Supersymmetry Without (Much) Prejudice

• The MSSM is very difficult to study due to the very large number of soft SUSY breaking parameters (~ 100).

• Analyses generally limited to a specific SUSY scenario(s) such as mSUGRA, GMSB, AMSB,… having few parameters.

• But how well do any or all of these reflect the true breadth of the MSSM?? Do we really know the MSSM as well as we think??

• Is there another way to approach this problem & yet remain more general? Some set of assumptions are necessary to make any such study practical. But what? There are many possibilities.
FEATURE Analysis Assumptions:

- The most general, CP-conserving MSSM with R-parity
- Minimal Flavor Violation at the TeV scale
- The lightest neutralino is the LSP.
- The first two sfermion generations are degenerate (sfermion type by sfermion type).
- The first two generations have negligible Yukawa’s.
- No assumptions about SUSY-breaking or GUT

This leaves us with the pMSSM:

→ the MSSM with 19 real, TeV/weak-scale parameters…

What are they??
19 pMSSM Parameters

sfermion masses: \( m_{Q1}, m_{Q3}, m_{u1}, m_{d1}, m_{u3}, m_{d3}, m_{L1}, \\
m_{L3}, m_{e1}, m_{e3} \)

gaugino masses: \( M_1, M_2, M_3 \)

tri-linear couplings: \( A_b, A_t, A_\tau \)
Higgs/Higgsino: \( \mu, M_A, \tan \beta \)

Note: These are TeV-scale Lagrangian parameters
What are the Goals of this Study???

- Prepare a large sample, ~50k, of MSSM models (= parameter space points) satisfying ‘all’ of the experimental constraints. A large sample is necessary to get a good feeling for the variety of possibilities. (Done)

- Examine the properties of the models that survive. Do they look like the model points that have been studied up to now? What are the differences? (In progress)

- Do physics analyses with these models for LHC, ILC/CLIC, dark matter, etc. etc. (In progress)
How? Perform 2 Random Scans

**Linear Priors**

- 10^7 points – emphasizes moderate masses
- 100 GeV ≤ m_{sfermions} ≤ 1 TeV
- 50 GeV ≤ |M_1, M_2, μ| ≤ 1 TeV
- 100 GeV ≤ M_3 ≤ 1 TeV
- ~0.5 M_Z ≤ M_A ≤ 1 TeV
- 1 ≤ tanβ ≤ 50
- |A_{t,b,τ}| ≤ 1 TeV

**Log Priors**

- 2x10^6 points – emphasizes lower masses but extends to higher masses
- 100 GeV ≤ m_{sfermions} ≤ 3 TeV
- 10 GeV ≤ |M_1, M_2, μ| ≤ 3 TeV
- 100 GeV ≤ M_3 ≤ 3 TeV
- ~0.5 M_Z ≤ M_A ≤ 3 TeV
- 1 ≤ tanβ ≤ 60
- 10 GeV ≤ |A_{t,b,τ}| ≤ 3 TeV

→ Comparison of these two scans will show the prior sensitivity.
→ This analysis required ~ 1 processor-century of CPU time. This is the real limitation of this study.
Successful models

WMAP & Direct Detection

Direct searches at LEP & Tevatron

Rare decays and flavor constraints

g-2

Precision data

Spectrum requirements
Constraints

- $-0.0007 < \Delta \rho < 0.0026$ (PDG'08)

- $b \rightarrow s \gamma : B = (2.5 - 4.1) \times 10^{-4}$; (HFAG) + Misiak et al. & Becher & Neubert

- $\Delta(g-2)_\mu ??? (30.2 \pm 8.8) \times 10^{-10}$ (0809.4062)
  $(29.5 \pm 7.9) \times 10^{-10}$ (0809.3085)
  $[-14.0 \pm 8.4] \times 10^{-10}$ [Davier/BaBar-Tau08]
  $\rightarrow (-10 \text{ to } 40) \times 10^{-10}$ to be conservative..

