05/21/2019
SUSY 2019

Higgs Parity GUT

Keisuke Harigaya (IAS)

with Lawrence Hall

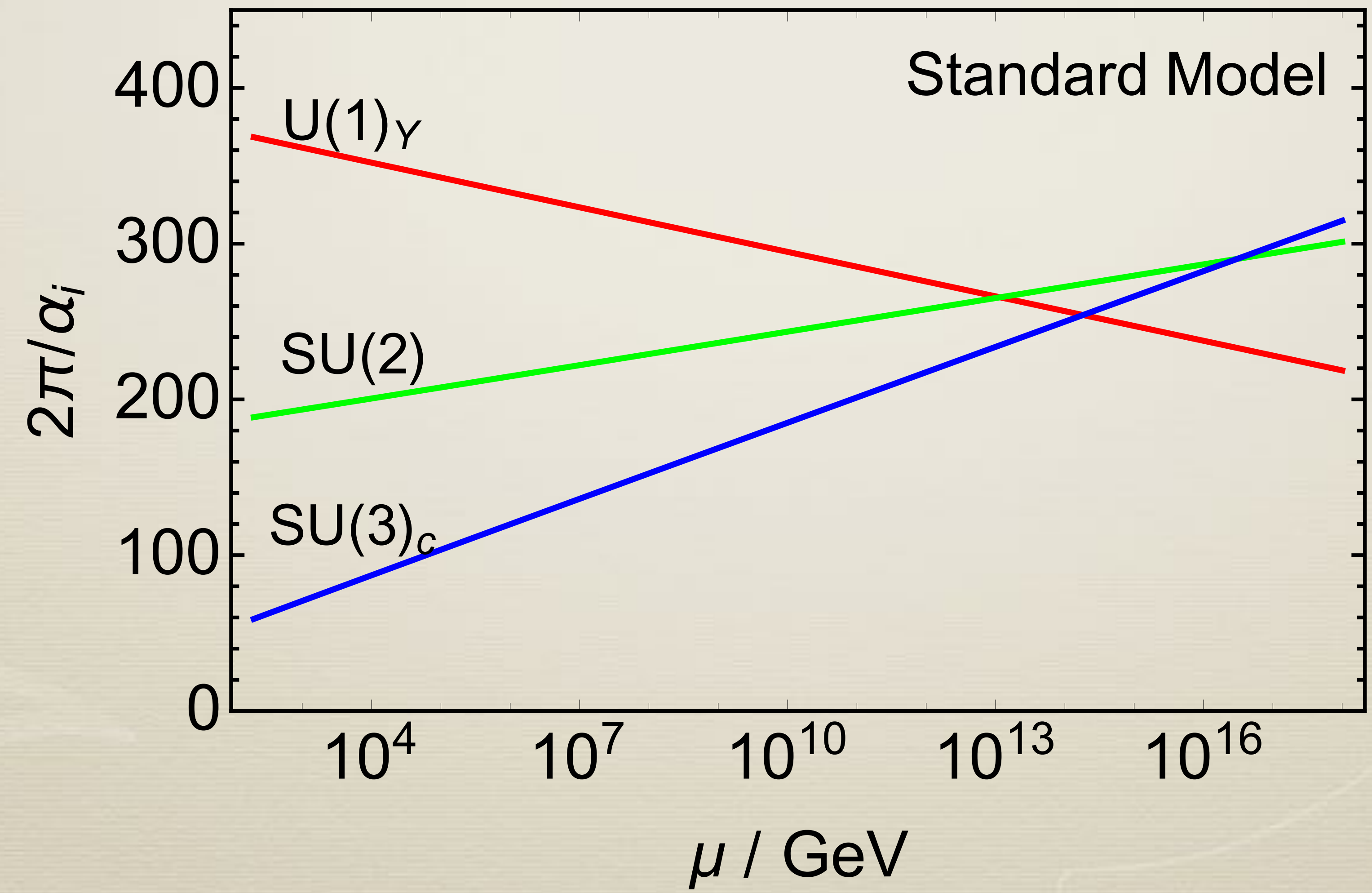
1803.08119

To appear

Grand unification

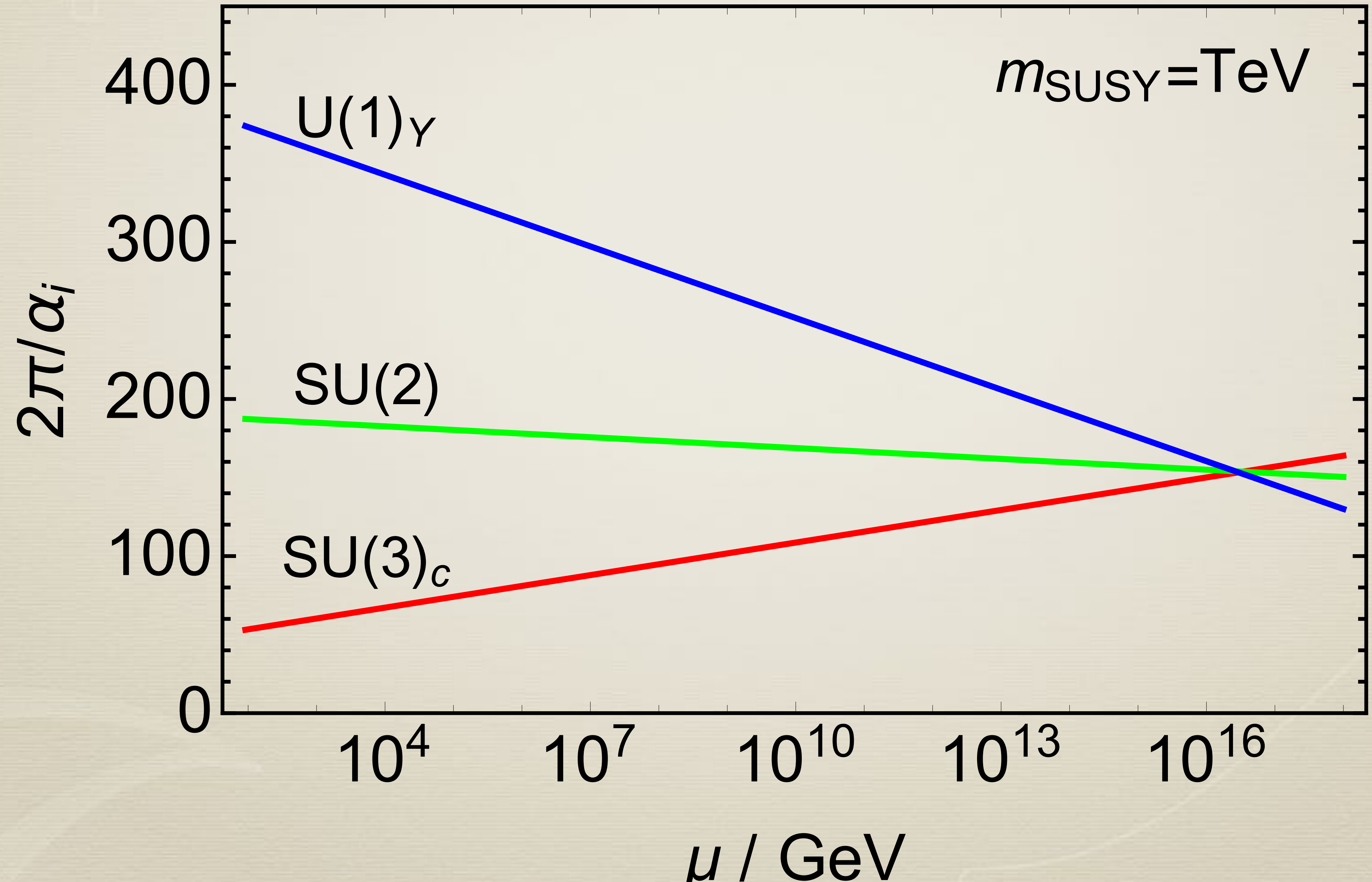
- The apparently complex structure of quarks and leptons are simplified

- Actually, gauge couplings roughly unify in the SM



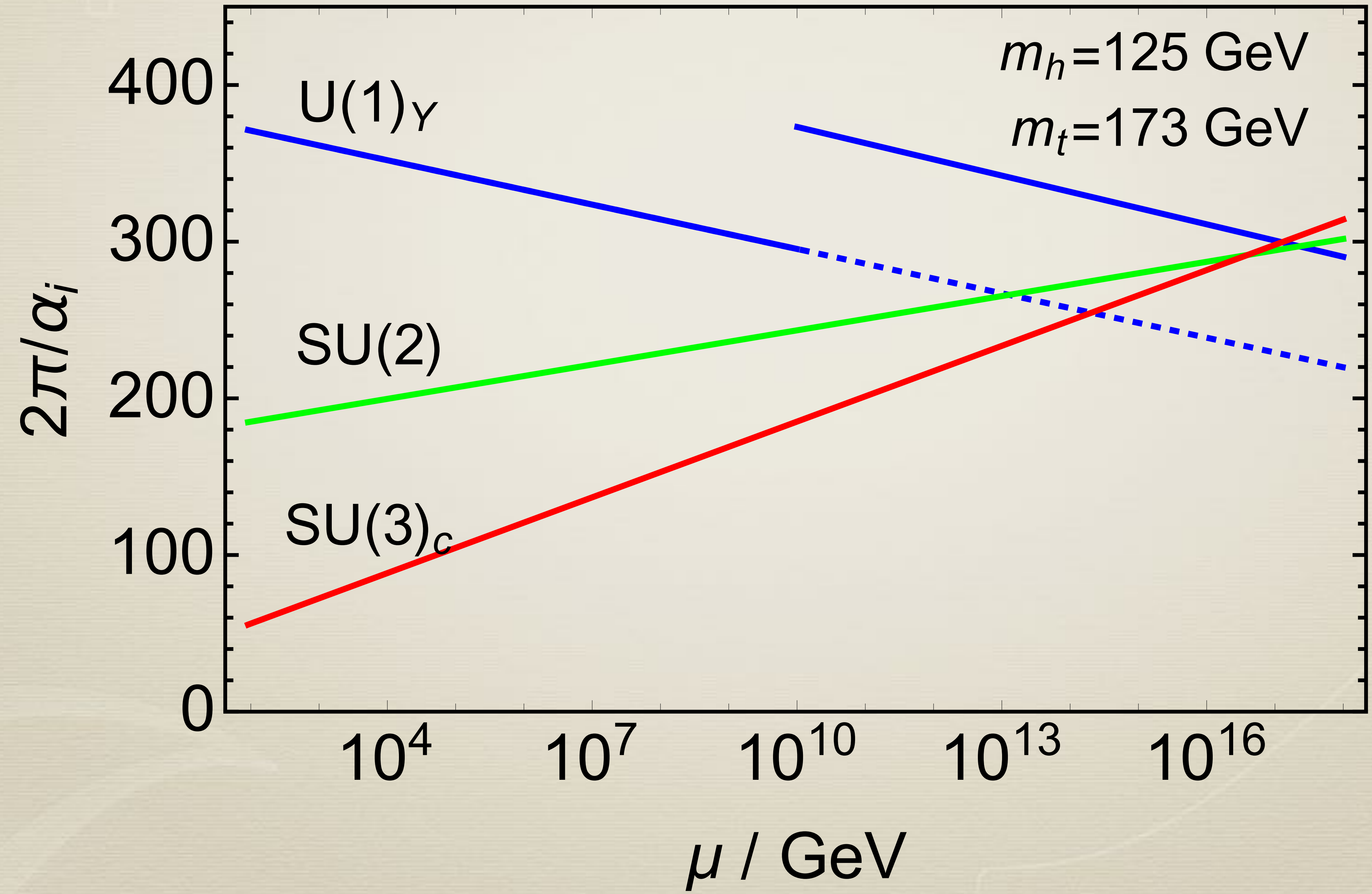
Precise unification by SUSY

After precise measurements of gauge couplings by LEP,



Higgs parity GUT

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

$$H_L \leftrightarrow H_R$$

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

$\langle H_R \rangle \neq 0$

$H_L, H_R \subset 16$

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

Prediction on <H_R>

Hall, KH (2018)

