Higgsino NLSPs at the Tevatron and the LHC

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Beyond the Standard Model : from the Tevatron to the LHC
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Work in progress with Patrick Meade and David Shih

Motivation

In this talk I'll be discussing some signatures of Higgsino NLSP in gauge mediation. I'm choosing a few (preliminary, incomplete) elements of an ongoing project to discuss. Another goal of the talk is to look at some capabilities of detectors that we might not often think about.

I'll also briefly review some facts about GMSB, and mention some of the Tevatron searches that place limits on minimal GMSB (and what they can tell us about non-minimal GMSB).

Basic Gauge Mediation Phenomenology

Some SUSY-breaking hidden sector has the Standard Model gauge group as a global symmetry, and the MSSM weakly gauges this global symmetry, with no other visible/hidden sector couplings (ignoring $\mu/B\mu$.) **Inherently flavor-respecting.**

Key feature for colliders: light gravitino LSP. Because the gravitino mass measures the size of gravity-mediated (Planck-suppressed) SUSY breaking, a GMSB solution to the flavor problem demands a light gravitino.

Minimal gauge mediation adds some messenger fields in the $\mathbf{5}$ and $\bar{\mathbf{5}}$ of SU(5). It predicts either a bino or stau NLSP.

Why Revisit Gauge Mediation?

There has been a revival of interest in building models of gauge mediation, in part due to the work of ISS showing that metastable SUSY-breaking vacua are common and easy to construct.

Several recent papers have emphasized that gauge mediation can, in principle, look very different from minimal gauge mediation: Extra-Ordinary Gauge Mediation (Cheung, Fitzpatrick, Shih); General Gauge Mediation (Meade, Seiberg, Shih; also Carpenter, Dine, Festuccia, Mason); Dynamical $\mu/B\mu$ in NMSSM (Liu, Wagner); many others....

Some of these models can also suggest concrete experimental signatures that are amusing to think about.

Higgsino NLSP

In this talk I'll mostly be discussing the case of mixed bino–Higgsino NLSP. One can't have small μ (with EWSB) in ordinary gauge mediation, which always has squarks much heavier than sleptons.

As Cheung &co. pointed out, one can construct GMSB models that still unify but have split doublet and triplet messengers. Mass relations are then modified: one can have different "effective messenger numbers" $N_{eff,3} \gg N_{eff,2}$.

A Cancellation in the Running

As first pointed out by Agashe & Graesser, if the squarks and sleptons are relatively degenerate one can have a cancellation in the running that accommodates a small μ. This can help to relieve some of the fine-tuning.

One balances a GMSB contribution to $m_{H_u}^2$, proportional to $\alpha_2(M_{mess,2})^2/N_{eff,2}$, against a stop loop contribution proportional to $\alpha_3(M_{mess,3})^2/N_{eff,3}$.

For this study we're not interested in detailed questions of how μ arises and how tuned the model is. We assume some scenario where μ is small, and see what the collider implications are.

NLSP Branching Ratios

Neutralino decays to gravitino + (photon/Z/Higgs) are controlled by a quantity:

$$\mathcal{A} = \frac{m_{\tilde{\chi}_1^0}^5}{32\pi F^2}, \quad (1)$$

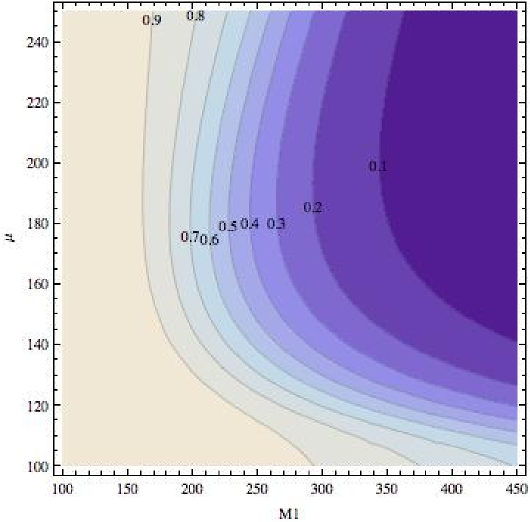
times some factors that depend on masses and mixings.

