Is SUSY still alive?

Dmitri Kazakov
JINR/ITEP

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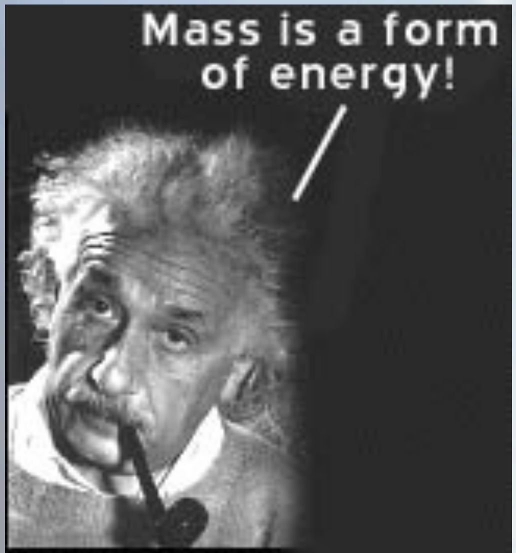
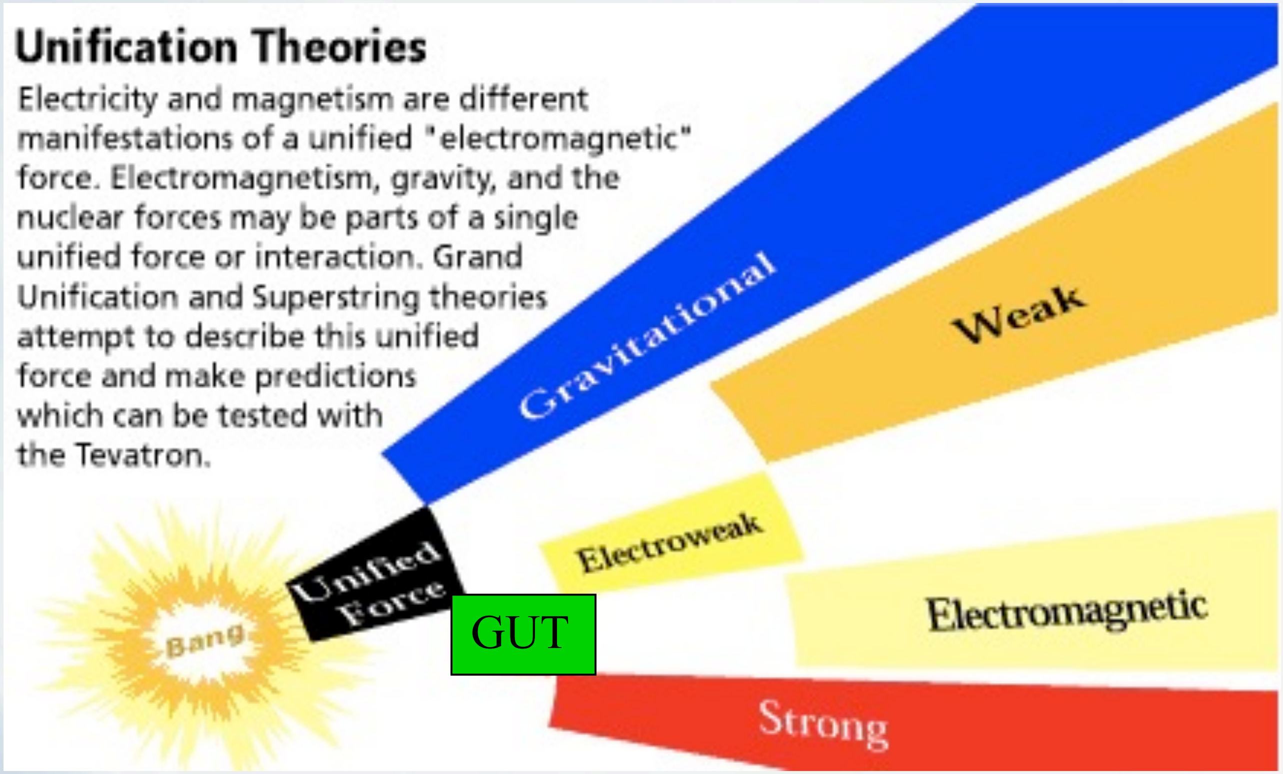
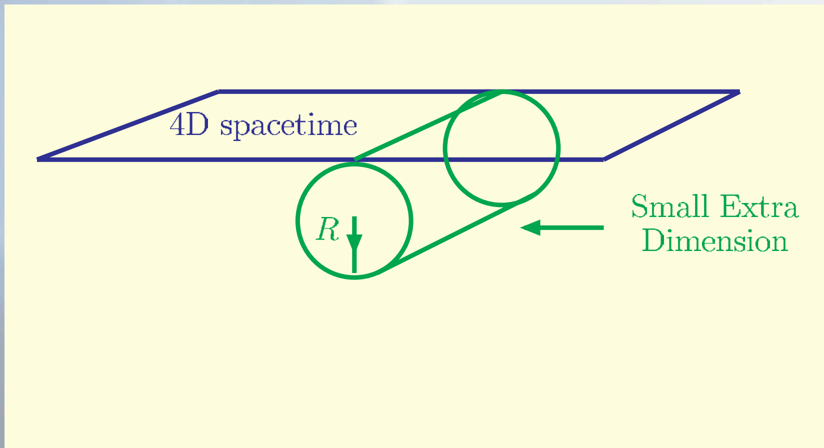
Unification Paradigm



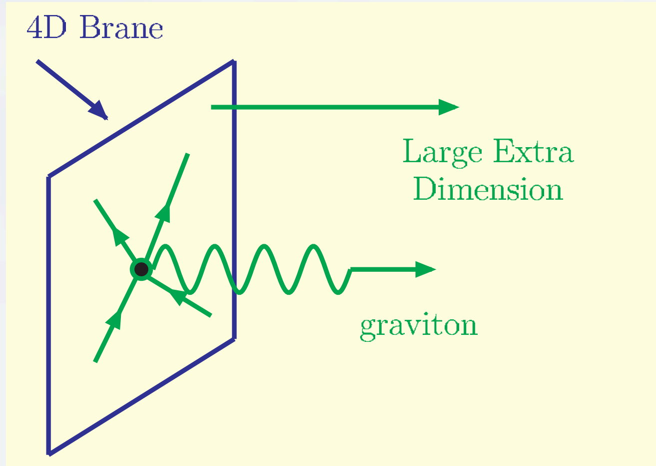


- Unification of strong, weak and electromagnetic interactions within Grand Unified Theories is the new step in unification of all forces of Nature
- Creation of a unified theory of everything based on string paradigm seems to be possible

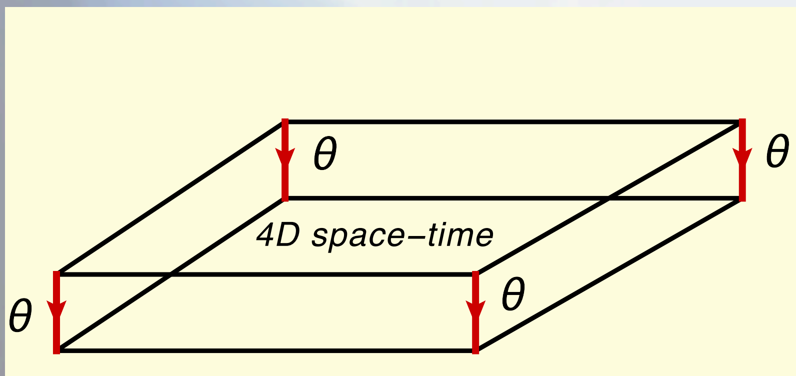
New Dimensions



Kaluza-Klein Picture



Brane-world Picture



Grassmannian extra dim

Superspace

Grassmannian numbers

$$x^\mu \qquad \theta_\alpha , \bar{\theta}_{\dot{\alpha}}$$

$$\mu = 0, 1, 2, 3 \qquad \alpha, \dot{\alpha} = 1, 2$$

$$\theta_1 \theta_1 = \theta_2 \theta_2 = 0$$

$$\theta_1 \theta_2 = -\theta_2 \theta_1 \neq 0$$

Superalgebra

(Super) Algebra

Lorentz Algebra

$$[P_\mu, P_\nu] = 0,\ [P_\mu, M_{\rho\sigma}] = i(g_{\mu\rho}P_\sigma - g_{\mu\sigma}P_\rho),$$

$$[M_{\mu\nu}, M_{\rho\sigma}] = i(g_{\nu\rho}M_{\mu\sigma} - g_{\nu\sigma}M_{\mu\rho} - g_{\mu\rho}M_{\nu\sigma} + g_{\mu\sigma}M_{\nu\rho}),$$

SUSY Algebra

$$[Q^i_\alpha, P_\mu] = [\bar{Q}^i_{\dot\alpha}, P_\mu] = 0,$$

$$[Q^i_\alpha, M_{\mu\nu}] = \tfrac{1}{2}(\sigma_{\mu\nu})^\beta_\alpha Q^i_\beta,\ [\bar{Q}^i_{\dot\alpha}, M_{\mu\nu}] = -\tfrac{1}{2}\bar{Q}^i_{\dot\beta}(\bar\sigma_{\mu\nu})^{\dot\beta}_{\dot\alpha},$$

$$\{Q^i_\alpha, \bar{Q}^j_{\dot\beta}\} = 2\delta^{ij}(\sigma^\mu)_{\alpha\dot\beta}P_\mu$$

$$\alpha, \dot\alpha, \beta, \dot\beta = 1,2;\ i, j = 1,2,\dots,N.$$

Superspace

$$x_\mu \to x_\mu, \theta_\alpha, \bar\theta_{\dot\alpha}$$

Grassmannian parameters $\alpha, \dot\alpha = 1,2$

$$\vartheta^2_\alpha = 0,\ \bar\vartheta^2_{\dot\alpha} = 0$$

SUSY Generators

$$Q_\alpha = \frac{\partial}{\partial\vartheta_\alpha} - i\sigma^\mu_{\alpha\dot\alpha}\bar\theta^{\dot\alpha}\partial_\mu$$

$$\bar{Q}_{\dot\alpha} = -\frac{\partial}{\partial\bar\vartheta_{\dot\alpha}} + i\theta_\alpha\sigma^\mu_{\alpha\dot\alpha}\partial_\mu$$

$$Q^2_\alpha = 0,\ \bar{Q}^2_{\dot\alpha} = 0$$

Supertranslation

$$x_\mu \to x_\mu + i\theta\sigma_\mu\bar\xi - i\xi\sigma_\mu\bar\theta,$$
$$\theta \to \theta + \xi,$$
$$\bar\theta \to \bar\theta + \bar\xi$$

Superfield in Superspace

N=1 SUSY Chiral supermultiplet: $\Phi(y,\theta)$

Expansion over grassmannian parameter

superfield

spin=0

spin=1/2

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

Auxiliary field

$$(y = x + i\theta\sigma\bar{\theta}) \qquad \theta^2 = \theta_1\theta_2, \quad \theta_1^2 = \theta_2^2 = 0!$$

(unphysical d.o.f. needed to close SYSY algebra)

$$= A(x) + i\theta\sigma^\mu\bar{\theta}\partial_\mu A(x) + \tfrac{1}{4}\theta\theta\bar{\theta}\bar{\theta}\Box A(x)$$
$$+\sqrt{2}\theta\psi(x) - i/\sqrt{2}\theta\theta\partial_\mu\psi(x)\sigma^\mu\bar{\theta} + \theta\theta F(x)$$

component fields

Gauge supermultiplet:

$$V(x,\theta,\bar{\theta}) = C(x) + i\theta\chi(x) - i\bar{\theta}\bar{\chi}(x) + i\theta\theta M(x) - i\bar{\theta}\bar{\theta}M^+(x)$$
$$-\theta\sigma^\mu\bar{\theta}v_\mu(x) + i\theta\theta\bar{\theta}[\bar{\lambda}(x) + i\bar{\sigma}^\mu\partial_\mu\chi(x)] - i\bar{\theta}\bar{\theta}\theta[\lambda(x) + i\sigma^\mu\partial_\mu\bar{\chi}(x)]$$
$$+\tfrac{1}{2}\theta\theta\bar{\theta}\bar{\theta}[D(x) + \tfrac{1}{2}\Box C(x)]$$

spin=1

Auxiliary fields

spin=1/2

SUSY Multiplets

Chiral multiplet $N=1,\ \lambda=0$

helicity	-1/2	0	1/2
# of states	1	2	1

scalar spinor

(φ, ψ)

Vector multiplet $N=1,\ \lambda=1/2$

helicity	-1	-1/2	1/2	1
# of states	1	1	1	1

(λ, A_μ)

spinor vector

Members of a supermultiplet are called **superpartners**

N=4	SUSY YM	helicity			-1	–1/2	0	1/2	1		
	λ = -1	# of states			1	4	6	4	1		
N=8	SUGRA	helicity	-2	–3/2	–1	–1/2	0	1/2	1	3/2	2
	λ = -2	# of states	1	8	28	56	70	56	28	8	1

$N \leq 4S$ ← spin

$N \leq 4$ For renormalizable theories (YM)

$N \leq 8$ For (super)gravity

Simplest (N=1) SUSY Multiplets

Bosons and Fermions come in pairs

$$(\varphi,\psi) \qquad (\lambda, A_\mu) \qquad (\tilde{g}, g)$$

Spin 0 Spin 1/2 Spin 1/2 Spin 1 Spin 3/2 Spin 2

scalar chiral fermion majorana fermion **vector** **gravitino** **graviton**

Minimal Supersymmetric Standard Model (MSSM)

- SUSY: # of fermions = # of bosons   N=1 SUSY: (φ,ψ) (λ, A_μ)
- SM: 28 bosonic d.o.f. & 90 (96) fermionic d.o.f.

There are no particles in the SM that can be superpartners

SUSY associates **known** bosons with **new** fermions
and **known** fermions with **new** bosons

- Even number of the Higgs doublets – min = 2

Cancellation of axial anomalies (in each generation)

$$Tr\ Y^3 = 3\left(\tfrac{1}{27}+\tfrac{1}{27}-\tfrac{64}{27}+\tfrac{8}{27}\right)-1-1+8=0$$

colour u_L d_L u_R d_R ν_L e_L e_R

Higgsinos

-1+1=0

Particle Content of the MSSM

Superfield	*Bosons*	*Fermions*	$SU_c(3)$	$SU_L(2)$	$U_Y(1)$
Gauge					
G^a	*gluon* g^a	*gluino* $\tilde{g}^a$	8	1	0
V^k	*Weak* $W^k(W^\pm, Z)$	*wino, zino* $\tilde{w}^k(\tilde{w}^\pm, \tilde{z})$	1	3	0
V'	*Hypercharge* $B(\gamma)$	*bino* $\tilde{b}(\tilde{\gamma})$	1	1	0
Matter					
L_i	sleptons $\tilde{L}_i = (\tilde{\nu}, \tilde{e})_L$	leptons $L_i = (\nu, e)_L$	1	2	-1
E_i	sleptons $\tilde{E}_i = \tilde{e}_R$	leptons $E_i = e_R$	1	1	2
Q_i	squarks $\tilde{Q}_i = (\tilde{u}, \tilde{d})_L$	quarks $Q_i = (u, d)_L$	3	2	$1/3$
U_i	squarks $\tilde{U}_i = \tilde{u}_R$	quarks $U_i = u_R^c$	3^*	1	$-4/3$
D_i	squarks $\tilde{D}_i = \tilde{d}_R$	quarks $D_i = d_R^c$	3^*	1	$2/3$
Higgs					
H_1	Higgses H_1	higgsinos $\tilde{H}_1$	1	2	-1
H_2	Higgses H_2	higgsinos $\tilde{H}_2$	1	2	1

How to write SUSY Lagrangians

- 1st step

Take your favorite Lagrangian written in terms of fields

- 2nd step

Replace $$Field\ (\varphi, \psi, A_\mu) \Rightarrow Superfield\ (\Phi, V)$$

- 3rd step

Replace

$$Action = \int d^4x\, L(x) \quad \Rightarrow \quad \int d^4x\, d^4\theta\, L(x, \theta, \bar{\theta})$$

Grassmannian integration in superspace $\int d\theta_\alpha = 0, \int \theta_\beta d\theta_\alpha = \delta_{\alpha\beta}$

The MSSM Lagrangian

$$L = L_{gauge} + L_{Yukawa} + L_{SoftBreaking}$$

The Yukawa Superpotential

Superfields

$$W_R = y_U Q_L H_2 U_R + y_D Q_L H_1 D_R + y_L L_L H_1 E_R + \mu H_1 H_2$$

Yukawa couplings

Higgs mixing term

$$W_{NR} = \lambda_L L_L L_L E_R + \lambda_L^{'} L_L Q_L D_R + \mu^{'} L_L H_2 + \lambda_B U_R D_R D_R$$

Violate: Lepton number Baryon number

$$\lambda_L, \lambda_L^{'} < 10^{-6}, \quad \lambda_B < 10^{-9}$$

These terms are forbidden in the SM

R-parity

$$R = (-)^{3(B-L)+2S}$$

The Usual Particle : R = + 1
SUSY Particle : R = - 1

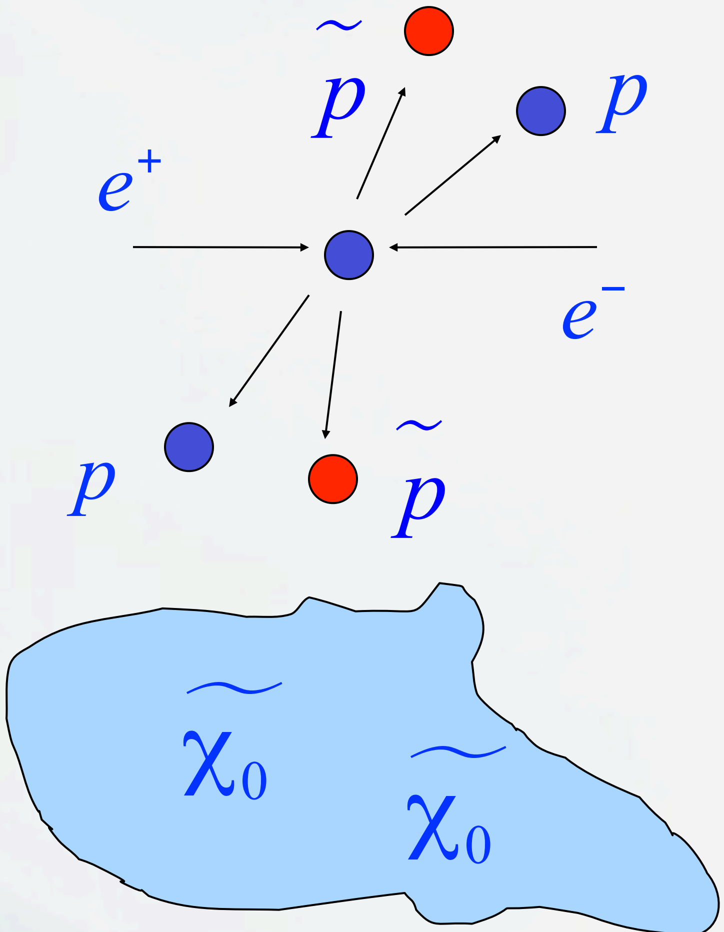
B - Baryon Number
L - Lepton Number
S - Spin

