Supersymmetry
Introduction and Overview

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Chapter 2: Supersymmetry

2.1 Introduction and Overview
- What is SUSY
- How can we find/measure it?

Chapter 2.1 will give a very general overview, ranging from the SUSY particle spectrum to SUSY at the LHC.
In Chapters 2.2-2.4, all this will be treated in more detail.

2.2 SUSY Theory/Phenomenology
- SUSY Lagrangian, MSSM
- SUSY interactions, masses, SUSY breaking

2.3 SUSY searches/measurements at experiments
- past and running experiments
- LHC / future linear collider

2.4 Searches for MSSM Higgs bosons

Literature

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

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)

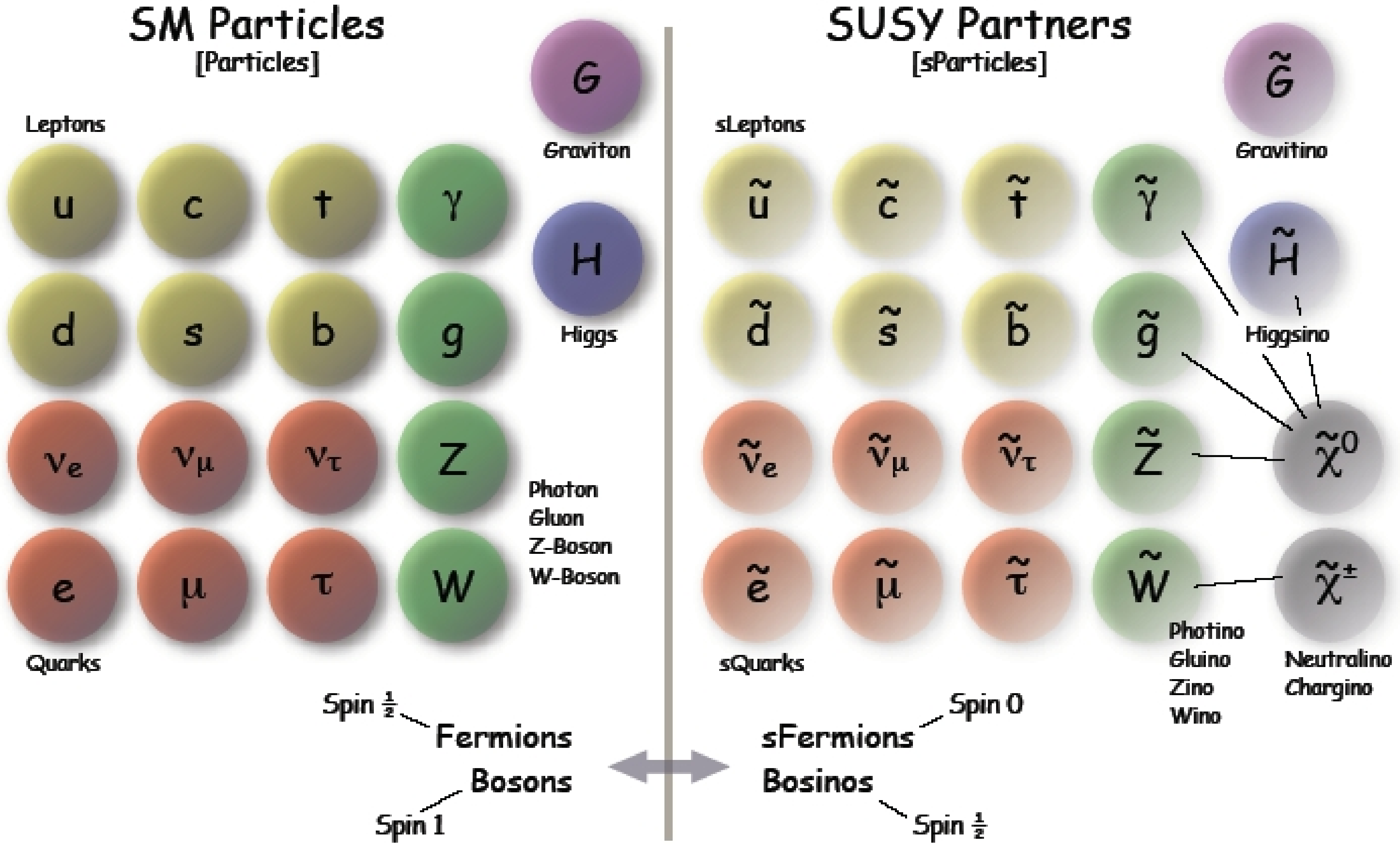
SUSY transformation (operator Q):

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

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

→ SUSY doubles the number of particles

The SUSY Particle Spectrum



The SUSY Particle Spectrum

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

The SUSY Particle Spectrum

	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)	

The SUSY Particle Spectrum

	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		

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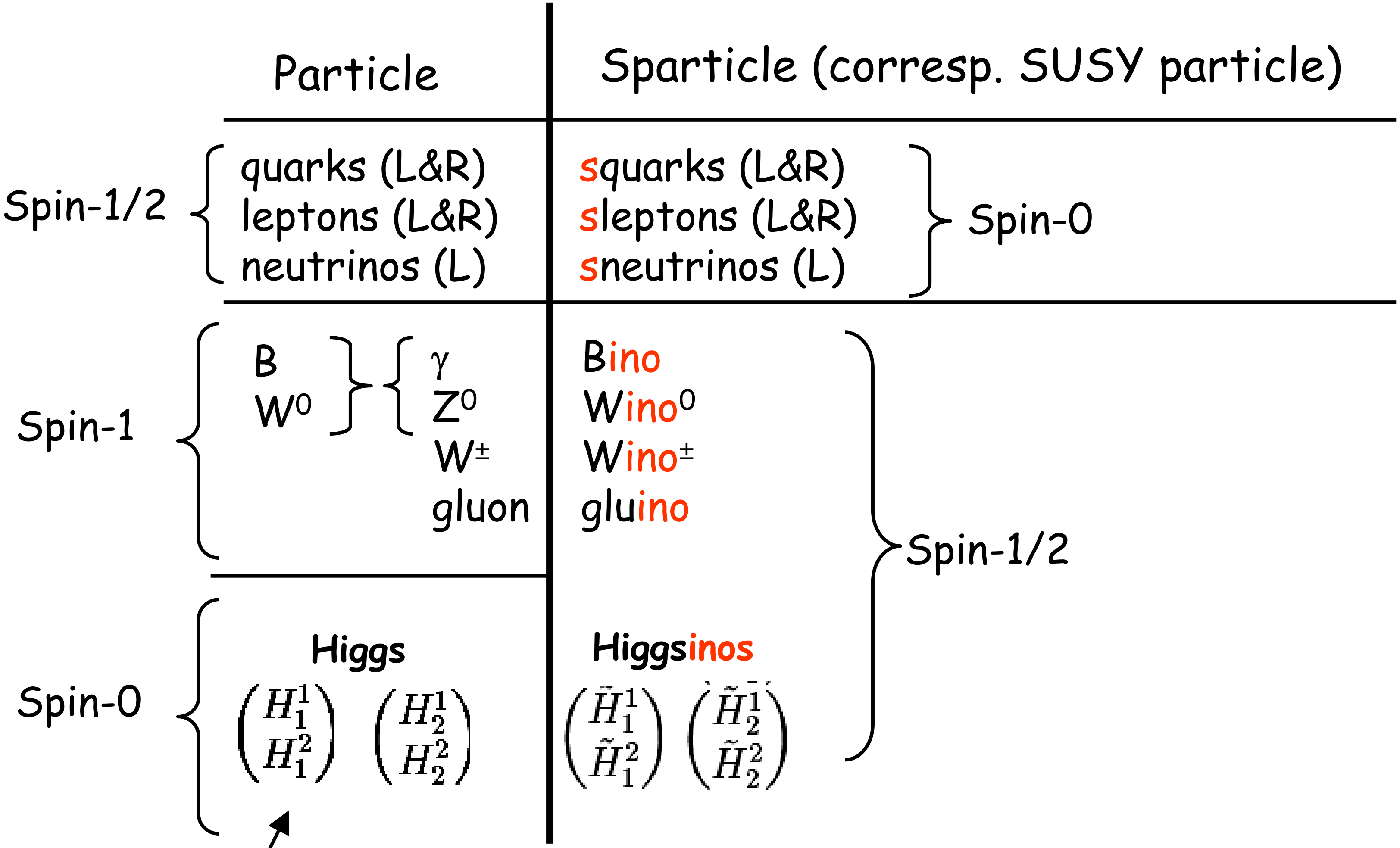
Spin-0	**Higgs** $\begin{pmatrix}H_1^1\\H_1^2\end{pmatrix}$ $\begin{pmatrix}H_2^1\\H_2^2\end{pmatrix}$		

Extended Higgs sector: 2 complex Higgs doublets

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

The SUSY Particle Spectrum



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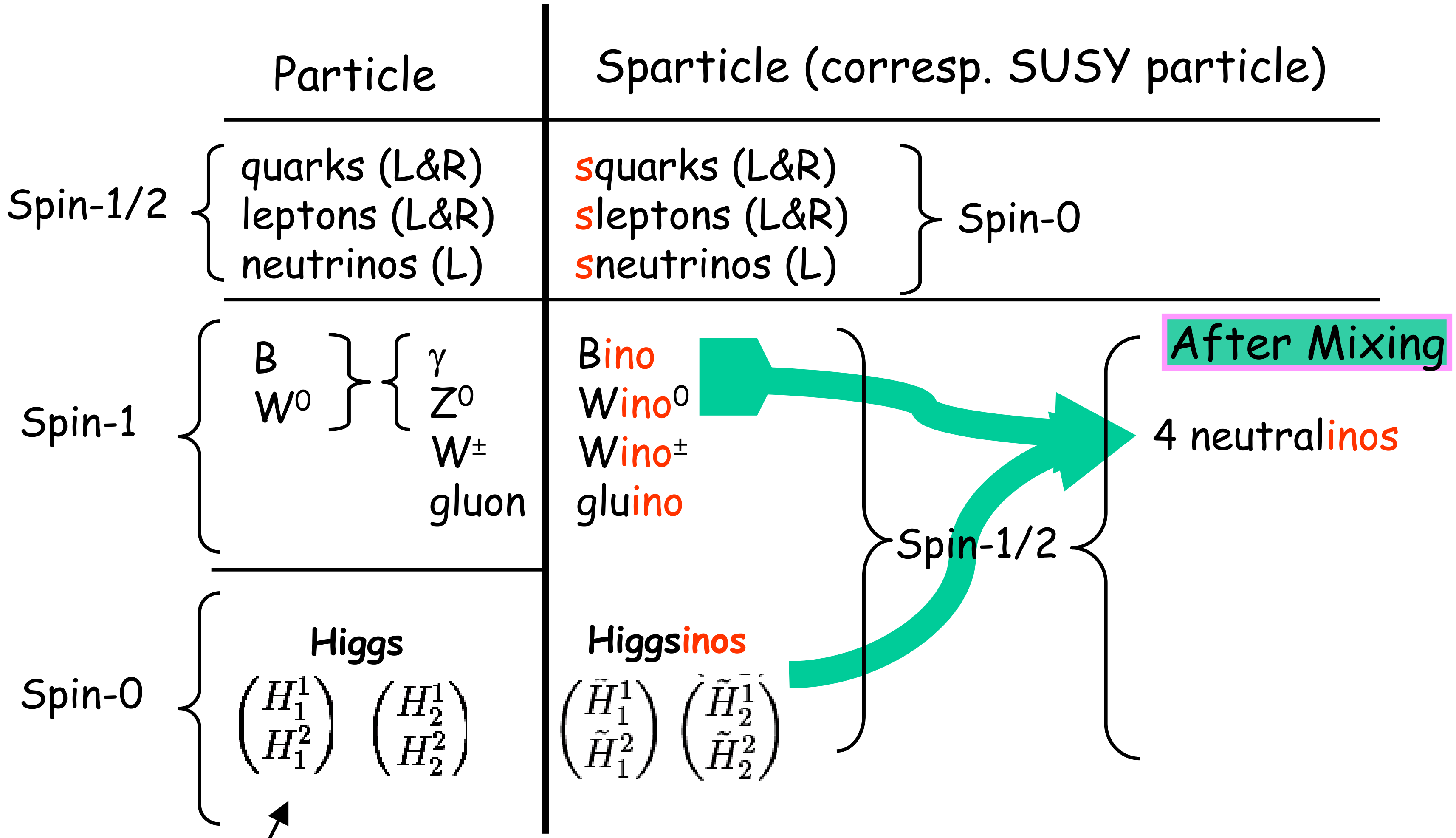

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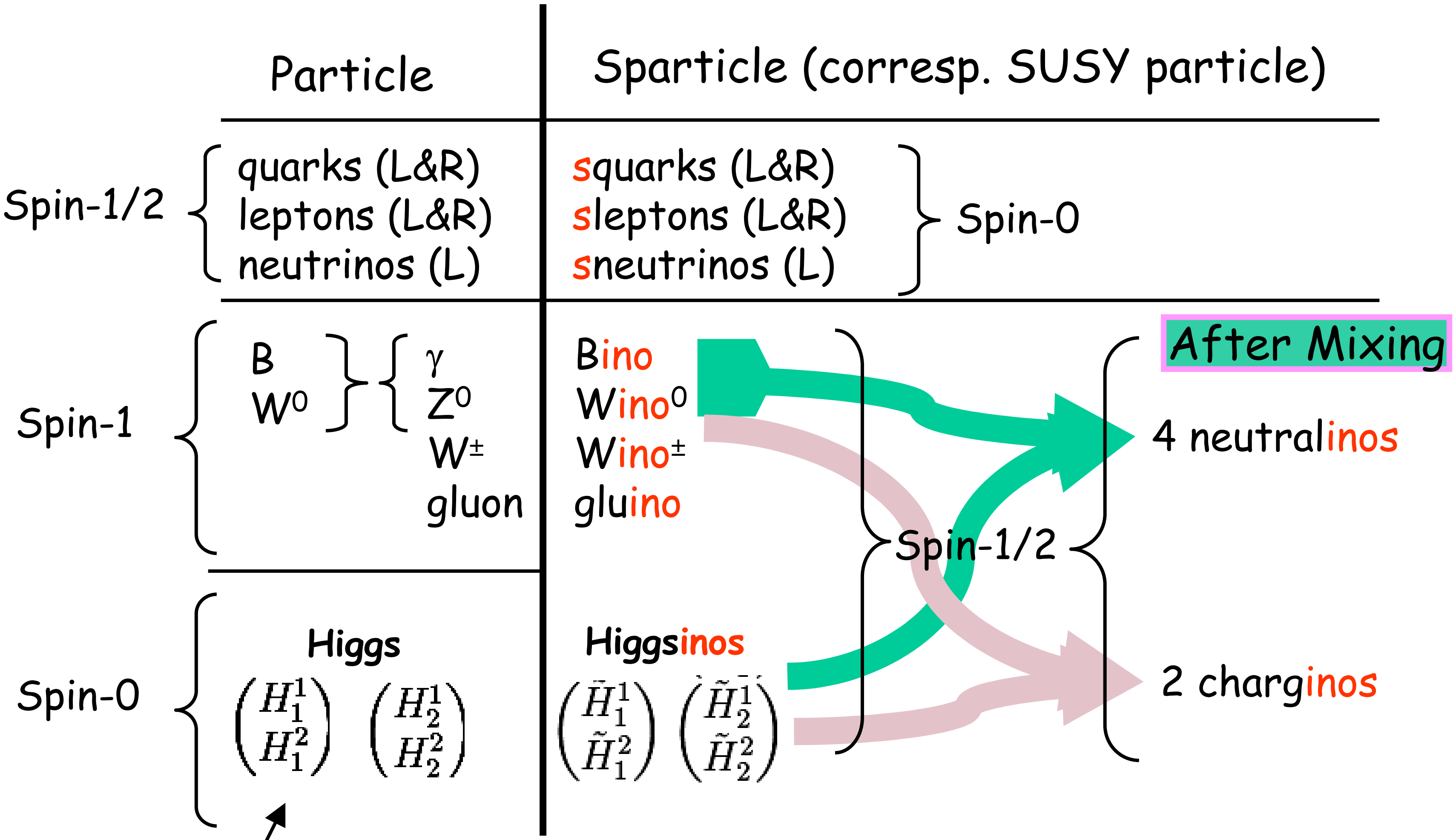
After Mixing

Spin-1/2: 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, $H^\pm$

The SUSY Particle Spectrum



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Spin-1/2	quarks (L&R) leptons (L&R) neutrinos (L)	squarks (L&R) sleptons (L&R) sneutrinos (L)	Spin-0
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After Mixing

Spin-1/2 { 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, $H^{\pm}$

Neutralino and Chargino Mixing

- 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:

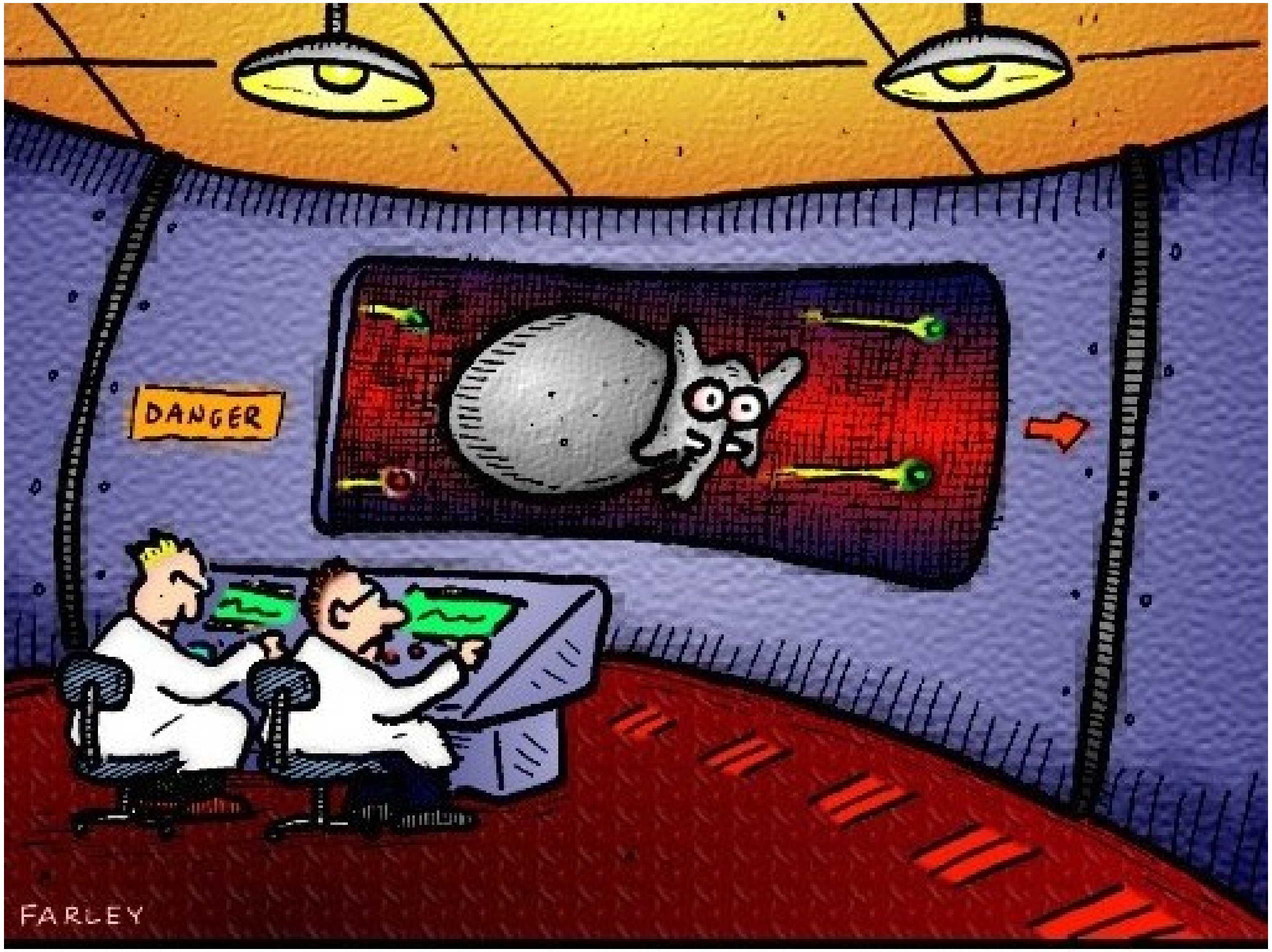
$$\begin{pmatrix} \chi_1^0 \\ \chi_2^0 \\ \chi_3^0 \\ \chi_4^0 \end{pmatrix} = \begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\ 0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W \\ -m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu \\ m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0 \end{pmatrix} \begin{pmatrix}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

