SELECTED SPECIAL SUSY SIGNALS IN THE SUSY UNIVERSE

J. F Gunion, Keystone Linear Collider Workshop (September, 1998)

OUTLINE OF TOPICS

- How big is the SUSY universe?
- A heavy gluino-LSP or gluino-NLSP.
- Delayed decays in SUSY.
- Exotic signals in L/R symmetric models.

1 The SUSY universe

- How many parameters are there? (JFG + Haber)

  Introducing $\widehat{L}_\alpha$ ($\alpha = 0,1,2,3$), where $\widehat{L}_0 \equiv \widehat{H}_d$, the full superpotential including RPV is:

$$
\begin{aligned}
W = \epsilon_{ij} \Big[& -\mu_\alpha \widehat{L}^i_\alpha \widehat{H}^j_u + \tfrac{1}{2}\lambda_{\alpha\beta m} \widehat{L}^i_\alpha \widehat{L}^j_\beta \widehat{E}_m + \lambda'_{\alpha n m} \widehat{L}^i_\alpha \widehat{Q}^j_n \widehat{D}_m - (y_u)_{nm} \widehat{H}^i_u \widehat{Q}^j_n \hat{U}_m \Big] \\
& + (\lambda_B)_{pnm} \widehat{U}_p \widehat{D}_n \widehat{D}_m \,, \qquad (1.1)
\end{aligned}
$$

  where $\lambda_{\alpha\beta m}$ is antisymmetric under interchange fo α and β, while $(\lambda_B)_{pnm}$ is antisymmetric under interchange of n and m (due to an implicit antisymmetric contraction of the color indices). In Eq. (1.1), Greek indices run from 0 to 3 while Roman indices run from 1 to 3; , p, n, m are family indices.

  The RPV soft SUSY breaking terms are:

$$
\begin{aligned}
V_{\rm soft} = & (m^2_Q)_{mn}\, \widetilde{Q}^{i*}_m \widetilde{Q}^i_n + (m^2_{\overline{u}})_{mn}\, \widetilde{U}^*_m \widetilde{U}_n + (m^2_{\overline{d}})_{mn}\, \widetilde{D}^*_m \widetilde{D}_n \\
& + (m^2_L)_{\alpha\beta}\, \widetilde{L}^{i*}_\alpha \widetilde{L}^i_\beta + (m^2_{\overline{e}})_{mn}\, \widetilde{E}^*_m \widetilde{E}_n + m^2_{H_u} |H_u|^2 - (\epsilon_{ij} b_\alpha \tilde{L}^i_\alpha H^j_u + \text{h.c.}) \\
& + \epsilon_{ij} \Big[\tfrac{1}{2} a_{\alpha\beta m} \widetilde{L}^i_\alpha \widetilde{L}^j_\beta \widetilde{E}_m + a'_{\alpha n m} \widetilde{L}^i_\alpha \widetilde{Q}^j_n \widetilde{D}_m - (a_u)_{nm} H^i_u \widetilde{Q}^j_n \widetilde{U}_m + \text{h.c.} \Big] \\
& + (a_B)_{pnm} \widetilde{U}_p \widetilde{D}_n \widetilde{D}_m + \tfrac{1}{2} \Big[M_3\, \tilde{g}\, \tilde{g} + M_2 \widetilde{W}^a \widetilde{W}^a + M_1 \widetilde{B} \widetilde{B} + \text{h.c.} \Big] \,, \qquad (1.2)
\end{aligned}
$$

  where the $a_{\alpha\beta m}$ are antisymmetric under interchange of α and β, and the $(a_B)_{pnm}$ are antisymmetric under the interchange of n and m. The single B term of the MSSM is extended to a four-component vector, b_α, the single squared-mass term for the down-type Higgs boson and the 3×3 lepton scalar squared-mass matrix is combined into a 4×4 matrix, and the matrix A-parameters of the MSSM are extended in the obvious manner.