- $\Gamma(Z \rightarrow \text{invisible}) < 2.0 \text{ MeV}$ (LEPEWWG)

- Meson-Antimeson Mixing $0.2 < R_{13} < 5$

- $B \rightarrow \tau \nu : B = (55 \text{ to } 227) \times 10^{-6}$ Isidori & Paradisi, hep-ph/0605012 & Erikson et al., 0808.3551 for loop corrections

- $B_s \rightarrow \mu \nu : B < 4.5 \times 10^{-8}$ (CDF + D0)
• Direct Detection of Dark Matter → Spin-independent limits are completely dominant here. We allow for a factor of 4 variation in the cross section from input uncertainties.

• Dark Matter density: $\Omega h^2 < 0.1210 \rightarrow$ 5yr WMAP data +.... We treat this only as an upper bound on the LSP DM density to allow for multi-component DM, e.g., axions, etc. Recall the lightest neutralino is the LSP & is a thermal relic here.

• LEP and Tevatron Direct Higgs & SUSY searches: there are many of these searches but they are very complicated with many caveats.... We need to be cautious here in how the constraints are used.
Example:

$\text{Zh, } h \rightarrow \text{bb, } \tau\tau$

Figure 1: The 95% c.l. upper bound on the coupling ratio $\xi^2 = (g_{\text{HZZ}}/g_{\text{SM}}^{\text{HZZ}})^2$ (see text). The dark (green) and light (yellow) shaded bands around the median expected line correspond to the 68% and 95% probability bands. The horizontal lines correspond to the Standard Model coupling. (a): For Higgs boson decays predicted by the Standard Model; (b): for the Higgs boson decaying exclusively into $\text{bb}$ and (c): into $\tau^+\tau^-$ pairs.
Note the holes where the leptons are too soft...

We need to allow for a mass gap with the LSP & also in the squark case when soft jets are possible... light guys may slip through.

Example:
Example:

Tevatron Constraints: Squark & Gluino Search

• This is the first SUSY analysis to include these constraints

• 2,3,4 Jets + Missing Energy (D0)

Multiple analyses keyed to look for:

Squarks -> jet + MET
Gluinos -> 2 j + MET

The search is based on mSUGRA type sparticle spectrum assumptions which can be VERY far from our model points.
SuSpect -> SUSY-Hit -> PROSPINO -> PYTHIA -> D0-tuned PGS4 fast simulation (to reproduce the benchmark points)…redo this analysis $\sim 10^5$ times!

D0 benchmarks

→ Feldman-Cousins 95% CL Signal limit: 8.34 events

Combos of the 3 analyses
Tevatron II: CDF Tri-lepton Analysis

We perform this analysis using CDF-tuned PGS4, PYTHIA in LO plus a PROSPINO K-factor

→ Feldman-Cousins 95% CL Signal limit: 4.65 events

• This is the first SUSY analysis to include these constraints

The non-‘3-tight’ analyses are not reproducible w/o a better detector simulation
This is an incredibly powerful constraint on our model set as we will have many close mass chargino-neutralino pairs. This search cuts out a huge parameter region as you will see later.

- No applicable bounds on charged sleptons..the cross sections are too small.
- This is the first SUSY analysis to include these constraints.
### Survival Rates

