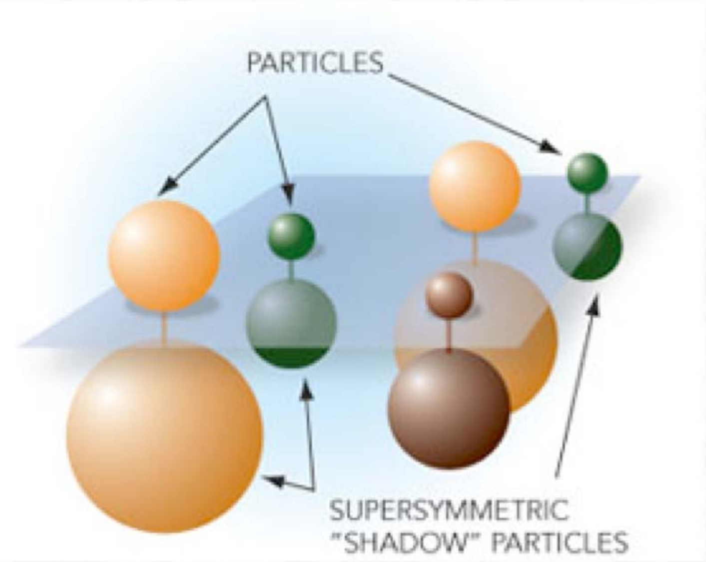
9. Supersymmetry



Why Physics Beyond the Standard Model?

1. Gravity is not yet incorporated in the Standard Model

2. Dark Matter not accommodated

3. Many open questions in the Standard Model
   - Hierarchy problem: m_W (100 GeV) → m_{Planck} (10^{19} GeV)
   - Unification of couplings
   - Flavour / family problem
   - …..

All this calls for a ***more fundamental theory*** of which
the Standard Model is a low energy approximation → **New Physics**

Candidate theories: Supersymmetry
Extra Dimensions
Technicolor
…….

Many extensions predict new physics at the TeV scale !!

Strong motivation for LHC,
mass reach ~ 3 TeV

9.1 Introduction: what is Supersymmetry (SUSY) ?

SUSY is an extension of the Standard Model (since ~ 1970)
that introduces a new symmetry between fermions and bosons:

Spin-½ matter particles (fermions) ⇔ Spin-1 force particles (bosons)

SUSY transformation (operator Q):

$$Q\,|\text{Fermion}\rangle \sim |\text{Boson}\rangle$$

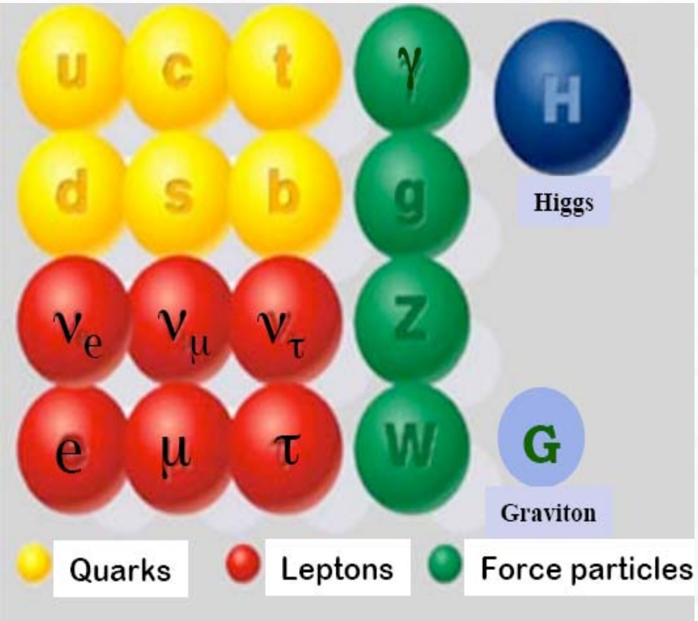
$$Q\,|\text{Boson}\rangle \sim |\text{Fermion}\rangle$$

→ SUSY doubles the number of particles

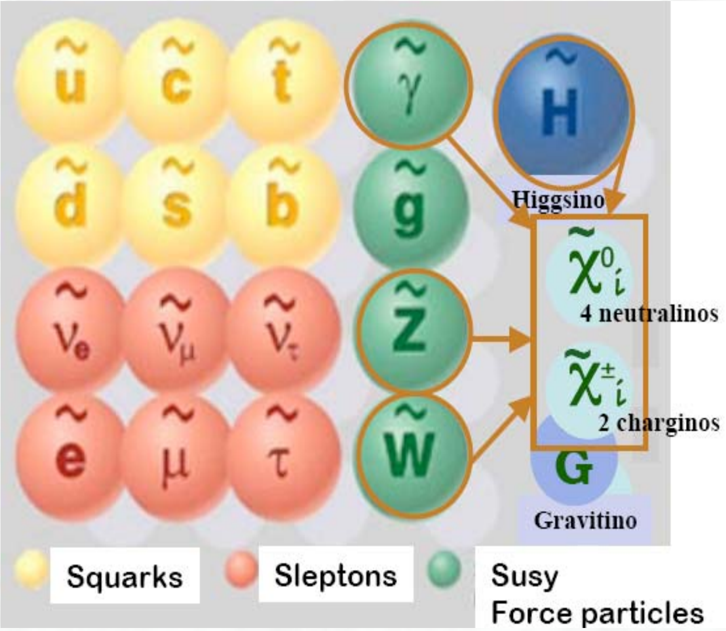
Supersymmetry

Extends the Standard Model by predicting a new symmetry
Spin ½ matter particles (fermions) ⇔ Spin 1 force carriers (bosons)

Standard Model particles



SUSY particles



Standard Model and supersymmetry partners can be distinguished by a discrete Quantum number: R-parity:

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

The SUSY particle spectrum

	Particle	Sparticle (corresp. SUSY particle)
Spin-1/2	quarks (L&R) leptons (L&R) neutrinos (L)	

	Particle	Sparticle (corresp. SUSY particle)	
Spin-1/2	quarks (L&R)	squarks (L&R)	Spin-0
	leptons (L&R)	sleptons (L&R)	
	neutrinos (L)	sneutrinos (L)	

	Particle	Sparticle (corresp. SUSY particle)	
Spin-1/2	quarks (L&R) leptons (L&R) neutrinos (L)	squarks (L&R) sleptons (L&R) sneutrinos (L)	Spin-0
Spin-1	$\left.\begin{matrix}B\\W^0\end{matrix}\right\}\left\{\begin{matrix}\gamma\\Z^0\end{matrix}\right.$ $W^\pm$ gluon		

	Particle		Sparticle (corresp. SUSY particle)	
Spin-1/2	quarks (L&R)		squarks (L&R)	Spin-0
	leptons (L&R)		sleptons (L&R)	
	neutrinos (L)		sneutrinos (L)	
Spin-1	B	γ	Bino	Spin-1/2
	W^0	Z^0	Wino^0	
		$W^\pm$	$\text{Wino}^\pm$	
		gluon	gluino	

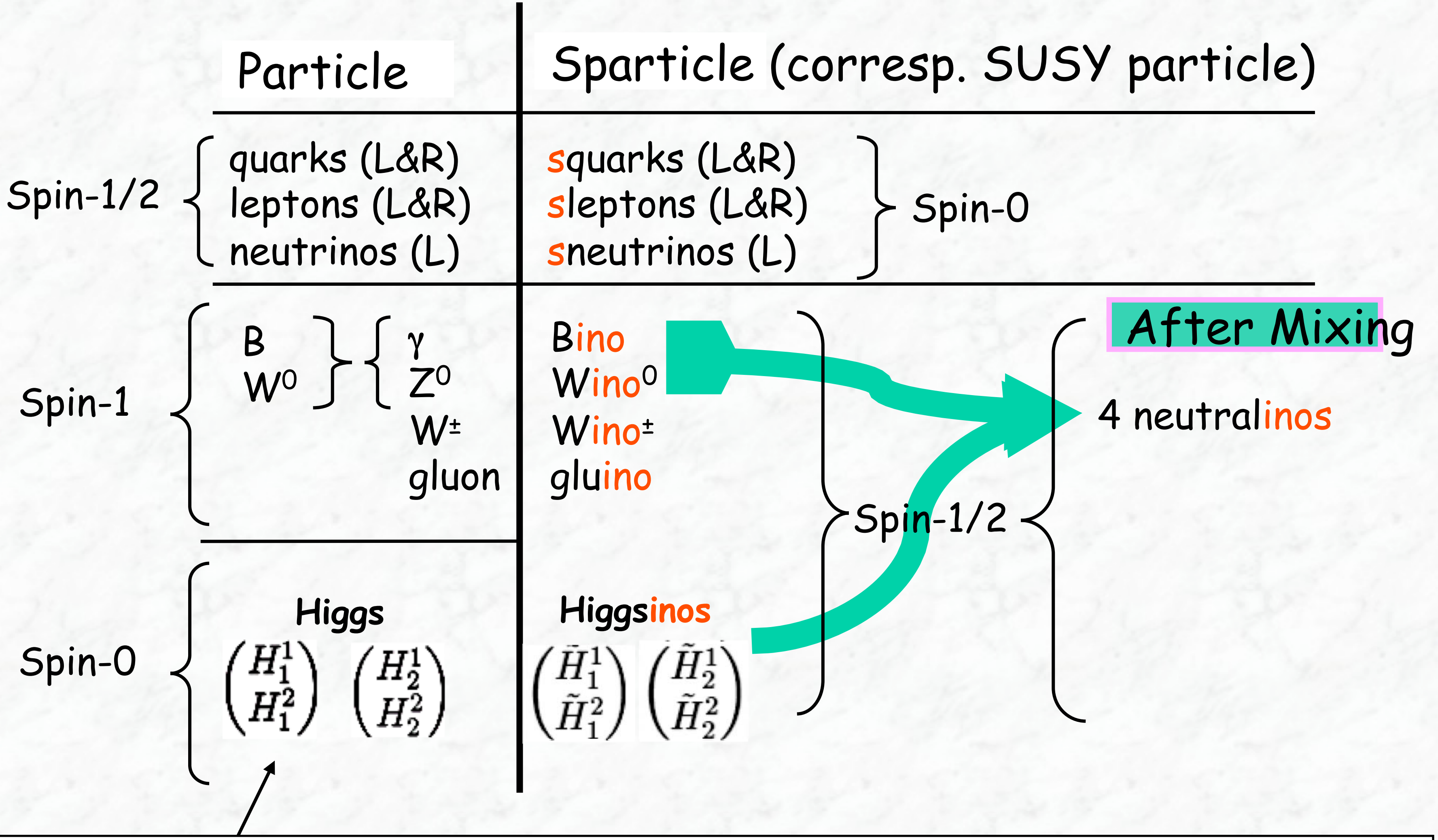
	Particle	Sparticle (corresp. SUSY particle)	
Spin-1/2	quarks (L&R) leptons (L&R) neutrinos (L)	squarks (L&R) sleptons (L&R) sneutrinos (L)	Spin-0
Spin-1	$\left.\begin{matrix}B\\W^0\end{matrix}\right\}\left\{\begin{matrix}\gamma\\Z^0\end{matrix}\right.$ $W^\pm$ gluon	Bino Wino^0 $\text{Wino}^\pm$ gluino	Spin-1/2
Spin-0	**Higgs** $\begin{pmatrix}H_1^1\\H_1^2\end{pmatrix}$ $\begin{pmatrix}H_2^1\\H_2^2\end{pmatrix}$		

Extended Higgs sector: 2 complex Higgs doublets
→ Degrees of freedom: 8 - 3 (Goldstone bosons) = 5 Higgs bosons: $h^0, H^0, A^0, H^\pm$

	Particle	Sparticle (corresp. SUSY particle)	
Spin-1/2	quarks (L&R) leptons (L&R) neutrinos (L)	squarks (L&R) sleptons (L&R) sneutrinos (L)	Spin-0
Spin-1	$\left.\begin{matrix}B\\W^0\end{matrix}\right\}\left\{\begin{matrix}\gamma\\Z^0\end{matrix}\right.$ $W^\pm$ gluon	Bino Wino^0 $\text{Wino}^\pm$ gluino	Spin-1/2
Spin-0	**Higgs** $\begin{pmatrix}H_1^1\\H_1^2\end{pmatrix}$ $\begin{pmatrix}H_2^1\\H_2^2\end{pmatrix}$	**Higgsinos** $\begin{pmatrix}\tilde{H}_1^1\\\tilde{H}_1^2\end{pmatrix}$ $\begin{pmatrix}\tilde{H}_2^1\\\tilde{H}_2^2\end{pmatrix}$	

Extended Higgs sector: 2 complex Higgs doublets

→ Degrees of freedom: 8 - 3 (Goldstone bosons) = 5 Higgs bosons: $h^0, H^0, A^0, H^\pm$

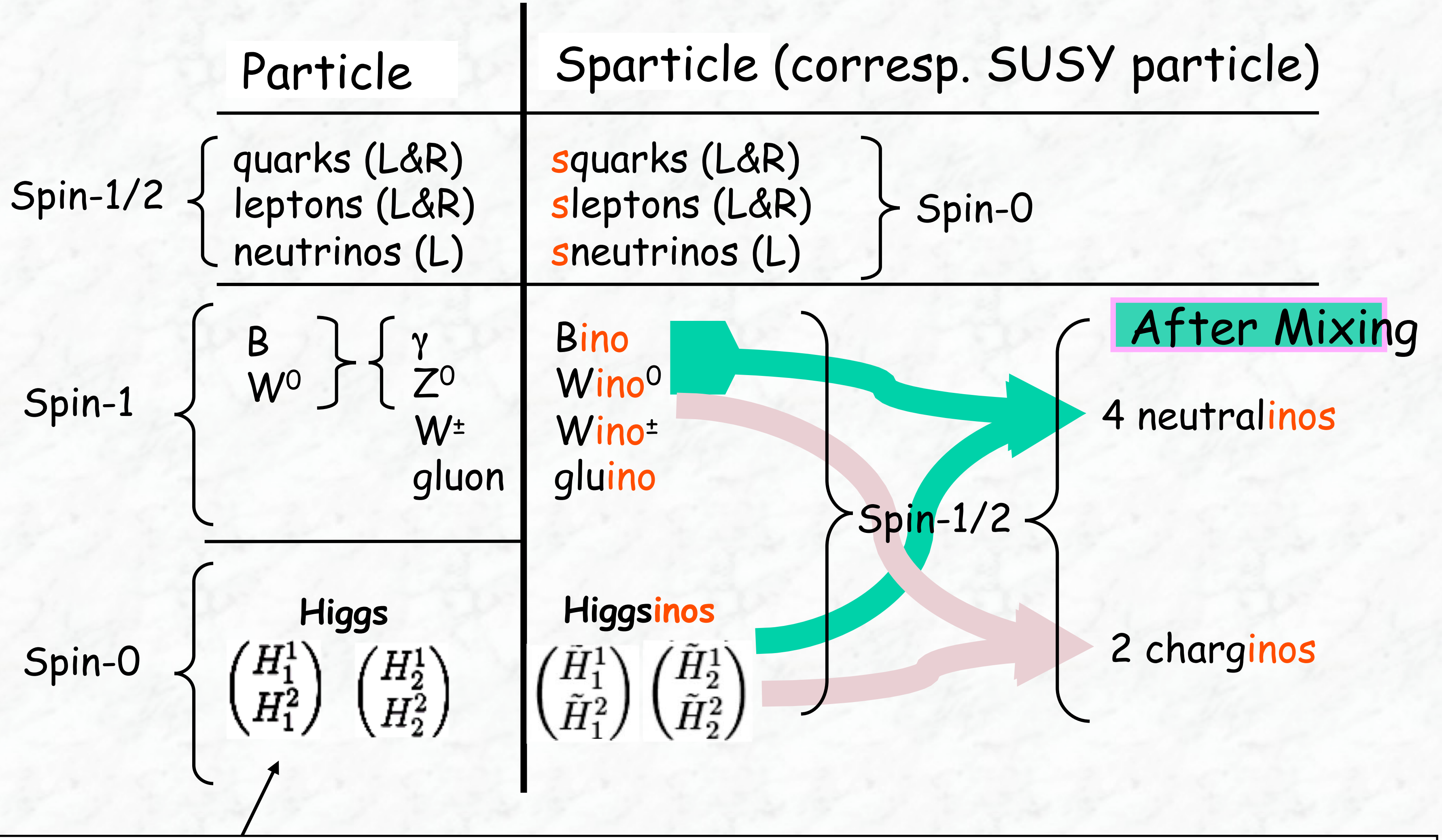


	Particle	Sparticle (corresp. SUSY particle)	
Spin-1/2	quarks (L&R) leptons (L&R) neutrinos (L)	squarks (L&R) sleptons (L&R) sneutrinos (L)	Spin-0
Spin-1	B W^0 γ Z^0 $W^\pm$ gluon	Bino Wino^0 $\text{Wino}^\pm$ gluino	Spin-1/2
Spin-0	**Higgs** $\begin{pmatrix}H_1^1\\H_1^2\end{pmatrix}$ $\begin{pmatrix}H_2^1\\H_2^2\end{pmatrix}$	**Higgsinos** $\begin{pmatrix}\tilde{H}_1^1\\\tilde{H}_1^2\end{pmatrix}$ $\begin{pmatrix}\tilde{H}_2^1\\\tilde{H}_2^2\end{pmatrix}$	

After Mixing

4 neutralinos

Extended Higgs sector: 2 complex Higgs doublets
→ Degrees of freedom: 8 - 3 (Goldstone bosons) = 5 Higgs bosons: $h^0, H^0, A^0, H^\pm$



	Particle	Sparticle (corresp. SUSY particle)	
Spin-1/2	quarks (L&R) leptons (L&R) neutrinos (L)	squarks (L&R) sleptons (L&R) sneutrinos (L)	Spin-0
Spin-1	B, W^0 → γ, Z^0 $W^\pm$ gluon	Bino Wino^0 $\text{Wino}^\pm$ gluino	Spin-1/2
Spin-0	**Higgs** $\begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix}$ $\begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix}$	**Higgsinos** $\begin{pmatrix} \tilde{H}_1^1 \\ \tilde{H}_1^2 \end{pmatrix}$ $\begin{pmatrix} \tilde{H}_2^1 \\ \tilde{H}_2^2 \end{pmatrix}$	

After Mixing

4 neutralinos

2 charginos

Extended Higgs sector: 2 complex Higgs doublets
→ Degrees of freedom: 8 - 3 (Goldstone bosons) = 5 Higgs bosons: $h^0, H^0, A^0, H^\pm$

- Physical neutralinos and charginos are mixtures of Wino, Bino, Higgsinos

- Charginos:

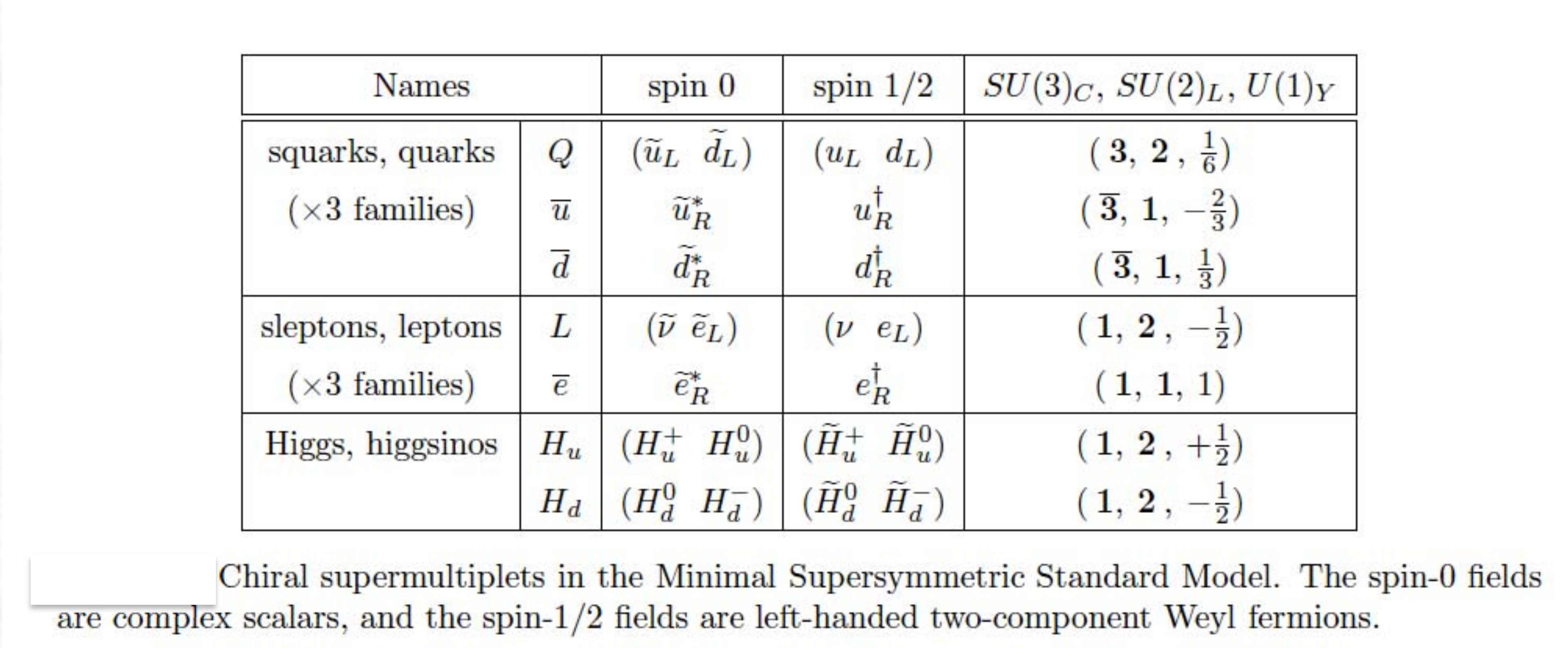
$$\begin{pmatrix} \chi_1^+ \\ \chi_2^+ \end{pmatrix} = \begin{pmatrix} M_2 & \sqrt{2} m_W \sin\beta \\ \sqrt{2} m_W \cos\beta & \mu \end{pmatrix} \begin{pmatrix} \tilde{W}^+ \\ \tilde{H}^+ \end{pmatrix}$$

- Neutralinos:

$$\begin{pmatrix} \chi_1^0 \\ \chi_2^0 \\ \chi_3^0 \\ \chi_4^0 \end{pmatrix} = \begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\ 0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W \\ -m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu \\ m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0 \end{pmatrix} \begin{pmatrix} \tilde{B} \\ \tilde{W}^3 \\ \tilde{H}_1^0 \\ \tilde{H}_2^0 \end{pmatrix}$$

