

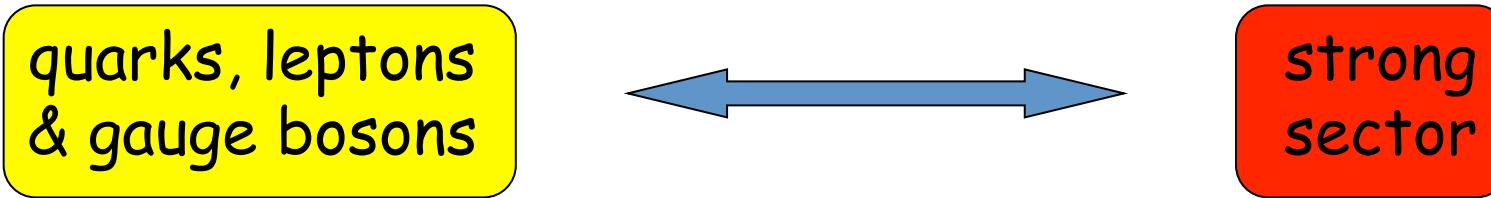
Higgs ~~BSM~~ physics in light of LHC8

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CERN Winter School on Supergravity, Strings,
and Gauge Theory, 4-8 February 2013

Structure of composite Higgs



Communicate via gauge (g_a)
and (proto)-Yukawa (λ_i)

Strong sector characterized by m_ρ mass of resonances
 g_ρ coupling of resonances

Take $\lambda_i, g_a \ll g_\rho < 4\pi$

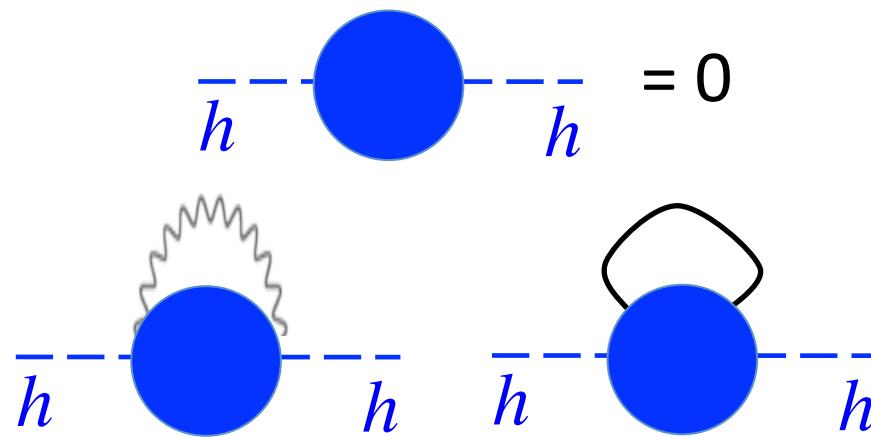
In the limit $\lambda_i, g_a = 0$, strong sector contains
Higgs as Goldstone bosons

Ex. $H = SU(3)/SU(2) \times U(1)$ or $H = SO(5)/SO(4)$

σ -model with $f = m_\rho / g_\rho$

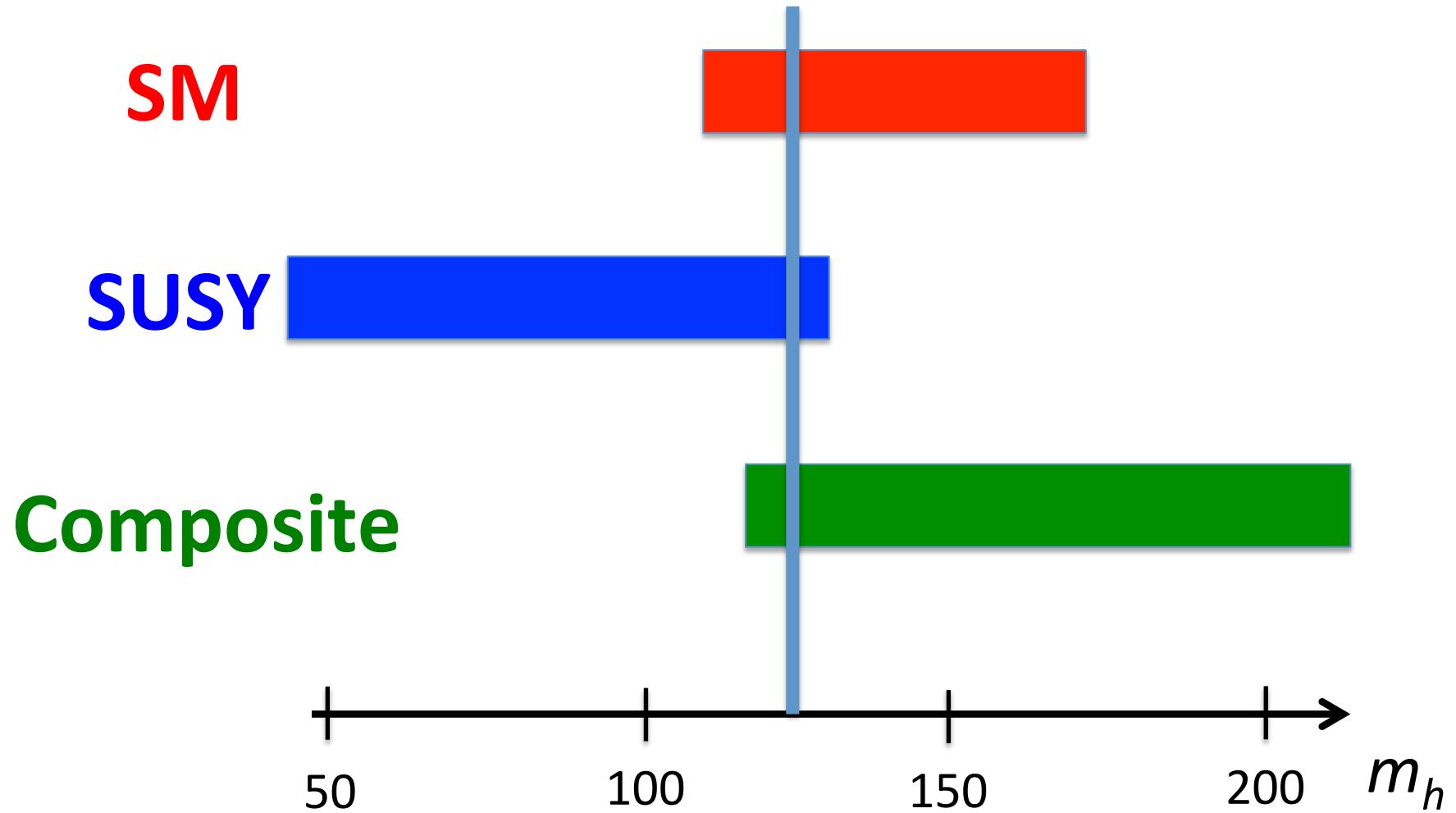
$$g_a, \lambda_i = 0 \Rightarrow V(H) = 0$$

Higgs potential, EW breaking, Higgs mass \Rightarrow computable
in terms of SM couplings (in a model-dependent way)

