Supersymmetry on the run: LHC & Dark Matter

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Outline

- Basics of SUSY
- MSSM
- SUSY Searches at LHC
- SUSY in the sky (DM)

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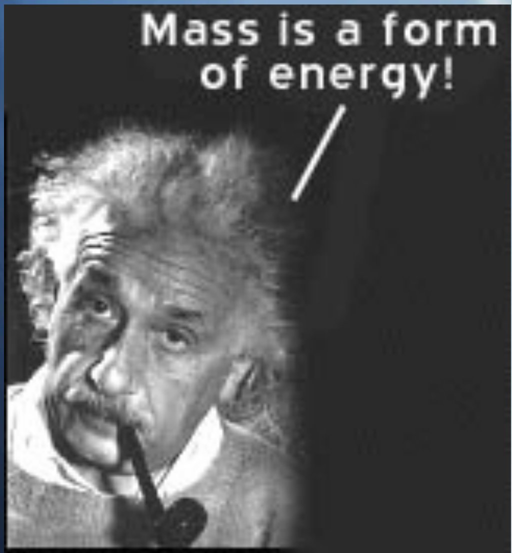
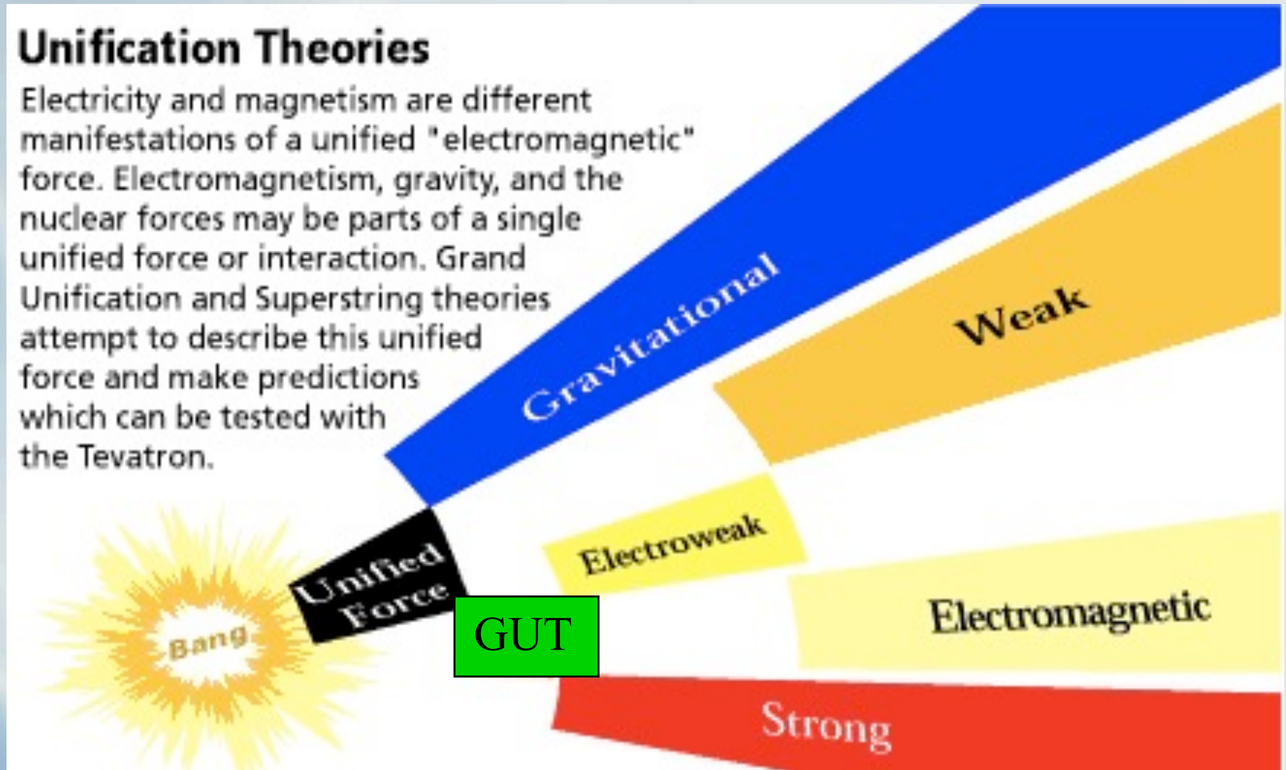
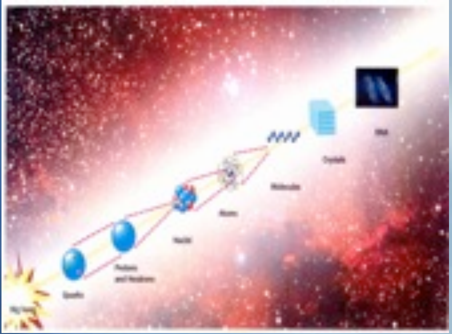
Unification Paradigm





- 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



What is SUSY?

- **Supersymmetry** is a boson-fe… …try that is aimed to unify all fo… …ding gravity within a sing…

$Q\,|\,boson$ … $oson >$

$[b,$ … $\}_{\dot{\beta}}\} = 2\delta^{ij}(\sigma^{\mu})_{\alpha\dot{\beta}} P_{\mu}$

- Mod… …mmetry in particle physics are base… …radigm, though low energy manifesta… …of SUSY can be found (?) at modern colliders and in non-accelerator experiments

First papers in 1971-1972

No evidence in particle physics yet

Motivation of SUSY in Particle Physics

- ☑ Unification with Gravity
- ☑ Unification of gauge couplings
- ☑ Solution of the hierarchy problem
- ☑ Dark matter in the Universe
- ☑ (Super)string consistency

Motivation of SUSY in Particle Physics

- Unification with Gravity

$$Q|boson> = |fermion> \qquad Q|fermion> = |boson>$$

$$spin\ 2 \Rightarrow spin\ 3/2 \Rightarrow spin\ 1 \Rightarrow spin\ 1/2 \Rightarrow spin\ 0$$

Unification of matter (fermions) with forces (bosons) naturally arises from an attempt to unify gravity with the other interactions

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

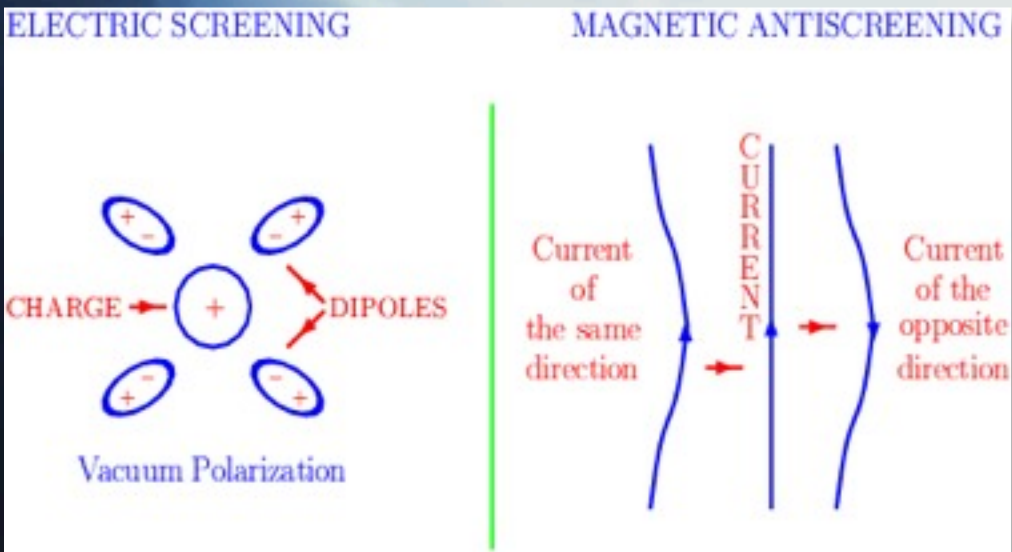
$$\varepsilon = \varepsilon(x) \ \text{ local coordinate transf. } \Rightarrow \text{ (super)gravity}$$

Local supersymmetry = general relativity !

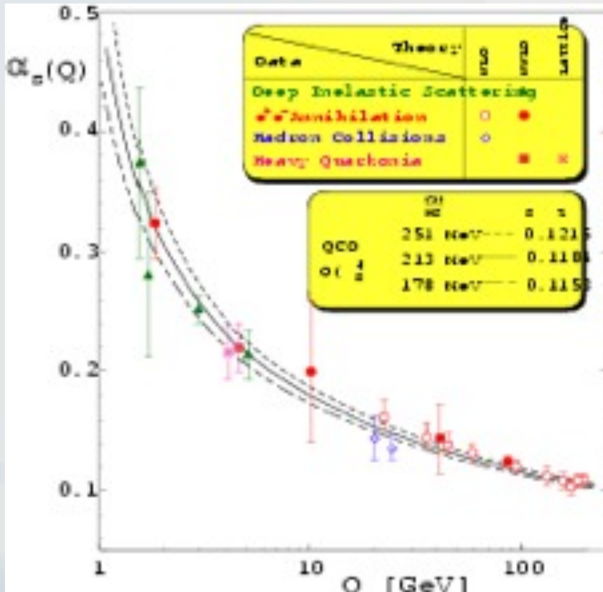
Motivation of SUSY in Particle Physics

- Unification of gauge couplings

	Low Energy		⇒	*High Energy*
$SU_c(3)$	$SU_L(2)$	$U_Y(1)$	⇒	G_{GUT} (or G^n + symm)
gluons	W, Z	*photon*	⇒	*gauge bosons*
quarks	*leptons*		⇒	*fermions*
g_3	g_2	g_1	⇒	g_{GUT}



$$\alpha_i = \alpha_i\left(\frac{Q^2}{\Lambda^2}\right) = \alpha_i(\text{distance})$$



Running of the strong coupling

Motivation of SUSY

RG Equations

$$\frac{d\tilde{\alpha}_i}{dt} = b_i \tilde{\alpha}_i^2, \quad \tilde{\alpha}_i = \alpha_i / 4\pi = g_i^2 / 16\pi^2, \quad t = \log(Q^2/\mu^2)$$

$$SM: \quad b_i = \begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} = \begin{pmatrix} 0 \\ -22/3 \\ -11 \end{pmatrix} + N_{Fam} \begin{pmatrix} 4/3 \\ 4/3 \\ 4/3 \end{pmatrix} + N_{Higgs} \begin{pmatrix} 1/10 \\ 1/6 \\ 0 \end{pmatrix}$$

$$MSSM: \quad b_i = \begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} = \begin{pmatrix} 0 \\ -6 \\ -9 \end{pmatrix} + N_{Fam} \begin{pmatrix} 2 \\ 2 \\ 2 \end{pmatrix} + N_{Higgs} \begin{pmatrix} 3/10 \\ 1/2 \\ 0 \end{pmatrix}$$

Unification of the Coupling Constants
in the SM and in the MSSM

Input

$$\alpha^{-1}(M_Z) = 128.978 \pm 0.027$$

$$\sin^2\theta_{\overline{MS}} = 0.23146 \pm 0.00017$$

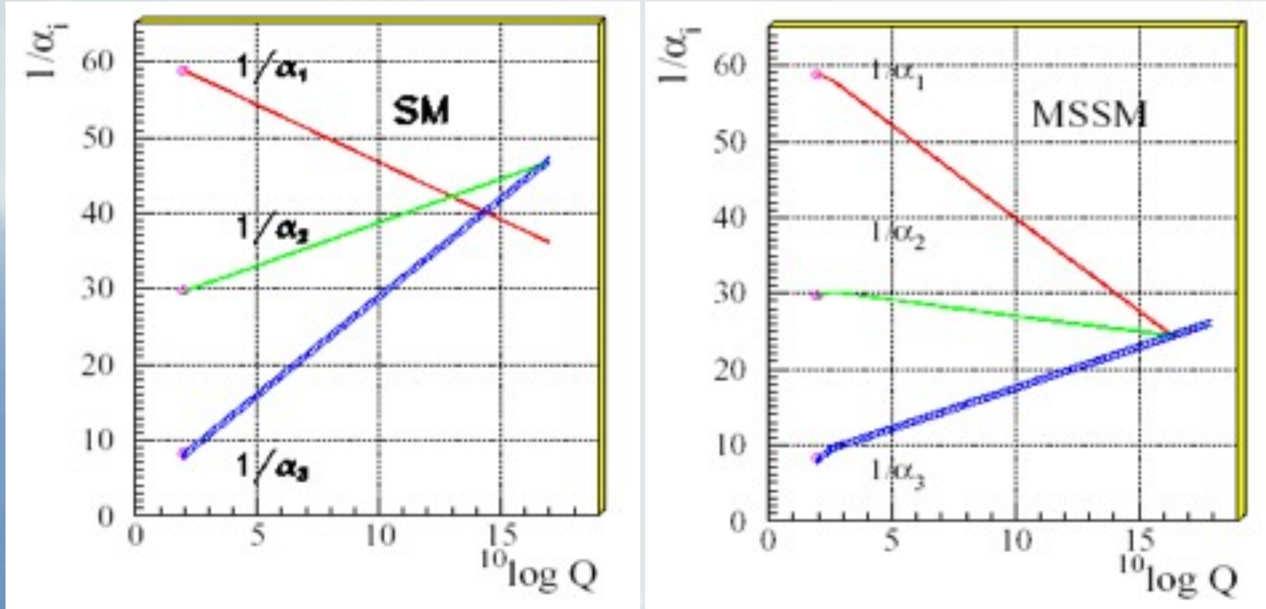
$$\alpha_s(M_Z) = 0.1184 \pm 0.0031$$

Output

$$M_{SUSY} = 10^{3.4 \pm 0.9 \pm 0.4} \text{ GeV}$$

$$M_{GUT} = 10^{15.8 \pm 0.3 \pm 0.1} \text{ GeV}$$

$$\alpha_{GUT}^{-1} = 26.3 \pm 1.9 \pm 1.0$$



SUSY yields unification!7

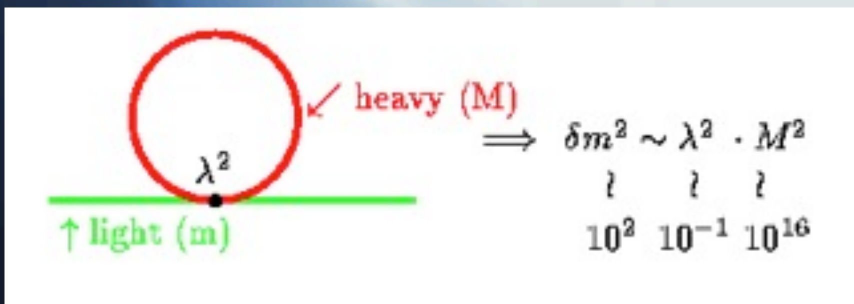
Motivation of SUSY

- Solution of the Hierarchy Problem

$$m_H \sim v \sim 10^2 \text{ GeV} \qquad \frac{m_H}{m_\Sigma} \sim 10^{-14} \ll 1$$

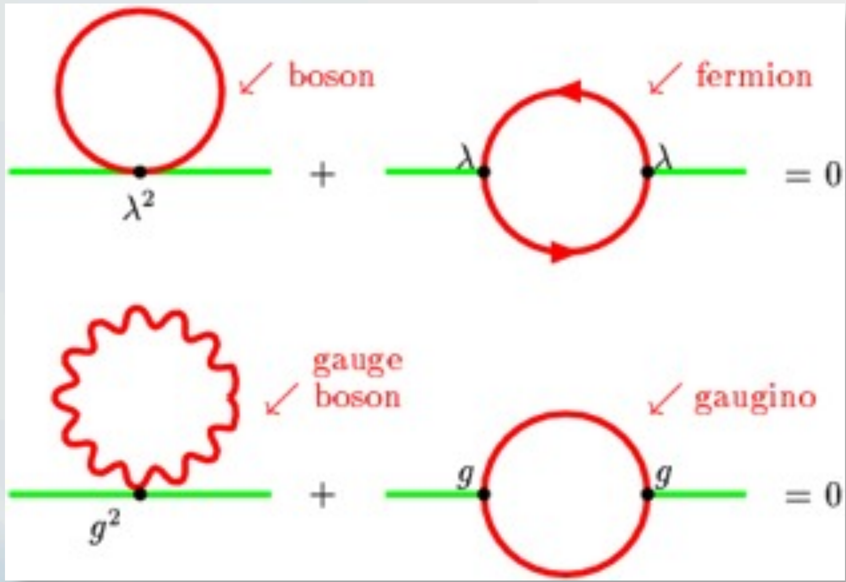
$$m_\Sigma \sim V \sim 10^{16} \text{ GeV}$$

Destruction of the hierarchy by radiative corrections



SUSY may also explain the origin of the hierarchy due to radiative mechanism

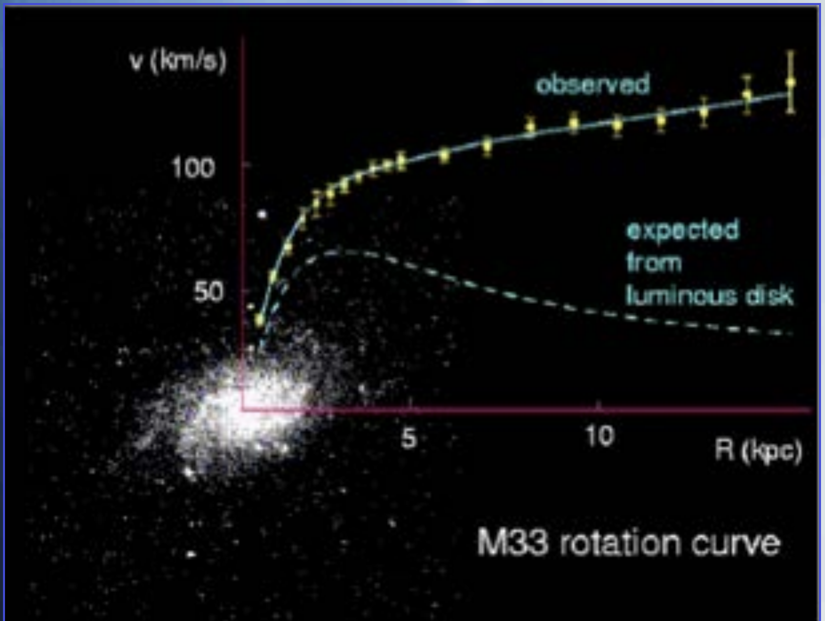
Cancellation of quadratic terms



$$\sum_{bosons} m^2 = \sum_{fermions} m^2$$

Motivation of SUSY

- Dark Matter in the Universe



The flat rotation curves of spiral galaxies provide the most direct evidence for the existence of large amount of the dark matter.

