Light Higgsino Precision Measurements at the ILC

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Particles, Strings, and the Early Universe
Collaborative Research Center SFB 676

DESY

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Light Higgsino Scenario

Motivated by naturalness which requires μ at the electroweak scale

Scenario contains

- 3 light Gauginos, Higgsinos like: $\tilde{\chi}_1^\pm$ & $\tilde{\chi}_1^0$ & $\tilde{\chi}_2^0$
- Almost mass degenerate: $\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ & $\Delta M(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ $\sim$ a few GeV
- All other supersymmetric particles are heavy up to a few TeV

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- All other supersymmetric particles are heavy up to a few TeV

Mass Spectrum

Particle	Mass (GeV)
h	**124**
$\tilde{\chi}_1^0$	164.17
$\tilde{\chi}_1^{\pm}$	165.77
$\tilde{\chi}_2^0$	166.87
H's	$\sim 10^3$
$\tilde{\chi}$'s	$\sim 2-3 \times 10^3$

$\Delta M(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) = 1.59$ GeV

Mass Spectrum

Particle	Mass (GeV)
h	**127**
$\tilde{\chi}_1^0$	166.59
$\tilde{\chi}_1^{\pm}$	167.36
$\tilde{\chi}_2^0$	167.63
H's	$\sim 10^3$
$\tilde{\chi}$'s	$\sim 2-3 \times 10^3$

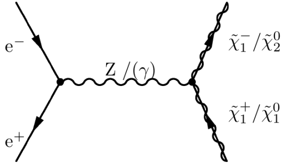
$\Delta M(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) = 0.77$ GeV

But also high scale models, for instance: "Hybrid Gauge-Gravity Mediated Supersymmetry Breaking Models" **Ref:** F. Brummer et al. hep-ph:1201.4338

Related Processes and Decay Modes

Two possible processes including the light Higgsinos

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



- Other combinations are kinematically allowed, but have negligible cross sections.

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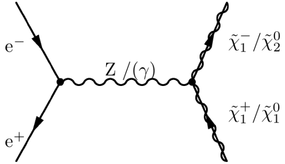
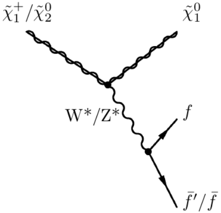


- Other combinations are kinematically allowed, but have negligible cross sections.

Decay Modes:

- For chargino:
  - $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 W^{\pm *}$
- For neutralino:
  - $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z^{0*}$



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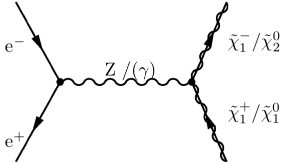

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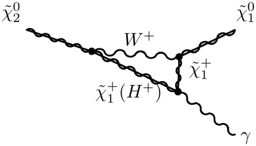
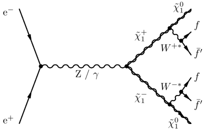
  - $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \gamma$



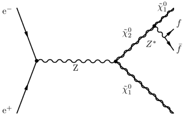
Separation of the Processes

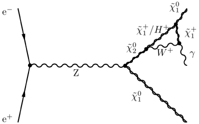
Chargino Process



➤ $\tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow 2\tilde{\chi}_1^0 +$
- * hadrons
- * leptons
- * semi-leptonic

Neutralino Process

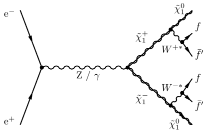




➤ $\tilde{\chi}_2^0\tilde{\chi}_1^0 \rightarrow 2\tilde{\chi}_1^0 +$
- * hadrons
- * leptons
- * photon

Separation of the Processes

Chargino Process



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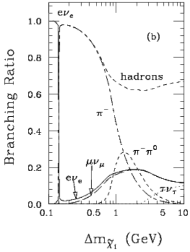
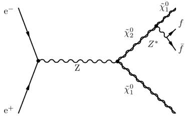
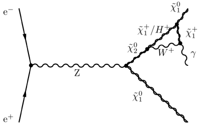
Ref: C.-H. Chen et al. hep-ph:9512230