Mass eigenstates depend on:

M_1, M_2, tan β, μ — SUSY masses and breaking parameters

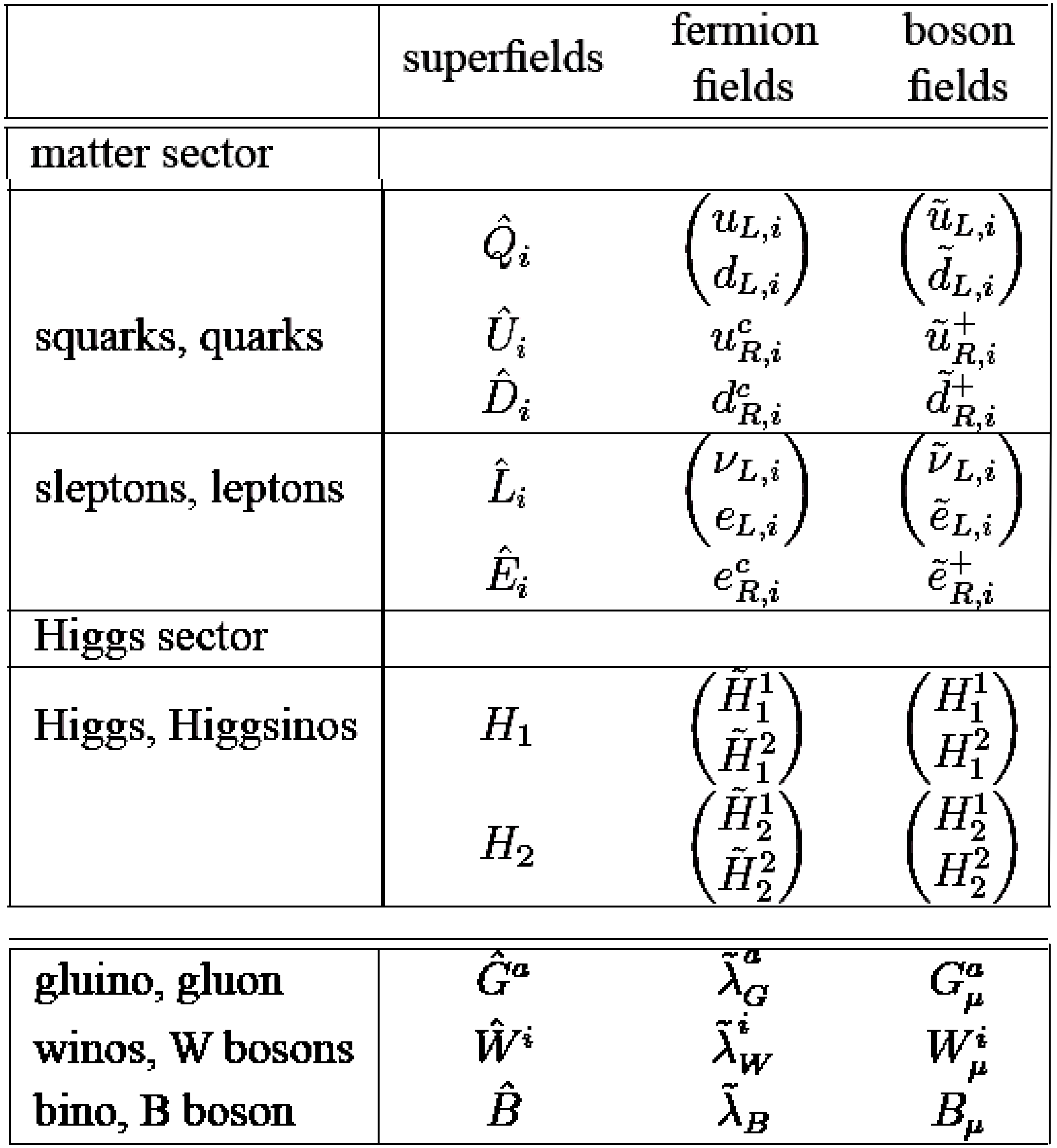
m_Z, $\sin^2\theta_W$ — EWSB (mixing: $B^0, W^0 \rightarrow Z, \gamma$)

… the Search for SUSY …



Deep within the atomic supercollider, the search continues for the elusive elephantino.

Superfields



	superfields	fermion fields	boson fields
matter sector			
squarks, quarks	$\hat{Q}_i$	$\begin{pmatrix} u_{L,i} \\ d_{L,i} \end{pmatrix}$	$\begin{pmatrix} \tilde{u}_{L,i} \\ \tilde{d}_{L,i} \end{pmatrix}$
	$\hat{U}_i$	$u^c_{R,i}$	$\tilde{u}^+_{R,i}$
	$\hat{D}_i$	$d^c_{R,i}$	$\tilde{d}^+_{R,i}$
sleptons, leptons	$\hat{L}_i$	$\begin{pmatrix} \nu_{L,i} \\ e_{L,i} \end{pmatrix}$	$\begin{pmatrix} \tilde{\nu}_{L,i} \\ \tilde{e}_{L,i} \end{pmatrix}$
	$\hat{E}_i$	$e^c_{R,i}$	$\tilde{e}^+_{R,i}$
Higgs sector			
Higgs, Higgsinos	H_1	$\begin{pmatrix} \tilde{H}^1_1 \\ \tilde{H}^2_1 \end{pmatrix}$	$\begin{pmatrix} H^1_1 \\ H^2_1 \end{pmatrix}$
	H_2	$\begin{pmatrix} \tilde{H}^1_2 \\ \tilde{H}^2_2 \end{pmatrix}$	$\begin{pmatrix} H^1_2 \\ H^2_2 \end{pmatrix}$

gluino, gluon	$\hat{G}^a$	$\tilde{\lambda}^a_G$	G^a_μ
winos, W bosons	$\hat{W}^i$	$\tilde{\lambda}^i_W$	W^i_μ
bino, B boson	$\hat{B}$	$\tilde{\lambda}_B$	B_μ

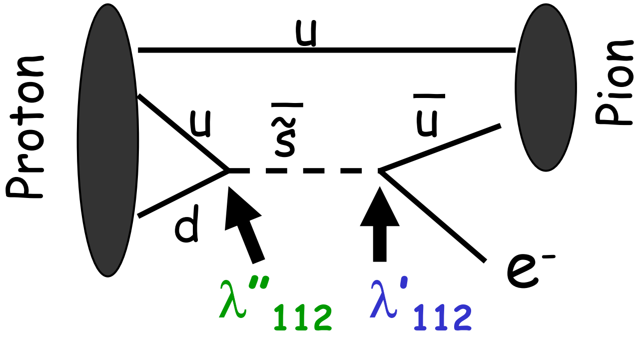
R-Parity

- New terms in Lagrangian:

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

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:

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

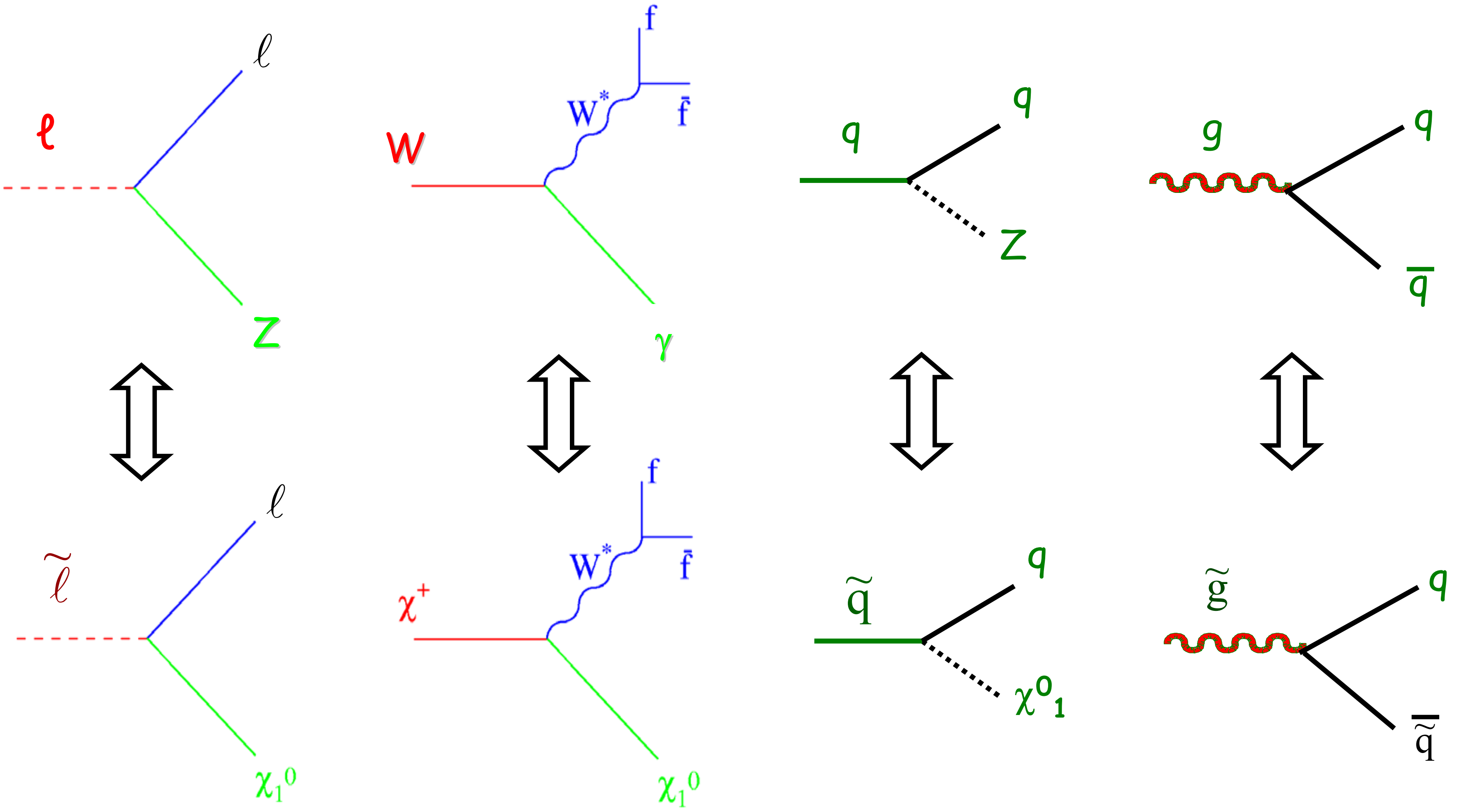
= +1 for SM particles
= -1 for SUSY particles

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

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

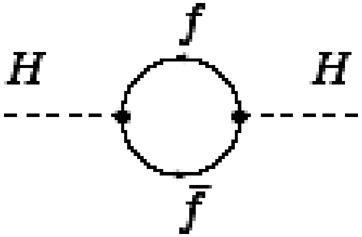


Motivation for SUSY

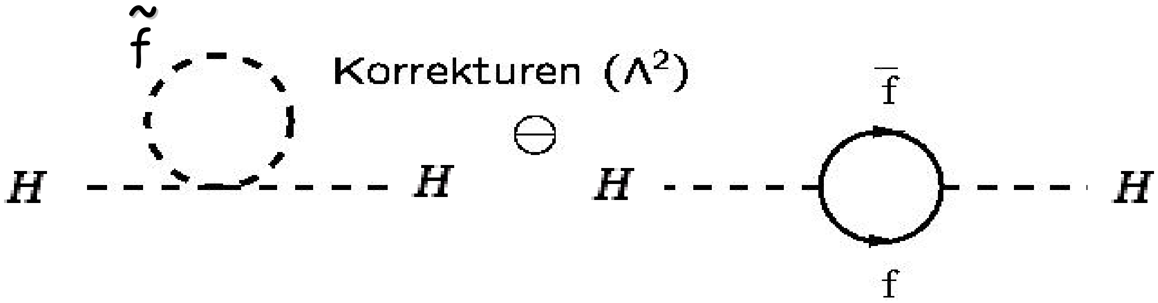
Reasons for SUSY (1) : Hierarchy Problem

- Reminder:

  In the SM, Higgs mass diverges due to quantum corrections.



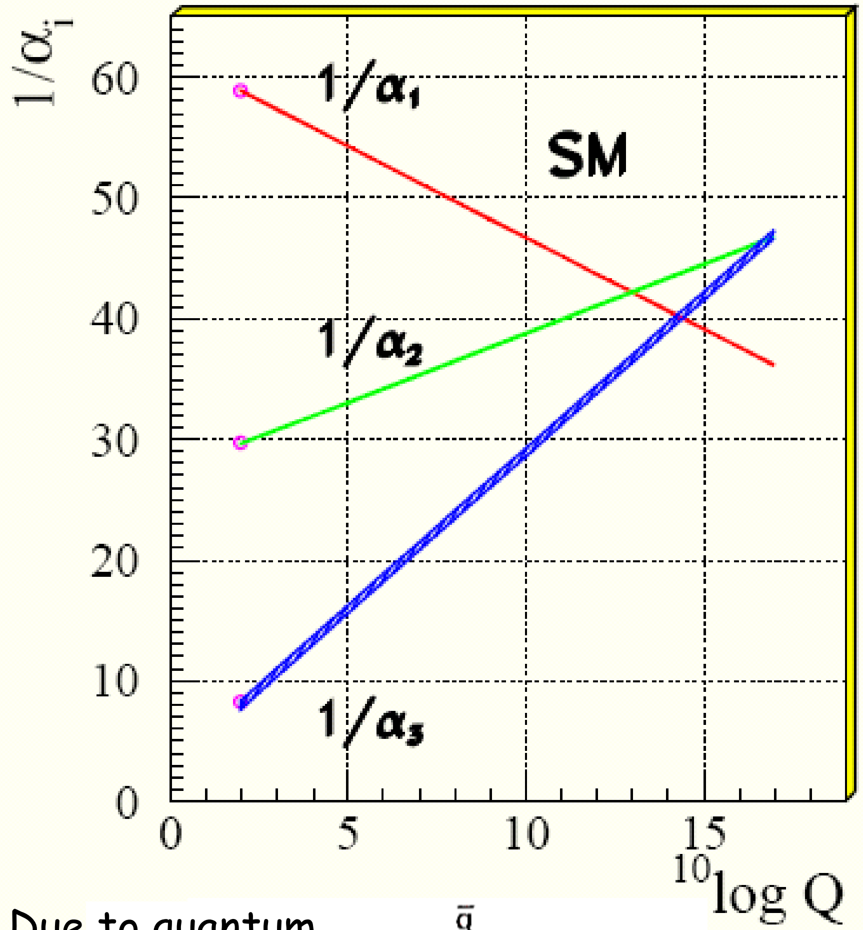
- The symmetry between bosons and fermions , which contribute with different sign (statistics), can cure this problem:

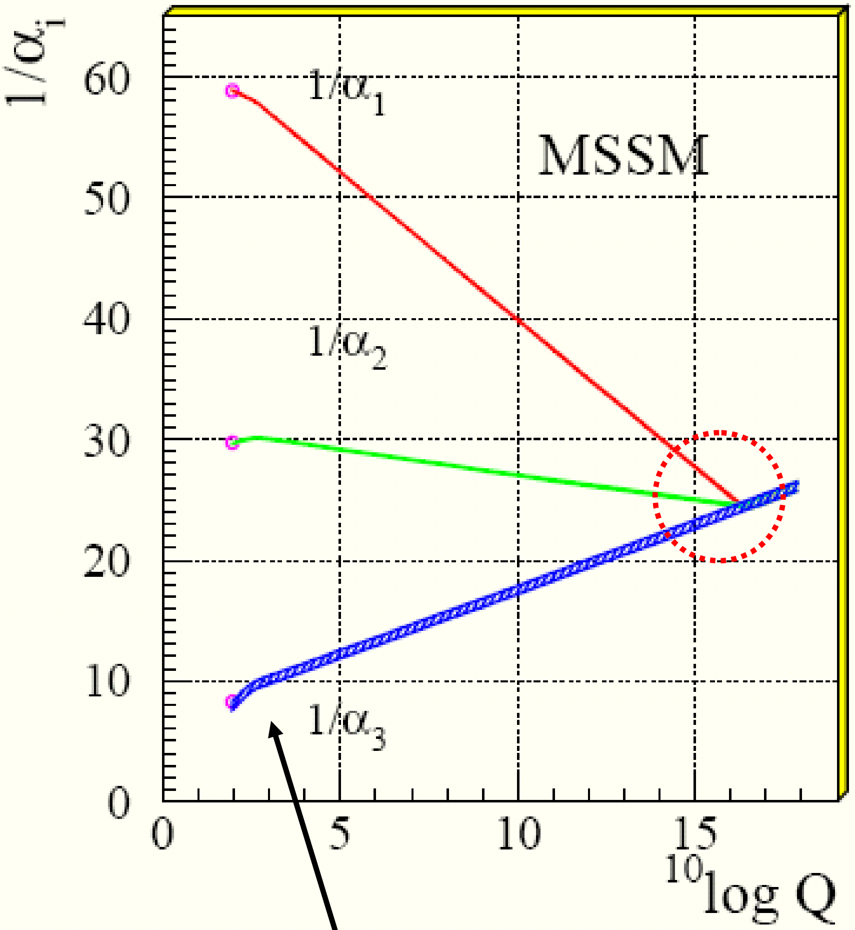


$$\Delta m_H = f(m_B^2 - m_f^2)$$

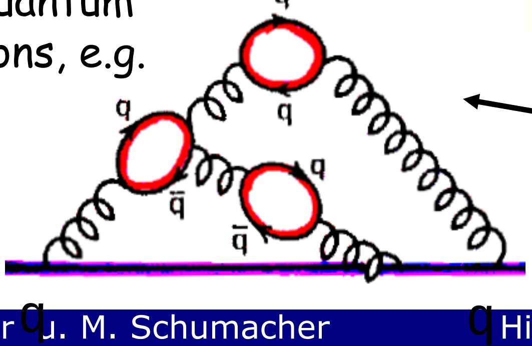
→ terms cancel one-by-one if SUSY perfect symmetry (i.e. if m(particle) = m(sparticle)). Since this is not the case, sparticles musn't be too heavy (M_{SUSY} <~ 1 TeV).

