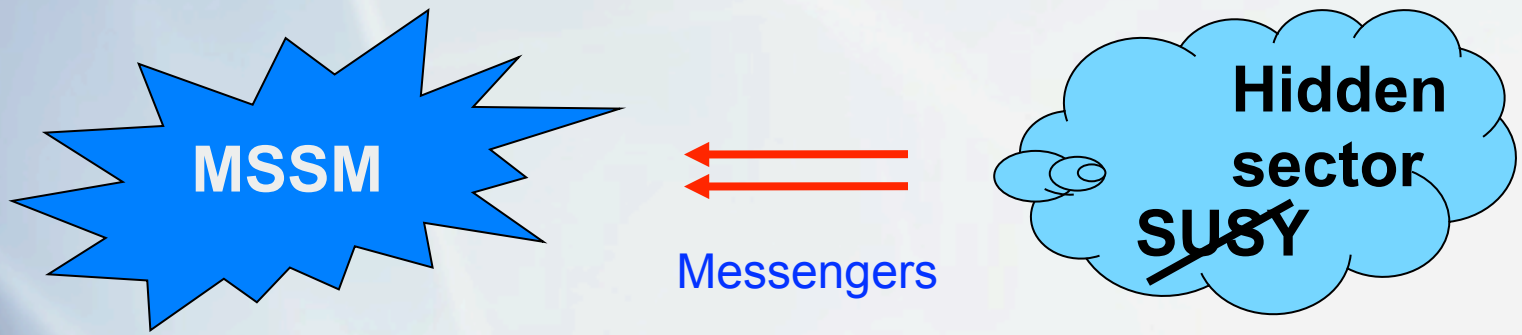
Soft SUSY Breaking



Gravitons, gauge, gauginos, etc

Breaking via F and D terms in a hidden sector

$$-L_{Soft} = \sum_{\alpha} M_i \tilde{\lambda}_i \tilde{\lambda}_i + \sum_i m_{0i}^2 \mid A_i \mid^2 + + \sum_{ijk} \mathrm{A}_{ijk} A_i A_j A_k + \sum_{ij} \mathrm{B}_{\mathrm{ij}} A_i A_j$$

gauginos

scalar fields

Over 100 of free parameters !

MSSM Parameter Space

- Three gauge couplings
- Three (four) Yukawa matrices
- The Higgs mixing parameter
- Soft SUSY breaking terms

mSUGRA Universality hypothesis (gravity is colour and flavour blind):
Soft parameters are equal at Planck (GUT) scale

$$-L_{Soft} = A\{y_t Q_L H_2 U_R + y_b Q_L H_1 D_R + y_L L_L H_1 E_R\} + B\mu H_1 H_2$$
$$+ m_0^2 \sum_i |\varphi_i|^2 + \tfrac{1}{2} M_{1/2} \sum_\alpha \tilde{\lambda}_\alpha \tilde{\lambda}_\alpha$$

Five universal soft parameters: $A,\ m_0,\ M_{1/2},\ B \leftrightarrow \tan\beta = v_2 / v_1$ and μ

versus m and λ in the SM

Mass Spectrum (spin=1/2)

$$L_{gaugino-Higgsino} = -\frac{1}{2} M_3 \bar{\lambda}_a \lambda_a - \frac{1}{2} \bar{\chi} M^{(0)} \chi - (\bar{\psi} M^{(c)} \psi + h.c.)$$

Chargino

$$\psi = \begin{pmatrix} \tilde{W}^+ \\ \tilde{H}^+ \end{pmatrix}$$

$$M^{(c)} = \begin{pmatrix} M_2 & \sqrt{2} M_W \sin\beta \\ \sqrt{2} M_W \cos\beta & \mu \end{pmatrix} \Rightarrow \begin{pmatrix} \chi_1^+ \\ \chi_2^+ \end{pmatrix}$$

Neutralino

$$(\chi_1^0,\ \chi_2^0,\ \chi_3^0,\ \chi_4^0)$$

$$\chi = \begin{pmatrix} \tilde{B}^0 \\ \tilde{W}^3 \\ \tilde{H}_1^0 \\ \tilde{H}_2^0 \end{pmatrix}$$

$$M^{(0)} = \begin{pmatrix} M_1 & 0 & -M_Z \cos\beta \sin W & M_Z \sin\beta \sin W \\ 0 & M_2 & M_Z \cos\beta \cos W & -M_Z \sin\beta \cos W \\ -M_Z \cos\beta \sin W & M_Z \cos\beta \cos W & 0 & -\mu \\ M_Z \sin\beta \sin W & -M_Z \sin\beta \cos W & -\mu & 0 \end{pmatrix}$$

Squarks & Sleptons

Mass Spectrum (spin=0)

$$\tilde{m}_t^2 = \begin{pmatrix} \tilde{m}_{tL}^2 & m_t(A_t - \mu\cot\beta) \\ m_t(A_t - \mu\cot\beta) & \tilde{m}_{tR}^2 \end{pmatrix} \Rightarrow \begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix}$$

$$\tilde{m}_b^2 = \begin{pmatrix} \tilde{m}_{bL}^2 & m_b(A_b - \mu\tan\beta) \\ m_b(A_b - \mu\tan\beta) & \tilde{m}_{bR}^2 \end{pmatrix} \Rightarrow \begin{pmatrix} \tilde{b}_1 \\ \tilde{b}_2 \end{pmatrix}$$

$$\begin{aligned}
\tilde{m}_{tL}^2 &= \tilde{m}_Q^2 + m_t^2 + \tfrac{1}{6}(4M_W^2 - M_Z^2)\cos 2\beta, \\
\tilde{m}_{tR}^2 &= \tilde{m}_U^2 + m_t^2 - \tfrac{2}{3}(M_W^2 - M_Z^2)\cos 2\beta, \\
\tilde{m}_{bL}^2 &= \tilde{m}_Q^2 + m_b^2 - \tfrac{1}{6}(2M_W^2 + M_Z^2)\cos 2\beta, \\
\tilde{m}_{bR}^2 &= \tilde{m}_D^2 + m_b^2 + \tfrac{1}{3}(M_W^2 - M_Z^2)\cos 2\beta,
\end{aligned}$$

$$\begin{aligned}
\tilde{m}_{\tau L}^2 &= \tilde{m}_L^2 + m_\tau^2 - \tfrac{1}{2}(2M_W^2 - M_Z^2)\cos 2\beta, \\
\tilde{m}_{\tau R}^2 &= \tilde{m}_E^2 + m_\tau^2 + (M_W^2 - M_Z^2)\cos 2\beta.
\end{aligned}$$

$$\tilde{m}_\tau^2 = \begin{pmatrix} \tilde{m}_{\tau L}^2 & m_\tau(A_\tau - \mu\tan\beta) \\ m_\tau(A_\tau - \mu\tan\beta) & \tilde{m}_{\tau R}^2 \end{pmatrix} \Rightarrow \begin{pmatrix} \tilde{\tau}_1 \\ \tilde{\tau}_2 \end{pmatrix}$$