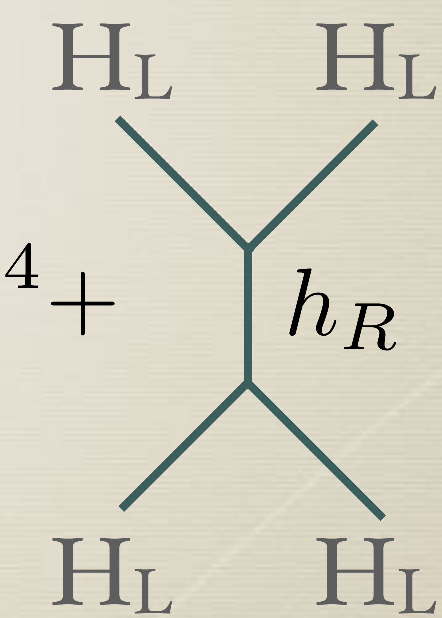
$$V(H_L, H_R) = \lambda(|H_L|^2 + |H_R|^2)^2 + \lambda' |H_L|^2 |H_R|^2 - m^2(|H_L|^2 + |H_R|^2)$$

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

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

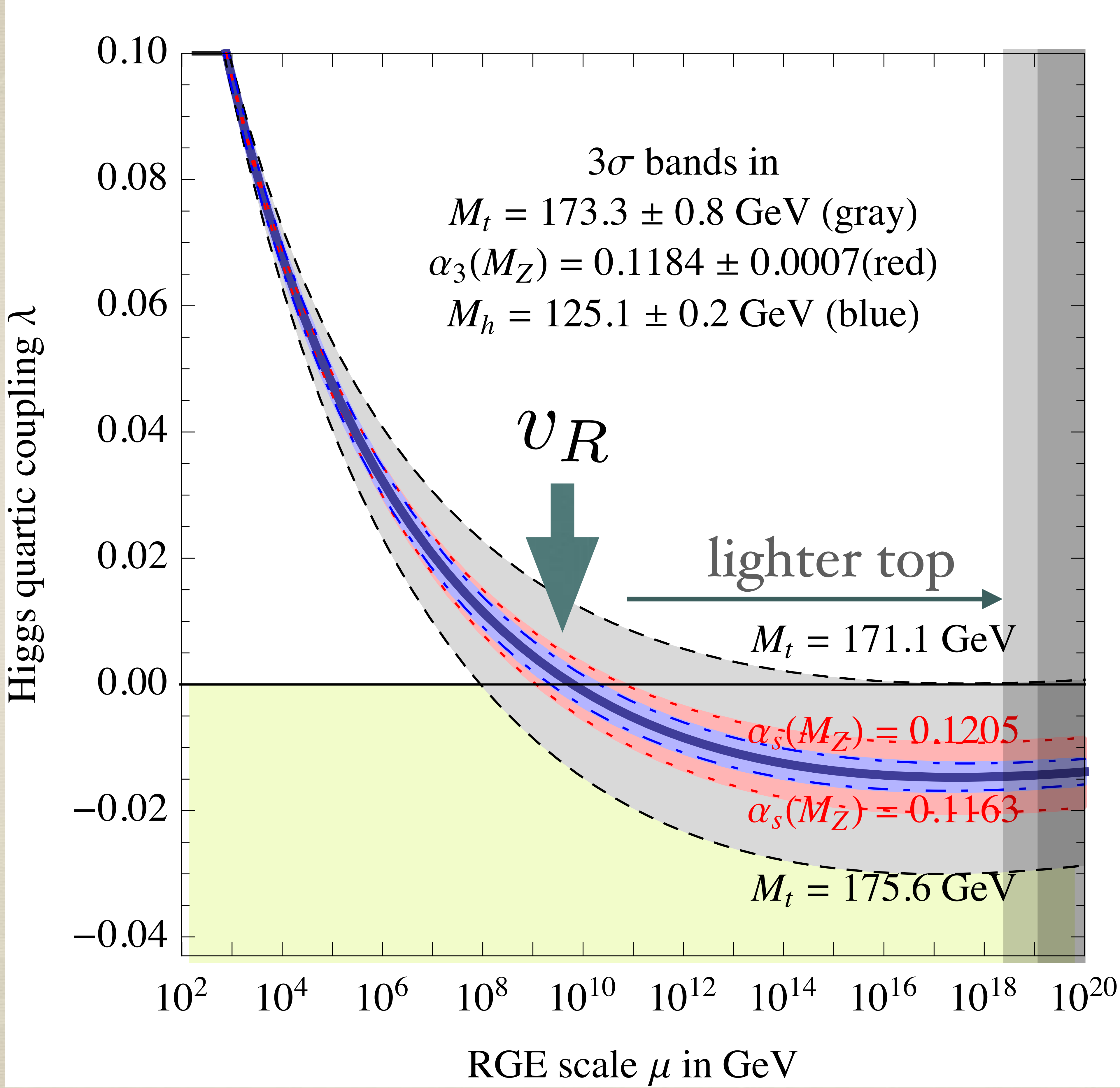


$$V_{\text{eff}} \simeq \lambda' v_R^2 |H_L|^2 - \lambda' (1 + \frac{\lambda'}{4\lambda}) |H_L|^4$$

$|\lambda'| \ll 1$

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

(up to threshold corrections)



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_R
lighter top
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

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

$$4 = (H_L, H_R)$$

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

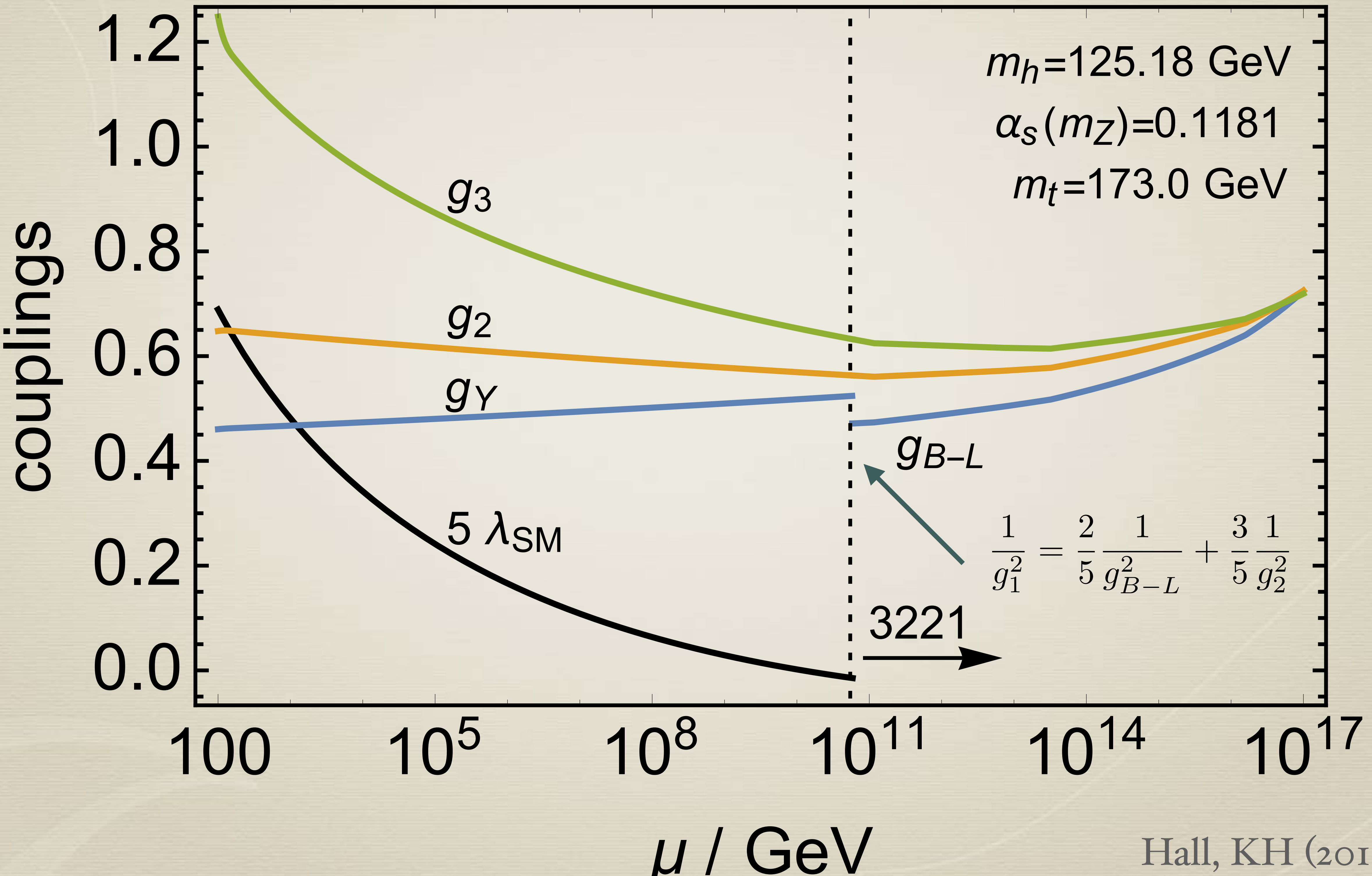
$$16 - 9 = 7 = 4 + 3$$

W', Z'

SM Higgs is a pseudo Nambu-Goldstone boson

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

Higgs Parity GUT



Hall, KH (2018)

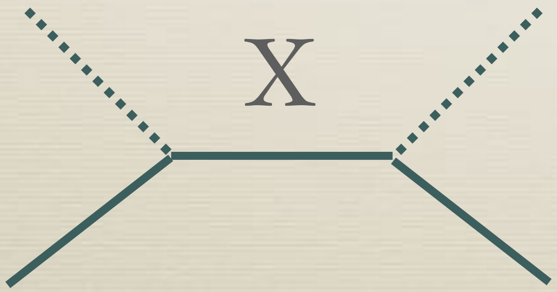
Yukawa coupling and Strong CP problem

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

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

Beg and Tsao, Mohapatra and Senjanovic (1978)

