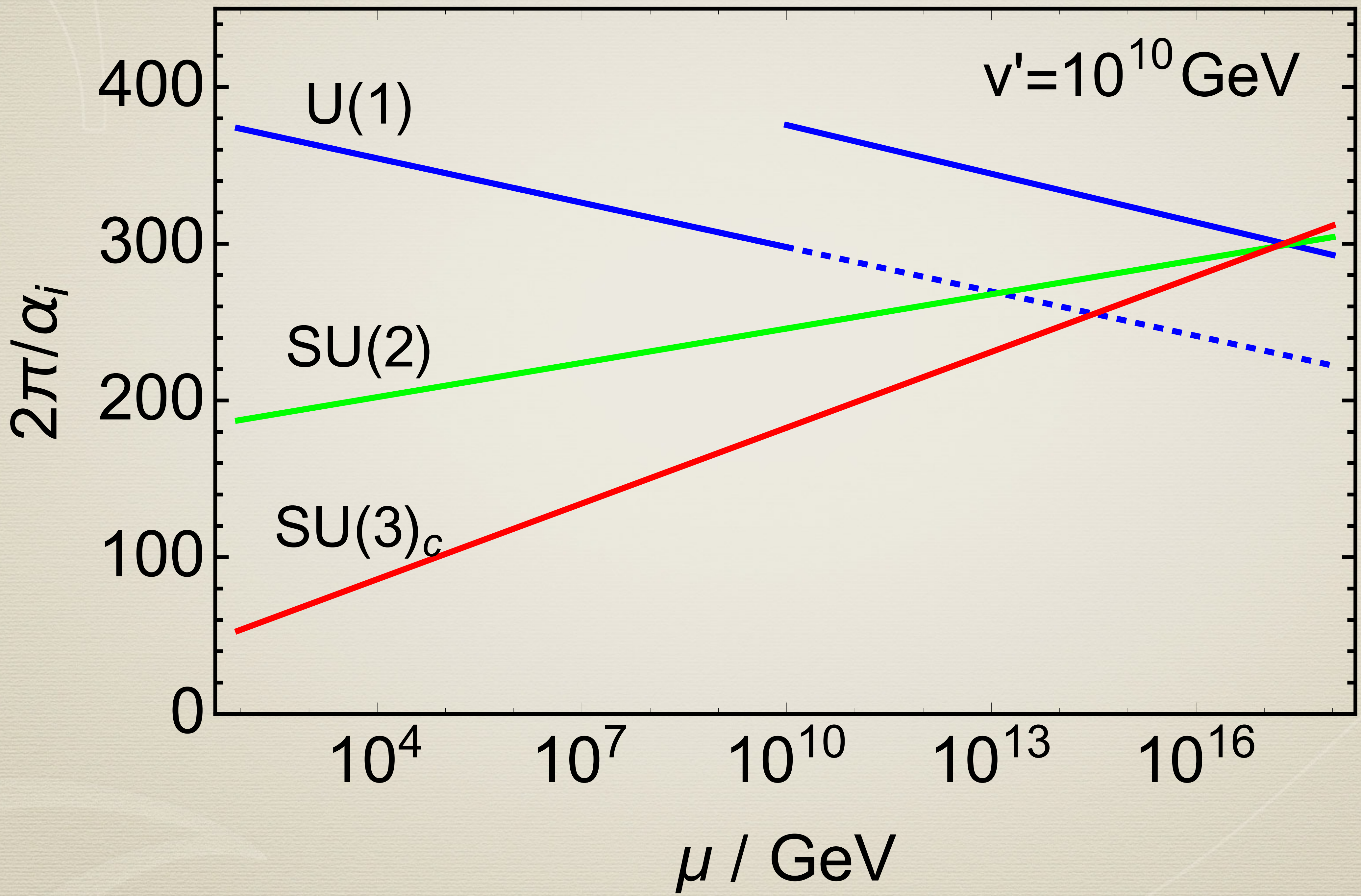
↓ Very High energy scale

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

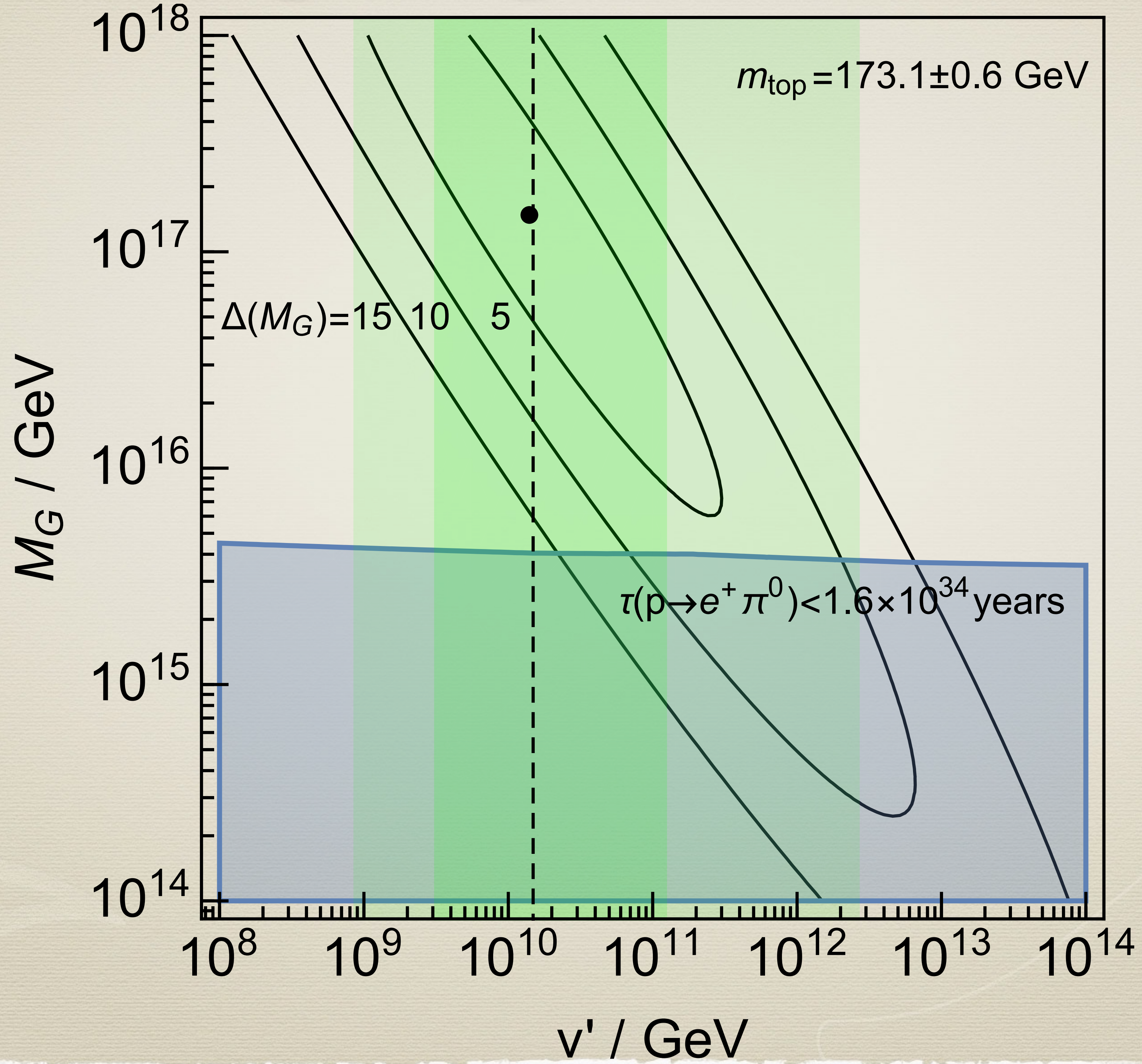
↓ H'

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

Coupling unification



Coupling unification



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

Z2 symmetry

$$C_{LR} \qquad q \leftrightarrow q'$$

Part of the SO(10) symmetry

Often unbroken even with GUT symmetry breaking

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

Z2 symmetry

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

SO(10) with 16 fermion is chiral. No parity?