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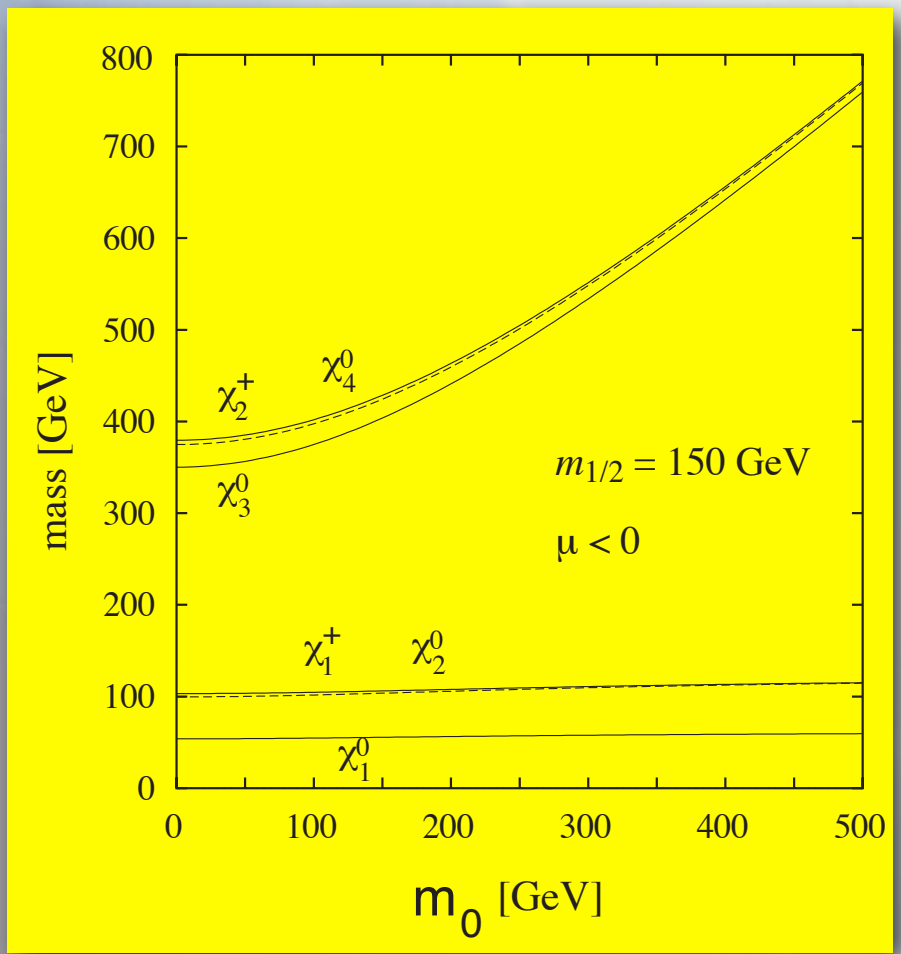
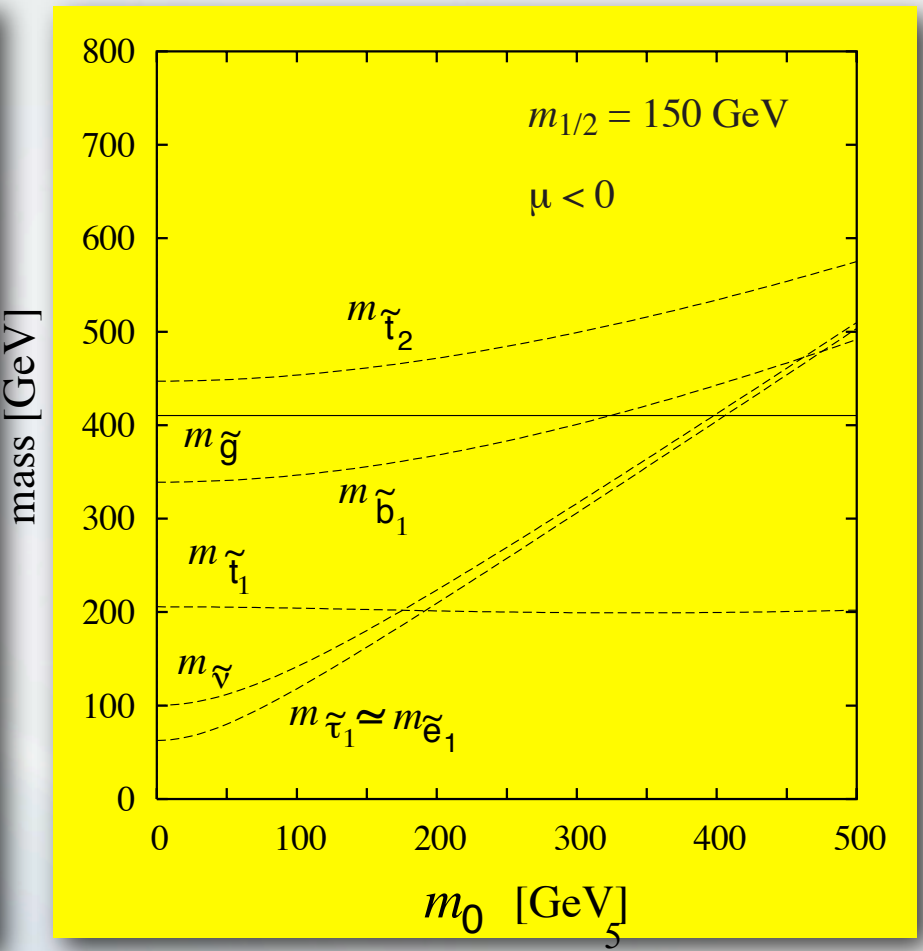
SUSY Masses in MSSM

Gauginos+Higgsinos



Squarks and Sleptons



SUSY Higgs Bosons

SM

$$H = \begin{pmatrix} H^0 \\ H^- \end{pmatrix} = \begin{pmatrix} \mathrm{v} + \dfrac{S + iP}{\sqrt{2}} \\ H^- \end{pmatrix} = \exp(i\frac{\vec{\xi}\vec{\sigma}}{2}) \begin{pmatrix} \mathrm{v} + \dfrac{S}{\sqrt{2}} \\ 0 \end{pmatrix}$$

$4=2+2=3+1$

$$H \rightarrow H' = \exp(i\frac{\vec{\alpha}\vec{\sigma}}{2})H \xrightarrow{(\vec{\alpha}=-\vec{\xi})} H' = \begin{pmatrix} \mathrm{v} + \dfrac{S}{\sqrt{2}} \\ 0 \end{pmatrix}$$

