Physics Beyond the Standard Model

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Beyond the Standard Model

Lecture I •Why do we need to go Beyond the SM ? •The Hierarchy Problem: what do we need to solve it ?

Lecture 2 • Supersymmetry and the Hierarchy Problem

Lecture 3 •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



Chiral symmetry protects m_e to all orders in PT

I.
$$\delta m_e \longrightarrow 0$$
 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

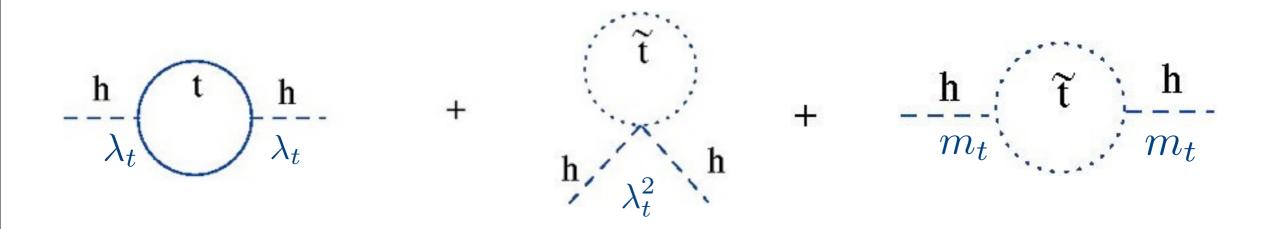
Need symmetry to relate Higgs (boson) to Higgsino (fermion)

 \implies Supersymmetry

Higgs and Higgsino form a SUSY multiplet (H, H)



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



Supersymmetric Theories

<u>Superspace</u>

Coordinates $y^{\mu} = x^{\mu} - \theta \bar{\sigma}^{\mu} \bar{\theta}$ θ : two-component Grassman spinor $\theta_{\alpha}, \quad \theta_{\alpha}^{\dagger} \equiv \bar{\theta}_{\dot{\alpha}}$

Chiral superfield

$$\begin{split} \Phi(y) &= \phi(y) + \sqrt{2} \,\theta\psi(y) + \theta^2 \,F(y) \\ &= \phi(x) - i\theta\sigma^\mu\bar{\theta} \,\partial_\mu\phi(x) - \frac{1}{4} \,\theta^2\bar{\theta}^2 \,\partial^2\phi(x) \\ &+ \sqrt{2}\theta \,\psi(x) + \frac{i}{\sqrt{2}} \,\theta^2\partial_\mu\psi(x)\sigma^\mu\bar{\theta} + \theta^2 \,F(x) \end{split}$$

SUSY in Superspace

- θ and $\overline{\theta} \Rightarrow \theta^n = 0$ for $n \ge 3$
- $\int d^2\theta \,\theta^2 = 1$ selects coefficient of θ^2

•
$$d^4\theta \equiv d^2\theta \, d^2\bar{\theta} \implies \int d^4\theta$$
 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

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

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

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

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

 $e^{t^a V^a} \rightarrow e^{t^a \Lambda^{a\dagger}} e^{t^a V^a} e^{t^a \Lambda^a}$ Λ^a : gauge parameter is superfield

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

For chiral superfields:

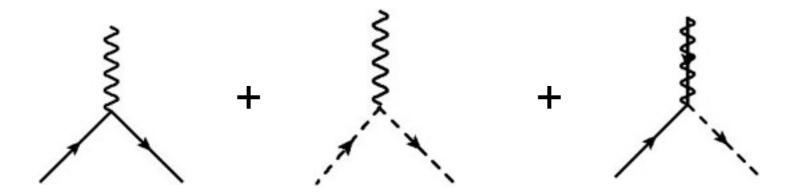
$$\Phi \to e^{-gt^a \Lambda^a} \Phi$$

SUSY Interactions

Gauge-invariant kinetic terms

$$\int d^{4}\theta \, \Phi^{\dagger} \, e^{gt^{a}V^{a}} \, \Phi = (D_{\mu}\phi)^{\dagger}D^{\mu}\phi + i\psi^{\dagger}\bar{\sigma}^{\mu} \, D_{\mu}\psi$$
$$-\sqrt{2}g \left[(\phi^{*}t^{a}\psi) \,\lambda^{a} + \lambda^{a\dagger}(\psi^{\dagger}t^{a}\phi) \right]$$
$$+g(\phi^{*}t^{a}\phi)D^{a}$$

