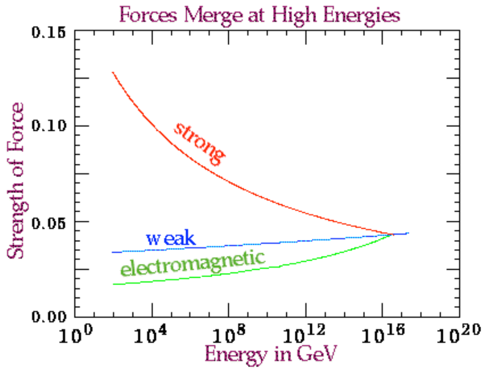
The Hierarchy problem

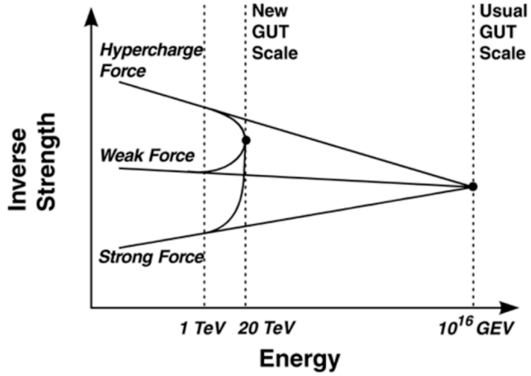
- This fine-tuning of parameters, this strong dependence of physics at the weak scale on the physics at (presumably) some much higher scale, is the hierarchy problem.
- If the loops are cut off at the scale of gravity, why is the scale of EW SSB so very different from the scale of gravity? Why is $M_W << M_{Pl}$?
- Equivalently, why is gravity so weak?

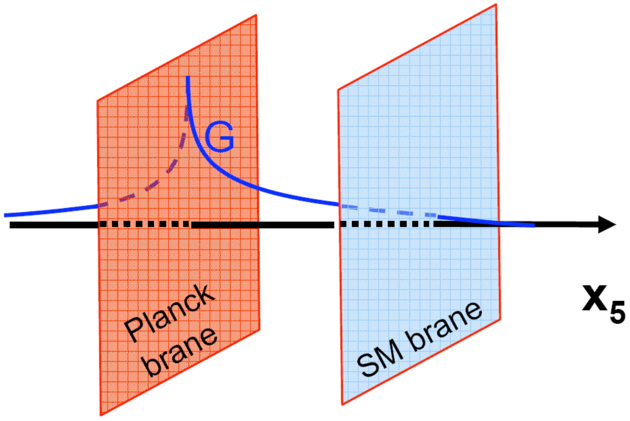
$$G_F = \frac{g^2}{4\sqrt{2}M_W^2} \quad >> \quad G_N = \frac{1}{M_{Pl}^2}$$

Possible solutions to the Hierarchy problem

- Some new physics appears at energy scales not far higher than the EW scale, to cut off (or otherwise "protect" against) the quadratic divergences. The "desert" between the EW and GUT/Planck scales is not empty!
- New physics changes the running of the couplings, bringing the GUT scale closer to the EW scale.
- Gravity is not as weak as we think, it's only diluted in our 4D world but it's EW-strong in, eg, 5 or more dimensions; $M_W \sim M_{Pl}^{5D}$.
- Fine-tuning is required; the theory is not natural. Theorists don't accept this solution!





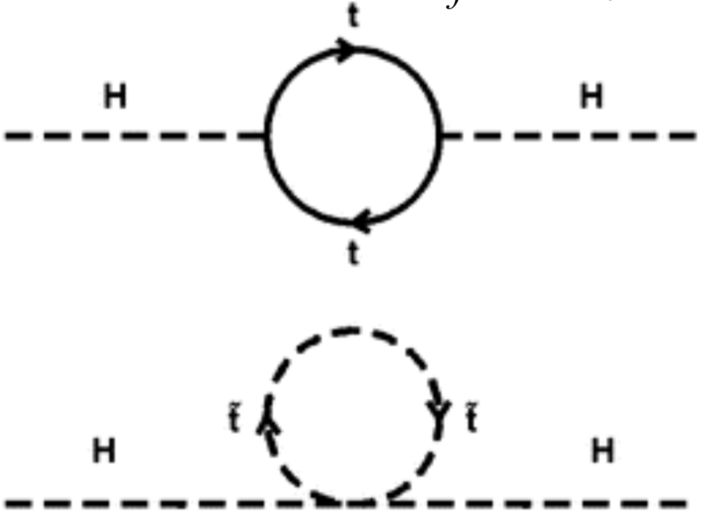


SUSY and the Hierarchy problem

- In SUSY, the loop diagrams that are quadratically divergent *cancel*, term by term, against equivalent diagrams involving superpartners.
- The cancellation is perfect if the particles and superpartners have the same mass.
- Else, the cancellation leaves residual contributions of order

  $$\delta m_H^2 \approx m_{\tilde{f}}^2 - m_f^2$$

- If m_H is of order 100 GeV, then the masses of the superpartners must be only a little larger (any smaller and we would have detected them already), and definitely less than 1000 GeV.
- With these masses, some of them will be detected at the next accelerator, the LHC!



Supersymmetry

Primary sources:

Drees, Godbole and Roy, Theory and Phenomenology of Sparticles,
World Scientific Press (2004)

Stephen Weinberg, Quantum Theory of fields,
Cambridge University Press (2000)

Song-Ming Wang, *SLAC Summer Institute (SSI04),*
http://www.slac.stanford.edu/econf/C040802/lec_notes/Wang/default.htm

Klaus Desch, *SLAC Summer Institute (SSI04),*
http://www.slac.stanford.edu/econf/C040802/lec_notes/Desch/default.htm

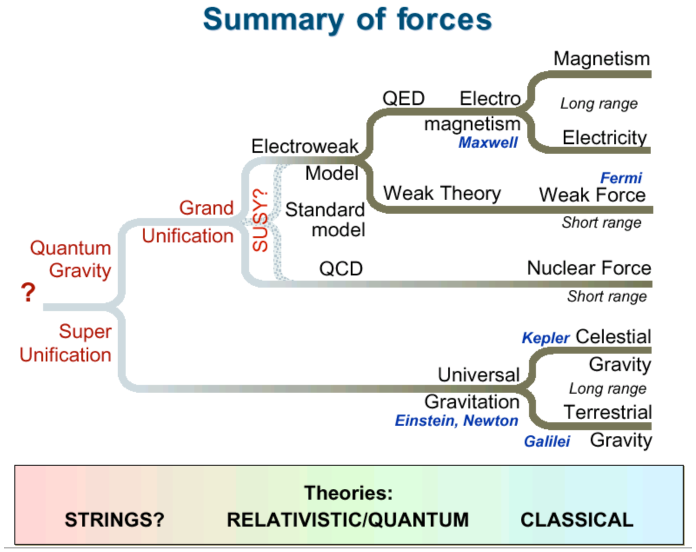
Joseph Polchinski, http://www.slac.stanford.edu/pubs/confproc/ssi85/ssi85-001.html

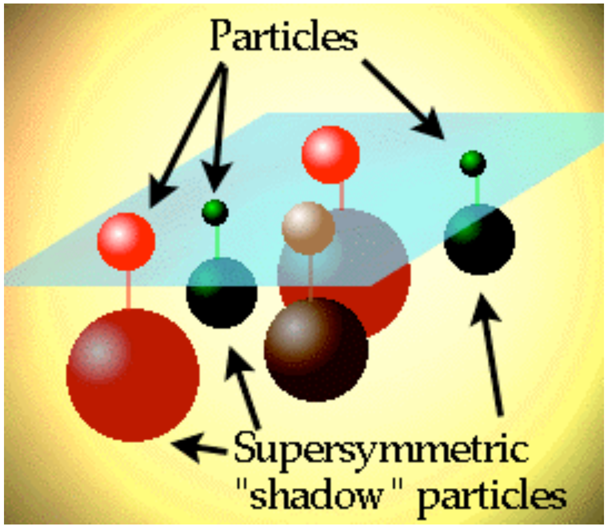
Joe Lykken, http://arxiv.org/abs/hep-th/9612114

Jonathan Feng, http://www.slac.stanford.edu/gen/meeting/ssi/2001/feng1/feng1.pdf

Supersymmetry

- SUSY is the latest in a long tradition of “unifications”:
  - Particles+waves (QM);
  - matter+energy ($E=mc^2$);
  - space+time (relativity);
  - E & M ⇒ EM ⇒ EW theory
  - strong & EW ⇒ Grand Unified Theories
  - matter-energy and space-time (General Relativity)
- SUSY connects matter (fermions, Pauli Exclusion) and forces (bosons) in a fully relativistic and quantum-mechanical way.
- SUSY predicts that for every fermion in the SM, there is a boson “partner”, and each boson has a fermion partner.
- Breaks down the rigid classification: matter ⇔ fermions, forces ⇔ bosons
- There are many new particles out there to be discovered!





Symmetries in the Standard Model

The known symmetries of the Standard Model, and related conserved currents and charges:

- Poincare invariance: $[P^{\mu},H] = 0$, $[M^{\mu\nu},H] = 0$
  - spatial translations (momentum conservation),
  - time translation (energy conservation),
  - rotations (angular momentum conservation),
  - Lorentz boosts (invariant mass conservation)

$$\left[\exp\left(i\vec{a}\cdot\vec{p}\right),H\right]=0 \quad \Rightarrow \quad \left[\vec{p},H\right]=0$$

$$\left[\exp\left(i\theta\vec{n}\cdot\vec{J}\right),H\right]=0 \quad \Rightarrow \quad \left[\vec{J},H\right]=0$$

- Internal global and gauge symmetries
  - isospin (approximate)
  - electroweak gauge symmetry (electric charge, EM current, CVC)
  - color gauge symmetry
- Discrete symmetries
  - **P**: Parity (conserved in strong and EM interactions)
  - **T**: time reversal (conserved in strong and EM interactions)
  - **C**: charge conjugation (conserved in strong and EM interactions)
  - **CPT**: conserved in all field theories

$$P:\vec{x}\rightarrow-\vec{x};\quad [P,H]=0$$

$$T:t\rightarrow -t;\quad [T,H]=0$$

Are there other symmetries?

