# PeV-Scale Supersymmetry

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hep-ph/0306127, hep-ph/0411041, hep-ph/0412424, ...

## Motivations for Supersymmetry

Here are some reasons people like supersymmetry, listed in no particular order:

- Gauge Coupling Unification
- "Obvious" space-time symmetry extension to explore
- String Theory seems to like it
- Source of dark matter (R-parity)
- Can solve gauge hierarchy problem

Other reasons: QFT laboratory, etc.

## Standard Supersymmetry Paradigm

Long history of trying to make supersymmetry into phenomenologically viable theory.

Much understanding of what works and does not work now: E.g., everybody's got a superpartner, sugra mediated, $F$-term supersymmetry breaking residing in

$$X = x + \sqrt{2}\psi\theta + F\theta^2$$

leading to

$$m_{3/2}^2 \sim \frac{F^\dagger F}{M_{\rm Pl}^2} \quad \text{gravitino mass}$$

Gaugino masses are generated via

$$\int d^2\theta \frac{X}{M_{\rm Pl}} \mathcal{W}\mathcal{W} \sim m_{3/2}\lambda\lambda$$

The scalar masses are generated by

$$\int d^2\theta d^2\bar{\theta} \frac{X^\dagger X}{M_{\rm Pl}^2} \Phi_i^\dagger \Phi_i \to m_{3/2}^2 \phi_i^* \phi_i$$

Everybody $\sim m_{3/2}$, and $m_{3/2} \sim m_W$ for naturalness.

## Challenges for Low-Energy Supersymmetry

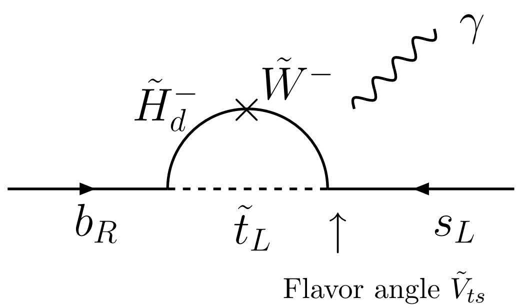
Throw dart into minimal supersymmetric parameter space, and what do you get?

*Observable predictions would be*
*wildly incompatible with experiment*

Let us briefly review some of the challenges.

## Flavor Changing Neutral Currents

Random superpartner masses and mixing angles creates FCNC far beyond those measured by experiment:

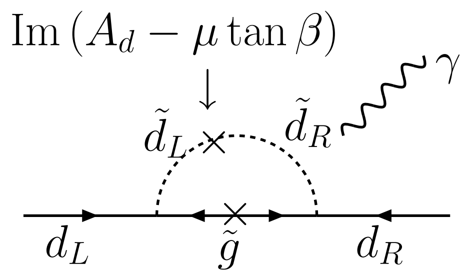



This diagram is much larger than SM amplitude if $\tilde{V}_{ts}$ sizeable.

*Remember: Very heavy scalars squash these new FCNC sources.*

## CP Violation

Supersymmetry has many new sources of CP phases that can affect observables adversely:




EDM of neutron requires $\phi \sim 10^{-3}$
or $\tilde{m} >$ several TeV.

*Remember: Very heavy scalars squash these new CP-violation sources.*

## Proton Decay

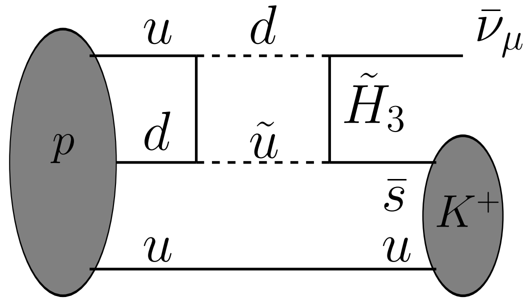
The most general superpotential consistent with gauge symmetries and renormalizability is

$$
\begin{aligned}
W \;=\;& \mu H_u H_d + y_u Q H_u u^c + y_d Q H_d d^c + y_e L H_d e^c \\
& \mu' L H_u + \lambda Q L d^c + \lambda' L L e^c + \lambda'' u^c d^c d^c
\end{aligned}
$$

The second row term, if allowed, mediate rapid proton decay.

Elegant solution: $R$-parity, which is $Z_2$ subgroup of $U(1)_{B-L}$. $H_u$ and $H_d$ are even and all other states are odd.