In addition to usual gauge interactions

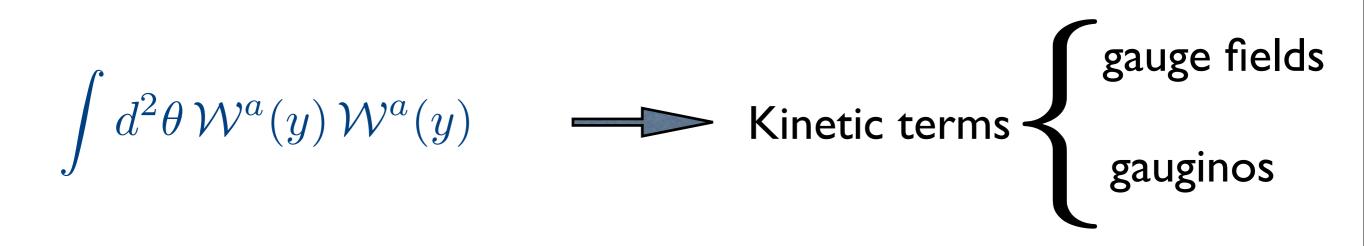


SUSY Interactions

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



Supersymmetric Theories

<u>Summary</u>

•Gauge and SUSY invariant kinetic terms for matter

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

•Gauge and SUSY invariant kinetic terms for gauge fields

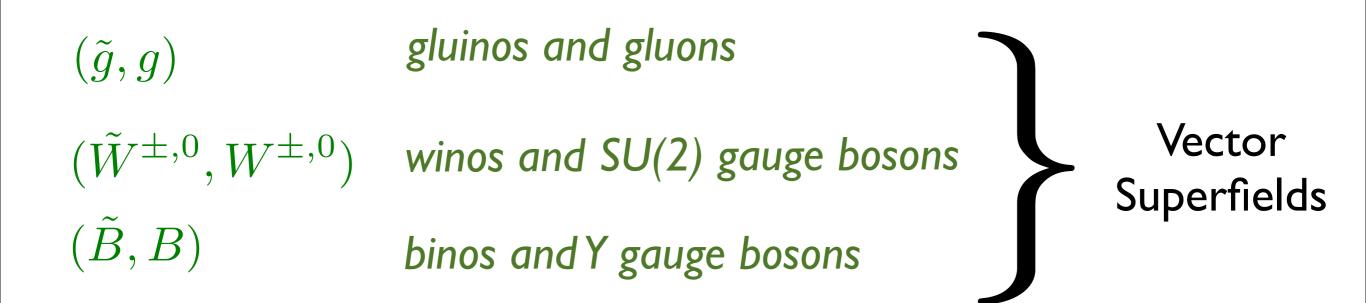
$$\int d^2\theta \, \mathcal{W}^a(y) \, \mathcal{W}^a(y)$$

•Gauge and SUSY invariant non-gauge interactions $\int d^2\theta \, W(\Phi)$

Supersymmetry

Supersymmetric extension of the SM

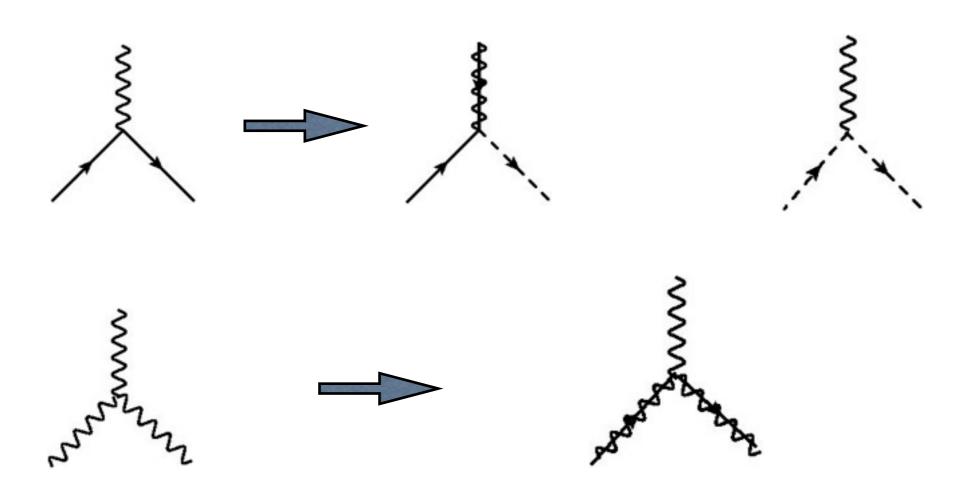




Supersymmetry

<u>MSSM</u>

•Interactions still determined by SM gauge $SU(3)_C imes SU(2)_L imes U(1)_Y$



Supersymmetry

•<u>Superpotential</u>

$W_{\rm MSSM} = \bar{u}Y_uQH_u - \bar{d}Y_dQH_d - \bar{e}Y_eLH_d + \mu H_uH_d$



Soft SUSY Breaking

• Need to break SUSY softly:

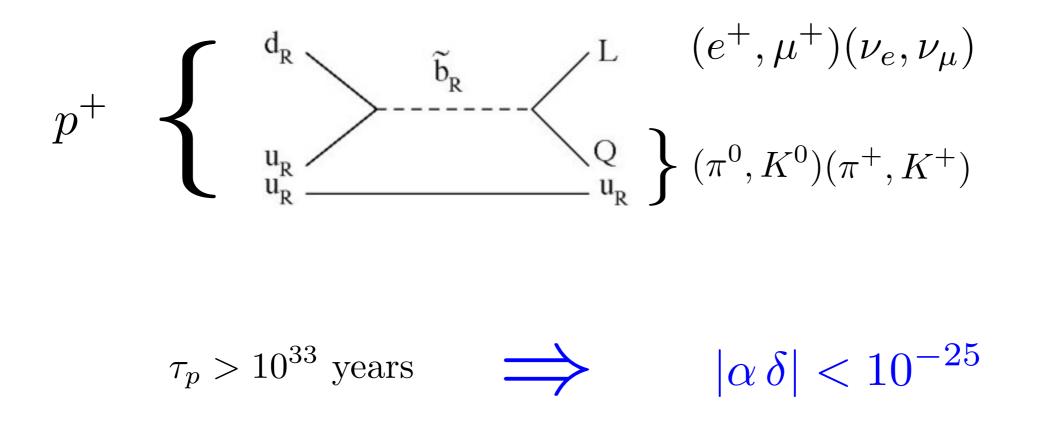
$$\begin{split} W_{\text{soft}} &= -\frac{1}{2} \left(M_1 \tilde{B} \tilde{B} + M_2 \tilde{W} \tilde{W} + M_3 \tilde{g} \tilde{g} + \text{h.c.} \right) \\ &- \tilde{Q}^{\dagger} m_Q^2 \tilde{Q} - \tilde{L}^{\dagger} m_L^2 \tilde{L} - \tilde{\bar{u}} m_u^2 \tilde{\bar{u}}^{\dagger} - \tilde{\bar{d}} m_d^2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

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 !



