Physics Beyond the Standard Model

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Beyond the Standard Model

<u>Lecture 1</u>
- •Why do we need to go Beyond the SM ?
- •The Hierarchy Problem: what do we need to solve it ?

<u>Lecture 2</u>
- •Supersymmetry and the Hierarchy Problem

<u>Lecture 3</u>
- •New Dynamics at the TeV scale: the Higgs as a (pseudo) Nambu-Goldstone Boson

Beyond the Standard Model II - SUSY

- Supersymmetry: a solution to the Hierarchy Proble

- Basic elements of SUSY theories

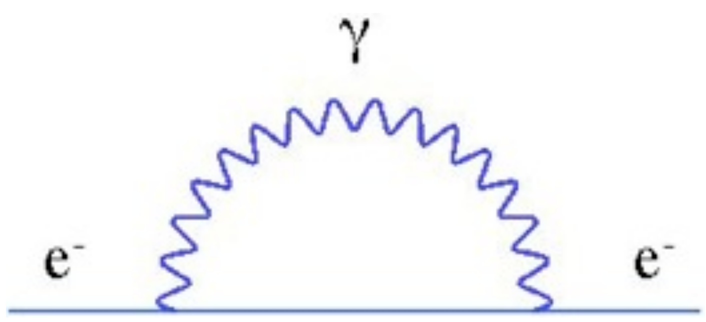
- The MSSM

- The MSSM and the Higgs

Supersymmetry and the Hierarchy Problem

Protecting Fermion Masses: Chiral Symmetry

Fermion masses only log divergent. E.g. QED



$$\delta m_e \simeq \frac{\alpha}{4\pi} m_e^0 \ln\left(\frac{\Lambda}{m_e}\right)$$

Chiral symmetry protects m_e to all orders in PT

1. $\delta m_e \longrightarrow 0$ for m_e^0
2. Divergence is logarithmic

Supersymmetry and the Hierarchy Problem

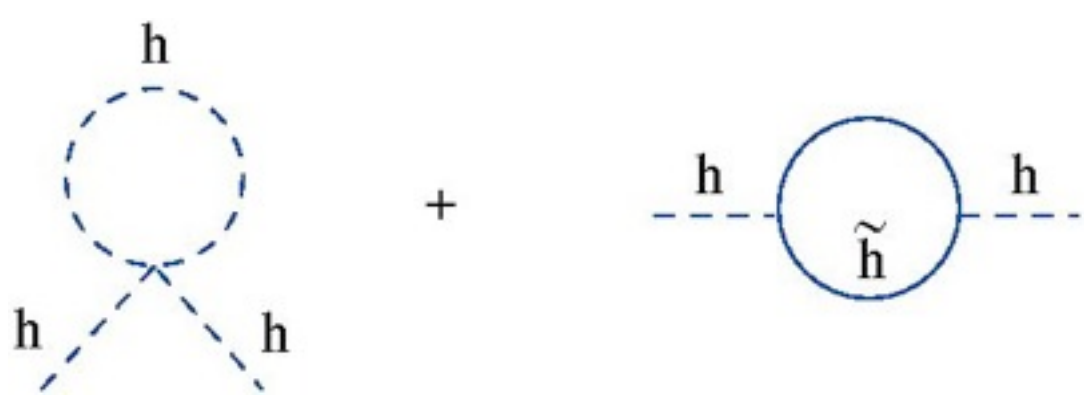
<u>How to protect the Higgs mass ?</u>

Introduce a fermionic partner of the Higgs: *Higgsino*

Need symmetry to relate Higgs (boson) to Higgsino (fermion)

$\Longrightarrow$ Supersymmetry

Higgs and Higgsino form a SUSY multiplet $(H, \tilde{H})$



no Λ dependence if SUSY exact

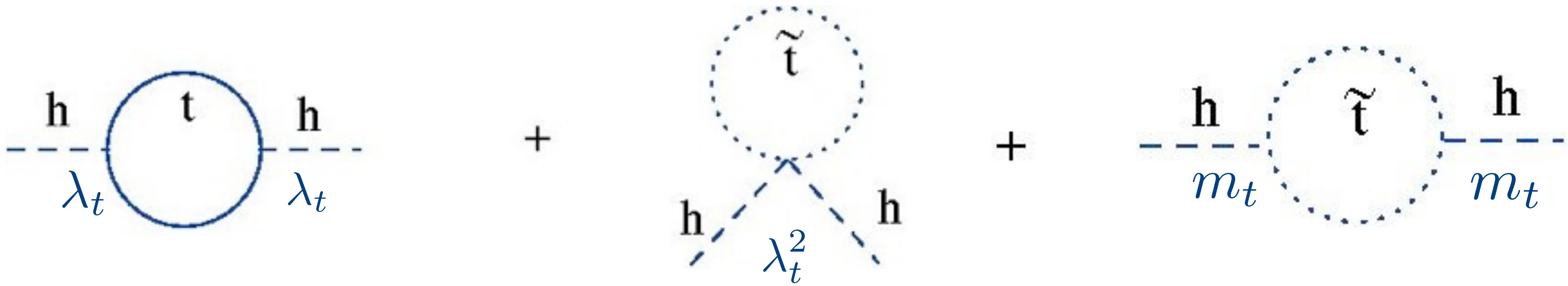
Supersymmetry and the Hierarchy Problem

What about the top quark Λ^2 divergence ?

All fermions will have a scalar partner and viceversa

stop quark $\tilde{t}$ forms SUSY multiplet with t

$$(t, \tilde{t})$$



No divergences in exact SUSY

Supersymmetric Theories

Matter in *Chiral Supermultiplets:*
- Complex scalar
- Weyl fermion

Gauge in *Vector Supermultiplets:*
- Vector field
- Fermion

Supersymmetric Theories

Superspace

Coordinates $y^\mu = x^\mu - \theta\bar{\sigma}^\mu\bar{\theta}$

θ: two-component Grassman spinor $\theta_\alpha, \quad \theta^\dagger_\alpha \equiv \bar{\theta}_{\dot{\alpha}}$

Chiral superfield

$$\Phi(y) = \phi(y) + \sqrt{2}\,\theta\psi(y) + \theta^2\,F(y)$$

$$= \phi(x) - i\theta\sigma^\mu\bar{\theta}\,\partial_\mu\phi(x) - \frac{1}{4}\,\theta^2\bar{\theta}^2\,\partial^2\phi(x)$$

$$+\sqrt{2}\theta\,\psi(x) + \frac{i}{\sqrt{2}}\,\theta^2\partial_\mu\psi(x)\sigma^\mu\bar{\theta} + \theta^2\,F(x)$$

SUSY in Superspace

- θ and $\bar{\theta}$ $\Rightarrow \theta^n = 0$ for $n \geq 3$
- $\int d^2\theta\, \theta^2 = 1$ selects coefficient of θ^2
- $d^4\theta \equiv d^2\theta\, d^2\bar{\theta} \Rightarrow \int d^4\theta$ selects coefficient of $\theta^2\, \bar{\theta}^2$
- The θ^2 component of a CSF is a total derivative under SUSY

$\Rightarrow \int d^2\theta\, W(\Phi)$ is SUSY invariant

- Same for $\theta^2\, \bar{\theta}^2$ components $\Rightarrow \int d^4\theta\, K(\Phi^\dagger, \Phi)$ invariant under SUSY

SUSY in Superspace

E.g. Kinetic terms in free theory

$$\int d^4\theta\, \Phi^\dagger \Phi = \partial_\mu \phi^* \partial^\mu \phi + i\psi^\dagger \bar{\sigma}^\mu \partial_\mu \psi + F^* F \quad \text{+ total derivatives}$$

$$= \mathcal{L}_{\text{free}}$$

Superpotential $W(\Phi)$: Generates interactions through

$$\int d^2\theta\, W(\Phi) = \mathcal{L}_{\text{int.}}$$

where $W(\Phi)$ is holomorphic function of Φ

SUSY in Superspace

Gauge Superfields

$$V^a_\mu = \theta\bar{\sigma}^\mu\bar{\theta}A^a_\mu + i\theta^2\bar{\theta}\lambda^{a\dagger} - i\theta\bar{\theta}^2\,\lambda^a + \frac{\theta^2\,\bar{\theta}^2}{2}\,D^a$$

