125GeV Higgs Boson and Radiative Natural SUSY

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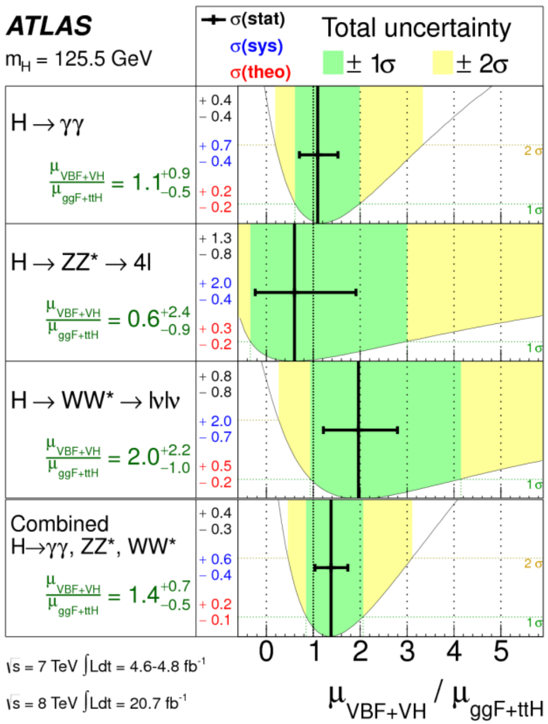
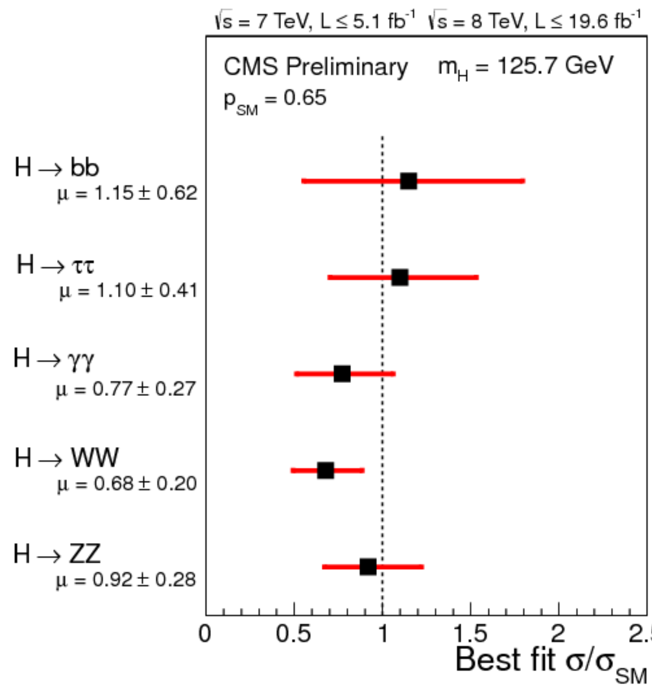
Higgs Data at LHC

Mass

- $M_h = 125.5 \pm 0.2 \pm 0.6$ GeV (ATLAS)
- $M_h = 125.7 \pm 0.3 \pm 0.3$ GeV (CMS)

Couplings

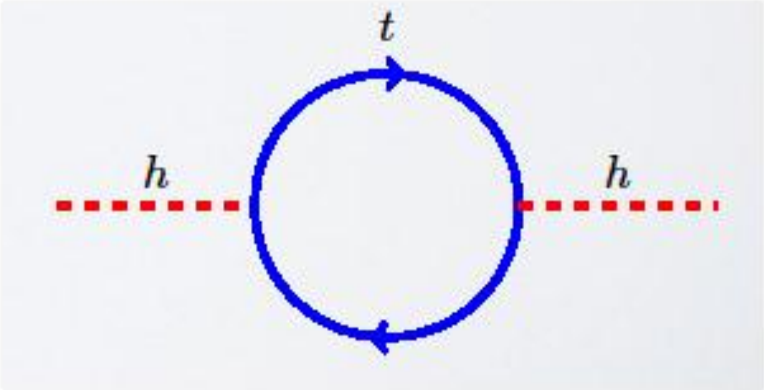




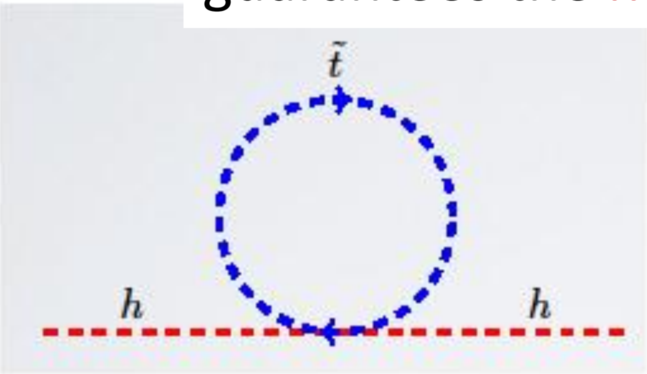
Ratios to the cross sections of SM Higgs are being measured for various channels.

The hierarchy problem

$$\Delta m^2 \sim \frac{y_t^2}{16\pi^2}\Lambda^2$$



- We need extreme fine tuning to give the cancellation
- Introduce Supersymmetry : Automatic cancellation guarantees the naturalness of values of parameters.



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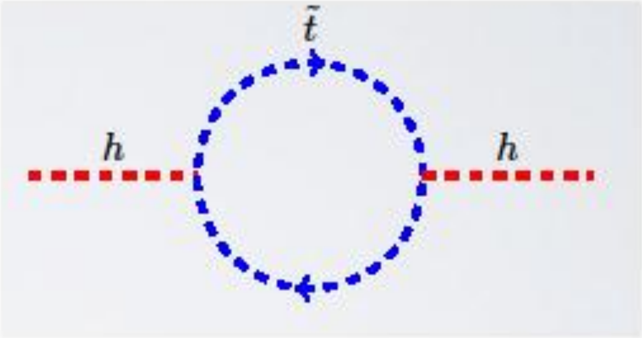


- SUSY is broken in nature.
- Soft Supersymmetry breaking gives different masses to the SUSY particles and their SM partners.

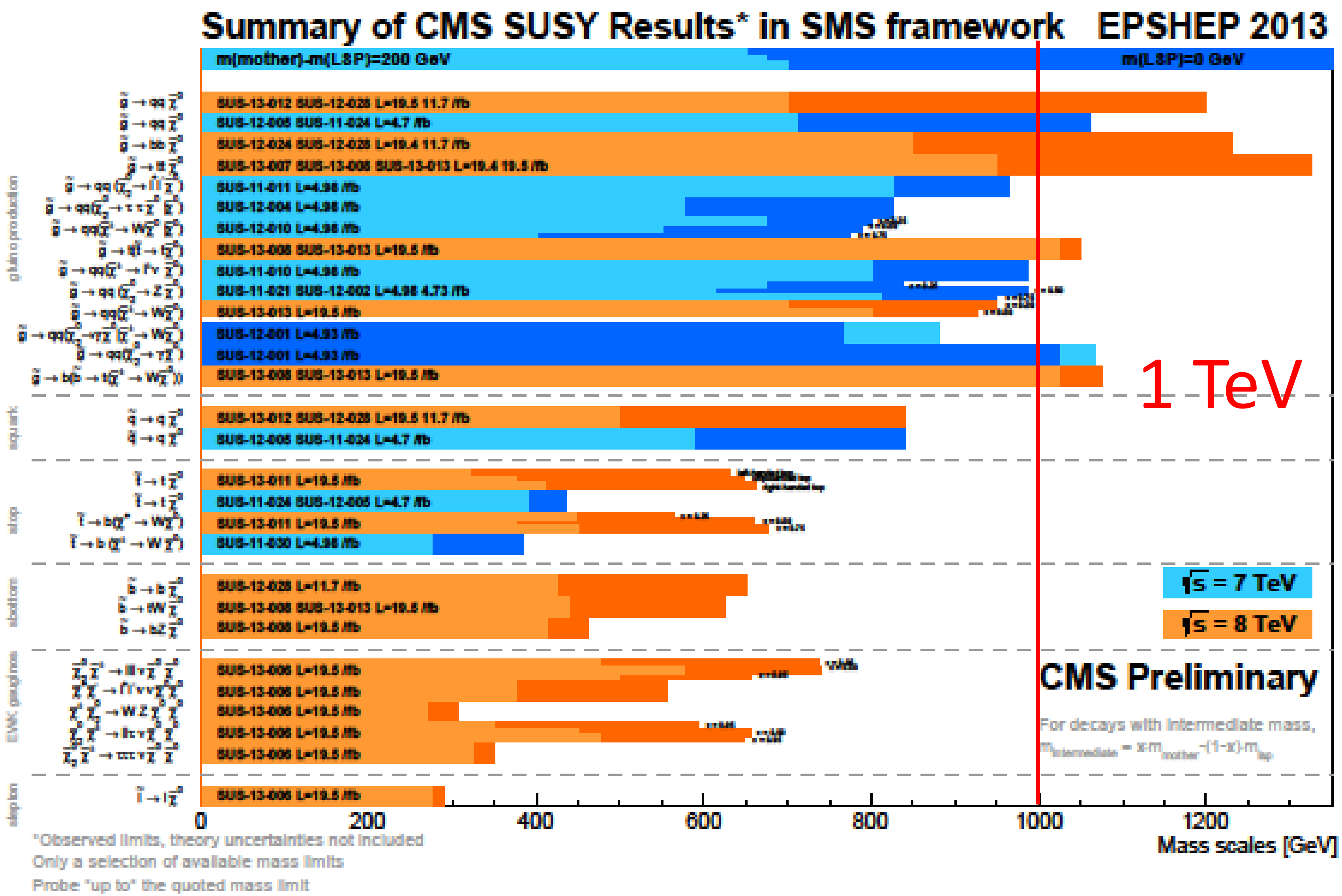
→ It gives different contribution to the Higgs potential.

$$V = (\mu^2 + m_{Hd}^2)|h_d^0|^2 + (\mu^2 + m_{Hu}^2)\,|h_u^0|^2 - \left(B\mu\, h_d^{0\dagger} h_u^0 + \mathrm{h.c.}\right) + \frac{1}{8}\,(g^2 + g'^2)\,(\,|h_u^0|^2 - |h_d^0|^2)^2$$

Radiative correction :

$$\Delta V = \sum_i \frac{(-1)^{2s_i}}{64\pi^2}\,(2s_i+1)\,c_i m_i^4(\Phi)\,\left[\log\frac{m_i^2(\Phi)}{Q^2} - \frac{3}{2}\right],$$ i : all fields couple to Higgs

LHC SUSY searches



How can the heavy SUSY particles accommodate the Higgs boson of mass 125 GeV ?

