04/11/2019
Kavli IPMU
Prospects of Neutrino Physics

Higgs parity GUT

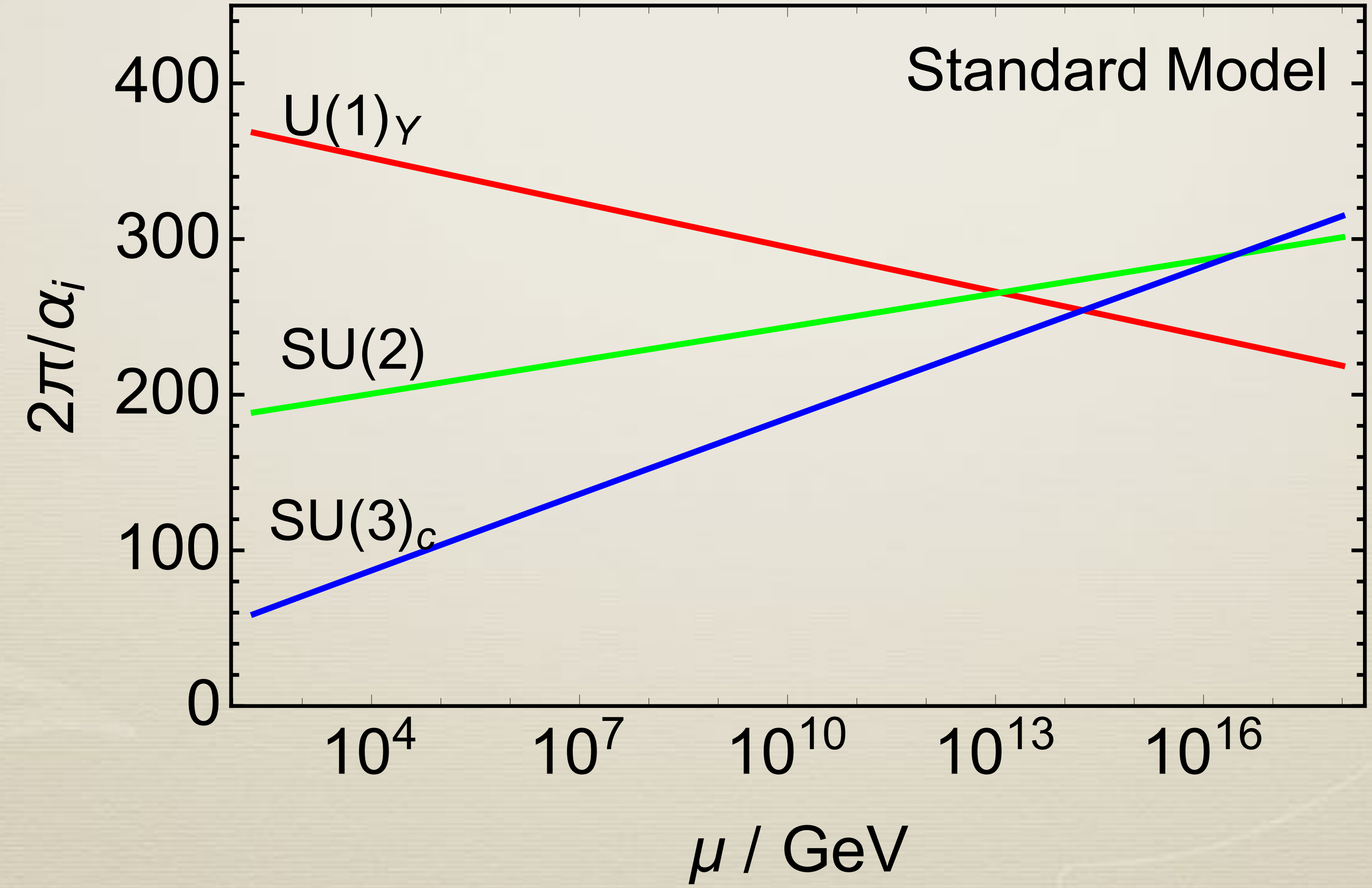
Keisuke Harigaya (IAS)

with Lawrence Hall 1803.08119

Grand unification

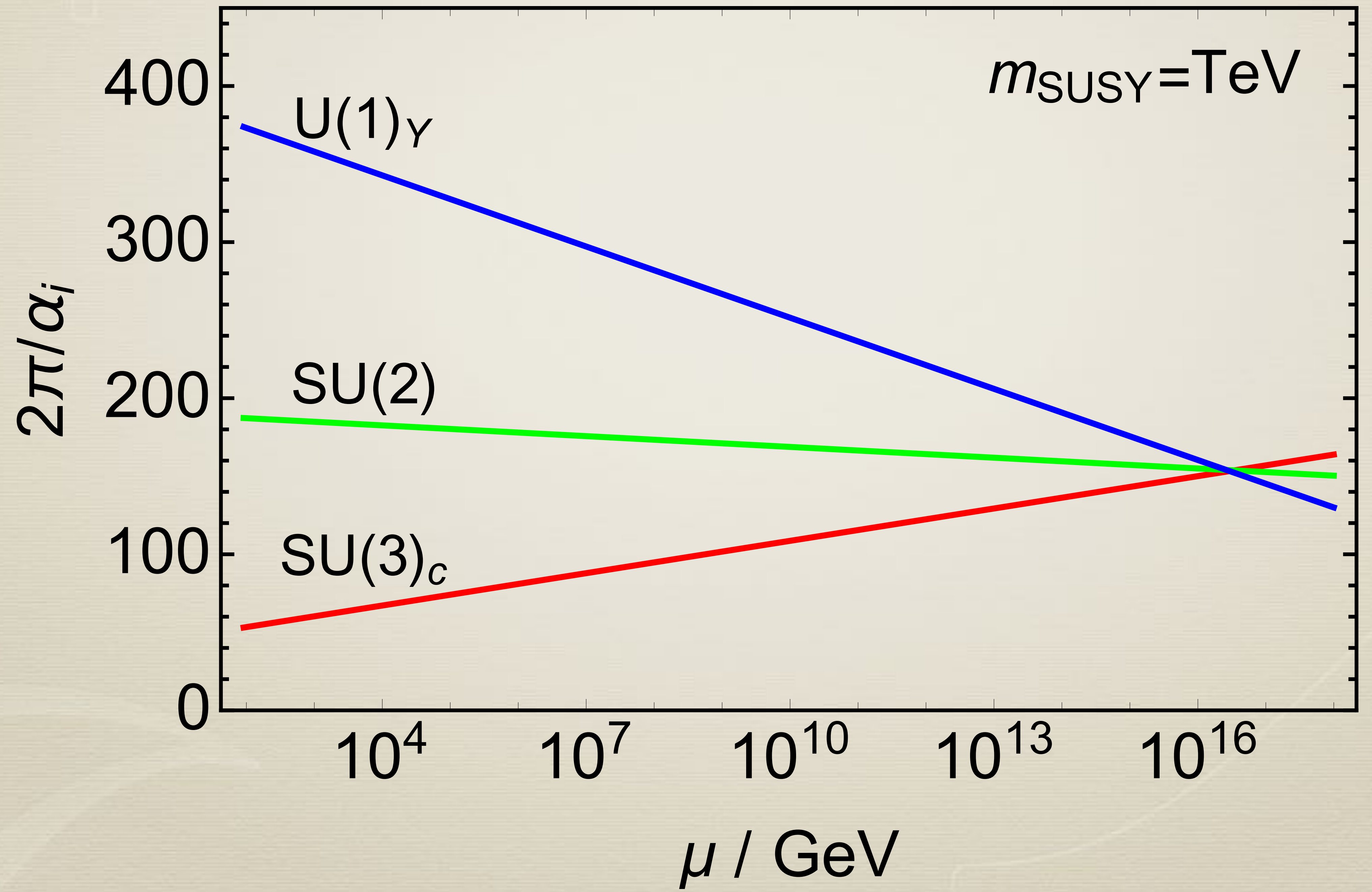
- The apparently complex structure of quarks and leptons are simplified

