Exploring light Higgsinos with the ILC

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Why light Higgsinos?

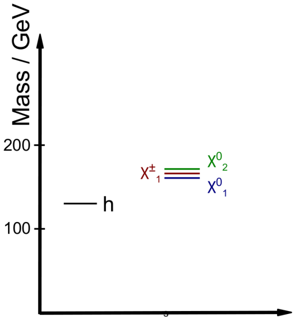
- Higgsino mass μ directly related to Z mass:

$$m_Z^2 = 2\frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - 2\mu^2 \ .$$

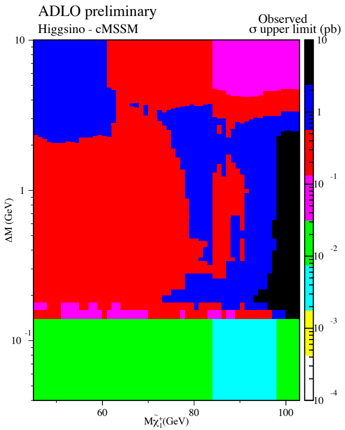
- at least μ should be small to avoid large cancellations, i.e. fine-tuning
  $\Rightarrow$ 3 light Higgsinos $\lesssim$ 200 GeV, with small mass splitting $\Delta m \lesssim 10$ GeV

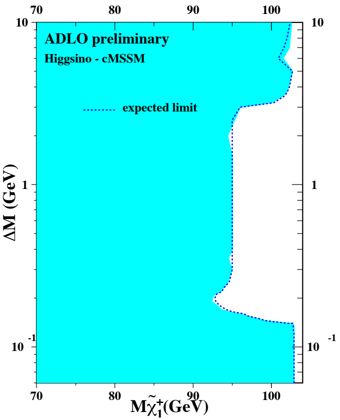
other SUSY partners

- some could be around $\sim$ 1 TeV, esp. $\tilde{t}$ and $\tilde{g}$
- extreme case "Higgsino world" / "LHC nightmare": all other SUSY particles multi-TeV



What do we know about light Higgsinos? → LEP!



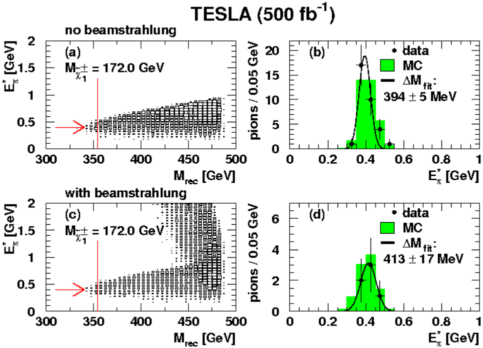


TESLA Study: $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 \pi^\pm$ in AMSB

Results for $M_{\tilde{\chi}_1^\pm} = 172$ GeV, $\Delta M = 0.4$ GeV:

[PhD thesis C. Hensel, Hamburg, 2002]

- uncertainty on $M_{\tilde{\chi}_1^\pm} = 1$ GeV
- uncertainty on $\Delta M = 17$ MeV
- including beamstrahlung / pair background
- main difference to Higgsino scenario: $\tilde{\chi}_2^0$ at higher mass



⇒ first thing to check for Higgsinos: $\tilde{\chi}_1^\pm$ vs $\tilde{\chi}_2^0$ separation!

The ILC Higgsino Study: Benchmark Choices

$m_h = 124$ GeV

- $M_{\tilde{\chi}_2^0} = 166.9$ GeV
- $M_{\tilde{\chi}_1^\pm} = 165.8$ GeV
- $M_{\tilde{\chi}_1^0} = 164.2$ GeV

$m_h = 127$ GeV

- $M_{\tilde{\chi}_2^0} = 167.6$ GeV
- $M_{\tilde{\chi}_1^\pm} = 167.4$ GeV
- $M_{\tilde{\chi}_1^0} = 166.6$ GeV

Higgsino Production

Allowed processes:

- $e^+e^- \to \tilde{\chi}^0_2\tilde{\chi}^0_1$
- $e^+e^- \to \tilde{\chi}^+_1\tilde{\chi}^-_1$