R Parity

Introduce new discrete symmetry, M parity

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

Forbids terms W that violate B, L

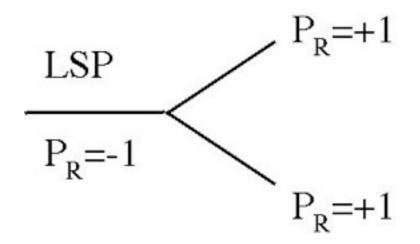
• Equivalent to R parity

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

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

R Parity

Lightest Supersymmetric Particle (LSP) is stable

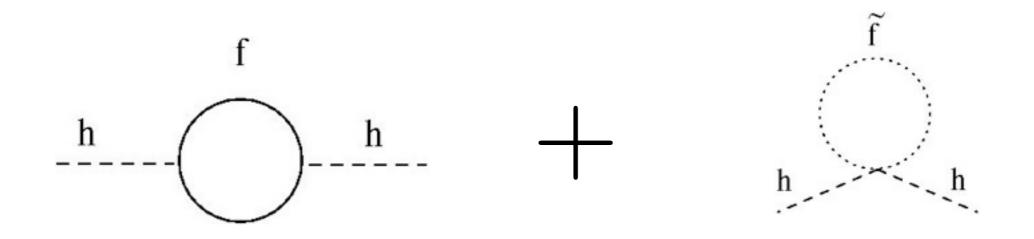


decay of LSP forbidden by R parity

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

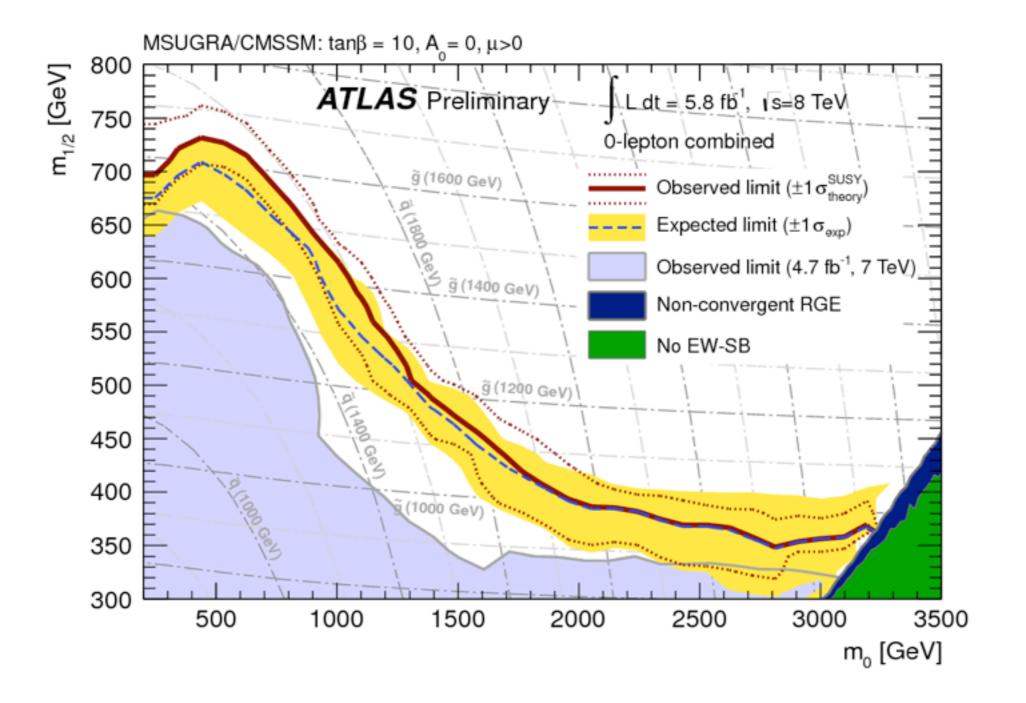
SUSY Phenomenology

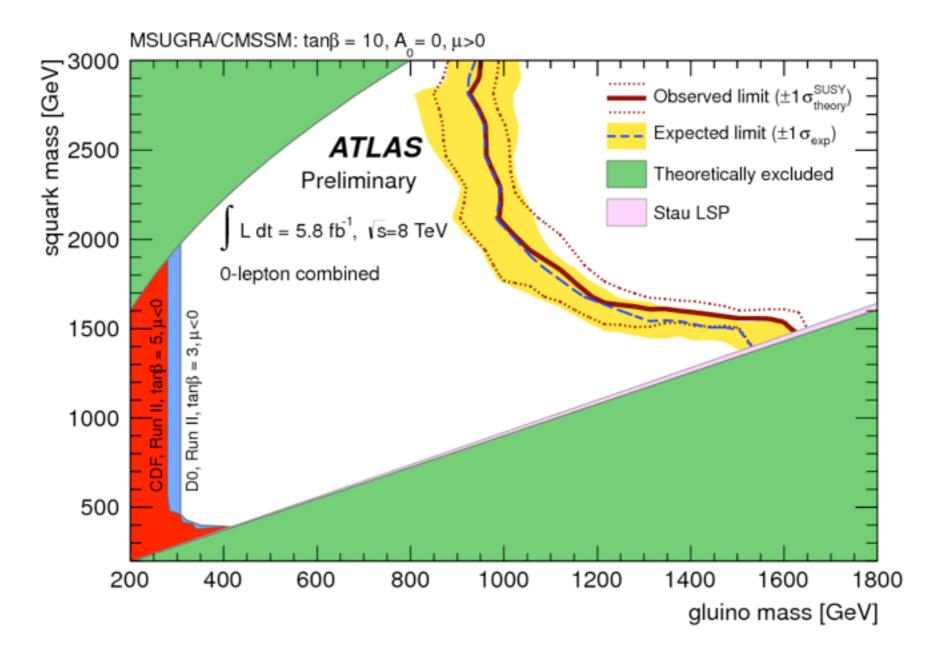
MSSM with R parity conservation

• 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 $\tilde{g} \to \tilde{q} q$

