The MSSM in the aftermath of the Higgs boson discovery

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Work done in collaboration
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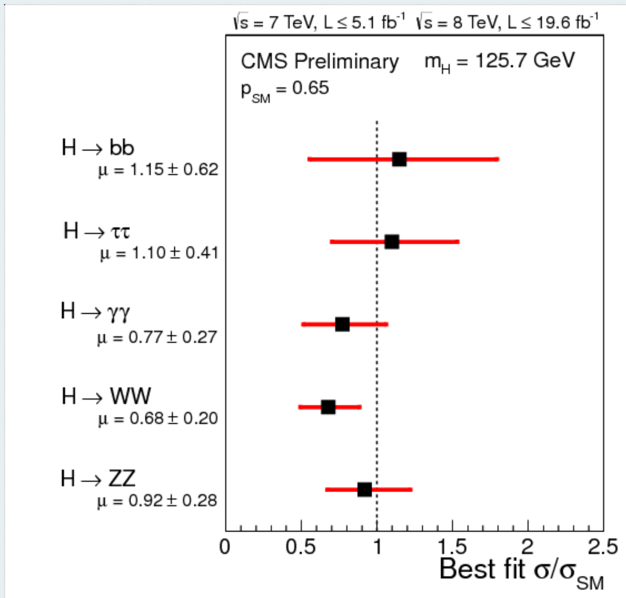
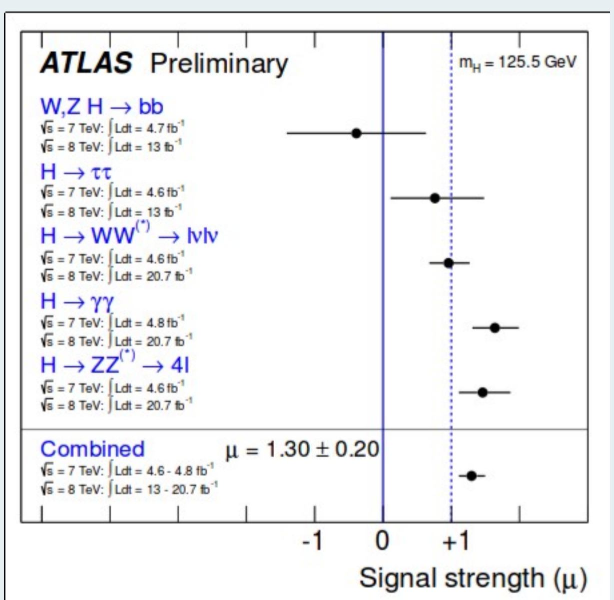
Introduction

- Higgs discovered July 2012
- Initially suggestive of di-photon excess
  - Results now largely consistent with SM
- Also consistent with MSSM Higgs?
  - $M_h \sim 125$ GeV → decoupling regime. ($M_A >> M_Z$)
  - Decoupling regime → Properties largely consistent with SM and therefore also LHC data
- What differences can MSSM predict?
- Main differences likely to show up through loop effects
- We looked at possible loop effects of light **staus**, **sbottoms** and **stops**

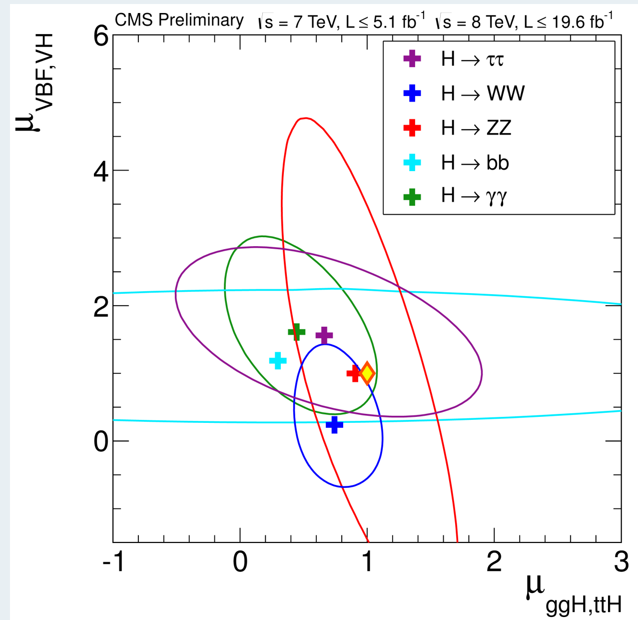
Summary of Experimental Results

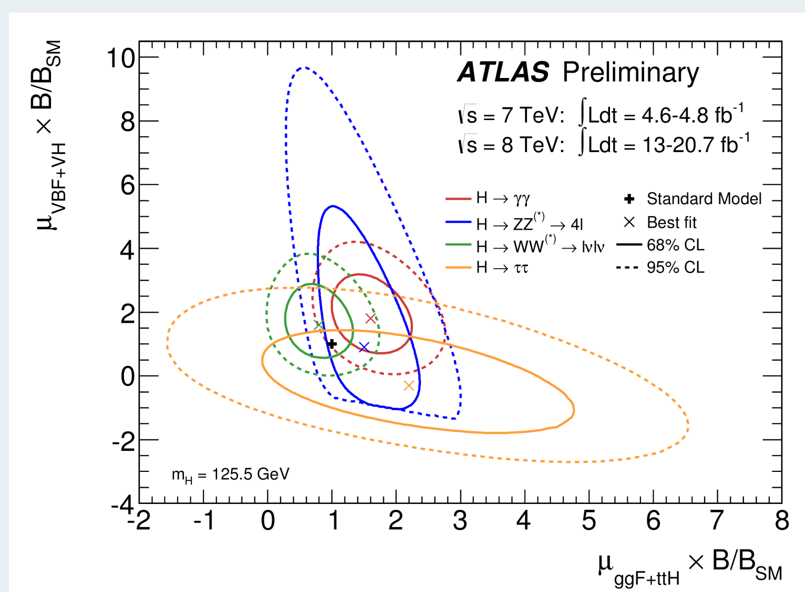
Combination of Production Channels





Separated Production Channels





- Combined results could hide differences between production channels
- Can the MSSM predict any patterns?

Decay to photons

- **SM**

$$\Gamma(h \to \gamma\gamma) = \frac{\alpha^2 m_h^3}{1024\pi^3}\left|\frac{g_{hVV}}{m_V^2}Q_V^2 F_1(x_V) + \frac{2g_{hf\bar{f}}}{m_f}N_{c,f}Q_f^2 F_{1/2}(x_f)\right|^2$$

- **MSSM**

$$\Gamma(h \to \gamma\gamma) = \frac{\alpha^2 m_h^3}{1024\pi^3}\left|\frac{g_{hVV}}{m_V^2}Q_V^2 F_1(x_V) + \frac{2g_{hf\bar{f}}}{m_f}N_{c,f}Q_f^2 F_{1/2}(x_f) \boxed{+ \frac{g_{hSS}}{m_S^2}N_{c,S}Q_S^2 F_0(x_S)}\right|^2$$

Extra factor for charged SUSY scalars

W boson - $F_1(x_W) \simeq -8.3$

Top quark - $N_{c,f}Q_f^2 F_{1/2}(x_f) \simeq 1.8$

Charged scalar - $F_0(x_S) \simeq 0.4$ $\quad M_S \sim \mathcal{O}(100\ \mathrm{GeV})$