Cross-sections with $E_\gamma > 10$ GeV, $Q^2 > 4$ GeV^2:

	$m_h = 124$ GeV		$m_h = 127$ GeV	
$P(e^+, e^-)$	(-1,+1)	(+1,-1)	(-1,+1)	(+1,-1)
$\sigma(\tilde{\chi}^+_1\tilde{\chi}^-_1\gamma)$ [fb]	133	26.9	130	26.3
$\sigma(\tilde{\chi}^0_2\tilde{\chi}^0_1\gamma)$ [fb]	80.1	61.6	80.0	60.8

Chargino Decays: important branching ratios

	$m_h = 124$ GeV	$m_h = 127$ GeV
$\mathrm{BR}(\tilde{\chi}_1^+ \to e^+ \nu_e \tilde{\chi}_1^0)$	17.3%	15.0%
$\mathrm{BR}(\tilde{\chi}_1^+ \to \mu^+ \nu_\mu \tilde{\chi}_1^0)$	16.6%	13.7%
$\mathrm{BR}(\tilde{\chi}_1^+ \to \pi^+ \tilde{\chi}_1^0)$	16.5%	60%
$\mathrm{BR}(\tilde{\chi}_1^+ \to \pi^+ n(\pi^0) n(\gamma) \tilde{\chi}_1^0)$	36.7%	7.3%
$\mathrm{BR}(\tilde{\chi}_1^+ \to$ 1-prong with Kaons	2.8%	3.5%
$\mathrm{BR}(\tilde{\chi}_1^+ \to$ 3-prong	9.8%	0.3%

Neutralino Decays: important branching ratios

	$m_h = 124$ GeV	$m_h = 127$ GeV
BR($\tilde{\chi}^0_2 \to \gamma\tilde{\chi}^0_1$)	23.6%	74.0%
BR($\tilde{\chi}^0_2 \to e^+e^-\tilde{\chi}^0_1$)	3.7%	1.6%
BR($\tilde{\chi}^0_2 \to \mu^+\mu^-\tilde{\chi}^0_1$)	3.7%	1.5%
BR($\tilde{\chi}^0_2 \to \nu\bar{\nu}\tilde{\chi}^0_1$)	21.9%	9.6%
BR($\tilde{\chi}^0_2 \to$ hadrons	44.8%	12.6%
BR($\tilde{\chi}^0_2 \to \tilde{\chi}^+_1$+X	2%	0.4%

Lifetime

very small Δm:

- phase space suppression $\rightarrow$ long lifetime
- examples:
  - $M_{\tilde{\chi}_2^0} = 167.6$ GeV, $\Delta M = 1.0$ GeV $\Rightarrow c\tau^* = 72\ \mu$m
  - $M_{\tilde{\chi}_1^\pm} = 167.4$ GeV, $\Delta M = 0.8$ GeV $\Rightarrow c\tau^* = 750\ \mu$m
- visibility?
  - $\tilde{\chi}_2^0$: $\sim 75\%$ to single photon $\rightarrow$ look at pair conversions?
  - $\tilde{\chi}_1^\pm$: $\sim 100\%$ to charged, mostly 1-prong $\rightarrow$ impact parameter,
but also 3-prong $\rightarrow$ vertexing
- interesting study!

Experimental Setup

Accelerator assumptions

- ILC TDR $\sqrt{s} = 500$ GeV
- $\int \mathcal{L} dt = 500$ fb^{-1}
- $P(e^+, e^-) = (+30\%, -80\%)$: not optimal → conservative!
- ILD detector;
  fast simulation SGV (signal)
  full sim. Mokka+Marlin (SM)

Simulation framework

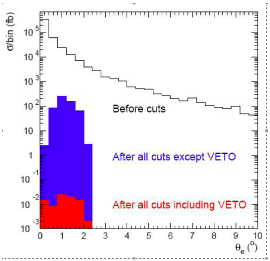
- generate Higgsino events in ILC-Whizard 1.95
- decay / hadronisation by Pythia → goes wrong for small mass differences: phase space vs hadron masses! not taken into account in hadronisation
- ⇒ *reweight* generated events to correct BR's