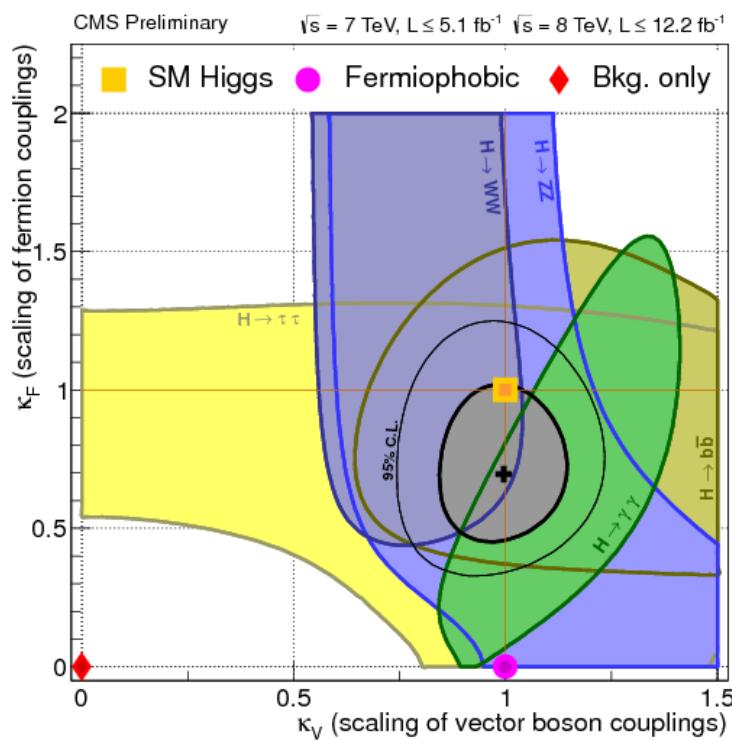


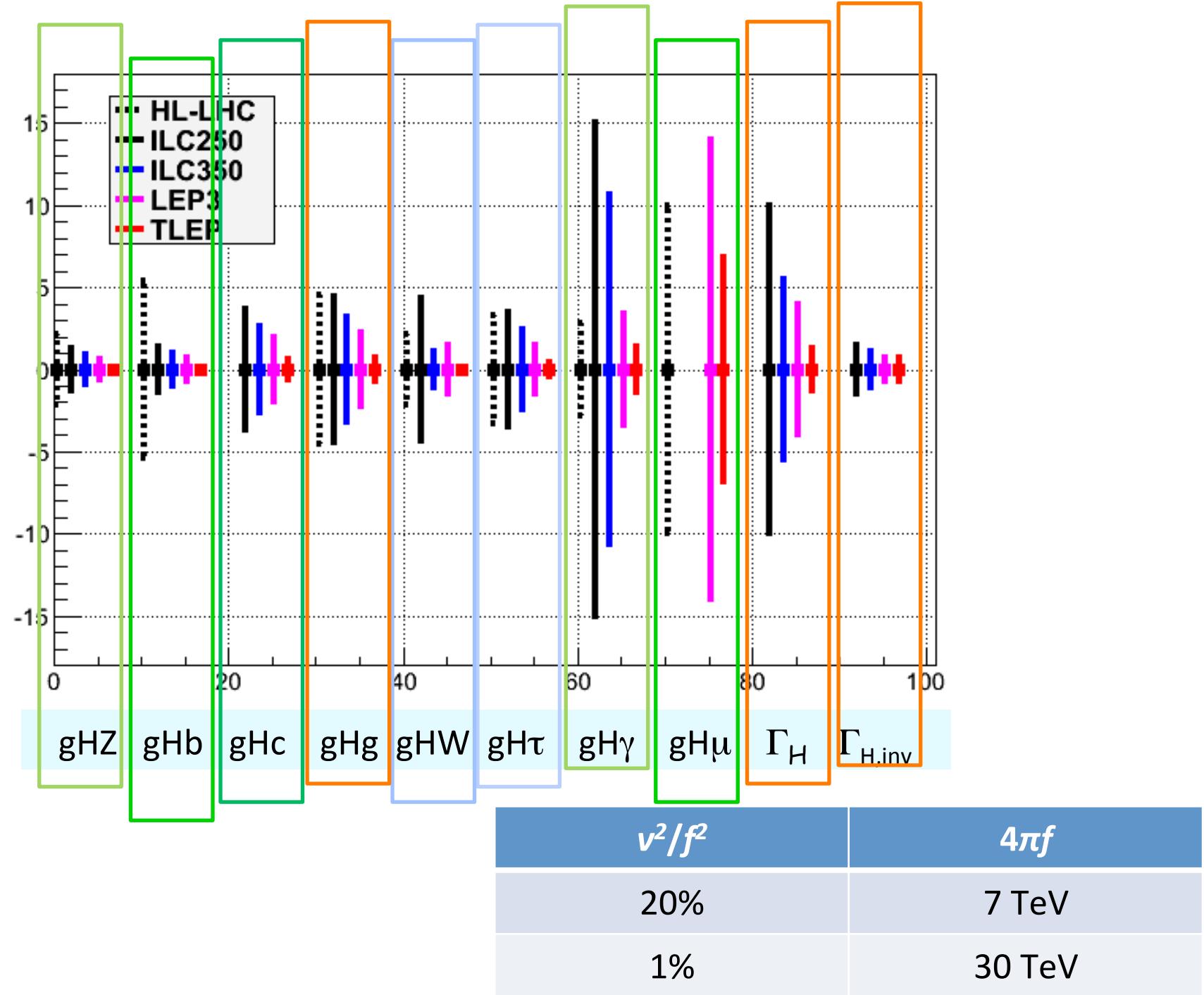
$$m_h^2 \approx \frac{\lambda_t^2}{16\pi^2} m_\rho^2 \quad \Rightarrow \quad m_\rho \approx 1.5 \text{ TeV}, \quad f = \frac{m_\rho}{g_\rho} = O(v)$$

New theory addresses hierarchy problem \Rightarrow reduced
sensitivity of m_h to short distances (below m_ρ^{-1})

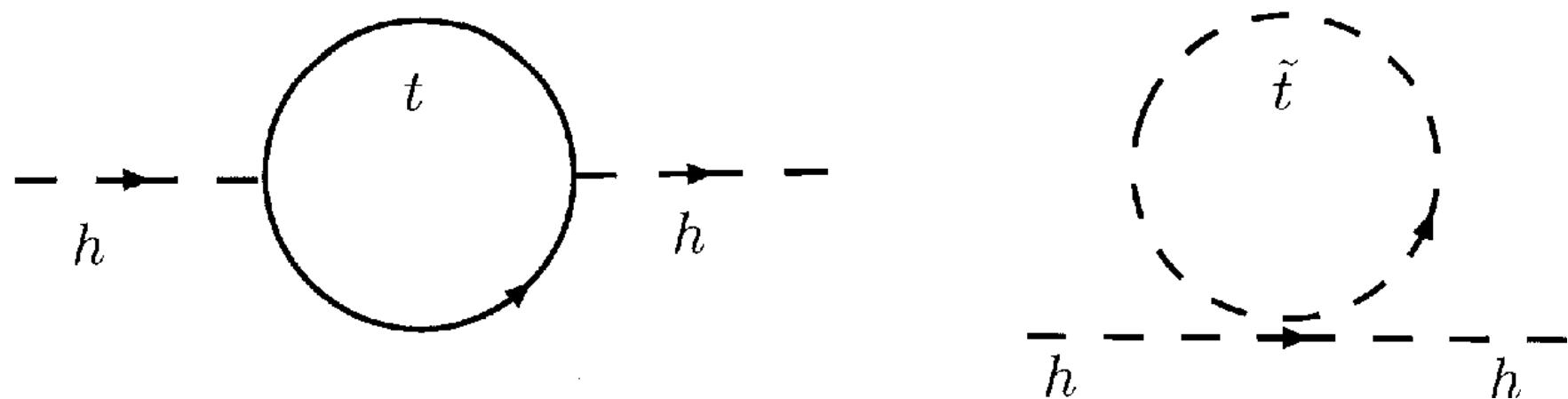


- Effective theory between the scales f and v
- Higgs couplings modified by terms $\mathcal{O}(v^2 / f^2)$
- Modifications to hgg and $h\gamma\gamma$ (but not $hZ\gamma$) are suppressed
- Present precision on H couplings 20-50 %



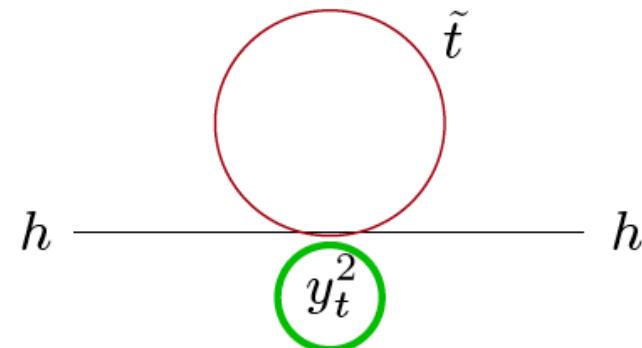
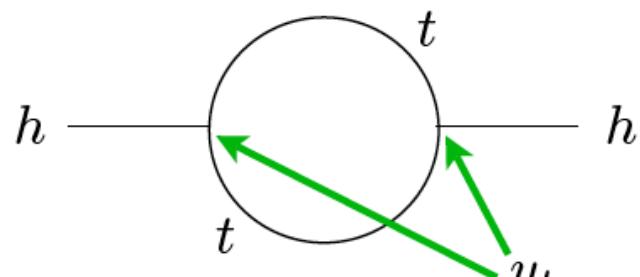


SUPERSYMMETRY



SUPERSYMMETRY BREAKING

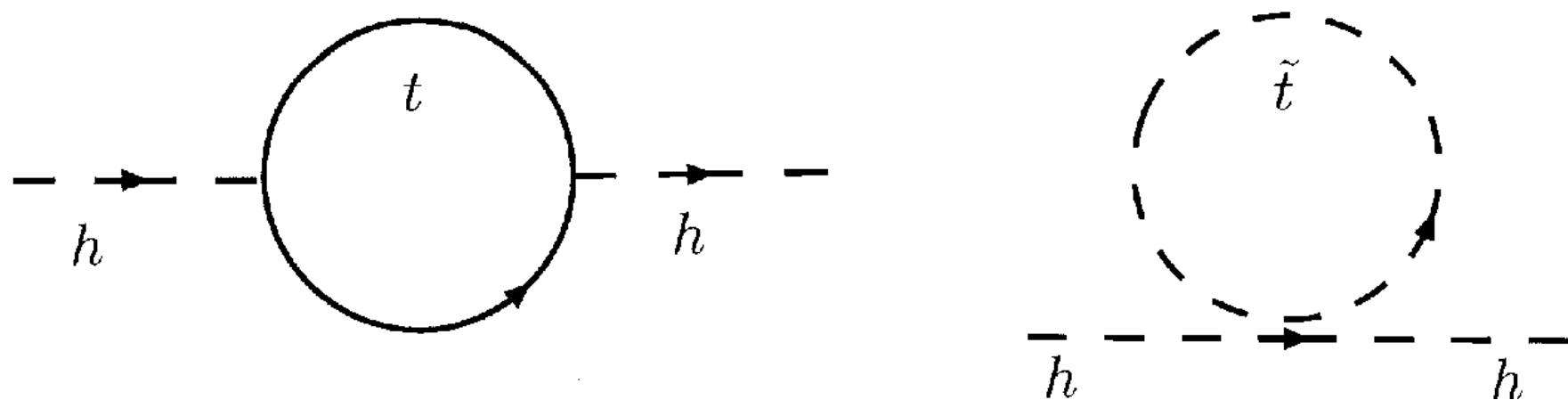
Break susy, but keep UV behavior \Rightarrow soft breaking



$$m_{\tilde{t}}^2 \neq m_t^2 \rightarrow \delta m_h^2 \propto (m_{\tilde{t}}^2 - m_t^2) \ln \Lambda \quad \text{Soft breaking}$$

$$y_{\tilde{t}}^2 \neq y_t^2 \rightarrow \delta m_h^2 \propto (y_{\tilde{t}}^2 - y_t^2) \Lambda^2 \quad \text{Hard breaking}$$