Reasons for SUSY (2) : Grand Unification



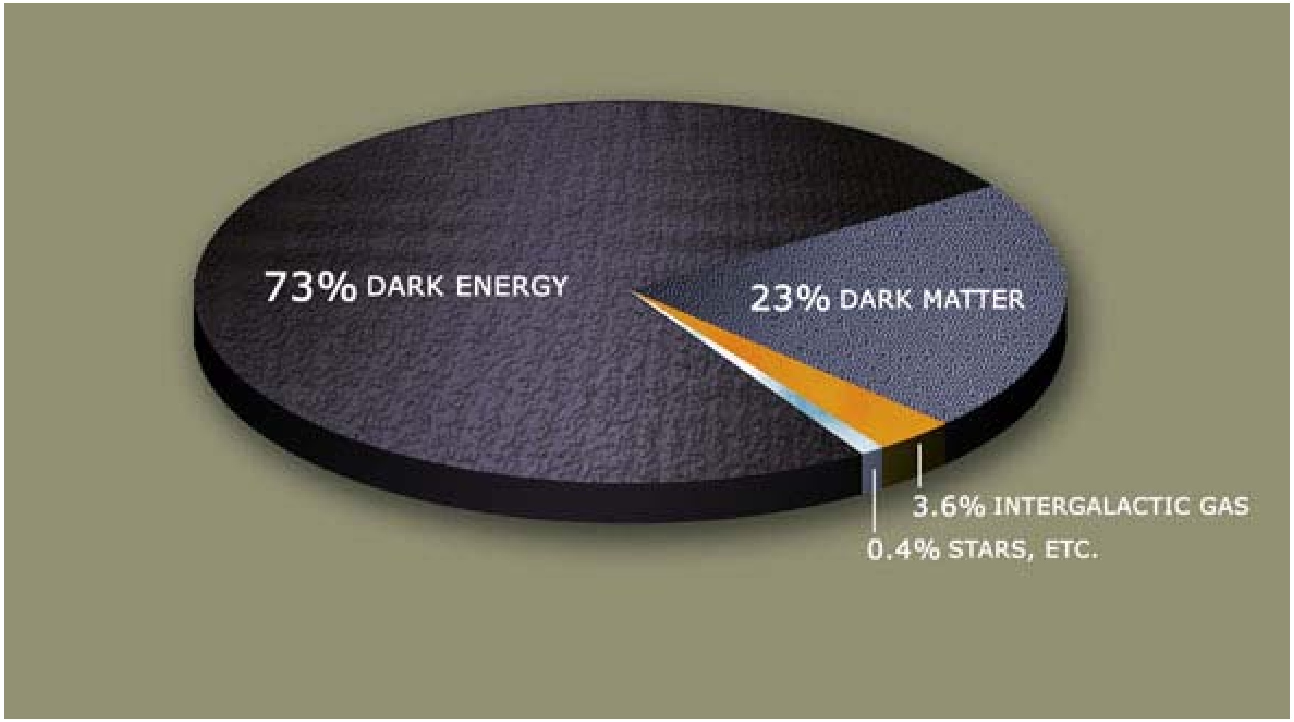


Due to quantum corrections, e.g.



slope is changed due to contributions from SUSY particles

Reasons for SUSY (3): Dark Matter in our Universe

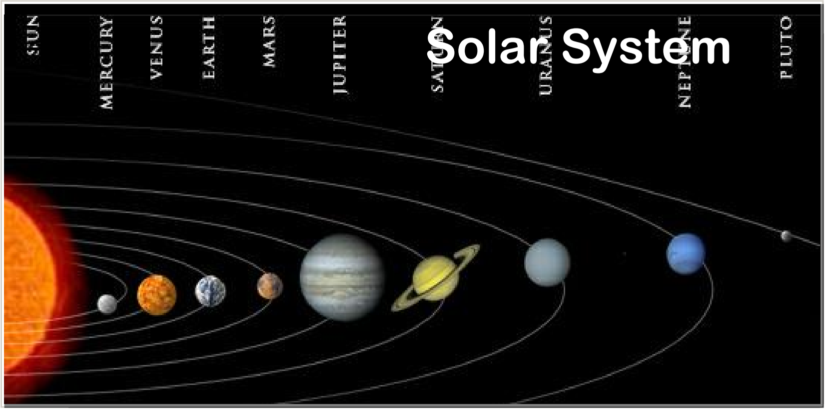


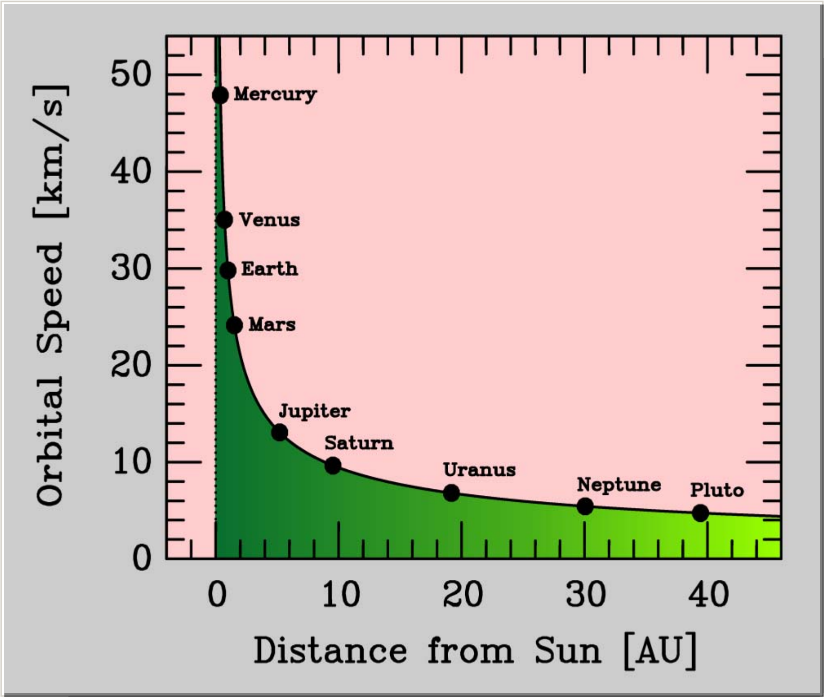
Evidence from:

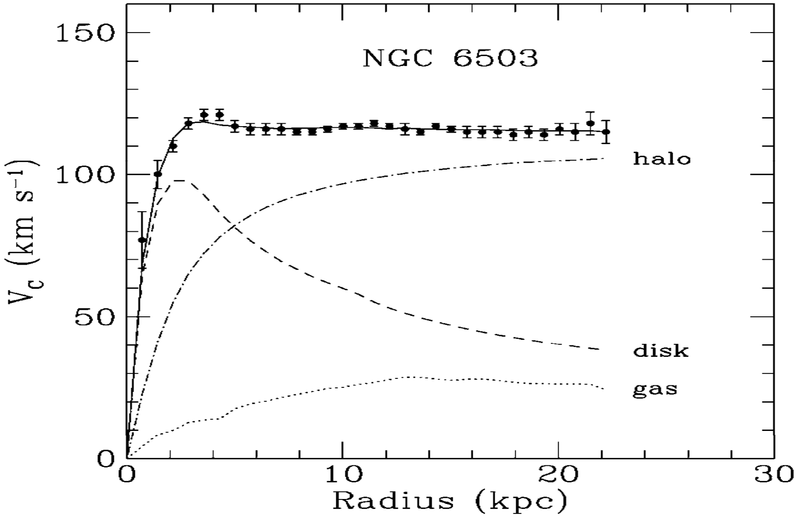
- ***Rotational curves of galaxies***
- ***Gravitational lensing***
- ***Cosmic microwave background (CMB)***

Excursion: Dark Matter in Galaxies

- ***Gravitation ~ $1/r^2$ → Rotation curves** à **la Keppler***





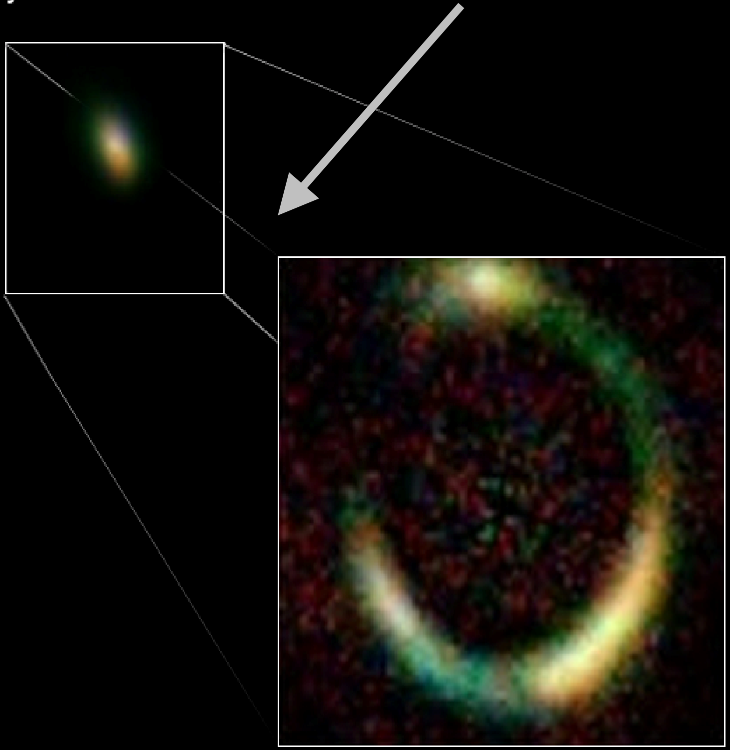


→ Halo of invisible matter

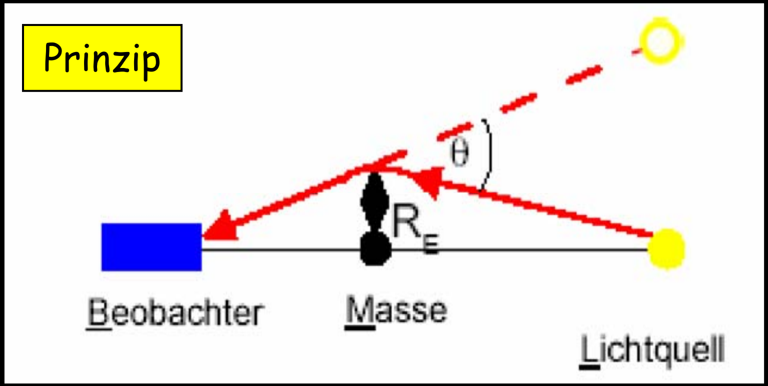
Excursion: Gravitational Lensing

Contribution from dark matter ?!

Reconstructed background galaxy SDSS J0737+3216

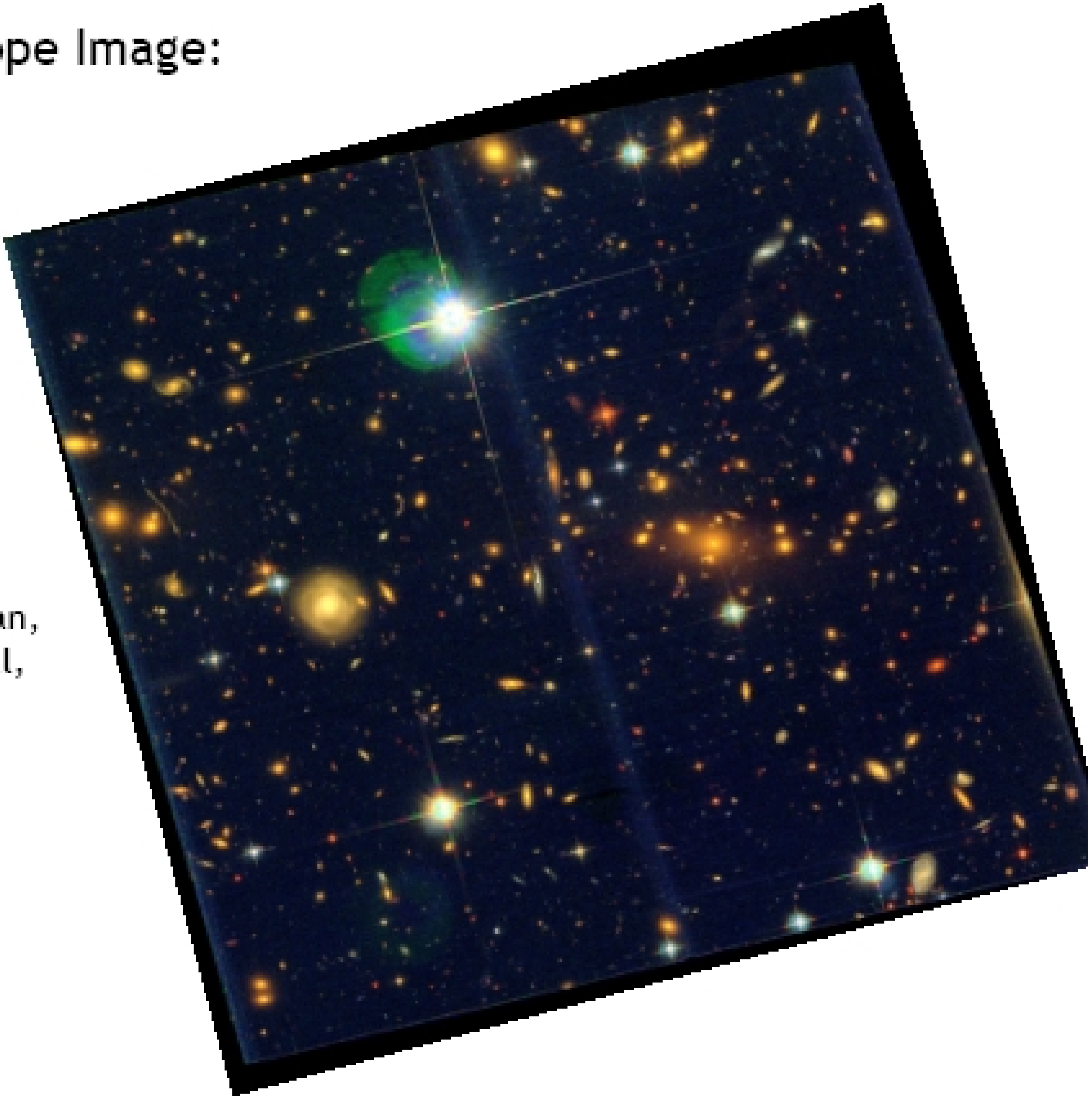


Gravitationally lensed galaxy SDSS J0737+3216 with foreground lensing source removed



Excursion: Dark Matter & Colliding Galaxies

Here is the
Hubble Space Telescope Image:

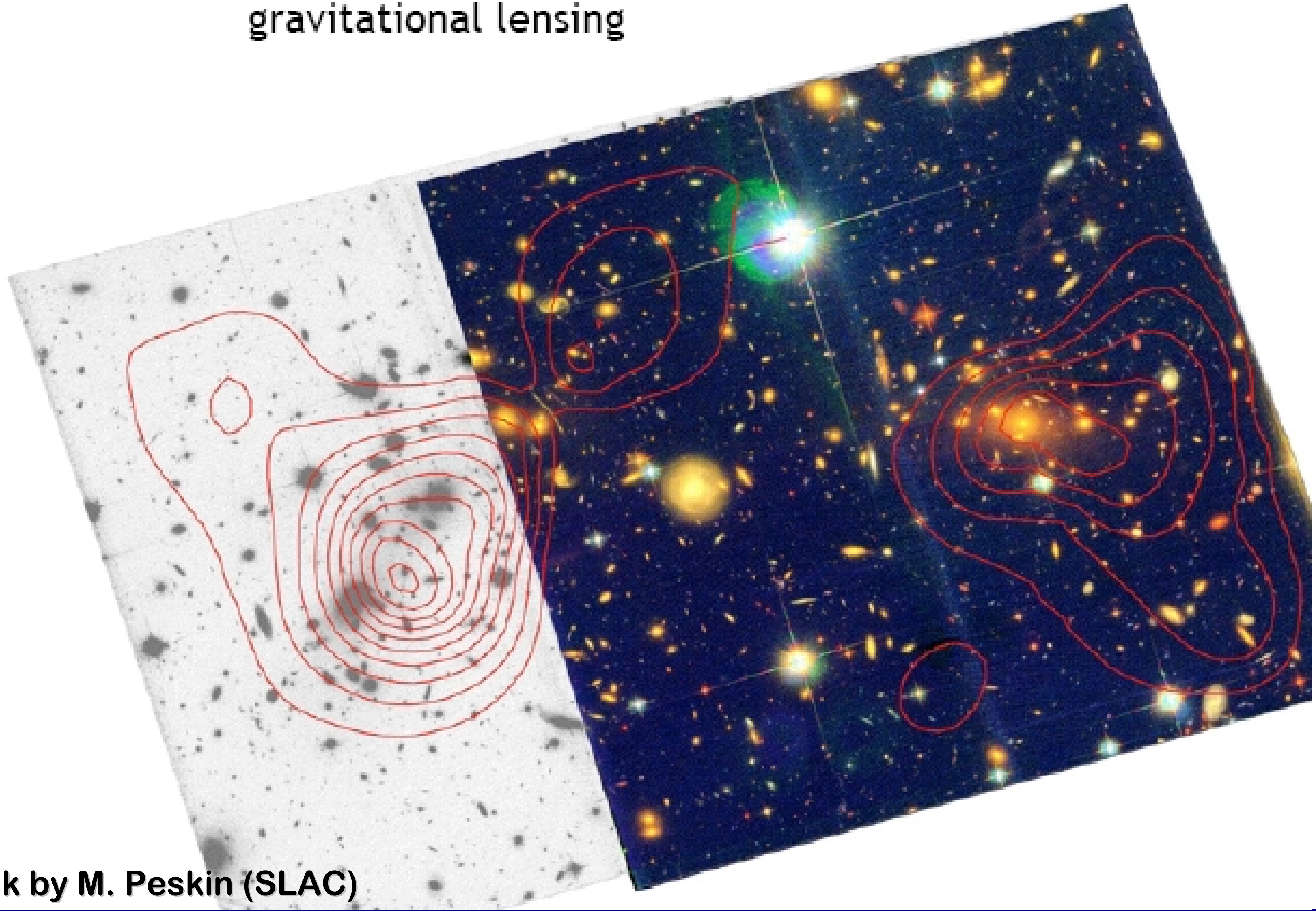


analysis of Bradac, Clowe, Gonzalez, Marshall, Forman, Jones, Markevitch, Randall, and Schrabback

From talk by M. Peskin (SLAC)