The consequences:

- The superpartners are created in pairs
- The lightest superparticle is stable

⇩

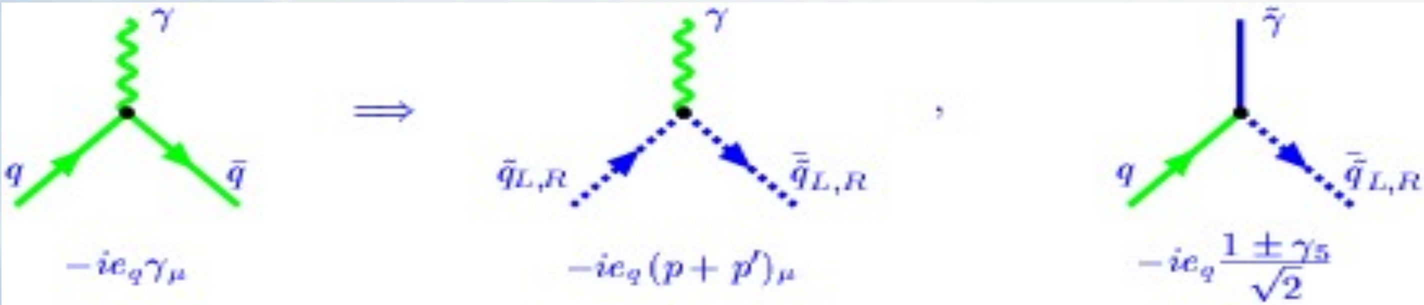
- The lightest superparticle (LSP) should be neutral - the best candidate is neutralino (photino or higgsino) $\tilde{\chi}_0$
- It can survive from the Big Bang and form the Dark matter in the Universe

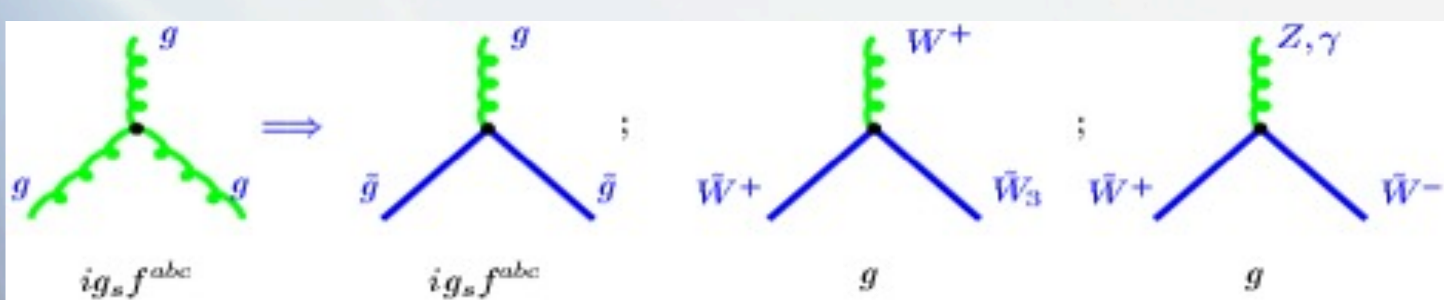


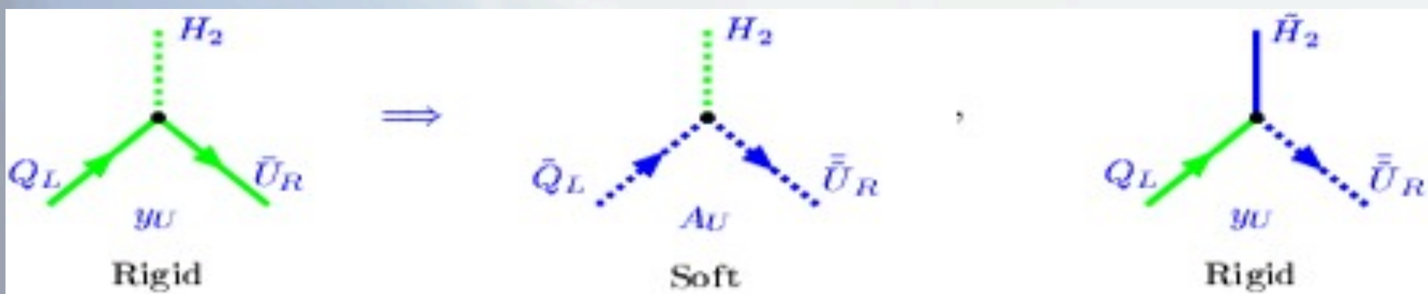
Interactions in the MSSM

SM → **MSSM**

Vertices

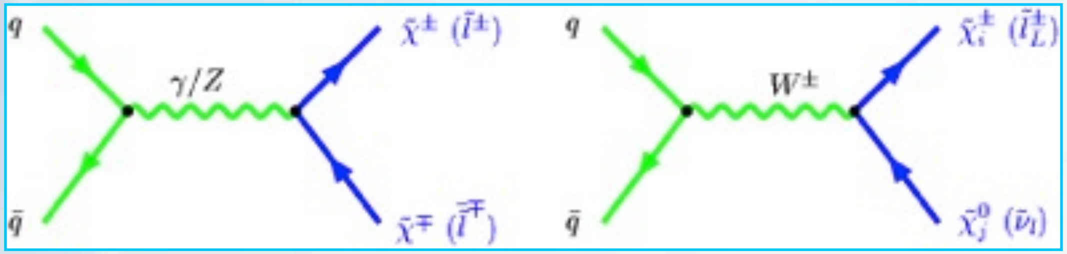




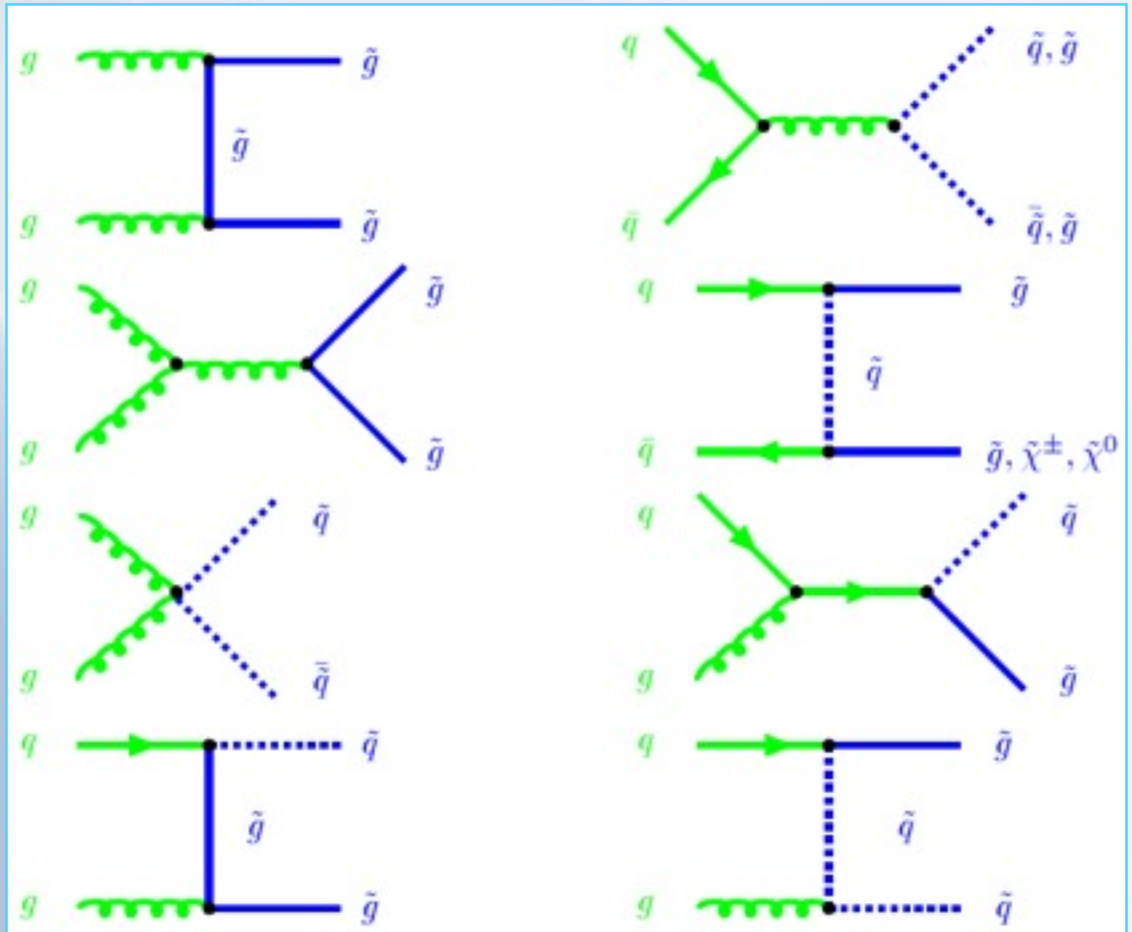


Superpartners Production at LHC

Annihilation



Quark- gluon Fusion



Decay of Superpartners

squarks

$$\tilde{q}_{L,R} \to q + \tilde{\chi}_i^0$$

$$\tilde{q}_L \to q' + \tilde{\chi}_i^\pm$$

$$\tilde{q}_{L,R} \to q + \tilde{g}$$

sleptons

$$\tilde{l} \to l + \tilde{\chi}_i^0$$

$$\tilde{l}_L \to \nu_l + \tilde{\chi}_i^\pm$$

chargino

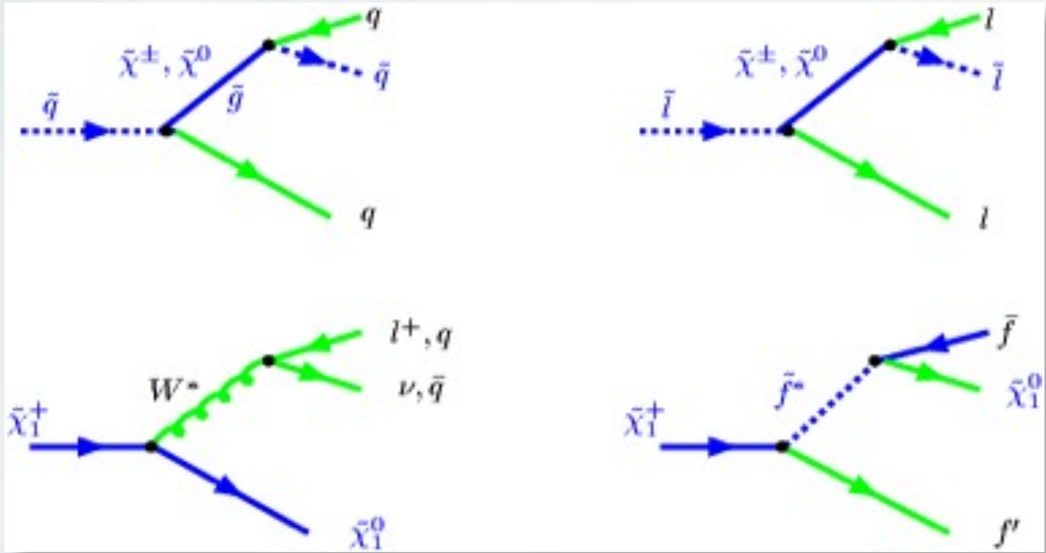
$$\tilde{\chi}_i^\pm \to e + \nu_e + \tilde{\chi}_i^0$$

$$\tilde{\chi}_i^\pm \to q + \bar{q}' + \tilde{\chi}_i^0$$

gluino

$$\tilde{g} \to q + \bar{q} + \tilde{\gamma}$$

$$\tilde{g} \to g + \tilde{\gamma}$$



neutralino

$$\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 + l^+ + l^-$$

$$\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 + q + \bar{q}'$$

$$\tilde{\chi}_i^0 \to \tilde{\chi}_1^\pm + l^\pm + \nu_l$$

$$\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 + \nu_l + \bar{\nu}_l$$

Final states

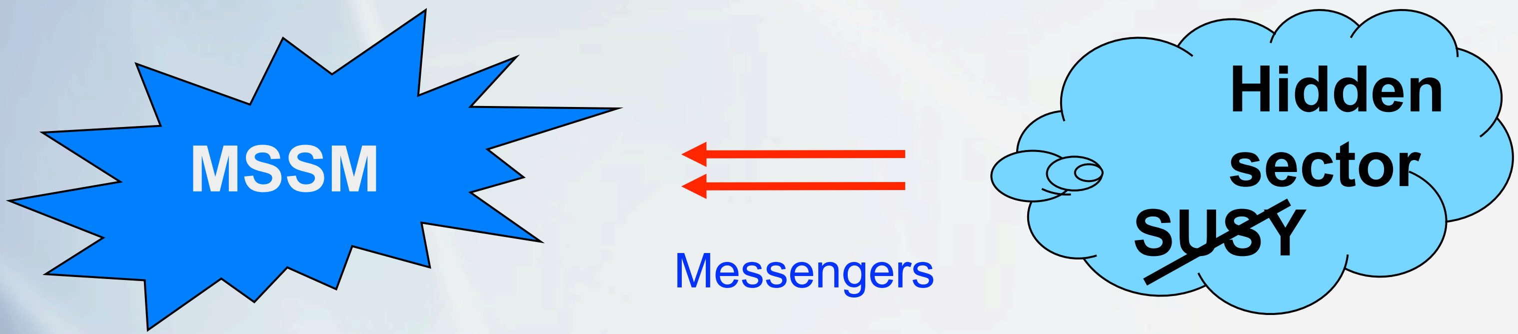
$l^+ l^- + \not{E}_T$

2 jets $+ \not{E}_T$

$\gamma + \not{E}_T$

$\not{E}_T$

Soft SUSY Breaking



Gravitons, gauge, gauginos, etc

Breaking via F and D terms in a hidden sector

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

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

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

Neutralino

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

$$\Uparrow$$

$$\chi = \begin{pmatrix} \tilde{B}^0 \\ \tilde{W}^3 \\ \tilde{H}_1^0 \\ \tilde{H}_2^0 \end{pmatrix} \qquad M^{(0)} = \begin{pmatrix} M_1 & 0 & -M_Z \cos\beta \sin W & M_Z \sin\beta \sin W \\ 0 & M_2 & M_Z \cos\beta \cos W & -M_Z \sin\beta \cos W \\ -M_Z \cos\beta \sin W & M_Z \cos\beta \cos W & 0 & -\mu \\ M_Z \sin\beta \sin W & -M_Z \sin\beta \cos W & -\mu & 0 \end{pmatrix}$$

Mass Spectrum (spin=0)

Squarks & Sleptons

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

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

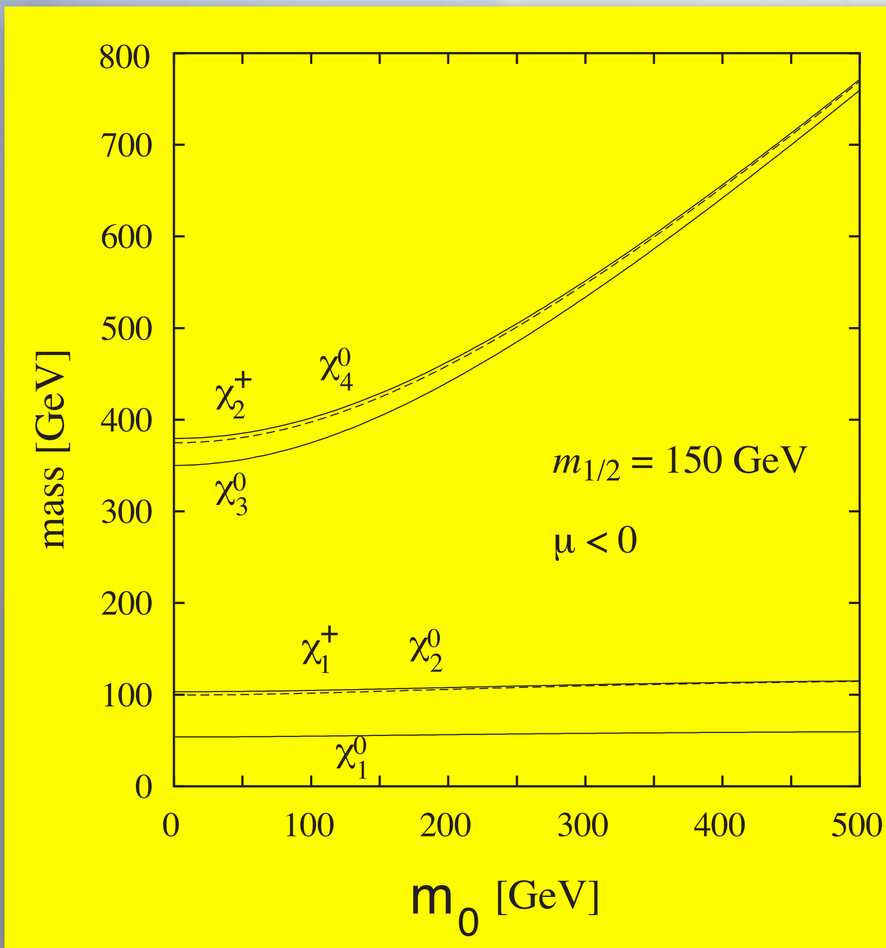
$$\tilde{m}_{tL}^2 = \tilde{m}_Q^2 + m_t^2 + \tfrac{1}{6}(4M_W^2 - M_Z^2)\cos 2\beta,$$
$$\tilde{m}_{tR}^2 = \tilde{m}_U^2 + m_t^2 - \tfrac{2}{3}(M_W^2 - M_Z^2)\cos 2\beta,$$
$$\tilde{m}_{bL}^2 = \tilde{m}_Q^2 + m_b^2 - \tfrac{1}{6}(2M_W^2 + M_Z^2)\cos 2\beta,$$
$$\tilde{m}_{bR}^2 = \tilde{m}_D^2 + m_b^2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