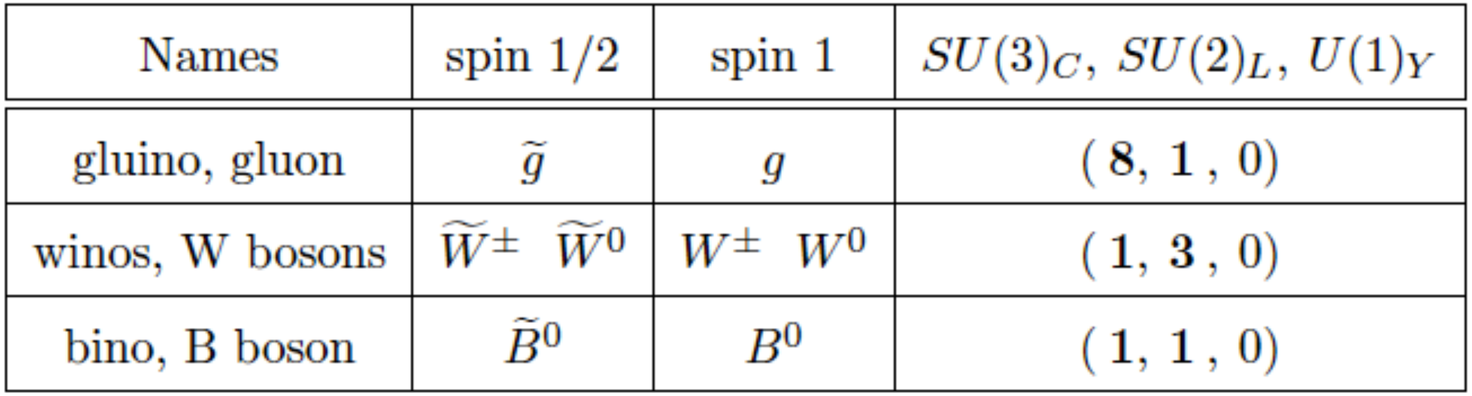
Mass eigenstates depend on:

M_1, M_2, tan β, μ	SUSY masses and breaking parameters
m_Z, $\sin^2\theta_W$	EWSB (mixing: B^0,W^0 → Z, γ)



Names		spin 0	spin 1/2	$SU(3)_C$, $SU(2)_L$, $U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L \ \ \widetilde{d}_L)$	$(u_L \ \ d_L)$	$(\,\mathbf{3},\ \mathbf{2}\,,\ \frac{1}{6})$
(×3 families)	$\overline{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}^*_R$	$d^\dagger_R$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu}\ \widetilde{e}_L)$	$(\nu \ \ e_L)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$
(×3 families)	$\overline{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$	$(\,\mathbf{1},\ \mathbf{1},\ 1)$
Higgs, higgsinos	H_u	$(H_u^+ \ \ H_u^0)$	$(\widetilde{H}_u^+ \ \ \widetilde{H}_u^0)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ +\frac{1}{2})$
	H_d	$(H_d^0 \ \ H_d^-)$	$(\widetilde{H}_d^0 \ \ \widetilde{H}_d^-)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$

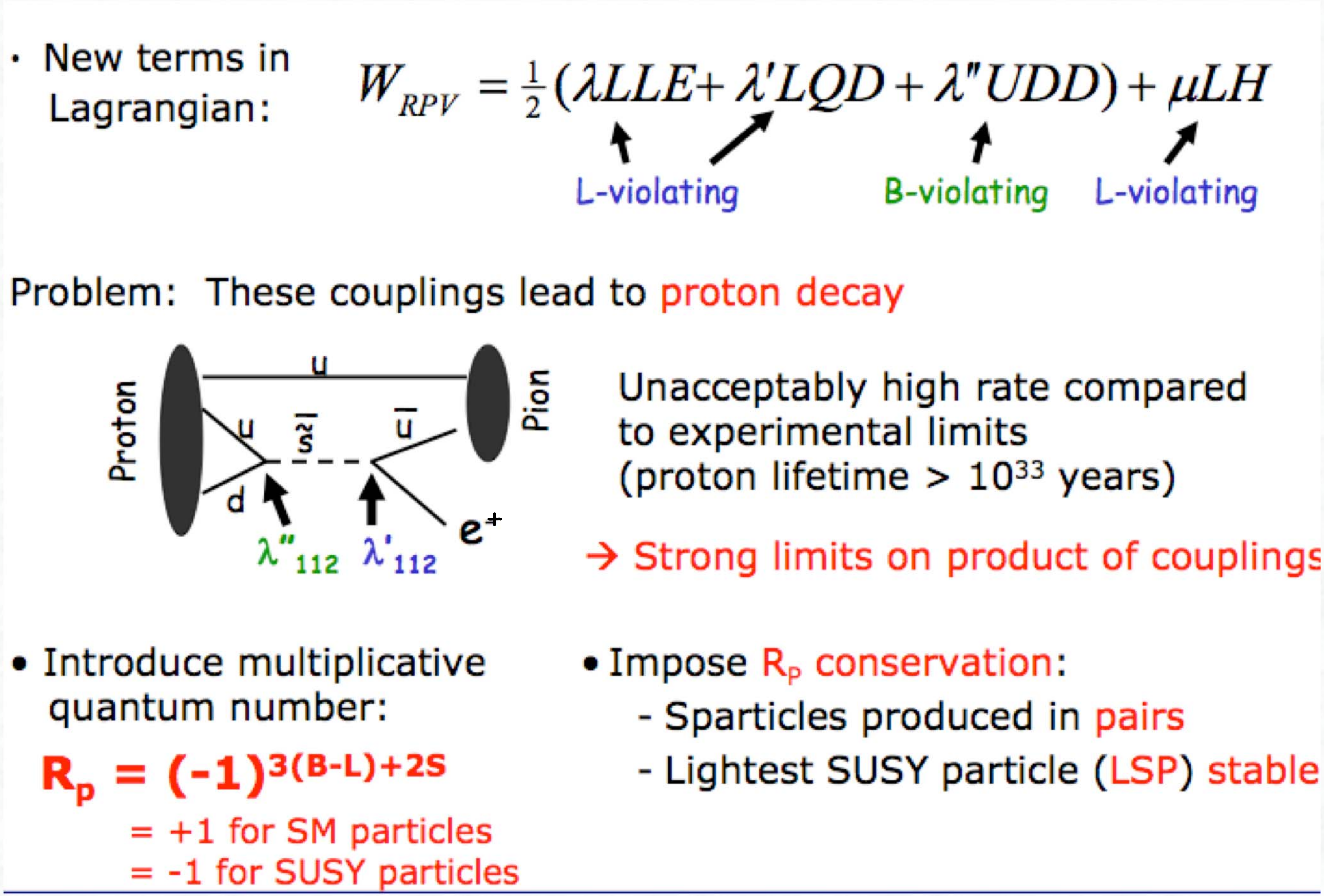
Chiral supermultiplets in the Minimal Supersymmetric Standard Model. The spin-0 fields are complex scalars, and the spin-1/2 fields are left-handed two-component Weyl fermions.



Names	spin 1/2	spin 1	$SU(3)_C$, $SU(2)_L$, $U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\mathbf{8}, \mathbf{1}, 0)$
winos, W bosons	$\widetilde{W}^{\pm} \quad \widetilde{W}^{0}$	$W^{\pm} \quad W^{0}$	$(\mathbf{1}, \mathbf{3}, 0)$
bino, B boson	$\widetilde{B}^{0}$	B^{0}	$(\mathbf{1}, \mathbf{1}, 0)$

Gauge supermultiplets in the Minimal Supersymmetric Standard Model.

R parity



- New terms in Lagrangian:

$$W_{RPV} = \tfrac{1}{2}(\lambda LLE + \lambda' LQD + \lambda'' UDD) + \mu LH$$

L-violating B-violating L-violating

Problem: These couplings lead to proton decay

Unacceptably high rate compared to experimental limits (proton lifetime > 10^{33} years)

→ Strong limits on product of couplings

- Introduce multiplicative quantum number:

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

= +1 for SM particles
= -1 for SUSY particles

- Impose R_p conservation:
  - Sparticles produced in pairs
  - Lightest SUSY particle (LSP) stable

Experimental consequences of R-parity conservation:

- SUSY particles are produced in pairs
- Lightest Supersymmetric Particle (LSP) is stable.

LSP is only weakly interacting:
LSP ≡ χ^0_1 (lightest neutralino, in many models)

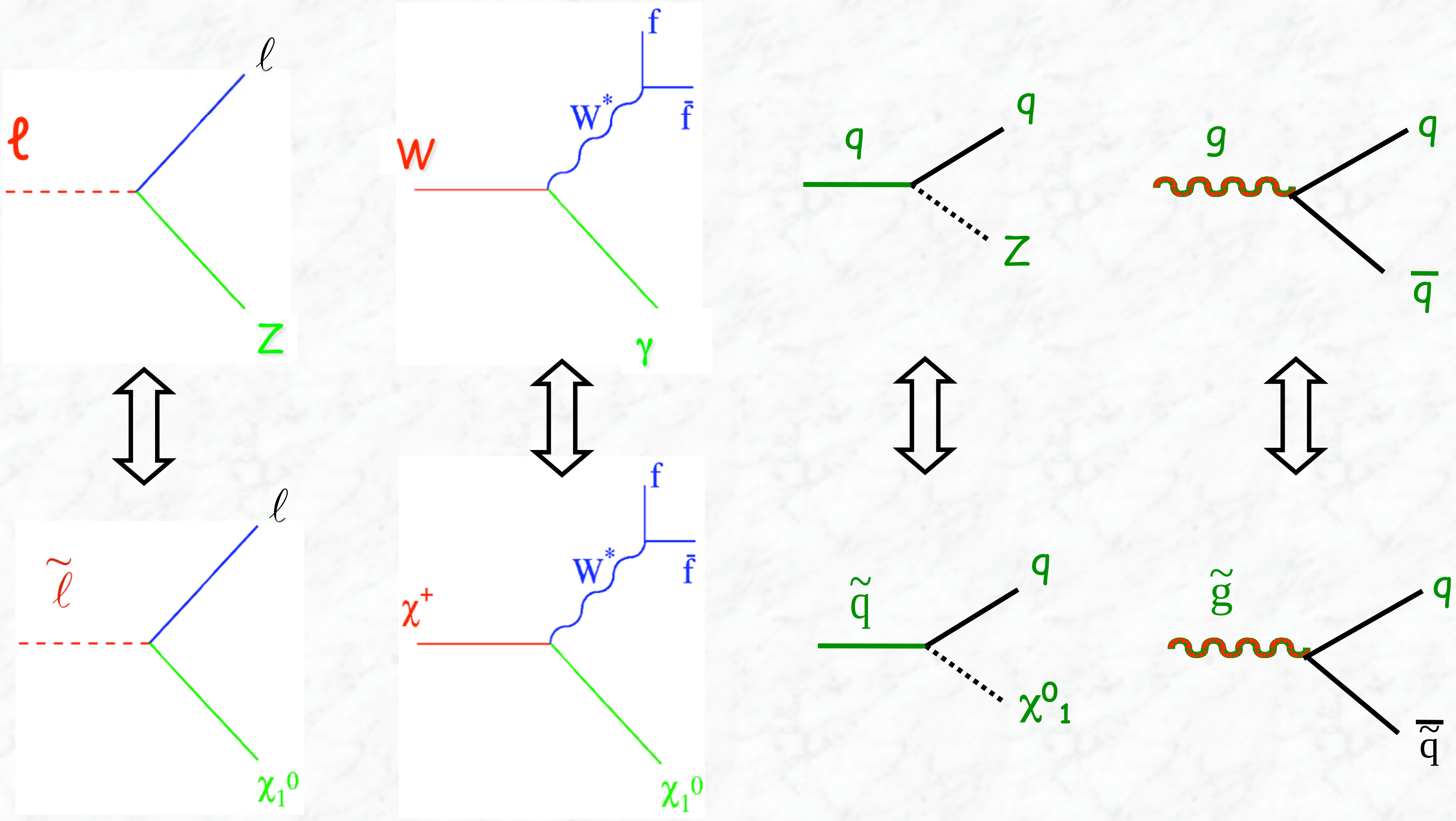
→ LSP behaves like a ν → it escapes detection

→ E_T^{miss} (typical SUSY signature)

SUSY interactions, some examples

The coupling constants are the same as in SM (strong, electroweak)

"Recipe" : Obtain SUSY interactions by exchanging
at a vertex two SM legs by corresponding SUSY legs

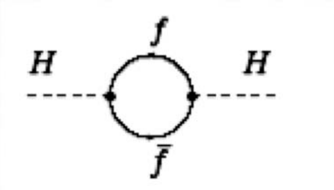


9.2 Motivation for supersymmetry

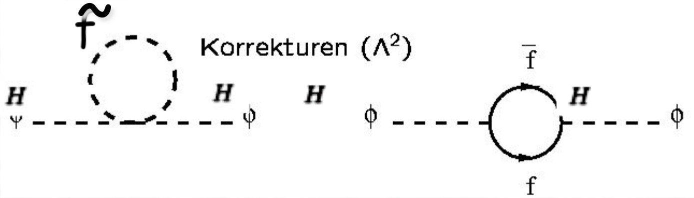
or what problems of the Standard Model does it solve ?

(i) The Hierarchy or naturalness problem

- In the Standard Model, quadratically divergent quantum corrections to the Higgs mass appear



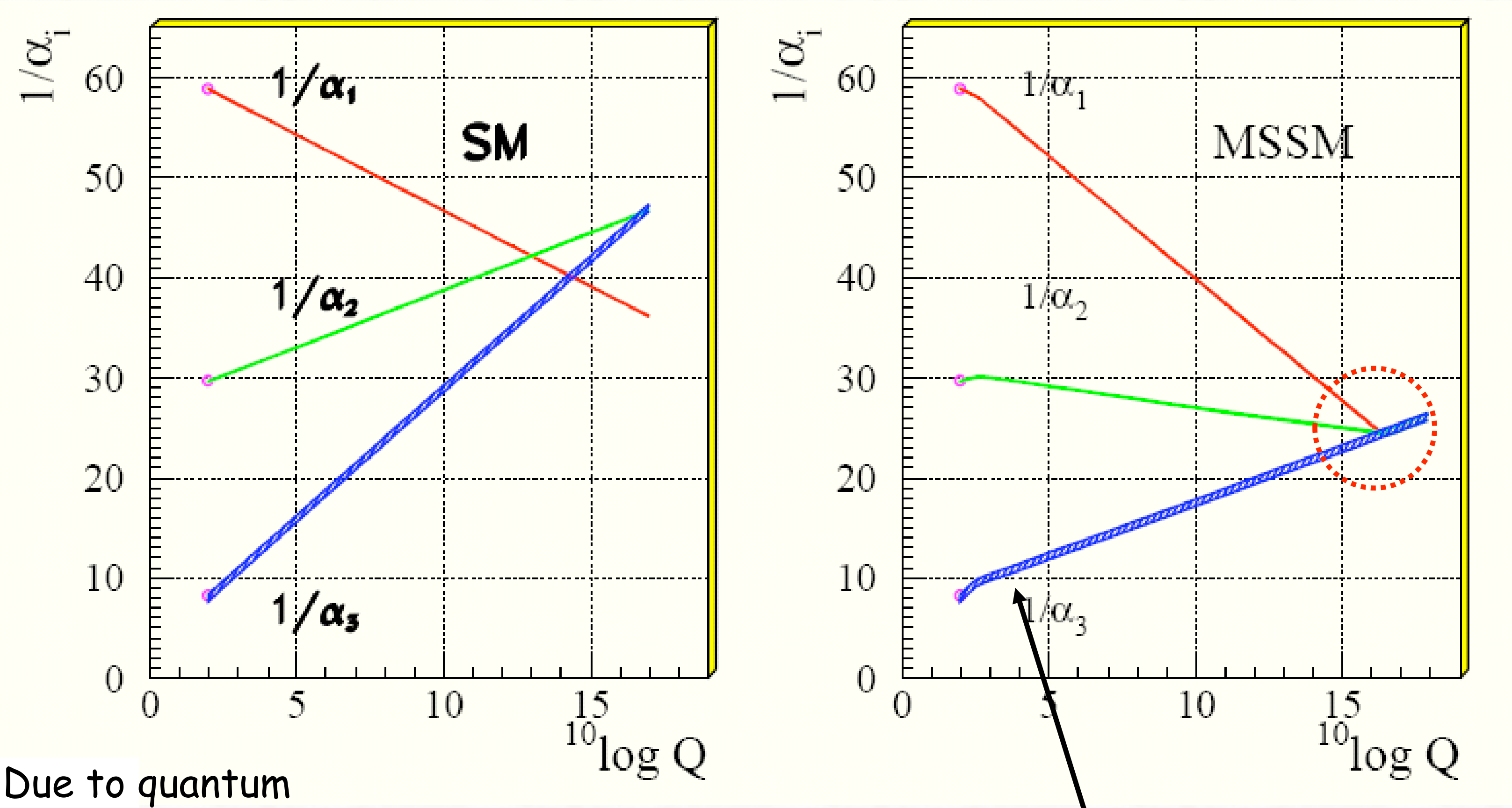
- The symmetry between bosons and fermions , which contribute with different sign (statistics), can cure this problem:



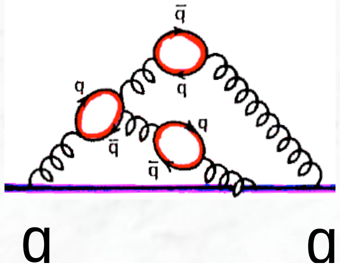
$$\Delta m_H = f(m_B^2 - m_f^2)$$

→ terms cancel one-by-one if SUSY were a perfect symmetry (i.e. if m(particle) = m(sparticle)). Since this is not the case, sparticles should not be too heavy (m_{SUSY} <~ 1 TeV).

(ii) The unification of the couplings of the three interactions seems possible in a SUSY model

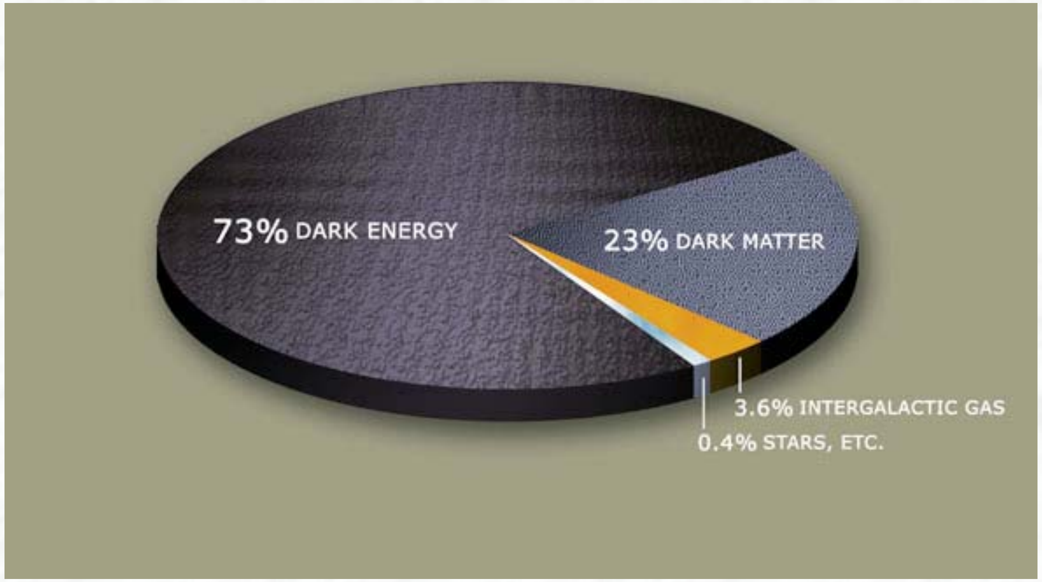


Due to quantum corrections, e.g.



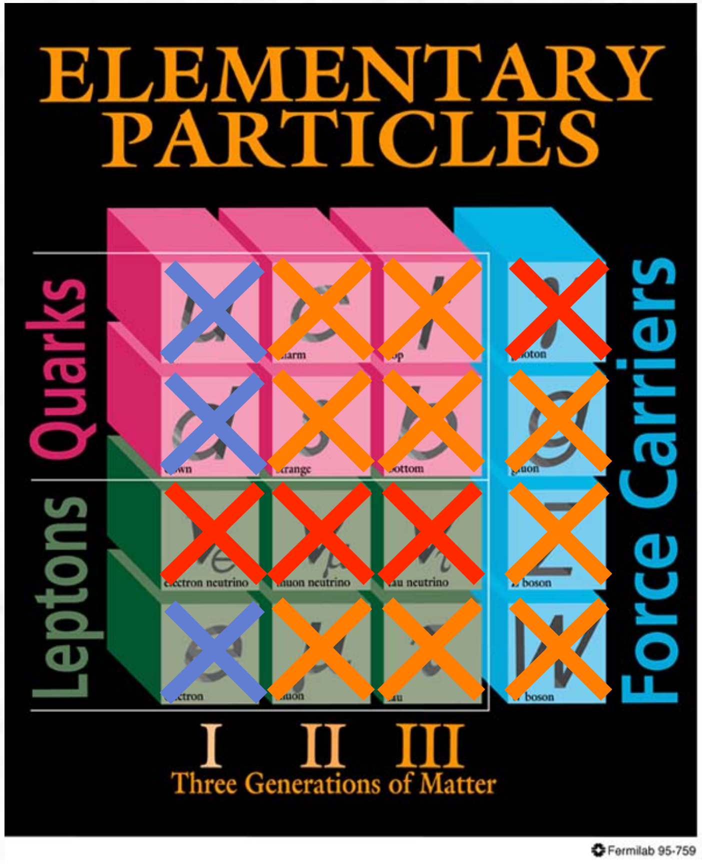
slope is changed due to contributions from SUSY particles

(ii) SUSY provides a candidate for Dark Matter in the universe



Evidence from:

- Rotational curves of galaxies
- Gravitational lensing
- Cosmic microwave background (CMB)



Fermilab 95-759

Dark-Matter properties:

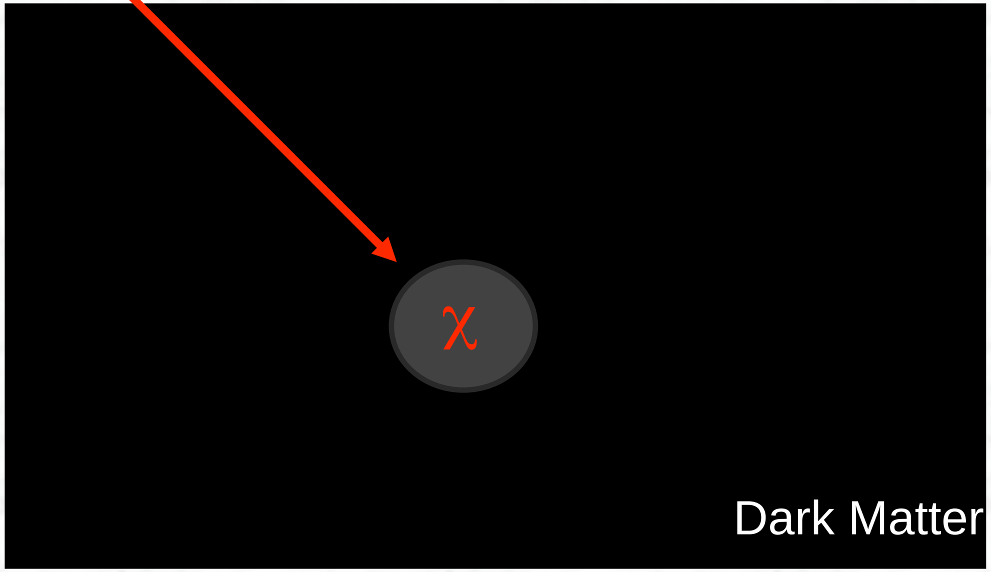
- Gravitationally interacting
- Not short-lived
- Not hot
- Not baryonic, no el. magnetic interaction

→ Unambiguous evidence for new physics !