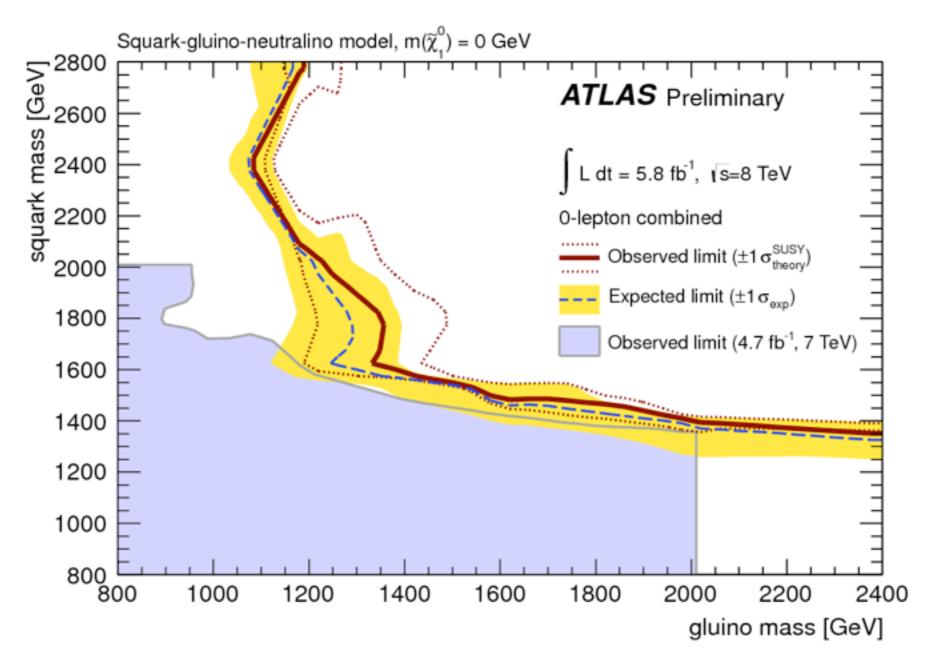
 \implies jets + $E_T^{\text{miss.}}$

- Or 3-body decays. E.g. $\tilde{g} \rightarrow q \, \bar{q} \, \chi_1^0$
- •Also decays with I or more leptons
- •Bounds depend on decay channels/models