Neutralino Process





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Separation of the Processes

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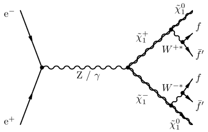

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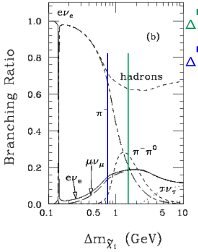
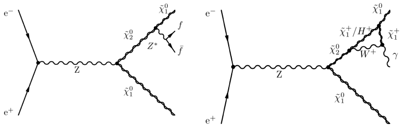


mh=124 GeV
$\Delta M = 1.59$ GeV

mh=127 GeV
$\Delta M = 0.77$ GeV

Neutralino Process



- $\tilde{\chi}_2^0\tilde{\chi}_1^0 \rightarrow 2\tilde{\chi}_1^0 +$
  - * hadrons
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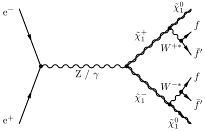
Separation of the Processes

Chargino Process



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* hadrons
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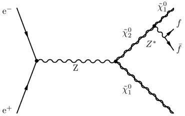
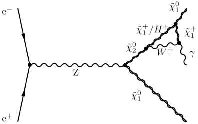
$m_h = 124$ GeV	$m_h = 127$ GeV
ΔM=1.59 GeV	ΔM=0.77 GeV
$e/\mu + \pi^{\pm}(\pi^0)$	$e/\mu + \pi^{\pm}$
$BR = 30.5\%$	$BR = 35\%$

Neutralino Process





➤ $\tilde\chi_2^0\tilde\chi_1^0 \rightarrow 2\tilde\chi_1^0 +$
* hadrons
* leptons
* photon

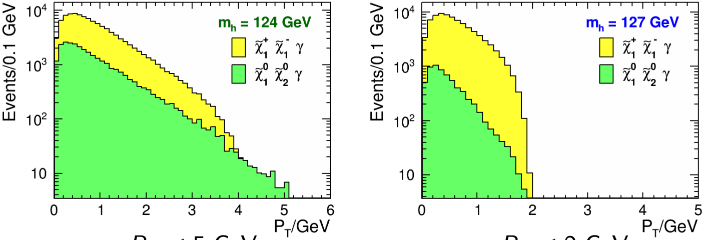
$m_h = 124$ GeV	$m_h = 127$ GeV
$BR(\gamma) = 23.6\%$	$BR(\gamma) = 74.0\%$

Higgsino Signatures and Challenges

In the Final State

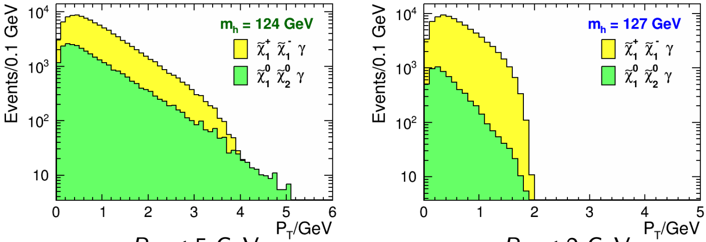
- A few soft visible particles
- A lot of missing energy (2 $\tilde{\chi}_1^0$)

Higgsino Signatures and Challenges



$P_T < 5$ GeV $P_T < 2$ GeV

Higgsino Signatures and Challenges



$P_T < 5$ GeV $\qquad$ $P_T < 2$ GeV

It is extremely challenging for LHC to observe or resolve such a low energetic and degenerate particles

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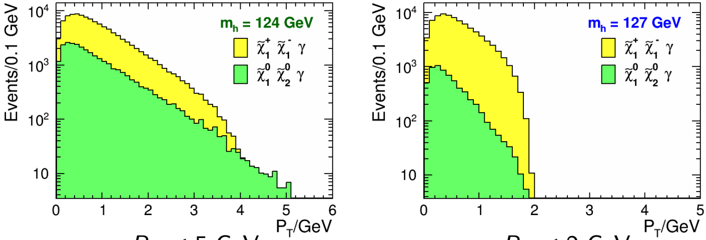