In GUT theories, need to worry also about dimension-5 operators:




*Remember: R-parity and very heavy scalars ensure proton stability.*

## Higgs boson mass

In minimal supersymmetry the lightest Higgs mass is computable:

$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3G_F m_t^4}{\sqrt{2}\pi^2} \log \frac{\tilde{m}_t^2}{m_t^2} + \cdots$$

Tree-level value is bounded by $m_Z = 91\,\mathrm{GeV}$. Current lower limit on Higgs boson mass is $114\,\mathrm{GeV}$. Thus, we need $\sim (70\,\mathrm{GeV})^2$ contribution from quantum correction.

Need $\tilde{m}_t \gtrsim 5\,\mathrm{TeV}(0.8\,\mathrm{TeV})$ for $\tan\beta = 2(30)$

For "radical naturalists," this is intolerable. [They go to NMSSM, etc.]

*However, Remember: Heavy scalar masses (in particular top squarks) solves this problem.*

## Gravitino problem

Weak scale $m_{3/2}$ in weak-scale susy has problem. Its lifetime is long enough to decay during BBN, disrupting it.

There are cosmological ways around this problem (low-enough reheat temperature, etc.), but there is essentially no constraint if $m_{3/2} > 100\,\mathrm{TeV}$ (rapid decay).

*Remember: If gravitino mass is very heavy there is no problem.*

## Naturalness

Many clever solutions exist for the above challenges.

However, what we have been seeing is that very heavy scalar masses effortlessly solve many problems.

Unqualified safety if scalar masses $\gtrsim 100\,\mathrm{TeV}$.

Ordinary views of naturalness are *strained*:

$$\frac{1}{2}m_Z^2 + \mu^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1}$$

Term(s) on LHS$\sim m_Z$, and terms on RHS $\gtrsim 100\,\mathrm{TeV}$.

## EW-scale naturalness

Appeals to naturalness are murky and controversial. Incompatible views can all be reasonable at this point.

String/M-theory vacua counting suggests maybe we will need to radically change our view of ew-scale naturalness.

*Agnostic approach:* Delete all reference to naturalness from consideration, and ask what is the “best” supersymmetric model we can come up with.

## Arbitrarily heavy supersymmetry?

After deleting naturalness from the discussion, previous considerations might imply all superpartner masses should go to some arbitrarily heavy scale.

However, we wish to keep the other good aspects of supersymmetry, in particular, gauge coupling unification and dark matter.

## Gauge coupling unification

"Proximity Factor" for gauge coupling unification is defined to be the factor $A$ needed such that

$$g_U = g_1(M_U) = g_2(M_U) = g_3(M_U) + A\frac{g_U^3}{16\pi^2}$$

where $g_i(M_U)$ are the gauge couplings run up from the weak scale to the unification scale where $g_1 = g_2$.

A is a measure of GUT-scale threshold corrections that one needs for exact unification.

In weak-scale MSSM $M_U \simeq 2 \times 10^{16}\,\mathrm{GeV}$ and $A \simeq 1$.

In SM unification $M_U \sim 10^{14}\,\mathrm{GeV}$ (problem for dim-6 proton decay) and $A \simeq 20$. If all superpartners decoupled to the GUT scale, we'd have this situation.

One finds that if gauginos and higgsinos are less than a few TeV, the "Proximity Factor" for unification is just as good as the MSSM and has almost no dependence on the scalar masses. (Arkani-Hamed and Dimopoulos have emphasized this.)

## Dark Matter

If superpartners are of order the GUT/String/Planck scale, then R-parity may not be needed for proton stability.

Nevertheless, a nice cold dark matter candidate should not be given up so easily. Assume R-parity.

Freeze-out occurs when particle interaction strengths are just not high enough to cause interactions when universe has expanded to a certain point.

$$\sigma v \sim \frac{\alpha}{\tilde{m}^2}$$

Relic abundance comes about

$$\Omega h^2 \sim \frac{1}{\kappa^2 \langle \sigma v^2 \rangle} \sim \frac{\tilde{m}^2}{\kappa^2}$$

where $\kappa \sim m_W$ (set by astrophysical things, etc.).

Thus if $\tilde{m} \gg m_W$ there is an overclosure problem.