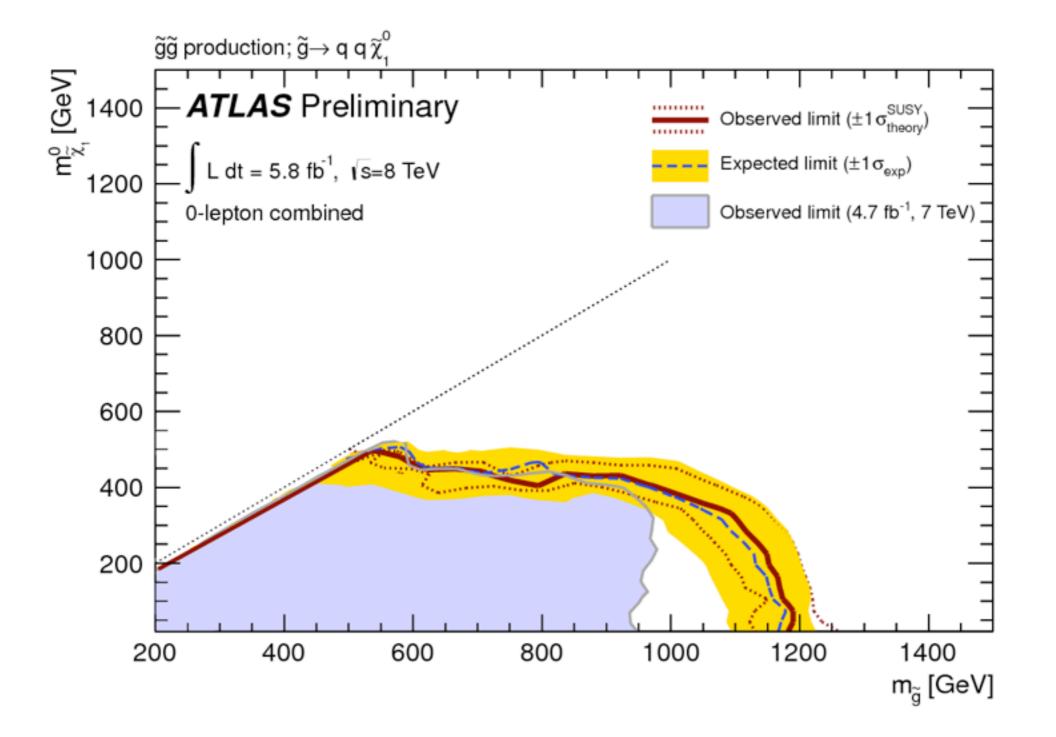




•Assuming direct decays to jets



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



		AILAS SUST	Searches" - 95% CL Lower Limits (Status: SUSY 2012)
Ś	MSUGRA/CMSSM : 0 lep + j's + $E_{T,miss}$	L=5.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-109]	1.50 TeV $\tilde{q} = \tilde{g}$ mass
Inclusive searches	MSUGRA/CMSSM : 1 lep + j's + $E_{T,miss}$	L=5.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-104]	1.24 TeV $\tilde{q} = \tilde{g}$ mass $\int Ldt = (1.00 - 5.8) \text{ fb}^{-1}$
arc	Pheno model : 0 lep + j's + $E_{T,miss}$	L=5.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-109]	1.18 lev g IIIass $(m(q) < 2$ lev, light χ_{\perp}
SO	Pheno model : 0 lep + j's + $E_{T,miss}$	L=5.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-109]	1.38 TeV \tilde{q} mass $(m\tilde{g}) < 2$ TeV, light $\tilde{\chi}_{1}^{0}$ $Is = 7, 8$ TeV
Ve	Gluino med. $\tilde{\chi}^{\pm}$ ($\tilde{g} \rightarrow q \bar{q} \tilde{\chi}^{\pm}$) : 1 lep + j's + $E_{T \text{ miss}}$	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-041]	900 GeV \widetilde{g} mass $(m(\widetilde{\chi}_1^0) < 200 \text{ GeV}, m(\widetilde{\chi}^{\pm}) = \frac{1}{2}(m(\widetilde{\chi}^0) + m(\widetilde{g}))$
INSI	GMSB : 2 lep (OS) + j's + $E_{T,miss}^{i,misc}$	L=4.7 fb ⁻¹ , 7 TeV [Preliminary]	1.24 TeV \widetilde{g} mass $(\tan\beta < 15)$ ATLAS
nci	Gluino med. $\tilde{\chi}^{\pm}$ ($\tilde{g} \rightarrow q \bar{q} \tilde{\chi}^{\pm}$) : 1 lep + j's + $E_{T,miss}$ GMSB : 2 lep (OS) + j's + $E_{T,miss}$ GMSB : 1-2 τ + 0-1 lep + j's + $E_{T,miss}$	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-112]	1.20 TeV \widetilde{g} mass $(\tan\beta > 20)$ Preliminary
	$GGM : \gamma\gamma + E_{T,miss}^{T,miss}$	L=4.8 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-072]	1.07 TeV \widetilde{g} mass $(m(\widetilde{\chi}^0) > 50 \text{ GeV})$
	$\widetilde{q} \rightarrow b \widetilde{p} \widetilde{\chi}^{0}$ (virtual \widetilde{b}) : 0 lep + 1/2 b-i's + $E_{T,min}$	L=2.1 fb ⁻¹ , 7 TeV [1203.6193]	900 GeV \widetilde{g} mass $(m(\widetilde{\chi}^0) < 300 \text{ GeV})$
S 7	$\widetilde{q} \rightarrow b\widetilde{b}\widetilde{\chi}^{0}$ (virtual \widetilde{b}) : 0 lep + 3 b-i's + $E_{T,miss}$	L=4.7 fb ⁻¹ , 7 TeV [1207.4686]	1.02 TeV \tilde{g} mass $(m(\chi_{*}^{0}) < 400 \text{ GeV})$
ark itec	$\widetilde{g} \rightarrow bb\widetilde{\chi}_{1}^{0}$ (virtual \widetilde{b}) : 0 lep + 3 b-j's + $E_{T,miss}$ $\widetilde{g} \rightarrow bb\widetilde{\chi}_{1}^{0}$ (real b) : 0 lep + 3 b-j's + $E_{T,miss}$	L=4.7 fb ⁻¹ , 7 TeV [1207.4686]	1.00 TeV \tilde{g} mass $(m(\tilde{\chi}_{1}^{0}) = 60 \text{ GeV})$
qua dia	$\widetilde{q} \rightarrow t \widetilde{t} \widetilde{\chi}^0$ (virtual \widetilde{t}) : 1 lep + 1/2 b-j's + $E_{T,miss}$	L=2.1 fb ⁻¹ , 7 TeV [1203.6193]	710 GeV \tilde{g} mass $(m(\tilde{\chi}^0) < 150 \text{ GeV})$
ı. s me	$\widetilde{g} \rightarrow tt \widetilde{\chi}_{10}^{0}$ (virtual \widetilde{t}) : 1 lep + 1/2 b-j's + $E_{T,miss}$ $\widetilde{g} \rightarrow tt \widetilde{\chi}_{10}^{0}$ (virtual \widetilde{t}) : 2 lep (SS) + j's + $E_{T,miss}$	L=5.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-105]	850 GeV \tilde{g} mass $(m(\tilde{\chi}_{1}^{0}) < 300 \text{ GeV})$
ger 10	$\widetilde{g} \rightarrow t t \widetilde{\chi}_{1}^{0}$ (virtual \widetilde{t}) : 3 lep + j's + $E_{T,miss}$	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-108]	760 GeV \widetilde{g} mass (any $m(\widetilde{\chi}_{4}^{0}) < m(\widetilde{g})$)
3rd gen. squarks gluino mediated	$\widetilde{g} \rightarrow tt \chi_{1}^{\gamma}$ (virtual t): 0 lep + multi-j's + $E_{\tau,miss}$	L=5.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-103]	1.00 TeV \tilde{g} mass $(m(\tilde{\chi}_{i}^{0}) < 300 \text{ GeV})$
60	$\widetilde{g} \rightarrow t \widetilde{t} \widetilde{\chi}_{1}^{0}$ (virtual \widetilde{t}) : 0 lep + 3 b-j's + $E_{T,miss}$	L=4.7 fb ⁻¹ , 7 TeV [1207.4686]	940 GeV \widetilde{g} mass $(m(\chi^0) < 50 \text{ GeV})$
	$\widetilde{g} \rightarrow \widetilde{t} \widetilde{\chi}_{1}^{0}$ (real \widetilde{t}) : 0 lep + 3 b-j's + $E_{T, miss}$	L=4.7 fb ⁻¹ , 7 TeV [1207.4686]	820 GeV \tilde{g} mass $(m(\tilde{\chi}_1^0) = 60 \text{ GeV})$
	$\widetilde{bb}, \widetilde{b_1} \rightarrow \widetilde{b\chi_1}^0$: 0 lep + 2-b-jets + $E_{T,\text{miss}}$	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-106]	480 GeV b mass $(m(\tilde{\chi}^0) < 150 \text{ GeV})$
ks nn	$\widetilde{bb}, \widetilde{b_1} \rightarrow t\widetilde{\chi_1^{\pm}}: 3 \text{ lep } + j' \text{s} + E_{T,\text{miss}}$	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-108]	380 GeV \widetilde{g} mass $(m(\widetilde{\chi}^{0}) = 2 m(\widetilde{\chi}^{0}))$