<table>
<thead>
<tr>
<th>file</th>
<th>Description</th>
<th>Percent of Models Remaining</th>
</tr>
</thead>
<tbody>
<tr>
<td>slha-okay.txt</td>
<td>SuSpect generates SLHA file</td>
<td>99.99 %</td>
</tr>
<tr>
<td>error-okay.txt</td>
<td>Spectrum tachyon, other error free</td>
<td>77.29 %</td>
</tr>
<tr>
<td>lsp-okay.txt</td>
<td>LSP the lightest neutralino</td>
<td>32.70 %</td>
</tr>
<tr>
<td>deltaRho-okay.txt</td>
<td>--</td>
<td>32.61 %</td>
</tr>
<tr>
<td>gMinus2-okay.txt</td>
<td>$g - 2$</td>
<td>21.69 %</td>
</tr>
<tr>
<td>b2sGamma-okay.txt</td>
<td>$b \rightarrow s \gamma$</td>
<td>6.17 %</td>
</tr>
<tr>
<td>Bs2MuMu-okay.txt</td>
<td>$B \rightarrow \mu \mu$</td>
<td>5.95 %</td>
</tr>
<tr>
<td>vacuum-okay.txt</td>
<td>No CCB, potential not UFB</td>
<td>5.92 %</td>
</tr>
<tr>
<td>Bu2TauNu-okay.txt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LEP-sparticle-okay.txt</td>
<td>LEP sfermion checks</td>
<td>4.72 %</td>
</tr>
<tr>
<td>invisibleWidth-okay.txt</td>
<td>Invisible Width of Z</td>
<td>4.71 %</td>
</tr>
<tr>
<td>susyhitProb-okay.txt</td>
<td>Heavy Higgs not problematic for SUSY-HIT</td>
<td>4.69 %</td>
</tr>
<tr>
<td>stableParticle-okay.txt</td>
<td>Tevatron stable chargino search</td>
<td>4.19 %</td>
</tr>
<tr>
<td>chargedHiggs-okay.txt</td>
<td>LEP/ Tevatron charged Higgs search</td>
<td>4.19 %</td>
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<tr>
<td>neutralHiggs-okay.txt</td>
<td>LEP neutral Higgs search</td>
<td>1.73 %</td>
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<tr>
<td>directDetection-okay.txt</td>
<td>WIMP direct detection</td>
<td>1.55 %</td>
</tr>
<tr>
<td>omega-okay.txt</td>
<td>$\Omega h^2$</td>
<td>0.74 %</td>
</tr>
<tr>
<td>Bs2MuMu-2-okay.txt</td>
<td>$B \rightarrow \mu \mu$</td>
<td>0.74 %</td>
</tr>
<tr>
<td>stableChargino-2-okay.txt</td>
<td>Tevatron stable chargino search</td>
<td>0.72 %</td>
</tr>
<tr>
<td>triLepton-okay.txt</td>
<td>Tevatron trilepton</td>
<td>0.72 %</td>
</tr>
<tr>
<td>jetMissing-okay.txt</td>
<td>Tevatron jet plus missing</td>
<td>0.70 %</td>
</tr>
<tr>
<td>final-okay.txt</td>
<td>Final after cutting models with e.g. light stop, sbottoms</td>
<td>0.68 %</td>
</tr>
</tbody>
</table>

- **Flat Priors**: $10^7$ models scanned, ~ 68.4 K (0.68%) survive
- **Log Priors**: $2 \times 10^6$ models scanned, ~ 2.7 K (0.13%) survive
LEP Higgs mass constraints avoided by either reducing the $ZZh$ coupling and/or reducing the, e.g., $h \rightarrow b\bar{b}$ branching fraction by decays to LSP pairs. We have both of these cases in our final model sets.
Distribution of Sparticle Masses By Species

Flat Priors

Log Priors
Distribution of Sparticle Masses By Species

Flat Priors

Log Priors
The identity of the nLSP is a critical factor in looking for SUSY signatures. Who can play that role here?????? Just about ANY of the 13 possibilities!
nLSP-LSP Mass Difference

1 MeV

D0 stable particle search

Accessible to ATLAS @10 TeV & 1 fb⁻¹ for stable winos
High-Purity LSPs

Flat

'High-Purity' LSPs

LSP Mass Versus LSP-nLSP Mass Splitting
• I have previously discussed the observation of hard jets resulting from possible squark/gluino production, the shortfall of simulation studies & our lack of knowledge of the final state.

• But here we see that another concern is generic stable and/or long-lived particles. These can have soft decay products (that may involve leptons, photons or ‘jets’ ) due to, e.g., some small mass splittings between the many possible nLSP’s & the LSP.

• Searches for detector-stable charged particles at the LHC should be relatively straightforward depending upon cross sections & whether or not they are ‘R-hadrons’. But note that the reaches for stable sleptons & charginos are NOT so great even at 14 TeV & full lumi .. leaving ‘open space’ for a TeV ILC.

• A more ‘problematic’ example of the long-lived possibility is provided by the second neutralino as the nLSP in the Higgsino limit. The decay products are often too soft to observe.
Long Lived/ Stable Sparticles in the 71k Sample

- 17407 models with at least 1 long-lived/stable state
- 353 have 2 long-lived states (e.g., 25 w/ chargino + gluino!)
- 12 have 3 of them!

