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Semi-natural Gauge Mediation from Product Group Unification

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with

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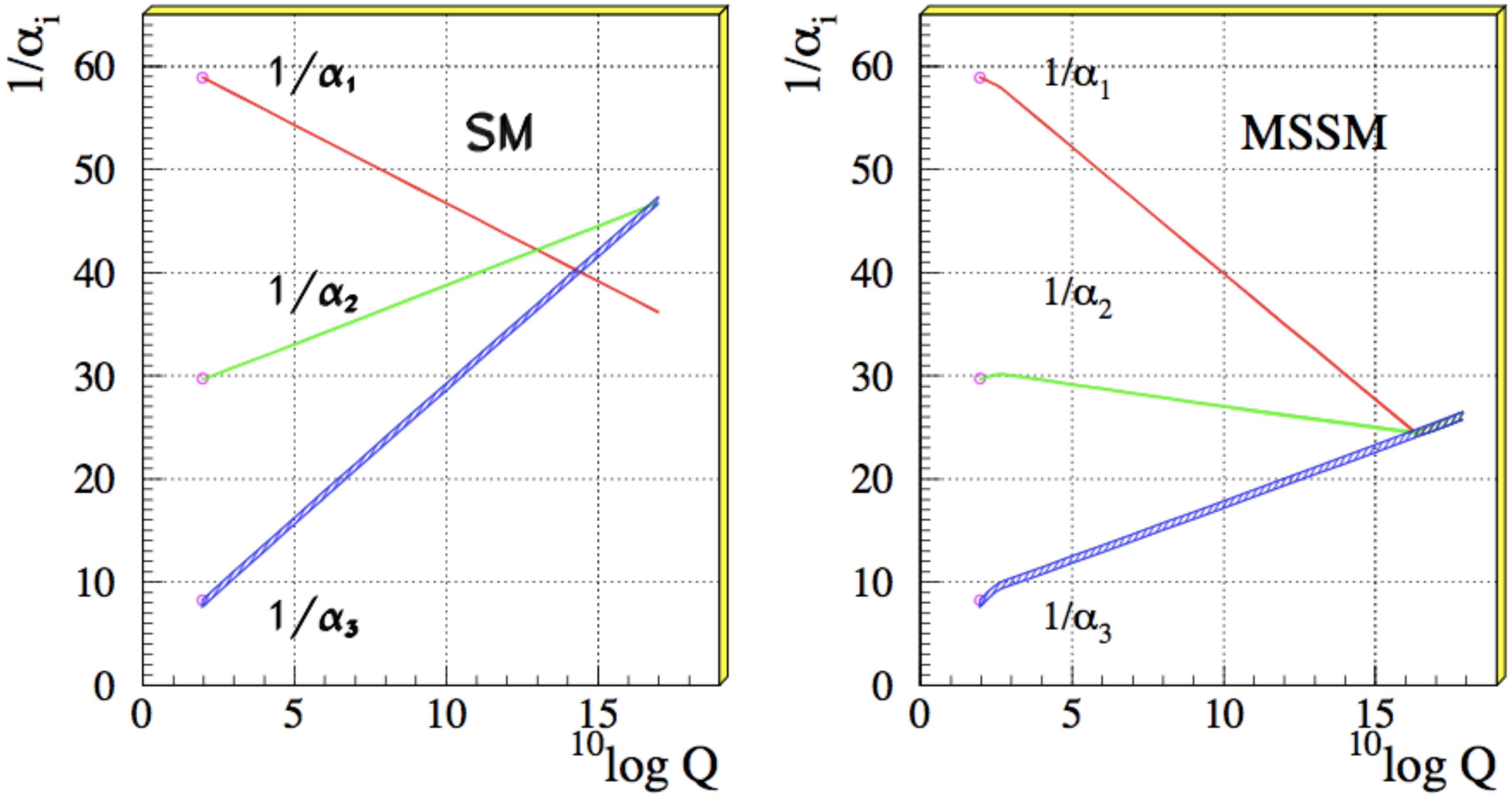
PRD, arXiv:1508.00445

I would like to thank the organizers!

Supersymmetric SM

- Gauge couplings unify around 10^{16} GeV.



[hep-ph/0012288]

- **The muon g-2 anomaly (>3σ)** is explained if weakly interacting SUSY particles are light. (with a help of **tanβ enhancement**)

- Stabilizing the large hierarchy between the Planck/GUT/PQ breaking scale and the EWSB scale

- **The EWSB scale is possibly understood from the SUSY particle mass scale**

- Negative quadratic term in the Higgs potential is induced from loops involving top-squark and gluino. (**because of Yt~1**: if Yt~0.5 radiative EWSB breaking is very difficult.)

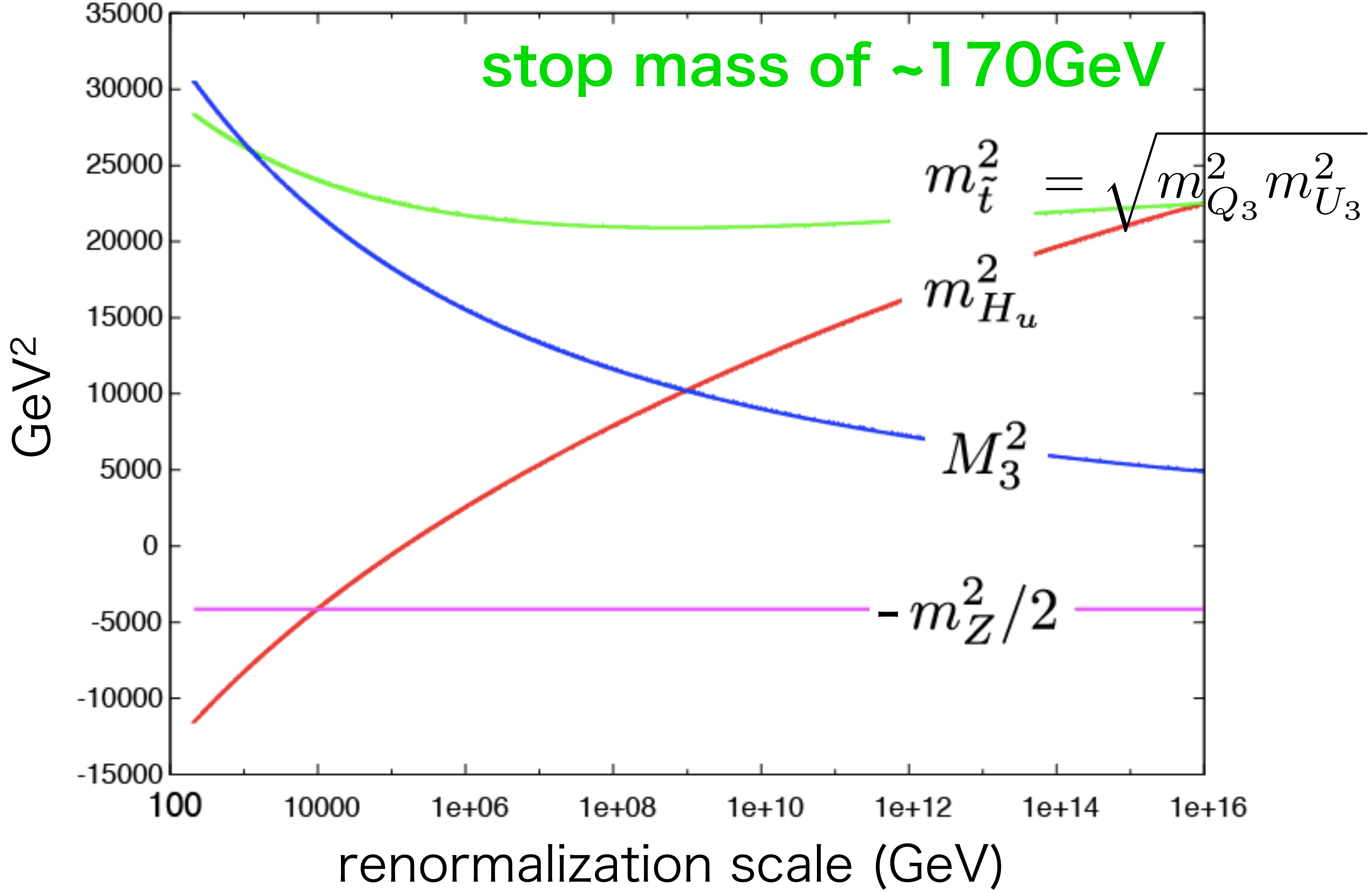
EWSB condition:

$$m_Z^2 \simeq -2\left[m_{H_u}^2 + \mu^2 + \frac{1}{2v_u}\frac{\partial \Delta V_{CW}}{\partial v_u}\right] + \mathcal{O}(1/\tan^2\beta) + \ldots$$