SUPERSYMMETRY



$$\delta m_{H_u}^2 = -\frac{3\lambda_t^2}{8\pi^2} \int^{\Lambda^2} \frac{k^2 dk^2}{k^2 + m_t^2} + \frac{3\lambda_t^2}{8\pi^2} \int^{\Lambda^2} \frac{k^2 dk^2}{k^2 + m_t^2 + m_S^2} = -\frac{3\lambda_t^2}{4\pi^2} m_S^2 \ln \frac{\Lambda}{m_S}$$

$m_S \lambda \lambda$ gaugino mass $m_S^2 \varphi^+ \varphi$ scalar mass $m_S \varphi^3$ A-term

- Soft susy breaking introduces a dimensionful parameter m_S
- Susy particles get masses of order m_S
- Susy mass terms are gauge invariant
- Treat soft terms as independent
- Different schemes make predictions for patterns of soft terms

ELECTROWEAK SYMMETRY BREAKING

$$f = Y_u Q U^c H_2 + Y_d Q D^c H_1 + Y_e L E^c H_1 + \mu H_1 H_2$$

Higgs potential

$$V = m_1^2 |H_1^0|^2 + m_2^2 |H_2^0|^2 - m_3^2 (H_1^0 H_2^0 + \text{h.c.}) + \frac{g_2^2 + g_Y^2}{8} (|H_1^0|^2 - |H_2^0|^2)^2$$

- $m_{1,2,3}^2 \sim m_S^2$ determined by soft terms
- quartic fixed by supersymmetry
- Stability along $H_1 = H_2 \Rightarrow m_1^2 + m_2^2 > 2|m_3^2|$
- EW breaking, origin unstable $\Rightarrow m_1^2 m_2^2 < m_3^4$

EW breaking induced by quantum corrections

RG running:

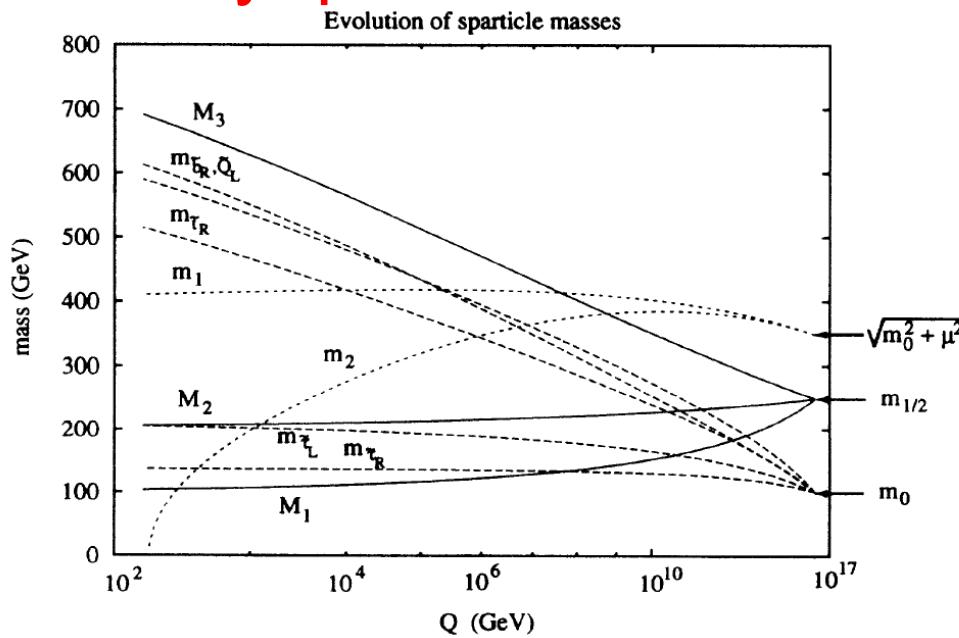
gauge effects 

Yukawa effects 

$$-8\pi^2 \frac{dM_3}{d \ln Q} = +3g_3^2 M_3 \quad \uparrow$$

$$-8\pi^2 \frac{dm_{\tilde{t}_L}^2}{d \ln Q} = +\frac{16}{3}g_3^2 M_3^2 - \lambda_t^2(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + |A_t|^2 + m_2^2 - \mu^2) + (\text{EW effects}) \quad \uparrow$$

$$-8\pi^2 \frac{dm_2^2}{d \ln Q} = -3\lambda_t^2(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + |A_t|^2 + m_2^2) + (\text{EW effects}) \quad \downarrow$$



- If λ_t large enough $\Rightarrow SU(2) \times U(1)$ spontaneously broken
- If α_s large enough $\Rightarrow SU(3)$ unbroken

HIGGS SECTOR

8 degrees of freedom - 3 Goldstones = **5 degrees of freedom**

2 scalars (h^0, H^0), 1 pseudoscalar (A^0), 1 charged (H^\pm)

3 parameters ($m_{1,2,3}^2$) - M_Z = **2 free parameters**

Usually m_A and $\tan\beta$ taken as free parameters

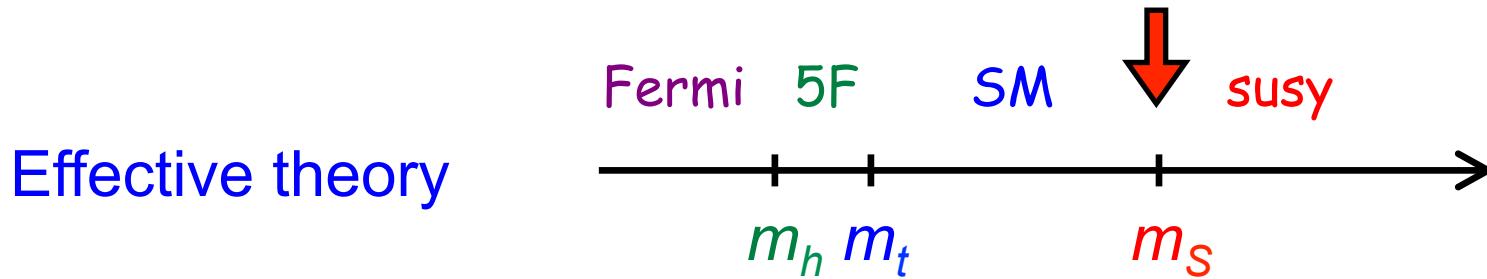
Several interesting tree-level mass relations

$$m_h \leq m_Z |\cos 2\beta|, \quad m_h < m_A < m_H, \quad m_{H^\pm}^2 = m_A^2 + m_W^2$$

$$m_{h,H}^2 = \frac{1}{2} \left[m_A^2 + m_Z^2 \mp \sqrt{\left(m_A^2 - m_Z^2 \right)^2 + 4 \sin^2 2\beta m_A^2 m_Z^2} \right]$$

In the decoupling limit $m_A \gg m_Z$, h^0 is the SM Higgs

IMPORTANT RADIATIVE CORRECTIONS

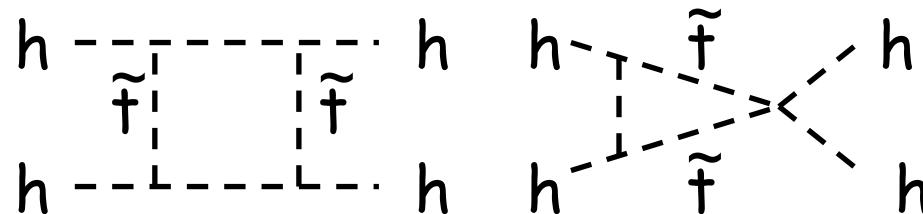


Matching at m_S : $h \equiv \cos \beta H_1 + \sin \beta H_2$ $V = \frac{\lambda}{4} h^4 + \frac{m^2}{2} h^2$

$$\lambda(m_S) = \frac{g^2 + g'^2}{8} \cos^2 2\beta \quad m^2 = -\cos 2\beta \cos^2 \beta (m_2^2 \tan^2 \beta - m_1^2)$$

$$\langle h \rangle \equiv v = \sqrt{\frac{-m^2}{\lambda}} \quad m_h^2 = 2\lambda v^2 \quad \Rightarrow \quad m_h = |\cos 2\beta| m_Z$$

A_t contribution



$$\delta \lambda = \frac{3\lambda_t^4}{32\pi^2} X_t$$

$$X_t = \frac{2(A_t - \mu \cot \beta)^2}{\tilde{m}_{t_1} \tilde{m}_{t_2}} \left[1 - \frac{(A_t - \mu \cot \beta)^2}{12 \tilde{m}_{t_1} \tilde{m}_{t_2}} \right]$$