- The Coleman-Mandula theorem (1967) says that the above are the *only possible* symmetries of the Lagrangian for a free field, or a collection of interacting fields (ie, the Lagrangian of the universe), assuming the symmetry operators and generators obey commutation rules.
- But our theory involve Dirac spinors, and the Dirac and Pauli matrices obey *anticommutation* rules.

$$\{\sigma^i, \sigma^j\} = \delta^{ij} I \qquad i, j = 1, 2, 3$$

- Spinors and the matrices that operate on them have one or two spinorial indices α=(1,2).
- So let's consider operators which have one spinorial index: $Q_{\alpha,}$ obeying anticommutation relations. – supersymmetry operators.
- When one operates on, eg, a scalar state (a boson), the result is a state with a spinor index: a spin-1/2 fermion. $Q_\alpha |\varphi\rangle = |\psi_\alpha\rangle$
- In general, such operators will change the spin of a free-particle state by ½ unit.
- If $[Q_\alpha, H]=0$, the theory is supersymmetric, and $m_\varphi = m_\psi$.
- Under some reasonable assumptions, *Supersymmetry is the* ***only*** *possible extension of the known spacetime symmetries of particle physics*.

Supersymmetry algebra

- Because of the spinor indices, the anticommutator must be proportional to the Pauli matrices.
- But there are four Pauli matrices, which form a space-time 4-vector σ^μ .
- The anticommutator has no spacetime index, so the result must be a Lorentz scalar.
- So we need to take the dot product of σ^μ with some other 4-vector (with no spinor index). The only one in the theory is P_μ .

$$\left\{Q_\alpha , \overline{Q}_\beta \right\} = 2\sigma^\mu_{\alpha\beta} P_\mu$$

- This completely defines supersymmetry!
- Note that the forced presence of P_μ , the generator of space-time translations, means that supersymmetry is related to an external property of a particle; it’s position.
- Apply a supersymmetry transformation twice, and because of the Pauli exclusion principle, you have translated it!
- This suggests (correctly) that supersymmetry is somehow related to gravity ⇒ SUGRA.

Conserved supercurrent

- We are familiar with conserved quantities that transform as spacetime 4-vectors; eg, EM:

$$J^{\mu} = q\bar{\psi}\gamma^{\mu}\psi$$

$$\partial_{\mu}J^{\mu} = 0 = \frac{d\rho}{dt} + \vec{\nabla}\cdot\vec{J}$$

- There are also conserved quantities with two spacetime indices, eg, the stress-energy tensor and the EM field strength tensor

$$T^{\mu\nu}; \quad \partial_{\mu}T^{\mu\nu} = 0$$

$$F^{\mu\nu}; \quad \partial_{\mu}F^{\mu\nu} = 0$$

- The conserved supercurrent has one spacetime index and one spinor index.

$$J^{\mu}{}_{\alpha}; \quad \partial_{\mu}J^{\mu}{}_{\alpha} = 0$$

Conserved supercharge

- The conserved charge associated with a conserved current is the spatial integral of the time component.

$$Q(t) = \int d\vec{r}\ J^0(\vec{r},t); \quad [H, Q] = 0 \quad \Rightarrow \quad \dot{Q} = 0$$

$$P^\mu(t) = \int d\vec{r}\ T^{\mu 0}(\vec{r},t) \quad [H, P^\mu] = 0 \quad \Rightarrow \quad \dot{P}^\mu = 0$$

$$Q_\alpha(t) = \int d\vec{r}\ J^0{}_\alpha(\vec{r},t) \quad [H, Q_\alpha] = 0 \quad \Rightarrow \quad \dot{Q}_\alpha = 0$$

- They transform, under Lorentz transformations, as scalars, 4-vectors, and spinors, respectively.
- These charges define “good quantum numbers” which do not change over time.
- As operators, when they act on a state, they produce a new state with the same energy.

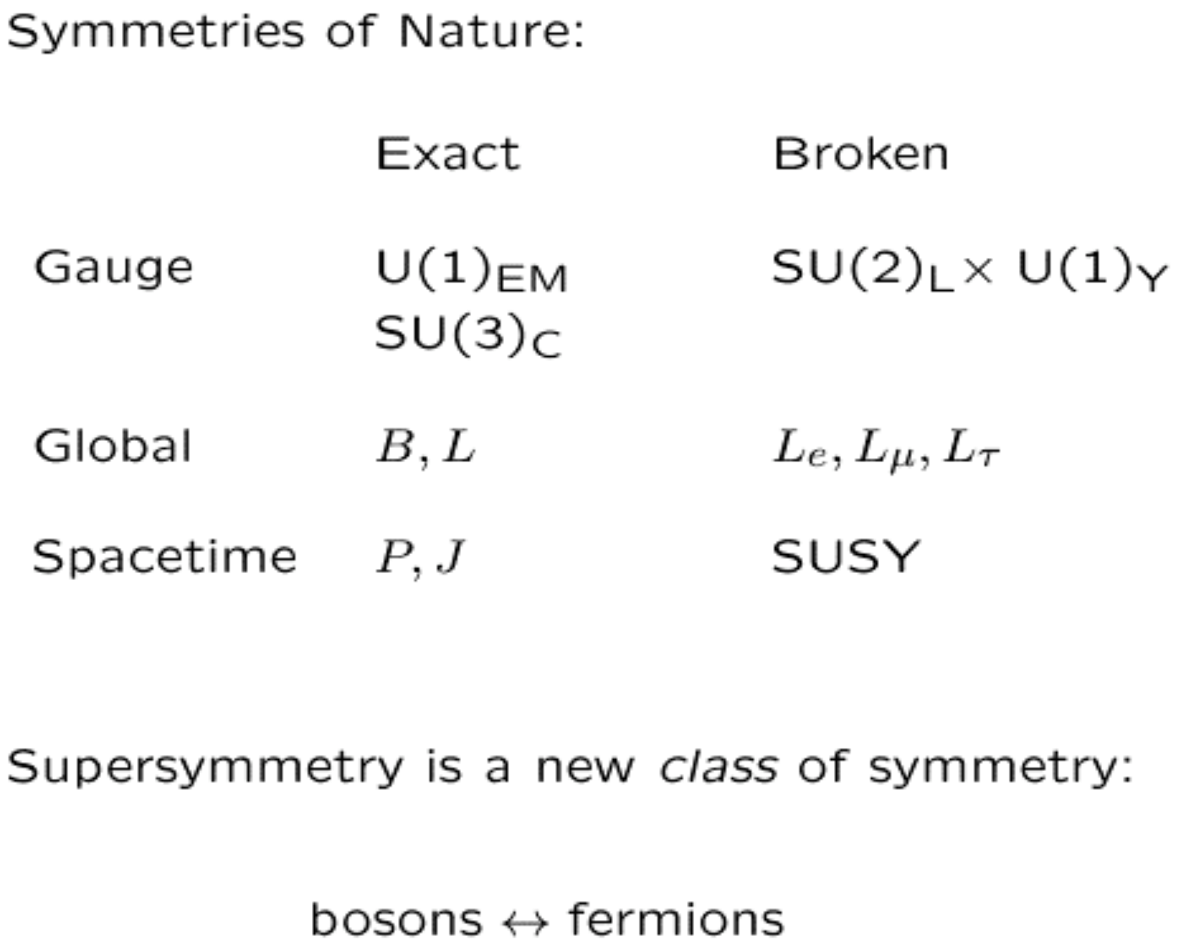
$$Q_\alpha \left|\varphi\right\rangle = \left|\psi_\alpha\right\rangle,$$

$$H\left|\varphi\right\rangle = H\left|\psi_\alpha\right\rangle$$

Why Supersymmetry?

- The above discussion emphasizes how naturally and compellingly supersymmetry arises in quantum field theories.
- because of this, SUSY is truly beloved amongst particle theorists, even through there's not a shred of experimental evidence for it.
- SUSY predicts that for every known fermion, there is a boson, and vice versa.
- If SUSY were an exact symmetry, the fermion/boson pairs would have the same masses; since we don't see the partners, their masses must be much higher; SUSY is a "broken" symmetry, manifest only at high energies.
- The doubling of the SM particle spectrum automatically resolves one of it's most fundamental mathematical inconsistencies (the "hierarchy problem").
- Fermions and bosons differ in the way they behave under Lorentz transformations. They are an *intrinsic* property of particles that relates to the *extrinsic* properties of space-time.
- SUSY transformations from fermion → boson → fermion can effect spacetime translations, and thus connect quantum mechanics with General Relativity.