Gauge transformation for gauge superfields

$e^{t^a V^a} \to e^{t^a \Lambda^{a\dagger}}\, e^{t^a V^a}\, e^{t^a \Lambda^a}$ $\qquad \Lambda^a$: gauge parameter is superfield

$$\Rightarrow V^a \to V^a + \Lambda^{a\dagger} + \Lambda^a + O(V^a\Lambda^a)$$

For chiral superfields:

$$\Phi \to e^{-g t^a \Lambda^a}\,\Phi$$

SUSY Interactions

Gauge-invariant kinetic terms

$$\int d^4\theta\, \Phi^\dagger e^{g t^a V^a}\, \Phi \quad = (D_\mu \phi)^\dagger D^\mu \phi + i\psi^\dagger \bar{\sigma}^\mu D_\mu \psi$$

$$-\sqrt{2} g \left[(\phi^* t^a \psi)\, \lambda^a + \lambda^{a\dagger} (\psi^\dagger t^a \phi) \right]$$

$$+g(\phi^* t^a \phi) D^a$$

In addition to usual gauge interactions

SUSY Interactions

Gauge fields kinetic terms: superfield strength

$$\mathcal{W}^a = -\sigma^{\mu\nu}\theta F^a_{\mu\nu}(y) - \theta^2\sigma_\mu D^\mu \lambda^a(y) - i\lambda^a(y) + \theta D^a(y)$$

is a chiral superfield

$$\int d^2\theta\, \mathcal{W}^a(y)\, \mathcal{W}^a(y) \quad \Longrightarrow \quad \text{Kinetic terms} \begin{cases} \text{gauge fields} \\ \text{gauginos} \end{cases}$$

Supersymmetric Theories

Summary

- Gauge and SUSY invariant kinetic terms for matter

$$\int d^4\theta \, \Phi^\dagger \, e^{g t^a V^a} \, \Phi$$

- Gauge and SUSY invariant kinetic terms for gauge fields

$$\int d^2\theta \, \mathcal{W}^a(y) \, \mathcal{W}^a(y)$$

- Gauge and SUSY invariant non-gauge interactions

$$\int d^2\theta \, W(\Phi)$$

Supersymmetry

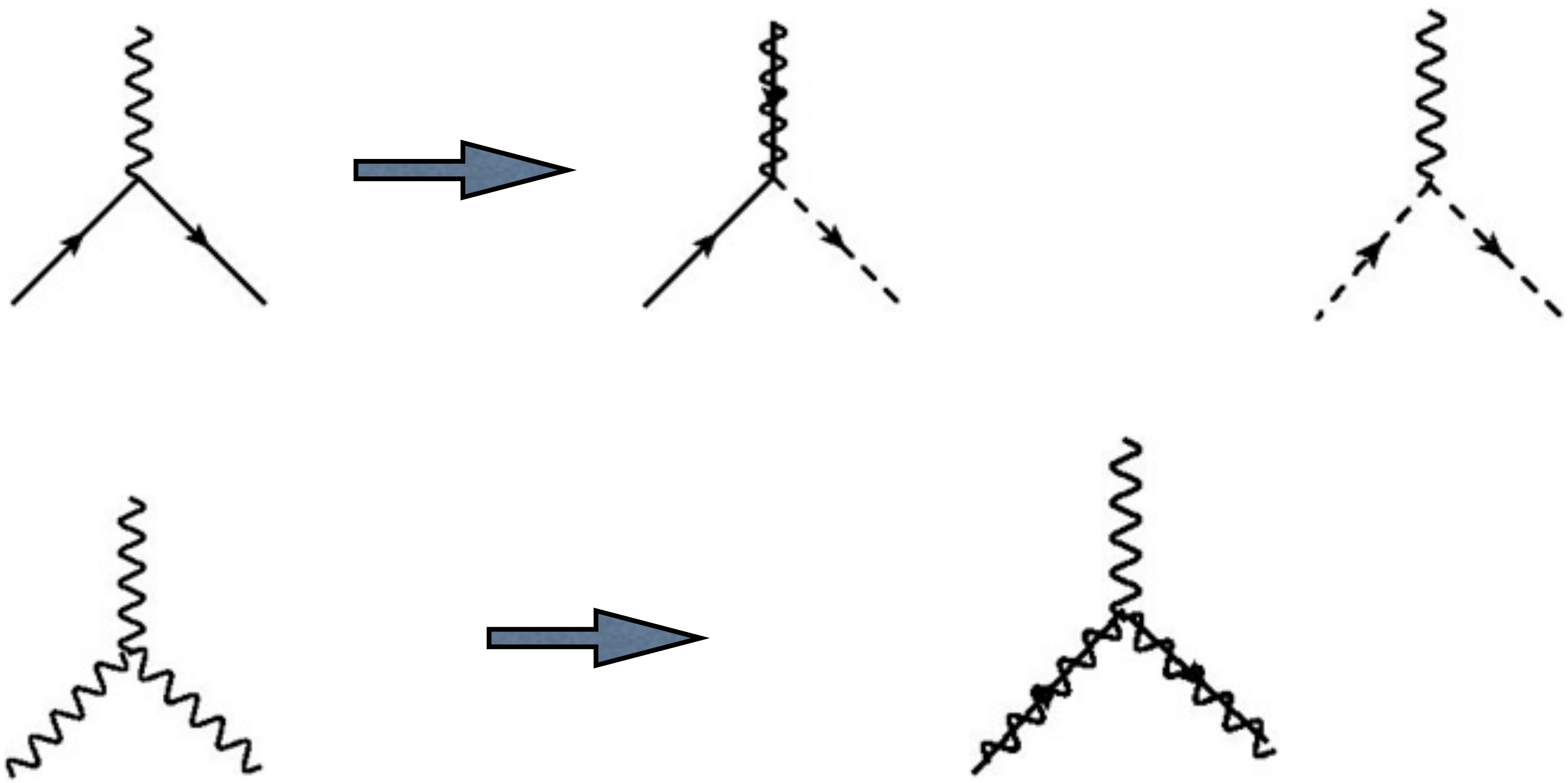
Supersymmetric extension of the SM

$Q, \ \bar{u}, \ \bar{d}$	*quarks and squarks*	Chiral Superfields
$L, \ \bar{e}$	*leptons and sleptons*	
$H_u, \ H_d$	*Higgs and higgsinos*	
$(\tilde{g}, g)$	*gluinos and gluons*	Vector Superfields
$(\tilde{W}^{\pm,0}, W^{\pm,0})$	*winos and SU(2) gauge bosons*	
$(\tilde{B}, B)$	*binos and Y gauge bosons*	

MSSM

- Interactions still determined by SM gauge

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$



Supersymmetry

- Superpotential

$$W_{\mathrm{MSSM}} = \bar{u} Y_u Q H_u - \bar{d} Y_d Q H_d - \bar{e} Y_e L H_d + \mu H_u H_d$$

Y_u, Y_d, Y_e Yukawa matrix in flavor space

μ term

g, g', v

} *parameters*

Soft SUSY Breaking

- Need to break SUSY softly:

$$
\begin{aligned}
W_{\rm soft} = & -\frac{1}{2}\left(M_1 \tilde{B}\tilde{B} + M_2 \tilde{W}\tilde{W} + M_3 \tilde{g}\tilde{g} + \text{h.c.}\right) \\
& -\tilde{Q}^\dagger\, m_Q^2\, \tilde{Q} - \tilde{L}^\dagger\, m_L^2\, \tilde{L} - \tilde{\bar{u}}\, m_u^2\, \tilde{\bar{u}}^\dagger - \tilde{\bar{d}}\, m_d^2\, \tilde{\bar{d}}^\dagger - \tilde{\bar{e}}\, m_e^2\, \tilde{\bar{e}}^\dagger \\
& - \left(\tilde{\bar{u}}\, A_u\, \tilde{Q} H_u - \tilde{\bar{d}}\, A_d\, \tilde{Q} H_d + \tilde{\bar{e}}\, A_e\, \tilde{L} H_d + \text{h.c.}\right) \\
& - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (b H_u H_d + \text{h.c})
\end{aligned}
$$