Spiral galaxies consist of a central bulge and a very thin disc, and surrounded by an approximately spherical halo of dark matter

SUSY provides a candidate for the Dark matter – a stable neutral particle

Cosmological Constraints

New precise cosmological data

$\Omega h^2 = 1 \quad \Longleftrightarrow \quad \rho = \rho_{crit}$

$\Omega_{vacuum} \approx 73\%$

$\Omega_{DarkMatter} \approx 23 \pm 4\%$

$\Omega_{Baryon} \approx 4\%$

•Supernova Ia explosion
• CMBR thermal fluctuations (measured by WMAP)

Dark Matter in the Universe:

→ Hot DM (not favoured by galaxy formation)

→ Cold DM (rotation curves of Galaxies) ← SUSY

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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

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

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

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

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

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

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

$$\theta \to \theta + \xi,$$

$$\bar\theta \to \bar\theta + \bar\xi$$

Quantum States

Quantum states: Vacuum = $|E,\lambda>$ $Q|E,\lambda>=0$

Energy (E), helicity (λ)

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

State	Expression	# of states
vacuum	$\|E,\lambda>$	1
1-particle	$\bar{Q}_i\|E,\lambda> = \|E,\lambda+1/2>$	$\binom{N}{1} = N$
2-particle	$\bar{Q}_i\bar{Q}_j\|E,\lambda> = \|E,\lambda+1>$	$\binom{N}{2} = \frac{N(N-1)}{2}$
...	...	...
N-particle	$\bar{Q}_1\bar{Q}_2...\bar{Q}_N\|E,\lambda> = \|E,\lambda+N/2>$	$\binom{N}{N} = 1$

Total # of states: $\sum_{k=0}^{N}\binom{N}{k} = 2^N = 2^{N-1}\, bosons + 2^{N-1}\, fermions$

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SUSY Multiplets

Chiral multiplet $\mathcal{N}=1,\ \lambda=0$

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

scalar spinor

(φ, ψ)

Vector multiplet $\mathcal{N}=1,\ \lambda=1/2$

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	

$\mathcal{N} \leq 4S$ ← spin

$\mathcal{N} \leq 4$ For renormalizable theories (YM)

$\mathcal{N} \leq 8$ For (super)gravity

Simplest (N=1) SUSY Multiplets

Bosons and Fermions come in pairs

(φ, ψ) (λ, A_μ) $(\tilde{g}, g)$

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

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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

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R-parity

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

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

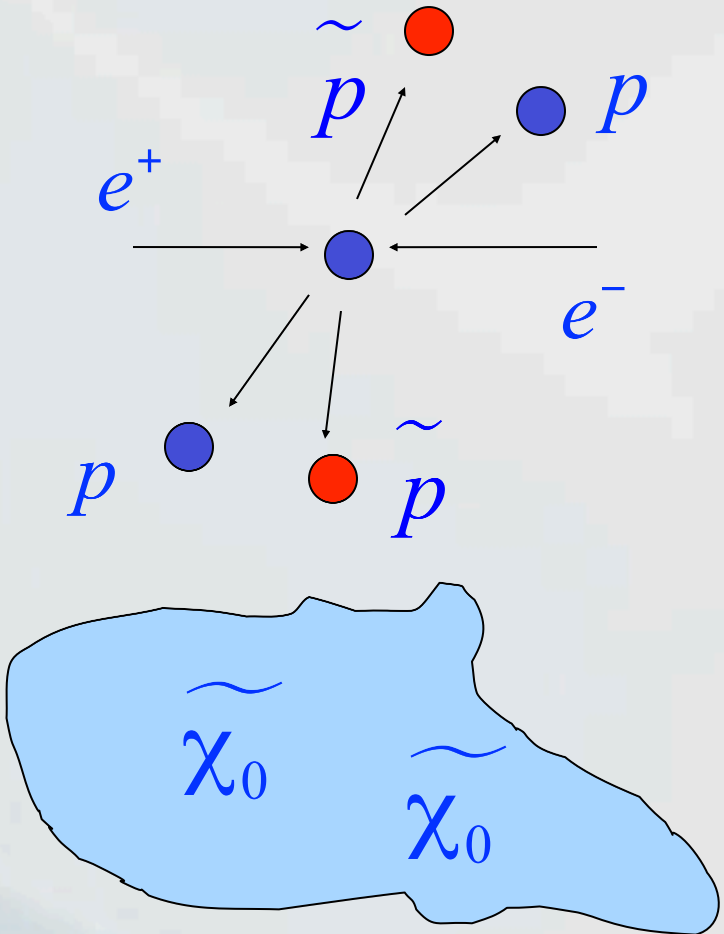
B - Baryon Number
L - Lepton Number
S - Spin

The consequences:

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

⬇

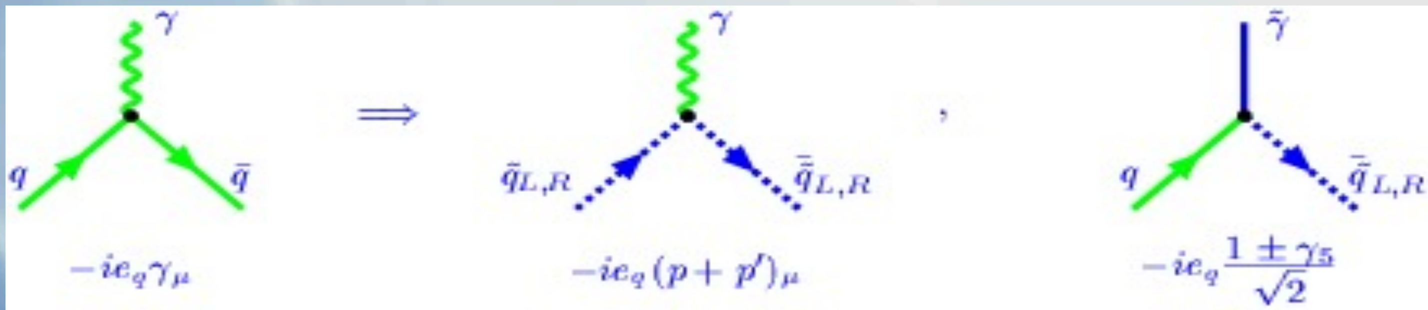
- The lightest superparticle (LSP) should be neutral - the best candidate is neutralino (photino or higgsino) $\tilde{\chi}_0$
- It can survive from the Big Bang and form the Dark matter in the Universe

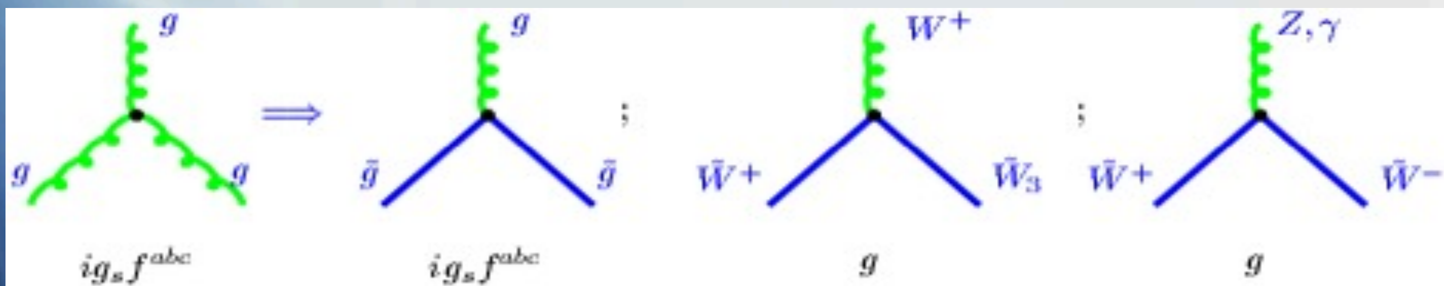


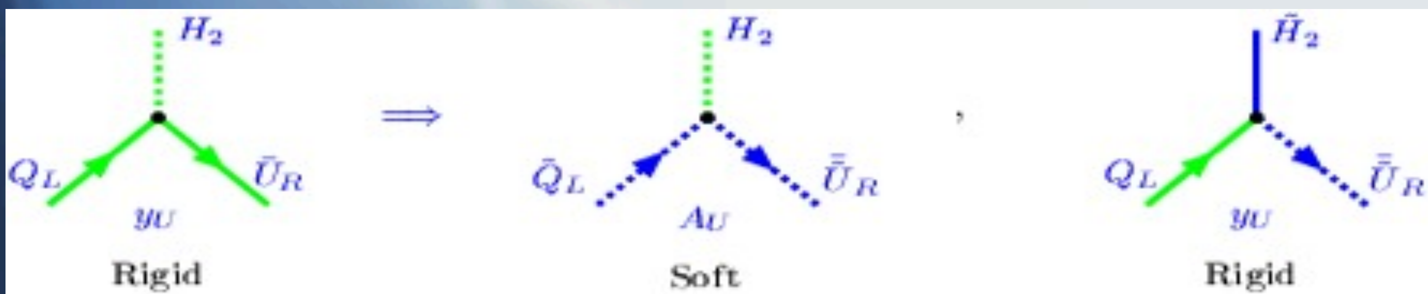
Interactions in the MSSM

SM → **MSSM**

Vertices

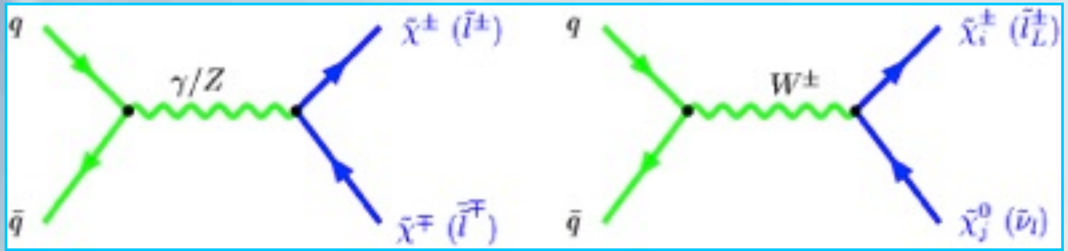




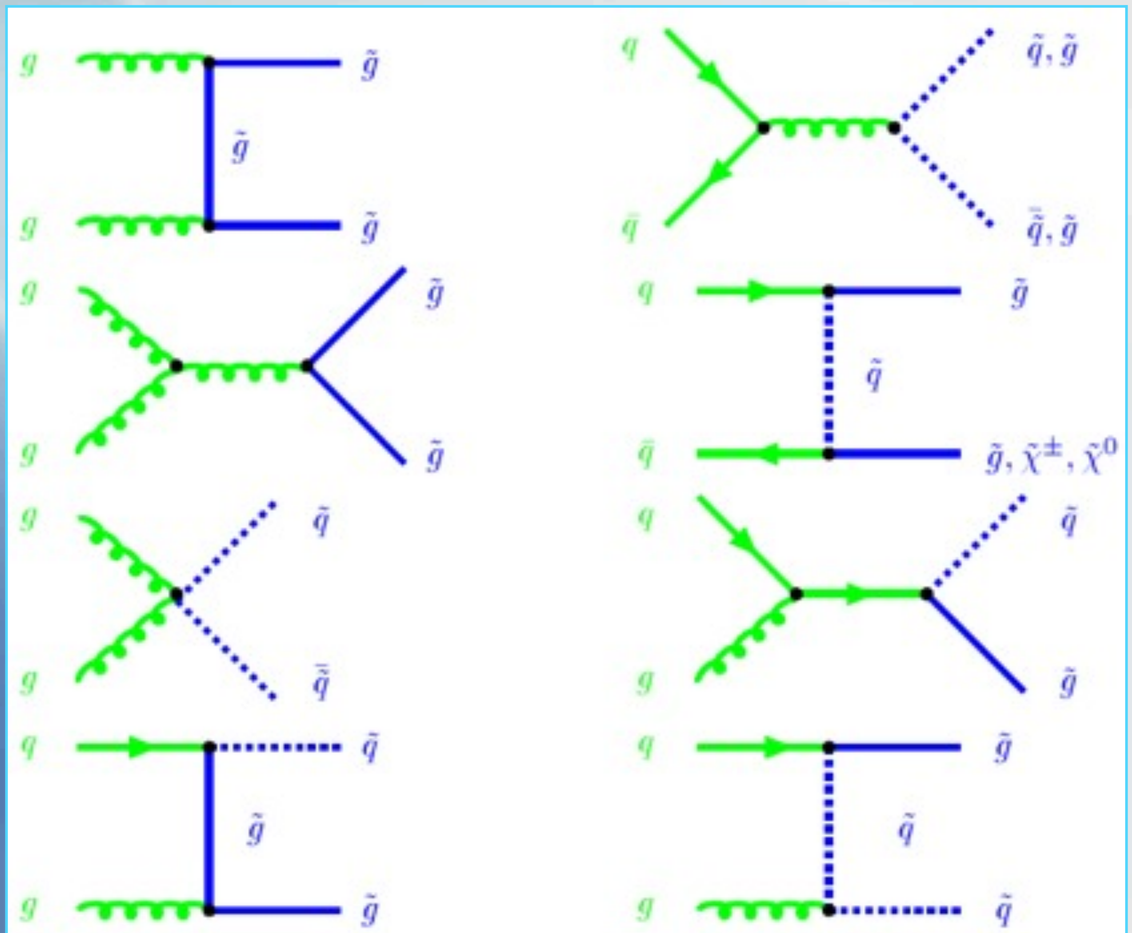


Superpartners Production at LHC

Annihilation



Quark- gluon Fusion



Decay of Superpartners

squarks

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

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

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

sleptons

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

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

chargino

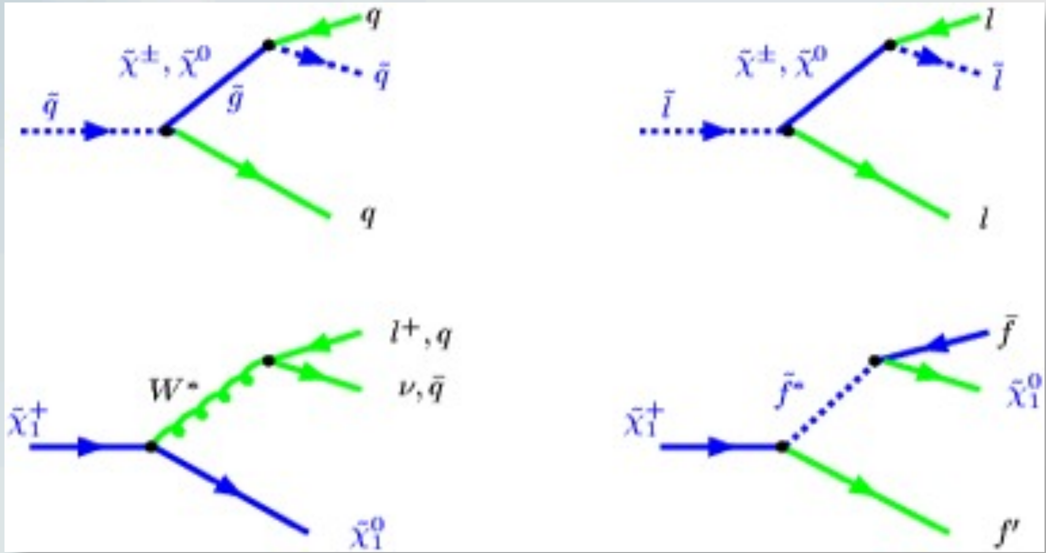
$$\tilde{\chi}_i^\pm \rightarrow e + \nu_e + \tilde{\chi}_i^0$$

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

gluino

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

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



neutralino

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

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

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

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

Final states

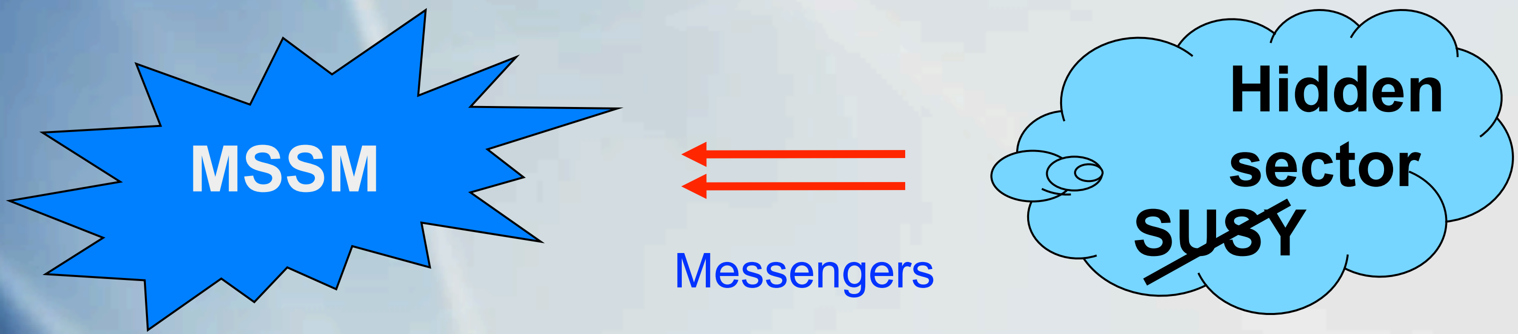
$l^+l^- + \not{E}_T$

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

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Mass Spectrum (spin=1/2)

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

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 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

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

MSSM

8=4+4=3+5

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

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

The Higgs Potential

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

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

Minimization

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

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

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

Solution

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

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

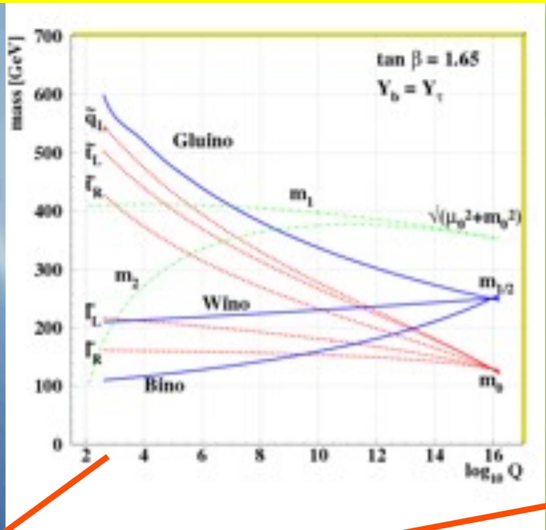
At the GUT scale

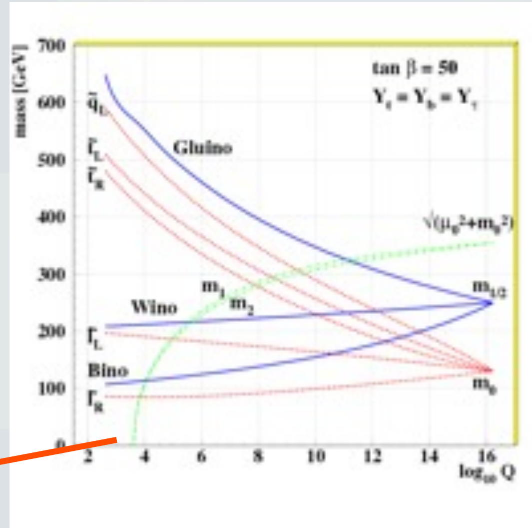
$$v^2 = -\frac{4}{g^2+g'^2}m^2 < 0$$

No SSB in SUSY theory !