Excursion: Dark Matter & Colliding Galaxies

Here is the mass distribution reconstructed from gravitational lensing



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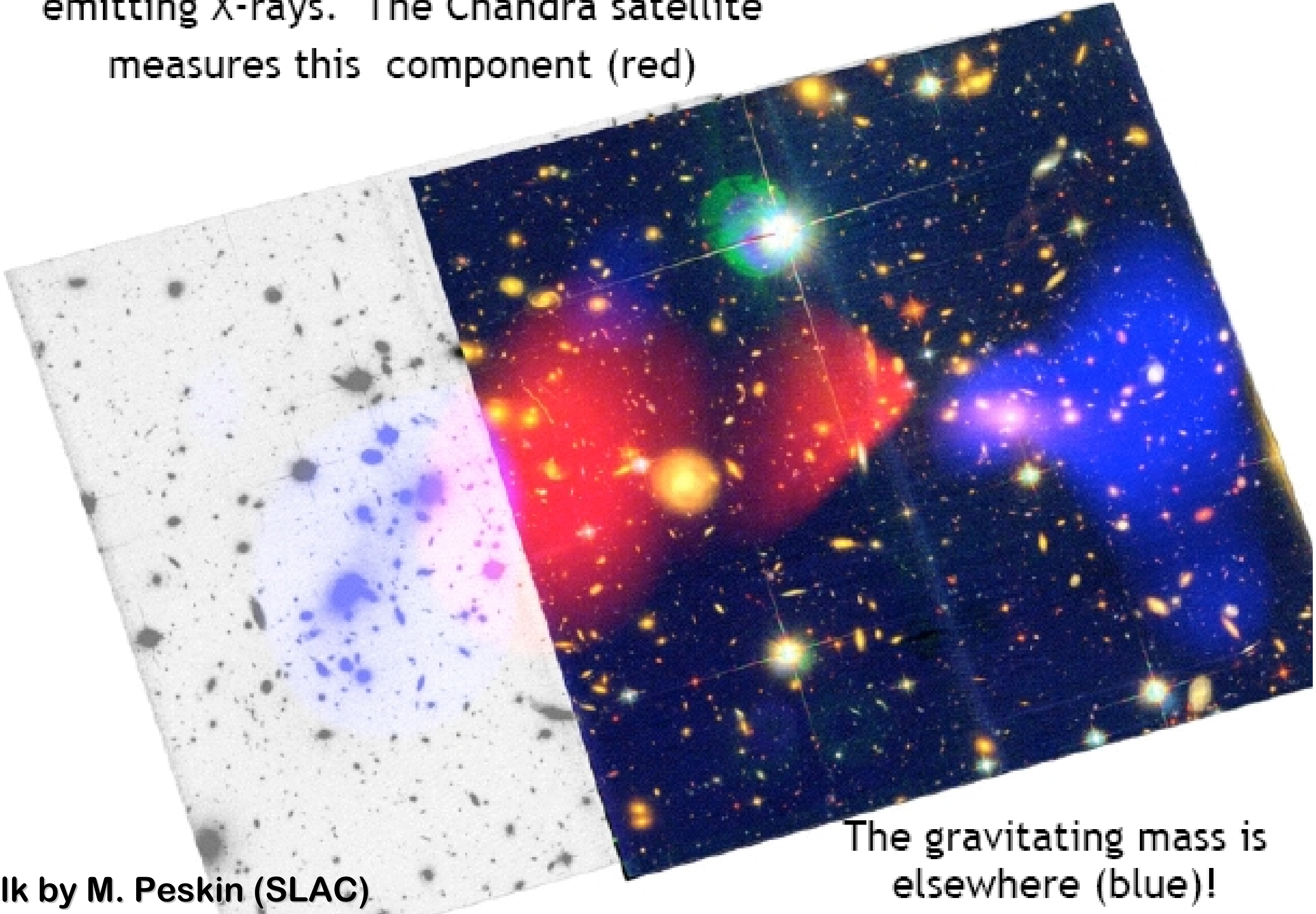
Excursion: Dark Matter & Colliding Galaxies

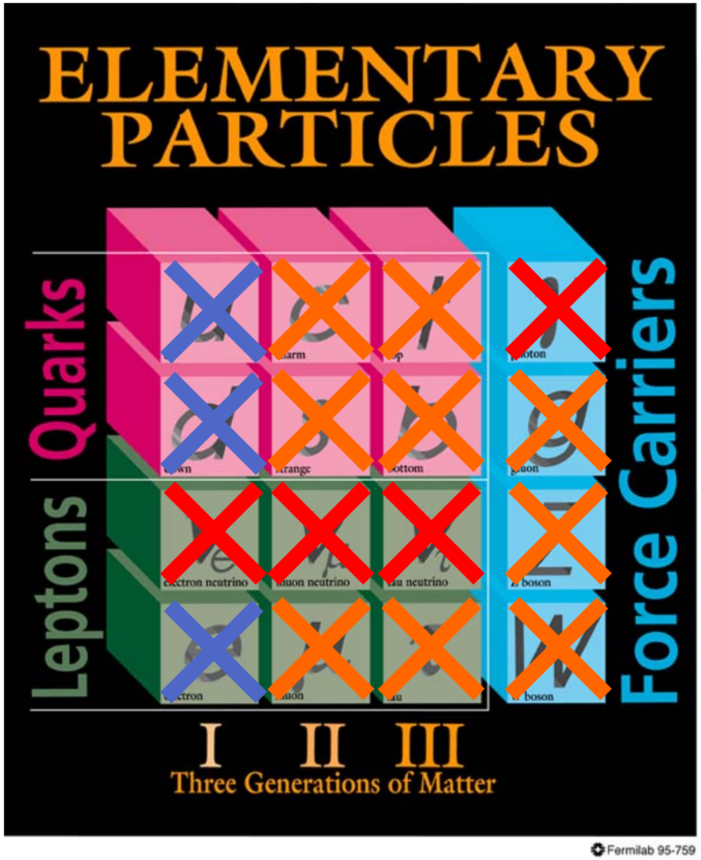


The atomic matter is mainly in hot gas, emitting X-rays. The Chandra satellite measures this component (red)

The gravitating mass is elsewhere (blue)!

From talk by M. Peskin (SLAC)

Dark Matter Properties



Dark-Matter properties:

- *Gravitationally interacting*
- *Not short-lived*
- *Not hot*
- *Not baryonic*

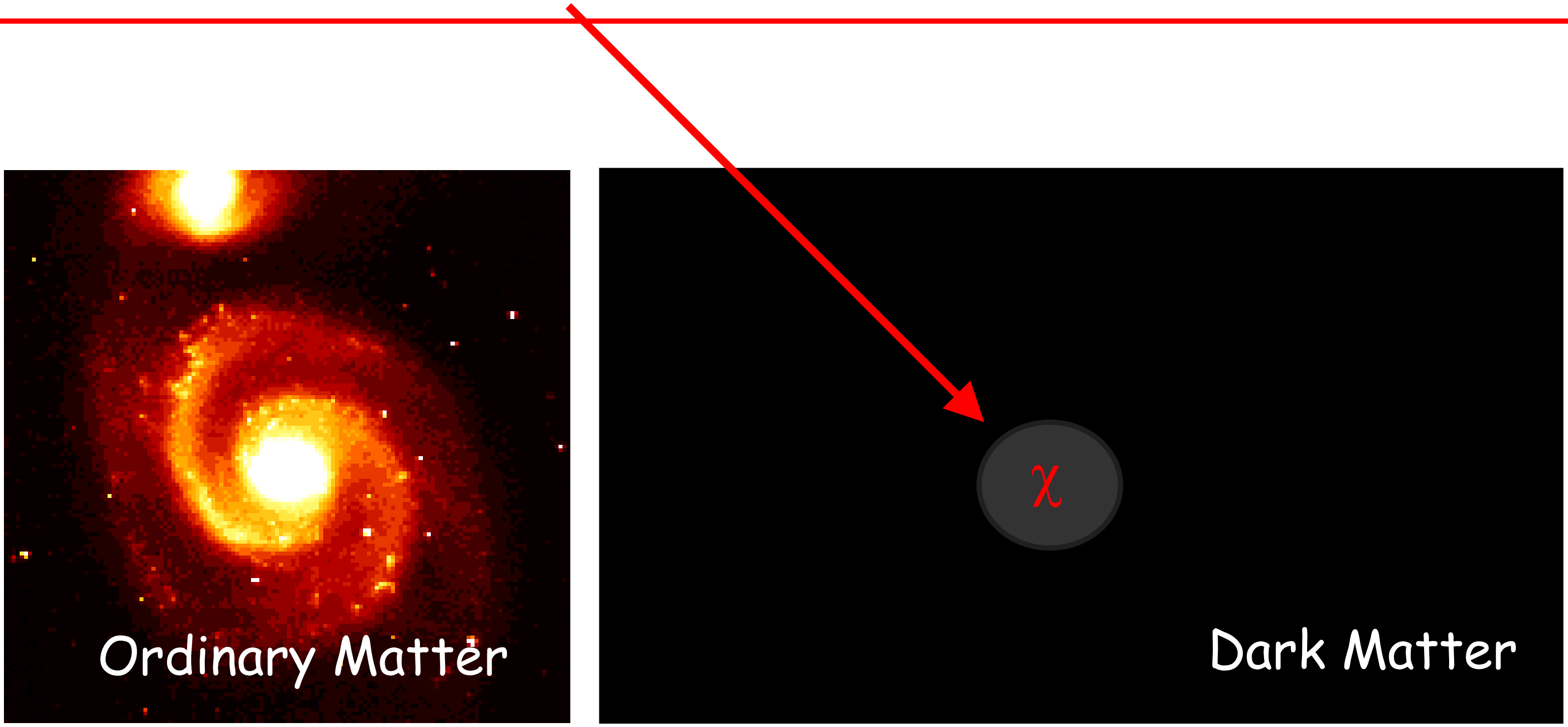
→ Unambiguous evidence for new physics !

Reasons for SUSY (3) : Dark Matter

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

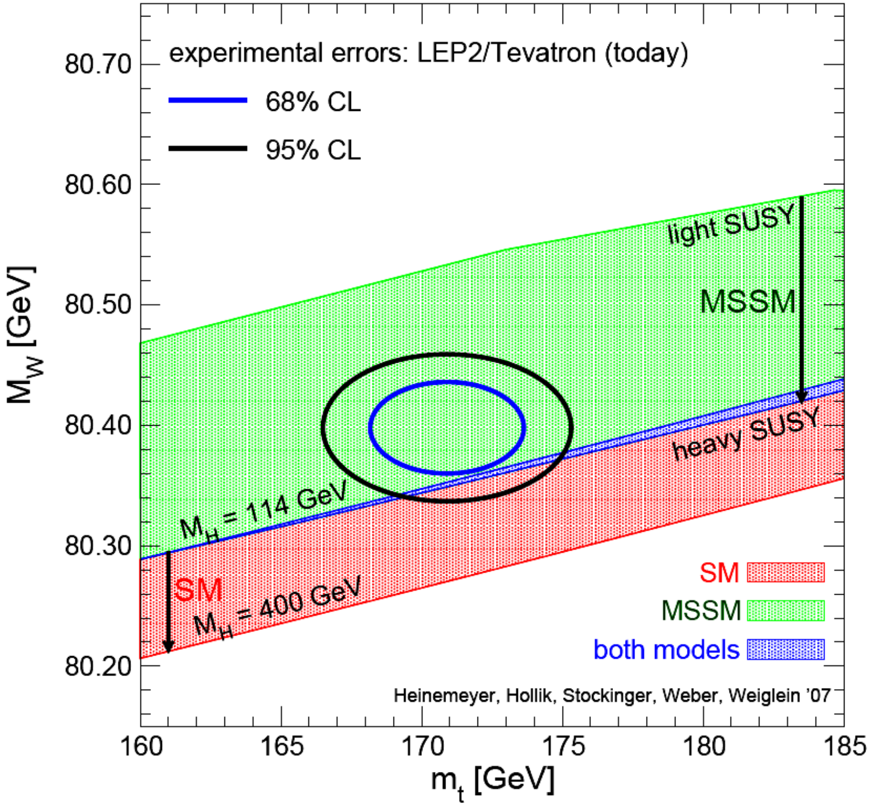
the lightest supersymmetric particle

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



Reasons for SUSY (4) : EW Measurements

SUSY is compatible with electroweak precision measurements

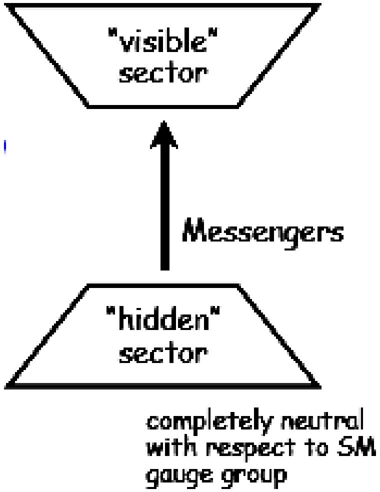


Leads to even tighter upper limit on Higgs mass: $m_h < \sim 130$ GeV
(h = lightest MSSM Higgs; it is expected to be similar to the SM Higgs)

The Problem: SUSY Breaking

SUSY Breaking

- Supersymmetry is not an exact symmetry, since particle and sparticle masses are not the same.
  A selectron with the mass of an electron would certainly have been seen by now.



- Need model for “SUSY breaking”:
  SUSY breaking occurs in a hidden sector and is transmitted to visible sector (where MSSM particles live) via certain mechanisms
  Particles in hidden sector are neutral to SM gauge group.

- SUSY breaking leads to additional parameters

-Unconstrained models (>100 parameters: masses, couplings,phases

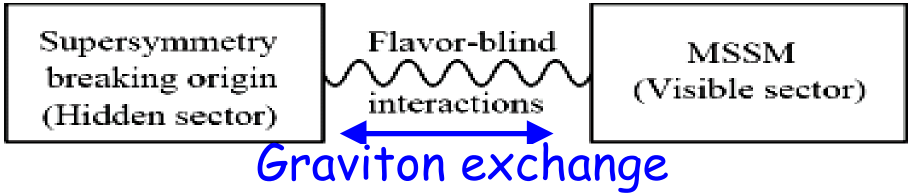
-Constrained models (e.g. mSUGRA, cMSSM: 5 parameters)

Models for SUSY Breaking

- Assumptions to reduce number of free parameters: "Unification at high energies"

- Assume universal masses for all bosons and all fermions at GUT scale, unification of couplings at GUT scale

- An example: mSUGRA (minimal SUper GRAvity)
  - SUSY breaking is mediated by gravity



- Remaining 5 parameters in mSUGRA:

  - m_0 : universal boson (scalar, spin-0) mass at GUT scale
  - $m_{1/2}$: universal gaugino (spin-½) mass at GUT scale
  - A_0 : universal triliniear coupling at GUT scale
  - $\tan\beta$: ratio of the two Higgs vacuum expectation values
  - sign(μ) : sign of the higgsino mass parameter

Some Models for SUSY Breaking

- mSUGRA: Gravity-mediated

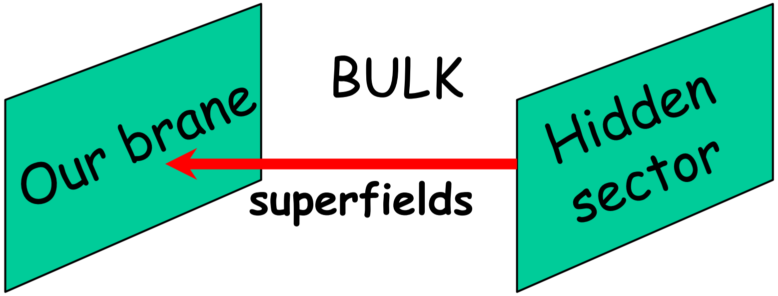
  LSP = lightest neutralino

- GMSB: Gauge-mediated

  LSP = gravitino

- AMSB: Anomaly-mediated

  LSP = lightest neutralino



SUSY Masses in mSUGRA

Evolution of SUSY masses: "Renormalization Group Equations (RGE)"

- Gaugino masses:

$$\boxed{\frac{M_1}{\alpha_1} = \frac{M_2}{\alpha_2} = \frac{M_3}{\alpha_3}}$$

$M_3 \equiv M_{\tilde{g}} \simeq 2.7 m_{1/2}$, **gluino**

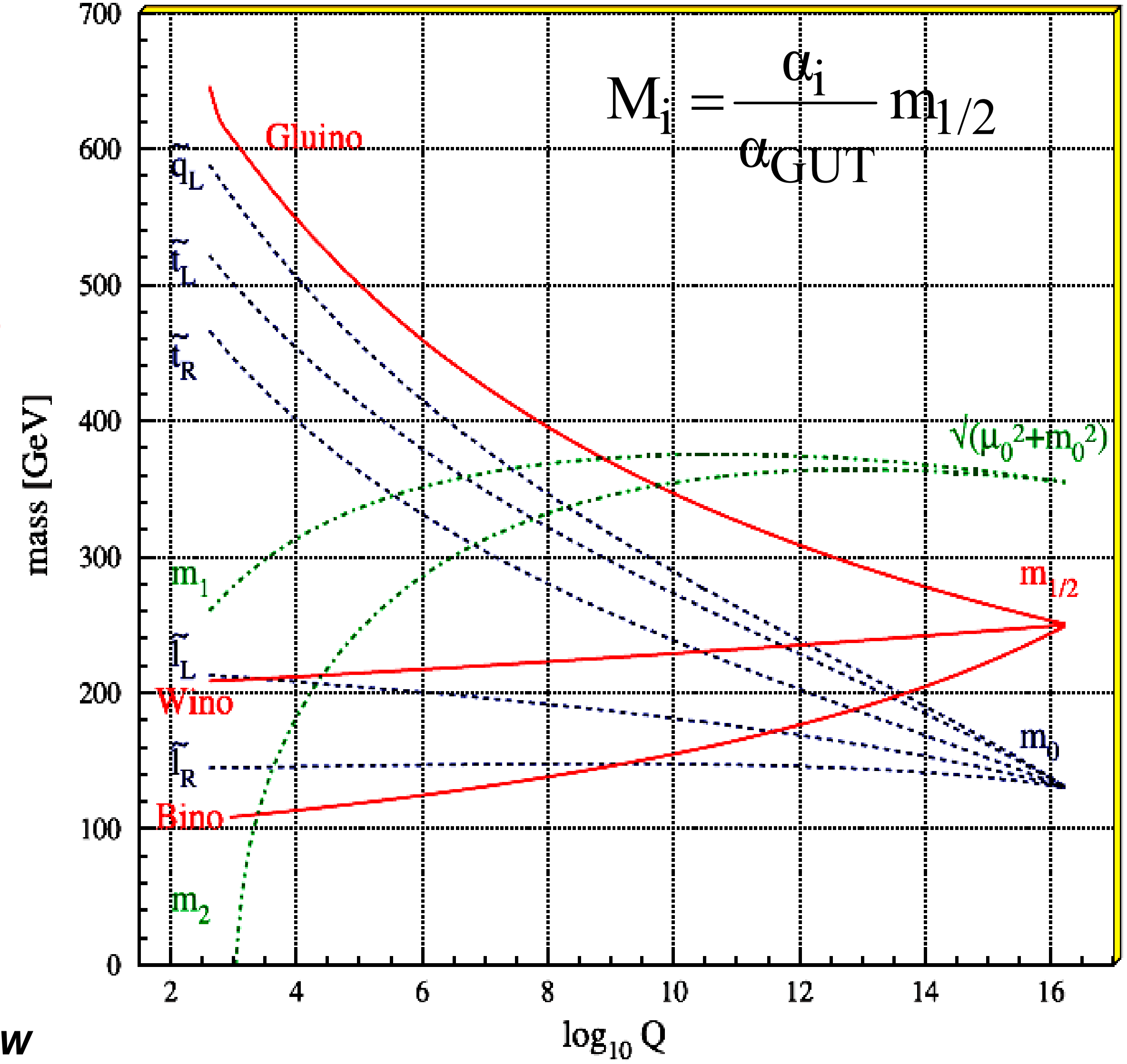
$M_2(M_Z) \simeq 0.8 m_{1/2}$, **wino**

$M_1(M_Z) \simeq 0.4 m_{1/2}$. **bino**

- Sfermion masses:

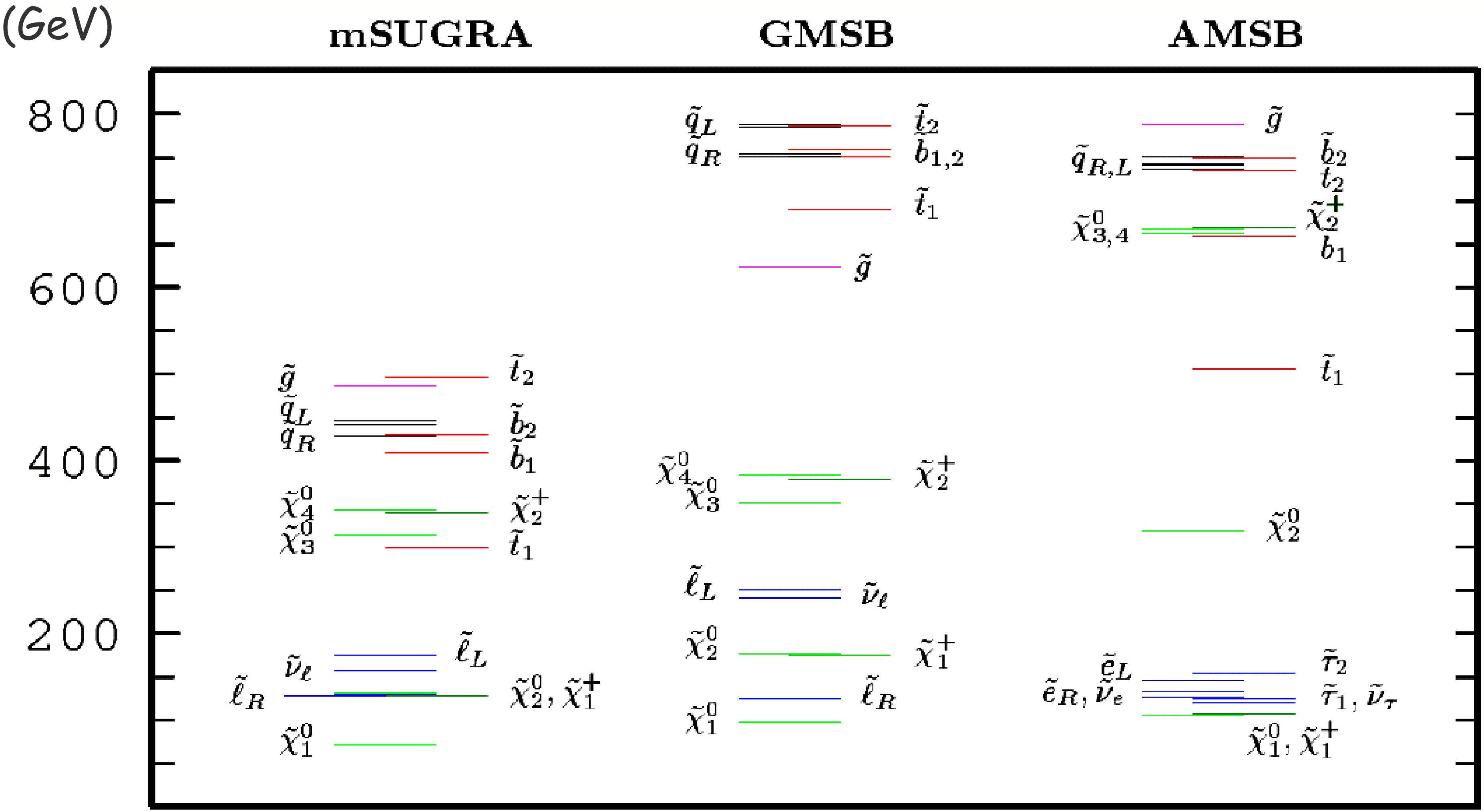
$$\boxed{m_{\tilde{l}} < m_{\tilde{q}} \simeq M_{\tilde{g}}}$$

- *Higgs masses:*
  - *$m_h < 130$ GeV*
  - *$m^2_{H,A,H\pm} \sim m^2_A + M^2_W$*



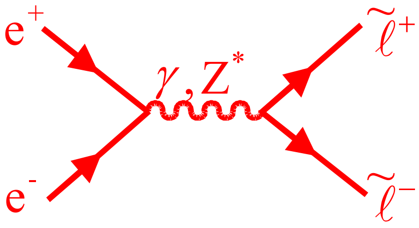
Example SUSY Mass Spectra

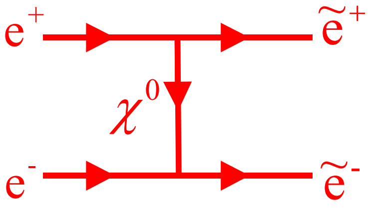
Typical examples for three different SUSY models



SUSY Constraints from Experiments

Direct Searches at LEP & TeVatron

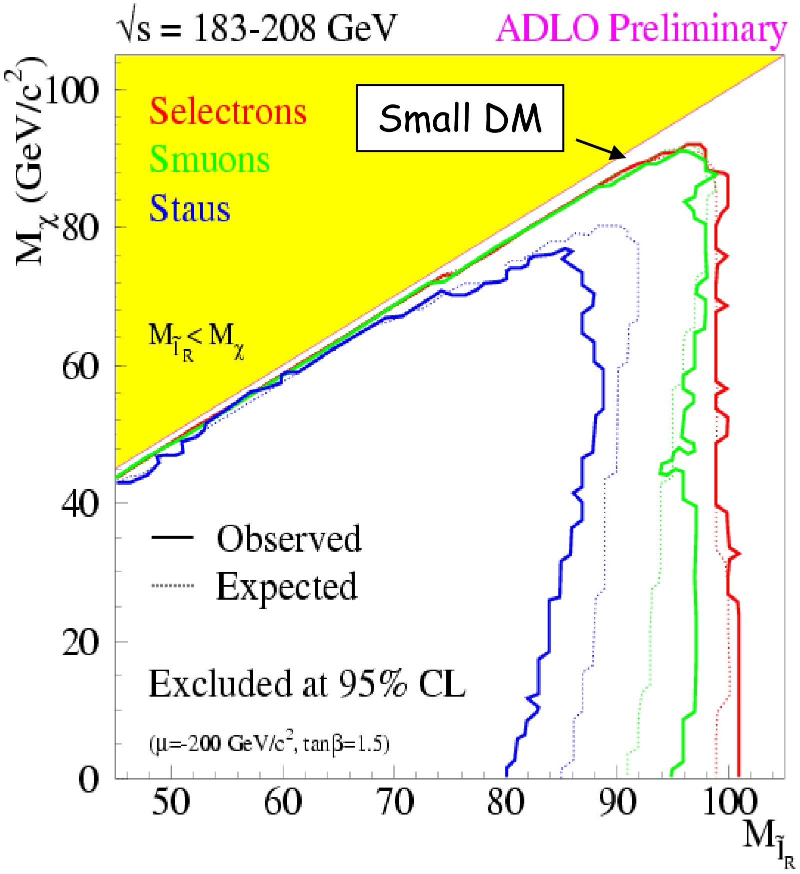




- Slepton & Chargino/Neutralino searches at LEP (e^+e^-, E_{cm}~ 200 GeV)

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

→ Excluded up to masses of 80 … 104 GeV



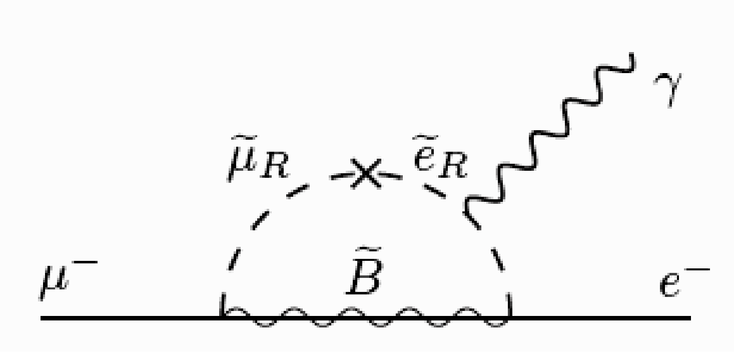
- Squark and gluino searches at TeVatron ($p\bar{p}$, E_{cm}~ 2 TeV)

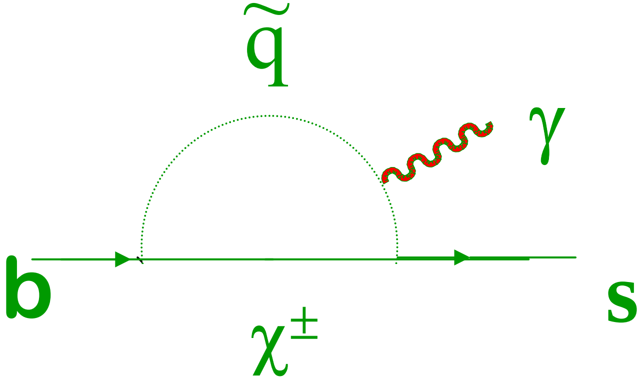
→ Excluded up to masses of ~ 400 GeV

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

Dark Matter: Relic Abundance

- Observed dark-matter abundance and properties of dark-matter particle annihilation and co-annihilation processes constrain SUSY parameters

(1) Assume new heavy particle in thermal equilibrium:

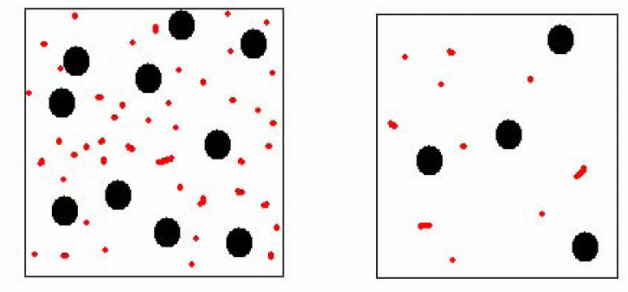
$$\chi\chi \leftrightarrow f\bar{f}$$

(2) The Universe cools:

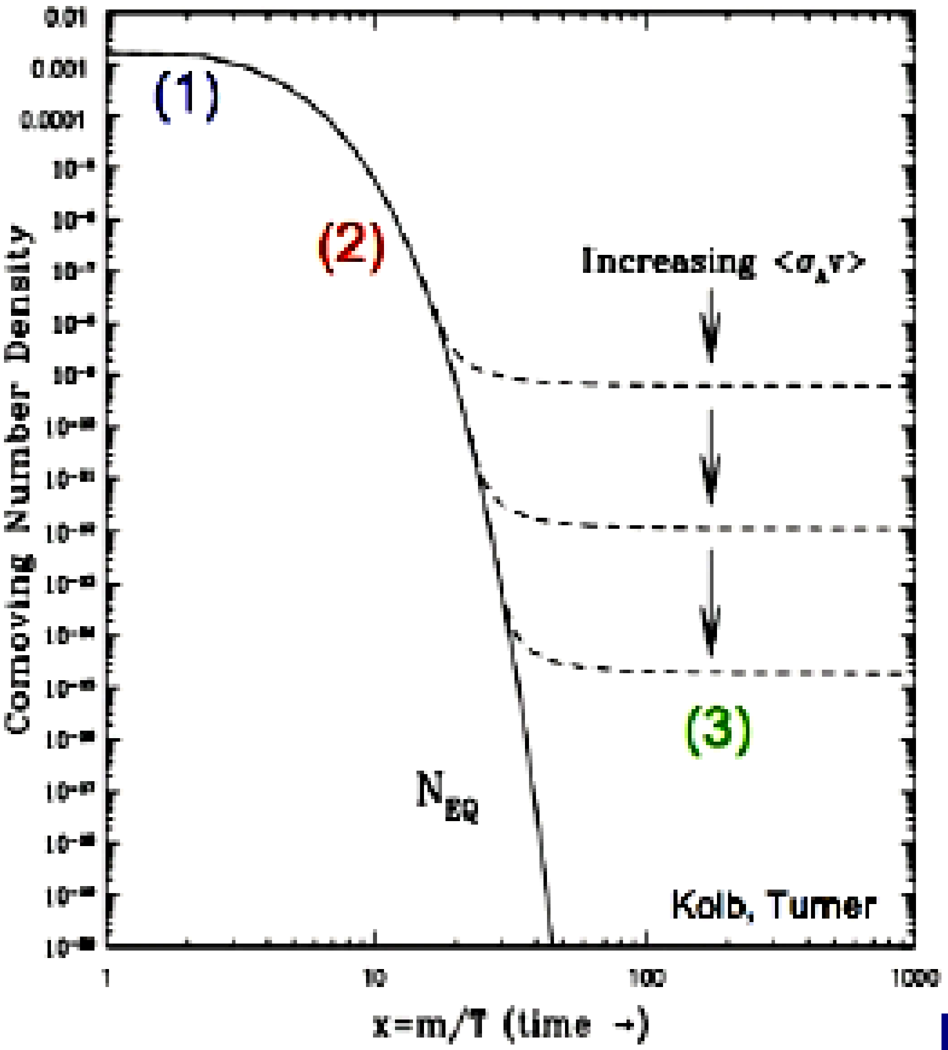
$$\chi\chi \rightarrow f\bar{f} \qquad \chi\chi \not\leftarrow f\bar{f}$$

(3) Chi freezes out

$$\chi\chi \not\leftrightarrow f\bar{f}$$

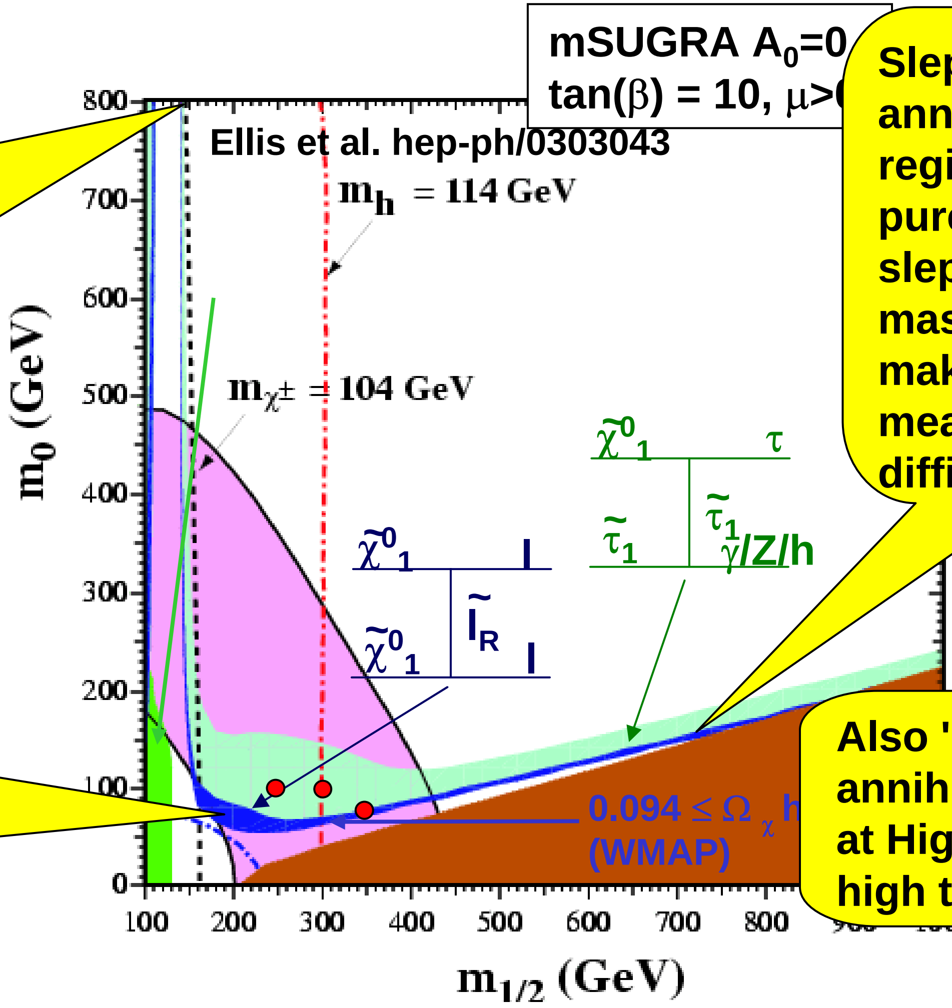


High Temp. **Low Temp.**



SUSY Dark Matter Constraints

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



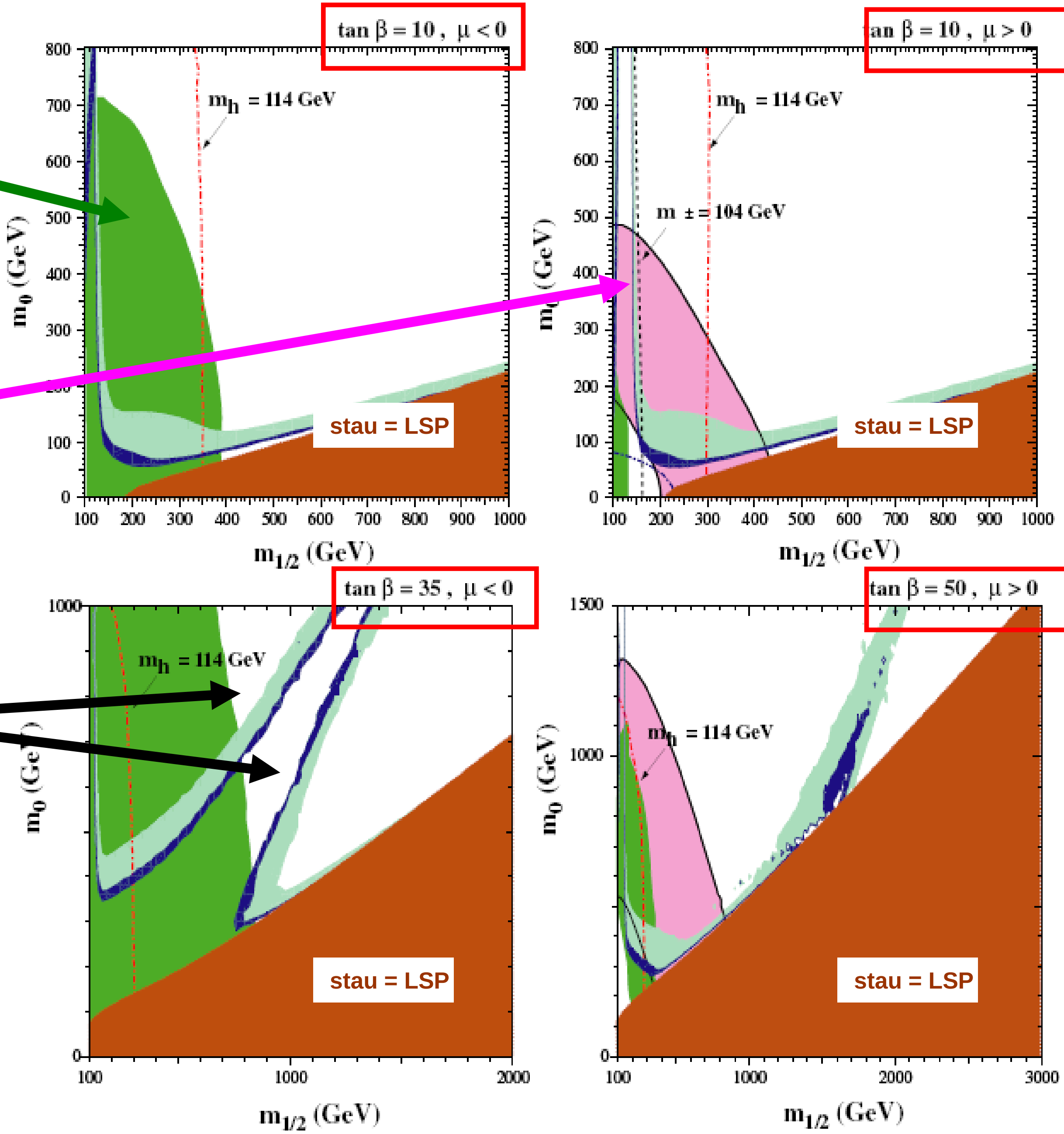
'Focus point' region: significant h component to LSP enhances annihilation to gauge bosons