- H(2,1) and H(1,2) actually solve the problem
soft breaking is assumed for v << v'

Babu and Mohapatra (1989)

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

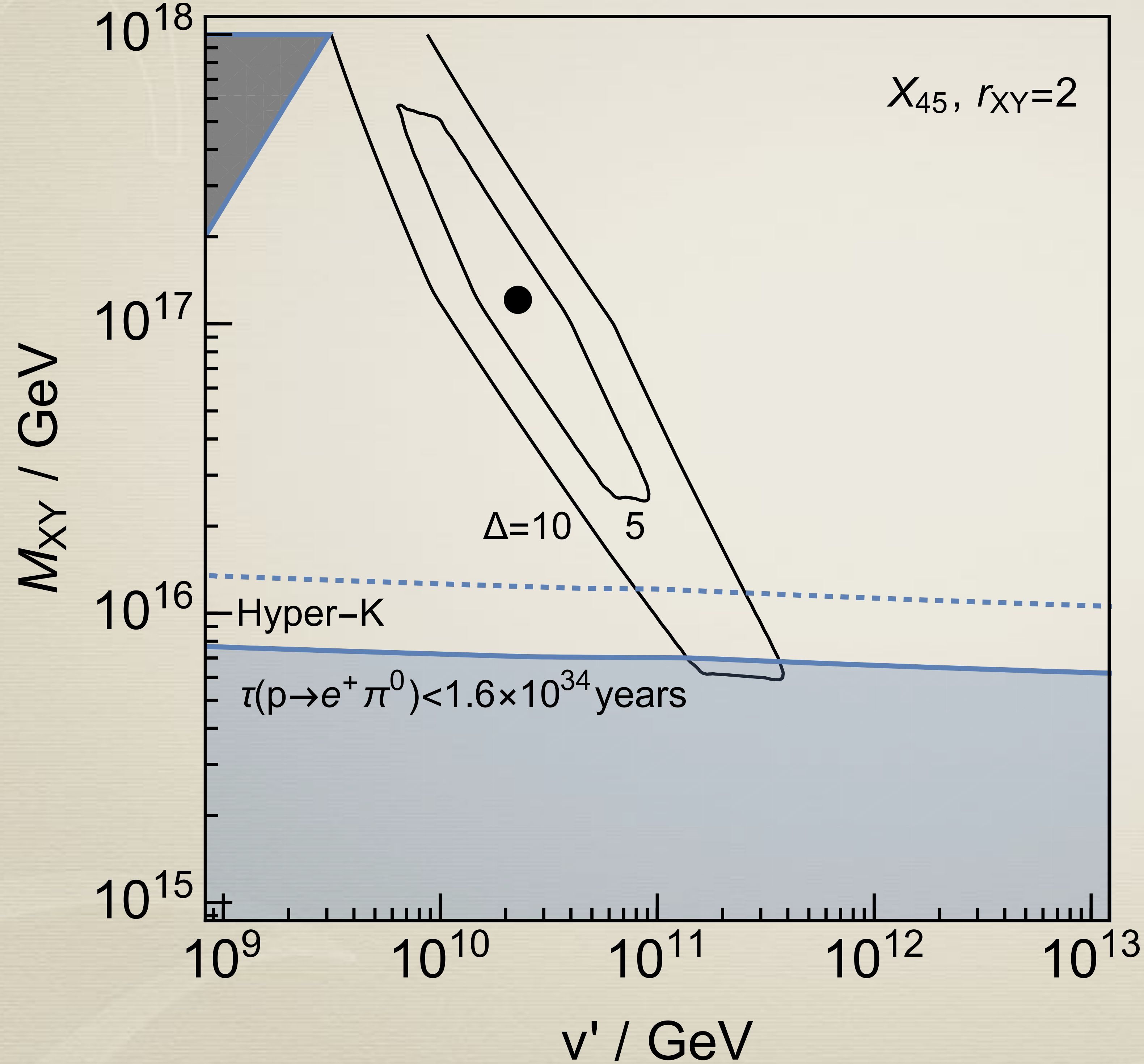
$$c = c^\dagger, \arg(\det[c]) = 0$$

- SO(10) embedding is possible,
SSB of parity explains the SM Higgs quartic

Hall, KH (2018)

Precise unification and SM parameters

Coupling unification



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

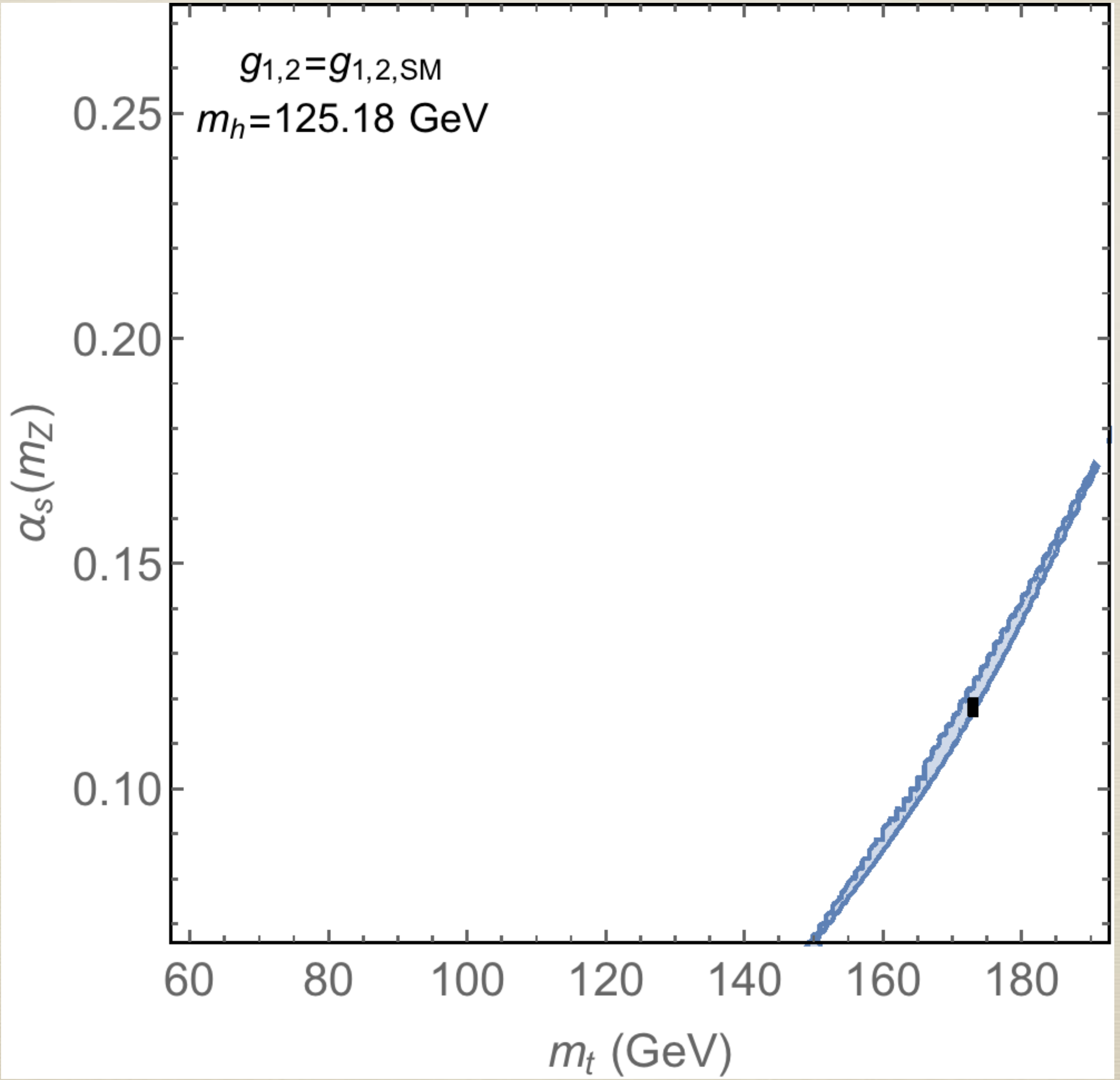
~ Casimir operator ×
Log(mass splitting)

$$r_{XY} = \frac{M_{(3,1,1)}}{M_{XY}}$$

(=2 in the minimal model)

Hall, KH (2019)

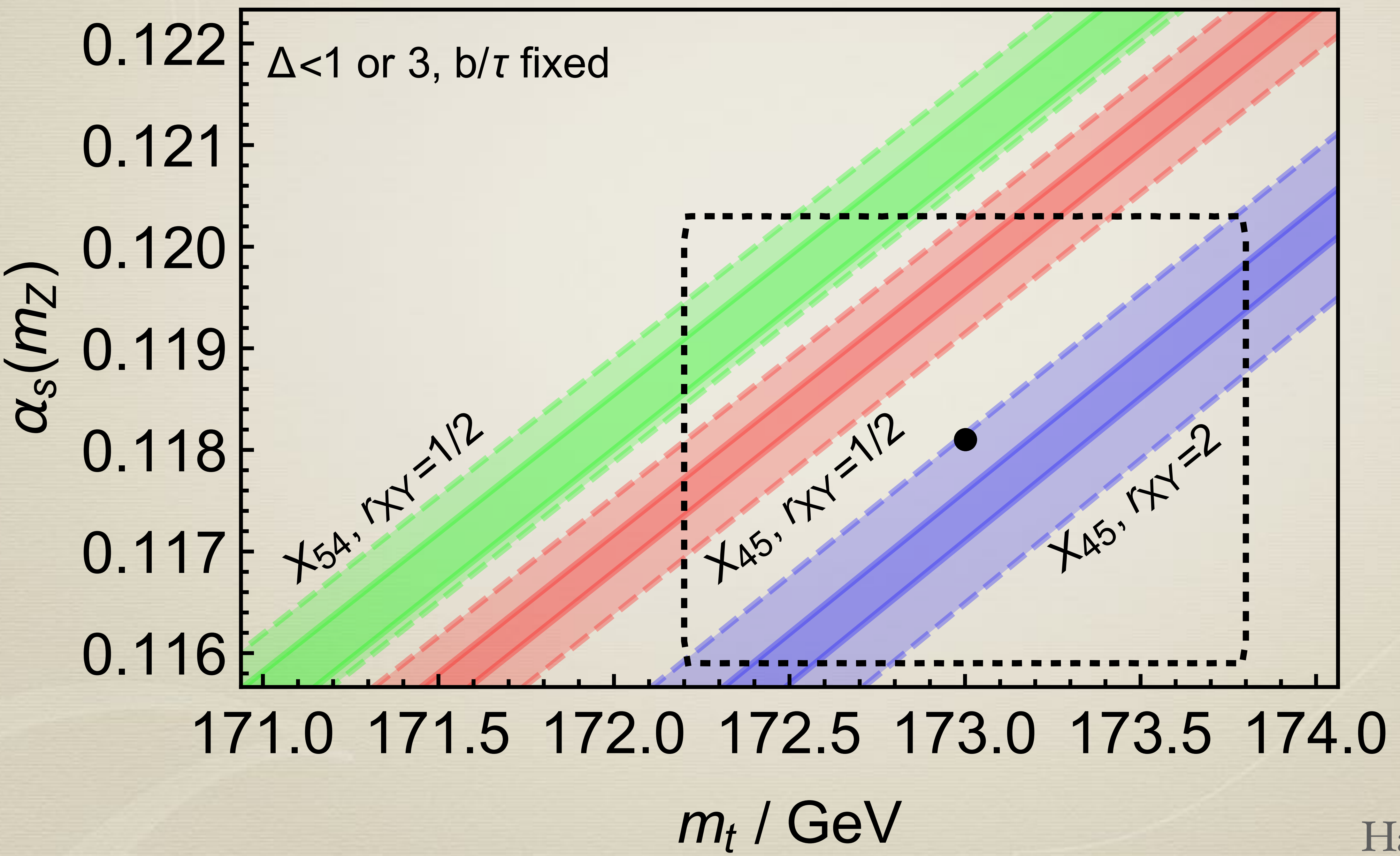
SM parameters



Hall, KH (2019)