## Dark Matter (continued)

In the space of supersymmetric parameters, good dark matter relic abundance comes about from:

- $\chi\chi$ annihilations through sleptons (bulk region)
- $\chi\psi$ co-annihilation regions (e.g., LSP with stau)
- $\chi\chi$ annihilations through heavy Higgs resonance (or perhaps light Higgs resonance)
- $\chi\chi$ annihilations through EW gauge bosons (significant higgsino and/or Wino content)

The first three options are not viable if scalars are extremely heavy.

Thus, the LSP should be either higgsino-like or wino-like.

**<u>Where we are at</u>**

Eliminating bad things (FCNC, CP violation, Higgs mass, etc.) but preserving good things (SUSY, dark matter, gauge coupling unification) has led us to

*Large scalar superpartner masses, but light fermion superpartner masses (gauginos and higgsino)*

Is there a good theory for this type of hierarchy?

A very general answer is YES. Gaugino and higgsino masses are charged (R-symmetry and PQ symmetry), whereas scalar masses are not.

## Supersymmetry breaking scenario

A particularly simple, and perhaps best, approach to this phenomenology is to assume that the susy breaking multiplet is charged (not a singlet).

Recall, we said supersymmetry breaking can be parametrized by chiral supermultiplet,

$$X = x + \sqrt{2}\psi\theta + F\theta^2$$

If $X$ is charged we cannot write down the simple gaugino mass terms

$$\int d^2\theta \frac{X}{M_{\rm Pl}} \mathcal{W}\mathcal{W} \quad \text{(not allowed)}$$

## Supersymmetry breaking scenario (cont.)

On the other hand, the scalar masses are allowed

$$\int d^2\theta d^2\bar{\theta}\frac{X^\dagger X}{M_{\rm Pl}^2}\Phi_i^\dagger\Phi_i \to m_{3/2}^2\phi_i^*\phi_i$$

If $S$ is charged (i.e., not a singlet) the scalar mass equation is unaffected but the gaugino mass expression is no longer gauge invariant (ignoring GUT group $S_{ab}\mathcal{W}^a\mathcal{W}^b$ possibilities).

The leading contribution to gaugino masses is the anomaly-mediated expression

$$M_\lambda = \frac{\beta(g_\lambda)}{g_\lambda}m_{3/2}$$

Randall, Sundrum; Giudice, Luty, Murayama, Rattazzi

## Superpartner spectrum

Unless there is a special Kähler potential suppressing scalar masses, they will be very heavy compared to the gauginos.

In terms of the gravitino mass $m_{3/2}$ the superpartner spectrum is

$$\begin{aligned} M_1 &\simeq m_{3/2}/120 \\ M_2 &\simeq m_{3/2}/360 \\ M_3 &\simeq m_{3/2}/45 \\ \tilde{m}_i &\sim m_{3/2} \end{aligned}$$

where $\tilde{m}_i$ are the various scalar superpartner masses.

Requiring $M_2 > m_W$ implies $m_{3/2} > 28\,\mathrm{TeV}$.

This is perhaps the simplest manifestation of "split supersymmetry."

## Dark Matter

Straightforward calculations of thermal relic abundance of a Wino LSP says

$$m_{\tilde{W}} = 2.3\,\mathrm{TeV} \longrightarrow \Omega h^2 = 0.1$$

which would enable it to constitute all the cold dark matter.

This would also imply that $m_{3/2} \simeq 0.8\,\mathrm{PeV}$.

If the Higgsino happens to be lighter than the Wino, it can be the CDM if its mass is about $1.2\,\mathrm{TeV}$.

## The gravitino as a source for non-thermal dark matter

When $m_{3/2} \gtrsim 50\,\mathrm{TeV}$ the gravitinos decay before nucleosynthesis.

However, the early decays of $\tilde{G} \to \mathrm{LSP} + X$ may lead to overclosing the universe:

$$\Omega^{G}_{\mathrm{LSP}} h^2 \simeq 30 \left( \frac{M_2}{100\,\mathrm{GeV}} \right) T_{13}(1 - 0.03 \ln T_{13}),$$

normalized to the Wino mass.

If $T_R \simeq 10^{10} - 10^{11}\,\mathrm{GeV}$ then the LSPs may have near-critical relic density, and can be an excellent cold dark matter candidate. In this model, the Wino LSP can then be a good dark matter candidate (Gherghetta, Giudice, JW; Moroi, Randall).