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

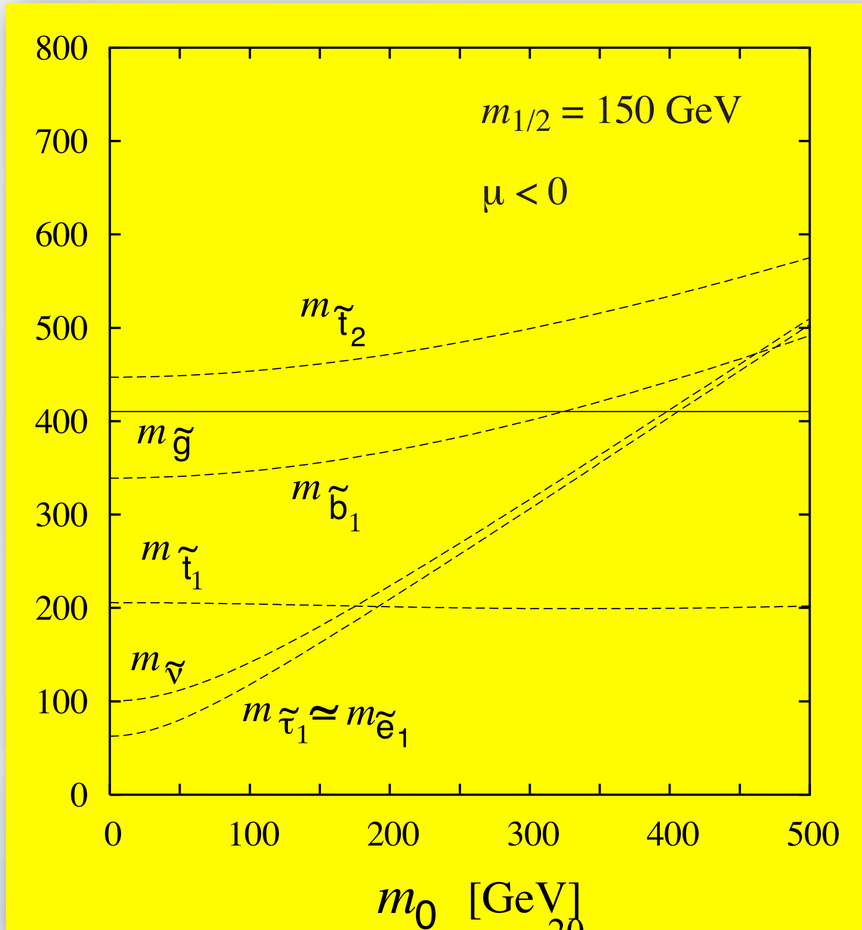
$$\tilde{m}_\tau^2 = \begin{pmatrix} \tilde{m}_{\tau L}^2 & m_\tau(A_\tau - \mu\tan\beta) \\ m_\tau(A_\tau - \mu\tan\beta) & \tilde{m}_{\tau R}^2 \end{pmatrix} \Rightarrow \begin{pmatrix} \tilde{\tau}_1 \\ \tilde{\tau}_2 \end{pmatrix}$$

SUSY Masses in MSSM

Gauginos+Higgsinos



Squarks and Sleptons



SUSY Higgs Bosons

SM

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

4=2+2=3+1

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

MSSM

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} = \begin{pmatrix} v_1 + \frac{S_1+iP_1}{\sqrt{2}} \\ H_1^- \end{pmatrix}, \quad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} = \begin{pmatrix} H_2^+ \\ v_2 + \frac{S_2+iP_2}{\sqrt{2}} \end{pmatrix},$$

8=4+4=3+5

$v_1^2+v_2^2=v^2$, $v_2/v_1 \equiv \tan\beta$

The Higgs Potential

$$V_{tree}(H_1,H_2) = m_1^2|H_1|^2 + m_2^2|H_2|^2 - m_3^2(H_1H_2 + h.c.) + \frac{g^2+g'^2}{8}(|H_1|^2 - |H_2|^2)^2 + \frac{g^2}{2}|H_1^+H_2|^2$$

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

Minimization

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

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

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

Solution

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

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

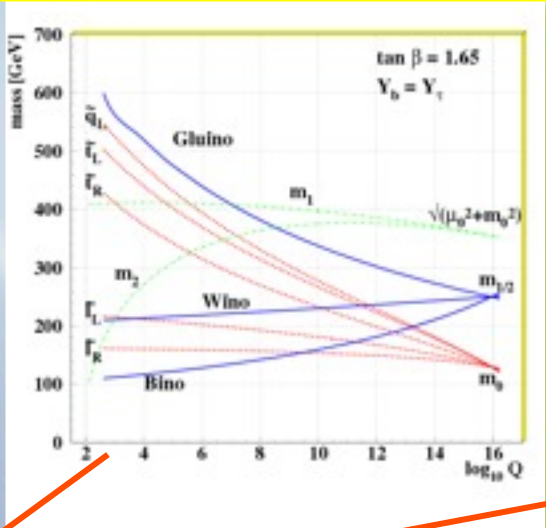
At the GUT scale

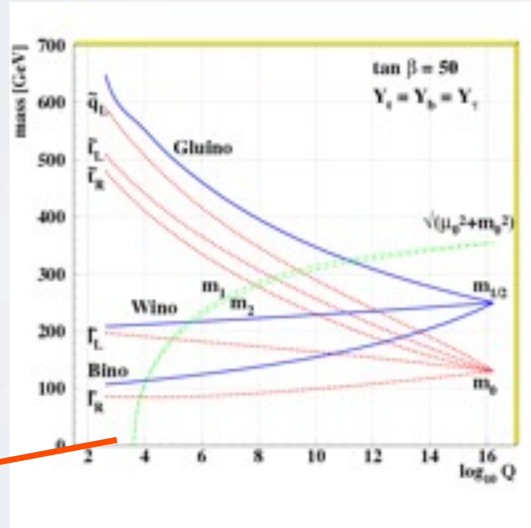
$$v^2 = -\frac{4}{g^2+g'^2}m^2 < 0$$

No SSB in SUSY theory !

Radiative EW Symmetry Breaking

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





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

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

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

Soft SUSY parameters

$\Rightarrow$ $\mu \sim 1$ TeV — μ - problem

Hard SUSY parameter

Higgs Boson's Masses

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

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

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

$G^0 = -\cos\beta\, P_1 + \sin\beta\, P_2$	*Goldstone boson* $\to Z_0$
$A = \sin\beta\, P_1 + \cos\beta\, P_2$	*Neutral* $CP = -1$ *Higgs*
$G^+ = -\cos\beta\, (H_1^-)^* + \sin\beta\, H_2^+$	*Goldstone boson* $\to W^+$
$H^+ = \sin\beta\, (H_1^-)^* + \cos\beta\, H_2^+$	*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*

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

The Higgs Bosons Masses

CP-odd neutral Higgs A

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

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

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

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

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

CP-even neutral Higgses h,H

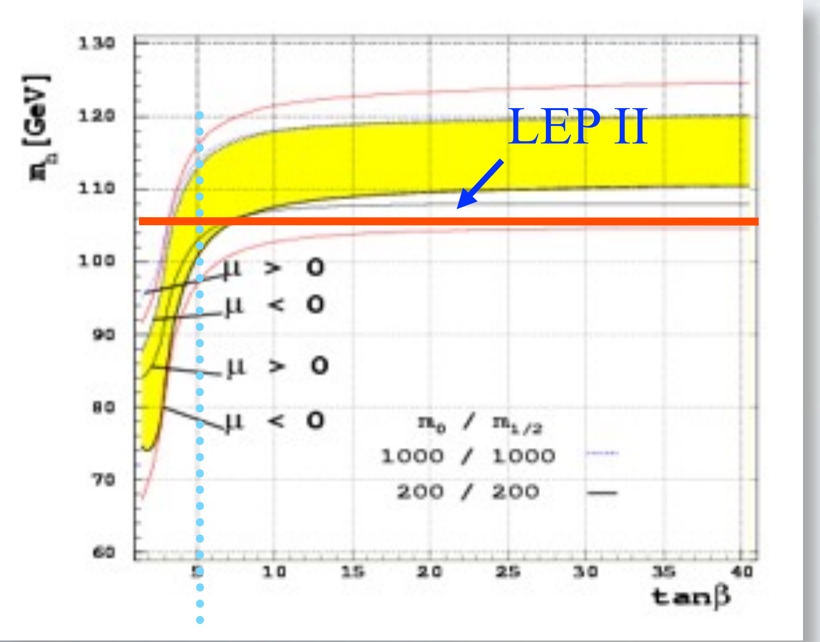
$$m_{h,H}^2 = \frac{1}{2}\left[m_A^2 + M_Z^2 \pm \sqrt{(m_A^2 + M_Z^2)^2 - 4 m_A^2 M_Z^2 \cos^2 2\beta}\,\right]$$

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

⇒ Radiative corrections

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

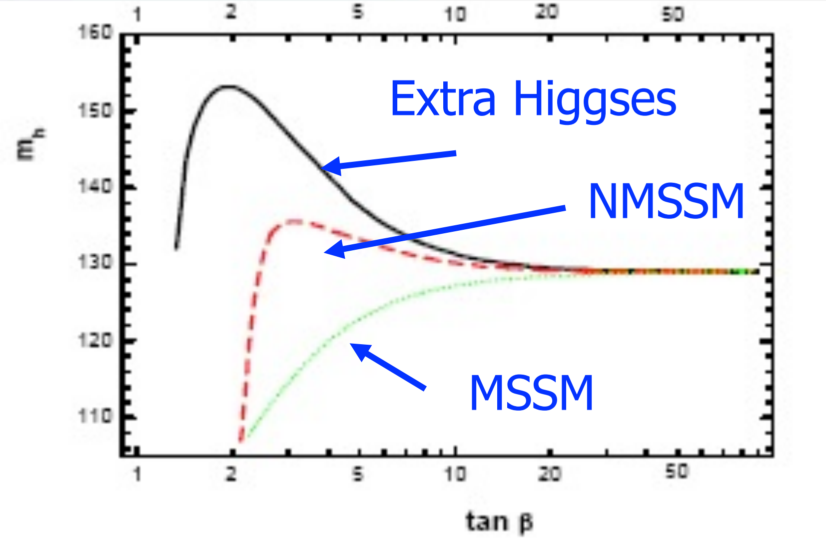
The Higgs Mass Limit (MSSM)



- MSSM Higgs

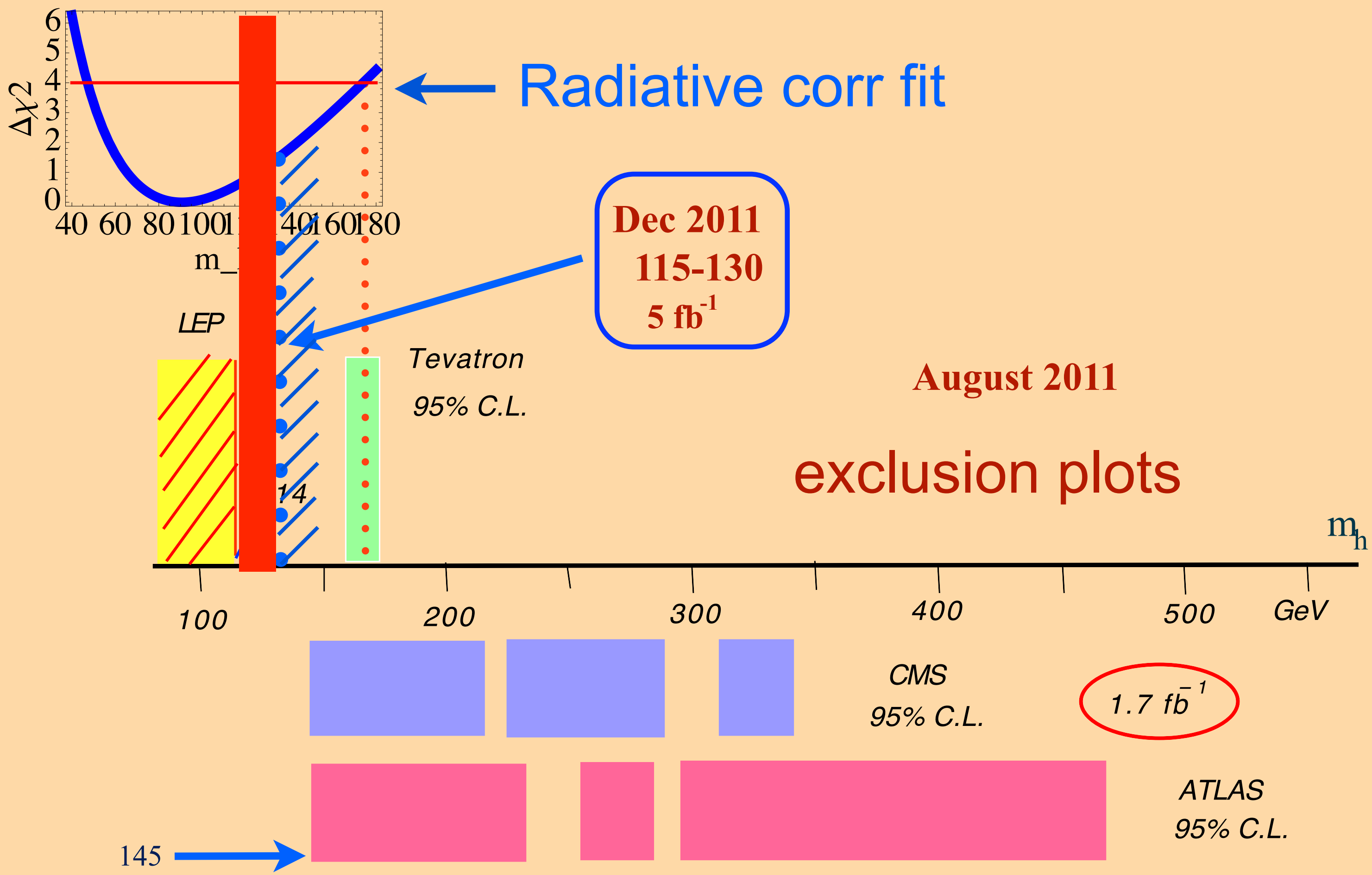
$m_H \leq 130$ GeV

NMSSM



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

Modern Higgs Boson Window



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

SUSY Search Strategy

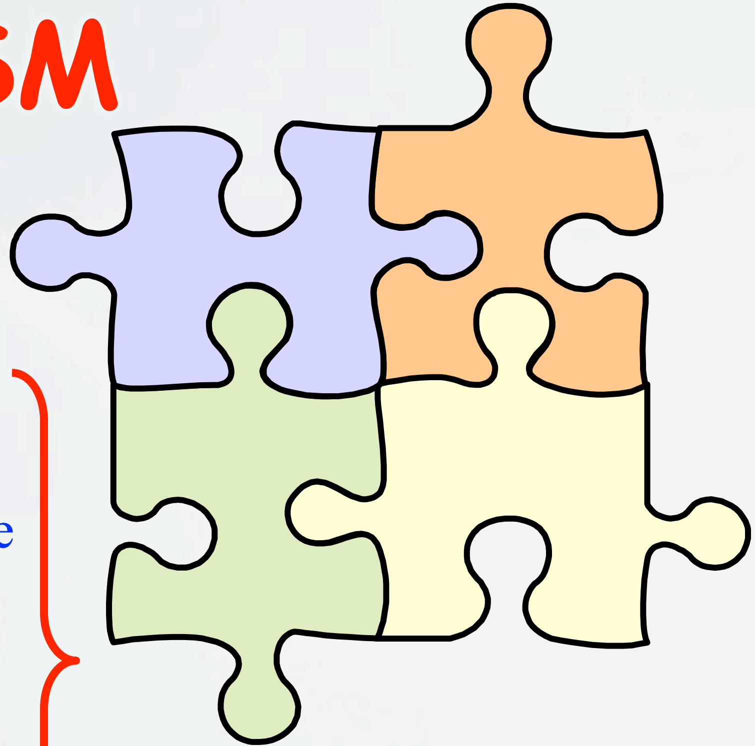
(Theory)

- ✓ 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: $m_0, \ m_{1/2}, \ A_0, \ \tan\beta$

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
- ...