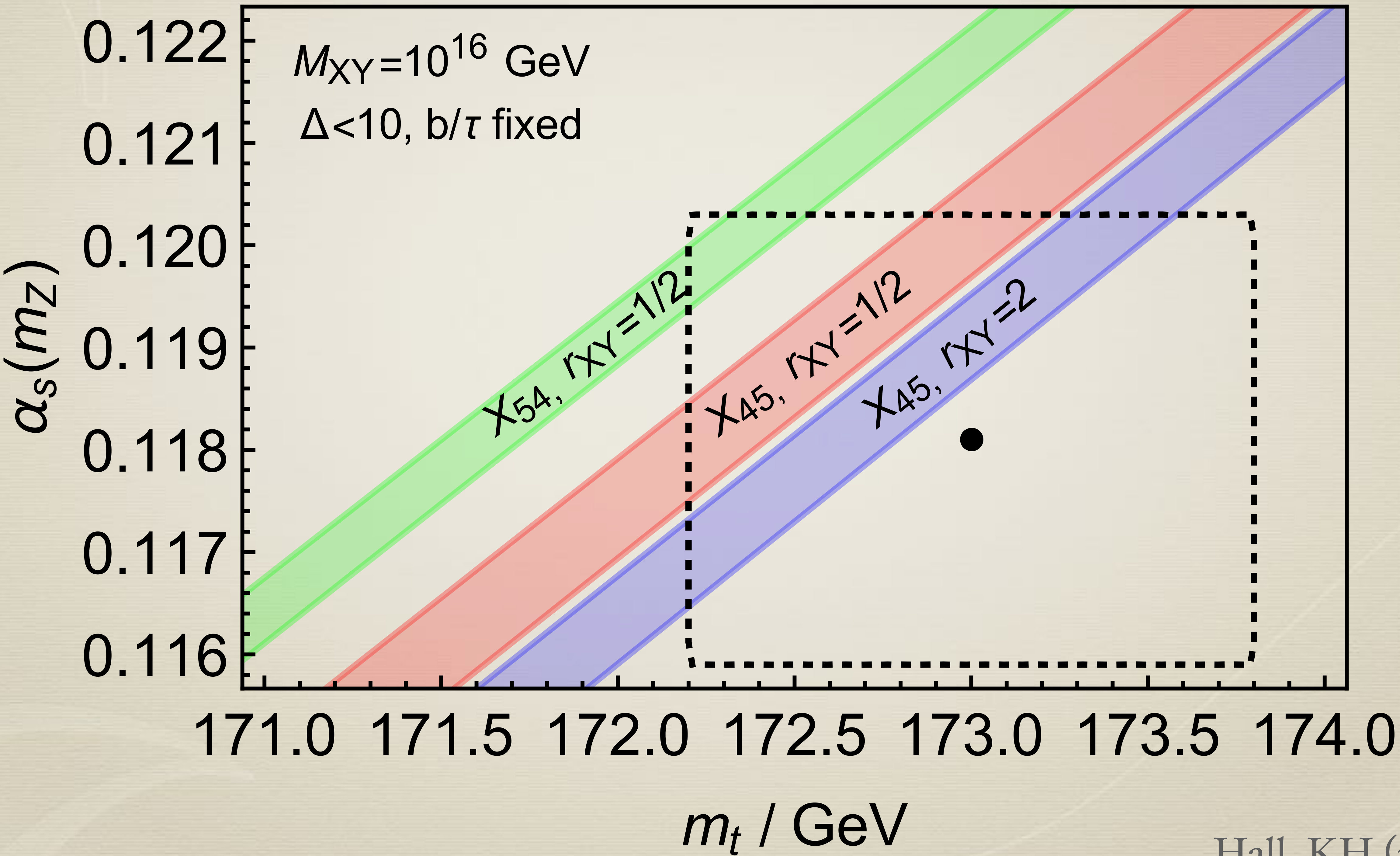
SM parameters

different threshold correction to λ(v')



Hall, KH (2019)

SM parameters

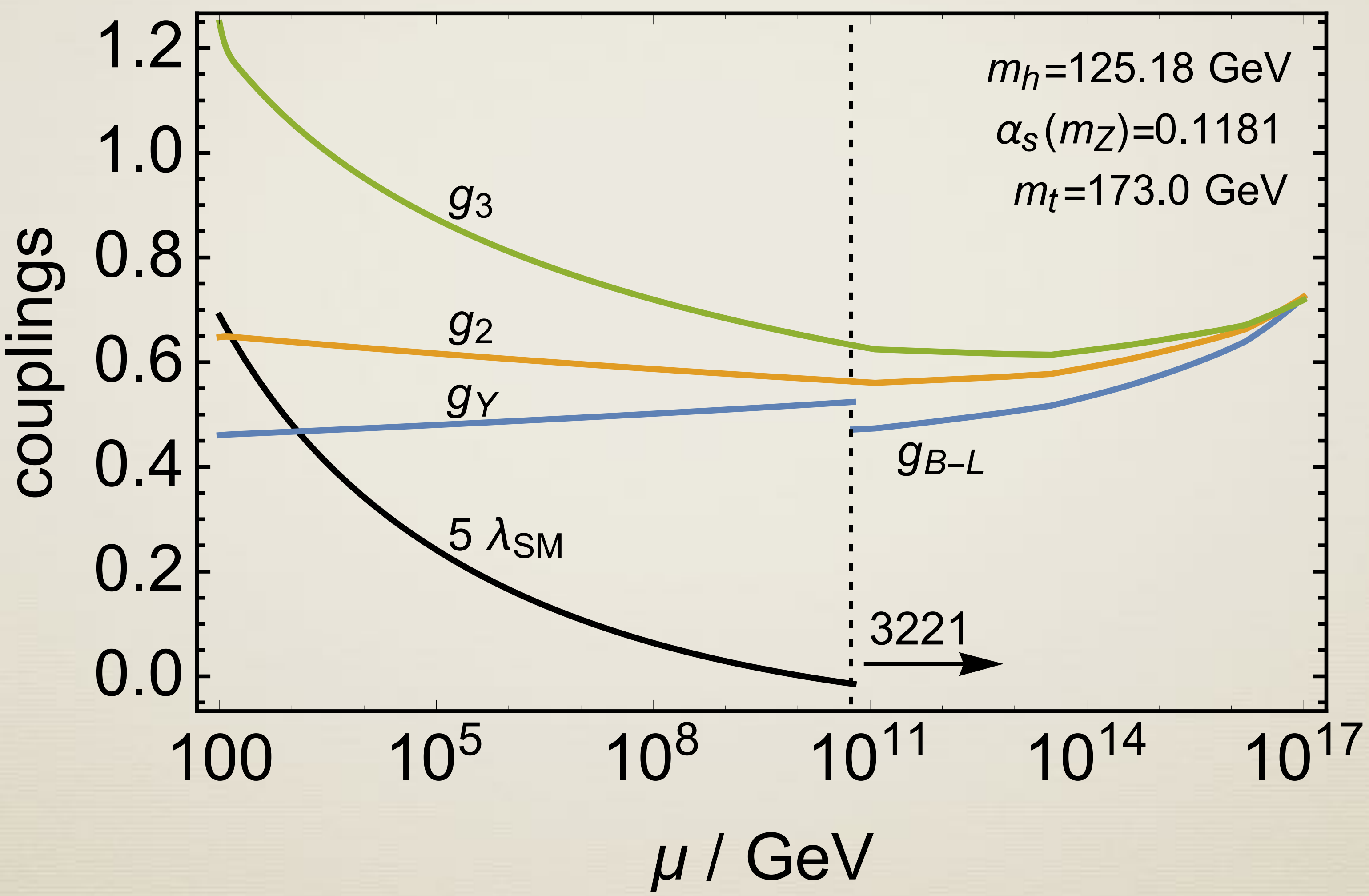


Hall, KH (2019)

Summary

1803.08119

* A new scheme of the coupling unification is proposed



* I omitted discussion on b/tau, neutrino mass:

Hall and KH, to appear

Discussion

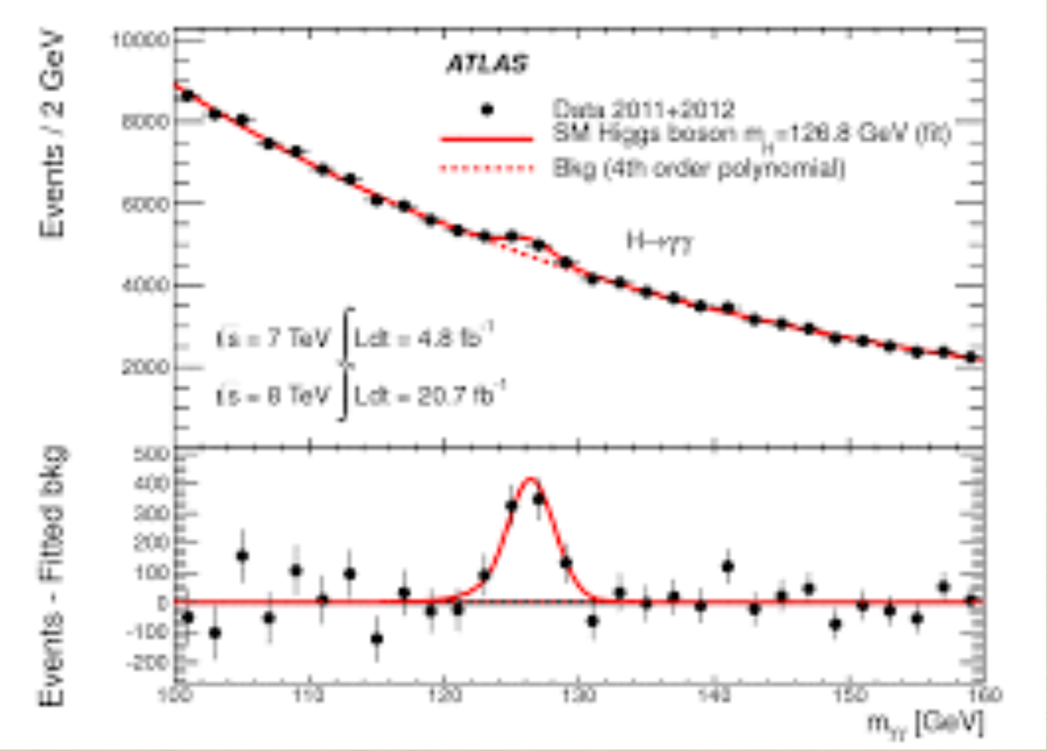
What colliders can do

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

Discussion

What colliders can do

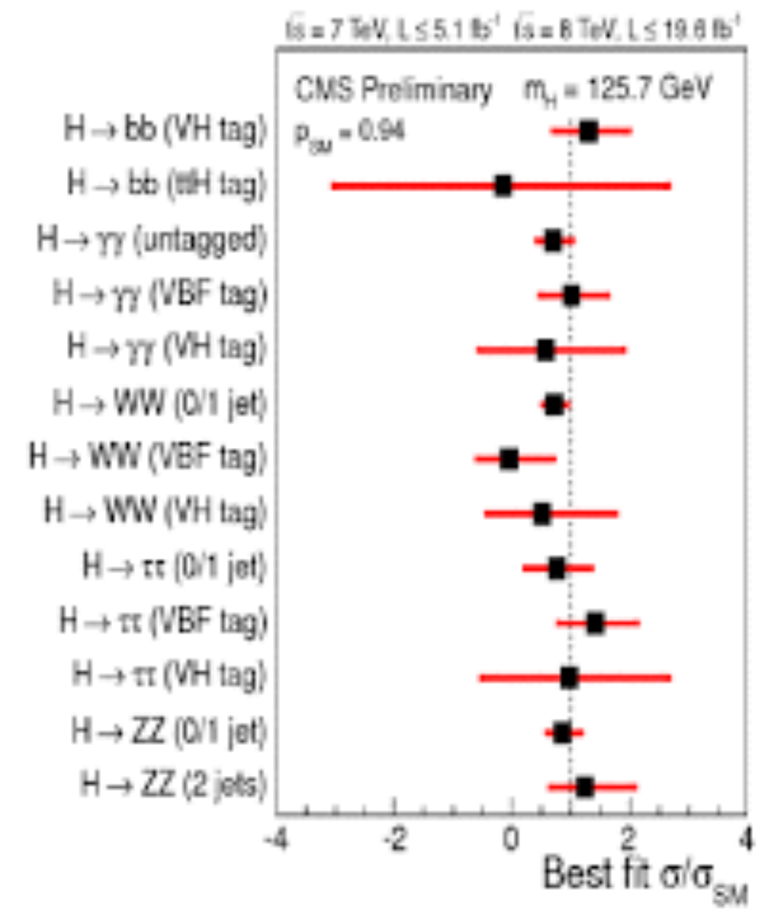
- Searches for new particles e.g. resonance searches
- Searches for deviation from SM
- Precise measurement of SM parameters



Discussion

What colliders can do

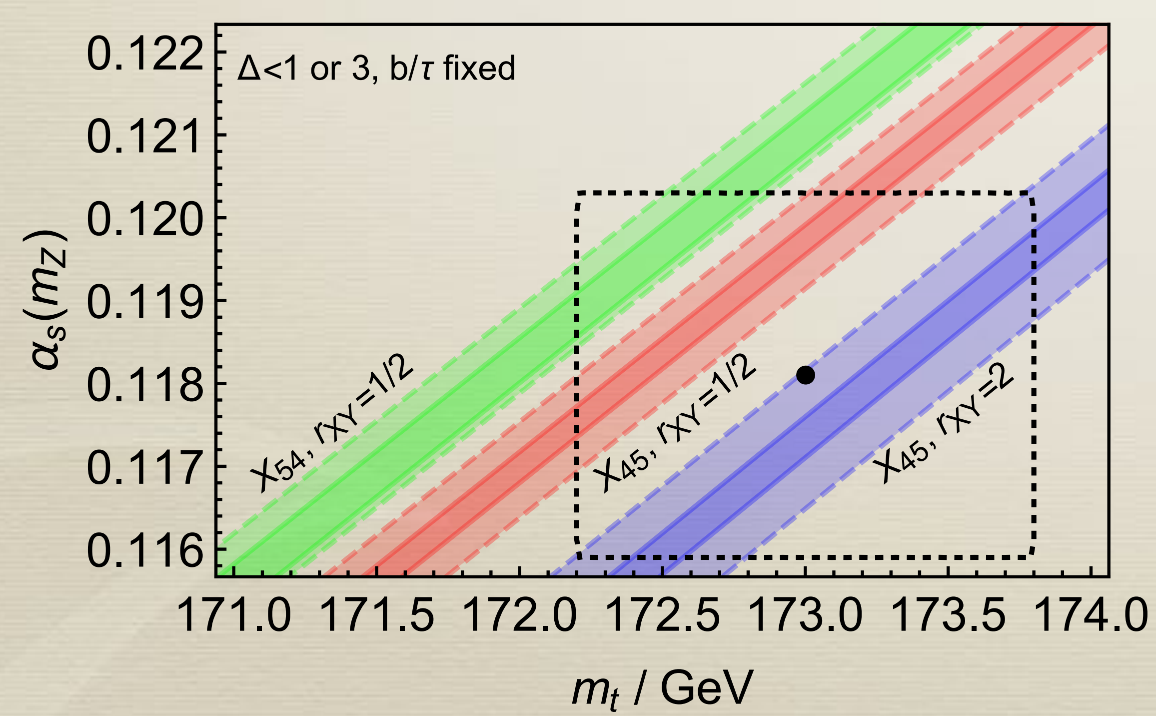
* Searches for new particles
* Searches for deviation from SM — e.g. higgs signal strength
* Precise measurement of SM parameters

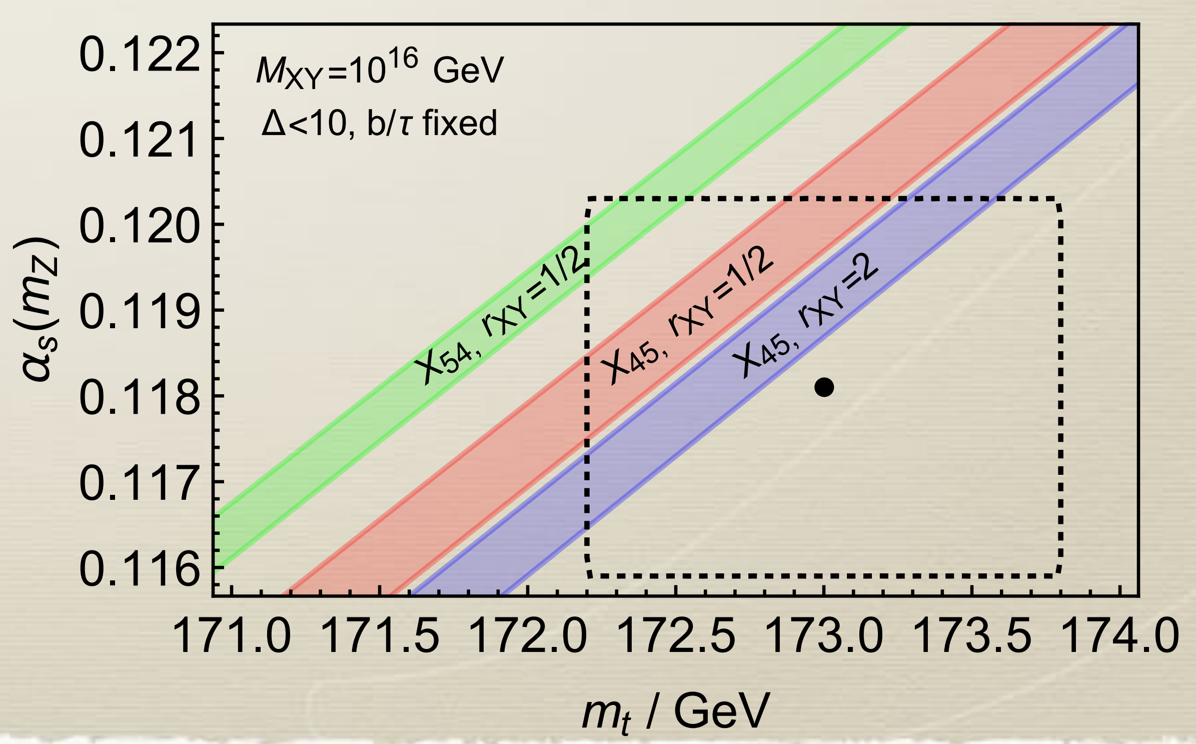


Discussion

What colliders can do

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

Another example via Higgs parity : David Dunsky, Thursday

We can enhance the potential of future colliders

Backup

Intermediate Pati-Salam

Hall, KH (2018)

$$SO(10)$$

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

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

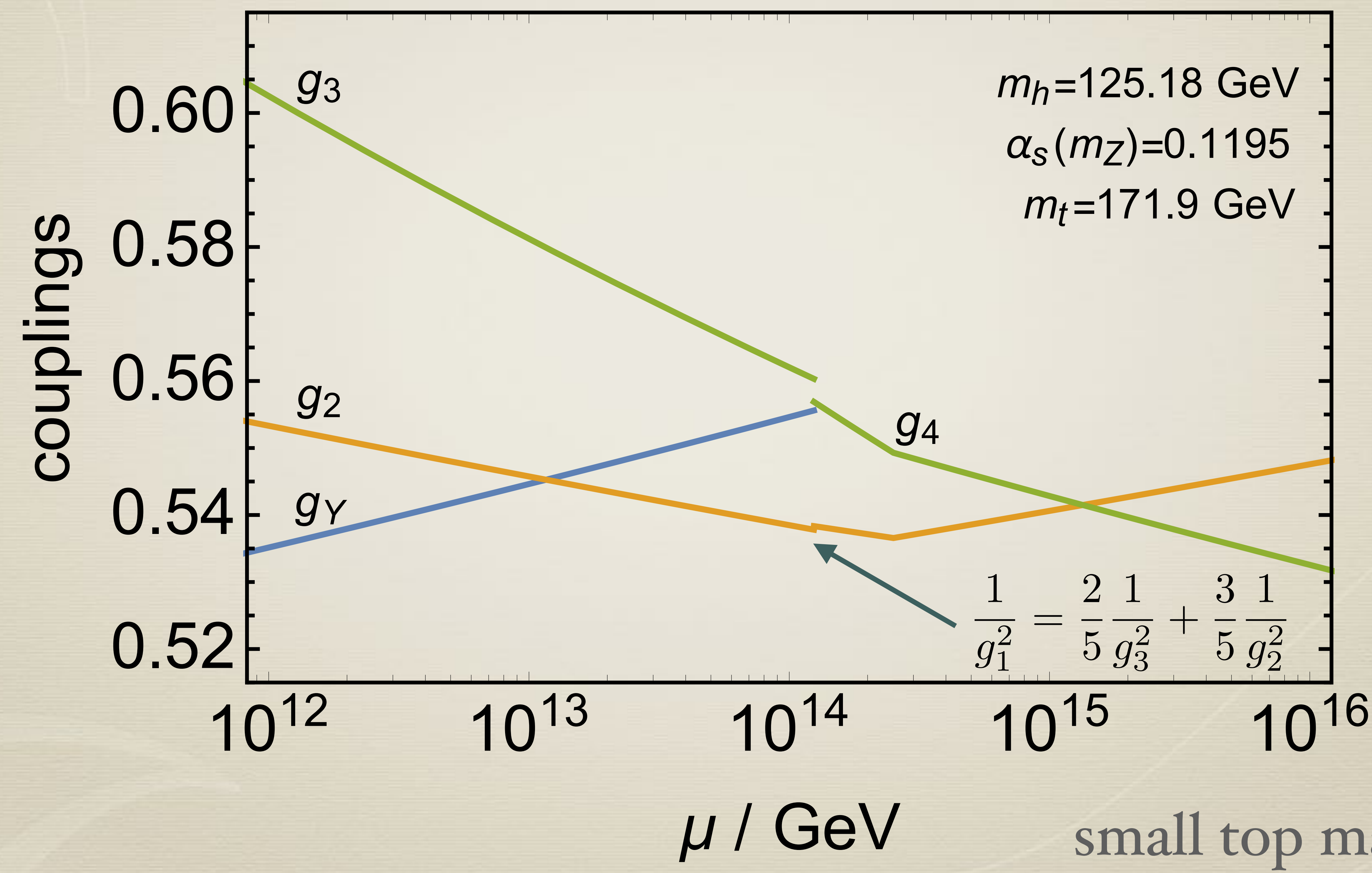
$$\langle H_R \rangle = \begin{pmatrix} 0 & 0 & 0 & v_R \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