Radiative EW Symmetry Breaking

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





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

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

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

Soft SUSY parameters

⇒ $\mu \sim 1$ 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* $\to Z_0$
$A = \sin\beta\, P_1 + \cos\beta\, P_2$	*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

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

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

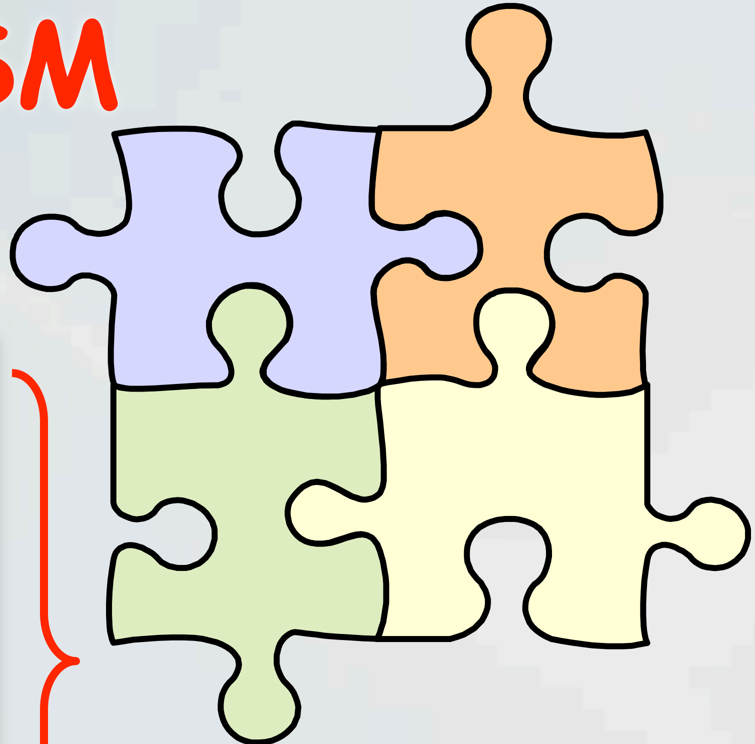
Radiative corrections

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

Constrained MSSM

Requirements:

- Unification of the gauge couplings
- Radiative EW Symmetry Breaking
- Heavy quark and lepton masses
- Rare decays (b -> sγ, b->μμ)
- Anomalous magnetic moment of muon
- LSP is neutral
- Amount of the Dark Matter
- Experimental limits from direct search



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

Allowed region in the parameter space of the MSSM

$$100\ \text{GeV} \le m_0, M_{1/2}, \mu \le 2\ \text{TeV}$$

$$-3m_0 \le A_0 \le 3m_0,\ 1 \le \tan\beta \le 70$$

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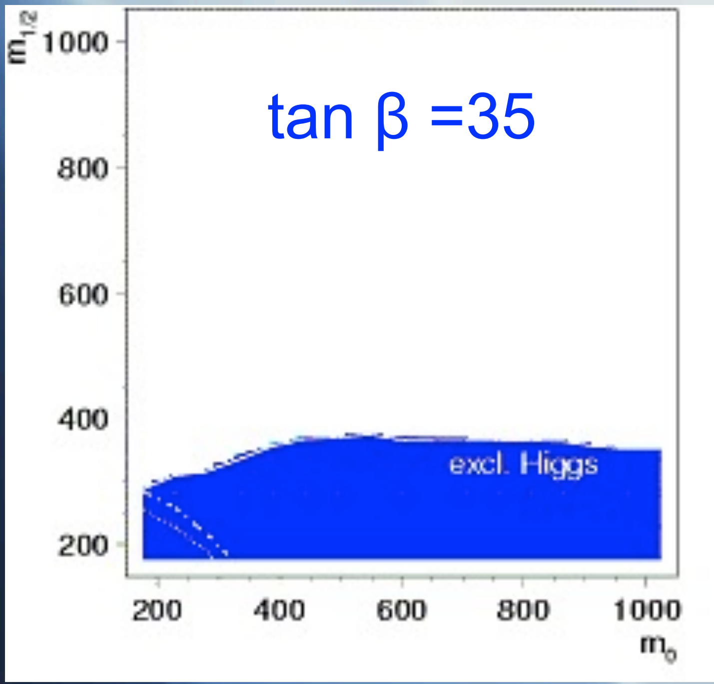
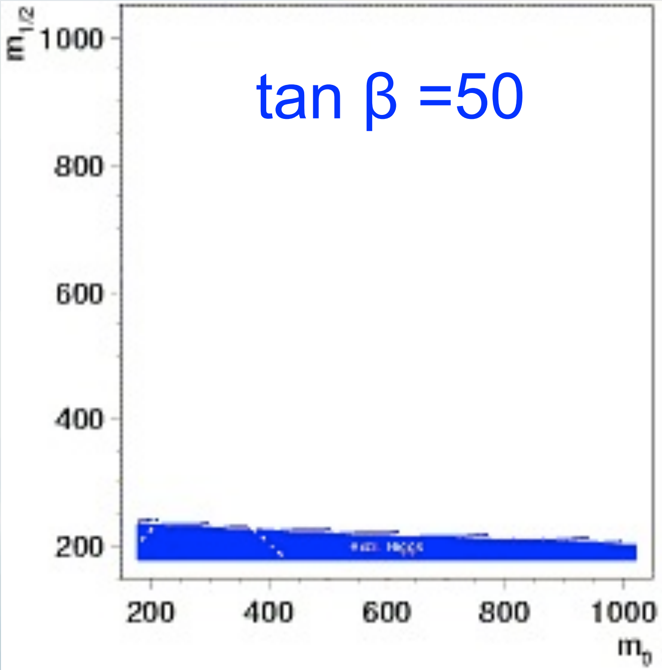
Constrained MSSM (Choice of constraints)

Experimental lower limits on Higgs and superparticle masses

Regions excluded by Higgs experimental limits provided by LEP2

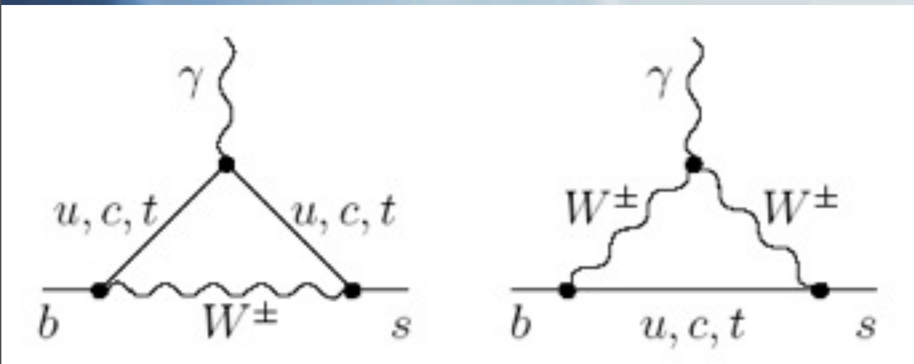
$$m_{Higgs} \geq 114.3 \text{ GeV}$$

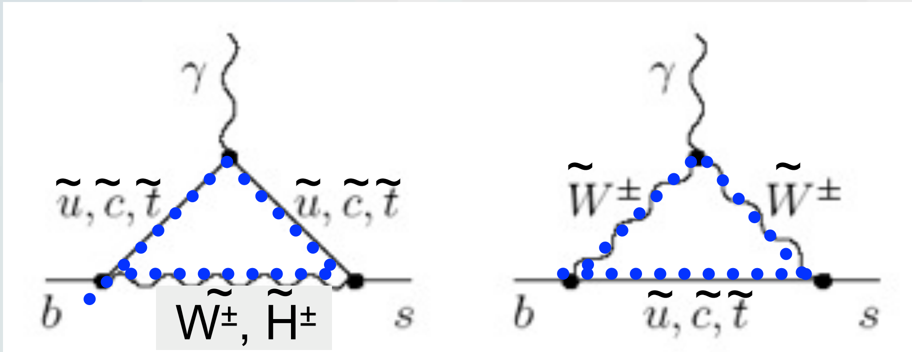




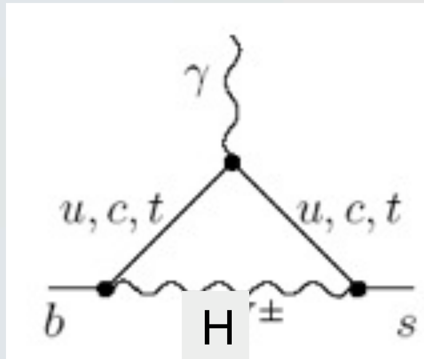
B->sγ decay rate

Standard Model | **MSSM**





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



MSSM

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

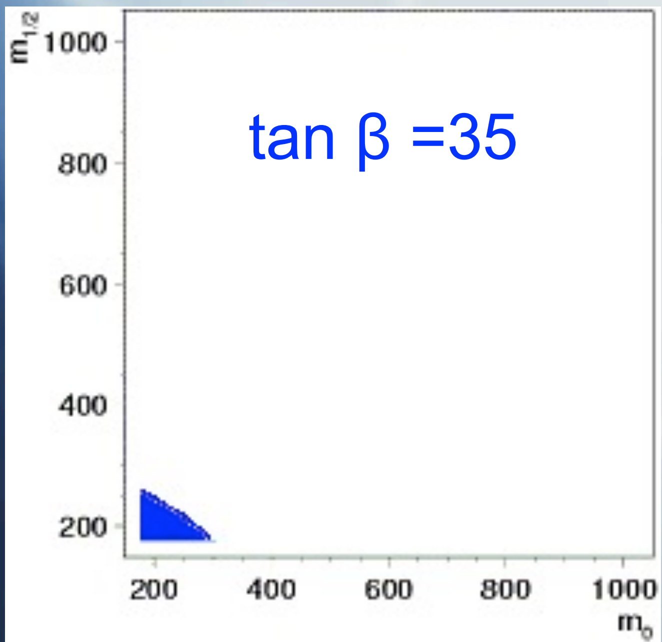
Experiment $B(B \to X_s\gamma) = (3.43 \pm 0.36) \times 10^{-4}$ 34

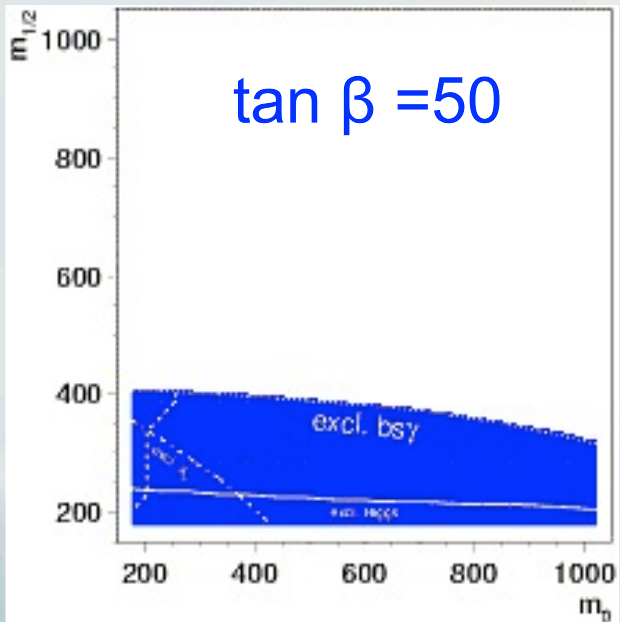
Constrained MSSM (Choice of constraints)

Data on rare processes branching ratios

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

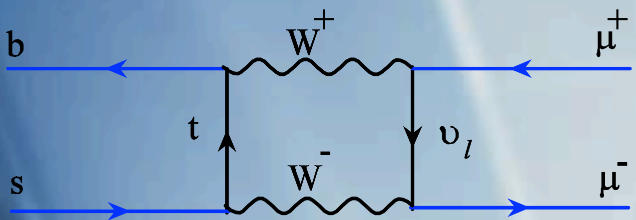
Regions excluded by experimental limits (for large tanβ)





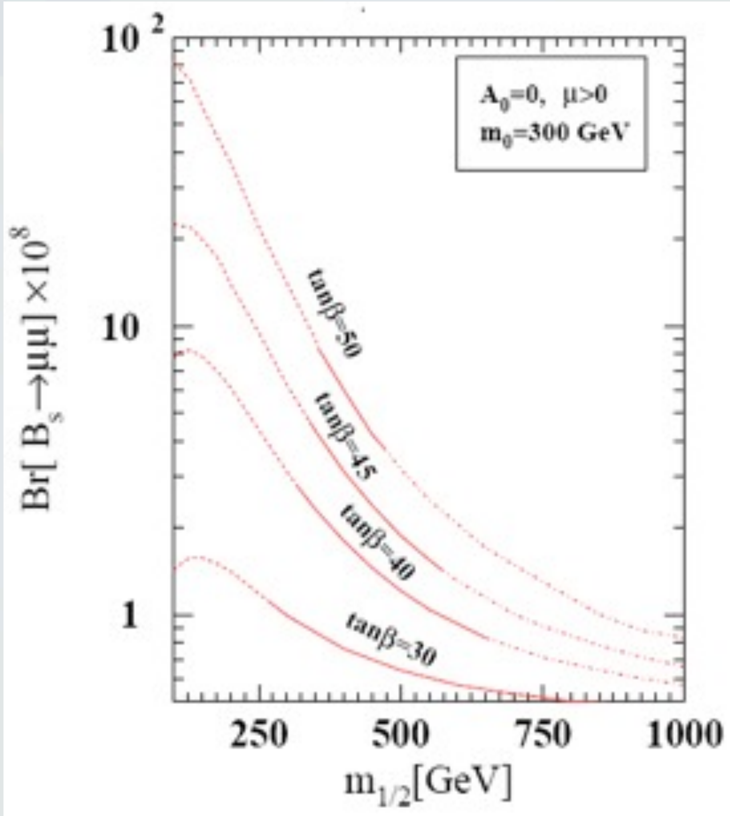
Rare Decay Bs → $\mu + \mu -$

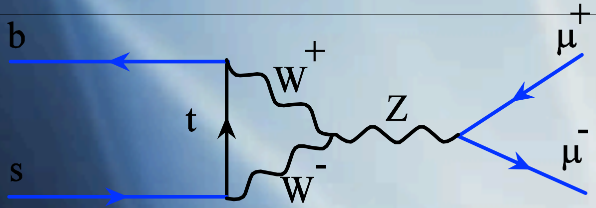
SM



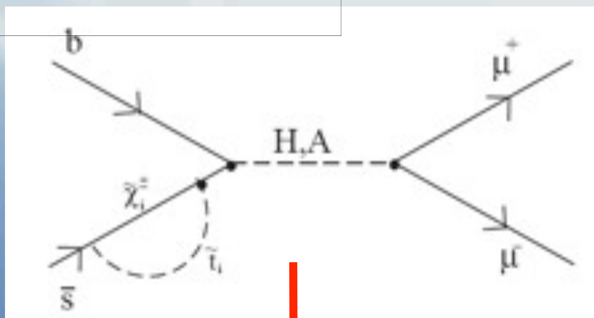
SM: Br=$3.5 \cdot 10^{-9}$

Ex: <$4.5 \cdot 10^{-8}$





Main SYSY contribution



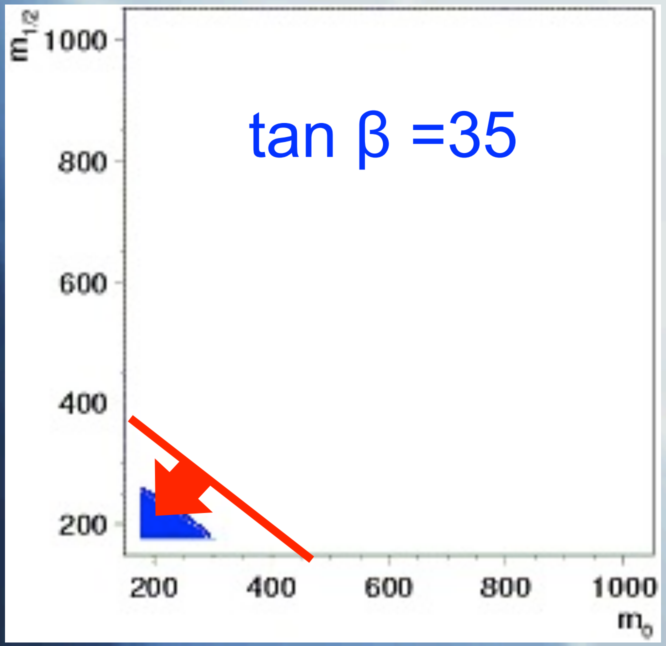
$$Br[B_s \to \mu^+\mu^-] \sim \left| \frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* \left(\frac{\tan^3 \beta}{4 \sin^2 \theta_W} \right) \left(\frac{m_b m_\mu m_t \mu}{M_W^2 M_A^2} \right) \frac{\sin 2\theta_{\tilde{t}}}{2} \left(\frac{m_{\tilde{t}_1}^2 \log\left[\frac{m_{\tilde{t}_1}^2}{\mu^2}\right]}{\mu^2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

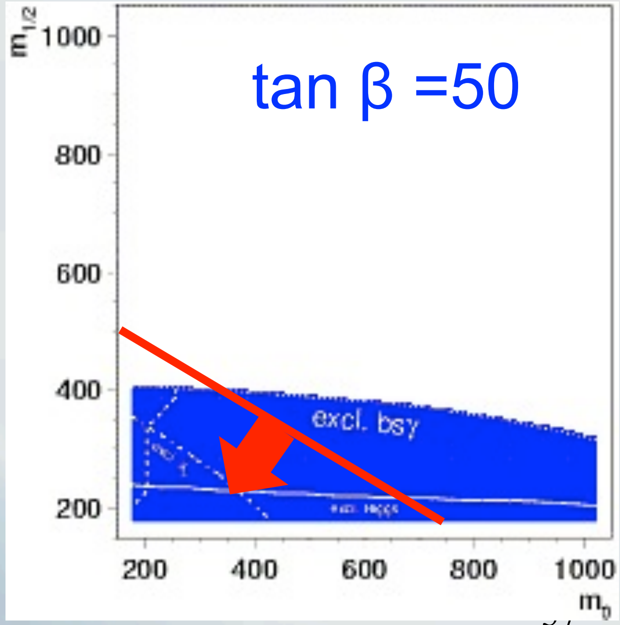
Constrained MSSM (Choice of constraints)

Data on rare processes branching ratios

$$\mathbf{B(B_s \to \mu^+\mu^-) < 3.7 \times 10^{-7}}$$

Regions excluded by experimental limits (for large tanβ)





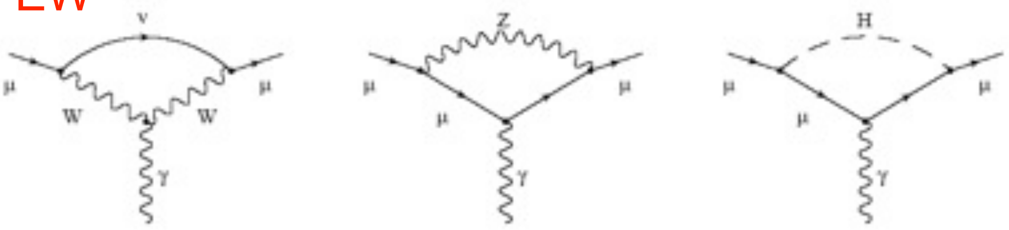
Anomalous magnetic moment

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

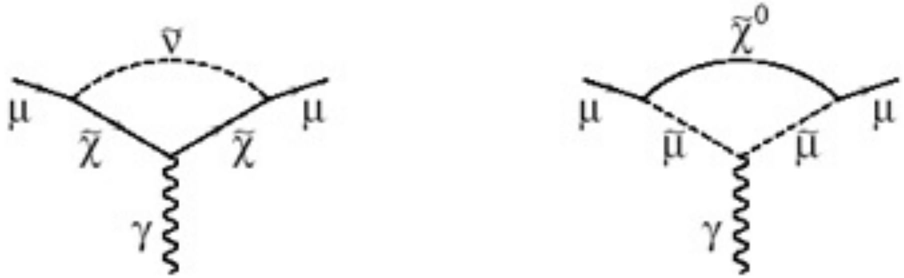
$$a_\mu^{exp} - a_\mu^{SM} = (27 \pm 10)\cdot 10^{-10}$$