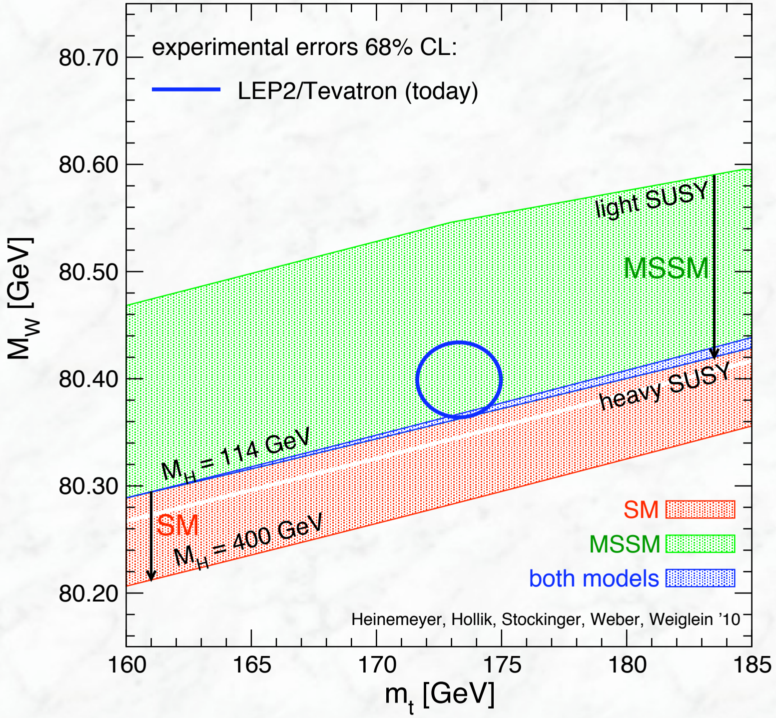
- SUSY has a weakly interacting massive particle (WIMP), if R-parity is conserved:

the lightest supersymmetric particle

- LSP = lightest neutralino, gravitino (depending on SUSY model)

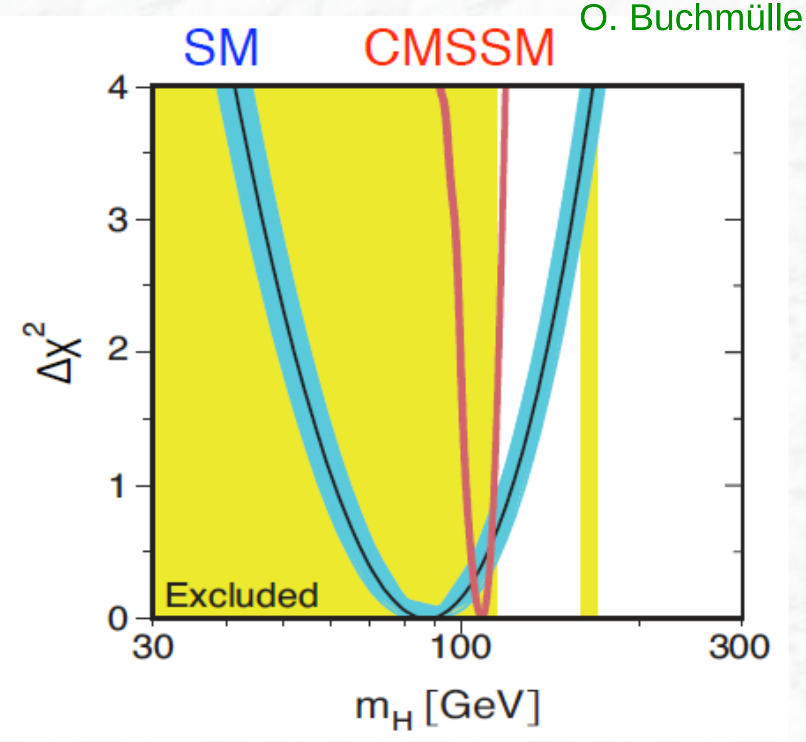


(iv) SUSY is compatible with the electroweak precision measurements



Fit in the constrained MSSM

O. Buchmüller et al. (2010)



Includes:

- WMAP
- $b \rightarrow s\gamma$
- a_μ

$$m_H = 108^{+6}_{-6}\ GeV$$

Leads to even tighter upper limit on Higgs mass: m_h < ~ 130 GeV

(h = lightest MSSM Higgs; it is expected to be similar to the SM Higgs)

9.3 Breaking of Supersymmetry

- or the dark side of SUSY -

- Supersymmetry cannot be an exact symmetry, since we have not seen SUSY particles with masses equal to the Standard Model particles (e.g. no scalar electrons with masses of 511 keV)

- It is expected that supersymmetry is broken spontaneously, i.e. the underlying model should have a Lagrangian density that is invariant under supersymmetry, but a vacuum state that is not.

- The mechanism of SUSY breaking is not known

- Our ignorance is parametrized by introducing extra terms that break SUSY explicitly (so called soft SUSY breaking terms*) into the Lagrangian and consider it as an “effective” Lagrangian

- → about 105 parameters are introduced:
  masses, couplings, mixing angles…..

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*) only such terms are allowed that guarantee that no new quadratically divergent radiative corrections appear

A general parametrization comprises:

- Scalar mass terms: $m_{0_i}^2 \phi_i^2$
- Gaugino mass terms $\frac{1}{2} M_a V_a^T C V_a$
- Coupling terms of scalar particles $A_\lambda \lambda \phi^3$, $B_\mu \mu \phi^2$

It is often assumed that these supersymmetry breaking terms originate at some high scale (Grand Unification scale (GUT scale), or gravity scale)
…. maybe linked to some supergravity or superstring mechanism

It is furthermore often assumed that the soft supersymmetry-breaking terms are universal at the GUT or supergravity scale

If one assumes universality for all masses and couplings at the GUT scale, the following five parameters suffice to characterize the MSSM (Minimal Supersymmetric Standard Model)

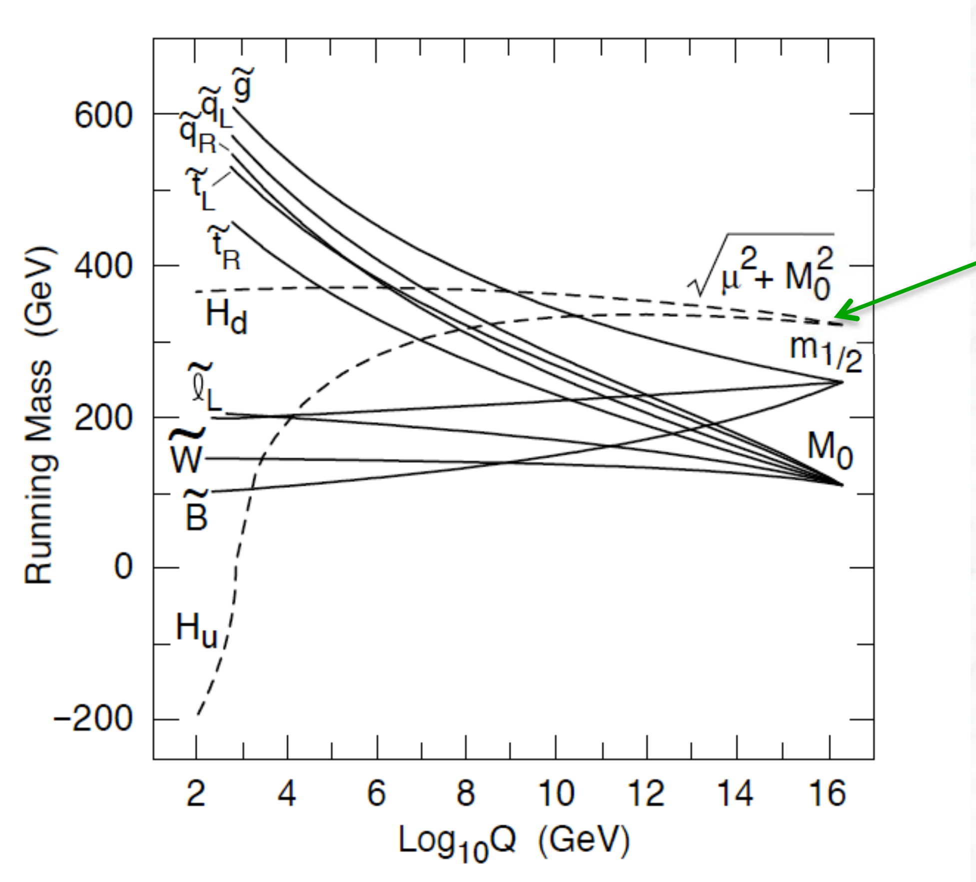
<u>Five parameters:</u>

m_0, $m_{1/2}$	particle masses at the GUT scale
A_0	common coupling term
$\tan\beta$	ratio of vacuum expectation value of the two Higgs doublets
μ	Higgs mass term

The parameters μ and $\tan\beta$ are related to the Higgs sector of the MSSM and determine this sector –together with one Higgs mass, e.g. m_A - at tree level completely.

This model is referred to as “constrained MSSM”

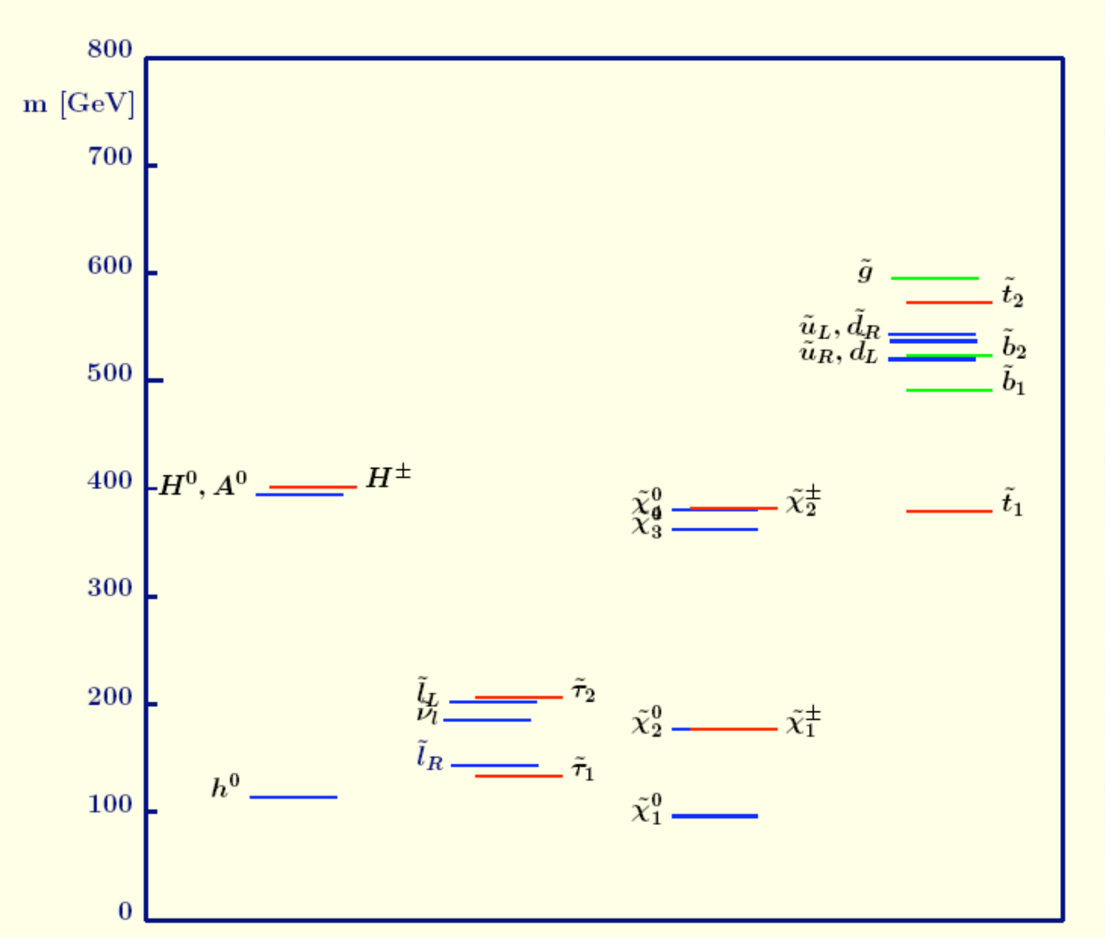
The energy dependence of the SUSY particle masses can be calculated (renormalization group equations)



In this example a separate Higgs mass term is used at the GUT scale

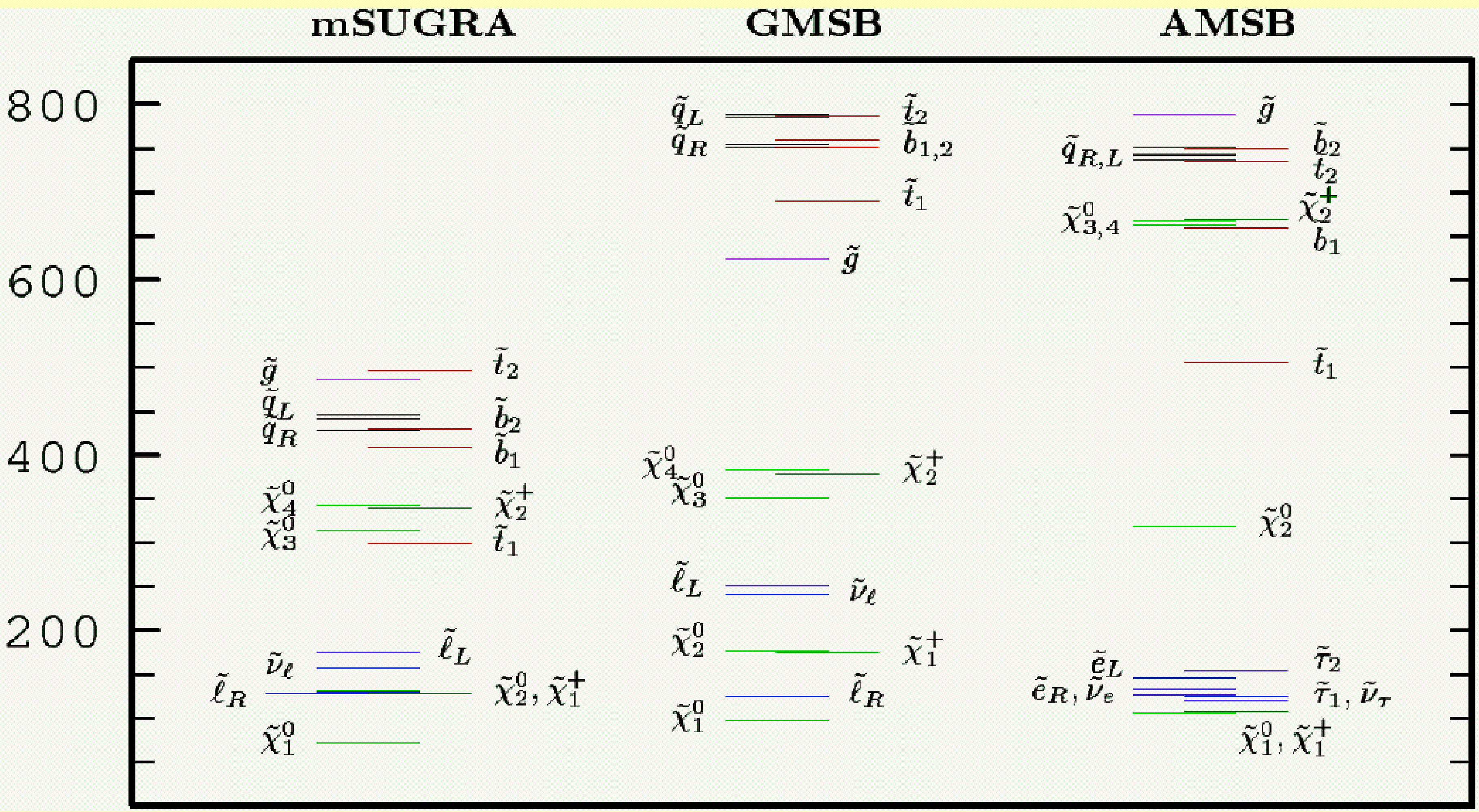
- In such models, squarks and/or gluinos are the heaviest sparticles
- Stops might be the lightest squarks
- Mixing effects (see later) can lead to mass splitting between t_L and t_R
- Sleptons / charginos / neutralinos are lightest sparticles

Example for a calculated mass spectrum at the electroweak scale:



- In many models, the lightest neutralino is the lightest SUSY particle (LSP)
- Lightest Higgs boson (h^0) might also be light, split from heavier Higgs particles
- Production of SUSY particles at the LHC is dominated by coloured squarks and gluinos

SUSY mass spectra for different SUSY breaking models:



mSUGRA: minimal SUperGRAvity model (gravity responsible for SUSY breaking)
GMSB: Gauge mediated SUSY Breaking (breaking via gauge interactions)
AMSB: Anomaly mediated SUSY Breaking

Sparticle Masses and Mixing

(i) Sfermions:

- Each flavour of charged lepton or quark has both left- and right handed components, $f_{L,R}$ and these have separate spin-0 boson superpartners $f'_{LR.}$
- The superpartners can mix, and the mass matrix in MSSM is given by:

$$M^2_{\tilde{f}} \equiv \begin{pmatrix} m^2_{\tilde{f}_{LL}} & m^2_{\tilde{f}_{LR}} \\ m^2_{\tilde{f}_{LR}} & m^2_{\tilde{f}_{RR}} \end{pmatrix}$$

where the off-diagonal mixing terms take the general form (with m_f being the corresponding fermion mass).

$$m^2_{\tilde{f}_{L,R}} = m_f \left(A_f + \mu^{\tan\beta}_{\cot\beta} \right) \quad \text{for} \quad f =^{e,\mu,\tau,d,s,b}_{u,c,t}$$

- Since mixing effects are proportional to the SM fermion masses, they are in particular important for third generation sfermions. They are as well enhanced for large tan β.

- Diagonalization of this mass matrix leads to the physical SUSY particle masses. Mixing might split the two states in mass, usually referred to as the lighter f'_1 and the heavier state f'_2.

Sparticle Masses and Mixing

(ii) Charginos:

- Charginos are the supersymmetric partners of the $W^{\pm}$ and charged Higgs bosons $H^{\pm}$.

  Their masses are determined via the parameters: $M_{2,}$ μ and tan β, via the mass mixing matrix M_C:

$$-\frac{1}{2}\,(\tilde{W}^-, \tilde{H}^-)\;\; M_C\;\; \begin{pmatrix} \tilde{W}^+ \\ \tilde{H}^+ \end{pmatrix} \;\; + \;\; \text{herm.conj.}$$

$$M_C \equiv \begin{pmatrix} M_2 & \sqrt{2} m_W \sin\beta \\ \sqrt{2} m_W \cos\beta & \mu \end{pmatrix}$$

where M_2 is the unmixed SU(2) gaugino mass and μ is the Higgs mass parameter.

Sparticle Masses and Mixing

(ii) Neutralinos:

- Masses of neutralinos, the supersymmetric partners of the neutral fields

  $(\tilde{W}^3, \tilde{B}, \tilde{H}_2^0, \tilde{H}_1^0)$

  are given by the following mixing matrix:

$$m_N = \begin{pmatrix} M_2 & 0 & \frac{-g_2 v_2}{\sqrt{2}} & \frac{g_2 v_1}{\sqrt{2}} \\ 0 & M_1 & \frac{g' v_2}{\sqrt{2}} & \frac{-g' v_1}{\sqrt{2}} \\ \frac{-g_2 v_2}{\sqrt{2}} & \frac{g' v_2}{\sqrt{2}} & 0 & \mu \\ \frac{g_2 v_1}{\sqrt{2}} & \frac{-g' v_1}{\sqrt{2}} & \mu & 0 \end{pmatrix}$$

where M_1, M_2 is the unmixed U(1), SU(2) gaugino mass, μ is the Higgs mass parameter, and g_2 and g’ are the gauge couplings of the SU(2) / U(1) group.

Link to the Dark Matter in the Universe ?