W	Top	Scalar
5	1	1/5

- Require a negative scalar coupling to increase $\Gamma(h \to \gamma\gamma)$

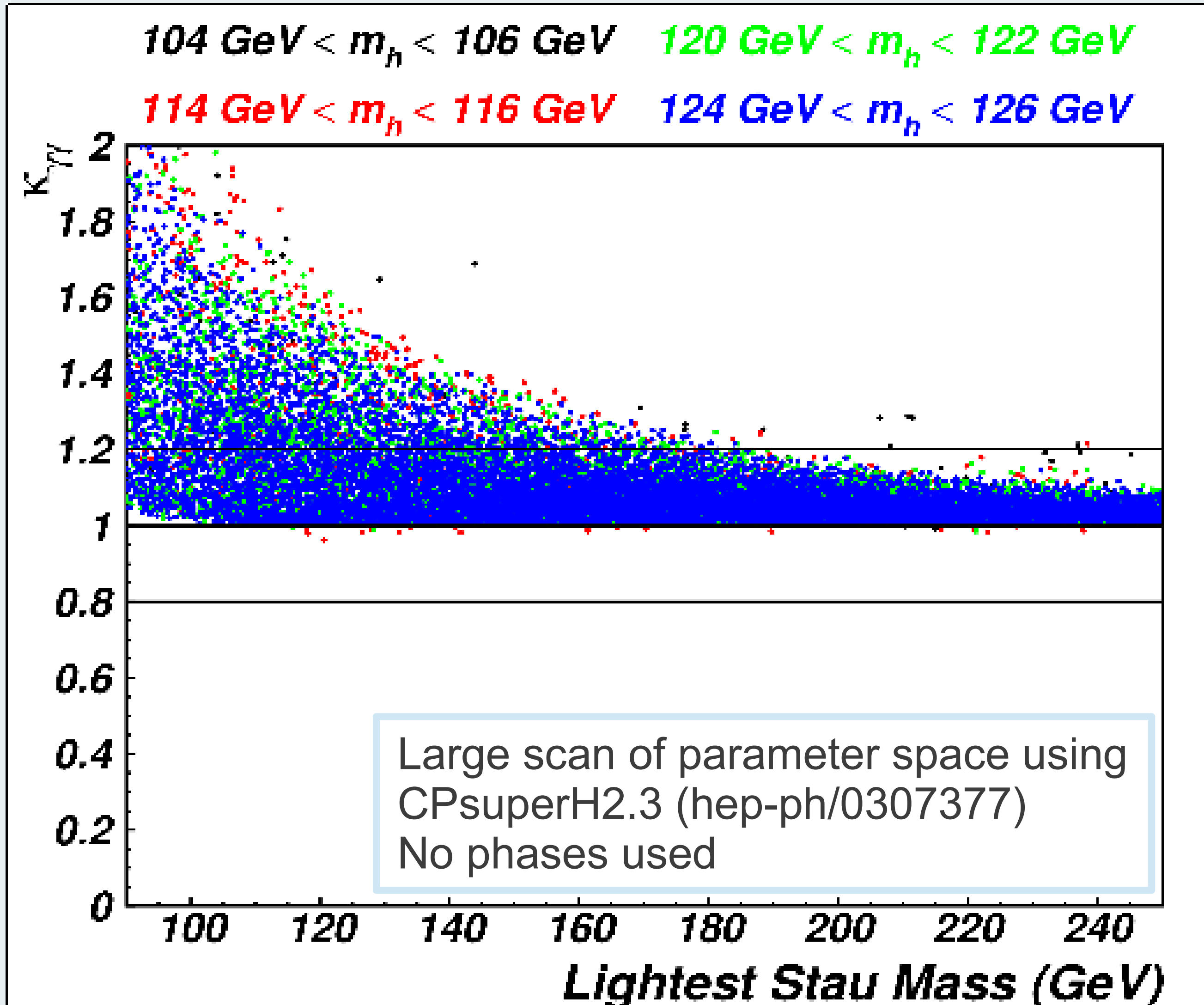
Light staus

$$\Gamma(h\to\gamma\gamma)=\frac{\alpha^2 m_h^3}{1024\pi^3}\left|\frac{g_{hVV}}{m_V^2}Q_V^2F_1(x_V)+\frac{2g_{hf\bar f}}{m_f}N_{c,f}Q_f^2F_{1/2}(x_f)+\frac{g_{hSS}}{m_S^2}N_{c,S}Q_S^2F_0(x_S)\right|^2$$

$$N_{c,\tilde\tau}Q_{\tilde\tau}^2=1$$

- $m_{\tilde\tau}\lesssim 180$ GeV is required to produce $\kappa_{\gamma\gamma}>1.2$
- No correlation between $\kappa_{\gamma\gamma}$ and m_h

$$\kappa_{\gamma\gamma}=\frac{\Gamma(h\to\gamma\gamma)^{MSSM}}{\Gamma(h\to\gamma\gamma)^{SM}}$$



(Similar previous results – e.g. Carena et. al., JHEP 1207 (2012)175)

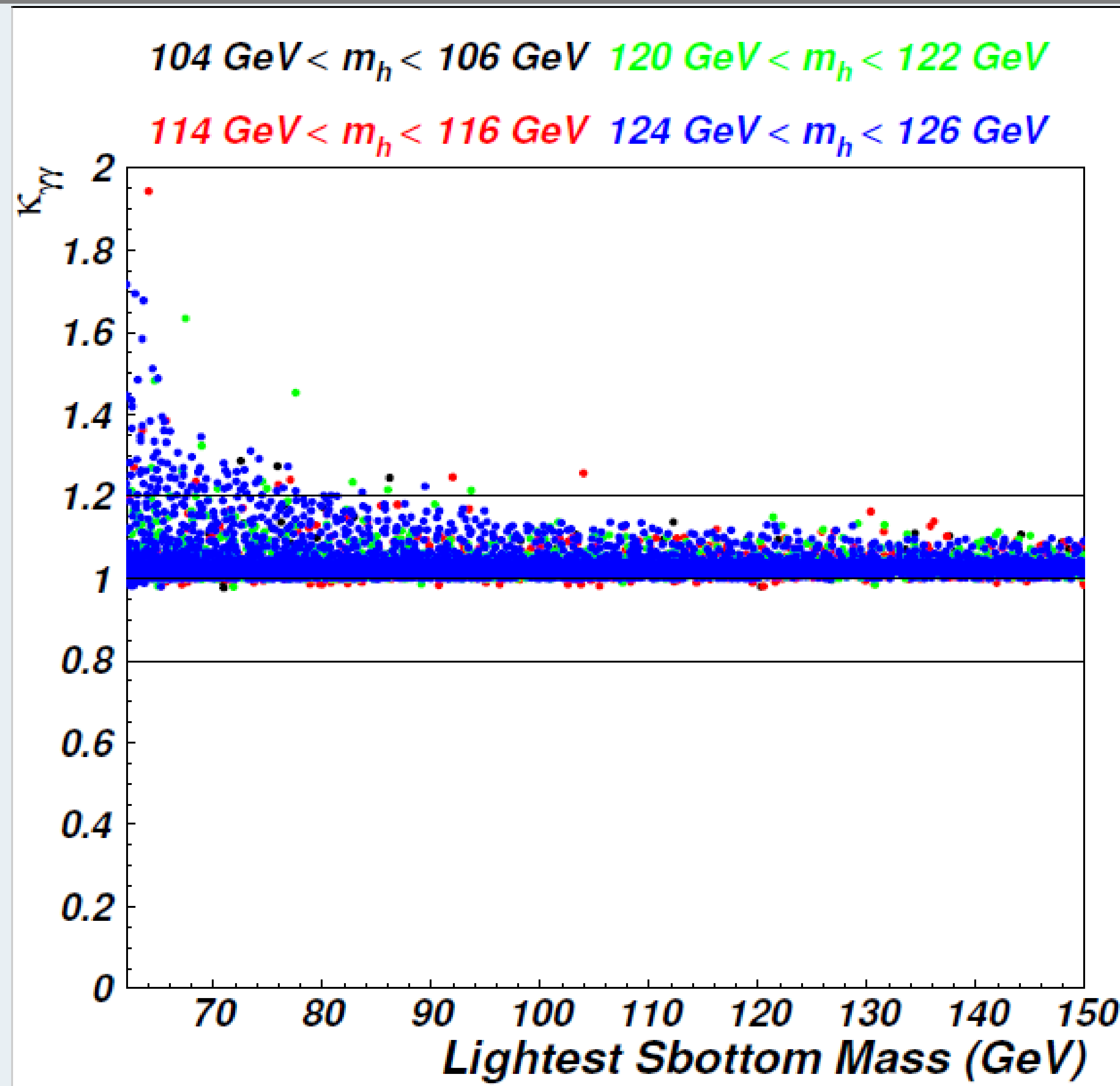
Light sbottoms

$$\Gamma(h \to \gamma\gamma) = \frac{\alpha^2 m_h^3}{1024\pi^3} \left| \frac{g_{hVV}}{m_V^2} Q_V^2 F_1(x_V) + \frac{2 g_{hf\bar{f}}}{m_f} N_{c,f} Q_f^2 F_{1/2}(x_f) + \frac{g_{hSS}}{m_S^2} N_{c,S} Q_S^2 F_0(x_S) \right|^2$$