Exact and broken symmetries



Symmetries of Nature:

	Exact	Broken
Gauge	$\mathrm{U(1)_{EM}}$ $\mathrm{SU(3)_C}$	$\mathrm{SU(2)_L \times U(1)_Y}$
Global	B, L	L_e, L_μ, L_τ
Spacetime	P, J	SUSY

Supersymmetry is a new *class* of symmetry:

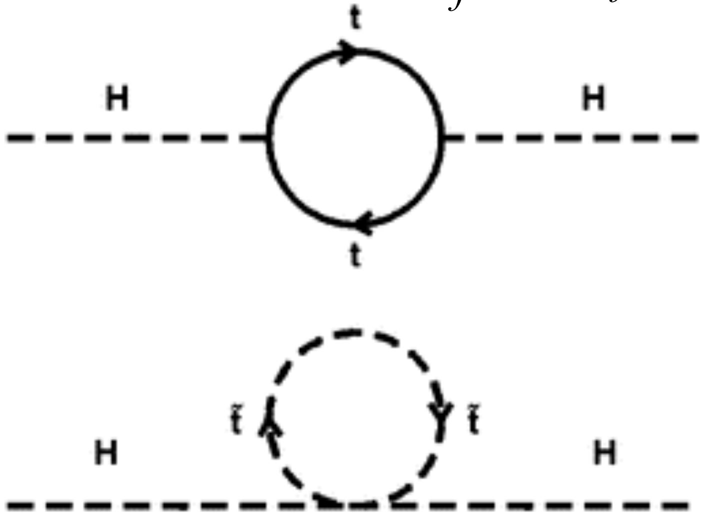
bosons $\leftrightarrow$ fermions

SUSY and the Hierarchy problem

- In SUSY, the loop diagrams that are quadratically divergent *cancel*, term by term, against equivalent diagrams involving superpartners.
- The cancellation is perfect if the particles and superpartners have the same mass.
- Else, the cancellation leaves residual contributions of order

$$\delta m_H^2 \approx m_{\tilde{f}}^2 - m_f^2$$

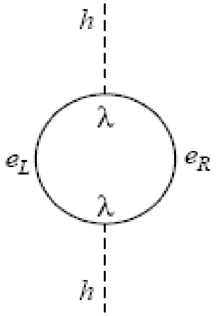
- If m_H is of order 100 GeV, then the masses of the superpartners must be only a little larger (any smaller and we would have detected them already), and should be less than 1000 GeV to give a natural solution to the hierarchy problem.
- With these masses, some of them will be detected at the next accelerator, the LHC!



SUSY solution to Higgs mass divergence

Large corrections to m_h appear in perturbation theory:

$$m_h^2 \;=\; (m_h^2)_0 \;+$$



$$(m_h^2)_0 \;-\; \frac{1}{16\pi^2}\lambda^2\Lambda^2 \;,$$

where Λ is some high energy cutoff.

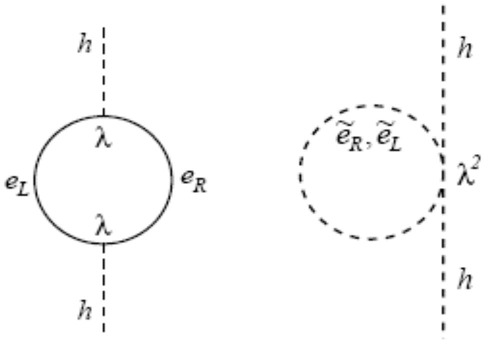
We know $m_h \sim \mathcal{O}(100\ \text{GeV})$.

$\Lambda \sim M_{\text{Pl}} \Rightarrow$ fine-tuning.

<u>The supersymmetric solution</u>

Introduce two partner particles: $\tilde{e}_L$, $\tilde{e}_R$, both complex scalar bosons, so $n_B = n_F$.

$$m_h^2 \;=\; (m_h^2)_0 \;+$$



$$\underbrace{-\frac{1}{16\pi^2}\lambda^2\Lambda^2 \;+\; \frac{1}{16\pi^2}\lambda^2\Lambda^2}$$

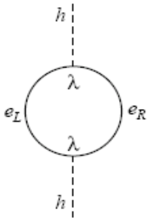
$$(m_h^2)_0 \;+\; \frac{1}{16\pi^2}\lambda^2(m_{\tilde{e}}^2 - m_e^2)\ln(\Lambda/m_h)$$

$\tilde{e}_{L,R}$ soften the self-energy divergence to a logarithm.

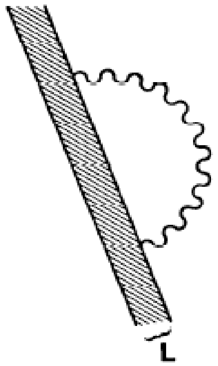
Analogy with the electron

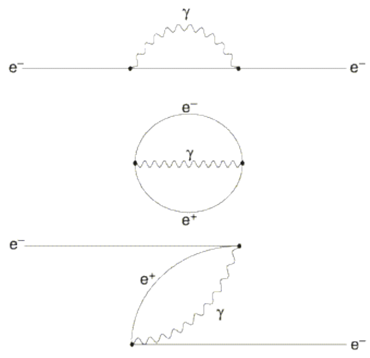
- The Higgs couples to itself; it is a repulsive force, tending to blow it apart. It’s self-energy to the other fields act in the same way.
- It requires a lot of energy to contain itself and keep it small (pointlike?).
- If its internal structure is constrained to be within a size L, it is sensitive to physics at energy scales as high as Λ ~ (hbar c)/L, and its mass (self-energy) must be of order Λ.
- The electron has the same problem! It requires more than 10^9 eV of energy to keep the electric charge packed into a ball of < 10^{-19} m.
- In the early days of quantum mechanics, this was seen as a fundamental breakdown of the theory!
- But the electron creates a force to counteract this intense repulsion: by polarizing the vacuum, creating virtual e^-e^+ pairs.
- The oppositely-charged antimatter cancels some of the repulsion, allowing the electron to hold itself together with only 5×10^5 eV of self-energy.
- To solve the problem of the electron’s self-energy, we needed to invent antimatter, doubling the number of particles in the universe.
- Superpartners do (more-or-less) precisely the same thing to keep the Higgs mass << Planck mass.
- Theorists love it when history repeats itself!

$$m_h^2 = (m_h^2)_0 +$$



$$(m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2$$





H. Murayama, 2001

The SUSY spectrum

We must do this for every SM particle. Introduce

$$\begin{array}{rlll} \text{Squarks :} & \tilde{u}_{L,R} & \tilde{c}_{L,R} & \tilde{t}_{L,R} \\ & \tilde{d}_{L,R} & \tilde{s}_{L,R} & \tilde{b}_{L,R} \\ \\ \text{Sleptons :} & \tilde{\nu}_e & \tilde{\nu}_\mu & \tilde{\nu}_\tau \\ & \tilde{e}_{L,R} & \tilde{\mu}_{L,R} & \tilde{\tau}_{L,R} \\ \\ \text{Gauginos :} & \tilde{B} \quad \tilde{W}^{\pm} & \tilde{W}^{0} & \tilde{g} \\ \\ \text{Higgsinos :} & \tilde{H}_u \quad \tilde{H}_d & & \end{array}$$

$$\begin{pmatrix} h_u^+ \\ h_u^0 \end{pmatrix} \Rightarrow \begin{pmatrix} \tilde{H}_u^+ \\ \tilde{H}_u^0 \end{pmatrix}$$

All SUSY models are (at least) two Higgs doublet models.

- quarks, leptons ⇔ squarks, sleptons
- gauge bosons: g, $W^{\pm}$, W_3^0, B^0 ⇔ gauginos: $\tilde{g}$, $\tilde{w}^{\pm}$, $\tilde{w}^0$, $\tilde{b}^0$
- Higgs bosons: h^0, H^0, A^0, $H^{\pm}$ ⇔ higgsinos: $\tilde{h}^{\pm}$, $\tilde{h}_u^0$, $\tilde{h}_d^0$
- graviton: G ⇔ gravitino: $\tilde{G}$

- The superpartners have
  - spins differing by 1/2
  - identical couplings
  - unknown masses (model-dependent)
- Discovering new particles with those properties IS discovering supersymmetry
- Potential SUSY DM candidates (neutral superpartners):
  - gauginos ($\tilde{w}^0$, $\tilde{b}^0$)
  - higgsinos ($\tilde{h}_u^0$, $\tilde{h}_d^0$)
  - sneutrinos ($\tilde{\nu}_e$, $\tilde{\nu}_\mu$, $\tilde{\nu}_\tau$)
  - gravitino ($\tilde{G}$)

particle		spin	sparticle		spin
quark	q	1/2	squarks	$\tilde{q}_{L,R}$	0
charged lepton	l	1/2	charged sleptons	$\tilde{l}_{L,R}$	0
neutrino	ν	1/2	sneutrino	$\tilde{\nu}$	0
gluon	g	1	gluino	$\tilde{g}$	1/2
photon	γ	1	photino	$\tilde{\gamma}$	1/2
	Z^0	1	zino	$\tilde{Z}$	1/2
neutral higgses	h, H, A	0	neutral higgsinos	$\tilde{H}^0_{1,2}$	1/2
	$W^\pm$	1	wino	$\widetilde{W^\pm}$	1/2
charged higgs	$H^\pm$	0	charged higgsino	$\tilde{H}^\pm$	1/2
graviton	G	2	gravitino	$\tilde{G}$	3/2

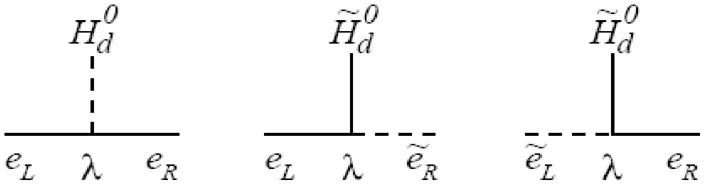
$\widetilde{W^\pm}$,$\widetilde{H^\pm}$ mix to form 2 chargino mass eigenstates $\chi_1^\pm$,$\chi_2^\pm$

$\tilde{\gamma}$, $\tilde{Z}$, $\tilde{H}^0{}_{1,2}$ mix to form 4 neutralino mass eigenstates $\chi_1^0, \chi_2^0, \chi_3^0, \chi_4^0$

$\tilde{t}_L, \tilde{t}_R$ (and $\tilde{b}, \tilde{\tau}$) mix to form the mass eigenstates $\tilde{t}_1, \tilde{t}_2$

SUSY couplings are strongly constrained

- Dimensionless couplings: must be identical to those of partners. This property *defines* superpartners.



For example, a scalar with $Q = -1$ and $I = 0$, but with a non-negligible coupling to a Higgsino, is *not* $\tilde{e}^-_R$.

- Dimensionful couplings (masses): unknown, but presumably not too large. (See below.)

Superpartners cannot completely decouple.