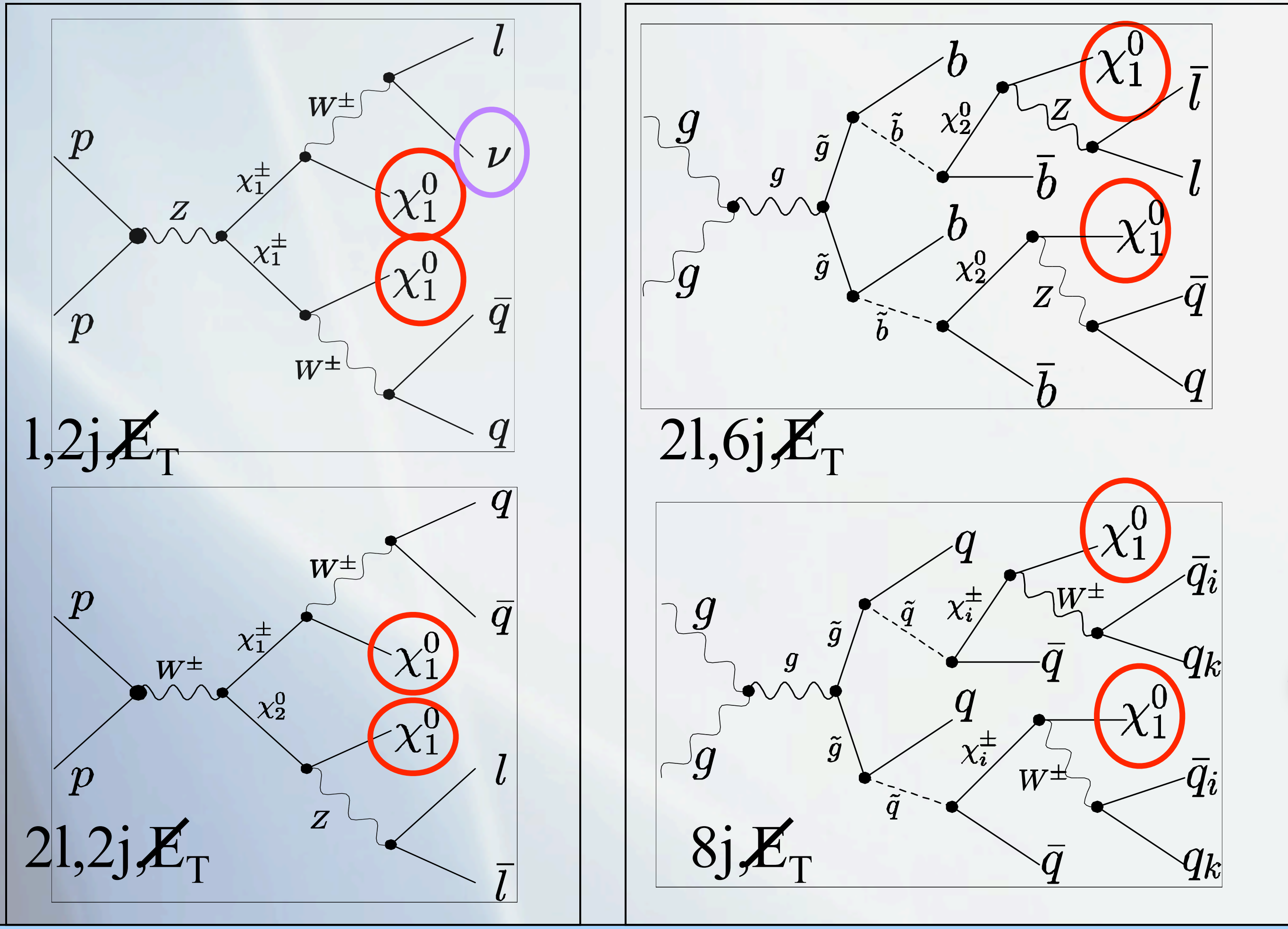
$A_0, m_0, M_{1/2}, \mu, \tan\beta$

Allowed region in the parameter space of the MSSM

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

Creation and Decay of Superpartners in Cascade Processes @ LHC

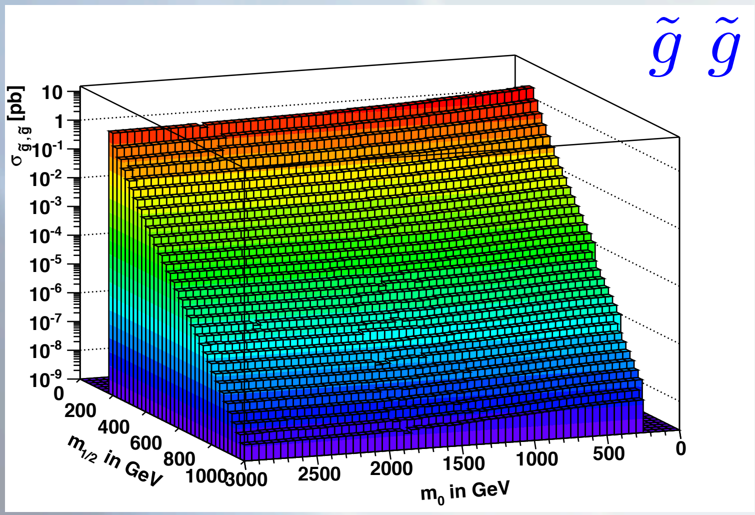
weak int's

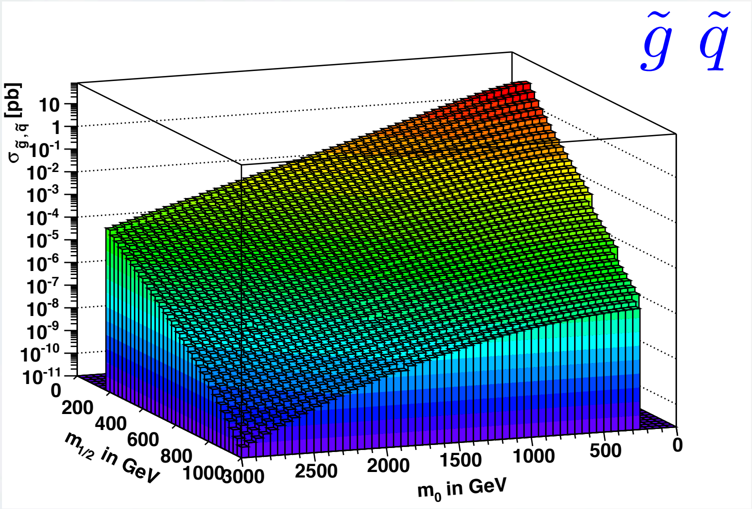


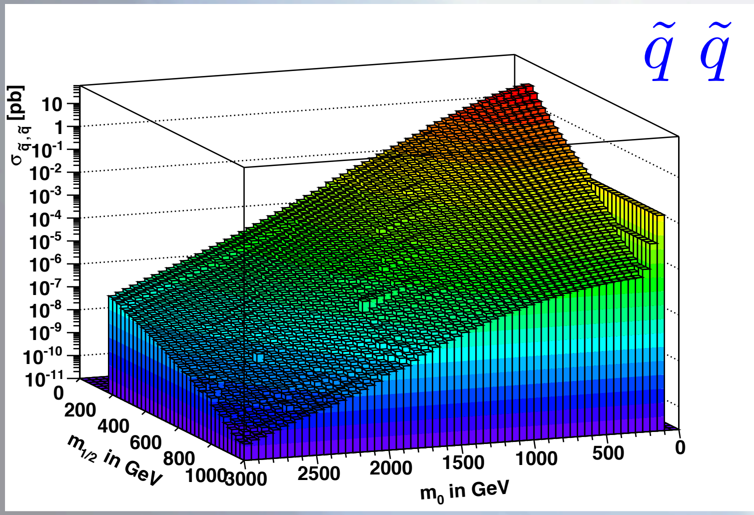
Strong int's

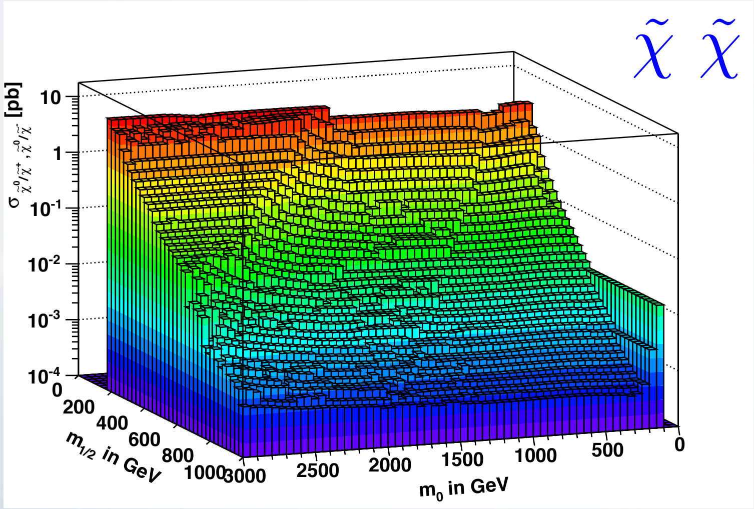
Typical SUSY signature: Missing Energy and Transverse Momentum

SUSY x-sections at the LHC @ 7 TeV



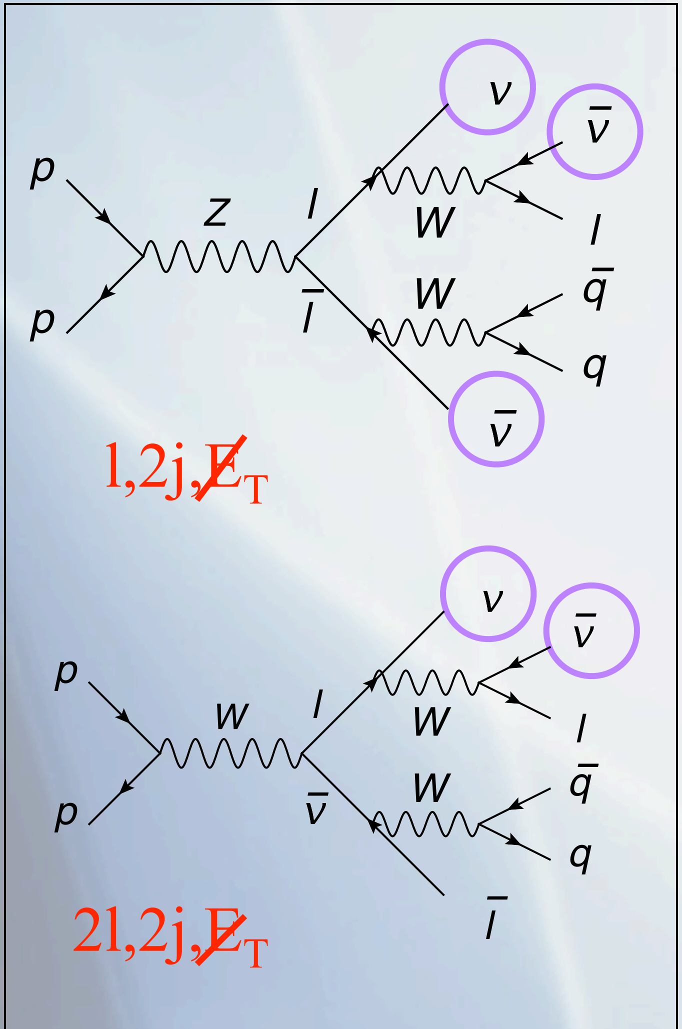


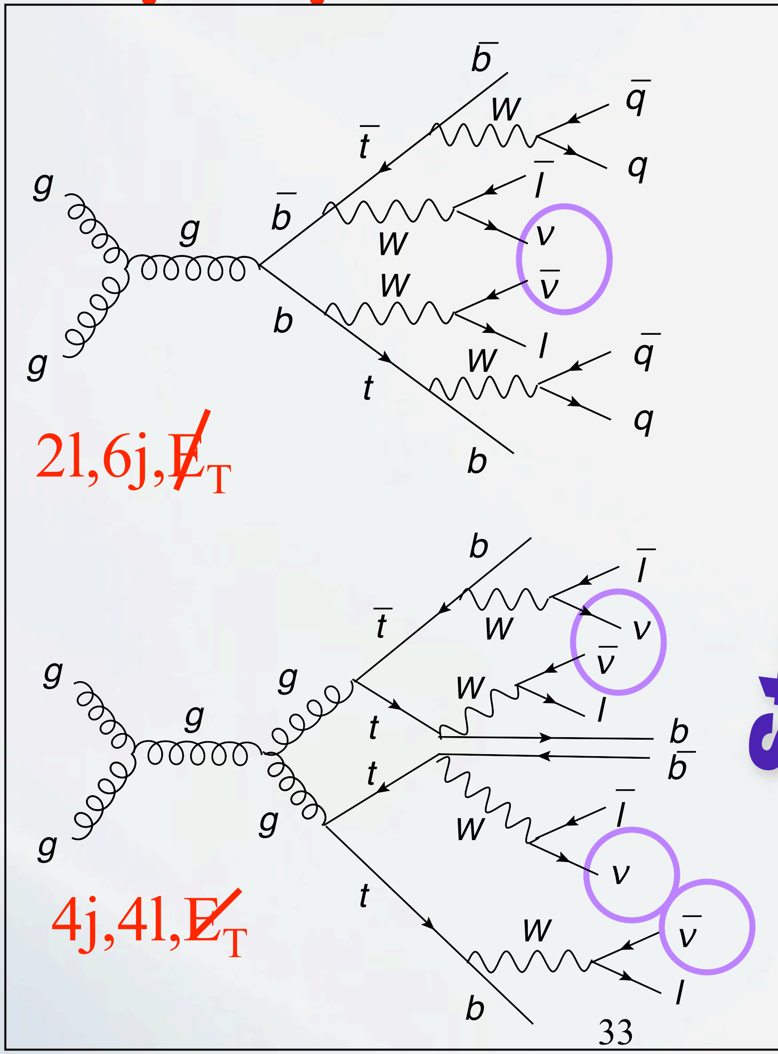




Background Processes of the SM for creation of Superpartners

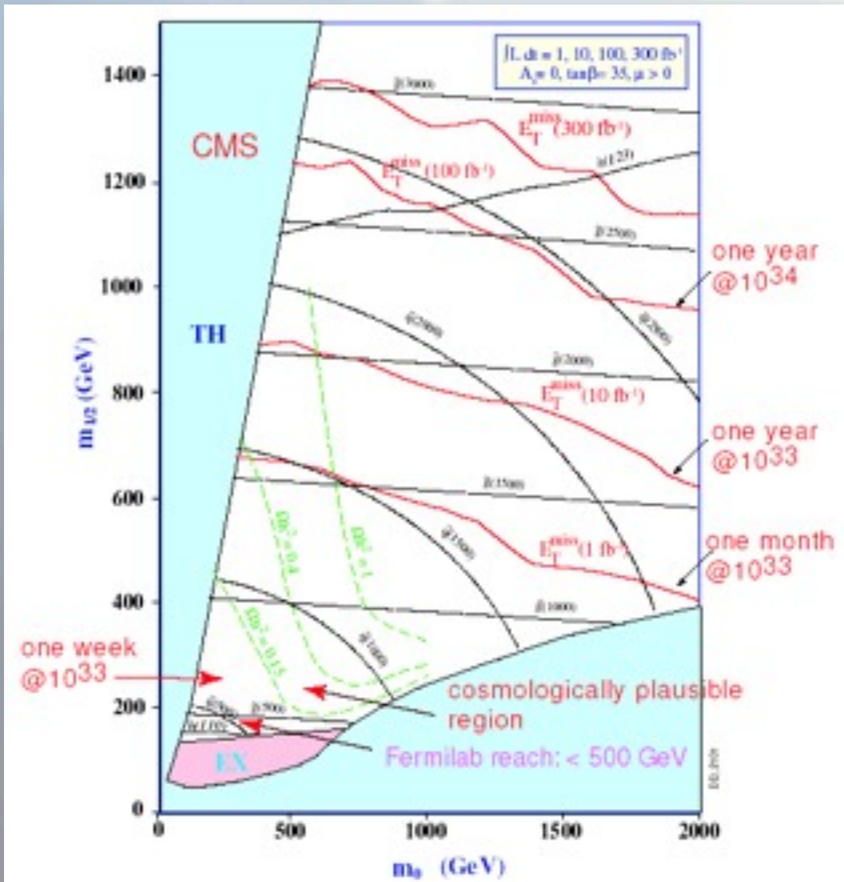
weak int's

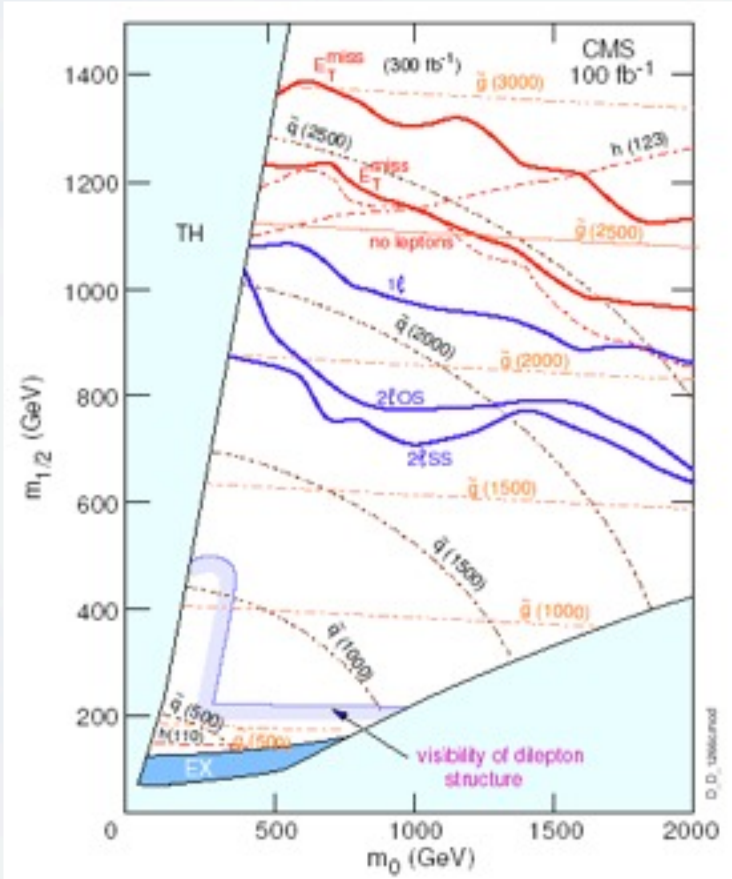




Strong int's

Search for Supersymmetry @ LHC





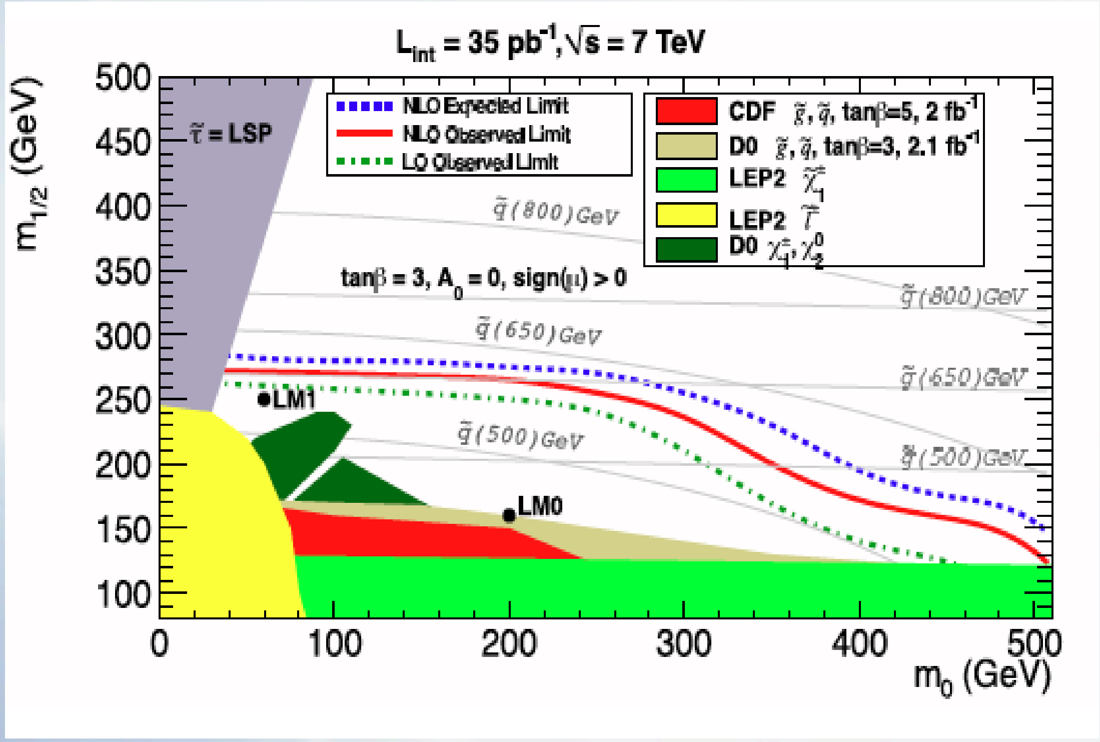
5 σ reach in jets $+\not{E}_T$ channel

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

First SUSY results @ LHC

Search for high-mass squark and gluino production in events with large missing transverse energy and two or more jets