$$N_{c,\tilde{b}} Q_{\tilde{b}}^2 = \frac{1}{3}$$

- Expect $\kappa_{\gamma\gamma}$ increase comparable to staus when $m_{\tilde{b}} \approx \frac{1}{\sqrt{3}} m_{\tilde{\tau}}$
- Results roughly consistent with expectation
- No correlation between $\kappa_{\gamma\gamma}$ and m_h

$$\kappa_{\gamma\gamma} = \frac{\Gamma(h \to \gamma\gamma)^{MSSM}}{\Gamma(h \to \gamma\gamma)^{SM}}$$



Light stops

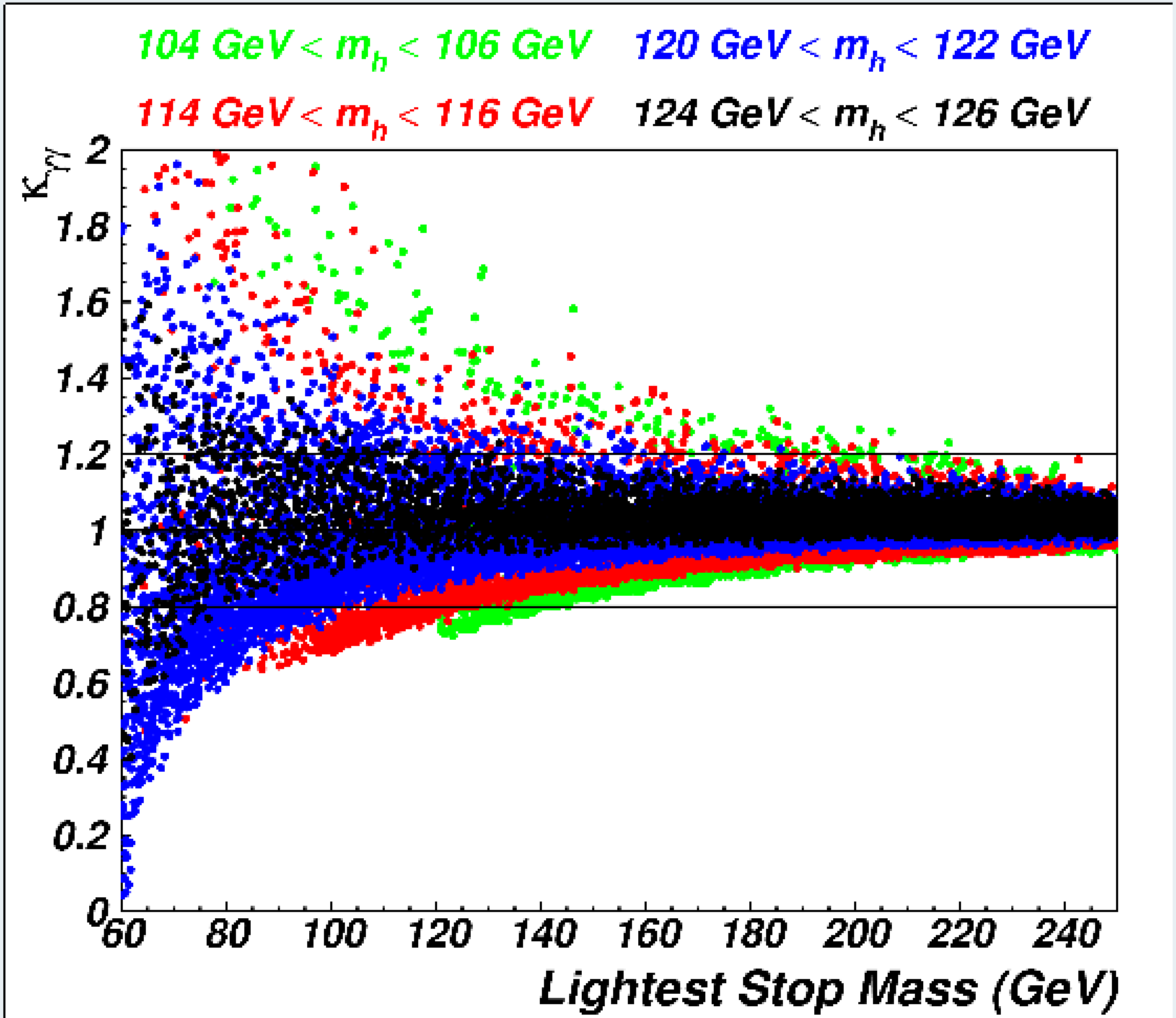
$$\Gamma(h \to \gamma\gamma) = \frac{\alpha^2 m_h^3}{1024\pi^3} \left| \frac{g_{hVV}}{m_V^2} Q_V^2 F_1(x_V) + \frac{2 g_{hf\bar{f}}}{m_f} N_{c,f} Q_f^2 F_{1/2}(x_f) + \frac{g_{hSS}}{m_S^2} N_{c,S} Q_S^2 F_0(x_S) \right|^2$$

$$N_{c,\tilde{t}} Q_{\tilde{t}}^2 = \frac{4}{3} \quad \text{vs} \quad N_{c,\tilde{\tau}} Q_{\tilde{\tau}}^2 = 1$$

- Therefore expect $\left(\text{stop loop contribution to } \kappa_{\gamma\gamma}\right) > \left(\text{stau loop contribution to } \kappa_{\gamma\gamma}\right)$

- However, **both stop coupling and m_h depend on mixing parameter** $X_t = A_t - \mu \cot \beta$

Light stops



- $m_{\tilde{t}} \lesssim 125$ GeV is required to produce $\kappa_{\gamma\gamma} > 1.2$ **with** $m_h > 124$ GeV (compare $m_{\tilde{\tau}} \lesssim 180$ GeV for similar increase)
- Correlation between m_h and $\kappa_{\gamma\gamma}$ which isn't observed for staus or sbottoms

Higgs Mass (one loop)

$$m_h \leq M_Z^2 + \frac{3g^2 m_t^4}{8\pi^2 M_W^2}\left[\ln\left(\frac{M_S^2}{M_t^2}\right) + \left(\frac{X_t}{M_{SUSY}}\right)^2\left(1 - \frac{1}{12}\left(\frac{X_t}{M_{SUSY}}\right)^2\right)\right]$$

$m_h \approx 125\ \mathrm{GeV}$ requires $X_t \approx \sqrt{6} M_{SUSY}$ (maximal stop mixing)