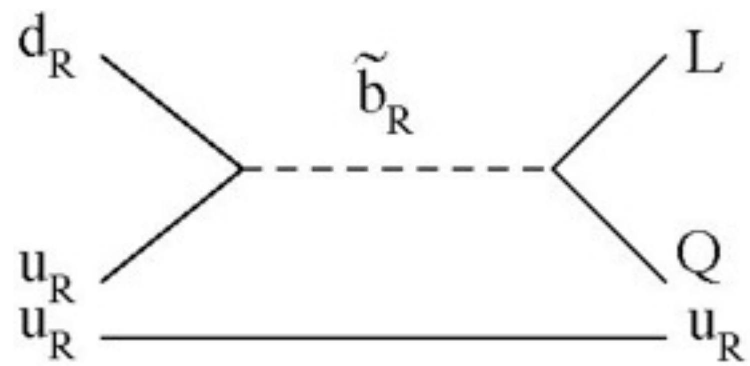
R Parity

- Additional SUSY-preserving terms in the superpotential

$$W_{\rm RPV} = \alpha^{ijk} Q_i L_j \bar{d}_k + \beta^{ijk} L_i L_j \bar{e}_k + \gamma^i L_i H_u + \delta^{ijk} \bar{d}_i \bar{d}_j \bar{u}_k$$

they violate B and L !

p^+



$(e^+, \mu^+)(\nu_e, \nu_\mu)$

$(\pi^0, K^0)(\pi^+, K^+)$

$$\tau_p > 10^{33} \text{ years} \quad \Longrightarrow \quad |\alpha\, \delta| < 10^{-25}$$

R Parity

- Introduce new discrete symmetry, M parity

$$P_M = (-1)^{3(B-L)}$$

Forbids terms W that violate B, L

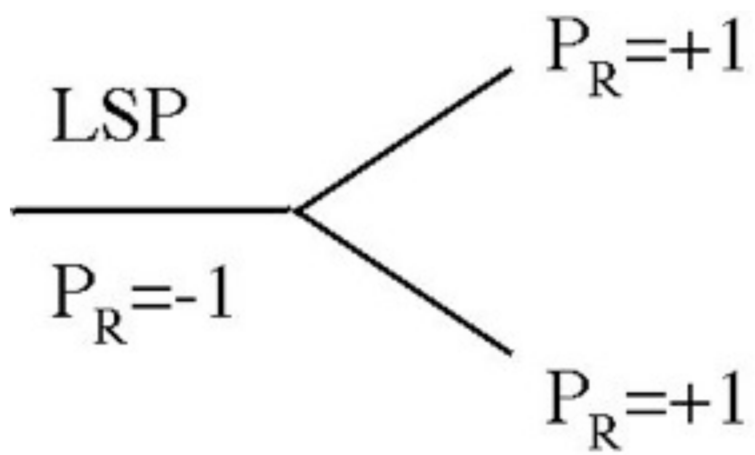
- Equivalent to R parity

$$P_R = (-1)^{3(B-L)+2s}$$

$$\Rightarrow \begin{cases} \text{Superpartners have } P_R = -1 \\ \text{SM particles have } P_R = +1 \end{cases}$$

R Parity

Lightest Supersymmetric Particle (LSP) is stable



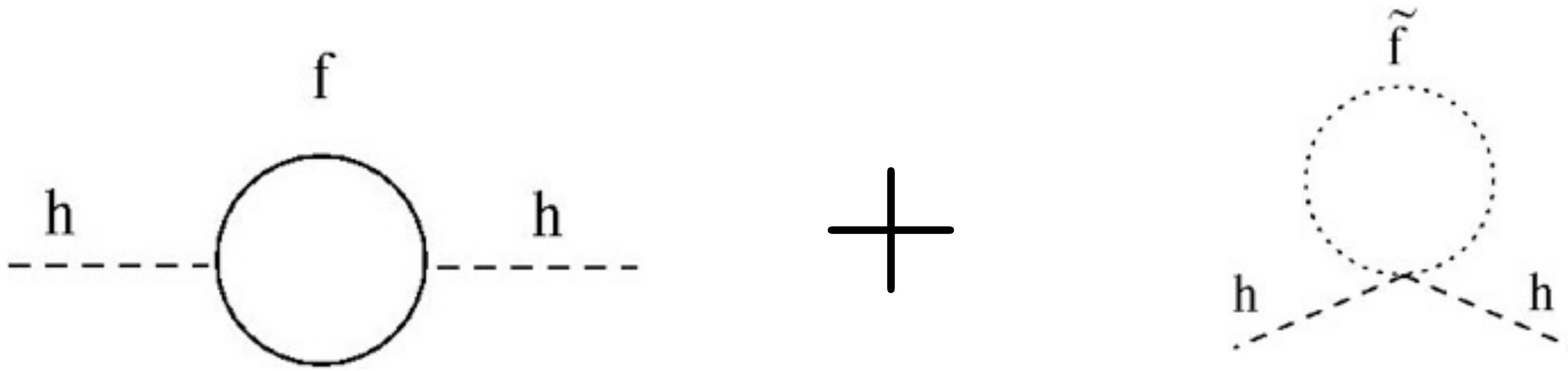
decay of LSP forbidden by R parity

Typical SUSY WIMP candidate:

neutralino: $\tilde{\chi}^0$ admixture of $\tilde{W},\ \tilde{B},\ \tilde{H}$

In generic SUSY models is possible to obtain the correct Ω_χ

Implications of m_h for SUSY



Superpartner loops cancel quadratic divergences

$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{M_S^2}\right)\right)$$

$M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$ Stop mass scale

$X_t = A_t - \mu \cot\beta$ Stop mixing

SUSY Phenomenology

<u>MSSM with R parity conservation</u>

- E.g. $pp \to \tilde{g}\tilde{g},\ \tilde{q}\tilde{q}^*,\ \tilde{q}\tilde{q}$ with $\tilde{q} \to q\,\chi_1^0$ or $\tilde{g} \to \tilde{q}\,q$

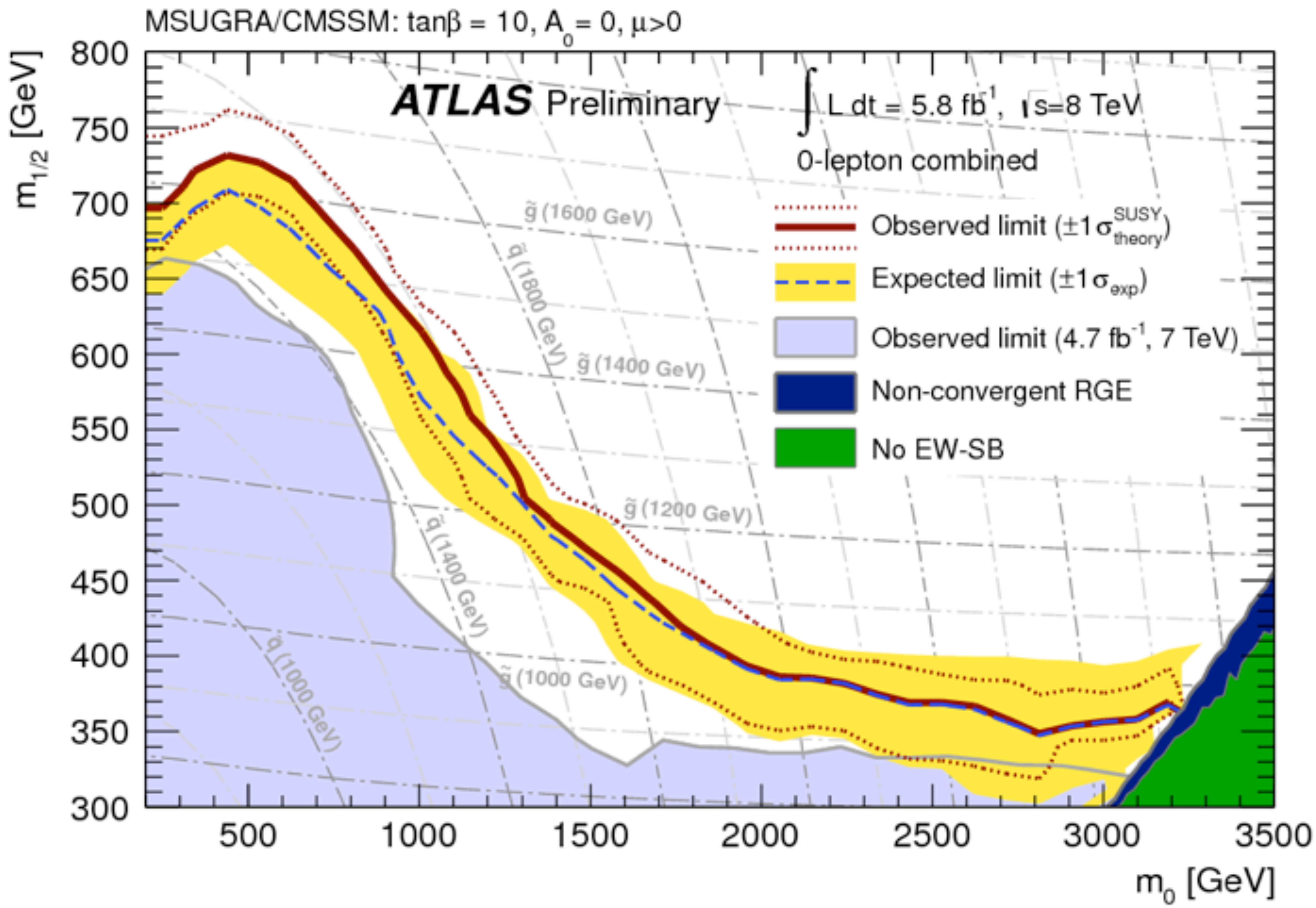
$$\Longrightarrow \text{ jets + } E_T^{\text{miss.}}$$