- 16061 are charginos
- 555 are second neutralinos
- 339 are sbottoms
- 179 are staus
- 100 are stops
- 79 are gluinos
- 49 are $c_R$
- 18 are $\mu_R$
- 11 are 2nd charginos
- 8 are $c_L$ etc.
Stable SUSY Searches at LHC

A. Raklev
A common long-lived state

Pure wino/Higgsino nLSP mass-independent lifetimes
As is well-known the observation of close mass objects is generally difficult at all colliders, even in $e^+e^-$ collisions.

As an example, in our past SUSY@ILC analysis we saw that charginos having small mass splittings with the LSP required many different searches: stable particles, photon tagging, soft jets, or a combination to cover all of the model space (47/53) for charginos as seen below.

![Graph showing close mass possibilities](image)

We have MANY close mass possibilities in our two model samples. Can $\gamma\gamma$ colliders possibly do any better??

For example, in the case of smuons (squarks) <2(10) GeV heavier than the LSP??
A typical second neutralino radiative decay lifetime for Higgsino LSP & nLSP case

These are INVISIBLE!
Kinematic Accessibility at the ILC: I

..the usual SuSpects

flat priors

accessible sparticles

<table>
<thead>
<tr>
<th>Final State</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e_L^+ e_L^-$</td>
</tr>
<tr>
<td>$e_R^+ e_R^-$</td>
</tr>
<tr>
<td>$e^+_L e^+_R$</td>
</tr>
<tr>
<td>$\mu^+_L \mu^+_R$</td>
</tr>
<tr>
<td>$\bar{\nu}_e \bar{\nu}_e$</td>
</tr>
<tr>
<td>$\bar{\nu}<em>e \bar{\nu}</em>\mu$</td>
</tr>
<tr>
<td>$\tilde{\chi}_1^+ \tilde{\chi}_1^-$</td>
</tr>
<tr>
<td>$\tilde{\tau}_1^+ \tilde{\tau}_1^-$</td>
</tr>
<tr>
<td>$\tilde{\tau}_2^+ \tilde{\tau}_2^-$</td>
</tr>
<tr>
<td>$\tilde{\tau}_1^+ \tilde{\tau}_2^-$</td>
</tr>
<tr>
<td>$\tilde{\chi}_1^0 \tilde{\chi}_1^0$ only</td>
</tr>
<tr>
<td>$\tilde{\chi}_1^0 + \bar{\nu}$ only</td>
</tr>
<tr>
<td>$\tilde{\chi}_1^0 \tilde{\chi}_2^0$</td>
</tr>
<tr>
<td>$\tilde{\chi}_1^0 \tilde{\chi}_3^0$</td>
</tr>
<tr>
<td>$\tilde{\chi}_2^0 \tilde{\chi}_2^0$</td>
</tr>
<tr>
<td>$\tilde{\chi}_2^0 \tilde{\chi}_3^0$</td>
</tr>
<tr>
<td>$\tilde{\chi}_3^0 \tilde{\chi}_3^0$</td>
</tr>
<tr>
<td>Nothing</td>
</tr>
</tbody>
</table>
Kinematic Accessibility at the ILC: III

Squarks & Gluinos!

% of models

accessible sparticles

500 GeV LC
1 TeV LC

flat priors

31
ATLAS SUSY Analyses w/ a Large Model Set

- We are running our ~71k MSSM models through the ATLAS SUSY (10&14 TeV) analysis suite, essentially designed for mSUGRA, to explore its sensitivity to this far broader class of SUSY models employing the ATLAS background estimates.

- We first need to verify that we can approximately reproduce the ATLAS results for their benchmark mSUGRA models with our analysis techniques for each channel. (Done)

- One finds MANY problems w/ our models not encountered in vanilla mSUGRA ...not to mention PYTHIA, etc., issues!

- By necessity there are some differences between the two analyses as we will soon see....