Running the SM RG
equation for λ

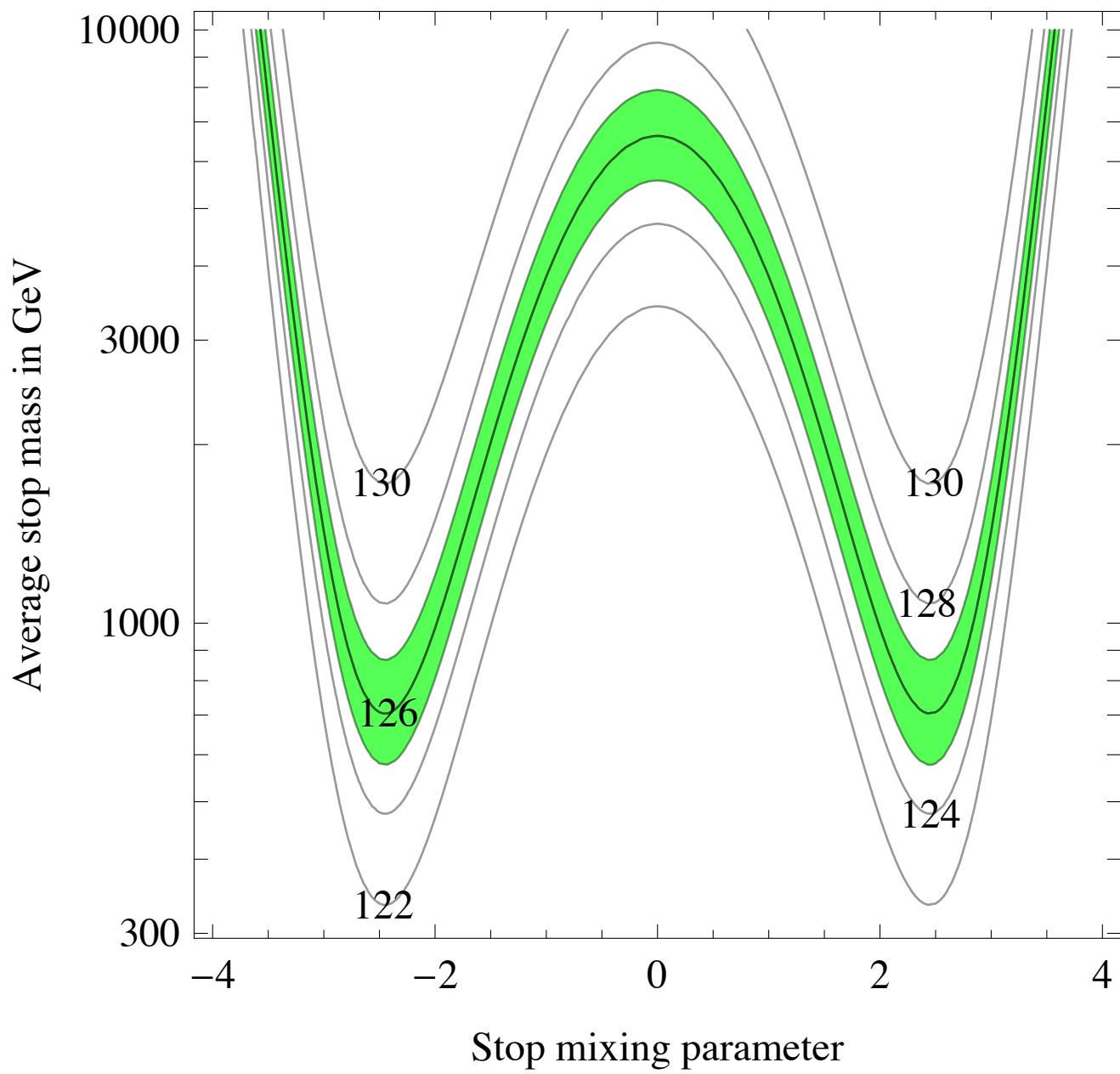


$$m_h^2 = m_Z^2 \cos^2 2\beta \left(1 - \frac{3\sqrt{2}}{4\pi^2} G_F m_t^2 t_s \right) + \frac{3\sqrt{2}}{2\pi^2} G_F m_t^4 \left\{ \frac{X_t}{2} + t_s + \frac{1}{16\pi^2} \left[3\sqrt{2} G_F m_t^2 - 32\pi\alpha_s \right] (X_t + t_s) t_s \right\}$$

Important effect because:

- 1) small tree-level m_h ,
- 2) large λ_t ,
- 3) heavy susy particles
- 4) large loop factor

$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3}{2\pi^2} \lambda_t^4 v^2 \ln \frac{\tilde{m}_t}{m_t}$$



SUSY makes two (fairly robust) predictions

$$m_Z^2 = \frac{3\lambda_t^2}{2\pi^2} \tilde{m}_t^2 \ln \frac{\Lambda}{\tilde{m}_t}$$

$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3\lambda_t^2}{2\pi^2} m_t^2 \ln \frac{\tilde{m}_t}{m_t}$$

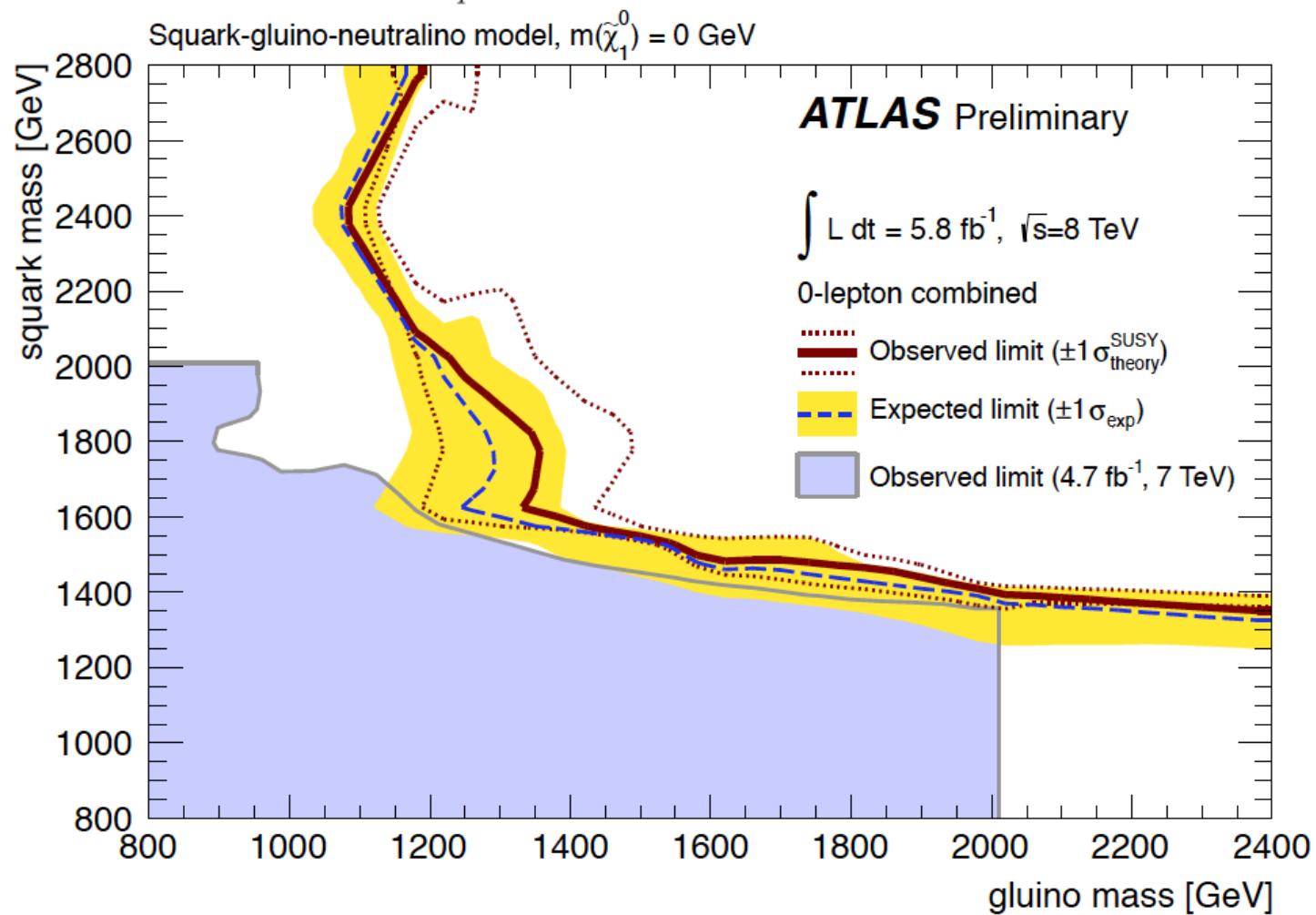
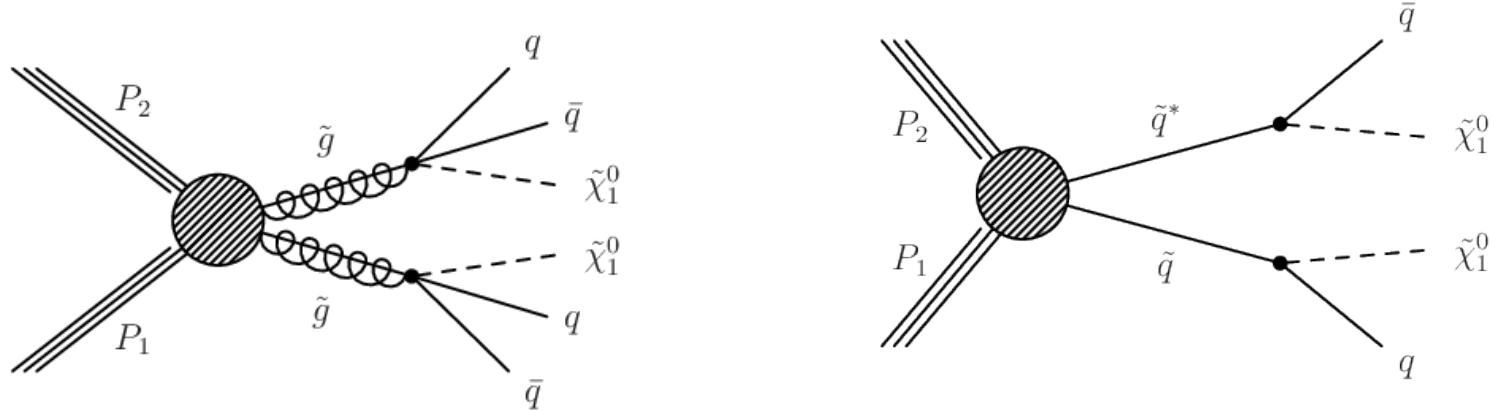
SUSY makes two (fairly robust) predictions

