# Discovering Gauge Mediation with Leptons/Photons at the Tevatron or LHC

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Princeton University

March 16, 2011

JTR and David Shih, **1009.1665, 11(03-04).xxxx**

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

**Tevatron**

**LHC**

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.

# Talk Outline

# Intro:
# Simplified Models of Gauge Mediation

# GMSB

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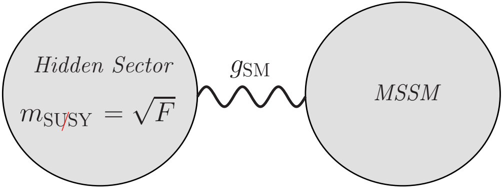


Gauge mediation has the virtues:

1. flavor blind
2. calculable

# Gravitino and collider pheno

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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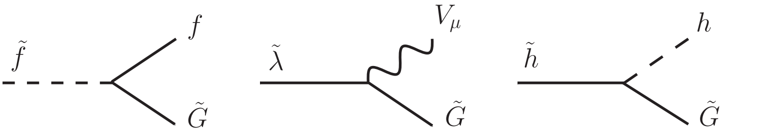
The identity of the NLSP and its lifetime define the collider physics.



# MGM

The SUSY spectrum depends on the model.

All experimental searches (pre-2011) have focused on one model:

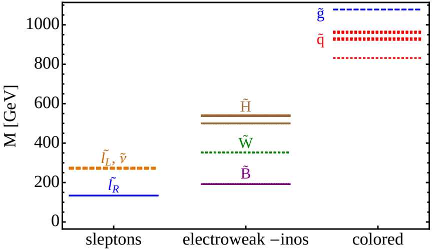
Minimal Gauge Mediation (*Dine, Nelson, Nir, Shirman,...*)

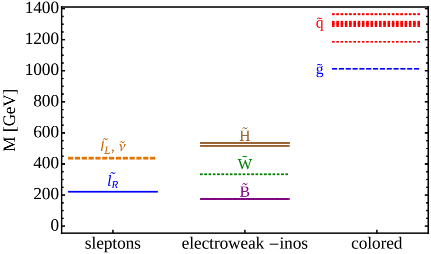
$$W = X\,\phi_i\bar{\phi}_i$$

- $\phi_i$ 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

# MGM

In MGM the spectrum pretty much always looks like,




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

# Beyond MGM

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- $m_Q$, $m_U$, $m_D$, $m_L$, $m_E$ are subject to sum rules

$$\begin{aligned} \mathrm{Tr}\, Y\, m^2 &= m_Q^2 - 2m_U^2 + m_D^2 - m_L^2 + m_E^2 = 0 \\ \mathrm{Tr}\, (B-L)\, m^2 &= 2m_Q^2 - m_U^2 - m_D^2 - 2m_L^2 + m_E^2 = 0 \end{aligned}$$

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\end{aligned}
$$

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 $g_{SM} \to 0$.

# NLSP Zoology

The possible NLSPs and signals in MGM are:

| NLSP | Prompt | Displaced |
|---|---|---|
| slepton | $e,\mu,\tau$ | displaced vertices, kinked tracks, CHAMPS, ... |
| neutralino | $\gamma,Z$ | non-pointing photons, displaced leptons... |

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| neutralino/ chargino | $\gamma, Z, W, h$ | non-pointing photons, displaced leptons... |
| squark gluino | jets | displaced vertices, R-hadrons |
| sneutrino | multileptons | |

The above signals include $\not{E}_{\mathrm{T}}$ carried by the gravitinos.

# NLSP Zoology

Some recent/ongoing model-independent studies:

| NLSP | Prompt | Displaced |
|---|---|---|
| slepton | *JTR & Shih* | |
| neutralino/ chargino | *Meade, Reece, Shih* *JTR, Shih* | *Meade, Reece, Shih* |
| squark gluino | | |
| sneutrino | *Katz, Tweedie* | |

This signature space was also surveyed by the SUSY working group before run II of the Tevatron.

# Our Goals

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

# Simplified Models

For a given signal we recommend,

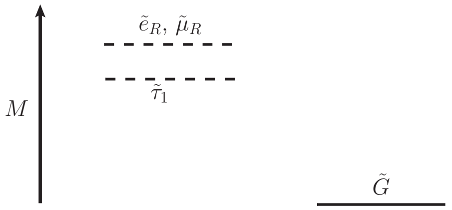
- choose spectra with as few light particles as possible, and decouple everything else ($m_{else} \gtrsim$ TeV).
- specify soft parameters at the weak scale, instead of using parameters of a UV theory
- these are *simplified models*, see also,
  - *Dube, Glatzer, Somalwar, Sood, Thomas*
  - *Alwall, 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



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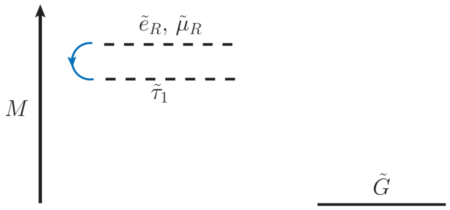
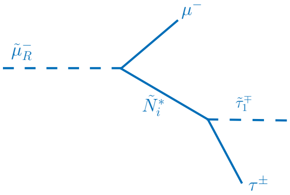



## Stau NLSP



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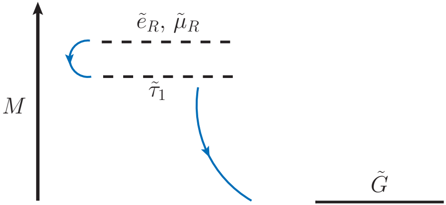


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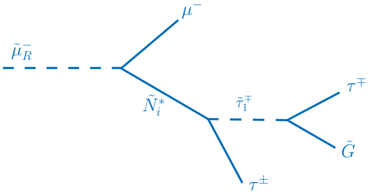

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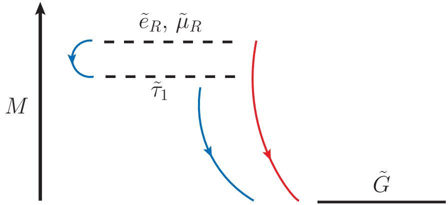
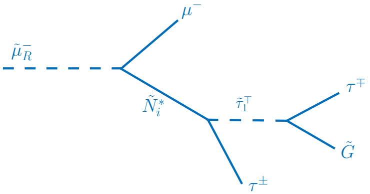
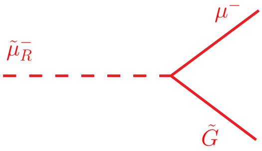



Stau NLSP




Slepton co-NLSP

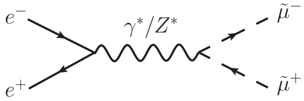



Slepton co-NLSP corresponds to $\delta m = m_{\tilde{e}_R} - m_{\tilde{\tau}_1} \lesssim 10$ GeV.