Natural SUSY

$$-\frac{m_h^2}{2} = \mu^2 + m_{Hu}^2(\Lambda) + \delta m_{Hu}^2(M_{SUSY})$$

- Fine-tuning measure $\Delta_i = C_i / \left(\frac{m_h^2}{2}\right)$,

$$C_i = |\mu^2|, m_{Hu}^2(\Lambda), -\delta m_{Hu}^2(M_{SUSY})$$

Requring all $\Delta_i < 5$ $(\Delta^{-1} = 20\%\ \text{tuning} : -1 = 4 - 5\ )$

Low Higgsino mass : $|\mu| < \sim 300$GeV is required.

$$-\delta m_{Hu}^2(M_{SUSY}) \cong \frac{3h_t^2}{8\pi^2}\left(m_{Q3}^2 + m_{U3}^2 + A_t^2 \right) \log \frac{\Lambda}{M_{SUSY}} < \left(\frac{m_h^2}{2}\right) 5$$

$$\rightarrow m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 \left(= m_{Q3}^2 + m_{U3}^2\right) < \frac{8\pi^2}{3h_t^2} \frac{\frac{m_h^2}{2} 5}{(1+R_t^2) log\frac{\Lambda}{M_{SUSY}}} \frac{\Delta}{5} = (700\ \text{GeV})^2 \frac{3}{log\frac{\Lambda}{M_{SUSY}}} \frac{\Delta}{5}$$

Light 3rd generations : Stop mass < ~700 GeV .

Kitano and Nomura'06

Natural SUSY

~10 TeV 1^{st} 2^{nd} squarks

- $\mu \approx 100 - 250$GeV
- m$(\widetilde{t_1}, \widetilde{t_2}, \widetilde{b_1}) \approx \sim 500$ GeV
- m$(\tilde{g}) \lesssim$ 1.5 TeV
- m$(\tilde{q}, \tilde{l}) \approx 10 - 20$ TeV

Arkani-Hamed, Pappuci et al., Brust et al., Essig et al., Baer,Barger, Huang,Tata, Wymant…

~1.5 TeV gluino

~500GeV stop

Low High-Scale fine-tuning Δ_i< 20%

~200GeV Higgsino

What about the Higgs mass in this scenario?

MSSM Higgs mass

- Two Higgs doublet model : H_u and H_d
- D-term $\frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 - |H_u^0|^2)^2$

→ Tree-level bound $M_h \leq M_Z$ |cos 2β|

Large quantum correction is needed to reproduce $M_h \cong 125$ GeV .

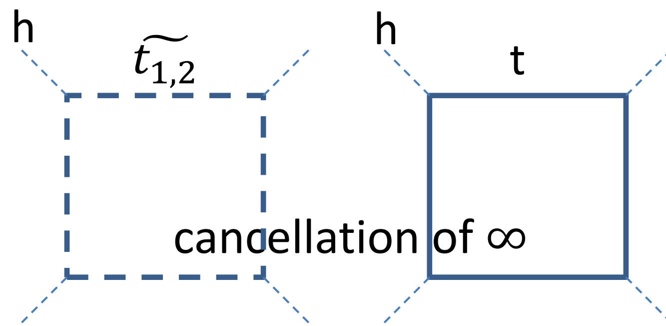
the largest contribution comes from

stop and top loop

Loop correction to MSSM Higgs mass

- *Stop squared mass matrix*

$$M_{\tilde{t}}^2 = \begin{pmatrix} m_t^2 + m_{Q_3}^2 + D_L & m_t X_t \\ m_t X_t & m_t^2 + m_{U_3}^2 + D_R \end{pmatrix}$$



$$M_{SUSY} = \sqrt{m_{\widetilde{t_1}} m_{\widetilde{t_2}}}$$ stop mass gives SUSY breaking scale

- *Higgs mass formula*

$$M_h^2 = M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2}\left[\log \frac{M_{SUSY}^2}{m_t^2} + x_t^2\left(1 - \frac{x_t^2}{12}\right)\right];$$

Logarithmic dependence of stop mass M_{SUSY}

polynomial dependence of stop mixing parameter $x_t = \frac{X_t}{M_{SUSY}}$

Large CP-odd higgs mass m_A , moderate and large values of tanβ

Tremendous efforts to calculate M_h in MSSM.

Carena,Wagner,Heinemeyer,Hempfling,Espinoza,Zhang,
Degrassi,Hollik,Zhang,Weiglein,Zwirner,Okada,Yamaguchi,Ellis,Brignole,Martin,... .

MSSM Higgs mass

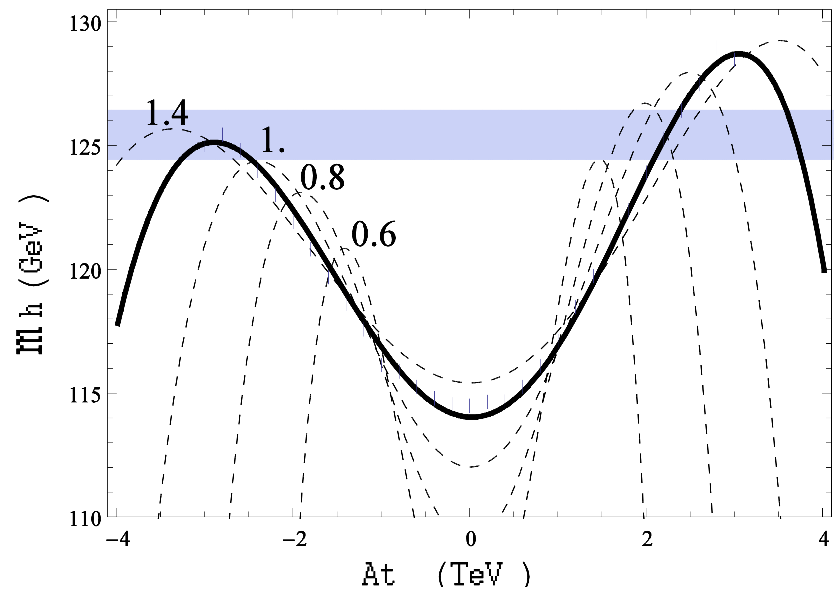
- 3-loop analysis of M_h by H3m package

- Analysis by Isajet

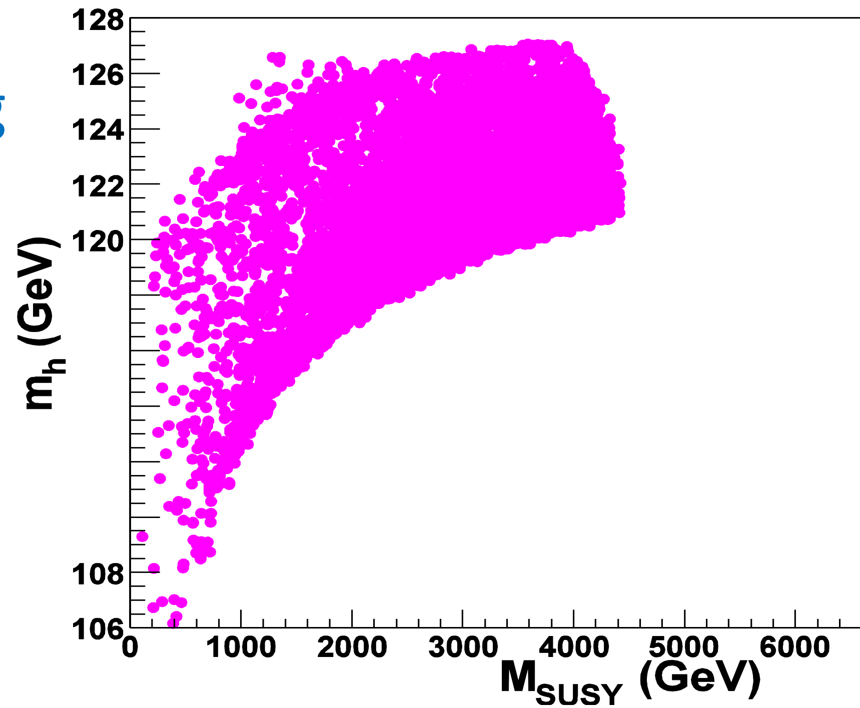
Natural SUSY scenario has great difficulty in accomodating a Higgs at 125 GeV.