Original success and present tension with data

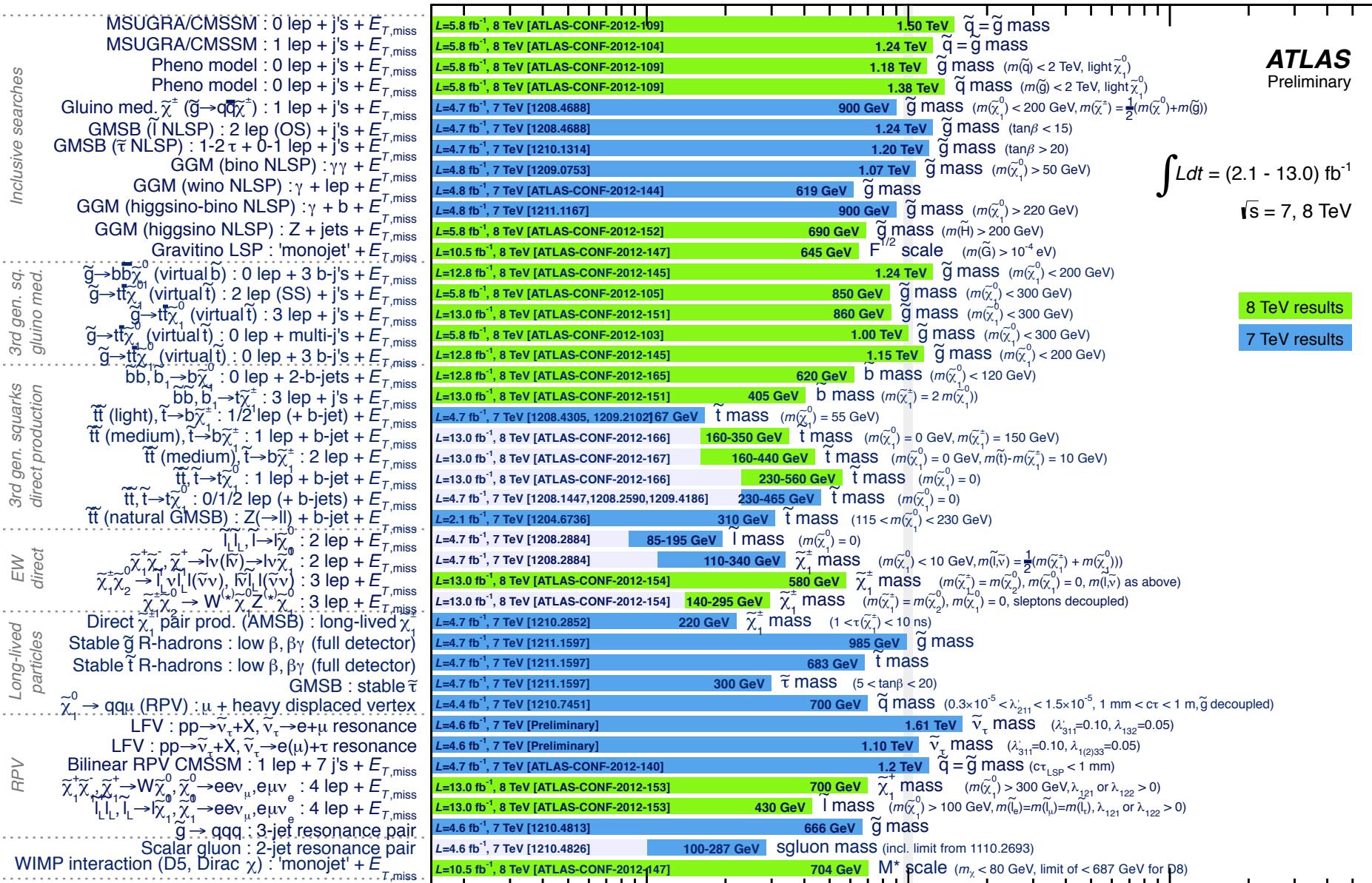
$$m_Z^2 = \frac{3\lambda_t^2}{2\pi^2} \tilde{m}_t^2 \ln \frac{\Lambda}{\tilde{m}_t} \text{ less than 10% tuning} \Rightarrow \tilde{m}_t \lesssim 300 \text{ GeV}$$

$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3\lambda_t^2}{2\pi^2} m_t^2 \ln \frac{\tilde{m}_t}{m_t}$$

$$m_h = 125 \text{ GeV} \Rightarrow \tilde{m}_t \gtrsim 5 \text{ TeV}$$



ATLAS SUSY Searches* - 95% CL Lower Limits (Status: Dec 2012)