## Dark Matter Detection

When $\mu, \tilde{m}_i \gg M_{\tilde{W}}$ there is no signal for table-top experiments. Dark matter is effectively invisible to LSP-nucleon scattering.

However, LSP annihiliations in the galactic halo are enhanced for Wino LSPs compared to ordinary Bino dark matter. Experiments looking for $\bar{p}$'s, $e^+$'s and photons are good ways to detect Wino dark matter.

LSP annihilations into monochromatic $\gamma\gamma$ are especially interesting, as they are enhanced and $E_\gamma = m_{\tilde{W}}$, which is otherwise difficult to know (even when produced at LHC).

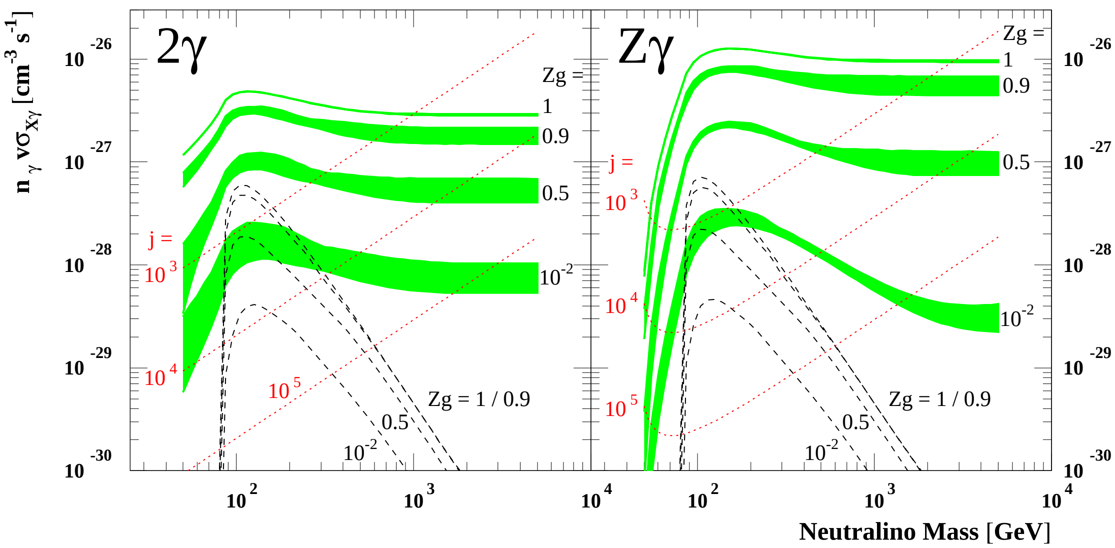
The annihilation cross-section into monochromatic photons is

$$2\sigma v(\gamma\gamma) = (3-5) \times 10^{-27}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$$

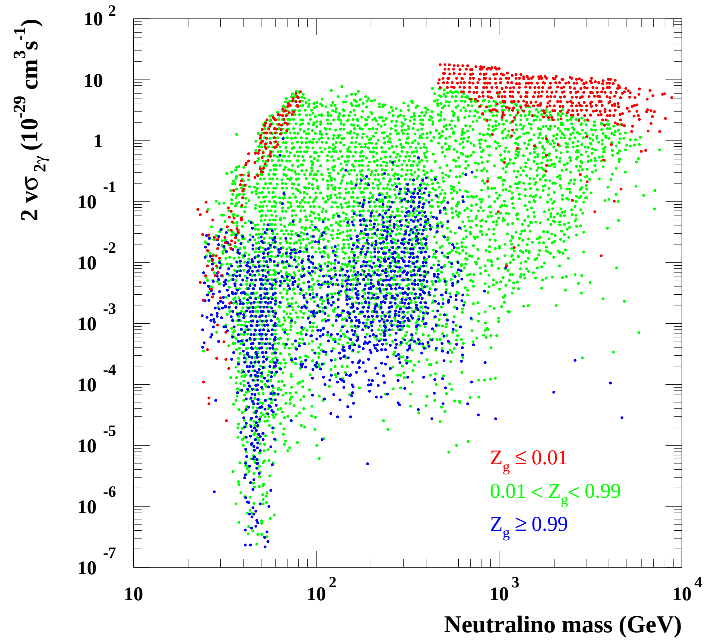
for $m_{\tilde{W}^0} = 1\,\mathrm{TeV} - 100\,\mathrm{GeV}$.