MSSM

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} = \begin{pmatrix} \mathrm{v}_1 + \dfrac{S_1 + iP_1}{\sqrt{2}} \\ H_1^- \end{pmatrix}, \quad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} = \begin{pmatrix} H_2^+ \\ \mathrm{v}_2 + \dfrac{S_2 + iP_2}{\sqrt{2}} \end{pmatrix},$$

$8=4+4=3+5$

$$\mathrm{v}_1^2 + \mathrm{v}_2^2 = \mathrm{v}^2 \ , \ \mathrm{v}_2/\mathrm{v}_1 \equiv \tan\beta$$

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The Higgs Potential

$$V_{tree}(H_1, H_2) = m_1^2 \mid H_1 \mid^2 + m_2^2 \mid H_2 \mid^2 - m_3^2 (H_1 H_2 + h.c.) + \frac{g^2 + g'^2}{8} (\mid H_1 \mid^2 - \mid H_2 \mid^2)^2 + \frac{g^2}{2} \mid H_1^+ H_2 \mid^2$$

At the GUT scale: $m_1^2 = m_2^2 = \mu_0^2 + m_0^2,\ m_3^2 = -B\mu_0$

Minimization

$$\frac{1}{2}\frac{\delta V}{\delta H_1} = m_1^2 v_1 - m_3^2 v_2 + \frac{g^2 + g'^2}{4}(v_1^2 - v_2^2)v_1 = 0,$$

$$\frac{1}{2}\frac{\delta V}{\delta H_2} = m_2^2 v_2 - m_3^2 v_1 - \frac{g^2 + g'^2}{4}(v_1^2 - v_2^2)v_2 = 0.$$

$< H_1 > \equiv v_1 = v\cos\beta,\ \ < H_2 > \equiv v_2 = v\sin\beta,$

No SSB in SUSY theory !

Solution

$$v^2 = \frac{4(m_1^2 - m_2^2 \tan^2\beta)}{(g^2 + g'^2)(\tan^2\beta - 1)},$$

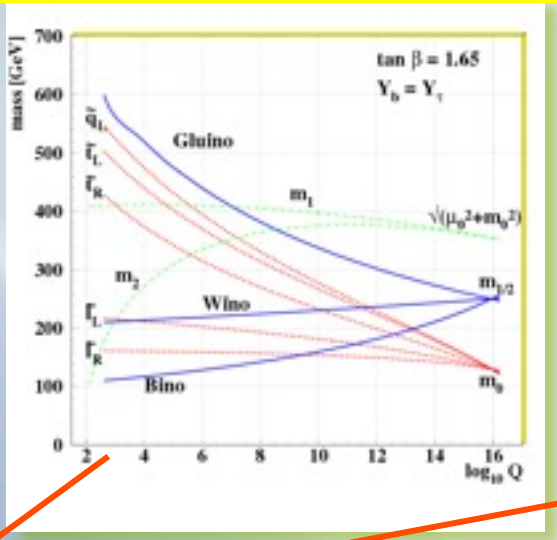
$$\sin 2\beta = \frac{2m_3^2}{m_1^2 + m_2^2}$$

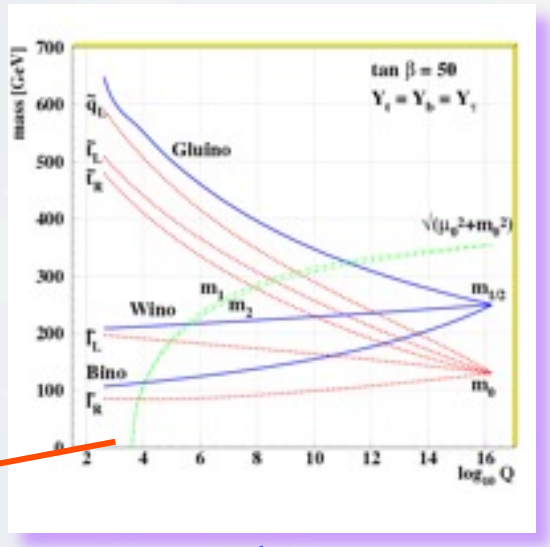
At the GUT scale

$$v^2 = -\frac{4}{g^2 + g'^2} m^2 < 0$$

Radiative EW Symmetry Breaking

Due to RG controlled running the mass terms from the Higgs potential may change sign and trigger the appearance of non-trivial minimum leading to spontaneous breaking of EW symmetry - this is called Radiative EWSB





$$\frac{M_Z^2}{2} = -\mu^2 + \frac{m_{H_1}^2 - m_{H_2}^2 \tan^2\beta}{\tan^2\beta - 1}$$

$$m_{H_1} \sim m_{H_2} \sim m_0 \sim 1\ TeV$$

Soft SUSY parameters

μ^2 { For given $\tan\beta$ and m_0 and $m_{1/2}$

$\mu \sim 1$ TeV — μ - problem

Hard SUSY parameter

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Higgs Boson's Masses

$$M^{odd} = \left.\frac{\partial^2 V}{\partial P_i \partial P_j}\right|_{H_i = v_i} = \begin{pmatrix} \tan\beta & 1 \\ 1 & \cot\beta \end{pmatrix} m_3^2$$

$$M^{even} = \left.\frac{\partial^2 V}{\partial S_i \partial S_j}\right|_{H_i = v_i} = \begin{pmatrix} \tan\beta & -1 \\ -1 & \cot\beta \end{pmatrix} m_3^2 + \begin{pmatrix} \cot\beta & -1 \\ -1 & \tan\beta \end{pmatrix} M_Z^2 \cos\beta \sin\beta$$

$$M^{ch} = \left.\frac{\partial^2 V}{\partial H_i^+ \partial H_j^-}\right|_{H_i = v_i} = \begin{pmatrix} \tan\beta & 1 \\ 1 & \cot\beta \end{pmatrix} (m_3^2 + M_W^2 \cos\beta \sin\beta)$$

$G^0 = -\cos\beta P_1 + \sin\beta P_2$	*Goldstone boson* $\rightarrow Z_0$
$A = \sin\beta P_1 + \cos\beta P_2$	*Neutral CP* $= -1$ *Higgs*
$G^+ = -\cos\beta (H_1^-)^* + \sin\beta H_2^+$	*Goldstone boson* $\rightarrow W^+$
$H^+ = \sin\beta (H_1^-)^* + \cos\beta H_2^+$	*Charged Higgs*
$h = -\sin\alpha S_1 + \cos\alpha S_2$	SM *Higgs boson CP* $= 1$
$H = \cos\alpha S_1 + \sin\alpha S_2$	*Extra heavy Higgs boson*

$$\tan 2\alpha = \tan 2\beta \frac{m_A^2 + m_Z^2}{m_A^2 - m_Z^2}$$

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The Higgs Bosons Masses

CP-odd neutral Higgs A

CP-even charged Higgses $H^{\pm}$

CP-even neutral Higgses h,H

$$m_A^2 = m_1^2 + m_2^2$$

$$m_{H^{\pm}}^2 = m_A^2 + M_W^2$$

$$M_W^2 = \frac{g^2}{2} v^2$$

$$M_Z^2 = \frac{g^2 + g'^2}{2} v^2$$

$$m_{h,H}^2 = \frac{1}{2}[m_A^2 + M_Z^2 \pm \sqrt{(m_A^2 + M_Z^2)^2 - 4 m_A^2 M_Z^2 \cos^2 2\beta}\,]$$

$$m_h \approx M_Z \,|\cos 2\beta| \; < \; M_Z \; !$$

➡ Radiative corrections

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3 g^2 m_t^4}{16\pi^2 M_W^2} \log \frac{\tilde{m}_{t_1}^2 \tilde{m}_{t_2}^2}{m_t^4} + 2\ loops$$