- Or 3-body decays. E.g. $\tilde{g} \to q\,\bar{q}\,\chi_1^0$

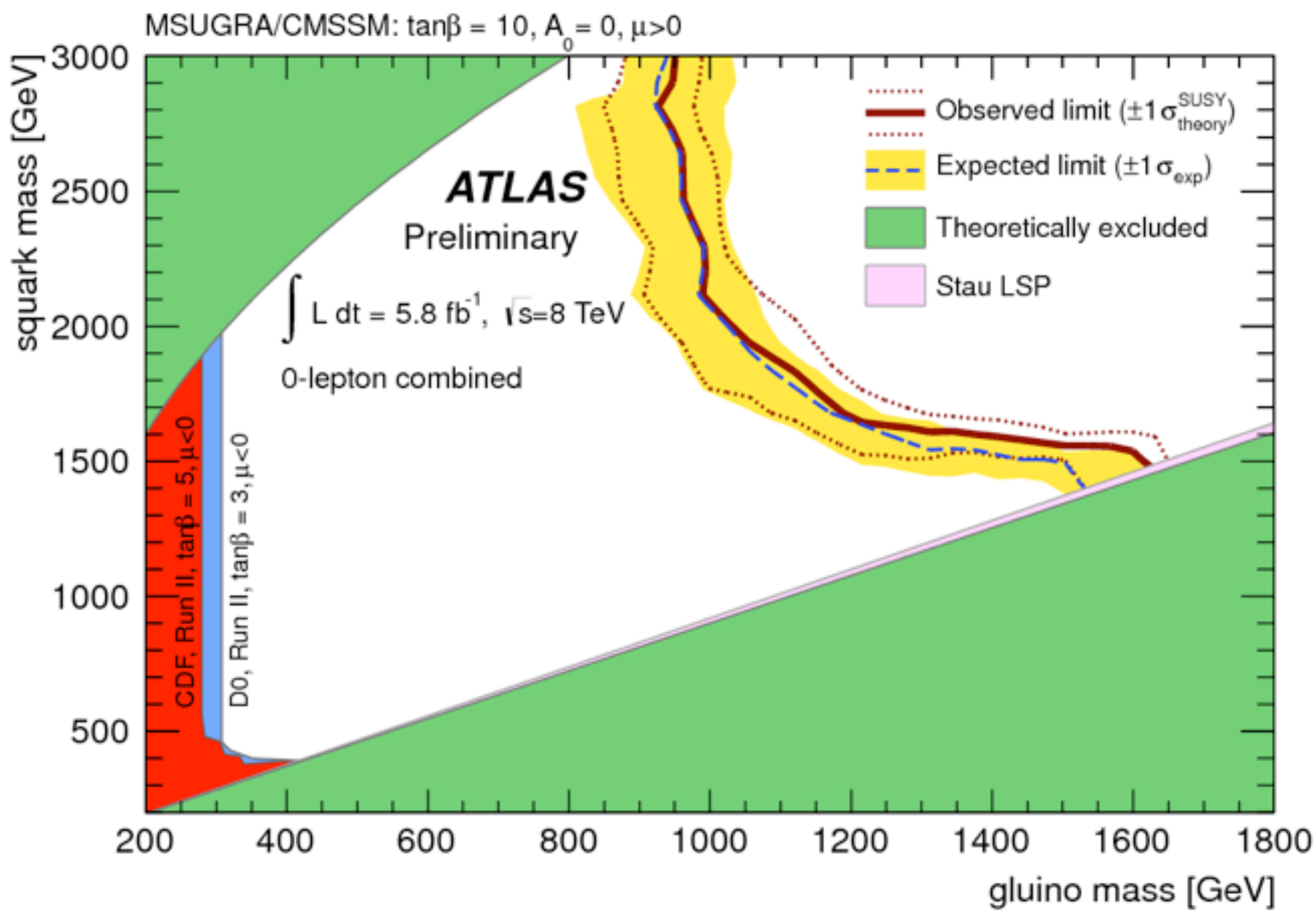
- Also decays with 1 or more leptons

- Bounds depend on decay channels/models

SUSY Searches at the LHC

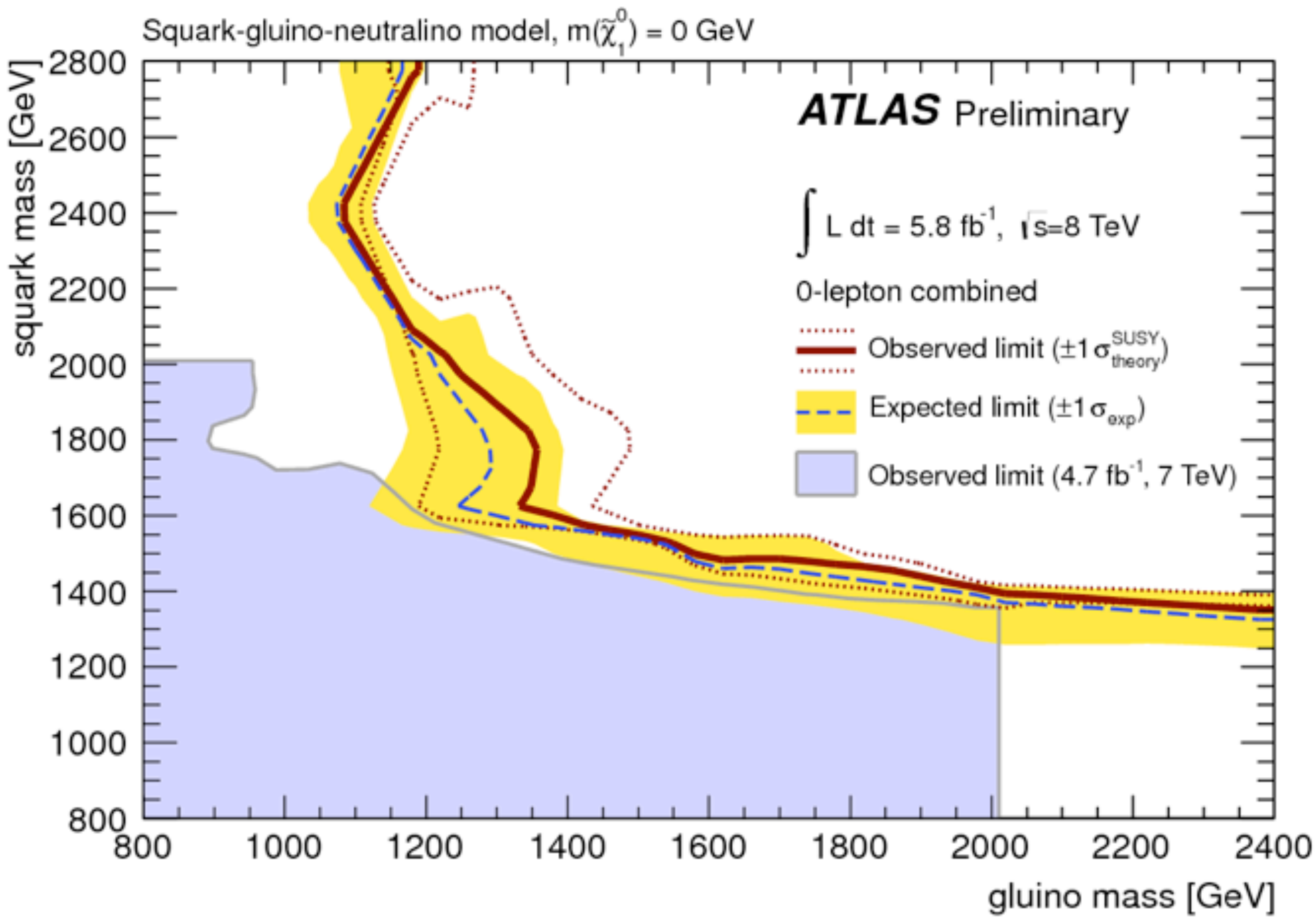


SUSY Searches at the LHC



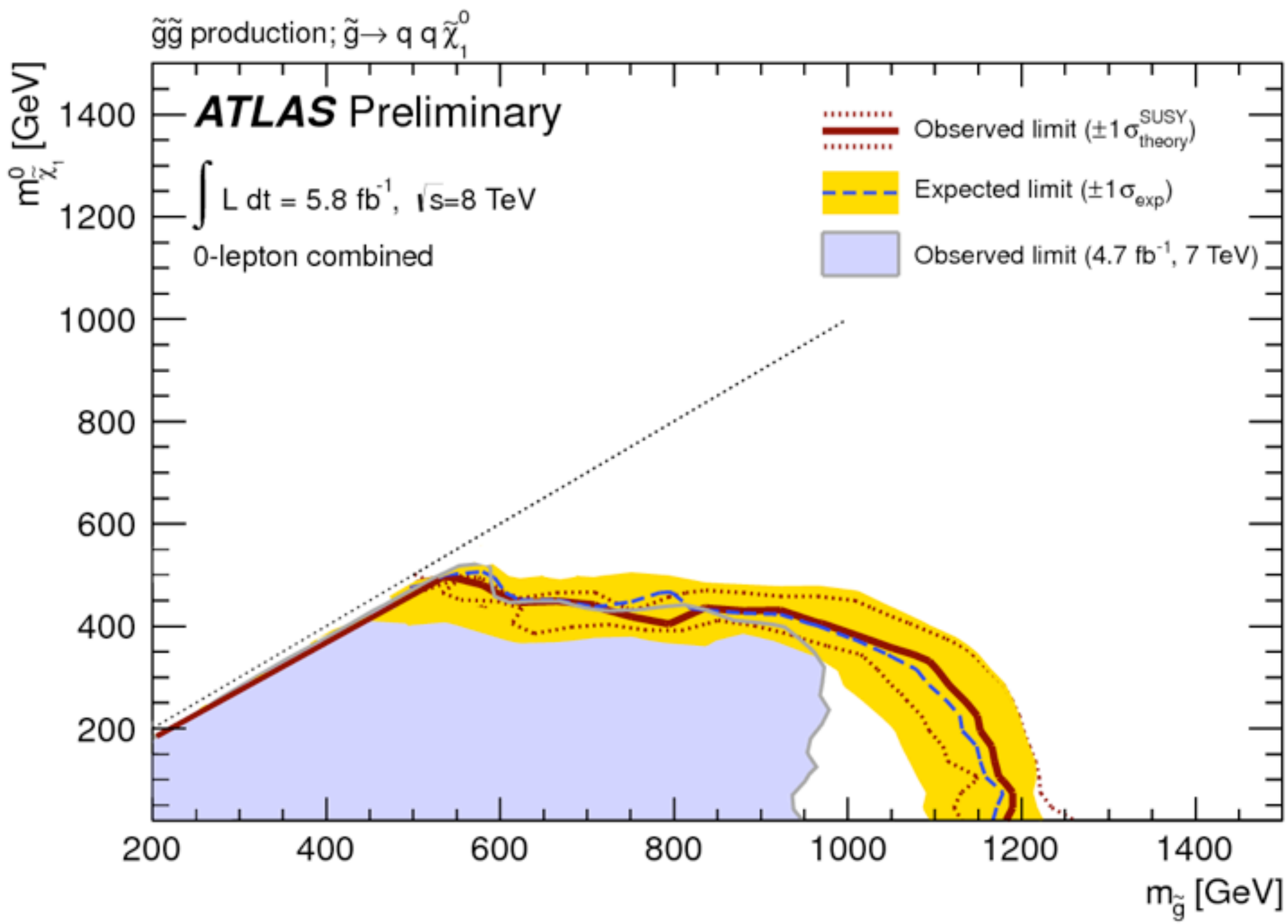