ctic	$\widetilde{\mathfrak{tt}}$ (very light), $\widetilde{\mathfrak{t}} \rightarrow b \widetilde{\chi}_{1}^{\pm}$: 2 lep + $E_{T,\text{miss}}$	L=4.7 fb ⁻¹ , 7 TeV [CONF-2012-059] 135 GeV	
3rd gen. squarks direct production	$\widetilde{t}t$ (light), $\widetilde{t} \rightarrow b \widetilde{\chi}_{1}^{\pm}$: 1/2 lep + b-jet + $E_{T,miss}$	L=4.7 fb ⁻¹ , 7 TeV [CONF-2012-070] 120-173 C	$\widetilde{t} \max_{i} (m_{i} \widetilde{v}^{0}) = 45 \text{ GeV}$
pro	\widetilde{tt} (heavy) $\widetilde{t} \rightarrow \widetilde{tv}^{-1}$: 0 lep + b-jet + F_{-1}	L=4.7 fb ⁻¹ , 7 TeV [1208.1447]	380-465 GeV \tilde{t} mass $(m(\tilde{\chi}^0) = 0)$
ge ect	$\underbrace{\widetilde{tt}}_{t} \text{ (heavy)}, \underbrace{\widetilde{t}}_{\to} + \underbrace{\widetilde{\chi}}_{0}^{0} : 0 \text{ lep } + b\text{-jet } + E_{T,\text{miss}}$ $\underbrace{\widetilde{tt}}_{t} \text{ (heavy)}, \underbrace{\widetilde{t}}_{\to} + \underbrace{\widetilde{\chi}}_{0}^{0} : 1 \text{ lep } + b\text{-jet } + E_{T,\text{miss}}$	L=4.7 fb ⁻¹ , 7 TeV [CONF-2012-073]	230-440 GeV \tilde{t} mass $(m(\tilde{\chi}_{4}^{0}) = 0)$
3ra dire	$TT (DOO(N)) T \rightarrow TV \rightarrow D D + D D T + E$	L=4.7 fb ⁻¹ , 7 TeV [CONF-2012-071]	298-305 GeV \tilde{t} mass $(m(\tilde{\chi}^0) = 0)$
	$\widetilde{tt} (GMSB) : Z(\rightarrow II) + b\text{-jet} + E^{T,miss}$	L=2.1 fb ⁻¹ , 7 TeV [1204.6736]	310 GeV \widetilde{t} mass $(115 < m(\tilde{\chi},)) < 230 \text{ GeV})$
t	$\widetilde{I}_{[1,1]}^{\tau}, \widetilde{I} \rightarrow \widetilde{I}_{\infty}^{\tau} : 2 \operatorname{lep} + E_{T,\operatorname{miss}}^{\tau}$	L=4.7 fb ⁻¹ , 7 TeV [CONF-2012-076] 93-180	
EW direct	$\widetilde{\chi}^+ \widetilde{\chi}^- \widetilde{\chi}^+ \rightarrow \widetilde{W}(\widetilde{W}) \rightarrow \widetilde{W}^- : 2 \operatorname{lep} + E$	L=4.7 fb ⁻¹ , 7 TeV [CONF-2012-076]	120-330 GeV $\widetilde{\chi}_{1}^{\pm}$ mass $(m(\widetilde{\chi}_{1}^{0}) = 0, m(\widetilde{l}, \widetilde{\nu}) = \frac{1}{2}(m(\widetilde{\chi}_{1}^{\pm}) + m(\widetilde{\chi}_{1}^{0})))$
Ш ij	$ \begin{array}{c} \widetilde{\chi}_{\pm}^{+}\widetilde{\chi}_{1}^{-}, \widetilde{\chi}_{1}^{+} \rightarrow \widetilde{I}v(\widetilde{k}) \rightarrow Iv\widetilde{\chi}_{01}^{-} : 2 \text{ lep } + E_{T,\text{miss}} \\ \widetilde{\chi}_{\pm}^{+}\chi_{2}^{-} \rightarrow 3I(\underline{k}v) + v + 2\widetilde{\chi}_{1}^{-}) : 3 \text{ lep } + E_{T,\text{miss}} \end{array} $	<i>L</i> =4.7 fb ⁻¹ , 7 TeV [CONF-201 <mark>2-077]</mark>	60-500 GeV $\widetilde{\chi}_{1}^{\pm}$ MASS $(m(\widetilde{\chi}_{1}^{\pm}) = m(\widetilde{\chi}_{2}^{0}), m(\widetilde{\chi}_{1}^{0}) = 0, m(\widetilde{l}, \widetilde{v})$ as above)
	AMSB (direct $\tilde{\chi}_1^+$ pair prod.) : long-lived χ_1^-		10 GeV $\tilde{\chi}_{1}^{\pm}$ MASS $(1 < \tau(\tilde{\chi}_{1}^{\pm}) < 10 \text{ ns})$
Long-lived particles	Stable \tilde{g} R-hadrons : Full detector	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-075]	985 GeV g mass
ong-live particles	E.	<i>L</i> =4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-075]	683 GeV T mass
ong	Stable t R-hadrons : Full detector Metastable g R-hadrons : Pixel det. only	<i>L</i> =4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-075]	910 GeV \widetilde{g} mass ($\tau(\widetilde{g}) > 10 \text{ ns}$)
р Гс	GMSB : stable T	<i>L</i> =4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-075]	310 GeV $\tilde{\tau}$ MASS (5 < tan β < 20)
	RPV : high-mass eµ	<i>L</i> =1.1 fb ⁻¹ , 7 TeV [1109.3089]	1.32 TeV \tilde{v}_{τ} mass $(\lambda'_{311}=0.10, \lambda_{312}=0.05)$
\geq	Bilinear RPV : 1 lep + j's + $E_{T,miss}$	L=1.0 fb ⁻¹ , 7 TeV [1109.6606]	760 GeV $\tilde{q} = \tilde{g}$ mass $(c\tau_{LSP} < 15 \text{ mm})$
RPV	BC1 RPV : 4 lep + $E_{T,miss}$	L=2.1 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-035]	1.77 TeV g mass
4	$PPV \sim 0^{-1} \rightarrow qqu \sim 1 + beavy displaced vertex$	<i>L</i> =2.11b ⁻¹ , 7 TeV [ATLAS-CONF-2012-035]	700 GeV $\widetilde{\mathbf{q}}$ mass $(3.0 \times 10^{-6} < \lambda_{211}^2 < 1.5 \times 10^{-5}, 1 \text{ mm} < ct < 1 \text{ m}, \widetilde{\mathbf{g}}$ decoupled)
	RPV $\widetilde{\chi}_{i}^{0} \rightarrow qq\mu : \mu + heavy displaced vertexHypercolour scalar gluons : 4 jets, m_{ij} \approx m_{kl}$		100-287 GeV Sgluon mass (incl. limit from 1110.2693)
Other	Spin dep. WIMP interaction : monojet $+E_{T,miss}$		709 GeV M* scale (m_{χ} < 100 GeV, vector D5, Dirac χ)
o Of	bin indep. WIMP interaction : monojet $+E_{T,miss}$	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-084] L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-084]	548 GeV M [*] SCale $(m_{\chi} < 100 \text{ GeV}, \text{ Vector DS}, \text{ Dirac}\chi)$ 548 GeV M [*] SCale $(m_{\chi} < 100 \text{ GeV}, \text{ tensor D9}, \text{ Dirac}\chi)$
9		2=4.715 , 7 TeV [ATLAS-CONF-2012-084]	
		41	
		10 ⁻¹	1 10