Stop coupling

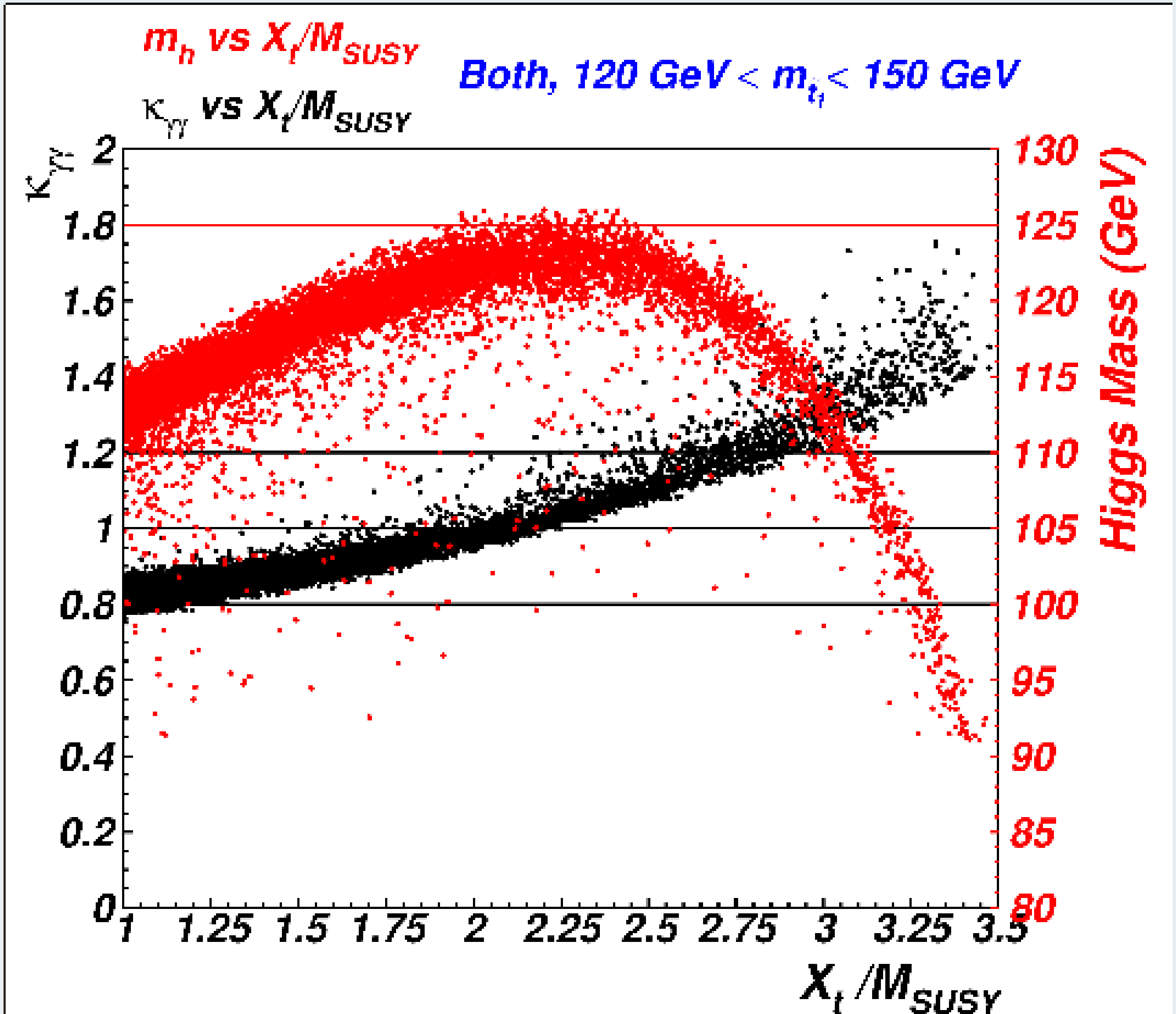
$$\hat{g}_{h\tilde{t}_1\tilde{t}_1} = \frac{1}{2}\cos 2\beta\left[\cos^2\theta_{\tilde{t}} - \frac{4}{3}\sin^2\theta_W \cos 2\theta_{\tilde{t}}\right] + \frac{m_t^2}{M_Z^2} + \frac{1}{2}\sin 2\theta_{\tilde{t}}\frac{m_t X_t}{M_Z^2}$$

substitute $X_t \approx \sqrt{6} M_{SUSY}$, $\quad M_{\mathrm{SUSY}}^2 = \frac{1}{2}(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2)$

$$\boxed{\hat{g}_{h\tilde{t}_1\tilde{t}_1} \approx \frac{m_t^2}{M_Z^2} - \frac{3m_t^2}{M_Z^2} = -\frac{2m_t^2}{M_Z^2}}$$

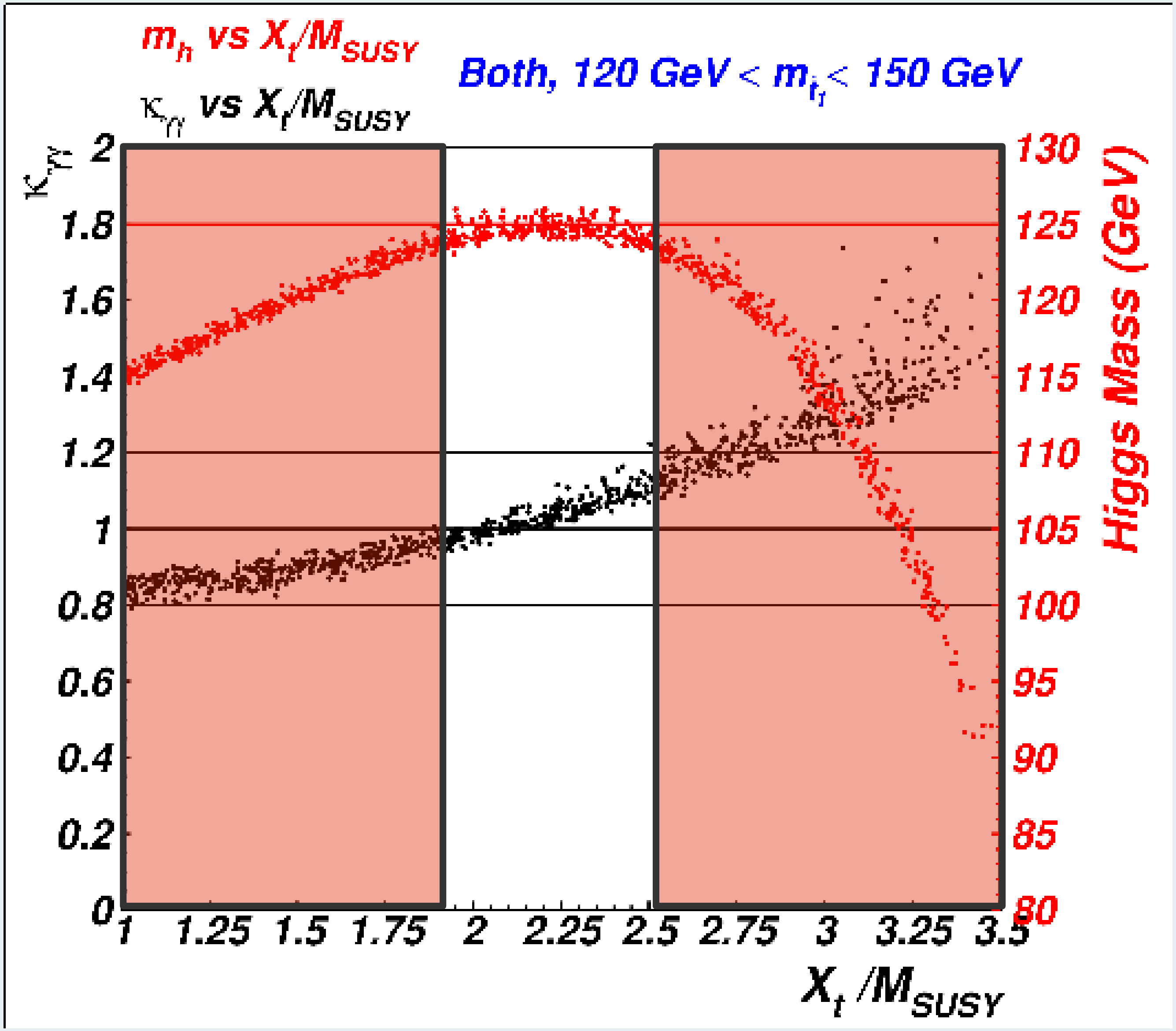
- stop coupling ~ fixed by requirement of maximal stop mixing