- This is extremely CPU intensive, e.g., 7M K-factors to compute.
ATLAS

ISASUGRA generates spectrum & sparticle decays
Partial NLO cross section using PROSPINO & CTEQ6M
Herwig for fragmentation & hadronization
GEANT4 for full detector sim

FEATURE

SuSpect generates spectra with SUSY-HIT# for decays
NLO cross section for ~85 processes using PROSPINO** & CTEQ6.6M
PYTHIA for fragmentation & hadronization
PGS4-ATLAS for fast detector sim

** version w/ negative K-factor errors corrected
# version w/o negative QCD corrections
The set of ATLAS SUSY analyses is large:

- 2, 3, 4-jet +MET
- 1–l, ≥4-jet +MET
- SSDL+multijet+MET
- OSDL+multijet+MET
- Trileptons + (0,1)-j +MET
- \( \tau + \geq 4j + \text{MET} \)
- \( \geq 4j \) w/ \( \geq 2\) btags + MET
- Stable particle search
- etc.

*Note* the importance of MET
ATLAS has already made use of some of these models!

Prospects for Supersymmetry and Universal Extra Dimensions discovery based on inclusive searches at a 10 TeV centre-of-mass energy with the ATLAS detector

The ATLAS collaboration

Abstract

This note presents an evaluation of the discovery potential of Supersymmetry and Universal Extra Dimensions for channels with jets, leptons and missing transverse energy. The LHC running scenario at a centre-of-mass energy of 10 TeV, delivering an integrated luminosity of 200 pb$^{-1}$ for the 2009-2010 run is investigated.
We do a good job at reproducing the mSUGRA benchmarks in this channel.
2j + MET
1l+4j+MET
Some Results From the First 6k Models @ 14 TeV & 1fb^{-1}

• Remove possibly difficult models where the nLSP is obviously long-lived which may require some specialized analyses

• Determine how many models are visible or not in each analysis @ the 5\sigma level allowing for a 50% systematic uncertainty in the ATLAS SM backgrounds

• The results are still HIGHLY PRELIMINARY with some exotic features, e.g., there are long-lived objects that can be fairly high in the mass spectrum & not just be the nLSPs…
Some Results From the First 6k Models

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Number missed at 5σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>4j + MET</td>
<td>230</td>
</tr>
<tr>
<td>2j + MET</td>
<td>225</td>
</tr>
<tr>
<td>1 lepton</td>
<td>2125</td>
</tr>
<tr>
<td>1 lepton+2j</td>
<td>1864</td>
</tr>
<tr>
<td>1 lepton+3j</td>
<td>1873</td>
</tr>
<tr>
<td>SSDL</td>
<td>4814</td>
</tr>
<tr>
<td>tau</td>
<td>264</td>
</tr>
<tr>
<td>b</td>
<td>1217</td>
</tr>
</tbody>
</table>
What can we conclude so far???

• There are many models which will show a respectable signal in these specific channels but a reasonably large fraction will --not--. We will need to understand why models ‘fail’ on a case by case basis and how analyses would need to be modified (cuts, etc.) to cover them. However, what we have completed so far is only a SMALL subset due to PYTHIA & SDECAY issues.

• Once we know why models fail we need to ask (i) how the LHC analyses might be changed & (ii) what a linear collider can do to assist in these many problematic cases. There is likely to be a sizeable set that require ILC/CLIC to discover a large fraction of the SUSY spectrum.
Summary

• The pMSSM has a far richer phenomenology than any of the conventional SUSY breaking scenarios. The many sparticle properties can be vastly different, e.g., the nLSP can be any other sparticle!

• Light partners may exist which have avoided LEP & Tevatron constraints and may be difficult to observe at the LHC due to rather common small mass differences = long-lived states

• Squarks may exist within the range accessible to a 0.5 -1TeV linear collider but have not been well studied there.

• A linear collider will likely be necessary to discover & study all of these new states in detail especially if the spectrum is ‘unusual’.