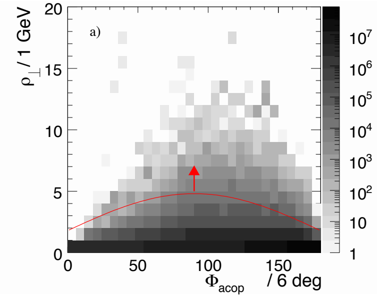
Backgrounds: $\gamma\gamma$ processes

$e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^- f\bar{f}$ $\gamma\gamma \rightarrow f\bar{f}$

- mimicks signal if beam e's go down beampipe!
- require ISR seen in detector $\Rightarrow$ kicks beam electron into acceptance of the low angle calorimeters!

- real photon component of the beam
- estalished technique: scalar sum of transverse momenta w.r.t. thrust axis

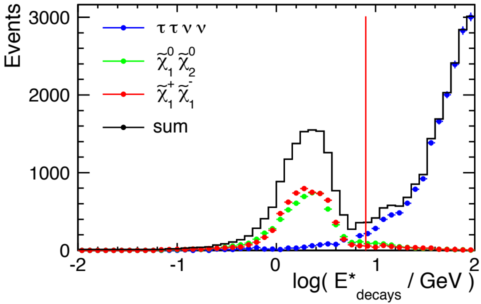




Backgrounds: e^+e^- processes

potentially dangerous:

- final states with lot of missing 4-momentum
- few visible particles, either soft photons or similar to τ's
- example: $e^+e^- \to \tau^+\tau^-\nu\bar{\nu}$
- $\Rightarrow$ boost decay products into $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ restframe

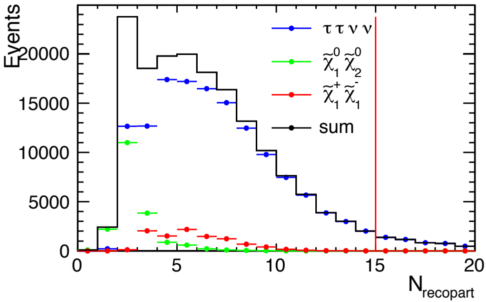


$$E^*_{\rm decay} = \frac{(\sqrt{s} - E_{\rm ISR})E_{\rm decay} - \vec{p}_{\rm decay} \cdot \vec{p}_{\rm ISR}}{2M_{\tilde{\chi}^\pm}}$$

Event Selection

Cuts for Charginos and Neutralinos:

- $N(\text{rec.part}) < 15$
- $E^{\text{ISR}} > 10$ GeV, $|\cos\theta^{\text{ISR}}| < 0.993$
- $|\cos\theta^{\text{decay}}| < 0.94$
- $E_{\text{miss}} > 350$ GeV
- $E^{*}_{\text{decay}} < 3$ GeV



$\Rightarrow$ most dangerous e^+e^- process can be dealt with

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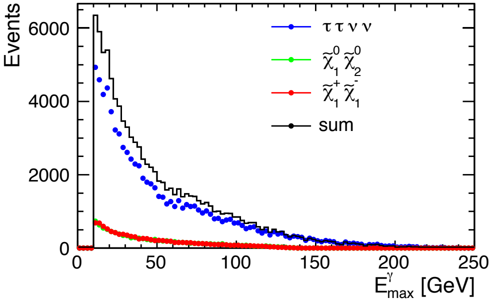

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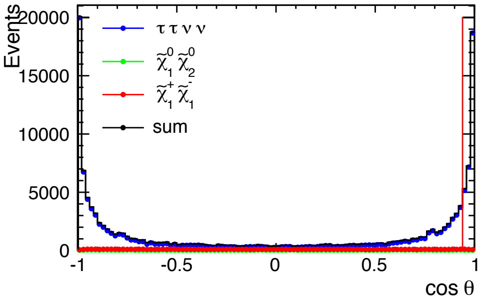