$$C_{LR} * CP = P_{LR}$$

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

Intermediate Pati-Salam

$$SO(10) \to SU(4) \times SU(2)_L \times SU(2)_R$$

$$SU(3)_c \times U(1)_{\mathrm{B-L}} \subset SU(4)$$

$$q(\mathbf{3}, 2, 1, \frac{1}{6}), \ell(\mathbf{1}, 2, 1, -\frac{1}{2}) = (\mathbf{4}, 2, 1)$$

$$q'(\bar{\mathbf{3}}, 1, 2, -\frac{1}{6}), \ell'(\mathbf{1}, 1, 2, \frac{1}{2}) = (\bar{\mathbf{4}}, 1, 2)$$

Intermediate Pati-Salam

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

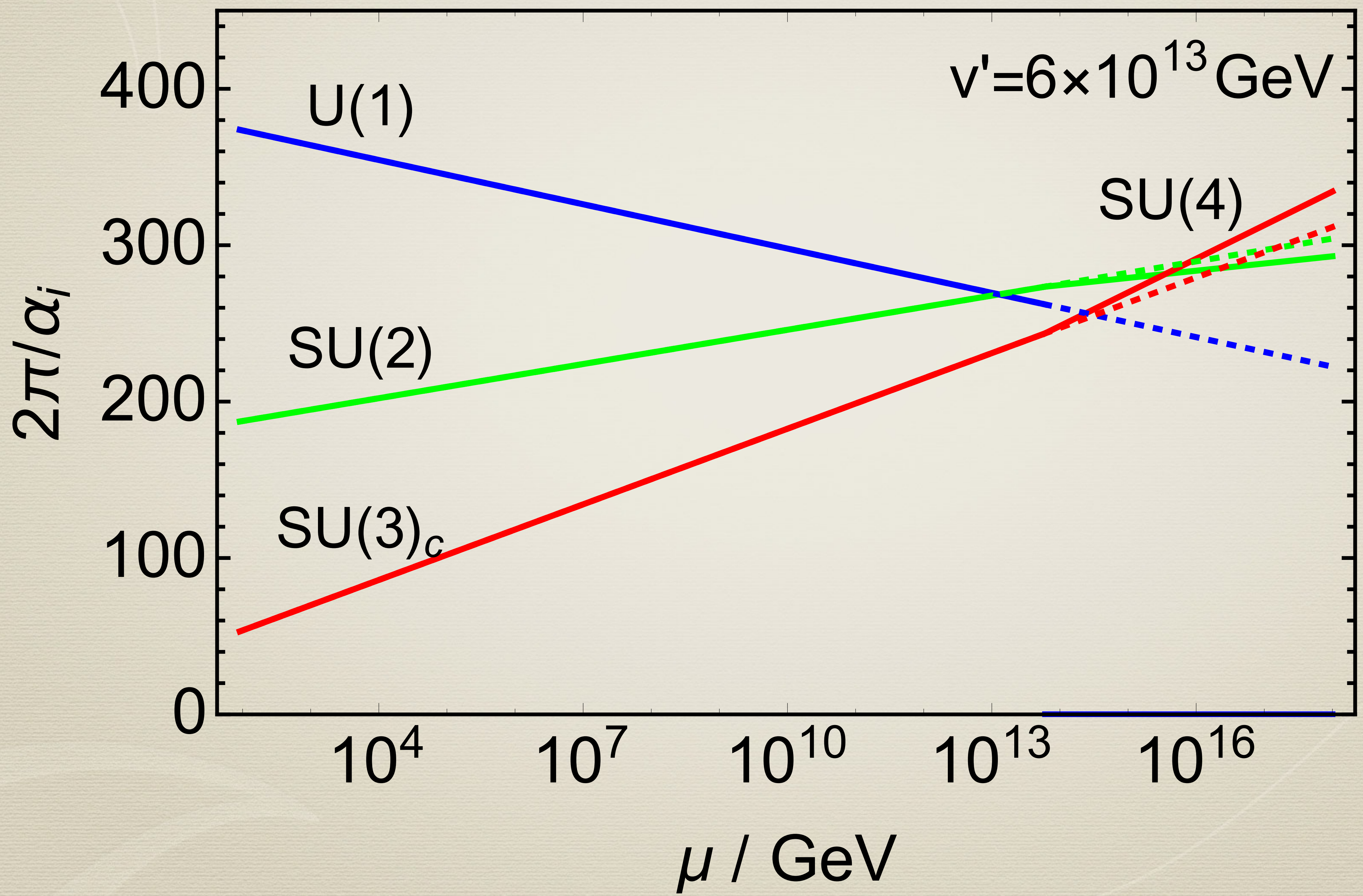
$$H'(\mathbf{1}, 1, 2, \frac{1}{2}) \subset (\bar{\mathbf{4}}, 1, 2)$$