The General MSSM

Given these new fields, add all possible renormalizable, gauge-invariant interactions:

$$\begin{aligned}\mathcal{L} \;=\; & y^u_{ij}\hat{H}_u\hat{Q}_i\hat{U}_j + y^d_{ij}\hat{H}_d\hat{Q}_i\hat{D}_j + y^e_{ij}\hat{H}_d\hat{L}_i\hat{E}_j \\ & +\mu\hat{H}_u\hat{H}_d \\ & +M_1\tilde{B}\tilde{B} + M_2\tilde{W}\tilde{W} + M_3\tilde{g}\tilde{g} \\ & +\sum_{f,ij} m^2_{ij}\tilde{f}^*_i\tilde{f}_j + m^2_{H_u}|H_u|^2 + m^2_{H_d}|H_d|^2 \\ & +A^u_{ij}h_u\tilde{q}_i\tilde{u}_j + A^d_{ij}h_d\tilde{q}_i\tilde{d}_j + A^e_{ij}h_d\tilde{l}_i e_j \\ & +Bh_uh_d \\ & +\lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}_k + \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}_k + \lambda''_{ij}\hat{U}_i\hat{D}_j\hat{D}_k \\ & +\mu'_i\hat{H}_u\hat{L}_i \\ & \rho_{ijk}\tilde{l}_i\tilde{l}_j\tilde{e}_k + \rho'_{ijk}\tilde{l}_i\tilde{q}_j\tilde{d}_k + \rho''_{ijk}\tilde{u}_i\tilde{u}_j\tilde{d}_k \\ & +B'_ih_u\tilde{l}_i \\ & +\text{gauge and other couplings}\end{aligned}$$

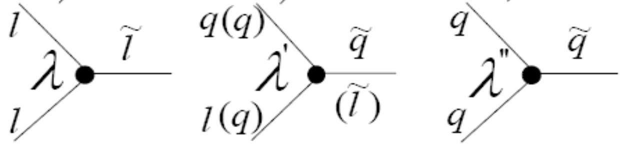
Here, $\hat{A}\hat{B} \equiv \psi_A\psi_B$, $\hat{A}\hat{B}\hat{C} \equiv \phi_A\psi_B\psi_C + \psi_A\phi_B\psi_C + \psi_A\psi_B\phi_C$.

370 new parameters!

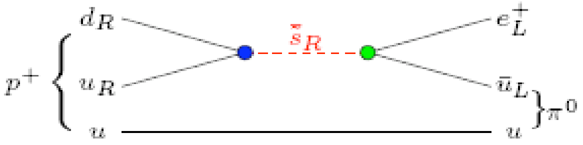
R Parity

Superpotential of general MSSM with
R-parity violation term :

$$W_{Rp} = \underbrace{\lambda_{ijk} L_i L_j E_k}_{\not{L}} + \underbrace{\lambda'_{ijk} L_i Q_j D_k}_{\not{L}} + \underbrace{\lambda''_{ijk} U_i D_j D_k}_{\not{B}}$$



- New supersymmetric Yukawa interactions violating baryon number and lepton number lead to too rapid proton decay



- Introduce R-parity $R = (-1)^{3(B-L)+2S}$
  - SM particles: $R = +1$
  - superpartners: $R = -1$
- Impose R-parity conservation $\Pi R_i = 1$ at each vertex $\Longrightarrow$ eliminate all dangerous proton decay diagrams

All interactions involve an even number of sparticles

R_p conservation $\Rightarrow \lambda, \lambda', \lambda'', \mu', \rho, \rho', \rho'', B' = 0$.

- 370 → 107 new parameters.

- All superpartners decay to the lightest supersymmetric particle (LSP).

To a large extent, the properties of the LSP determine the signature of supersymmetry.

- LSP is stable (unless it finds another superpartner) — dark matter!

In many SUSY models, LSP = WIMP.

Note: R_p is overkill for proton decay, but required for dark matter.

Unification of gauge couplings

Matter unification: $Q, U, D, L, E, N \rightarrow \mathbf{16}$ of SO(10)

Gauge coupling constants RG evolve:

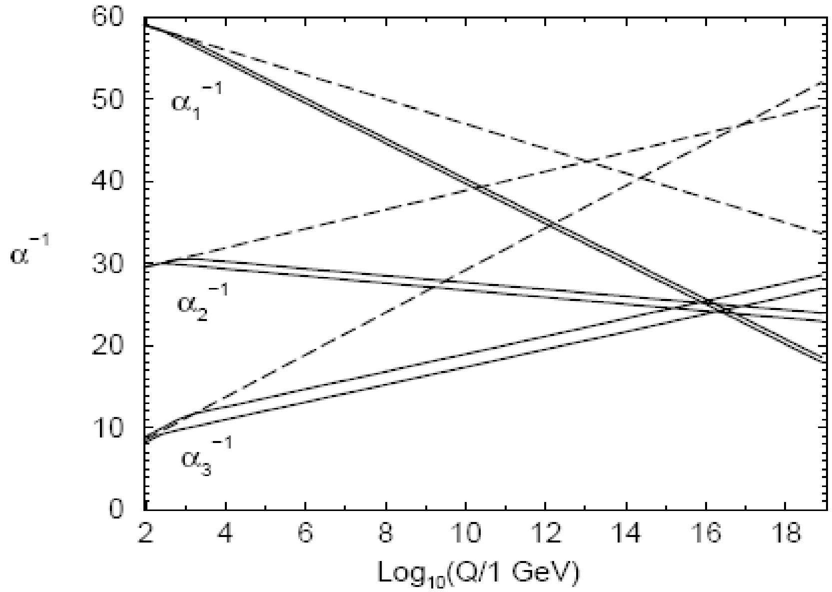
$$\frac{dg_i}{dt} = \frac{1}{16\pi^2} b_i g_i^3$$

where $t \equiv \ln(Q_0/Q)$ (so asymptotic freedom $\Rightarrow b_i > 0$).

$$\text{SM}: \quad b_i = (-\tfrac{41}{10}, \tfrac{19}{6}, 7)$$

$$\text{MSSM}: \quad b_i = (-\tfrac{33}{5}, -1, 3)$$

The introduction of many new superpartners modifies the RG evolution above the superpartner mass scale.



Martin (1997)

- No free parameters
- Requires α_i as measured at % level
- Coupling at unification: $\alpha_{\text{unif}}^{-1} \gtrsim 1$
- Scale of unification:
  - $\mu_{\text{unif}} \gtrsim 10^{16}$ GeV [SuperK proton decay]
  - $\mu_{\text{unif}} \lesssim 10^{18}$ GeV [Quantum gravity]

Neutralino dark matter

In supergravity, as we've seen, the LSP is often the lightest neutralino

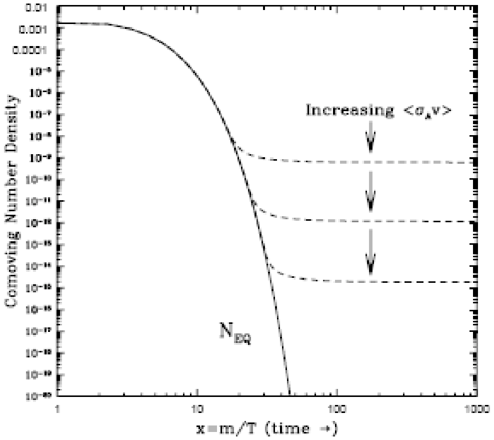
$$\chi \in \{\tilde{B}, \tilde{W}^0, \tilde{H}_u^0, \tilde{H}_d^0\}$$

This LSP is

- Stable (given R_P conservation)
- Non-baryonic
- Neutral
- Cold

Interacts only via the Weak interaction

- χ annihilates to correct thermal relic density



$$\Omega_m \sim \frac{10^{-10}\ \text{GeV}^{-2}}{\langle \sigma_A v \rangle}$$

For supersymmetric DM,

$$\langle \sigma_A v \rangle \sim \frac{\alpha^2}{m_W^2} 0.1 \sim 10^{-9\pm1}\ \text{GeV}^{-2} \Rightarrow \Omega_\chi \sim 10^{-1\pm1}$$

Particle physics considerations alone guarantee an excellent cold dark matter candidate.

Supersymmetry

Supersymmetry is a very beautiful, idea, well motivated by general symmetry considerations.

It is highly developed theoretically, and has several important consequences:

- Predicts a light Higgs mass (mass divergences cancel)
- Predicts that the Higgs field condenses (breaking EW symmetry), if the top quark is heavy (coupling to a heavy top drives $\mu^2 < 0$).
- In a unified theory, can explain the values of the standard-model coupling constants
- Predicts cosmological cold dark matter (the LSP)

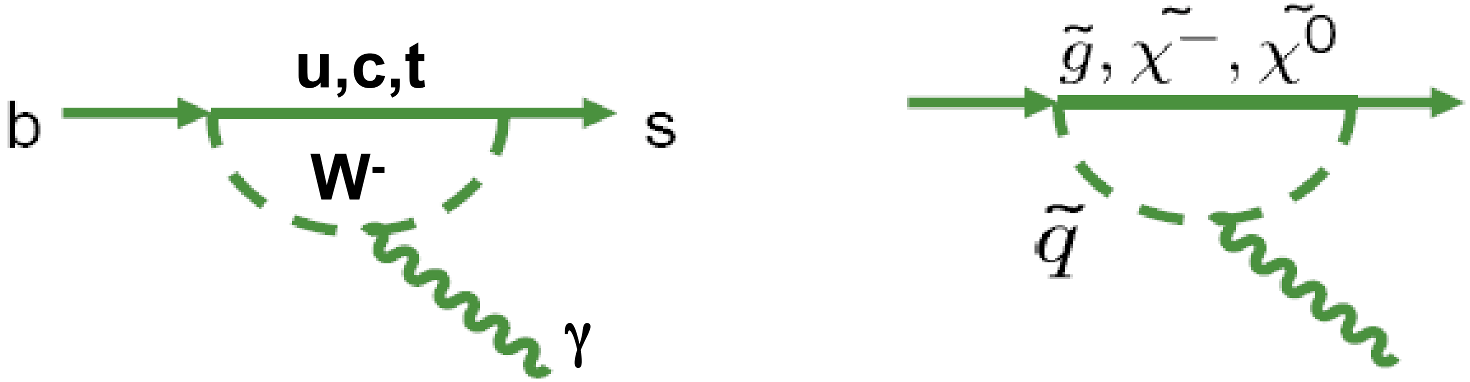
- But the symmetry is broken, presumably by a new set of Higgs mechanisms and particles, at some higher mass scale (~ a few hundred GeV, to fix the hierarchy problem). Other symmetry-breaking mechanisms ("soft symmetry breaking") exist, but
- We generically get a NEW hierarchy problem: why is the SUSY scale << Planck scale? higher order corrections to SUSY SSB parameters (Higgs masses) will diverge, just like EW SSB Higgs mass does!
- These hierarchy problems will go on until we have a theory that works all the way up to, and including, the Planck scale!