Table 1: Parameter Count in the SM and MSSM Extensions: BV=baryon-number violating; LV=lepton-number violating; BLV=both B and L violating.

model	masses and mixing angles	CP-violating phases	TOTAL
Standard Model	17	2	19
MSSM	79	45	124
$(\mathrm{MSSM})_{\mathrm{BV}}$	97	62	159
$(\mathrm{MSSM})_{\mathrm{LV}}$	157	122	279
$(\mathrm{MSSM})_{\mathrm{BLV}}$	175	140	315

- Of course, in all cases, most of the parameter space is excluded due to constraints from EDM's, absence of FCNC's, *etc.*
- If there is R-parity violation, much experimental input will be required to get a handle on all these parameters.
- The above parameter count is only for MSSM particle content. If we add in extra matter fields and/or gauge fields, *e.g.* as in left-right symmetric models, the SUSY universe expands very dramatically.
- The big question: how to probe and maintain full sensitivity to all non-excluded parameter choices.

2 A heavy gluino-LSP or gluino-NLSP. JFG + K. Cheung + H. Baer, hep-ph/9806361

- The possibility that the LSP is a stable heavy gluino cannot be ruled out a priori.

  All that is required is for a gaugino mass ordering at low-energy in which $M_3 < M_{1,2}$. Reasonably-motivated string and GMSB models exist in which this is the case.

- A gluino-NLSP decaying via $\tilde{g} \to g\widetilde{G}$ is also a possibility in the GMSB context.

- Cosmology and relic density limits in the $\tilde{g}$-LSP case are quite weak if strong-interaction non-perturbative effects enhance $\tilde{g}\tilde{g}$ annihilation rates (as is probable).

  Such limits are irrelevant in the $\tilde{g}$-NLSP case.

- What would be the role of the NLC?

  - Currently, LEP (OPAL) and Tevatron (CDF and probably also D0) rule out 3 GeV $\lesssim m_{\tilde{g}} \lesssim$ 130 GeV for a $\tilde{g}$-LSP and $m_{\tilde{g}} <$ 240 GeV for a $\tilde{g}$-NLSP.

    There is little sensitivity of these limits to detector assumptions unless the probability of $\tilde{g} \to R^{\pm}$ fragmentation (with $R^{\pm}$ gluino-hadron pseudo-stable in the detector) is close to 1.

  - RunII at the Tevatron should be able to extend the $\tilde{g}$-LSP reach to $m_{\tilde{g}} \sim 170 - 180$ GeV and the $\tilde{g}$-NLSP reach to ~ 280 GeV.

– A $\sqrt{s} = 500$ GeV machine is then not adequate, unless we are on the verge of discovery the $\tilde{g}$-LSP at RunII.