Under somewhat favorable astrophysical assumptions, GLAST and the next generation Cerenkov detectors will find these.

# Wino annihilations into photons




Ullio, hep-ph/0105052 – Wino-like LSP with highest rates being pure Winos




Bergstrom, Ullio, Buckley, hep-ph/9712318 – Scatter Plot in normal MSSM with highest rates being pure Higgsinos

# Wino mass splitting

Mass splitting of the charged and neutral Wino ($\tilde{W}^{\pm}$, $\tilde{W}^{0}$) occurs by operators

$$\mathcal{O} \sim M_{ab}\tilde{W}^a\tilde{W}^b,$$

where $M_{ab}$ must transform non-trivially under $SU(2)$. Lowest order operator is

$$\mathcal{O}_{\text{splitting}} = \frac{1}{\Lambda^3}(H^\dagger\tau^a H)(H^\dagger\tau^b H)\tilde{W}^a\tilde{W}^b.$$

Therefore, mass splitting at tree-level scales like $\sim m_W^4/\Lambda^3$, where $\Lambda$ is heavy mass scale of integrated out particles. Expression for large $\mu$ and $M_1$ is

$$m_{\chi_1^\pm} - m_{\chi_1^0} = \frac{m_W^4 \sin^2 2\beta}{(M_1 - M_2)\mu^2}\tan^2\theta_W + \frac{2m_W^4 M_2 \sin 2\beta}{(M_1 - M_2)\mu^3}\tan^2\theta_W + \ldots$$

There are also important loop corrections. In the $\mu \to \infty$ limit,

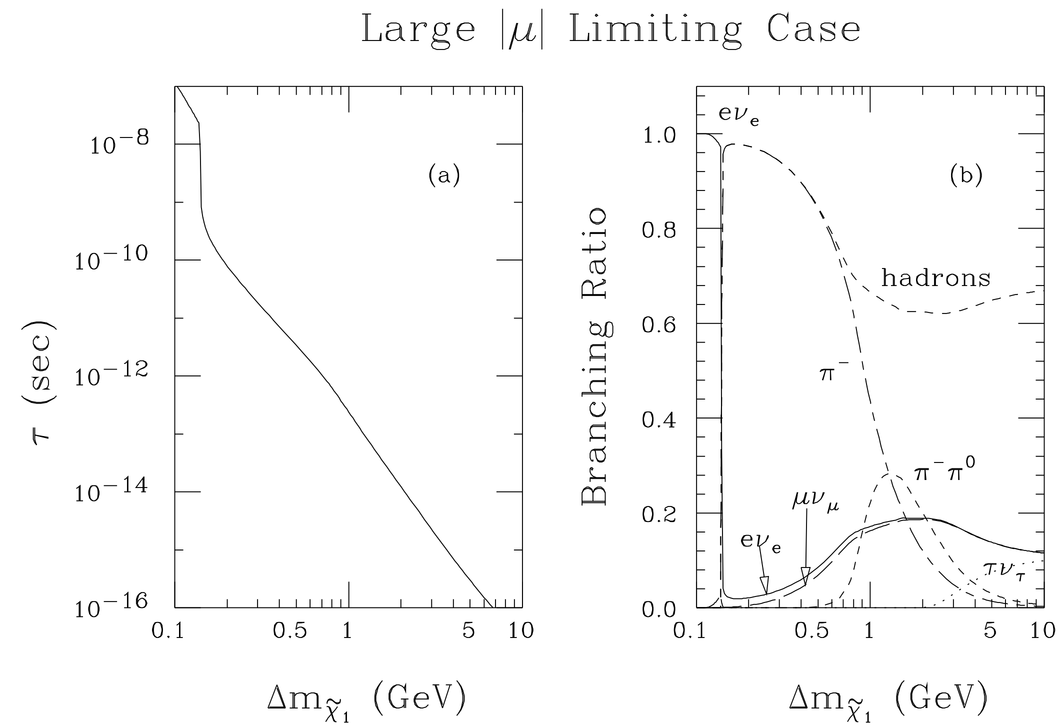
$$\begin{aligned}(m_{\chi_1^\pm} - m_{\chi_1^0})_{\text{loop}} &= \frac{\alpha M_2}{\pi \sin^2\theta_W}\left[f\left(\frac{m_W^2}{M_2^2}\right) - \cos^2\theta_W f\left(\frac{m_Z^2}{M_2^2}\right)\right] \\ \lim_{M_2\to\infty}(\cdots) &\Longrightarrow \frac{\alpha m_W}{2(1+\cos\theta_W)} \simeq 165\,\text{MeV}.\end{aligned}$$