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

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

Coupling Unification

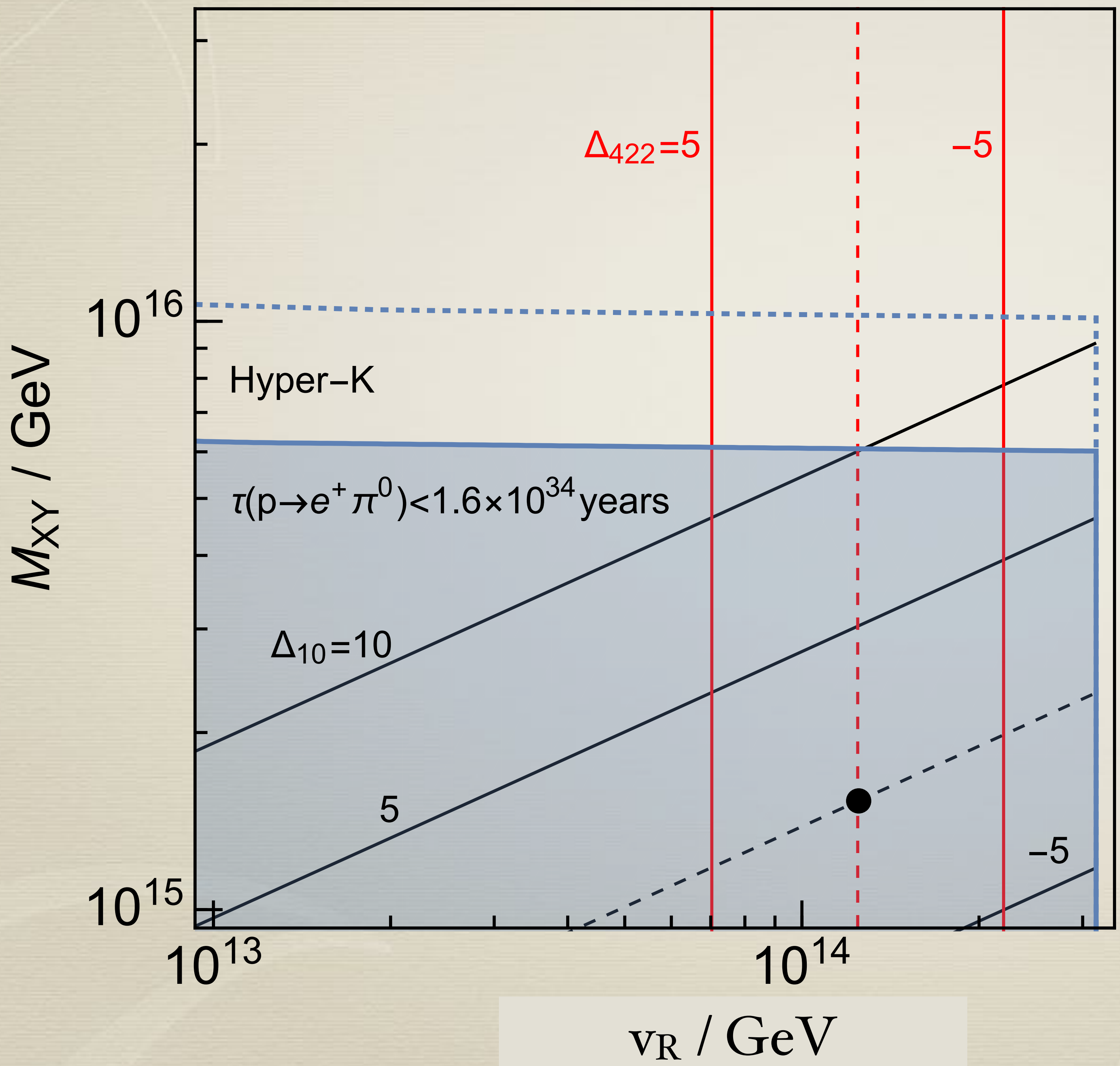
Hall, KH (2019)



small top mass

Coupling Unification

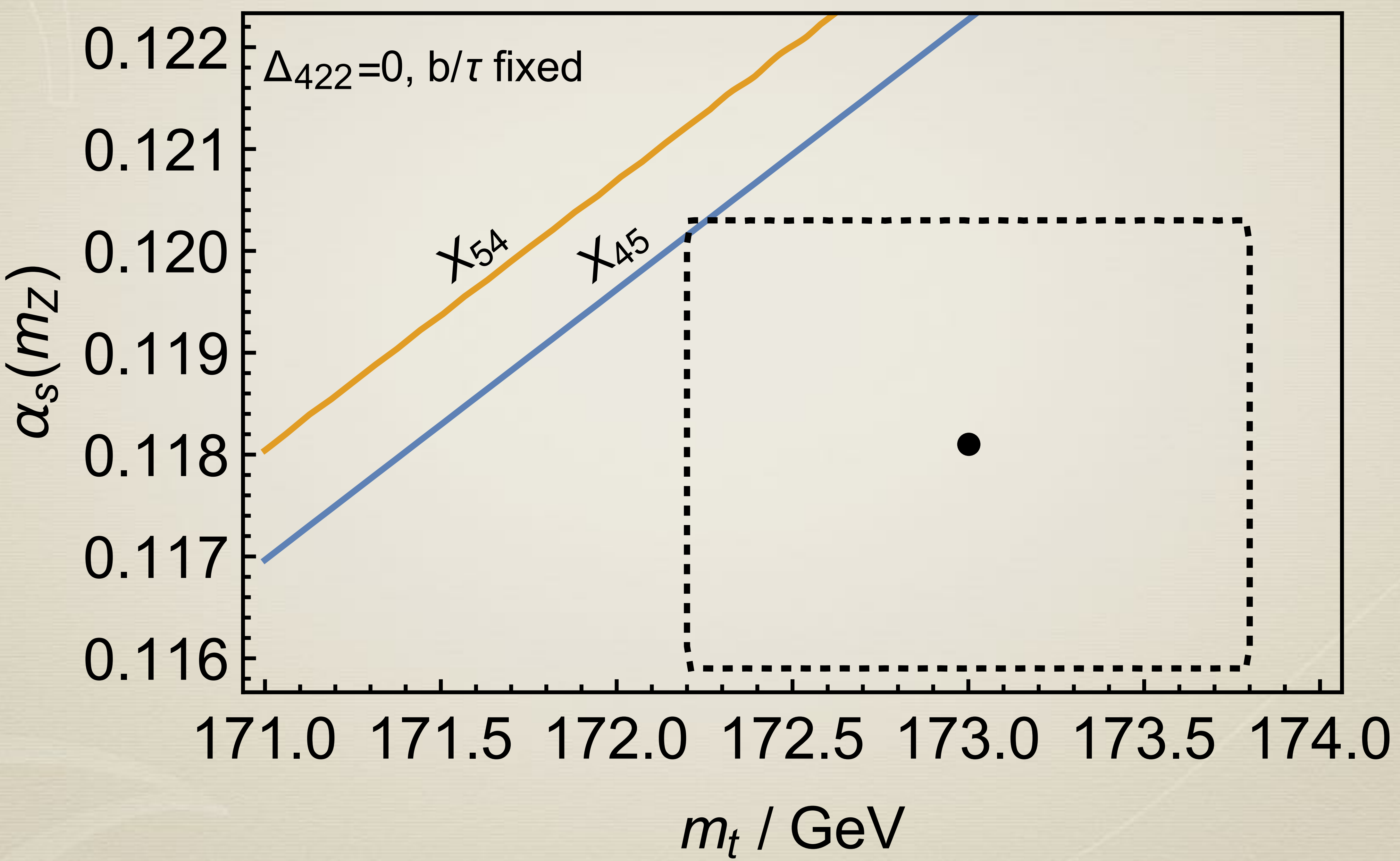
Hall, KH (2019)



Moderate threshold correction is required

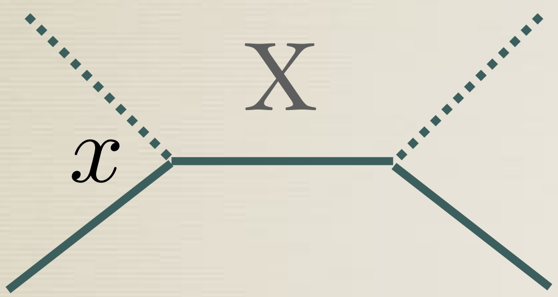
SM parameters

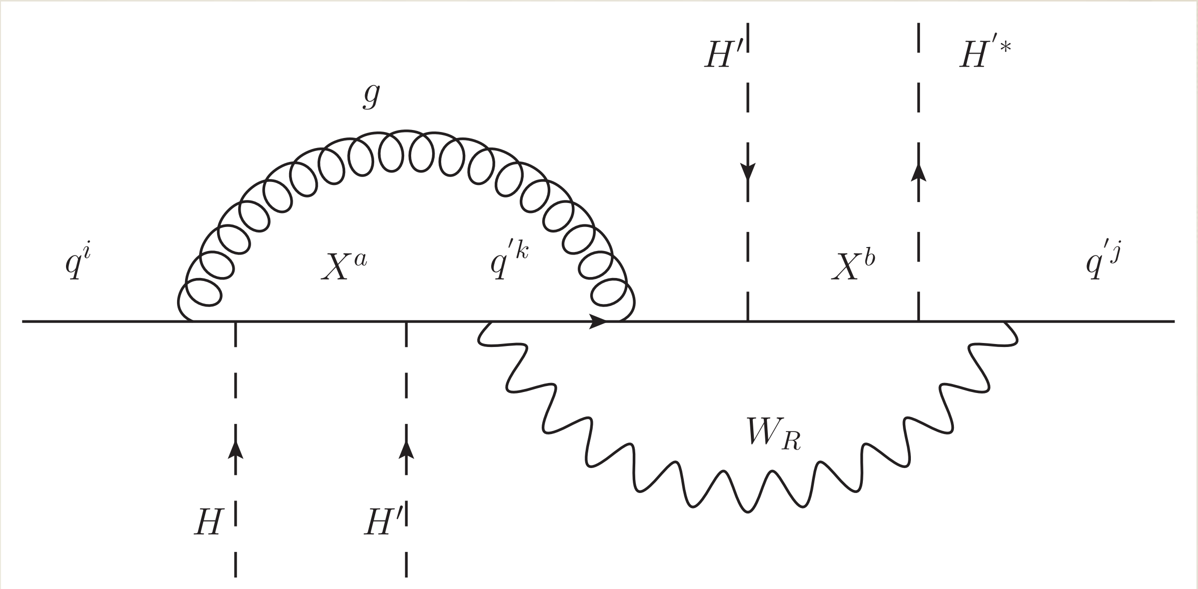
Hall, KH (2019)