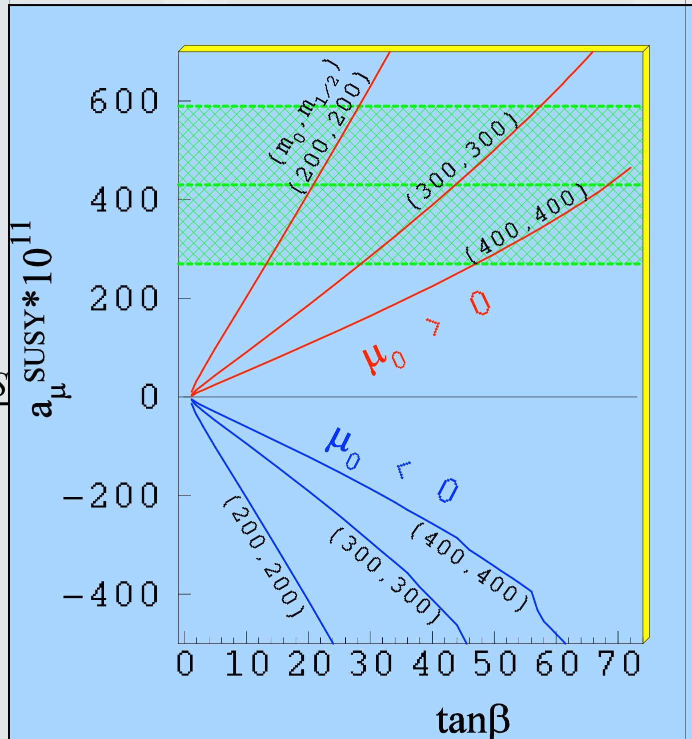
$$a_\mu^{QED} = 11\,658\,470.56\,(0.29)\cdot 10^{-10}$$
$$a_\mu^{weak} = 15.1\,(0.4)\cdot 10^{-10}$$
$$a_\mu^{hadr} = 673.9\,(6.7)\cdot 10^{-10}$$

EW



$$|a_\mu^{SUSY}| \simeq \frac{\alpha(M_Z)}{8\pi\, Sin^2\theta_W}\frac{m_\mu^2}{M_{SUSY}^2}\tan\beta\left(1-\frac{4\alpha}{\pi}\log\frac{M_{SUS\ldots}}{m_\mu}\ldots\right)\ldots\beta$$





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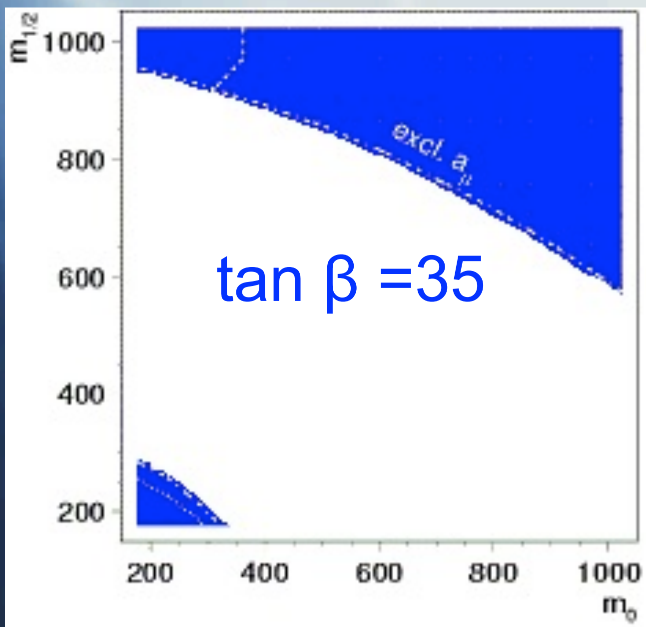
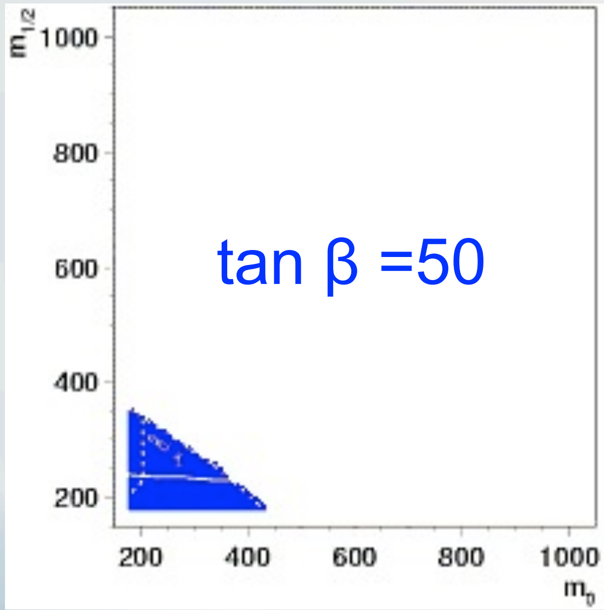
Constrained MSSM (Choice of constraints)

Muon anomalous magnetic moment

$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{th} = (27 \pm 10) \cdot 10^{-10}$$

Regions excluded by muon amm constraint





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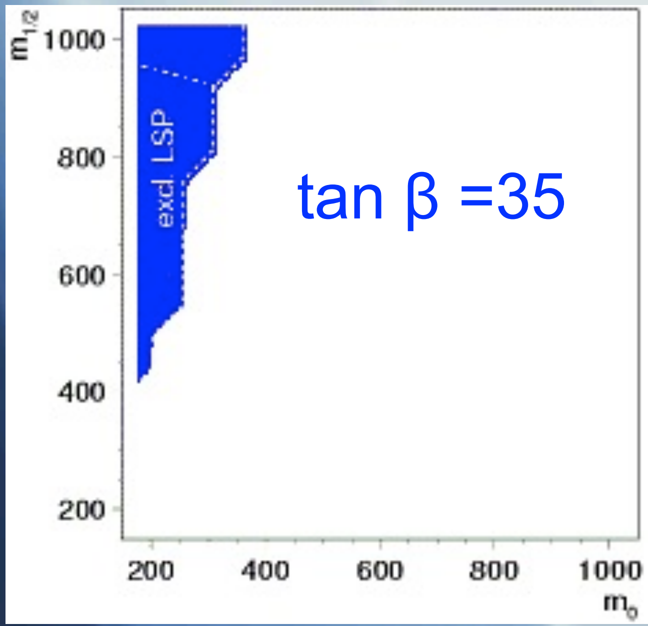
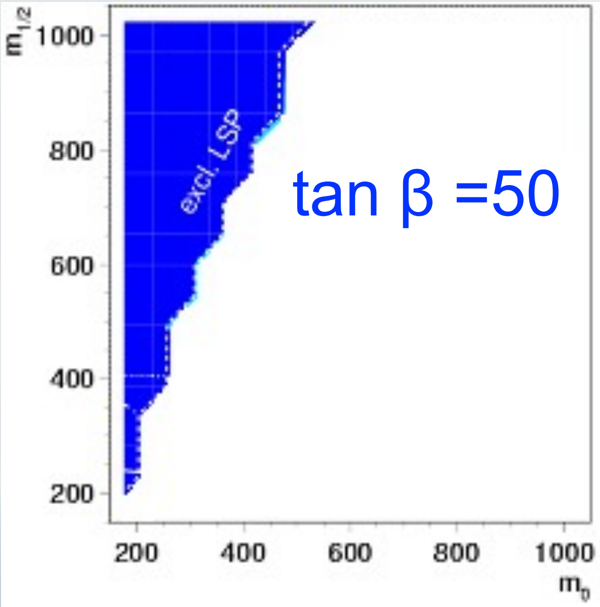
Constrained MSSM (Choice of constraints)

The lightest supersymmetric particle (LSP) is neutral.

This constraint is a consequence of *R*-parity conservation requirement

Regions excluded by LSP constraint





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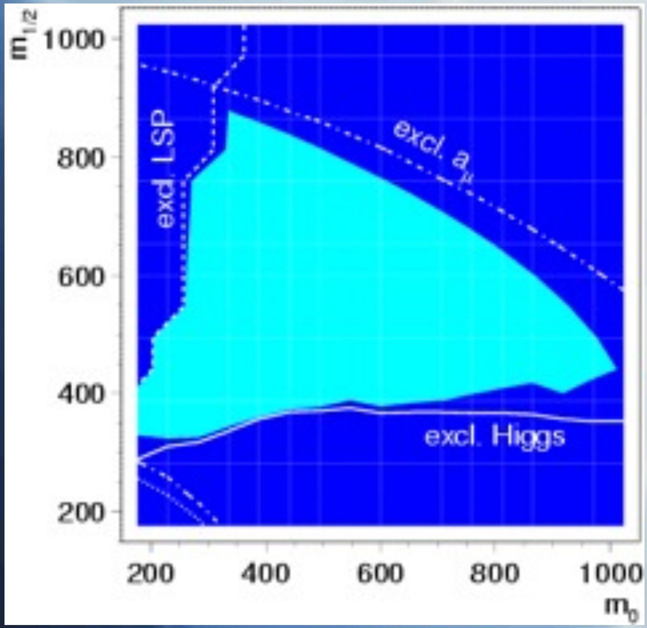
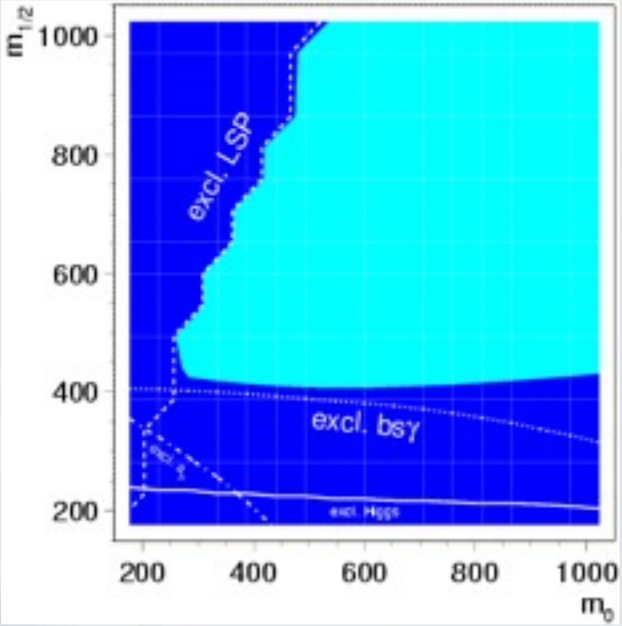
Favoured regions of parameter space (mSUGRA)

Pre-WMAP allowed regions in the parameter space.

From the Higgs searches tan β >4, from a_μ measurements μ >0



tan β =35



tan β =50

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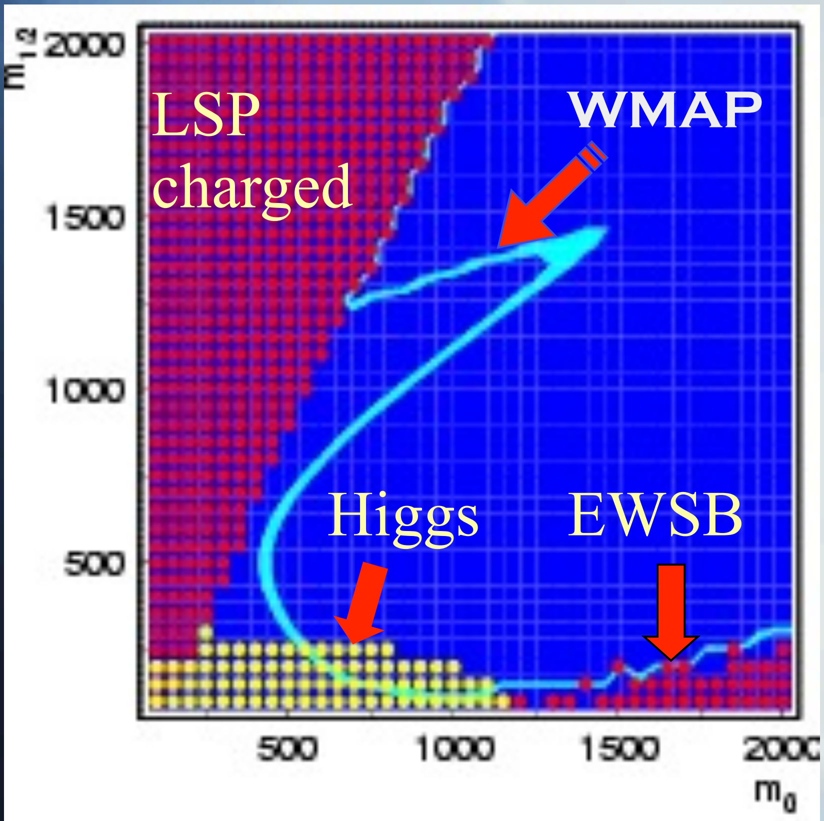
Allowed regions after WMAP



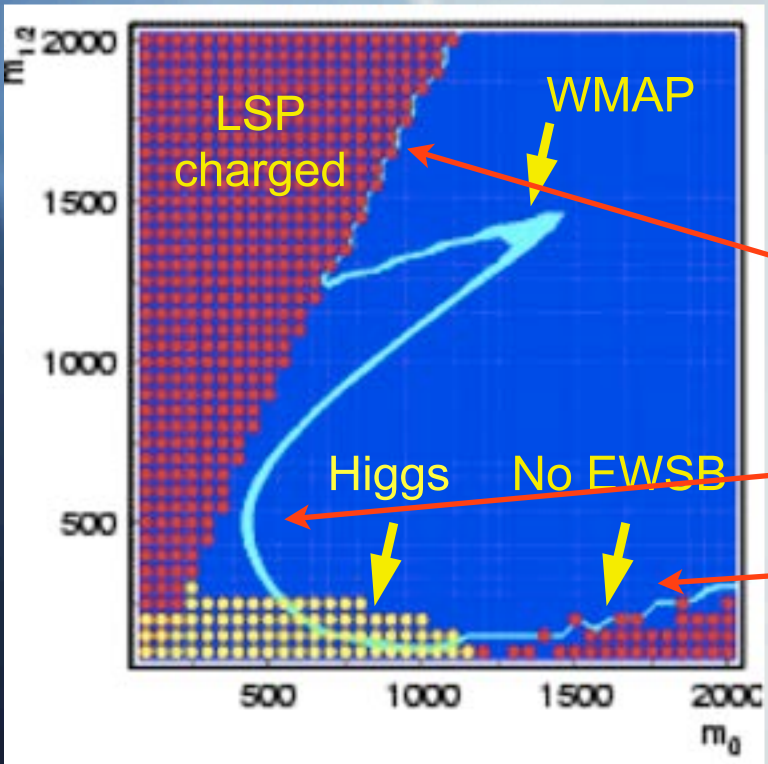
tan β =50

In allowed region one fulfills all the constraints simultaneously and has the suitable amount of the dark matter

Narrow allowed region enables one to predict the particle spectra and the main decay patterns

Phenomenology essentially depends on the region of parameter space and has direct influence on the strategy of SUSY searches

Long-lived Superparticles



The reason for long life-time is mass degeneracy with the LSP

Long-lived $\tilde{\tau}$

Long-lived $\tilde{t}$

Long-lived $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$

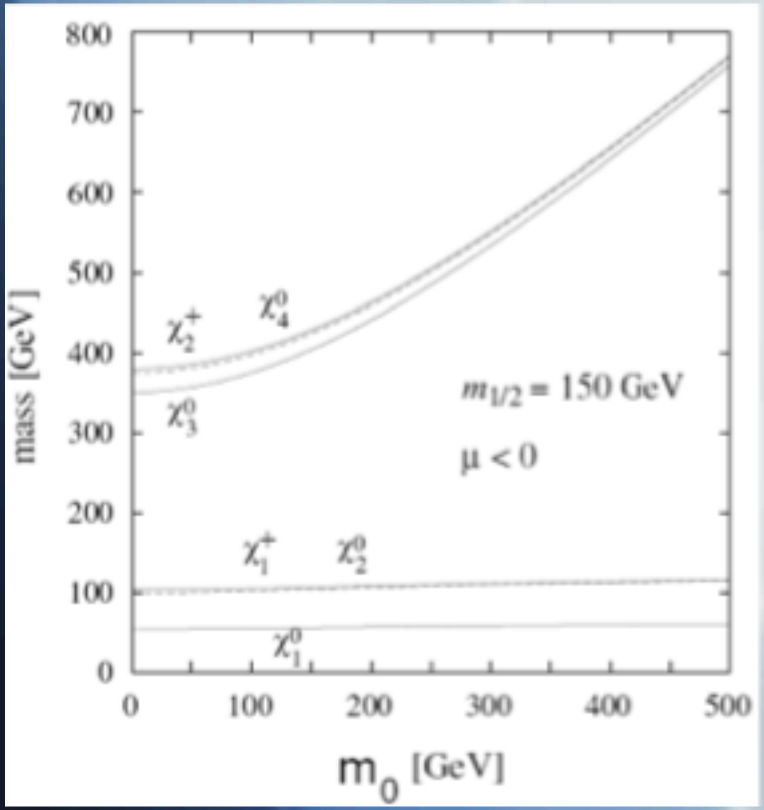
Life-time ~ 10^{-10} sec, M ~ 100 GeV

Decayses in a secondary vertex or flyes through detector

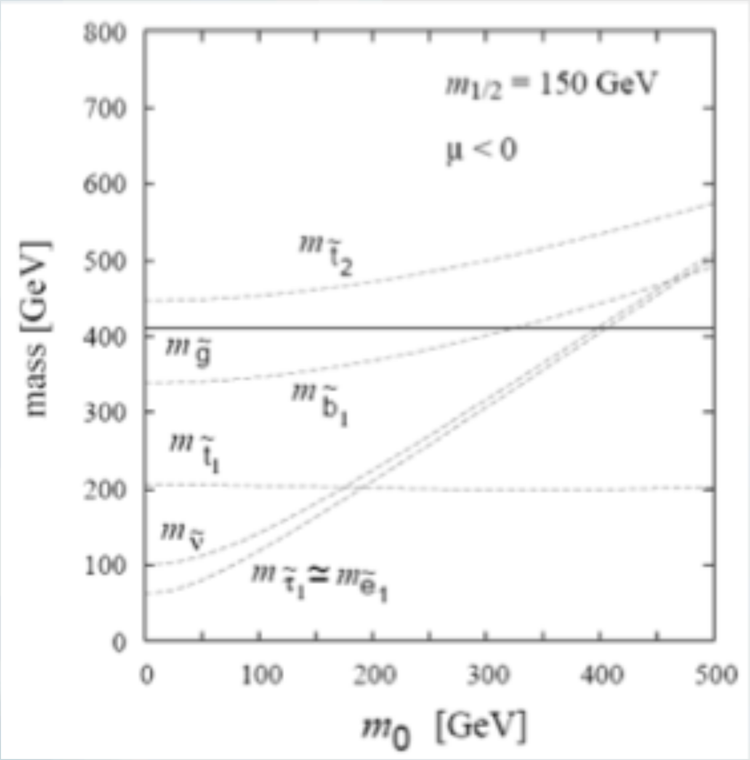
Requires fine-tuning of parameters !