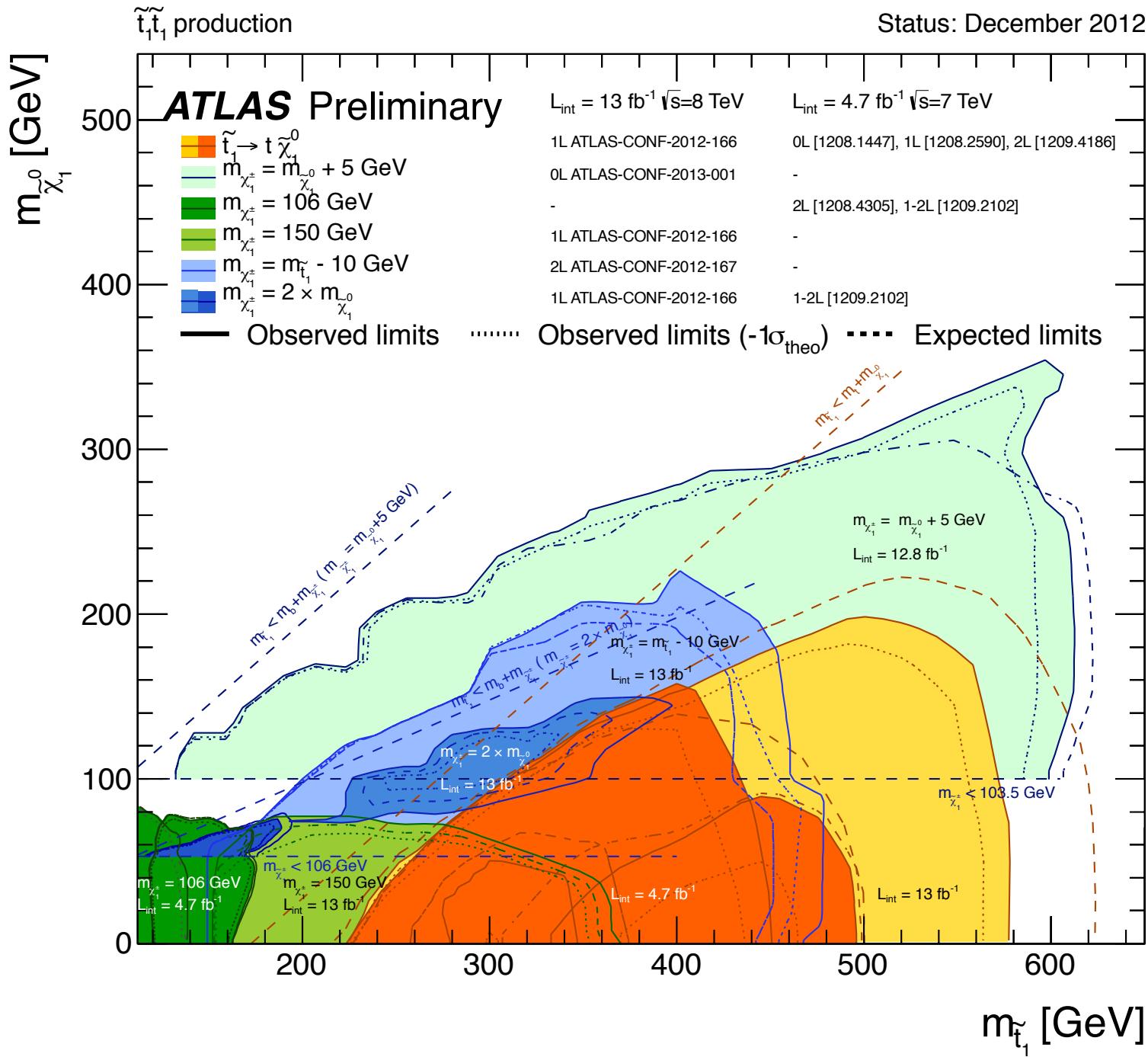


$\int L dt = (2.1 - 13.0) \text{ fb}^{-1}$
 $\sqrt{s} = 7, 8 \text{ TeV}$

8 TeV results
7 TeV results

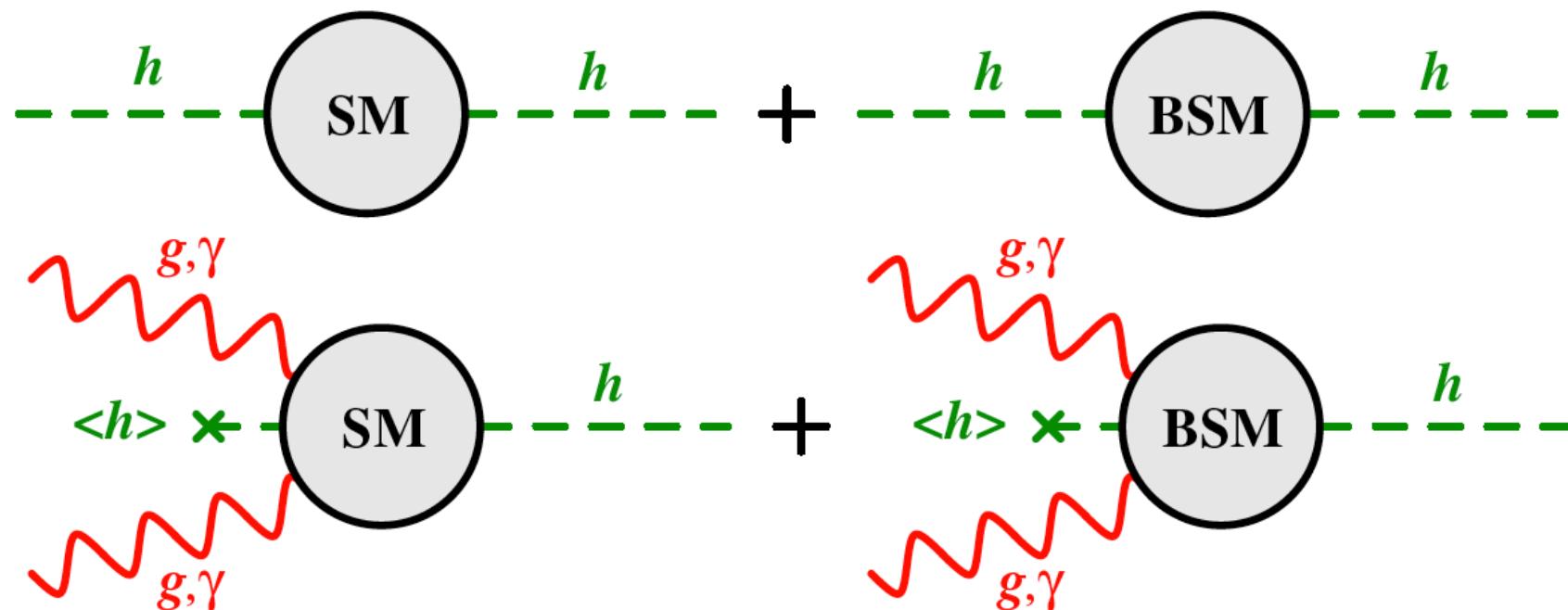
*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1 σ theoretical signal cross section uncertainty.

10⁻¹ 1 10
Mass scale [TeV]



In weakly-interacting BSM (like SUSY),
deviations are expected in γ and g couplings.

The more natural the Higgs is,
the more its properties deviate from SM.



$$\frac{\Gamma(h \leftrightarrow gg)}{\Gamma(h \leftrightarrow gg)_{\text{SM}}} = (1 + \Delta_t)^2 , \quad \frac{\Gamma(h \rightarrow \gamma\gamma)}{\Gamma(h \rightarrow \gamma\gamma)_{\text{SM}}} = (1 - 0.28 \Delta_t)^2 ,$$

$$\Delta_t \approx \frac{m_t^2}{4} \left[\frac{1}{m_{\tilde{t}_1}^2} + \frac{1}{m_{\tilde{t}_2}^2} - \frac{A_t^2}{m_{\tilde{t}}^4} \right]$$

$$\frac{\delta \Gamma(h \rightarrow \gamma\gamma)}{\Gamma(h \rightarrow \gamma\gamma)_{\text{SM}}} \approx \left(\frac{500 \text{ GeV}}{m_{\tilde{t}}} \right)^2 2\%$$

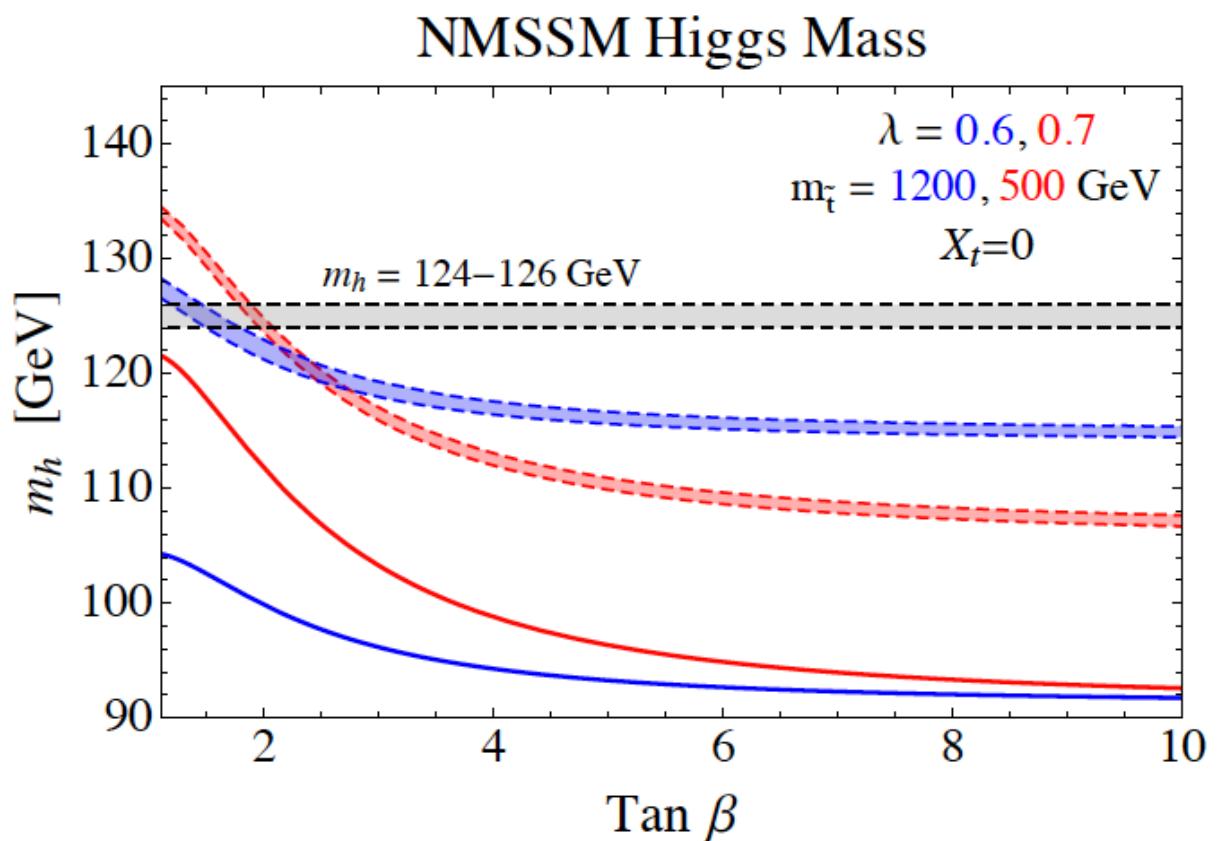
A posteriori: deviations in Higgs BR
larger than 10% are rather special.

Can we increase the Higgs mass prediction of minimal supersymmetry?

1) Add $W = \lambda N H_u H_d + \kappa N^3$

At tree level: $m_h^2 < M_Z^2 \left(\cos^2 2\beta + \frac{\lambda^2}{g^2} \sin^2 2\beta \right)$

If λ perturbative up to the GUT scale

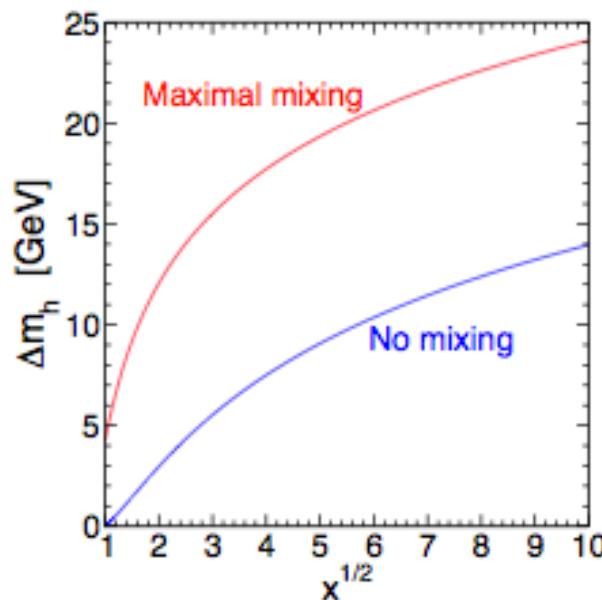


2) Add triplets

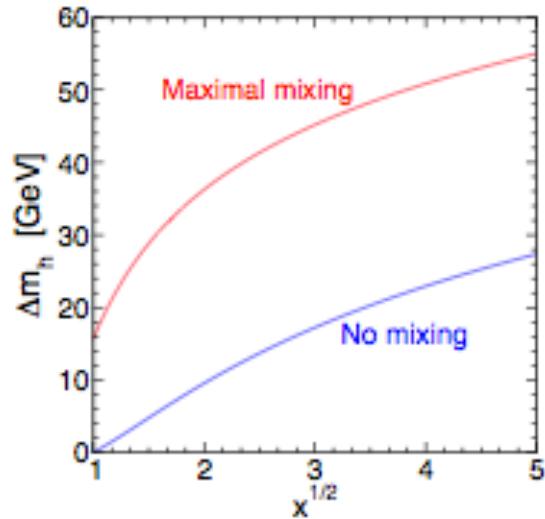
$$W = \lambda_T T H_u H_u + \lambda_{\bar{T}} \bar{T} H_d H_d + M T \bar{T}$$

Mass increase at large $\tan\beta$

Gauge coupling unification can be preserved (with new states)



3) Add new vectorlike particles (loop effect)