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 favored*

- *Dark matter favored*

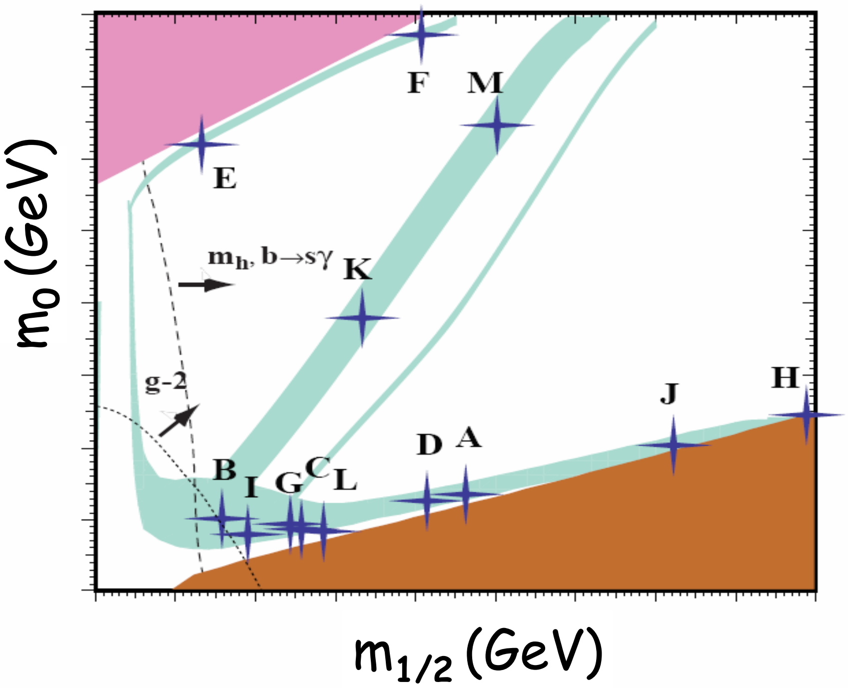
SUSY already quite confined, but there are still many possibilities

→ Need discovery at LHC

Studying SUSY Points

- Particle physicists use Monte Carlo simulations to study SUSY and to discover new physics by comparing data with simulation.
- But SUSY parameter space is huge! The most sensitive parameters are the SUSY masses (determined by $m_0,m_{1/2}$ in mSUGRA)
- Need to choose some strategical "points" in parameter space to generate simulated events (later perform scans of other par.'s).

e.g. choice of SUSY points inspired by cosmological constraints

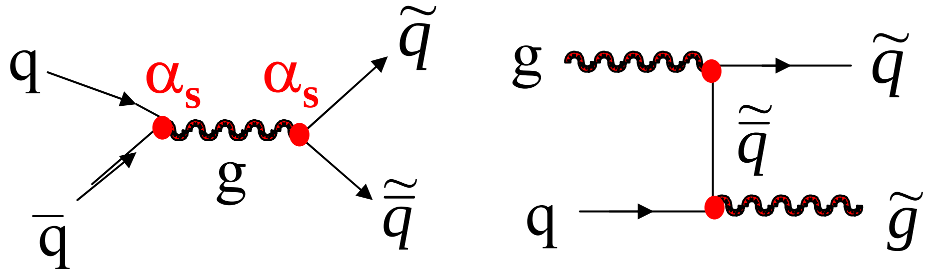


SUSY at the LHC

Production and Decay

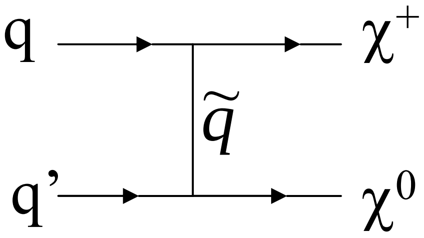
How are Sparticles Produced?

- Squarks and gluinos produced via strong processes → large rates



M (GeV)	*σ (pb)*	*Evts/yr*
500	100	10^6-10^7
1000	1	10^4-10^5
2000	0.01	10^2-10^3

- Charginos, neutralinos, sleptons via direct electroweak production → much smaller rates

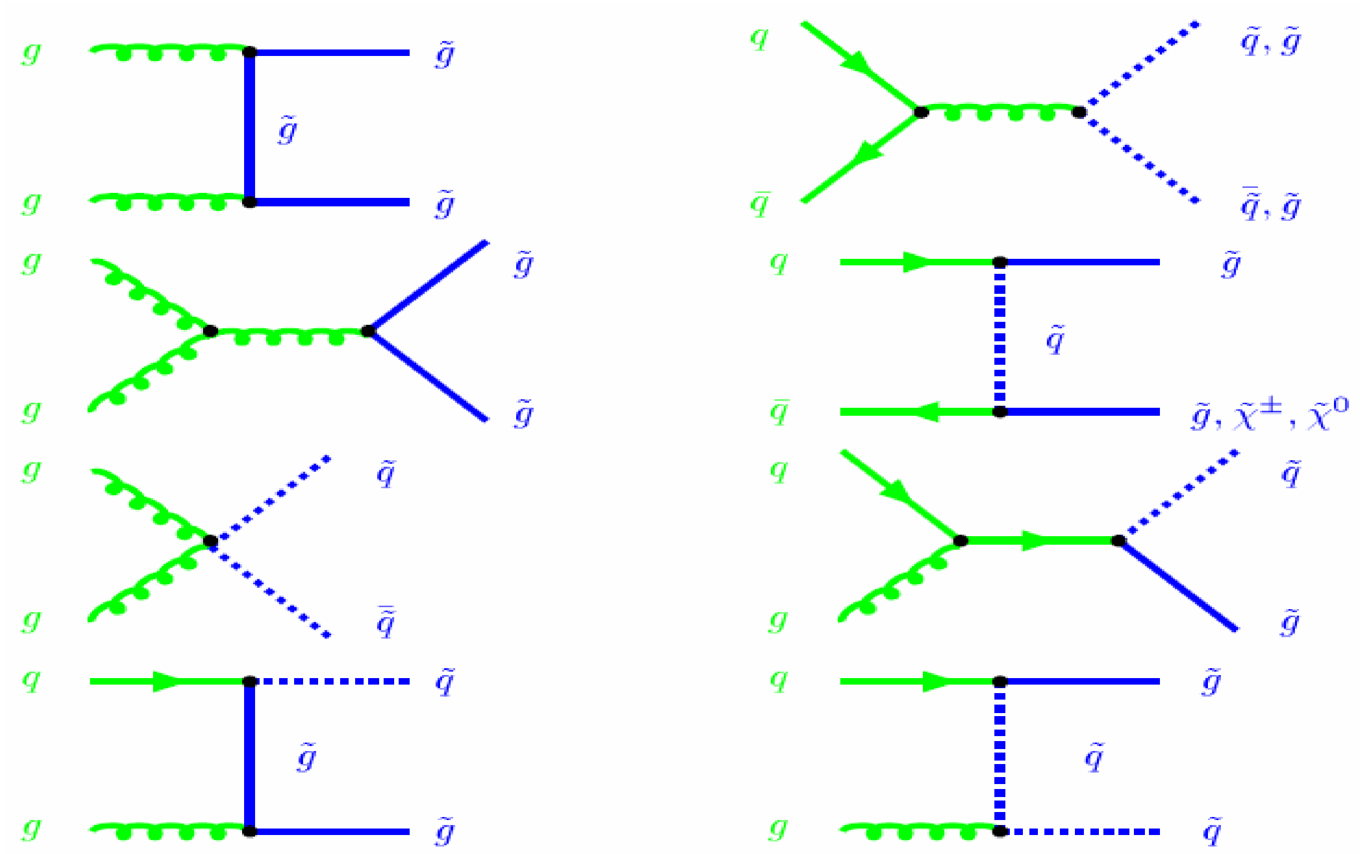


$\sigma \approx 1$ pb for $m_\chi \approx 150$ GeV

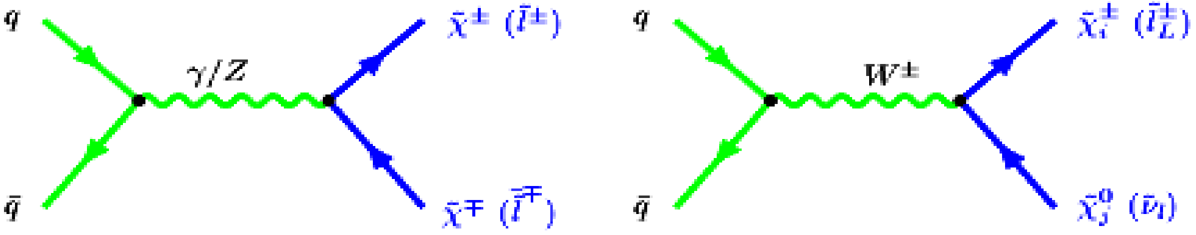
- $\tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$ production are dominant SUSY processes at LHC
- Charginos/Neutralinos mostly from decays of squarks or gluinos

IV.25 Sparticle Production at LHC

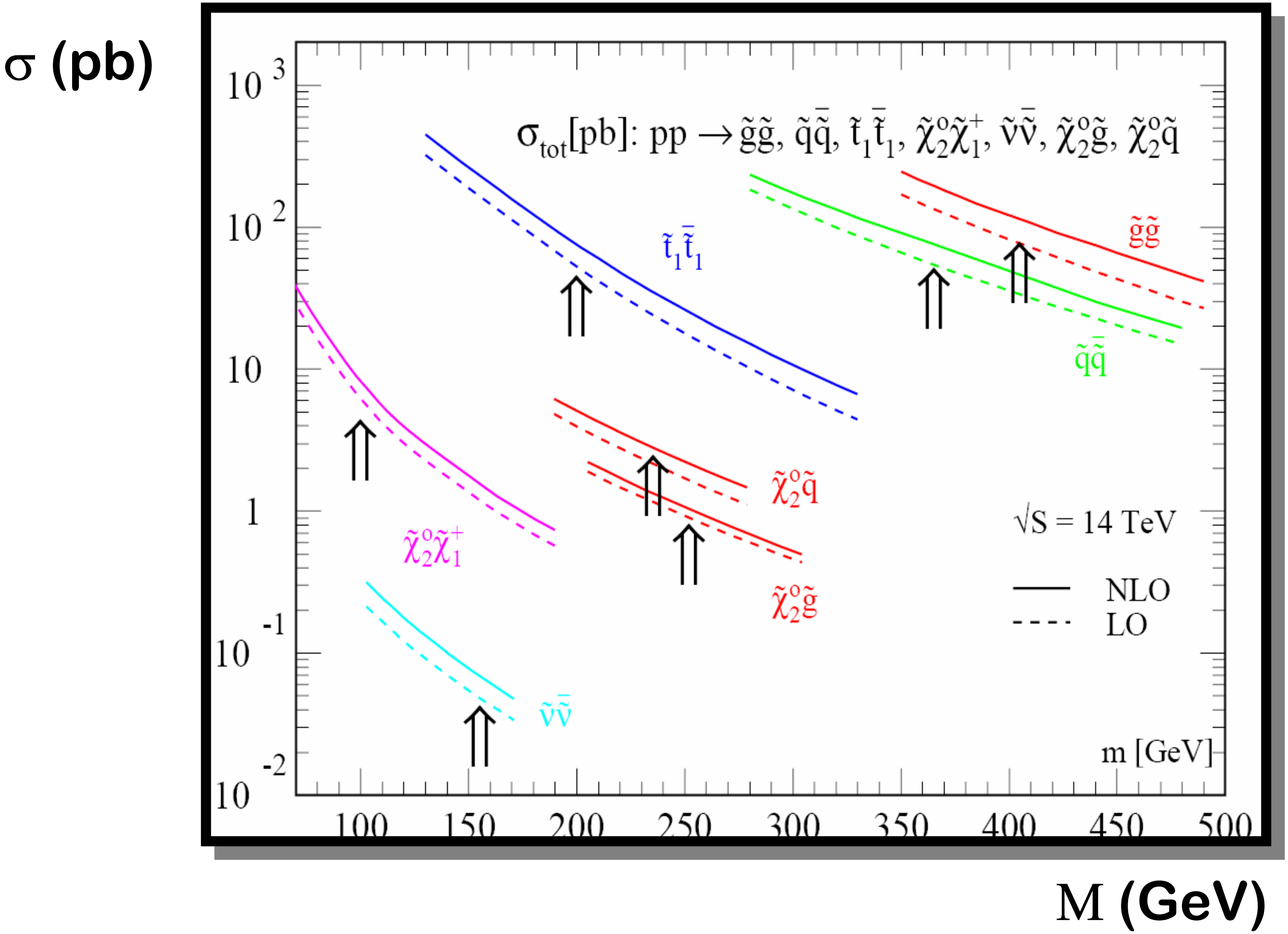
Quark-gluon fusion



Quark annihilation

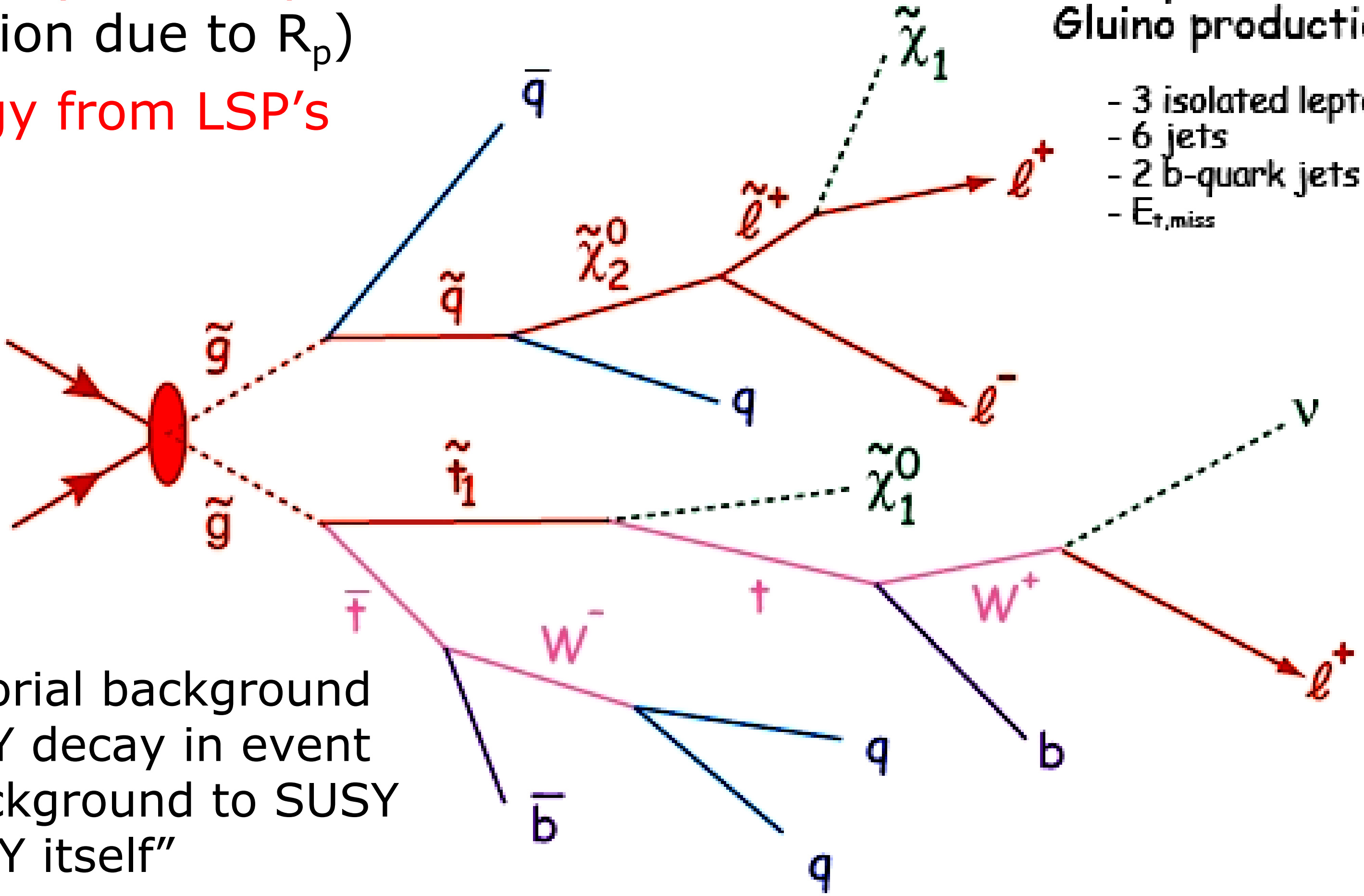


SUSY Cross Sections (An Example)



SUSY Decay Cascade

- 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



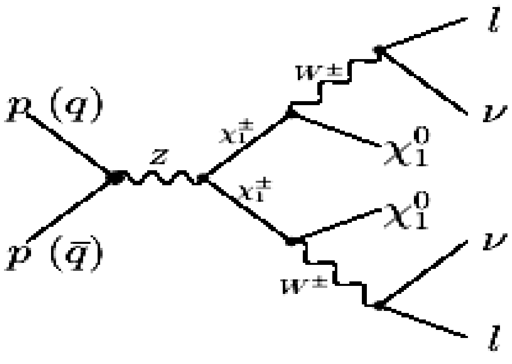
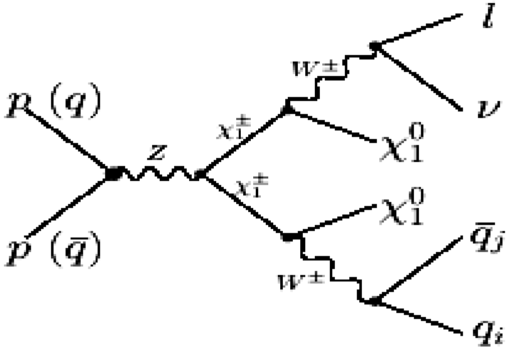
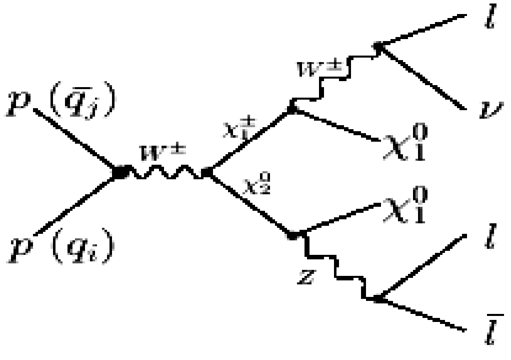
Example:
Gluino production

