Higgs & gauge mediation

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arXiv:1208.3748, K Bae, TH Jung and HD Kim
arXiv:1211.6479, HD Kim, DY Mo and M Seo

Higgs Identification
KITP at UCSB
2012. 12. 14
Santa Barbara, USA

125GeV Higgs and gauge mediation

mu problem in gauge mediation

Higgs as a pseudo-Goldstone boson in supersymmetry

125GeV Higgs
and gauge mediation

Minimal Supersymmetric Standard Model

For $\tan\beta \geq 5$

Up type Higgs gives mass to Z : $\phi \simeq H_u$

susy breaking

$$-m^2 = \boxed{m^2_{H_u}} + \boxed{\mu^2}$$

supersymmetric

$$2\lambda = g^2 + g'^2$$

$$M_Z^2 = 2m^2$$

Problematic relations

i) weak scale : $\dfrac{M_Z^2}{2} = -m^2_{H_u} - \mu^2$

ii) Higgs mass : $m^2_{\mathrm{phys}} = M_Z^2$

$$\mu^2 + m_{H_u}^2 \xrightarrow{\hspace{4em}} -M_Z^2$$

SUSY ~~SUSY~~

run

In the absence of theory predicting $\left|\frac{m_{H_u}^2}{\mu^2}\right| \simeq 1$

no run

$\mu^2 \sim \mathcal{O}(M_Z^2)$

$|m_{H_u}^2| \sim \mathcal{O}(M_Z^2)$

similarly for $\frac{m_A^2}{\tan\beta}$

The largest loop correction to the Higgs mass comes from stop

$$\frac{dm_{H_u}^2}{d\log Q} = \frac{3y_t^2}{8\pi^2}\left(m_{\tilde{Q}_3}^2 + m_{\tilde{t}^c}^2 + m_{H_u}^2 + |A_t|^2\right) + \cdots \longrightarrow m_{\tilde{t}}^2 \sim \frac{4\pi}{\log\frac{\Lambda}{m_{\tilde{t}}}}\mathcal{O}(M_Z^2)$$

$$\downarrow$$

$$\begin{aligned}\delta M_{H_u}^2 = &-\frac{3y_t^2}{8\pi^2}(m_{\tilde{Q}_3}^2 + m_{\tilde{u}_3}^2 + m_{H_u}^2 + |A_t|^2)\log\left(\frac{\Lambda}{m_{\text{soft}}}\right)\\ &-\frac{2y_t^2}{\pi^2}\left(\frac{\alpha_s}{\pi}\right)|M_g|^2\log^2\left(\frac{\Lambda}{m_{\text{soft}}}\right)\end{aligned}$$

more precisely $m_{\tilde{t}}^2 + \frac{1}{2}|A_t|^2$

Large stop mixing

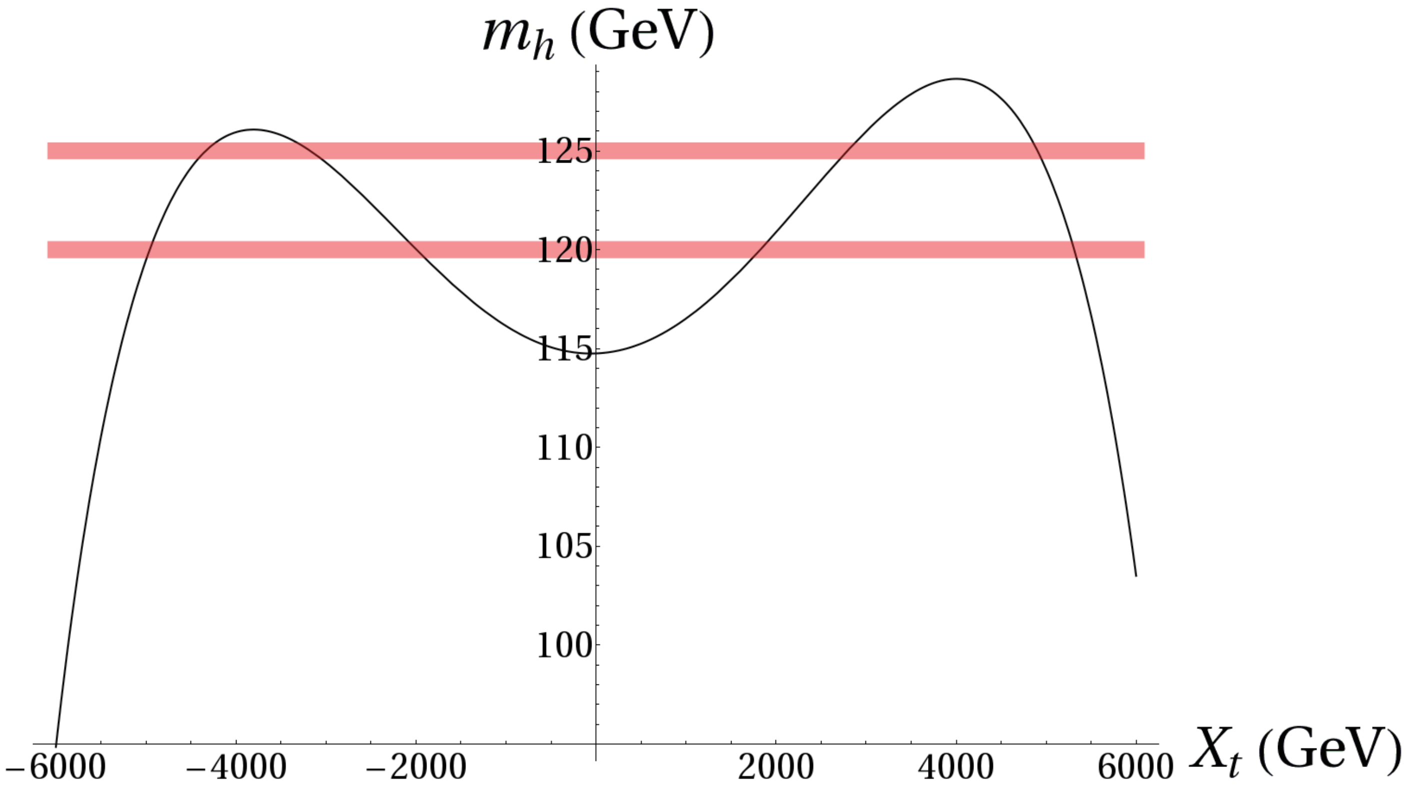
In addition to log correction from stop to top, we have finite threshold correction when we integrate out stop.

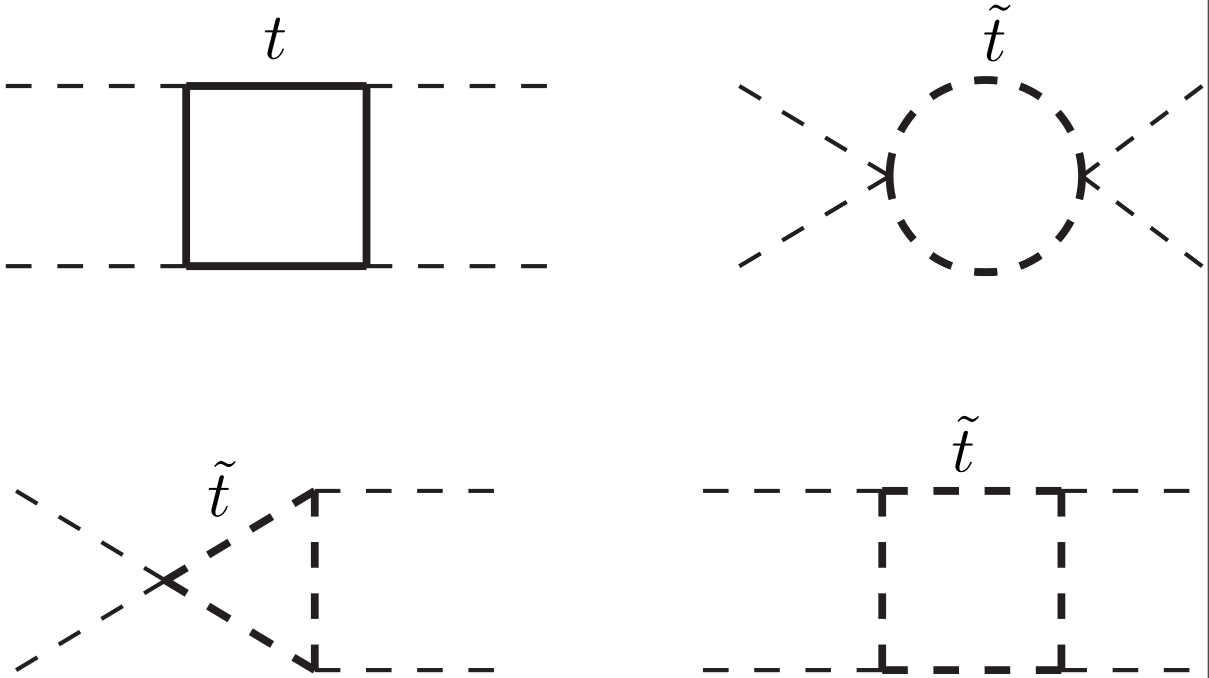
$$m_h^2 = M_Z^2 + \frac{3G_F m_t^4}{\sqrt{2}\pi^2}\left(\log\frac{m_{\tilde{t}}^2}{m_t^2} + X^2(1 - \frac{X^2}{12})\right)$$

$$X^2 = \frac{|A_t^2|}{m_{\tilde{t}}^2}$$

Maximum at $X = \pm\sqrt{6}$

2 TeV stop





S. Martin, A Supersymmetry Primer

tree=loop

(125 GeV)^2 = (90 GeV)^2 + (90 GeV)^2

$$m_h^2 = M_Z^2 + \frac{3G_F m_t^4}{\sqrt{2}\pi^2}\left(\log\frac{m_{\tilde{t}}^2}{m_t^2} + X^2(1 - \frac{X^2}{12})\right)$$

(90 GeV)^2 = (60 GeV)^2 + (60 GeV)^2

log = finite th. cor.

Large stop mixing is not possible from RG

$$\frac{dA_t}{d\log Q} = \frac{18}{16}\frac{1}{\pi^2}y_t^2 A_t + \frac{32}{3}\frac{\alpha_s}{4\pi}M_3$$

$$e^{-\int \frac{18 y_t^2}{16\pi^2} d\log Q} \simeq 0.2$$

exponential damping

For $\tan\beta = 10$

$$A_t(M_Z) \simeq -2.3M_3 + 0.2A_t$$

$$m_{\tilde{t}}^2(M_Z) \simeq 5.0M_3^2 + 0.6m_{\tilde{t}}^2$$

$$\left|\frac{A_t}{m_{\tilde{t}}}\right| \leq 1$$

Very large A term is needed at the GUT scale
to make X large (> 1).

Meta-Stability

- Negative stop mass squared helps by making stop to be light at the weak scale.

- It is not possible in mSUGRA (or in any model with universal boundary condition) since slepton (the same as stop) can not be too negative due to small bino contribution.

Radiatively generated maximal stop mixing

R. Dermisek, H.D. Kim, PRL 96 (2006) 211803

- The most natural solution predicts light stop.
- Light stop can imply meta-stability.

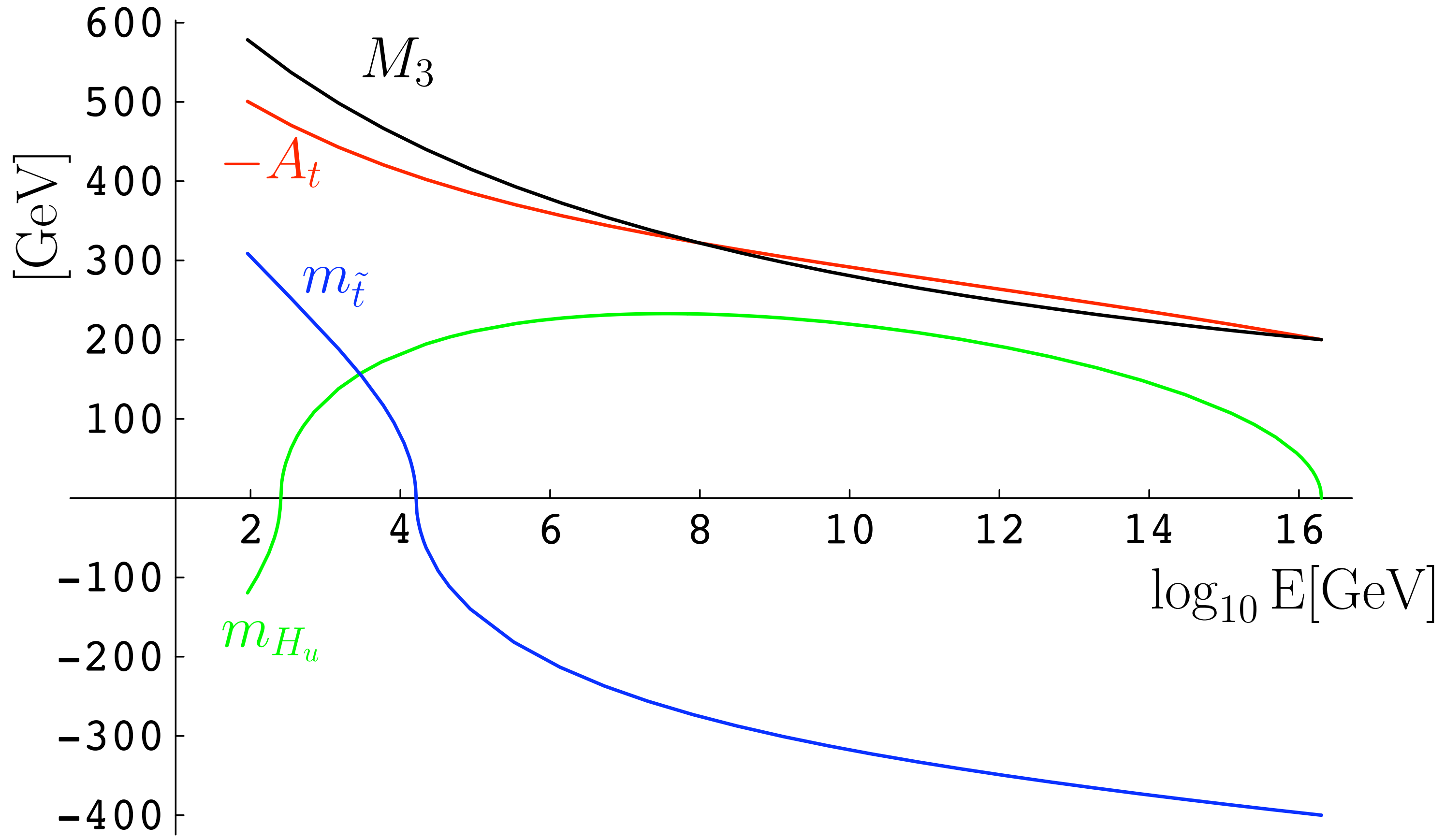


FIG. 1: Renormalization group running of relevant SSBs for $\tan\beta = 10$ and GUT scale boundary conditions: $-A_t = M_3 = 200$ GeV, $m^2_{\tilde{t}} = -(400\,\text{GeV})^2$ and $m^2_{H_u} = 0\,\text{GeV}^2$. In order to have both mass dimension one and two parameters on the same plot and keep information about signs, we define $m_{H_u} \equiv m^2_{H_u}/\sqrt{|m^2_{H_u}|}$ and $m_{\tilde{t}} \equiv m^2_{\tilde{t}}/\sqrt{|m^2_{\tilde{t}}|}$.

Gauge mediation

SUSY breaking sector

SUSY breaking messengers

visible sector

Gauge mediation

SUSY breaking sector

SUSY breaking messengers

visible sector

Meade Seiberg Shih 0801.3278

In the limit that the MSSM gauge couplings go to zero, the theory decouples into the MSSM and the separate hidden sector that breaks SUSY.