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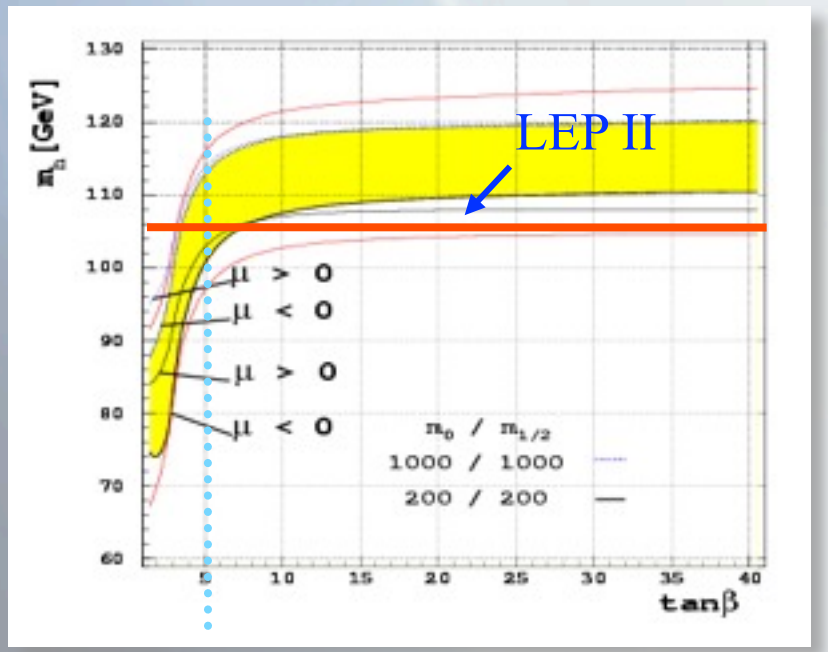
The Higgs Mass Limit (MSSM)

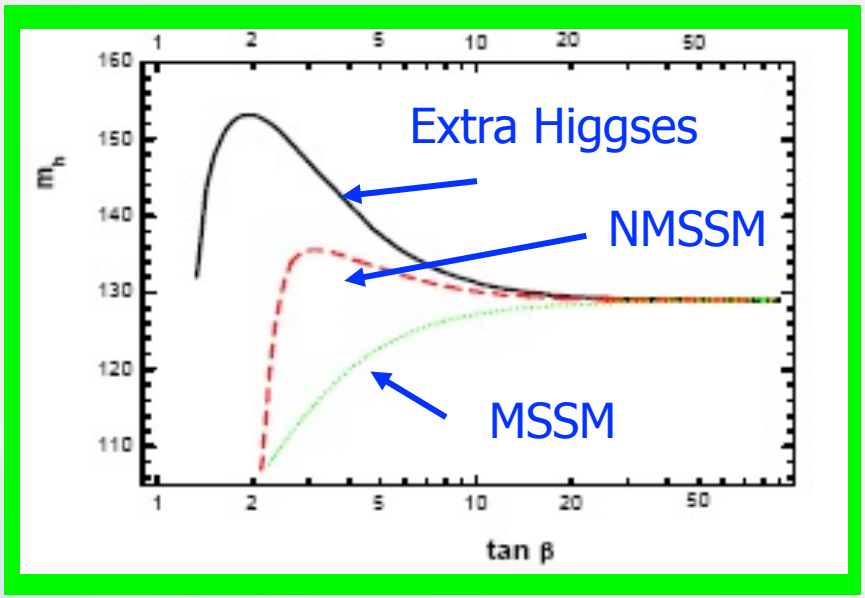


- MSSM Higgs

$m_H \leq 130$ GeV

NMSSM

$$m_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \ldots$$



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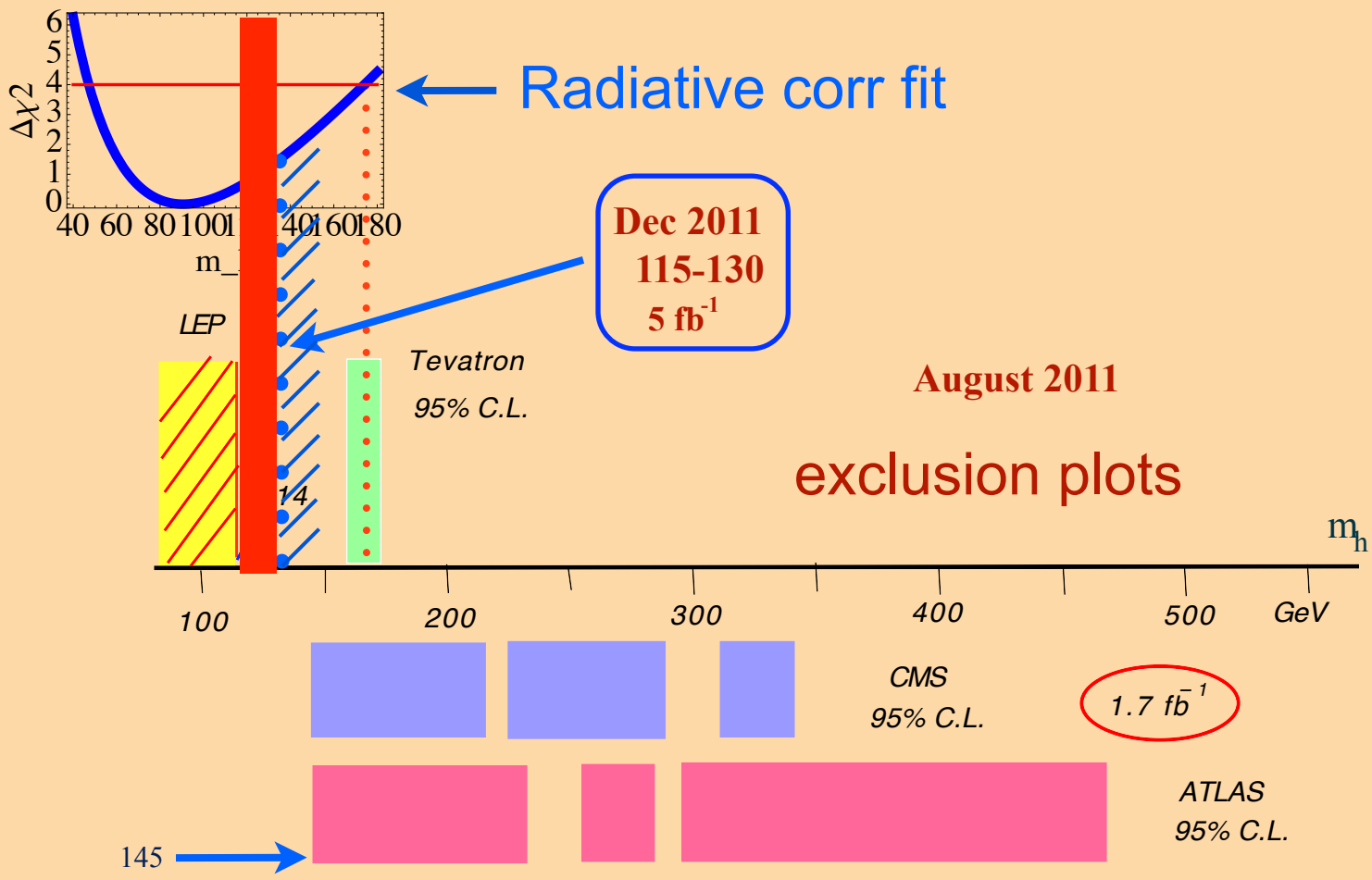
Modern Higgs Boson Window