Parameters of the SUSY model ⇒ predictions for the relic density of dark matter

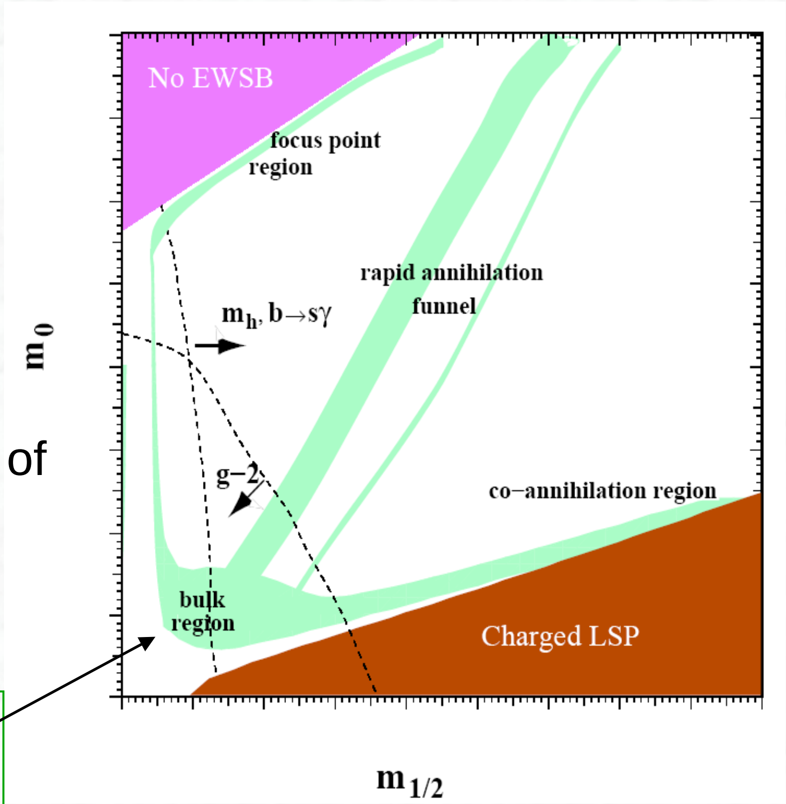
Interpretation in a simplified model

$$\rho_\chi \sim m_\chi n_\chi\,, \quad n_\chi \sim \frac{1}{\sigma_{ann}(\chi\chi \to \ldots)}$$

cMSSM
(constrained Minimal Supersymmetric
Standard Model)

Five parameters:

m_0, $m_{1/2}$	particle masses at the GUT scale
A_0	common coupling term
tan β	ratio of vacuum expectation value of the two Higgs doublets
μ (sign μ)	Higgs mass term



🟩 regions of parameter space which are consistent with the measured relic density of dark matter (WMAP,…..)

9.4 Summary of pre-LHC limits on SUSY masses

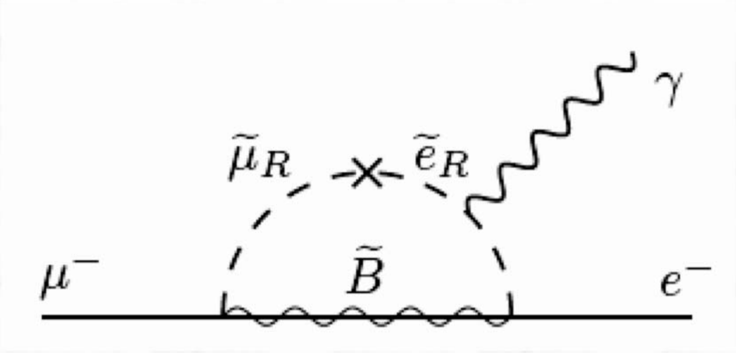
The Search for

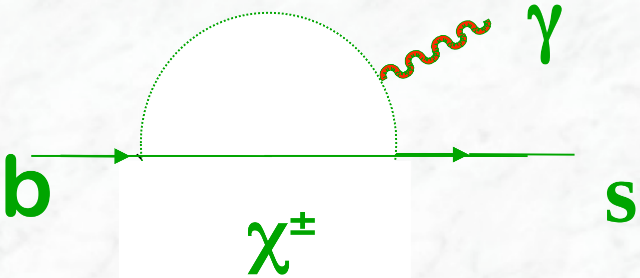
SUSY at LEP and
at the Tevatron

9.4.1 Indirect SUSY searches

- Measure branching fractions of rare decays or search for forbidden decays.

→ Potentially enhanced by SUSY particles “in loops”:

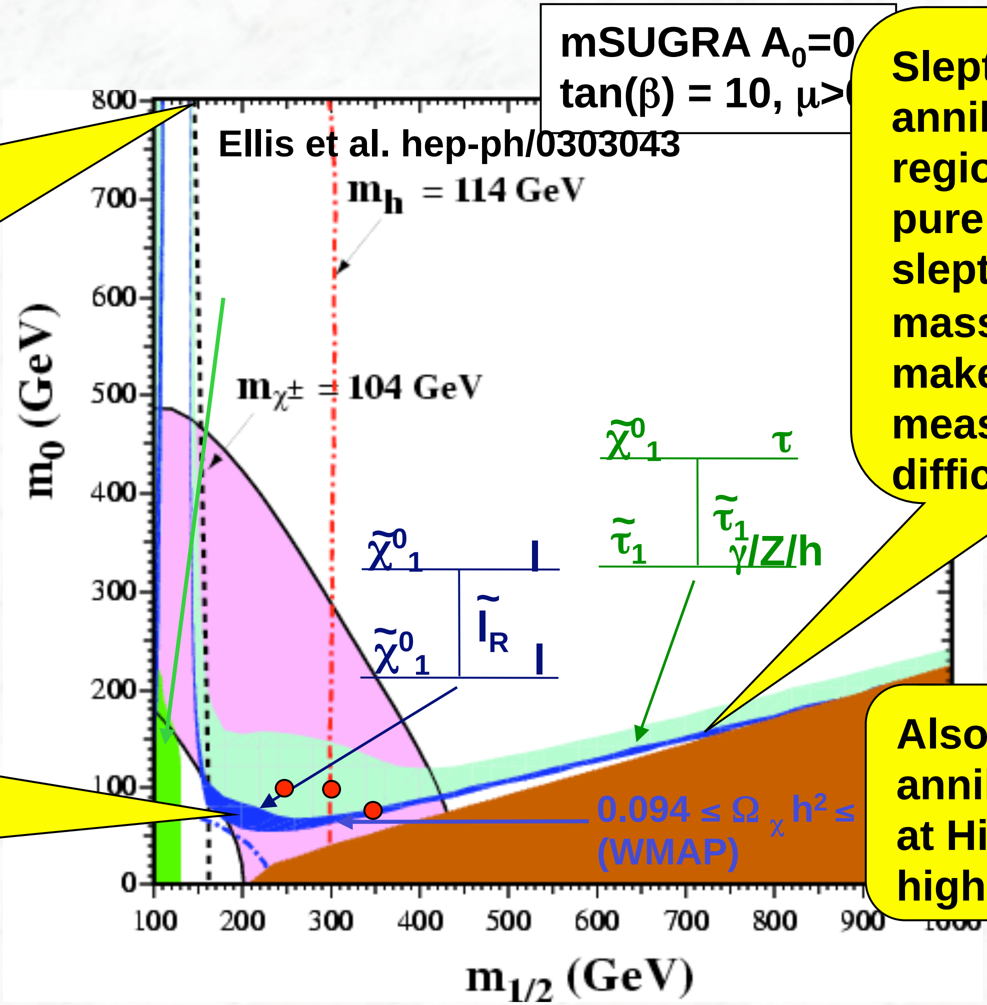




- Measurement of μ anomalous magnetic moment (g_μ-2): Brookhaven

SUSY Dark Matter constraint

- mSUGRA parameter strongly constrained by cosmology (“blue bands”)
- Annihilation and co-annihhilation of dark-matter particles, etc.



'Focus point' region: significant h component to LSP enhances annihilation to gauge bosons

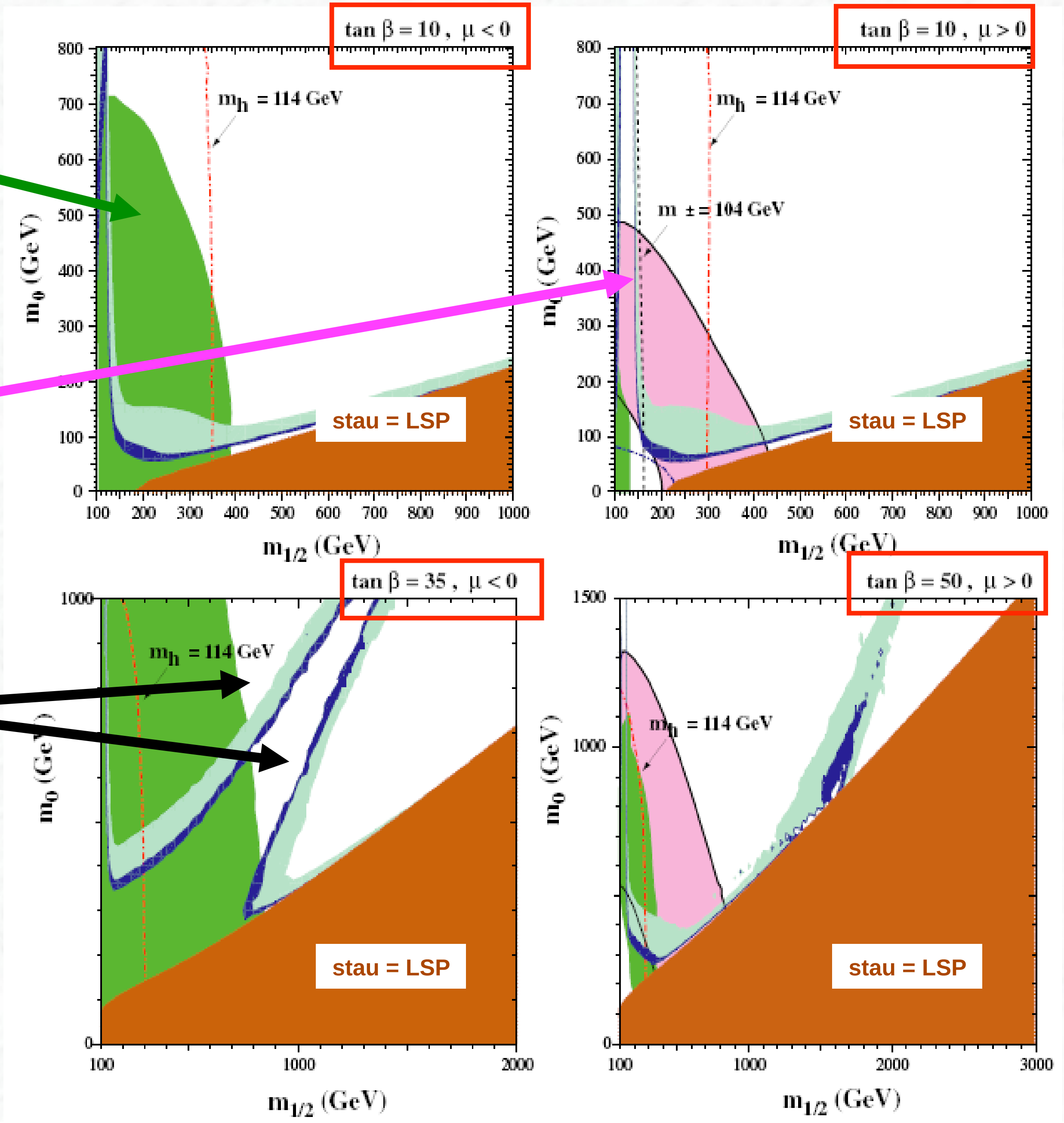
Slepton Co-annihilation region: LSP ~ pure Bino. Small slepton-LSP mass difference makes measurements difficult.

'Bulk' region: t-channel slepton exchange - LSP mostly Bino.

Also 'rapid annihilation funnel' at Higgs pole at high tan(β),

Precision experiments and cosmology

- $b \rightarrow s\gamma$ excluded
- g_μ-2 favoured
- Dark matter favoured

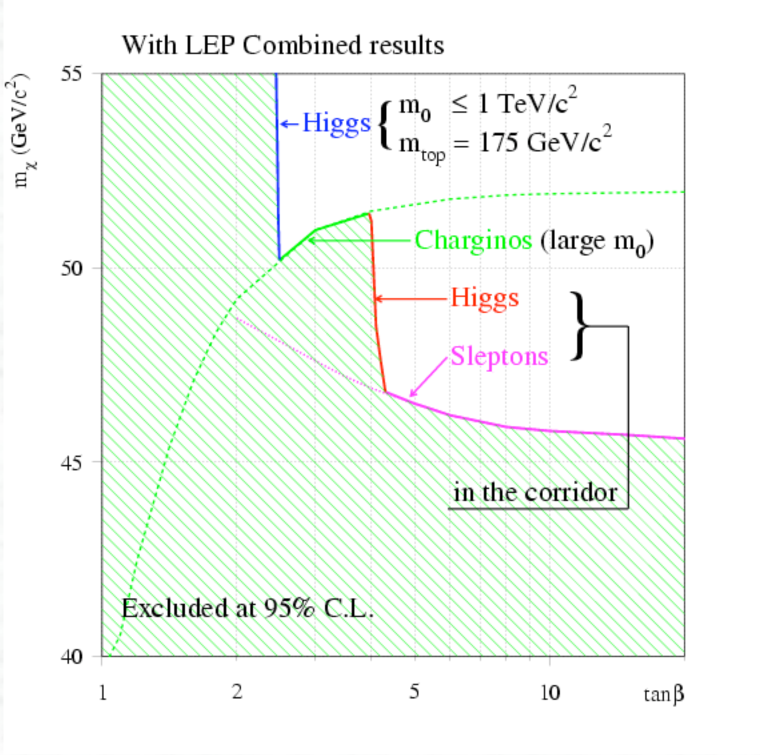


SUSY already quite confined, but there are still many possibilities

→ Need discovery at LHC

Summary of present **SUSY mass limits** from colliders

m (sleptons, charginos) > 90-103 GeV LEP II
m (squarks, gluinos) > ~ 350 GeV Tevatron
m (LSP, lightest neutralino) > ~ 45 GeV LEP II



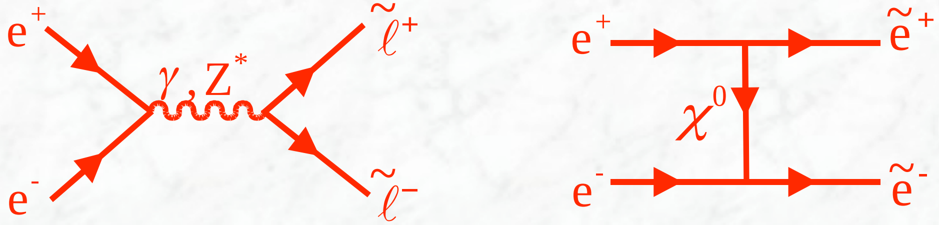
LEP-II limit on the mass of the Lightest SUSY particle

assumption:
lightest neutralino = LSP

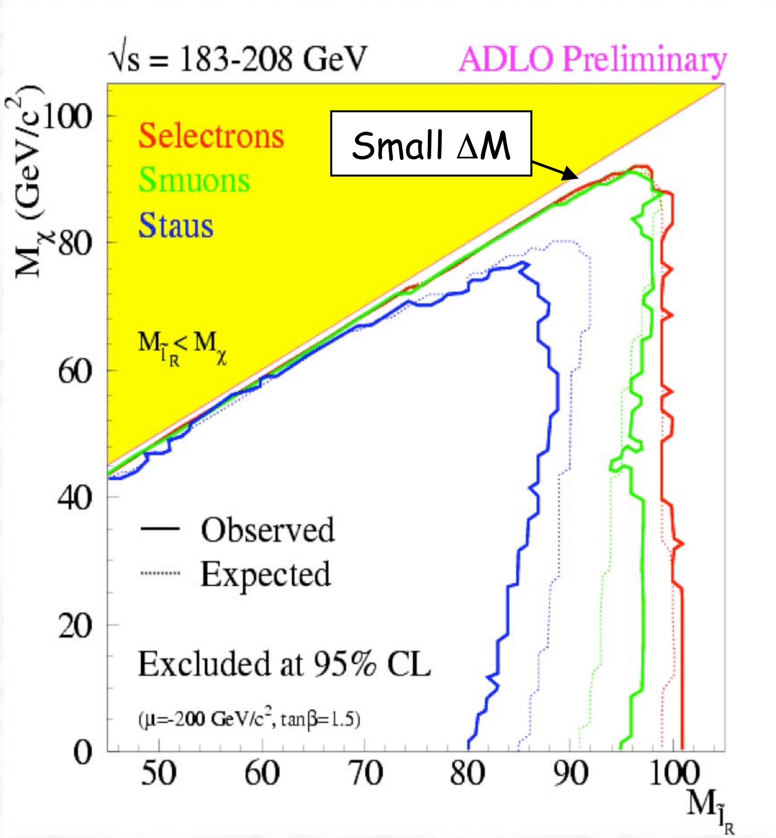
Direct searches for sleptons at LEP

- Clear domain of LEP are Slepton & Chargino/Neutralino searches (e^+e^-, E_{cm}~ 200 GeV)

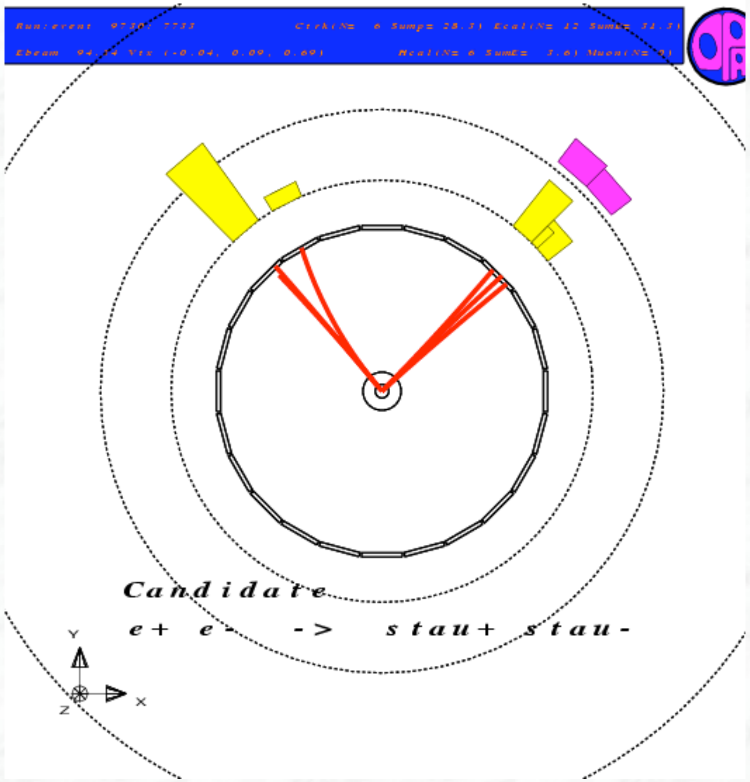
→ Excluded up to masses of 80 … 100 GeV (~ $E_{cm}/2$)



$\tilde{\ell} \to \ell\, \chi^0_1$ **(2 leptons + missing E)**

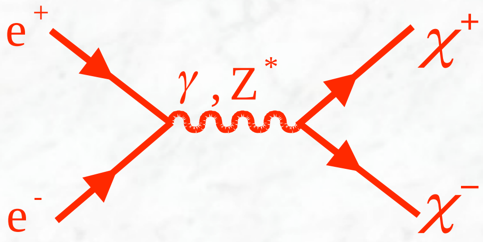


OPAL stau event candidate



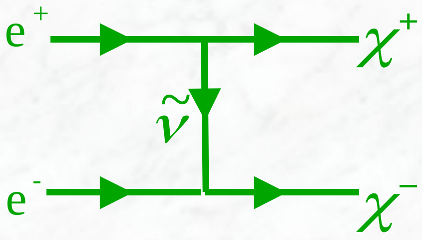
Direct searches for charginos at LEP

Large m_0 ($\tilde{\ell}$ are heavy)



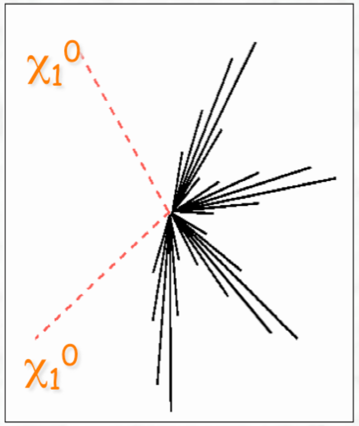
$$\chi^+\chi^- \to W^*\chi^0{}_1 W^*\chi^0{}_1$$

Small m_0 ($\tilde{\ell}$ are light)

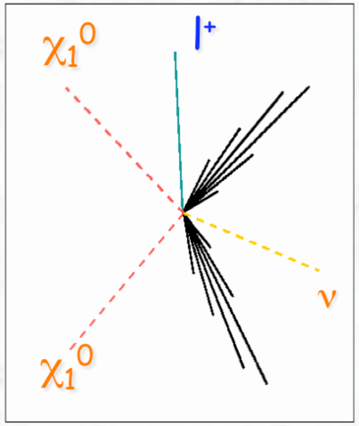


$$\chi^+\chi^- \to \ell^+\tilde{\nu}\,\ell^-\tilde{\nu} \to \ell^+\nu\chi^0{}_1\ell^-\nu\chi^0{}_1$$

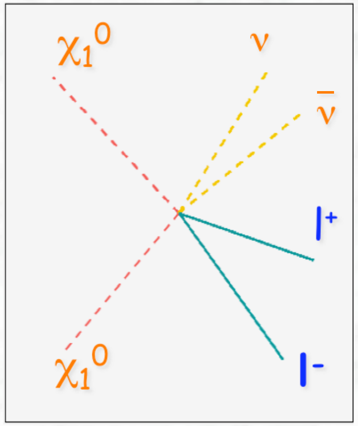
WW → qqqq



WW → lνqq



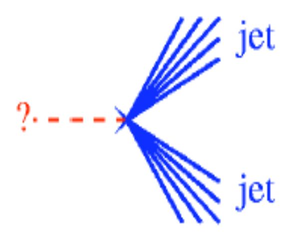
WW → lν lν

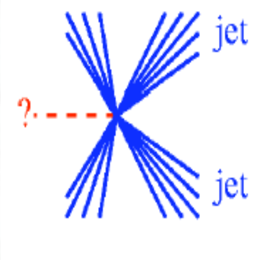


Main SM backgrounds (WW, ZZ production) suppressed by requiring large missing mass or missing energy in the event.