Stop masses M_{SUSY} < 600 GeV is

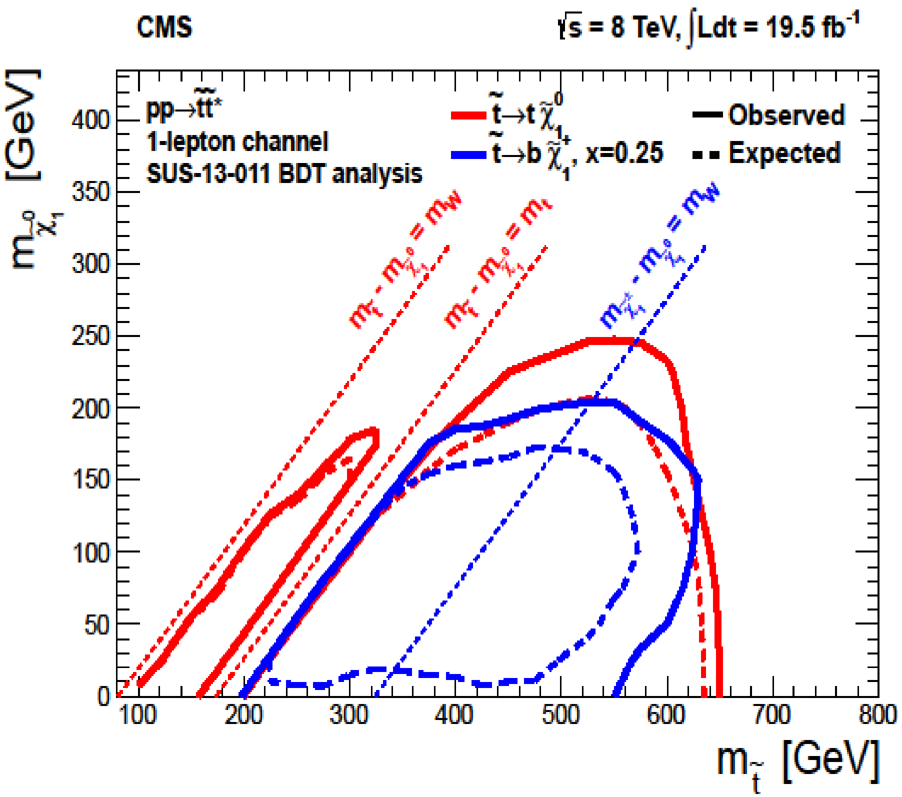
- inconsistent with $M_h = 125$ GeV
- too small b→s γ ratio .

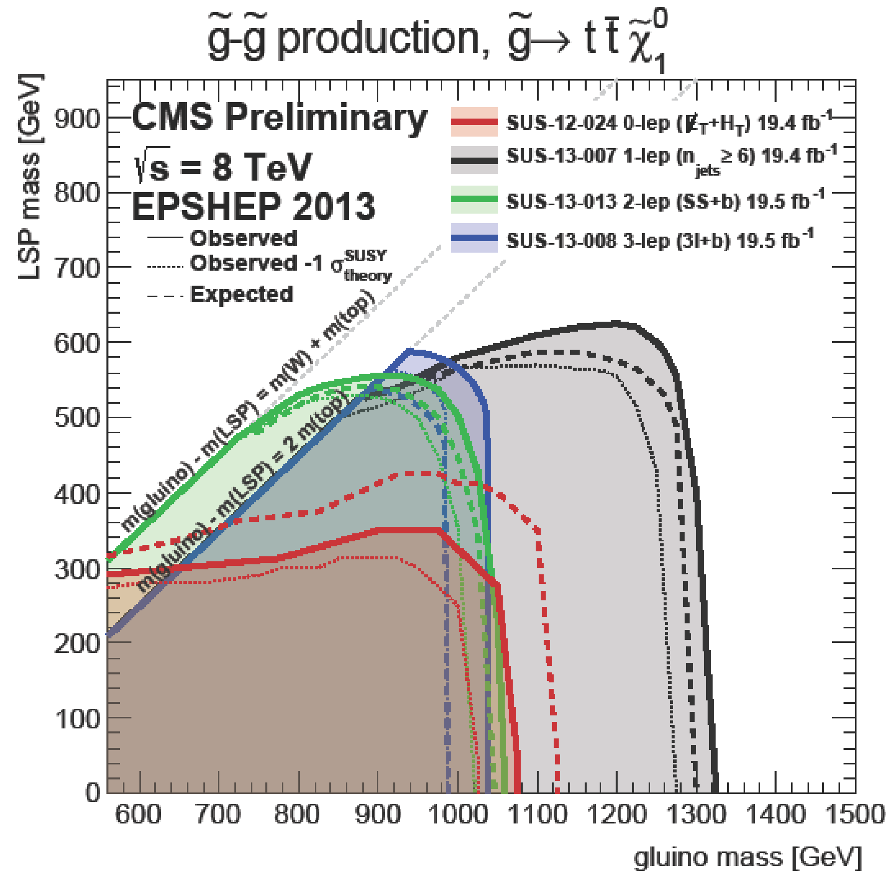


V. Barger, MI, P. Huang, W-Y. Keung, PRD (2012)



SUSY searches at LHC





stop $m_{\widetilde{t_1}} > \sim 0.65$ TeV

gluino $m_{\tilde{g}} > 1.4(0.9)$ TeV when $m_{\tilde{q}} \sim (\gg) m_{\tilde{g}}$,

→ Natural SUSY seems to be incorrect .

A weaker condition

- We do not know exactly what is the High-Scale SUSY model at present.
- Some cancellation mechanism between

  $m_{Hu}^2(\Lambda)$ and $\delta m_{Hu}^2(M_{SUSY})$ is needed in the HS model.

We stand on a phenomenological viewpoint:

don't specify HS model, and

require Naturalness only at EW scale .

Radiaitve Natural SUSY (RNS)

- A kind of SUSY GUT model : $\Lambda = M_{GUT}$.
- $m_{Hu}^2(M_{GUT})$ is adjusted to reproduce a small negative

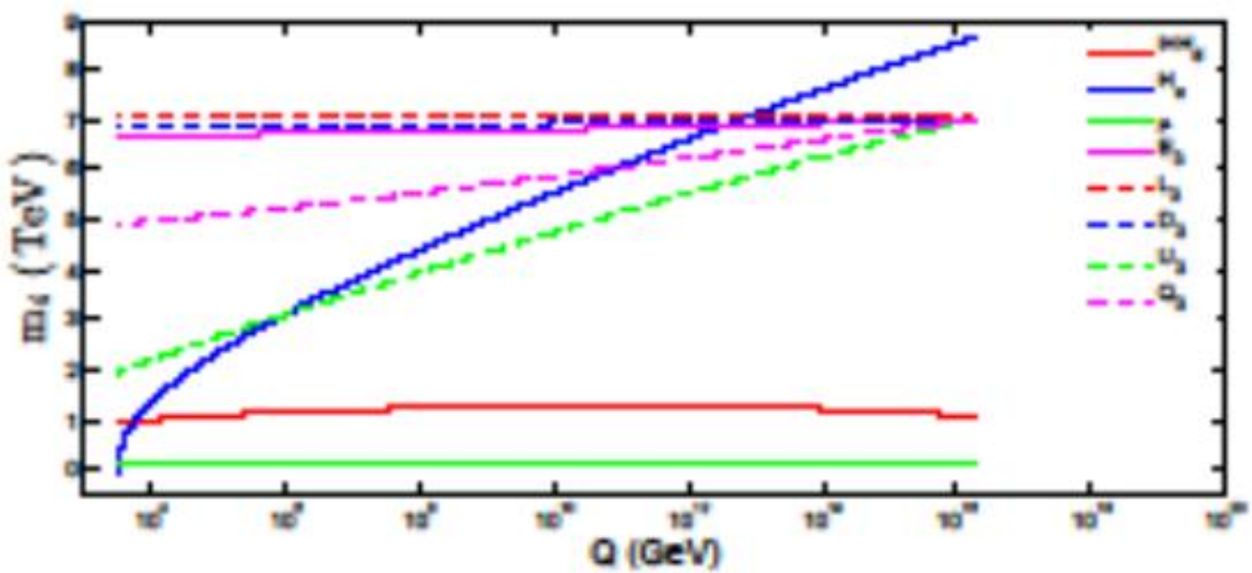
$$m_{Hu}^2(M_{SUSY}) \ (= m_{Hu}^2(M_{GUT}) + \delta m_{Hu}^2 \ ) \ \sim \ -\frac{M_Z^2}{2} < 0$$

EW symmetry breaking occurs by large radiative correction $\delta m_{Hu}^2 < 0$.

Non universal Higgs mass model

2 parameters : $m_{Hu}^2(M_{GUT}) \gg m_{Hd}^2 \ (M_{GUT})$, traded as μ and m_A .

The model specified by the parameters: $m_0, m_{1/2}$, tanβ, μ , m_A , A_0



How to get Electroweak Naturalness

Minimization of Higgs potential gives another relation.

$$\frac{M_Z^2}{2} = \frac{m_{Hd}^2 + \Sigma_d^d - t_\beta^2\,(m_{Hu}^2 + \Sigma_u^u)}{t_\beta^2 - 1} - \mu^2 \approx -m_{Hu}^2 - \Sigma_u^u - \mu^2$$

ElectroWeak Fine-Tuning measure:

$$\Delta_{EW} = \max C_i / \left(\frac{M_Z^2}{2}\right).$$

$$C_i = m_{Hd}^2/(t_\beta^2 - 1), \Sigma_d^d/(t_\beta^2 - 1), \quad m_{Hu}^2, \Sigma_u^u, \quad \mu^2$$

Requring Low Δ_{EW}<10–30 , 3–10% FT

→ Small Higgsino mass |μ|~ 100—300GeV

Radiative correction

- $\sum_u^u = \dfrac{\partial\, \Delta V}{\partial(|h_u|^2)}$

  includes stop and other SUSY particle loop effects.

  gives the largest Δ_{EW} in the relevant parameter region.

- The largest contribution comes from stops.

$$\Sigma_u^u(\widetilde{t_{1,2}}) = \frac{3}{16\pi^2} \mathrm{H}(m_{\widetilde{t_{1,2}}}^2) \times \left[\, h_t^2 - g_Z^2 \mp \frac{h_t^2 A_t^2 - 8 g_Z^2 (\frac{1}{4} - \frac{2}{3} x_W) \Delta_t}{m_{\widetilde{t_2}}^2 - m_{\widetilde{t_1}}^2} \right]$$

$$\mathrm{H}(m^2) = m^2 (log \frac{m^2}{Q^2} - 1), \quad Q^2 = m_{\widetilde{t_2}}\, m_{\widetilde{t_1}}$$

Low Δ_{EW} requires fairly light stops.

larger $m_{\widetilde{t_1}}$ than that of NS is due to cancellation by A_t.

larger $\widetilde{t_2}$: its contribution canbe suppressed in large mass splitting.