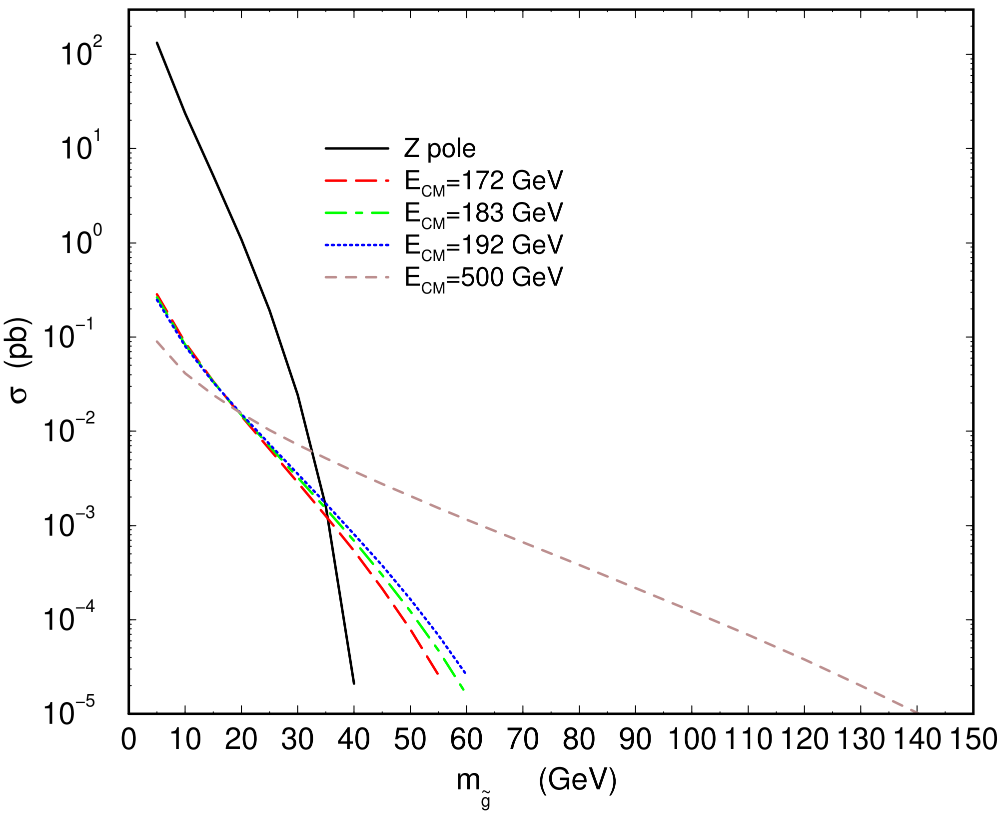

Figure 1: $\sigma(e^+e^- \to q\bar{q}\tilde{g}\tilde{g})$ as a function of $m_{\tilde{g}}$ for $\sqrt{s} = m_Z$ (solid), 172 GeV (dashes), 183 GeV (dot-dash), 192 GeV (dots) and 500 GeV. No cuts.

For $L = 500$ fb^{-1} we expect < 5 $q\bar{q}\tilde{g}\tilde{g}$ events if $m_{\tilde{g}} > 140$ GeV.

3 Delayed decay scenarios in SUSY

- With the recent exploration of SUSY models that go beyond mSUGRA, there is increasing realization that delayed decays could provide a very crucial signal for SUSY and a means for determining the most crucial SUSY parameters.

- The two important examples are encountered in the context of gauge mediated supersymmetry breaking (GMSB) and R-parity violating (RPV) models.

  A less interesting, but entirely possible, case is near degeneracy $\widetilde{\chi}_1^0$ and $\widetilde{\chi}_1^\pm$.

  GMSB Models:

  - For the goldstino, one finds

    $$m_{\widetilde{G}} = F/(\sqrt{3}M_{\rm P}) \sim 2.5 \left(\sqrt{F}/100 \text{ TeV}\right)^2 \text{ eV}\,, \qquad (3.1)$$

    where $\sqrt{F}$ is the energy scale that underlies supersymmetry breaking in the hidden sector. In GMSB models, $\sqrt{F} \sim \mathcal{O}(100 - 1000 \text{ TeV})$ is envisioned $\Rightarrow \widetilde{G}$ =LSP.

    Most early-universe scenarios lead to the requirement $m_{\widetilde{G}} \lesssim 1$ keV (equivalent to $\sqrt{F} \lesssim 2000$ TeV) to avoid overclosing the universe.

  - The coupling of a sparticle to its SM partner plus the $\widetilde{G}$ is inversely proportional to F and is very weak for all F values of interest.

    $\Rightarrow$ all the sparticles other than the next-to-lightest super particle (NLSP), *i.e.* the $\widetilde{\chi}_1^0$ or $\tilde{\ell}_R$, undergo chain decay down to the NLSP. The NLSP finally decays to the $\widetilde{G}$: *e.g.* $\widetilde{B} \to \gamma\widetilde{G}$ or $\tilde{\ell}_R \to \ell\widetilde{G}$.

– The $c\tau$ for NLSP decay depends on $\sqrt{F}$; *e.g.* for $N_m = 1$

$$(c\tau)_{\tilde{\chi}_1^0 = \tilde{B} \to \gamma \tilde{G}} \sim 130 \left(\frac{100 \text{ GeV}}{M_{\tilde{B}}} \right)^5 \left(\frac{\sqrt{F}}{100 \text{ TeV}} \right)^4 \mu\text{m} \qquad (3.2)$$

If $\sqrt{F} \sim 2000$ TeV (the upper limit from cosmology), then $c\tau \sim$ 21m for $M_{\tilde{B}} = 100$ GeV; $\sqrt{F} \sim 100$ TeV implies a short but vertexable decay length.

Thus, the signatures for GMSB models are crucially dependent on $\sqrt{F}$.

– In GMSB models containing three-sectors,

1. hidden sector where SUSY-breaking occurs,
2. messenger sector which communicates SUSY-breaking,
3. MSSM sector of TeV scale particles,

one can show that $\sqrt{F} \geq 1000$ TeV is expected.