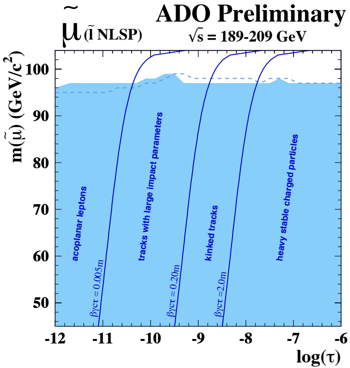
Every event has at least two $e, \mu$, or $\tau$, plus MET.

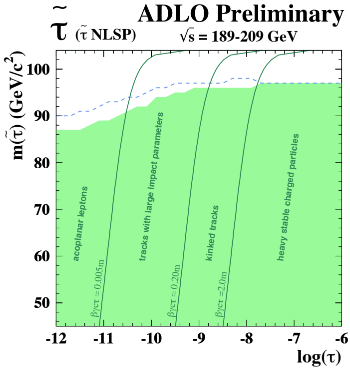
# LEP limit

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.

# Sleptons at Tevatron and LHC

- 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 ($WW$, ...).

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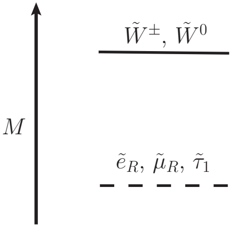
  2. Colored production ($\tilde{g}$, $\tilde{q}$) $\rightarrow$ multileptons + jets + MET
     The LHC already has discovery reach

We will now consider $\tilde{l}_L$ and $\tilde{g}$ production as examples.

# Electroweak: Wino Production

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



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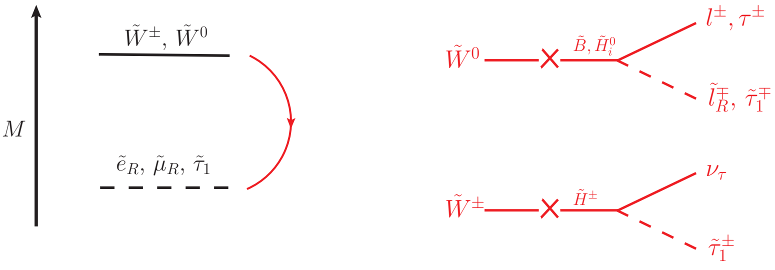


The signal is trileptons plus MET with 1 or 3 tau.

**Parameters**: $m_{\tilde{W}}$, $m_{\tilde{l}_R}$, $\mathrm{Br}(\tilde{W}^0 \to \tilde{\tau}_1)$

# Tevatron Lepton Searches

Tevatron searched for multileptons in the channels,

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

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

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

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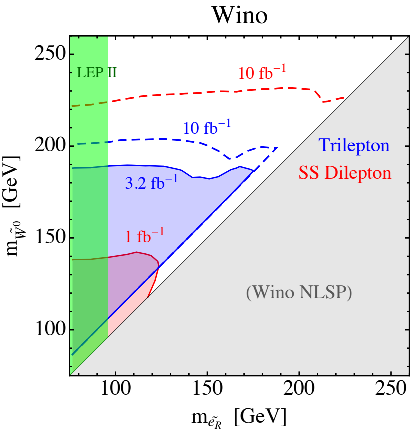
3. private Mathematica code for event analysis

# Tevatron Limits

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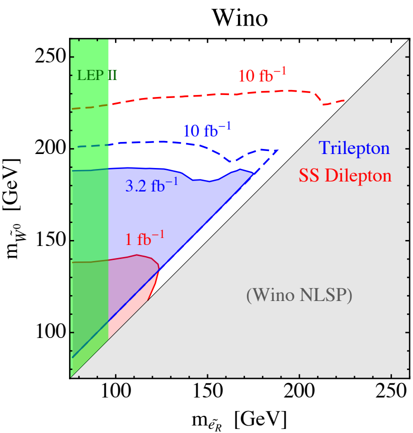


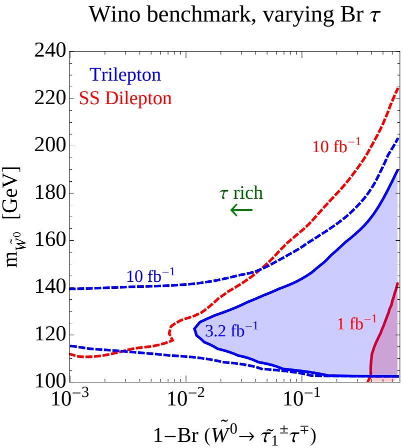


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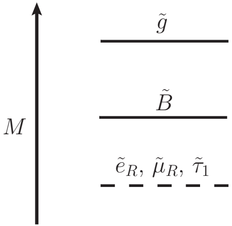
fixing $m_{\tilde{l}_R} = 96$ GeV

# Colored Production of Slepton NLSPs

For the early LHC lets consider colored production.



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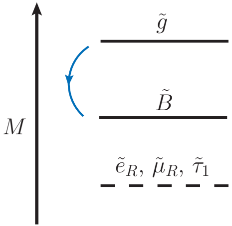


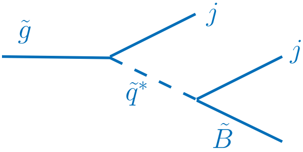

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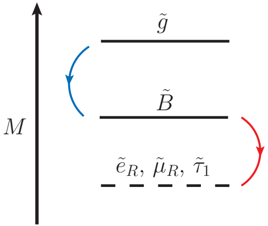
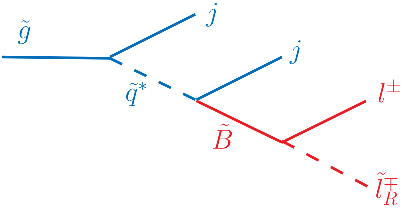
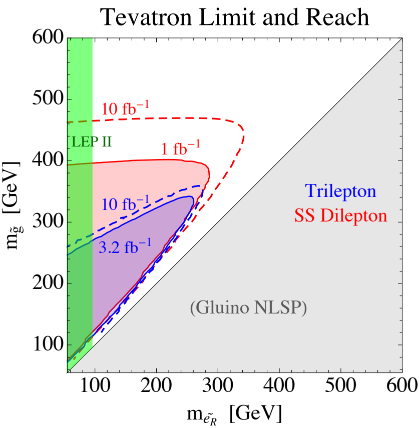