- Actually, gauge couplings roughly unify in the SM



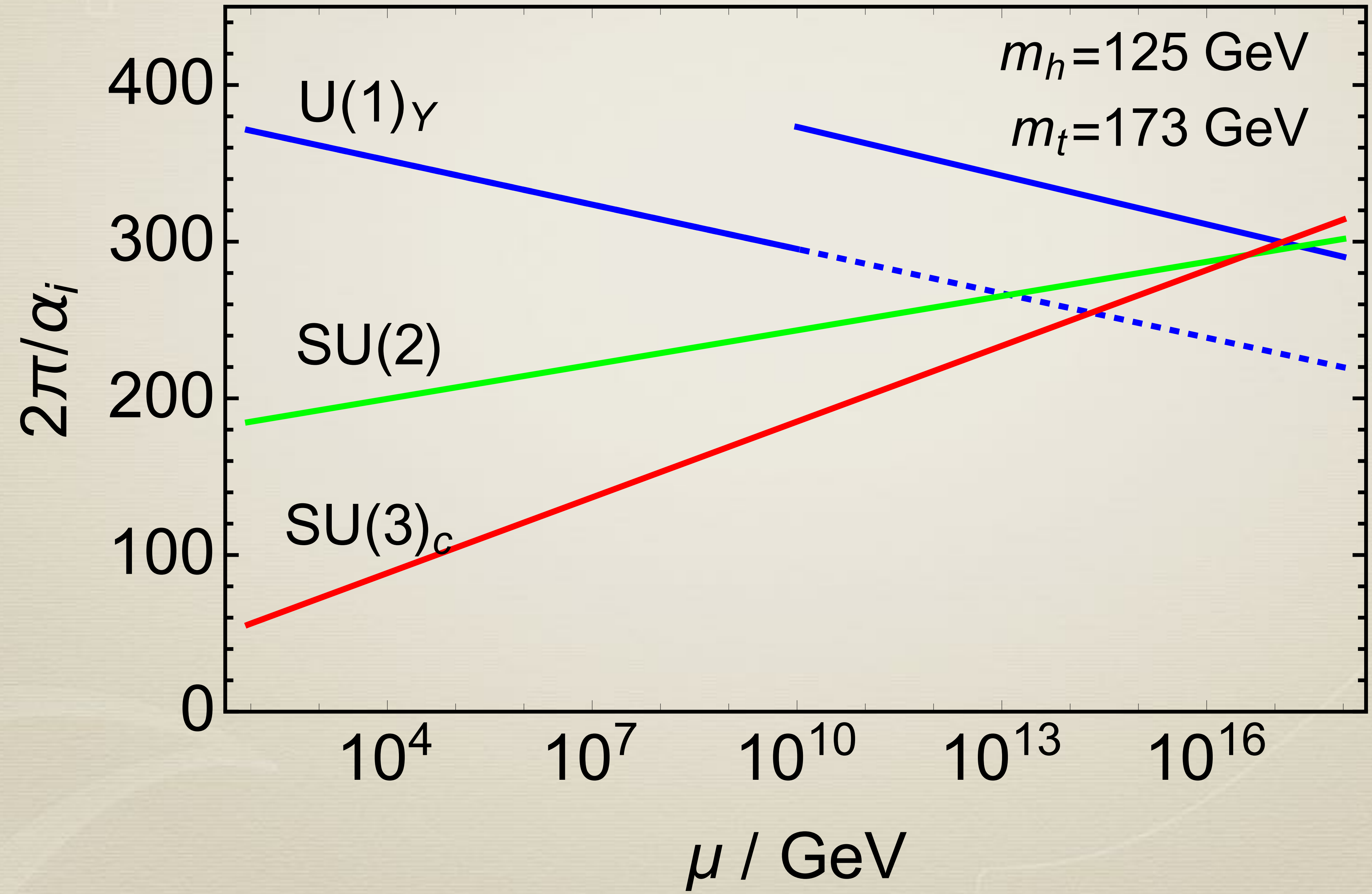
Miracle of SUSY GUT

After precise measurements of gauge couplings by LEP,



Miracle after Higgs discovery

Hall and KH (2018)



Higgs Parity GUT

An SO(10) GUT

Hall, KH (2018)

$$SO(10)$$

$q, \ell, \bar{u}, \bar{d}, \bar{e} = 16$

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

Left-right symmetry

$q \leftrightarrow (\bar{u}, \bar{d})$

$\ell \leftrightarrow (\bar{e}, N)$

Higgs parity

$$H_L \leftrightarrow H_R$$

$(1,2,1,\frac{1}{2})$ $(1,1,2,\frac{1}{2})$

$H_L, H_R \subset 16$

$\langle H_R \rangle \neq 0$

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

Prediction on $<H_R>$

Hall, KH (2018)

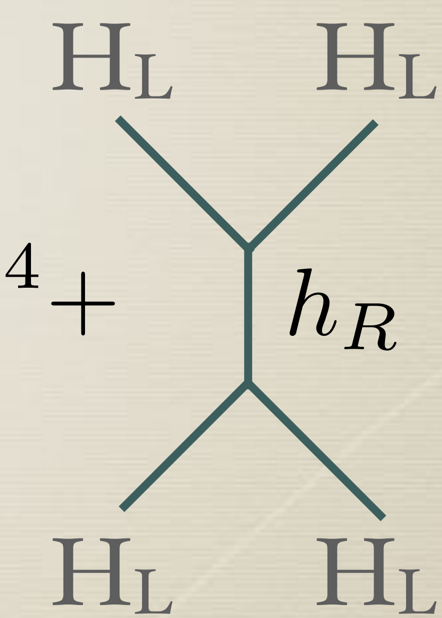
$$V(H_L, H_R) = \lambda(|H_L|^2 + |H_R|^2)^2 + \lambda'|H_L|^2|H_R|^2 - m^2(|H_L|^2 + |H_R|^2)$$

No W_R boson observed $\quad \langle H_R \rangle = v_R \gg v_{EW}$

$$v_R^2 = \frac{m^2}{2\lambda}$$

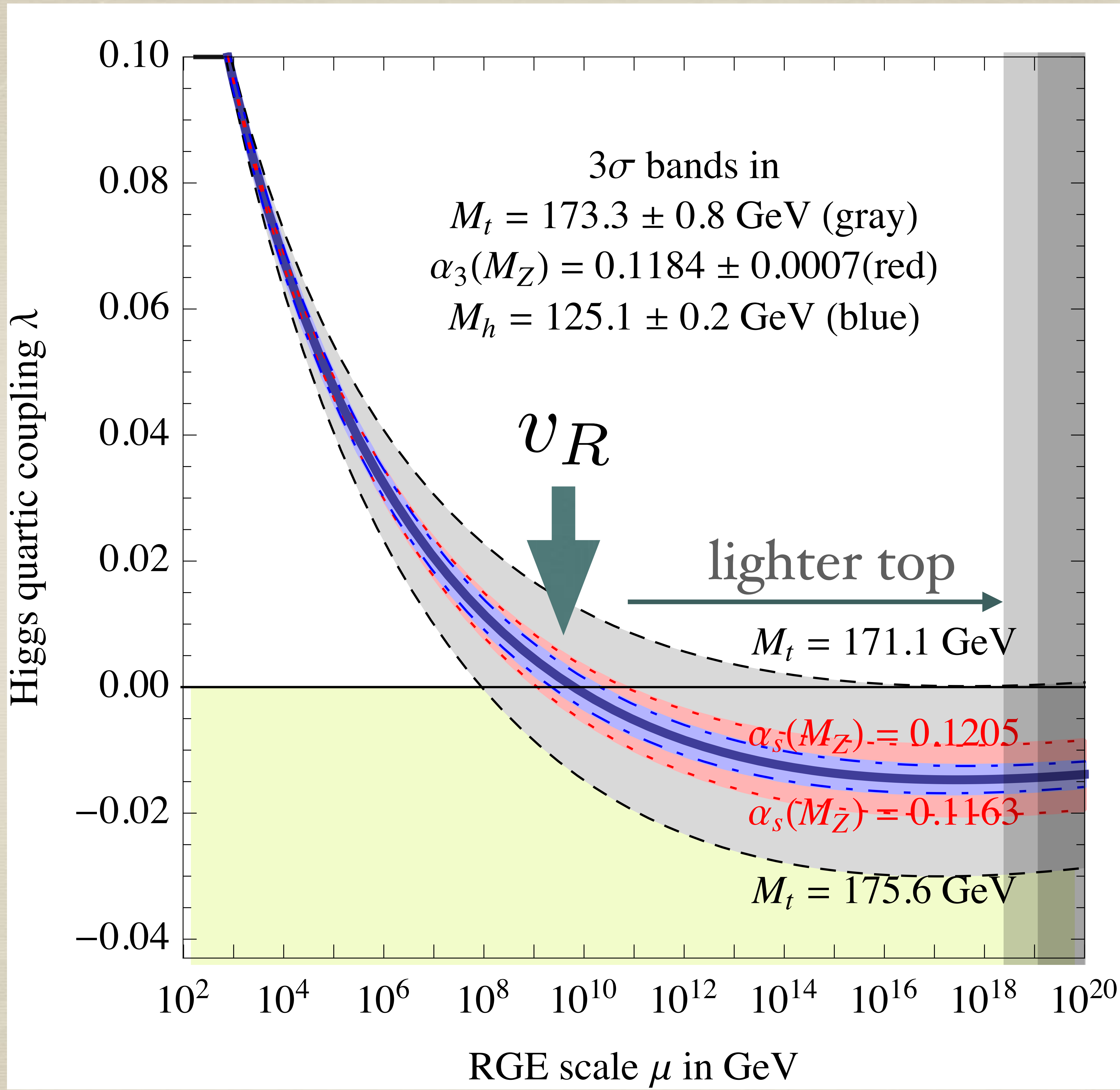
Effective theory below v_R

$$\lambda|H|^4 +$$



$$V_{\text{eff}} \simeq \underbrace{\lambda' v_R^2}_{|\lambda'| \ll 1}|H_L|^2 - \underbrace{\lambda'(1 + \frac{\lambda'}{4\lambda})|H_L|^4}_{\lambda_{\text{SM}}(v_R) = 0}$$

(up to threshold corrections)



Higgs quartic coupling λ
RGE scale μ in GeV
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_R
lighter top
M_t = 171.1 GeV
$\alpha_s(M_Z)$ = 0.1205
$\alpha_s(M_Z)$ = 0.1163
M_t = 175.6 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}

pseudo-NGB Higgs

Hall, KH (2018)

$$V(H_L, H_R) = \lambda(|H_L|^2 + |H_R|^2)^2 + \cancel{\lambda' |H_L|^2 |H_R|^2} - m^2(|H_L|^2 + |H_R|^2)$$