Important qualitative feature: if F (and hence $m_{3/2}$) is a little bit large, can have displaced vertices in a detector. If $m_{3/2}$ is significantly heavier, particles escape the detector entirely.

Bino to photon + gravitino

$$c\tau = \frac{10^{-2}\mathrm{cm}}{|N_{11}\cos\theta_W + N_{12}\sin\theta_W|^2}\left(\frac{100\ \mathrm{GeV}}{m_{\tilde{\chi}_1^0}}\right)^5\left(\frac{\sqrt{F}}{100\ \mathrm{TeV}}\right)^4.$$

NLSP BR to Photon + Gravitino



Branching ratio $\tilde{\chi}_1^0 \to \tilde{G}\gamma$, in the (M_1, μ) plane with $M_2 = 2M_1$.

Clean photon events

In minimal gauge mediation, at a collider one can make wino pairs that decay down through sleptons to the bino. (Bino-bino events are rare.) Even the sparsest events are likely to have some hard leptons.

With Higgsino NLSP, pair production of NLSPs is not so rare. Substantial numbers of events can be very clean, due to the small splitting: diphoton + nothing.

However, even if we make the splitting tiny, $\tilde{\chi}_1^+ \tilde{\chi}_1^0$ events will frequently have at least one hard jet, just from ISR.

Constraints

A number of existing experiments constrain this scenario. Limit on μ from LEP chargino bound of 103 GeV, as long as M_1 and M_2 are not hugely far above μ.

If the chargino and neutralino were exactly degenerate, this would also imply the NLSP has a bound of 103 GeV. However, mixing with the bino splits the neutral Higgsinos and allows a lighter NLSP. In particular, $m_{\tilde{\chi}_1^0} \approx 90$ GeV can be achieved without violating the chargino mass bound. Such a light NLSP will decay almost entirely to photons, so the usual minimal GMSB searches involving photons come into play.

D0 Diphoton Search

Search for GMSB in diphoton final states by D0 at $\sqrt{s} = 1.96$ TeV

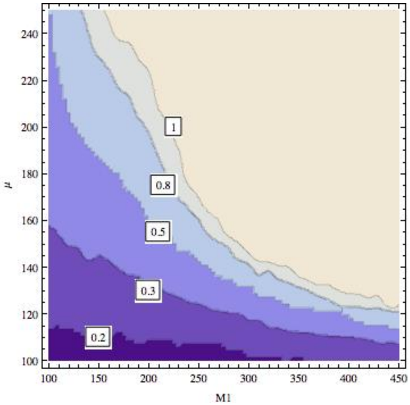
The DØ Collaboration
URL http://www-d0.fnal.gov
(Dated: July 26, 2007)

We report results of a search for Supersymmetry (SUSY) with gauge-mediated breaking in diphoton events using 1100 ± 70 pb^{-1} of data collected by the D0 experiment at the Fermilab Tevatron Collider in 2002–2006. No excess of events above the standard model background is found. We set the most stringent limits for a standard benchmark model on the lightest neutralino and chargino mass of about 126 and 231 GeV, respectively, at the 95% C.L.

PACS numbers: 14.80.Ly, 12.60.Jv, 13.85.Rm

www-d0.fnal.gov/Run2Physics/WWW/results/prelim/NP/N54/N54.pdf
D0 Note 5427-CONF

D0 Diphoton Search: 95% Exclusion Implications



The limits here are on P_{decay}, the probability that the neutralino decays inside the detector. This is a preliminary plot which doesn't take into account some aspects of the D0 study (work in progress).

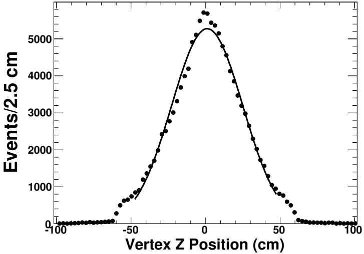
Long Lifetimes at the Tevatron?