Loop correction to θ

Hall, KH (2018)





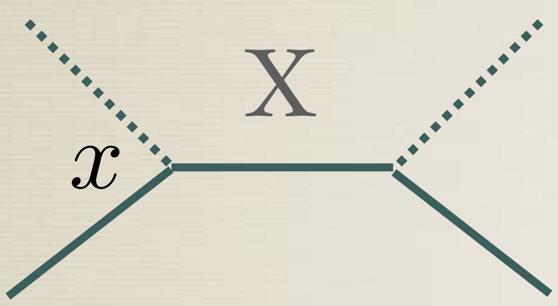
$$\text{For } x = O(1), \quad \delta\theta \sim 10^{-11} \frac{\theta_{23}^u \theta_{23}^d}{V_{cb}^2}$$

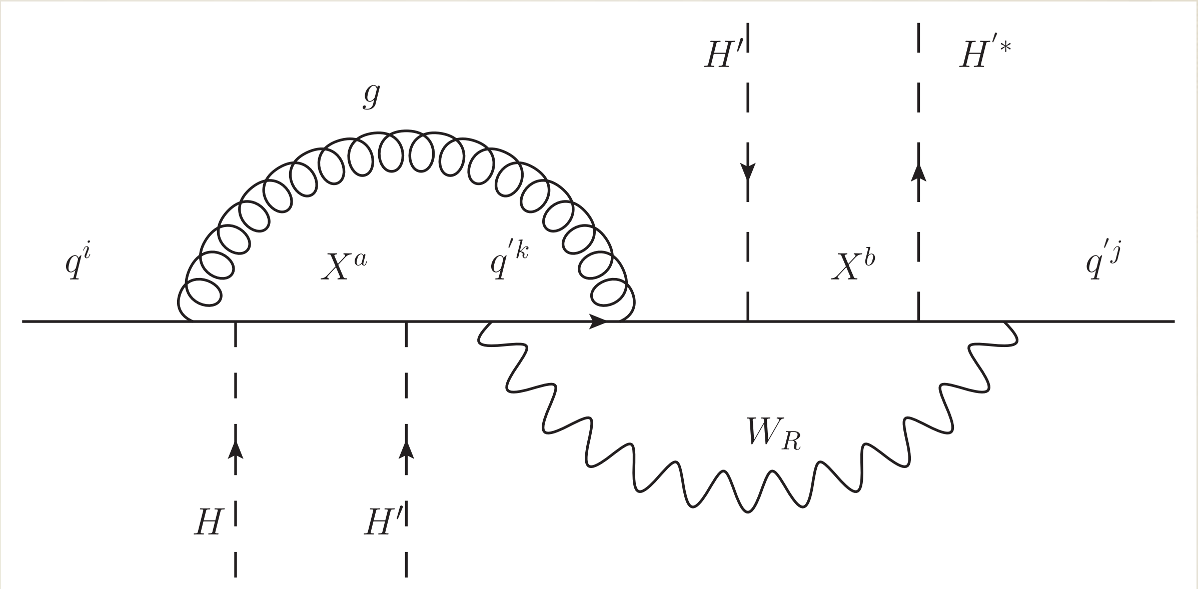
Suppressed by loop factors, flavor mixing

$\theta > 10^{-12}$ will be proved in near future by neutron EDM

Loop correction to θ

Hall, KH (2018)





Generically, $\delta\theta < 10^{-6}$

The prediction depends on the flavor structure

What is the prediction in your favorite model?

Fine-tuning

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

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

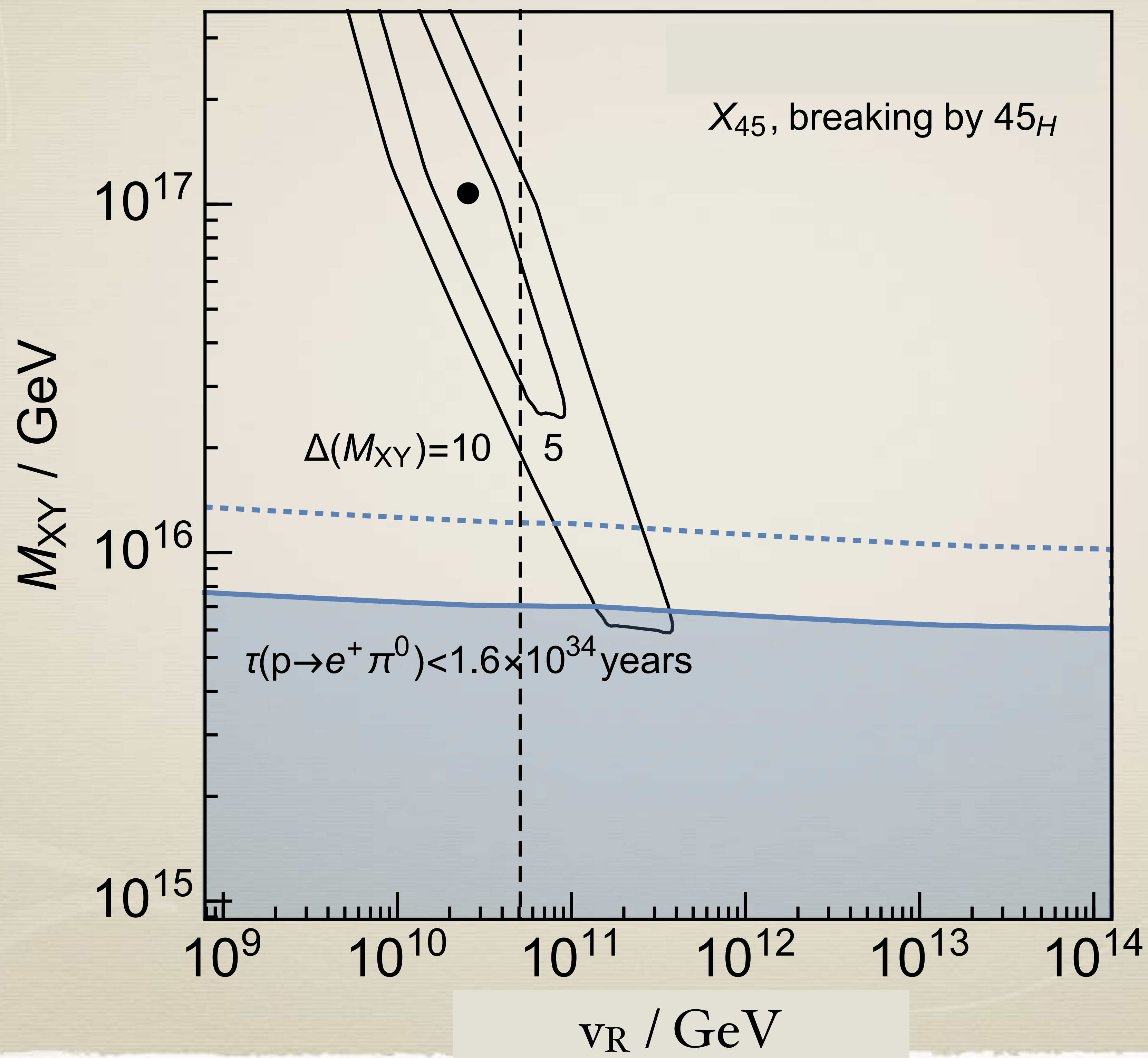
$$\lambda' = \lambda'_0 \pm \frac{v^2}{m^2} \qquad m^2 \ll \Lambda{\rm cut}^2$$

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 → 4 parameters

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

(or more, e.g. $\Omega_{\rm DM}$)