Desperately seeking SUSY

- The discovery of Supersymmetry (at LHC in 2007-08?) would profoundly change our understanding of matter/energy/space/time –
  if it is found, it would certainly rank as one of the greatest discoveries in the history of science!

Indirect search for SUSY in loops

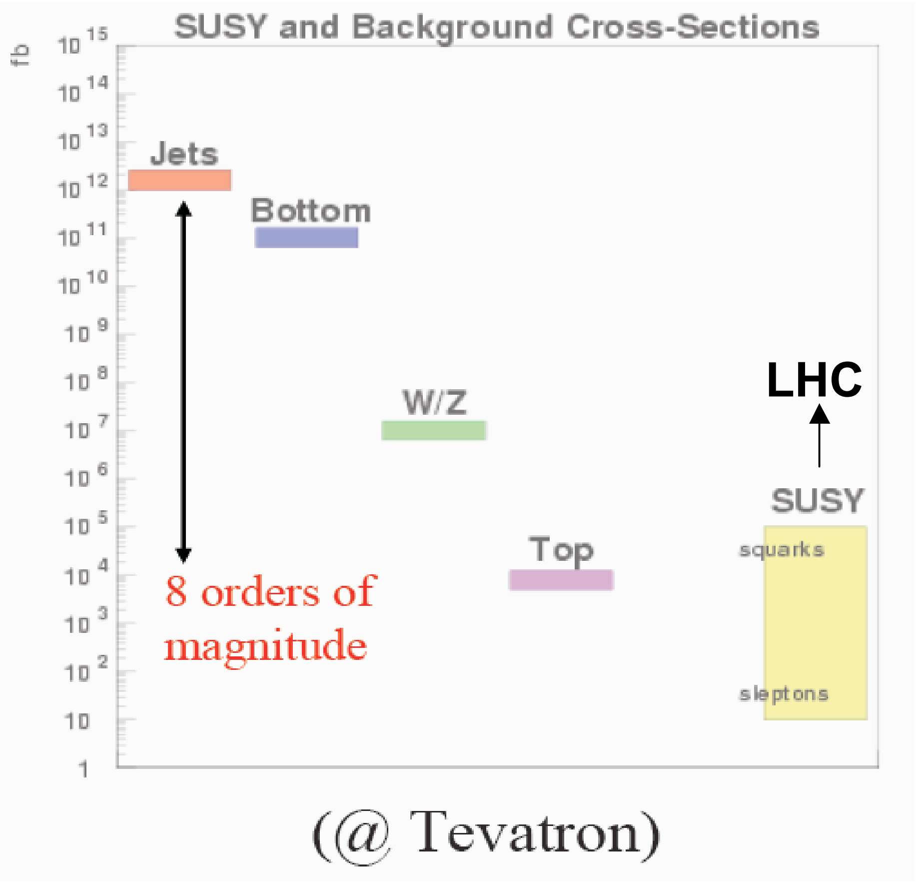
$b \to s\gamma$



- Flavor-changing neutral currents (FCNC) like b → s γ are forbidden in the Standard Model at “tree” level.
- But they do occur as 2nd order weak transitions, with loops.
- Even then, they are suppressed (GIM suppression), because the three quarks in the loop contribute with different signs; in the limit that the masses of the up, charm, top quarks are equal, the rate is 0 in the SM.
- But the top quark is quite massive; the rate is very sensitive to m_t.
- Now that we know m_t very well, we can predict the SM rate well: $B(b \to s\gamma) \sim 3\times10^{-4}$
- But loops are sensitive to high-mass virtual particles!
- Any deviation from SM prediction is a sign of new physics running around the loop … harder to tell *what* it is.
- Experimental branching fraction agrees well with theory, excluding light sparticles.

Search for SUSY at colliders

- Produce SUSY particles directly.
- Controlled environment, predictable cross-sections, depending only on (unknown) mass of sparticles.
- Energetic quark-quark collisions produce squarks with strong-interaction coupling.
- But sparticles are very massive, so the production cross sections at Tevatron (2 TeV) are pretty low.
- For masses ~< 500 GeV, much higher cross sections at the LHC (14 TeV).



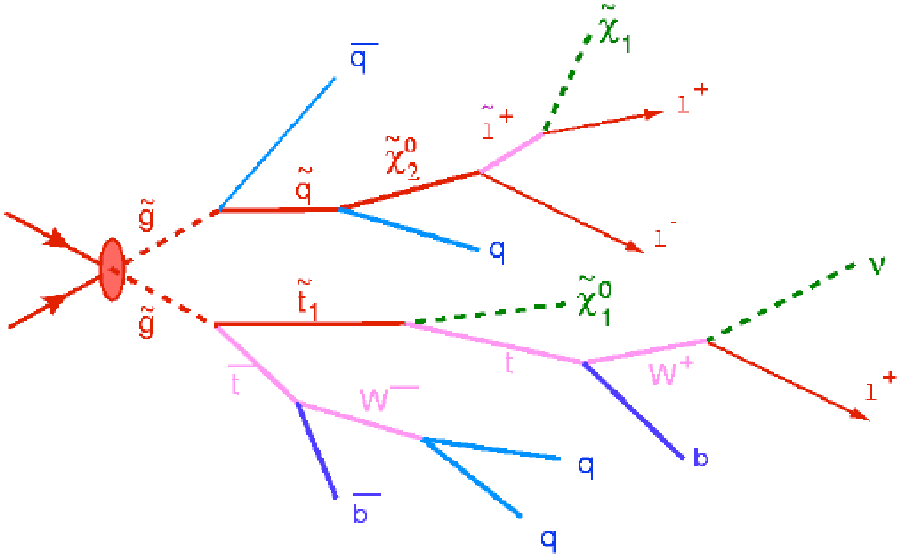
SUSY production at LHC

Dominant production modes in MSSM with R-Parity conservation:

$$gg, q\bar{q}, qq, qg \rightarrow \tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{q}\tilde{g}$$

Production of EW-interacting sparticles through Drell-Yan,
but typically too low cross-sections/ too large BG from W/Z

Normally: gluinos, squarks = heaviest sparticles
→ long decay chains, quite complex final states



- jets
- leptons
- LSPs

Phenomenology depends
crucially on
LSP and NLSP properties

Phenomenology of SUSY (Models)

- MSSM has > 100 parameters ! $\Rightarrow$ Difficult to make prediction
- Some models make some assumption about SUSY breaking
  - To reduce # parameters
  - Thus make the theory more predictable
- Therefore PREDICTION depends on WHAT models used
- Common models used by collider experiments :

mSUGRA

- ~~SUSY~~ mediated by gravity
- LSP most likely is : $\tilde{\chi}_1^0$
- $M_{\tilde{\chi}_1^\pm} \approx M_{\tilde{\chi}_2^0} \approx 2M_{\tilde{\chi}_1^0}$

GMSB

- ~~SUSY~~ mediated by gauge fields
- LSP : $\tilde{G}$
- Phenomenology mostly determined by the NLSP (slepton or neutralino)

- These models allow different colliding experiments to have a **common bench mark** to compare results

SUSY production at LHC

With R-Parity conserved:

LSP stable, neutral, weakly interacting

type	LSP	NLSP	LSP/NLSP Signature(s)
mSuGra-like	$\tilde{\chi}_1^o$	$\tilde{\ell} \rightarrow \tilde{\chi}_1^o \ell$	miss. energy, hard→soft leptons
AMSB-like	$\tilde{\chi}_1^o$	$\tilde{\chi}_2^o \rightarrow \tilde{\chi}_1^o f\bar{f}$	miss. energy, soft hadrons/leptons
GMSB-like	$\tilde{G}$	$\tilde{\chi}_1^o \rightarrow \tilde{G}\gamma/Z$	miss. energy, lifetime, photons
		$\tilde{\ell} \rightarrow \tilde{G}\ell$	

at large tanβ sfermion mixing effects
→ large for 3rd generation
→ stau, sbottom lighter than other gen.