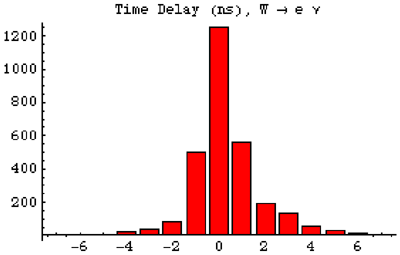
CDF has an **EM timing** system added in Run II, motivated by the (in?)famous $ee\gamma\gamma \not{E}_T$ event. Measures arrival time of electrons and photons with a resolution of about 0.6 ns.
Search for long-lived neutralinos decaying to photons: 0804.1043.
Limit of 101 GeV for 5 ns lifetime, from 570 pb^{-1}.

D0 does not do timing, but it does **pointing**. Fits shower position in the EM calorimeter and the central preshower detector to obtain a distance of closest approach to the beamline within 2 cm.
Search for long-lived particles decaying to electron or photon pairs: 0806.2223

Challenging? Timing in $W \to e\nu$, with $e \to \gamma$

Wrong vertex can bias E_T measurement and allow more events to pass cuts. Clean $\gamma + \not{E}_T$ is not as simple as it looks at the Tevatron!





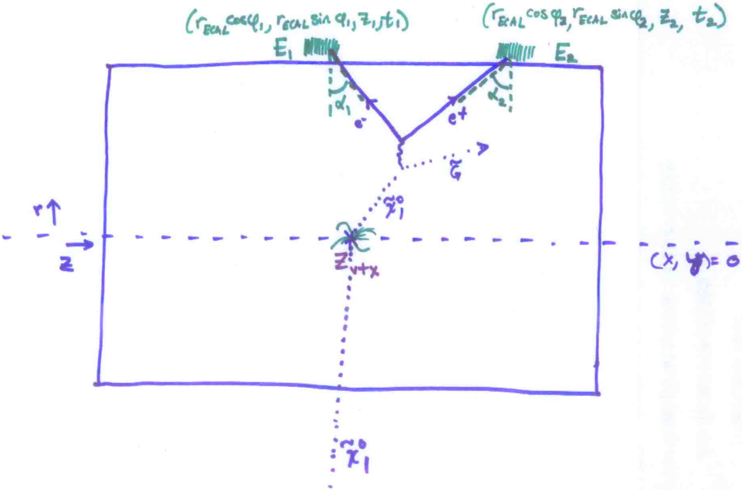
CDF vertex distribution from 0804.1043; Time delay from modified PGS (several assumptions, but at least morally correct)

Delayed Z Boson Events

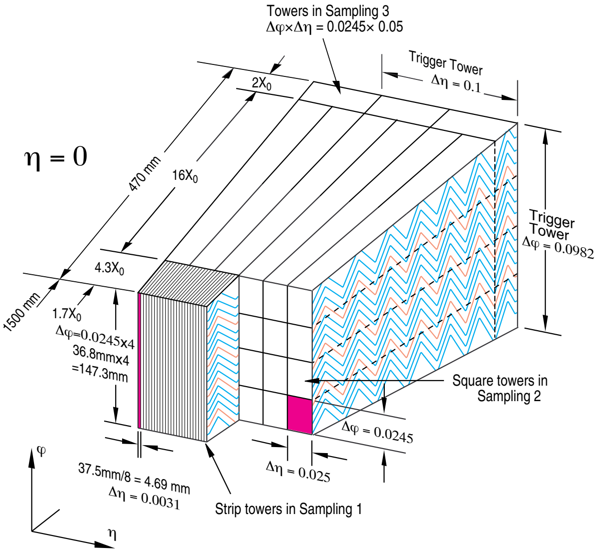
With Higgsino NLSP one can have delayed, non-pointing Z or Higgs bosons, which have been studied less than delayed photons. Understanding what these events look like in the detector and what we can learn from them is interesting and potentially challenging.

I'll discuss one of the most accessible cases: a delayed Z that decays to e^+e^-, at ATLAS for specificity.