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

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

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

Coupling Unification



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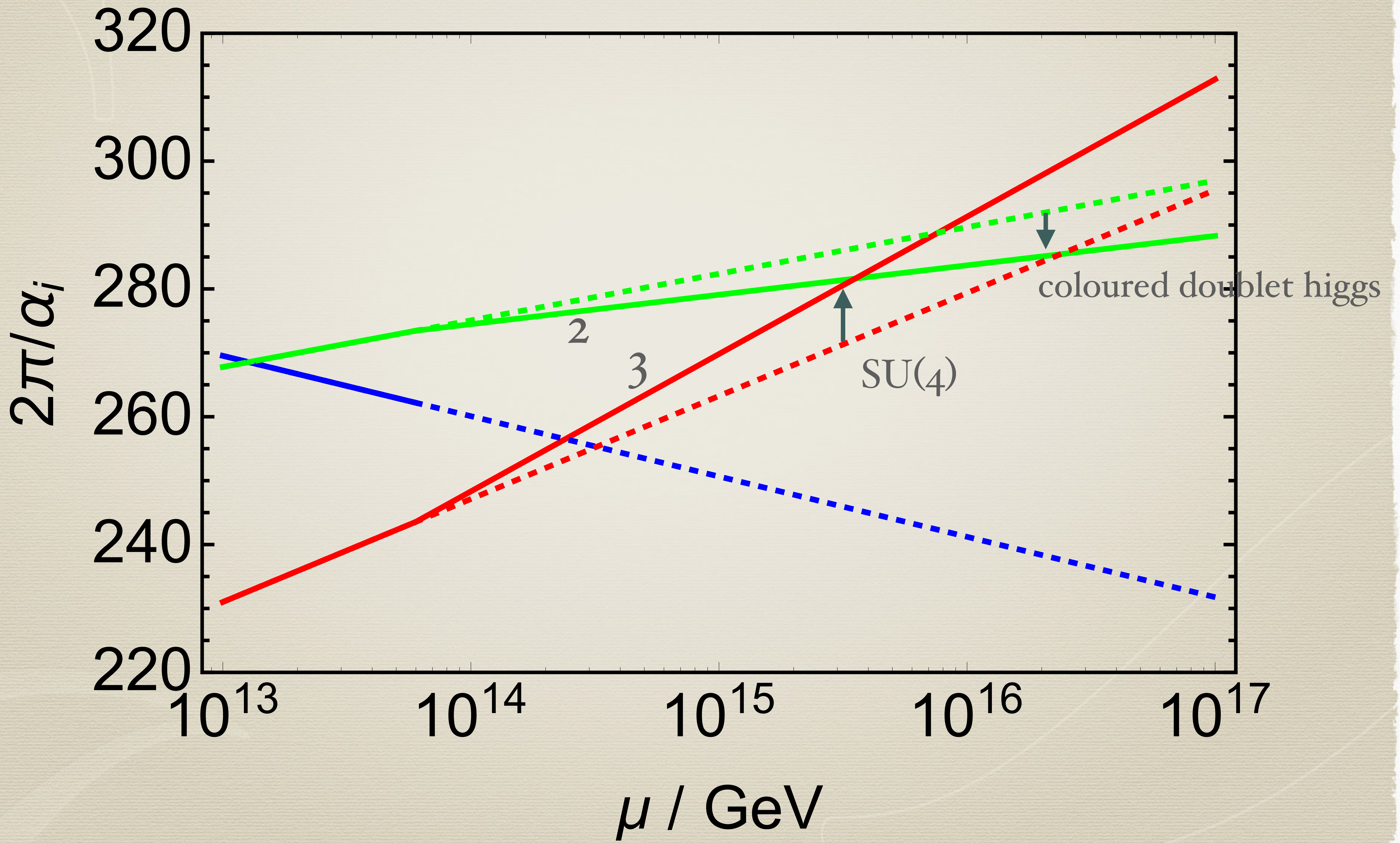