The signal is: $4l + \text{jets} + MET$

**Parameters**: $m_{\tilde{g}},\ m_{\tilde{B}},\ m_{\tilde{l}_R}$

# Tevatron Limit and Early LHC Reach

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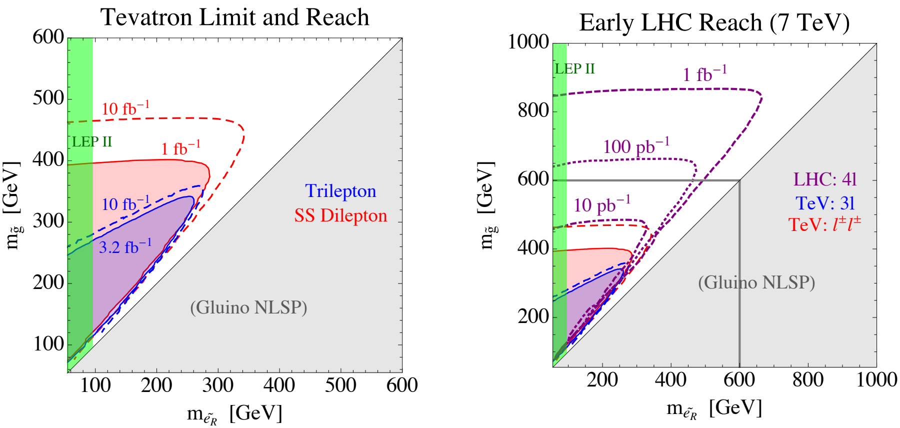


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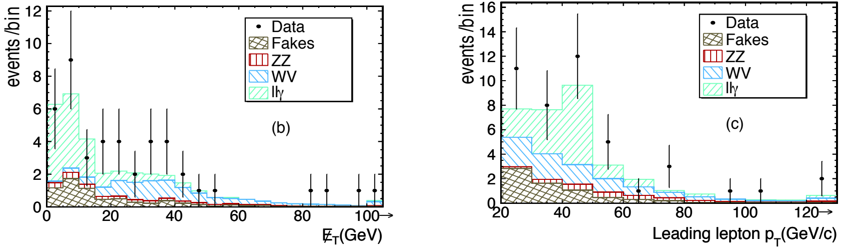
LHC cuts:

- $\geq 4l$ with $p_T > 10$ GeV and $|\eta| < 2$
- $\not{E}_T > 60$ 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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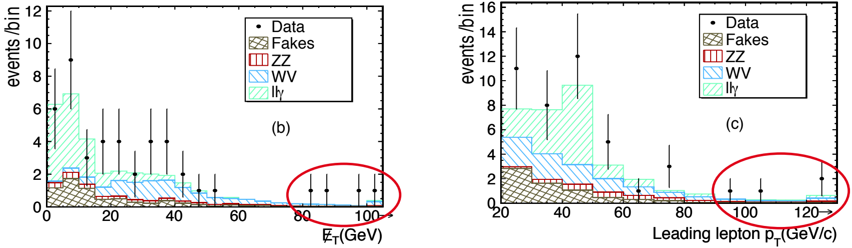


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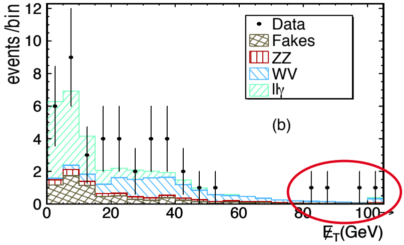


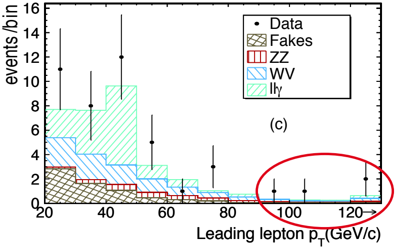


Could this excess have been produced by slepton co-NLSPs consistently with the latest trilepton limit (3.2 $\text{fb}^{-1}$)?

| channel | Number of Events (1 $\text{fb}^{-1}$) | |
|---|---|---|
| | MET $>$ 80 GeV | $p_T^1 >$ 90 GeV |
| wino | 1.8 | 0.9 |
| slepton$_L$ + bino | 3.9 | 2.9 |
| gluino | 5.6 | 6.8 |

# Neutralino NLSPs

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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,

$$\tilde{N}_1 \to (\gamma, Z, h) + \tilde{G}$$

with branching ratios that depend on the neutralino mixing angles.

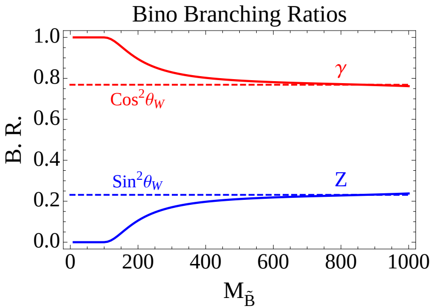
For this talk I'm going to specialize to gauge eigenstates and consider,

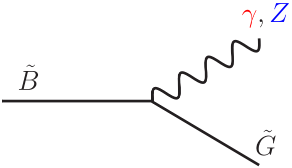
1. bino NLSP
2. wino NLSP
3. higgsino NLSP

bino-like

# Bino NLSP

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



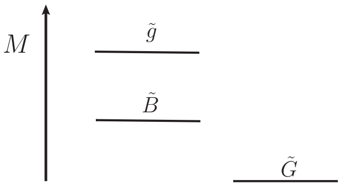




$$\Gamma(\tilde{B} \to \gamma + \tilde{G}) = \cos^2\theta_W \left(\frac{m_{\tilde{B}}^5}{16\pi F^2}\right)$$

$$\Gamma(\tilde{B} \to Z + \tilde{G}) = \sin^2\theta_W \left(1 - \frac{m_Z^2}{m_{\tilde{B}}^2}\right)^4 \left(\frac{m_{\tilde{B}}^5}{16\pi F^2}\right)$$

# Colored Production of Binos

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



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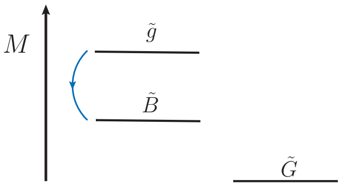