Accidentally U(4) symmetric

$$4 = (H_L, H_R)$$

$$U(4) \to U(3) \text{ by } H_R$$

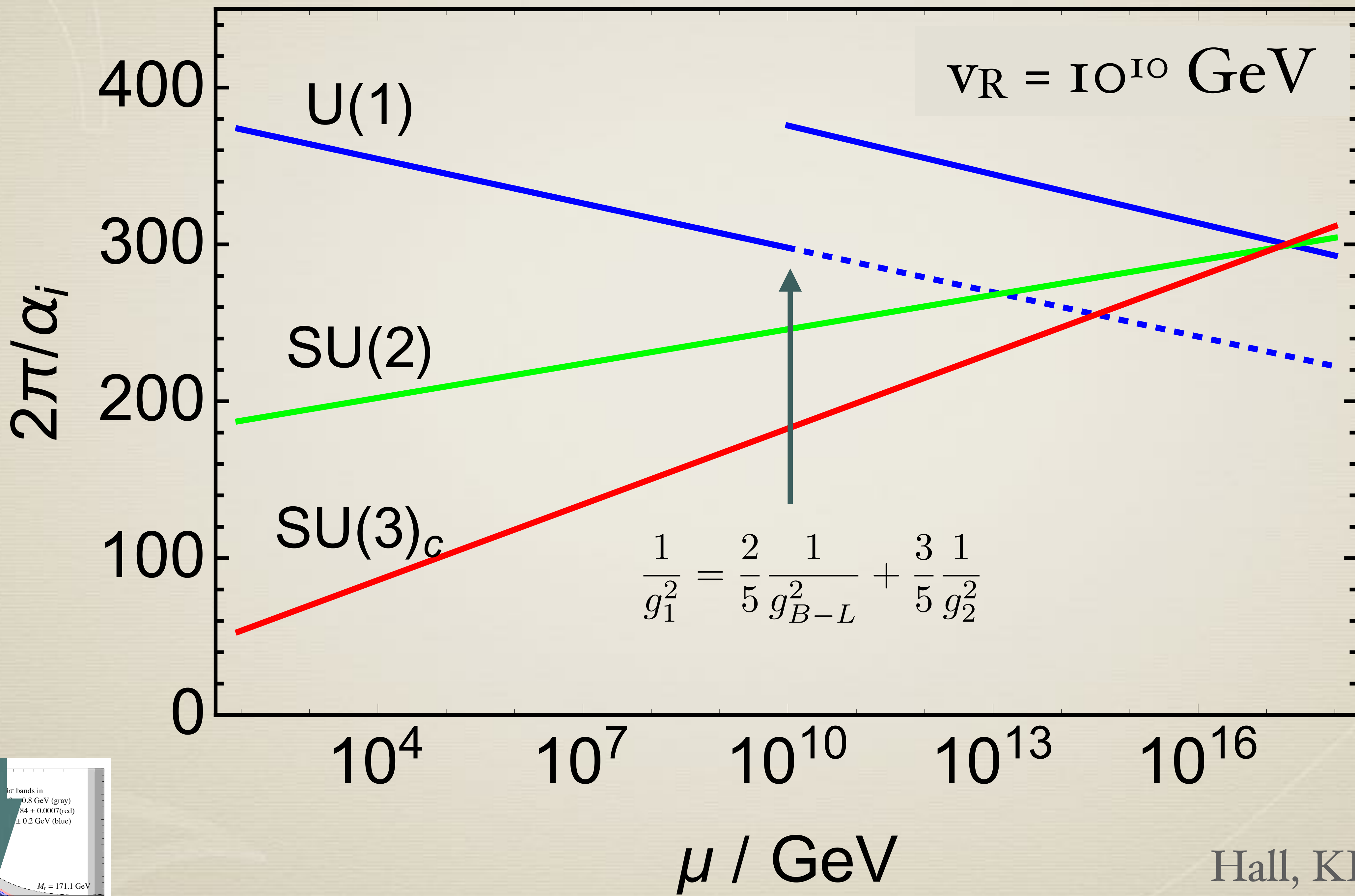
$$16 - 9 = 7 = 4 + 3$$

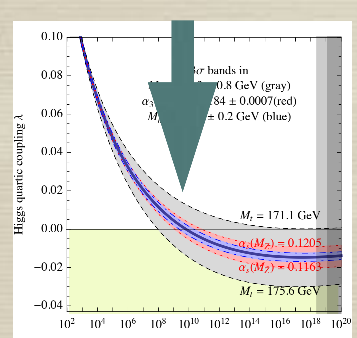
W', Z'

SM Higgs is a pseudo Nambu-Goldstone boson

$$\lambda_{\rm SM}(v_R) = 0$$

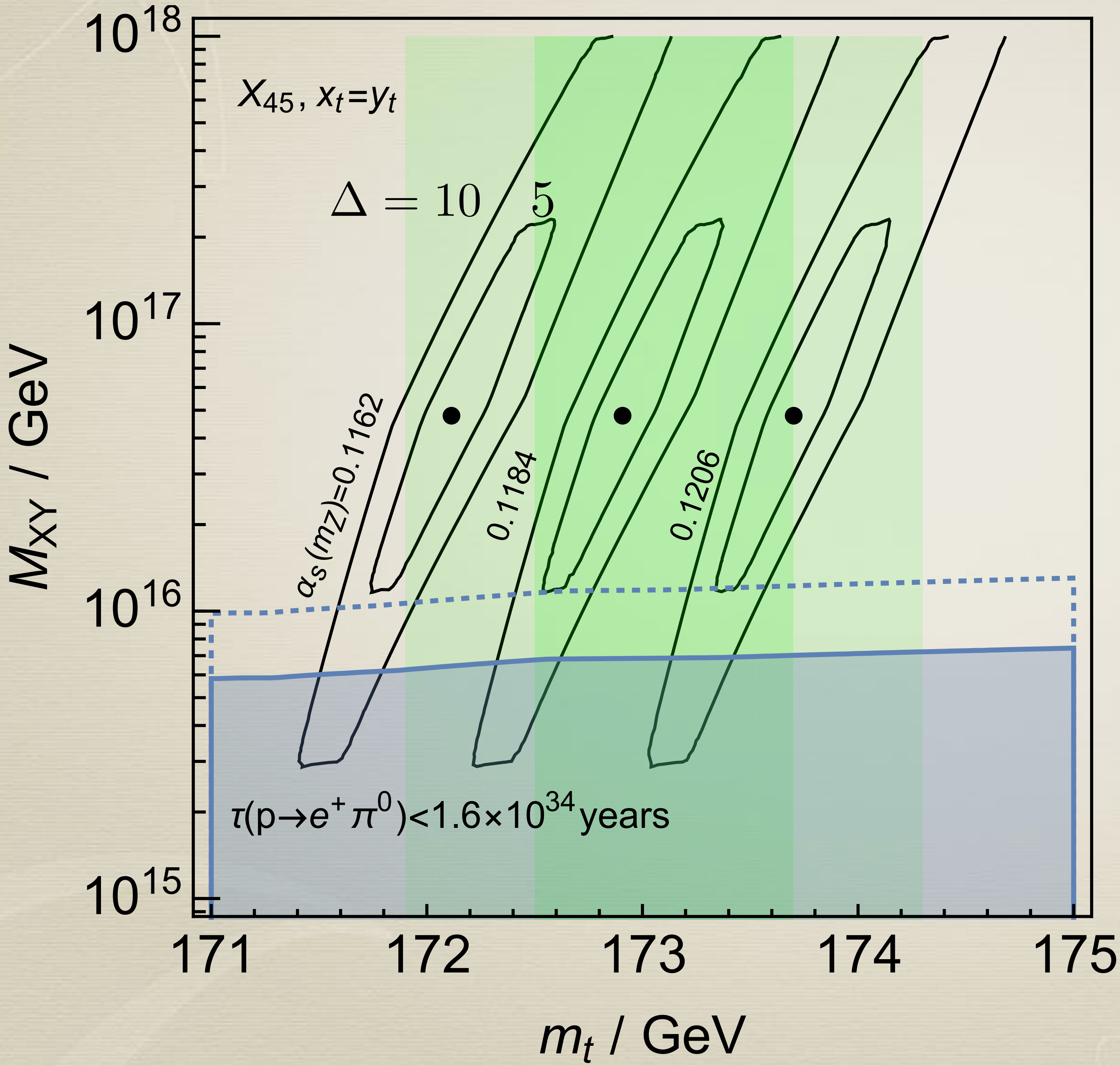
Coupling unification





Hall, KH (2018)

Coupling unification



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

~ Casimir operator × Log(mass splitting)

Hyper-K

Intermediate Pati-Salam

Hall, KH (2018)

$$SO(10)$$

$$\Downarrow$$

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

$$H_L \subset (4, 2, 1)$$

$$H_R \subset (4, 1, 2)$$

$$\langle H_R \rangle = \begin{pmatrix} 0 & 0 & 0 & v_R \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