SUSY Searches at the LHC

- Assuming direct decays to jets

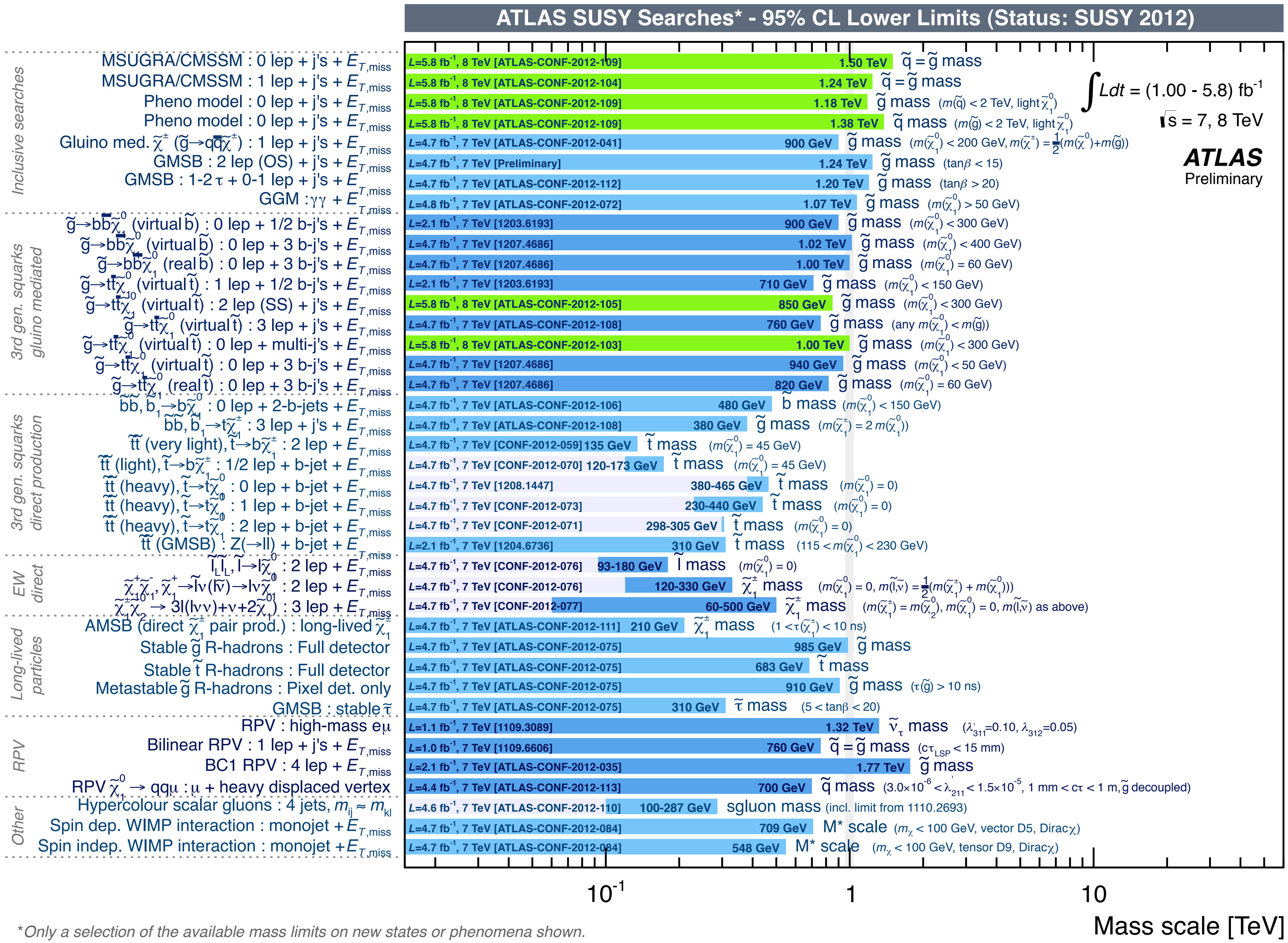


SUSY Searches at the LHC

- Assume $\tilde{g} \rightarrow q\,\bar{q}\,\chi_1^0$



SUSY Searches at the LHC



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

Sunday, March 10, 2013

Hiding SUSY

Why haven't we seen it ?