The two classical SUSY signatures at the Tevatron

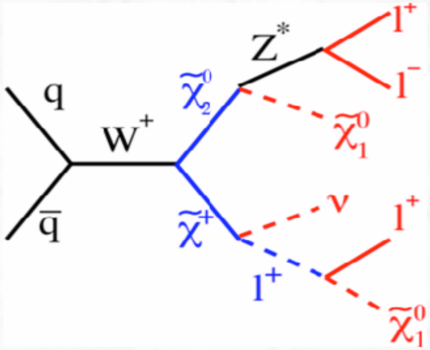
1. Search for Squarks and Gluinos: Jet + E_T^{miss} signature
   produced via QCD processes





2. Search for Charginos and Neutralinos: Multilepton + E_T^{miss} signature
   produced via electroweak processes (associated production)

$$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow l^\pm l^\mp l^\pm \tilde{\chi}_1^0 \tilde{\chi}_1^0 X$$



Search for Squarks and Gluinos

- Three different analyses, depending on squark / gluinos mass relations:

  (i) dijet analysis
  small m_0, m(squark) < m(gluino)

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

  (ii) 3-jet analysis
  intermediate m_0 m(squark) ≈ m(gluino)

  $$\tilde{q}\tilde{g} \rightarrow q\tilde{\chi}_1^0 q\bar{q}\tilde{\chi}_1^0$$

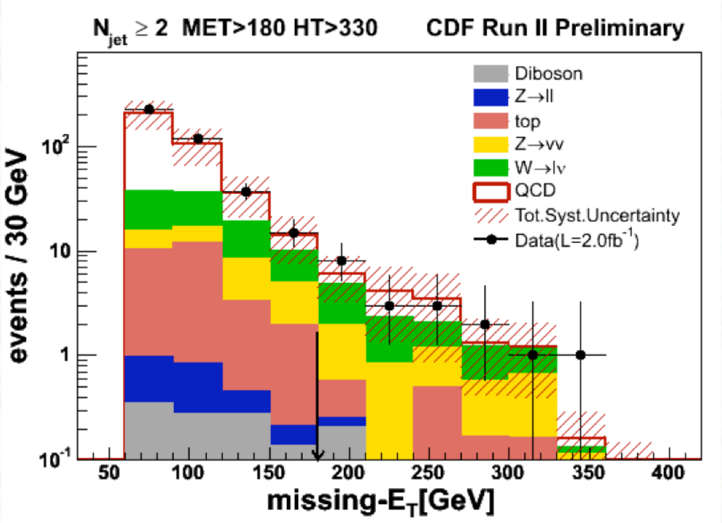
  (iii) Gluino analysis
  large m_0, m(squark) > m(gluino)

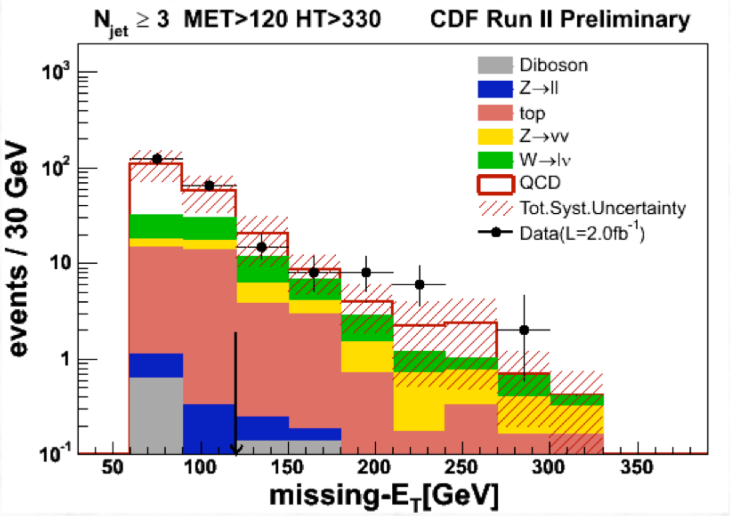
  $$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0 q\bar{q}\tilde{\chi}_1^0$$

- Main backgrounds: Z → νν + jets, tt, W + jet production

- Event selection:
  - * require at least 2, 3 or 4 jets with P_T > 60 / 40 / 30 / 20 GeV
  - * veto on isolated electrons and muons
  - * isolation of E_T^{miss} and all jets
  - * optimization of the final cuts → discriminating variables

Search for Squarks and Gluinos (cont.)





Expected background:

samples	2-jets	3-jets	4-jets
QCD	4.37±2.01	13.34±4.67	15.26±7.60
top	1.35±1.22	7.56±3.85	22.14±7.29
Z→ $\nu\nu$+jets	3.95±1.09	5.39±1.74	2.74±0.95
Z→ ll+jets	0.09±0.04	0.16±0.11	0.14±0.08
W→ $l\nu$+jets	6.08±2.15	10.69±3.84	7.68±2.85
WW/WZ/ZZ	0.21±0.19	0.35±0.17	0.49±0.34
tot SM	16±5	37±12	48±17

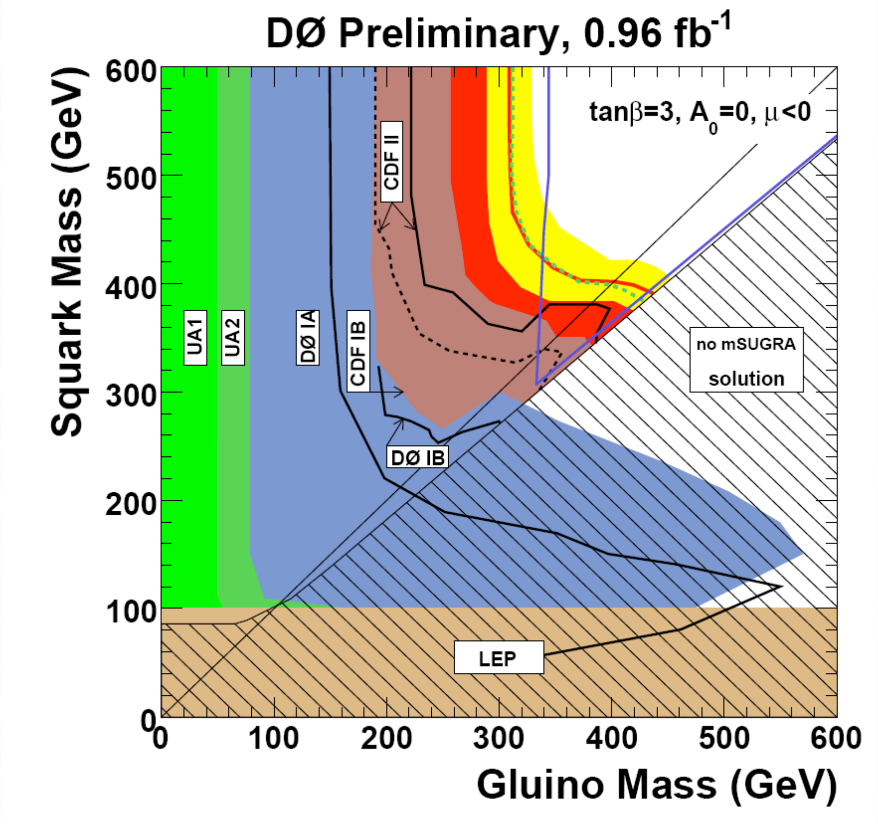
Observed events in data:

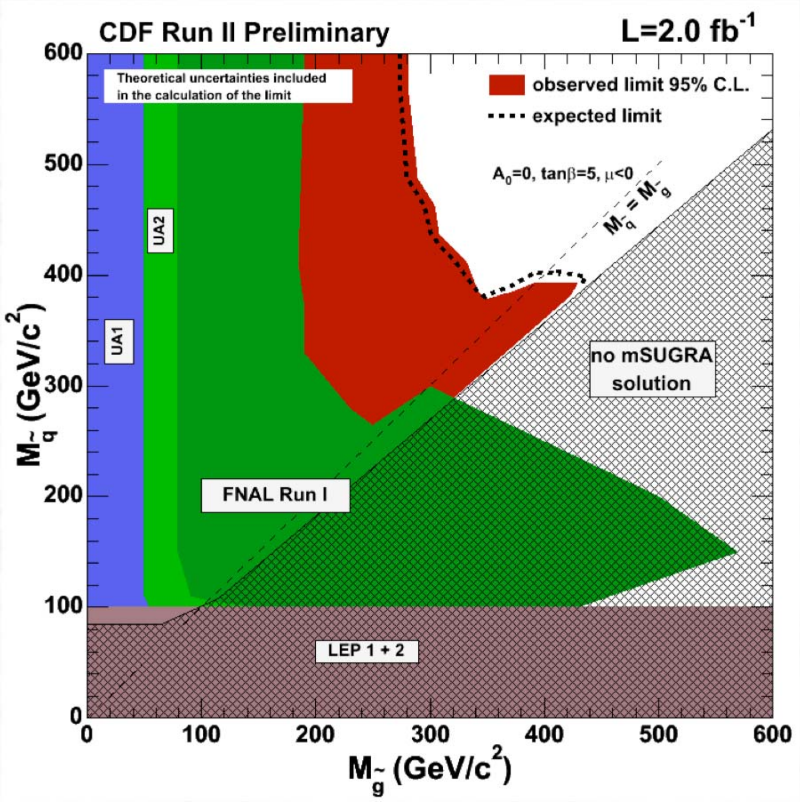
Region	Observed data
4-jets	45
3-jets	38
2-jets	18

No excess above background from Standard Model processes

→ No evidence for SUSY (yet) → Set limits on masses of SUSY particles

Excluded regions in the m(squark) vs. m(gluino) plane





Exclusion limits

(incl. systematic uncertainties)*:

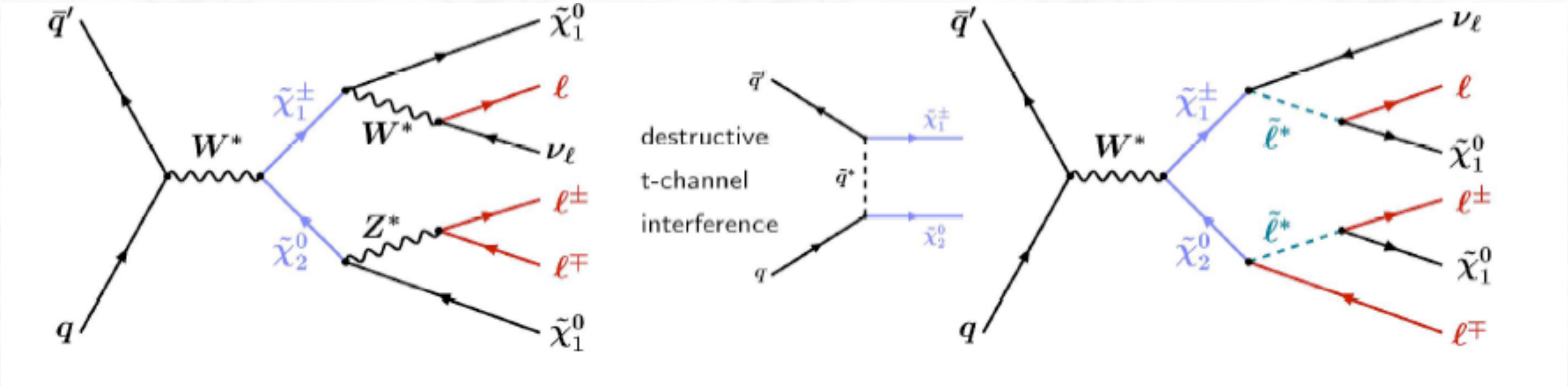
m(gluino) > 290 GeV/c^2

m(squark) > 375 GeV/c^2

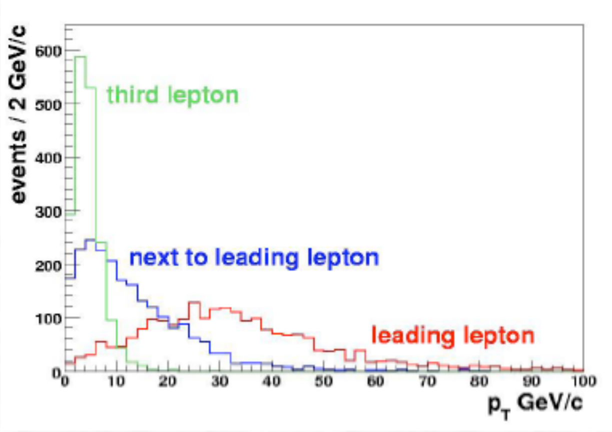
)* uncertainties from structure functions, change of renormalization and factorization scale μ by a factor of 2, NLO calculation, default choice: μ = m(gluino), m(squark) or ½(m(gluino)+m(squark)) for gg, qq, qg production

Search for Charginos and Neutralinos
- the tri-lepton channel-

- Gaugino pair production via electroweak processes
  (small cross sections, ~0.1 – 0.5 pb, however, small expected background)



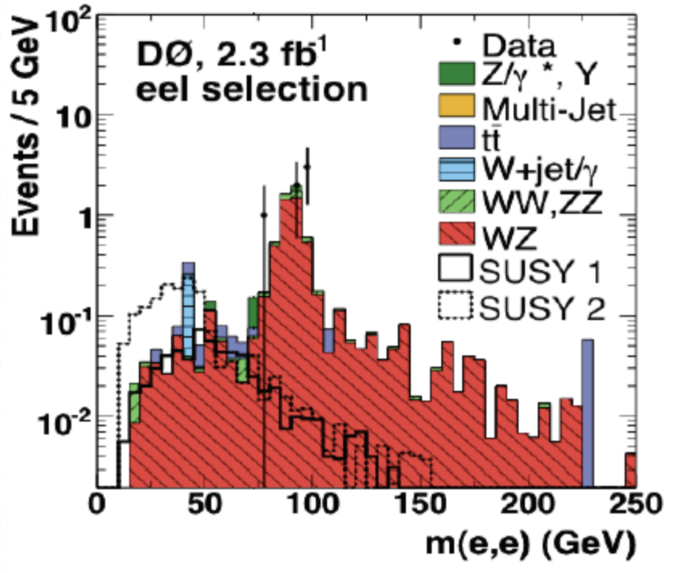
- For small gaugino masses (~100 GeV/c^2)
  one needs to be sensitive to low P_T leptons

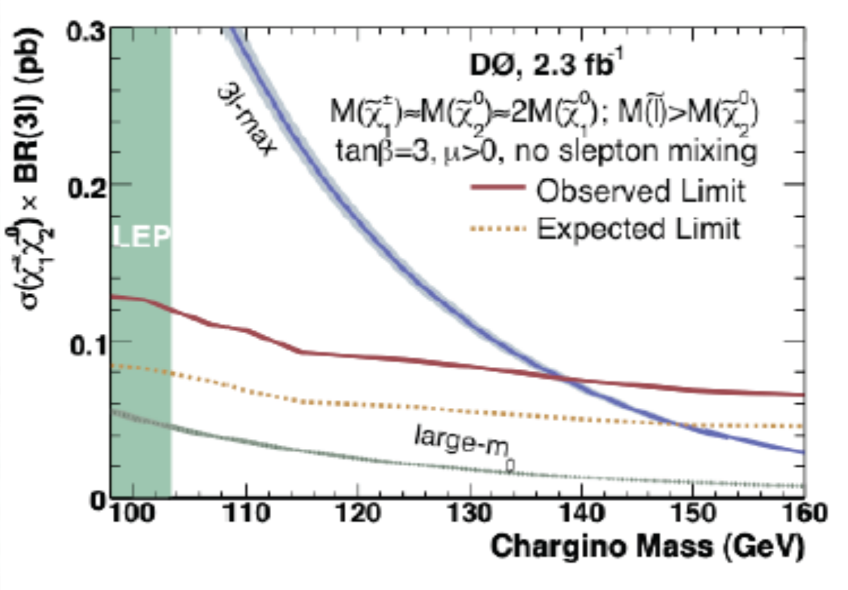


Analysis:

- Search for different (ℓℓℓ) + like-sign μμ final states with missing transverse momentum
- In order to gain efficiency, no lepton identification is required for the 3rd lepton, select: two identified leptons + a track with p_T > 4 GeV/c

mSUGRA interpretation





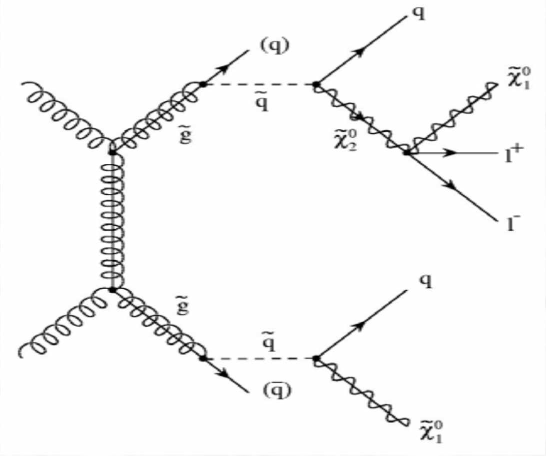
For specific scenarios: sensitivity / limits above LEP limits;
e.g., $M(\chi^\pm)$ > 140 GeV/c^2 for the 3l-max scenario

9.5 Search for Supersymmetry at the LHC

- If SUSY exists at the electroweak scale, a discovery at the LHC should be easy

- Squarks and Gluinos are strongly produced

  They decay through cascades to the lightest SUSY particle (LSP)



⇒ combination of
Jets, Leptons, E_T^{miss}

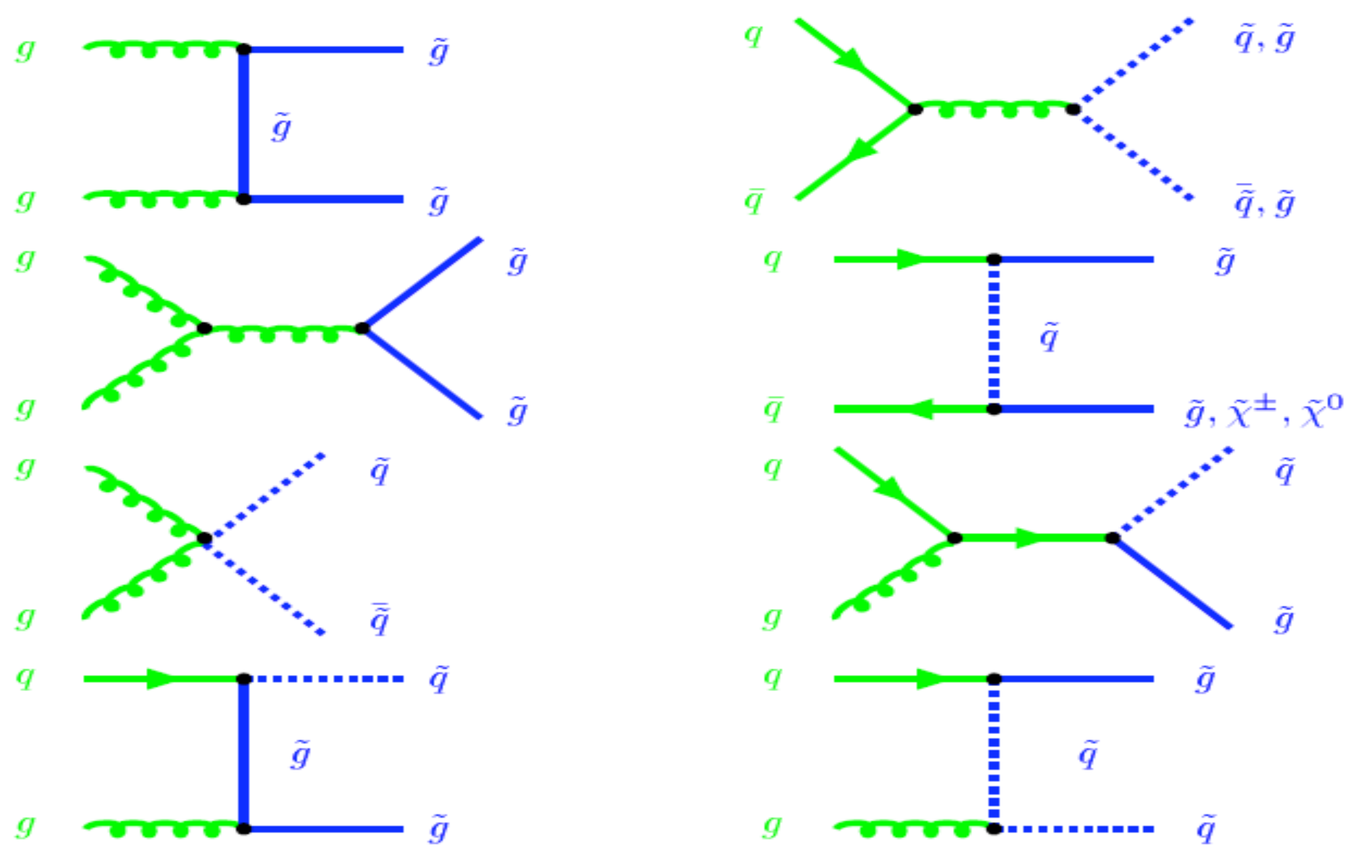
1. Step: Look for deviations from the Standard Model
   Example: Multijet + E_T^{miss} signature

2. Step: Establish the SUSY mass scale use inclusive variables, e.g. effective
   mass distribution

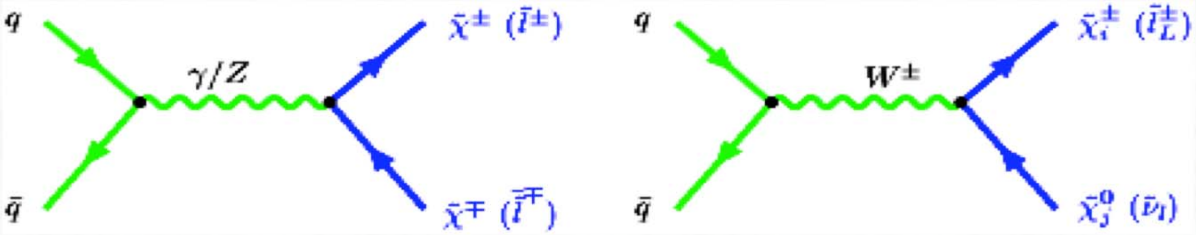
3. Step: Determine model parameters (difficult)
   Strategy: select particular decay chains and use kinematics to
   determine mass combinations