Generic prediction for gauge mediation

Meade Seiberg Shih 0801.3278

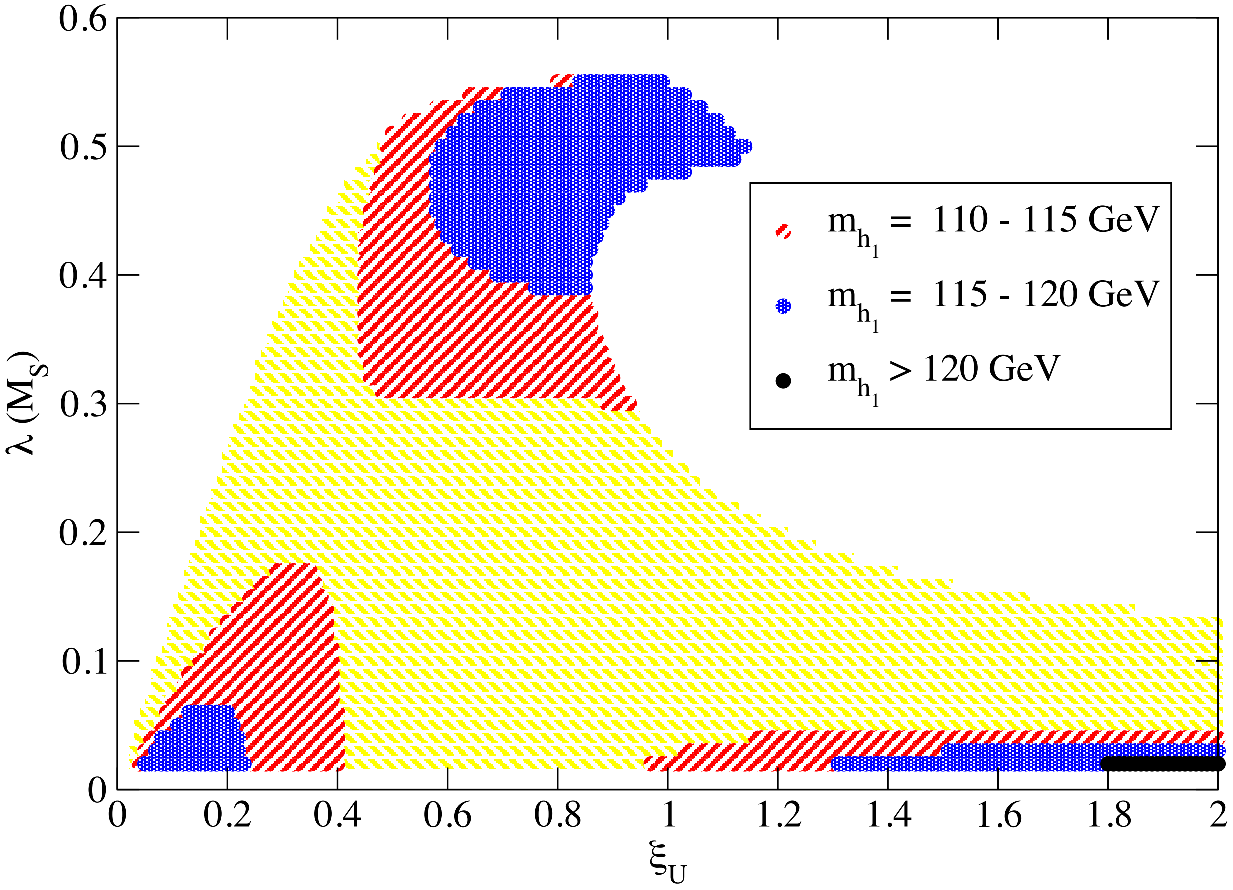
flavor universality among the sfermion masses

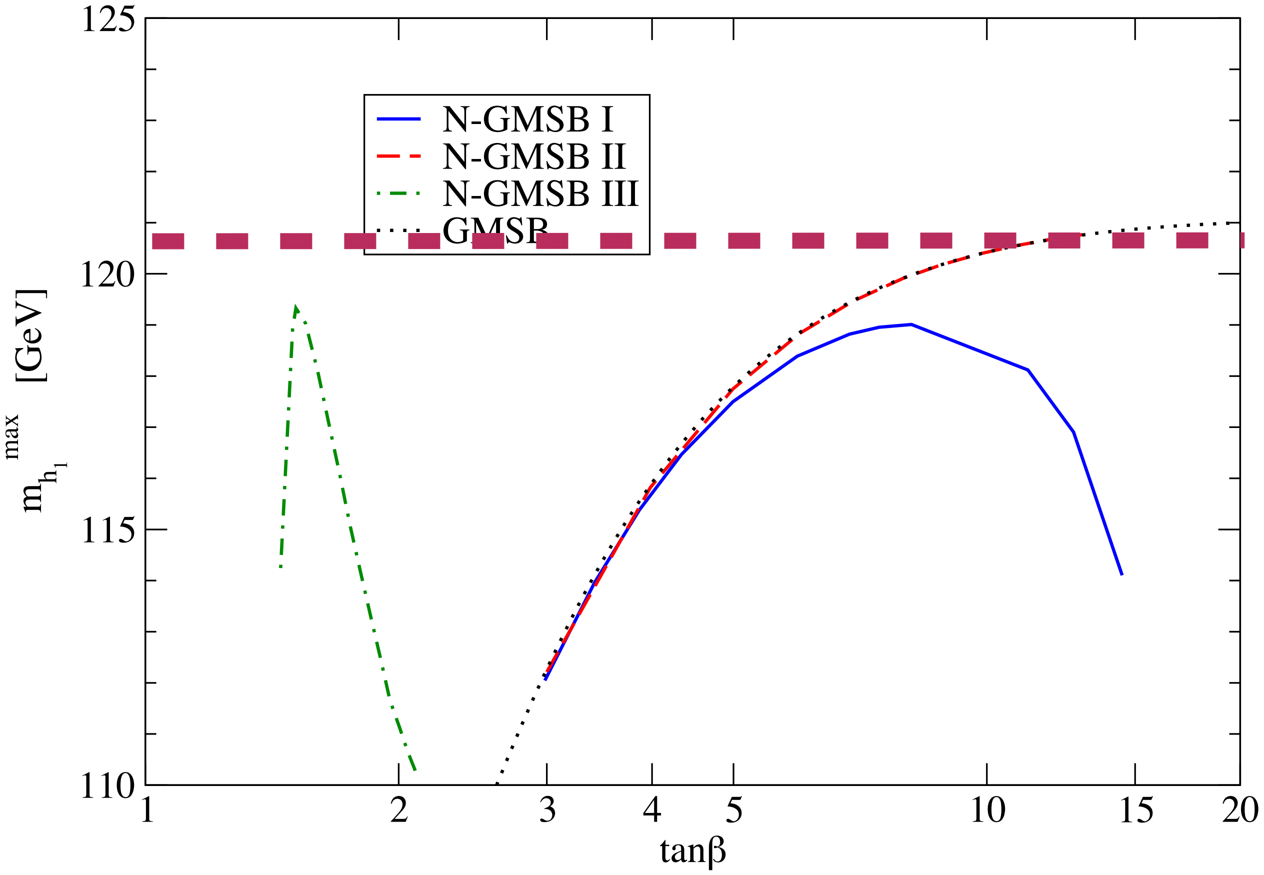
small A terms

gravitino LSP

sum rules Tr Ym^2=0, Tr (B-L)m^2=0

Delgado Giudice Slavich 0706.3873





120 GeV is the upper bound of the Higgs mass in gauge mediation

(for stop mass 2 TeV)

Yukawa assisted gauge mediation

Chacko Ponton, hep-ph/0112190

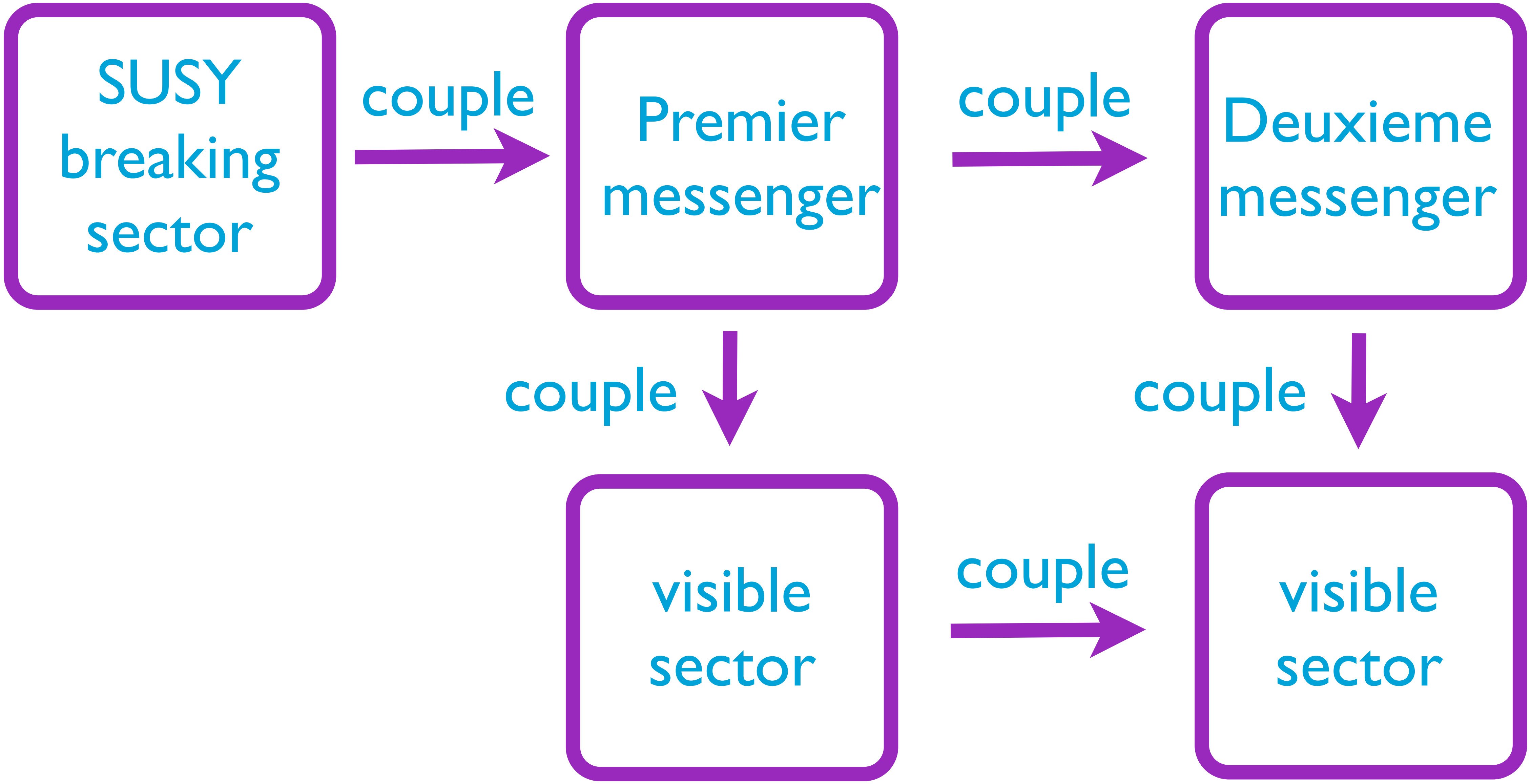
mass mixing between Higgs and messenger

induces matter-matter-messenger coupling from matter-matter-Higgs Yukawa coupling