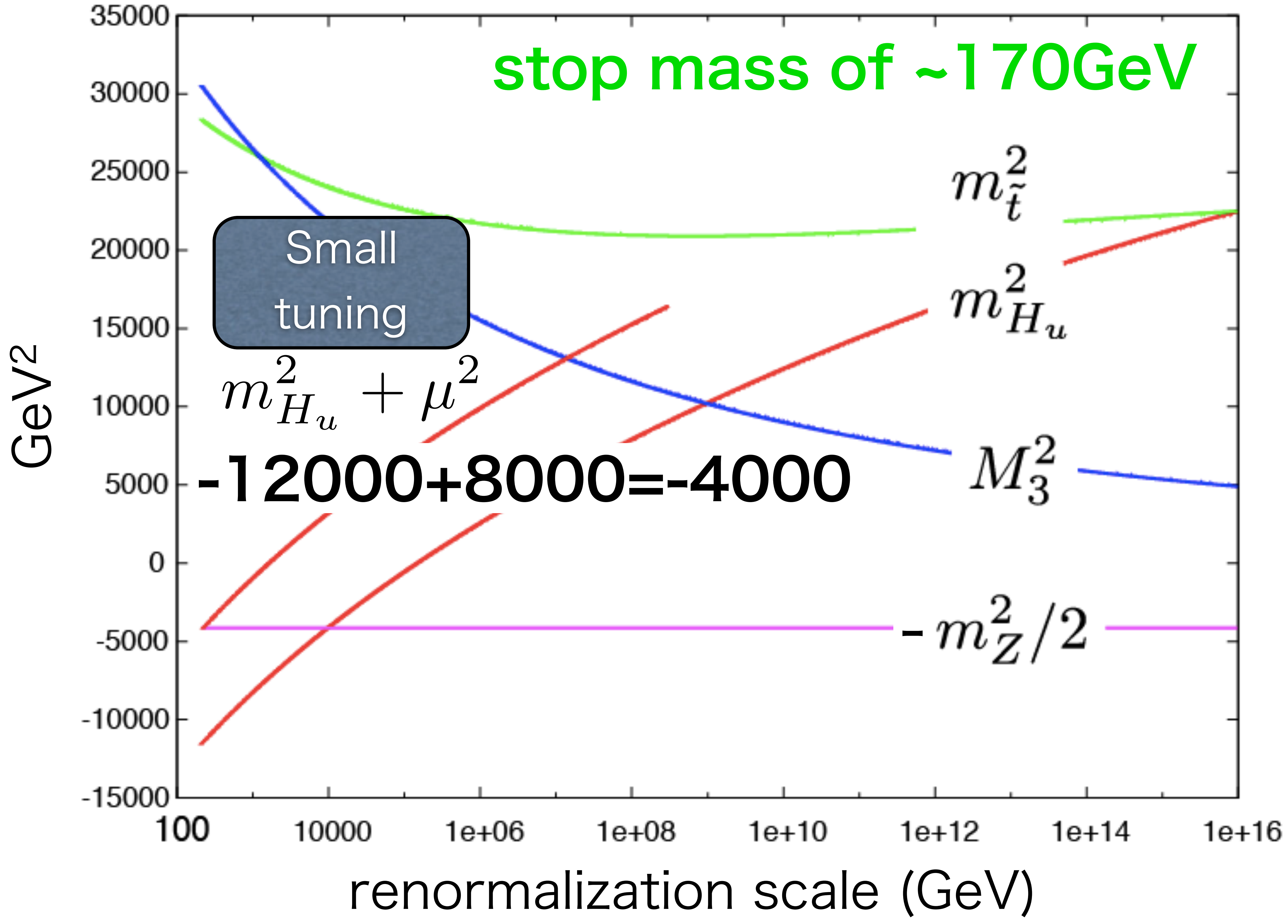
($\tan\beta = v_u/v_d$ is determined by the other EWSB condition)

- The size of negative $m_{H_u}^2$ is around the stop mass → the natural size of m_Z is the stop mass