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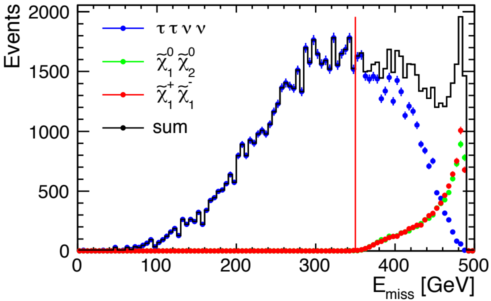

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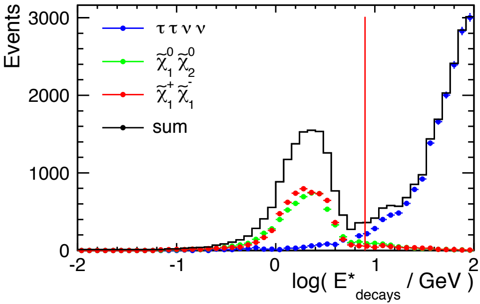

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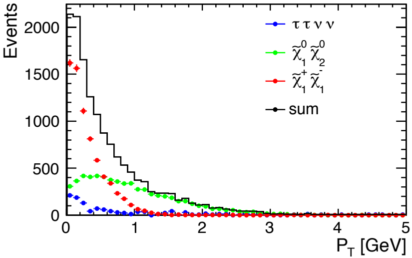
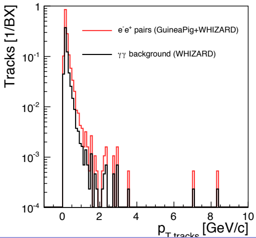
Separate Charginos and Neutralinos

For now use exclusive decay modes:

- $\tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow e/\mu\nu + \text{hadrons} + 2\tilde{\chi}_1^0$: BR $\simeq$ 50%
- $\tilde{\chi}_2^0 \tilde{\chi}_1^0 \rightarrow \gamma + 2\tilde{\chi}_1^0$: BR $\simeq$ 75%
- decay products are very soft
- effect of beam background and overlay from $\gamma\gamma \rightarrow$ low p_t hadrons needs to be studied
- changed by factor $\sim$ 2.5 from LoI / RDR

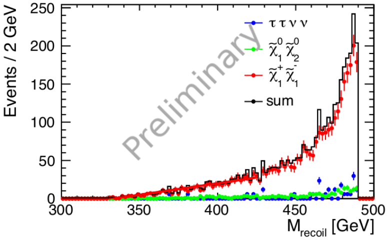




Mass Measurements

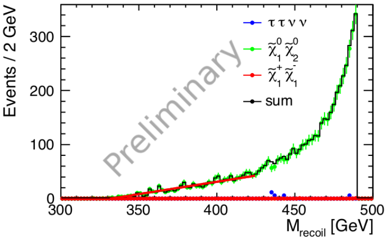
Chargino mass reconstruction

- select only $e/\mu+$ hadrons



Neutralino mass reconstruction

- select only radiative decaya



chargino – neutralino separation works well

- $\Rightarrow$ expect resolution for mass difference similar to AMSB study
- resolution on recoil mass < 1 GeV

Polarised cross-sections, ex $P(e^+, e^-) = (+30\%, -80\%)$

Preliminary!

Charginos: semi-leptonic events

- efficiency $\times$ BR $= 42\%$
- purity $= 85\%$
- $\delta\sigma/\sigma = \pm 2\%$(stat.)

Neutralinos: radiative events

- efficiency $\times$ BR $= 78\%$
- purity $= 98\%$
- $\delta\sigma/\sigma = \pm 1\%$ (stat.)

assumes BRs to be calculable and no systematics yet!

- for $P(e^+, e^-) = (-30\%, +80\%)$:
  signal increases, background decreases $\rightarrow$systematics?