Displaced Z Event in the Detector



ATLAS ECAL Granularity



ATLAS ECAL: Key Numbers

The basic measurements made by the ECAL are:

- Energy: resolution $\delta E/E \sim 10\%/\sqrt{E/\mathrm{GeV}} \oplus 0.7\%$
- Position in η, φ: resolution $\sigma_\eta = 0.002$, $\sigma_\varphi = 0.004$
- Direction in η: $\sigma_\theta = 0.060/\sqrt{E/\mathrm{GeV}}$
- Arrival time: $\sigma_t = 100$ ps

The use of these quantities for precision mass determination in *ordinary* gauge mediation, using events with leptons and nonpointing photons, has been discussed by Kawagoe, Kobayashi, Nojiri, and Ochi (hep-ph/0309031).

ATLAS Vertexing

The beam spot is essentially Gaussian with $\sigma_z = 5.6$ cm ($\sigma_{x,y} = 15\mu\mathrm{m}$). We would like to know the vertex position much more precisely for this study.

The ATLAS TDR contains a range of estimates for the precision of the primary vertex, which depends on physics process and on luminosity. Pile-up, obviously, makes the issue more difficult.

For now we'll go to the pessimistic end of the TDR range and smear the vertex with a Gaussian of width 100 μm. Pile-up could make this too optimistic, but this is just a first estimate....

ATLAS Tracking

TRT: straws parallel to the beamline give accurate information about direction in the (r, φ) plane.

Software can find photons that convert. Can this be adapted to look for displaced Z vertices? Need to be sure not to restrict to things that point back to the beamline.

I won't use this information in my reconstruction, but it should be used: it's redundant information, to some extent, but doing a fit to all the information we have should help overcome limitations from experimental resolutions.

A Sample Point

I'm going to run through an example of some events. The point chosen is $M_1 = 320$ GeV, $M_2 = 640$ GeV, $\mu = 140$ GeV, $\tan\beta = 20$, $m_{\tilde{G}} = 25$ eV, and for simplicity all squarks, sleptons, and the gluino are decoupled so that we just focus on production of charginos and neutralinos for now.

Chargino/Neutralino Masses

$$
\begin{aligned}
m_{\tilde{\chi}_1^0} &= 134.0 \\
m_{\tilde{\chi}_2^0} &= -150.5 \\
m_{\tilde{\chi}_1^0} &= 324.0 \\
m_{\tilde{\chi}_1^0} &= 702.0 \\
m_{\tilde{\chi}_1^\pm} &= 142.6 \\
m_{\tilde{\chi}_1^\pm} &= 702.0
\end{aligned}
$$

Reconstructing the decay vertex

We would like to solve for the decay vertex position (x_d, y_d, z_d) and time t_d. We assume the two particles that gave us the signal in the ECAL are massless, so we have two equations

$$c(t_i - t_d) = |\mathbf{x}_i - \mathbf{x}_d|^2 \tag{2}$$

The pointing measurement tells us $\frac{z_i - z_d}{\sqrt{(x_i-x_d)^2+(y_i-y_d)^2}}$. These four equations allow us to solve for (x_d, y_d, z_d, t_d).

Discrete ambiguities are reduced by demanding that $t_d < t_i$. A further reduction comes from noting that we can compute the velocity of the neutralino:

$$(v_x, v_y, v_z) = \left(\frac{x_d}{ct_d}, \frac{y_d}{ct_d}, \frac{z_d - z_{vtx}}{ct_d}\right), \tag{3}$$

which must square to a number less than one.

Reconstructing the Higgsino mass

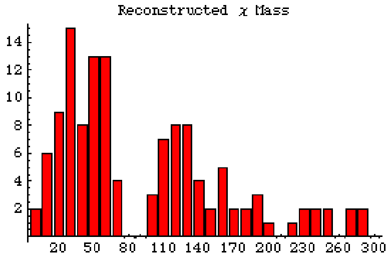
Reconstructing the decay vertex position and time is already interesting, as we can try to infer from it the neutralino lifetime and hence the parameter F characterizing the scale of SUSY breaking.

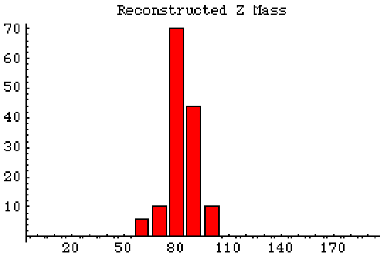
In fact there is more that we can do; as we already noted we know the neutralino velocity $(v_x, v_y, v_z)_\chi$, so the only unknown quantity in its 4-momentum is the energy E_χ. If we *assume* a massless gravitino, we have:

$$m_{\tilde{G}}^2 = (E_\chi - E_1 - E_2)^2 - (E_\chi \mathbf{v}_\chi - \mathbf{p}_1 - \mathbf{p}_2)^2 = 0, \qquad (4)$$

and we can solve for E_χ and use it to compute m_χ, up to quadratic ambiguity.

Higgsino mass results: after smearing



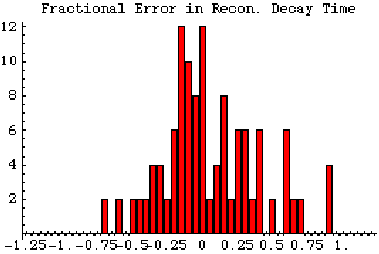


With all observables smeared by the appropriate Gaussians, the result is not sharp, but there is a cluster of results near the correct answer 134 GeV.

We still haven't used the φ direction information from tracking, so I'm optimistic that this can be cleaned up somewhat.

Error in Reconstructed Decay Time

We would like to be able to use the reconstructed vertex and time to understand the $\tilde{\chi}_1^0$ lifetime and hence the gravitino mass. Here's the fractional error $\frac{t_{recon} - t_{sim}}{t_{sim}}$:



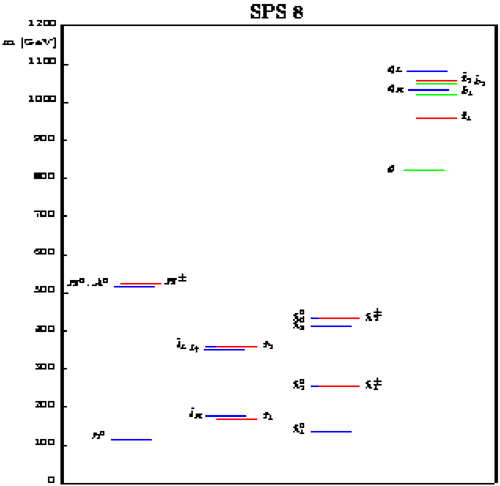
Percentage errors can be large, but many are within 20%. Again, need to try to clean this up, doing a full fit with tracking.

Conclusions

- The phenomenology of Higgsino NLSP is not as extensively explored as bino and stau, and much work remains to be done.
- The case with long-lived NLSP gives interesting phenomenology, with delayed photon, Z, or Higgs. The delayed photon case can be distinct from ordinary GMSB because the sleptons may not be light, and Higgsinos are directly produced.
- The ATLAS electromagnetic calorimeter gives precision direction and timing information that could play a key role in understanding the mass spectrum and the SUSY breaking scale. Still a chance for CDF and D0!
- Much more fun to be had.

Backup?

Minimal Gauge Mediation Spectrum



SPS Point 8: $\tilde{B}$ NLSP GMSB (hep-ph/0202233)
Note squark/slepton mass ratio is large: $\sqrt{3}\alpha_s/\alpha$

Higgsino Branching Ratios

When Higgs and Z decays are on-shell, we can summarize the decay widths as:

$$\begin{aligned}
\Gamma(\tilde{\chi}_1^0 \to \tilde{G} + \gamma) &= 2\left|N_{11}c_W + N_{12}s_W\right|^2 \mathcal{A} \\
\Gamma(\tilde{\chi}_1^0 \to \tilde{G} + Z) &= \left(2\left|N_{12}c_W - N_{11}s_W\right|^2 + \left|N_{13}c_\beta - N_{14}s_\beta\right|^2\right) \\
&\times \left(1 - \frac{M_Z^2}{m_{\tilde{\chi}_1^0}^2}\right)^4 \mathcal{A} \\
\Gamma(\tilde{\chi}_1^0 \to \tilde{G} + h) &= \left|N_{14}c_\alpha - N_{13}s_\alpha\right|^2 \left(1 - \frac{M_h^2}{m_{\tilde{\chi}_1^0}^2}\right)^4 \mathcal{A}
\end{aligned}$$

The ATLAS Detector

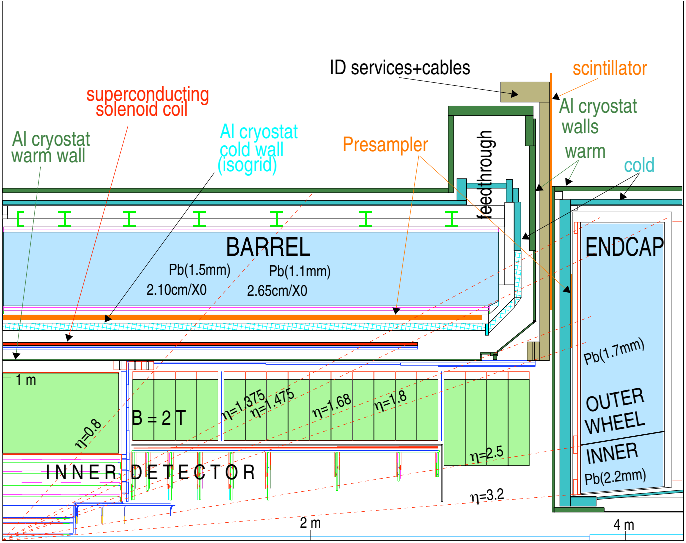
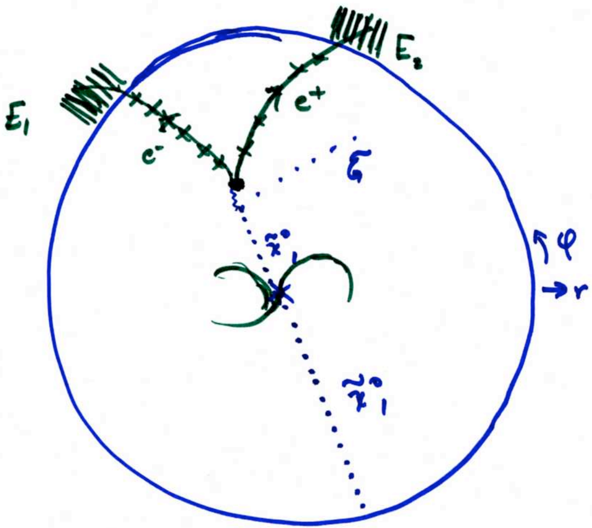


Figure 2-i Longitudinal view of a quadrant of the EM calorimeter.

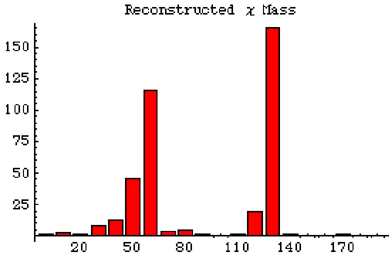
ATLAS Electromagnetic Calorimeter

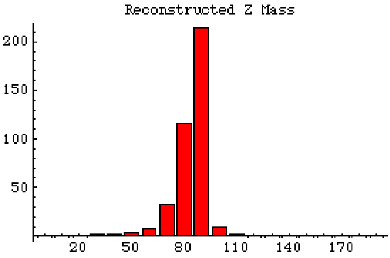
The ATLAS electromagnetic calorimeter uses LAr and lead. In the barrel it extends to $|\eta| < 1.475$, while the endcap covers $1.375 < |\eta| < 3.2$. The fast response time of LAr allows precision timing, used to reject pile-up and to detect long-lived particles.

Displaced Z Event in the Detector



Higgsino mass results: before smearing





Even before smearing, have some spread from radiation in Pythia. Also note the unphysical low-mass solutions for m_χ (it's below the Z mass, so clearly nonsensical!)