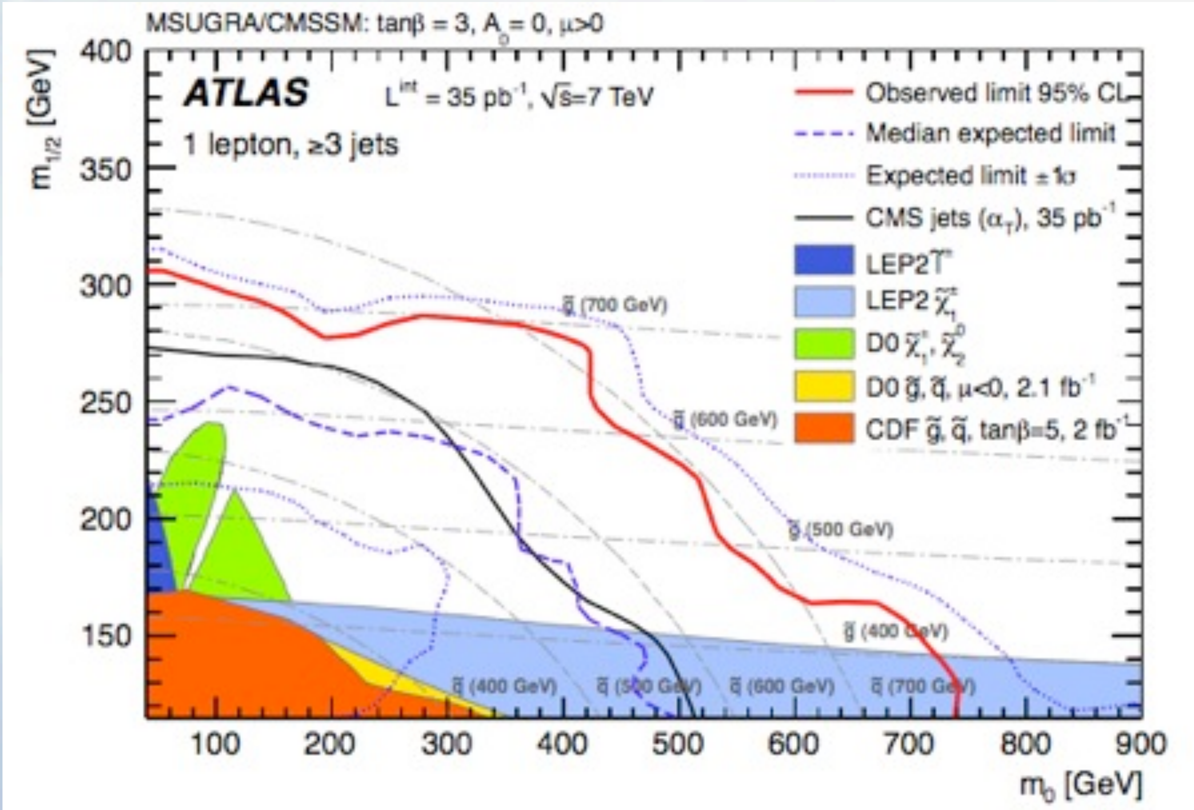
CMS



Expanded the excluded range established during
The last 20 years (!) by factor of two with only 35 pb^-1

First SUSY results @ LHC

ATLAS



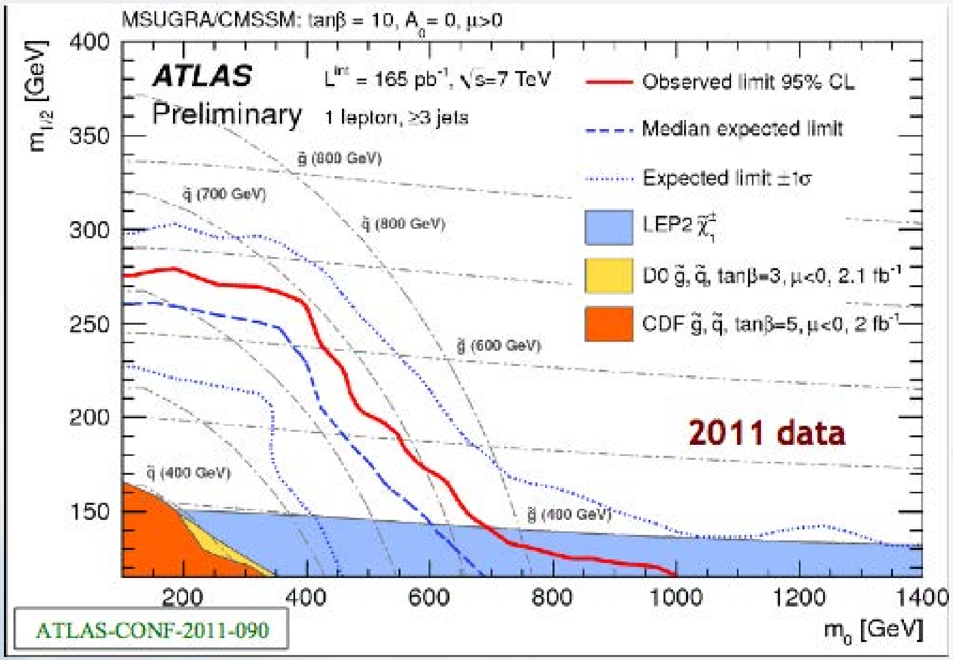
Search for lepton + jets + missing transverse energy with 35 pb^-1

First SUSY results @ LHC

SUSY in 1-lepton channel

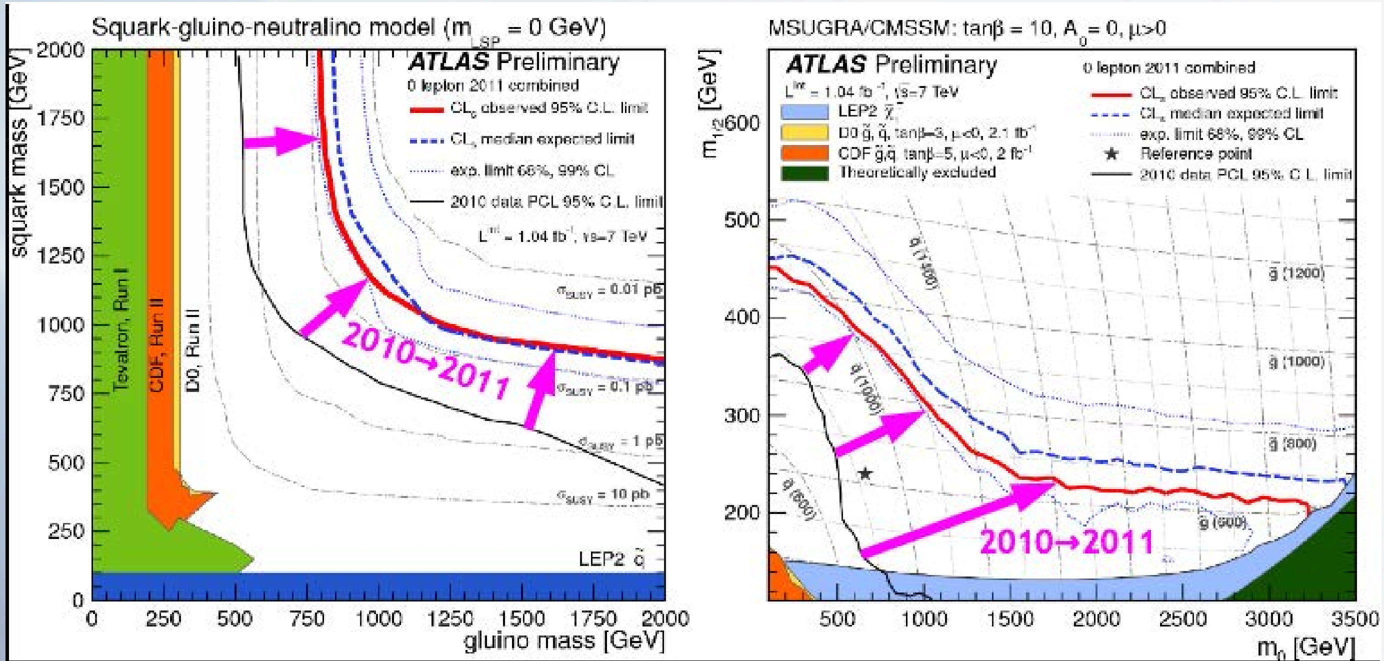
$\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, $\tilde{q}\tilde{q}$ may give isolated leptons

Single e/μ, jets, E miss



First SUSY results @ LHC

SUSY in 0-lepton channel

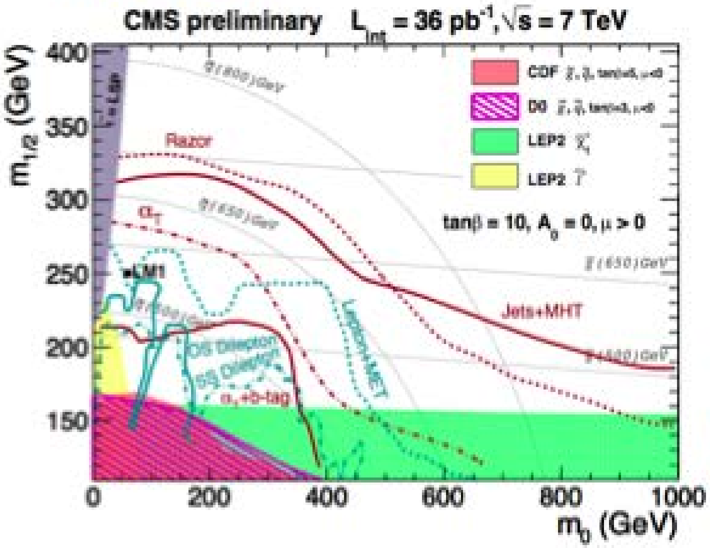


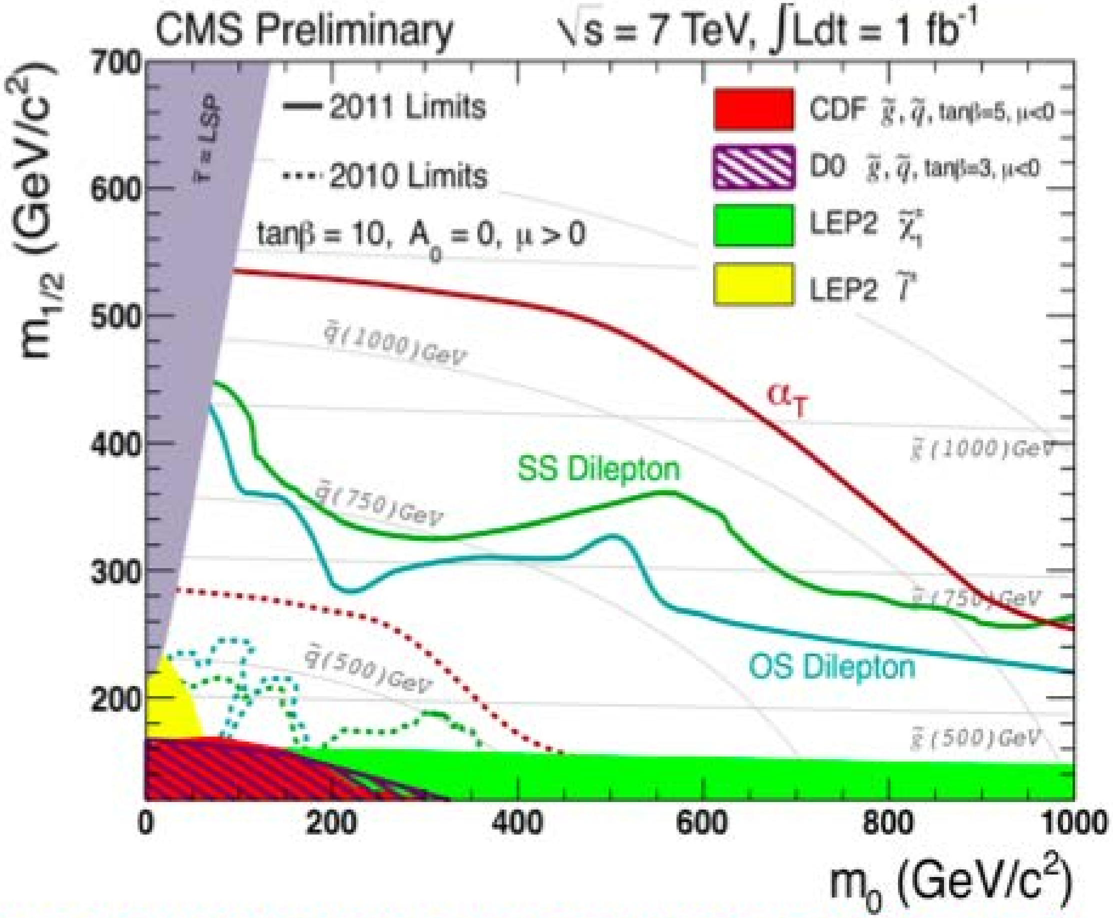
Simplified model with two q generations, m(χ 0)~01mg>800 GeV mq>850 GeV
Equal mass case: mg=mq>1.075 TeV

MSUGRA/CMSSM: tanβ=10, A0=0, μ>0 Equal mass case: mq=mg > 980 GeV

Progress on SUSY

Results of the first three SUSY analyses completed on 2011 data (α_T , Same Sign and Opposite Sign dileptons).





Within the constrained SSM models we are crossing the border of excluding gluinos and squarks up to 1TeV and beyond. The air is getting thin for constrained SUSY. More conclusive results after summer.

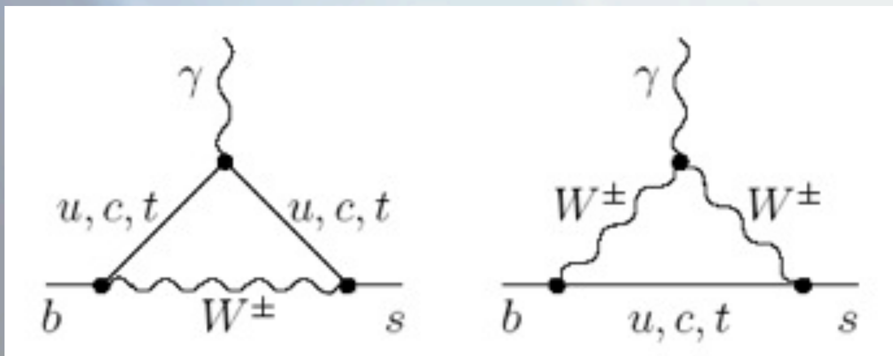
Summary

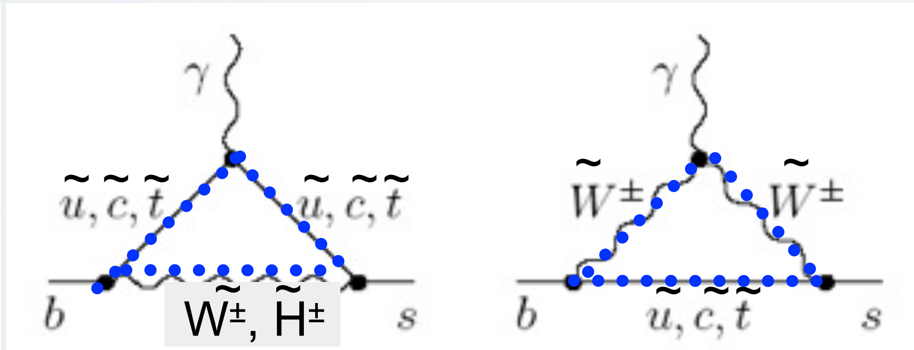
- Variety of searches for SUSY events with third generation squarks and sleptons
- Exploring signatures with heavy quarks or tau leptons using 2 fb^{-1} of data:
  - 1 or 2 τ leptons: gluino or squark mediated $\tilde{\tau}_1$ production
  - 2 b-jets + lepton veto: direct $\tilde{b}_1\tilde{b}_1^*$ production
  - 0 lepton + b-jets: gluino mediated $\tilde{b}_1$ production
  - 1 lepton + b-jets: direct $\tilde{t}_1\tilde{t}_1^*$ and gluino mediated $\tilde{t}_1$ production
  - 2 SS leptons: gluino mediated $\tilde{t}_1$ production
- No significant excess observed over SM expectations → Limits on the masses of the sparticles in a various SUSY scenarios

$\tilde{b}_1\tilde{b}_1^*$ (MSSM)	$\tilde{b}_1 \to b\tilde{\chi}_1^0$	$m_{\tilde{b}_1} = 390$ GeV ($m_{\tilde{\chi}_1^0} = 0$)	2 b-jets
$\tilde{b}_1\tilde{b}_1^*$ (MSSM)	$\tilde{b}_1 \to b\tilde{\chi}_1^0$	$m_{\tilde{b}_1} = 350$ GeV ($m_{\tilde{\chi}_1^0} = 120$ GeV)	2 b-jets
$\tilde{g}\tilde{g}$, $\tilde{b}_1\tilde{b}_1^*$ (MSSM)	$\tilde{g} \to \tilde{b}_1 b$, $\tilde{b}_1 \to b\tilde{\chi}_1^0$	$m_{\tilde{g}} = 920$ GeV ($m_{\tilde{b}_1} < 800$ GeV)	0ℓ + b-jets
$\tilde{g}\tilde{g}$ (simpl. model)	$\tilde{g} \to \bar{b}\tilde{\chi}_1^0$	$m_{\tilde{g}} = 900$ GeV ($m_{\tilde{\chi}_1^0} < 300$ GeV)	0ℓ + b-jets
$\tilde{g}\tilde{g}$, $\tilde{t}_1\tilde{t}_1^*$ (MSSM)	$\tilde{g} \to \tilde{t}_1 t$, $\tilde{t}_1 \to t\tilde{\chi}_1^0$	$m_{\tilde{g}} = 620$ GeV ($m_{\tilde{t}_1} < 440$ GeV)	1ℓ + b-jets
$\tilde{g}\tilde{g}$, $\tilde{t}_1\tilde{t}_1^*$ (MSSM)	$\tilde{g} \to \tilde{t}_1 t$, $\tilde{t}_1 \to t\tilde{\chi}_1^0$	$m_{\tilde{g}} = 650$ GeV ($m_{\tilde{t}_1} < 450$ GeV)	2ℓSS
$\tilde{g}\tilde{g}$ (simpl. model)	$\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$	$m_{\tilde{g}} = 700$ GeV ($m_{\tilde{\chi}_1^0} < 100$ GeV)	1ℓ + b-jets
$\tilde{g}\tilde{g}$ (simpl. model)	$\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$	$m_{\tilde{g}} = 650$ GeV ($m_{\tilde{\chi}_1^0} < 215$ GeV)	2ℓSS
$\tilde{g}\tilde{g}$ (simpl. model)	$\tilde{g} \to tb + \tilde{\chi}_1^0$	$m_{\tilde{g}} = 710$ GeV ($m_{\tilde{\chi}_1^0} < 100$ GeV)	1ℓ + b-jets

B->sγ decay rate

Standard Model | **MSSM**

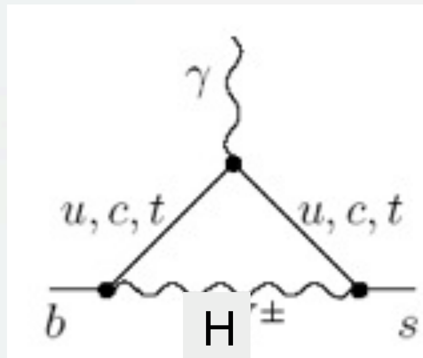




SM: $\mathcal{B}(B \to X_s\gamma) = (3.28 \pm 0.33) \times 10^{-4}$.