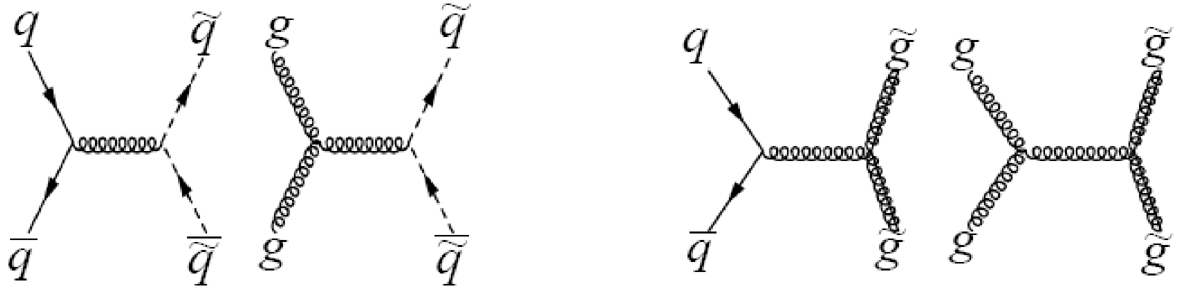
With R-Parity violated:

LSP can decay B or L violating to qqq or $\ell\ell\ell$

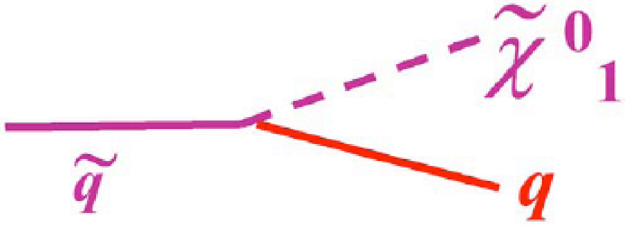
qqq decay most challenging at LHC

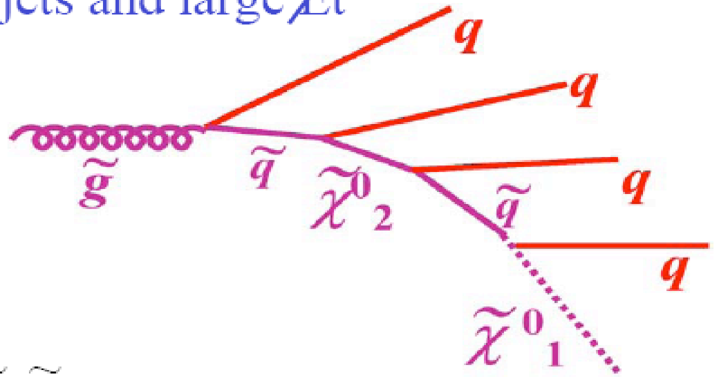
Searches for Squarks and Gluinos in MET + Jets

- Light colored sparticles($\tilde{q},\tilde{g}$) can be copiously pair produced at Tevatron



- Decays of $\tilde{q},\tilde{g}$ may produce multiple jets and large $\not{E}$t



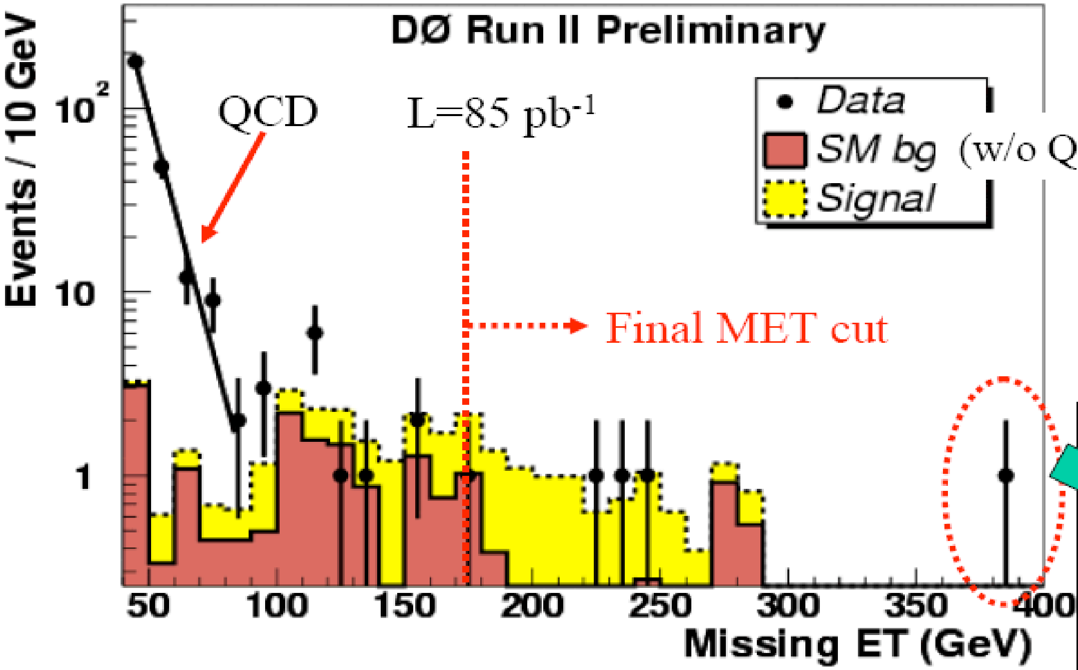


$\tilde{\chi}^0_1$: LSP

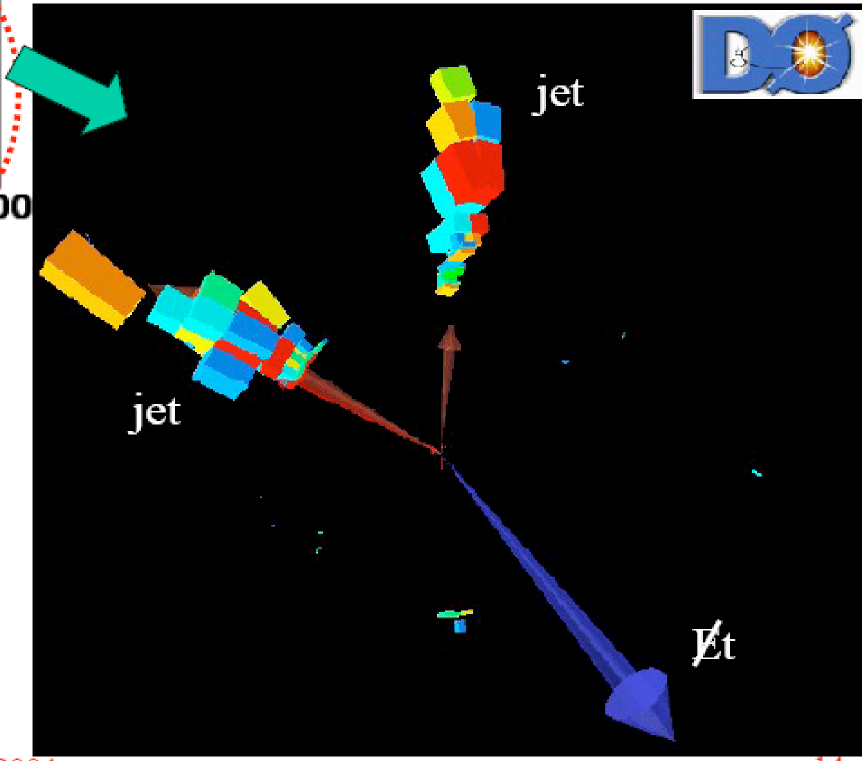
- D∅ has performed direct search for $\tilde{q},\tilde{g}$:
  - Using Jets+$\not{E}$t data sample (~85 pb^{-1})
  - Require ≥2 jets (Et$_1$>60 GeV, Et$_2$>50 GeV)
  - Jets to be acoplanar , not pointing in same direction as $\not{E}$t (reduce QCD multi-jets)
  - No isolated leptons (e,μ)
  - $\not{E}$t > 175 GeV
  - $H_T = \sum_i Et^i_{jet} > 275$ GeV

} Reduce W/Z+jets

Searches for Squarks and Gluinos in MET + Jets



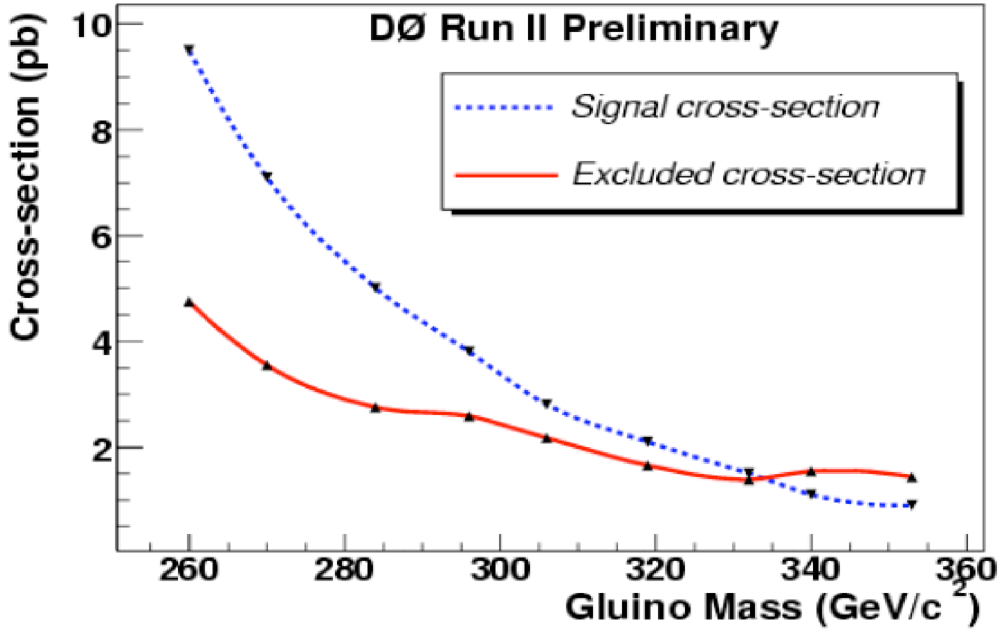
- A large $\not{E}$t event (w/ 2 large Et jets)
  - $\not{E}$t = 381 GeV
  - Et_1=289 GeV, Et_2=117 GeV