- *Compressed Spectrum*

Not enough $E_T^{\text{miss.}}$

- *R-parity Violation*

LSP not stable. Different decay modes. Not enough $E_T^{\text{miss.}}$

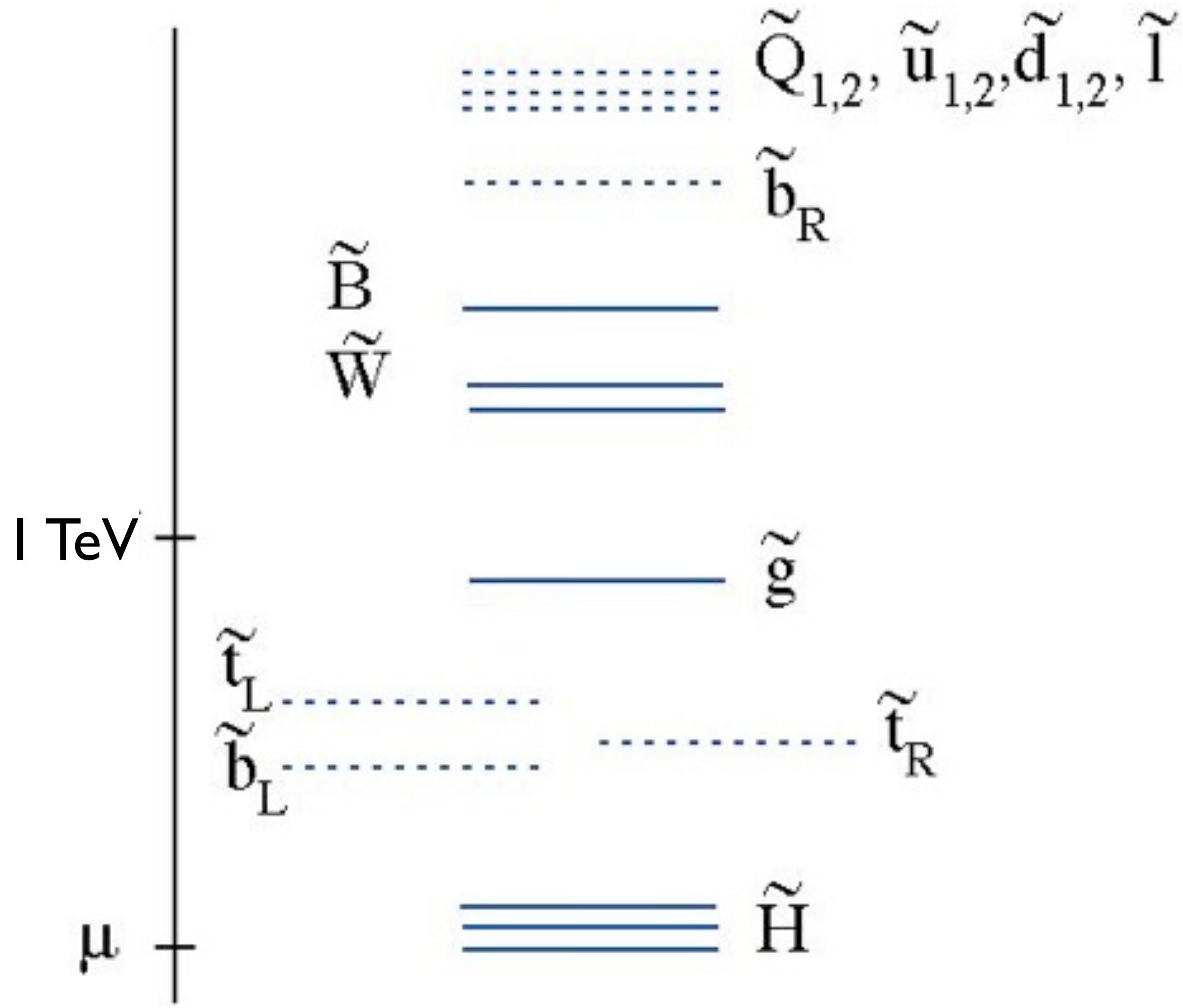
- *Natural SUSY*

Light *higgsinos*, *3rd. gen. squarks*

Everybody else heavy

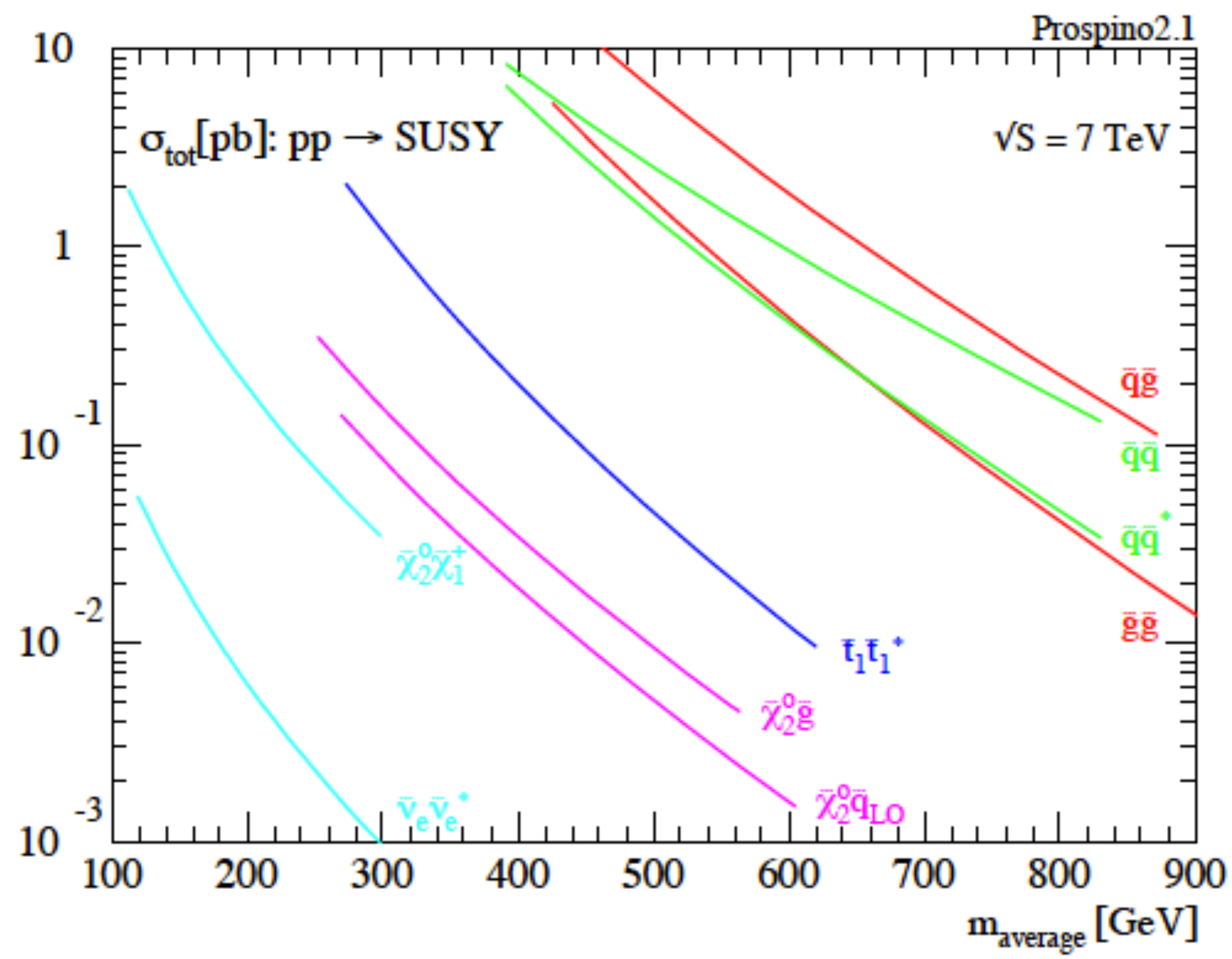
Natural SUSY

Naturalness only requires Higgsinos, stops and gluinos to be “light”