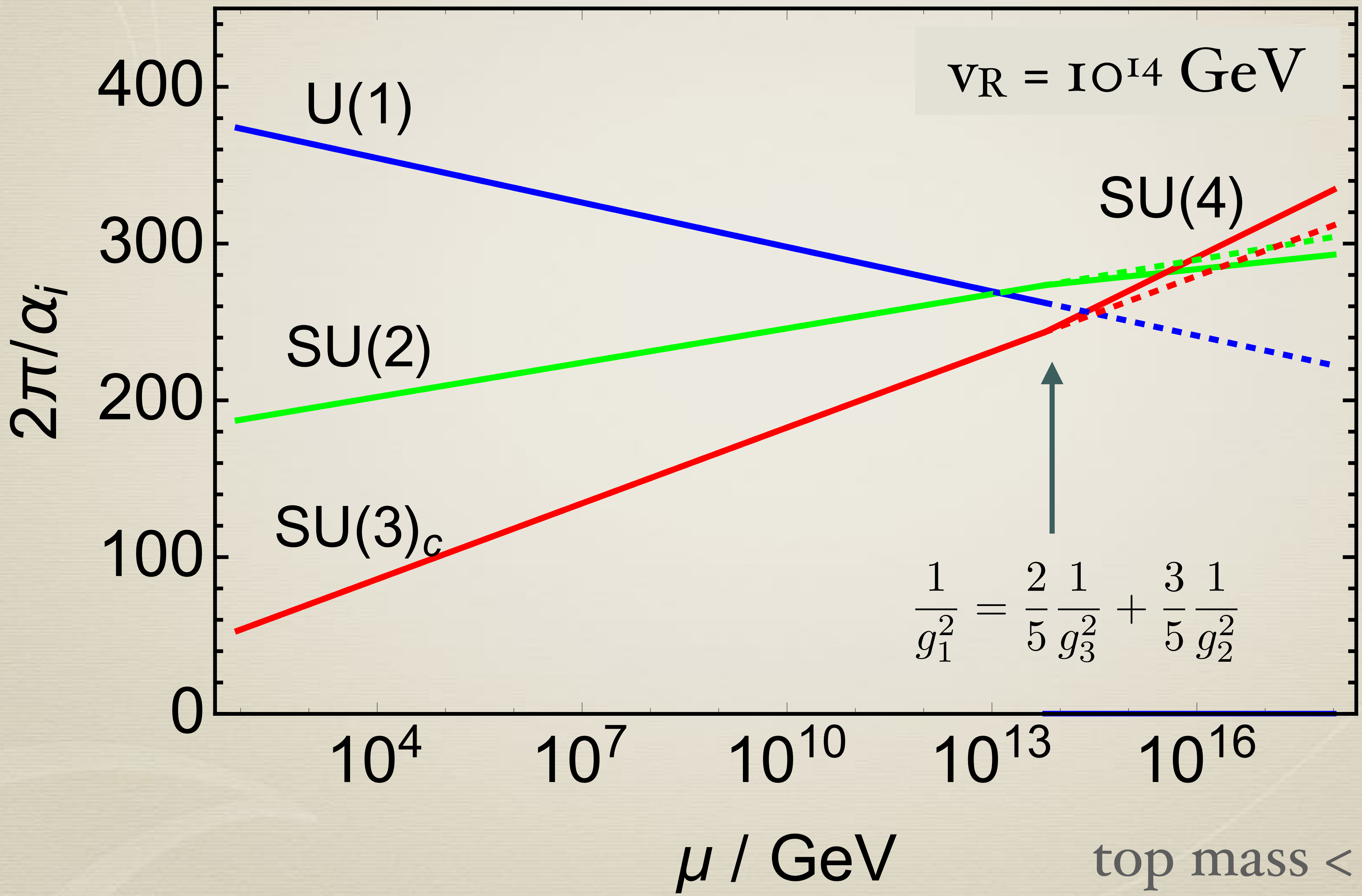
$$\Downarrow$$

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

$$\frac{1}{g_1^2} = \frac{2}{5}\frac{1}{g_3^2} + \frac{3}{5}\frac{1}{g_2^2}$$

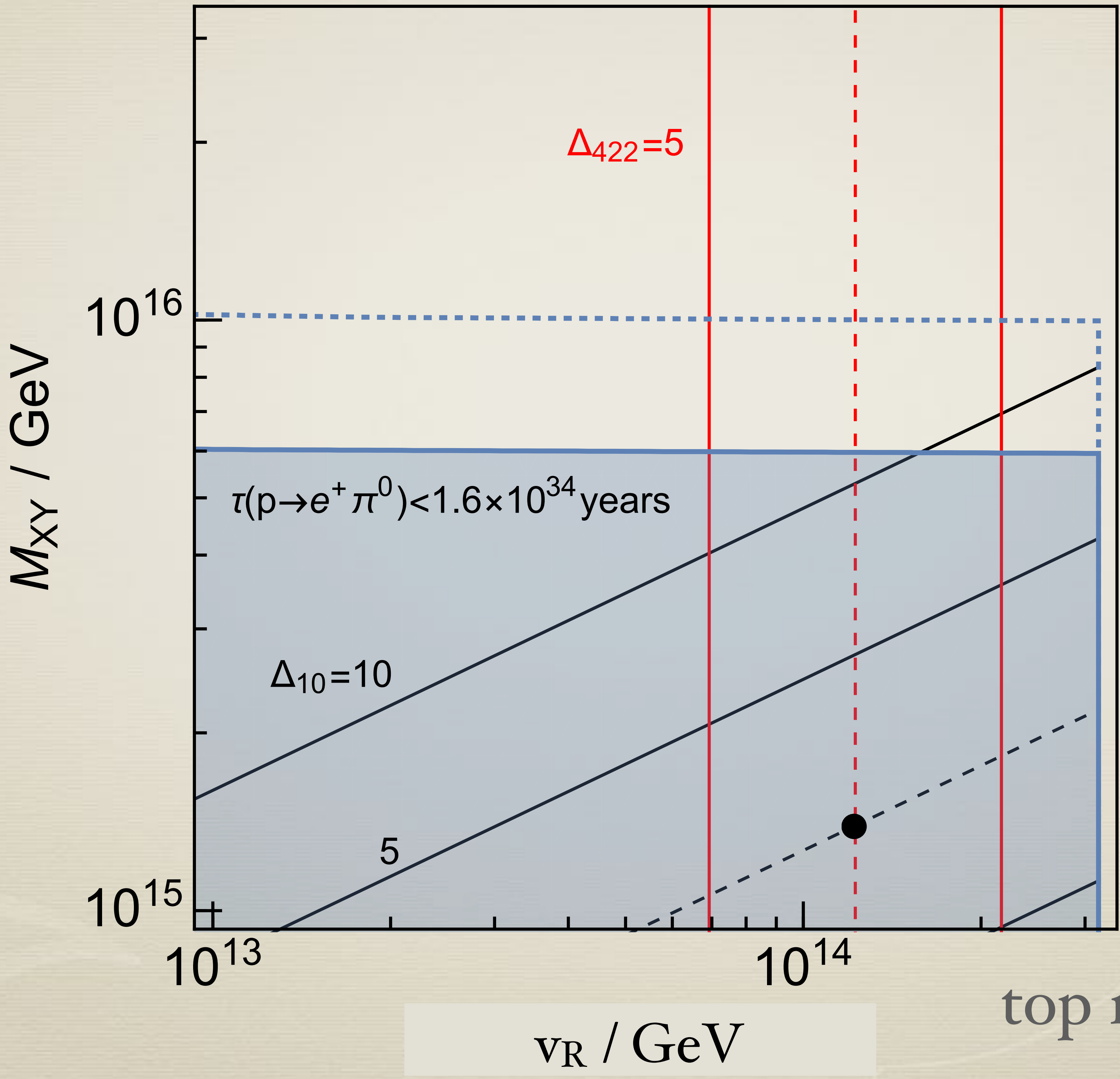
Coupling Unification

Hall, KH (2018)



top mass < 172 GeV

Coupling Unification



Hall, KH (2018)

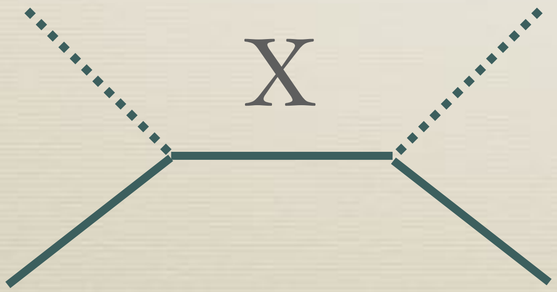
top mass < 172 GeV

Yukawa couplings

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

$$H_L(2,1), H_R(1,2), q(2,1), \bar{q}(1,2) = (\bar{u}, \bar{d})$$

$$\frac{c_{ij}}{M} H_L H_R q_i \bar{q}_j$$



X: 45 or 54 for up
10 for down and electron

Hall, KH (2018)

Strong CP problem

* Strong CP problem may be solved by a space-time parity

$$\cancel{+\frac{\theta_{QCD}}{32\pi^2} G\tilde{G}}$$

Beg and Tsao, Mohapatra and Senjanovic (1978)

* H(2,1) and H(1,2) actually solve the problem

Babu and Mohapartra (1989)

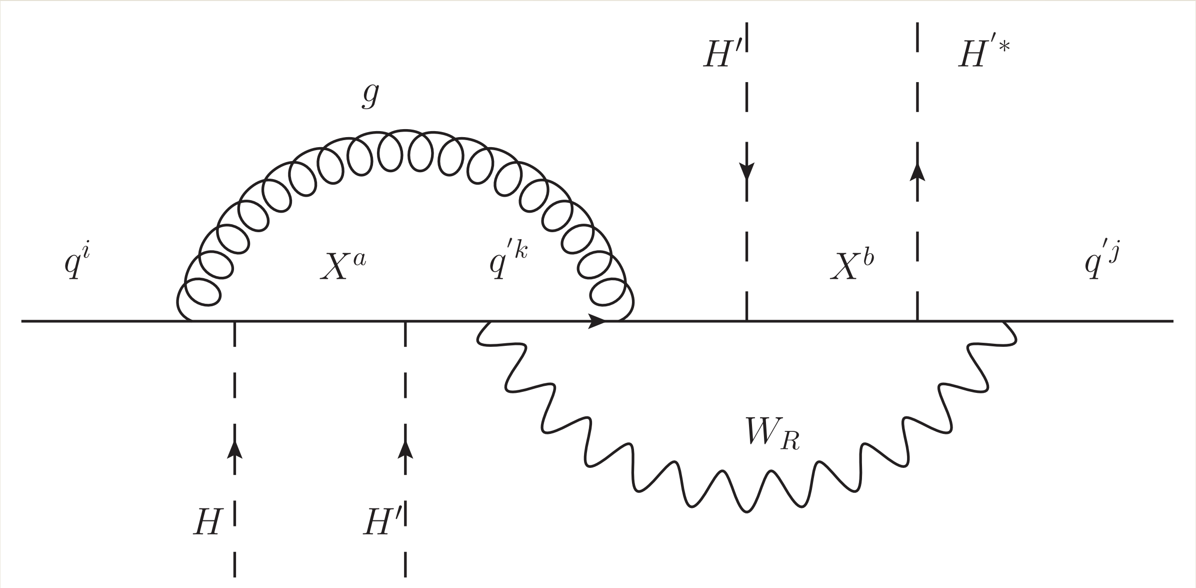
$$\frac{c_{ij}}{M} H_L H_R q_i \bar{q}_j \qquad q(t,x) \leftrightarrow \bar{q}^*(t,-x)$$