Light stops



- $\kappa_{\gamma\gamma} > 1.6$ possible for large values of X_t
- Requirement for $m_h \approx 125$ GeV limits maximum possible $\kappa_{\gamma\gamma}$

Light stops



- Only really interested in the heaviest Higgs
- Cut for any m_h more than 2 GeV below the maximum for each value of X_t/M_{SUSY}
- **Very limited range of possible $\kappa_{\gamma\gamma}$**

What about production?

$$\Gamma(h \to gg) = \frac{\alpha_s^2 m_h^3}{512\pi^3} \left| \frac{2\hat{g}_{ht\bar{t}}}{m_t} F_{1/2}(x_t) + \frac{\hat{g}_{h\tilde{t}\tilde{t}}}{m_{\tilde{t}}^2} F_0(x_{\tilde{t}}) \right|^2$$

~~**W boson** - $F_1(x_W) \simeq -8.3$~~

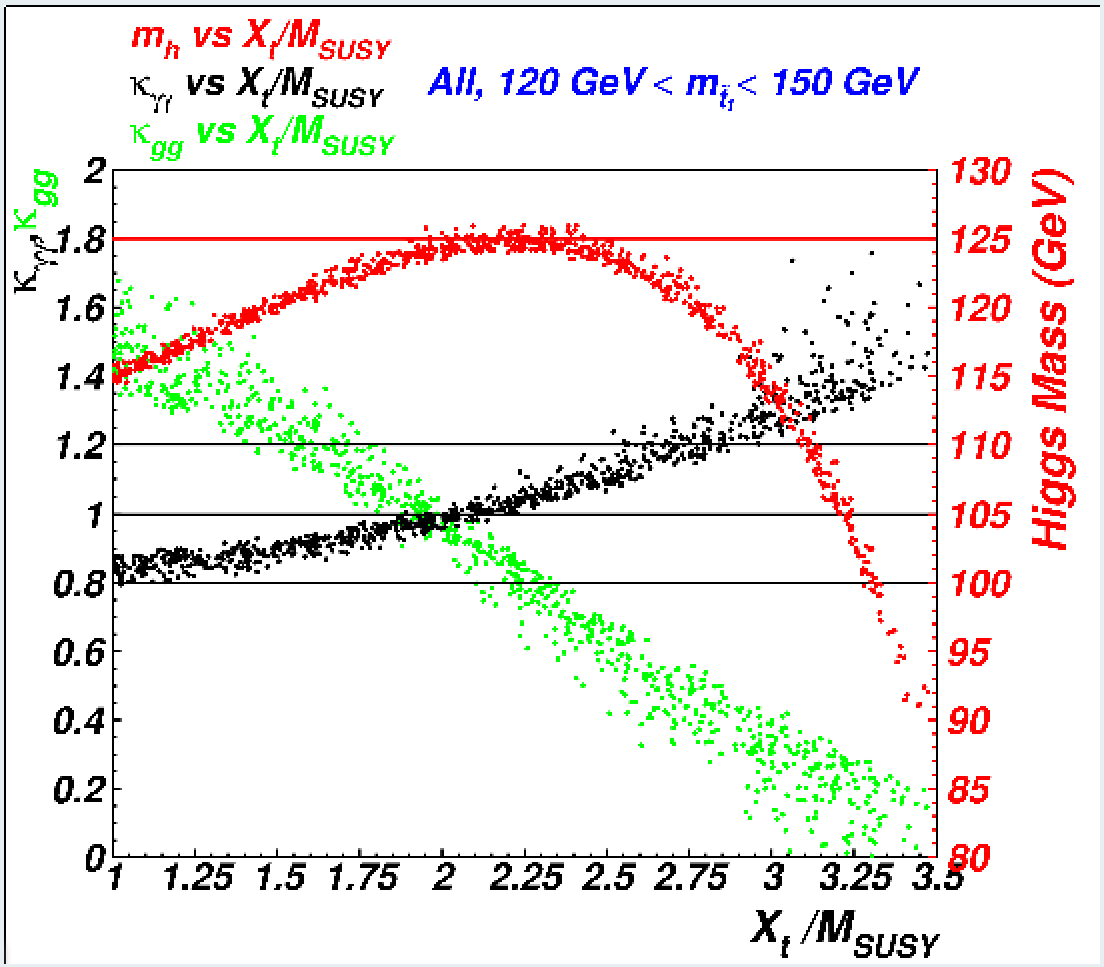
Top quark - $N_{c,f} Q_f^2 F_{1/2}(x_f) \simeq 1.8$

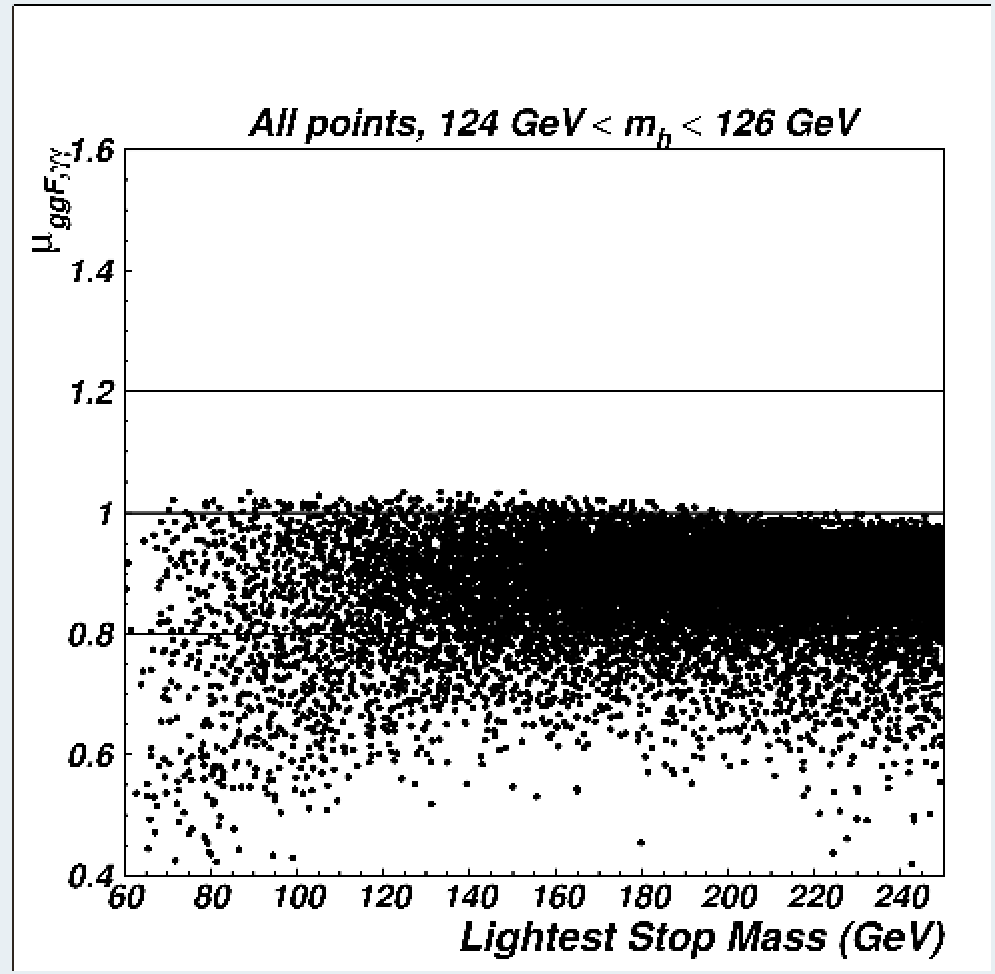
Charged scalar - $F_0(x_S) \simeq 0.4$ $\quad M_S \sim \mathcal{O}(100 \text{ GeV})$

- Relative stop contribution to κ_{gg} is larger than for $\kappa_{\gamma\gamma}$
- For maximal stop mixing, reduction in κ_{gg} is larger than increase in $\kappa_{\gamma\gamma}$