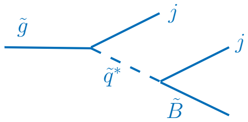

# Colored Production of Binos

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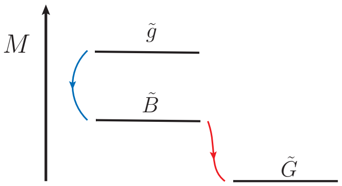
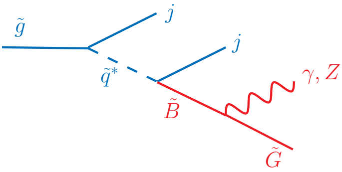
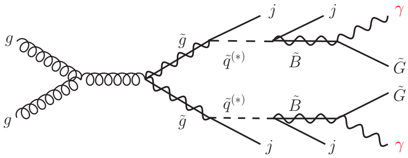



The discovery mode is $\gamma\gamma + jets + \not{E}_{\mathrm{T}}$.



## Tevatron:

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

$$N_\gamma \geq 2$$
$$p_T^\gamma > 25 \text{ GeV}, \; |\eta^\gamma| < 1.1$$
$$\not{E}_{\mathrm{T}} > 75 \text{ GeV}$$

$$N_{\mathrm{data}} = 1$$
$$\sigma_{\mathrm{back}} = 0.3 \text{ fb}$$

# Tevatron Limit and LHC Search

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$$N_{\rm data}{=}1$$
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## LHC:

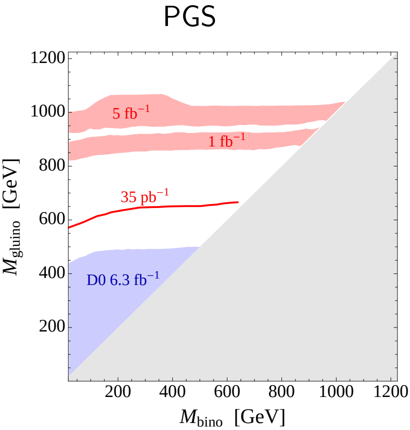
We will use the example LHC cuts:

$$N_\gamma \geq 2$$
$$p_T^\gamma > 50 \text{ GeV}, \ |\eta^\gamma| < 1.5$$
$$\not{E}_{\rm T} > 100 \text{ GeV}$$

The background is dominated by QCD, which is hard to simulate.

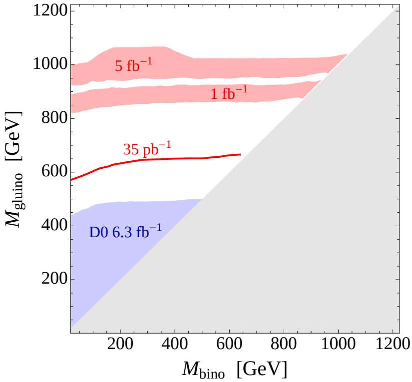
Instead I'll consider the range $\sigma_{\rm back} = 1 - 10$ fb.

# Tevatron Limit and LHC Search

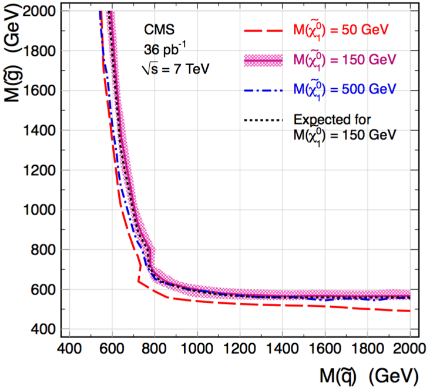


# Tevatron Limit and LHC Search

PGS



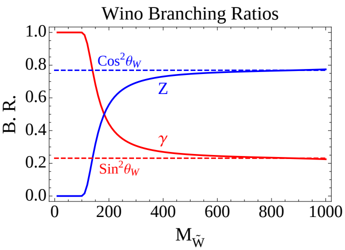

real life (CMS: **1103.0953**)

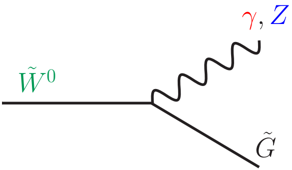


wino-like

# Wino co-NLSPs

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



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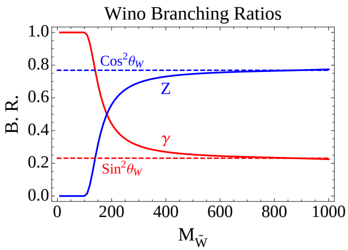
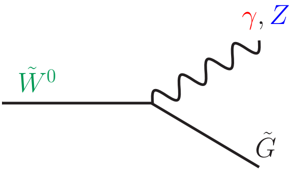
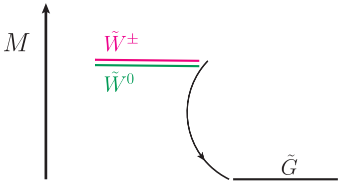
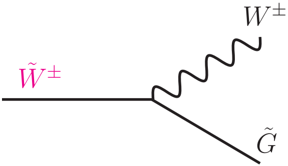



The charged and neutral winos are nearly degenerate, so $\tilde{W}^{\pm}$ prefers to decay directly to the gravitino for prompt NLSP,

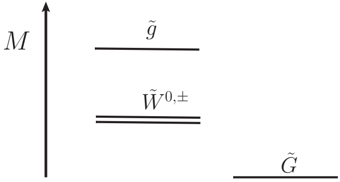


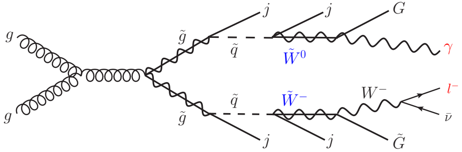




$$m_{\tilde{W}^{\pm}} - m_{\tilde{W}^0} \sim m_Z^4/\mu^3$$

# Colored Production of Winos

Colored production of winos can also lead to an easy early discovery,



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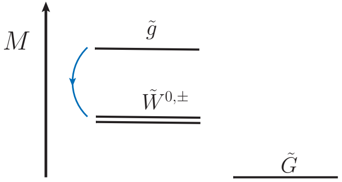