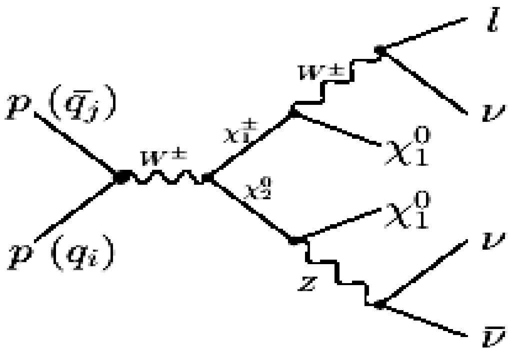
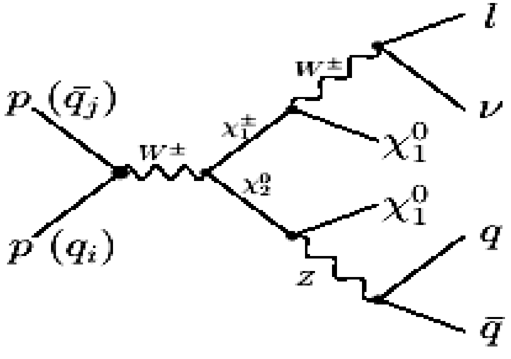
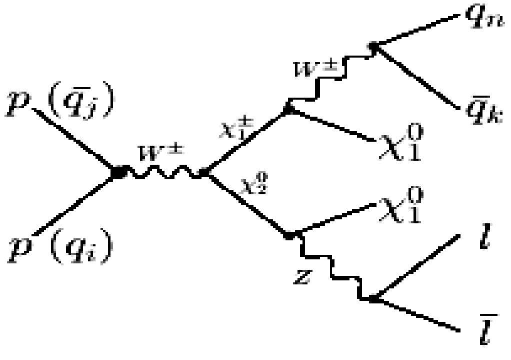
- 3 isolated leptons
- 6 jets
- 2 b-quark jets
- $E_{t,miss}$

Huge combinatorial background
from second SUSY decay in event
→ “dominant background to SUSY
is SUSY itself”

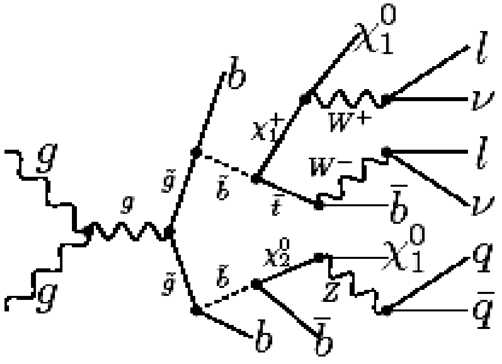
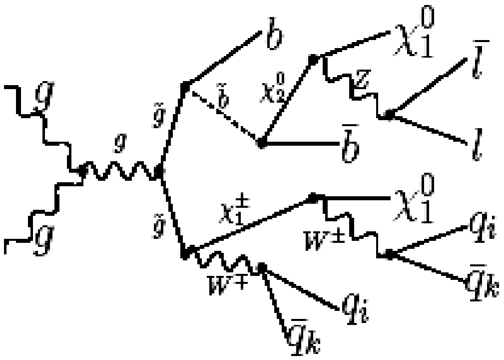
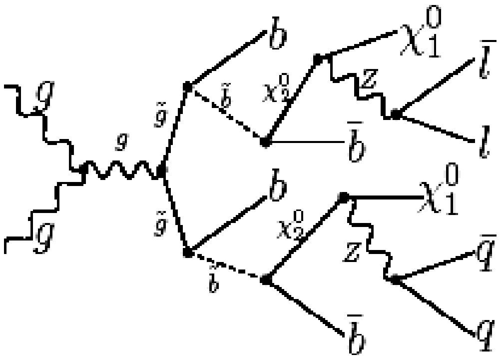
Typical final states: jets + E_T^{miss} (+ leptons)

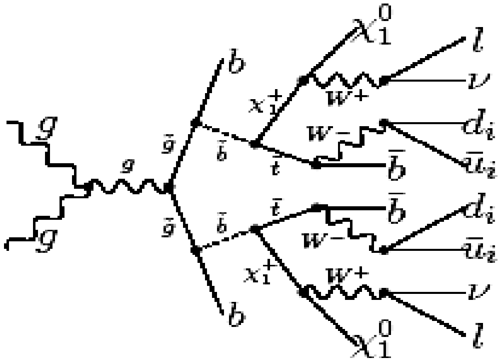
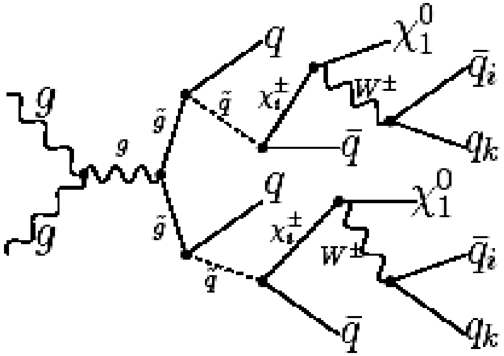
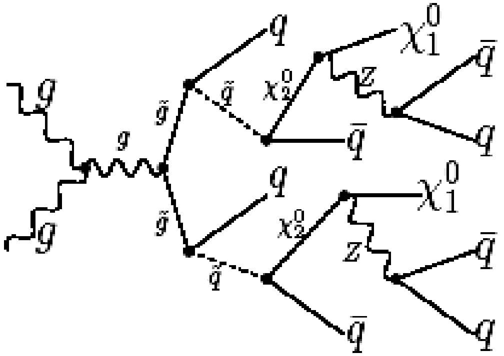
SUSY Final States ... there are many

process	final states
	2ℓ 2ν $\not{E}_T$
	1ℓ $2j$ ν $\not{E}_T$
	3ℓ ν $\not{E}_T$

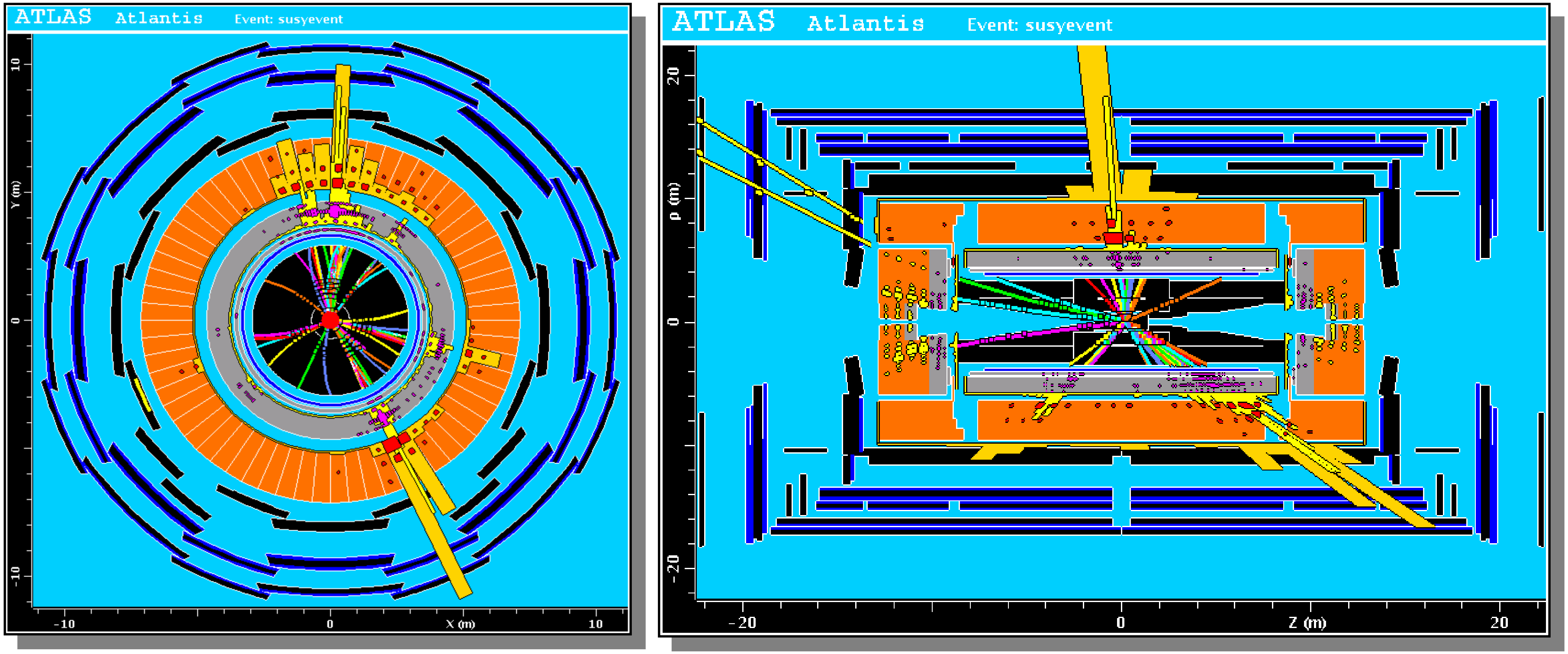
process	final states
	ℓ 3ν $\not{E}_T$
	ℓ ν $2j$ $\not{E}_T$
	2ℓ $2j$ $\not{E}_T$

SUSY Final States ... there are many

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

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

Simulated SUSY Event in ATLAS



Missing transverse momentum

Jets

Heavy quarks

Leptons

SUSY Searches at LHC

Strategy for SUSY Searches

- Step 1: Discovery
  - Look for deviations from the Standard Model
- Step 2: Mass scale
  - Establish the approximate SUSY mass scale

Inclusive

- Step 3: Measurements
  - Determine masses, branching fractions, etc.
- Step 4: Parameter studies
  - Study underlying theory / SUSY model

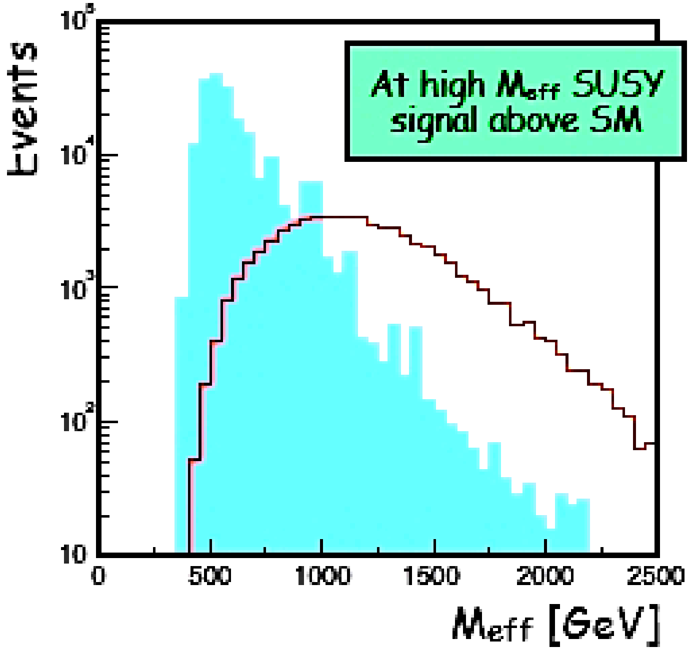
Specific Decays

Inclusive Searches – Mass Scale

- Select: > 4 jets, $E_{T,miss}$
- Reconstruct effective mass

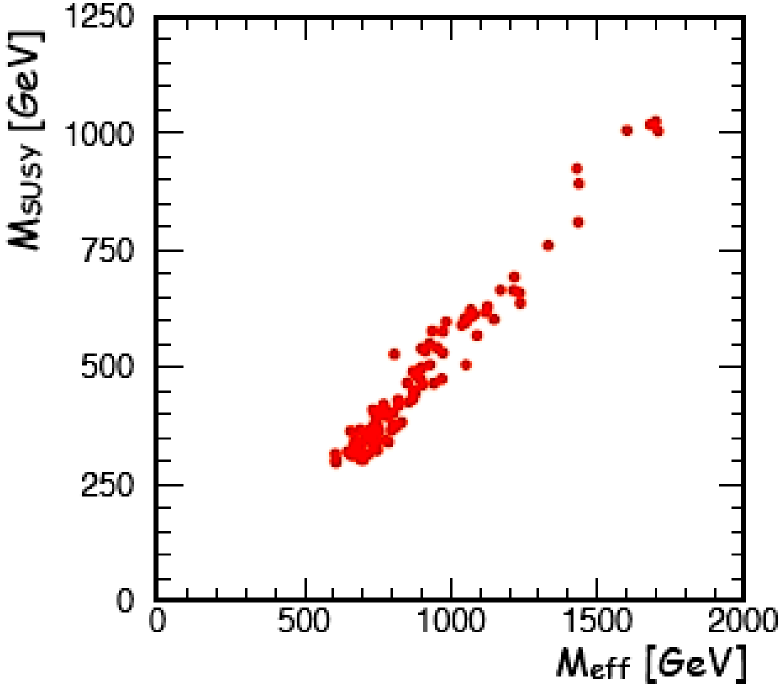
$$M_{\text{eff}} = \sum_{i=1}^{4} |P_{T,i}| + |E_{T,\text{miss}}|$$

Look at multi-jet and E_T^{miss} final states



Inclusive signature for squarks and gluinos

From Simulation



Peaking M_{eff} distribution correlates well with M_{SUSY}

Experimental Challenge: E_T^{miss}

- One of the most important SUSY signatures: $E_T^{\mathbf{miss}}$ from the LSP's
- Difficult to measure and is very sensitive to instrumental effects
- Lesson learned from the TeVatron experiments:

Partial List:

machine background

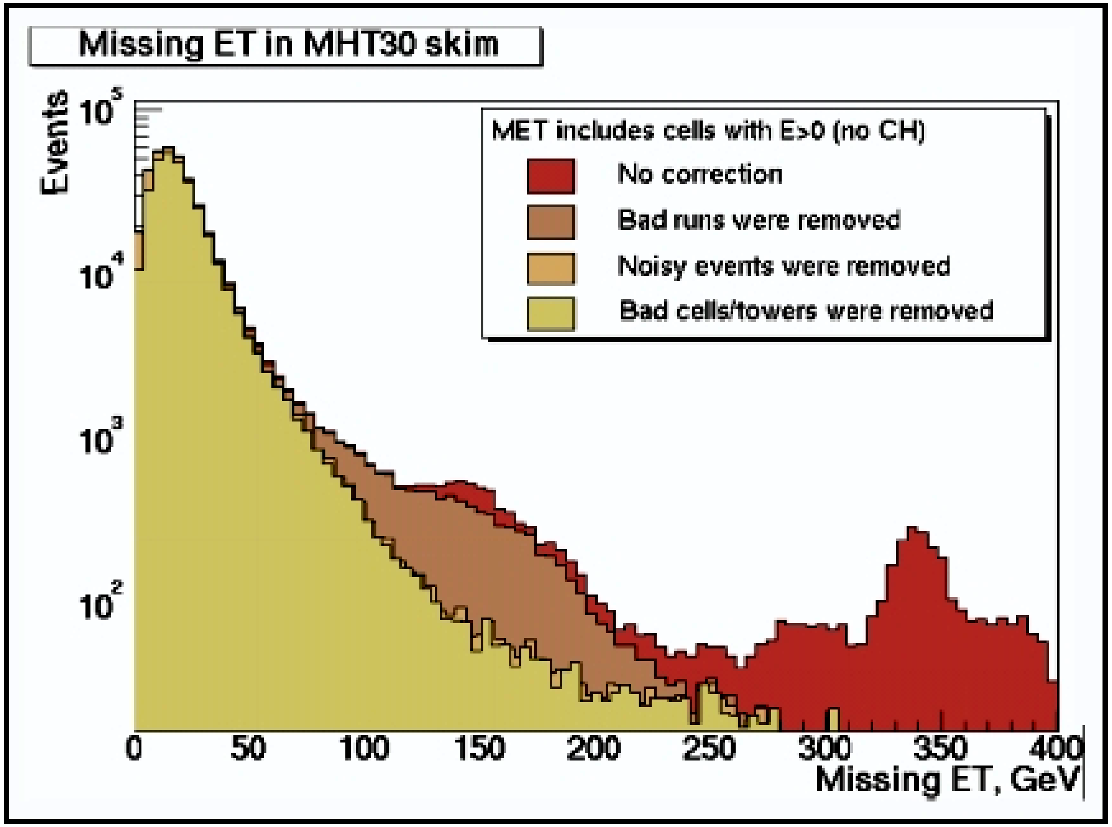
beam-gas events

hot cells

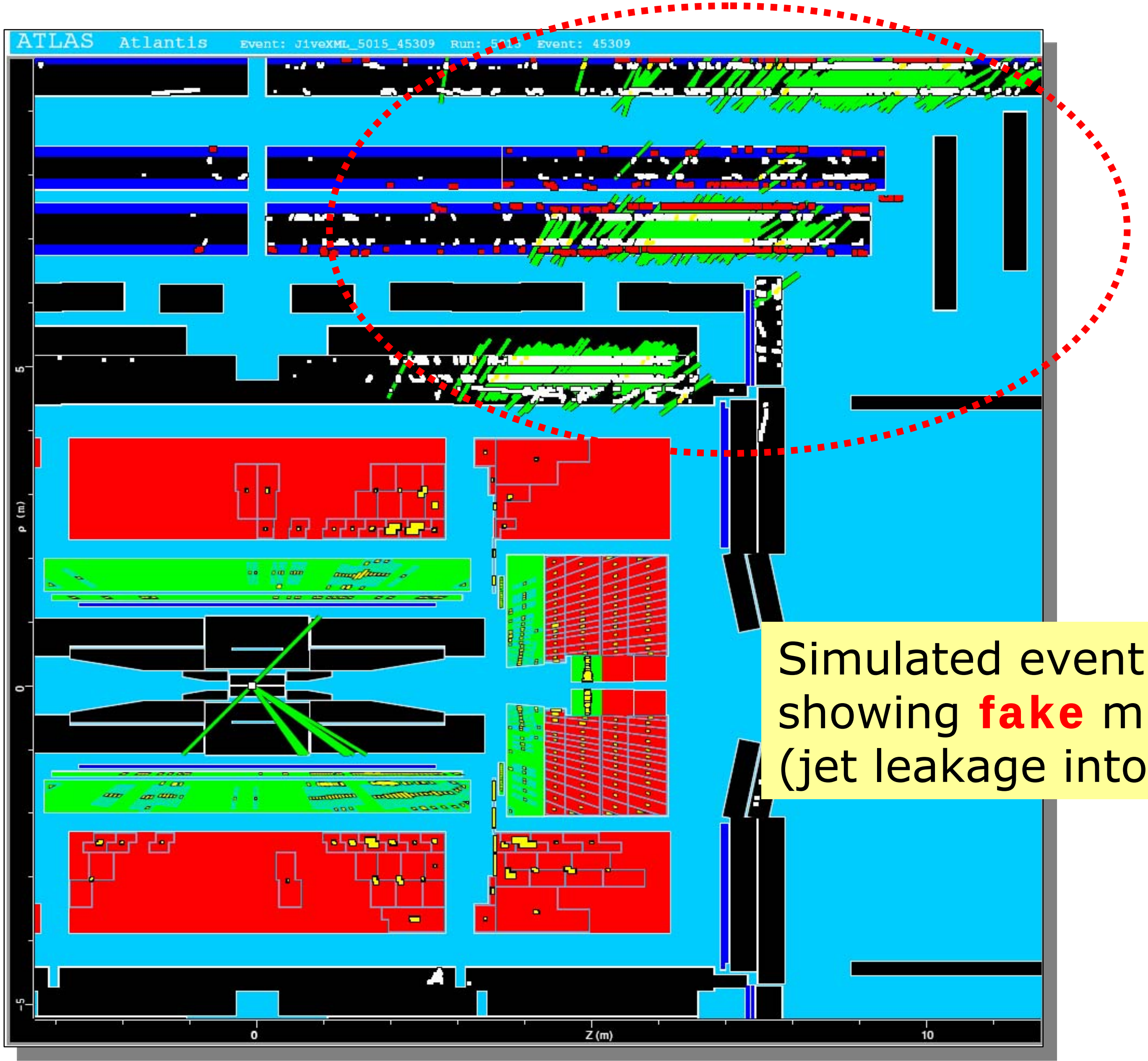
regions with poor jet response

displaced vertices

and many more ...