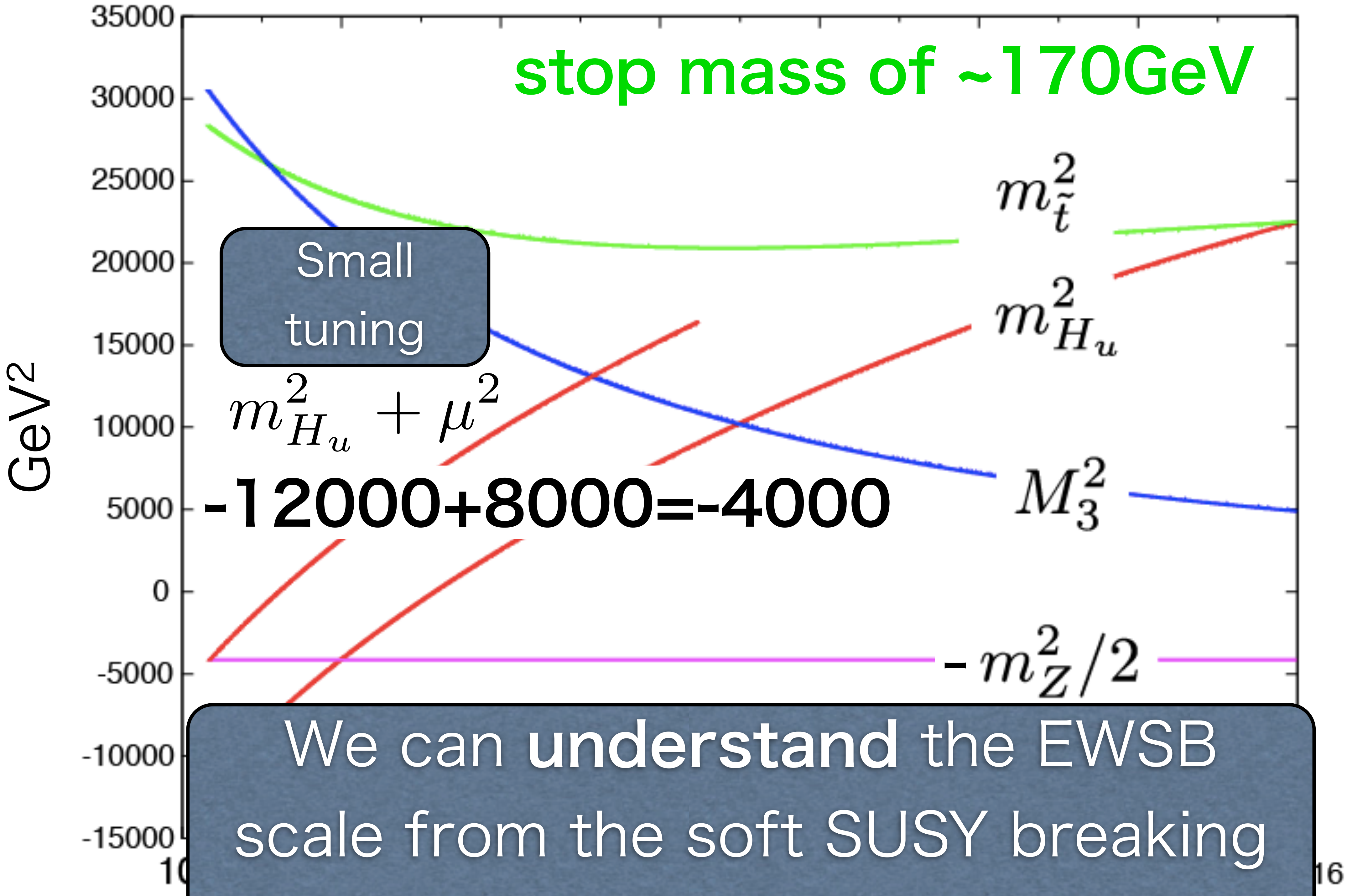
Radiative Electroweak Symmetry Breaking



Radiative Electroweak Symmetry Breaking



Radiative Electroweak Symmetry Breaking



stop mass of ~170GeV

Small tuning

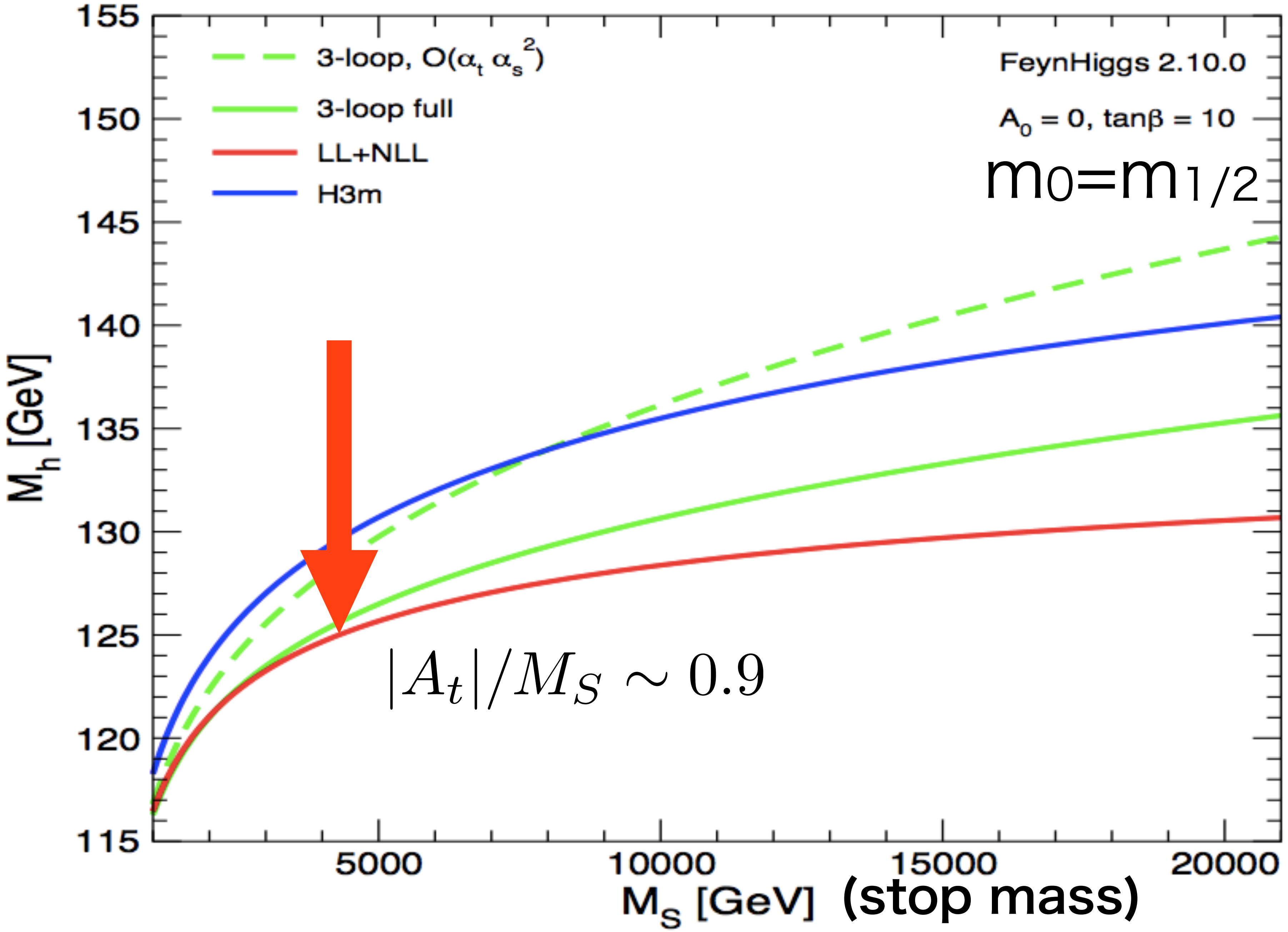
$m_{H_u}^2 + \mu^2$

-12000+8000=-4000

We can **understand** the EWSB scale from the soft SUSY breaking mass scale

- However, the LHC excludes,
  top-squark (stop) < 600 GeV, gluino < 1.4 TeV

- **The observed Higgs boson mass of 125 GeV requires, stop > 3-5 TeV**

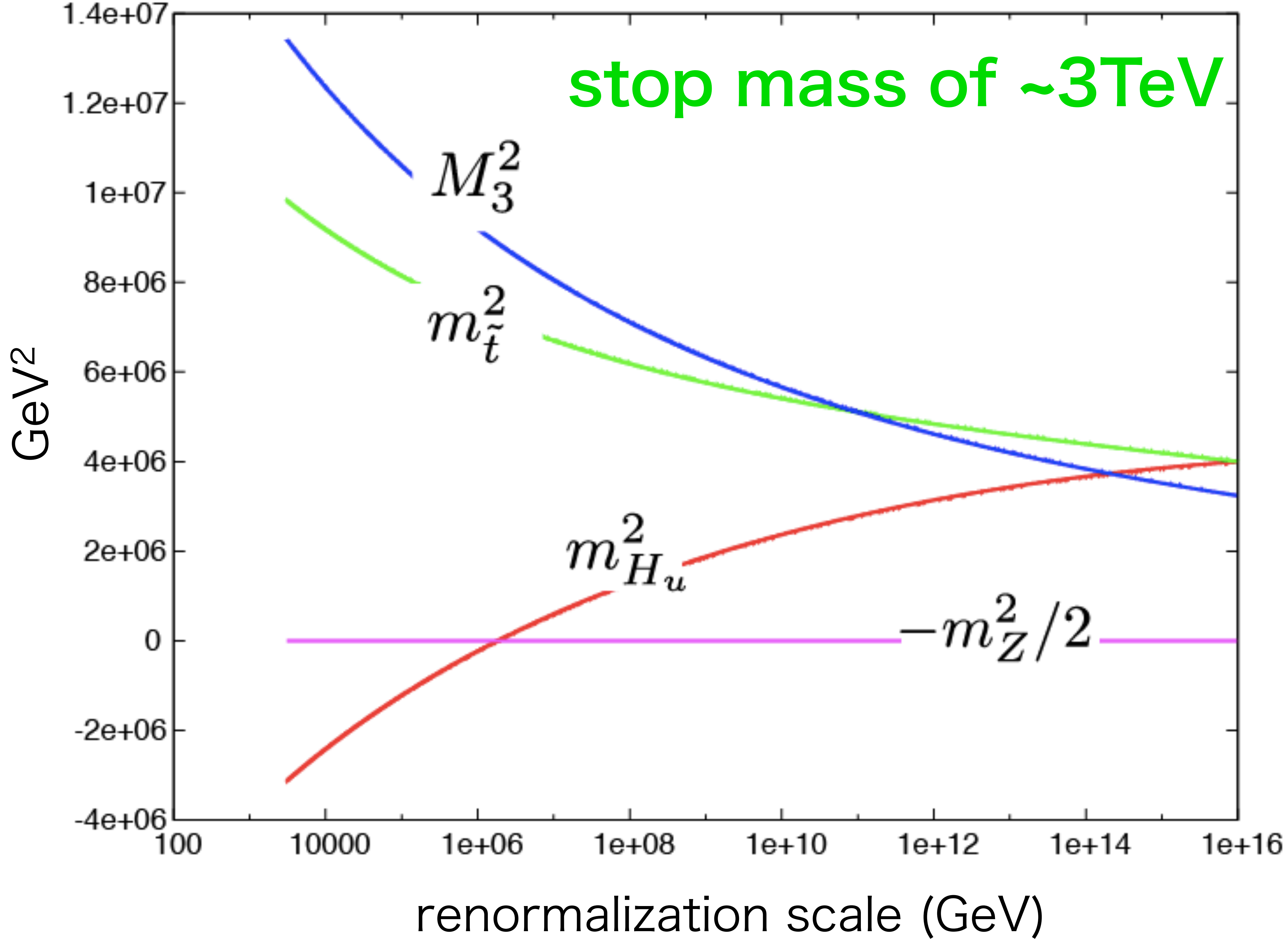


$m_0 = m_{1/2}$

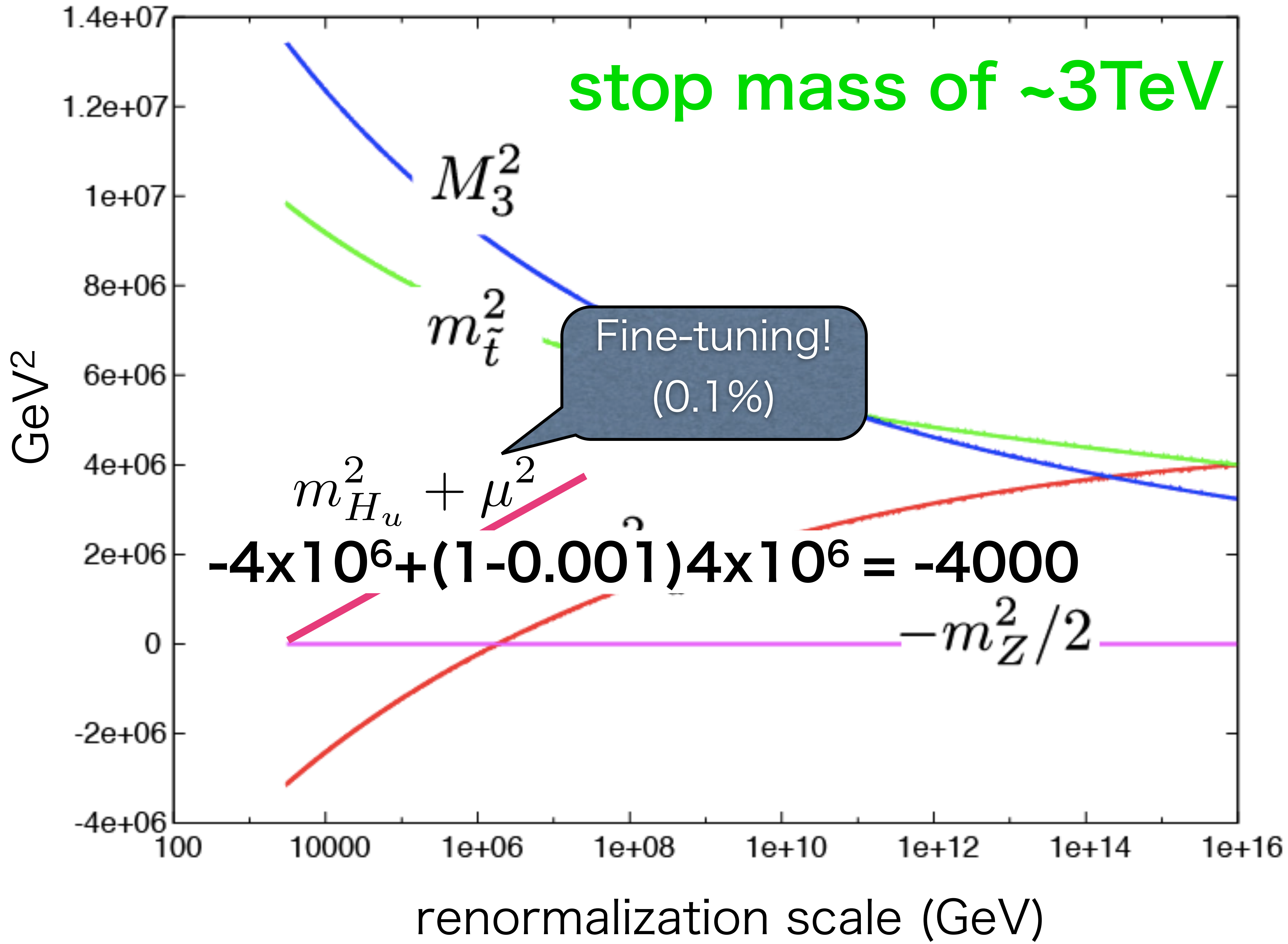
$|A_t|/M_S \sim 0.9$

(stop mass)

[T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak, G. Weiglein, 2013]



We need an elaborate choice of μ-parameter to explain the EWSB scale.



stop mass of ~3TeV

Fine-tuning!
(0.1%)

$$-4\text{x}10^6+(1-0.001)4\text{x}10^6 = -4000$$

We need an elaborate choice of μ-parameter to explain the EWSB scale.

Approaches to the origin of the EWSB scale

- The best way is to consider the SUSY mass scale as well as the mediation scale is low, **though difficult**.
- Never mind (just a little hierarchy)

Approaches to the origin of the EWSB scale

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Focus point!

- **Special relation(s) among parameters at UV physics, reducing the fine-tuning.**

Original Focus Point

universal scalar mass

gaugino mass

$$m_0 \quad >> \quad M_{1/2}$$

Arises from minimal Kahler

input parameters at the GUT scale

$m_{H_u}^2(m_Z)$ becomes much smaller than the expected value m_0^2, and does not sensitive to the change of m_0