Only GMSB models where 1) and 2) are one and the same can have $\sqrt{F}$ values in the ~ 100 TeV region for which NLSP decay would be prompt.

– $\Rightarrow$ The ability to see signals involving delayed decays could be very crucial; certainly you do not want to throw away events that have the unusual characteristics that come with such decays.

– In fact, **The ability to measure the path length $\Rightarrow$ measurement of $\sqrt{F}$, the most important parameter in SUSY**!!!

RPV Models:

– The tri-linear superpotential RPV terms are often written:

$$\lambda_{pnm}\widehat{L}_p\widehat{L}_n\widehat{E}_m + \lambda'_{pnm}\widehat{L}_p\widehat{Q}_n\widehat{D}_m + \lambda''_{pnm}\widehat{U}_p\widehat{D}_n\widehat{D}_m \,, \tag{3.3}$$

where gauge group indices have been suppressed and p, n, m are family indices.

There are also soft-SUSY-breaking potential RPV terms.

– There are two possible means of measuring the RPV couplings which are undoubtedly the most interesting parameters of the model.

  * Observe a production rate that is directly proportional to an RPV coupling, e.g. at an e^+e^- collider we might see $e^-e^+ \to \tilde{\nu}_\tau$ if λ_{131} is large.
  * If the relevant RPV coupling is small, we might observe a finite, perhaps very long, path length for the LSP, which, by the way, could be anything in RPV models.

– What is the decay length of the $\widetilde{\chi}^0_1$ in RPV models? (JFG + K. Cheung).

To just get an idea, we looked at the mode $\widetilde{\chi}^0_1 \to c\tilde{c}^*_L \to c(e^-_L d_R)$. The $\widetilde{\chi}^0_1 \to c\tilde{c}_L$ vertex is $\propto (m_c/m_W)N_{14}$, where N_{14} gives the Higgsino content of the $\widetilde{\chi}^0_1$. The $\tilde{c}_L \to e^-_L d_R$ vertex is $\propto \lambda'_{121}$.

One finds:

$$\Gamma = \frac{3\alpha}{512\pi^2}\frac{m_c^2 m_{\widetilde{\chi}^0_1}}{mw^2\sin^2\beta\sin^2\theta_W}|\lambda'_{121}|^2|N_{14}|^2 \times \left[6x - 5 + (1-x)(2-6x)\ln(1-x)\right] \,, \tag{3.4}$$

where $x = m^2_{\tilde{c}_L}/m^2_{\tilde{\chi}^0_1}$.

Taking $m_{\tilde{c}_L} = 200$ GeV and $\lambda'_{121} \sim 0.03$. (as once motivated by direct RPV HERA 'signal'), $m_{\tilde{\chi}^0_1} = 100$ GeV, $|N_{14}| = 1$, $\sin^2\beta = 1$, $\Rightarrow$

$$\Gamma = 8 \times 10^{-12}\ \mathrm{GeV}\,, \quad \Rightarrow L = 2.4 \times 10^{-5}\ \mathrm{m}\,.$$

$\Rightarrow \lambda'_{121} \sim 10^{-4}$ will result in decay well into or outside detector.

– Substantially delayed decays become interesting more or less as the direct RPV production signals cease to be visible because of low rate.

So, maybe, we will always have a chance to measure the RPV coupling magnitude, **if** we can measure path length distributions. Must study event rates as a function of L for interesting crazy vertices.

– In BRPV, Hempfling finds path lengths that range from 1 mm to 1 m over a region of parameter space interesting for neutrino masses of current interest.

The $\widetilde{\chi}^0_1 \to 7$ important channels: 1) $qq\nu$ (1st and 2nd generation); 2) $ud\ell$ (1st and 2nd generation); 3) 3ν; 4) $bb\nu$; 5) $\tau\tau\nu$; 6) $\ell^\pm\ell^\mp\nu$ ($\ell = e, \mu$); 7) $\tau^\pm\ell^\mp\nu$ ($\ell = e, \mu$).

Depending upon $m_{\tilde{\chi}^0_1}$, all modes can be equally important at $BF = 0.1 - 0.15$. For $m_{\tilde{\chi}^0_1} \sim m_W$, 2) is enhanced and dominant.