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

* SO(10) embedding is possible   Hall, KH (2018)

Loop correction to θ

Hall, KH (2018)



$$\delta\theta \sim 10^{-11} \frac{\theta_{23}^u \theta_{23}^d}{V_{cb}^2}$$

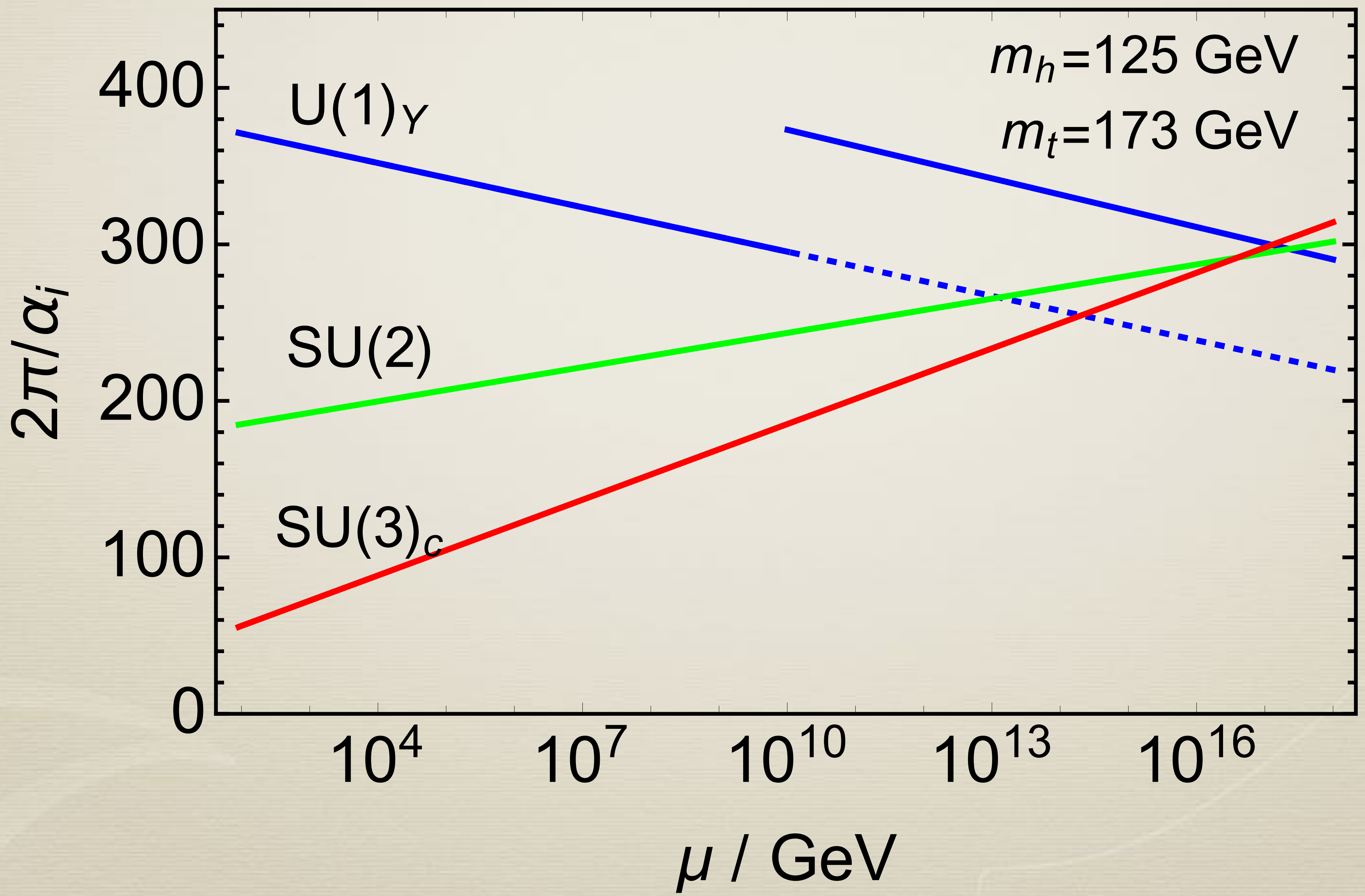
Suppressed by loop factors, flavor mixing

