It’s a good time to discover new physics! Where will we find it?

For the purposes of this talk, the new physics to find (or exclude) is SUSY.

The Tevatron and LHC are still complementary probes of SUSY.
1 Intro: Simplified Models of GMSB

2 Slepton NLSPs

3 Neutralino NLSPs
   - Bino-like
   - Wino-like
   - Higgsino-like
Intro:
Simplified Models of Gauge Mediation
How is SUSY breaking mediated to the SM?

Precision flavor tests suggest that SUSY breaking respects flavor.
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Precision flavor tests suggest that SUSY breaking respects flavor.

Gauge mediation has the virtues:

1. flavor blind
2. calculable
Gauge mediation predicts a light gravitino.

\[ m_{3/2} = \frac{\langle F \rangle}{\sqrt{3} M_p} \]

where \( \sqrt{\langle F \rangle} \sim 10^4 \) to \( 10^{11} \) GeV.
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The NLSP decays to the gravitino and its superpartner.

\[ \Gamma_{NLSP} = \frac{m_{NLSP}^5}{16\pi F^2} = (0.1 \text{ mm})^{-1} \times \left( \frac{m_{NLSP}}{100 \text{ GeV}} \right)^5 \left( \frac{100 \text{ TeV}}{\sqrt{F}} \right)^4 \]
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The identity of the NLSP and its lifetime define the collider physics.
The SUSY spectrum depends on the model.

All experimental searches (pre-2011) have focused on one model: Minimal Gauge Mediation (Dine, Nelson, Nir, Shirman,...)

\[ W = X \phi_i \bar{\phi}_i \]

- \( \phi_i \) and \( \bar{\phi}_i \) are messengers charged under the SM.
- \( X \) is a SUSY breaking spurion with VEV: \( \langle X \rangle + \theta^2 \sqrt{F} \)
- At tree-level, \( \phi_i \) and \( \bar{\phi}_i \) experience SUSY breaking
In MGM the spectrum pretty much always looks like,

- NLSP is a bino or right-handed slepton.
- heavy colored states
- gaugino unification relations, $M_1 : M_2 : M_3 \sim 1 : 2 : 6.$
Beyond MGM

But there are many different realizations of gauge mediation.

The general features are:

\[ \text{flavor symmetric boundary condition} \]

\[ \text{small } A \]

\[ M_1, M_2, M_3 \text{ are unconstrained} \]

\[ m_{Q}, m_{U}, m_{D}, m_{L}, m_{E} \text{ are subject to sum rules} \]

\[ \text{Tr} \ Y m_2^2 = m_Q^2 - 2m_U^2 + m_D^2 - 2m_L^2 + m_E^2 = 0 \]

\[ \text{Tr} \ (B - L) m_2^2 = 2m_Q^2 - m_U^2 - m_D^2 - 2m_L^2 + m_E^2 = 0 \]

Any sparticle can be the NLSP!

These features have been familiar to model builders.

And were recently proved for a wide-class of models, General Gauge Mediation, (Meade, Seiberg, Shih) where the hidden sector and SM decouple when \[ g_{\text{SM}} \to 0. \]
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- flavor symmetric boundary condition
- small $A$-terms

$\text{Tr} m^2 = m^2_Q - 2 m^2_U + m^2_D - m^2_L + m^2_E = 0$

$\text{Tr}(B - L)m^2 = 2m^2_Q - m^2_U - m^2_D - 2m^2_L + m^2_E = 0$

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The possible NLSPs and signals in MGM are:

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The above signals include $E_T$ carried by the gravitinos.
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<tr>
<td>neutralino/chargino</td>
<td>$\gamma, Z, W, h$</td>
<td>non-pointing photons, displaced leptons...</td>
</tr>
<tr>
<td>squark gluino</td>
<td>jets</td>
<td>displaced vertices, R-hadrons</td>
</tr>
<tr>
<td>sneutrino</td>
<td></td>
<td>multileptons</td>
</tr>
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The above signals include $\not{E}_T$ carried by the gravitinos.
Some recent/ongoing model-independent studies:

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<td><em>JTR &amp; Shih</em></td>
<td></td>
</tr>
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</tr>
<tr>
<td>sneutrino</td>
<td><em>Katz, Tweedie</em></td>
<td></td>
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</tbody>
</table>

This signature space was also surveyed by the SUSY working group before run II of the Tevatron.
As theorists in the pre-discovery era, we have the goals:

1. identify minimal inclusive signatures for discovery naturally characterized by NLSP type and lifetime
2. cover full space of gauge mediation, model-independently
3. identify simple parameter spaces ($\leq 2d$) for experimentalists
4. determine current limits and future Tevatron/LHC reach
For a given signal we recommend,

- choose spectra with as few light particles as possible, and decouple everything else ($m_{\text{else}} \gtrsim \text{TeV}$).

- specify soft parameters at the weak scale, instead of using parameters of a UV theory

- these are simplified models, see also,
  - *Dube, Glatzer, Somalwar, Sood, Thomas*
  - *Alwall, Schuster, Toro*
  - *Alves, Alwall, Izaguirre, Le, Lisanti, Manhart, Wacker*
  - http://www.lhcnewphysics.org/

**Caveat:** This approach neglects naturalness, RG evolution of soft parameters, UV completion, ...

It will be important to address these issues post-discovery.
Slepton NLSPs
Slepton co-NLSPs

\[ \delta m = m_{\tilde{e}_R} - m_{\tilde{\tau}_1} \lesssim 10 \text{ GeV} \]

Every event has at least two e, µ, or τ, plus MET.
Slepton co-NLSPs

\[ \delta m = \tilde{e}_R - \tilde{\tau}_1 \ll 10 \text{ GeV}. \]

Every event has at least two \( e, \mu, \text{ or } \tau \), plus MET.

Stau NLSP

\[ \tilde{\mu}_R, \tilde{\tau}_1 \]

\[ \widetilde{G} \]
Slepton co-NLSPs

\[ \delta m = m_{\tilde{e}_R} - m_{\tilde{\mu}_R} \lesssim 10 \text{ GeV}. \]

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Stau NLSP

\[ \tilde{\mu}_R, \tilde{\tau}_1 \]

\[ \tilde{e}_R, \tilde{\mu}_R \]

\[ \tilde{N}_i^* \]

\[ \tilde{\tau}_1^\mp \]

\[ \tilde{\tau}_1 \]

\[ \tilde{\tau}^\pm \]

\[ \tilde{G} \]
Slepton co-NLSPs corresponds to \( \delta m = m_{\tilde{e}_R} - m_{\tilde{\tau}_1} \lesssim 10 \text{ GeV} \).

Every event has at least two e, \( \mu \), or \( \tau \), plus MET.
LEP limit

LEP looked systematically for slepton NLSPs.

Some preliminary (2002) results courtesy of the LEP2 SUSY working group:

The prompt limit is $m_{\tilde{e}, \tilde{\mu}} > 96$ GeV and $m_{\tilde{\tau}} > 87$ GeV.
Opposite-sign dilepton plus MET is a less promising channel at the Tevatron and LHC because of large backgrounds from $t\bar{t}$ and dibosons ($WW$, ...).

Stronger limits can be placed on the production of heavier states that decay to the sleptons, producing extra leptons along the way,
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Electroweak production ($\tilde{W}, \tilde{H}, \tilde{l}_L$) → multileptons + MET

Tevatron has advantage for now
Sleptons at Tevatron and LHC

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1. Electroweak production ($\tilde{W}, \tilde{H}, \tilde{l}_L$) $\rightarrow$ multileptons + MET
   Tevatron has advantage for now

2. Colored production ($\tilde{g}, \tilde{q}$) $\rightarrow$ multileptons + jets + MET
   The LHC already has discovery reach

We will now consider $\tilde{l}_L$ and $\tilde{g}$ production as examples.
Wino production, $p\bar{p} \rightarrow \tilde{W}^0 \tilde{W}^\pm$
Electroweak: Wino Production

Wino production, \( p\bar{p} \rightarrow \tilde{W}^0 \tilde{W}^\pm \)

The signal is trileptons plus MET with 1 or 3 tau.