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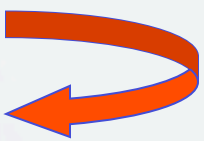
The Lightest Superparticle

		property	signature
• Gravity mediation	LSP = $\tilde{\chi}_1^0$	stable	jets/leptons + $\not{E}_T$
• Gauge mediation	LSP = $\tilde{G}$	stable	$\not{E}_T$
	NLSP = $\tilde{\chi}_1^0$	$\tilde{\chi}_1^0 \to \gamma\tilde{G}, h\tilde{G}, Z\tilde{G}$	photons/jets + $\not{E}_T$
	NLSP = $\tilde{l}_R$	$\tilde{l}_R \to \tau\tilde{G}$	lepton + $\not{E}_T$
• Anomaly mediation	LSP = $\tilde{\chi}_1^0$	stable	lepton + $\not{E}_T$
	LSP = $\tilde{\nu}_L$	stable	

• R-parity violation LSP is unstable -> SM particles

Rare decays

Neutrinoless double β decay



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SUSY Search Strategy

(Theory)

- ✓ Choose the model (MSSM)
- ✓ Choose the parameter space
- ✓ Impose all (reasonable) constraints
  MSSM -> CMSSM
- ✓ Define the allowed parameter space
- ✓ Make predictions for allowed regions

In what follows we choose the mSUGRA framework

Min parameter set: $m_0,\ m_{1/2},\ A_0,\ \tan\beta$

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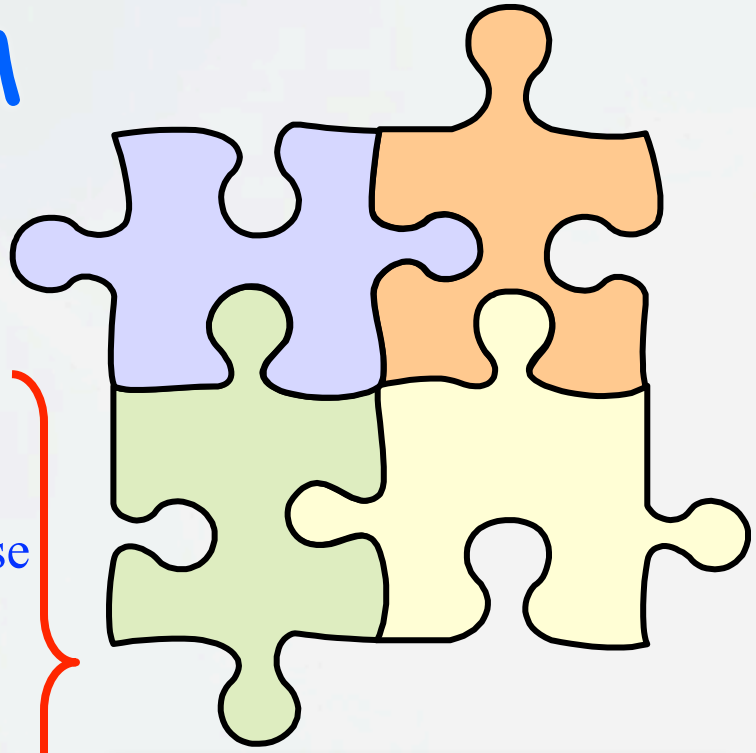
Constrained MSSM

Requirements:

- LEP II limits on SUSY particle masses
- Higgs searches
- Rare decays ($B_s \to s\gamma,\ B_s \to \mu^+\mu^-, B_s \to \tau\nu$)
- Relic abundancy of Dark Matter in the Universe
- Direct search for the DM
- g-2 of the muon
- Radiative electroweak symmetry breaking
- Unification of the gauge couplings
- Neutrality of the LSP
- Tevatron & LHC limits on SUSY
- ...



$A_0, m_0, M_{1/2}, \mu, \tan\beta$

Allowed region in the parameter space of the MSSM

$$100\ GeV \leq m_0, M_{1/2}, \mu \leq 3\ TeV$$
$$-3m_0 \leq A_0 \leq 3m_0,\ 1 \leq \tan\beta \leq 70$$