Can one find such a diffuse signal? Will delayed decays help?

One should not ignore the possiblity of a mixture of delayed decays due to GMSB and RPV.

$\boldsymbol{m_{\widetilde{\chi}_1^0} \simeq m_{\widetilde{\chi}_1^\pm}}$:

– This scenario (JFG, C.H. Chen, M. Drees) is a natural in certain string and non-singlet F-term SUSY breaking models, which predict that $M_2 < M_{1,3}$.

– Extreme degeneracy for the $\widetilde{\chi}_1^0$ and $\widetilde{\chi}_1^\pm$, $\Delta m_{\widetilde{\chi}_1} \equiv m_{\widetilde{\chi}_1^\pm} - m_{\widetilde{\chi}_1^0} <$ 0.5 GeV, is quite possible.

– Detection of the standard first SUSY signal $e^+e^- \to \widetilde{\chi}_1^+\widetilde{\chi}_1^-$ with $\widetilde{\chi}_1^\pm \to \widetilde{\chi}_1^0 X$ ($X = \ell\nu$ or $\overline{q}q'$) becomes very difficult when X consists only of very slow moving particles.

– Actually, for small $\Delta m_{\widetilde{\chi}_1}$, the $\widetilde{\chi}_1^+ \to \pi^+\pi^0$ channel is often dominant and provides a good topological signal when the π^+ is not too slow.

– Detection of $e^+e^- \to \gamma\widetilde{\chi}_1^+\widetilde{\chi}_1^-$ provides one possible alternative, but at least as interesting might be X detection after a substantial delay in the decay.

For $\Delta m_{\widetilde{\chi}_1} \sim 0.3$ GeV we get a mm path length.

For $\Delta m_{\widetilde{\chi}_1} \sim 0.1$ GeV we get many meters.