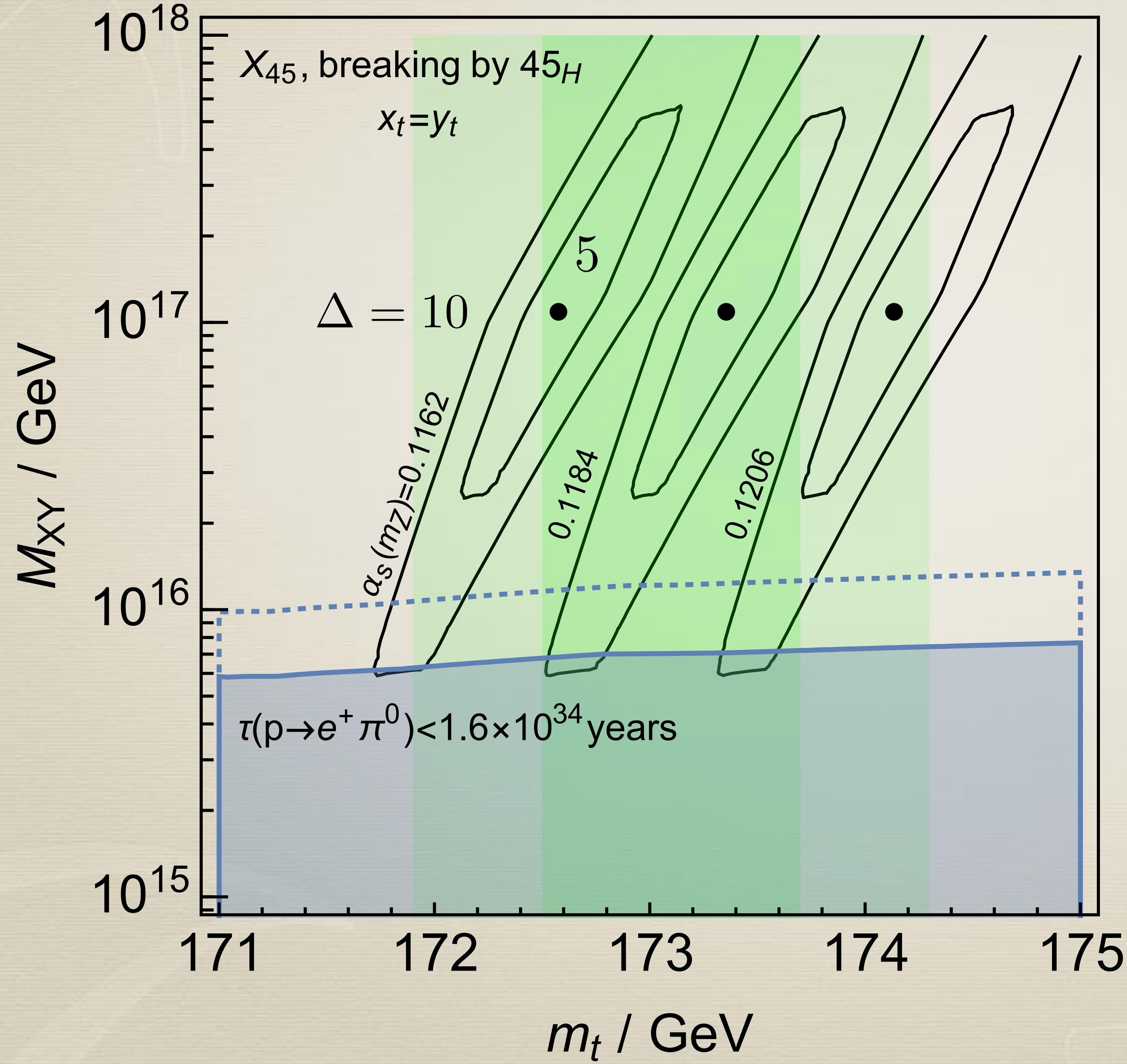
Similar structures

Higgs parity GUT

4 parameters → 5 parameters

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

Coupling unification



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

~ Casimir operator × Log(mass splitting)

Hyper-K

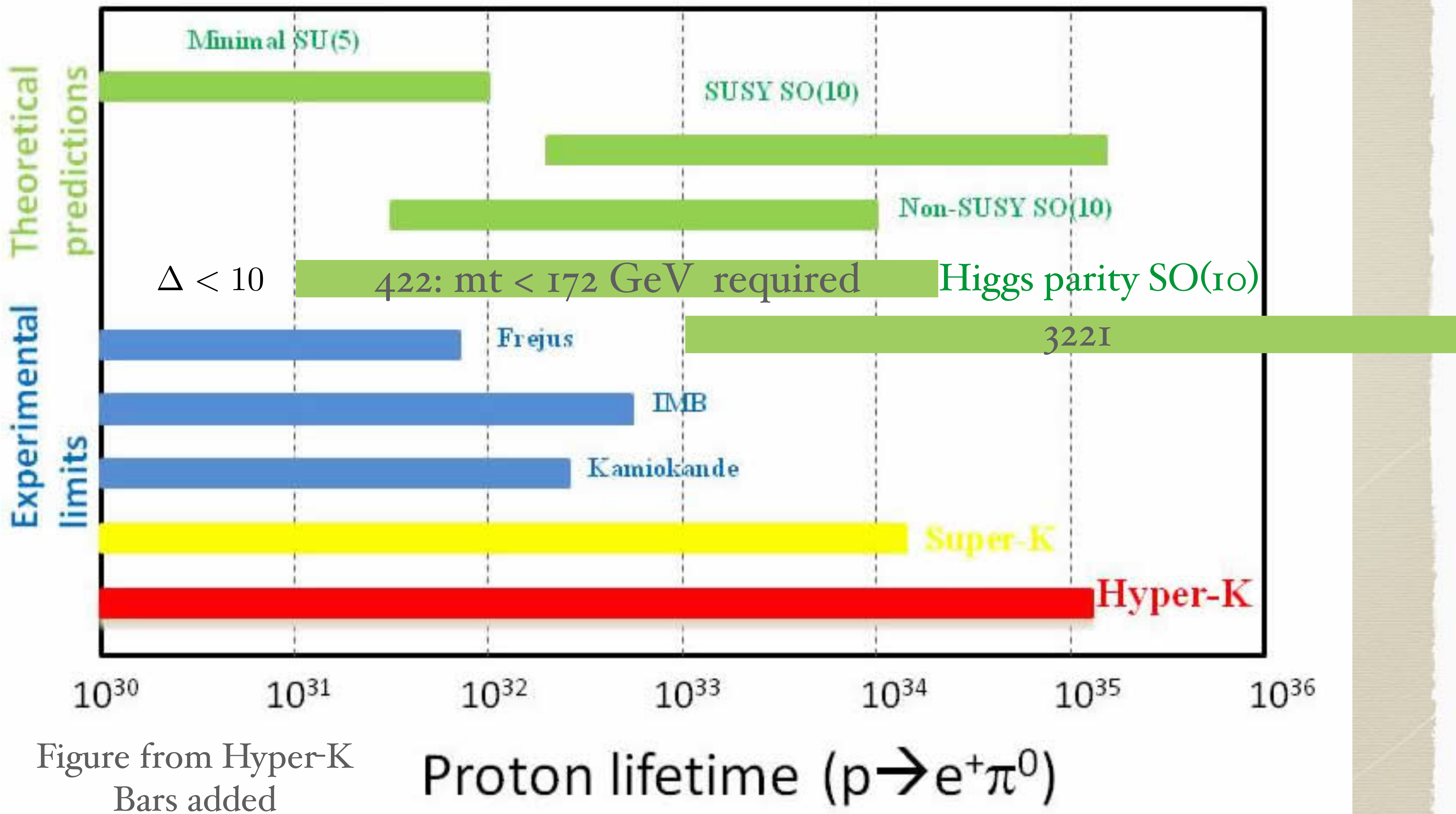
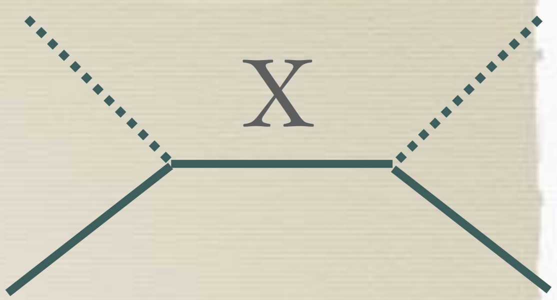


Figure from Hyper-K
Bars added

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**	$X \ell' H'^\dagger$

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

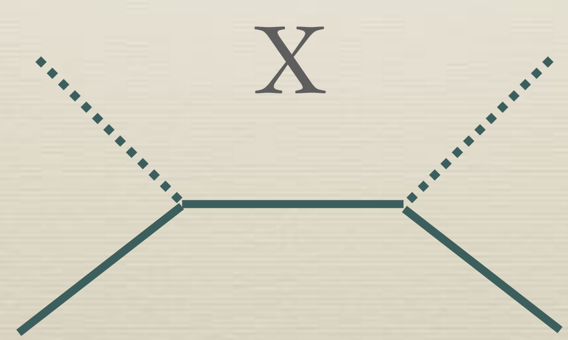
$$SO(10) \times CP \xrightarrow{\phi_{45}^{-}} SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times P_{LR}$$

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?

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

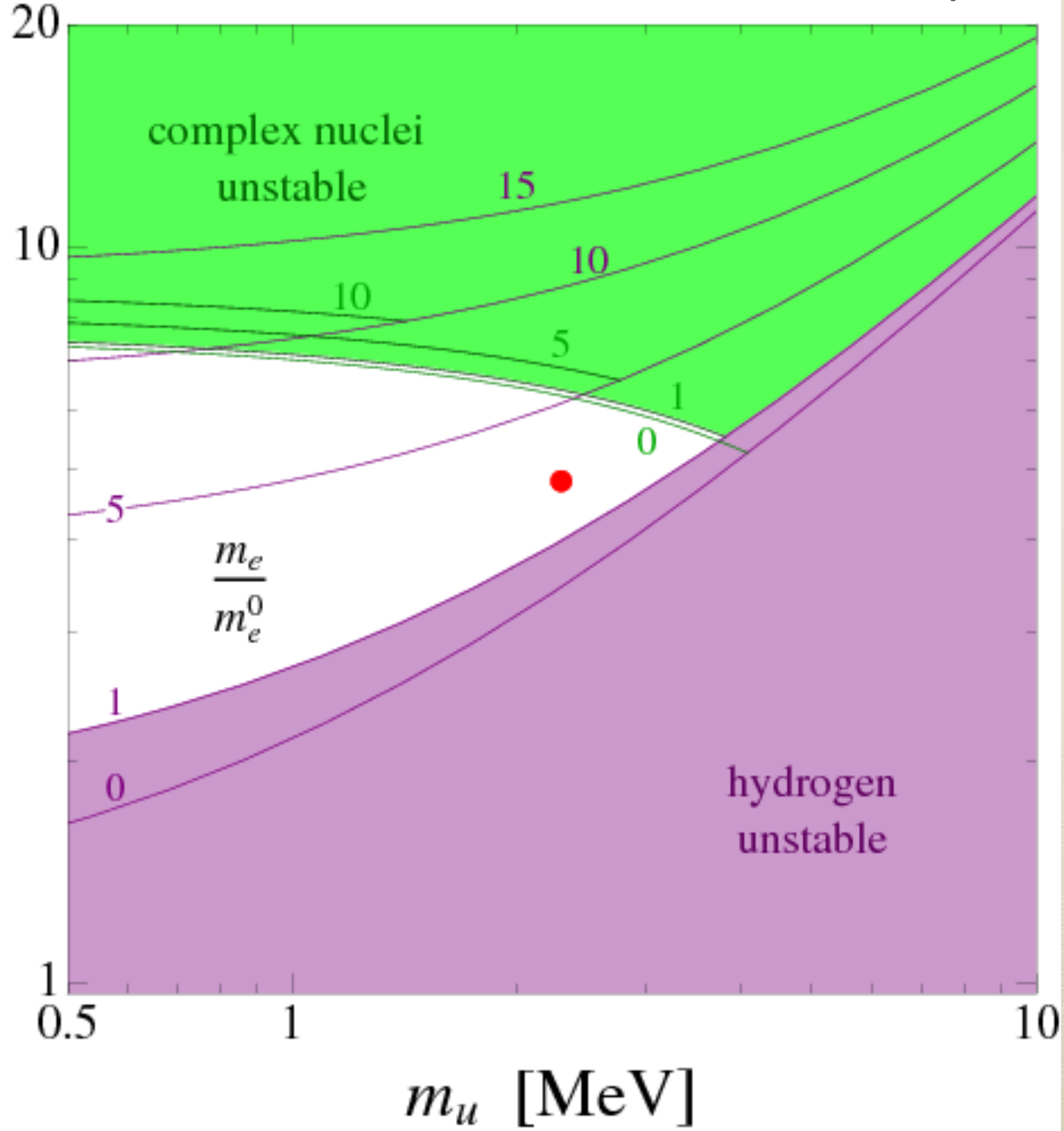
Might be requirement for us to emerge,
rather than a prediction of a theory

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

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

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

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

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