Light stops

- **Effect on production**





- Light stops loops **alone** cannot produce any increase in

$$\mu_{ggF,\gamma\gamma} = \frac{\sigma_{ggF}^{\rm MSSM}}{\sigma_{ggF}^{\rm SM}} \times \frac{BR_{\gamma\gamma}^{\rm MSSM}}{BR_{\gamma\gamma}^{\rm SM}} = \kappa_{gg} \times \frac{\Gamma_{\gamma\gamma}^{\rm MSSM}/\Gamma_{\rm tot}^{\rm MSSM}}{\Gamma_{\gamma\gamma}^{\rm SM}/\Gamma_{\rm tot}^{\rm SM}} = \kappa_{gg} \times \kappa_{\gamma\gamma} \times \frac{\Gamma_{\rm tot}^{\rm SM}}{\Gamma_{\rm tot}^{\rm MSSM}}$$

Total Width Effects

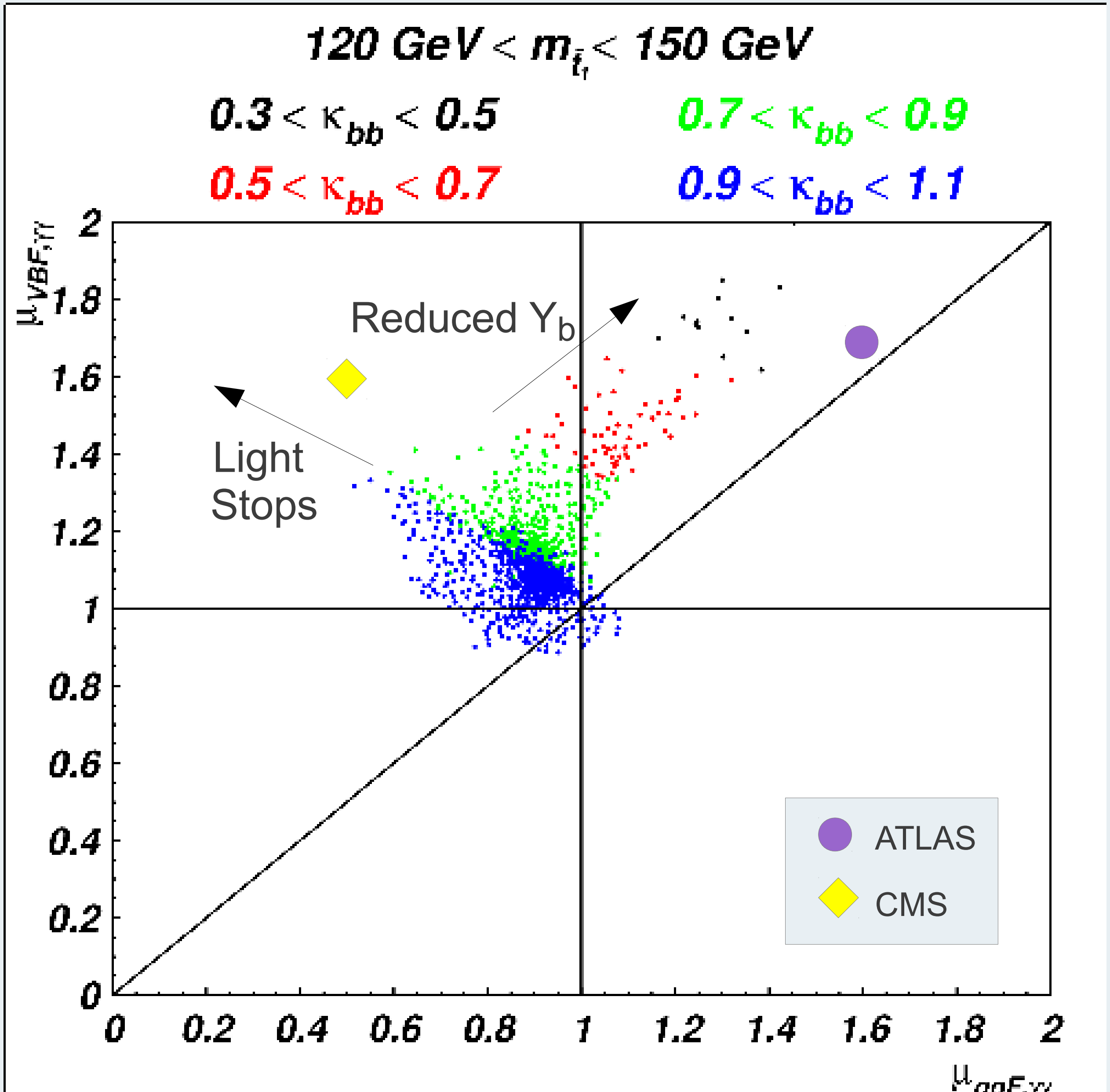
- Main decay channel is $h \to b\bar{b}$
  - reducing Y_b will reduce Γ_{tot}
    increasing $\mu_{ggF,\gamma\gamma} = \kappa_{gg} \times \kappa_{\gamma\gamma} \times \frac{\Gamma_{\rm tot}^{\rm SM}}{\Gamma_{\rm tot}^{\rm MSSM}}$
    and all other decay rates

- Bottom Yukawa can receive large SUSY corrections (e.g. Spira et. al. Phys.Rev. D68 (2003) 115001)

$$Y_b \simeq -\frac{m_b \sin\alpha}{v\cos\beta}\left[1 - \frac{\Delta m_b}{1+\Delta m_b}\left(1 + \frac{1}{\tan\alpha\tan\beta}\right)\right]$$

$$\Delta m_b \approx \frac{2\alpha_3}{3\pi} M_{\tilde{g}}\mu\tan\beta\ I(M_{\tilde{b}_1}, M_{\tilde{b}_2}, M_{\tilde{g}})$$