## Wino mass splitting and decay lifetime

The mass splitting in the large $\mu$ limit is

$$m_{\pi^\pm} < m_{\tilde{W}^\pm} - m_{\tilde{W}^0} < 165\,\mathrm{MeV}$$

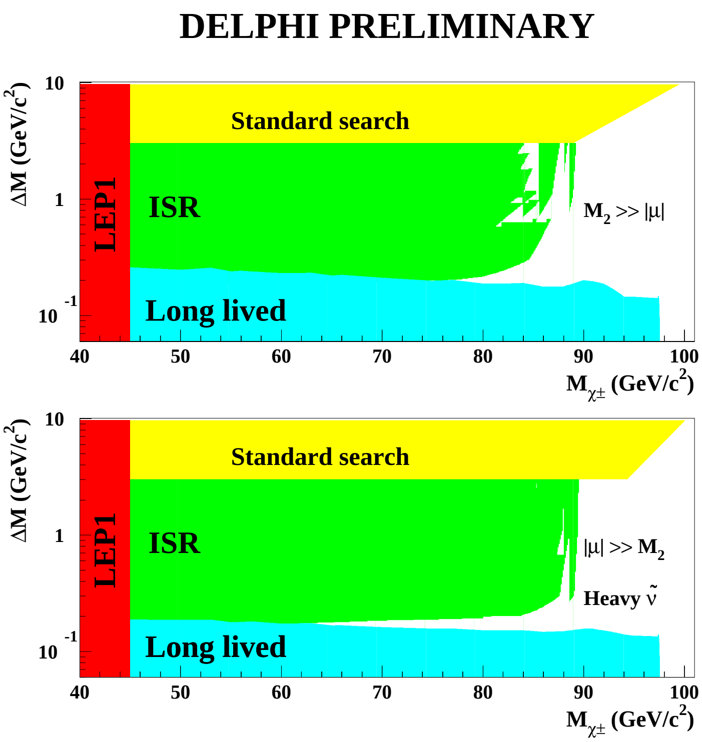
for $m_{\tilde{W}} > 80\,\mathrm{GeV}$.



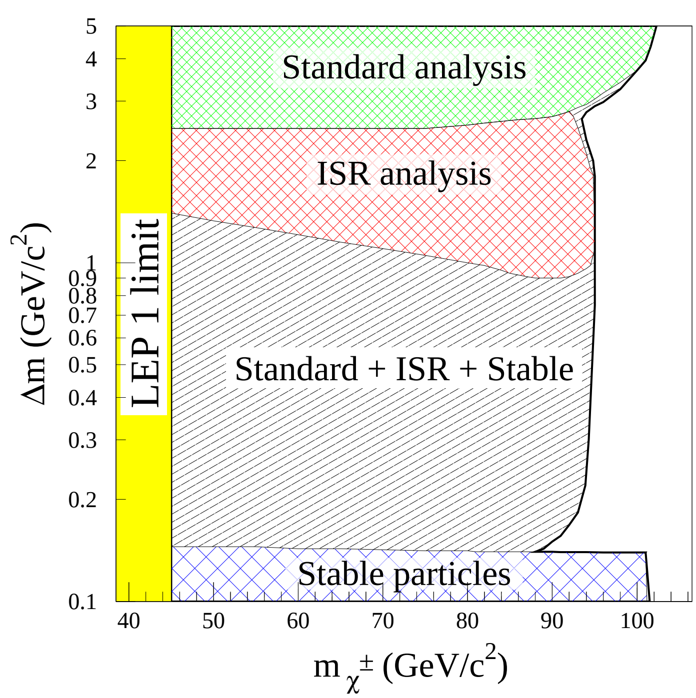

C. Chen, M. Drees, J.F. Gunion, hep-ph/9902309.

At LEP, Tag events with hard initial state radiated photon, and look for soft pions.