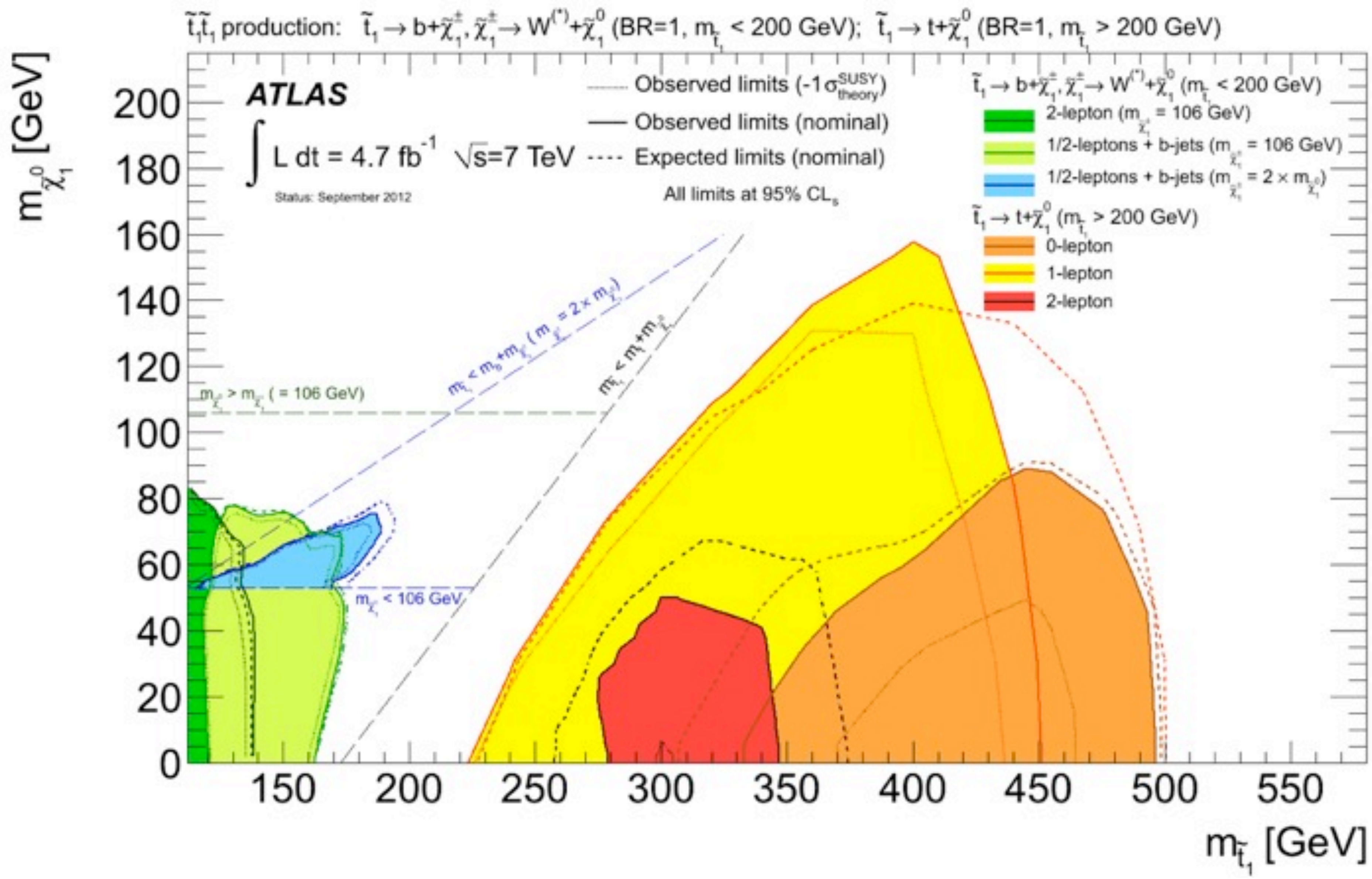
Natural SUSY

It's hard to produce light stops



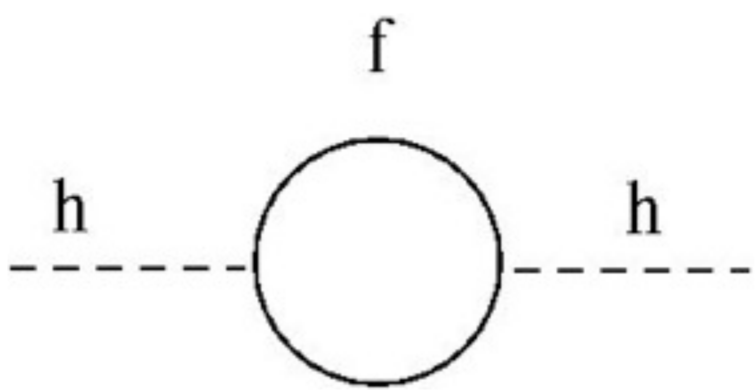
Hiding SUSY

Stop limits



Finding Natural SUSY is hard

Implications of m_h for SUSY



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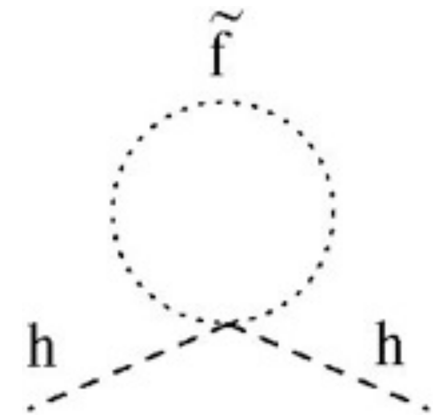