Predicted Mass spectra in RNS

parameter	RNS2
m0(1, 2)	7025.0
m0(3)	7025.0
m1/2	568.3
A0	-11426.6
tanβ	8.55
μ	150
mA	1000
m˜g	1562.8
m˜uL	7020.9
m˜uR	7256.2
m˜eR	6755.4
m˜t1	1843.4
m˜t2	4921.4
m˜b1	4962.6
m˜b2	6914.9
m˜τ1	6679.4
m˜τ2	7116.9
m˜ντ	7128.3
m˜W2	513.9
m˜W1	152.7
m˜Z4	525.2
m˜Z3	268.8
m˜Z2	159.2
m˜Z1	135.4
mh	125.0

Baer,Barger,Huang, Mustafayev,Tata, PRL

- $m_{\widetilde{t_1}} = 1 \sim 2\text{TeV}$ heavier light stop than that in generic NS
- $m_{\widetilde{t_2}} = 2 \sim 5\text{TeV}$
- $m_{\tilde{g}} = 1 \sim 4\text{TeV}$
- Light higgsino-like $\widetilde{W_1}, \widetilde{Z_{1,2}}$ have masses $\approx |\mu| = 100 - 300\text{GeV}$ from Naturalness.
- $1^{st}, 2^{nd}$ generation squarks & sleptons masses 1-8 or 20-30TeV.

Successfully reproduces the Higgs mass 125 GeV.
Consistent with the present LHC data.

Consistent with BF(b→sγ)
(because of the heavier stops) .

$Bs \rightarrow \mu^+\mu^-$

- Recent measurement by LHCb: $(3.2^{+1.5}_{-1.2}) \times 10^{-9}$ time-integrated cross section

Consistent with the SM prediction

$BF_{SM}(Bs \rightarrow \mu^+\mu^-) = (3.54 \pm 0.30) \times 10^{-9}$

CP-averaged branching fraction R.Fleischer arXiv:1212.4967

$y_s = \frac{\Gamma_L - \Gamma_H}{2\Gamma} = 0.088 \pm 0.014$ light/heavy mass eigenstates

$BF_{SM}(Bs \rightarrow \mu^+\mu^-) = (3.53 \pm 0.38) \times 10^{-9}$.

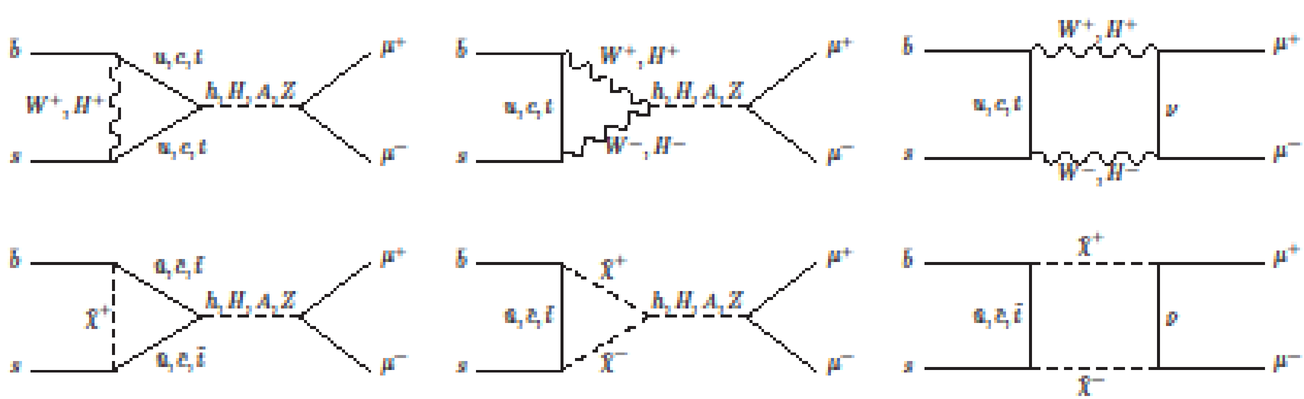
using $C_{10} = -4.16 \pm 0.04$ A.Arbey, M. Battaglia et al., arXiv:1212.4887

→ New physics contributions must be small.

$$BF(B_s \rightarrow \mu^+\mu^-) = \frac{G_F^2\alpha^2}{64\pi^3} f_{Bs}^2 m_{Bs}^3 |V_{tb}V_{ts}^*|^2 \tau_{Bs} \sqrt{1 - \frac{4m_\mu^2}{m_{Bs}^2}} \times \left\{ \left(1 - \frac{4m_\mu^2}{m_{Bs}^2}\right) |C_{Q1} - C'_{Q1}|^2 + \left| (C_{Q2} - C'_{Q2}) + 2(C_{10} - C'_{10}) \frac{m_\mu}{m_{Bs}} \right|^2 \right\}$$

$$C_{Q1} \approx -C_{Q2} \approx -\bar{\mu} a_t \frac{tan^3\beta}{(1+\epsilon_b tan\beta)^2} \frac{m_t^2 m_b m_\mu}{4x_W M_W^2 m_A^2} f\left(\frac{1}{\bar{\mu}^2}\right) \propto \frac{tan^3\beta}{m_A^2}, \quad \bar{\mu} = \frac{\mu}{M_{SUSY}}, a_t = \frac{A_t}{M_{SUSY}}, \quad f(x) = -\frac{x}{1-x} - \frac{x}{(1-x)^2} \log x > 0$$

Large tanβ($> \sim 50$) and small $m_A < 0.5$ TeV region is disfavored.



LHC gg→A → bb,ττ

Enhanced compared with

Standard model in large tanβ

LEPII pair production of H+ H-

Combining Bs→μμ ,

Small m_A region has

been almost excluded .

→ $m_A \geq \sim 500$ GeV

3 < tanβ ≤ ~ 30

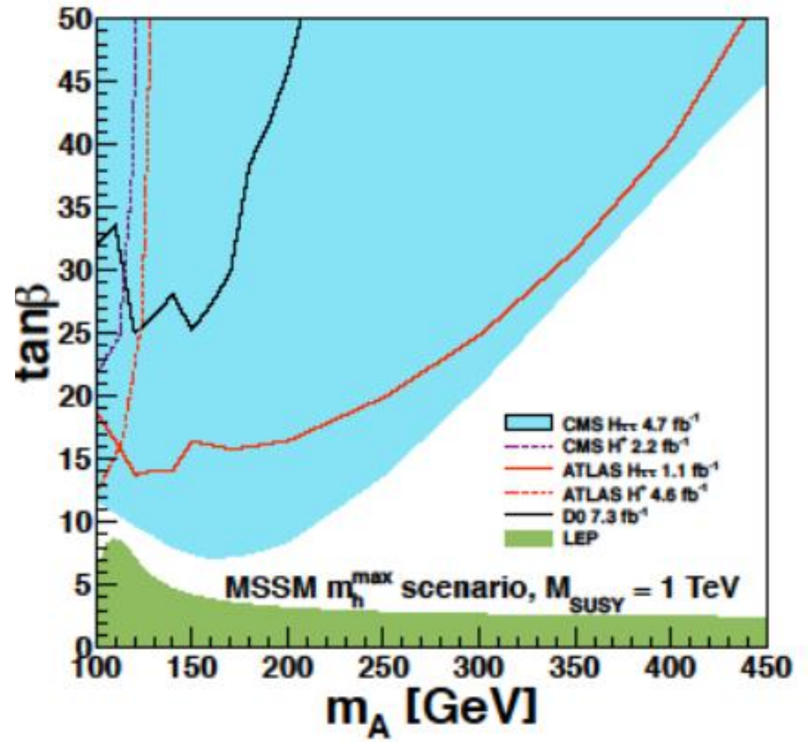


Figure 15: The 95% C.L. MSSM exclusion contours m_h-max benchmark scenario obtained by the ATLAS [234], CMS [138], and DØ [232] collaborations. The LHC collaborations contribute searches for $H \to \tau^+\tau^-$ and $H^\pm \to \tau\nu_\tau$ while DØ combines $H \to \tau^+\tau^-$ with $H \to b\bar{b}$ searches for these results. Also shown is the region excluded by LEP searches [34]. assuming a top quark mass of 174.3 GeV.

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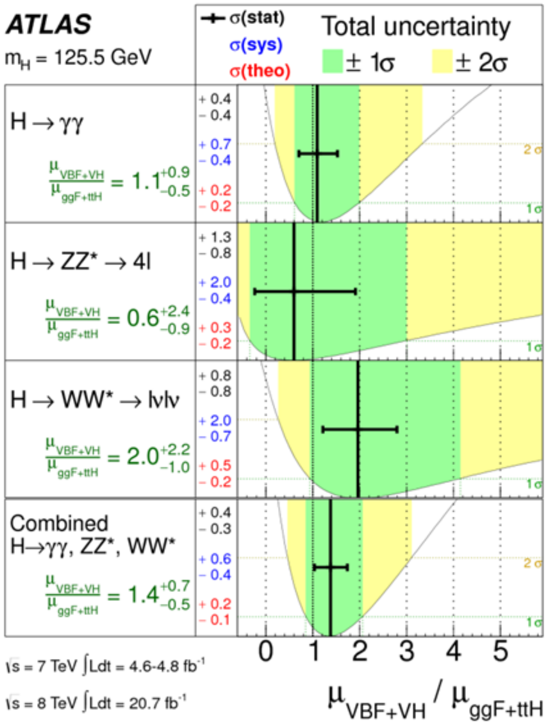
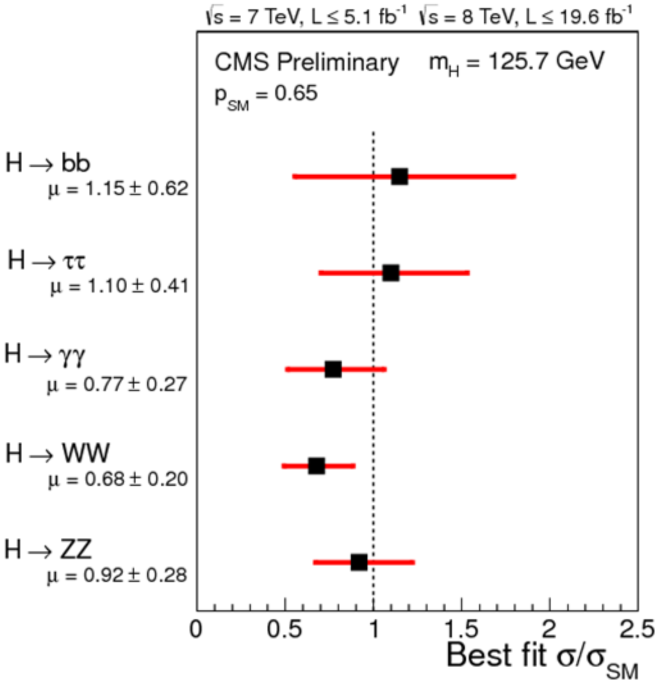
Cross section ratios of 125 GeV Higgs in MSSM/RNS





Its cross sections have no deviation from SM predictions at present.