Sparticle production at the LHC

Quark-gluon fusion

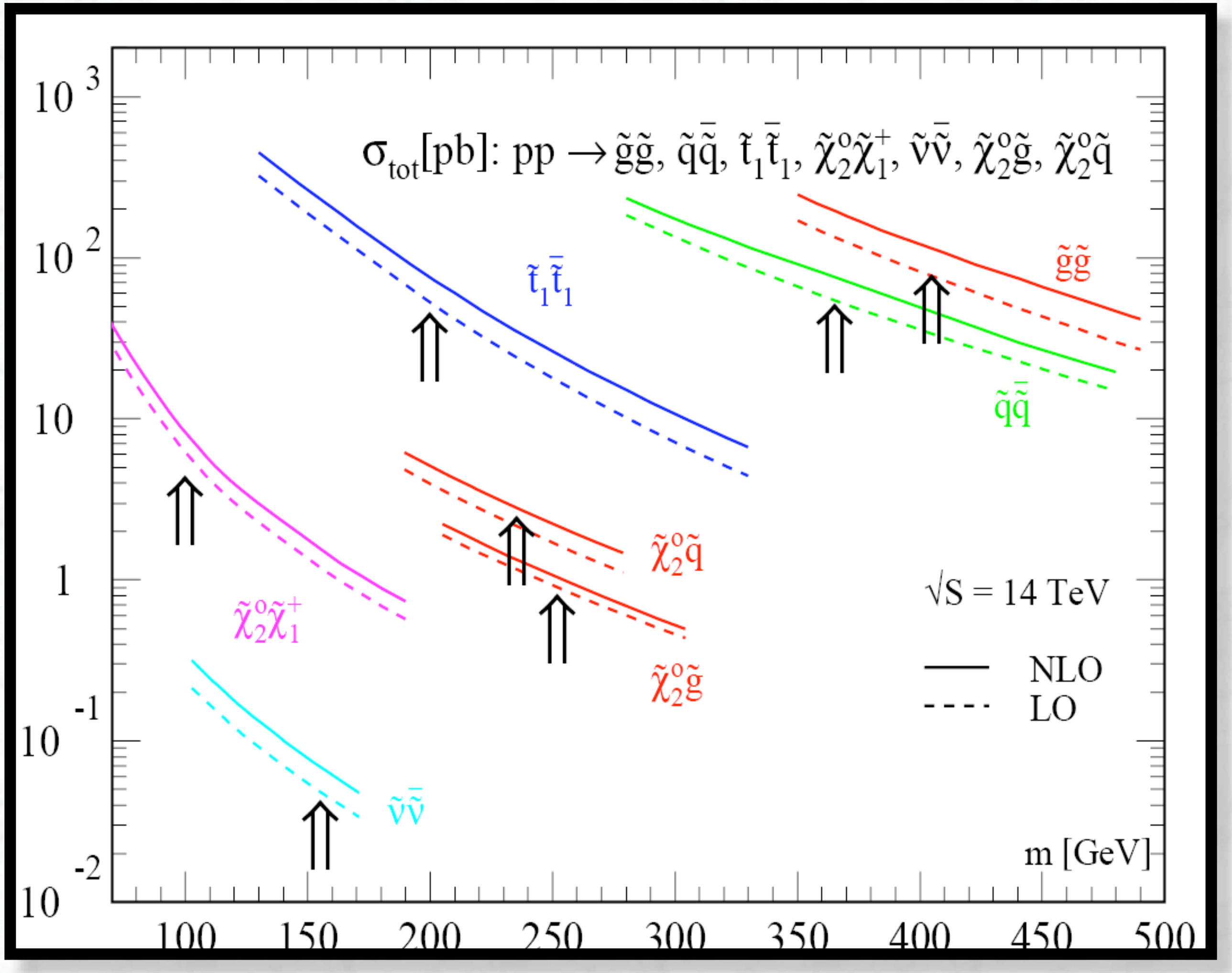


Quark annihilation



Cross sections for SUSY production processes

σ (pb)



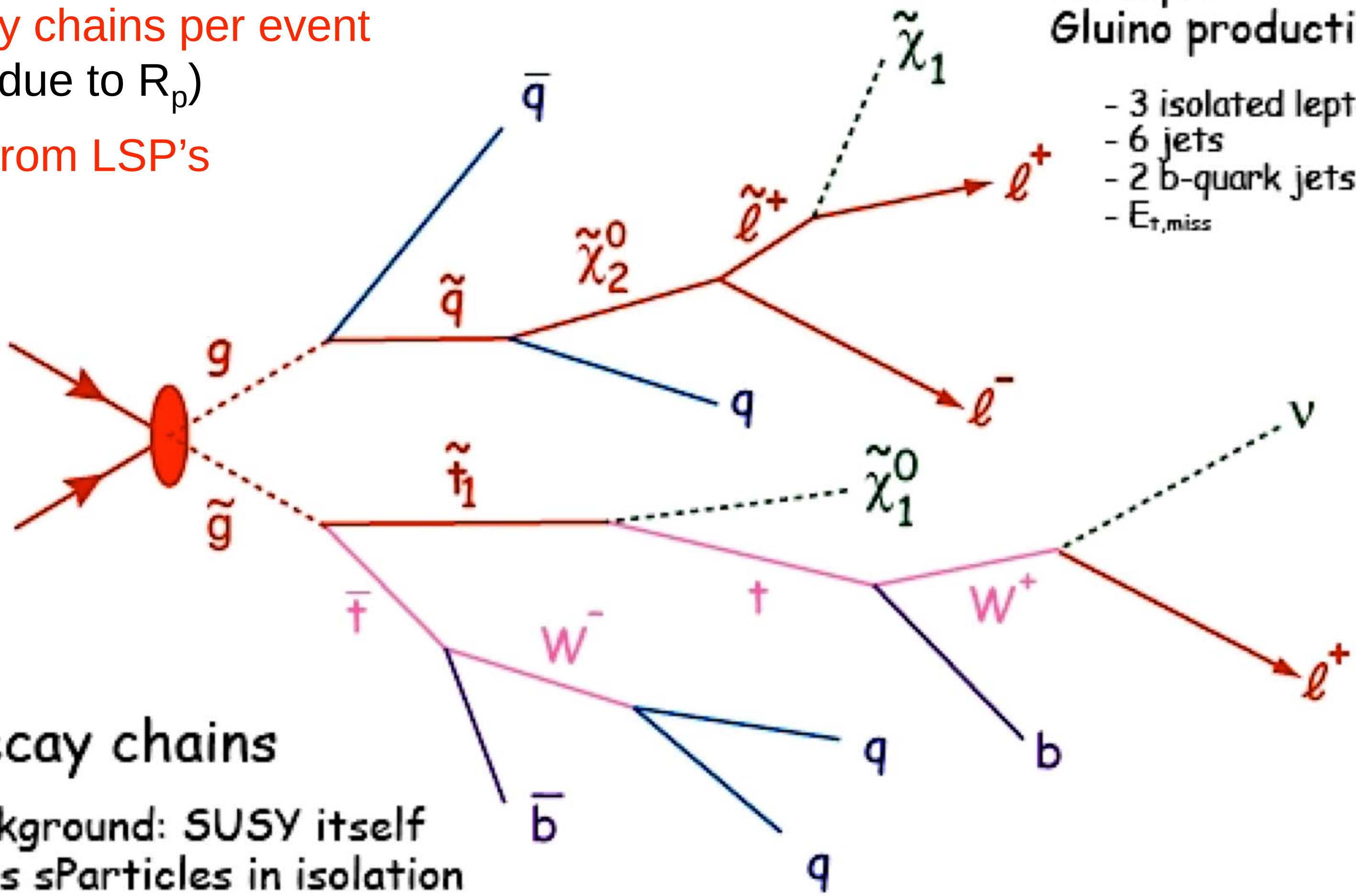
M (GeV)

Examples of SUSY decay chains at the LHC:

- Long, complex decay chains (at the end: SM particles and LSP's)
- Two SUSY decay chains per event
  (pair production due to R_p)
- Missing energy from LSP's

Example:
Gluino production

- 3 isolated leptons
- 6 jets
- 2 b-quark jets
- $E_{t,miss}$

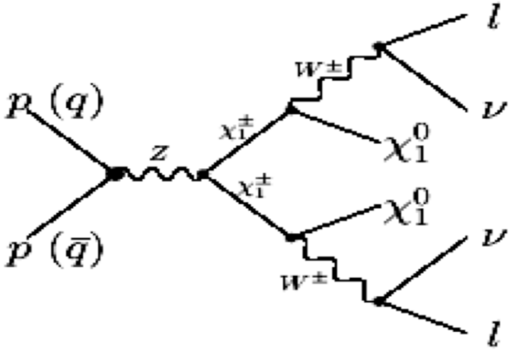
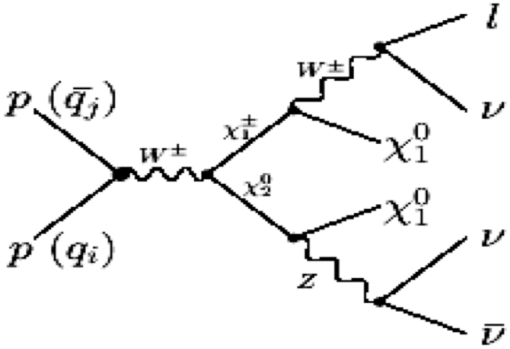
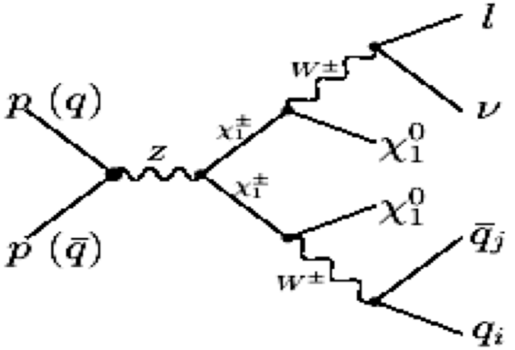
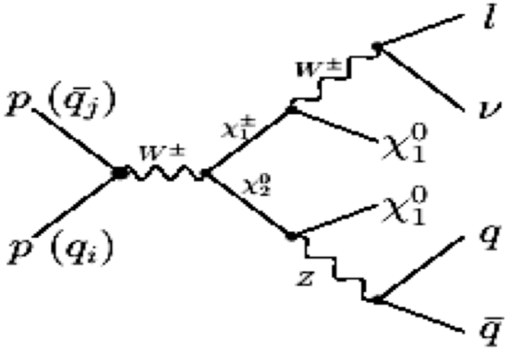
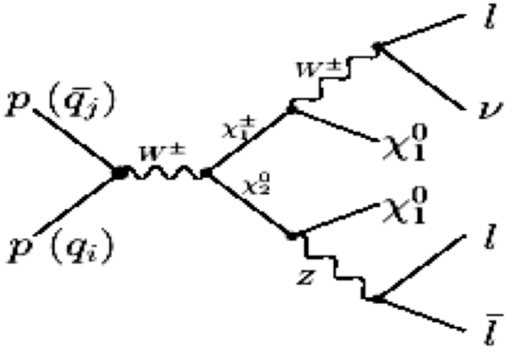
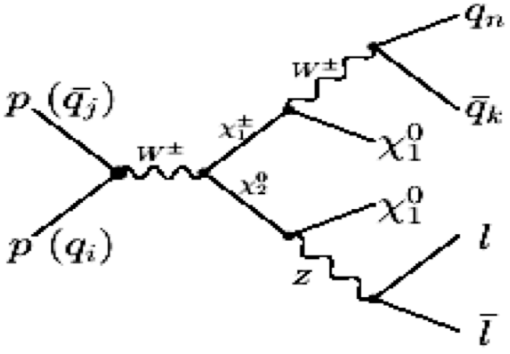


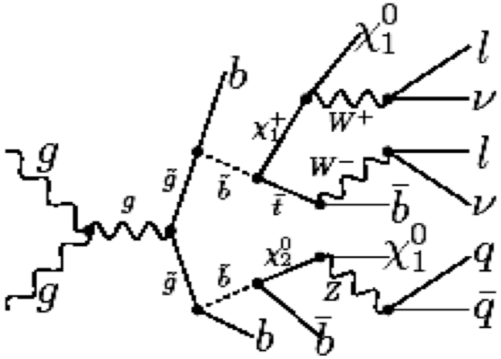
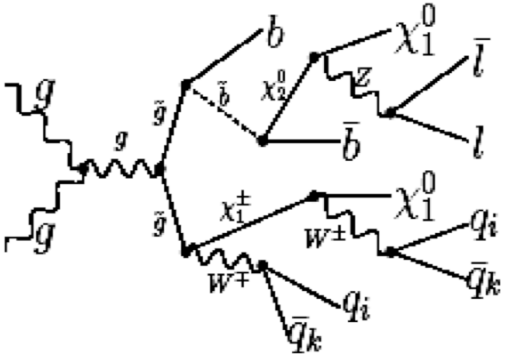
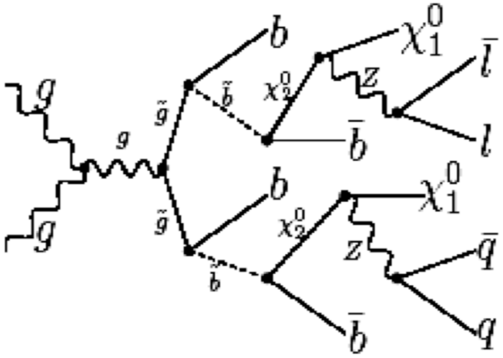
But: Long decay chains

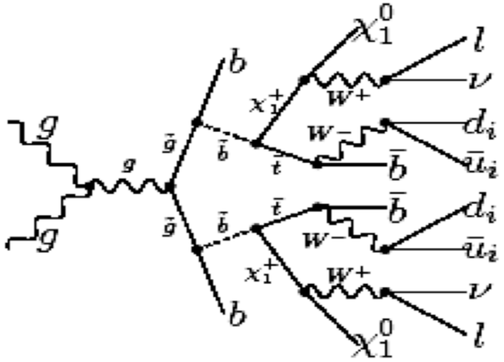
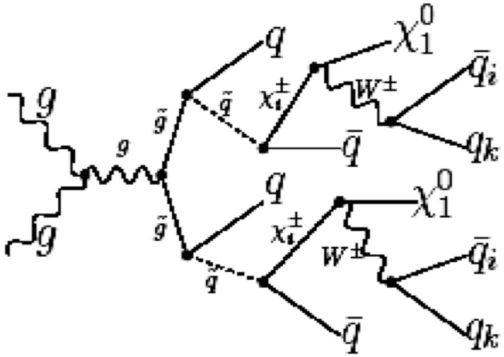
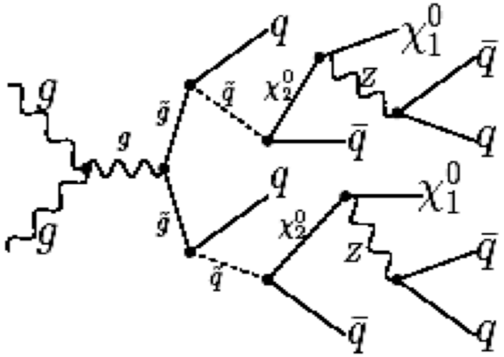
- dominant background: SUSY itself
- cannot discuss sParticles in isolation
- use consistent model for simulation

Typical final states: jets + E_T^{miss} (+ leptons)

SUSY final states, there are many ….

process	final states	process	final states
	2ℓ 2ν $\not\!\!E_T$		ℓ 3ν $\not\!\!E_T$
	1ℓ $2j$ ν $\not\!\!E_T$		ℓ ν $2j$ $\not\!\!E_T$
	3ℓ ν $\not\!\!E_T$		2ℓ $2j$ $\not\!\!E_T$

process	final states
	2ℓ 2ν $6j$ $\not{E}_T$
	2ℓ $6j$ $\not{E}_T$
	2ℓ $6j$ $\not{E}_T$

process	final states
	2ℓ 2ν $8j$ $\not{E}_T$
	$8j$ $\not{E}_T$
	$8j$ $\not{E}_T$

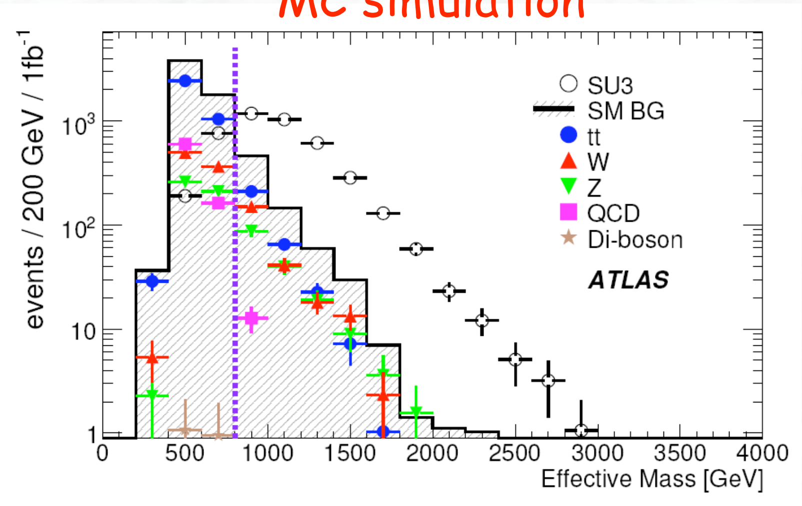
A typical search for squark and gluino production

- If R-parity conserved, cascade decays produce distinctive events: multiple jets, leptons, and E_T^{miss}

- Typical selection: $N_{jet} > 4$, $E_T > 100, 50, 50, 50$ GeV, $E_T^{miss} > 100$ GeV

- Define: $M_{eff} = E_T^{miss} + P_T^1 + P_T^2 + P_T^3 + P_T^4$ (effective mass)

MC simulation



example: mSUGRA, point SU3 (bulk region)
m_0 = 100 GeV, $m_{1/2}$ = 300 GeV
tan β = 6, A_0 = -300 GeV, $\mu > 0$

Expectations from simulations:

LHC reach for squark- and gluino masses:
0.1 fb^{-1} ⇒ M ~ 750 GeV
1 fb^{-1} ⇒ M ~ 1350 GeV
10 fb^{-1} ⇒ M ~ 1800 GeV

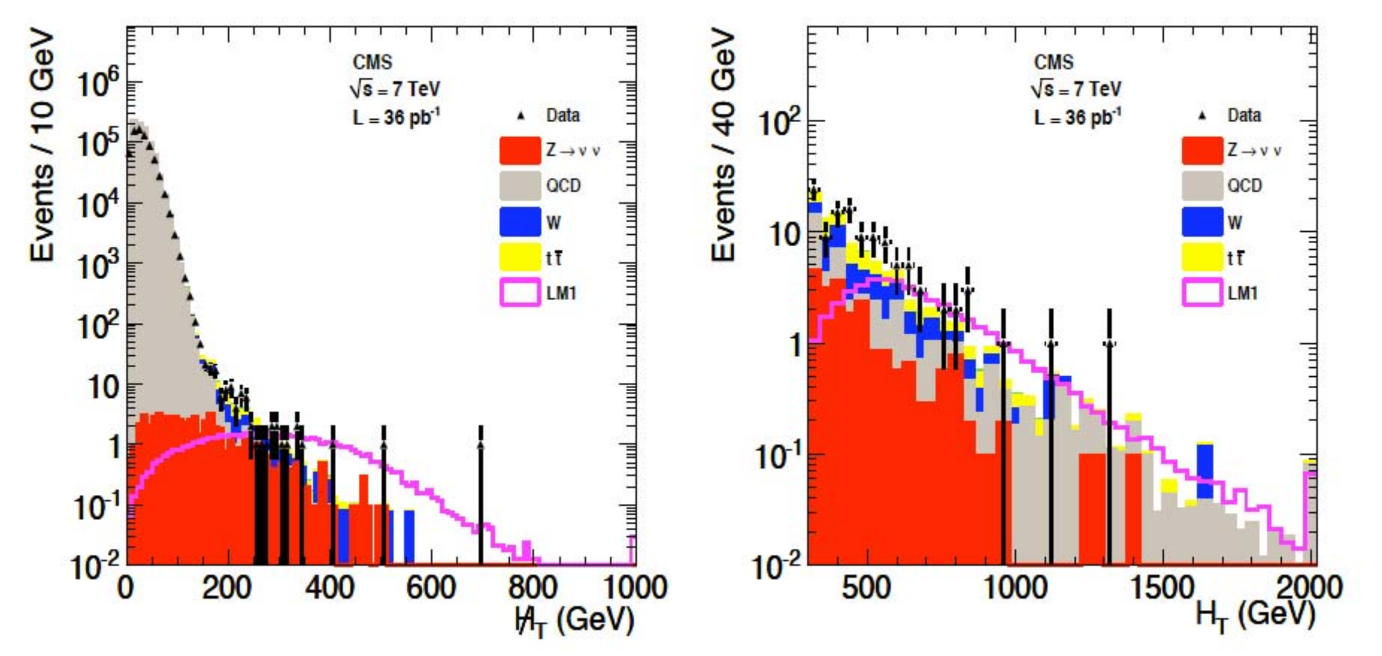
Deviations from the Standard Model due to SUSY at the TeV scale can be detected fast !

What do the LHC data say ?