MSSM

$$\mathcal{BR}(b \to s\gamma)|_{\chi^\pm} \propto \mu A_t \tan\beta f(m_{\tilde{t}_1}, m_{\tilde{t}_2}, m_{\chi^\pm}) \frac{m_b}{v(1+\Delta m_b)}$$



Experiment $\mathbf{B(B \to X_s\gamma) = (3.43 \pm 0.36) \times 10^{-4}}$

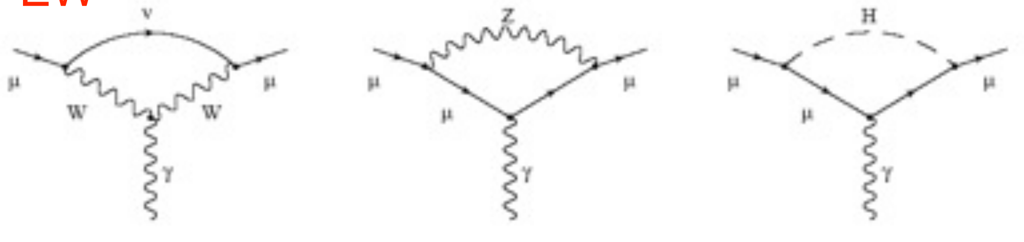
Anomalous magnetic moment

$$a_\mu^{exp} = 11\,659\,202\,(14)(6)\cdot 10^{-10}$$
$$a_\mu^{SM} = 11\,659\,159.6\,(6.7)\cdot 10^{-10}$$

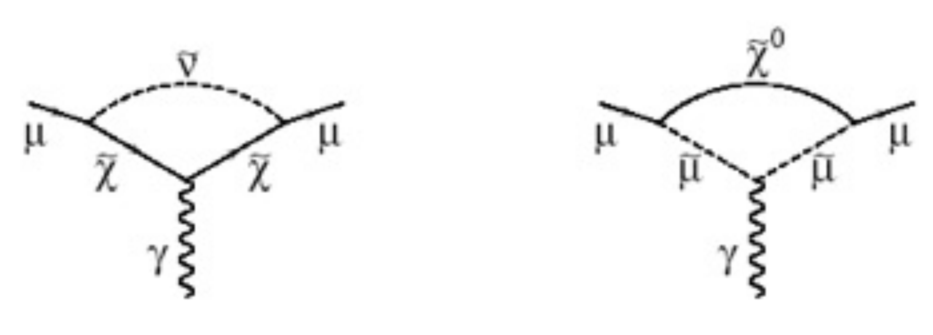
$$a_\mu^{exp} - a_\mu^{SM} = (27\pm10)\cdot 10^{-10}$$

$$a_\mu^{QED} = 11\,658\,470.56\,(0.29)\cdot 10^{-10}$$
$$a_\mu^{weak} = 15.1\,(0.4)\cdot 10^{-10}$$
$$a_\mu^{hadr} = 673.9\,(6.7)\cdot 10^{-10}$$

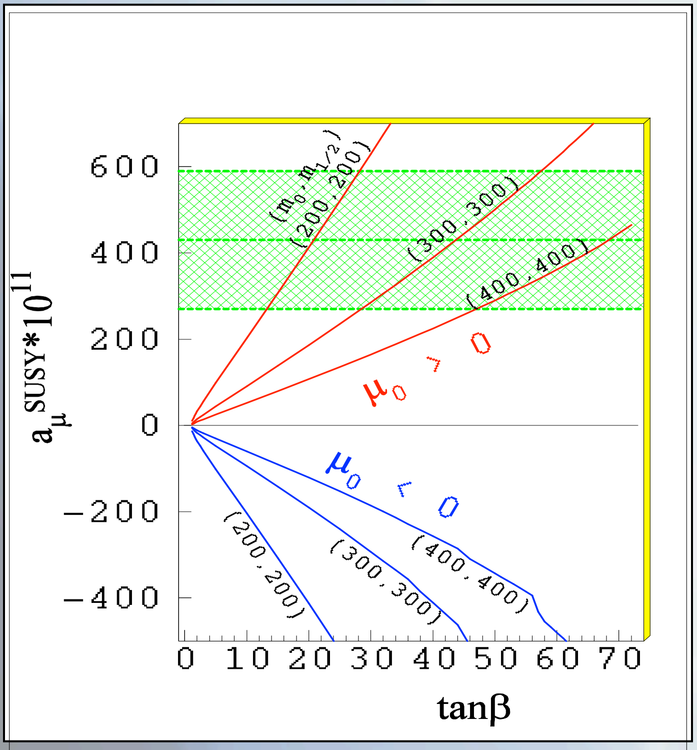
EW

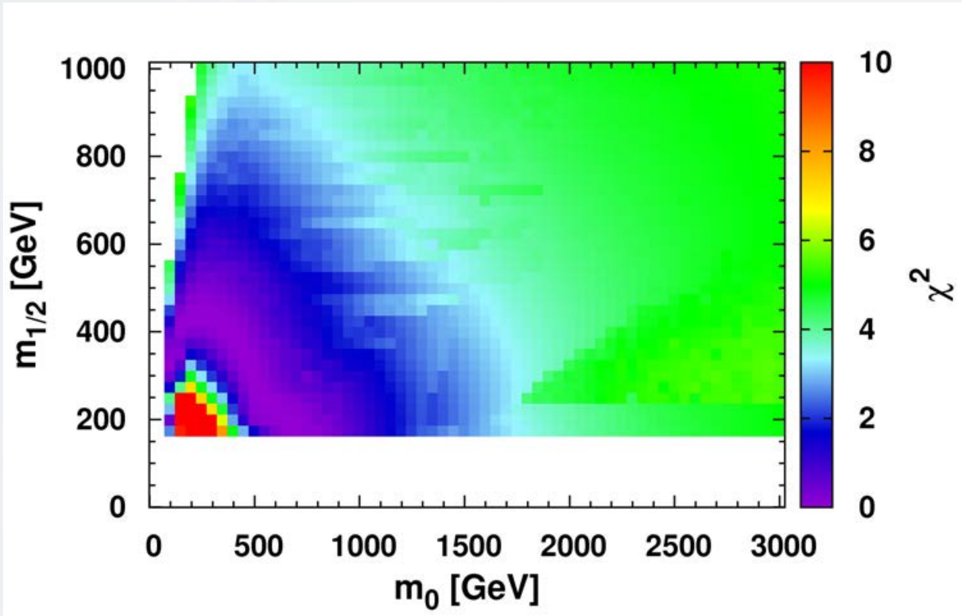


$$|a_\mu^{SUSY}| \simeq \frac{\alpha(M_Z)}{8\pi\,Sin^2\theta_W}\frac{m_\mu^2}{M_{SUSY}^2}tan\beta\left(1-\frac{4\alpha}{\pi}log\frac{M_{SUSY}}{m_\mu}\right) \simeq 140\cdot10^{-11}\left(\frac{100\ \mathrm{GeV}}{M_{SUSY}}\right)^2 tan\beta$$



g-2 Constraint on Parameter space

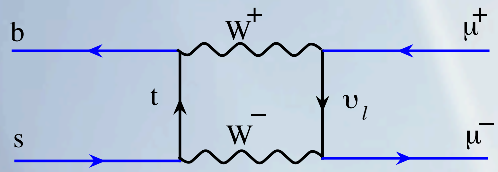


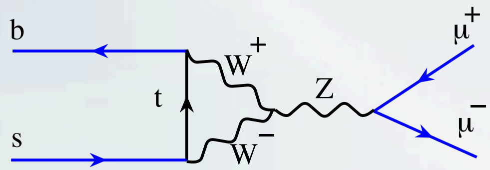


Fixes the sign of μ

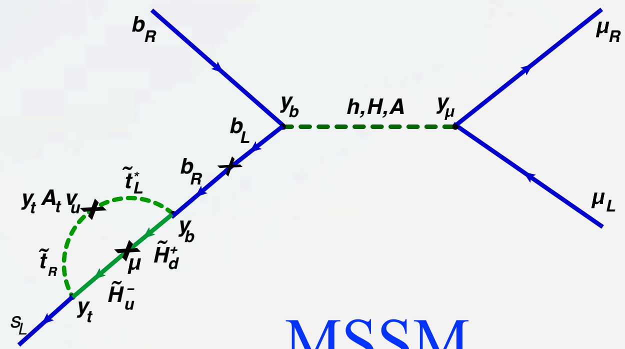
The only requirement that limits the SUSY masses from above

Rare Decays: $Br[B_s \to \mu^+\mu^-]$





SM



MSSM

SM: Br=3.5·10^{-9}

Ex: <4.5· 10^{-8}

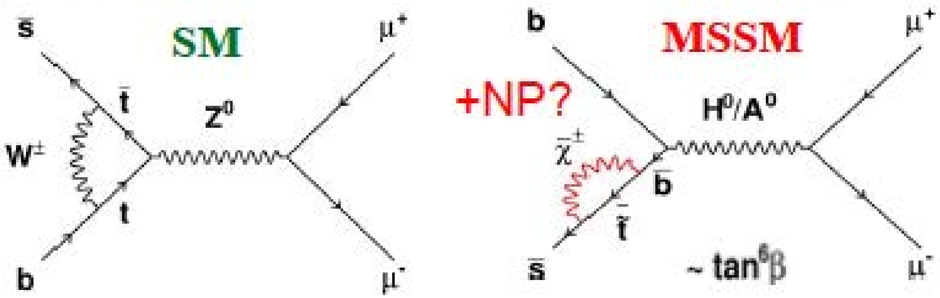
$$Br[B_s \to \mu\mu] = \frac{2\tau_B m_B^5}{64\pi} f_{B_s}^2 \sqrt{1-\frac{4m_l^2}{m_B^2}}$$

$$\left[\left(1-\frac{4m_l^2}{m_B^2}\right)\left|\frac{(C_S-C_S')}{(m_b+m_s)}\right|^2 + \left|\frac{(C_P-C_P')}{(m_b+m_s)} + 2\frac{m_\mu}{m_{B_s}^2}(C_A-C_A')\right|^2\right]$$

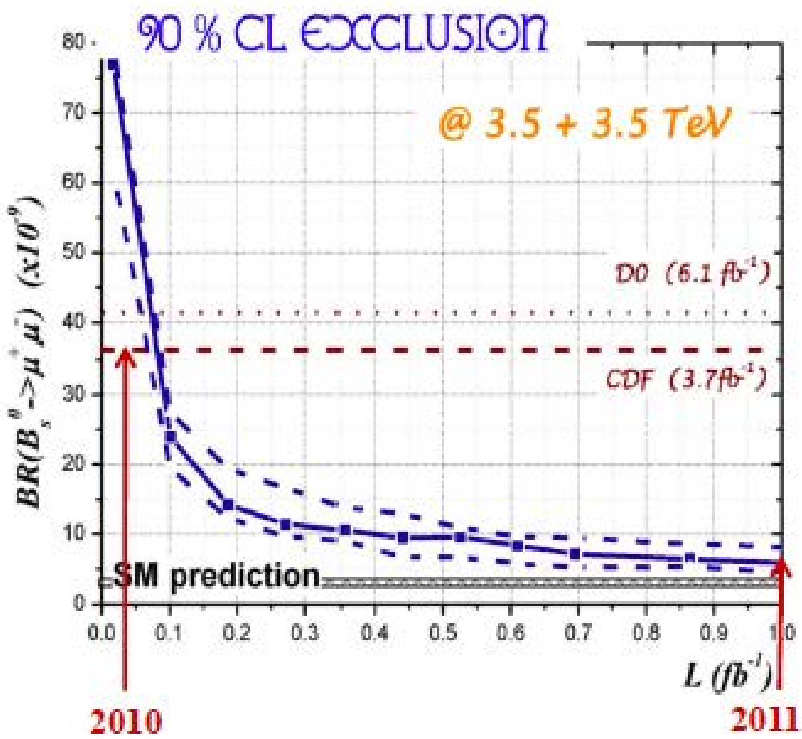
$$C_S \simeq \frac{G_F\alpha}{\sqrt{2}\pi} V_{tb}V_{ts}^* \left(\frac{\tan^3\beta}{4\sin^2\theta_W}\right)\left(\frac{m_b m_\mu m_t \mu}{M_W^2 M_A^2}\right)\frac{\sin 2\theta_{\tilde{t}}}{2}\left(\frac{m_{\tilde{t}_1}^2 \log\left[\frac{m_{\tilde{t}_1}^2}{\mu^2}\right]}{\mu^2-m_{\tilde{t}_1}^2} - \frac{m_{\tilde{t}_2}^2 \log\left[\frac{m_{\tilde{t}_2}^2}{\mu^2}\right]}{\mu^2-m_{\tilde{t}_2}^2}\right)$$

Probing New Physics in loop decays: $B_s \to \mu\,\mu$

$B_s \to \mu\,\mu$: the **super** rare loop decay



BR = $(3.2 \pm 0.2)\times\mathbf{10^{-9}}$ in SM



✓ sensitive to New Physics, can be strongly enhanced in SUSY with scalar Higgs exchange

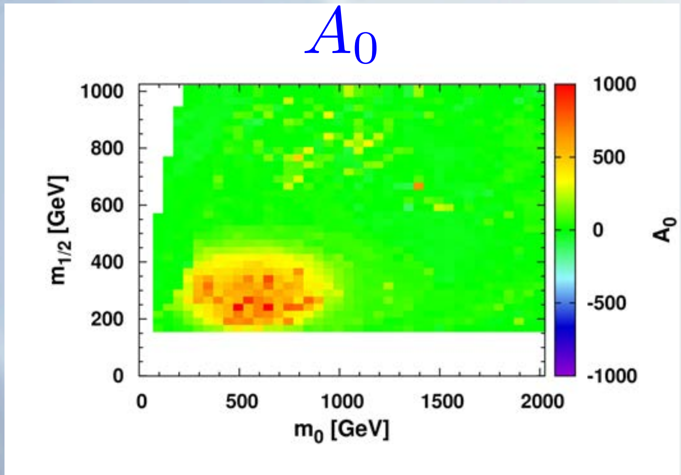
✓ sensitive probe for MSSM with large tanβ:
$B(B_S \to \mu^+\mu^-) \sim \tan\beta^{\,6} / M_A^{\,4}$

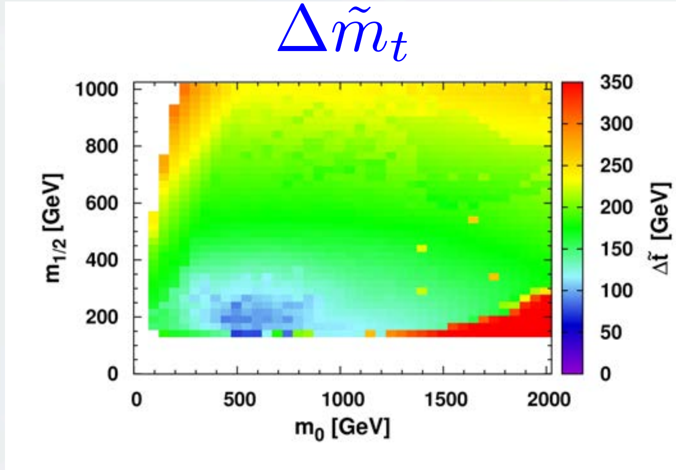
✓ analysis of 2010 data well advanced, “un-blinding” for winter conferences!

➢ expect competitive result with best world measurements, with this years data set

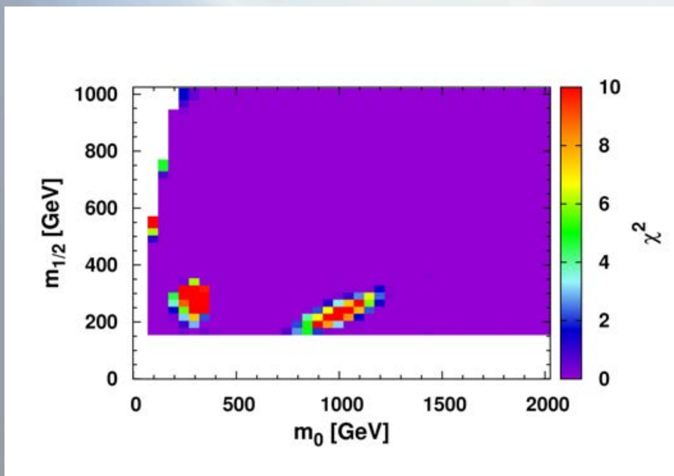
➢ potential to discover New Physics down to the SM predictions with next year’s data