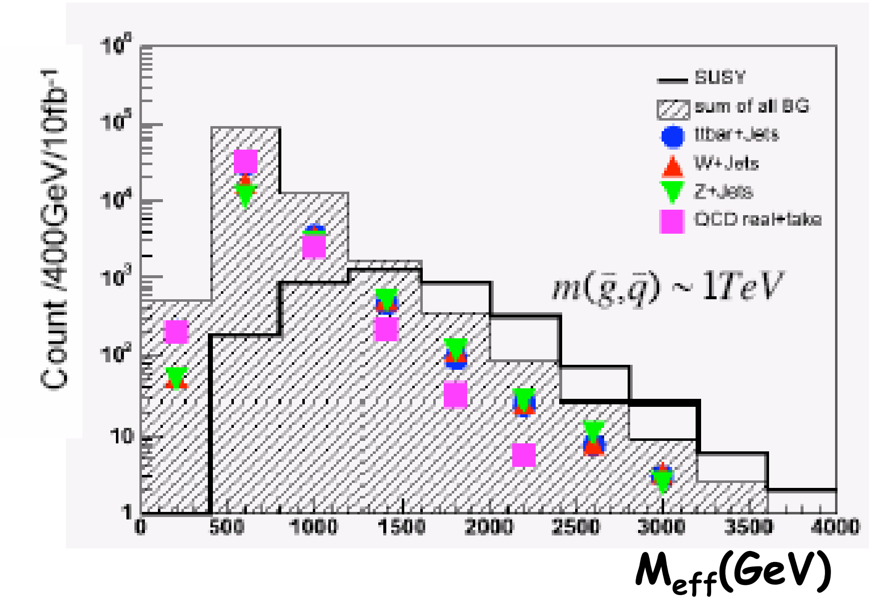
Understanding the Detector !!!



Simulated event in detector showing **fake** missing energy (jet leakage into muon system)

Example: 10 fb^{-1}, m(squark) = 1 TeV

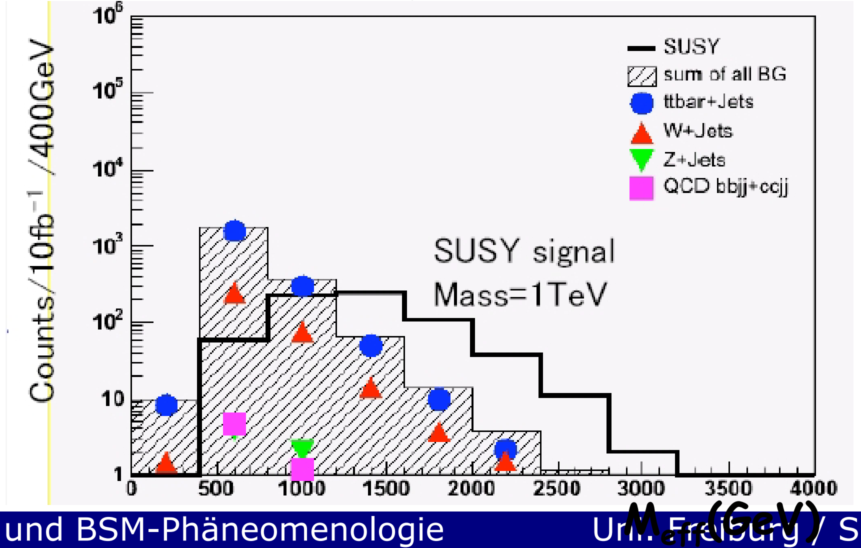
jets + E_T^{miss}



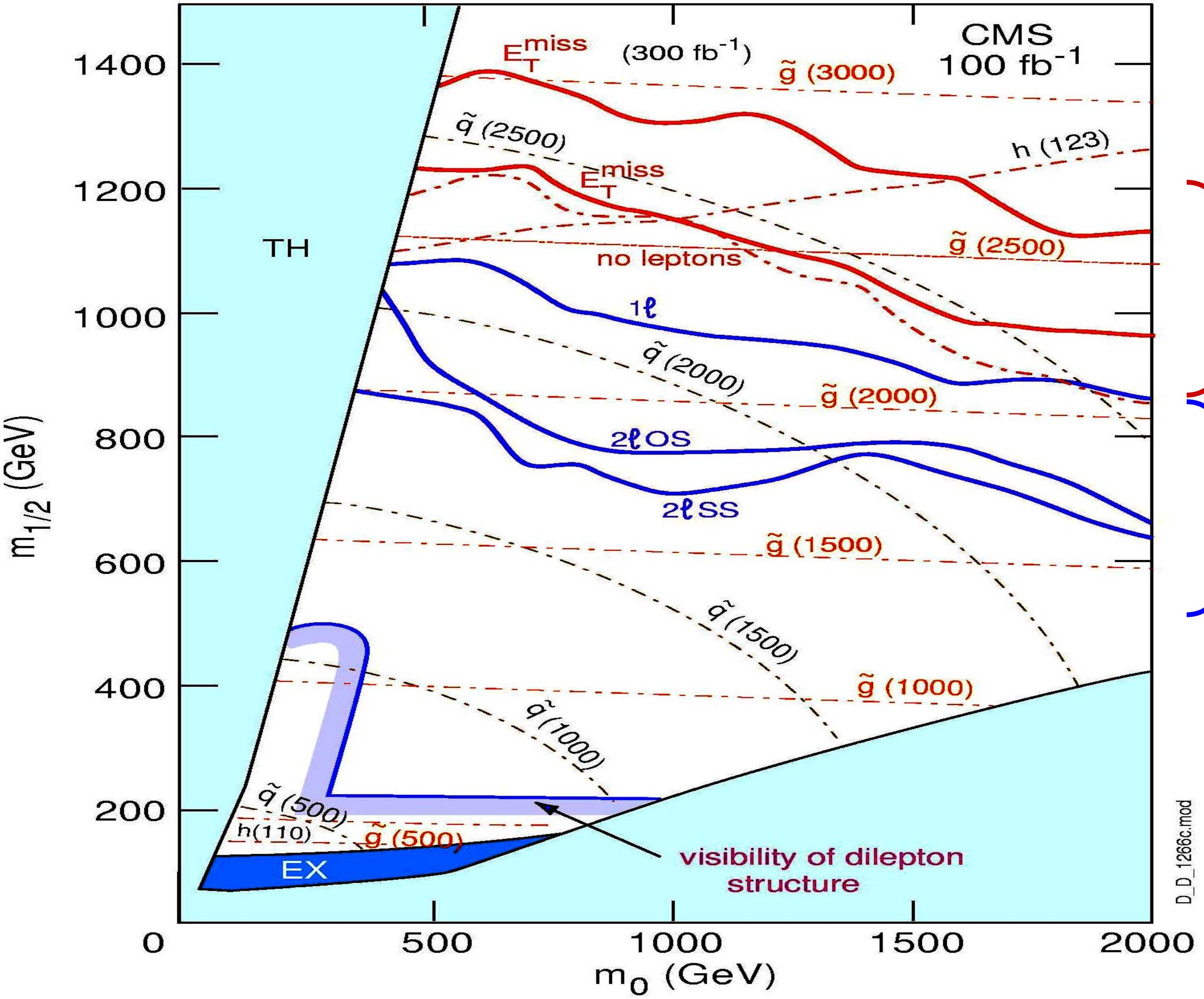
- jet+E_T^{miss} final states are the key for SUSY discovery
- Signal/bkg ratio can be improved by identifying leptons in the decay, e.g.

jets + E_T^{miss} + 1 lepton

→ Lower background, but also much fewer events!



LHC Reach for SUSY Masses

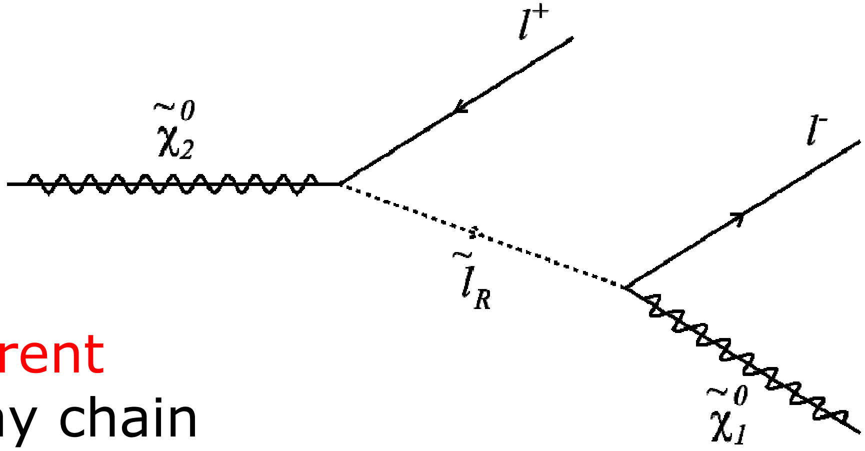


jets + E_T^{miss}

add. lepton(s)

Determining SUSY Masses: The Basic Idea

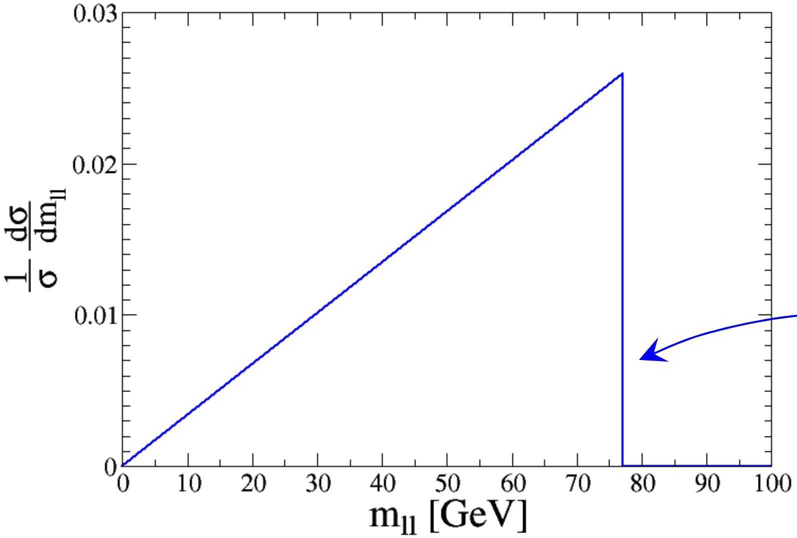
- Reconstruct SUSY masses in decay chain, e.g.
- Cannot reconstruct masses directly due to undetected LSP
- Study invariant masses for different combinations of particles in decay chain



$$m_{ll} = m_{ll}^{\text{max}} \sqrt{(1 - \cos\theta)/2}$$

angle between leptons

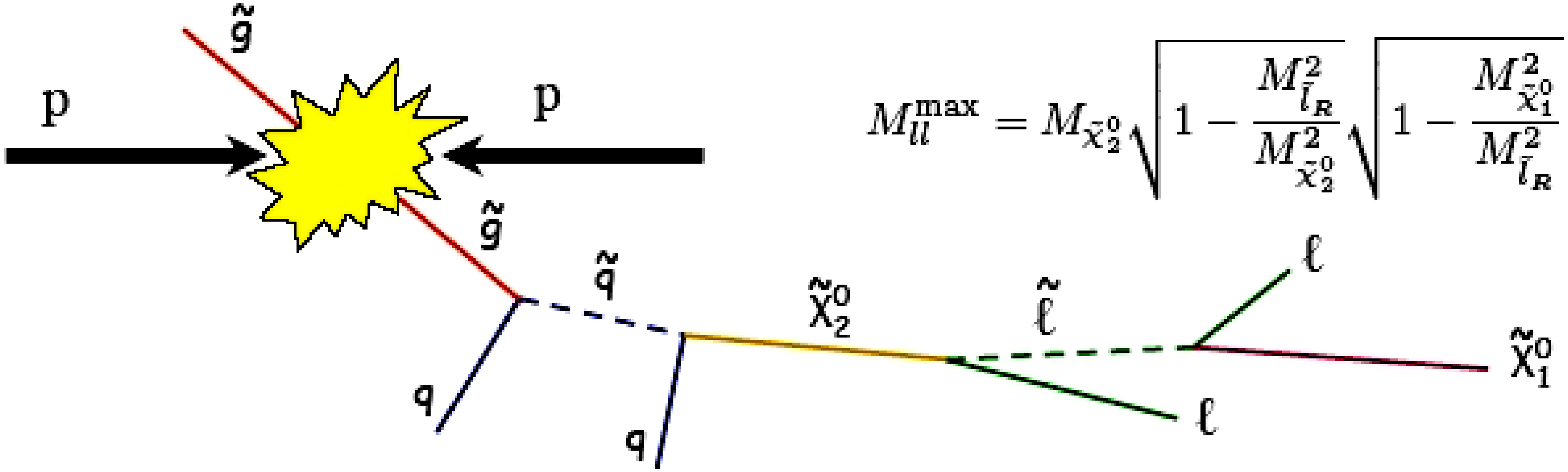
m_{ll} is maximal when leptons are back-to-back in slepton rest frame



Enpoint of inv. mass spectrum:

$$\left(m_{ll}^{\text{max}}\right)^2 = \left(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R}^2\right)\left(m_{\tilde{l}_R}^2 - m_{\tilde{\chi}_1^0}^2\right)/m_{\tilde{l}_R}^2$$

Determining SUSY Masses



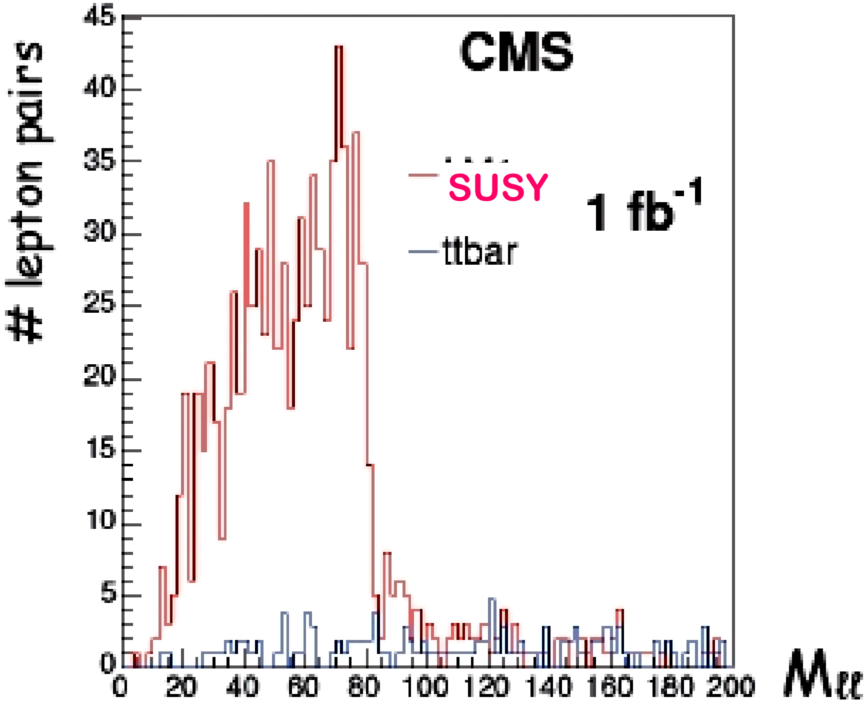
$$M_{ll}^{\max} = M_{\tilde\chi_2^0}\sqrt{1-\frac{M^2_{\tilde l_R}}{M^2_{\tilde\chi_2^0}}}\sqrt{1-\frac{M^2_{\tilde\chi_1^0}}{M^2_{\tilde l_R}}}$$

$$M_{lq}^{\max} = \sqrt{\frac{(M^2_{\tilde q_L} - M^2_{\tilde\chi_2^0})(M^2_{\tilde\chi_2^0} - (M^2_{\tilde l_R})}{M^2_{\tilde\chi_2^0}}}$$

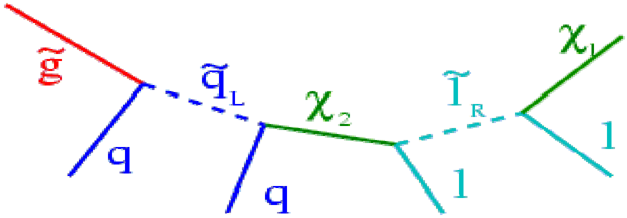
$$M_{lqq}^{\max} = \sqrt{\frac{(M^2_{\tilde q_L} - M^2_{\tilde\chi_2^0})(M^2_{\tilde\chi_2^0} - (M^2_{\tilde\chi_1^0})}{M^2_{\tilde\chi_2^0}}}$$

$$M_{qq}^{\max} = \ldots$$

Determine SUSY masses from endpoints of $M_{\ell\ell}$, $M_{\ell q}$ and $M_{\ell qq}$ ...

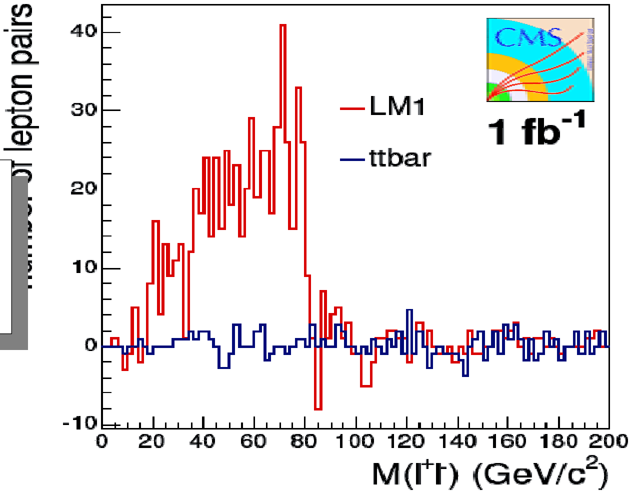


Mass Determinations: Overview



Try various decay chains

Look for sensitive variables (inv. masses, many of them)



Extract masses