**Parameters:** \( m_{\tilde{W}}, m_{\tilde{\ell}_R}, \text{Br}(\tilde{W}^0 \rightarrow \tilde{\tau}_1) \)
Tevatron Lepton Searches

Tevatron searched for multileptons in the channels,

1. same-sign dilepton, $l^\pm l^\mp$
   CDF 1 fb$^{-1}$

2. trileptons, $lll$
   CDF 3.2 fb$^{-1}$

The backgrounds are small:

- leptonic decays of dibosons, $ZW, ZZ$

- Drell-Yan or $t\bar{t}$ plus an untagged conversion or fake lepton
Simulating the searches

No Tevatron searches have explicitly set limits on slepton NLSP. So we estimate limits by simulating the searches ourselves.

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So we estimate limits by simulating the searches ourselves.

Our procedure:

1. Pythia 6 for event generation
   ↓
2. Tuned PGS4 for crude detector sim
   ↓
3. Private Mathematica code for event analysis
Here we fix,

\[ \text{Br}(\tilde{W}^0 \to \tilde{\tau}_1) = \frac{1}{3} \]
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fixing \( m_{\tilde{l}_R} = 96 \text{ GeV} \)
For the early LHC lets consider colored production.
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Parameters:

$$\tilde{g}, \tilde{B}, \tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_1$$
Colored Production of Slepton NLSPs

For the early LHC lets consider colored production.

The signal is: $4l + \text{jets} + MET$

Parameters: $m_{\tilde{g}}, m_{\tilde{B}}, m_{\tilde{l}_R}$
Here we fix

\[ m_{\tilde{B}} = \frac{1}{2} (m_{\tilde{g}} + m_{\tilde{\tau}_R}) \]
Here we fix

\[ m_{\tilde{B}} = \frac{1}{2} (m_{\tilde{g}} + m_{\tilde{\nu}_R}) \]

LHC cuts:
- \( \geq 4l \) with \( p_T > 10 \text{ GeV} \) and \(|\eta| < 2\)
- \( E_T > 60 \text{ GeV} \)
Excess in Same-Sign?

The 1 fb$^{-1}$ CDF same-sign search saw a mild ($\sim 2\sigma$) excess of events at high MET and high leading lepton $p_T$,
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Could this excess have been produced by slepton co-NLSPs consistently with the latest trilepton limit (3.2 fb$^{-1}$)?
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Could this excess have been produced by slepton co-NLSPs consistently with the latest trilepton limit (3.2 fb$^{-1}$)?

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</tr>
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<tbody>
<tr>
<td></td>
<td>MET $&gt; 80$ GeV</td>
</tr>
<tr>
<td>wino</td>
<td>1.8</td>
</tr>
<tr>
<td>slepton$_L$ + bino</td>
<td>3.9</td>
</tr>
<tr>
<td>gluino</td>
<td>5.6</td>
</tr>
</tbody>
</table>
Neutralino NLSPs
In the MSSM, the bino, winos, and Higgsinos mix, giving 4 neutral and 2 charged mass eigenstates,

\[ (\tilde{N}_1, \tilde{N}_2, \tilde{N}_3, \tilde{N}_4) \quad \text{and} \quad (\tilde{C}_1, \tilde{C}_2) \]

General neutralino NLSPs have three possible decays,

\[ \tilde{N}_1 \rightarrow (\gamma, Z, h) + \tilde{G} \]

with branching ratios that depend on the neutralino mixing angles.