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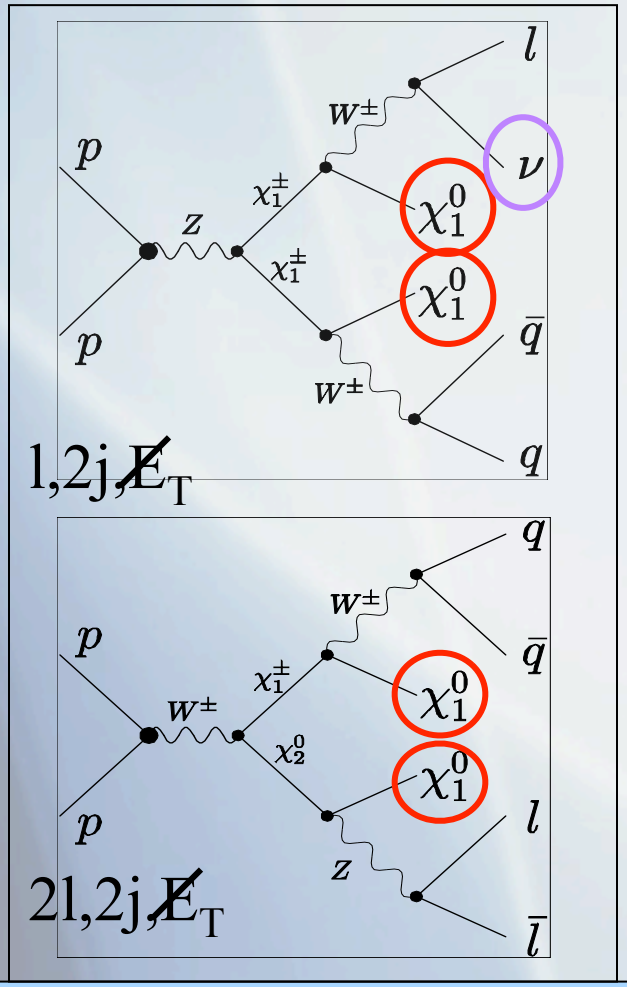
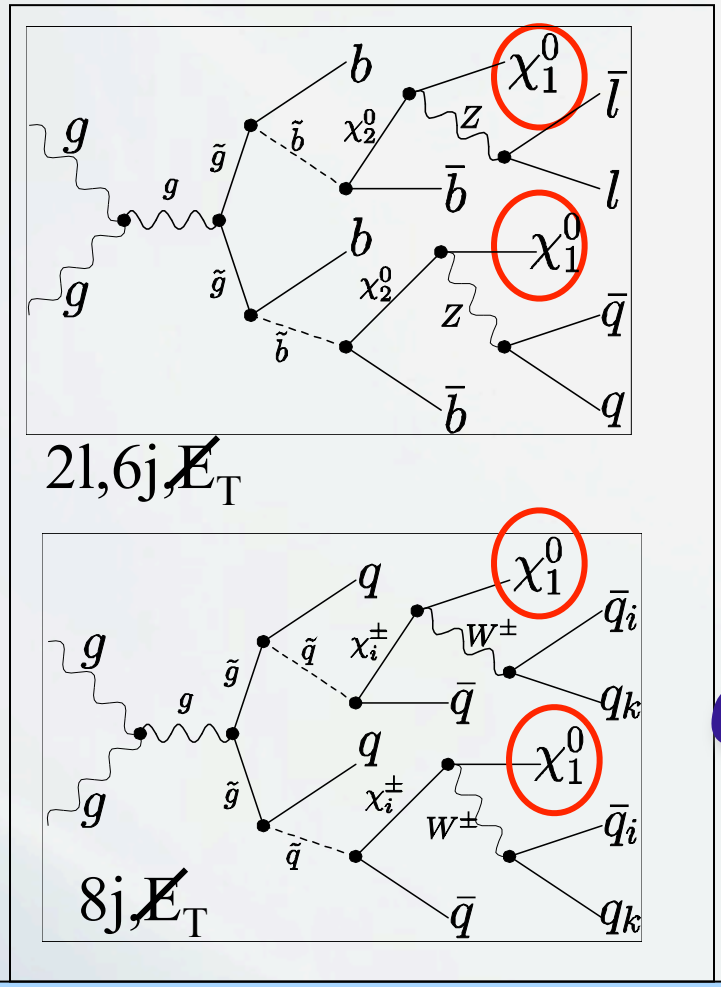
Creation and Decay of Superpartners in Cascade Processes @ LHC