$\theta < 10^{-12}$ in near future

Summary

1803.08119

* New scheme of the coupling unification is proposed



Summary

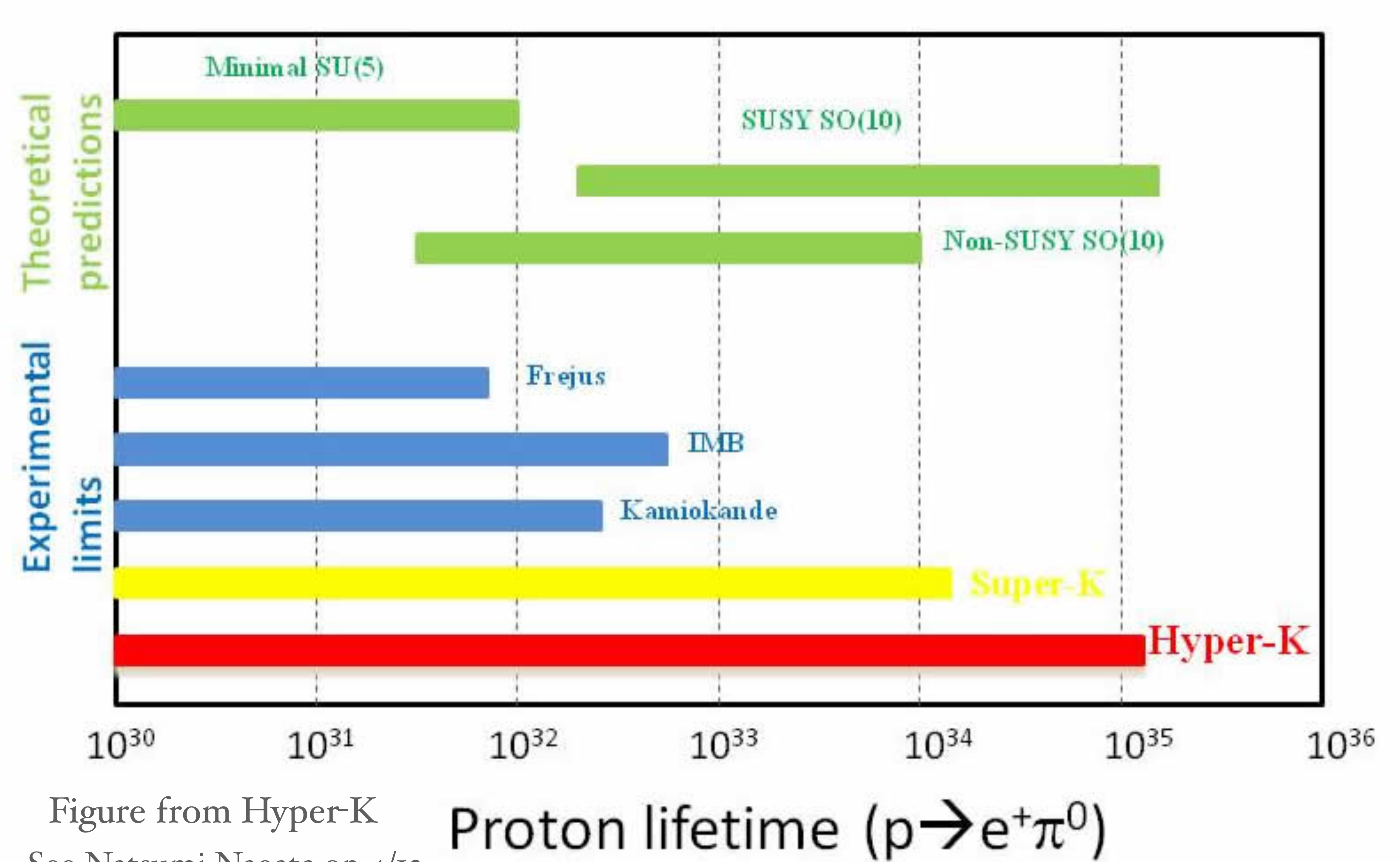


Figure from Hyper-K

See Natsumi Nagata on 4/12

Summary

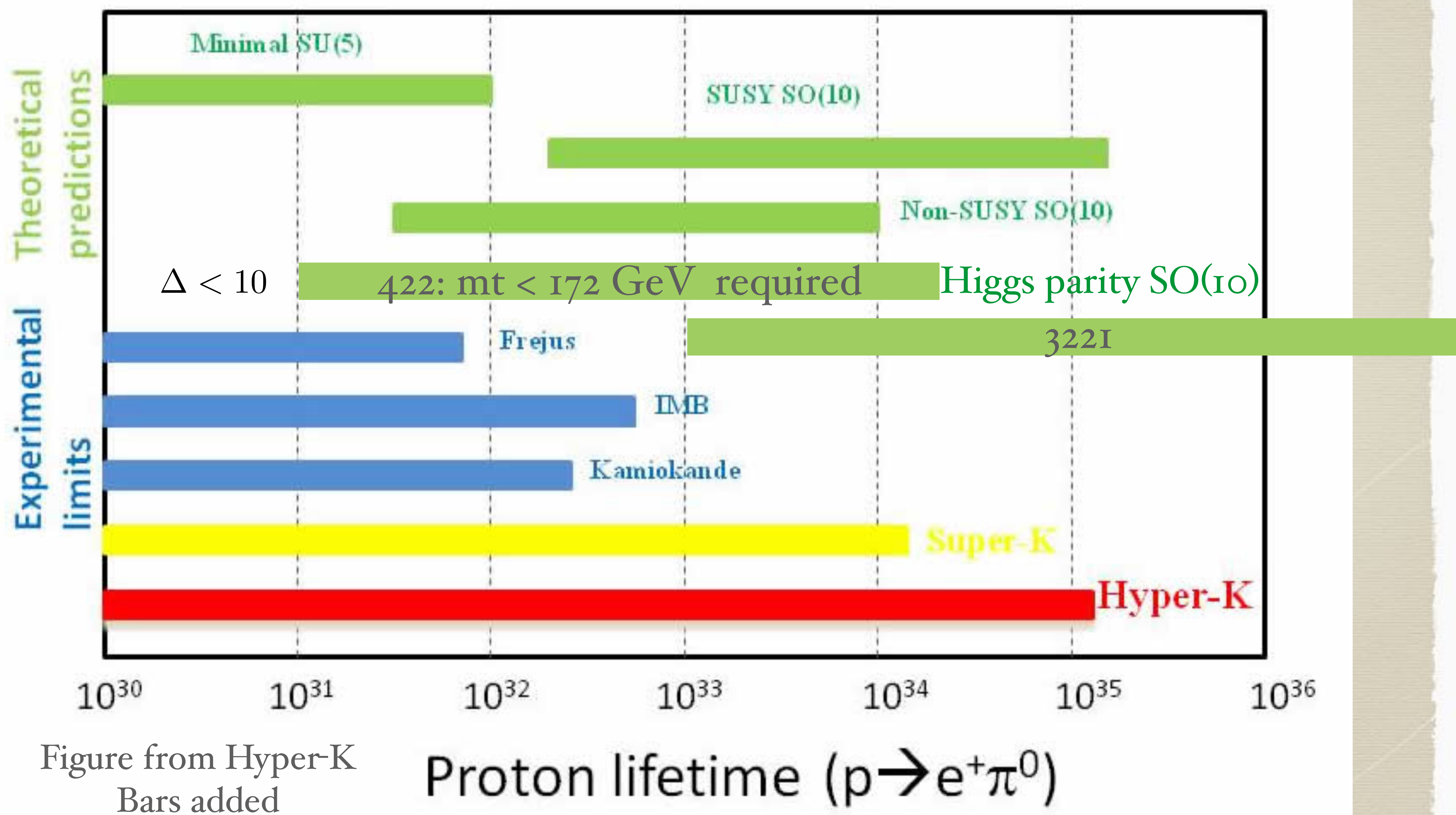


Figure from Hyper-K
Bars added

Discussion

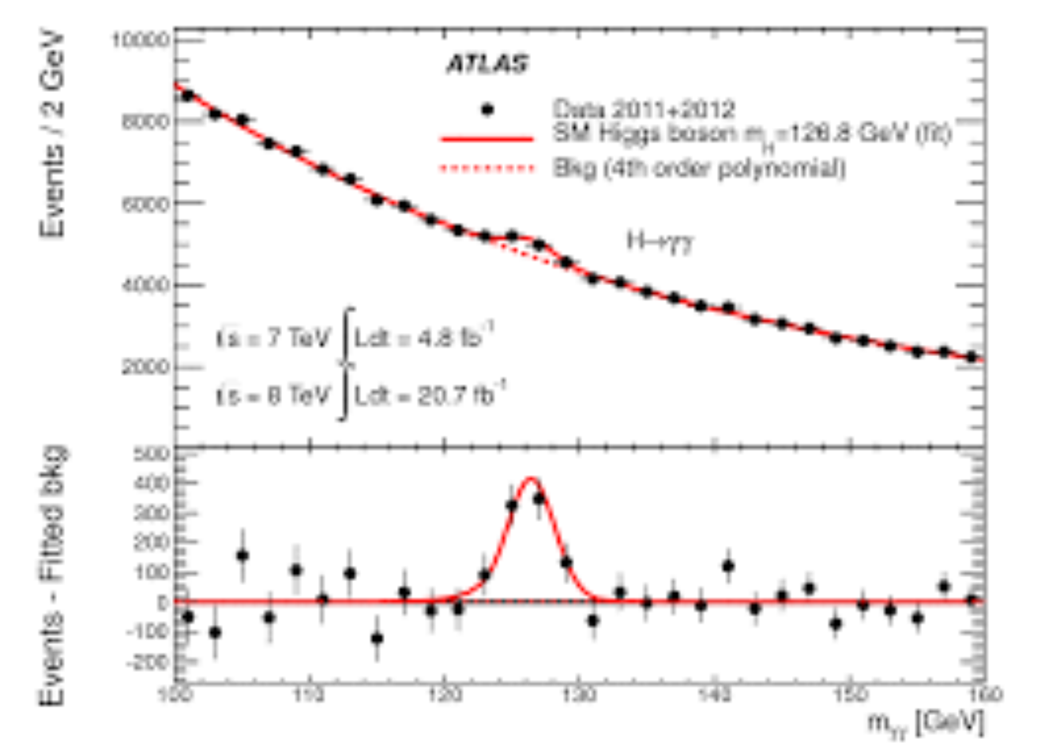
What colliders can do

* Searches for new particles
* Searches for deviation from SM
* Precise measurement of SM parameters

Discussion

What colliders can do

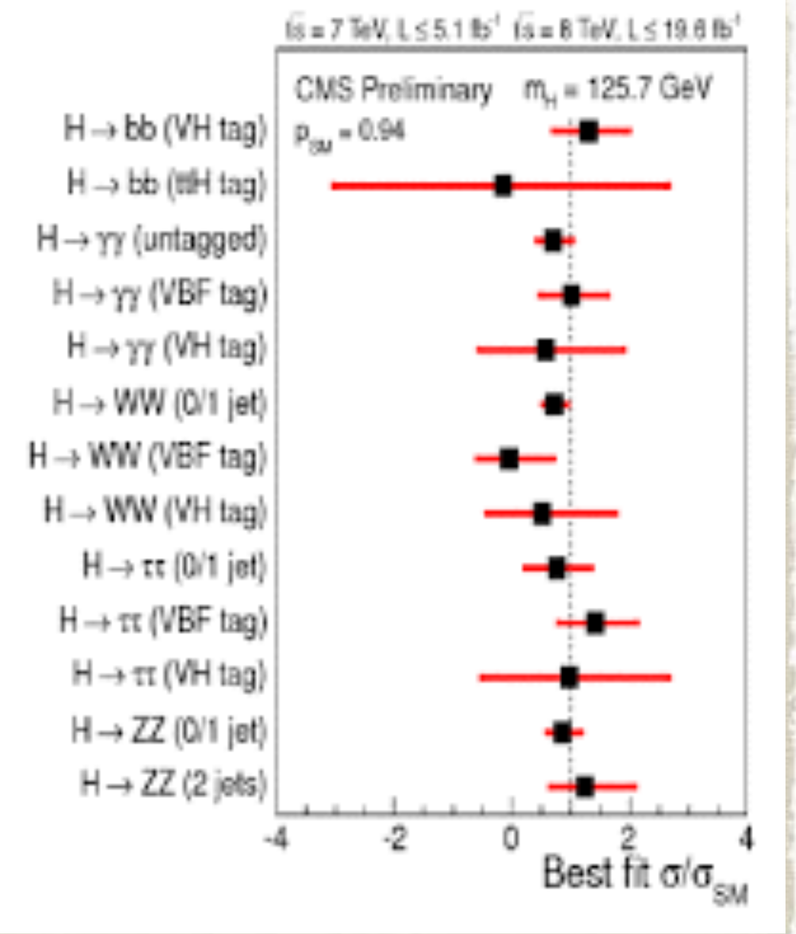
* Searches for new particles   e.g. resonance searches
* Searches for deviation from SM
* Precise measurement of SM parameters



