Signatures of Long-Lived Neutral Particles

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work in progress with Patrick Meade and David Shih

Motivation

I'll be discussing some signatures of Higgsino NLSPs in gauge mediation. This is a well-motivated scenario, but for this talk I'm mostly using it as a motivated example of some unusual signatures.

These signatures are not easily understood with the current detector simulations available outside the collaborations, so one question I want to provoke some discussion of: should we have tools for such things? Do they occur in enough different models, and are enough people interested, that it's worth taking the time to produce reusable code instead of ad hoc calculations?

GMSB

Gauge-mediation (GMSB) is the scenario where some SUSY-breaking sector has global symmetries that are weakly gauged by the Standard Model. Makes calculable, flavor-blind contributions to soft SUSY breaking parameters.

The phenomenology is largely driven by the gravitino: for GMSB to dominate over gravity mediation, need F/M_{Pl} small: gravitino mass at most around 1 GeV, could be much less than 1 eV. **Lightest MSSM partner (NLSP) decays to gravitino.** Size of $m_{3/2}$ dictates decay lengths: $\tau \sim F^2/m^5_{\tilde{\chi}^0_1}$. **Anywhere from prompt decay to much larger than size of detector.**

NLSP

With a few exceptions (Matchev and Thomas; Baer, Mercadante, Tata, Wang; ...), almost all of the phenomenology assumes the NLSP is either a **bino** (decays to $\gamma + \tilde{G}$) or a **stau** (decays to $\tau + \tilde{G}$). These are the only options in "ordinary gauge mediation" (minimal model).

However, there are plenty of theoretical reasons to be interested in models with Higgsino NLSP, or possibly others. The Higgsino is the NLSP in many "extra-ordinary gauge mediation" models (Cheung, Fitzpatrick, Shih), or in the $\mu/B\mu$ solution of Csáki, Falkowski, Nomura, Volansky. (See also early work of Agashe and Graesser.) Helps with fine-tuning, etc.

Signals

This has led to a standard, narrow view of GMSB phenomenology: either lots of events with two photons, or lots of taus. Going to the non-prompt case, look for stau as long-lived charged particle ("CHAMP"), or for non-pointing or delayed photons.

These are interesting signatures – and GMSB gives a well-motivated example driving many searches for these non-standard signatures – but looking at other NLSPs gives a much richer spectrum of (also well-motivated) possibilities!

Branching ratio: NLSP to γ, Z, $h + \tilde{G}$

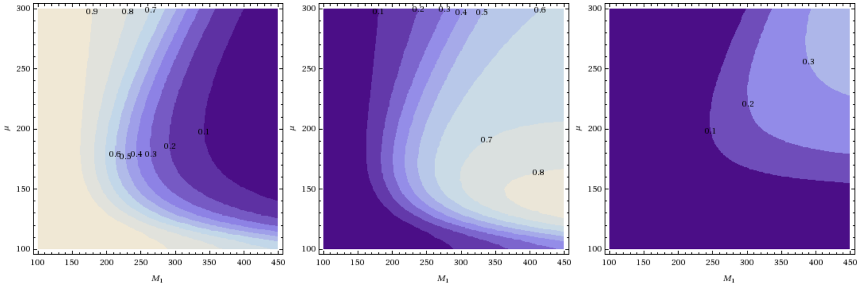
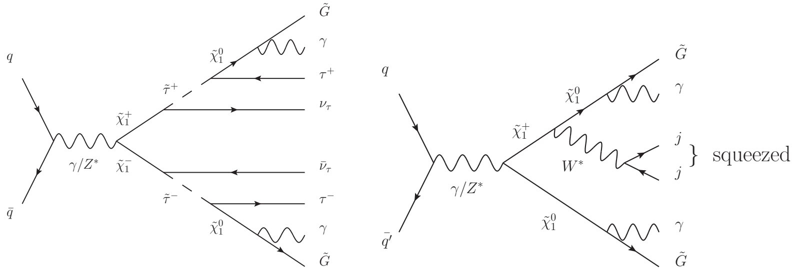


Figure: Branching ratios, from left to right, of $\tilde{\chi}_1^0 \to \tilde{G} + (\gamma, Z, h)$, in the (M_1, μ) plane with $M_2 = 2M_1$, $\tan\beta = 20$, and in the decoupling limit $\alpha = \beta - \pi/2$. The Higgs mass is taken to be 115 GeV.