4) Add new gauge interactions: Higgs mass from D-term

Strong new gauge group broken close to the TeV scale

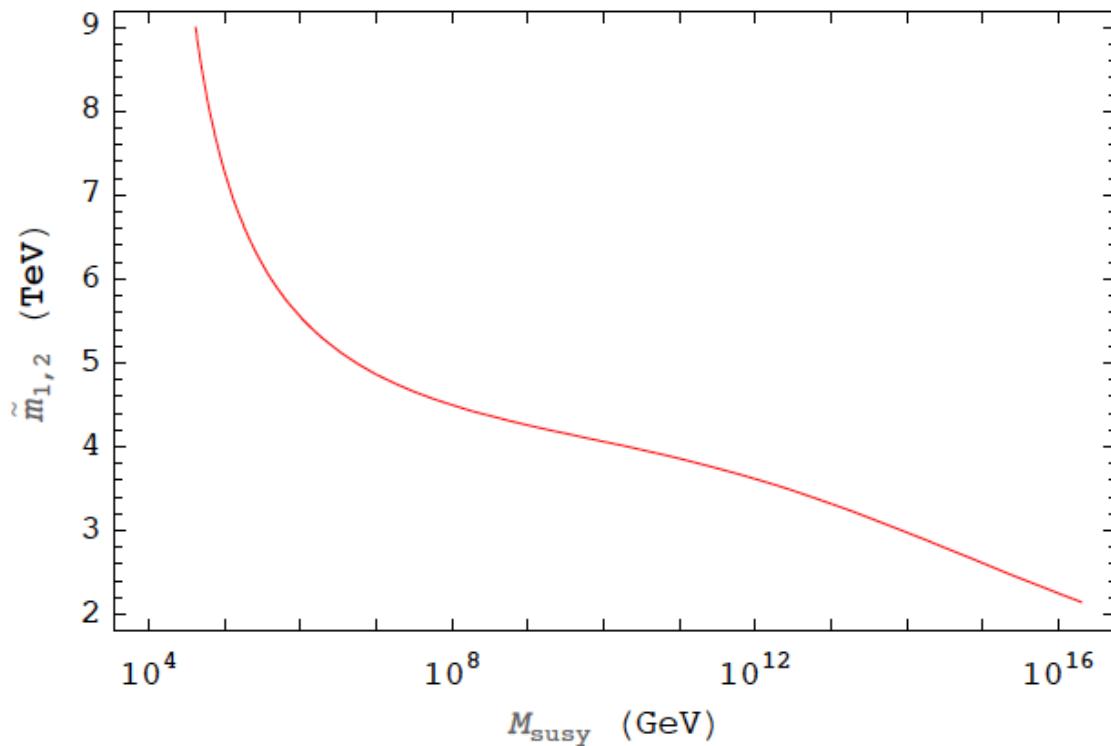
Can we improve naturalness?

$$\delta m_h^2 = \frac{3G_F}{4\sqrt{2}\pi^2} (4m_t^2 - 2m_W^2 - m_Z^2 - m_h^2) \Lambda^2 < m_h^2$$

$$\Rightarrow \Lambda_t < 500 \text{ GeV}$$

$$\Rightarrow \Lambda_W < 1.4 \text{ TeV}$$

$$\Rightarrow \Lambda_Z < 1.8 \text{ TeV}$$



An alternative approach

Motivations for supersymmetry

Underlying symmetry: relation with gauge-gravity unification and superstrings

Naturalness problem: link with the weak scale

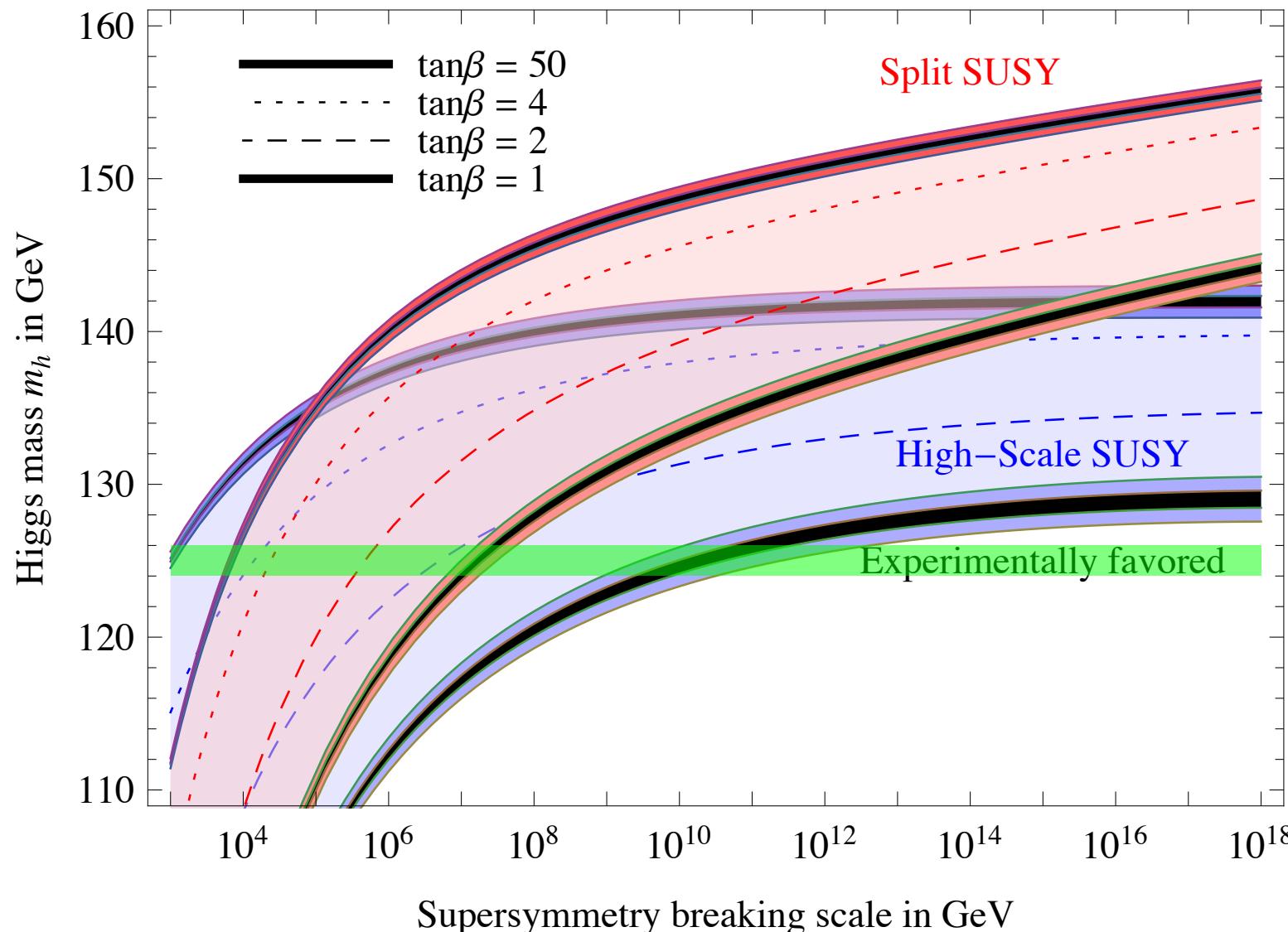
Gauge-coupling unification: motivated by theory that addresses fundamental structure of SM and by measurements on α_i

Dark matter: connection between weak scale and new particle masses

$$\Omega_{\text{rel}} h^2 \approx \frac{0.1 \text{ pb}}{\langle \sigma v \rangle}$$

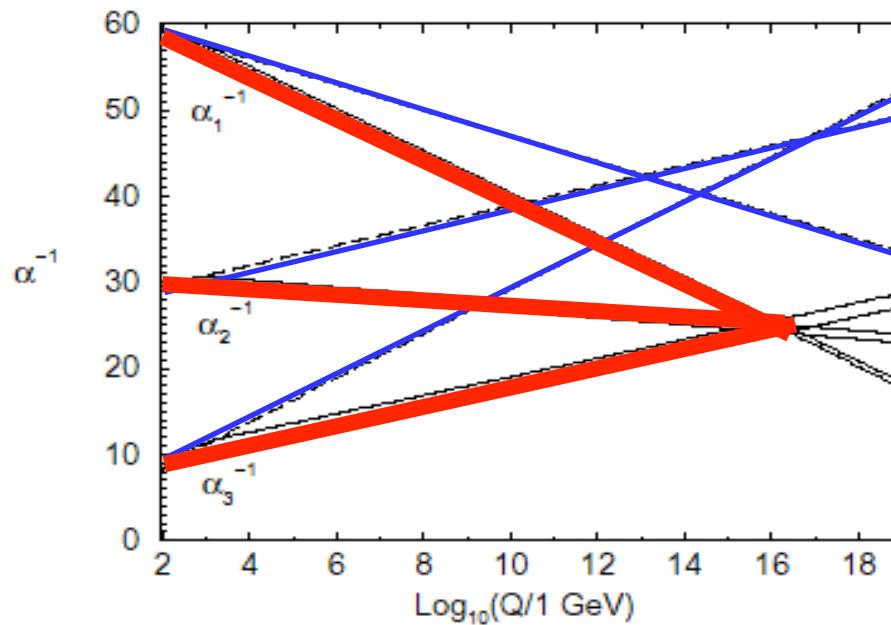
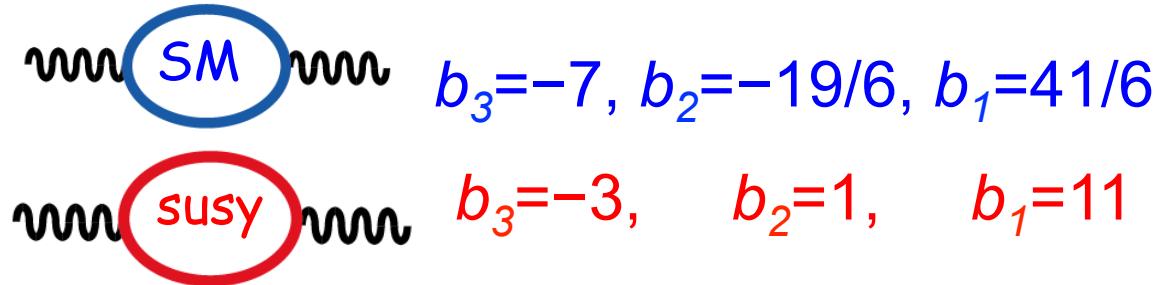
High-scale susy