Discussion

What colliders can do

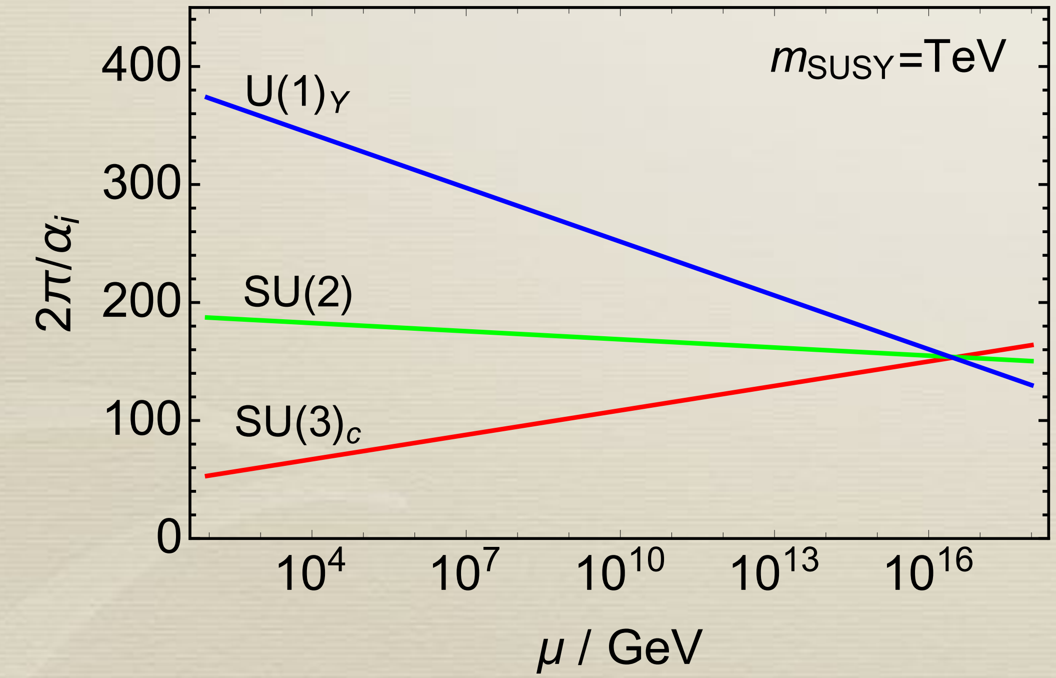
* Searches for new particles
* Searches for deviation from SM   e.g. higgs signal strength
* Precise measurement of SM parameters

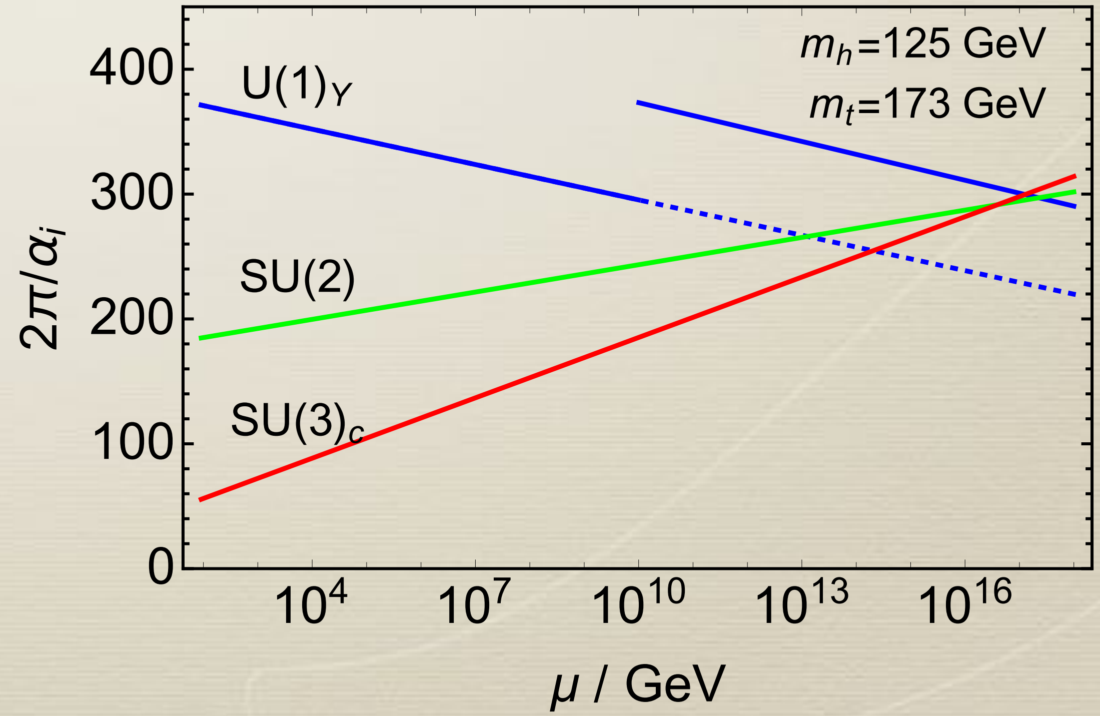


Discussion

What colliders can do

* Searches for new particles
* Searches for deviation from SM
* Precise measurement of SM parameters $m_t, g_3, \text{etc.}$





Discussion

What colliders can do

* Searches for new particles
* Searches for deviation from SM
* Precise measurement of SM parameters m_t, g_3, etc.

How do the measurements impact new physics models?

We can enhance the potential of future colliders

Backup

Fine-tuning

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

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

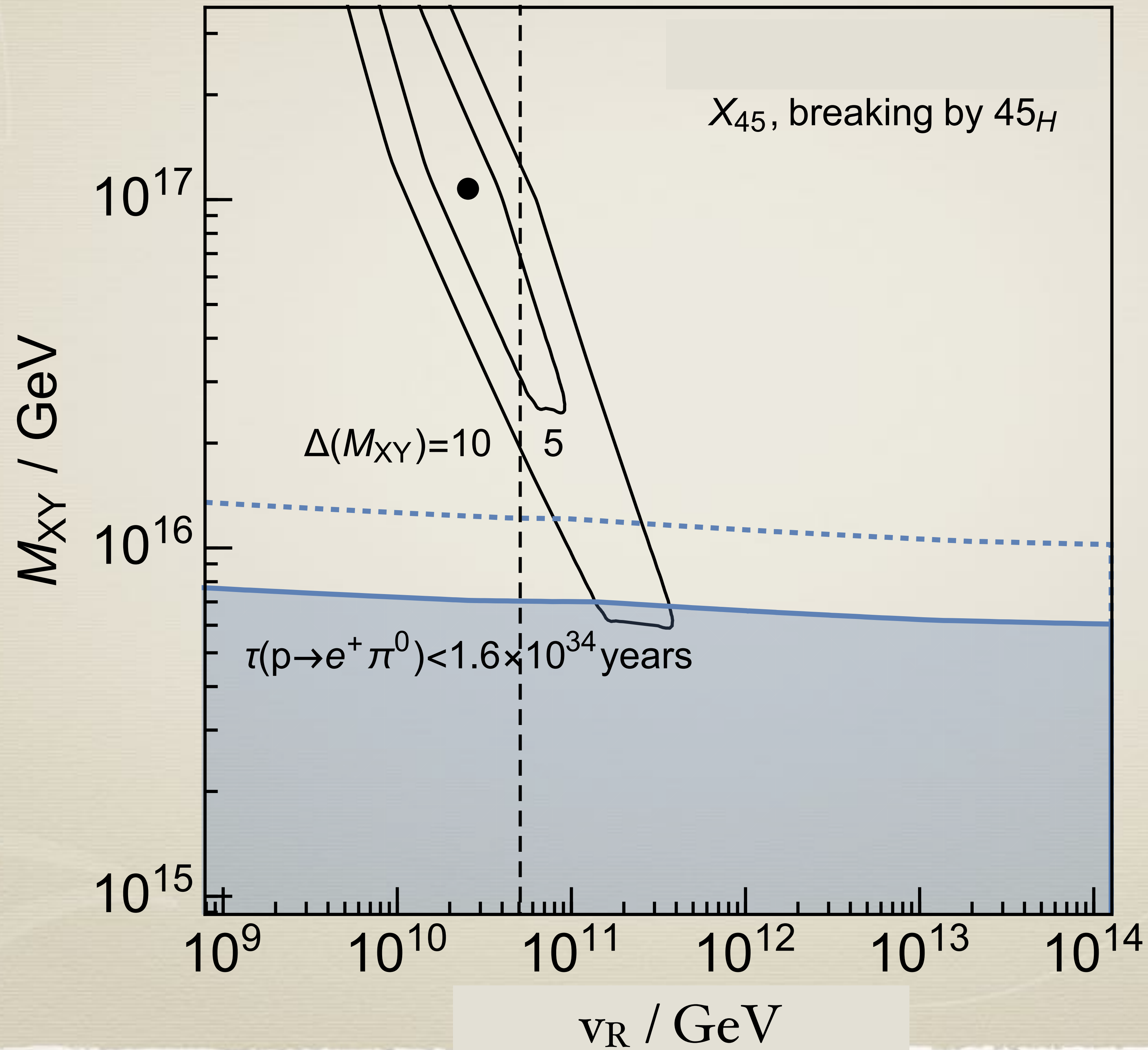
$$\lambda' = \lambda'_0 \pm \frac{v^2}{m^2} \qquad m^2 \ll \Lambda\mathrm{cut}^2$$

Same as that of SM

(with a UV mass scale e.g. the GUT scale)

Coupling unification

Hall, KH in prep.