$$W = y_{ij} Q_i H_u u_j^c \rightarrow W = y'_{ij} Q_i \Phi u_j^c$$

$$\frac{y'_{ij}}{y_{ij}} = \text{const}$$ independent of flavor indices

Schematic diagram for mediation



SUSY breaking sector

couple

Premier messenger

couple

Deuxieme messenger

couple

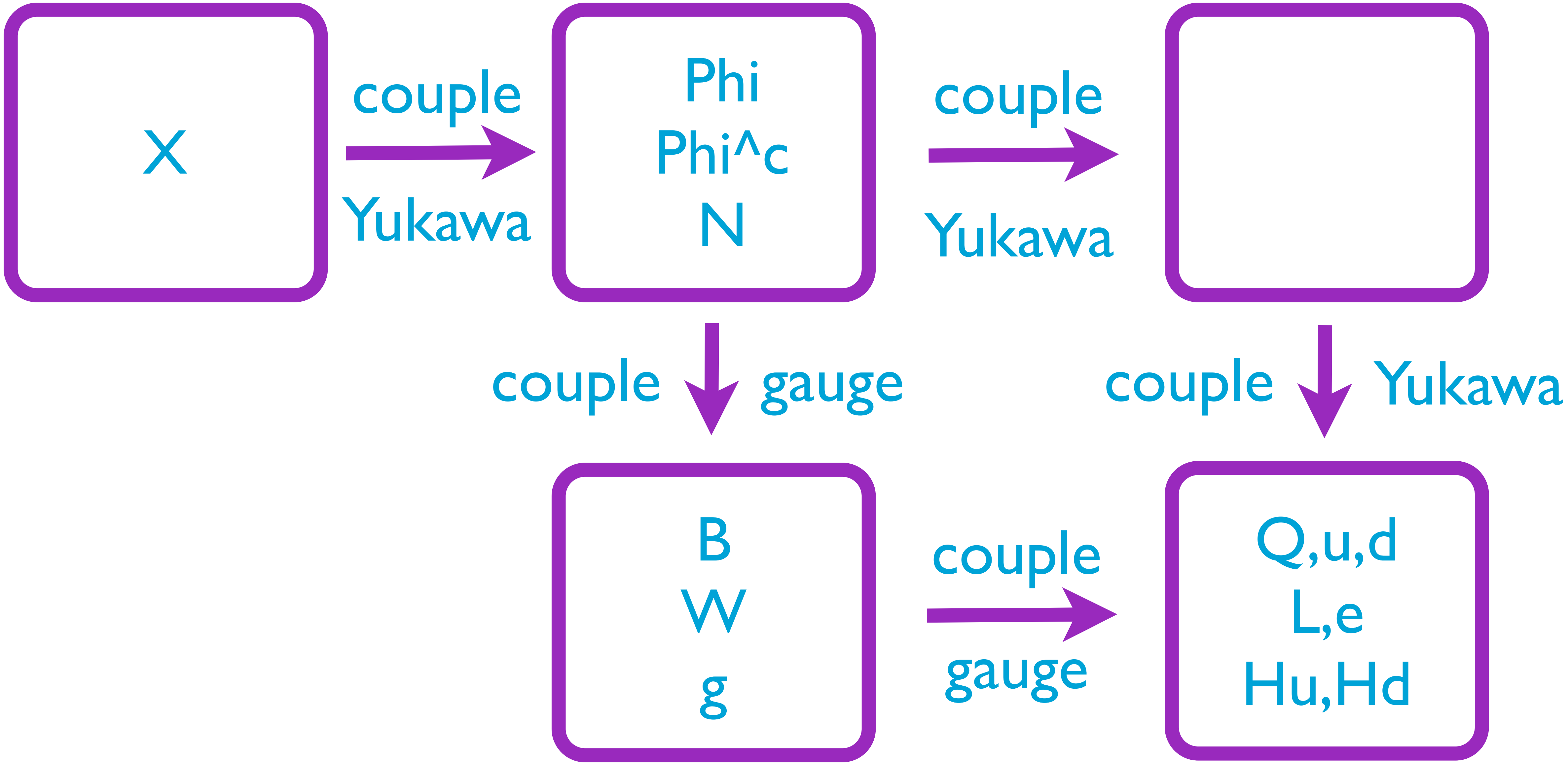
couple

visible sector

couple

visible sector

Minimal/general gauge mediation



X

couple

Yukawa

Phi
Phi^c
N

couple

Yukawa

couple

gauge

couple

Yukawa

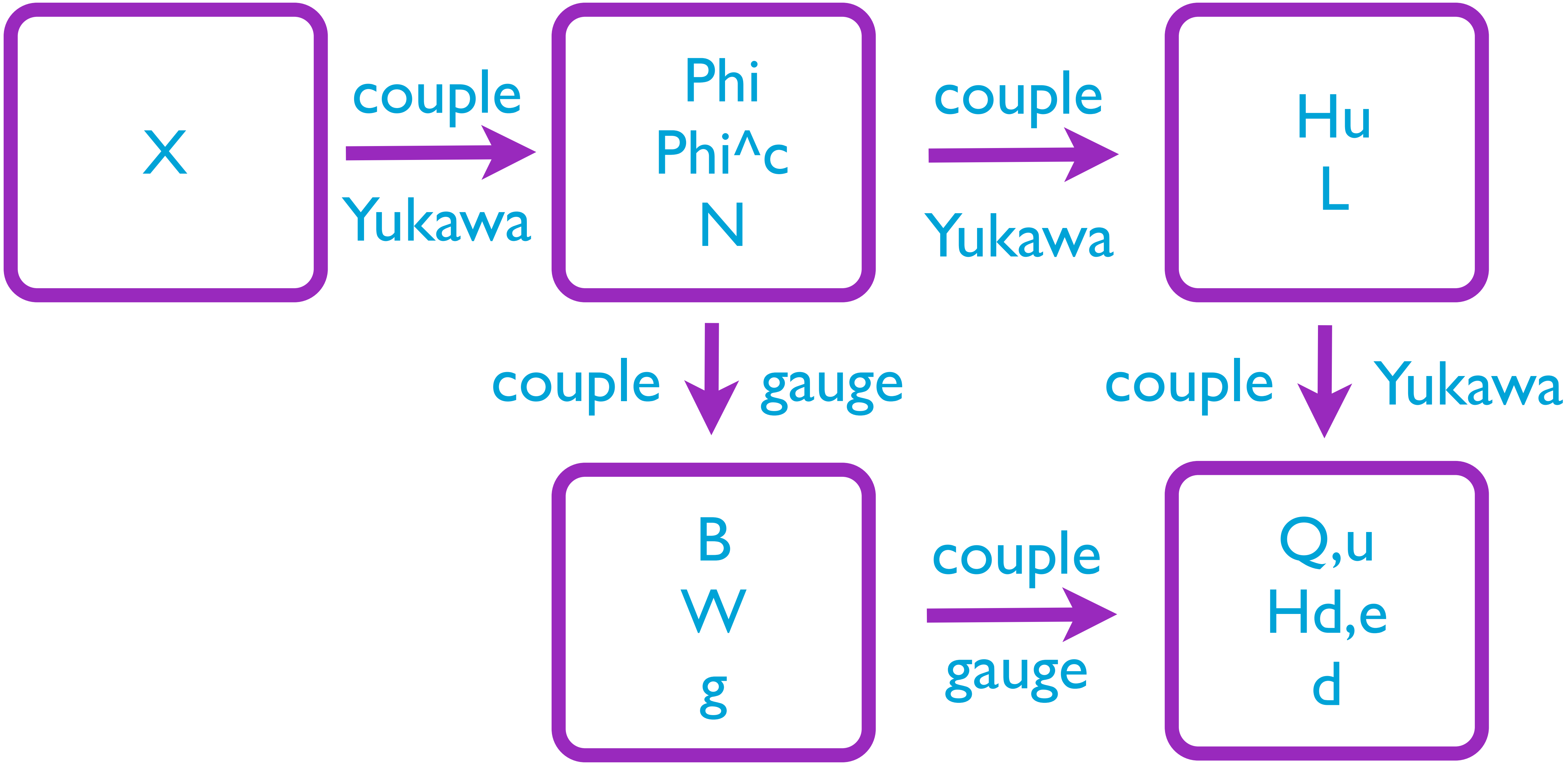
B
W
g

couple

gauge

Q,u,d
L,e
Hu,Hd

Neutrino assisted gauge mediation



X

couple

Yukawa

Phi
Phi^c
N

couple

Yukawa

Hu
L

couple

gauge

couple

Yukawa

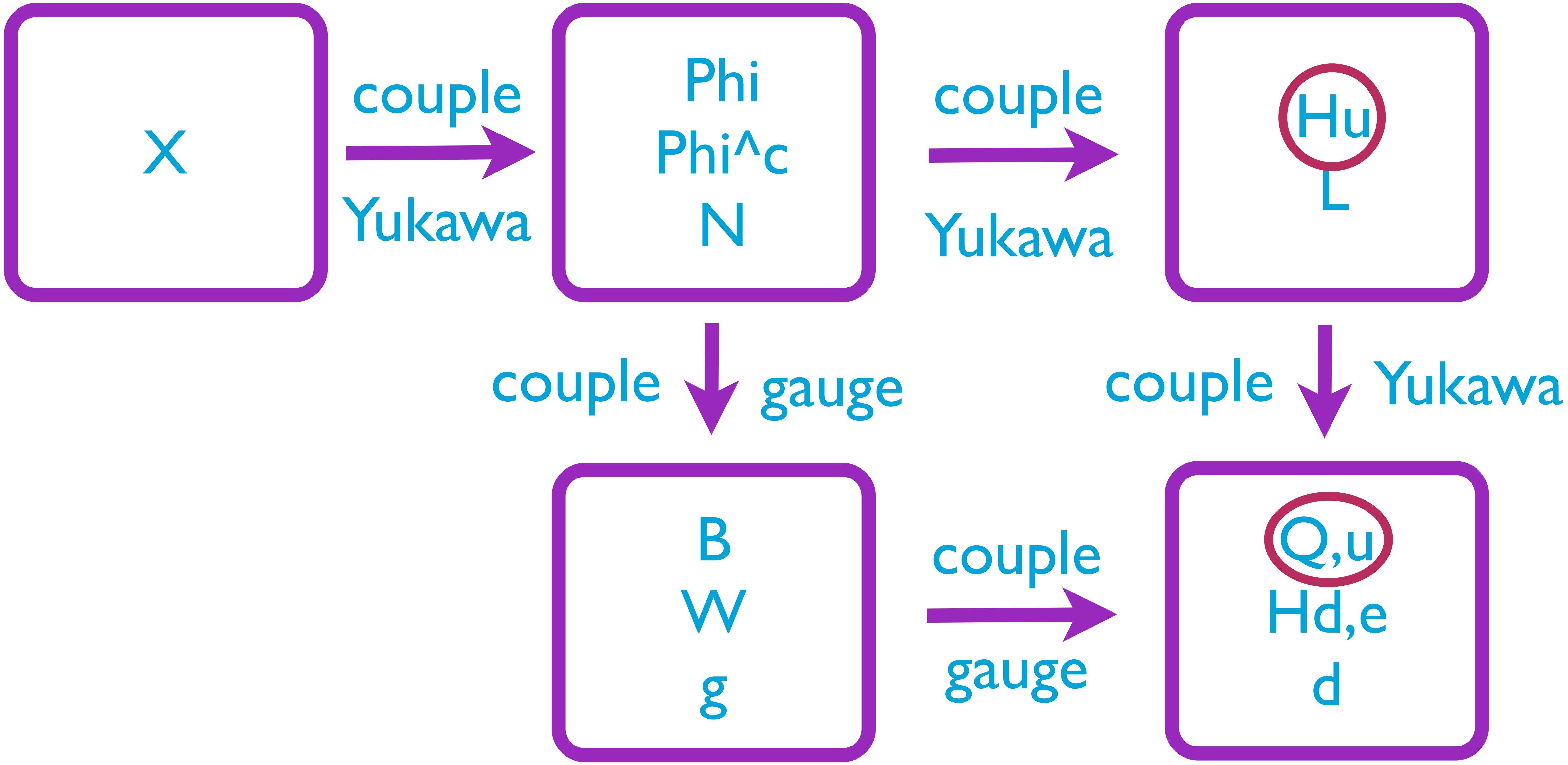
B
W
g

couple

gauge

Q,u
Hd,e
d

Neutrino assisted gauge mediation



X

couple → Yukawa

Phi
Phi^c
N

couple → Yukawa

Hu
L

couple ↓ gauge

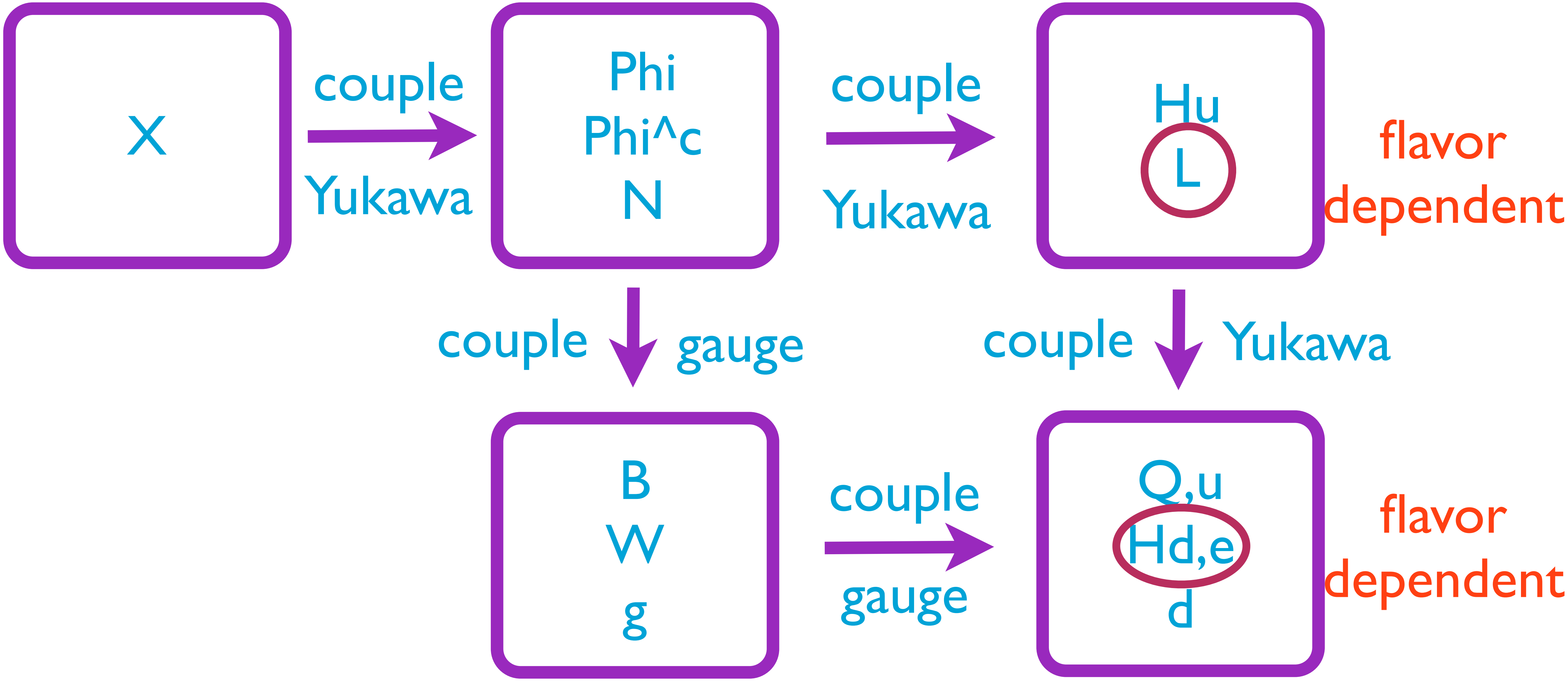
B
W
g

couple ↓ Yukawa

couple → gauge

Q,u
Hd,e
d

Neutrino assisted gauge mediation



X

couple

Yukawa

Phi

Phi^c

N

couple

Yukawa

Hu

L

flavor dependent

couple

gauge

couple

Yukawa

B

W

g

couple

gauge

Q,u

Hd,e

d

flavor dependent

Neutrino assisted gauge mediation

1211.6479 HD Kim DY Mo M Seo

$$\begin{aligned} W &= \lambda X \Phi \Phi^c \\ &+ \lambda' X N N \\ &+ Y_\nu N L H_u \end{aligned}$$

RH neutrinos can be messengers $M_N \sim 5 \times 10^{14}\ \mathrm{GeV}$

$$M_N = \lambda' \langle X \rangle$$

$$M_N \rightarrow (1 + \theta^2 B_N) M_N$$

$$B_N = F_X / X$$

analytic continuation in superspace works

Analytic continuation into superspace

$$A_i(\mu) = \left.\frac{\partial \ln Z_{Q_i}(X, X^\dagger, \mu)}{\partial \ln X}\right|_{X=M} \frac{F}{M}$$

1 loop :change of anomalous dimension at M

$$A_{abc}\Big|_{\mu=M} = \frac{1}{2}\left(\lambda_{a'bc}\Delta\gamma^{a'}{}_{a} + \lambda_{ab'c}\Delta\gamma^{b'}{}_{b} + \lambda_{abc'}\Delta\gamma^{c'}{}_{c}\right)\Big|_{\mu=M}\frac{F}{M}$$

$$\tilde{m}_Q^2(\mu) = -\left.\frac{\partial^2 \ln Z_Q(X, X^\dagger, \mu)}{\partial \ln X\ \partial \ln X^\dagger}\right|_{X=M} \frac{FF^\dagger}{MM^\dagger}$$

2 loop :change of anomalous dimension at M

$$m^2_{\tilde{Q}}\Big|_{\mu=M} = -\frac{1}{4}\left\{\sum_\lambda\left(\frac{d\Delta\gamma}{d\lambda}\beta_>[\lambda] - \frac{d\gamma_<}{d\lambda}\Delta\beta[\lambda]\right) + [\gamma_>, \gamma_<]\right\}\Big|_{\mu=M}\frac{FF^\dagger}{MM^\dagger}$$

Giudice Paradish Strumia 1003.2388

$$\delta Z_L = \frac{Y_\nu^{R\dagger}}{16\pi^2}\left(1 - \ln\frac{M^{R\dagger}M^R}{\Lambda^2}\right)Y_\nu^R, \qquad \delta Z_{H_u} = \mathrm{Tr}\delta Z_L$$

$$\lambda_N^R = [Z_N^{-1/2}]^T \lambda_N Z_L^{-1/2} Z_{H_u}^{-1/2}, \qquad M^R = [Z_N^{-1/2}]^T M_N Z_N^{-1/2},$$

$$L \to (1 - \frac{\delta Z_L|_0}{2})(1 - \theta^2 \delta Z_L|_{\theta^2})L$$

$$H_u \to (1 - \frac{\delta Z_{H_u}|_0}{2})(1 - \theta^2 \delta Z_{H_u}|_{\theta^2})H_u,$$

$$\Phi^\dagger(1 + \delta Z_\Phi)\Phi \to \Phi^\dagger(1 + \theta^2\bar\theta^2 \delta Z_\Phi|_{\theta^2\bar\theta^2})\Phi$$

$$A \propto \frac{y^2}{16\pi^2} \frac{F}{M}$$

deuxieme messengers

$$\delta m^2 \propto (y^4 - g^2 y^2) | \frac{F}{16\pi^2 M} |^2$$

visible fields

$$\delta m^2 \propto -y^4 | \frac{F}{16\pi^2 M} |^2$$

1 loop : A term is generated for Hu and L

$$\delta A_E = -\delta Z_L|_{\theta^2}, \quad \delta A_U = -\mathbb{I}\delta Z_{H_u}|_{\theta^2},$$

$$\delta A_D = 0, \quad \delta B = -\delta Z_{H_u}|_{\theta^2}.$$

$$A_E = \frac{B_N}{16\pi^2} Y_\nu^\dagger Y_\nu \longleftarrow$$

PMNS if
RH neutrino mass diagonal
charged lepton Yukawa diagonal

$$A_U = \quad \mathrm{Tr} A_E \times \mathbb{I}_{3\times 3}$$

$$B = \mathrm{Tr} A_E.$$

2 loop :   soft scalar mass for L, Hu and (L) Hd, e, (Hu), Q, u

$$\delta m_L^2 = \frac{B_N^2}{(4\pi)^4}\left[\left(\mathrm{Tr}[Y_\nu Y_\nu^\dagger] + 3\mathrm{Tr}[Y_U Y_U^\dagger] - 3g_2^2 - \frac{1}{5}g_1^2\right)Y_\nu^\dagger Y_\nu + 3Y_\nu^\dagger Y_\nu Y_\nu^\dagger Y_\nu\right]$$

$$\delta m_{H_u}^2 = \frac{B_N^2}{(4\pi)^4}\left[4\mathrm{Tr}[Y_\nu Y_\nu^\dagger Y_\nu^\dagger Y_\nu] - \left(3g_2^2 + \frac{1}{5}g_1^2\right)\mathrm{Tr}[Y_\nu Y_\nu^\dagger]\right].$$

$$\delta m_Q^2 = -\frac{B_N^2}{(4\pi)^4}\mathrm{Tr}[Y_\nu Y_\nu^\dagger]Y_U^\dagger Y_U$$

$$\delta m_U^2 = -\frac{B_N^2}{(4\pi)^4}\mathrm{Tr}[Y_\nu Y_\nu^\dagger]Y_U Y_U^\dagger$$

$$\delta m_E^2 = -\frac{B_N^2}{(4\pi)^4}Y_E Y_\nu^\dagger Y_\nu Y_E^\dagger$$

the origin of flavor violation

$$\delta m_{H_d}^2 = -\frac{B_N^2}{(4\pi)^4}\mathrm{Tr}[Y_E Y_\nu^\dagger Y_\nu Y_E^\dagger].$$