weak int's

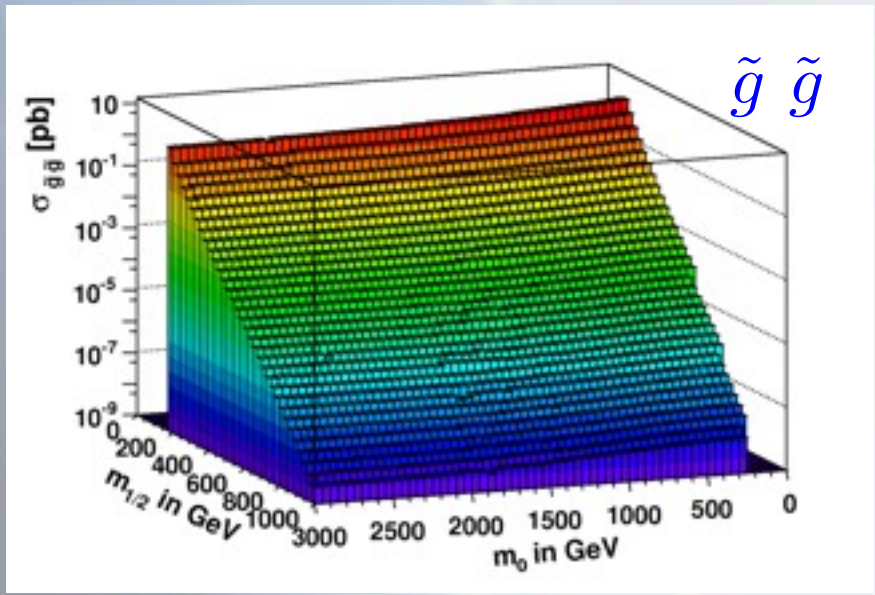


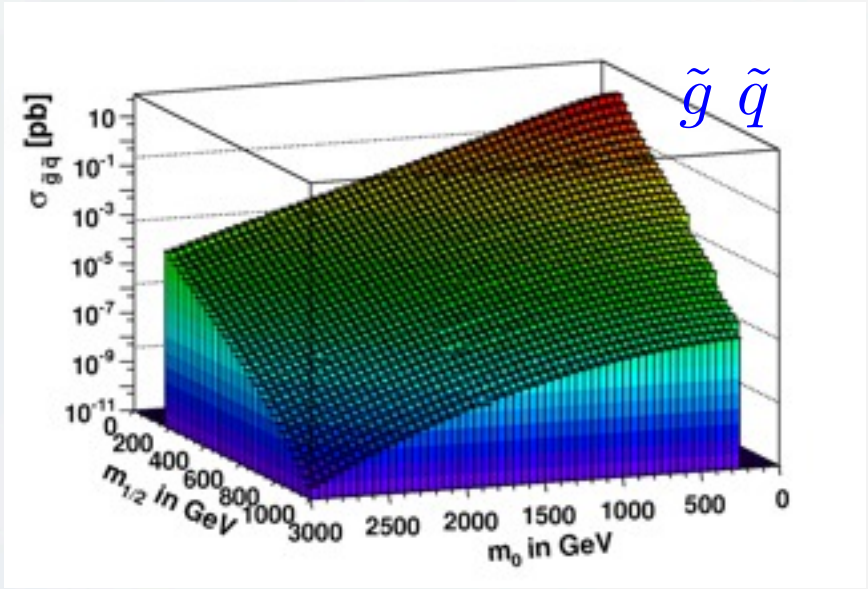


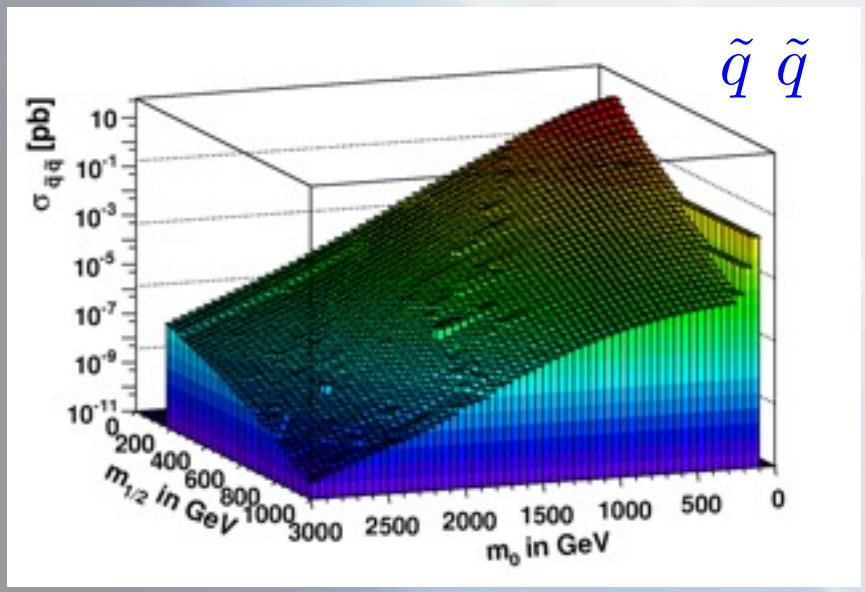
Strong int's

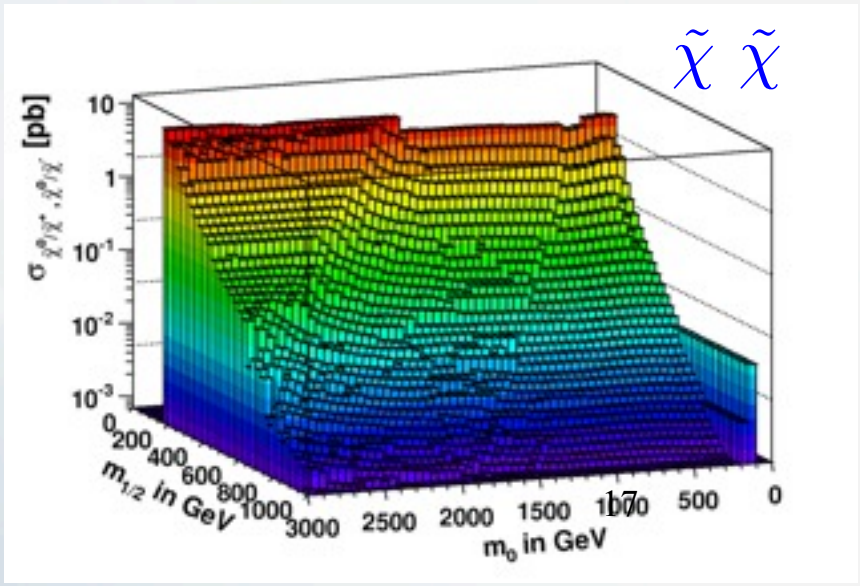
Typical SUSY signature: Missing Energy and Transverse Momentum