For this talk I’m going to specialize to gauge eigenstates and consider,

1. bino NLSP
2. wino NLSP
3. higgsino NLSP
bino-like
The bino decays to a $\gamma$ or $Z$ and gravitino,

\[
\Gamma(\tilde{B} \rightarrow \gamma + \tilde{G}) = \cos^2 \theta_W \left( \frac{m_{\tilde{B}}^5}{16\pi F^2} \right)
\]

\[
\Gamma(\tilde{B} \rightarrow Z + \tilde{G}) = \sin^2 \theta_W \left( 1 - \frac{m_Z^2}{m_{\tilde{B}}^2} \right)^4 \left( \frac{m_{\tilde{B}}^5}{16\pi F^2} \right)
\]
Colored production of binos is a promising scenario for discovery at the early LHC,
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Colored Production of Binos

Colored production of binos is a promising scenario for discovery at the early LHC,

\[ \tilde{g} \rightarrow \tilde{B} \rightarrow \tilde{G} \]

The discovery mode is \( \gamma \gamma + \text{jets} + \not{E}_T \).
Tevatron Limit and LHC Search

The strongest limit is by D0 with $6.3 \text{ fb}^{-1} (1008.2133)$.

For Tevatron:

$N_\gamma \geq 2$

$p_T^\gamma > 25\text{ GeV}, |\eta^\gamma| < 1.1$

$E_T > 75\text{ GeV}$

$N_{\text{data}} = 1$

$\sigma_{\text{back}} = 0.3\text{ fb}$

We will use the example LHC cuts:

$N_\gamma \geq 2$

$p_T^\gamma > 50\text{ GeV}, |\eta^\gamma| < 1.1$

$E_T > 100\text{ GeV}$

The background is dominated by QCD, which is hard to simulate. Instead I’ll consider the range $\sigma_{\text{back}} = 1 - 10\text{ fb}$. 
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**LHC:**

We will use the example LHC cuts:

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Instead I'll consider the range $\sigma_{\text{back}} = 1 - 10 \text{ fb}$. 
Tevatron Limit and LHC Search

PGS

real life (CMS: 1103.0953)

$M_{\text{bino}}$ [GeV] vs. $M_{\tilde{\chi}_1^0}$ [GeV]

CMS

$\sqrt{s} = 7$ TeV

$M_{\chi_1^0} = 50$ GeV

$M_{\chi_1^0} = 150$ GeV

$M_{\chi_1^0} = 500$ GeV

Expected for $M_{\chi_1^0} = 150$ GeV

$M(\tilde{g})$ [GeV] vs. $M(\tilde{\chi}_1^0)$ [GeV]
wino-like
The neutral wino decays to a $Z$ or $\gamma$ and gravitino,
Wino co-NLSPs

The neutral wino decays to a $Z$ or $\gamma$ and gravitino,

![Wino Branching Ratios graph]

The charged and neutral winos are nearly degenerate, so $\tilde{W}^\pm$ prefers to decay directly to the gravitino for prompt NLSP,

$$m_{\tilde{W}^\pm} - m_{\tilde{W}^0} \sim \frac{m_Z^4}{\mu^3}$$
Colored production of winos can also lead to an easy early discovery,

\[ \tilde{g} \rightarrow \tilde{W}^{0,\pm} \rightarrow \tilde{G} \]
Colored production of winos can also lead to an easy early discovery,

There's also a contribution from direct wino production, $pp \rightarrow \tilde{W}^0 \tilde{W}^\pm$.

Promising channels include $(\gamma l^\pm, \gamma\gamma, l^\pm l^\pm)$ + jets + $\not{E_T}$.
Colored production of winos can also lead to an easy early discovery,

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Promising channels include \( (\gamma l^\pm, \gamma \gamma, l^\pm l^\pm) + jets + E_T \).
Tevatron Limits and LHC Reach

Tevatron:

1. $\gamma\gamma$ from above

2. $D_0$ jets + $E_T$, 2.1 fb$^{-1}$
   - 2,3,4 jet channels requiring
     $E_T > 100, 175, 225$ GeV

3. CDF $l + \gamma$ search, 0.93 fb$^{-1}$
   - Increase $E_T$ cut from 25 to 50 GeV
Tevatron Limits and LHC Reach

**Tevatron:**

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   increase $E_T$ cut from 25 to 50 GeV