2 loop : soft scalar mass for L, Hu and (L) Hd, e, (Hu), Q, u

$$\delta m_L^2 = \frac{B_N^2}{(4\pi)^4}\left[\left(\mathrm{Tr}[Y_\nu Y_\nu^\dagger] + 3\mathrm{Tr}[Y_U Y_U^\dagger] - 3g_2^2 - \frac{1}{5}g_1^2\right)Y_\nu^\dagger Y_\nu + 3Y_\nu^\dagger Y_\nu Y_\nu^\dagger Y_\nu\right]$$

$$\delta m_{H_u}^2 = \frac{B_N^2}{(4\pi)^4}\left[4\mathrm{Tr}[Y_\nu Y_\nu^\dagger Y_\nu^\dagger Y_\nu] - \left(3g_2^2 + \frac{1}{5}g_1^2\right)\mathrm{Tr}[Y_\nu Y_\nu^\dagger]\right].$$

$$\delta m_Q^2 = -\frac{B_N^2}{(4\pi)^4}\mathrm{Tr}[Y_\nu Y_\nu^\dagger]Y_U^\dagger Y_U$$

$$\delta m_U^2 = -\frac{B_N^2}{(4\pi)^4}\mathrm{Tr}[Y_\nu Y_\nu^\dagger]Y_U Y_U^\dagger$$

the seed for maximal stop mixing

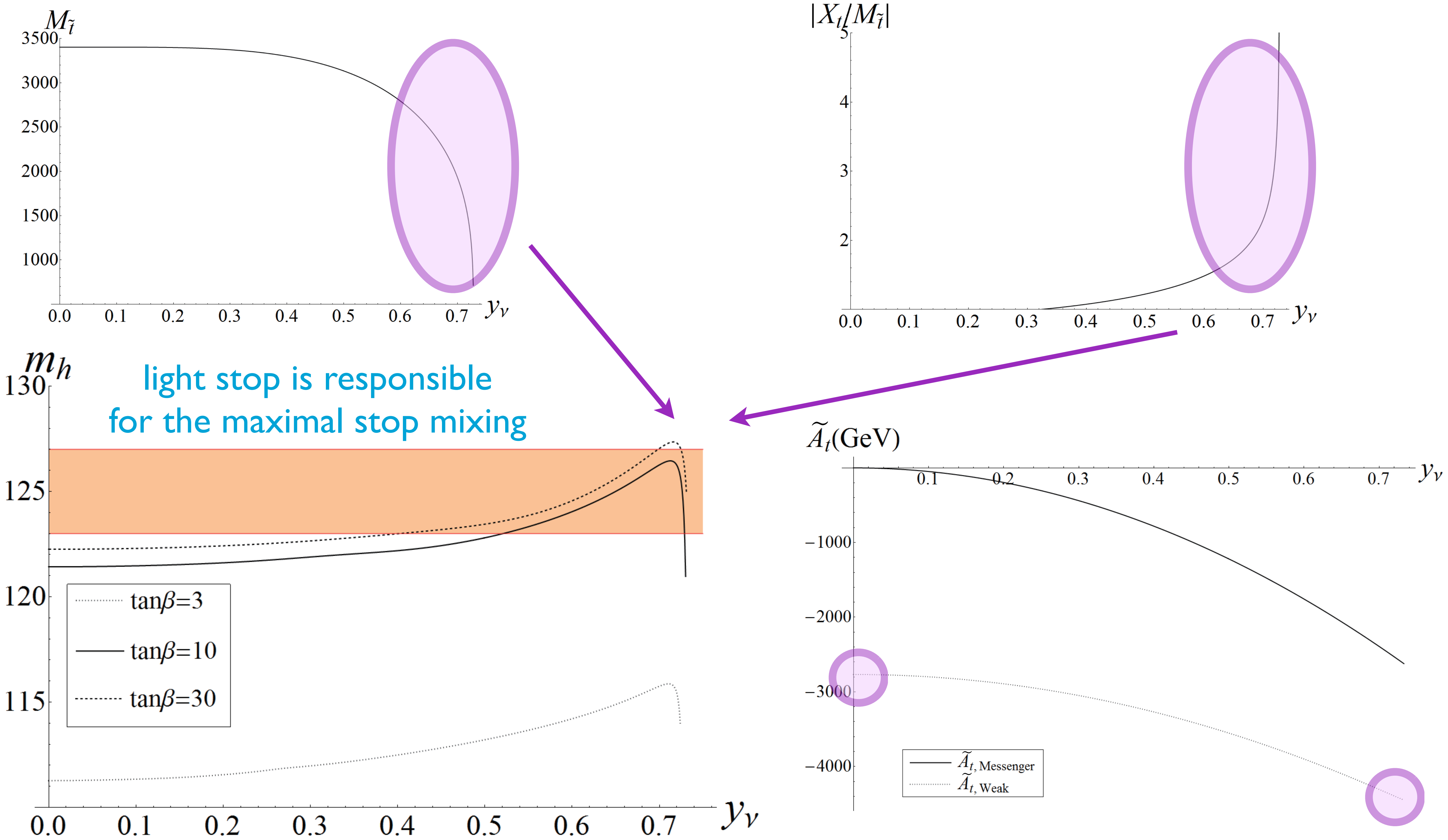
$$\delta m_E^2 = -\frac{B_N^2}{(4\pi)^4}Y_E Y_\nu^\dagger Y_\nu Y_E^\dagger$$

$$\delta m_{H_d}^2 = -\frac{B_N^2}{(4\pi)^4}\mathrm{Tr}[Y_E Y_\nu^\dagger Y_\nu Y_E^\dagger].$$

the origin of flavor violation

Neutrino assisted gauge mediation

B=500 TeV

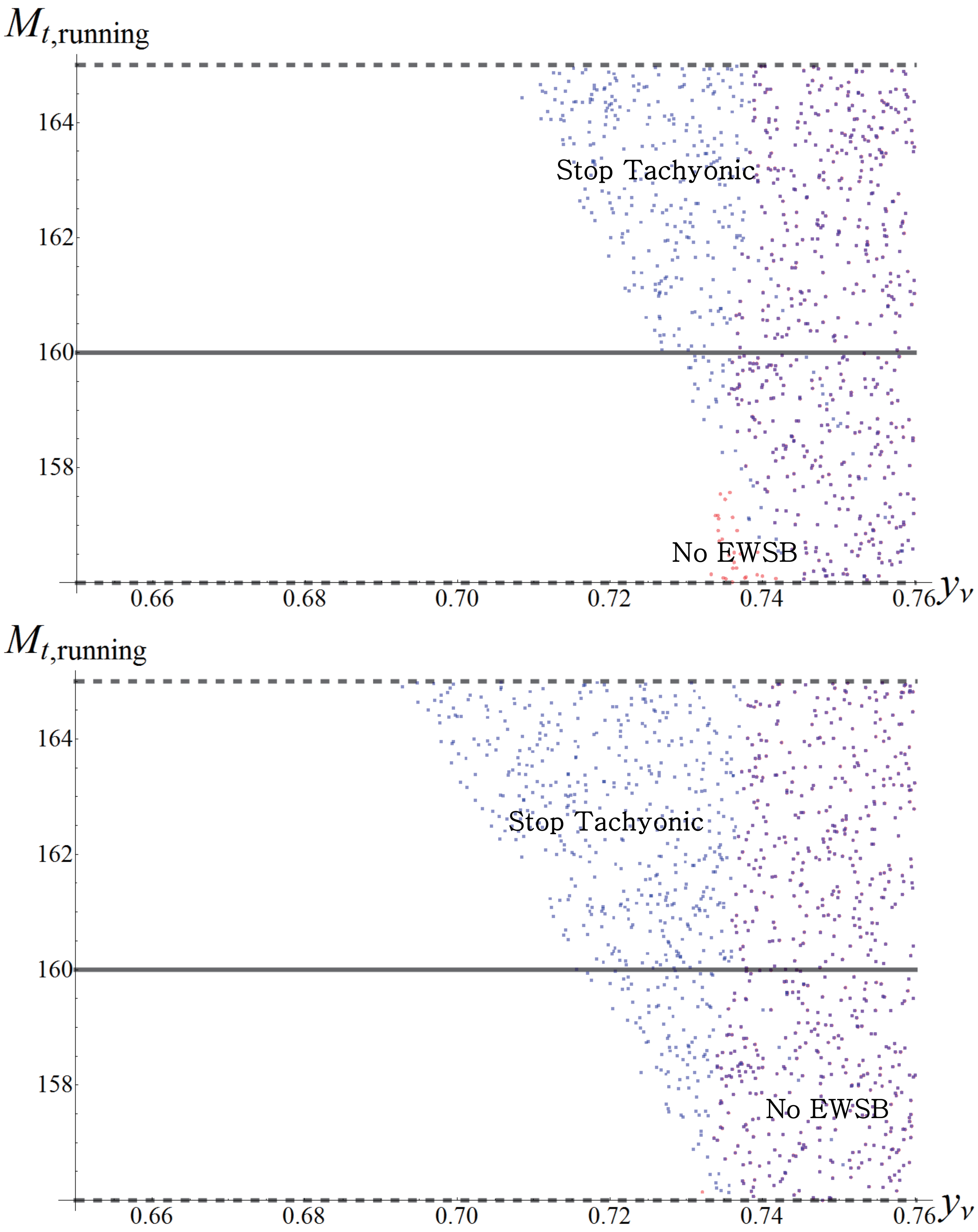


light stop is responsible
for the maximal stop mixing

Two critical problems for the large Yukawa

Tachyonic stop at EW scale

No EWSB due to large mHu



Charged lepton flavor violation

$$Y_E = \lambda_E \frac{1}{\sqrt{3}} \begin{pmatrix} c & c & c \\ a & a\omega & a\omega^2 \\ b & b\omega^2 & b\omega \end{pmatrix} \longrightarrow V_L^l = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & \omega^2 & \omega \\ 1 & \omega & \omega^2 \end{pmatrix}$$

$$W = -l_{1ij} \bar{E}_i \Phi L_j H_d + l_{2ij} N_i L_j H_u + \frac{1}{2} l_{3ij} X N_i \chi N_j ,$$

$$Y_\nu \propto (1, 1, 1)$$

Superfield	S_4	Z_4	$\mathrm{U}(1)_L$	$\mathrm{U}(1)_R$
L	$\mathbf{3}$	1	1	1
$\bar{E}$	$\mathbf{2}+\mathbf{1}$	2	-1	0
N	$\mathbf{3}$	3	-1	0
Φ	$\mathbf{3}+\mathbf{3}'$	1	0	0
χ	$\mathbf{1}+\mathbf{2}+\mathbf{3}$	2	2	0
H_u	$\mathbf{1}$	0	0	1
H_d	$\mathbf{1}$	0	0	1
X	$\mathbf{1}$	0	0	2

$$M_N = \begin{pmatrix} w_1 & 0 & w_2 \\ 0 & w_1 & 0 \\ w_2 & 0 & w_1 \end{pmatrix} \longrightarrow V_L^\nu = \begin{pmatrix} \frac{1}{\sqrt{2}} & 0 & -\frac{1}{\sqrt{2}} \\ 0 & 1 & 0 \\ \frac{1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$$M_\nu = -v_u^2 Y_\nu^T M_N^{-1} Y_\nu$$

$$V_{\mathrm{PMNS}} \equiv (V_L^l)^\dagger V_L^\nu = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\omega \frac{1}{\sqrt{6}} & \omega \frac{1}{\sqrt{3}} & e^{-i5\pi/6} \frac{1}{\sqrt{2}} \\ -\omega^2 \frac{1}{\sqrt{6}} & \omega^2 \frac{1}{\sqrt{3}} & e^{i5\pi/6} \frac{1}{\sqrt{2}} \end{pmatrix}$$

tri-bimaximal PMNS

Nonzero theta13 from two sources

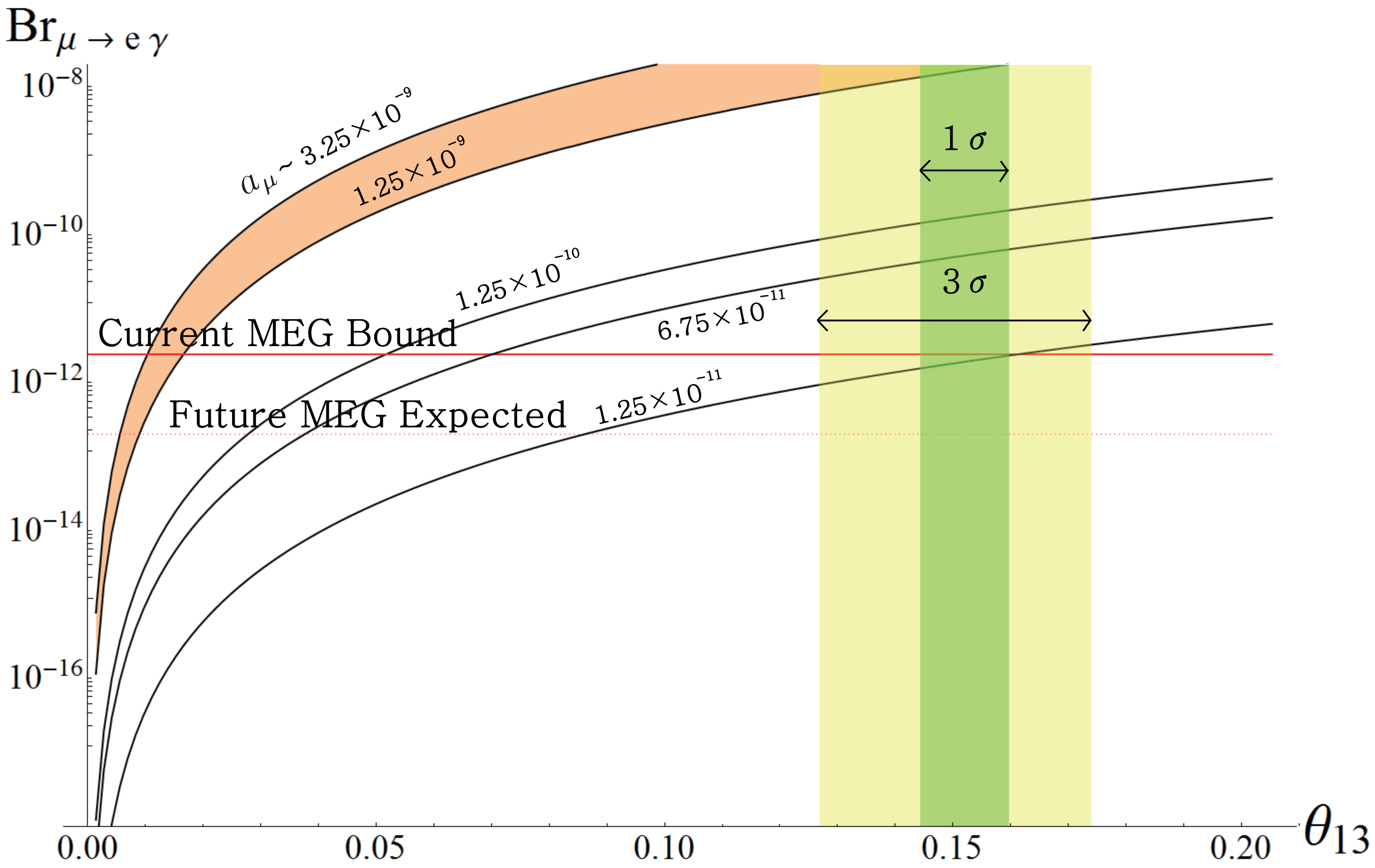
$$Y_\nu = y_\nu \begin{pmatrix} 1+2i\rho & 0 & 0 \\ 0 & 1-i\rho & 0 \\ 0 & 0 & 1-i\rho \end{pmatrix}$$

LFV

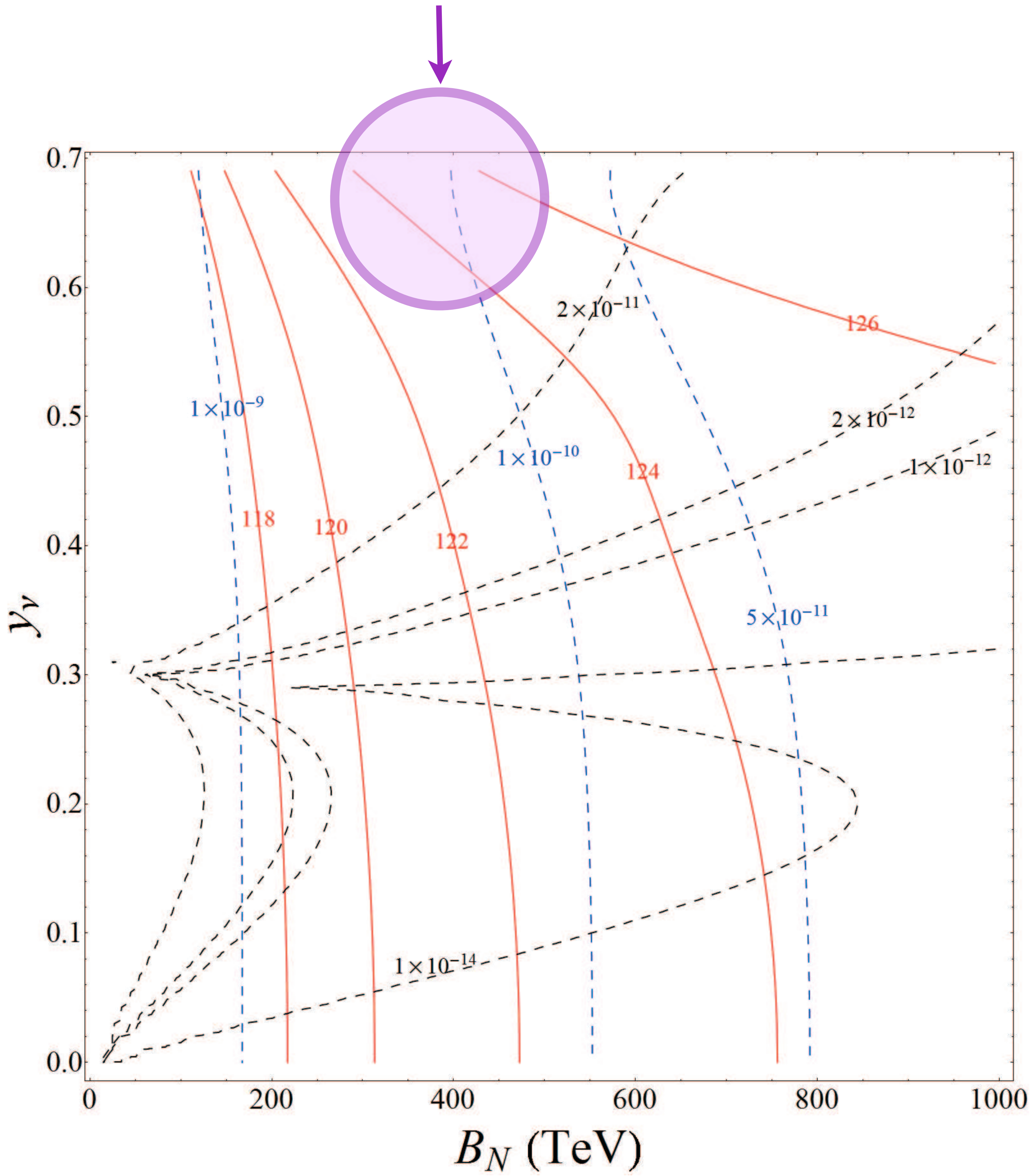
$$M_N = \begin{pmatrix} w_1 & 0 & w_2 \\ 0 & w_1 & 0 \\ w_2 & 0 & w_1(1-\zeta) \end{pmatrix} .$$

no LFV

$$(\delta m_L^2)_{12} \propto \left[3(1+2\rho^2)y_\nu^2 + 3y_t^2 - 3g_2^2 - \frac{1}{5}g_1^2\right]y_\nu^2\rho^2 + 3y_\nu^4 2\rho^2$$



