Phenomenology of Higgsino NLSPs

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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, but another goal of the talk is to look at some of the capabilities of the LHC detectors (choosing ATLAS for concreteness) that we theorists don't always 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).

SUSY Breaking Phenomenology

If the LHC discovers supersymmetry, possibly the most important follow-up question becomes: how is SUSY breaking mediated to the Standard Model?

Broadly speaking, the main options are some form of gravity mediation with a special flavor-respecting structure (some modification of anomaly mediation, Kähler-dominated moduli mediation in IIB strings, ...) or gauge mediation.

In this talk I want to look at a few aspects of how gauge mediation could show up at the LHC. The work is still preliminary.

What is Gauge Mediation?

In its purest form, gauge mediation means that 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.

In this case the MSSM soft supersymmetry breaking terms are all calculable in terms of simple correlation functions of the hidden sector, even if it is strongly coupled (Meade, Seiberg, Shih).

More generally, one adds additional visible/hidden sector interactions, e.g. for $\mu/B\mu$.

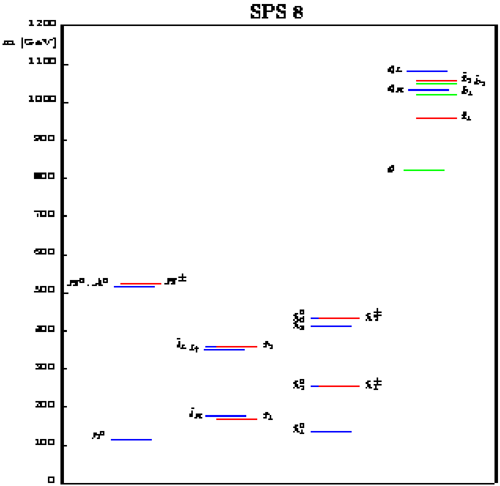
Basic Gauge Mediation Phenomenology

Gauge mediation is inherently flavor-respecting.

One key feature for collider physics is the 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.

Minimal Gauge Mediation Spectrum



SPS Point 8: $\tilde{B}$ NLSP GMSB (hep-ph/0202233)

Note squark/slepton mass ratio is large: $\sqrt{3}\alpha_s/\alpha$

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....

Apart from the interesting question of how we can know if what the LHC sees is GMSB, 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:

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

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

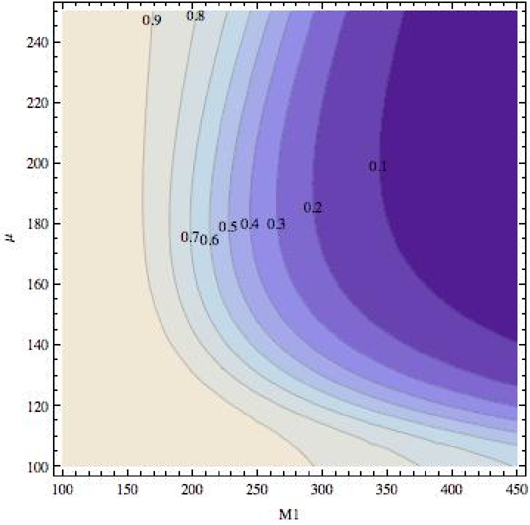
$$c\tau = \frac{10^{-2}\mathrm{cm}}{|N_{11}\cos\theta_W + N_{12}\sin\theta_W|^2}\left(\frac{100\ \mathrm{GeV}}{m_{\tilde{\chi}_1^0}}\right)^5\left(\frac{\sqrt{F}}{100\ \mathrm{TeV}}\right)^4.$$

Higgsino Branching Ratios

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

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

NLSP BR to Photon + Gravitino



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

Decays to Z and h

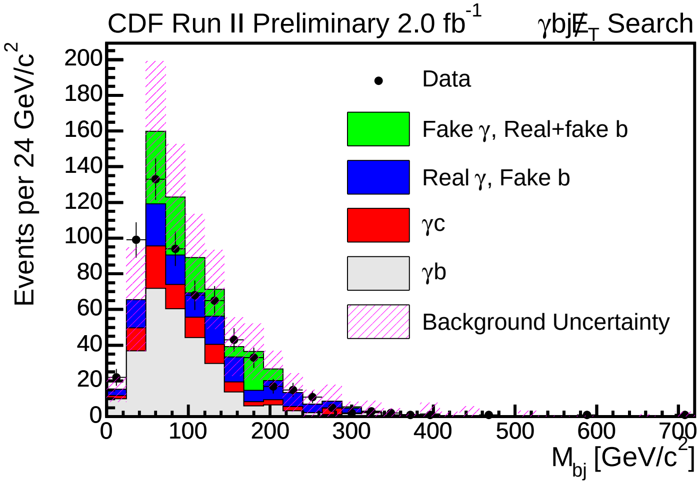
Tevatron signatures for Z and h decays were discussed in K. Matchev and S. Thomas, hep-ph/9908482

Let's examine when we expect decays to h to be significant. Focusing on the decoupling limit $m_A, m_H, m_{H^\pm} \gg m_h$, where $\alpha = \beta - \pi/2$, we have:

$$\frac{\Gamma(\tilde{\chi}_1^0 \to \tilde{G} + Z_L)}{\Gamma(\tilde{\chi}_1^0 \to \tilde{G} + h)} = \frac{|N_{13} c_\beta - N_{14} s_\beta|^2}{|N_{13} c_\beta + N_{14} s_\beta|^2} \left(\frac{1 - m_Z^2/m_{\tilde{\chi}_1^0}^2}{1 - m_h^2/m_{\tilde{\chi}_1^0}^2} \right)^4 . \tag{2}$$

So, two important cases: large $m_{\tilde{\chi}_1^0}$, or $\mu < 0$ and $\tan\beta \approx 1$.

CDF Search for $\gamma + b + j + \not{E}_T$



www-cdf.fnal.gov/physics/exotic/r2a/20080410.gbjmet/public_gbjmet/

CDF Public Note 9296

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. There is a fairly general chargino mass bound from LEP of 103 GeV. It breaks down in the limit of extreme degeneracy of the charged and neutral Higgsino, but provided M_1 and M_2 are below a TeV, it should be reliable. This is essentially a limit on 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

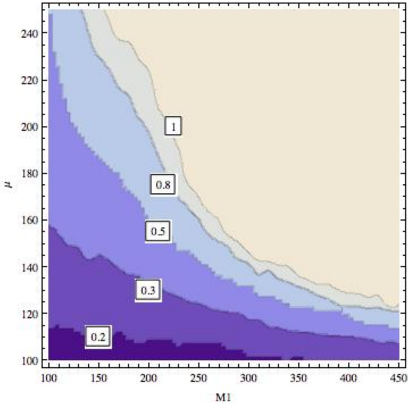
The DØ Collaboration
URL http://www-d0.fnal.gov
(Dated: July 26, 2007)

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 conservative preliminary plot, as we haven't yet taken into account some aspects of the D0 study that should strengthen the limit (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 ($\gamma + j + \not{E}_T$): 0804.1043. Limit for bino 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

CDF Search for Long-Lived Particles Decaying to Photons

Search for Heavy, Long-Lived Particles that Decay to Photons at CDF II

We present the first search for heavy, long-lived particles that decay to photons at a hadron collider. We use a sample of γ+jet+missing transverse energy events in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV taken with the CDF II detector. Candidate events are selected based on the arrival time of the photon at the detector. Using an integrated luminosity of 570 pb^{-1} of collision data, we observe 2 events, consistent with the background estimate of 1.3$\pm$0.7 events. While our search strategy does not rely on model-specific dynamics, we set cross section limits in a supersymmetric model with $\widetilde{\chi}_1^0 \to \gamma\widetilde{G}$ and place the world-best 95% C.L. lower limit on the $\widetilde{\chi}_1^0$ mass of 101 GeV/c^2 at $\tau_{\tilde{\chi}_1^0} = 5$ ns.

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

0704.0760

Cuts in the CDF Search

Preselection Requirements	Cumulative (individual) Efficiency (%)
$E_T^\gamma > 30$ GeV, $\not\!\!E_T > 30$ GeV	54 (54)
Photon ID and fiducial, $\lvert\eta\rvert < 1.0$	39 (74)*
Good vertex, $\sum_{\text{tracks}} p_T > 15$ GeV$/c$	31 (79)
$\lvert\eta^{\text{jet}}\rvert < 2.0$, $E_T^{\text{jet}} > 30$ GeV	24 (77)
Cosmic ray rejection	23 (98)*
Requirements after Optimization	
$\not\!\!E_T > 40$ GeV, $E_T^{\text{jet}} > 35$ GeV	21 (92)
$\Delta\phi(\not\!\!E_T, \text{jet}) > 1$ rad	18 (86)
2 ns $< t_c^\gamma <$ 10 ns	6 (33)

TABLE I: The data selection criteria and the cumulative and individual requirement efficiencies for an example GMSB model point at $m_{\tilde{\chi}_1^0} = 100$ GeV$/c^2$ and $\tau_{\tilde{\chi}_1^0} = 5$ ns. The efficiencies listed are, in general, model-dependent and have a fractional uncertainty of 10%. Model-independent efficiencies are indicated with an asterisk. The collision fiducial requirement of $\lvert z_i\rvert < 60$ cm is part of the good vertex requirement (95%) and is estimated from data.

0704.0760

Clean $\gamma + \not{E}_T$?

With light, largely Higgsino NLSP, and long lifetime, can have some events where the signal is one hard photon and no other hard objects. Very clean – is it a good search channel at the Tevatron?

SM physics backgrounds include the irreducible $Z(\to \nu\bar{\nu}) + \gamma$, $W \to e\nu$ with $e \to \gamma$ fake, $\gamma\gamma$ with one lost photon.

Instrumental backgrounds: beam halo, cosmic rays.

Non-collision backgrounds

Peter Wagner's CDF thesis (August 2007, Texas A&M) is a good reference for learning about these issues.

Beam halo comes from interactions of beam bunches with material near the beam pipe, before reaching the detector. This can produce muons moving roughly parallel to the proton beam, which pass through several calorimeter cells. One cell may get a large deposit and become a photon candidate. (Typically at early times.)

Cosmic rays, on the other hand, will sometimes interact in the EM calorimeter and produce a fake photon, without leaving significant amounts of energy elsewhere in the detector. These will have flat timing distributions.

Early/late asymmetry as indication of new physics?

Suppose the early-time beam halo events can be filtered out entirely from the way they deposit energy in the calorimeter.

Physics backgrounds will have a Gaussian timing distribution. (By "timing", we mean time the hit is registered in EM Timing versus time it should take a photon to propagate from the vertex.) Cosmics will have a flat timing distribution.

New physics could occur at positive timing, because the path length for a neutralino to its decay position plus the photon from the decay position to the calorimeter is longer than the direct path from the vertex to the calorimeter. Is (late - early)/(late + early) a new physics analyzer?

Wrong vertices

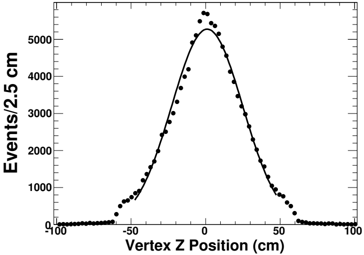
These are relatively clean events, and a good photon candidate has no associated track. So the vertex must be found from tracks from the underlying event. If a min-bias event happening elsewhere in the detector has a higher $\sum |p_T|$, the event might be reconstructed as if that is the true vertex.

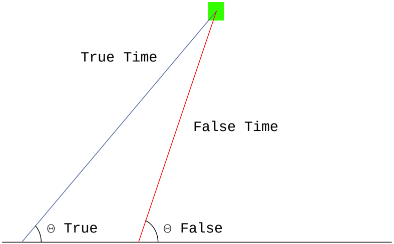
How often does this happen? Underlying event is usually somewhat harder than min bias, but at high instantaneous luminosity we can have a few min bias events happening at once, each with some probability to have higher $\sum |p_T|$. Assuming Pythia (Rick Field's Tune A) is modeling this correctly for the Tevatron, can happen 25-30% of the time.

(This is of course an experimental question; we can only give a rough guide to whether it's important!)

Vertex distribution at the Tevatron

The z vertex distribution at the Tevatron is broad (easily gives nanosecond delays). **Larger time delays** correlate with **larger measured** E_T, so a wrong vertex allow more events to pass cuts! (z vtx distribution at LHC is much narrower.)





CDF vertex distribution from 0804.1043.

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

The upshot is that even the background distributions will be very asymmetric between early and late times. The amount of asymmetry depends on cuts; e.g. for $W \to e\nu$, the electron p_T has an edge at 40 GeV. So if a cut is placed on photon E_T *above* 40 GeV, it will be *selecting* wrong-vertex events and enhancing the asymmetry in the background.

One outcome of all this is that re-interpreting a CDF analysis of $\gamma + \not{E}_T$ with timing as a constraint on the Higgsino NLSP scenario is an almost hopeless task for a theorist. We are trying to convince some of the relevant experimentalists to set a limit on (at least some slice of the parameter space of) this model. Our clean search channel is not so clean!

Delayed Z Boson Events

While the details differ and work remains to be done to understand the exclusion contours, in the case of delayed (non-pointing) photons there is a substantial amount of literature to draw on.

On the other hand, with Higgsino NLSP one can have delayed, non-pointing Z or Higgs bosons, which have been studied less. 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^-. Understanding what to do with these events requires some detailed discussion of the ATLAS detector.

The ATLAS Detector

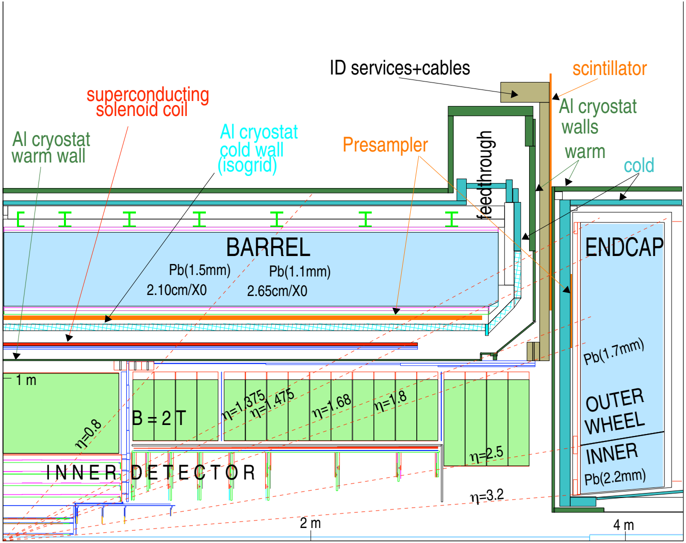
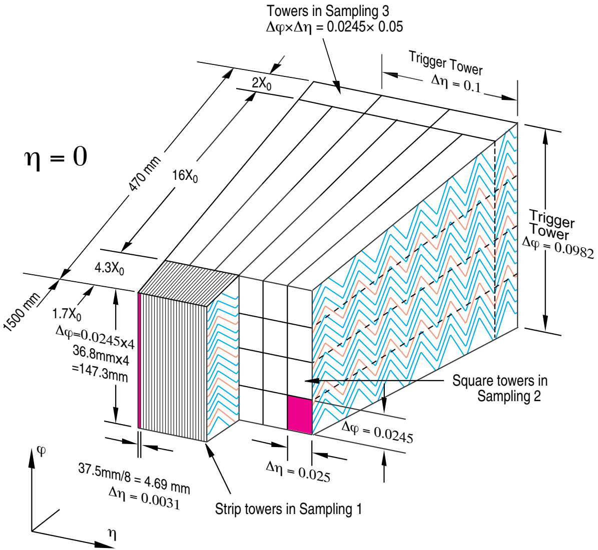


Figure 2-i Longitudinal view of a quadrant of the EM calorimeter.

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.

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....

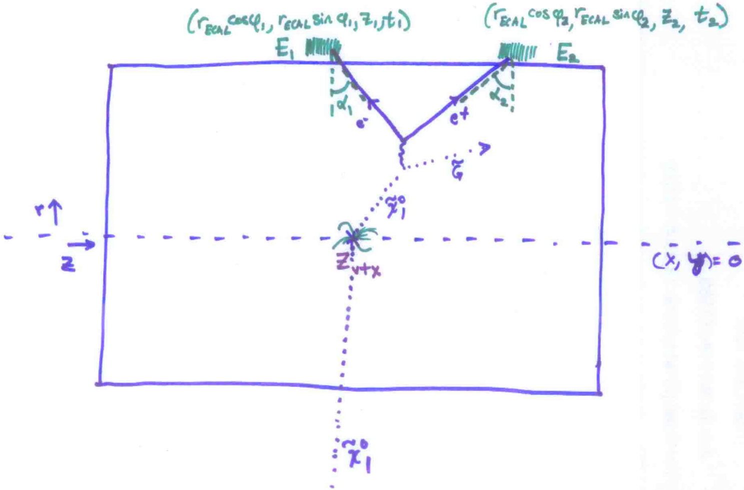
ATLAS Tracking

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

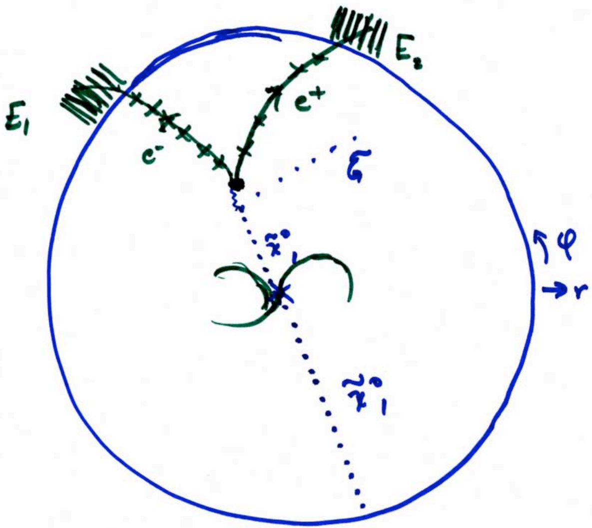
Software can find photons that convert. Can this be adapted to look for displaced Z vertices? Need to be sure not to restrict to things that point back to the beamline.

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.

Displaced Z Event in the Detector



Displaced Z Event in the Detector



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

$$
\begin{aligned}
m_{\tilde{\chi}_1^0} &= 134.0 \\
m_{\tilde{\chi}_2^0} &= -150.5 \\
m_{\tilde{\chi}_3^0} &= 324.0 \\
m_{\tilde{\chi}_4^0} &= 702.0 \\
m_{\tilde{\chi}_1^\pm} &= 142.6 \\
m_{\tilde{\chi}_1^\pm} &= 702.0
\end{aligned}
$$

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

$$c(t_i - t_d) = |\mathbf{x}_i - \mathbf{x}_d|^2 \tag{3}$$

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:

$$(v_x, v_y, v_z) = \left(\frac{x_d}{ct_d}, \frac{y_d}{ct_d}, \frac{z_d - z_{vtx}}{ct_d}\right), \tag{4}$$

which must square to a number less than one.

Reconstructing the Higgsino mass

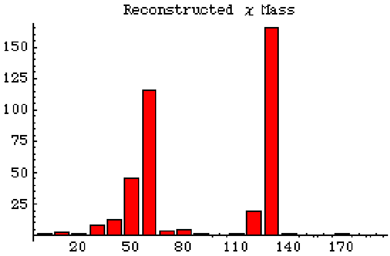
Reconstructing the decay vertex position and time is already interesting, as we can try to infer from it the neutralino lifetime and hence the parameter F characterizing the scale of SUSY breaking.

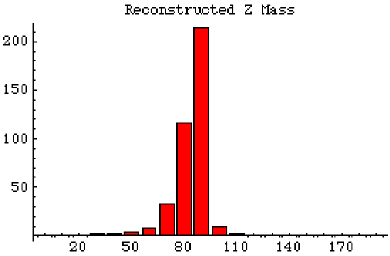
In fact there is more that we can do; as we already noted we know the neutralino velocity $(v_x, v_y, v_z)_\chi$, so the only unknown quantity in its 4-momentum is the energy E_χ. If we *assume* a massless gravitino, we have:

$$m_{\tilde{G}}^2 = (E_\chi - E_1 - E_2)^2 - (E_\chi \mathbf{v}_\chi - \mathbf{p}_1 - \mathbf{p}_2)^2 = 0, \qquad (5)$$

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

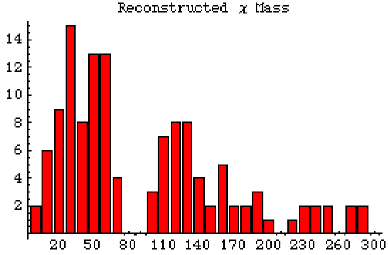
Higgsino mass results: before smearing

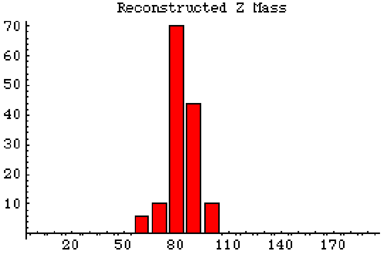




Even before smearing, have some spread from radiation in Pythia. Also note the unphysical low-mass solutions for m_χ (it's below the Z mass, so clearly nonsensical!)

Higgsino mass results: after smearing



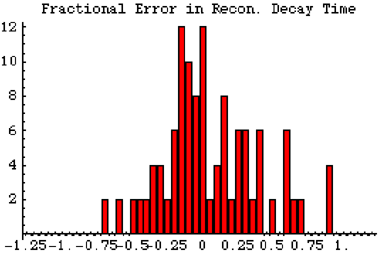


With all observables smeared by the appropriate Gaussians, the result is not sharp, but there is a cluster of results near the correct answer 134 GeV.

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.
- Much more fun to be had.