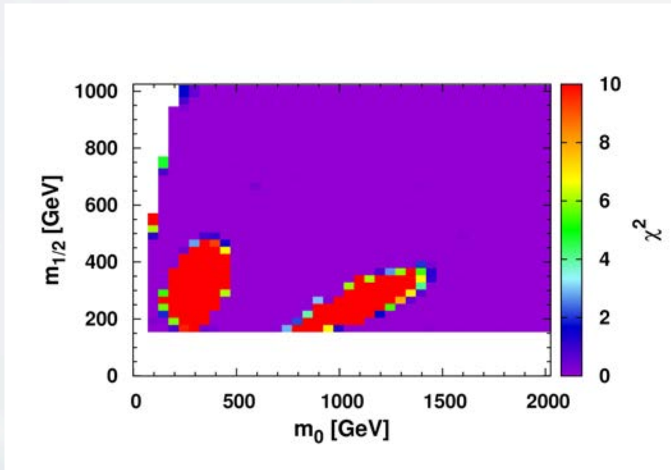
Rare Decays: $Br[B_s \to \mu^+\mu^-]$ Constraint





$$Br[B_s \to \mu^+\mu^-] < 4.7 \cdot 10^{-8}$$



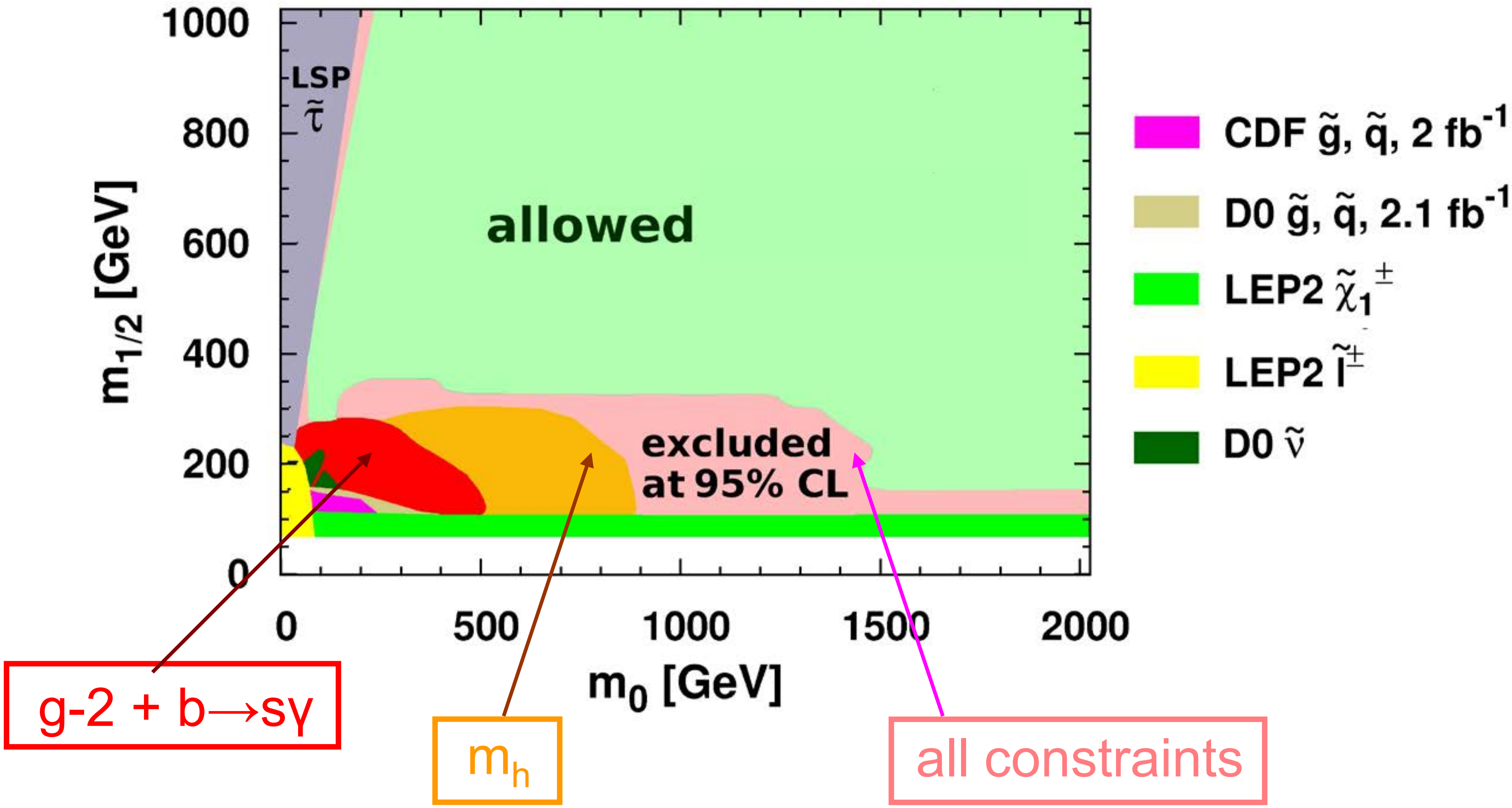


95% C.L. Excluded regions for

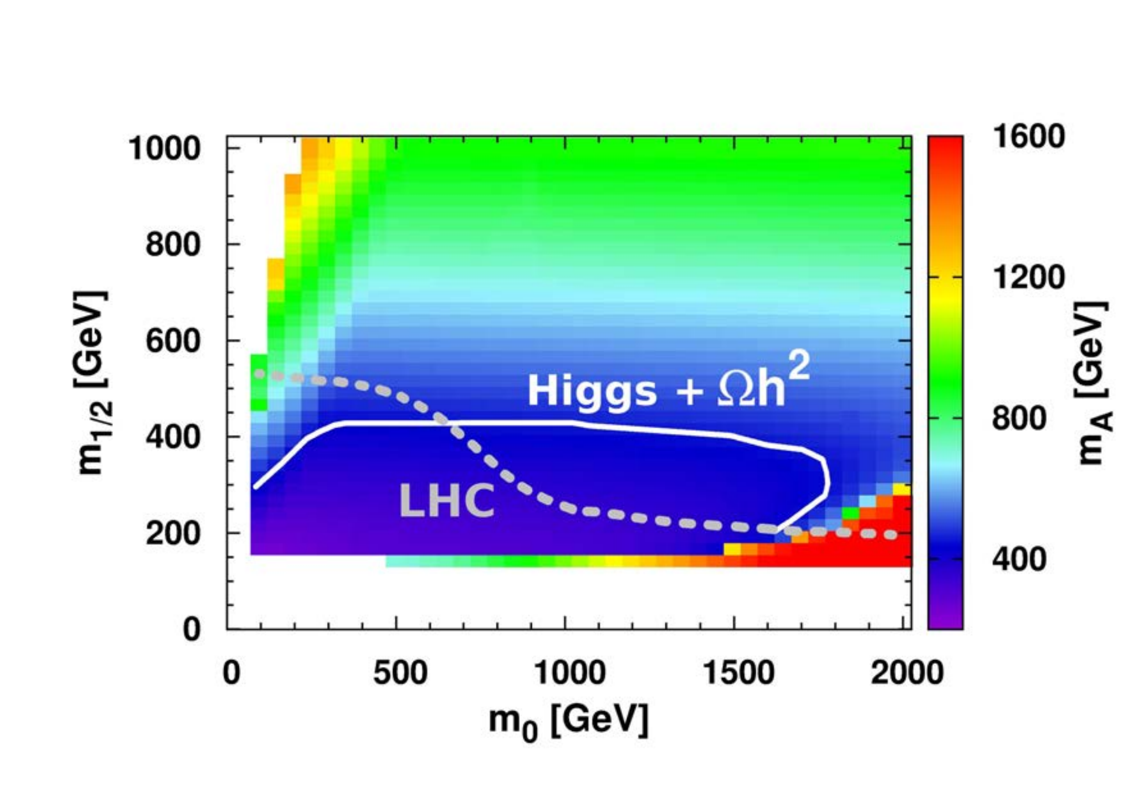
$$Br[B_s \to \mu^+\mu^-] < 1.1 \cdot 10^{-8}$$ $$Br[B_s \to \mu^+\mu^-] < 0.66 \cdot 10^{-8}$$

Pre-LHC Constraints

- Allowed parameter space (95% CL contour) in the m_0-$m_{1/2}$ plane including all constraints



SUSY Limits including the LHC without Direct DM Search

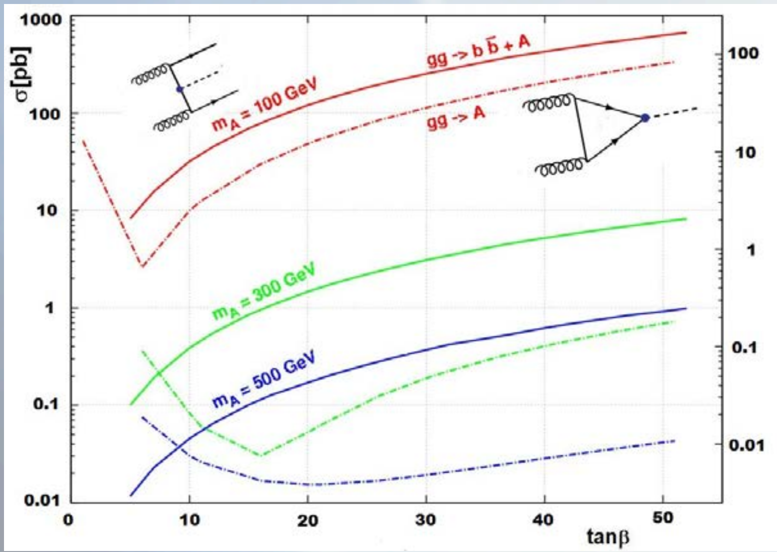


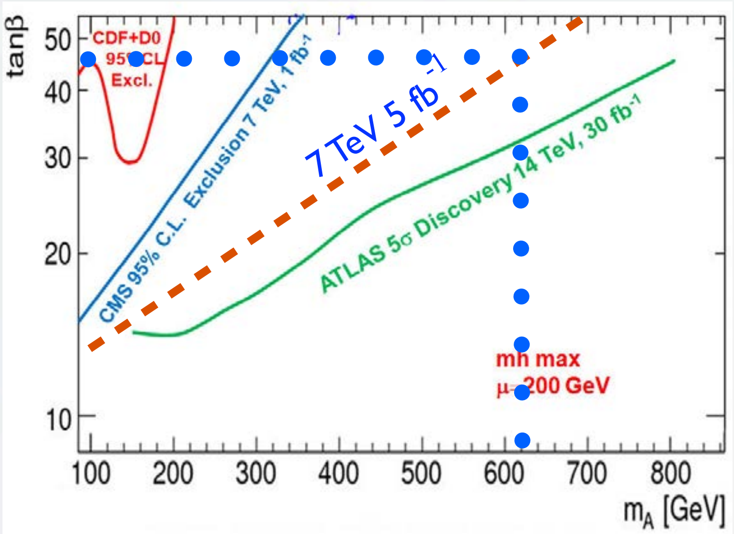
This includes:

- the Higgs searches,
- the rare decays,
- the relic abundancy
- and collider limits

The values of A_0 and $\tan\beta$ are ajusted

Heavy Higgs Production at the LHC





$$\sigma_{Higgs} = \frac{1}{32}\int_0^1 dx_1 dx_2 \; g[x_1] \; g[x_2] \; |\mathcal{M}_{Higgs}|^2 \frac{2\pi}{m^2_{Higgs}} \delta(E^2 x_1 x_2 - m^2_{Higgs})$$

$$\mathcal{M}_h = \frac{\alpha_s}{4\pi}\frac{m_h^2}{2\sqrt{2}v}\left(\frac{\cos\alpha}{\sin\beta}F^h_{1/2}[\frac{4m_t^2}{m_h^2}] - \frac{\sin\alpha}{\cos\beta}F^h_{1/2}[\frac{4m_b^2}{m_h^2}]\right),$$

$$\mathcal{M}_H = \frac{\alpha_s}{4\pi}\frac{m_H^2}{2\sqrt{2}v}\left(\frac{\sin\alpha}{\sin\beta}F^H_{1/2}[\frac{4m_t^2}{m_H^2}] + \frac{\cos\alpha}{\cos\beta}F^H_{1/2}[\frac{4m_b^2}{m_H^2}]\right),$$

$$\mathcal{M}_A = \frac{\alpha_s}{4\pi}\frac{m_A^2}{2\sqrt{2}v}\left(\frac{\cos\beta}{\sin\beta}F^A_{1/2}[\frac{4m_t^2}{m_A^2}] + \frac{\sin\beta}{\cos\beta}F^A_{1/2}[\frac{4m_b^2}{m_A^2}]\right)$$

Dark Matter Detection

Direct detection

DAMA, Zeplin,
CDMS, Edelweiss

No convincing evidence so far
Hope for new results soon

Indirect detection

- EGRET -> GLAST(FERMI)
Diffuse Gamma Rays
- HEAT, AMS01 -> PAMELA
Positrons in Cosmic Rays
- BESS -> AMS02
Antiprotons in Cosmic Rays

Search for DM annihilation!

Why WIMP?

Boltzman Equation

Hubble constant

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -<\sigma v>(n_\chi^2 - n_{\chi,eq}^2), \qquad H = \dot{R}/R$$

Relic Abundance

$$\Omega_\chi h^2 = \frac{m_\chi n_\chi}{\rho_c} \approx \frac{3\cdot 10^{-27} cm^3 \sec^{-1}}{<\sigma v>}$$

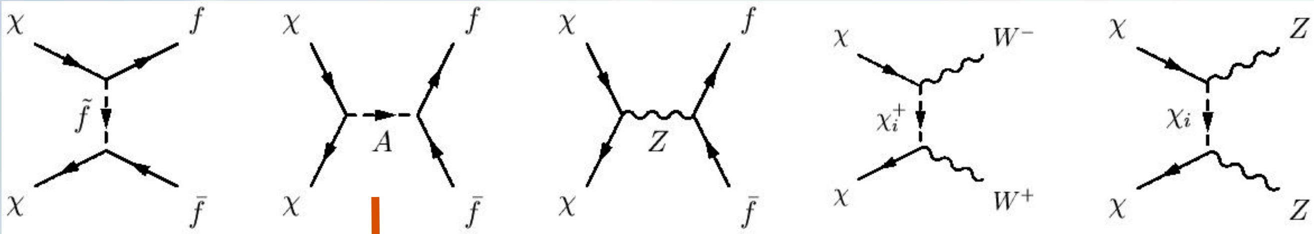
$$\Omega_\chi h^2 \sim 0.113 \pm 0.009,$$

$$v \sim 300 \; km/\sec$$

$$\sigma \sim 10^{-34} cm^2 = 100\, pb$$

Typical EW x-section

Relic Abundace of the Dark Matter



$\propto \frac{m_\chi \cdot m_f}{m_{\tilde{f}}^2}$

$\propto \frac{\tan\beta \cdot m_{f_d}}{m_W} N_1 N_{3(4)}$, $\tan\beta \cdot m_{f_d} \leftrightarrow \frac{m_{f_u}}{\tan\beta}$

$\propto \frac{m_f \cdot m_\chi}{m_Z^2} N_{3(4)}^2$

$\propto \frac{1}{1+(m_{\chi_i^+}/m_\chi)^2-(m_W/m_\chi)^2}$, $(m_{\chi_i^+}, m_W) \leftrightarrow (m_{\chi_i}, m_Z)$

$$\tilde{\chi}^0 = N_1 \tilde{\gamma} + N_2 \tilde{z} + N_3 \tilde{H}_1^0 + N_4 \tilde{H}_2^0$$

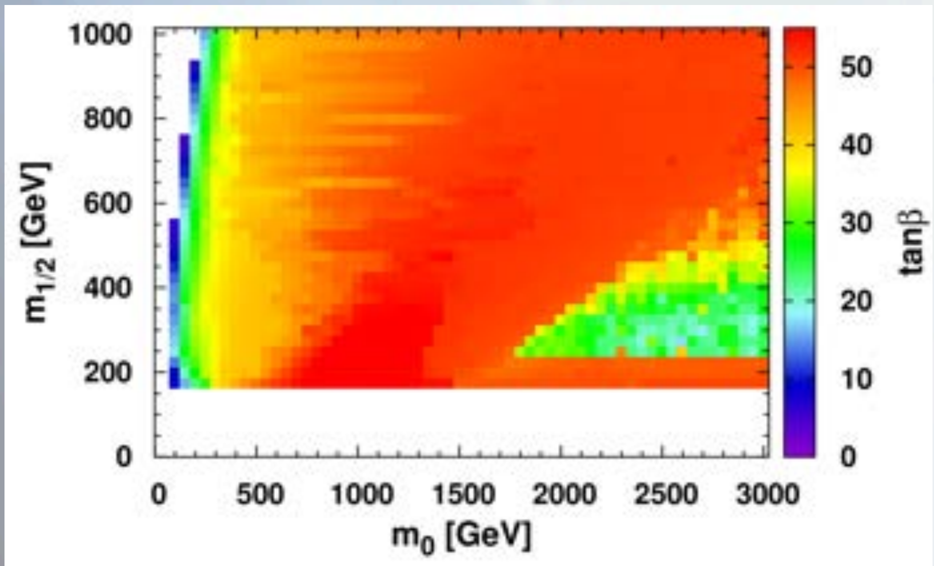
The Dark Matter Annihilation

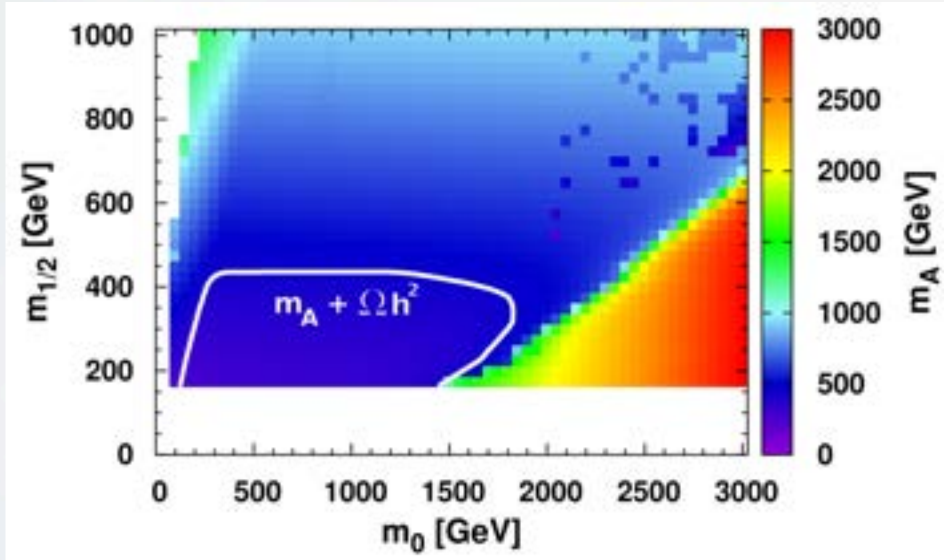
$$< \sigma v >= 2 \cdot 10^{-26} cm^3/s$$

Resonance in s-channel

$$< \sigma v >\sim \frac{M_\chi^4 m_b^2 \tan^2\beta}{\sin^4 2\theta_W\, M_Z^2} \frac{(N_{31}\sin\beta - N_{41}\cos\beta)^2 (N_{21}\cos\theta_W - N_{11}\sin\theta_W)^2}{(4M_\chi^2 - M_A^2)^2 + M_A^2\Gamma_A^2}$$