Large $|\mu|$ Limiting Case

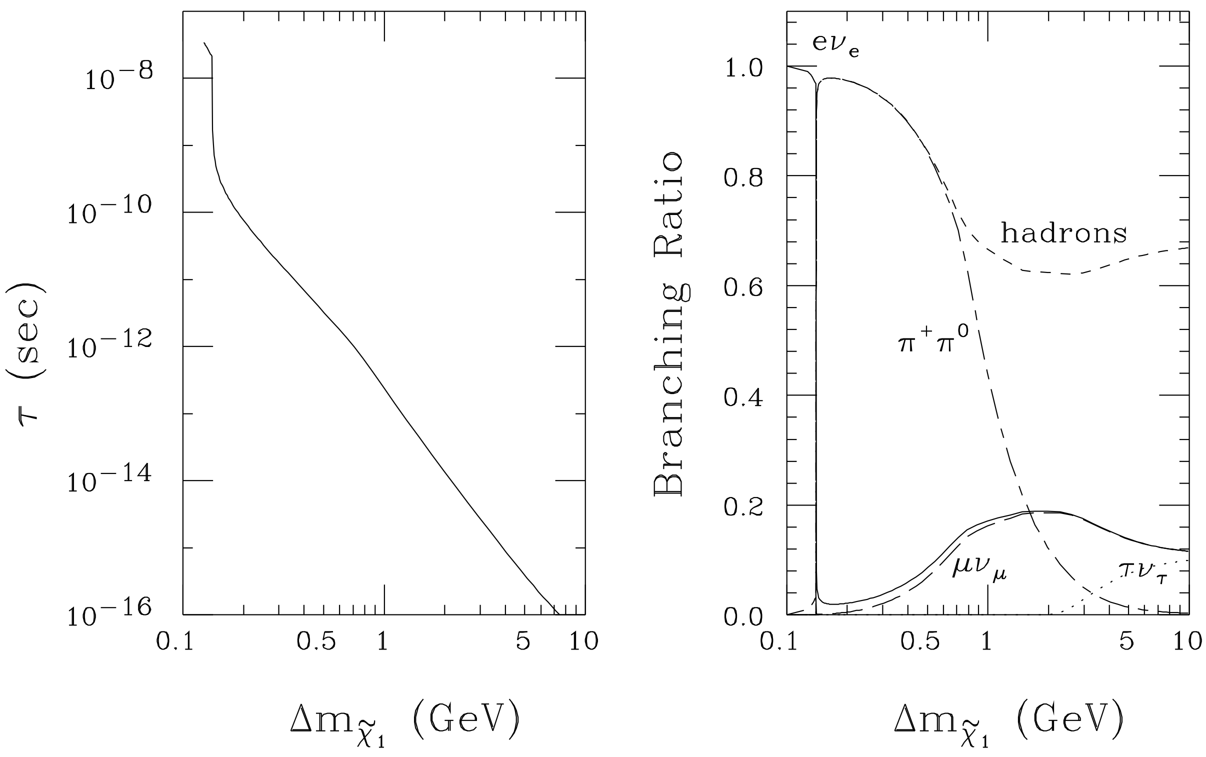

Figure 2: Lifetime and branching ratios for the $\widetilde{\chi}_1^{\pm}$ as a function of $\Delta m_{\widetilde{\chi}_1}$.

- Techniques for accessing delayed decays.
  - Short path lengths in vertex chamber.
  - Non-zero impact parameter for:

    photons ($\widetilde{\chi}_1^0$-NLSP);

    leptons ($\widetilde{\ell}_R$-NLSP);

    many things in RPV, including $\lambda'' \neq 0$ case of delayed spray of three hadron jets;

    e or π's in $\Delta m_{\widetilde{\chi}_1} \to 0$ scenario.
  - Timing of tracks and energy deposits in EM and HAD calorimeters (need segmentation) will be useful if the produced source object is heavy enough to have a low to moderate velocity.

– Extra external arrays outside the detector.

Must make sure that your triggering and detector options do not preclude observation of a large array of delayed decays.

4 L/R symmetric models

Doubly-charged Higgsinos and the SUSY-LR context (Mohapatra and collaborators, *e.g.* Dutta and Mohapatra, hep-ph/9804277)

- L-R symmetry in the SUSY context implies that $\mathcal{L}$ cannot contain terms that explicitly violate R-parity. The presence or absence of RPV is determined by whether or not there is spontaneous RPV. There are two generic possibilities:
  - If certain higher dimensional operators are small or absent, then it can be shown that the scalar field potential is such that L-R symmetry breaking induces RPV through some combination of non-zero $\langle\tilde{\nu}_i^c\rangle$'s. In this case, the W_R mass scale is low and, of course, there are lots of new phenomena associated with RPV.

    In this scenario, the triplet Higgs and higgsinos, including $\Delta_{L,R}^{--}$ and their fermionic partners, are not necessarily light.
  - If the above-mentioned higher-dimensional operators are present and are of full strength (but, of course, $\propto 1/M_U$ or $1/M_{\rm P}$), then LR symmetry breaking does not require RPV.

    In this case, the W_R mass scale must be very large. Also the Δ_L triplet members and their superpartners must be very heavy unless one removes the naturally present parity-odd singlet from the theory (which is normally included in order to avoid $v_L \neq 0$ vacua).

    However, when the R-sector Higgs mechanism comes in at high scale (assumed to be above SUSY breaking scale) to give $v_R \neq 0$

and generate W_R mass, one is breaking a U(3) symmetry and there are 4 surviving massless (goldstone) fields, which are the Δ^{--} superfield and its charge conjugate, whose component fields only become massive via the higher-dimensional operators.

Thus, it is natural for the mass scales of the Δ_R^{--} and $\widetilde{\Delta}_R^{--}$, $\sim v_R^2/M_{\rm P}$, to be at the ~ 100 GeV level.

- Explore phenomenology of these latter objects. $\Rightarrow \tau$'s!!!

  Non-GMSB SUSY:

  - If $h_{\tau\tau}$ (Majorana coupling) is full strength (~ 0.5) then influences RGE's.

    (a) for $m_{\tilde\tau}$: $\tilde\tau$'s (esp. $\tilde\tau_R$) are lighter than $\tilde e$ and $\widetilde\mu$, even if $\tan\beta$ is not large.

    (b) for $m_{\Delta^{--}}$ and $m_{\tilde\Delta^{--}}$: starting with a common mass at v_R scale $\Rightarrow m_{\Delta^{--}} < m_{\tilde\Delta^{--}} \Rightarrow$ constraints on allowed parameter space, esp. m_0.
  - The Δ_R^{--} phenomenology has been thoroughly explored (JFG, JFG+Loomis+Pitts).