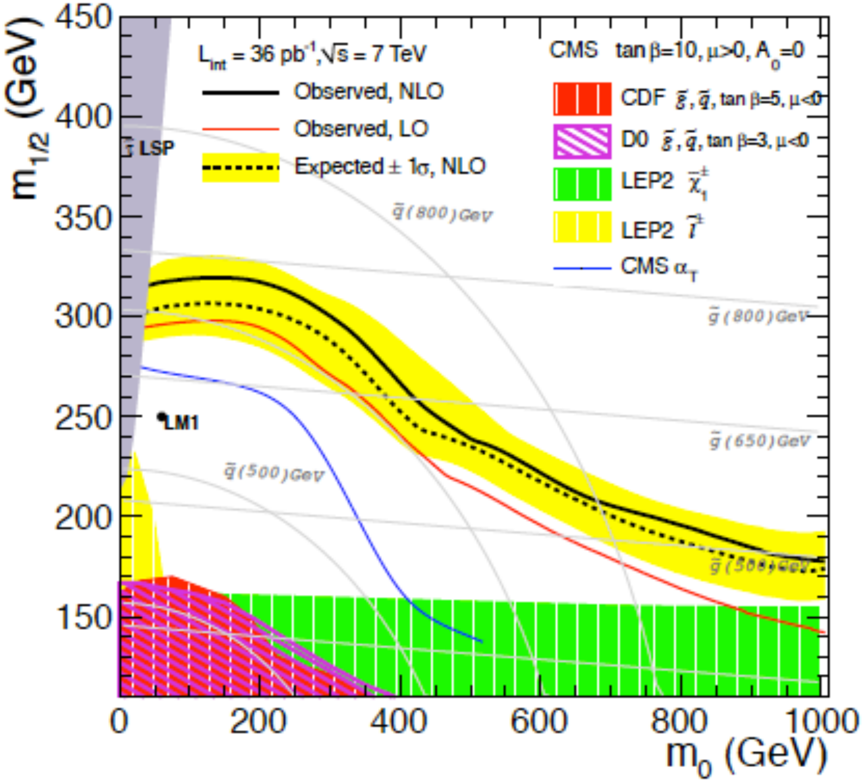
First results on the search for Etmiss + jets, no leptons
(2010 data)

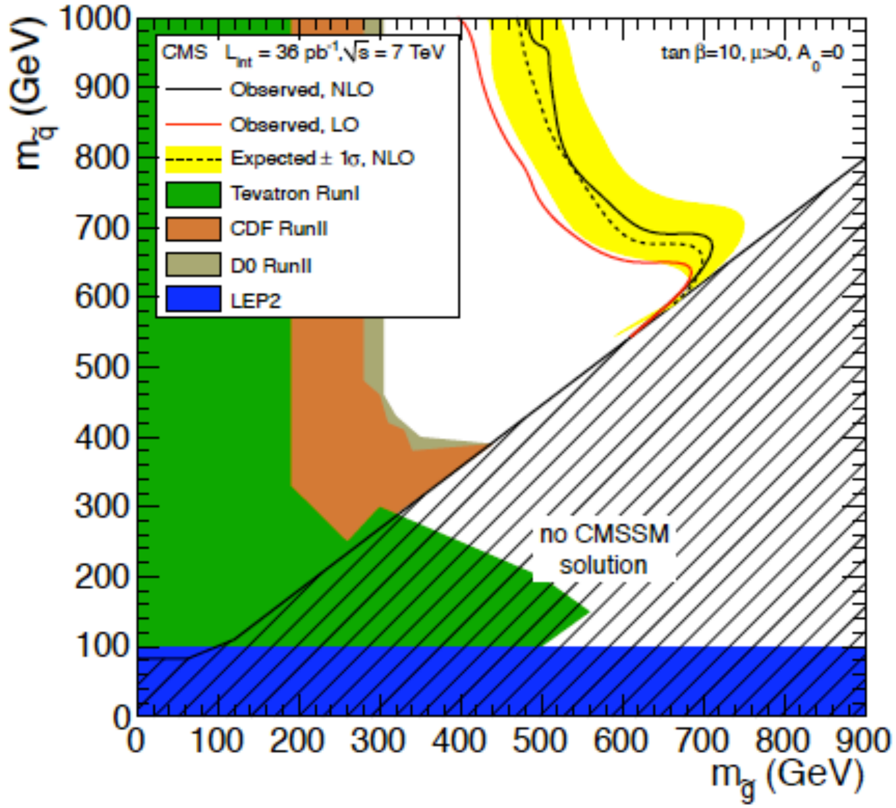
Simple selection:

- 3 jets with $p_T > 50$ GeV , $\eta < 2.5$
- $H_T > 300$ GeV (scalar sum of jets with $p_T > 50$ and $\eta < 2.5$)
- $H_T^{miss} > 150$ GeV (modulus of vector sum of jets with $p_T > 30$ GeV and $\eta < 5$)



- Good agreement between data and expectations from Standard Model processes
- No evidence for an excess → limits in SUSY parameter space





- Significant extension of exclusion contours in the squark-gluino mass plane
- Gluinos below 500 GeV are excluded for m(squarks) < 1000 GeV

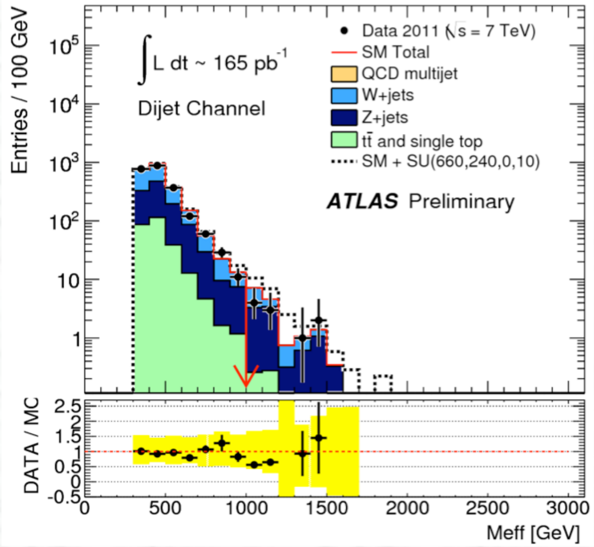
First results on the search for E_T^{miss} + jets (165 pb^{-1})

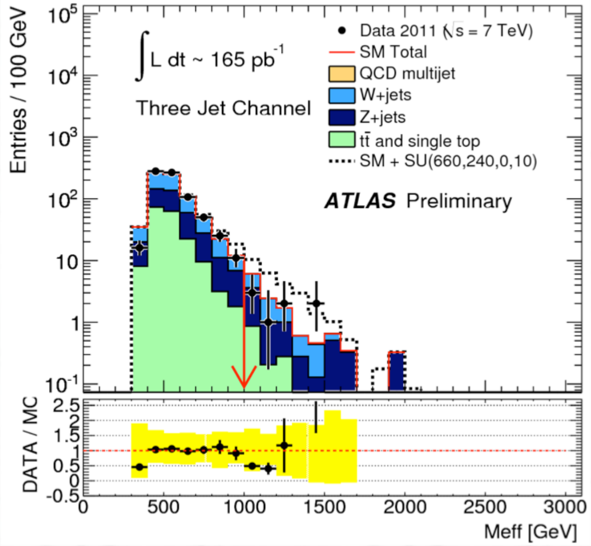
(part of 2011 data already included)

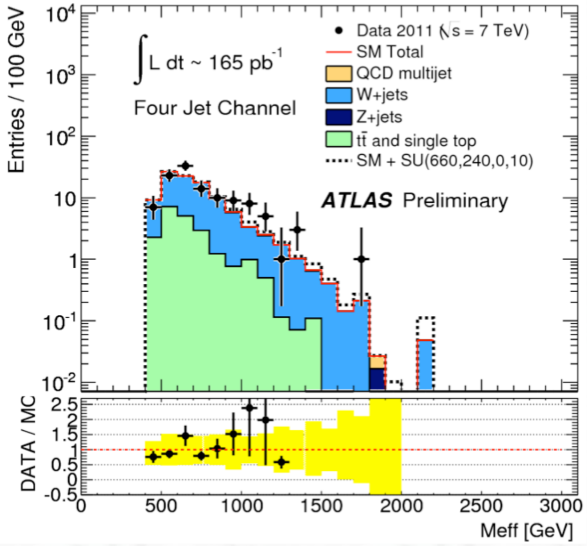
Selection of events with E_T^{miss} + jets

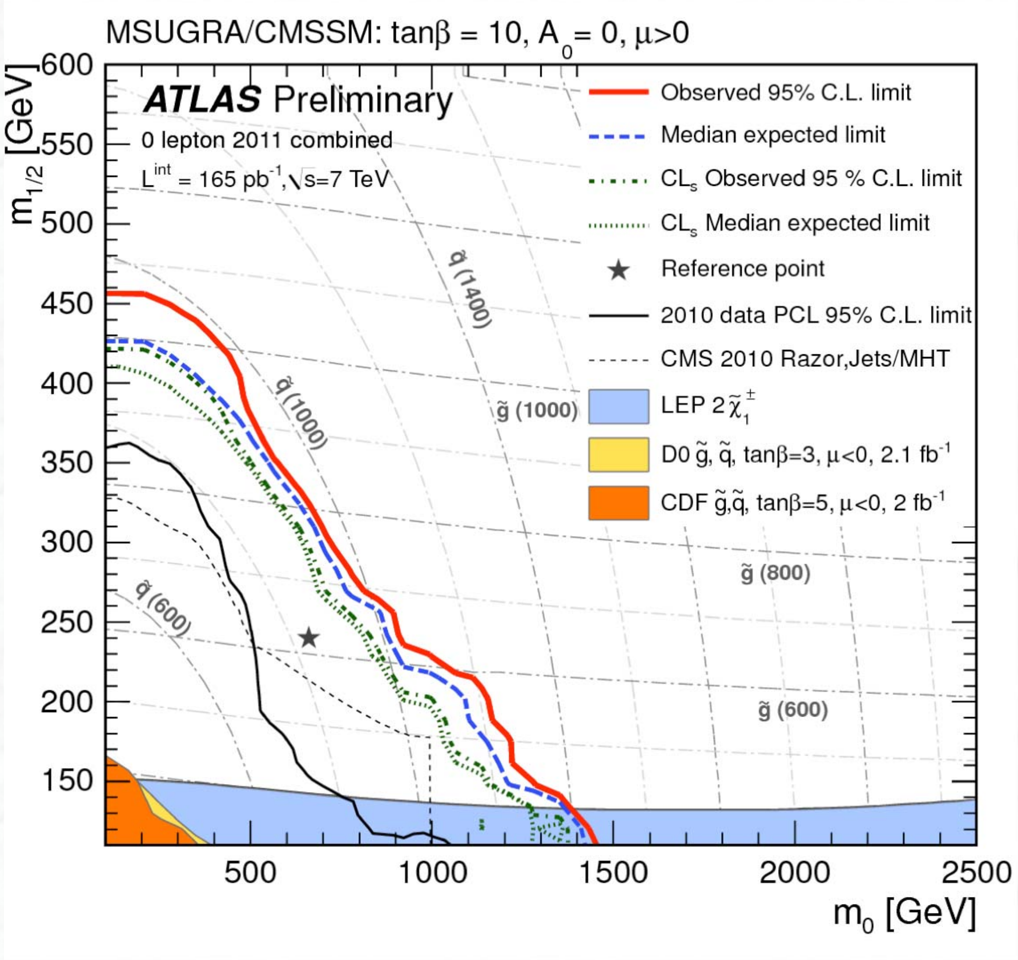
Split the analysis according to jet multiplicities: 2,3 and 4 jets

(different sensitivity for different squark/gluino mass combinations, i.e. in different regions of SUSY parameter space)



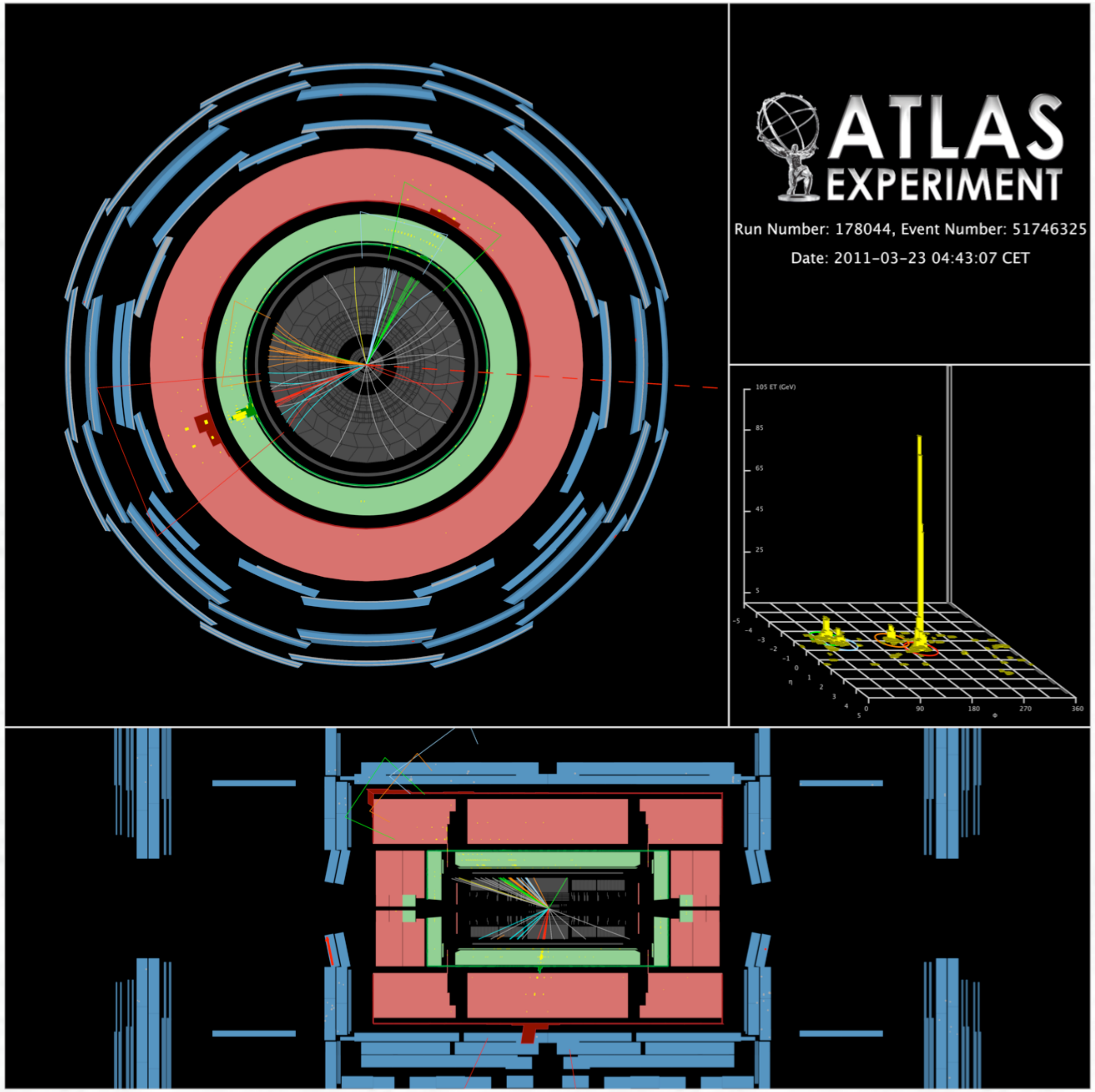






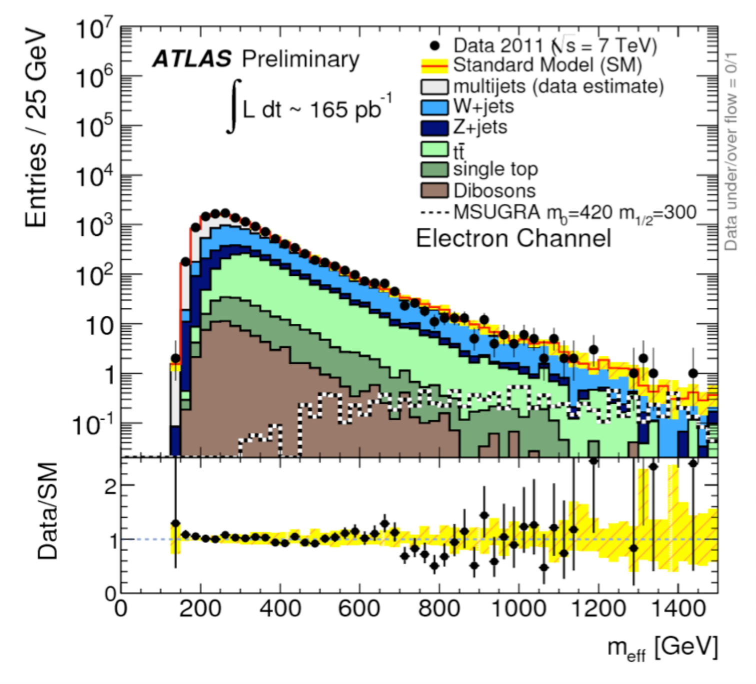
MSSM/cMSSM interpretation (for equal squark and gluino masses):

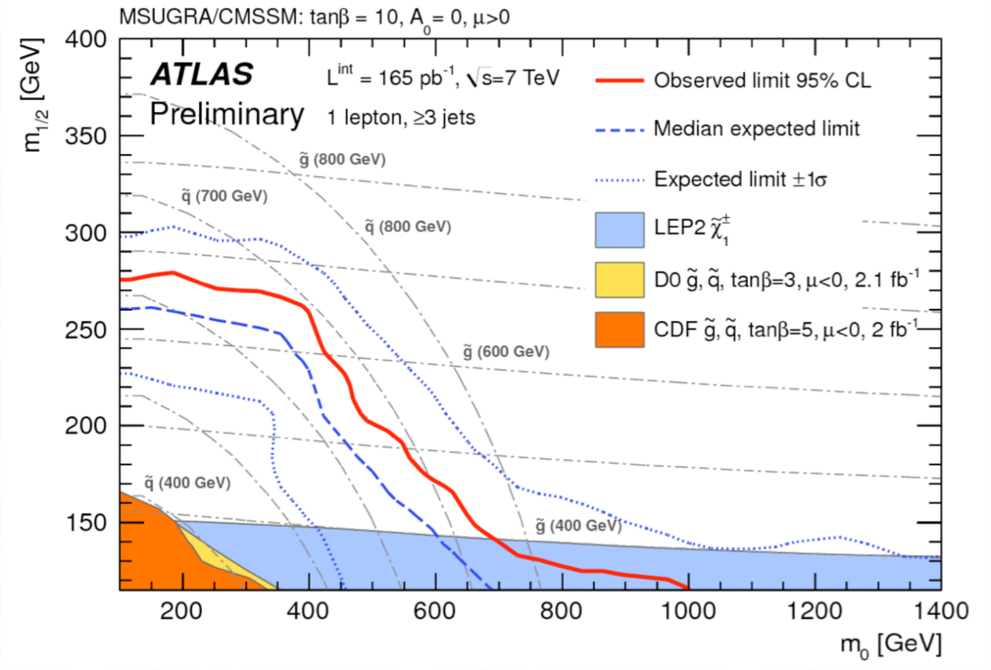
L = 165 pb^{-1}: m(squark), m(gluino) > 950 GeV



A display of the reconstructed event with the highest m_{eff} (1548 GeV) found in the ATLAS data sample. This event possesses four jets with p_T > 40 GeV (p_T = 636, 189, 96 and 81 GeV respectively) and E_T^{miss} = 547 GeV.

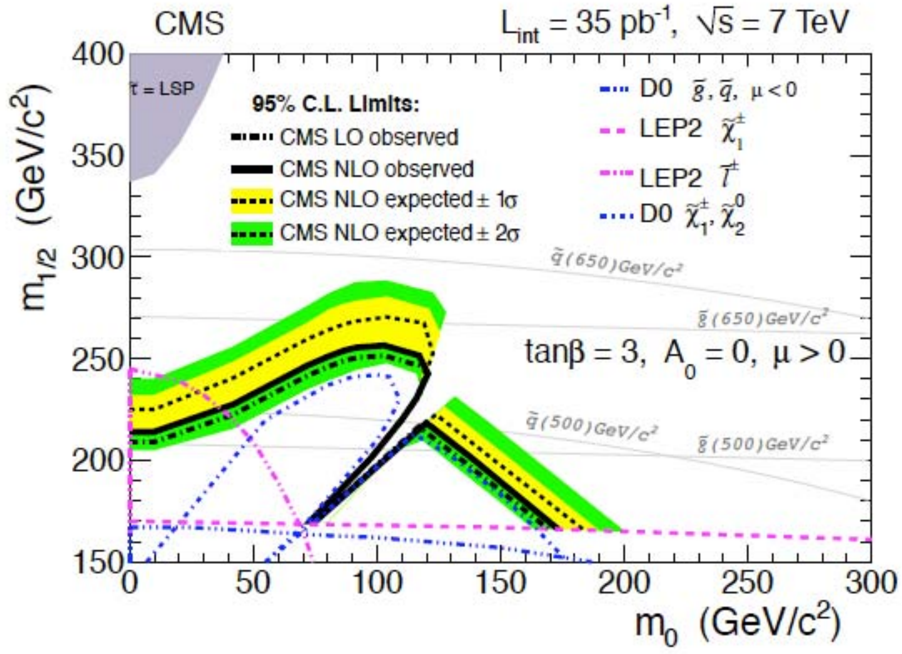
…additional potential: inclusive searches with leptons i.e. E_T^{miss}, jets + leptons

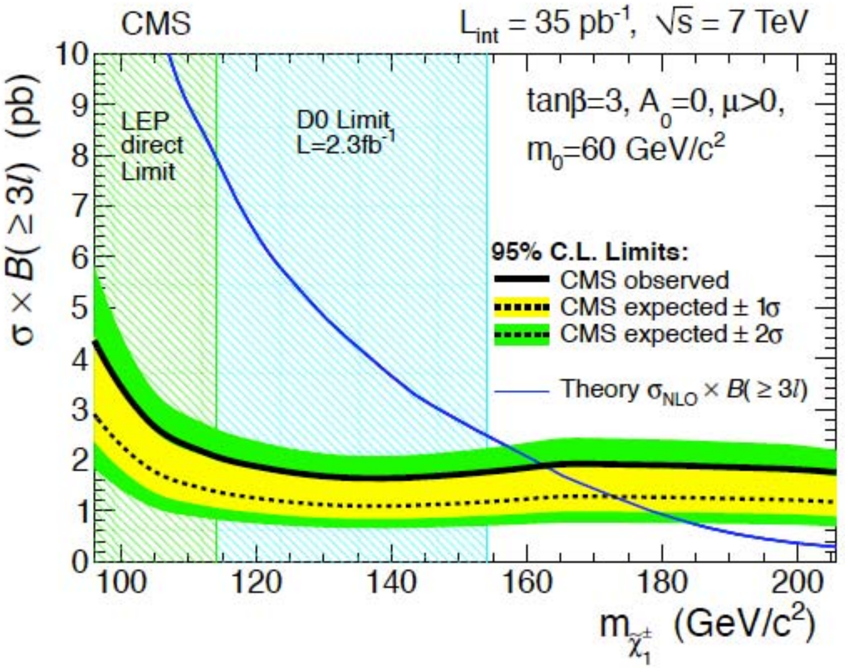




- Smaller signal rates, but different background composition
- Again: data are well described by contributions from Standard Model processes
- Similar exclusions in the MSSM models

Multi-lepton search in CMS





- Multi-leptons are produced via associated production of charginos and neutralinos (like at Tevatron, see above)

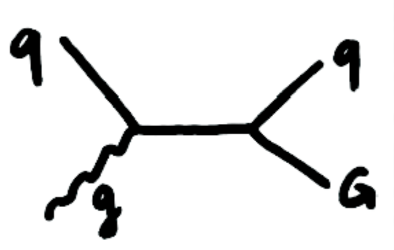
- Limits extracted are already beyond the Tevatron

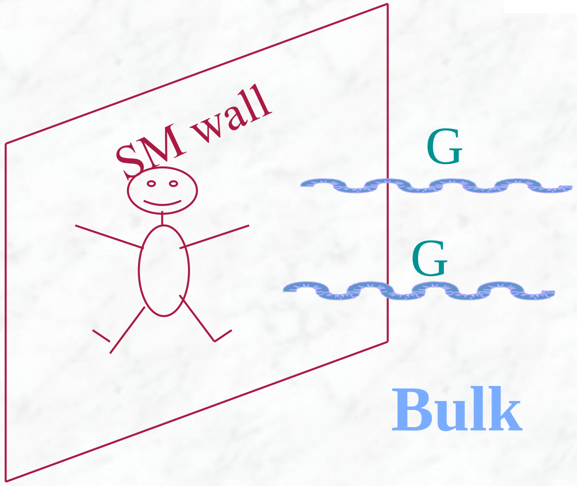
9.6 How can the parameter of the SUSY model be constrained ?