→ We must wait for future measurements with higher statistics to get a definite conclusion.

- RNS can be tested from Higgs cross section ratios.

Cross section ratio: σ_P

- Production and Decay Cross section of XX → h → PP

$$\sigma(XX \to h \to PP) = \sigma_{XX \to h} \times BF(h \to PP)$$

Prod.cross sect. from XX × Branching Fraction to PP

$$BF(h \to PP) = \frac{\Gamma_{h \to PP}}{\Gamma_h^{tot}} \quad , \qquad \sigma_{XX \to h} \propto \Gamma_{h \to XX}$$

$$\sigma_P = \frac{\sigma(XX \to h \to PP)}{\sigma(XX \to h_{SM} \to PP)} = \frac{r_{XX}^2 r_{PP}^2}{R}$$

Ratios of the couplings:

$$r_{XX} = \frac{g_{hXX}}{g_{h_{SM}XX}}$$

Ratio of the total width: Assuming no exotic channels

$$R = \frac{\Gamma_h^{tot}}{\Gamma_{h_{SM}}^{tot}} = 0.57 r_{bb}^2 + 0.06 r_{\tau\tau}^2 + 0.25 r_{VV}^2 + 0.09 r_{gg}^2 + 0.03 r_{cc}^2$$

Tree-level Higgs mass matrix

MSSM : a kind of 2 Higgs Doublet Model(2HDM).

- $H_u = \begin{pmatrix} H_u^+ \\ h_u^0 = (H_u^0 + iA_u^0)/\sqrt{2} \end{pmatrix}$ $\quad H_d = \begin{pmatrix} H_d^+ \\ h_d^0 = (H_d^0 + iA_d^0)/\sqrt{2} \end{pmatrix}$

  H_u couples to up-type quarks, $\quad H_d$ couples to down-type quarks.

$$\begin{pmatrix} M_Z^2 s_\beta^2 + m_A^2 c_\beta^2 & -(M_Z^2 + m_A^2) s_\beta c_\beta \\ -(M_Z^2 + m_A^2) s_\beta c_\beta & M_Z^2 c_\beta^2 + m_A^2 s_\beta^2 \end{pmatrix} : (H_u^0, H_d^0) \text{ base}$$

- $\begin{pmatrix} h_u^0 \\ h_d^0 \end{pmatrix} = \begin{pmatrix} v_u \\ v_d \end{pmatrix} + \frac{1}{\sqrt{2}} \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix} + \frac{i}{\sqrt{2}} \begin{pmatrix} s_\beta & c_\beta \\ -c_\beta & s_\beta \end{pmatrix} \begin{pmatrix} G \\ A \end{pmatrix}$

  two CP-even neutral Higgs : h and H $\qquad v_u/v_d = \tan\beta$

  with mixing angle α defined in (h_u^0, h_d^0) basis.

  a CP-odd neutral Higgs : A , $\qquad$ a charged Higgs : H^+

- When m_A is large, $\alpha \to \beta - \frac{\pi}{2}$ decoupling limit.

Couplings to weak gauge bosons

Close to the decoupling limit $\alpha \to \beta - \frac{\pi}{2}$

Moderate value of $\tan\beta > 5$, *(where* $\beta \approx \frac{\pi}{2}$*).*

- $r_{VV} = \frac{g_{hVV}}{g_{h_{SM}VV}} = \frac{v_u c_\alpha - v_d s_\alpha}{v} = \sin(\beta - \alpha) = s_{\beta-\alpha} \cong 1$

No deviation from SM prediction.

Couplings to up-type fermions

- $r_{tt} = \frac{c_\alpha}{s_\beta} \cong 1$

No deviation from SM prediction.

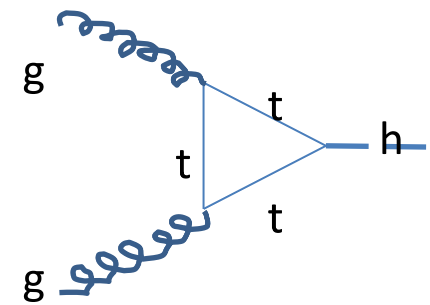
Couplings to down-type fermions

- $r_{bb} = \frac{-s_\alpha}{c_\beta} \cong 1$ in tree-level . But $-s_\alpha$, $c_\beta << 1$.

r_{bb} can deviate from unity by quantum correction.

Loop induced gg and γγ couplings

gg fusion $\quad r_{tt} = \frac{c_\alpha}{s_\beta} = 1$, $\quad r_{bb}$



$$r_{gg} = \frac{1.03\left(\frac{c_\alpha}{s_\beta}\right)+(-0.059+i0.081)(r_{bb})}{1.03+(-0.059+i0.081)}$$

top bottom

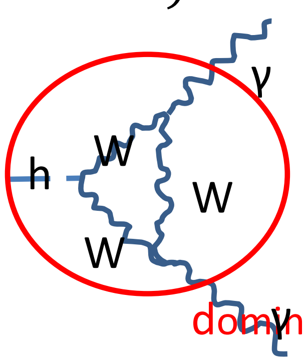
top loop is dominant.

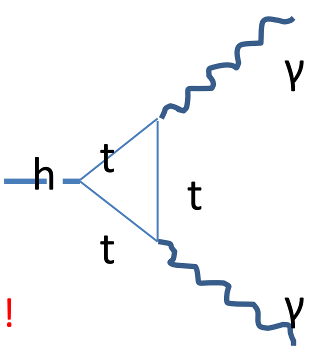
γγ production

$$r_{\gamma\gamma} = \frac{\left(\frac{7}{4}\right)1.19\sin(\beta-\alpha)-\left(\frac{4}{9}\right)1.03\left(\frac{c_\alpha}{s_\beta}\right)-(1/9)(-0.059+i0.081)(r_{bb})}{(7/4)1.19-(4/9)1.03-(1/9)(-0.059+i0.081)}$$

W top bottom

W loop is dominant





Sum rule of Cross section ratio σ_P

- In large $m_A(\geq 500\text{GeV})$ region close to the decoupling limit,

$$\alpha = \beta - \frac{\pi}{2} + \epsilon < 0, \quad \epsilon < \frac{\pi}{2} - \beta \ll 1\,, \quad -\alpha \ll 1$$

$$r_{VV} = s_{\beta-\alpha} \cong 1\,, \quad r_{tt} = r_{cc} = \frac{c_\alpha}{s_\beta} \cong 1 + \frac{\epsilon}{t_\beta} \cong 1\,,$$

$$r_{gg} \cong r_{\gamma\gamma} \cong 1\,, \quad R\left(= \frac{\Gamma_h^{tot}}{\Gamma_{h_{SM}}^{tot}}\right) \cong 0.6 r_{bb}^2 + 0.4$$

Prediction for cross section ratio:

$$\sigma_\gamma = \sigma_W = \sigma_Z = \frac{1}{0.6 r_{bb}^2 + 0.4}\,, \qquad \sigma_b = \frac{r_{bb}^2}{0.6 r_{bb}^2 + 0.4}$$

$$0.4\,\sigma_\gamma + 0.6\,\sigma_b = 1$$

It can be used to check MSSM.

γγ enhancement/suppression

means bb suppression/enhamcement

bb and ττ couplings

$$r_{\tau\tau} = \frac{-s_\alpha}{c_\beta} \cong 1 - \epsilon\, t_\beta \cong 1 - \frac{\epsilon}{\epsilon_\beta}$$

$$r_{bb} = \frac{-s_\alpha}{c_\beta}\left[1 - \frac{\Delta_b}{1+\Delta_b}\left(1 + \frac{1}{t_\alpha t_\beta}\right)\right] \cong 1 - \frac{1}{1+\Delta_b}\epsilon\, t_\beta \cong 1 - \frac{1}{1+\Delta_b}\frac{\epsilon}{\epsilon_\beta}$$

$$\alpha = -\epsilon_\beta + \epsilon \,, \qquad \frac{\pi}{2} - \beta = \epsilon_\beta \cong \frac{1}{\tan\beta} \ll 1$$

$$\Delta_b = \bar{\mu} t_\beta \left[\frac{2\alpha_s}{3\pi}\widehat{m_g} I\left(\widehat{m_g}^2, \widehat{m_{b1}}^2, \widehat{m_{b2}}^2\right) + \frac{h_t^2}{16\pi^2} a_t I\left(\bar{\mu}^2, \widehat{m_{t1}}^2, \widehat{m_{t2}}^2\right)\right]$$

sbottom-gluino + stop-chargino loops

- $\Delta_b \propto \mu$: small, but not negligible in Natural SUSY

$\epsilon > 0$: bb suppression, $\epsilon < 0$: bb enhancement

Its correction $-\frac{\epsilon}{\epsilon_\beta}$: small/small delicate problem!