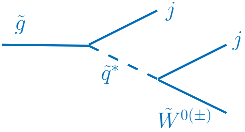


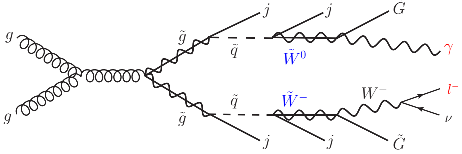

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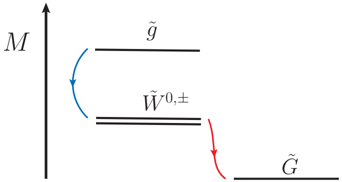
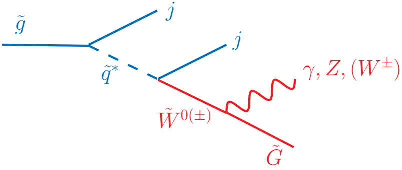
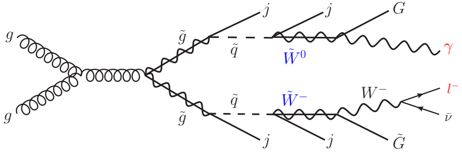



There's also a contribution from direct wino production, $pp \to \tilde{W}^0 \tilde{W}^{\pm}$.

Promising channels include $(\gamma l^{\pm}, \gamma\gamma, l^{\pm} l^{\pm}) + jets + \not{E}_{\mathrm{T}}$.



## Tevatron:

1. $\gamma\gamma$ from above
2. $D0$ jets $+ \not{E}_{\mathrm{T}}$, 2.1 $\mathrm{fb}^{-1}$

   2,3,4 jet channels requiring $\not{E}_{\mathrm{T}} > 100, 175, 225$ GeV
3. CDF $l + \gamma$ search, 0.93 $\mathrm{fb}^{-1}$

   increase $\not{E}_{\mathrm{T}}$ cut from 25 to 50 GeV

# Tevatron Limits and LHC Reach

## Tevatron:

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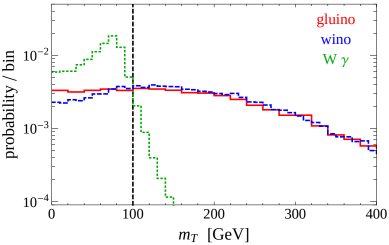
3. CDF $l + \gamma$ search, 0.93 fb$^{-1}$

   increase $\not{E}_T$ cut from 25 to 50 GeV

## LHC:

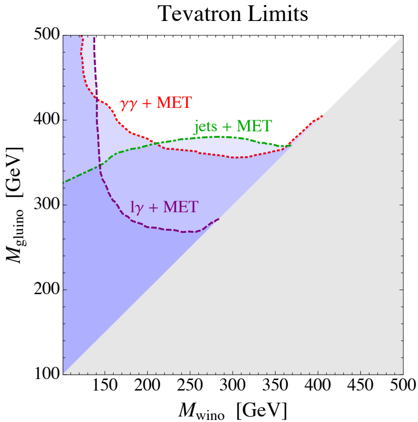
1. $\gamma\gamma$ from above
2. $l + \gamma + \not{E}_T$

$$p_T^l > 25 \text{ GeV and } p_T^\gamma > 80 \text{ GeV}$$
$$\not{E}_T > 100 \text{ GeV}$$
$$m_T > 100 \text{ GeV}$$

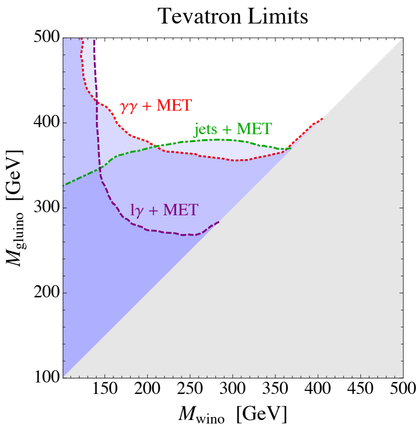


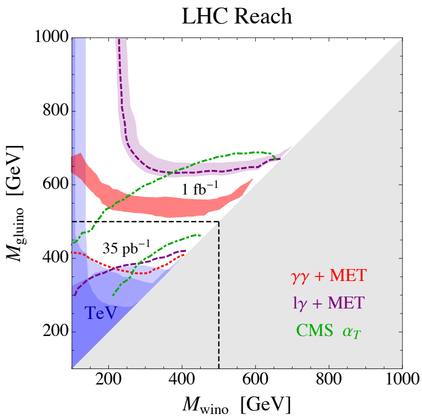

3. CMS $\alpha_T$ search, 35 pb$^{-1}$

# Tevatron Limit and LHC Search



# Tevatron Limit and LHC Search



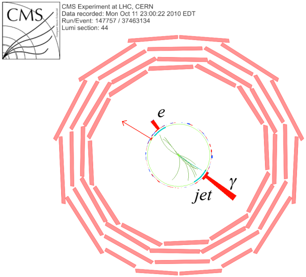



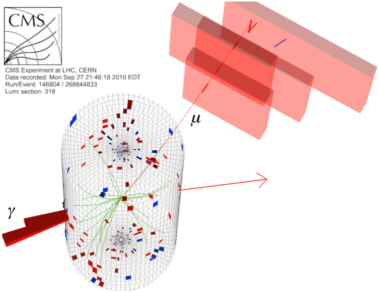

We used Madgraph to simulate the $l\gamma$ backgrounds:
$W\gamma$, $t\bar{t}\gamma$, $t\bar{t}$ (+ fake $e \to \gamma$).

Their sum is about $\sigma \sim 1.4$ fb.

# CMS $l + \gamma$ search

The Rutgers CMS group has searched in the $l + \gamma$ channel, motivated by GMSB with wino co-NLSPs.



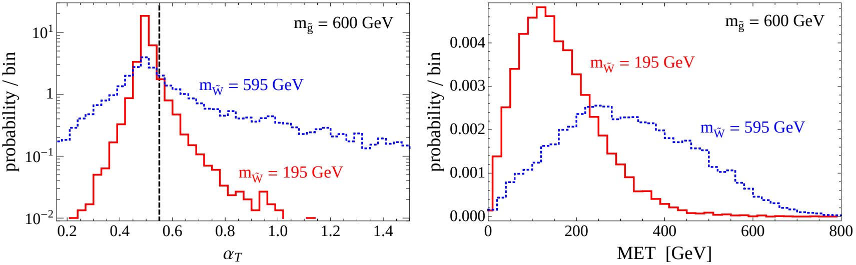



# MET and $\alpha_T$

The CMS search requires,

$$\alpha_T = \frac{E_T^{j_2}}{M_T} > 0.55$$

Roughly speaking, this amounts to requiring $\not{E}_T \gtrsim 250$ GeV.