SUSY Masses in MSSM

Gauginos+Higgsinos



Squarks and Sleptons



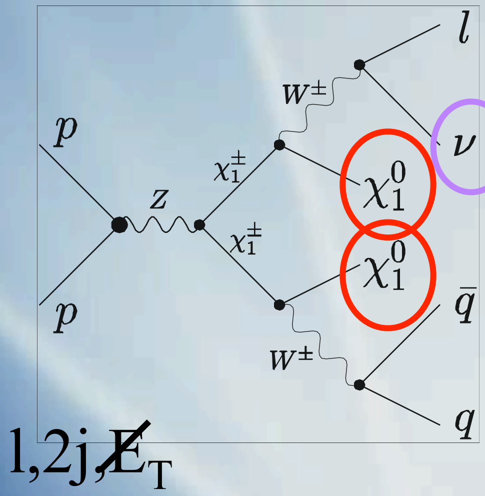
The Lightest Superparticle

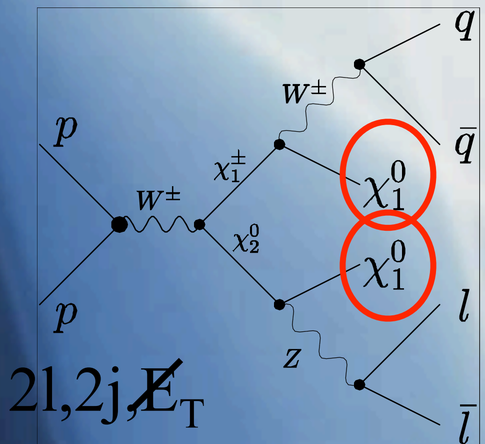
		property	signature
• Gravity mediation	$LSP = \tilde{\chi}_1^0$	stable	jets/leptons $+ \not{E}_T$
• Gauge mediation	$LSP = \tilde{G}$	stable	$\not{E}_T$
	$NLSP = \tilde{\chi}_1^0$	$\tilde{\chi}_1^0 \to \gamma\tilde{G}, h\tilde{G}, Z\tilde{G}$	photons/jets $+ \not{E}_T$
	$NLSP = \tilde{l}_R$	$\tilde{l}_R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

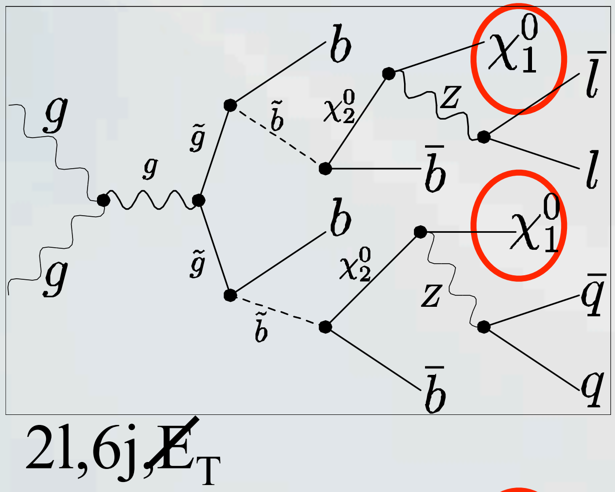
Creation and Decay of Superpartners in Cascade Processes @ LHC

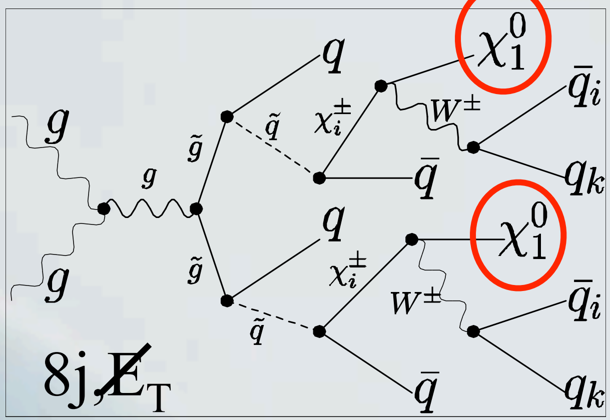
weak int's





Strong int's

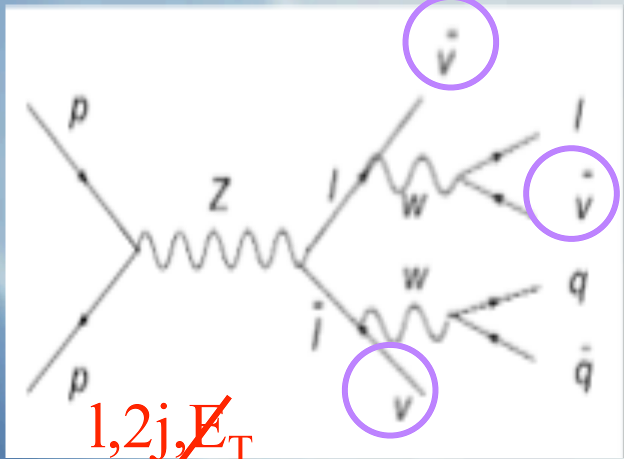


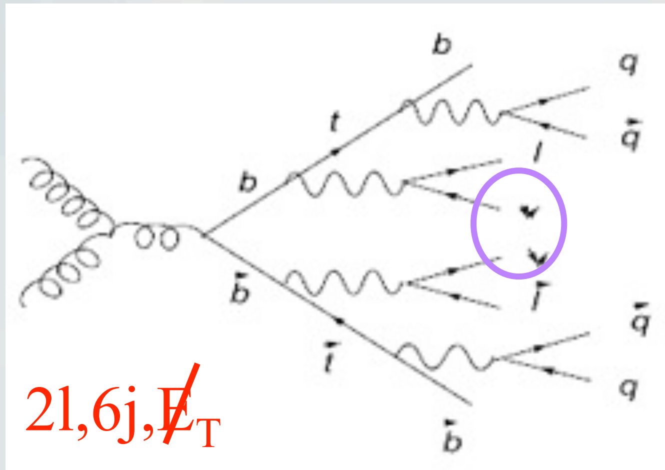


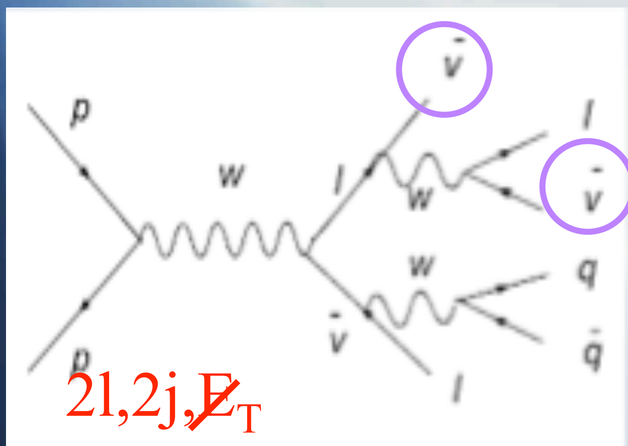
Typical SUSY signature: Missing Energy and Transverse Momentum

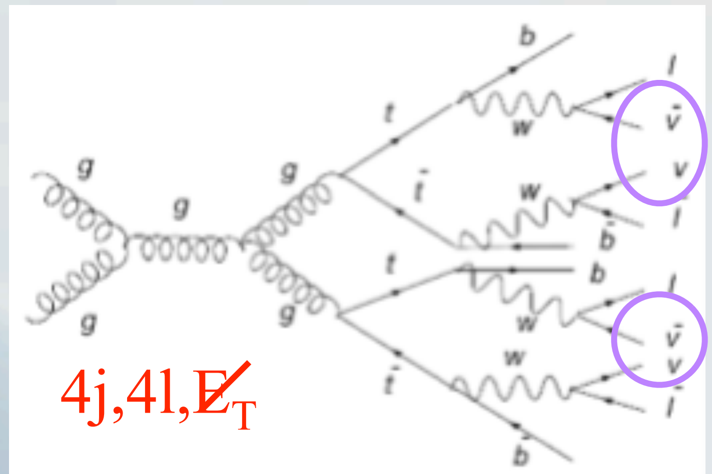
Background Processes of the SM for creation of Superpartners

weak int's









Strong int's

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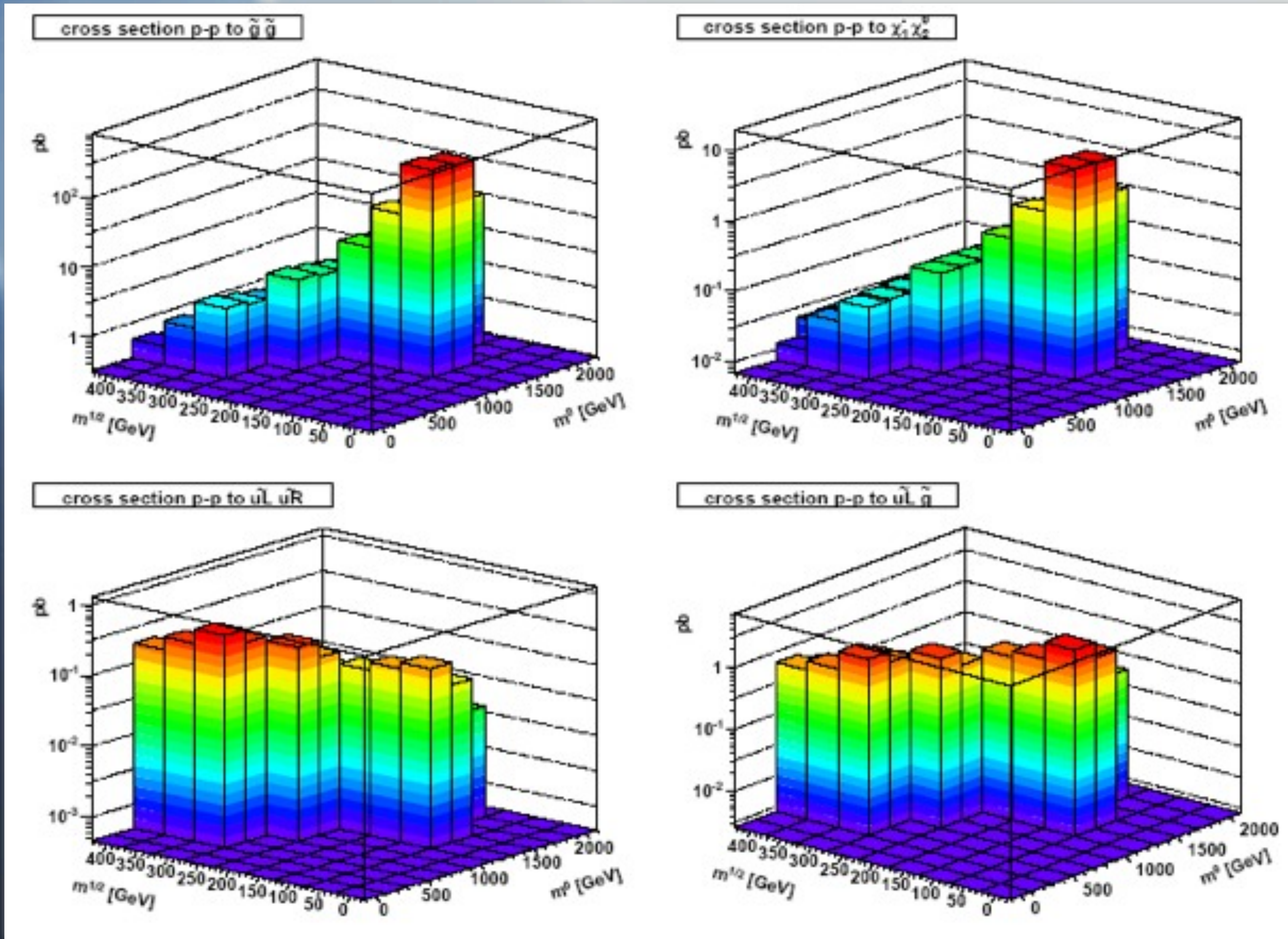
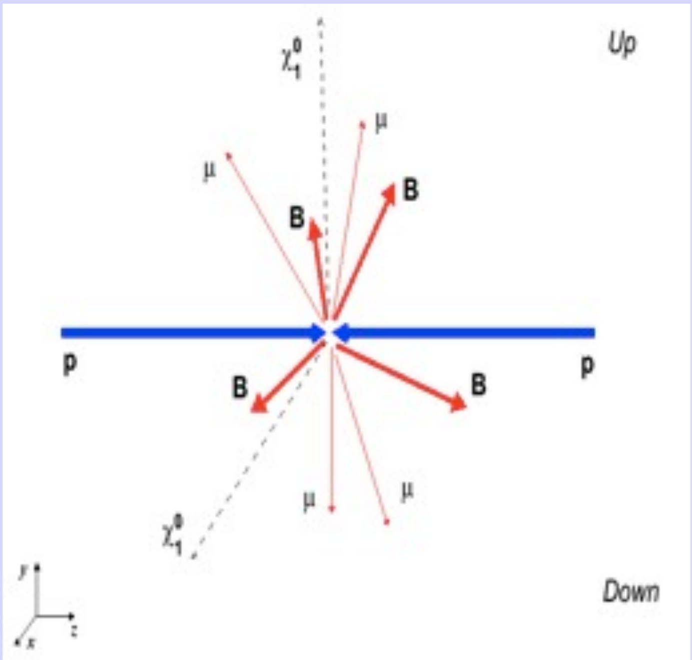
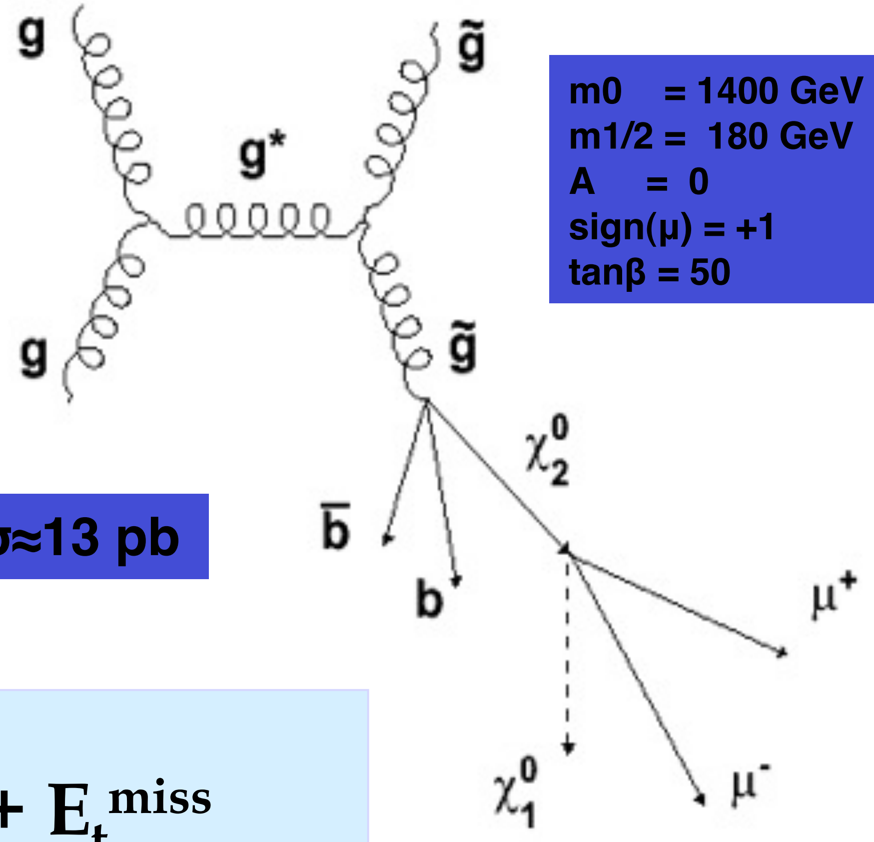
Cross-Sections at LHC



SUSY Production AT LHC





m0 = 1400 GeV
m1/2 = 180 GeV
A = 0
sign(μ) = +1
tanβ = 50

σ≈13 pb

SIGNATURE:
4 b-jets + 4 muons + E_t^{miss}

LARGE!