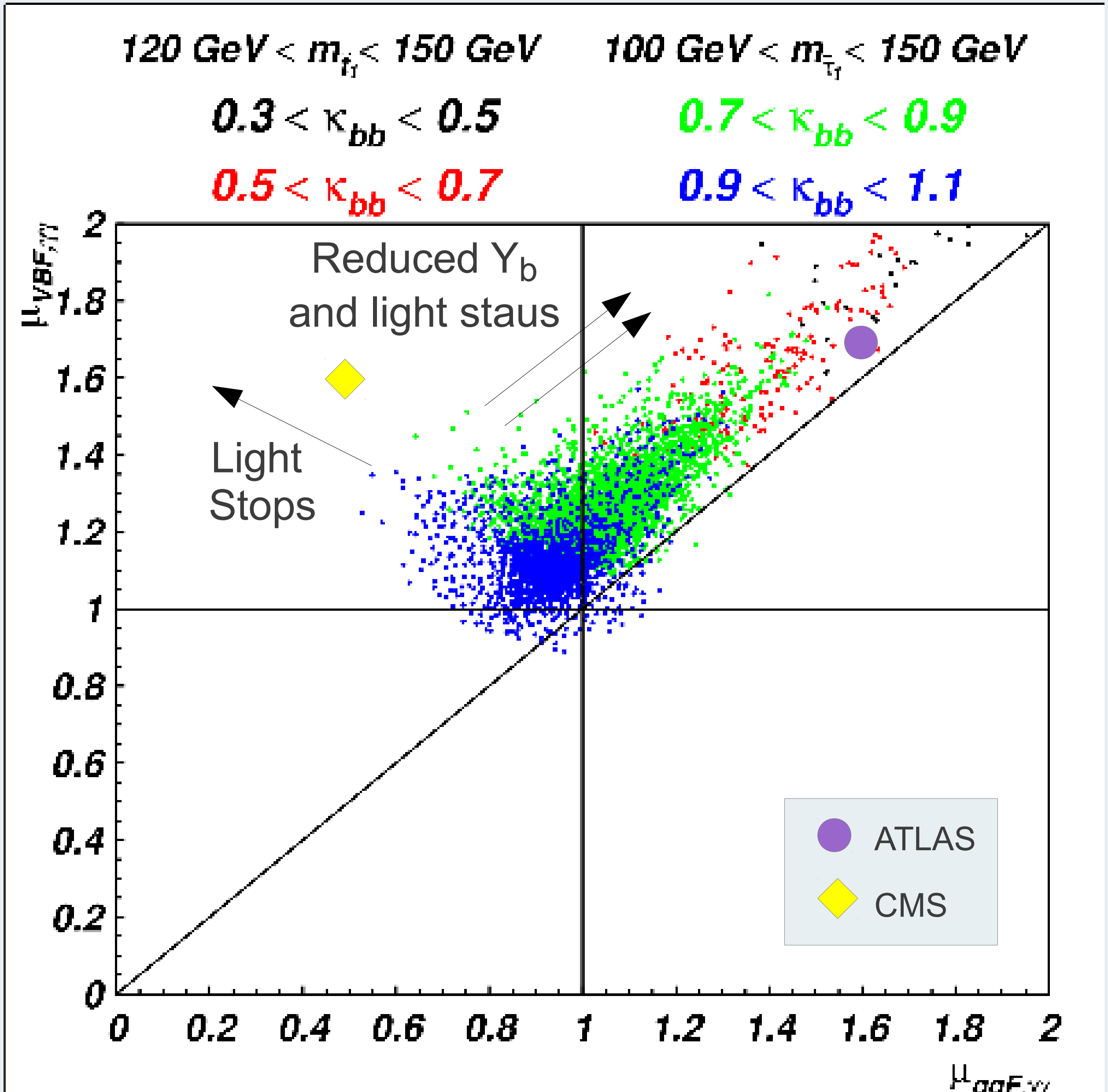
Light stops with reduced Y_b



- $\mu_{ggF,\gamma\gamma} \approx 1$ with $\mu_{VBF,\gamma\gamma} \approx 1.4$ can occur in light stop scenario with reduced Y_b

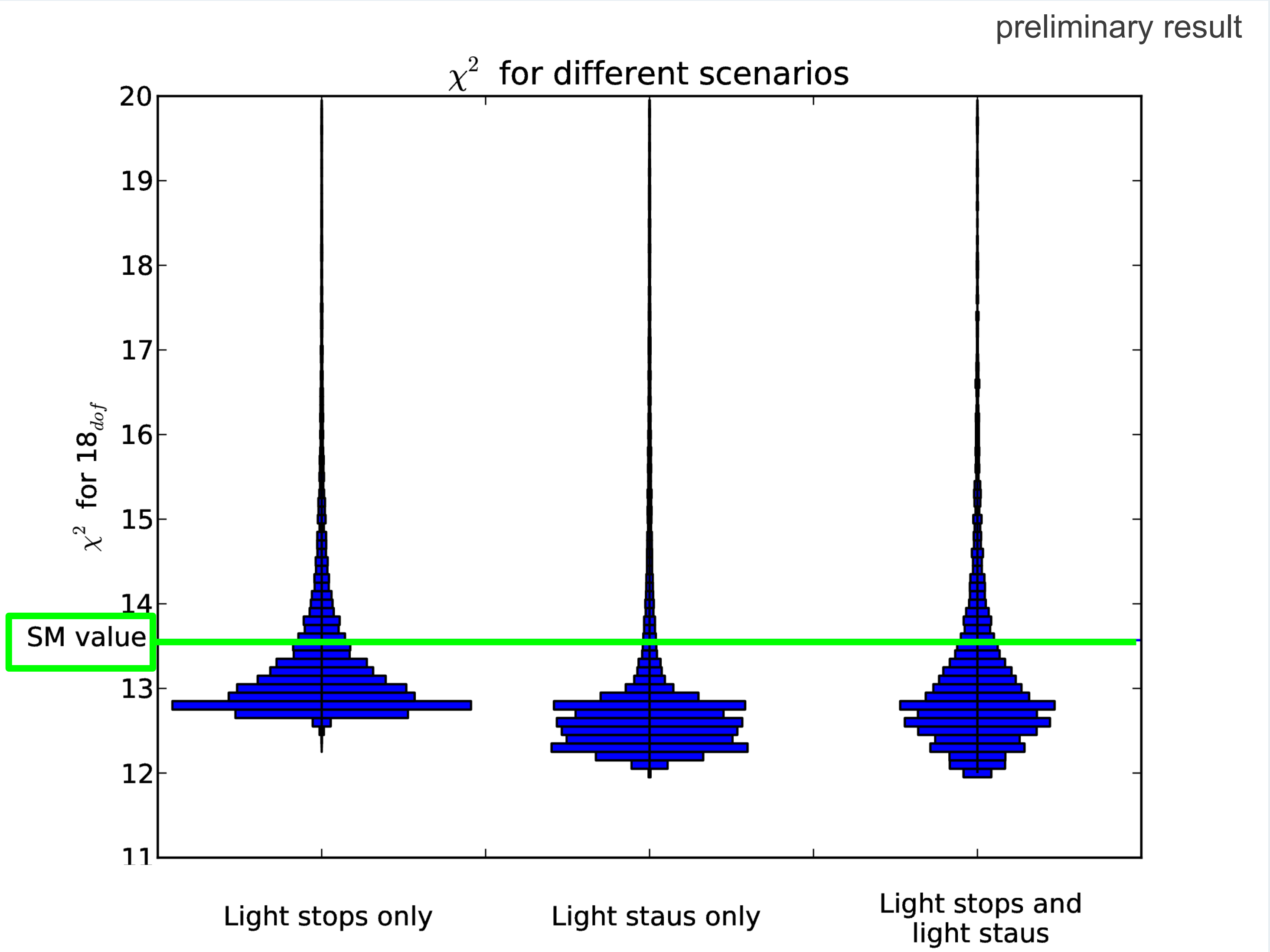
- Would also predict increase in all VBF production channels relative to ggF, and decrease in $BR(h \to b\bar{b})$

Light stops with reduced Y_b and light staus



- Adding light staus produces a further universal increase in $\mu_{VBF,\gamma\gamma}$ and $\mu_{ggF,\gamma\gamma}$

Are these scenarios better than the SM?