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

Mass scale [TeV]

*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.

Hiding SUSY

Why haven't we seen it ?

•Compressed Spectrum

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

•R-parity Violation

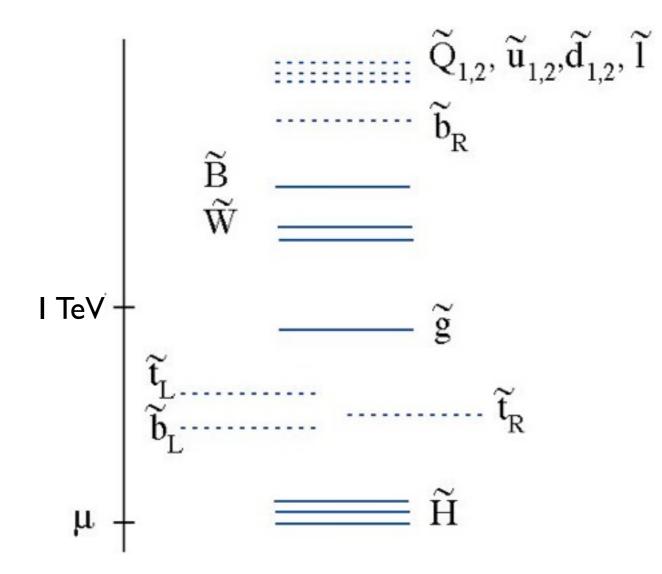
LSP not stable. Different decay modes. Not enough $E_T^{miss.}$

•Natural SUSY

Light higgsinos, 3rd. gen. squarks Everybody else heavy

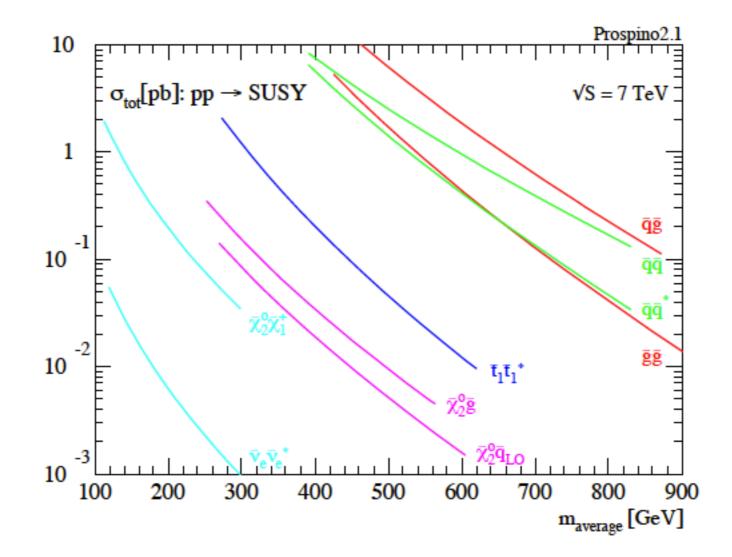
Natural SUSY

Naturalness only requires Higgsinos, stops and gluinos to be "light"