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

Hyper-K

Top-down perspective

SUSY GUT

3 parameters

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

4 parameters

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

(or more, e.g. Ω_{DM})

Similar structures

Higgs parity GUT

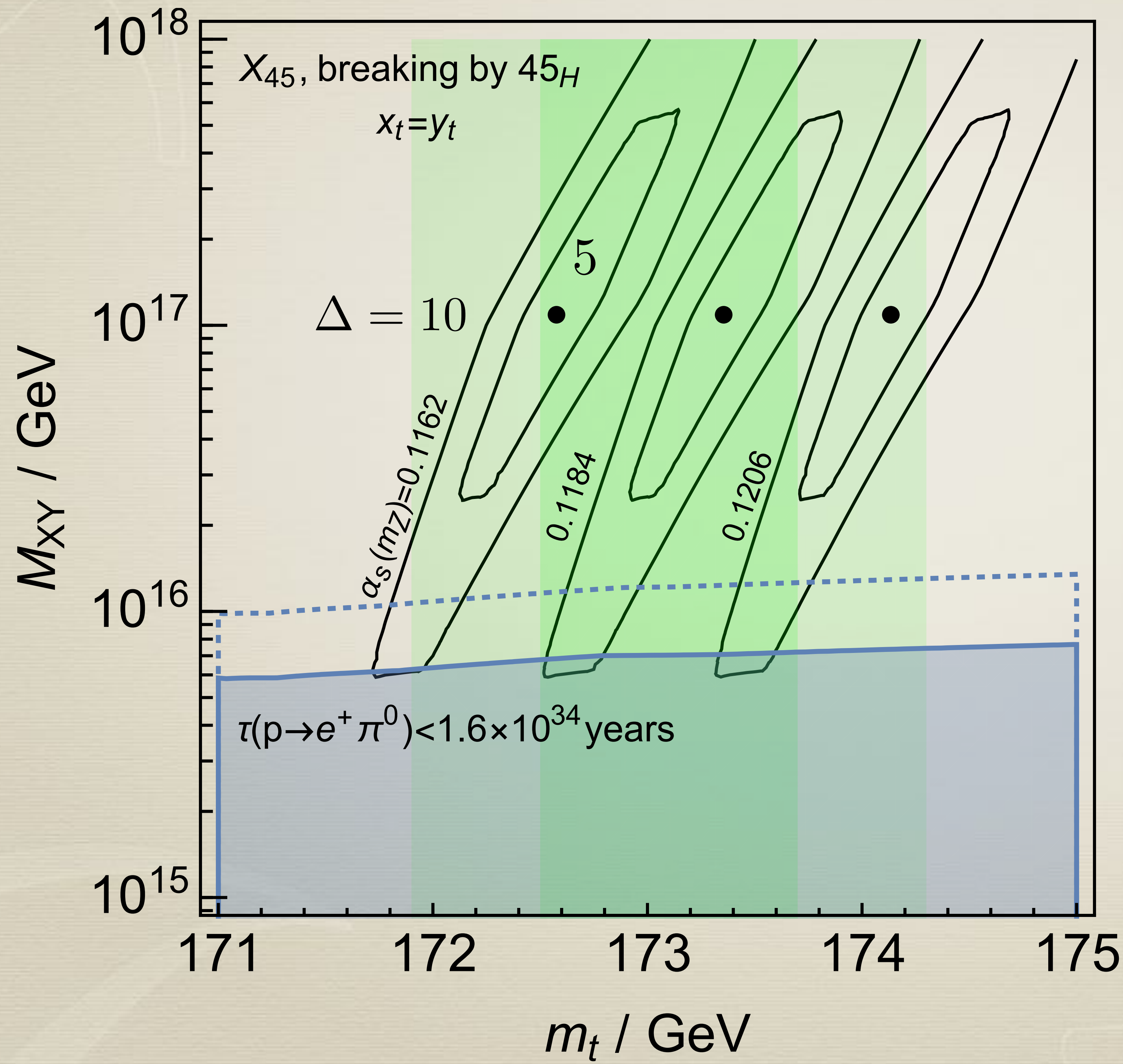
4 parameters

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

5 parameters

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

Coupling unification

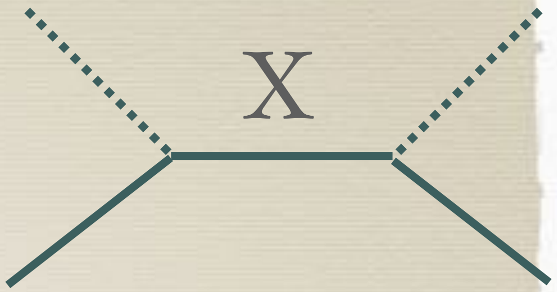


$$\Delta \sim \delta \left(\frac{2\pi}{\alpha} \right)$$

~ Casimir operator ×
Log(mass splitting)

Hyper-K

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	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$2/3$	$\mathbf{15}$	$\mathbf{45}$	$\bar{X}qH^\dagger + Xq'H'^\dagger$
	$\mathbf{3}$	$\mathbf{2}$	$\mathbf{2}$	$-1/3$	$\mathbf{6}/\mathbf{10}$	$\mathbf{45}, \mathbf{54}, \mathbf{210}/\mathbf{210}$	$\bar{X}qH'^\dagger + Xq'H^\dagger$
down	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$-1/3$	$\mathbf{6}/\mathbf{10}$	$\mathbf{10}, \mathbf{126}/\mathbf{120}$	$\bar{X}qH + Xq'H'$
	$\mathbf{3}$	$\mathbf{2}$	$\mathbf{2}$	$2/3$	$\mathbf{15}$	$\mathbf{120}, \mathbf{126}$	$\bar{X}qH' + Xq'H$
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	$\mathbf{1}/\mathbf{15}$	$\mathbf{10}, \mathbf{120}/\mathbf{120}, \mathbf{126}$	$X\ell H' + X\ell' H$
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	$\mathbf{1}$	$\mathbf{45}$	$X\ell' H'^\dagger$

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

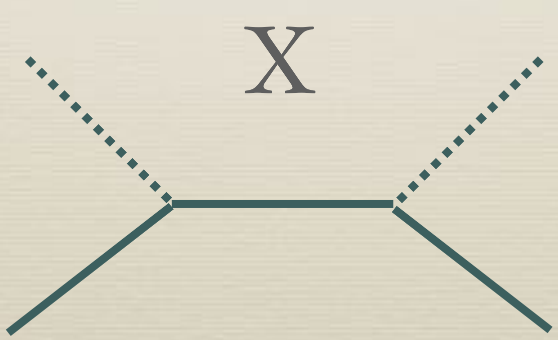
$$SO(10) \times CP \xrightarrow{\phi_{45}^{-}} SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times P_{LR}$$

Real yukawas, without CP symmetry breaking...

A simple renormalizable example to obtain CP phases

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

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



Anthropic principle?

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

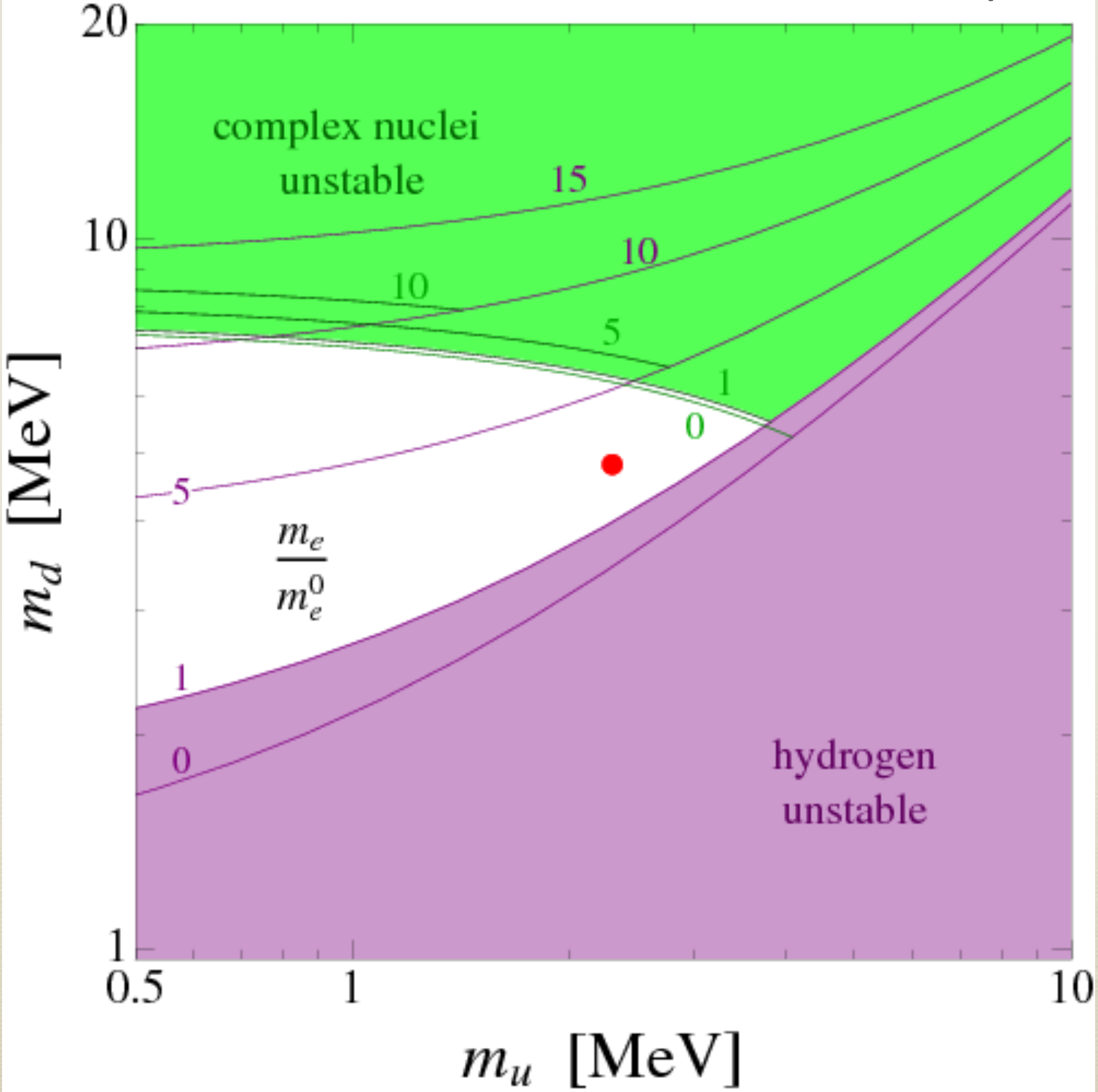
Might be requirement for us to emerge,
rather than a prediction of a theory

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

The electroweak scale may not be a guiding principle
to look for new physics

Stability of nuclei

Plot from Hall, Pinner, Ruderman (2014)



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

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

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

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

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