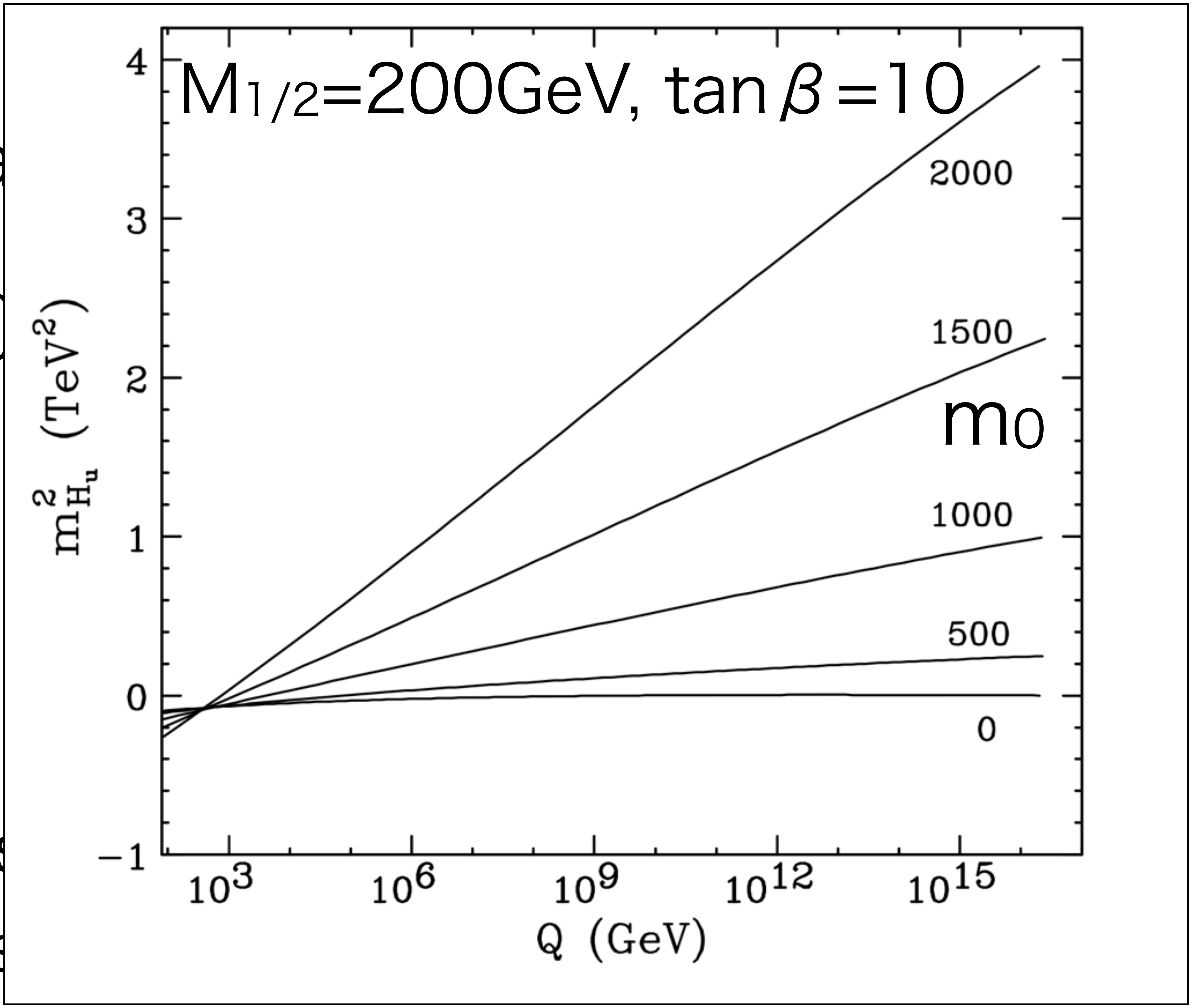
[Feng, Matchev, Moroi, ‘99]

Original Focus Point

universal scala

$$m_0$$

Arises from minimal Kahler



$m_{Hu}^2(m_Z)$ becomes

value m_0^2, and does

[Feng, Matchev, Moroi, '99]

- Usually, fine-tuning of the EWSB scale is estimated using the following measure:

$$\boxed{\Delta = \max(\Delta_a)} \quad \Delta_a = \left| \frac{\partial \ln m_{\hat{Z}}}{\partial \ln a} \right|_{m_{\hat{Z}} = 91.2\mathrm{GeV}}$$

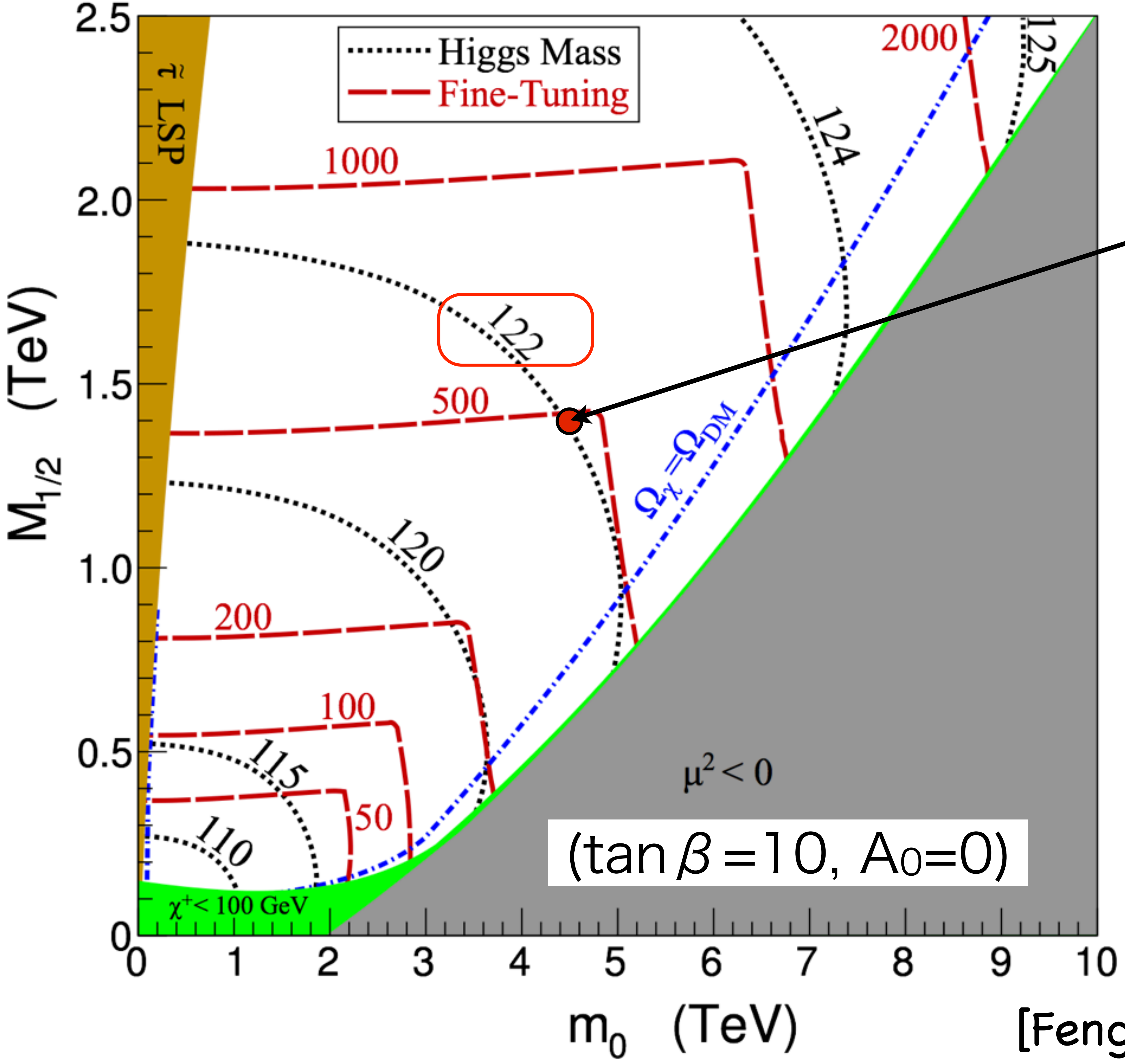
[Barbieri and Giudice, 1988]

“a” is a fundamental parameter

e.g., mSUGRA

$$\{a_i\} = m_0, M_{1/2}, A_0, \mu, B_0$$

(The Higgs potential can be written as a function of these fundamental parameters)



($\tan\beta = 10$, $A_0 = 0$)

mh=123.7 GeV
(using FeynHiggs)

stop=3.8 TeV
gluino=3.2 TeV

mh=124.7 GeV
for tanb=25

[Feng, Sanford, 2012]

Fine-tuning and Focus Point

- In the original scenario, the fine-tuning is reduced, but it is not significant.
  (**If** the ratio of **$m_0/M_{1/2}$ (=4-5)** is fixed by the UV physics, it will be improved.)
  [Harigaya, Yanagida, Yokozaki, 2015]

- Generally, the SUSY Flavor problem is **severe** in gravity mediation.
- It is better to consider the scenario with a convincing solution to the SUSY flavor problem.

Focus point gauge mediation

Good things in GMSB

- The masses of the SUSY particles are generated from **the messenger loops**.
- **The absence of the FCNC processes** is guaranteed.
  (The masses of the SUSY particles are generated via gauge interactions.)
- A SUSY mass spectrum is unambiguously calculated in minimal gauge mediation.