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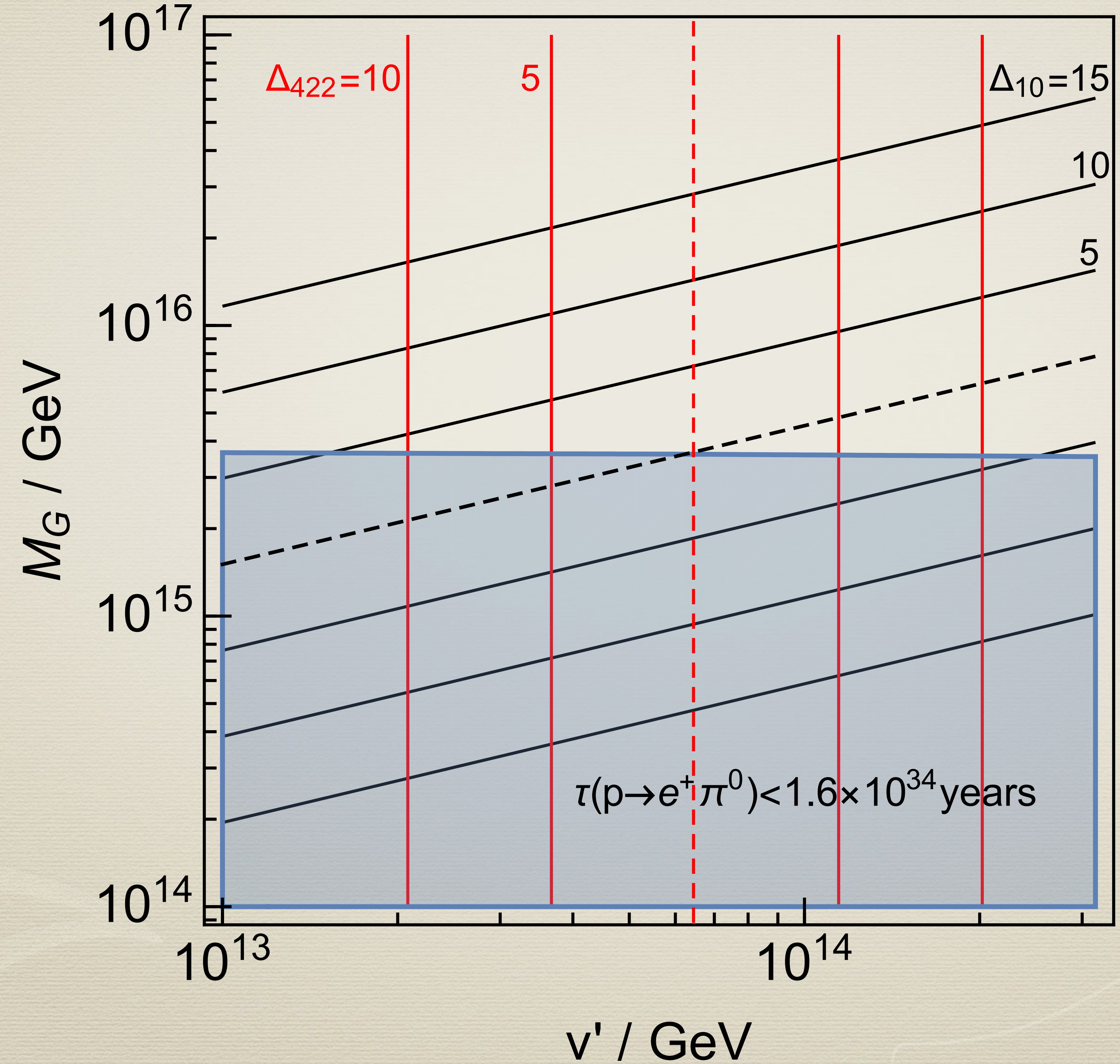

Summary

$\lambda \sim 0$

top quark mass
to determine v'

Accidental SU(4)

Z2 and its SSB by H'

Parity

Extra gauge group

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

Unification

neutron EDM?

Proton decay

Backup

Loop correction to θ

Suppressed by loop factors, flavor mixing

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

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

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

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

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