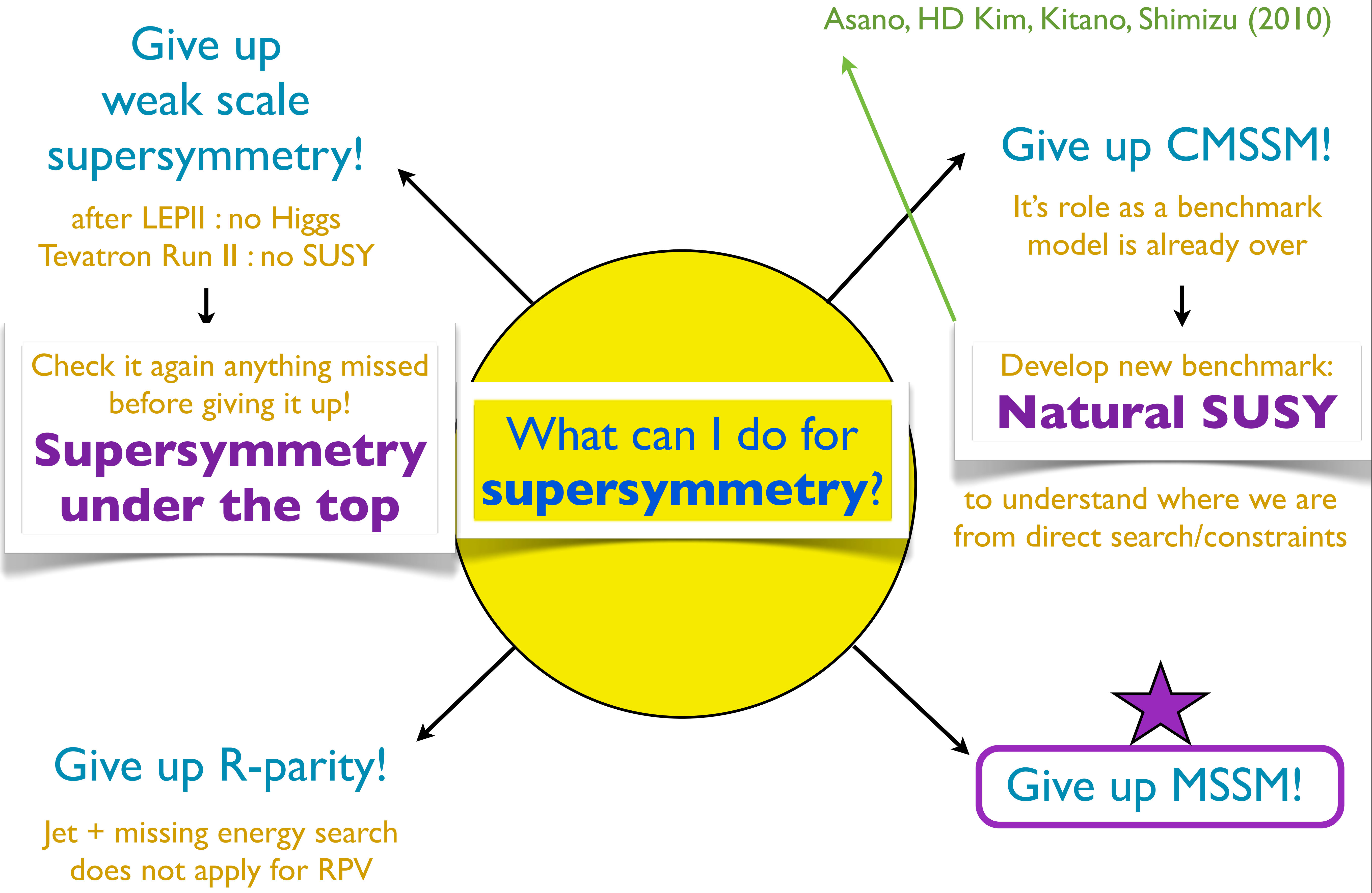
Interesting parameter space



Red : Higgs mass (GeV)

Blue : muon g-2

Black : $\mathrm{Br}(\mu \to e\gamma)$



What can I do for **supersymmetry?**

Give up weak scale supersymmetry!

after LEPII : no Higgs
Tevatron Run II : no SUSY

↓

Check it again anything missed before giving it up!

Supersymmetry under the top

Give up CMSSM!

It's role as a benchmark model is already over

↓

Develop new benchmark:

Natural SUSY

to understand where we are from direct search/constraints

Asano, HD Kim, Kitano, Shimizu (2010)

Give up R-parity!

Jet + missing energy search does not apply for RPV

★

Give up MSSM!

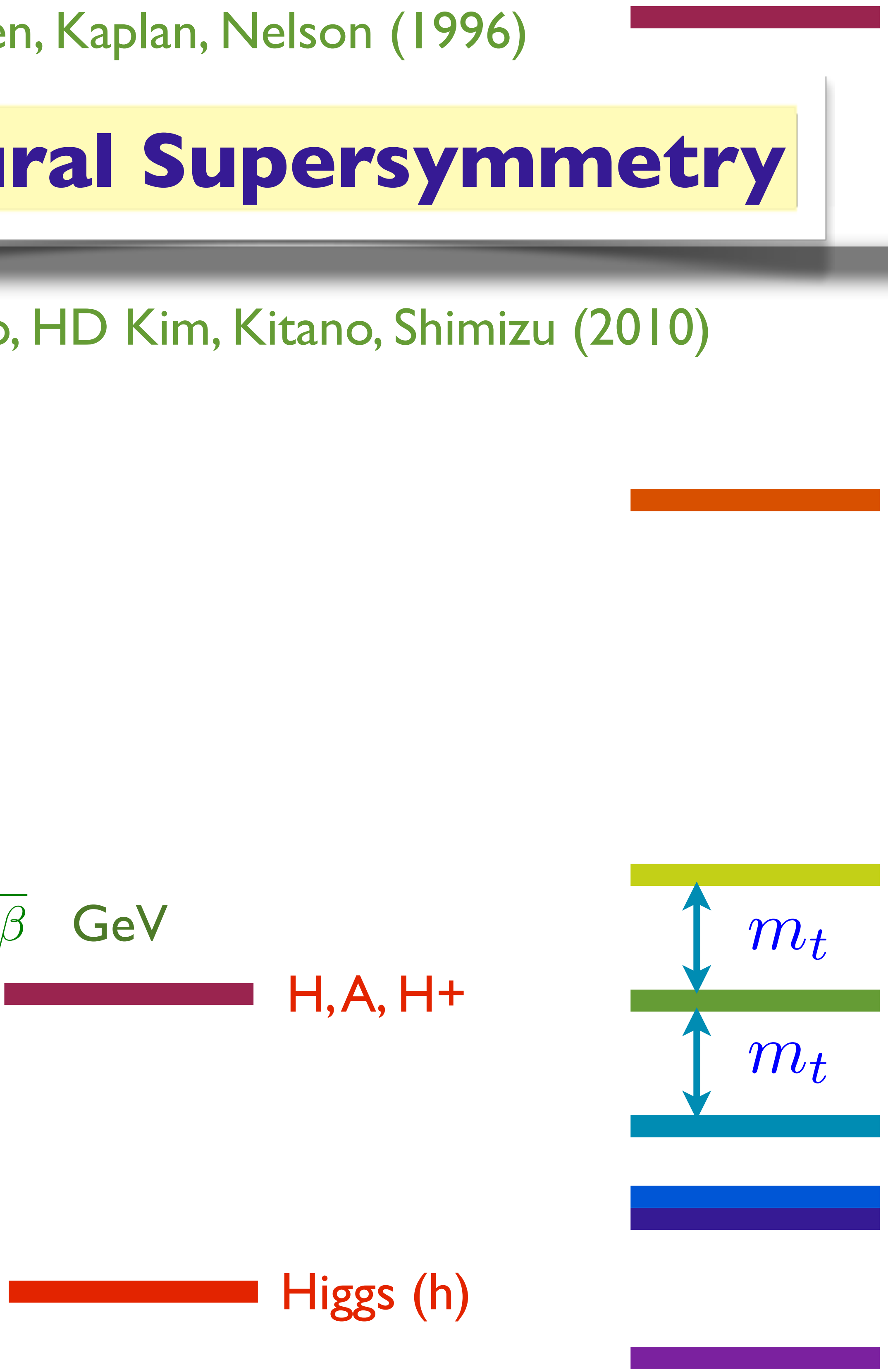
Natural Supersymmetry

Dimopoulos, Giudice (1995)

Cohen, Kaplan, Nelson (1996)

Asano, HD Kim, Kitano, Shimizu (2010)

fine tuning ~ 10%



bino, wino,
1&2nd squarks & sleptons,
stau, tau sneutrino — > 2 TeV

gluino — < 1.1 TeV

stop' — < 550 GeV

m_t

sbottom

m_t

stop — < 200 GeV

chargino/neutralino — < 300 GeV

goldstino — > eV

< 200*$\sqrt{\tan\beta}$ GeV — H, A, H+

< 120 GeV — Higgs (h)

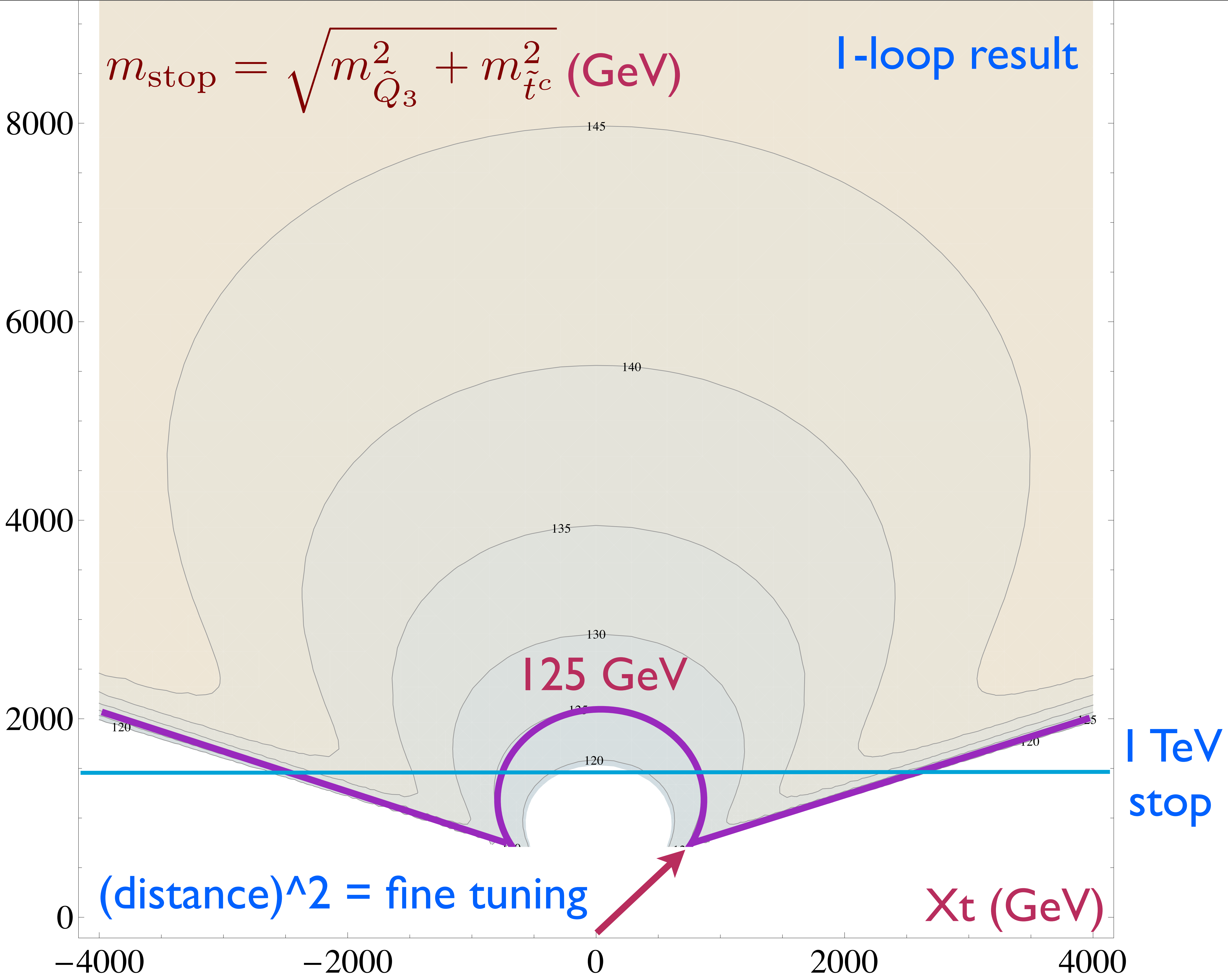
Fine tuning

$-\delta m_H^2$ = $\dfrac{3y_t^2}{8\pi^2} R^2 \log(M/m_{\text{soft}})$ vs $\dfrac{m_h^2}{2}$ = $\dfrac{(125\ \text{GeV})^2}{2}$ ~ M_Z^2

where $R^2 = m_{\tilde{Q}3}^2 + m_{\tilde{t}^c}^2 + |A_t|^2$

4% fine tuning in the MSSM : $\dfrac{1}{5}\left(\dfrac{R}{M_Z}\right)^2$ ~ 25 for R = 1 TeV

$\log(M/m_{\text{soft}})$ ~ 5



$m_{\rm stop} = \sqrt{m^2_{\tilde{Q}_3} + m^2_{\tilde{t}^c}}$ (GeV)

1-loop result

125 GeV

1 TeV stop

(distance)^2 = fine tuning

Xt (GeV)

Mu problem in gauge mediation

Mu problem in supersymmetry

JE Kim HP Nilles (1984)

$$W = \mu H_u H_d$$

Why is the supersymmetric mass for the Higgs the same as other supersymmetry breaking parameters?

1) $\mu \neq M_{\rm Pl}$ Pecci-Quinn symmetry can forbid it

PQ charge : Q(Hu)=Q(Hd)=1

2) $\mu \sim M_{\rm soft}$ Giudice-Masiero mechanism works gravity mediation

$$K = \frac{X^\dagger}{M_{\rm Pl}} H_u H_d \longrightarrow W = m_{\rm soft} H_u H_d$$

$$K = H_u H_d \longrightarrow K = \frac{\phi^\dagger}{\phi} H_u H_d$$

When the mediation scale is different from Planck scale,
Bmu in general causes a big problem.

Gauge mediation is of typical example.
(The problem is common in anomaly mediation,
gaugino mediation, mirage mediation, etc.)

Natural mu & Bmu in Gauge Mediation

G. Giudice, H. D. Kim and R. Rattazzi, PLB(2008)

G. Giudice, H. D. Kim and R. Rattazzi, PLB(2008)

New proposal for mu/Bmu problem

$$K = H_u H_d[f(X) + g(X^\dagger) + D^2 h(X, X^\dagger)] + \text{h.c.}$$

$$\to W = H_u H_d[\bar{D}^2 g(X^\dagger) + \bar{D}^2 D^2 h(X, X^\dagger)]$$

$$\to V = D^2 W = 0$$

No Bmu is generated at one loop

$g(X^\dagger)$ anti-holomorphic vs $D^2 h(X, X^\dagger)$ supercovariant derivative

G. Giudice, H. D. Kim and R. Rattazzi, PLB(2008)

Effective potential in supersymmetry (Grisaru formula; supersymmetric Coleman-Weinberg potential)

$$K = -\frac{1}{16\pi^2}\int d^4\theta \mathcal{M}^\dagger \mathcal{M} \log \frac{\mathcal{M}^\dagger \mathcal{M}}{\Lambda^2}$$

after integrating out messengers with mass

$$W = \bar{\Phi}\mathcal{M}\Phi$$

$$\mathcal{M} = \left(\begin{array}{cc} X & S \\ 0 & X \end{array} \right)$$

The Model

G. Giudice, H. D. Kim and R. Rattazzi, PLB(2008)

$$W = N\left(H_uH_d + \frac{S^2}{2} - M_s^2\right)$$

$$+S\bar{\Phi}_1\Phi_2 + X(\bar{\Phi}_1\Phi_1 + \bar{\Phi}_2\Phi_2)$$

$$\langle X\rangle = M + \theta^2 F$$

$$M_Z \ll M_s \ll M$$

$H_uH_d \log X^\dagger$ is generated in Kahler potential at one loop.