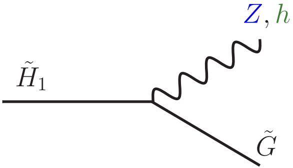

In our parameter spaces, this favors heavier winos.

The best sensitivity is for $m_{\tilde{W}} \sim m_{\tilde{g}}$, where the jets come entirely from $Z$ and $W$.

# higgsino-like

# Higgsino NLSP

The lightest neutral Higgsino, $\tilde{H}_1$, decays to a $Z$ or $h$.




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

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 $\text{fb}^{-1}$ for $(Z \to e^+e^-) + (W \to jj) + \not{E}_{\mathrm{T}}$,

2. $D0$ jets + $\not{E}_{\mathrm{T}}$, 2.1 $\text{fb}^{-1}$

# Tevatron Limit and LHC Reach

## Tevatron:

1. CDF search with 3 fb$^{-1}$ for $(Z \to e^+e^-) + (W \to jj) + \not{E}_{\mathrm{T}}$,
2. $D0$ jets $+ \not{E}_{\mathrm{T}}$, 2.1 fb$^{-1}$

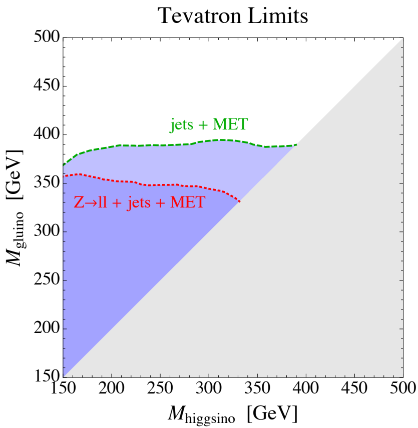
## LHC:

- $Z \to l^+l^- + \not{E}_{\mathrm{T}}$

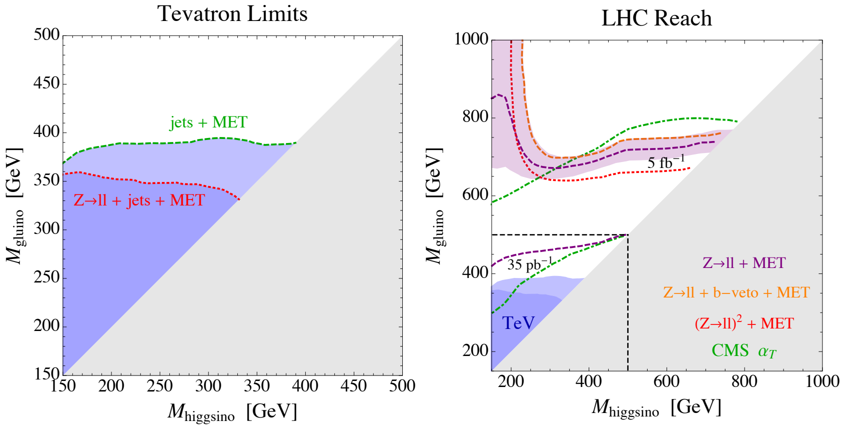
$$\boxed{\begin{array}{c} p_T^{l_i} > 20 \text{ GeV} \\ m_{ll} \in (85, 95) \text{ GeV} \\ H_T > 100 \text{ GeV} \\ \not{E}_{\mathrm{T}} > 100 \text{ GeV} \end{array}}$$

- $(Z \to l^+l^-)^2 + \not{E}_{\mathrm{T}}$
- CMS $\alpha_T$

# Tevatron Limit and LHC Reach



# Tevatron Limit and LHC Reach



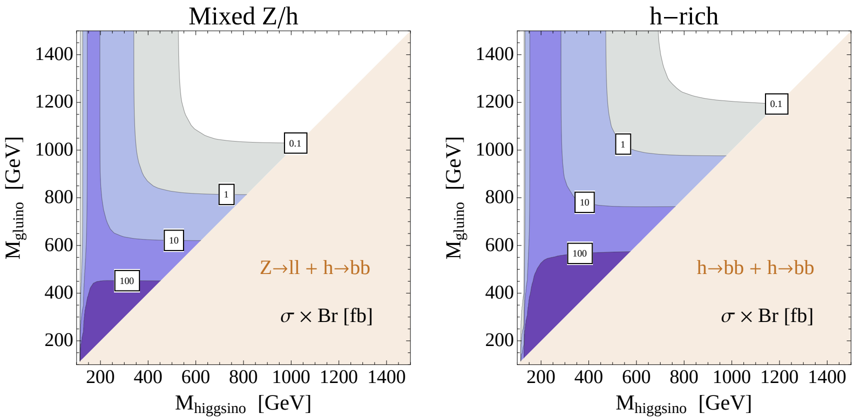

We estimate the biggest backgrounds for $Z \to l^+l^- + \not{E}_T$ to be:

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

dibosons, $\sigma \sim 7$ fb.

# Other Higgsino Varieties

Final states with b-jets are interesting for higgsinos that decay into higgses,

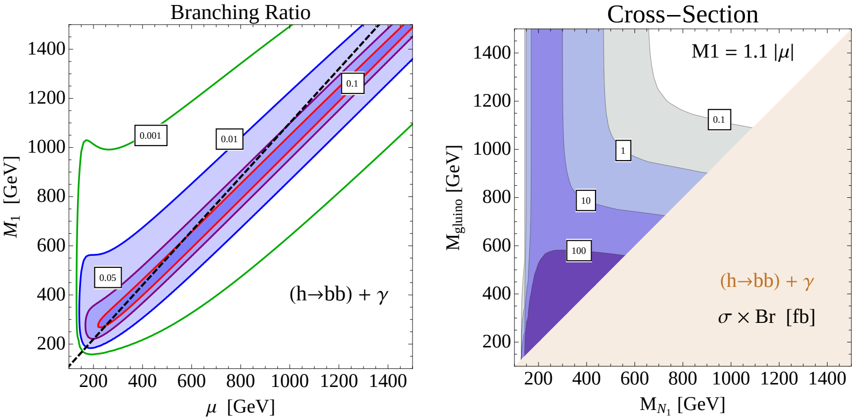



It's possible that the higgs could be discovered, first, in SUSY cascades!

# Higgsino-Bino Admixture

Another interesting possibility is if the NLSP is a higgsino-bino mixture.