SUSY x-sections at the LHC @ 7 TeV



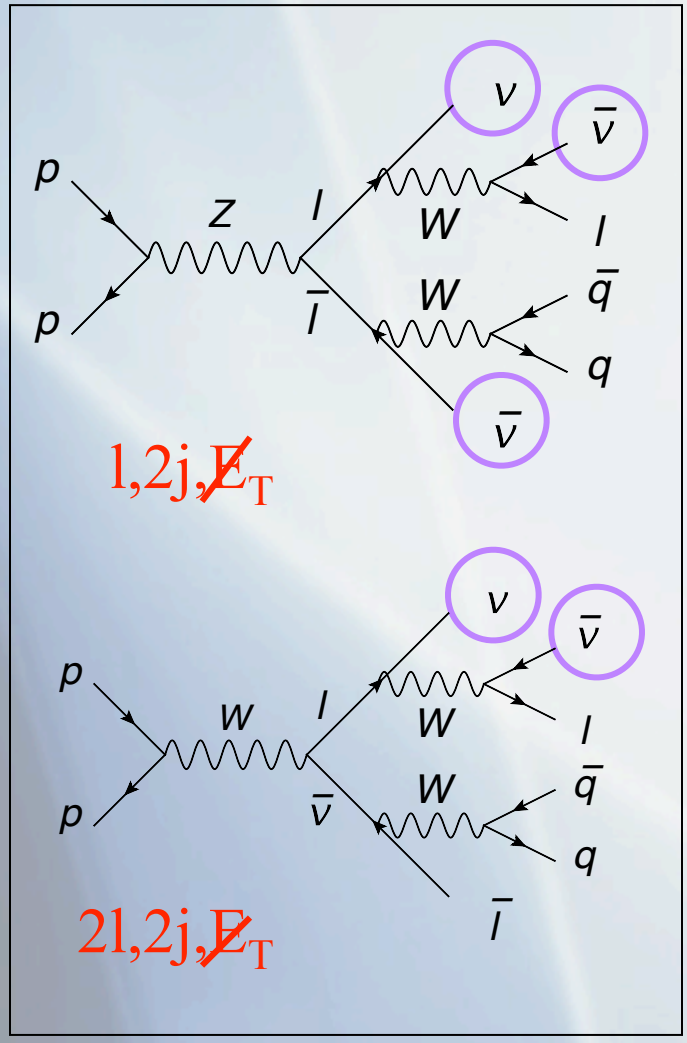


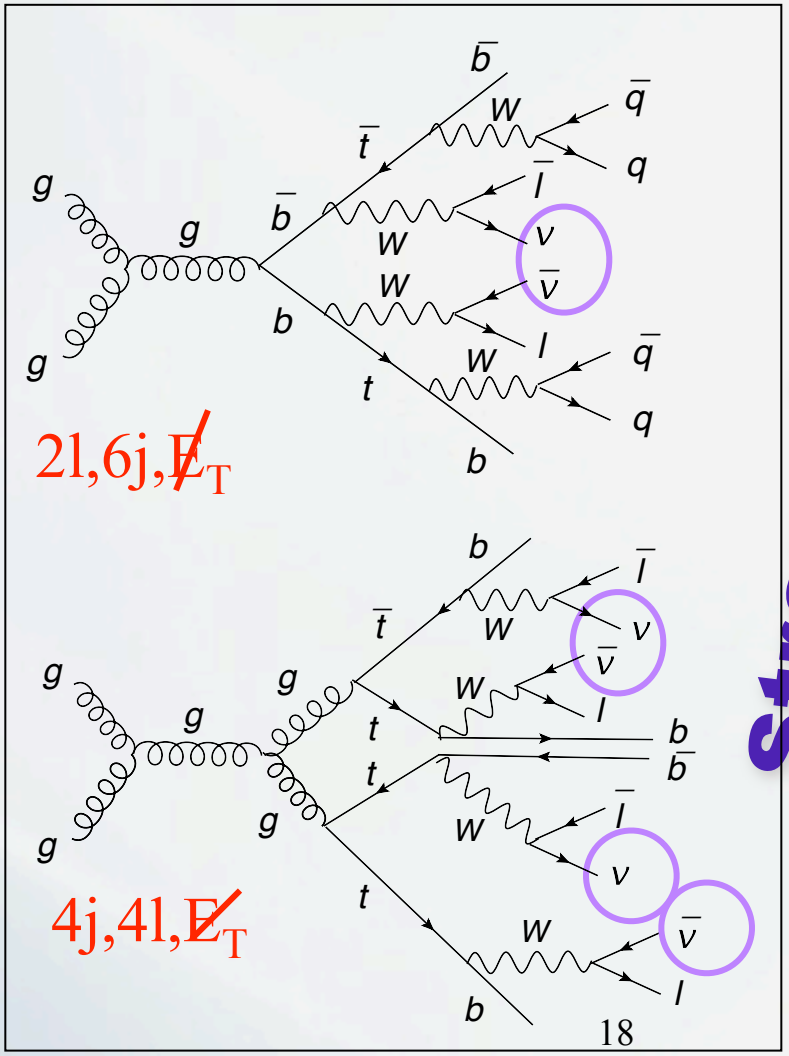




Background Processes of the SM for creation of Superpartners

weak int's





Strong int's

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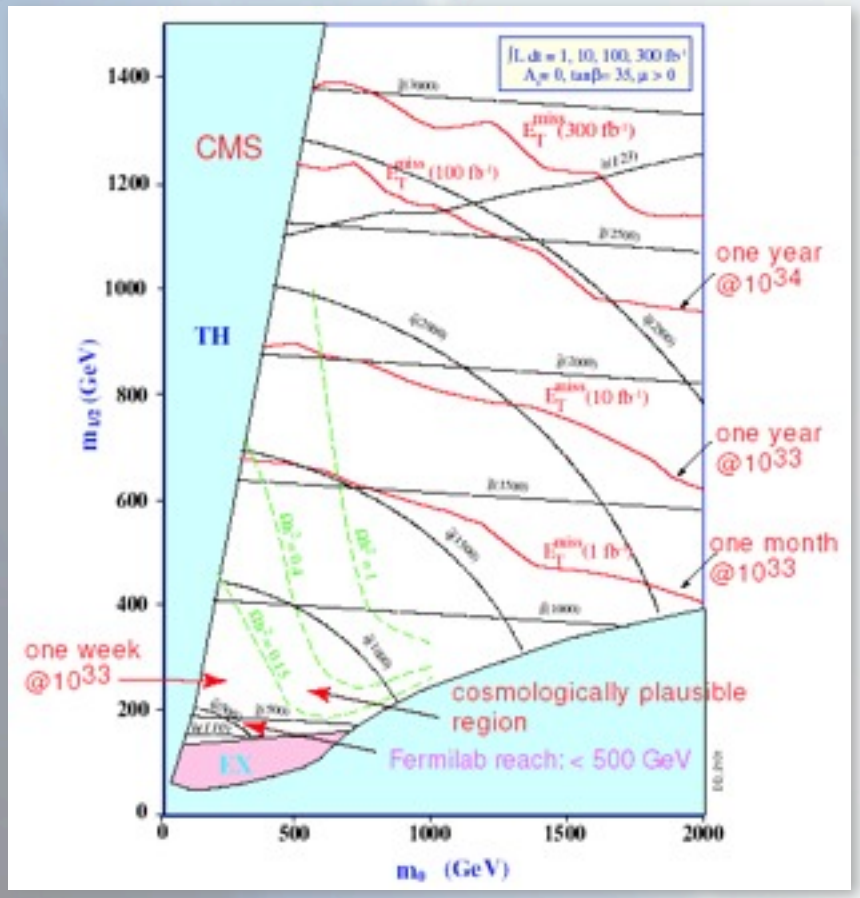
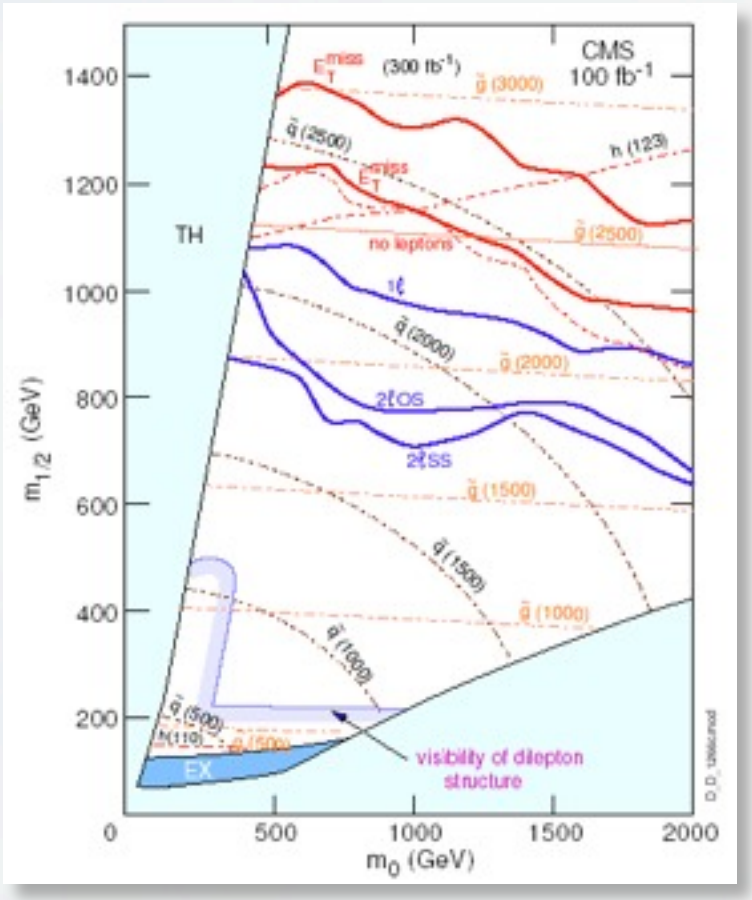
Search for Supersymmetry @ LHC



5 σ reach in jets $+\not{E}_T$ channel



Reach limits for various channels at 100 fb $^{-1}$

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