Improved 2LL formula

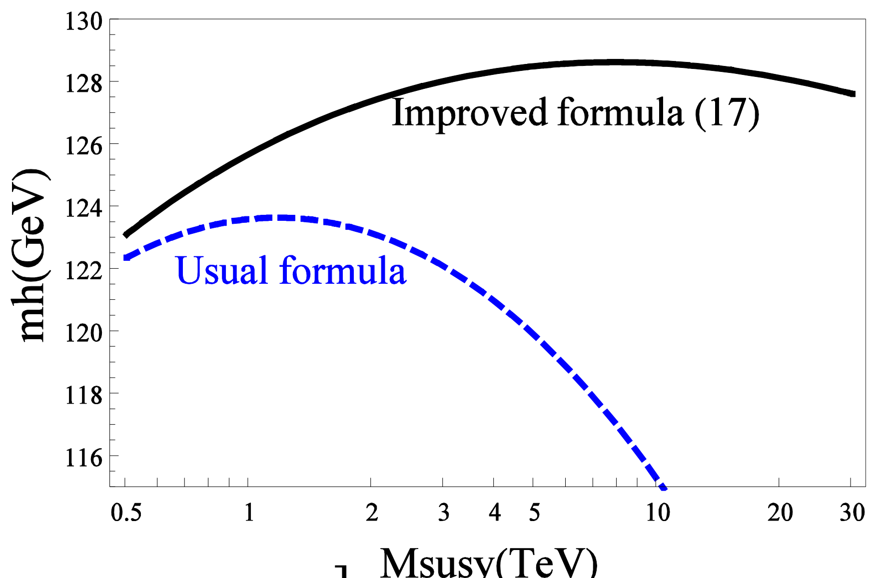
- $\begin{pmatrix} M_Z^2 s_\beta^2 + m_A^2 c_\beta^2 + \delta_{11} & -(M_Z^2 + m_A^2) s_\beta c_\beta + \delta_{12} \\ -(M_Z^2 + m_A^2) s_\beta c_\beta + \delta_{12} & M_Z^2 c_\beta^2 + m_A^2 s_\beta^2 + \delta_{22} \end{pmatrix} \frac{1}{\sqrt{2}} \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$
- $\delta_{11} = F_3 \frac{3\overline{m_t}^4}{4\pi^2 v^2 s_\beta^2} \left[t\left(1 - G_{\frac{15}{2}} t\right) + a_t x_t \left(1 - \frac{a_t x_t}{12}\right)\left(1 - 2G_{\frac{9}{2}} t\right)\right] - M_Z^2 s_\beta^2 (1 - F_3)$
- $\delta_{22} = -F_{\frac{3}{2}} \frac{\overline{m_t}^4}{16\pi^2 v^2 s_\beta^2} \left[\left(1 - 2G_{\frac{9}{2}} t\right)(x_t \bar{\mu})^2\right]$
- $\delta_{12} = -F_{\frac{9}{4}} \frac{3\overline{m_t}^4}{8\pi^2 v^2 s_\beta^2} \left[\left(1 - 2G_{\frac{9}{2}} t\right) x_t \bar{\mu} \left(1 - \frac{a_t x_t}{6}\right)\right] + M_Z^2 s_\beta c_\beta \left(1 - F_{\frac{3}{2}}\right)$

$F_l = \frac{1}{1 + l\, h_t^2 t/(8\pi^2)}$: Higgs WF ren.

$G_l = -\frac{1}{16\pi^2}\left(l\, h_t^2 - 32\pi\alpha_s\right)$

$x_t = \frac{X_t}{M_{SUSY}}$, $a_t = \frac{A_t}{M_{SUSY}}$

$\bar{\mu} = \frac{\mu}{M_{SUSY}}$, $t = ln \frac{M_{SUSY}^2}{m_t^2}$



In decoupling limit

$m_h^2 = M_Z^2 c_{2\beta}^2 + F_3 \frac{3\overline{m_t}^4}{4\pi^2 v^2} \left[t\left(1 - G_{\frac{15}{2}} t\right) + x_t^2 \left(1 - \frac{x_t^2}{12}\right)\left(1 - 2G_{\frac{9}{2}} t\right)\right] - M_Z^2 s_\beta^4 (1 - F_3)$...(17)

Decoupling base and Flavor-Tuned (FT) Higgs boson.

- $\alpha = -\epsilon_\beta + \epsilon$

$$\rightarrow \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} = \begin{pmatrix} c_{\epsilon\beta} & -s_{\epsilon\beta} \\ s_{\epsilon\beta} & c_{\epsilon\beta} \end{pmatrix} \begin{pmatrix} c_\epsilon & s_\epsilon \\ -s_\epsilon & c_\epsilon \end{pmatrix} = \begin{pmatrix} s_\beta & -c_\beta \\ c_\beta & s_\beta \end{pmatrix} \begin{pmatrix} c_\epsilon & s_\epsilon \\ -s_\epsilon & c_\epsilon \end{pmatrix}$$

Rotating $-\epsilon_\beta$ *: decoupling base*

- $$\frac{1}{\sqrt{2}}\begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} M_Z^2 s_\beta^2 + m_A^2 c_\beta^2 + \delta_{11} & -(M_Z^2 + m_A^2) s_\beta c_\beta + \delta_{12} \\ -(M_Z^2 + m_A^2) s_\beta c_\beta + \delta_{12} & M_Z^2 c_\beta^2 + m_A^2 s_\beta^2 + \delta_{22} \end{pmatrix} \frac{1}{\sqrt{2}} \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

$$= \frac{1}{\sqrt{2}} \begin{pmatrix} c_\epsilon & -s_\epsilon \\ s_\epsilon & c_\epsilon \end{pmatrix} \begin{pmatrix} M_Z^2 c_{2\beta}^2 + \delta_{11} s_\beta^2 + \delta_{22} c_\beta^2 + 2\delta_{12} s_\beta c_\beta & (M_{12}^\beta)^2 \\ (M_{12}^\beta)^2 & m_A^2 + M_Z^2 s_{2\beta}^2 + \delta_{22} s_\beta^2 + \delta_{11} c_\beta^2 - 2\delta_{12} s_\beta c_\beta \end{pmatrix} \frac{1}{\sqrt{2}} \begin{pmatrix} c_\epsilon & s_\epsilon \\ -s_\epsilon & c_\epsilon \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

- $(M_{12}^\beta)^2 = -\frac{M_Z^2}{2}(-s_{4\beta}) + (\delta_{22} - \delta_{11}) s_\beta c_\beta + \delta_{12}(s_\beta^2 - c_\beta^2) \cong -\frac{2M_Z^2 + \delta_{11} - \delta_{22}}{tan\beta} + \delta_{12}$

$$\rightarrow \frac{\epsilon}{\epsilon_\beta} \approx \frac{\left(M_{12}^\beta\right)^2}{m_A^2 \epsilon_\beta} \cong -\frac{2M_Z^2 + \delta_{11} - \delta_{22} - \delta_{12} tan\beta}{m_A^2}$$

In tree-level, $\frac{\epsilon}{\epsilon_\beta} = -\frac{2M_Z^2}{m_A^2}$. ϵ to be small negative → bb enhancement.

When large μ, Cancellation by the off-diagonal element $\delta_{12} tan\beta$ is possible. → bb suppression.

Flavor-Tuned (FT) Higgs boson.

Barger, Huang,Ishida,Keung, PRD (2012)

Carena et al.,PRD62, 055008(2000)

$$\delta_{12} \cong -\frac{3\overline{m}_t^{\,4}}{8\pi^2 v^2 s_\beta^2}\left[\left(1 - 2G_{\frac{9}{2}} t\right) x_t \bar{\mu} \left(1 - \frac{a_t x_t}{6}\right)\right]$$

For small μ in RNS, its effect is small, but not negligible.

Prediction for the cross section ratios

- 124GeV < m_h : constraint.

  By using Improved 2LL formula

  → 1.95 < $|x_t|$ < 2.86 : nearby the maximal mixing $\sqrt{6}$

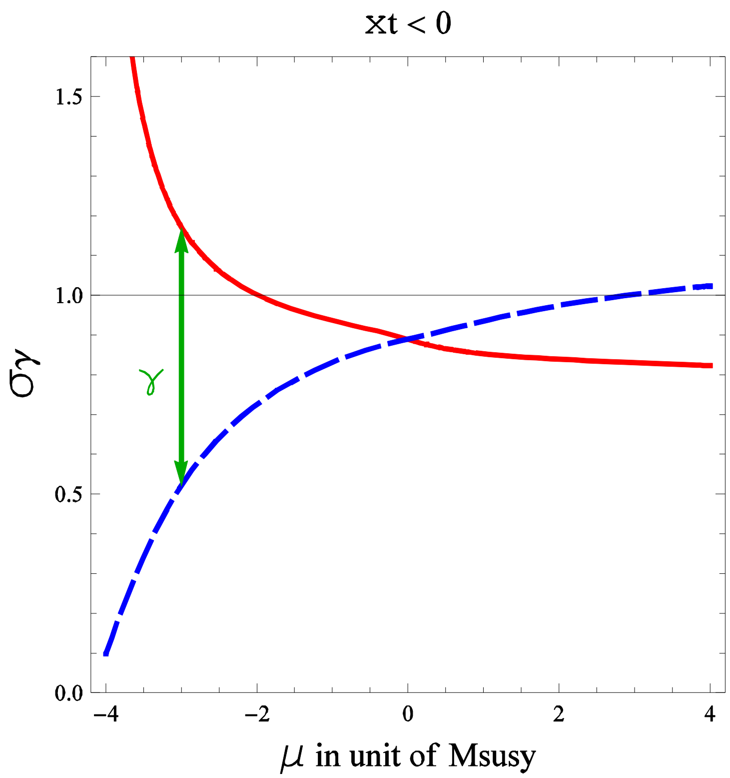
  m_A=500GeV, tanβ=20.

- x_t>0 is favored in RNS : the running down from the GUT scale.