• The study of these complex models is still at early stage.
BACKUP SLIDES
Kinematic Accessibility at the ILC: II

Final State

- $\bar{\nu}_e \nu_e$
- $\bar{\nu}_\mu \nu_\mu$
- $\bar{\nu}_\tau \nu_\tau$
- $\bar{\nu}_\tau \nu_\tau$
- $\mu^+_L \mu^-_L$
- $\mu^+_R \mu^-_R$
- Any selectron or smuon
  - $\tilde{\tau}_1^\pm \tilde{\tau}_1^\mp$
  - $\tilde{\tau}_2^\pm \tilde{\tau}_2^\mp$
  - $\tilde{\tau}_1^0 \tilde{\tau}_2^0$
  - $\nu_\tau \bar{\nu}_\mu$
  - $\tilde{\nu}_\tau \tilde{\nu}_\mu$
  - $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$
- Any charged sparticle
  - $\tilde{\chi}_1^\pm \tilde{\chi}_2^\mp$
  - $\tilde{\chi}_1^0 \tilde{\chi}_1^0$
  - $\tilde{\chi}_2^0 \tilde{\chi}_2^0$
  - $\tilde{\chi}_1^0 + \tilde{\nu}$ only
  - $\tilde{\chi}_1^0 + \tilde{\nu}$ only
  - $\tilde{\chi}_1^0 + \tilde{\nu}$ only
- $\tilde{\chi}_2^0 \tilde{\chi}_2^0$
- $\tilde{\chi}_1^0 \tilde{\chi}_3^0$
- $\tilde{\chi}_2^0 \tilde{\chi}_3^0$
- $\tilde{\chi}_1^0 \tilde{\chi}_3^0$
- $\tilde{\chi}_2^0 \tilde{\chi}_3^0$
- $\tilde{\chi}_1^0 \tilde{\chi}_3^0$
- Nothing
Kinematic Accessibility at the ILC: IV

Log Squarks!
SUSY decay chains are very important...especially the end of the chain at the LHC.

Top 25 most common mass patterns for the 4 lightest SUSY & heavy Higgs particles.

There were 1109 (267) such patterns found for the case of flat (log) priors

Only ~20 are found to occur in mSUGRA!!

<table>
<thead>
<tr>
<th>Linear Priors</th>
<th>% of Models</th>
<th>Log Priors</th>
<th>% of Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tilde{\chi}_1^0 &lt; \tilde{\chi}_1^+ &lt; \tilde{\chi}_2^0 &lt; \tilde{\chi}_3^0)</td>
<td>9.82</td>
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<td>18.59</td>
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<td>6.67</td>
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<td>(\tilde{\chi}_1^0 &lt; \tilde{\chi}_1^+ &lt; \tilde{\chi}_2^0 &lt; \tilde{d}_R)</td>
<td>5.18</td>
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<td>(\tilde{\chi}_1^0 &lt; \tilde{\chi}_1^+ &lt; \tilde{\chi}_2^0 &lt; \tilde{\nu}_t)</td>
<td>4.50</td>
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<td>(\tilde{\chi}_1^0 &lt; \tilde{\chi}_1^+ &lt; \tilde{\chi}_2^0 &lt; \tilde{b}_1)</td>
<td>3.76</td>
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<td>2.96</td>
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<td>3.73</td>
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<td>(\tilde{\chi}_1^0 &lt; \tilde{\chi}_1^+ &lt; \tilde{\nu}_t &lt; \tilde{\tau}_1)</td>
<td>2.27</td>
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<td>2.19</td>
<td>(\tilde{\chi}_1^0 &lt; \tilde{\chi}_2^0 &lt; \tilde{\chi}_1^+ &lt; \tilde{\chi}_3^0)</td>
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</tr>
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</table>
Predicted Dark Matter Density: $\Omega h^2$

It is not likely that the LSP is the dominant component of dark matter in ‘conventional’ cosmology…but it can be in some model cases.. (1240+76)
$\chi_1^+$

$\chi_2^0$

e_R : 1433

$\tau_1 : 1499$
Gluino Can Be Light!!
Squarks CAN Be Light !!!

Light squarks can be missed by Tevatron searches for numerous reasons.
First two generation of squarks are heavy; gluinos -> stop + top
The stop hadronizes first & then decays as: stop-> bW+ LSP 
w/ Q=4 GeV so b-jet is soft & MET is small
Model 12

This case is even more unusual as it didn’t even show up in any of the histograms! Here sbottom_1 is the nLSP with a mass splitting of only ~1.5 GeV so we get lots of soft jets + MET only. The other squarks are rather heavy:

Note that SDECAY treats the sbottom in this case as stable but really an R-hadron forms which then undergoes a 4-body decay or a 1-loop suppressed decay with a $c\tau \sim 10-100\ \mu m$.