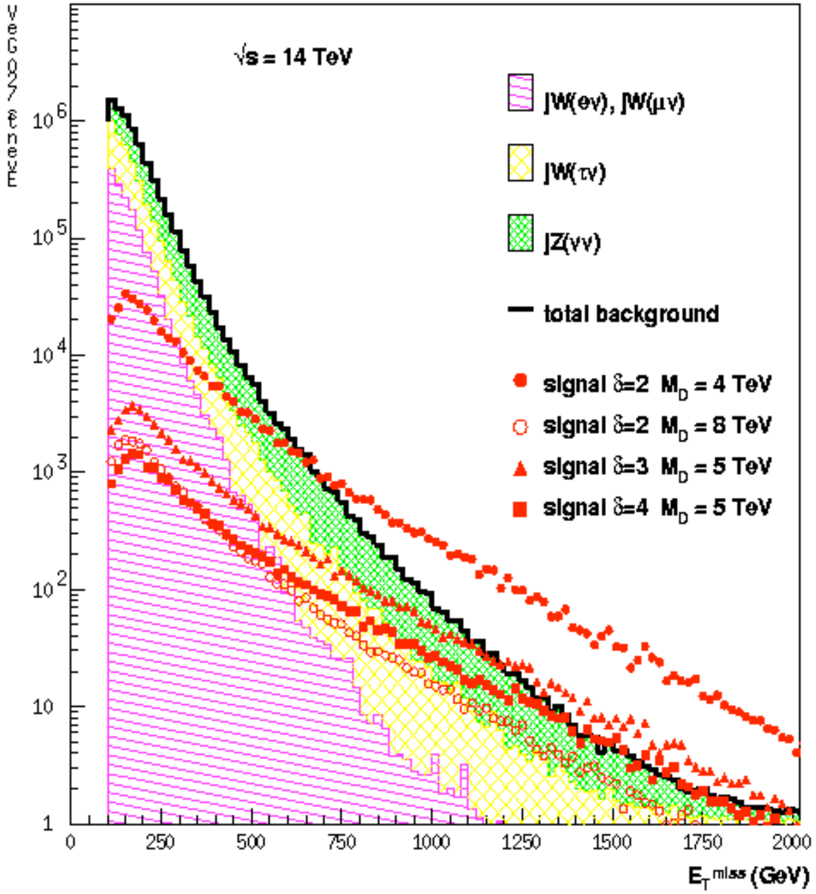
- Not easy !!
- Other possible scenarios for Physics Beyond the Standard Model could lead to similar final state signatures
  e.g. search for direct graviton production in extra dimension models

$gg \rightarrow gG,\ qg \rightarrow qG,\ q\bar{q} \rightarrow Gg$

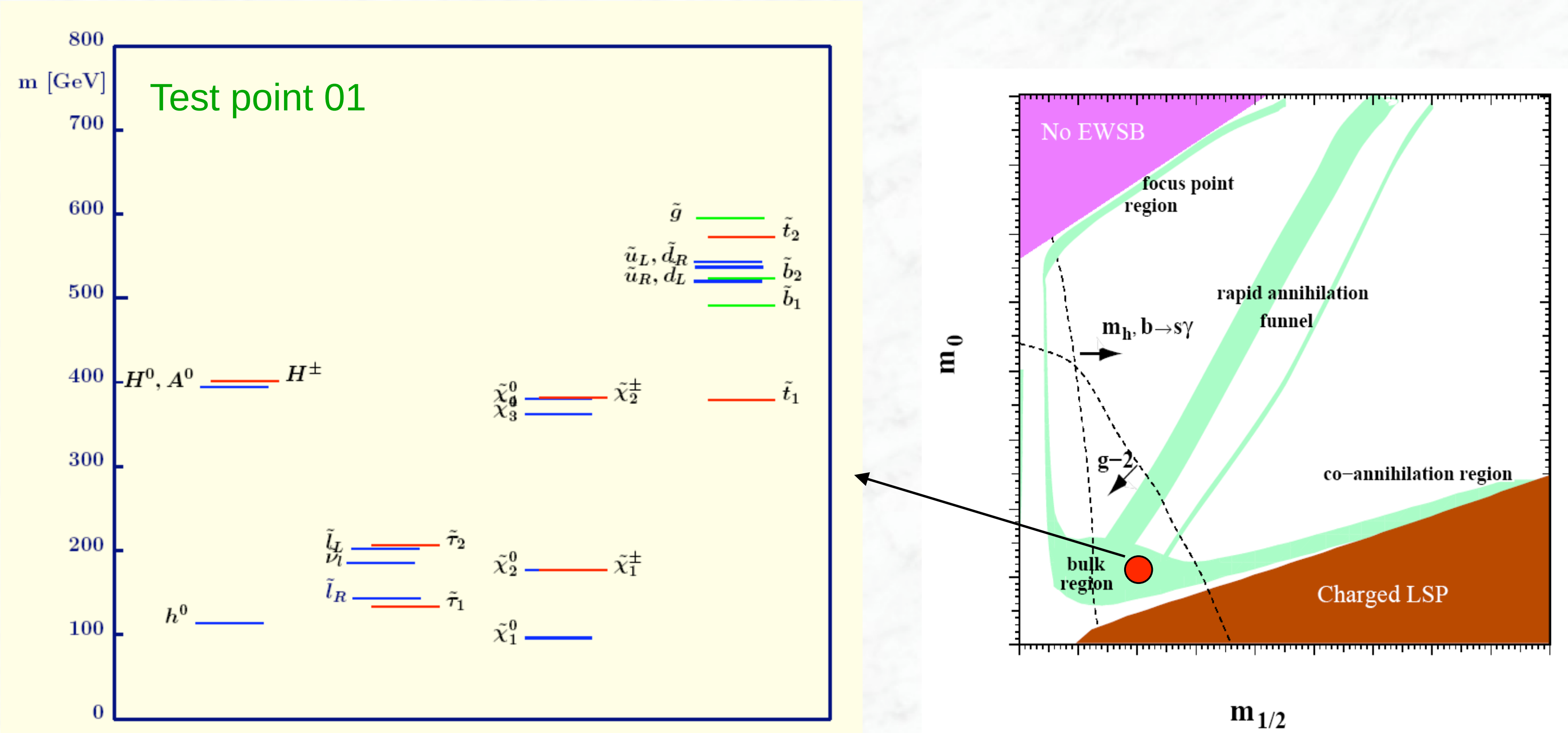
$q\bar{q} \rightarrow G\gamma$







Measurement of the SUSY spectrum → Parameter of the theory

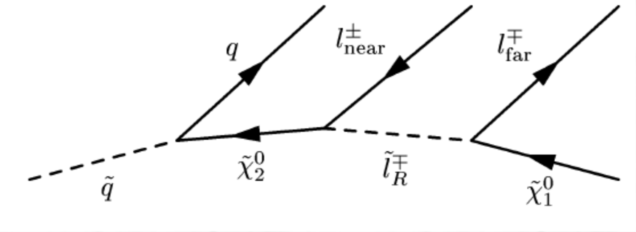


LHC: strongly interacting squarks and gluinos

ILC / CLIC: precise investigation of electroweak SUSY partners

LHC Strategy: End point spectra of cascade decays

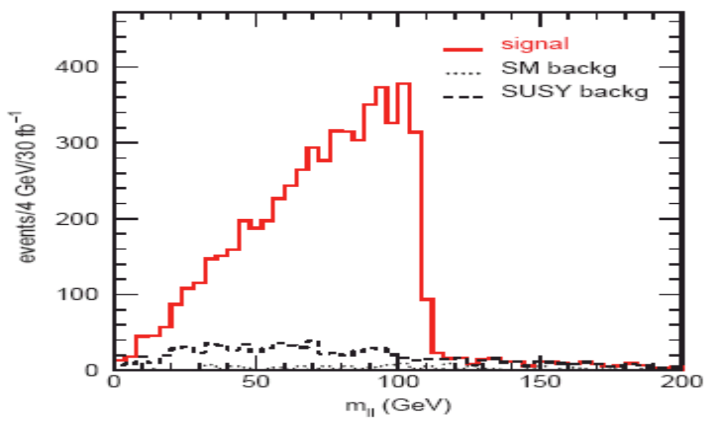
Example: $\tilde q \rightarrow q\tilde\chi^0_2 \rightarrow q\tilde\ell^\pm\ell^\mp \rightarrow q\ell^\pm\ell^\mp\tilde\chi^0_1$

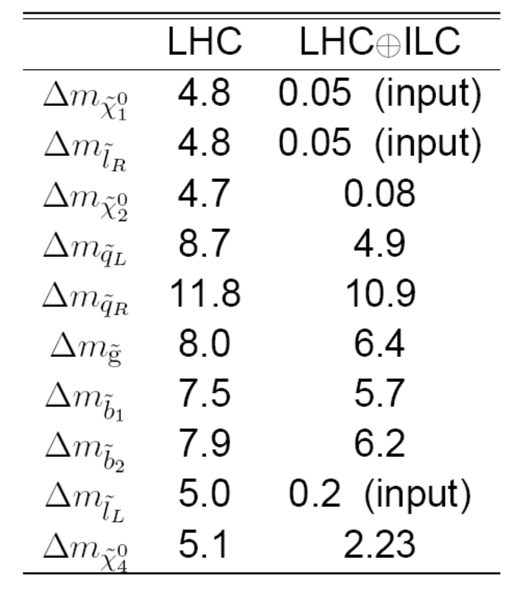


$$M^{max}_{\ell^+\ell^-} = \frac{\sqrt{(m^2_{\chi^0_2} - m^2_{\tilde\ell})(m^2_{\tilde\ell} - m^2_{\chi^0_1})}}{m_{\tilde\ell}}$$

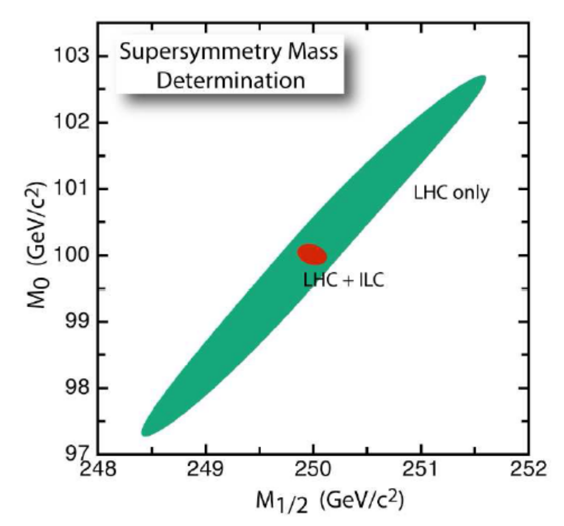
$$M^{max}_{\ell_1 q} = \frac{\sqrt{(m^2_{\chi^0_2} - m^2_{\tilde\ell})(m^2_{\tilde q} - m^2_{\chi^0_2})}}{m_{\chi^0_2}}$$

Results for point 01:



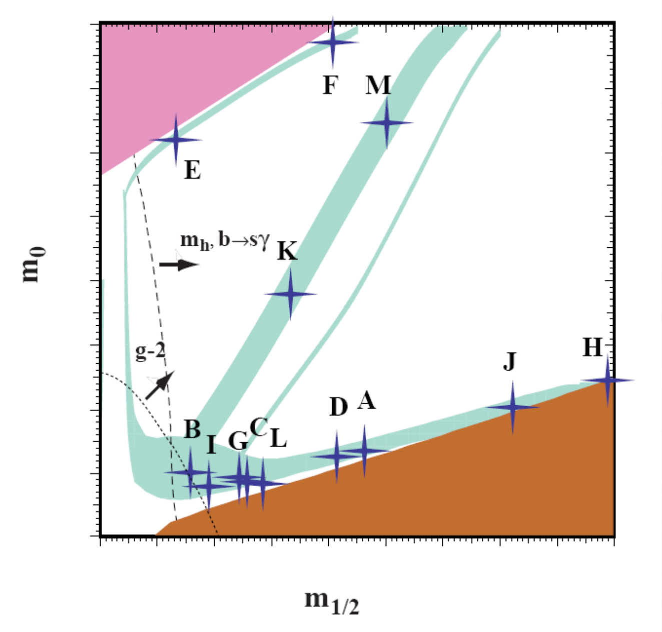


	LHC	LHC⊕ILC
$\Delta m_{\tilde\chi^0_1}$	4.8	0.05 (input)
$\Delta m_{\tilde l_R}$	4.8	0.05 (input)
$\Delta m_{\tilde\chi^0_2}$	4.7	0.08
$\Delta m_{\tilde q_L}$	8.7	4.9
$\Delta m_{\tilde q_R}$	11.8	10.9
$\Delta m_{\tilde g}$	8.0	6.4
$\Delta m_{\tilde b_1}$	7.5	5.7
$\Delta m_{\tilde b_2}$	7.9	6.2
$\Delta m_{\tilde l_L}$	5.0	0.2 (input)
$\Delta m_{\tilde\chi^0_4}$	5.1	2.23



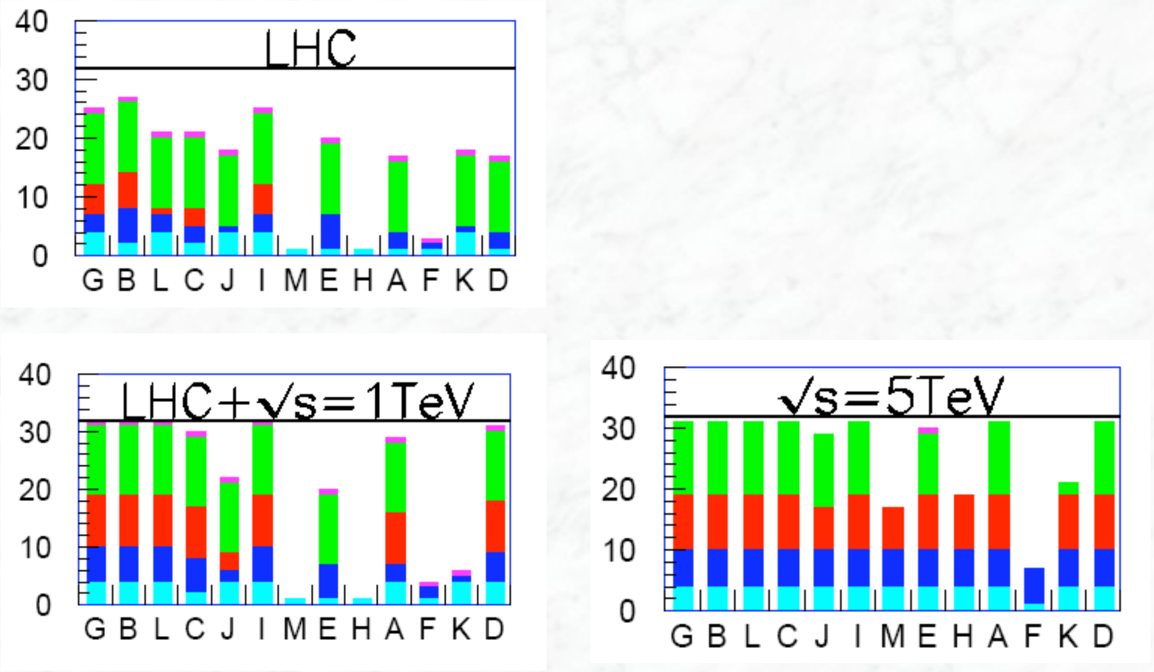
L = 300 fb^{-1}

The LHC and the ILC (International Linear Collider, in study/planning phase) are complementary in SUSY searches



🟪 gluino 🟩 squarks 🟥 sleptons 🟦 $\chi^{0,\pm}$ 🟦 H

Number of observable SUSY particles:



)* Study by J. Ellis et al., hep-ph/0202110

Strategy in SUSY Searches at the LHC:

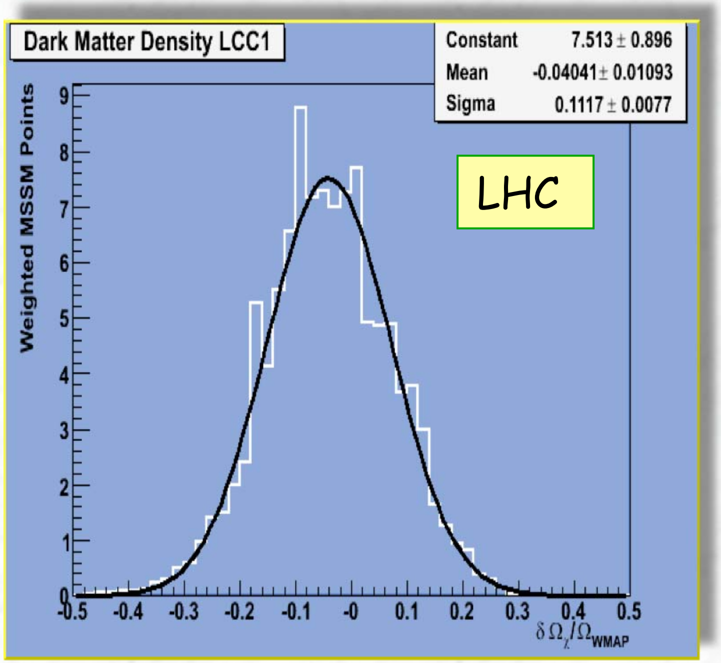
- Search for multijet + E_T^{miss} excess
- If found, select SUSY sample (simple cuts)
- Look for special features (γ's , long lived sleptons)
- Look for $\ell^\pm$, $\ell^+ \ell^-$, $\ell^\pm \ell^\pm$, b-jets, τ's
- End point analyses, global fit → SUSY model parameters

Dark Matter at Accelerators ?

Parameter of the SUSY-Model ⇒ Predictions for the relic density of Dark Matter

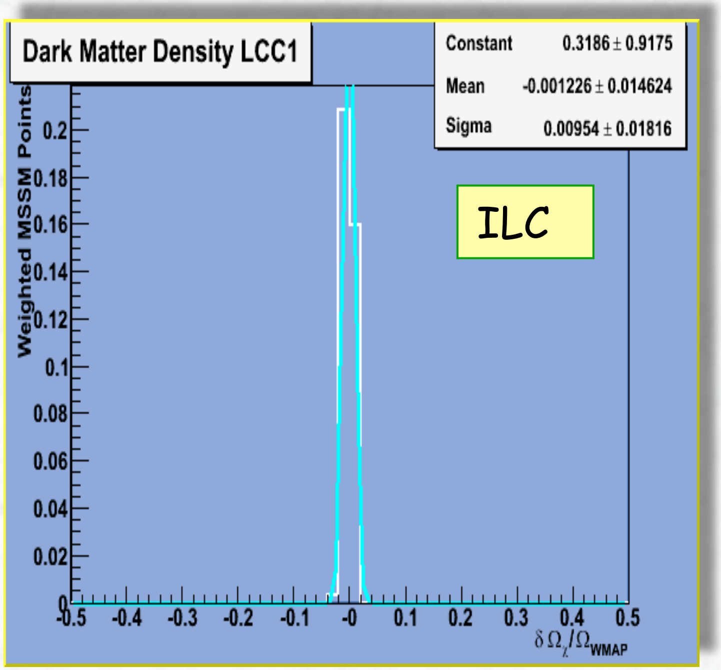
$$\rho_\chi \sim m_\chi n_\chi \,, \quad n_\chi \sim \frac{1}{\sigma_{ann}(\chi\chi \to \ldots)}$$

Battaglia et al.



L = 300 fb^{-1}

δΩ / Ω ~ 11%

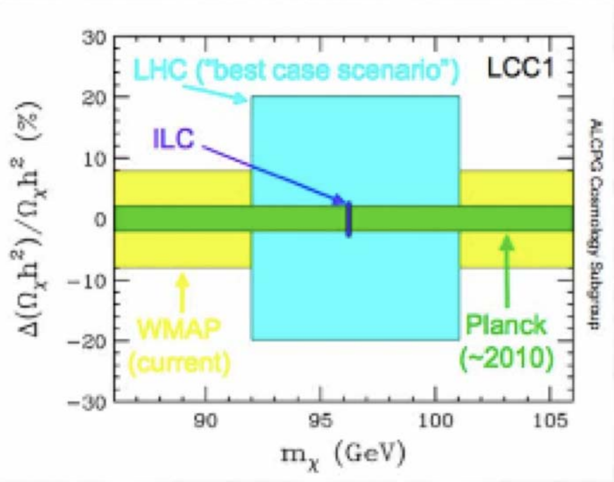


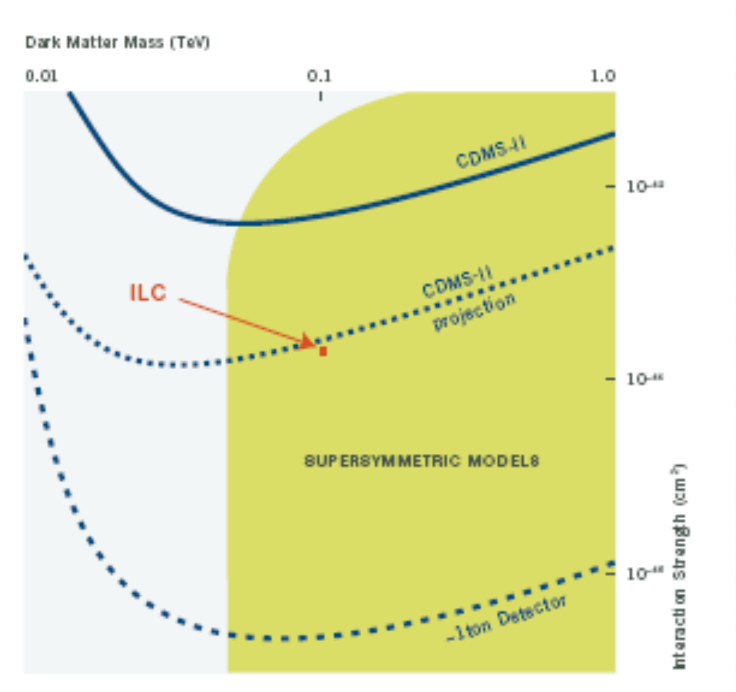
L = 1000 fb^{-1}

δΩ / Ω ~ 1%

Importance for the interplay between direct and indirect Dark Matter searches

- Following a discovery of New Physics at the LHC (deviation from the Standard Model) the LHC will aim to test the Dark Matter hypothesis
- Estimation of relic density in a simple model-dependent scenario will be the first goal
- Less model-dependent scenarios will follow, detailed studies probably require the ILC
- Conclusive result is only possible in conjunction with astroparticle physics experiments
- Ultimate goal: observation of LSP at the LHC, confirmed by a signal in a direct dark matter experiment with predicted mass and cross-section





Further reading, available on the web:

- S. Martin, "A Supersymmetry Primer", hep-ph/97093
  http://arxiv.org/abs/hep-ph/9709356

- D.I. Kazakov, „Beyond the Standard Model", CERN school 2004
  http://doc.cern.ch/yellowrep/2006/2006-003/p169.pdf

- J. Ellis, Supersymmetry for Alp Hikers

  http://arxiv.org/abs/hep-ph/0203114

Lehrbücher:

- H.Baer, X. Tata, „Weak Scale Supersymmetry", 2006

- Drees, Godbole, Roy, „Theory and Phenomenology of Sparticles", 2004