μ problem is the biggest obstacle in supersymmetry

Unavoidable tuning between μ^2 and $m^2_{\rm soft}$

$$m_h^2 = -2m_H^2 = -2\mu^2 - 2m^2_{\rm soft}$$

Model building should start from mu problem.

Higgs as a pseudo-Goldstone boson in supersymmetry

arXiv:1208.3748, K Bae, TH Jung and HD Kim

pGB Higgs : toy example

$$K = H_u H_d \longrightarrow K = \frac{\phi^\dagger}{\phi} H_u H_d$$

$$m_H^2 = \begin{pmatrix} \mu^2 & B\mu \\ B\mu & \mu^2 \end{pmatrix} \qquad m_H^2 = F_\phi^2 \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$$

$$\mu = F_\phi$$

$$B\mu = F_\phi^2$$

$$m_h^2 = 0 \qquad \tan\beta = 1$$

pGB Higgs : toy example

$$K = \lambda H_u H_d \xrightarrow{\qquad\qquad} K = \lambda \frac{\phi^\dagger}{\phi} H_u H_d$$

$$m_H^2 = \begin{pmatrix} \mu^2 & B\mu \\ B\mu & \mu^2 \end{pmatrix} \qquad m_H^2 = F_\phi^2 \begin{pmatrix} \lambda^2 & \lambda \\ \lambda & \lambda^2 \end{pmatrix}$$

$$\mu = F_\phi$$

$$B\mu = F_\phi^2$$

$\lambda = 1$ is a fine tuning

For large mu, tan beta is close to 1.

It holds as long as soft scalar mass is small compared to mu.

Higgs as a pseudo-Goldstone boson

$$W = S(\lambda_1 H\bar{H} + \lambda_2 N\bar{N} + \lambda\Phi\bar{\Phi} - M_N^2)$$

$$+X\Phi\bar{\Phi}$$

Dvali Giudice Pomarol (1996)

S : SU(2) singlet

H : SU(2) doublet

N : SU(2) singlet

Phi : SU(5) doublet (messenger)

SU(3) global symmetry if $\lambda_1 = \lambda_2$

(H,N) : SU(3) triplet

M_N : Supersymmetric mass scale
~ f : spontaneous breaking of SU(3)

arXiv:1208.3748, K Bae, TH Jung and HD Kim

$$K = (X+S)^\dagger (X+S) \log (X+S)^\dagger (X+S)$$

$$\uparrow$$

$$X^\dagger S \log X^\dagger X$$

For the SUSY breaking spurion $X = M_N + \theta^2 F$

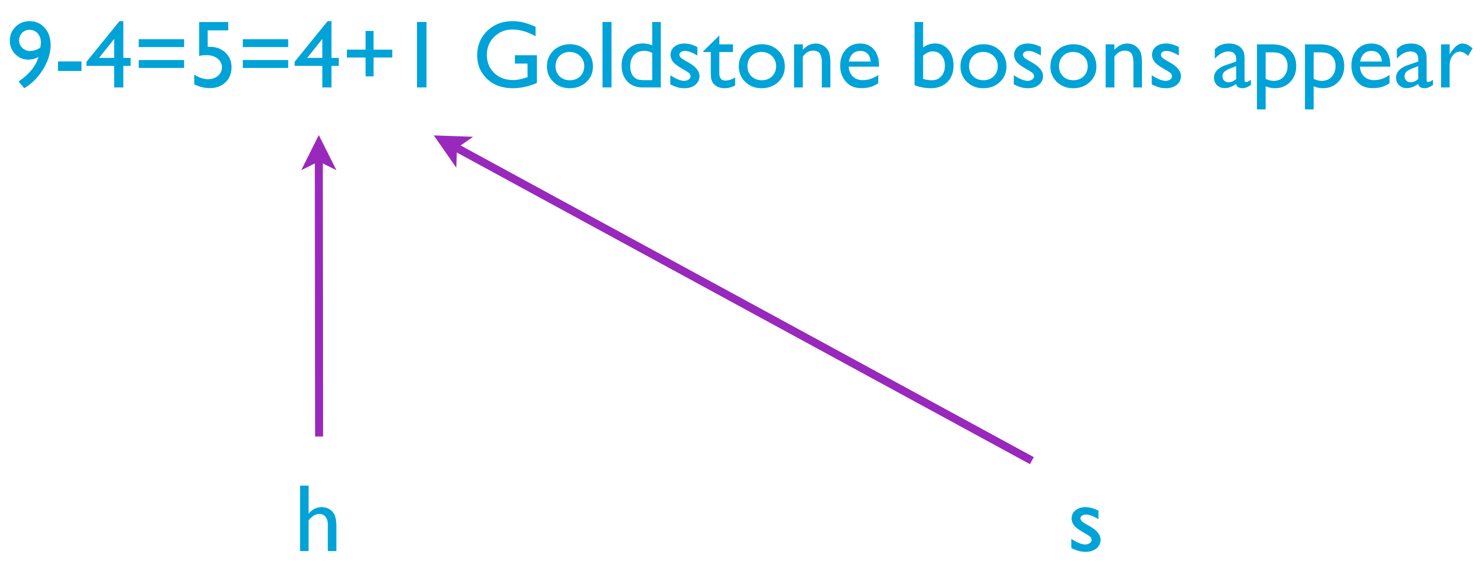
Tadpole for S is generated $V \simeq F M_N S$

With the supersymmetric mass $V \simeq M_N^2 |S|^2$

Mu term is generated $\langle S \rangle \simeq \frac{F}{M_N}$

Bmu appear at two loop $F_S \simeq (\frac{F}{M_N})^2$

arXiv:1208.3748, K Bae, TH Jung and HD Kim



9-4=5=4+1 Goldstone bosons appear

h

s

One SU(2) doublet Higgs + One singlet

One Higgs doublet remains massless

$$B\mu = \mu^2$$

tan beta =1

$$V(h) = 0.$$

Global SU(3) is explicitly broken
by top Yukawa and gauge couplings.

arXiv:1208.3748, K Bae, TH Jung and HD Kim

RG running from f to Mz determines the physical Higgs mass

$$V(h) = -c m_{\rm soft}^2 \log(\frac{m_{\rm susy}}{m_{\rm soft}})|h|^2 + \delta\lambda |h|^4 .$$

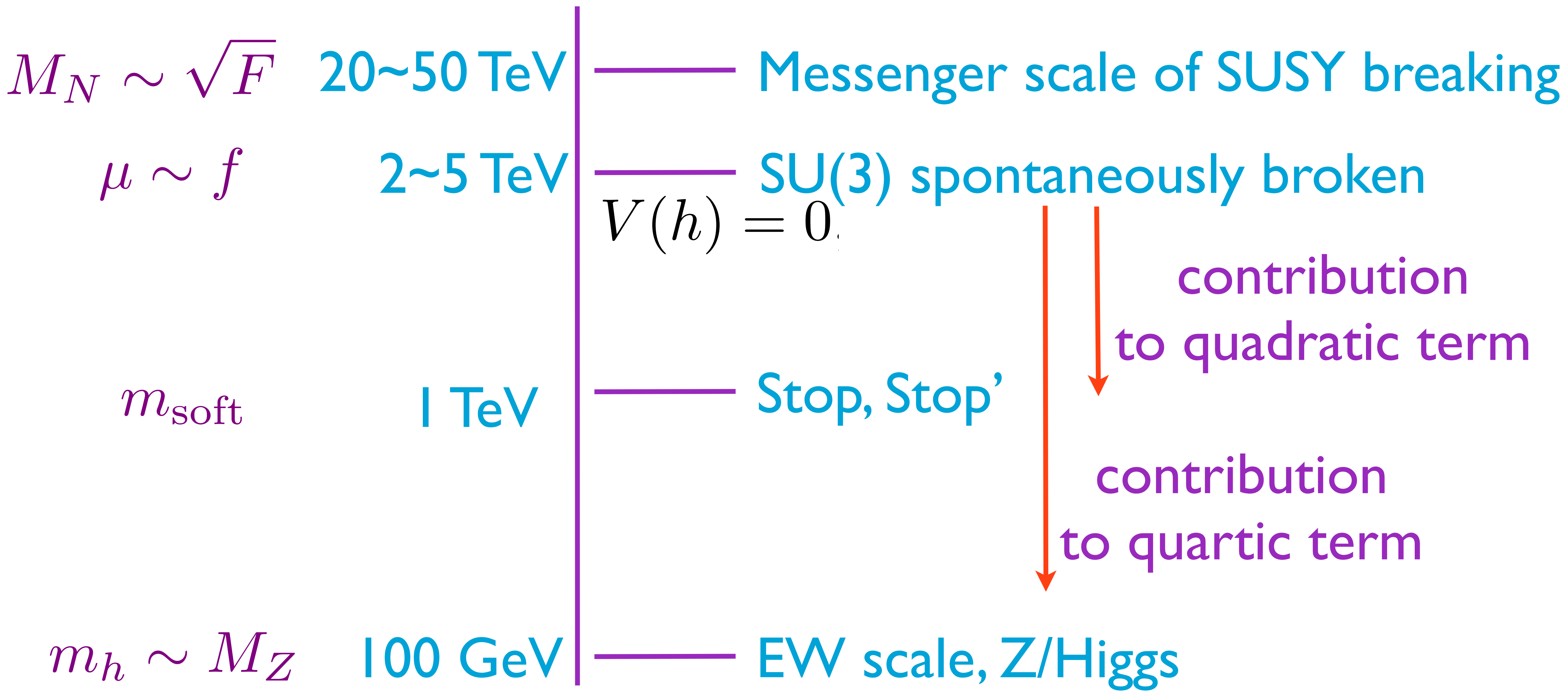
Now the electroweak scale is not tied to mu
and mu can be very large, e.g., 2 ~ 10 TeV.

We can get a help from stop mixing
without spoiling the quadratic term.

$$X_t = A_t - \mu / \tan\beta$$

Xt=mu can be very large

arXiv:1208.3748, K Bae, TH Jung and HD Kim



$M_N \sim \sqrt{F}$ 20~50 TeV — Messenger scale of SUSY breaking

$\mu \sim f$ 2~5 TeV — SU(3) spontaneously broken

$V(h) = 0$

contribution to quadratic term

m_{soft} 1 TeV — Stop, Stop'

contribution to quartic term

$m_h \sim M_Z$ 100 GeV — EW scale, Z/Higgs

T. Moroi Y. Okada (1992)

K. S. Babu et al (2004/2008)

S. Martin (2009)

P. Graham et al (2009)

Vector-like matters in supersymmetry

LND model

$$W = M_L L\bar{L} + M_N N\bar{N} + M_D D\bar{D} + k_N H_u L\bar{N} - h_N H_d \bar{L} N,$$

$$L = (\mathbf{1}, \mathbf{2}, -1/2), \qquad \bar{L} = (\mathbf{1}, \mathbf{2}, 1/2),$$

$$N = (\mathbf{1}, \mathbf{1}, 0), \qquad \bar{N} = (\mathbf{1}, \mathbf{1}, 0),$$

$$D = (\mathbf{3}, \mathbf{1}, -1/3), \qquad \bar{D} = (\bar{\mathbf{3}}, \mathbf{1}, 1/3).$$

QUE model

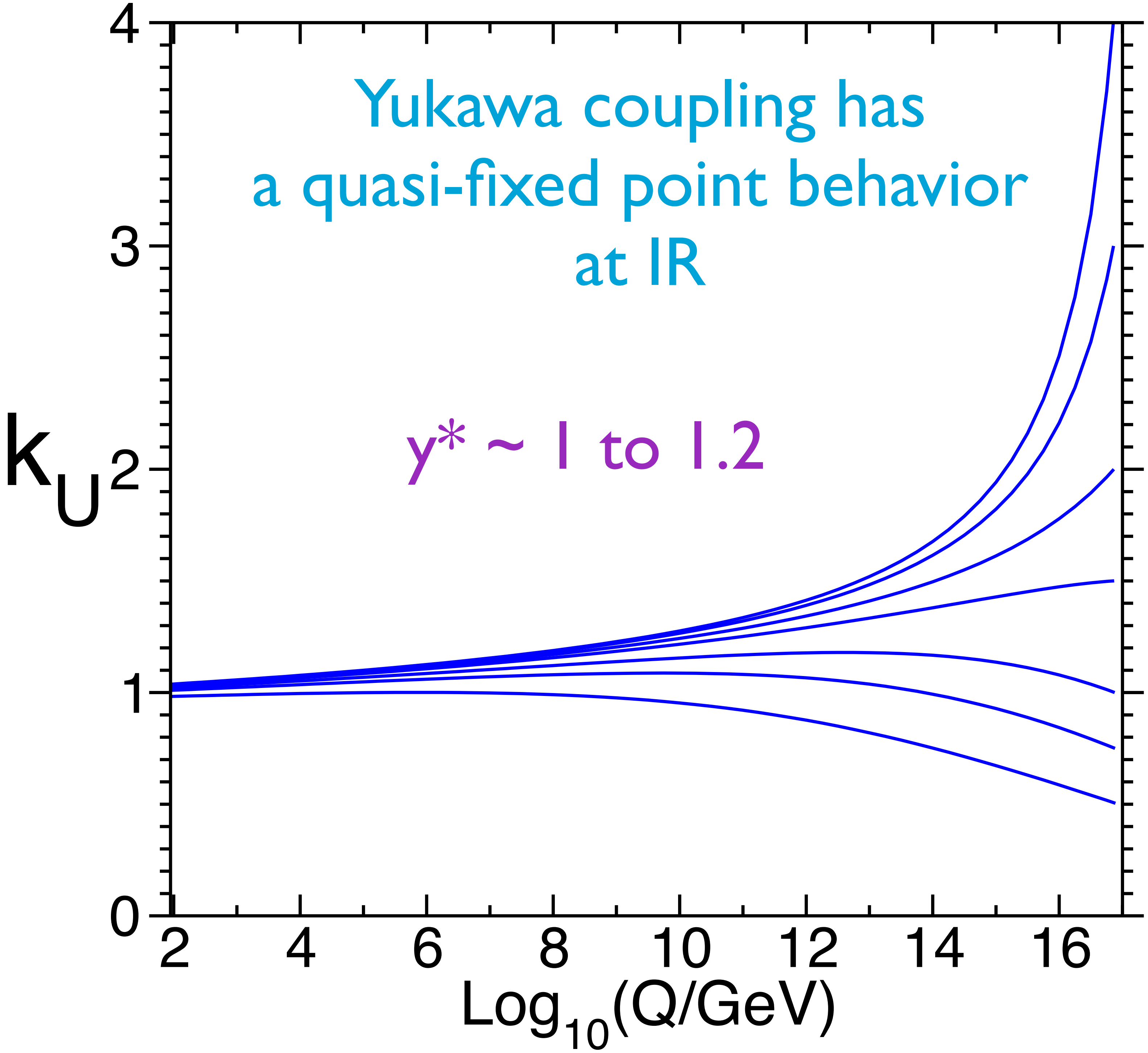
$$W = M_Q Q\bar{Q} + M_U U\bar{U} + M_E E\bar{E} + k_U H_u Q\bar{U} - h_U H_d \bar{Q} U,$$

$$Q = (\mathbf{3}, \mathbf{2}, 1/6), \qquad \bar{Q} = (\bar{\mathbf{3}}, \mathbf{2}, -1/6),$$

$$U = (\mathbf{3}, \mathbf{1}, 2/3), \qquad \bar{U} = (\bar{\mathbf{3}}, \mathbf{1}, -2/3),$$

$$E = (\mathbf{1}, \mathbf{1}, -1), \qquad \bar{E} = (\mathbf{1}, \mathbf{1}, 1).$$

IR quasi-fixed point of Yukawa couplings



Yukawa coupling has
a quasi-fixed point behavior
at IR

y* ~ 1 to 1.2

IR quasi-fixed point of Yukawa couplings

$$\beta_{y_t} \equiv \frac{d}{dt} y_t = \frac{\boxed{y_t}}{16\pi^2}\left[\overset{A}{\boxed{6y_t^* y_t}} + y_b^* y_b - \overset{B}{\boxed{\frac{16}{3} g_3^2}} - 3g_2^2 - \frac{13}{15} g_1^2\right],$$

For order one Yukawa (top Yukawa),

(i) Yt is driven to be small if A > B

(ii) Yt is driven to be small if A < B

(iii) Yt runs slowly if A ~ B

*It is not the exact fixed point as strong coupling runs

125 GeV Higgs from supersymmetry with vector-like matters

arXiv:1208.3748, K Bae, TH Jung and HD Kim

125 GeV Higgs : $m_h^2 \simeq 2M_Z^2$ Discovered in 2012

160 GeV Higgs : $m_h^2 \simeq 3M_Z^2$ Babu et al (2008)

$$\downarrow$$

$$m_h^2 \simeq \underset{\underset{\text{tree level}}{\uparrow}}{M_Z^2} + \underset{\underset{\text{one loop level}}{\uparrow}}{2M_Z^2}$$