Can be constrained using the final state, $\gamma + 2b + \not{E}_{\mathrm{T}}$,

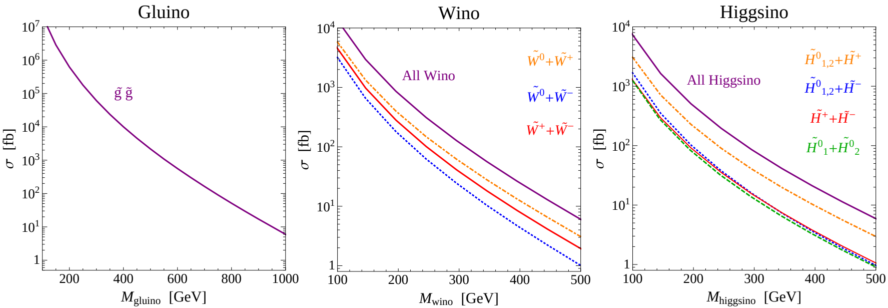


# Take Away Points

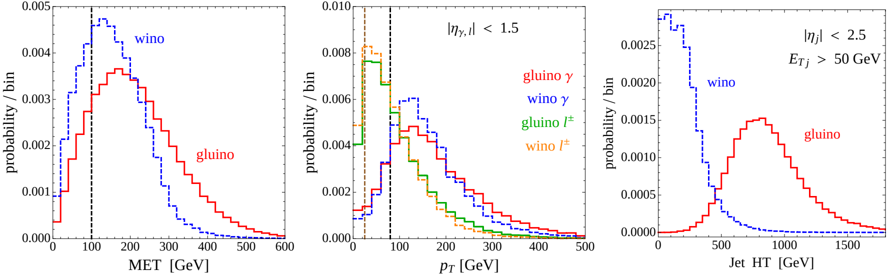
- Gauge mediation is a promising scenario with distinctive collider pheno at the Tevatron and LHC
- MGM is the mSUGRA of Gauge Mediation
(i.e. there's a much bigger space of interesting possibilities!)
- We suggest using *simplified models* by choosing parameters at the weak scale and using spectra with 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

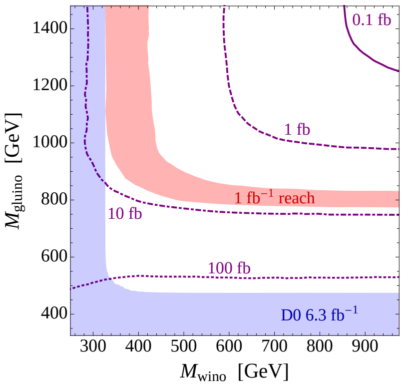


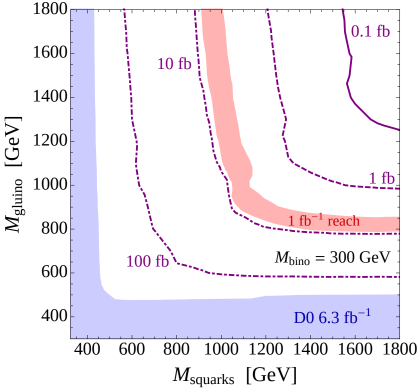
# Kinematics



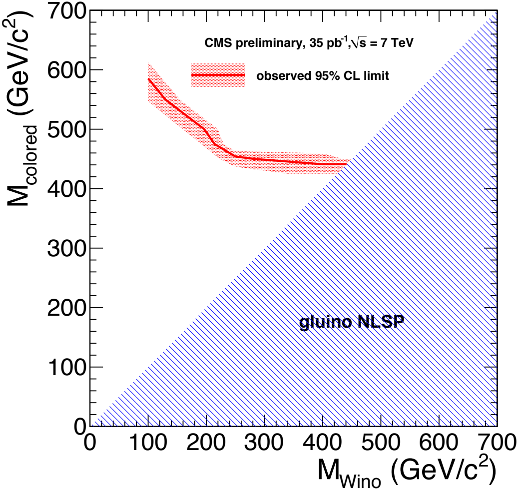
probability / bin
wino
gluino
MET [GeV]
$|\eta_{\gamma,l}| < 1.5$
gluino $\gamma$
wino $\gamma$
gluino $l^{\pm}$
wino $l^{\pm}$
$p_T$ [GeV]
$|\eta_j| < 2.5$
$E_{Tj} > 50$ GeV
Jet HT [GeV]

# Other Bino Spaces



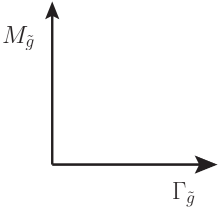
# CMS Wino Exclusion

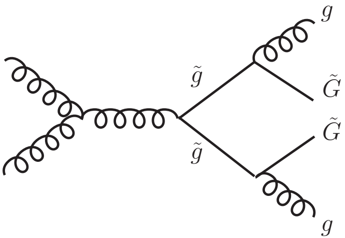


# Simplest simplified model

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.

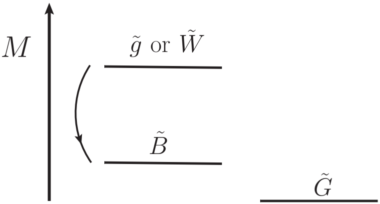
# A little less-simple simplified models

Sometimes it's interesting to consider production of a state heavier than the NLSP,

# A little less-simple simplified models

Sometimes it's interesting to consider production of a state heavier than the NLSP,

for a large enough cross-section,



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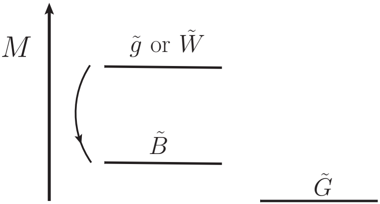
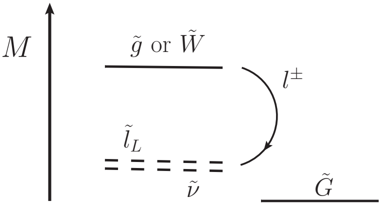



or because particles produced in a cascade are necessary for discovery,



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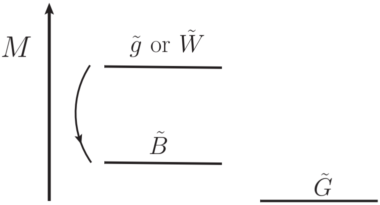


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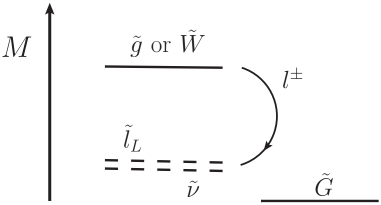



We've gotten a lot of milage in signature space by considering models with only 1 or 2 light sparticles!