Superpartner loops to make Higgs heavier

$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{M_S^2}\right)\right)$$

$M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$ Stop mass scale

$X_t = A_t - \mu \cot\beta$ Stop mixing

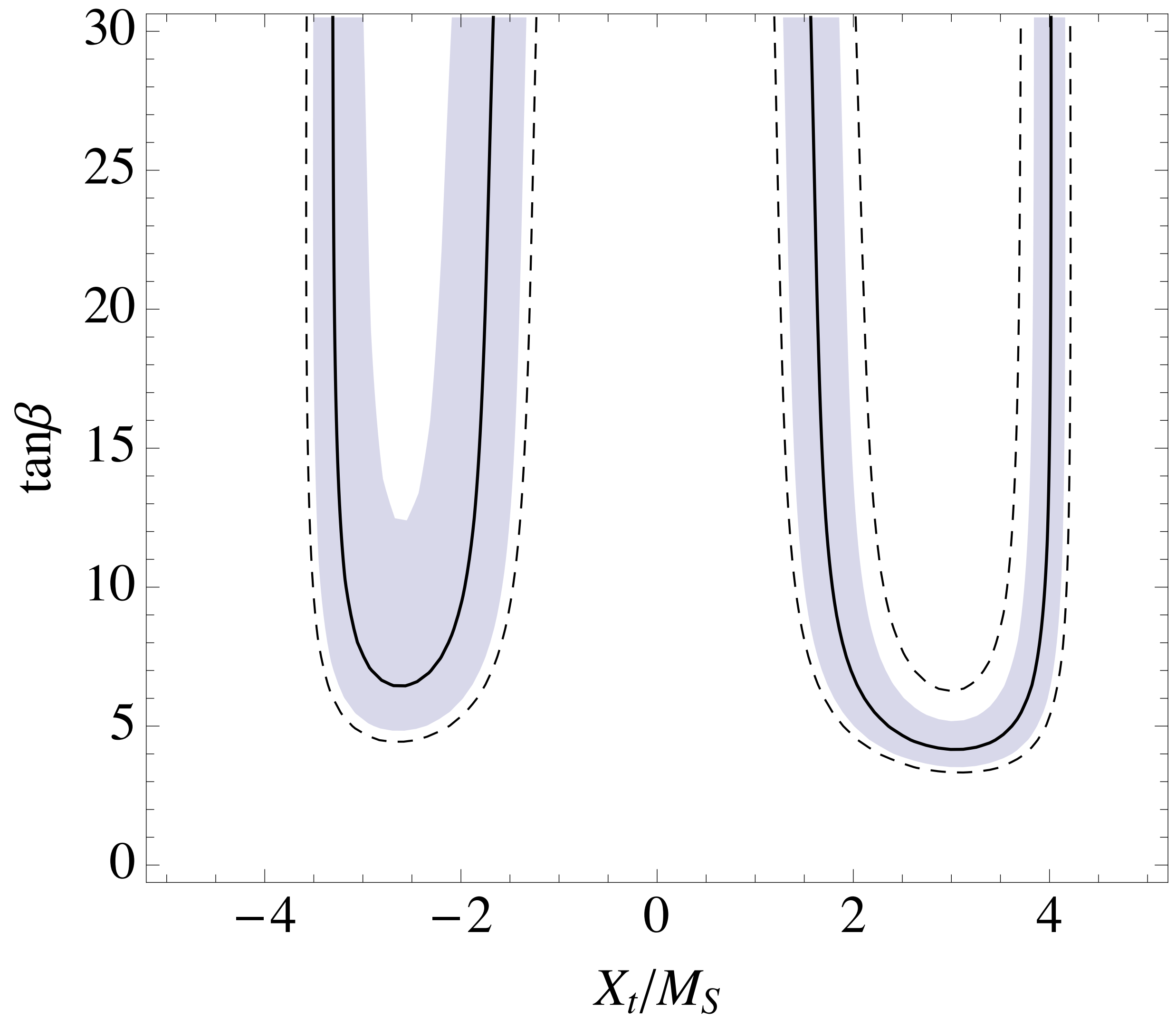
SUSY and the Higgs

$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{M_S^2}\right)\right)$$

For $m_h = 125 \text{ GeV}$

$\Rightarrow \tan\beta > 3.5$

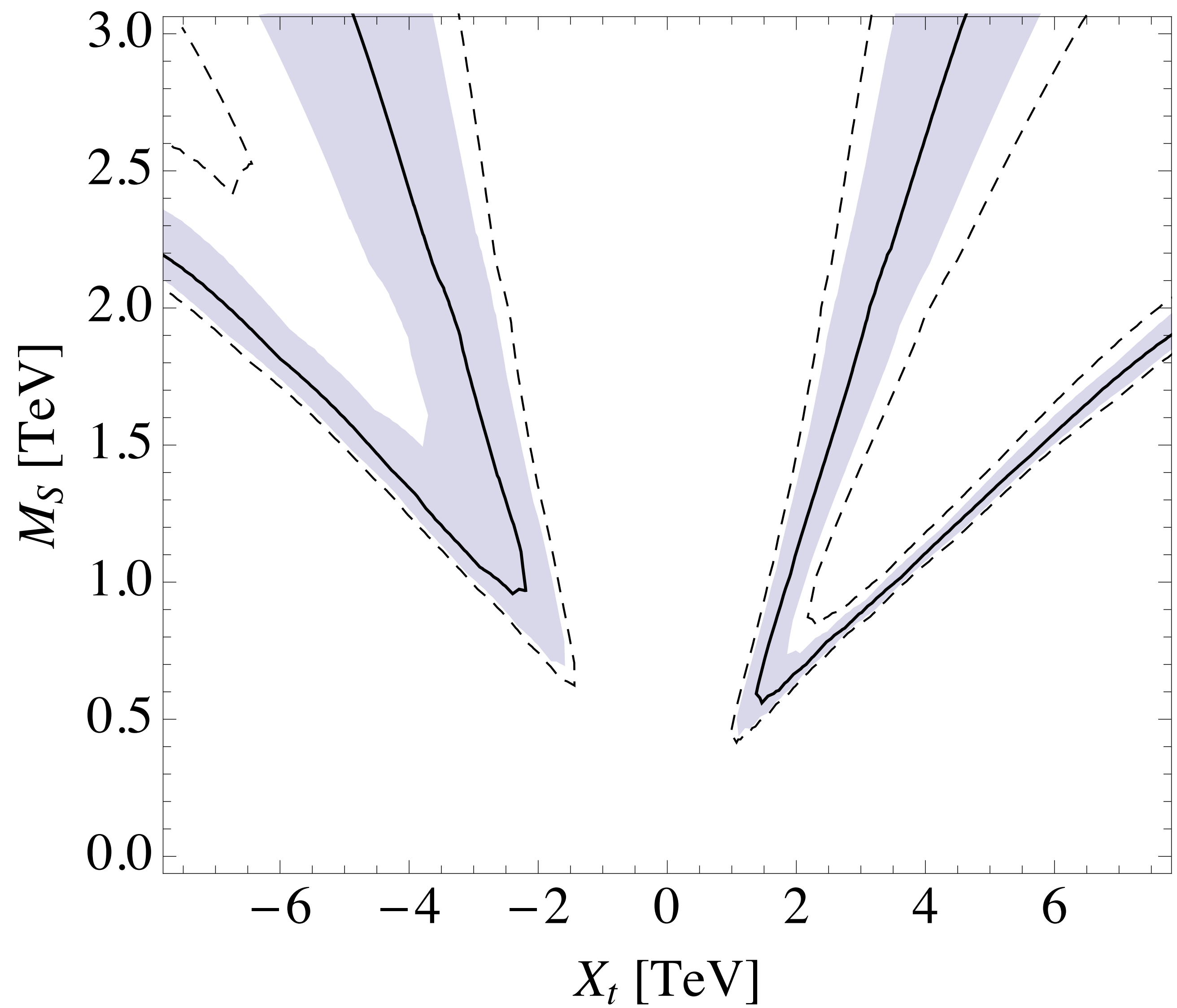
Draper, Meade, Reece, Shih '12



SUSY and the Higgs

For fixed $\tan\beta = 30$

$$\Rightarrow \begin{cases} |X_t| > 1 \text{ TeV} \\ M_S > 500 \text{ GeV} \end{cases}$$



$\Rightarrow$ Trouble for GMSB:

pressure on M_{mess} to be large

to get large enough superpartner masses

Beyond the MSSM

Problem in the MSSM:

$$V(H_u, H_d) = \frac{(g^2 + g'^2)}{2} (H_u^2 - H_d^2)^2 \qquad \Rightarrow m_h^2 = M_Z^2 \, cos^2(2\beta)$$

NMSSM Add a singlet chiral superfield

$$\lambda_S \, S \, H_u \, H_d$$

$\langle S \rangle = v_s \quad \Rightarrow \quad \lambda_S v_s \, H_u H_d$ gives μ term

and an extra quartic $\lambda_S^2 \; H_u^2 \, H_d^2$

$$\Longrightarrow \quad m_h^2 = M_Z^2 \, cos^2(2\beta) + \lambda_S^2 \, v^2 \; \sin^2(2\beta) + \cdots$$

SUSY - Conclusions/Outlook

- SUSY is a beautiful solution to the Hierarchy Problem

- The MSSM spectrum is highly constrained if we want

$$\tilde{m}_Q \leq O(1)\ \mathrm{TeV}$$

- But natural spectrum very much viable

- Bottom-up approach: look for natural SUSY signals if we really want to exclude SUSY

- The measurement of m_h posses additional constraints.

- Extensions of the MSSM (NMSSM, extended gauge sectors) should be explored, as long as they remain natural solutions to the HP