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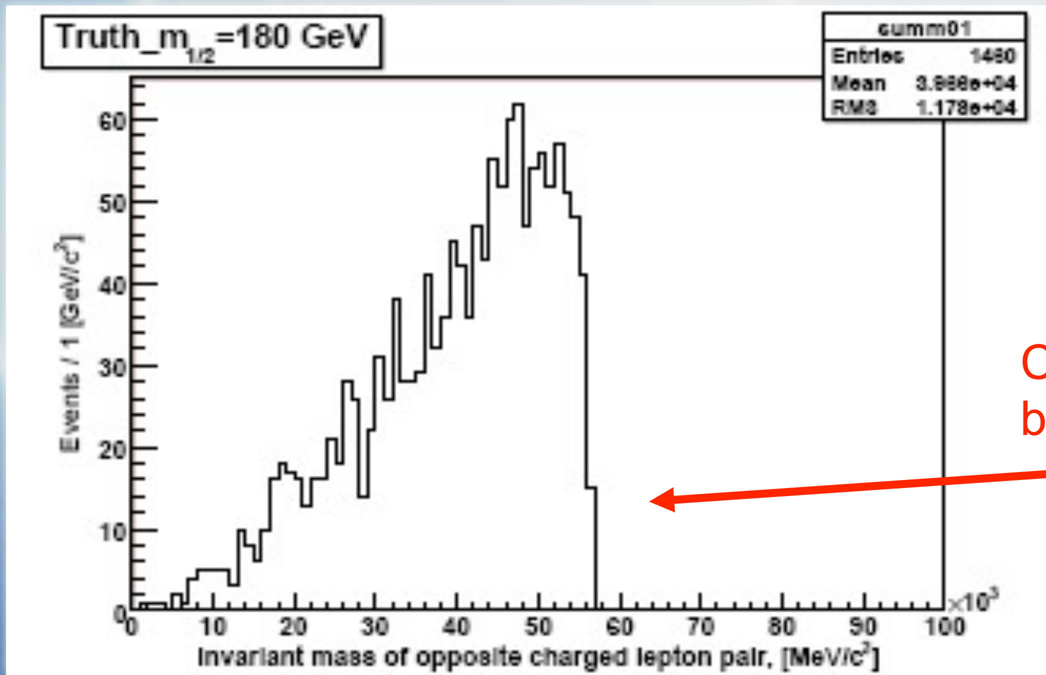
SUSY Signal @ LHC

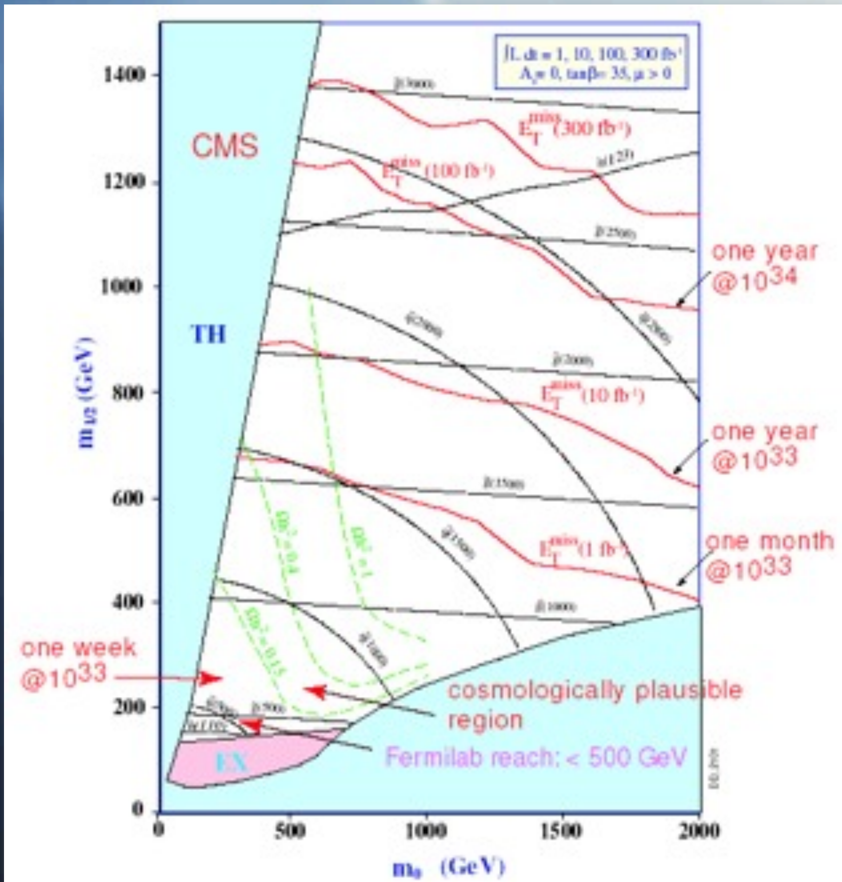


Clear end-point behaviour

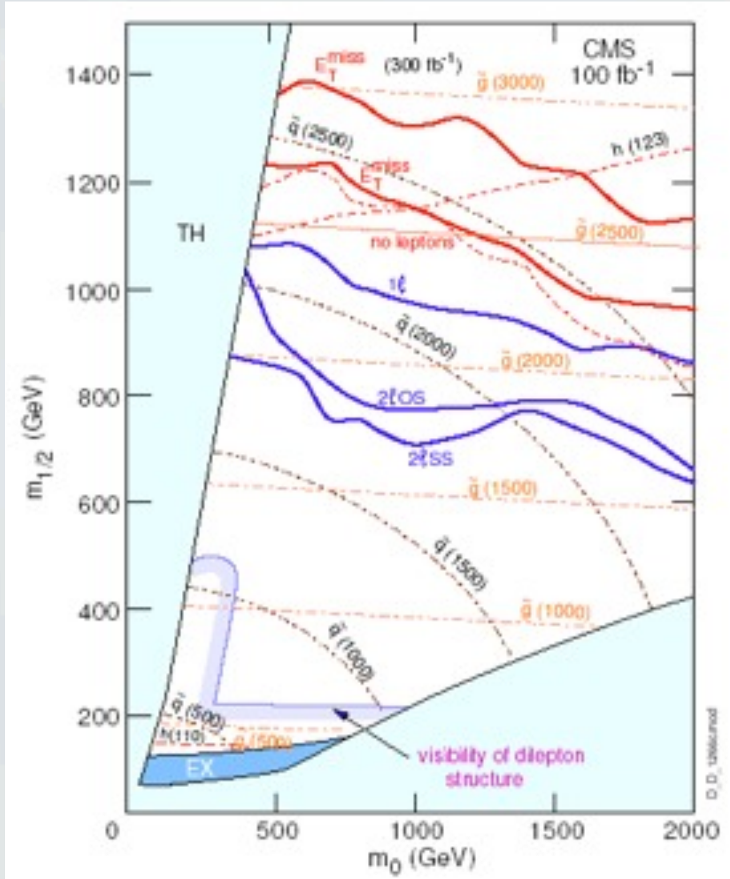
Important to distinguish true from false events

Invariant mass distribution of OS charged lepton pair

Search for Supersymmetry @ LHC



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



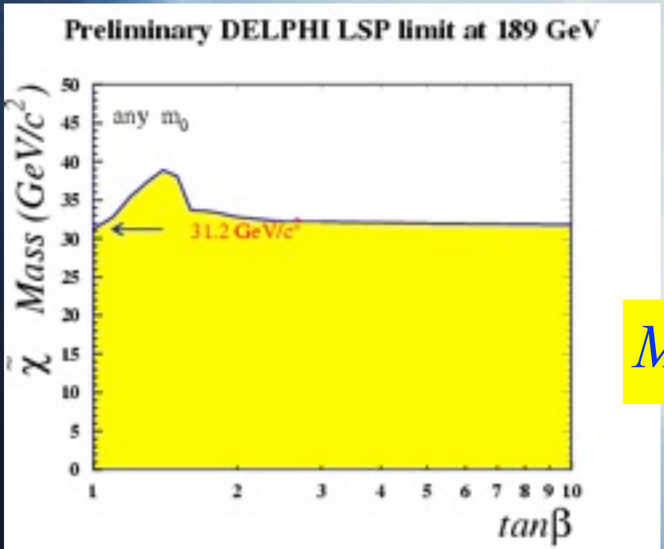
Reach limits for various channels at 100 fb $^{-1}$

SUSY Dark Matter

Neutralino = SUSY candidate for the cold Dark Matter
Neutralino = the Lightest Superparticle (LSP) = WIMP

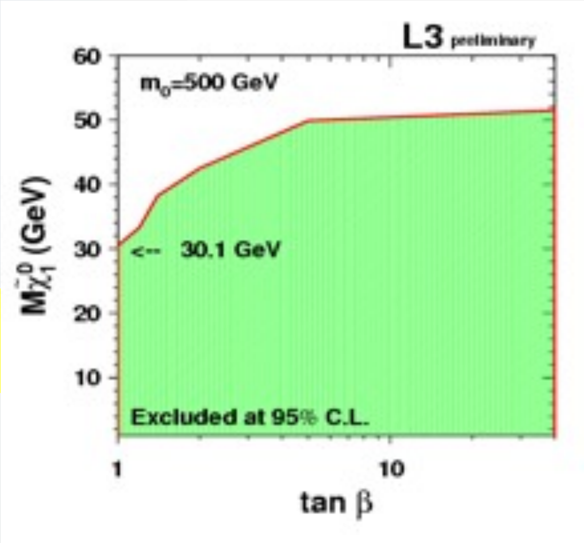
$$\tilde{\chi}^0 = N_1 \tilde{\gamma} + N_2 \tilde{z} + N_3 \tilde{H}_1^0 + N_4 \tilde{H}_2^0$$

photino zino higgsino higgsino



$$M_\chi^{exp} \geq 40 \text{ GeV}$$

$$M_\chi^{theor} = 40 \div 400 \text{ GeV}$$



$$R = (-1)^{3(B-L)+2S}$$

$$R_p = +1, \; R_{\tilde{p}} = -1$$

- **Superparticles are created in pairs**
- **The lightest superparticle is stable**

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

Evidence of DM annihilation!

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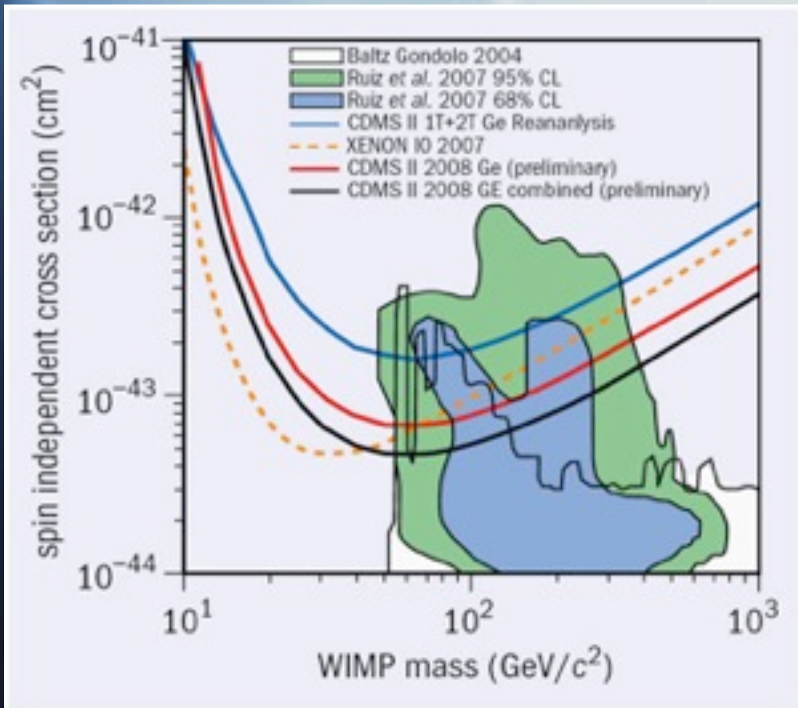
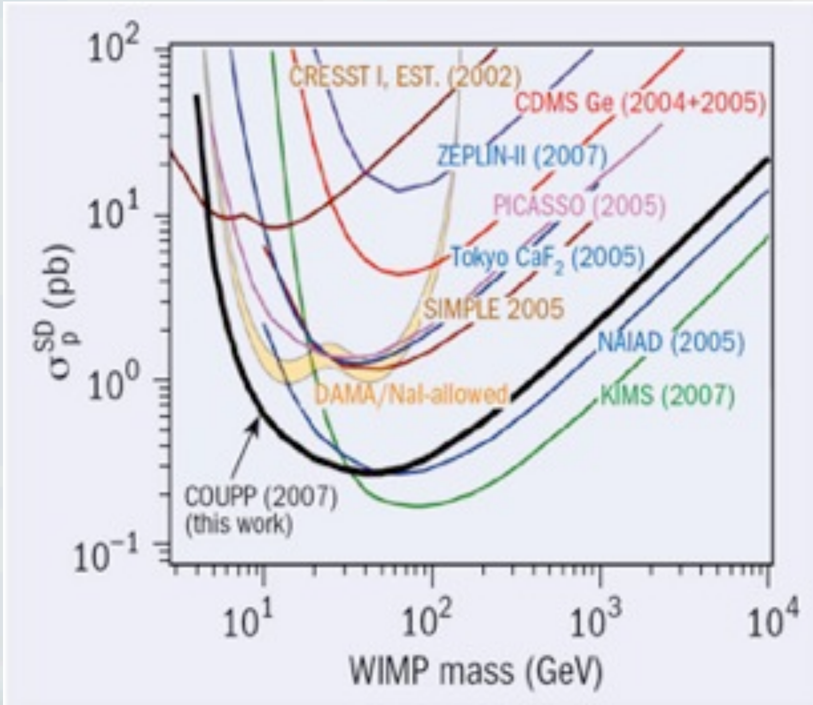
Recent Results on Direct Detection

Spin Independent



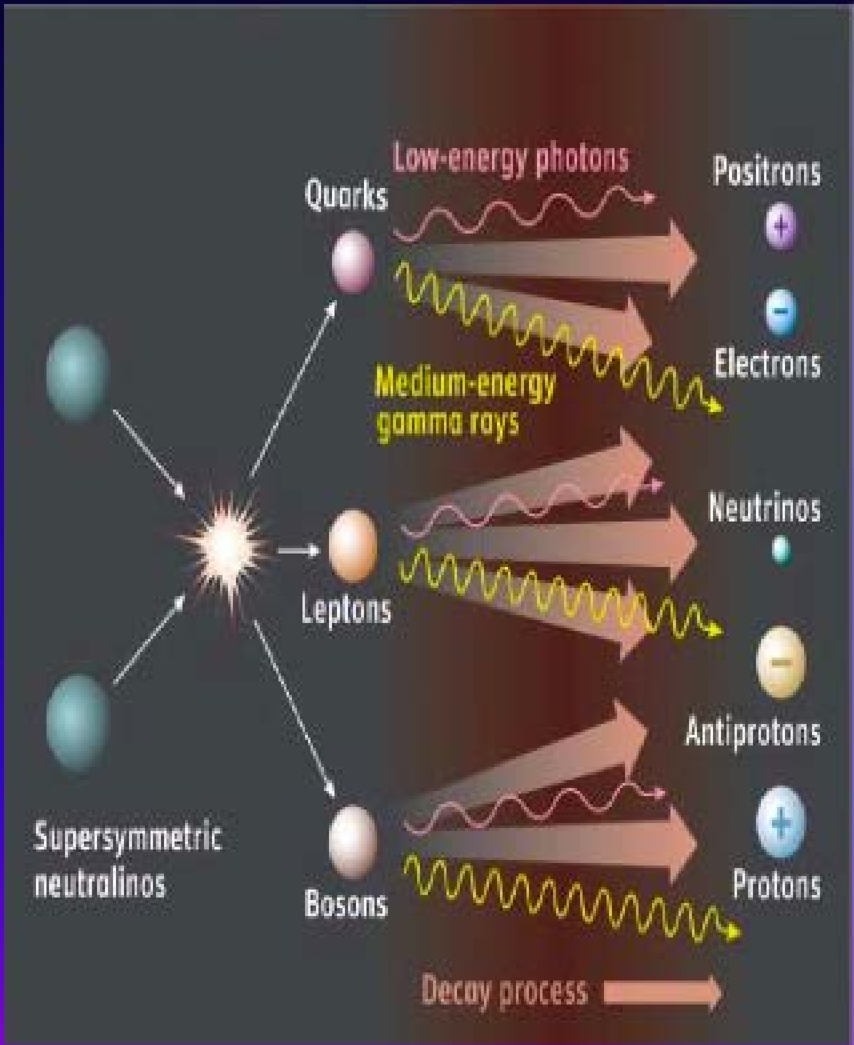
The Chicagoland Observatory for Underground Particle Physics (COUPP)

Spin Dependent



Cryogenic Dark Matter Search (CDMS)

Dark Mattter Annihilation



Annihilation products from dark matter annihilation:

Gamma rays
(EGRET, FERMI)

Positrons (PAMELA)

Antiprotons (PAMELA)

e+ + e-
(ATIC, FERMI, HESS, PAMELA)

Neutrinos (Icecube, no results yet)

e-, p drown in cosmic rays?

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

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

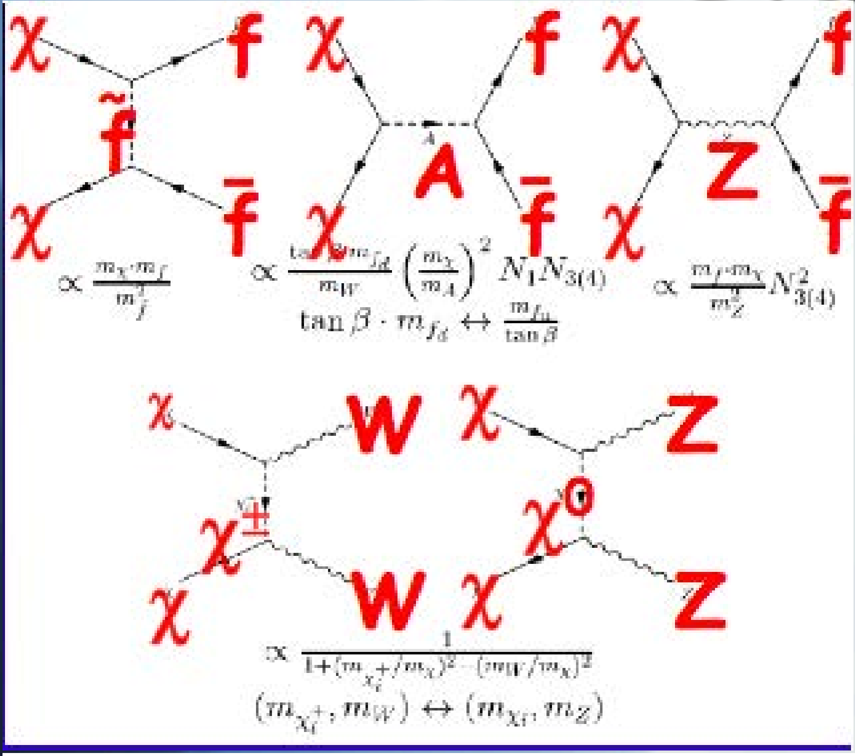
$$\Omega_\chi h^2 \sim 0.113 \pm 0.009,$$