160 GeV Higgs mass

arXiv:1208.3748, K Bae, TH Jung and HD Kim

$$m_h^2 \simeq \overset{\text{tree level}}{\overset{\big\downarrow}{M_Z^2}} + \underset{\text{top/stop one loop}}{\underset{\big\uparrow}{M_Z^2}} + \overset{\text{vector-like matter one loop}}{\overset{\big\downarrow}{M_Z^2}}$$

125 GeV Higgs mass

arXiv:1208.3748, K Bae, TH Jung and HD Kim

$$m_h^2 \simeq \overset{\text{tree level}}{\xcancel{M_Z^2}} + \boxed{\underbrace{M_Z^2}_{\text{top/stop one loop}} + \overbrace{M_Z^2}^{\text{vector-like matter one loop}}}$$

It is possible to obtain 125 GeV Higgs using one loop correction.

arXiv:1208.3748, K Bae, TH Jung and HD Kim

RG running from f to Mz : quadratic terms

$$m_h^2 = -2m_H^2$$

$$m_H^2 = -\frac{3}{8\pi^2} F \log\frac{M}{m_{\rm soft}},$$

small log is better

$$F = (y_t/\sqrt{2})^2 (m^2_{\tilde{Q}_3} + m^2_{\tilde{t}^c}) + (y_{t'}/\sqrt{2})^2 (m^2_{\tilde{Q}'_3} + m^2_{\tilde{t}'^c})$$

$$-g_2^2 M_2(\mu + M_2) - \frac{g_1^2}{5} M_1(\mu + M_1).$$

RG running from f to Mz :quartic terms

$$m_h^2 = c_t \left[A_t + B_t\right] + c_{t'} \left[A_{t'} + B_{t'}\right],$$

$$A_t = \log\frac{m^2_{\tilde{t}}}{m^2_t},$$

$$B_t = \frac{X_t^2}{m^2_{\tilde{t}}}\left(1 - \frac{1}{12}\frac{X_{t'}^2}{m^2_{\tilde{t}}}\right),$$

$$A_{t'} = \log\frac{m^2_{\tilde{t}'}}{m^2_{t'}},$$

$$\xcancel{B_{t'} = \frac{X_{t'}^2}{m^2_{\tilde{t}'}}\left(1 - \frac{1}{12}\frac{X_{t'}^2}{m^2_{\tilde{t}'}}\right),}$$

$$\Delta(m_h^2)^{(\mathrm{vec})} = \frac{2Nv^2(k_E^4 + k_N^4)}{4\pi^2}\left[\ln x + f(x)\right] + \Delta m_{hb}^2,$$

where

$$x = \frac{(M_F^2 + m_s^2)}{M_F^2},$$

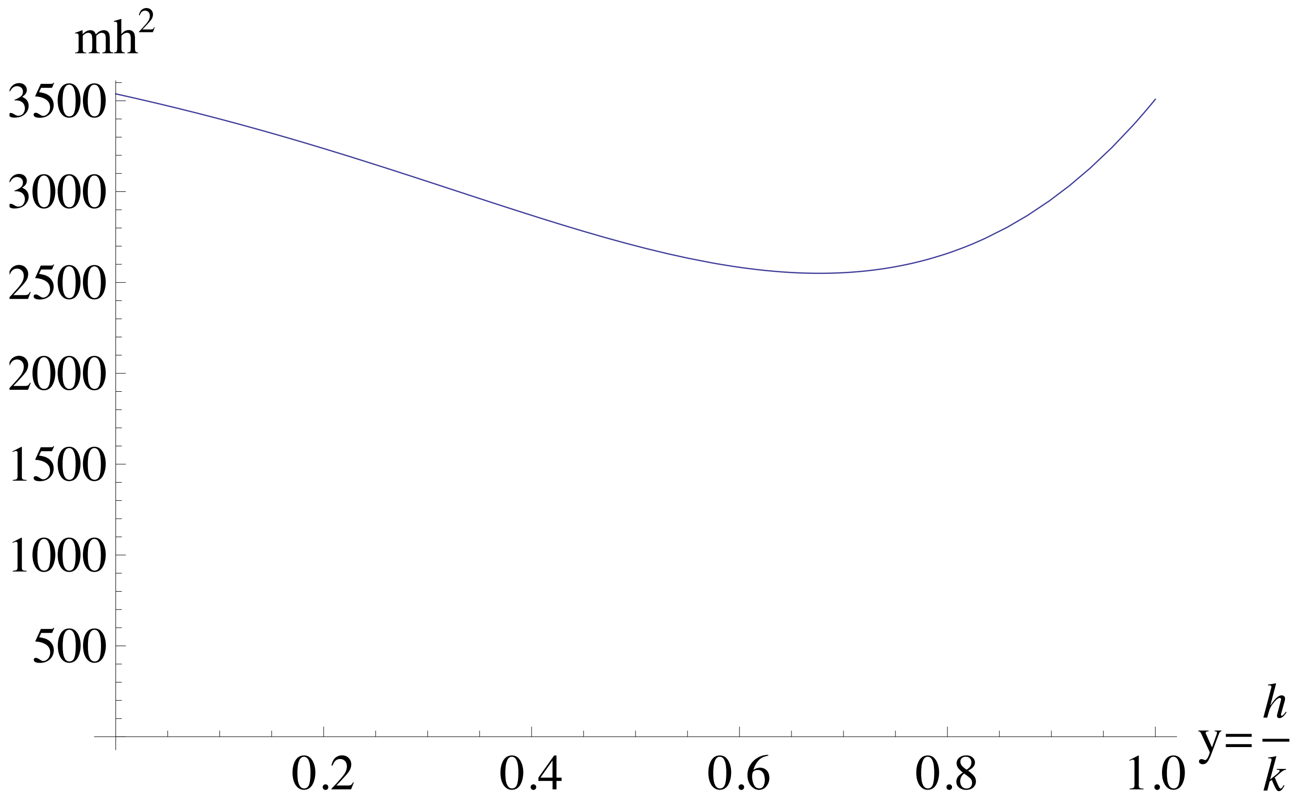
and

$$\begin{aligned} f(x) &= -\frac{1}{12}\left[\frac{\mu^4}{(M_F^2+m_s^2)^2} - 24(\frac{1}{2}-\frac{1}{x})\frac{\mu^2}{M_F^2+m_s^2} + 16(1-\frac{1}{x})(2-\frac{1}{x})\right], \\ &= -\frac{1}{12}\left[\frac{\mu^2}{(M_F^2+m_s^2)} - 12(\frac{1}{2}-\frac{1}{x})\right]^2 + \frac{32}{3}\left[(\frac{1}{x}-\frac{3}{8})^2 - \frac{7}{64}\right]. \end{aligned}$$

$$\mu^2 = 12(\frac{1}{2}-\frac{1}{x})(M_F^2+m_s^2) = \boxed{6(m_s^2 - M_F^2),}$$

f(x)=1/3 is the maximum

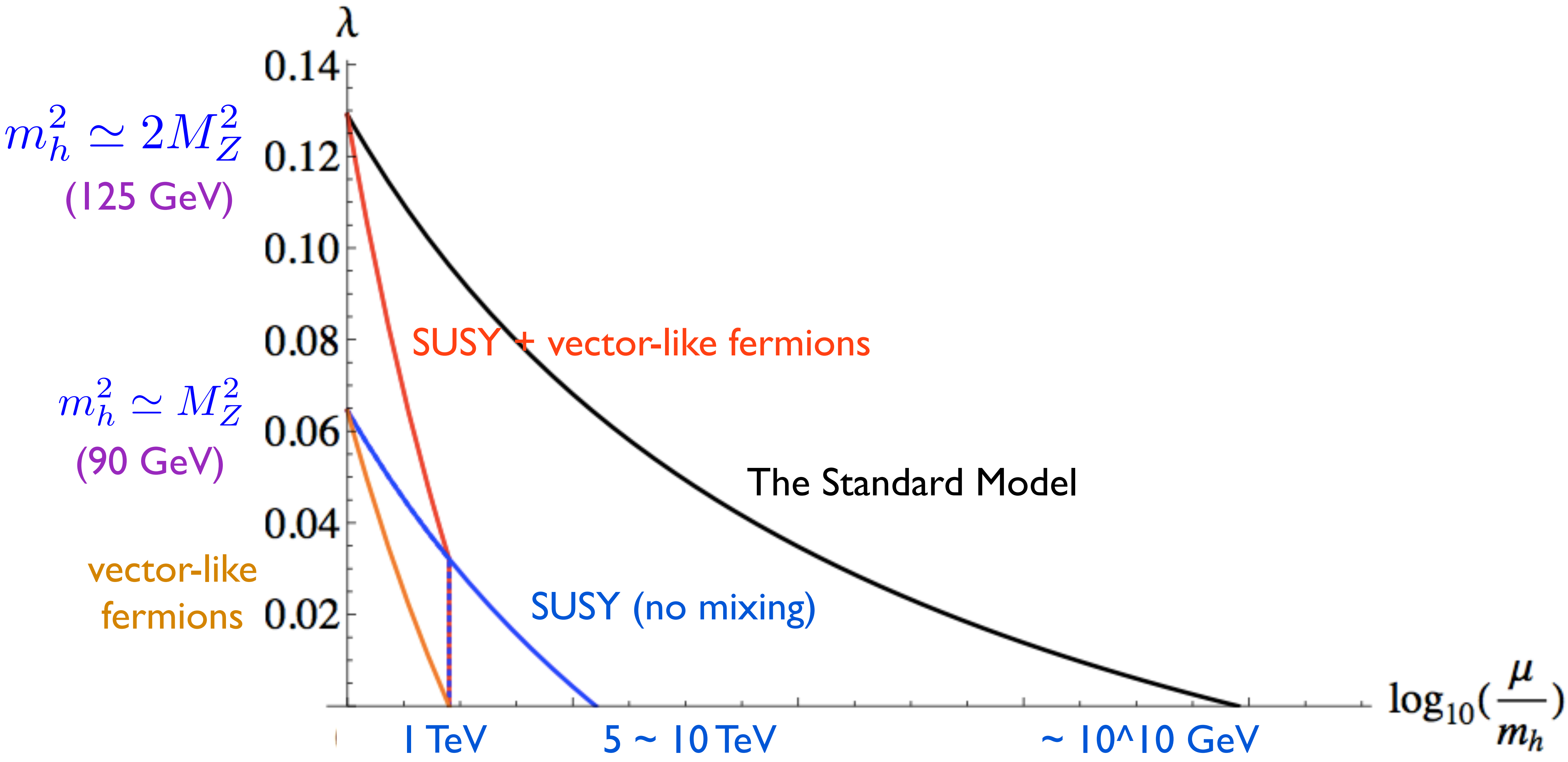
Even if one Yukawa is turned off, we get the same size of correction to the Higgs mass.



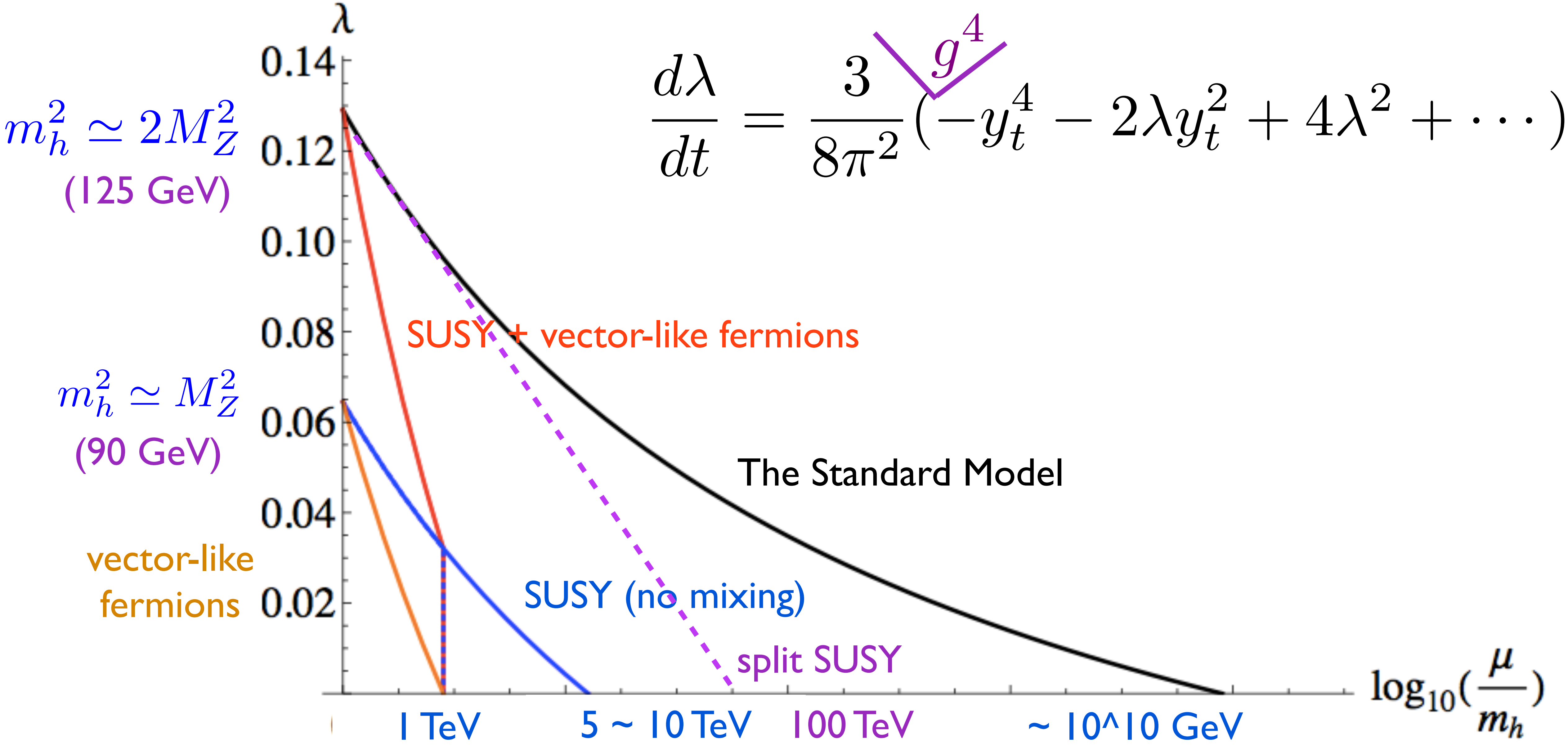
$$\frac{d\lambda}{dt} = \boxed{\frac{3}{8\pi^2}(-y_t^4} - 2\lambda y_t^2 + 4\lambda^2 + \cdots)$$

$$m_{\mathrm{phys}}^2 = 2\lambda v^2$$

v=246 GeV



maximal mixing
of stop with large mu



$$\frac{d\lambda}{dt} = \frac{3}{8\pi^2}(\overset{g^4}{\vee}-y_t^4 - 2\lambda y_t^2 + 4\lambda^2 + \cdots)$$

Higgs mass is raised by vector-like fermions.
(Instability of vector-like fermions is a virtue.)