Relic Abundace of the DM Constraint





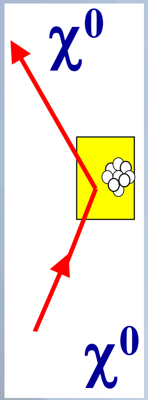
The value of $\tan\beta$

$\tan\beta \approx 50$ almost everywhere except for the coannihilation regions

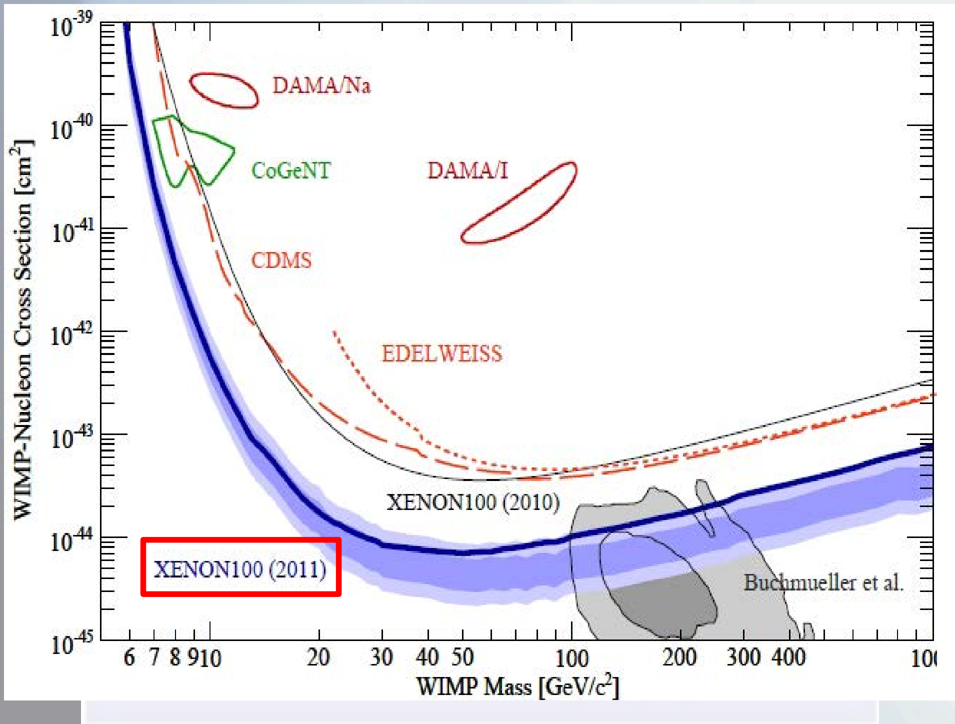
The value of m_A

m_A may be as low as 500 Ge except for the coannihilation regions

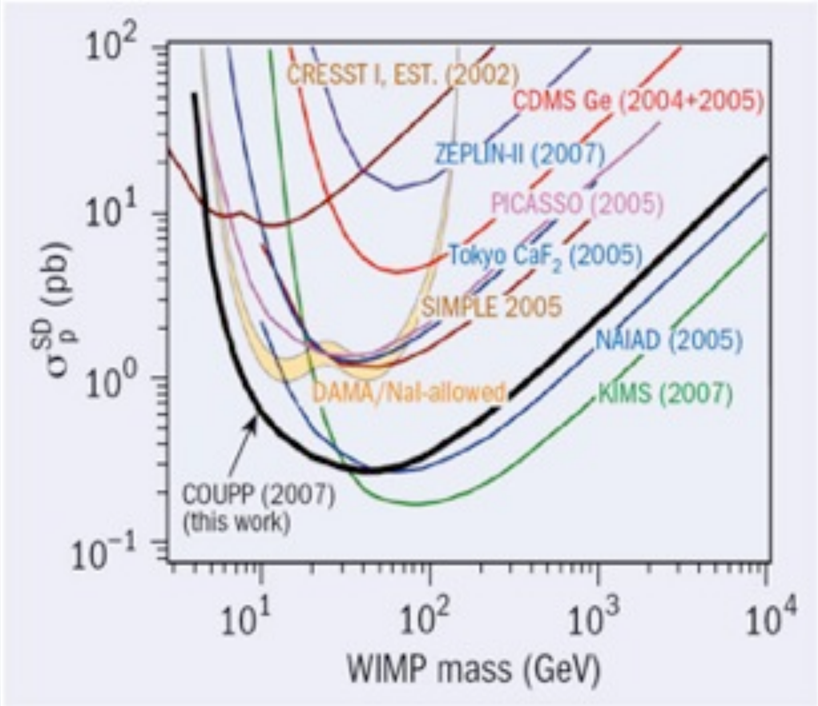
Recent Results on Direct Detection



Spin Independent



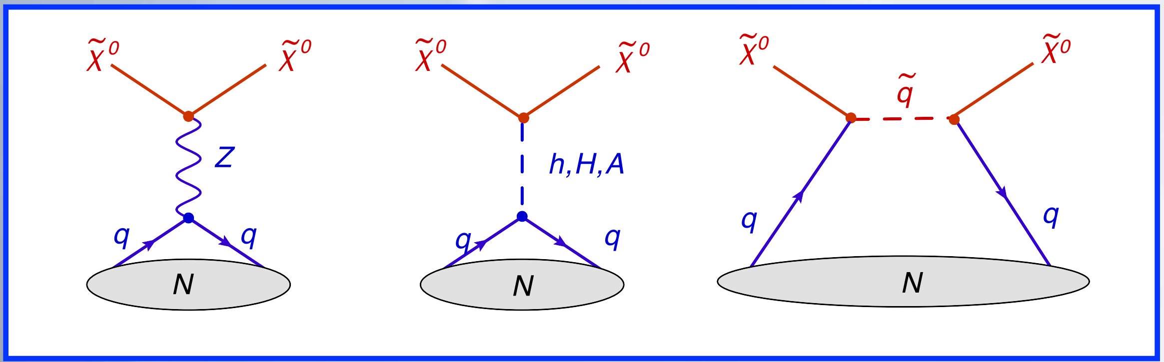
Spin Dependent

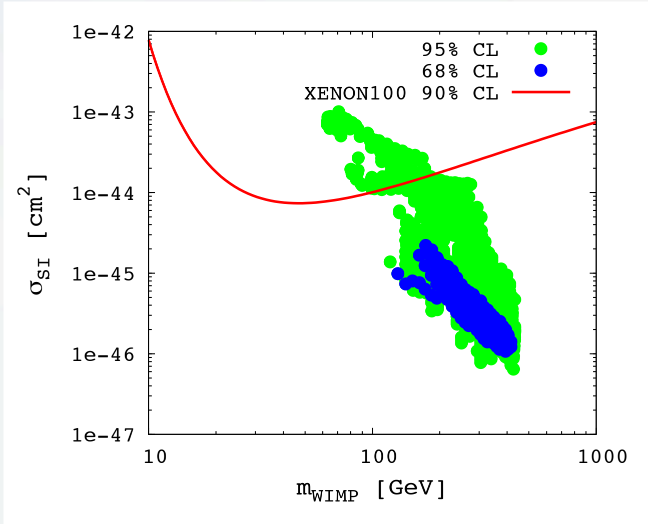


The Chicagoland Observatory for Underground Particle Physics (COUPP)

Cryogenic Dark Matter Search (CDMS)

Direct DM Searches



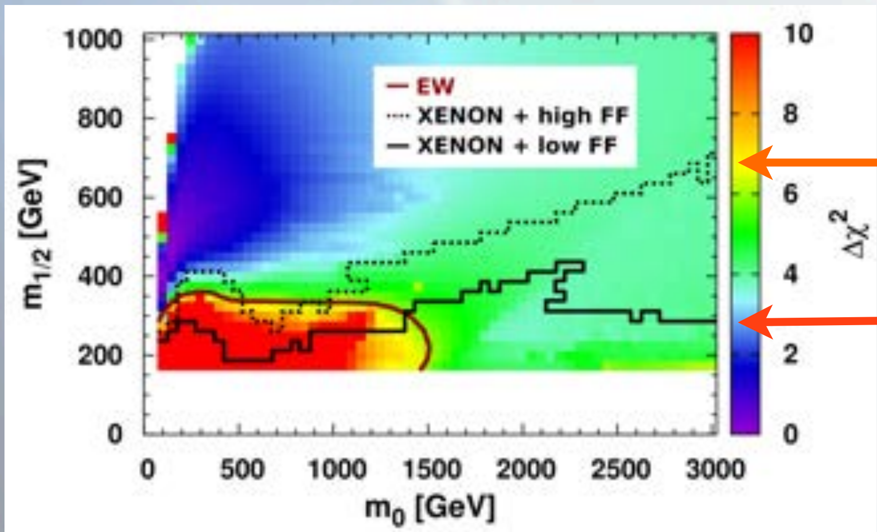


$$\sigma = \frac{4}{\pi} \frac{m_{\rm DM}^2 m_N^2}{(m_{\rm DM} + m_N)^2} (Z f_p + (A - Z) f_n)^2$$

$$f_{p,n} = \sum_{q=u,d,s} G_q f_{Tq}^{(p,n)} \frac{m_{p,n}}{m_q} + \frac{2}{27} f_{TG}^{(p,n)} \sum_{q=c,b,t} G_q \frac{m_{p,n}}{m_q} \qquad m_p f_{Tq}^{(p)} \equiv \langle p | m_q \bar{q} q | p \rangle$$

$$\begin{aligned}
G_q(A) &= 0, \\
G_u(h) &= \frac{-e^2 m_u}{2\sin^2 2\theta_W M_Z} (N_{21}\cos\theta_W - N_{11}\sin\theta_W) \frac{\cos\alpha}{\sin\beta} \frac{(N_{41}\cos\alpha + N_{31}\sin\alpha)}{M_h^2}, \\
G_d(h) &= \frac{e^2 m_d}{2\sin^2 2\theta_W M_Z} (N_{21}\cos\theta_W - N_{11}\sin\theta_W) \frac{\sin\alpha}{\cos\beta} \frac{(N_{41}\cos\alpha + N_{31}\sin\alpha)}{M_h^2}, \\
G_u(H) &= \frac{-e^2 m_u}{2\sin^2 2\theta_W M_Z} (N_{21}\cos\theta_W - N_{11}\sin\theta_W) \frac{\sin\alpha}{\sin\beta} \frac{(N_{41}\sin\alpha - N_{31}\cos\alpha)}{M_H^2}. \\
G_d(H) &= \frac{-e^2 m_d}{2\sin^2 2\theta_W M_Z} (N_{21}\cos\theta_W - N_{11}\sin\theta_W) \frac{\cos\alpha}{\cos\beta} \frac{(N_{41}\sin\alpha - N_{31}\cos\alpha)}{M_H^2}
\end{aligned}$$

SUSYLimits including Direct DM Search



The values of A_0 and $\tan\beta$ are ajusted

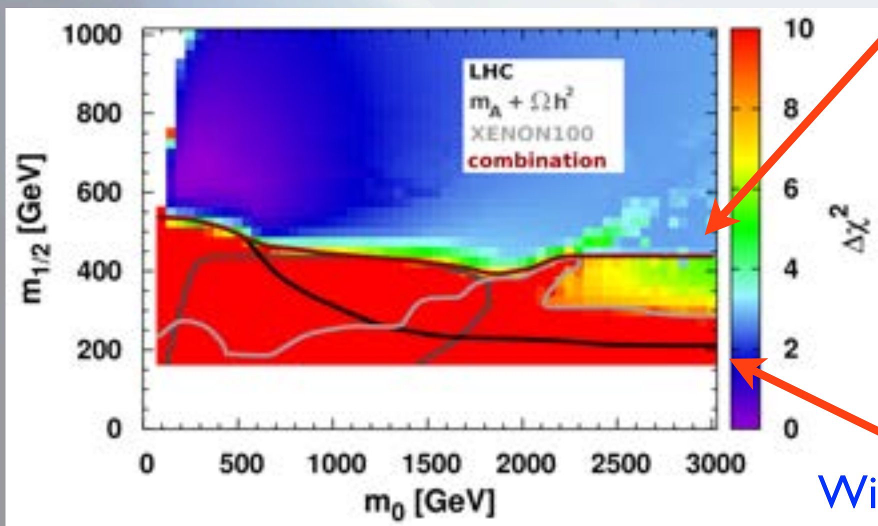
Low Energy Form Factors

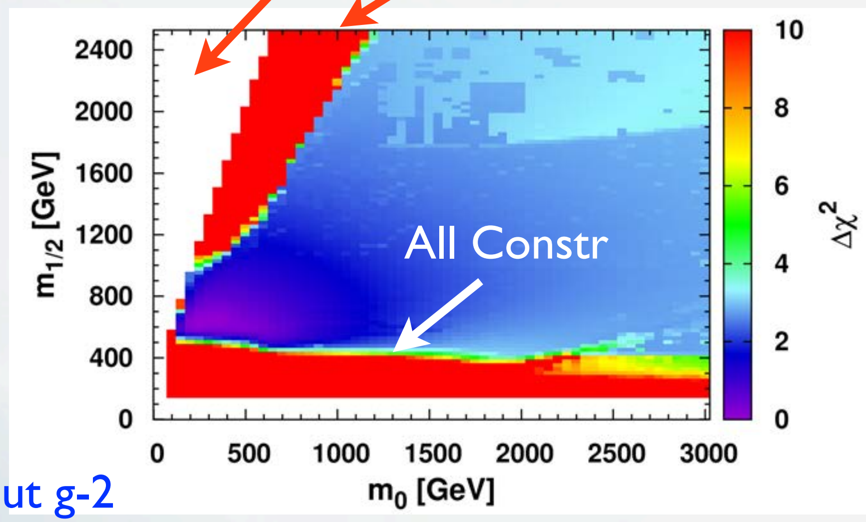
Lattice Form Factors

All included

LSP

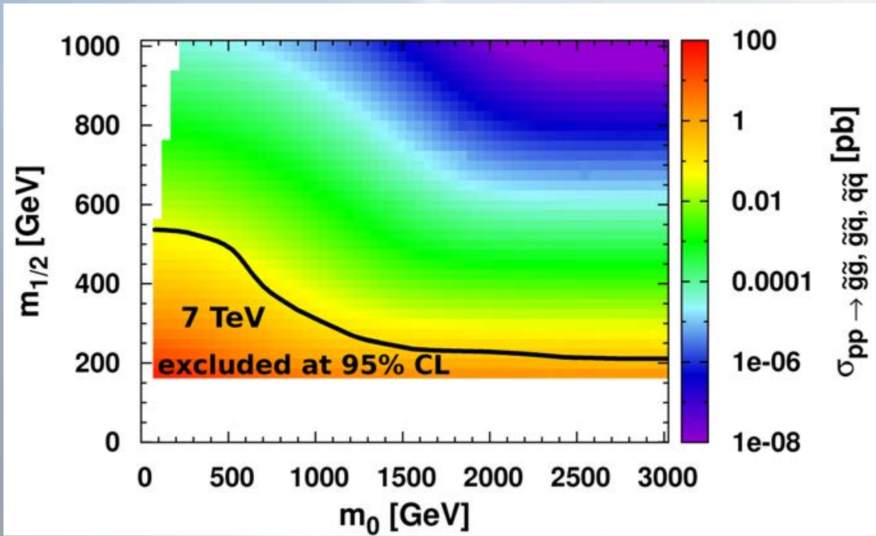
LSP+DM

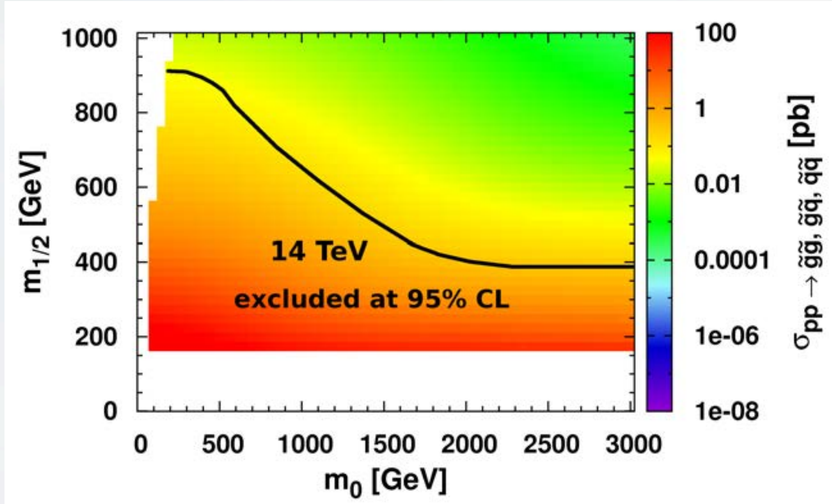


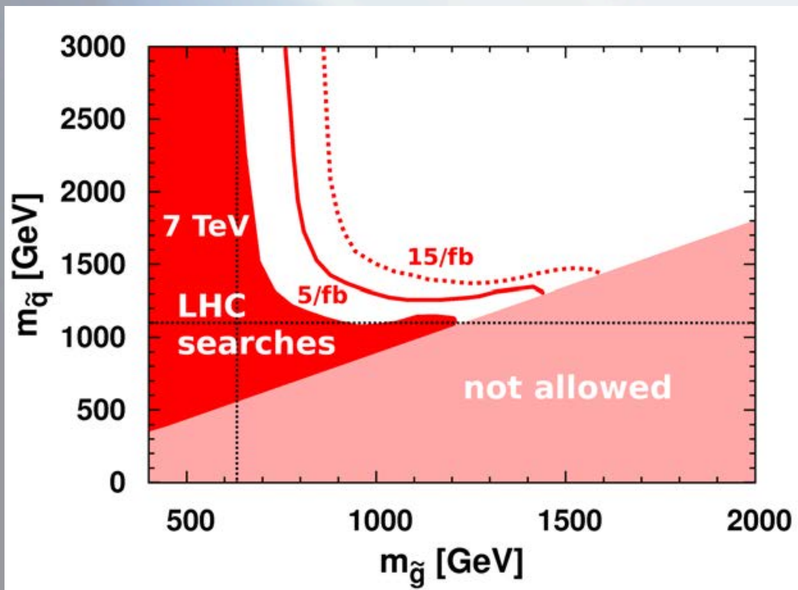


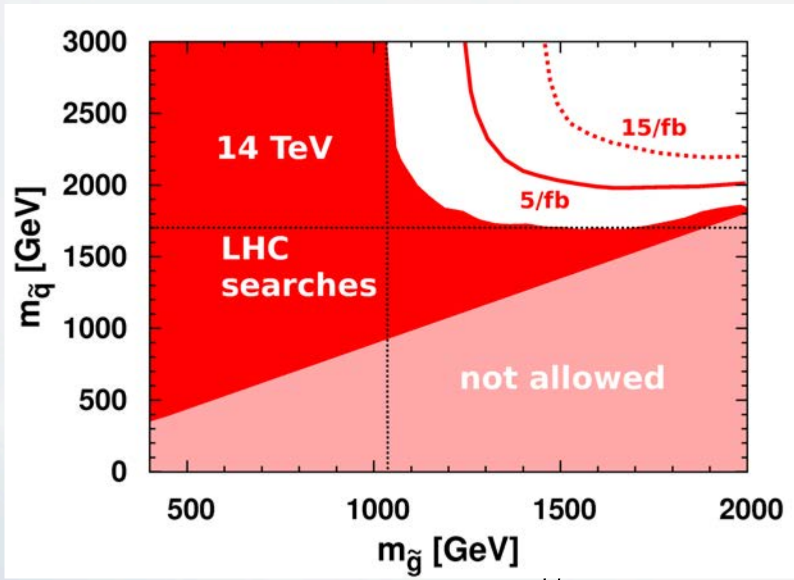
Without g-2

LHC Reach at 7 and 14 TeV









Conclusions

- LHC is on the way of covering the parameter space of the MSSM
- It is rather insensitive to large values of m_0
- This can be supplemented by direct DM searches
- Modern combined limit on $m_{1/2}$ is about 400 GeV independently of m_0
- This implies the lower limit on the WIMP mass of 160 GeV
- Today's lower limit on squark masses (except $\tilde{t}$) is 1000 GeV and gluino mass is 650 GeV
- They can reach 1700 GeV and 1000 GeV for 14 TeV

Let 2012 be the year of Higgs discovery and SUSY evidence!

SUSY: Pros and Cons

Pro :

- Provides natural framework for unification with gravity
- Leads to gauge coupling unification (GUT)
- Solves the hierarchy problem
- Provides the mechanizm for spontaneous EWSB
- Is a solid quantum field theory
- Provides natural candidate for the WIMP cold DM
- Predicts new particles and thus generates new job positions

Contra :

Does not shed new light on the problem of

- Quark and lepton mass spectrum
- Quark and lepton mixing angles
- the origin of CP violation
- Number of flavours
- Baryon assymetry of the Universe

Doubles the number of particles