Roughly, three regions: γ-rich, Z-rich, Z/h-shared

Even γ-rich is novel



At left, the typical process in OGM, where $\tilde{\chi}_1^\pm$ are mostly wino and decay through sleptons to the mostly-bino $\tilde{\chi}_1^0$. The final state includes energetic tau leptons. At right, a typical process with mostly-Higgsino NLSPs, which are produced directly. The small splitting between $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ leads to a three-body decay through off-shell W with very little phase space, so there are relatively soft leptons or jets in the final state.

Long Lifetime Events

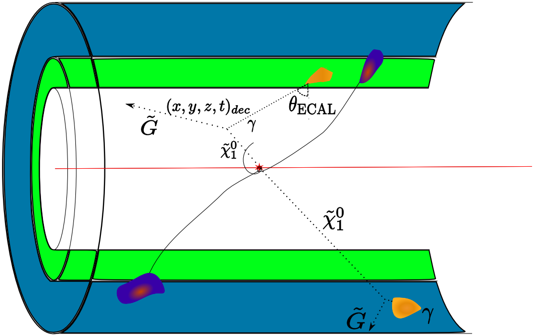


Illustration of what a two-photon GMSB event could look like when the lifetime of the NLSP is on the order of the size of the detector. Tools: timing, pointing, conversions, ...

Note that standard physics objects may be distorted; ID cuts can fail!

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

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

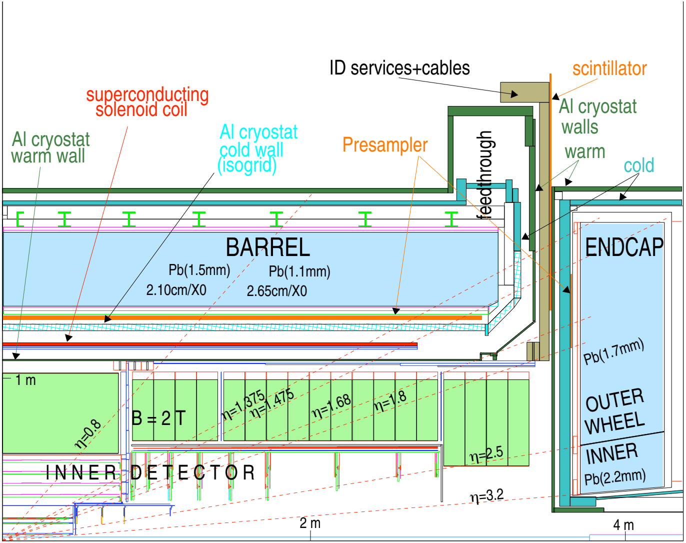
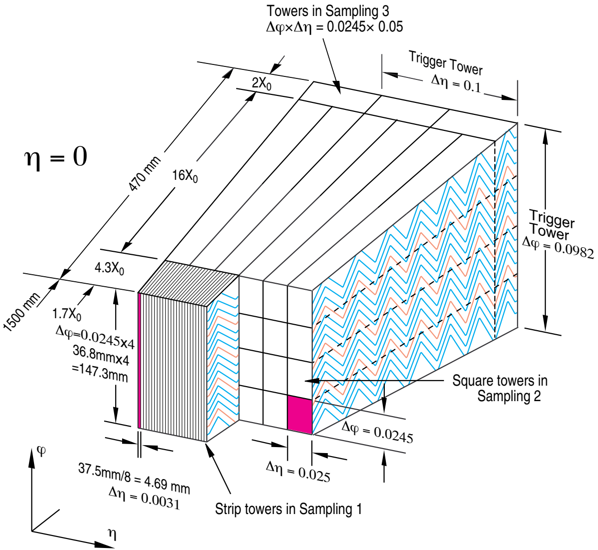


Figure 2-i Longitudinal view of a quadrant of the EM calorimeter.

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....

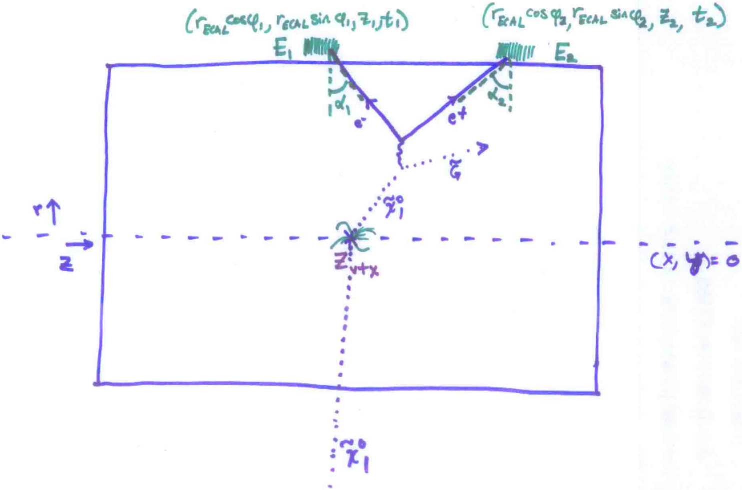
ATLAS Tracking

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



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.

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

$$c(t_i - t_d) = |\mathbf{x}_i - \mathbf{x}_d|^2 \tag{1}$$

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:

$$(v_x, v_y, v_z) = \left(\frac{x_d}{ct_d}, \frac{y_d}{ct_d}, \frac{z_d - z_{vtx}}{ct_d} \right), \tag{2}$$

which must square to a number less than one.

Reconstructing the Higgsino mass

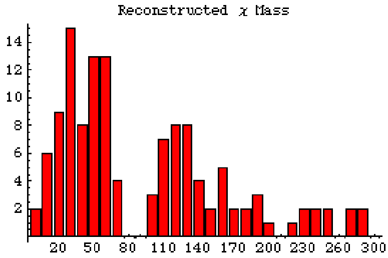
Reconstructing the decay vertex position and time is already interesting, as we can try to infer from it the neutralino lifetime and hence the parameter F characterizing the scale of SUSY breaking.

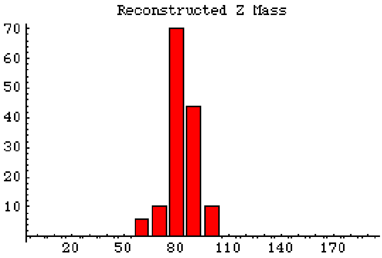
In fact there is more that we can do; as we already noted we know the neutralino velocity $(v_x, v_y, v_z)_\chi$, so the only unknown quantity in its 4-momentum is the energy E_χ. If we *assume* a massless gravitino, we have:

$$m_{\tilde{G}}^2 = (E_\chi - E_1 - E_2)^2 - (E_\chi \mathbf{v}_\chi - \mathbf{p}_1 - \mathbf{p}_2)^2 = 0, \qquad (3)$$

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.

Conclusions

Higgsino NLSPs give a well-motivated example where many exotic signatures are possible for non-prompt decays. Relatively little systematic effort so far at understanding what is possible in such scenarios.

We've made some progress on understanding cases where the EM calorimeters can be used to their full potential (timing and pointing).

Some similarities to other scenarios of recent interest (hidden valleys, gluinos in split SUSY, quirks) that depart from the standard paradigm of SM particles emerging from a common vertex. Is there a possibility of a useful common tool?