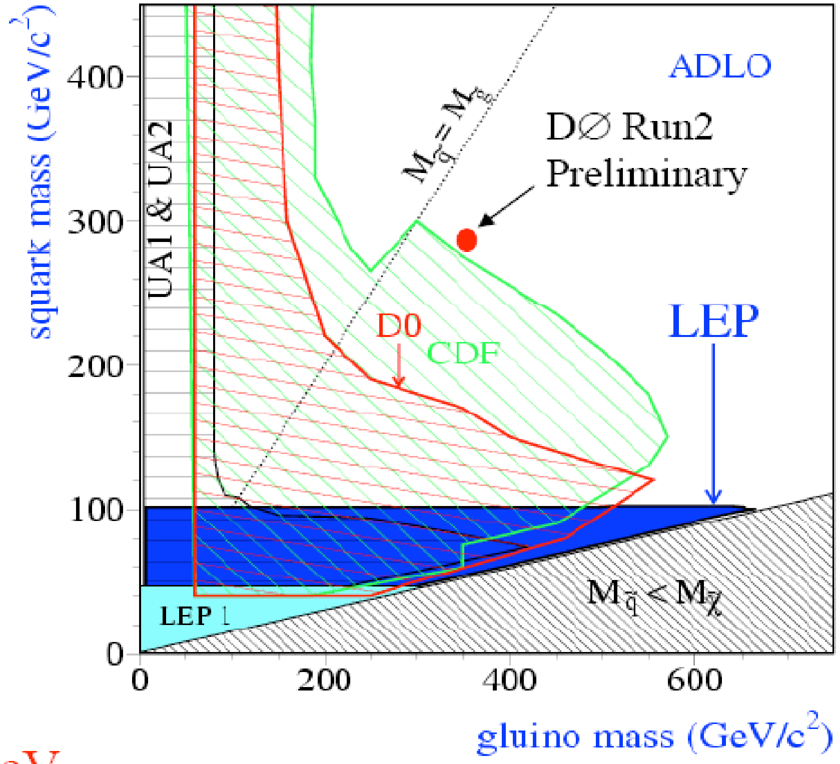


- Observed 4 events, expect 2.7±1.0 (stat)
- SM background mostly from :
  - $Z(\rightarrow \nu\nu)$+jets
  - $W(\rightarrow \tau\nu)$+jets

Searches for Squarks and Gluinos in MET + Jets

- Interpret results in mSUGRA scenario :
  - m_0=25 GeV, tanβ=3, A_0=0, μ<0
- Signal efficiency : ~2 - 7 % ($m_{1/2}$ = 100-140 GeV)





- Set gluino (squark) mass limit at 333 (292) GeV

- **Have extended Run1 limit !**

SUSY discovery at LHC

Exclusive reconstruction of SUSY final states is difficult and also needs model-dependent strategy

With (quasi-) stable LSP, discovery of SUSY through inclusive simple analysis

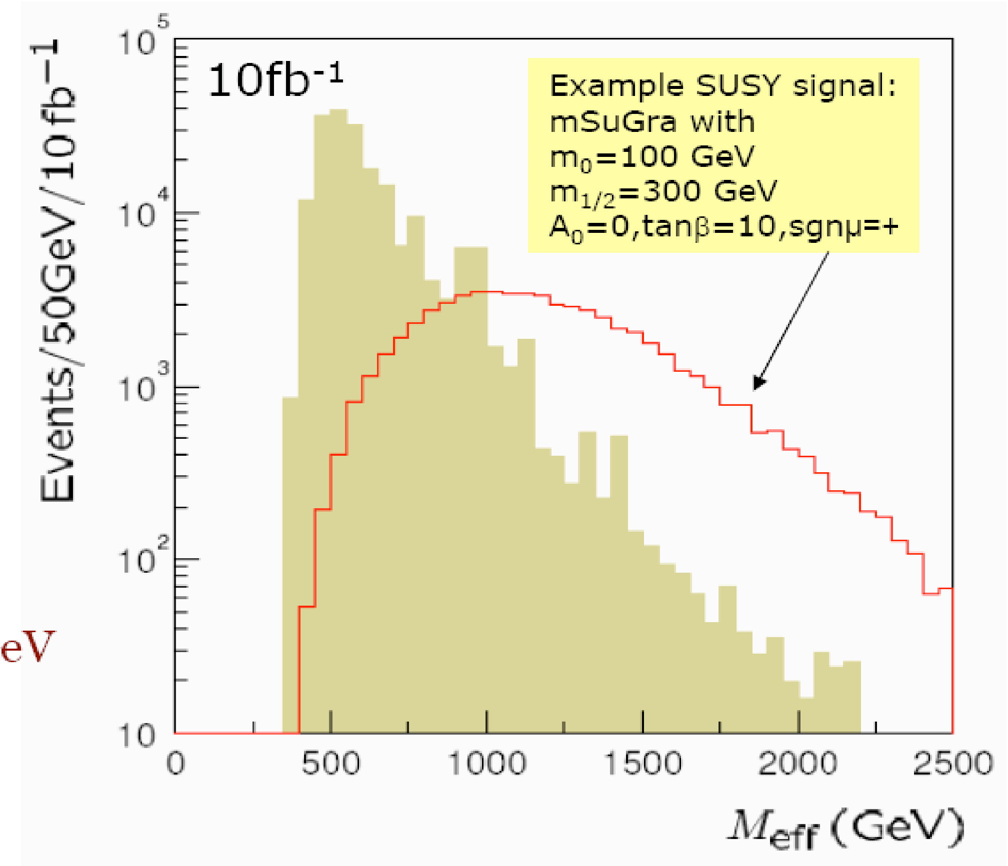
e.g. require

$\not{E}_T > 100\,\mathrm{GeV}$

≥ 4 jets with $E_T^i > 100, 50, 50, 50\,\mathrm{GeV}$

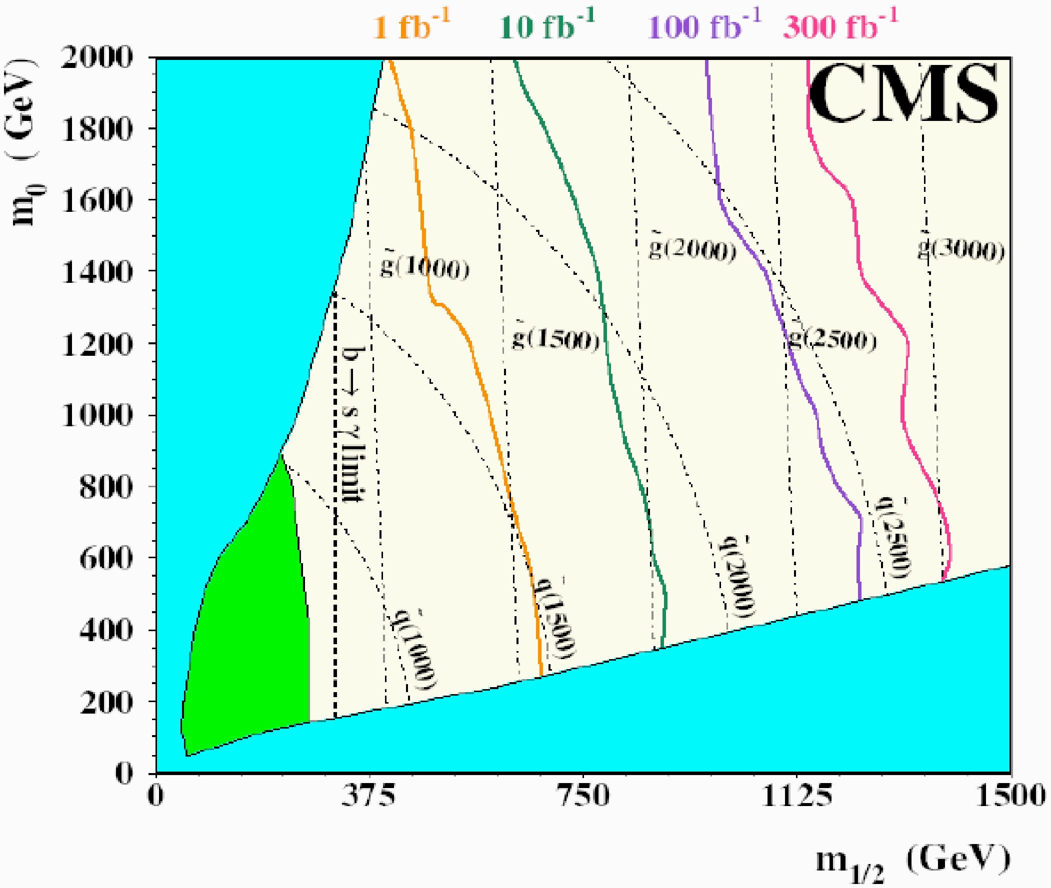
and plot

$$M_{\mathrm{eff}} := \not{E}_T + \sum_{i=1}^{4} E_T^{\mathrm{jet}=i}$$



Mass reach for squarks and gluinos

Inclusive discovery can be fast (after detectors are understood):



5σ discovery mass reach for squarks and gluinos:

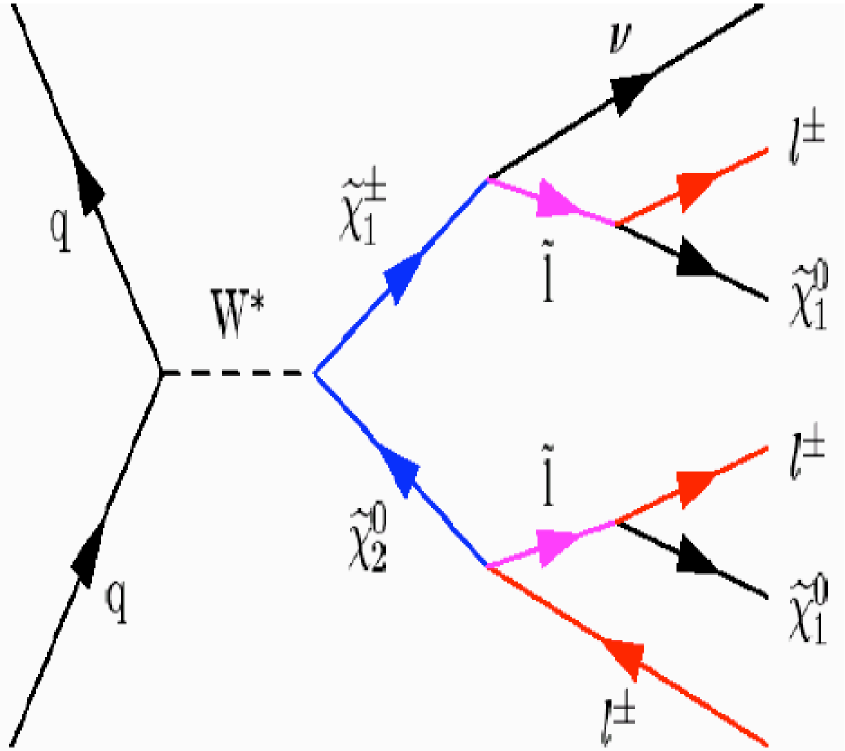
Lumi	Mass reach
1 fb^{-1}	~1 TeV
10 fb^{-1}	~2 TeV
300 fb^{-1}	~2.5-3 TeV