Conclusions

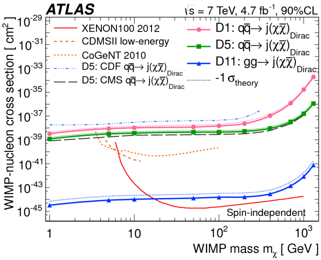
- Higgsinos at the ILC:
  - can be studied with percent level precision
    → SUSY parameter determination!
  - fragile signature:
    - still need to study machine backgrounds in TDR conditions
    - low background option for machine operation might be important
  - just starting to explore the possibilities:
    - *measure* branching ratios
    - exploit exclusive decay modes
    - lifetime

If light Higgsinos exist, the ILC will not only to Higgs precision measurements, but also Higgsino precision physics!

Higgsinos at the LHC

- will all look like $E_{\mathrm{t,miss}}$, thus indistinguishable
- direct production: $\rightarrow$ mono-jet / -photon searches
- Higgsinos: Z-exchange, Majorana
- but Higgsino cross-section than contact interactions assumed in WIMP interpretations
- irreducible background from $Z \rightarrow \nu\bar{\nu} \rightarrow$ very challenging:

[plot J.Hajer *et al*]



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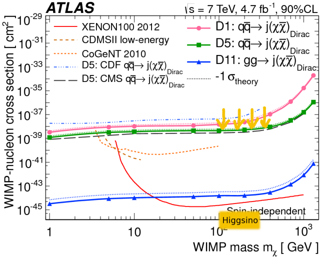

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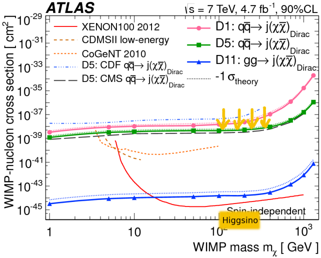
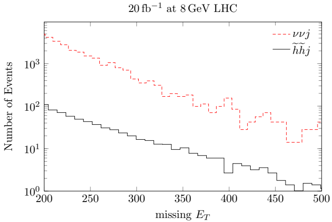




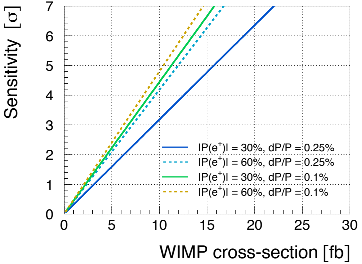
Higgsinos at the Linear Collider

Production

- $e^+e^- \to Z \to \tilde{\chi}_2^0\tilde{\chi}_1^0/\tilde{\chi}_1^+\tilde{\chi}_1^-$
- unpolarised cross-sections: **several 100 fb**
- beautiful beam polarisation dependence

"No-loose" approach [arXiv:1206.6639]

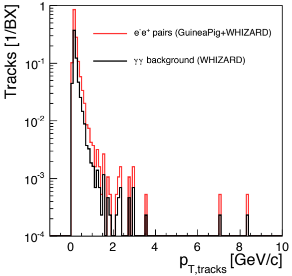
- mono-photon search: treat all higgsinos as missing energy à la LHC
- discover cross-sections down to 10 fb
- measure polarised x-sections to $\mathcal{O}(10\%)$
- measure M_χ to $\mathcal{O}(1)$ GeV
- distinguish s- and p-wave production



Re-evaluate

impact of e^+e^- pairs

- reduces efficiency of e veto in BeamCal
- backscatter from QD0 / BeamCal surface, fake tracks
- increased with RDR $\rightarrow$ TDR machine parameters



impact of parasitic soft $\gamma\gamma$ interactions in the same bunch:

- low p_t hadrons create extra activity, mostly in forward region
- has been studied with ILC-RDR ($\sqrt{s} = 500$ GeV)
- RDR $\rightarrow$ TDR: no. of overlay events grew by factor of ~ 2.5

Requirements for Higgsinos Studies

fragile signature → not trivial even at LC

- high polarisation, also at “low” energies (e.g. 350 GeV)
- efficient *e* veto in BeamCal → moderate pair background
- clean events → moderate soft $\gamma\gamma$ parasitic interactions
- important: flexibility to adjust background conditions, e.g. increase number of bunches per train and lower bunch lumi

CLIC

- 0.5 ns bunch spacing → whole bunch train piles up in detector
- even more interactions per BX
- impact on “fragile” final states ?