**LHC:**

1. $\gamma \gamma$ from above

2. $l + \gamma + E_T$

   $p_T^l > 25$ GeV and $p_T^\gamma > 80$ GeV
   
   $E_T > 100$ GeV
   
   $m_T > 100$ GeV

3. CMS $\alpha_T$ search, 35 pb$^{-1}$
We used Madgraph to simulate the $l\gamma$ backgrounds: $W\gamma$, $t\bar{t}\gamma$, $t\bar{t}$ (± fake $e\rightarrow \gamma$). Their sum is about $\sigma \sim 1.4$ fb.
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Their sum is about $\sigma \sim 1.4$ fb.
The Rutgers CMS group has searched in the $l + \gamma$ channel, motivated by GMSB with wino co-NLSPs.
MET and $\alpha_T$

The CMS search requires,

$$\alpha_T = \frac{E_{Tj}^2}{M_T} > 0.55$$

Roughly speaking, this amounts to requiring $E_T \gtrsim 250$ GeV.

In our parameter spaces, this favors heavier winos.

The best sensitivity is for $m_{\tilde{W}} \sim m_{\tilde{g}}$, where the jets come entirely from $Z$ and $W$. 
higgsino-like
The lightest neutral Higgsino, $\tilde{H}_1$, decays to a $Z$ or $h$.

The branching fraction depends on $\tan \beta$ and $\text{sign}(\mu)$.

I will highlight a few interesting regimes:

1. $Z$-rich, $\tan \beta \sim 2$, $\mu > 0$
2. $h$-rich, $\tan \beta \sim 2$, $\mu < 0$
3. $Z/h$-mixed, moderate $\tan \beta \sim 20$

Similarly to above, we consider a simplified model with just a gluino and a Higgsino.
Tevatron:

1. CDF search with 3 fb$^{-1}$ for 
   \((Z \rightarrow e^+e^-) + (W \rightarrow jj) + \not{E}_T,\)

2. \(D0\) jets + \(\not{E}_T\), 2.1 fb$^{-1}$

LHC:
Tevatron Limit and LHC Reach

**Tevatron:**

1. CDF search with 3 fb\(^{-1}\) for 
   \((Z \rightarrow e^+e^-) + (W \rightarrow jj) + E_T,\)

2. D0 jets + \(E_T\), 2.1 fb\(^{-1}\)

**LHC:**

- \(Z \rightarrow l^+l^- + E_T\)
  - \(p_T^{l_i} > 20\) GeV
  - \(m_{ll} \in (85, 95)\) GeV
  - \(H_T > 100\) GeV
  - \(E_T > 100\) GeV

- \((Z \rightarrow l^+l^-)^2 + E_T\)

- CMS \(\alpha_T\)
We estimate the biggest backgrounds for $Z \rightarrow l^+ l^-$ to be: $t \bar{t}$, $\sigma \sim 20$ fb for dibosons, $\sigma \sim 7$ fb.
We estimate the biggest backgrounds for $Z \rightarrow l^+ l^- + E_T$ to be:

$t\bar{t}$, $\sigma \sim 20$ fb

dibosons, $\sigma \sim 7$ fb.
Final states with b-jets are interesting for higgsinos that decay into higgses,

It’s possible that the higgs could be discovered, first, in SUSY cascades!
Another interesting possibility is if the NLSP is a higgsino-bino mixture.

Can be constrained using the final state, $\gamma + 2b + \not{E}_T$.
Take Away Points

- Gauge mediation is a promising scenario with distinctive collider pheno at the Tevatron and LHC

- MGM is the mSUGRA of Gauge Mediation (i.e. there’s a much bigger space of interesting possibilities!)

- We suggest using simplified models by choosing parameters at the weak scale and using spectra with as few light particles as possible

- Tevatron still wins for EW production, and there remains significant reach for discovery in multilepton channels.