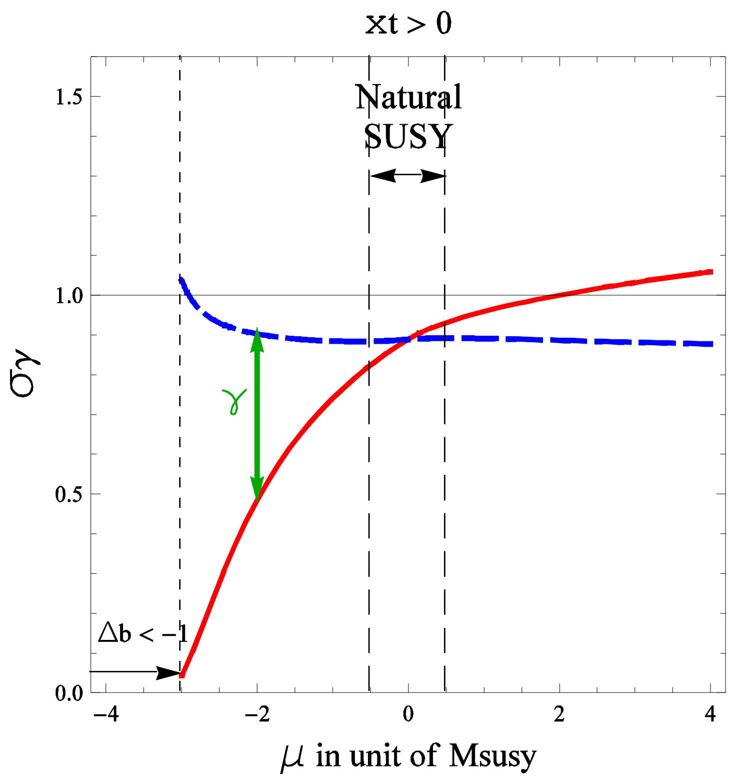
- predict $\bar{\mu} = \frac{\mu}{M_{SUSY}}$ dependence

  of $\sigma_\gamma, \sigma_b, \sigma_\tau$

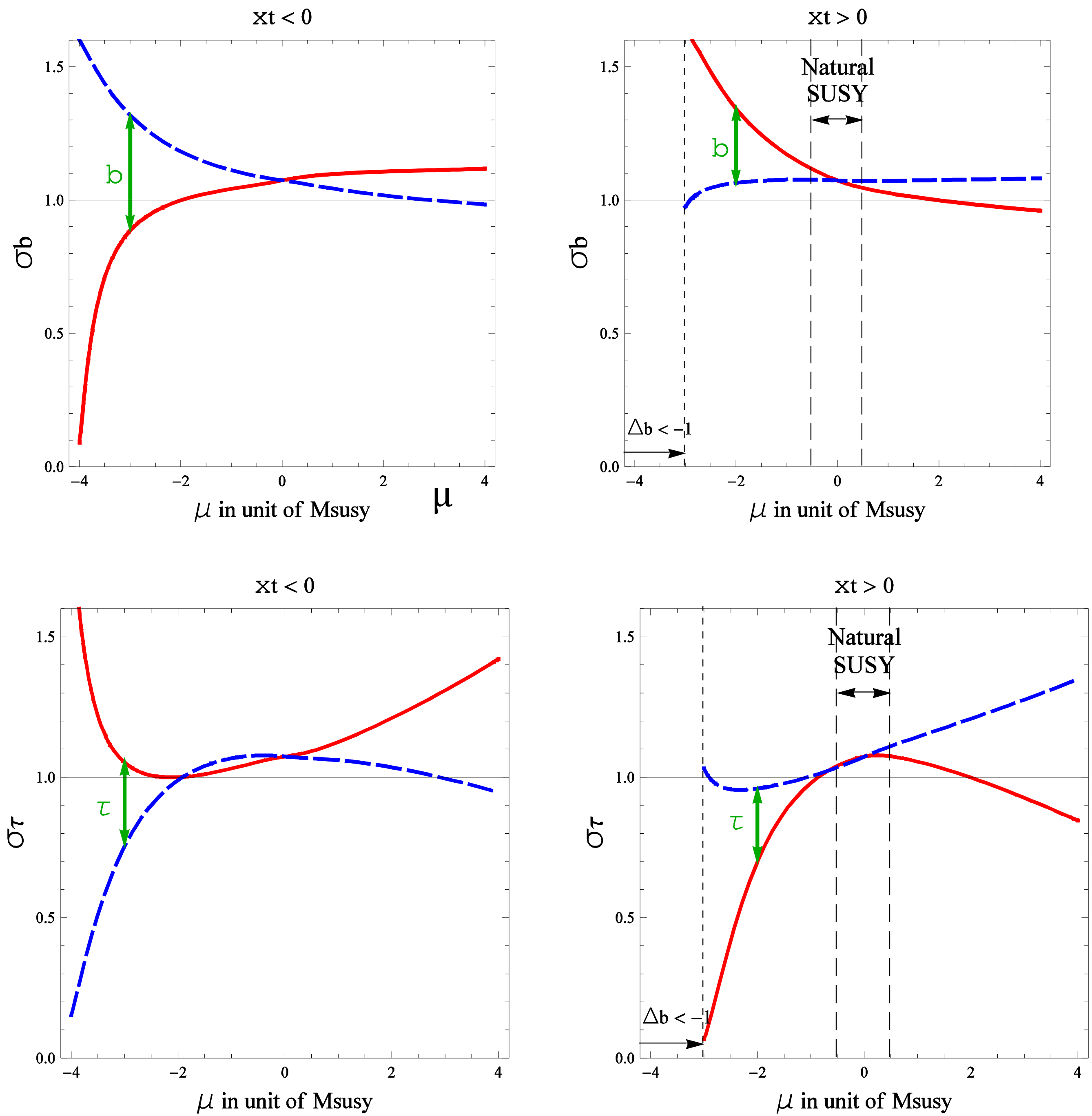
Prediction



xt < 0
1.5
1.0
0.5
0.0
−4
−2
0
2
4
σγ
γ
μ in unit of Msusy



xt > 0
Natural
SUSY
1.5
1.0
0.5
0.0
−4
−2
0
2
4
σγ
γ
Δb < −1
μ in unit of Msusy



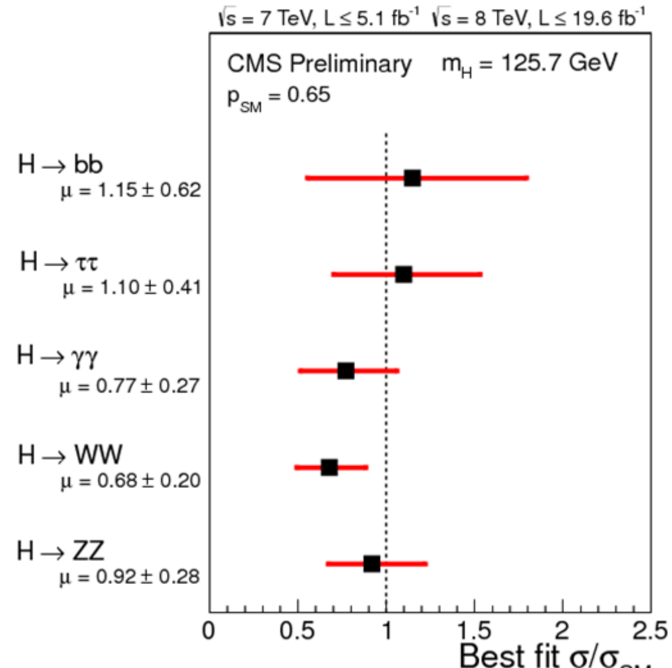
xt < 0
xt > 0
Natural
SUSY
b
τ
Δb < −1
σb
στ
μ
μ in unit of Msusy
1.5
1.0
0.5
0.0
−4
−2
0
2
4

- FT Higgs boson can give γγ enhancement σγ ~ 1.5 when $\bar{\mu} \approx -3$ → $\mu = -3$ TeV (Large!) when $M_{SUSY} = 1$ TeV case.

- Natural SUSY which requires small μ always predicts γγ suppression.

	σγ	σb	στ
mA = 500 GeV	0.82 ~ 0.91	1.06 ~ 1.12	1.04 ~ 1.08
mA = 1000 GeV	0.95 ~ 0.98	1.01 ~ 1.03	1.01 ~ 1.02

Its deviation from unity is negligible for mA > 1 TeV case.



Other method of testing RNS

- Light Higgsino-like chargino and neutralino are main feature of RNS. (Small μ ~ 150GeV.)

  → RNS can be fully tested by future ILC experiment.

  $e^+ e^- \to \widetilde{W}_1^+ \widetilde{W}_1^-, \widetilde{Z}_1 \widetilde{Z}_2$ ILC is Higgsino factory.

- $\widetilde{W}_1 \widetilde{Z}_2, \widetilde{W}_1 \widetilde{Z}_1, \widetilde{W}_1 \widetilde{W}_1, \widetilde{Z}_1 \widetilde{Z}_2,$ Large production cross section at LHC.

  $m_{\widetilde{W}_1} - m_{\widetilde{Z}_1}$ and $m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$ are typically

  5 ~20GeV : Higgsinos are almost degenerate.

Very low visible energy release from $\widetilde{W}_1$ and $\widetilde{Z}_2$ decays.

→ beneath SM background at LHC.

Other method testing RNS

- Assuming $M_1 = M_2 = M_3 = m_{\frac{1}{2}}$ at GUT scale.

  → $M_1 : M_2 : M_3 \approx 1 : 2 : 7$ at weak scale.
- $m_{\tilde{g}} > 1.4$TeV at LHC.

  → $M_2 > 400$ GeV, $M_1 > 200$ GeV .

- Wino-like $\widetilde{W}_2\, \widetilde{Z}_4$ production.

  and Same-sign diboson signals at LHC is promising.

Baer,Barger,Huang,Mickelson,Mustafayev,Sreethawong,Tata arXiv:1302.5816

$\widetilde{W}_2^+\, \widetilde{Z}_4 \rightarrow W^+\, \widetilde{Z}_{1,2} + W^+\, \widetilde{W}_1^-$

For integrated luminosity 100(1000) fb^{-1}

M_2 can be tested up to 550(800) GeV at LHC14.

Concluding Remarks

- MSSM and Natural SUSY can be tested by the Measurements of the Cross section ratios of the 125GeV Higgs boson to the SM preditions at LHC.
- Test of MSSM: Sum rule : $\sigma_\gamma = \sigma_W = \sigma_Z$, $0.4\,\sigma_\gamma + 0.6\,\sigma_b = 1$
- Radiative Natural SUSY requires small |μ| < ~0.5 TeV.