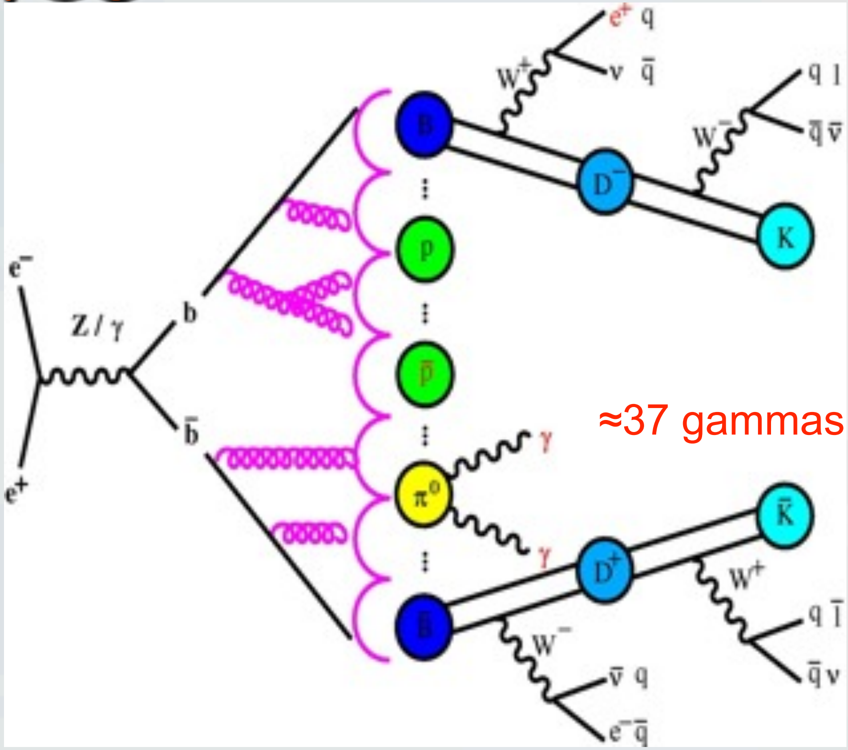
$$v \sim 300\ km/\sec$$

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

Typical EW x-section

DM Neutralino Annihilation Final States

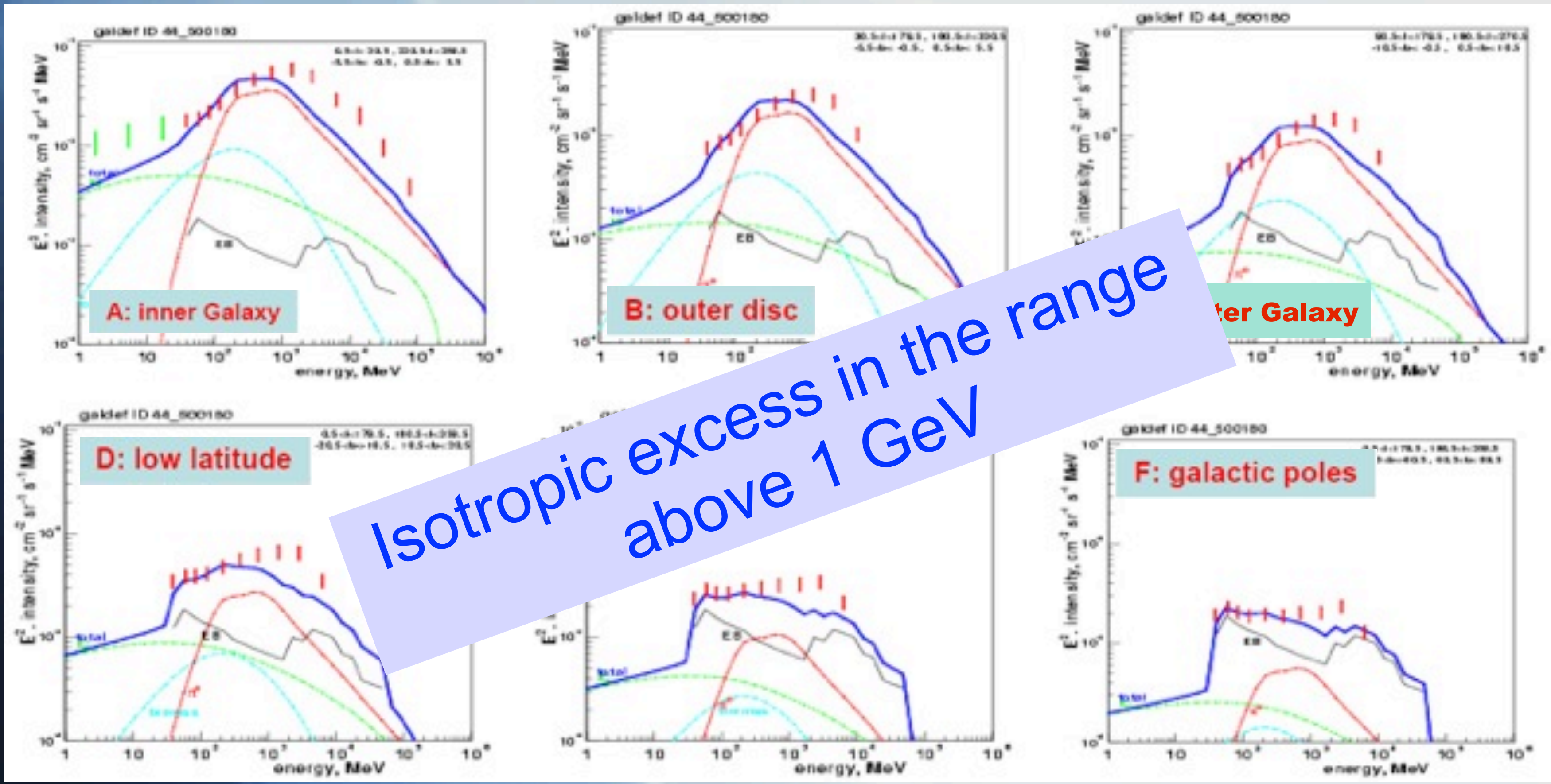




Dominant
χ + χ ⇒ A ⇒ b bbar quark pair
Sum of diagrams should yield
$\langle\sigma v\rangle = 2.10^{-26}$ cm³/s to get correct relic density

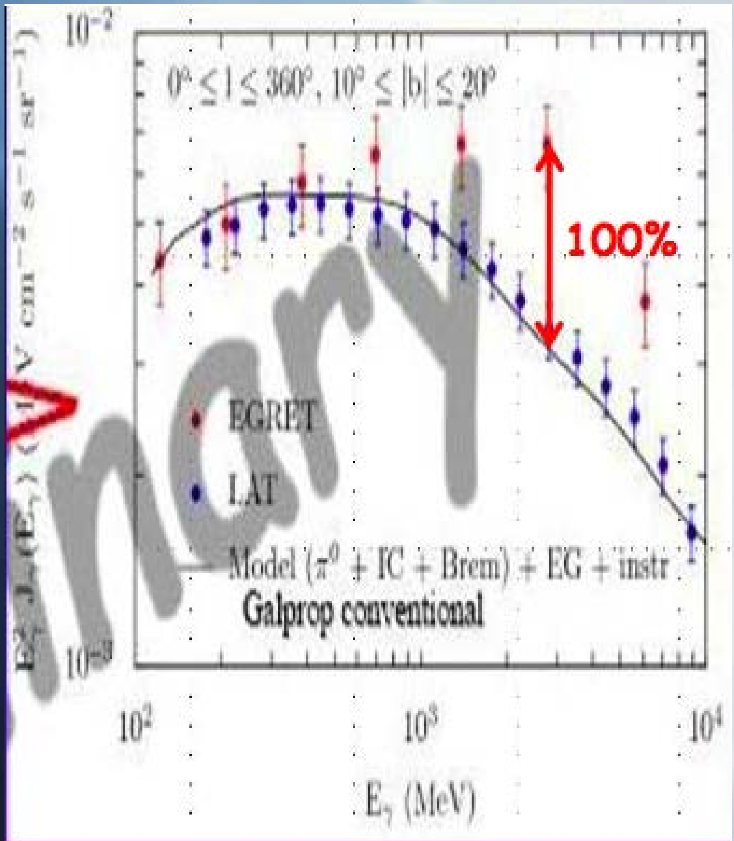
Quark-fragmentation known!
Hence spectra of positrons, gammas and antiprotons known!
Relative amount of γ,p,e+ known as well.

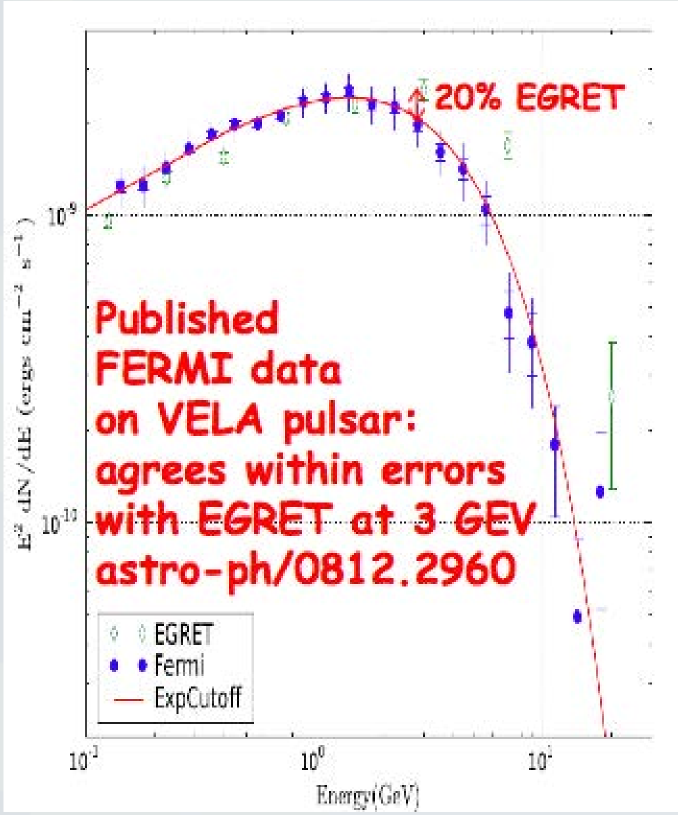
Analysis of EGRET Data in 6 Sky Directions



Total χ^2 for all regions: 28/36⇒Prob.=0.8 Excess above background > 10σ

Diffuse gamma rays from FERMI





Why diffuse spectrum disagrees 100% with EGRET at 3 GeV while VELA spectrum agrees with EGRET at 3 GeV within 20%?

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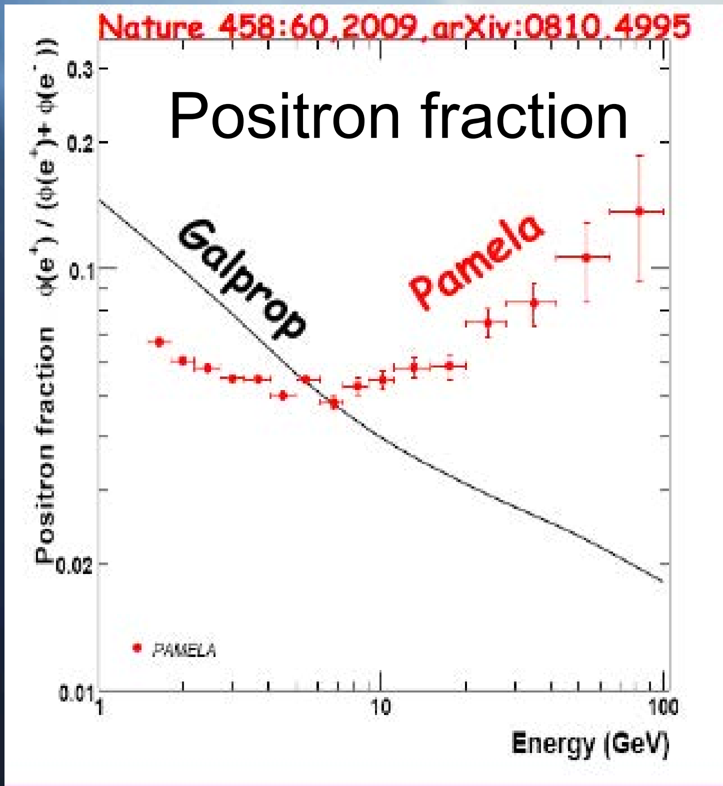
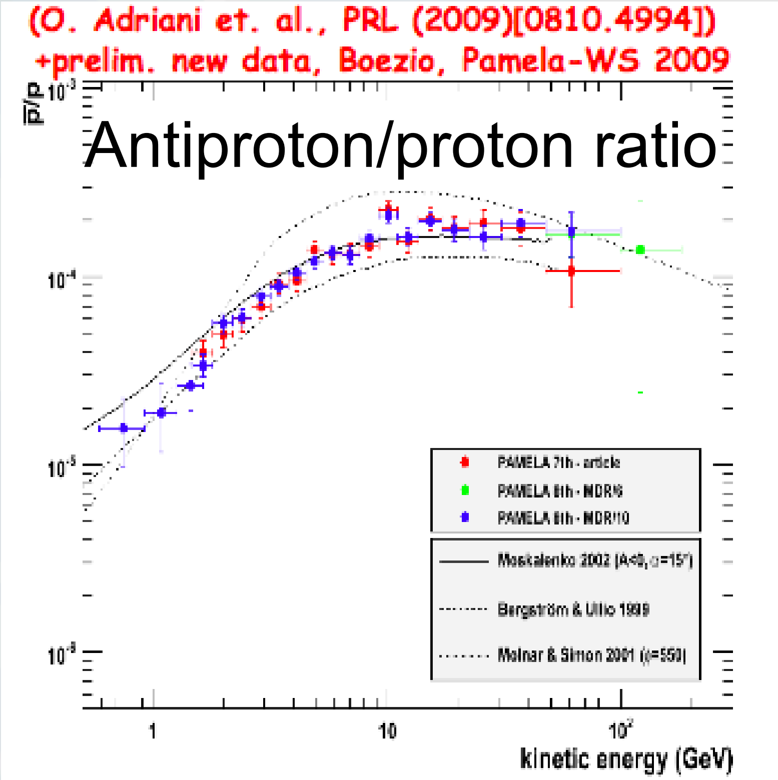
PAMELA: positron and antiproton measurements





Positrons: excess

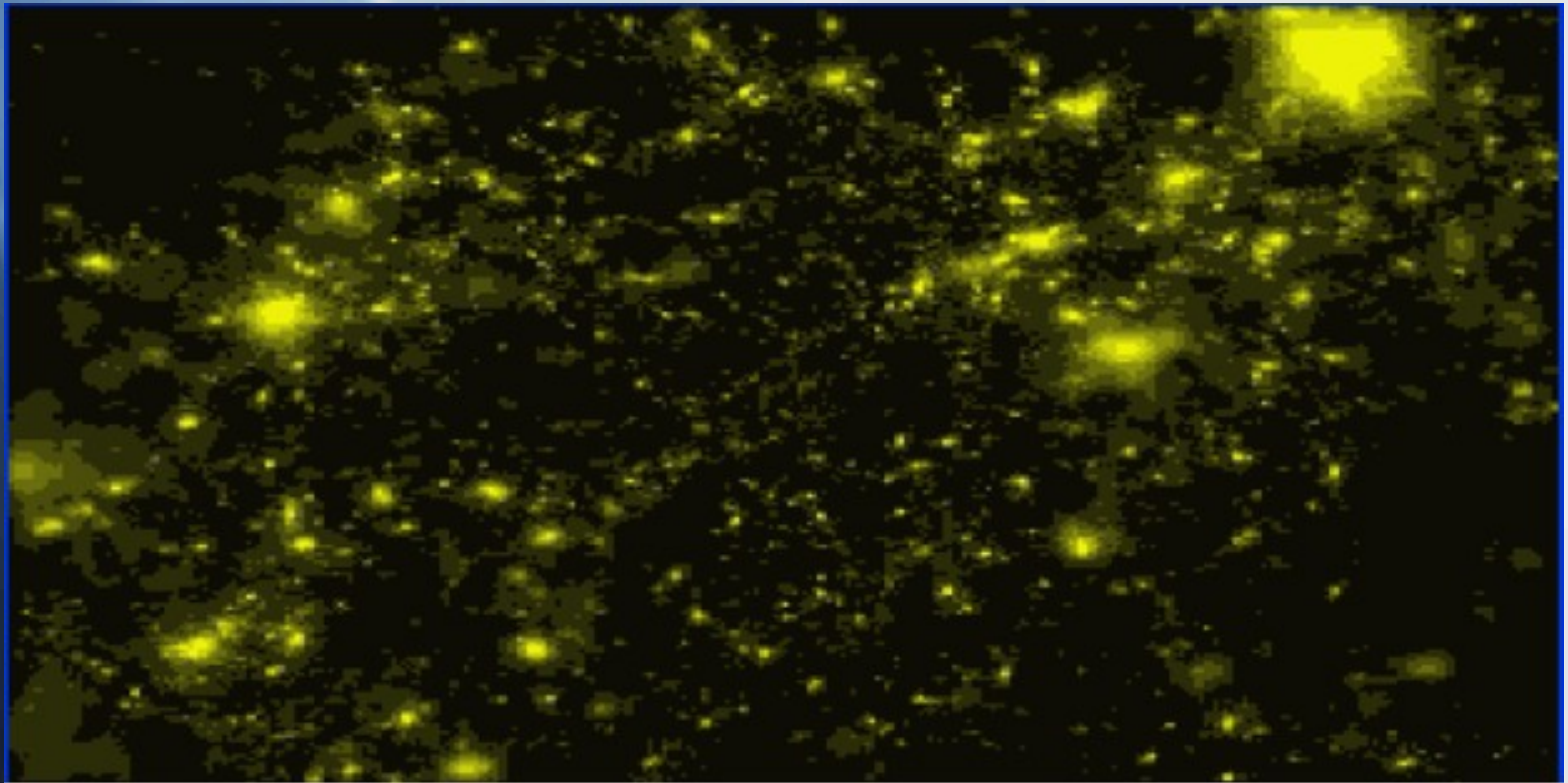
Antiprotons: NO excess

Interpretation of PAMELA Excess

Many possibilities:

- Background from hadronic showers with large electromagnetic component -> $a_{p->\pi 0}$
- astrophysical sources
  - pulsars -> a_{pulsar}
  - positron acceleration in SNR -> a_{sec}
  - locality of sources -> a_{SNR}
- dark matter annihilation -> a_{DMA}
  - leptophilic?
  - bound states?
  - Kaluza-Klein

Clustering of of Dark Matter



Cluster size: ≈ Solar system?
$M_{min} \cong 10^{-8} - 10^{-6}$ M☉?
Steeply falling mass spectrum.
Boost factor ~ $<\rho^2>/<\rho>^2$ ~ 20-2000
From fit: B≈100 for WIMP of 60 GeV

Clumps with M_{min} -> dominant contribution -> MANY clumps in given direction -> same boostfactor in all directions

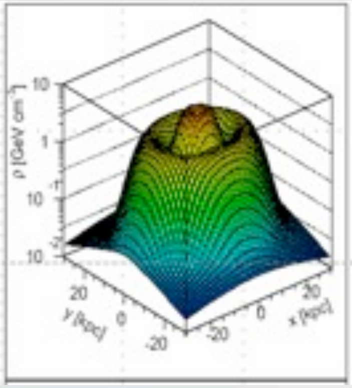
Fitted Hallo Parameters

Gamma Ray Flux: (<σv> from WMAP)

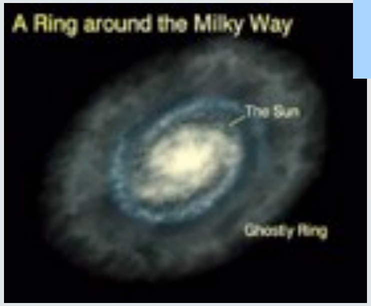
$$\phi_\chi(E,\psi) = \frac{\langle\sigma v\rangle}{4\pi}\sum_f \frac{dN_f}{dE} b_f \int_{line\ of\ sight} B_l \frac{1}{2}\frac{\langle\rho_\chi^2\rangle}{M_\chi^2} dl_\psi$$

$$\rho_\chi(\tilde r) = \rho_0\left(\frac{R_0}{\tilde r}\right)^\gamma \left[\frac{1+\left(\frac{\tilde r}{a}\right)^\alpha}{1+\left(\frac{R_0}{a}\right)^\alpha}\right]^{\frac{\gamma-\beta}{\alpha}} + \sum_{n=1}^{N} \rho_n \exp\left(-\frac{(\tilde r_{gc}-R_n)^2}{2\sigma_{R_n}^2} - \frac{(z_n)^2}{2\sigma_{z_n}^2}\right)$$

Parameter	Value	Parameter	Value
α	2	R_a	4.3 kpc
β	2	$\sigma_{R,a}$	3.4 kpc
γ	0	$\sigma_{z,a}$	0.3 kpc
R_0	8.5 kpc	ρ_b	2.3 GeV cm^{-3}
a	4 kpc	R_b	14 kpc
ρ_0	0.47 GeV cm^{-3}	$\sigma_{R,b}$	2.1 kpc
ρ_a	3.3 GeV cm^{-3}	$\sigma_{z,b}$	1.3 kpc
b/a	0.9	c/a	0.8