# Experimental Limits from LEP




DELPHI Collaboration, ICHEP, Osaka, $\sqrt{s} = 202\,\mathrm{GeV}$




ALEPH Collaboration, hep-ex/0203020, $\sqrt{s}$ up to $209\,\mathrm{GeV}$.

## Hadron Colliders

Tevatron will likely not improve on LEPII bounds (Mrenna, Gunion).

LHC should focus on gluino pair production. Ordinarily most of the jets plus missing $E_T$ events at LHC come from $\tilde{g}\tilde{q}$ associated production. No squarks light enough for this.

Gluinos three body decay to $\tilde{q} \to q_1 q_2 + \tilde{\chi}$. $q_1$ and $q_2$ depend on relative masses of heavy squarks. $\tilde{\chi}$ can also have interesting cascade decays to SM particles ($W$, $Z$ and $h$ bosons) and LSP.

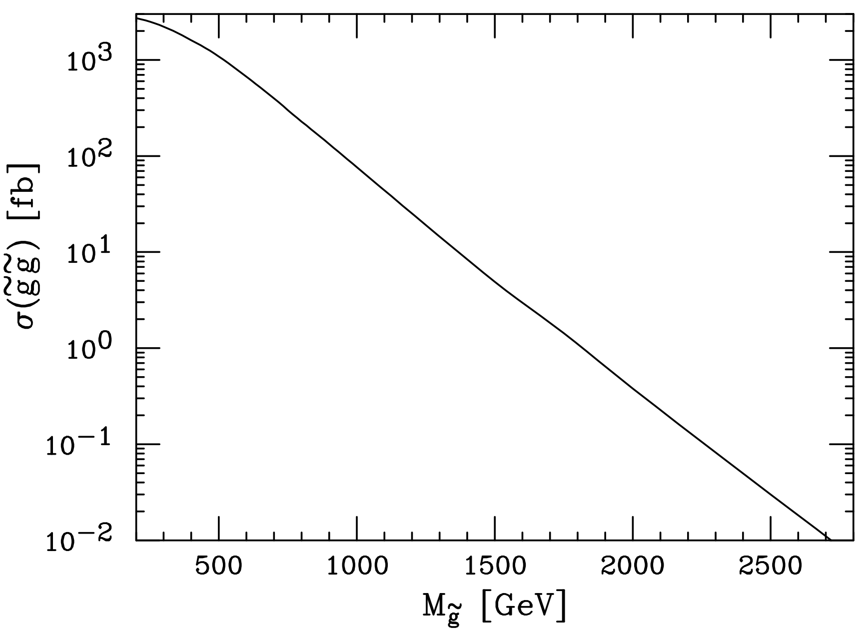
If top squarks are somewhat preferentially lighter than other squarks, expect signals such as

$$pp \to \tilde{g}\tilde{g} \to tt\bar{t}\bar{t}\tilde{W}^0\tilde{W}^0 \;\text{ and }\; tt\bar{b}\bar{b}\tilde{W}^-\tilde{W}^-, \;\text{ etc.}$$

With the high multiplicities of high-$p_T$ SM particles and little SM background (easily cut). Expect event rates to be only roadblock to discovery.