Decouple susy \Rightarrow SM + boundary condition on λ



Gauge coupling unification

$$\frac{dg_i^{-2}}{d\ln Q} = \frac{b_i}{4\pi}$$

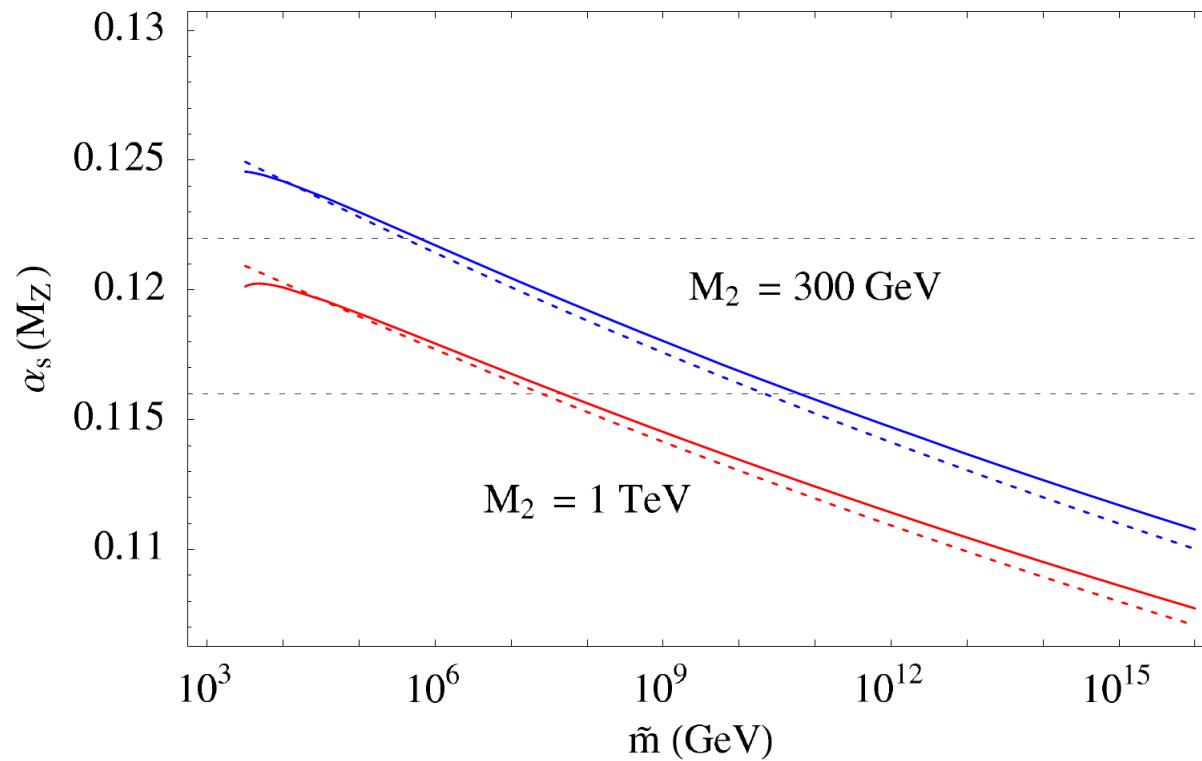


3 equations, 2 unknowns
(α_{GUT} , M_{GUT}): predict α_S
in terms of α and $\sin^2 \theta_W$

- does not strongly depend on details of soft terms
- remarkable that M_{GUT} is predicted below M_P and above p -decay limit

Matter in a complete GUT representation \Rightarrow equal contribution to b_i

$$\alpha_s = \alpha \frac{(b_1 - b_2)}{\sin^2 \theta_W (b_1 - b_3) + \frac{3}{5} \cos^2 \theta_W (b_3 - b_2)} + \text{higher orders}$$



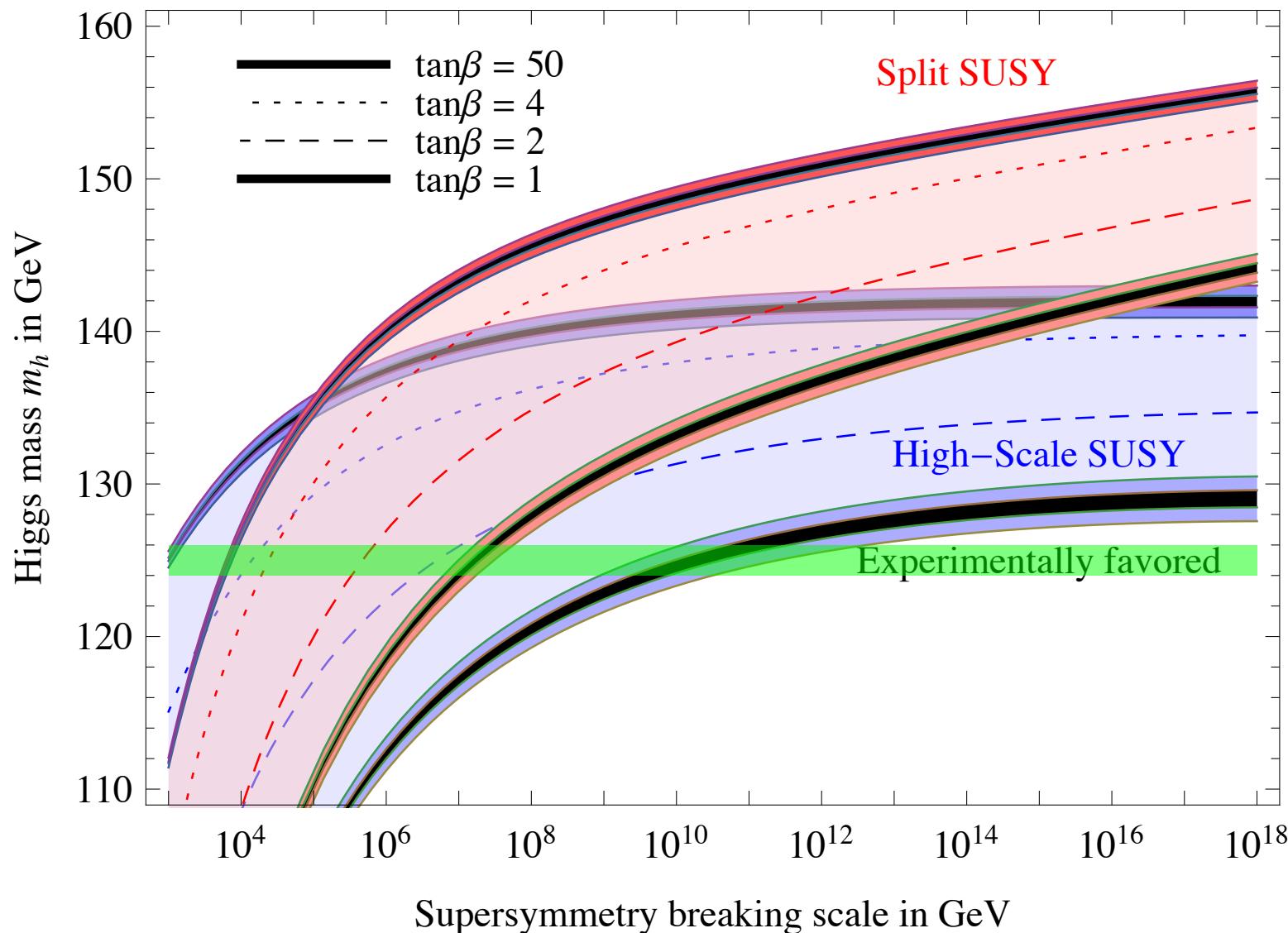
Gauge-coupling unification as successful (or better) than in ordinary SUSY

Split Supersymmetry

(Decouple squarks and sleptons)

- Give up naturalness
- Maintain gauge-coupling unification
- Maintain DM (under some conditions)
- Alleviate flavor problem
- Increases Higgs mass prediction

Split Supersymmetry



Relatively low-scale of susy breaking

Fairly generic situation: susy breaking is not directly communicated
 by gauge-singlet R-breaking fields to gauginos
 \Rightarrow gaugino masses determined by anomaly mediation

$$M_1 = \frac{\alpha}{4\pi \cos^2 \theta_W} m_{3/2} \left[11 - f\left(\mu^2 / m_A^2\right) \right]$$

$$\tilde{m} = m_{3/2}$$

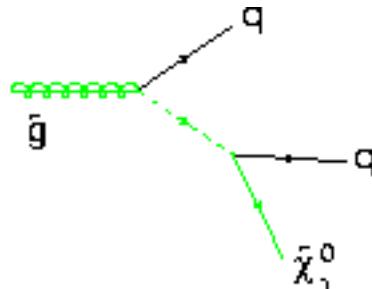
$$M_2 = \frac{\alpha}{4\pi \sin^2 \theta_W} m_{3/2} \left[1 - f\left(\mu^2 / m_A^2\right) \right]$$

$$M_\lambda = \frac{\beta_g}{g} m_{3/2}$$

$$M_3 = -\frac{3\alpha_s}{4\pi} m_{3/2}$$

$$f(x) = \frac{2x \ln x}{x - 1}$$

Will we be able to tell?



Gluino lifetime $c\tau = \left(\frac{\text{TeV}}{M_3}\right)^5 \left(\frac{\tilde{m}}{1000 \text{ TeV}}\right)^4 10^3 \mu\text{m}$

decay inside detector ($c\tau < 10 \text{ m}$) $\tilde{m} < 10^{4-5} \text{ TeV}$

measurable displacement ($c\tau > 100 \text{ } \mu\text{m}$) $\tilde{m} > 10^{2-3} \text{ TeV}$

Conclusions