Focus point gauge mediation

$$W_{\rm mess} = \lambda_D Z \Psi_D^a \overline{\Psi}_D^a + \lambda_T Z \Psi_T^A \overline{\Psi}_T^A$$

$$a = 1 \ldots N_D \qquad A = 1 \ldots N_T$$

N_D pairs of SU(2) doublet messengers

N_T pairs of SU(3) triplet messengers

Z is a SUSY breaking field $Z = \langle Z \rangle + \langle F_Z \rangle \theta^2$

If messengers are SU(5) complete multiplets, $N_D=N_T$

If N_D/N_T~5/2, the fine-tuning can be significantly reduced

[In High scale GMSB, Brummer and Buchmuller, 2012; Brummer, Ibe and Yanagida, 2013]

Focus point gauge mediation

weakly interacting particles (charged under SU(2))

$$M_{\tilde{W}} \simeq \frac{\alpha_2}{4\pi} \overset{\Delta b_2}{\underline{N_D}} \Lambda \qquad m_L^2 = m_{H_u}^2 \simeq \frac{3}{2} \left(\frac{\alpha_2}{4\pi} \right)^2 \underline{N_D} \Lambda^2$$

strongly interacting particles (charged under SU(3))

$$M_{\tilde{g}} \simeq \frac{\alpha_3}{4\pi} \underset{\Delta b_3}{\underline{N_T}} \Lambda \qquad m_{\rm squark}^2 \simeq \frac{8}{3} \left(\frac{\alpha_3}{4\pi} \right)^2 \underline{N_T} \Lambda^2$$

$$\boxed{(16\pi^2) \frac{dg_i}{dt} = [(b_i)_{\rm MSSM} + \Delta b_i] g_i^3} \qquad \Lambda = \langle F_Z \rangle / \langle Z \rangle$$

The masses **do not depend on** the Yukawa couplings, λ_D and λ_T

(squark corresponds to a RH squark, omitting U(1) contributions)

$$m_{H_u}^2(4\mathrm{TeV}) \simeq \Big[-0.236 m_{\tilde{Q}}^2 - 0.140 m_{\tilde{U}}^2 - 0.253 M_{\tilde{g}}^2 + 0.789 m_{H_u}^2 + 0.139 M_{\tilde{W}}^2 + \ldots\Big]_{M_{\mathrm{inp}}=10^9\mathrm{GeV}}$$

(=M_{mess})

⇓

$$m_{H_u}^2(4\,\mathrm{TeV}) = [-0.253 N_T^2 - 0.011 N_D N_T - 1.073 N_T + 0.058 N_D^2 + 0.380 N_D] \left(\frac{\alpha_3}{4\pi}\Lambda\right)^2,$$

⇓ Putting **(N_D, N_T)=(5,2)**

$$m_{H_u}^2(4\,\mathrm{TeV}) = \underline{0.020} \cdot M_{\tilde{g}}^2(M_{\mathrm{inp}})$$

If N_D=N_T, $m_{H_u}^2(4\,\mathrm{TeV}) \sim -M_{\tilde{g}}^2(M_{\mathrm{inp}})$

Good things

- The focus point behavior is controlled by the messenger numbers. (not continuous valuables)
- The behavior is stable against radiative correction.

Bad things

- No reason for (N_D, N_T)=(5, 2).
- **GUT is messy!**

- As shown later, $N_D/N_T=5/2$ is explained in the product group unification model, **based on SU(5)xU(3)$_H$**
- Why do we need the product group unification?

- As shown later, $N_D/N_T=5/2$ is explained in the product group unification model, **based on SU(5)xU(3)$_H$**
- Why do we need the product group unification?

The product group unification provides a simple way to solve the doublet-triplet splitting problem

Severe fine-tuning in the minimal SU(5)

Doublet-Triplet splitting problem
(another fine-tuning problem!)

In the minimal SU(5), the Higgs doublets belong to 5 and 5* representations

$$\begin{aligned} H &= H_5 = (\boxed{H_C}, H_u)^T \\ \bar{H} &= H_{\bar{5}} = (\boxed{\bar{H}_C}, H_d)^T \end{aligned}$$

The colored Higgs should have the GUT scale mass, otherwise the proton decays quickly

Severe fine-tuning in the minimal SU(5)

Doublet-Triplet splitting problem
(another fine-tuning problem!)

In the minimal SU(5), the Higgs doublets belong to 5 and 5* representations

$$H = H_5 = (H_C, H_u)^T$$
$$\bar{H} = H_{\bar{5}} = (\bar{H}_C, H_d)^T$$

Triplet ~$10^{16\text{-}17}$GeV **Doublet** ~100GeV

10^{17}GeV - **$(1-10^{-15})$** 10^{17}GeV ~ 100GeV

- It is **not easy** to solve this doublet-triplet (DT) splitting problem in GUT models based on simple gauge groups (e.g. SU(5) and SO(10))

There is no solution **based on a symmetry**, which is not broken at the GUT scale.
(If only MSSM particles exist below the GUT scale)

- There even exists the **no-go theorem** in simple cases [Witten, 2002; Fallbacher, Ratz, Vaudrevange, 2011; Ibe, Harigaya, Suzuki, 2015]

$$\frac{\langle W_0 \rangle}{M_P^2} H_u H_d, \quad \frac{\langle PQ \rangle^2}{M_P} H_u H_d \quad \Longleftrightarrow \quad M_{\mathrm{GUT}} H_C \bar{H}_C \ ?$$

R-sym. PQ-sym.

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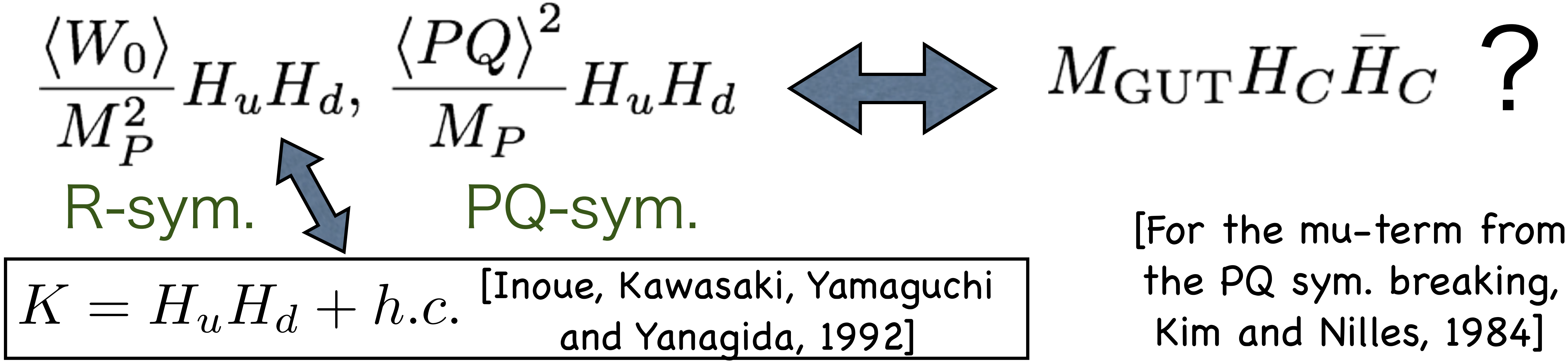


$$\frac{\langle W_0\rangle}{M_P^2} H_u H_d,\quad \frac{\langle PQ\rangle^2}{M_P} H_u H_d \quad \Longleftrightarrow \quad M_{\mathrm{GUT}} H_C \bar{H}_C \ ?$$

R-sym.