# The Tevatron Searches

Same-sign dileptons were searched for by CDF with 1 $\mathrm{fb}^{-1}$.

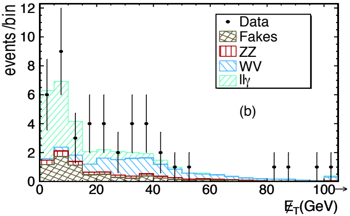
PRL **98,** 221803 (2007) PHYSICAL REVIEW LETTERS week ending 1 JUNE 2007

**Inclusive Search for New Physics with Like-Sign Dilepton Events in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV**

A. Abulencia,[24] J. Adelman,[13] T. Affolder,[10] T. Akimoto,[56] M. G. Albrow,[17] D. Ambrose,[17] S. Amerio,[44] D. Amidei,[35] A. Anastassov,[53] K. Anikeev,[17] A. Annovi,[19] J. Antos,[14] M. Aoki,[56] G. Apollinari,[17] J.-F. Arguin,[34] T. Arisawa,[58]

the lepton cuts:

$$p_T^1, p_T^2 > 20, 10 \text{ GeV}$$
$$|\eta_{1,2}| < 1$$
$$m_{12} > 25 \text{ GeV}$$




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, $\not{E}_\mathrm{T} > 60$ GeV.

# Trilepton Search Details

Trileptons were searched for by CDF with 3.2 $fb^{-1}$.

The lepton cuts:

| | |
|---|---|
| *lll* | $p_T^1, p_T^2, p_T^3 > 15, 5, 5$ GeV |
| *llT* | $p_T^1, p_T^2, p_T^t > 15, 5, 10$ GeV |
| $\lvert\eta\rvert \lesssim 1$ | |
| $\not{E}_{\mathrm{T}} > 20$ GeV | |

# Trilepton Search Details

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| | |
|---|---|
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| $llT$ | $p_T^1, p_T^2, p_T^t > 15, 5, 10$ GeV |
| $\lvert\eta\rvert \lesssim 1$ | |
| $\not{E}_\mathrm{T} > 20$ GeV | |

CDF optimized for an mSUGRA signal with exactly 3 leptons by including a number of non-inclusive vetoes,

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

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

# Trilepton Search Details

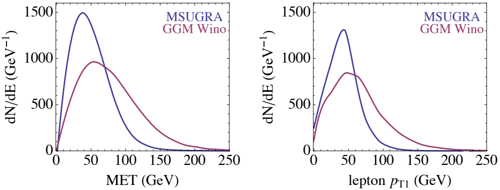
Trileptons were searched for by CDF with 3.2 fb$^{-1}$.

The lepton cuts:

| | |
|---|---|
| $lll$ | $p_T^1, p_T^2, p_T^3 > 15, 5, 5$ GeV |
| $llT$ | $p_T^1, p_T^2, p_T^t > 15, 5, 10$ GeV |
| $\lvert\eta\rvert \lesssim 1$ | |
| $\not{E}_\mathrm{T} > 20$ GeV | |

CDF optimized for an mSUGRA signal with exactly 3 leptons by including a number of non-inclusive vetoes,

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

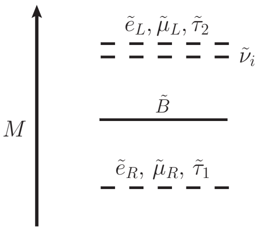


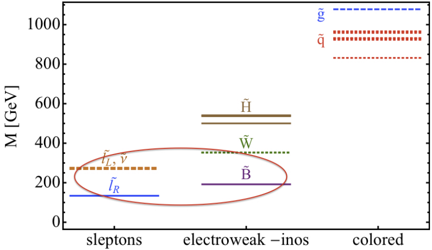

The result is a low efficiency for GMSB-type signals.

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

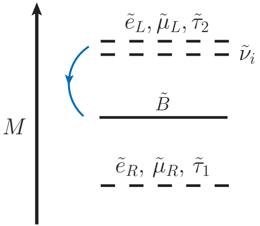
## MGM-like spectrum: left-handed slepton production

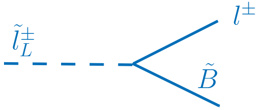


# Electroweak: take II

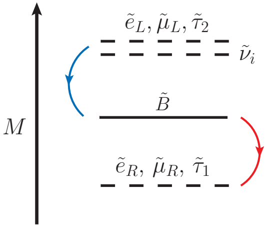
MGM-like spectrum: left-handed slepton production

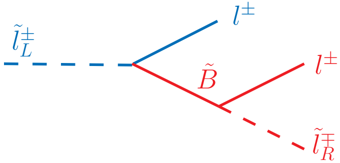


# Electroweak: take II

MGM-like spectrum: left-handed slepton production

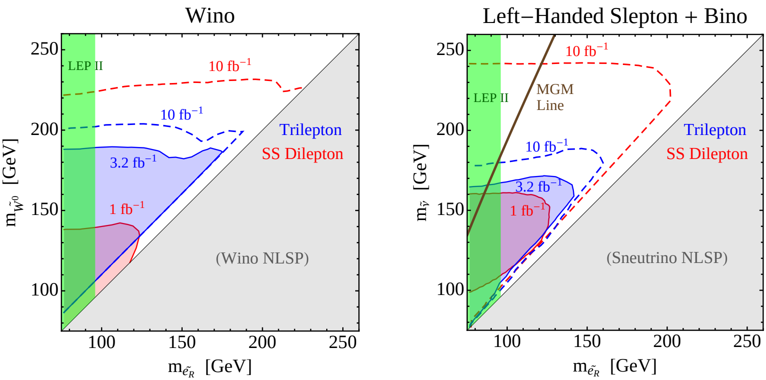



Up to six leptons per event.

**Parameters**: $m_{\tilde{l}_L}$, $m_{\tilde{B}}$, $m_{\tilde{l}_R}$

# Tevatron Limits




Here we fix,

$$\mathrm{Br}(\tilde{W}^0 \to \tilde{\tau}_1) = 1/3 \qquad\qquad m_{\tilde{B}} = \frac{1}{2}(m_{\tilde{l}_L} + m_{\tilde{l}_R})$$