- The LHC has covered new ground for colored production, and will soon cover a lot more!
Backup Slides
Cross-Sections

Gluino

\[ \sigma \text{ [fb]} \]

Wino

\[ \tilde{W}^0 + \tilde{W}^+ \]

\[ \tilde{W}^0 + \tilde{W}^- \]

\[ \tilde{W}^+ + \tilde{W}^- \]

All Wino

Higgsino

\[ \tilde{H}^{0,1,2} + \tilde{H}^+ \]

\[ \tilde{H}^{0,1,2} + \tilde{H}^- \]

\[ \tilde{H}^+ + \tilde{H}^- \]

\[ \tilde{H}^{0,1,2} + \tilde{H}^{0,1,2} \]

All Higgsino
Other Bino Spaces

- $M_{\text{wino}}$ [GeV]
- $M_{\text{gluino}}$ [GeV]
- $D_0 = 6.3\ fb^{-1}\ reach$
- $M_{\text{bino}} = 300\ GeV$

- $1\ fb^{-1}$
- $10\ fb$
- $100\ fb$
- $0.1\ fb$

- $M_{\text{squarks}}$ [GeV]
CMS Wino Exclusion

CMS preliminary, 35 pb$^{-1}$, $\sqrt{s} = 7$ TeV

observed 95% CL limit

$M_{\text{colored}}$ (GeV/c$^2$) vs. $M_{\text{Wino}}$ (GeV/c$^2$)

gluino NLSP
The simplest possibility is a model with only the NLSP (and gravitino).

For example gluino NLSP, parameterized by $m_{\tilde{g}}$ and $\Gamma_{\tilde{g}}$.

Depending on the lifetime, the signal is prompt dijet+MET or R-hadron production.
Sometimes it’s interesting to consider production of a state heavier than the NLSP,
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for a large enough cross-section,
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or because particles produced in a cascade are necessary for discovery,
Sometimes it’s interesting to consider production of a state heavier than the NLSP, for a large enough cross-section, or because particles produced in a cascade are necessary for discovery.

We’ve gotten a lot of milage in signature space by considering models with only 1 or 2 light sparticles!
Same-sign dileptons were searched for by CDF with 1 fb$^{-1}$.

The leptons cuts:

\[
\begin{align*}
    p_T^1, p_T^2 &> 20, 10 \text{ GeV} \\
    |\eta_{1,2} | &< 1 \\
    m_{12} &> 25 \text{ GeV}
\end{align*}
\]

The cuts are inclusive, and pretty soft, but CDF shows the MET distribution of data and background.

So its easy to infer the limit with a harder MET cut, $E_T > 60 \text{ GeV}$.
Trileptons were searched for by CDF with 3.2 fb\(^{-1}\).

The lepton cuts:

<table>
<thead>
<tr>
<th>Cut</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(III)</td>
<td>(p_T^1, p_T^2, p_T^3 &gt; 15, 5, 5) GeV</td>
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<tr>
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<td>(p_T^1, p_T^2, p_T^t &gt; 15, 5, 10) GeV</td>
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<td>(E_T &gt; 20) GeV</td>
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Trileptons were searched for by CDF with $3.2 \text{ fb}^{-1}$.

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<td>$l/T$</td>
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CDF optimized for an mSUGRA signal with exactly 3 leptons by including a number of non-inclusive vetoes,

- veto $\Sigma Q = \pm 3$
- jet veto
- 4th lepton veto
- $Z$ veto

The result is a low efficiency for GMSB-type signals.
Trileptons were searched for by CDF with $3.2 \text{ fb}^{-1}$.

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The result is a low efficiency for GMSB-type signals.

It would have been better to relax the vetoes and take advantage of the harder $p_T$ and MET spectra of GMSB.
Electroweak: take II

MGM-like spectrum: left-handed slepton production

Parameters:

\[ \tilde{e}_L, \tilde{\mu}_L, \tilde{\tau}_2 \]

\[ \tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_1, \tilde{\nu}_i, \tilde{B} \]
MGM-like spectrum: left-handed slepton production
MGM-like spectrum: left-handed slepton production

Up to six leptons per event.

Parameters: $m_{\tilde{l}_L}$, $m_{\tilde{B}}$, $m_{\tilde{l}_R}$
Here we fix,

\[
\text{Br}(\tilde{W}^0 \rightarrow \tilde{\tau}_1) = 1/3
\]

\[
m_{\tilde{B}} = \frac{1}{2}(m_{\tilde{\tau}_L} + m_{\tilde{\tau}_R})
\]