## Event rates from $\tilde{g}\tilde{g}$ production

Gluino pair production in the appropriate limit of heavy squarks is

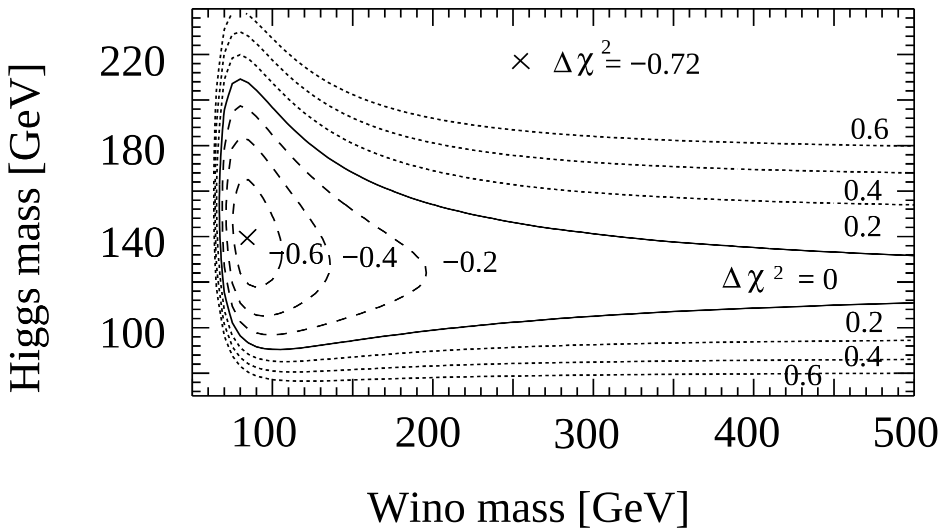


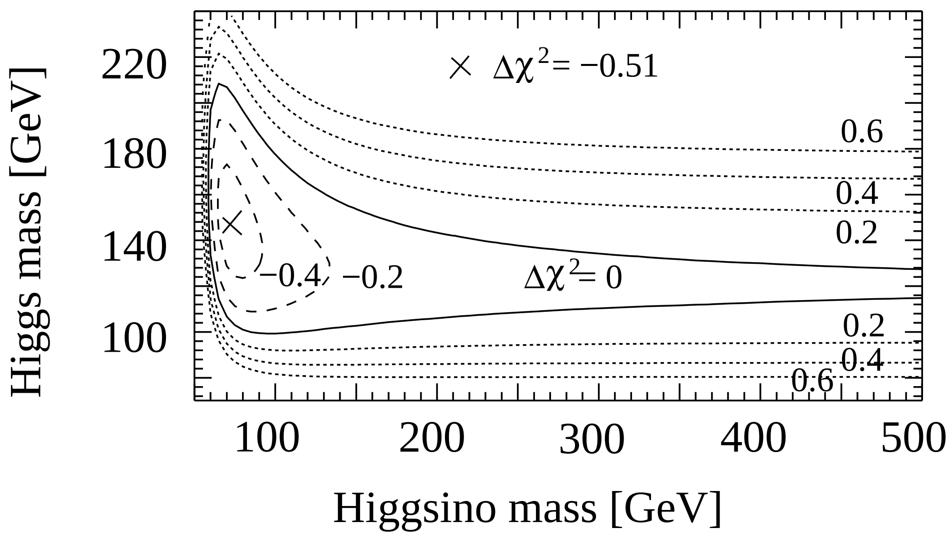

Obtained from Isajet v7.44

Expect mass reach of gluinos to almost 2 TeV with 200 $\text{fb}^{-1}$ of data. (Nearly 100 events to work with.) 2 TeV gluino mass is equivalent to gravitino mass, and therefore scalar mass, of nearly 90 TeV in this scenario.

Scalars and Winos are probed indirectly from gluino decays, and decays cascading through the Bino. Direct probes of the Wino (scalars) would have to wait for the LC (VLHC) ....

# Precision Electroweak Fits




Martin, Tobe, JW, hep-ph/0412424

## Neutrinos and the PeV scale

The PeV scale might be of independent interest to neutrinos.

Grander picture: Many sectors live at the scale of supersymmetry breaking masses (PeV scale). EW scale happens to be much lighter.

$\nu^c$ is not a pure singlet under all the symmetries of these extra sectors. $\nu^c$ (and other MSSM states) are charged under a $U(1)'$ such that $LH_u\nu^c$ is not invariant, but we have

$$W = \frac{\lambda}{M_{\mathrm{Pl}}}\phi L H_u \nu^c$$

where $\phi$ is an exotic field that breaks the $U(1)'$ at the PeV scale and whose charge assignments allow the above operator (but not $\phi^2\nu^c\nu^c$).

We find that

$$m_\nu = \frac{\lambda}{M_{\mathrm{Pl}}}\langle\phi H_u\rangle = (0.07\,\mathrm{eV})\,\lambda\sin\beta\left(\frac{\langle\phi\rangle}{1\,\mathrm{PeV}}\right)$$

This is a very interesting scale for neutrinos.

Atmospheric neutrinos $\Delta m_\nu \simeq 10^{-3}\,\mathrm{eV}$, which can be nicely accommodated by the PeV-scale Dirac neutrinos.

## Conclusions

If we dismiss Naturalness from all consideration in supersymmetry, heavy scalars and light gauginos/higgsinos are both *phenomenologically interesting* (problems are mass suppressed, while retaining good things) and *theoretically interesting* (charged supersymmetry breaking).

Experimental tests of scenario are more difficult than standard susy scenarios but not impossible.