    Two basic results:

    * Can see $\Delta^{--}\Delta^{++}$ pair production at the Tevatron up to quite large mass (~ 150 GeV) if $\Delta^{--} \to \tau^-\tau^-$ (via Majorana couplings) and even higher if $\Delta^{--} \to \mu^-\mu^-$ or e^-e^-.

      Look for like sign τ pairs from common vertex, *etc.*

      The LHC will probe up to $m_{\Delta^{--}} \sim 500$ GeV.
    * If we see such a signal, especially if we see it in the e^-e^- decay mode (but, even if not) an e^-e^- collider becomes of

great interest.

$e^- e^- \to \Delta^{--}$ can provide a measurement of the relevant Majorana coupling down to very small values, in particular values such that this coupling is relevant for the neutrino masses of recent interest.

– Less attention has been paid to $\widetilde{\Delta}^{--}$, which could be produced at the Tevatron and the NLC in pairs.

  * $\widetilde{\Delta}^{--} \to \tilde{\tau}_R \tau$ is usually open and will dominate over all other lepton channels because of larger coupling, followed by $\tilde{\tau}_R \to \widetilde{\chi}_1^0 \tau$.
  * For same mass, the $\widetilde{\Delta}^{--}\widetilde{\Delta}^{++}$ pair cross section is bigger than the scalar counterpart $\Delta^{--}\Delta^{++}$ (quicker threshold rise since not p-wave).
  * Sample signature: $e^+e^- \to \widetilde{\Delta}^{--}\widetilde{\Delta}^{++} \to \tau^-\tau^-\tau^+\tau^+ + \not{E}_T$.
    Note: reconstruction of the Δ^{--} and Δ^{++} masses would not be possible.

Introduction of GMSB context $\Rightarrow$ some changes:

– $\widetilde{\Delta}^{--}$ now lighter than Δ^{--}, which gets additional (two-loop) gauge contributions to its mass-squared $\Rightarrow$ no m_0 constraints from this source.

  * $\widetilde{\Delta}^{--}$ could even be the NLSP.
    If so, it decays virtually via $\widetilde{\Delta}^{--} \to (\Delta^{--})^* \widetilde{G} \to \ell^-\ell^- \not{E}_T$, but if the $\Delta^{--} \to \ell^-\ell^-$ coupling is small (as expected) this decay could have a very long lifetime.

$\Rightarrow$ all the standard SUSY signals would be drastically altered, with $\widetilde{\chi}_1^0 \to (\Delta^{--})^* \widetilde{\Delta}^{--} \to \ldots$.

$\Rightarrow$ Look for $\ell^- \ell^-$ pair with significant vertex separation, large impact parameter, . . ., in association with $\not{E}_T$ from the final $\widetilde{G}$.

* If the $\widetilde{\Delta}^{--}$ is not the NLSP, then the $\tilde{\tau}_R$ very probably is (even for $N_m = 1$), with $\tilde{\tau}_R \to \tau \widetilde{G}$.

  Phenomenology: $\Rightarrow$

  Sample signature: $e^+ e^- \to \widetilde{\Delta}^{--} \widetilde{\Delta}^{++} \to \tau^- \tau^- \tau^+ \tau^+ + \not{E}_T$.

  same as earlier except $\not{E}_T$ now from $\widetilde{G}$'s in $\tilde{\tau} \to \tau \widetilde{G}$ (rather than from $\widetilde{\chi}_1^0$'s).

* In the small portion of parameter space where $\widetilde{\chi}_1^0$ is the NLSP, the signature for $\widetilde{\Delta}^{--} \widetilde{\Delta}^{++}$ production changes to $4\tau 2\gamma + \not{E}_T$, where the γ's come from the $\widetilde{\chi}_1^0 \to \gamma \widetilde{G}$ decays.

5 Discussion and Conclusions

- There are many models in the SUSY universe.
- Some of the models yield signatures that are strikingly different from the normal mSUGRA type phenomenology.
- Experimentalists should make sure that their procedures and detector do not preclude observation of these signatures.
- Indeed, one should be certain that sensitivity to delayed decays, . . ., is maintained so as to take full advantage of all the information that might allow determination of *all* the SUSY parameters and *all* the possible matter and gauge-field content.