PQ-sym.

$$\boxed{K = H_u H_d + h.c.}$$

[Inoue, Kawasaki, Yamaguchi and Yanagida, 1992]

[For the mu-term from the PQ sym. breaking, Kim and Nilles, 1984]

$SU(5) \times U(3)_H$ product group unification

- The DT-splitting is easily achieved
- Gauge coupling unification is still **hold** approximately if the coupling of $U(3)_H$ is strong
- Charge quantization of the MSSM particles is **hold**

[Hotta, Izawa, Yanagida, 1995; Watari, Yanagida, 2002]

- SU(5)xU(3)$_H$ is broken to the SM gauge group, by the VEVs of bi-fundamental fields

$$B = (\mathbf{5}, \bar{\mathbf{3}}) \qquad \bar{B} = (\bar{\mathbf{5}}, \mathbf{3})$$

$$\langle B^i_\alpha \rangle = v_{\rm GUT} \delta^i_\alpha \qquad \langle \bar{B}^\alpha_i \rangle = v_{\rm GUT} \delta^\alpha_i$$

i=1..5
α=1..3

Then, $$W = H^i \bar{B}^\alpha_i \bar{T}_\alpha + \bar{H}_i B^i_\alpha T^\alpha$$

$$\Downarrow$$

$$v_{GUT} H_C \bar{T} + v_{GUT} \bar{H}_C T$$

Colored Higgs multiplets become heavy, while doublets remain massless.

(The doublet mass can arise from a symmetry breaking term.)

Adjoint messenger

- Consider the messenger field in the adjoint representation of SU(5), **24**

$SU(3)\times SU(2)\times U(1)_Y$:

(**8**, **1**, 0) ⇒ $\Delta b_2 = 0$, $\Delta b_3 = 3$

if this is heavy!

(**1**, **3**, 0) ⇒ $\Delta b_2 = 2$, $\Delta b_3 = 0$

(**3**, **2**, -5/6)
(**3***, **2**, 5/6) ⇒ $\Delta b_2 = 3$, $\Delta b_3 = 2$

⇒ $(\Delta b_2)_{\mathrm{total}} = 5$, $(\Delta b_3)_{\mathrm{total}} = 2$

corresponding to $(N_D, N_T)=(5,2)$

Realization:

SU(3)$_H$ adjoint

$$W = \lambda_{24} Z (\Sigma_{24})^i_j (\Sigma_{24})^j_i + \frac{c_0}{M_P} \bar{B}^\alpha_i (\Sigma_{24})^i_j (\Sigma'_8)^\beta_\alpha B^j_\beta,$$

$$\Downarrow$$

$$\mu_8 \mathrm{Tr}(\Sigma_8 \Sigma'_8)$$

~(v_{GUT}^2/M_P)~$10^{12\text{-}14}$ GeV

For $\lambda_{24} \langle Z \rangle \ll \mu_8$

the desired SUSY mass spectrum,
corresponding to (N_D, N_T)=(5,2) is obtained.

Estimation of the fine-tuning

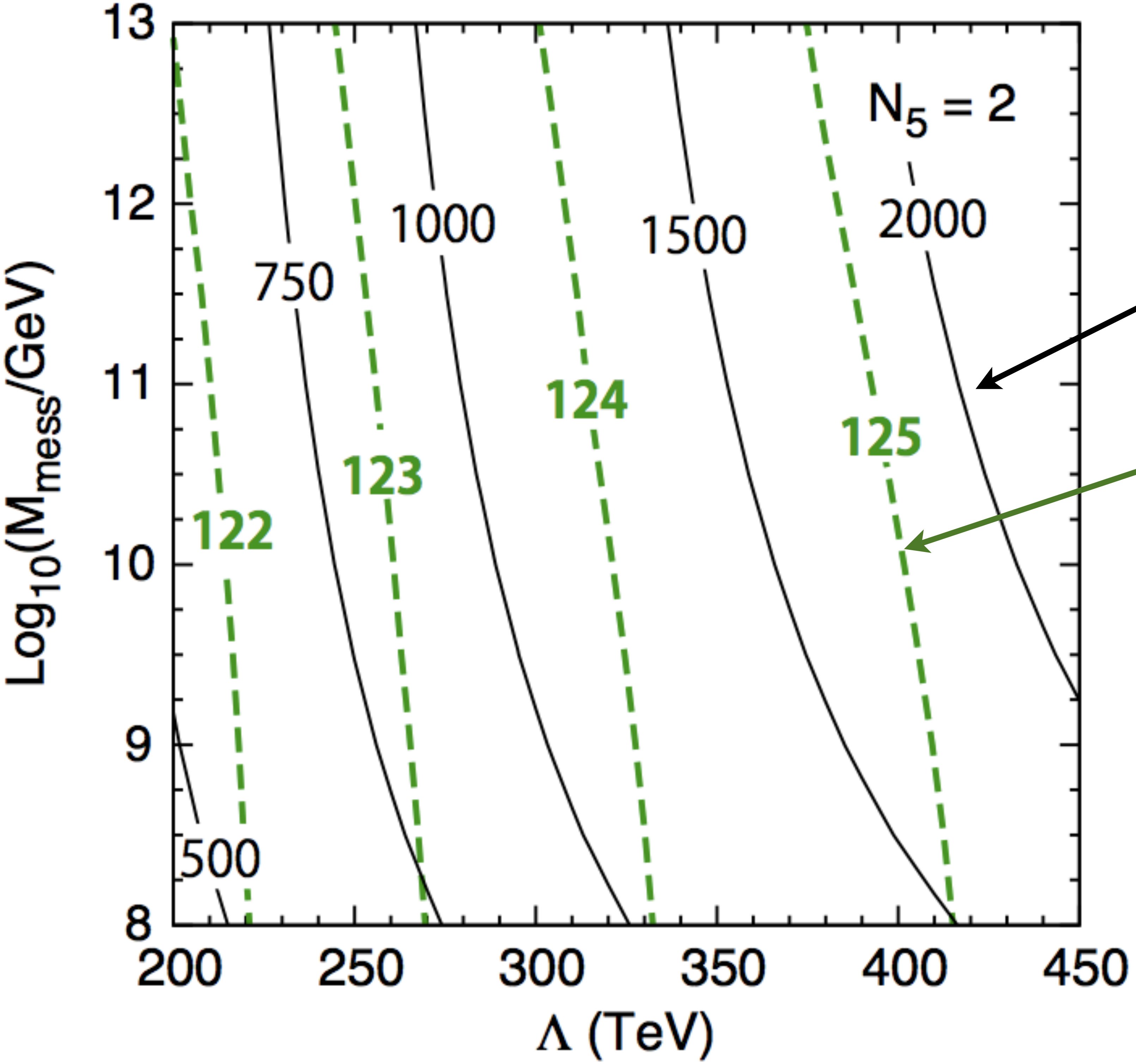
- Finally, we estimate the fine-tuning using the following measure:

$$\Delta = \max\{\Delta_a\}, \quad \Delta_a = \left\{ \frac{\partial \ln m_{\hat{Z}}}{\partial \ln |\mu|}, \frac{\partial \ln m_{\hat{Z}}}{\partial \ln |F_Z|}, \frac{\partial \ln m_{\hat{Z}}}{\partial \ln |B_{\rm mess}|} \right\}_{m_{\hat{Z}}=91.2{\rm GeV}}$$

We regard F_Z, μ and $B_{\rm mess}$ as independent fundamental parameters

Minimal GMSB with 5 5* messengers

($N_T=N_D=2$)