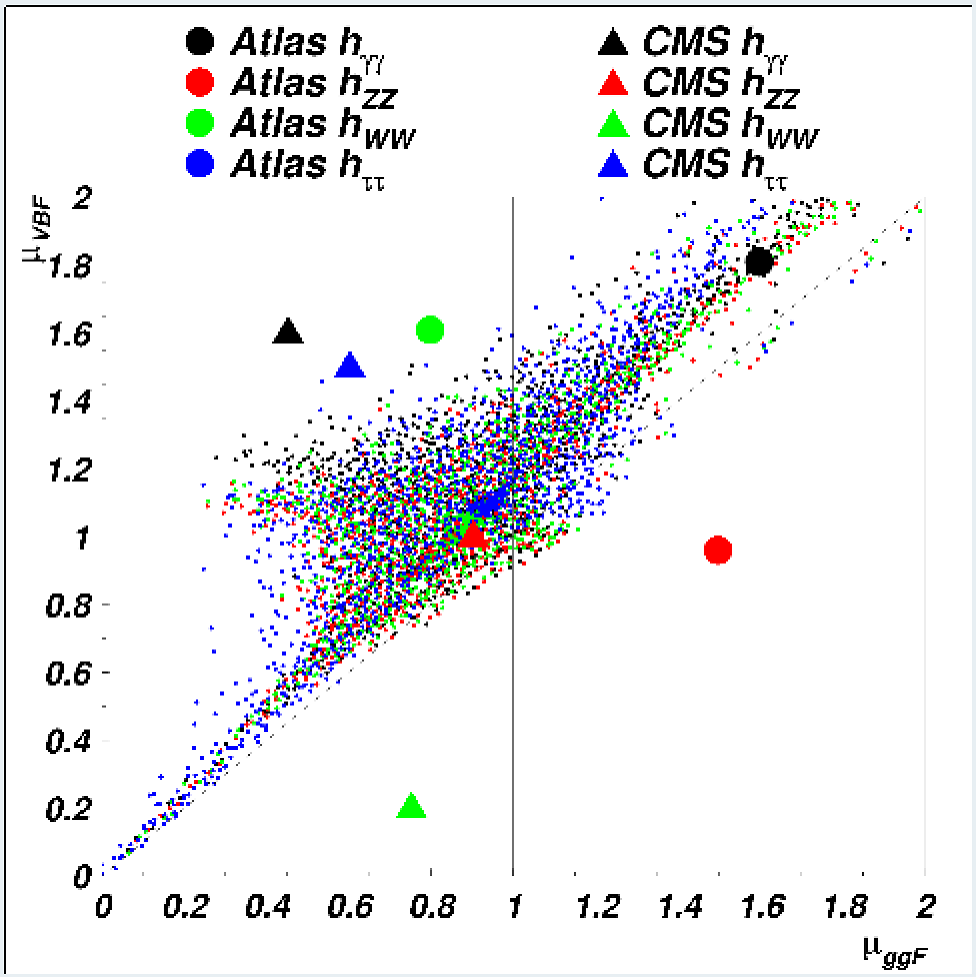


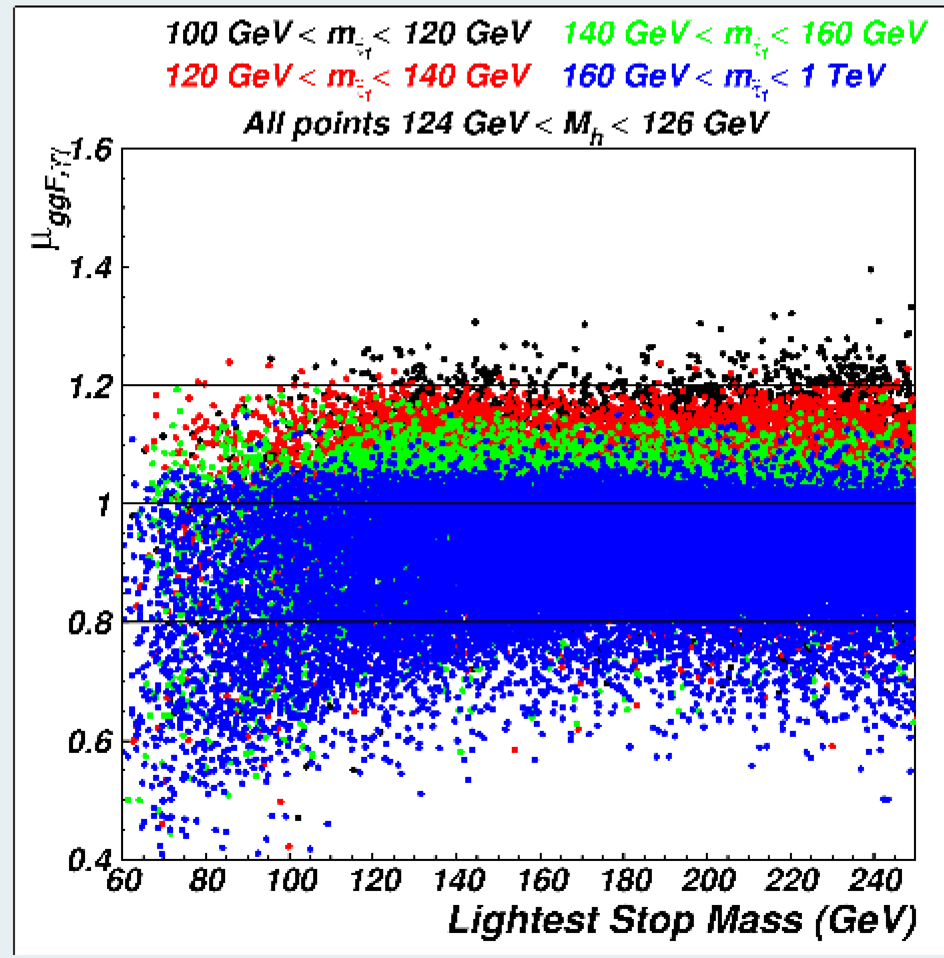
- Improvements are modest and SM already fits data fairly well
- χ^2 slightly improved because light stops can explain non-universal alteration of μ_{ggF} vs μ_{VBF} – would be important if confirmed in the future

Conclusions

- Light stops can explain non-universal μ_{ggF} vs μ_{VBF}
  - could be important if confirmed in the future
- μ_{ggF} is not necessarily decreased in a light stop scenario if Y_b is reduced
- Light staus can explain a universal increase in $(h \to \gamma\gamma)$
- Light stop, light staus or a combination of both fits data slightly better than the SM

Back up slides





Scan over parameter space

$$2 \leq \tan\beta \leq 60$$
$$200 \text{ GeV} \leq M_{H^\pm} \leq 2 \text{ TeV}$$
$$0 \text{ TeV} \leq \mu \leq 5 \text{ TeV}$$
$$100 \text{ GeV} \leq m_{\tilde{g}} \leq 5 \text{ TeV}$$
$$100 \text{ GeV} \leq M_{Q3} \leq 10 \text{ TeV}$$
$$50 \text{ GeV} \leq M_{U3} \leq 5 \text{ TeV}$$
$$50 \text{ GeV} \leq M_{D3} \leq 30 \text{ TeV}$$
$$100 \text{ GeV} \leq M_{E3} \leq 5 \text{ TeV}$$
$$100 \text{ GeV} \leq M_{L3} \leq 5 \text{ TeV}$$
$$0 \text{ TeV} \leq A_t \leq 10 \text{ TeV}$$
$$0 \text{ TeV} \leq A_b \leq 10 \text{ TeV}$$
$$0 \text{ TeV} \leq A_\tau \leq 5 \text{ TeV}$$

Light stops

- Putting $X_t \approx \sqrt{6} M_{SUSY}$ into stop coupling,

$$g_{\hat{h}\tilde{t}_1\tilde{t}_1} = \frac{1}{2}\cos 2\beta\Big[\cos^2\theta_{\tilde{t}} - \frac{4}{3}\sin^2\theta_W \cos 2\theta_{\tilde{t}}\Big] + \frac{m_t^2}{M_Z^2} + \frac{1}{2}\sin 2\theta_{\tilde{t}}\frac{m_t X_t}{M_Z^2}$$

with, $M^2_{\rm SUSY} = \frac{1}{2}(m^2_{\tilde{t}_1} + m^2_{\tilde{t}_2})$ and $\sin 2\theta_t = \frac{2m_t X_t}{m^2_{\tilde{t}_1} - m^2_{\tilde{t}_2}}$

and ignoring the first term which is small

$$\hat{g}_{h\tilde{t}_1\tilde{t}_1} \sim \frac{m_t^2}{M_Z^2} + \frac{3m_t^2}{M_Z^2}\left(\frac{m^2_{\tilde{t}_1} + m^2_{\tilde{t}_2}}{m^2_{\tilde{t}_1} - m^2_{\tilde{t}_2}}\right)$$

and $m^2_{\tilde{t}_1} \ll m^2_{\tilde{t}_2}$

$$\hat{g}_{h\tilde{t}_1\tilde{t}_1} \to \frac{m_t^2}{M_Z^2} - \frac{3m_t^2}{M_Z^2} = -\frac{2m_t^2}{M_Z^2}$$

Back up – coupling normalisation

$$\hat{g}_{hSS} = \frac{g_{hSS}}{M_W/g} = \frac{g_{hSS}}{(4\sqrt{2}G_F)^{-\frac{1}{2}}} = g_{hSS}\sqrt{4\sqrt{2}G_F}$$

ATLAS limits