Enhancement of rings over $1/r^2$ profile 2 and 7, respectively.
Mass in rings 1.6 and 0.3% of total DM

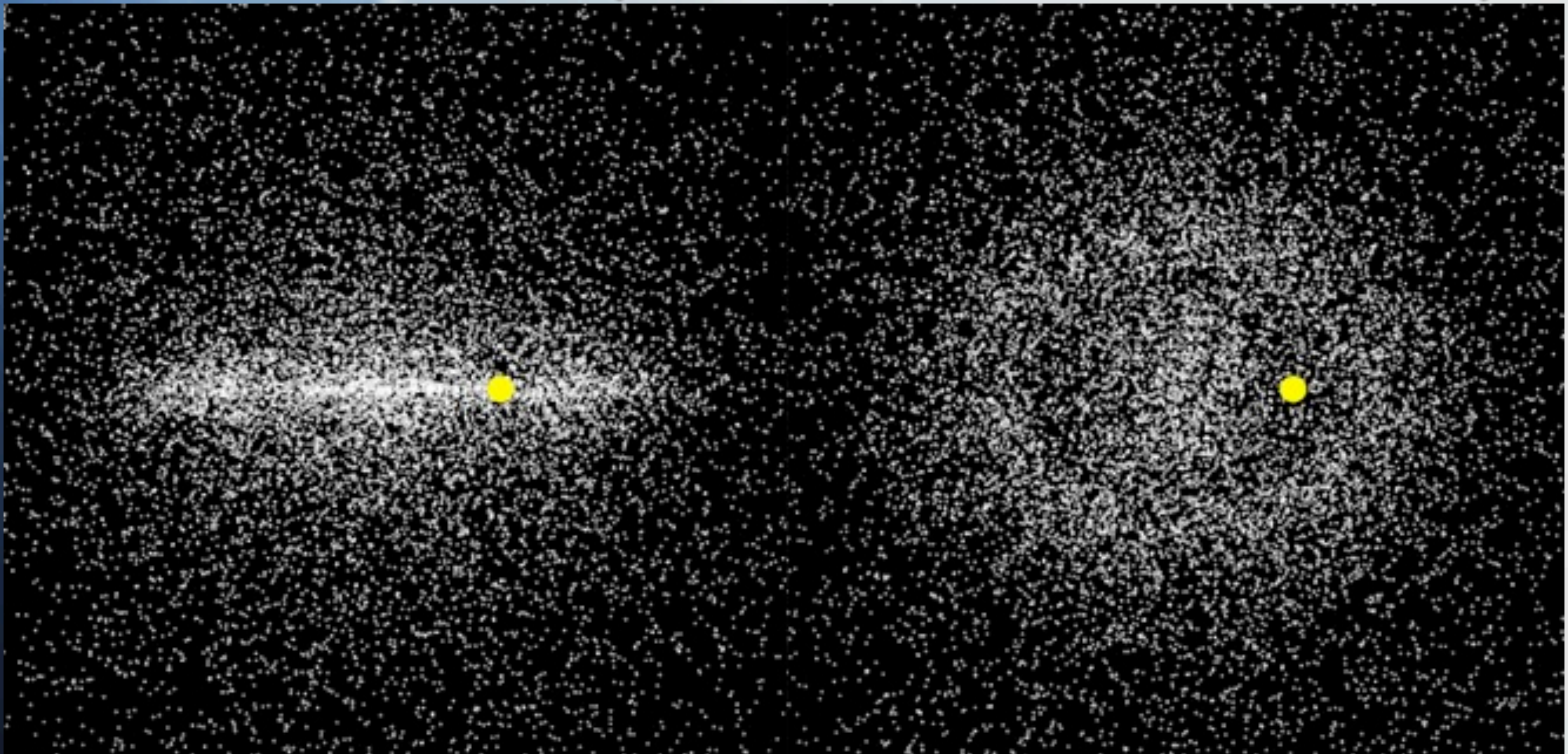


14 kpc coincides with ring of stars at 14-18 kpc due to infall of dwarf galaxy

4 kpc coincides with ring of neutral hydrogen molecules!

W.de Boer, C.Sander, V.Zhukov, A.Gladyshev, and D.Kazakov, A&A 444 (2005)17

Hallo Density on Scale of 30 Kpc



Side view

Top view

	Isother.	NFW
R200	295 kpc	145 kpc
DM:	3.10^{12} M⊙	3.10^{11} M⊙
Vis.:	6.10^{10} M⊙	
Outer Ring:	3.10^{10} M⊙	
Inner Ring:	3.10^{9} M⊙	

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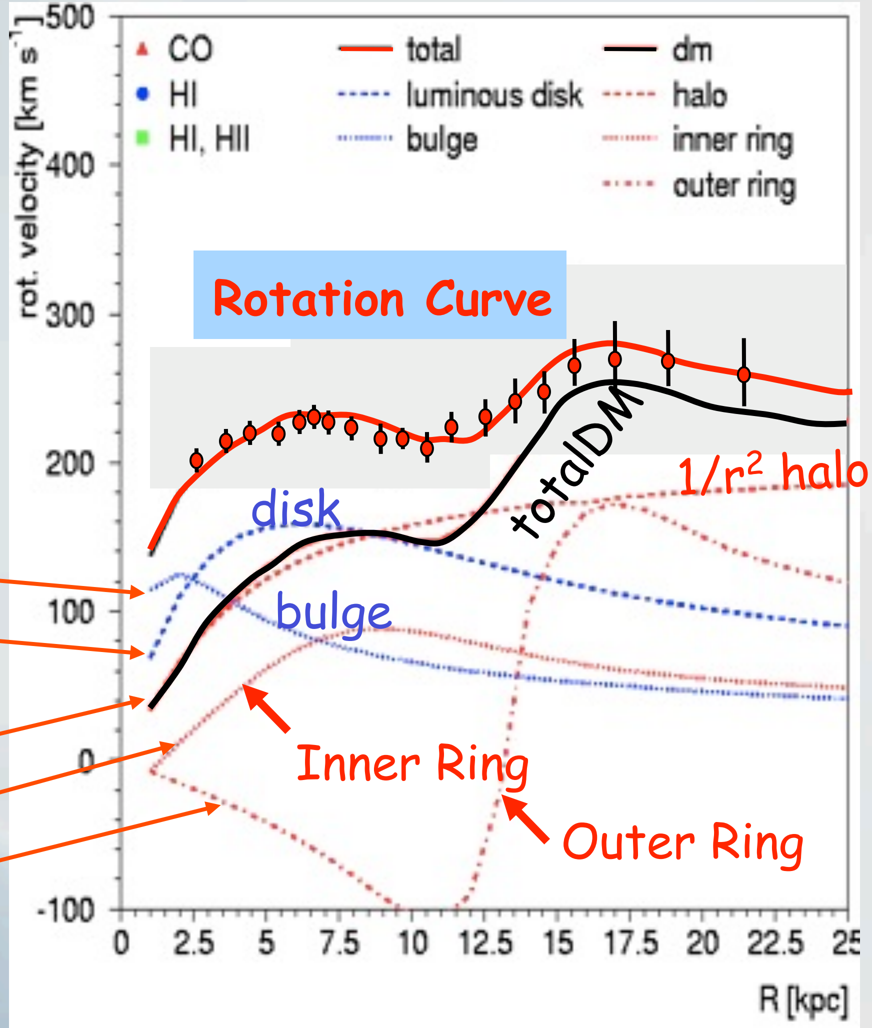
Rotation Curve for the Milky Way

Contributions to the rotation curve of the Milky Way from

Visible bulge
Visible disk

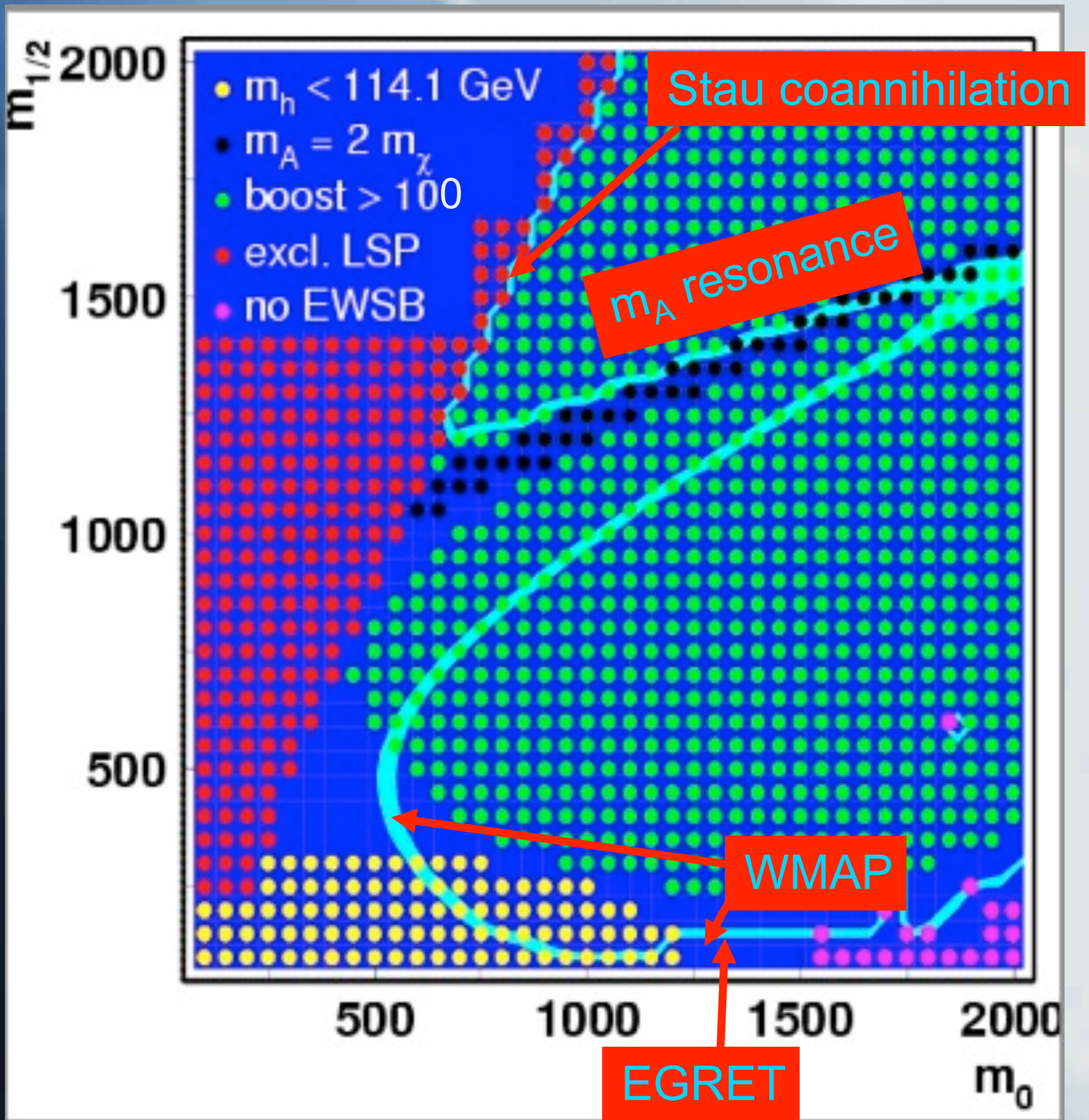
Dark halo
Inner dark ring
Outer dark ring



Normalize to solar velocity of 220 km/s

R [kpc] 5

Allowed SUSY Parameter



MSUGRA can fulfill all constraints from WMAP, LEP, b->sγ, g-2 and EGRET simultaneously, if DM is neutralino with mass in range 50-100 GeV and squarks and sleptons are O(1 TeV)

m_0 common spin 0 mass

$m_{1/2}$ common spin ½ mass

$\tan\beta = v_2/v_1$

High $\tan\beta$ solution

$\tan\beta$ = 50

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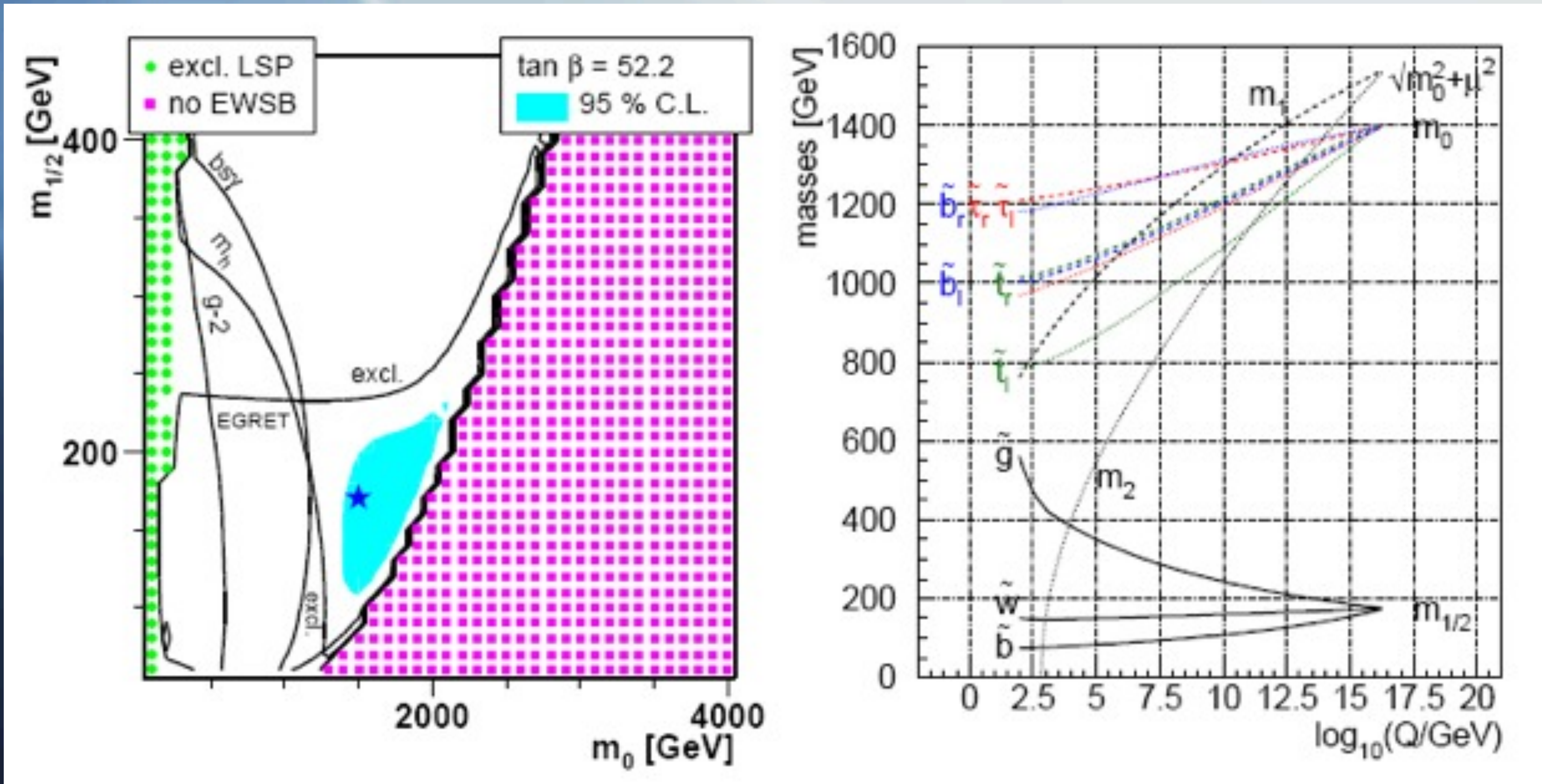
EGRET Point and Mass Spectrum



W.de Boer et al PL B636 (2006)13

SUSY DM: $m_{\chi^0} \sim 60$ GeV $m_{\chi^\pm} \sim 120$ GeV

PHYSICS PROBLEMS

Cosmologists:

What is CDM and Dark Energy made of?

Astrophysicists:

What is the origin of excess of diffuse Galactic Gamma Rays?

Particle physicists :

Where are the Supersymmetric Particles?

Astronomers:

Why a change of slope in the galactic rotation curve at 1.1 R_0?

Solution: DM is made of WIMPs which are SUSY particles distributed in Halo of our Galaxy with a mass around 70 GeV

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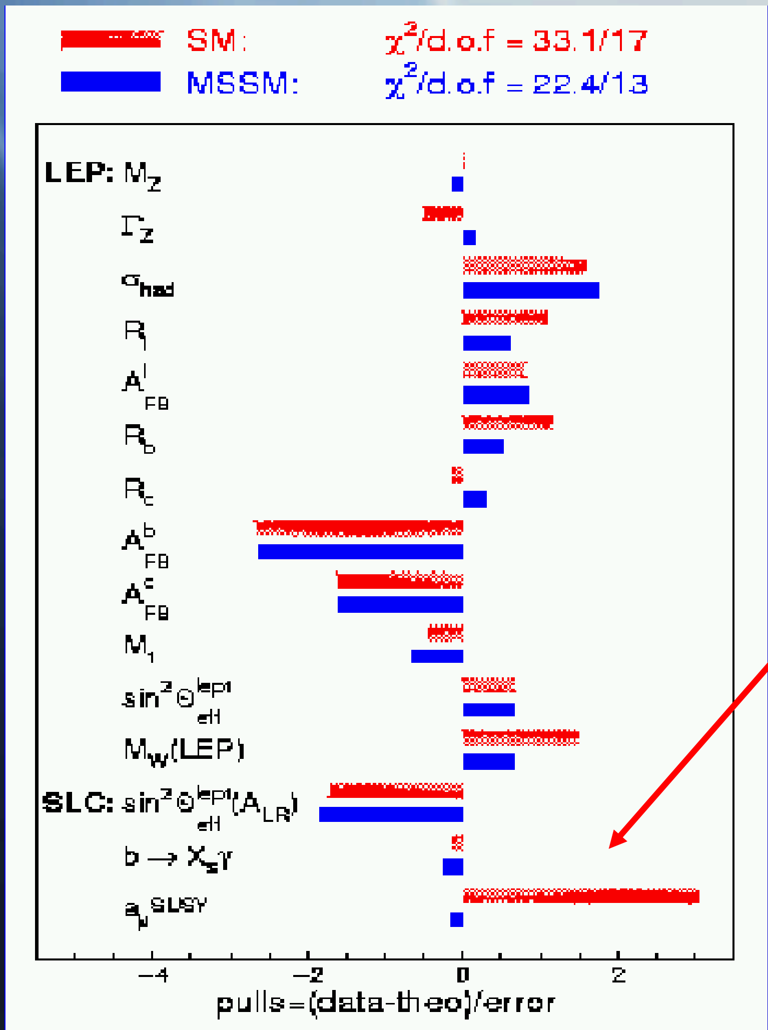
MSSM versus SM



- ***MSSM is as good as SM***
- ***B->s*** γ
- ***a*** $_\mu$

} Better than in the SM

Ω_{DM} Is not described in the SM but naturally predicted by MSSM

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SUSY: Pros and Cons

Pro :

- Provides natural framework for unification with gravity
- Leads to gauge coupling unification (GUT)
- Solves the hierarchy problem
- 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