Higgs - photon - photon coupling : LNE model

$$W_{LNE} = M_L L\overline{L} + M_E E\overline{E} + M_N N\overline{N} + \hat{k}_E H_u \overline{L} E - \hat{h}_E H_d L \overline{E} + \hat{k}_N H_u L \overline{N} - \hat{h}_N H_d \overline{L} N$$

Higgs mass

charged lepton mass term

$$L \equiv \begin{pmatrix} N_L \\ E_L \end{pmatrix}, \qquad \bar{E} \equiv E_R^c, \quad \bar{N} = N_R^c$$

$$\bar{L} \equiv \begin{pmatrix} E_L^c \\ N_L^c \end{pmatrix}, \qquad E \equiv E_R. \quad N = N_R$$

$$\begin{pmatrix} E_L^c & E_R^c \end{pmatrix} \begin{pmatrix} M_L & k_E v_u \\ h_E v_d & M_E \end{pmatrix} \begin{pmatrix} E_L \\ E_R. \end{pmatrix}$$

$$\mathcal{M}_f^\dagger \mathcal{M}_f = \begin{pmatrix} M_L^2 + h_E^2 v_d^2 & M_L k_E v_u + M_E h_E v_d \\ M_L k_E v_u + M_E h_E v_d & M_E^2 + k_E^2 v_u^2 \end{pmatrix},$$

Constructive interference with W if $M_L M_E > k_E h_E v_{d(u)}^2$

1206.1082 Carena Low Wagner

$$\frac{\partial}{\partial v}\log\left(\det \mathcal{M}_f^\dagger \mathcal{M}_f\right)$$
$$= \frac{2}{\det \mathcal{M}_f^\dagger \mathcal{M}_f}\{(M_L^2 + h_E^2 v^2)k_E^2 v + (M_E^2 + k_E^2 v^2)h_E^2 v - (M_L k_E + M_E h_E)^2 v\}$$
$$= -\frac{4 k_E h_E v}{M_E M_L - k_E h_E v^2},$$

$$M_L M_E > k_E h_E v^2$$

Higgs to di-photon rate is enhanced

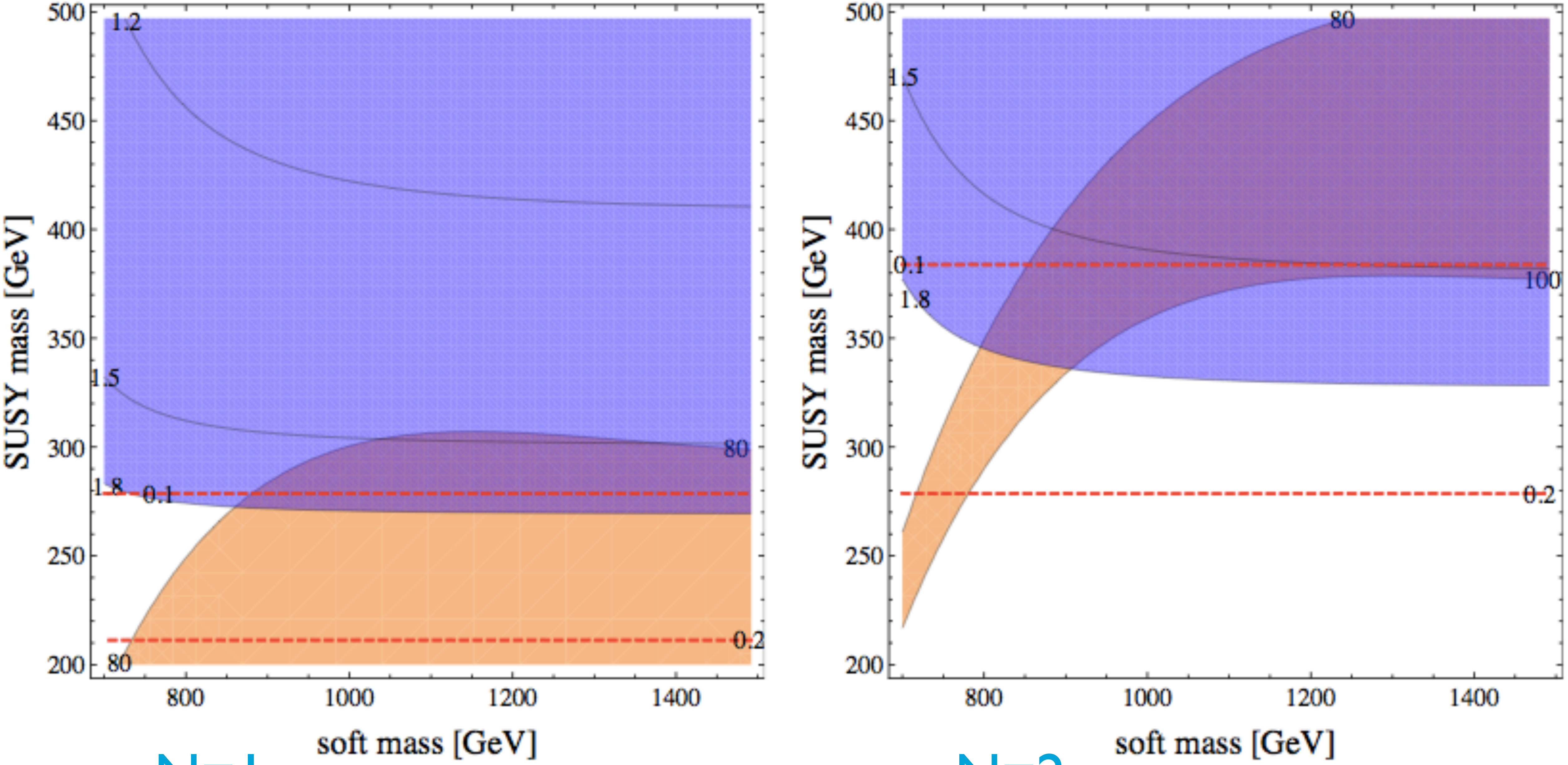
$$R_{\gamma\gamma} = \left[1 + \frac{\mathcal{A}_{\rm NP}}{\mathcal{A}_{\rm SM}}\right]^2$$
$$\simeq \left[1 + \left(\frac{v}{\sqrt{2}(-8.32 + 1.84)}\right)\left(\frac{8\sqrt{2}}{3}\frac{-\ h_E k_E v}{M_L M_E - h_E k_E v^2}\right)\right]^2,$$

$$R_{\gamma\gamma} - 1 \simeq 0.8\frac{h_E k_E v^2}{M_L M_E} + \mathcal{O}(h_E^2 K_E^2 v^4 / M_L^2 M_E^2).$$

$$R_{\gamma\gamma} - 1 \gtrsim 0.8 \frac{N k^2 v^2}{m_s^2} \exp\left(\frac{\pi^2 M_Z^2}{N k^4 v^2} - \frac{1}{3}\right)$$

N=1 → 1.6 (1.3) for 1 (1.4) TeV

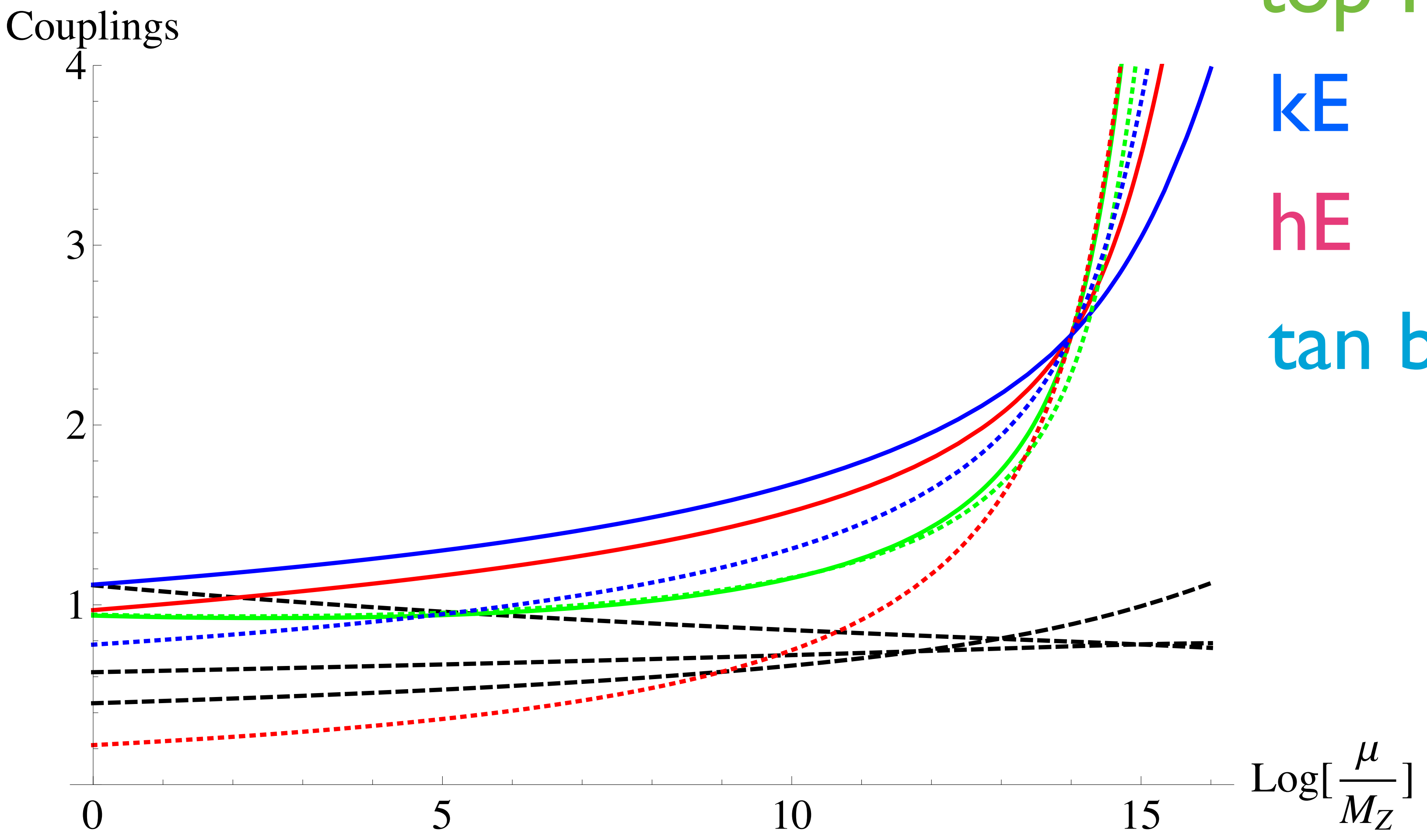
N=2 → 1.3 (1.2) for 1 (1.4) TeV



N=1

N=2

mu : 2 TeV,   stop, scalar : 1 TeV,   k=1



top Yukawa

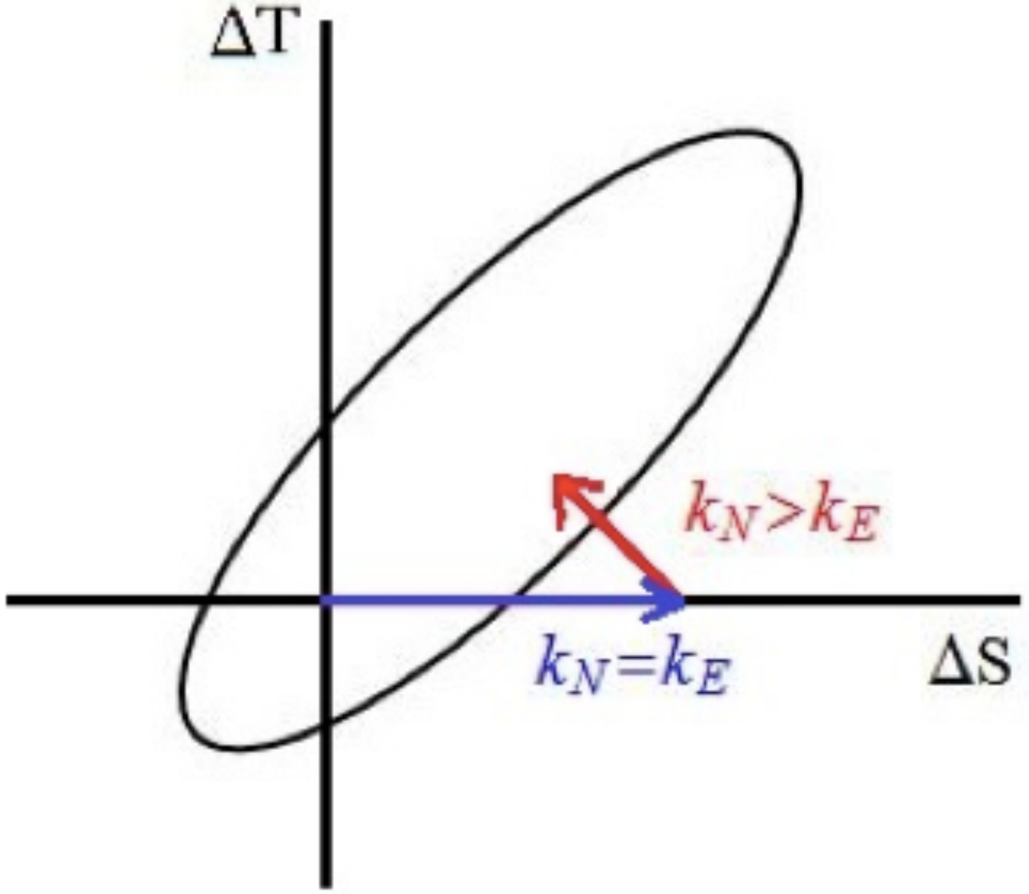
kE

hE

tan beta = 1.3

Oblique corrections from vector-like fermions

Maekawa (1996)



$$\Delta S = \frac{N}{6\pi}\left[-2Y\log(\frac{m^2_{U_1}m^2_{U_2}}{m^2_{D_1}m^2_{D_2}})\right] + \frac{11N}{30\pi}\left[(\frac{k_U v}{M_F})^2 + (\frac{k_D v}{M_F})^2 + \mathcal{O}((\frac{kv}{M_F})^4)\right]$$

$$\Delta T = \frac{N}{10\pi \sin^2\theta_W m_W^2}\left[\frac{(k_U^2 - k_D^2)^2 v^4}{M_F^2} + \mathcal{O}(\frac{(kv)^6}{M_F^4})\right]$$

Summary

Relatively light Higgs has been discovered on July 4.

Higgs mass is at around the weak scale. $m_h^2 = 2M_Z^2$

Gauge mediation is not compatible with H125 and TeV stop.

Neutrino assisted gauge mediation works.
(and also [redacted] assisted gauge mediation)

Mu problem should be the start of model building in SUSY.

Large mu is compatible with pGB Higgs. (tan beta close to 1)

Diphoton rate can be enhanced by vector-like fermions.

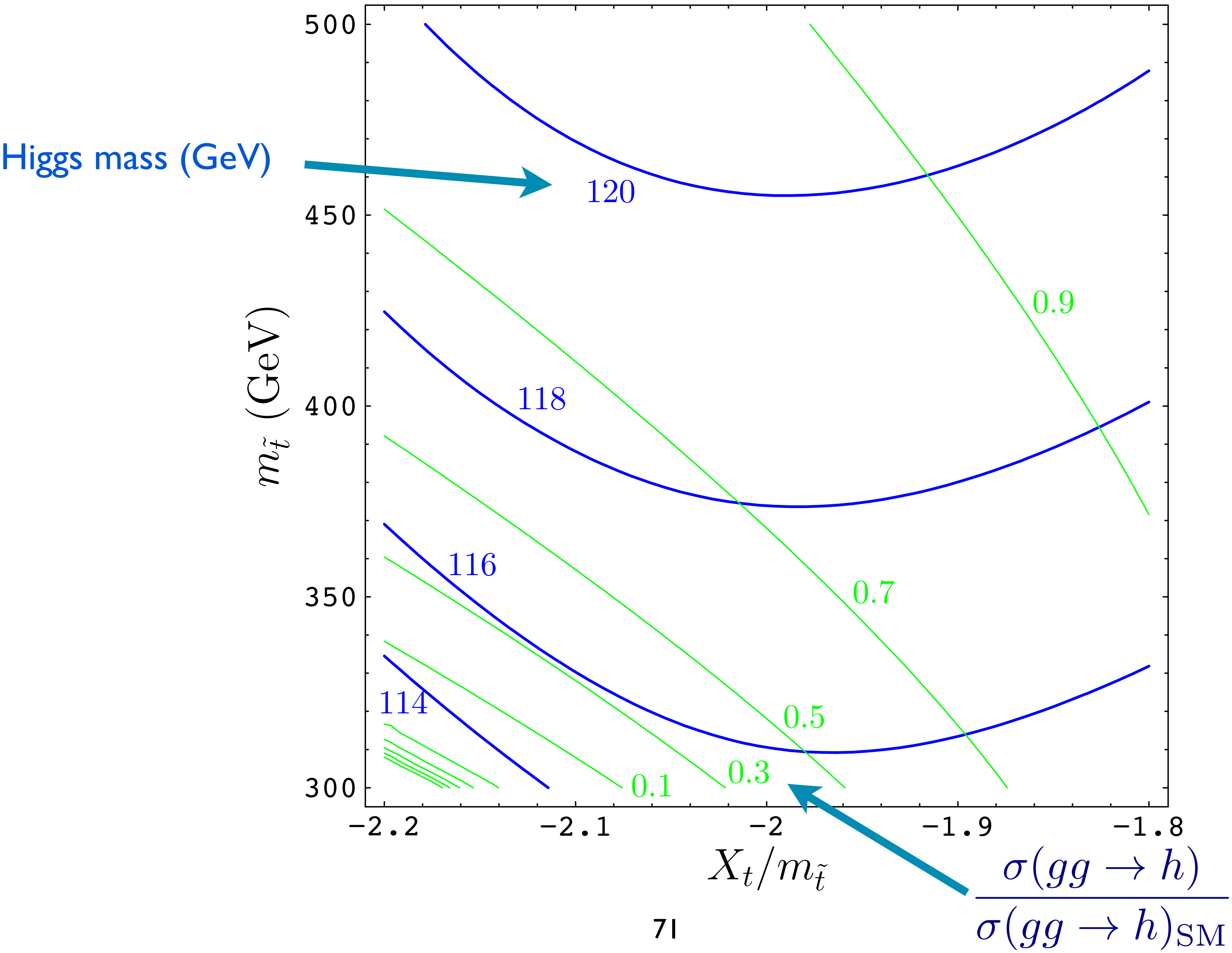
Higgs mass is raised by vector-like fermions.
(Instability of vector-like fermions is a virtue.)

Higgs as a pGB can survive with the help of these fermions.

Higgs production (gluon fusion) is suppressed in all theories dealing with the hierarchy problems.

Low and Rattazzi (2009)

Djouadi (1998) Dermisek and Low (2007)



Recall predictions before the discovery of 125 GeV Higgs

NMSSM : Modified Higgs decay (SM decay is suppressed)

MSSM with maximal stop mixing : gluon fusion suppressed

Little Higgs : top friends suppress gluon fusion

Composite Higgs : Similar suppression of the standard channel

And many models with sizable invisible decay width

Recall predictions before the discovery of 125 GeV Higgs

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And many models with sizable invisible decay width

After the discovery

SM : consistent

New leptons can explain enhanced diphoton rate