Below 2-2.5 TeV, further inclusive signatures (multi-lepton) can also be used

Searches for Chargino/Neutralino in Tri-Lepton

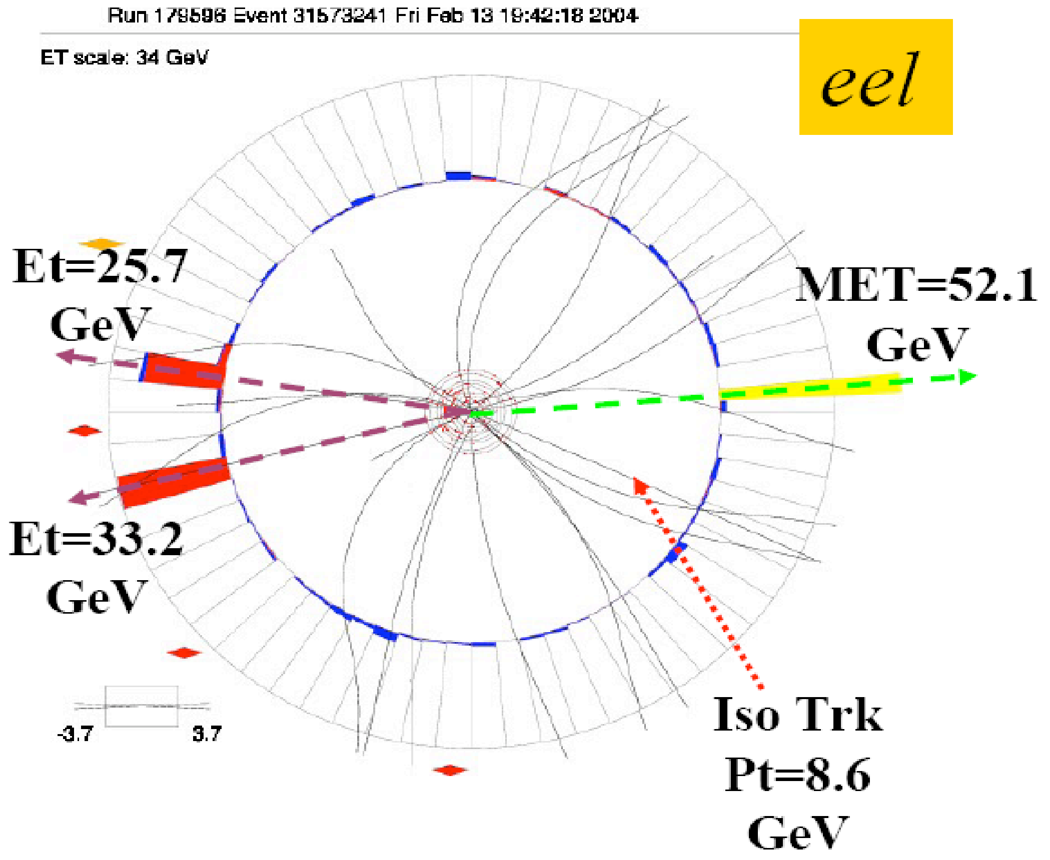
- Pair production of chargino/neutralino can produce multi-lepton and $\not{E}t$ in final state
- Small contributions from SM processes in this signature

  ⇒Very clean, "Gold Plated" signature to find SUSY



- Searches at D∅:
  - $e + e +$ lepton
  - $e + \mu +$ lepton
  - $\mu + \mu +$ lepton
  - Like sign di-muon $(\mu^+\mu^+, \mu^-\mu^-)$
- Search optimized for mSUGRA parameter space near LEP 2 limit :
  - $\tan\beta=3$, $A_0=0$, $\mu>0$
  - $m_0=[72,88]$ GeV, $m_{1/2}=[165,185]$ GeV
- Search using data ~ 147 – 249 pb^{-1}

Searches for Chargino/Neutralino in Tri-Lepton



eel

Et=25.7 GeV

Et=33.2 GeV

MET=52.1 GeV

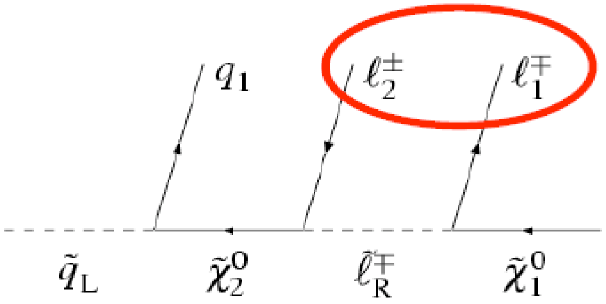
Iso Trk Pt=8.6 GeV

An event candidate from *e*+*e*+*l* search

After Discovery: Sparticle Mass Reconstruction

Due to escaping LSP and unknown initial state momentum
full mass reconstruction cannot be performed event-by-event at LHC

'standard' trick:
kinematic endpoints



Example: $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell\ell$

calculate diplepton mass

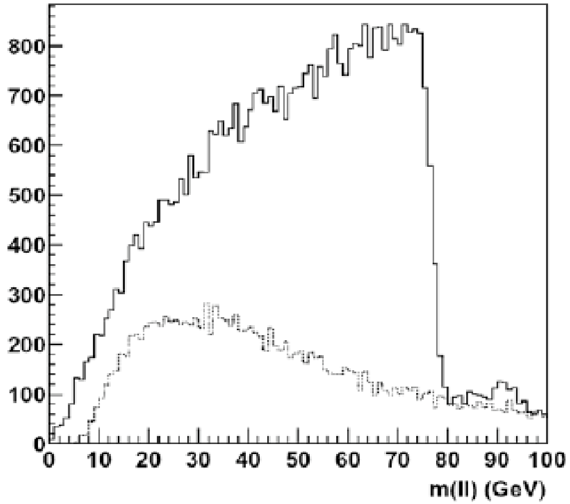
endpoint at: $M_{\ell\ell}^{\max} = M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0}$

But for cascade decay

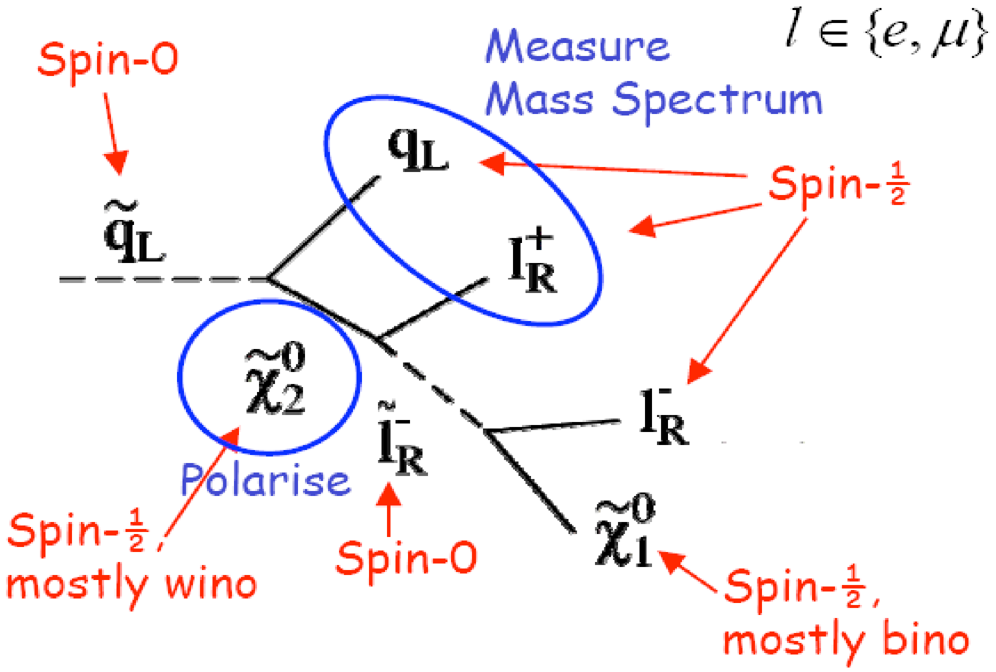
$$\tilde{\chi}_2^0 \to \tilde{\ell}\ell \to \tilde{\chi}_1^0 \ell\ell$$

endpoint at:

$$M_{\ell\ell}^{\max} = \frac{1}{M_{\tilde{\ell}}} \sqrt{(M_{\tilde{\chi}_2^0} - M_{\tilde{\ell}})(M_{\tilde{\ell}} - M_{\tilde{\chi}_1^0})}$$



Is it SUSY? – Spin reconstruction



Measure Mass Spectrum

$l \in \{e, \mu\}$

Spin-0

Spin-$\frac{1}{2}$

Polarise

Spin-$\frac{1}{2}$, mostly wino

Spin-0

Spin-$\frac{1}{2}$, mostly bino

Barr

Expect charge asymmetry in mass spectrum shape

Experimentally, need to know:

- squark or anti-squark?
  get statistically from pdf's

-'near' or 'far' lepton
  don't know, average the two

Theoretical expectation: