General Features of Supersymmetric Signals at the ILC

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General Features of Supersymmetric Signals at the ILC

- Work done with C. F. Berger, J. L. Hewett, B. H. Lillie and T. G. Rizzo
- First part of talk based on 0711.1374 and 0712.2965
- At the end I will discuss some recent work which is an extension of these efforts

LHC Inverse Problem

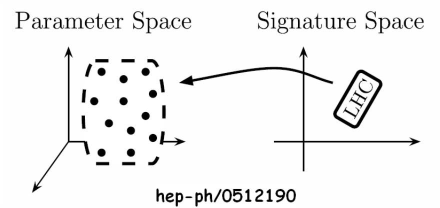
Arkani-Hamed, Kane, Thaler, and Wang (hep-ph/0512190)

1. Pick random points in an MSSM parameter space ("models")
    - No experimental constraints applied
2. Generate 10 fb^{-1} of SUSY events, no backgrounds.
3. Make histograms of observables
4. Compare histograms from different models
5. If models are sufficiently similar, LHC will not be able to tell them apart (models have "degenerate" or "indistinguishable" signatures).

Parameter	Min.	Max.
M_1, M_2, μ	100 GeV	1 TeV
$m_{l1,2}$, $m_{e1,2}$, m_{l3}, m_{e3}	100 GeV	1 TeV
M_3	600 GeV	1 TeV
$m_{q1,2}$, $m_{u1,2}$, $m_{d1,2}$	600 GeV	1 TeV
m_{q3}, m_{u3}, m_{d3}	600 GeV	1 TeV
$\tan\beta$	2	50
M_A	800 GeV	800 GeV
A_τ	0	0
A_b, A_t	850 GeV	850 GeV

LHC Inverse Problem

- Out of 43,026 models for which the above procedure was performed 282 pairs of models had indistinguishable signatures. These accounted for 383 models.
- This may seem like a small number. However for one to find this many degeneracies for the number of models generated suggests that each model would be degenerate with $\mathcal{O}(10)$ other points in parameter space (for discussion see hep-ph/0512190).
- Adding backgrounds probably makes things significantly worse.



So how do we solve the LHC Inverse problem?

Some Attempts to Solve the LHC Inverse Problem

In work described in 0711.1374 and 0712.2965, we tried to answer the question of how good of a job the ILC can do of distinguishing between models whose signatures are degenerate at the LHC. (This, and recent extensions of this, is discussed in subsequent slides.)

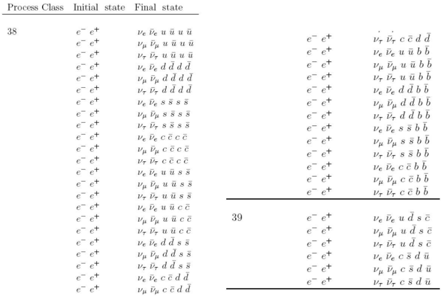
Altunkaynak, Holmes and Nelson (0804.2899) have investigated using direct and indirect detection of dark matter to distinguish models that are degenerate at LHC.

What We Did

- Simulated SUSY signals for each of 242* models that AKTW found to be in LHC degeneracies
  - *Only **242** of the 383 models AKTW found to be in degeneracies are physical, due to an issue with the PYTHIA spectrum generator. This set of 242 models contained **162 pairs** of models with degenerate LHC signatures.
- Generated 250 fb^{-1} for each of 80% left and 80% right electron beam polarizations
- For the ILC design energy: $\sqrt{s} = 500$ GeV
- Used a design specific (cold technology) beam spectrum to incorporate the effects of beamstrahlung
- Used CompHEP (matrix elements) for more accurate treatment of radiative processes, PYTHIA for everything else

What We Did

- Obtained large SM background samples which were generated by Tim Barklow using WHIZARD/ O'Mega (which use full matrix elements) and which used the same design specific beam spectrum as the signal
- This background contains 78 process classes and a total of 1016 processes. The total background sample takes up 1.7 TB.
- The background includes all 2 → 2, 2 → 4, 2 → 6, and some 2 → 8 processes from each of e^+e^-, $e\gamma$, and $\gamma\gamma$ initial states.



Process Class	Initial state	Final state
38	$e^- \, e^+$	$\nu_e \, \bar{\nu}_e \, u \, \bar{u} \, u \, \bar{u}$
	$e^- \, e^+$	$\nu_\mu \, \bar{\nu}_\mu \, u \, \bar{u} \, u \, \bar{u}$
	$e^- \, e^+$	$\nu_\tau \, \bar{\nu}_\tau \, u \, \bar{u} \, u \, \bar{u}$
	$e^- \, e^+$	$\nu_e \, \bar{\nu}_e \, d \, \bar{d} \, d \, \bar{d}$
	$e^- \, e^+$	$\nu_\mu \, \bar{\nu}_\mu \, d \, \bar{d} \, d \, \bar{d}$
	$e^- \, e^+$	$\nu_\tau \, \bar{\nu}_\tau \, d \, \bar{d} \, d \, \bar{d}$
	$e^- \, e^+$	$\nu_e \, \bar{\nu}_e \, s \, \bar{s} \, s \, \bar{s}$
	$e^- \, e^+$	$\nu_\mu \, \bar{\nu}_\mu \, s \, \bar{s} \, s \, \bar{s}$
	$e^- \, e^+$	$\nu_\tau \, \bar{\nu}_\tau \, s \, \bar{s} \, s \, \bar{s}$
	$e^- \, e^+$	$\nu_e \, \bar{\nu}_e \, c \, \bar{c} \, c \, \bar{c}$
	$e^- \, e^+$	$\nu_\mu \, \bar{\nu}_\mu \, c \, \bar{c} \, c \, \bar{c}$
	$e^- \, e^+$	$\nu_\tau \, \bar{\nu}_\tau \, c \, \bar{c} \, c \, \bar{c}$
	$e^- \, e^+$	$\nu_e \, \bar{\nu}_e \, u \, \bar{u} \, s \, \bar{s}$
	$e^- \, e^+$	$\nu_\mu \, \bar{\nu}_\mu \, u \, \bar{u} \, s \, \bar{s}$
	$e^- \, e^+$	$\nu_\tau \, \bar{\nu}_\tau \, u \, \bar{u} \, s \, \bar{s}$
	$e^- \, e^+$	$\nu_e \, \bar{\nu}_e \, u \, \bar{u} \, c \, \bar{c}$
	$e^- \, e^+$	$\nu_\mu \, \bar{\nu}_\mu \, u \, \bar{u} \, c \, \bar{c}$
	$e^- \, e^+$	$\nu_\tau \, \bar{\nu}_\tau \, u \, \bar{u} \, c \, \bar{c}$
	$e^- \, e^+$	$\nu_e \, \bar{\nu}_e \, d \, \bar{d} \, s \, \bar{s}$
	$e^- \, e^+$	$\nu_\mu \, \bar{\nu}_\mu \, d \, \bar{d} \, s \, \bar{s}$
	$e^- \, e^+$	$\nu_\tau \, \bar{\nu}_\tau \, d \, \bar{d} \, s \, \bar{s}$
	$e^- \, e^+$	$\nu_e \, \bar{\nu}_e \, c \, \bar{c} \, d \, \bar{d}$
	$e^- \, e^+$	$\nu_\mu \, \bar{\nu}_\mu \, c \, \bar{c} \, d \, \bar{d}$
	$e^- \, e^+$	$\nu_\tau \, \bar{\nu}_\tau \, c \, \bar{c} \, d \, \bar{d}$
	$e^- \, e^+$	$\nu_e \, \bar{\nu}_e \, u \, \bar{u} \, b \, \bar{b}$
	$e^- \, e^+$	$\nu_\mu \, \bar{\nu}_\mu \, u \, \bar{u} \, b \, \bar{b}$
	$e^- \, e^+$	$\nu_\tau \, \bar{\nu}_\tau \, u \, \bar{u} \, b \, \bar{b}$
	$e^- \, e^+$	$\nu_e \, \bar{\nu}_e \, d \, \bar{d} \, b \, \bar{b}$
	$e^- \, e^+$	$\nu_\mu \, \bar{\nu}_\mu \, d \, \bar{d} \, b \, \bar{b}$
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	$e^- \, e^+$	$\nu_e \, \bar{\nu}_e \, s \, \bar{s} \, b \, \bar{b}$
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	$e^- \, e^+$	$\nu_e \, \bar{\nu}_e \, c \, \bar{c} \, b \, \bar{b}$
	$e^- \, e^+$	$\nu_\mu \, \bar{\nu}_\mu \, c \, \bar{c} \, b \, \bar{b}$
	$e^- \, e^+$	$\nu_\tau \, \bar{\nu}_\tau \, c \, \bar{c} \, b \, \bar{b}$
39	$e^- \, e^+$	$\nu_e \, \bar{\nu}_e \, u \, \bar{d} \, s \, \bar{c}$
	$e^- \, e^+$	$\nu_\mu \, \bar{\nu}_\mu \, u \, \bar{d} \, s \, \bar{c}$
	$e^- \, e^+$	$\nu_\tau \, \bar{\nu}_\tau \, u \, \bar{d} \, s \, \bar{c}$
	$e^- \, e^+$	$\nu_e \, \bar{\nu}_e \, c \, \bar{s} \, d \, \bar{u}$
	$e^- \, e^+$	$\nu_\mu \, \bar{\nu}_\mu \, c \, \bar{s} \, d \, \bar{u}$
	$e^- \, e^+$	$\nu_\tau \, \bar{\nu}_\tau \, c \, \bar{s} \, d \, \bar{u}$

What We Did

- Signal and backgrounds were piped through the SiD fast detector simulation package org.lcsim.
- Used org.lcsim to implement optimized cut-based analyses and make histograms of resulting observables.
- Determined how often various signals were visible above background
- Determined how often degenerate models could be distinguished

One CPU century later...

Our Conclusions

We found the ILC could distinguish between pairs of models degenerate at the LHC in 57(63)/162 cases (at $5(3)\sigma$).

Q: Why so rarely? (Given the many advantages of a lepton collider)

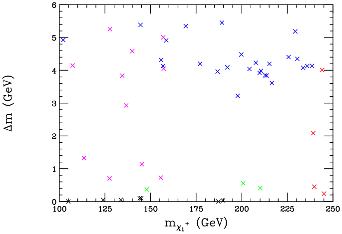
A: A major reason is that we were only able to even see SUSY signatures in 82 of 242 cases.

1. Sparticles Too Heavy

Final State	500 GeV	1 TeV
$\tilde{e}_L^+\tilde{e}_L^-$	9	82
$\tilde{e}_R^+\tilde{e}_R^-$	15	86
$\tilde{e}_L^\pm\tilde{e}_R^\mp$	2	61
$\tilde{\mu}_L^+\tilde{\mu}_L^-$	9	82
$\tilde{\mu}_R^+\tilde{\mu}_R^-$	15	86
Any selectron or smuon	22	137
$\tilde{\tau}_1^+\tilde{\tau}_1^-$	28	145
$\tilde{\tau}_2^+\tilde{\tau}_2^-$	1	23
$\tilde{\tau}_1^\pm\tilde{\tau}_2^\mp$	4	61
$\tilde{\nu}_{e\mu}\tilde{\nu}_{e\mu}^*$	11	83
$\tilde{\nu}_\tau\tilde{\nu}_\tau^*$	18	83
$\tilde{\chi}_1^+\tilde{\chi}_1^-$	53	92
Any charged sparticle	85	224
$\tilde{\chi}_1^\pm\tilde{\chi}_2^\mp$	7	33
$\tilde{\chi}_1^0\tilde{\chi}_1^0$	180	236
$\tilde{\chi}_1^0\tilde{\chi}_1^0$ only	91	0
$\tilde{\chi}_1^0 + \tilde{\nu}$ only	5	0
$\tilde{\chi}_1^0\tilde{\chi}_2^0$	46	178
Nothing	61	3

This table shows the number of models, out of 242, which have a given final state kinematically accessible at $\sqrt{s} = 500$ GeV and 1 TeV.

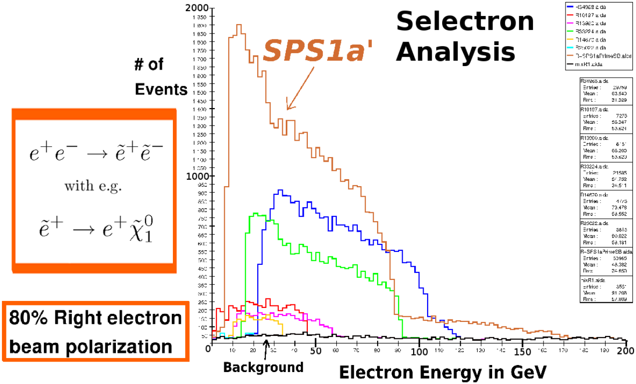
2. Small Mass Splittings Make Things More Difficult



This plot shows the mass splitting between the lightest chargino and the LSP neutralino versus the lightest chargino mass for 51 of the 53 models with charginos accessible. Colors are used to indicate the analysis or analyses for which the given model is visible.

blue	chargino decay through off-shell W
green	radiative chargino production
magenta	radiatve & off-shell W
black	stable chargino analysis
red	not observable

3. Small Cross Sections



$$e^+e^- \to \tilde{e}^+\tilde{e}^-$$

with e.g.

$$\tilde{e}^+ \to e^+\tilde{\chi}^0_1$$

80% Right electron beam polarization

Signal plus background for various AKTW models, as well as SPS1a′, and the standard model signature in on of our selectron analyses. We note that the AKTW models tend to have significantly lower cross sections than the benchmark model shown here; these are the **high** cross section models.

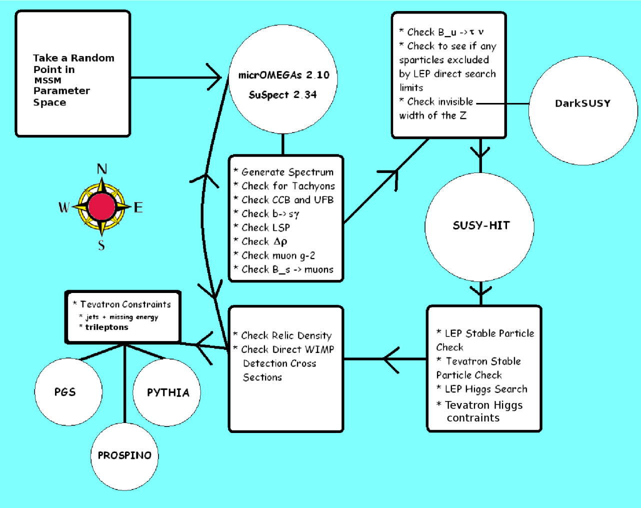
Questions

1. Randomly chosen points in an MSSM parameter space can be harder to study at ILC than most benchmark points.
2. But are these models "realistic"?
    - 2.1 How would taking to account experimental constraints on SUSY affect these results?
    - 2.2 How would opening up the parameter space (e.g. varying M_A, A-terms) affect these results?
    - 2.3 Does having the models be degenerate at LHC introduce a significant selection bias?

Beyond AKTW: New Model Generation

To answer these questions we are generating a set of models by picking random points in a SUSY parameter space (that includes varying M_A, A-terms, etc. as well as the sparticle masses and $\tan\beta$). We only keep models that satisfy the following experimental and theoretical constraints. This is the first study that looks at a large number of generic models in the ~ 20 parameter MSSM with all major experimental constraints included.

Our Procedure



Take a Random Point in MSSM Parameter Space

micrOMEGAs 2.10

SuSpect 2.34

- Generate Spectrum
- Check for Tachyons
- Check CCB and UFB
- Check b-> sγ
- Check LSP
- Check Δρ
- Check muon g-2
- Check B_s -> muons

- Check B_u -> τ ν
- Check to see if any sparticles excluded by LEP direct search limits
- Check invisible width of the Z

DarkSUSY

SUSY-HIT

- LEP Stable Particle Check
- Tevatron Stable Particle Check
- LEP Higgs Search
- Tevatron Higgs contraints

- Check Relic Density
- Check Direct WIMP Detection Cross Sections

- Tevatron Constraints
  - jets + missing energy
  - **trileptons**

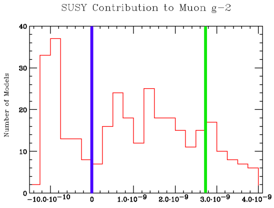
PGS

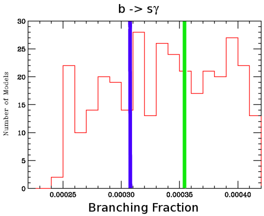
PYTHIA

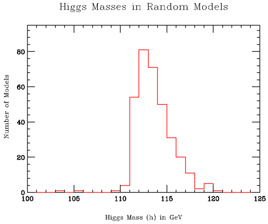
PROSPINO

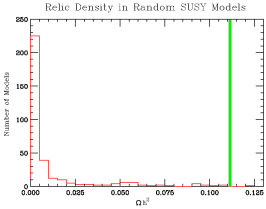
Super-Preliminary Results

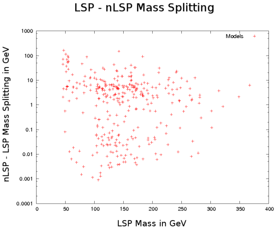
We ran 117,659 models through the above checks (except for Tevatron jet + missing and trilepton). We obtained 333 models (.28%).


SUSY Contribution to Muon g−2


b -> sγ


Higgs Masses in Random Models


Relic Density in Random SUSY Models


LSP - nLSP Mass Splitting

Conclusions

- We performed the largest study of the general MSSM at ILC, in part to see if the ILC could solve the LHC Inverse Problem
- We find that for the models studied by AKTW, the ILC is only able to break LHC degeneracies in about 1/3 of cases
- We are generating large new sets of MSSM models which will satisfy existing theoretical and experimental constraints
- This is the first study that looks at a large number of generic models in the ~ 20 parameter MSSM with all major experimental constraints included.

Why Small Mass Splittings

In 260 of 333 models, nLSP is a chargino. Following Martin's SUSY Primer (hep-ph/9709356v4), if

$$m_Z \ll |\mu \pm M_1|, \, |\mu \pm M_2|,$$

then there will be a wino-like neutralino with mass

$$m_{\widetilde{N}_2} = M_2 - \frac{m_W^2(M_2 + \mu \sin 2\beta)}{\mu^2 - M_2^2} + \ldots$$

and a wino-like chargino with mass

$$m_{\widetilde{C}_1} = M_2 - \frac{m_W^2(M_2 + \mu \sin 2\beta)}{\mu^2 - M_2^2} + \ldots$$

So in these cases the neutralino and chargino are nearly degenerate.