- 2 Mechanism of leading γγ enahncement : large μ required

  FT model $\sigma_\gamma = 1.5$ possible for large μ=2 TeV for M_{SUSY}=$1TeV$.

  light stau μ tanβ = 30 TeV or more is needed.

- Rad. Natural SUSY (RNS) always predicts γγ suppression.

	σγ	σb	στ
mA = 500 GeV	0.82 ~ 0.91	1.06 ~ 1.12	1.04 ~ 1.08
mA = 1000 GeV	0.95 ~ 0.98	1.01 ~ 1.03	1.01 ~ 1.02

- Light higgsino contribution is expected to be negligible in higgs γγ decay in RNS.
- Wino-like $\widetilde{W}_2\ \widetilde{Z}_4$ production.

  and Same-sign diboson signals at LHC is promising

SUSY RGE

$$L = \lambda_2(M_{SUSY}^{+})\Phi(M_{SUSY}^{+})^4, \quad \lambda_2(M_{SUSY}^{+}) = \frac{g^2(t)+g'^2(t)}{4}$$

$\mu = M_{SUSY}$

$$L = \lambda_2(M_{SUSY}^{-})\Phi(M_{SUSY}^{-})^4$$
$$= \lambda_2(M_{SUSY}^{+})\Phi(M_{SUSY}^{-})^4 + \Delta\lambda_2^{th}(M_{SUSY})\Phi(M_{SUSY}^{-})^4$$

non-SUSY 2HDM RGE

does not run by RGE

' Frozen' at M_{SUSY}

$$L = \lambda_2(m_t) \quad \Phi(m_t)^4 \quad + \Delta\lambda_2^{th}(M_{SUSY})\Phi(M_{SUSY}^{-})^4$$

$\mu = m_t$

Scale down from t → 0 ($\mu = M_{SUSY} \rightarrow m_t$)

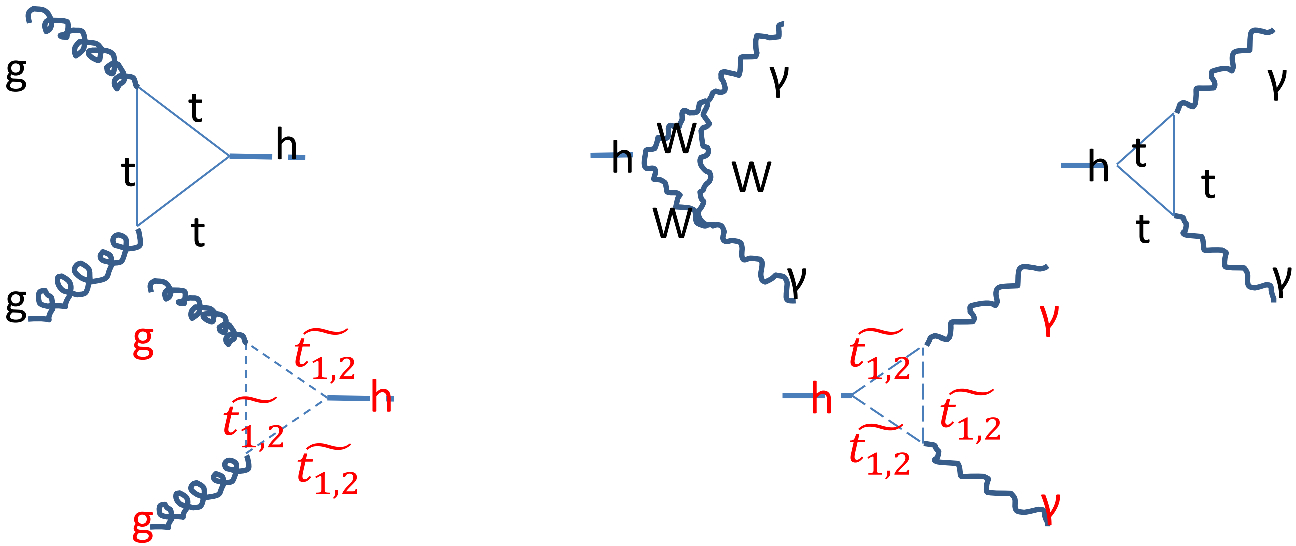
$$\Phi(m_t)^4 = \left(1 + t\frac{3h_t^2}{8\pi^2}\right)\Phi(M_{SUSY}^{-})^4 :$$ Higgs WF renormalization factor

$$\rightarrow \Phi(M_{SUSY}^{-})^4 = \frac{1}{1+t\frac{3h_t^2}{8\pi^2}}\Phi(m_t)^4 = \frac{1}{1-2\gamma_2 t}\Phi(m_t)^4 \neq (1+2\gamma_2 t)\Phi(m_t)^4$$

improvement

$$\Delta\lambda_2^{th}(M_{SUSY})\Phi(M_{SUSY}^{-})^4 = F_3\, \Delta\lambda_2^{th}(M_{SUSY})\Phi(m_t)^4, \quad F_3 = \frac{1}{1+t\frac{3h_t^2}{8\pi^2}}$$

Exotic loops : Effect from stop



$$r_{gg} = 1 - \frac{m_t^2(X_t^2 - m_{\widetilde{t_1}}^2 - m_{\widetilde{t_2}}^2)}{4m_{\widetilde{t_1}}^2 m_{\widetilde{t_2}}^2} \approx 1 - \frac{m_t^2(m_{\widetilde{t_1}}^2 + m_{\widetilde{t_2}}^2)}{2m_{\widetilde{t_1}}^2 m_{\widetilde{t_2}}^2}$$ where $X_t^2 = 6(m_{\widetilde{t_1}}^2 + m_{\widetilde{t_2}}^2)/2$

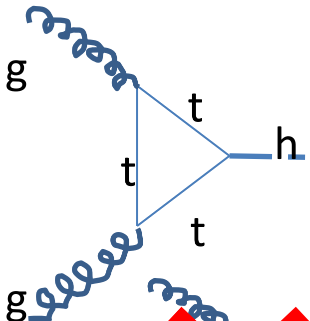
$$1 - \frac{8}{3}\frac{Ft}{Fw} = 1 - \frac{8}{3}\frac{\frac{2.06}{3}}{8.32} = \frac{7.}{9.}, \quad \frac{Fs}{Fw} = \frac{-0.5}{8.32}$$

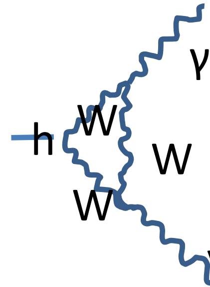
$$r_{\gamma\gamma} = \frac{1 - \frac{8Ft}{3Fw} + \frac{2m_t^2\left(X_t^2 - m_{\widetilde{t_1}}^2 - m_{\widetilde{t_2}}^2\right)}{3m_{\widetilde{t_1}}^2 m_{\widetilde{t_2}}^2}\frac{Fs}{Fw}}{1 - \frac{8Ft}{3Fw}} \approx 1 + \frac{m_t^2(m_{\widetilde{t_1}}^2 + m_{\widetilde{t_2}}^2)}{7.28\, m_{\widetilde{t_1}}^2 m_{\widetilde{t_2}}^2}$$

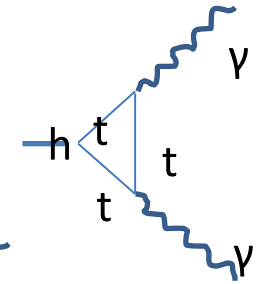
$$r_{gg} r_{\gamma\gamma} \approx 1 - 0.36\frac{m_t^2(m_{\widetilde{t_1}}^2 + m_{\widetilde{t_2}}^2)}{m_{\widetilde{t_1}}^2 m_{\widetilde{t_2}}^2} \approx 1 - 0.36\frac{m_t^2}{m_{\widetilde{t_1}}^2} = 0.99$$ for $m_{\widetilde{t_1}}$=1TeV << $m_{\widetilde{t_2}}$

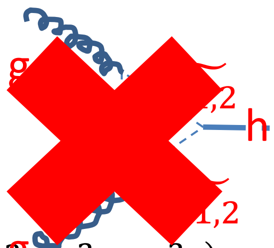
Negligible

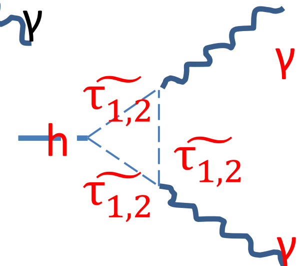
Exotic loops : Effect from stau











$$r_{\gamma\gamma} = \frac{1-\frac{8\,Ft}{3Fw}-\frac{m_\tau^2\left(X_\tau^2-m_{\tilde{\tau}_1}^2-m_{\tilde{\tau}_2}^2\right)}{m_{\tilde{\tau}_1}^2 m_{\tilde{\tau}_2}^2}\frac{Fs}{Fw}}{1-\frac{8\,Ft}{3Fw}} \approx 1 + 0.052\,\frac{m_\tau^2\left(X_\tau^2-m_{\tilde{\tau}_1}^2-m_{\tilde{\tau}_2}^2\right)}{m_{\tilde{\tau}_1}^2 m_{\tilde{\tau}_2}^2}$$

Vacuum stability of Scalar Higgs potential. Hisano,Sugiyama2011

$$|\mu\, tan\beta| < 76.9\sqrt{m_{L3} m_{E3}} + 38.7(m_{L3} + m_{E3}) - 10.4\text{TeV}$$

Rough estimate $m_{\tilde{\tau}_1} \sim m_{E3} = 0.1TeV,\ m_{\tilde{\tau}_2} \sim m_{L3} \sim 0.6TeV,\quad X\tau = |\mu\, tan\beta| < 36TeV$

→ $r_{\gamma\gamma}$ =1.1

→ $\sigma_\gamma \leq 1.25$ for $m_{\tilde{\tau}_1}$>100 GeV   Kitahara,arXiv:1208.4792

$\sigma_\gamma \leq 1.5$ for very large tanβ≈ 100, Carena,Gori,Low,Shah,Wagner,arXiv:1211.6136