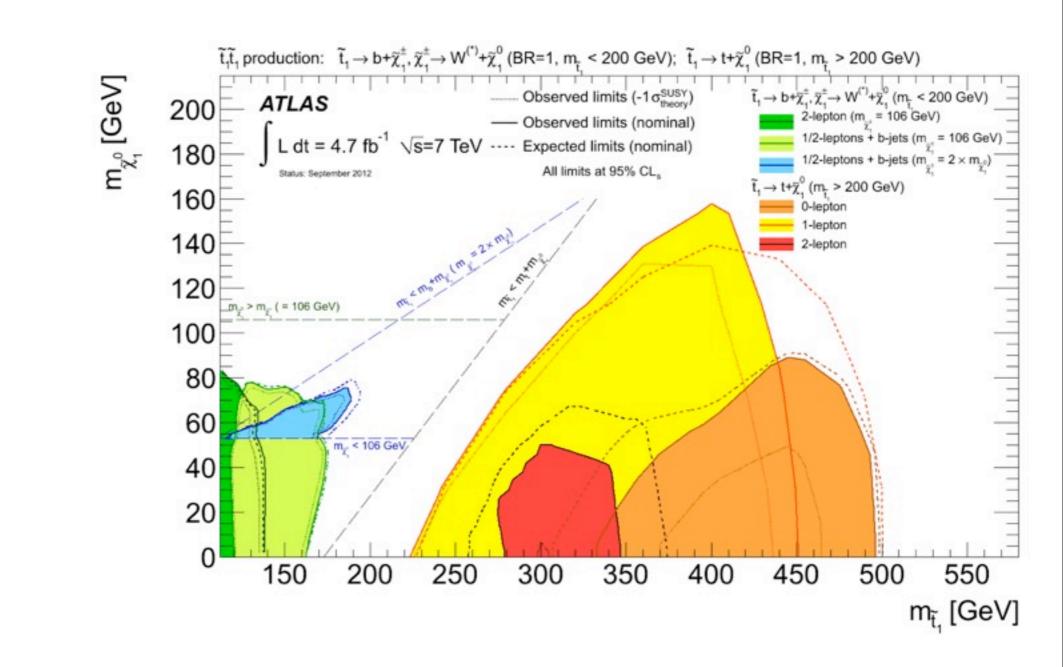
Natural SUSY

It's hard to produce light stops



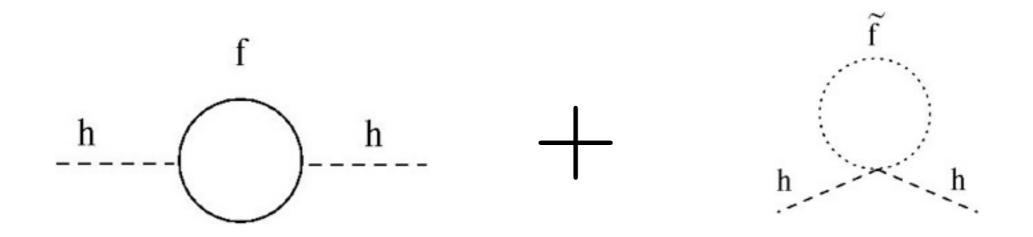
Hiding SUSY

Stop limits



Finding Natural SUSY is hard

Implications of m_h for SUSY



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

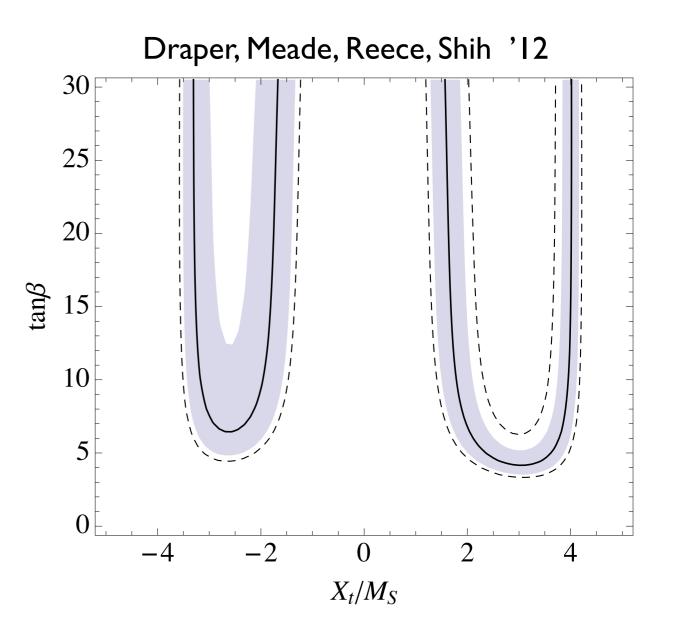
 $X_t = A_t - \mu \cot \beta$ Stop mixing

SUSY and the Higgs

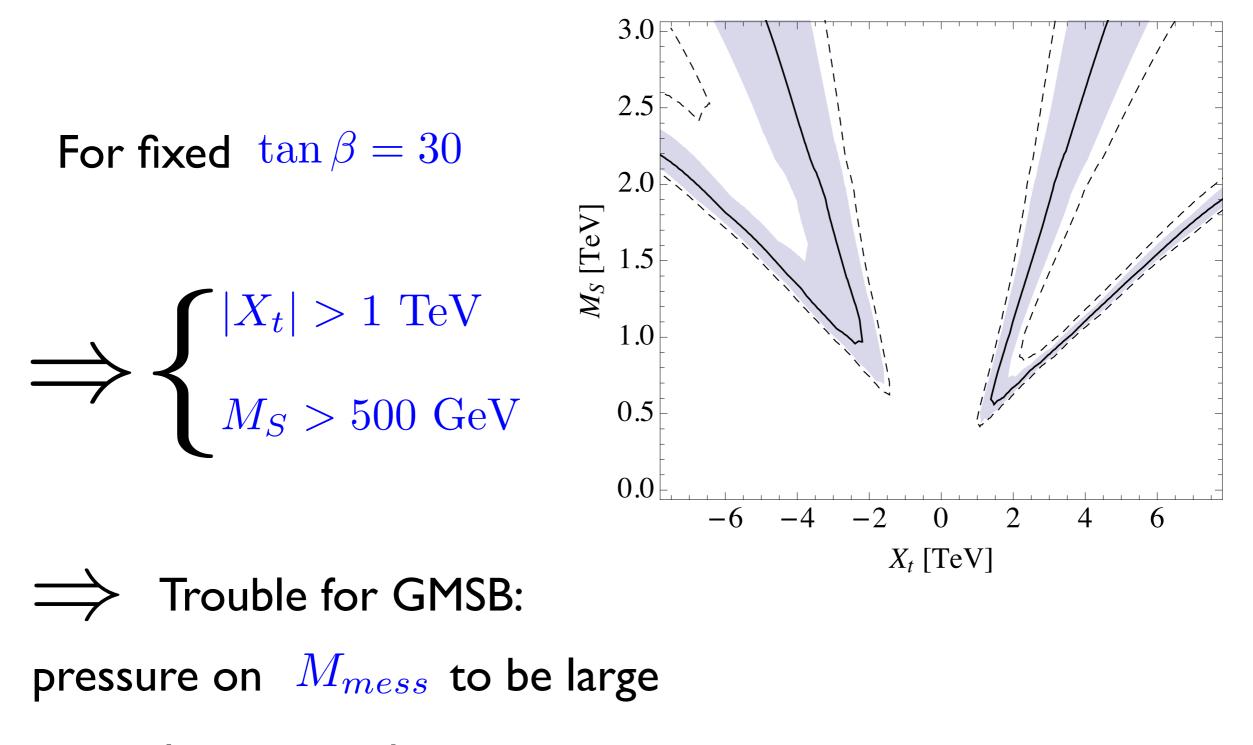
$$m_h^2 = m_Z^2 \, \cos^2 2\beta + \frac{3m_t^4}{4\pi v^2} \left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2} \, \left(1 - \frac{X_t^2}{M_S^2}\right) \right)$$

For $m_h = 125 \text{ GeV}$

 $\Rightarrow \tan \beta > 3.5$



SUSY and the Higgs



to get large enough superpartner masses

Beyond the MSSM

Problem in the MSSM:

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

$\underline{\text{NMSSM}} \quad \text{Add a singlet chiral superfield} \\ \lambda_S \, S \, H_u \, H_d$

$$\langle S \rangle = v_s \quad \Rightarrow \quad \lambda_S v_s H_u H_d \qquad \text{gives } \mu \text{ term}$$

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

$$\implies m_h^2 = M_Z^2 \cos^2(2\beta) + \lambda_S^2 v^2 \sin^2(2\beta) + \cdots$$

SUSY - Conclusions/Outlook

- •SUSY is a beautiful solution to the Hierarchy Problem
- •The MSSM spectrum is highly constrained if we want ${ ilde m}_Q \leq O(1)~{
 m TeV}$
- 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