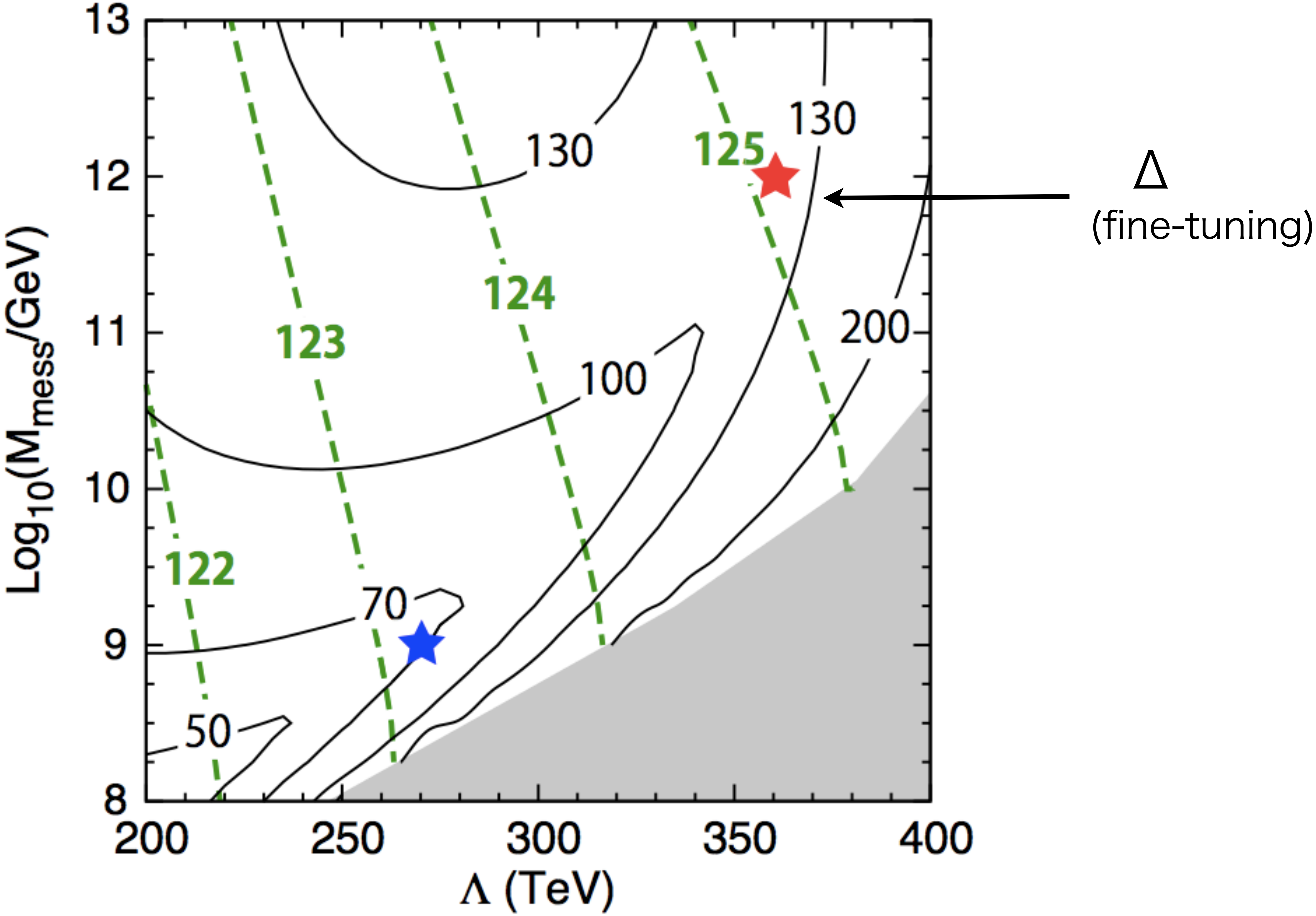


Δ (fine-tuning)

Higgs mass

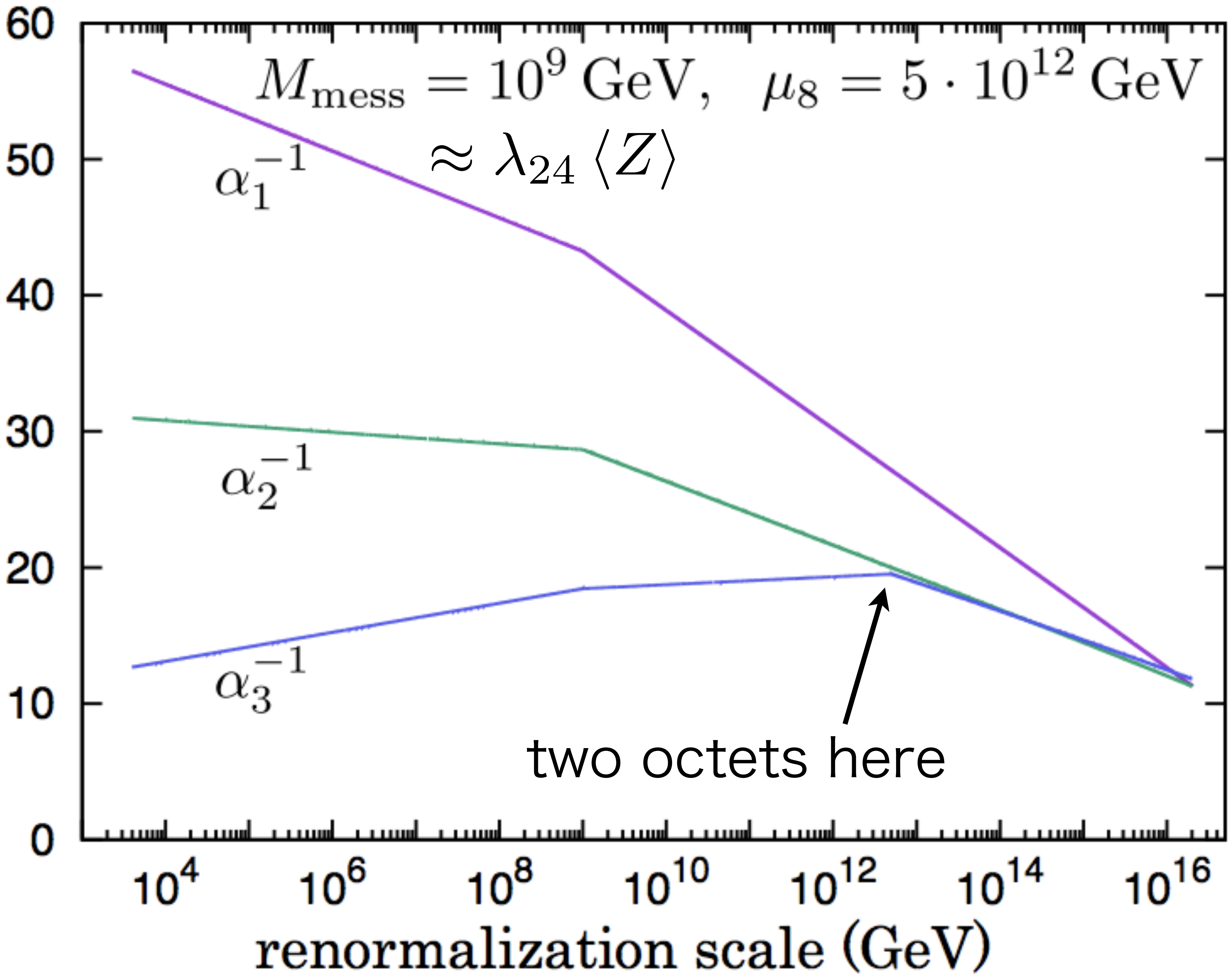
$\tan\beta = 25$, $m_t(\mathrm{pole}) = 173.34\,\mathrm{GeV}$ and $\alpha_s(m_Z) = 0.1185$.

SU(5)xU(3)$_H$ Product Group Unification



There exist solutions with B_{mess}=0 for μ<0 and tanb~25-30, where the SUSY CP-problem is solved.

The gauge couplings unify consistently



(2-loop RGEs are used)

Summary

- There still exist a hope to understand the origin of the EWSB scale **if the UV physics provides certain relation(s)** among soft SUSY breaking masses.
- The **semi-natural SUSY** may be as a result of the product group unification, which is somewhat natural from the view point of the doublet-triplet splitting.
- To be completed, we need to explain **why the EWSB is sensitive to the top Yukawa coupling**.

Consistency with gravitino cosmology (briefly)

- The thermalized **gravitino can be dark matter without over-closure of the universe**.
- This is achieved with **a late-time entropy production** from the decay of the messenger, diluting the gravitino abundance.
- Baryon number is explained via **the thermal Leptogenesis** with $M_N=10^{(11\text{-}12)}$ GeV and $T_R > M_N$.
  (M_N is a RH neutrino mass, T_R is a Reheating temperature)