$P_T < 5$ GeV　　$P_T < 2$ GeV

It is extremely challenging for LHC to observe or resolve such a low energetic and degenerate particles

It is also non-trivial for ILC

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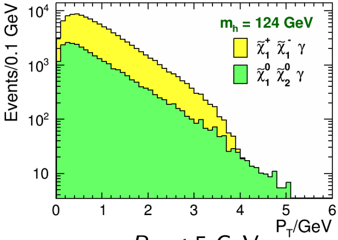
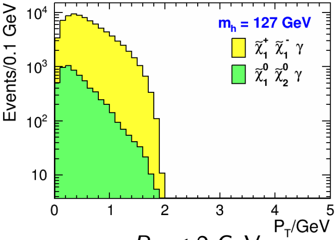


$P_T < 5$ GeV



$P_T < 2$ GeV

It is extremely challenging for LHC to observe or resolve such a low energetic and degenerate particles

It is also non-trivial for ILC

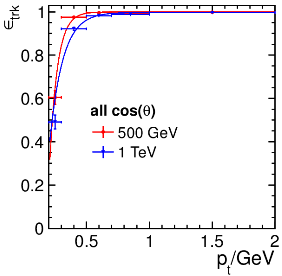
- It is very similar to some SM background final states, especially $\gamma\gamma \to f\bar{f}$.
- We have required hard ISR photon, to avoid this similarity.

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

Analysis Overview

Software:

- Generate events with Whizard (ILC-Whizard by generator group)
  Ref: Wolfgang Kilian et al., hep-ph: 0708.4233v2
  - Branching ratios are calculated by Herwig++
    Ref: M. Bahr et.al., *Eur.Phys.J.*, C58:639–707, 2008
- DBD generated samples for SM backgrounds
- Apply fast detector simulation SGV (ILD DBD version of SGV)
  Ref: M. Berggren, physics.ins-det: 1203.0217
- Track efficiency, which is obtained from full simulation including pair backgrounds, is applied for low P_t
  - Signals
  - Dominating SM background



Analysis Overview

Data Set:

- $\sqrt{s} = 500$ GeV
- $\int \mathcal{L} dt = 500\ \text{fb}^{-1}$ for each polarization
- Polarization:
  - $P_{e^+} = +30\%$, $P_{e^-} = -80\%$
  - $P_{e^+} = -30\%$, $P_{e^-} = +80\%$
- Cross Sections are calculated by whizard

	$m_h = 124$ GeV		$m_h = 127$ GeV	
Processes	$\tilde{\chi}_1^+ \tilde{\chi}_1^- \gamma$	$\tilde{\chi}_2^0 \tilde{\chi}_1^0 \gamma$	$\tilde{\chi}_1^+ \tilde{\chi}_1^- \gamma$	$\tilde{\chi}_2^0 \tilde{\chi}_1^0 \gamma$
$\sigma(e_L^+ e_R^- \to \tilde{\chi}\tilde{\chi}\gamma)$	26.83 ± 0.05	61.66 ± 0.10	26.28 ± 0.05	60.92 ± 0.10
$\sigma(e_R^+ e_L^- \to \tilde{\chi}\tilde{\chi}\gamma)$	132.99 ± 0.23	80.12 ± 0.13	130.05 ± 0.22	79.16 ± 0.13

Aim of the Study: To measure

- mass of the $\tilde{\chi}_1^+$ & $\tilde{\chi}_2^0$.
- mass difference between $\tilde{\chi}_1^+$ & $\tilde{\chi}_1^0$.
- precision on the polarized cross section

Measurement Strategy

$\tilde{\chi}_1^+$ & $\tilde{\chi}_2^0$ Mass Measurement ($M_{\tilde{\chi}_1^\pm}$ & $M_{\tilde{\chi}_2^0}$):

Recoil mass of hard ISR photon is used to measure mass of $\tilde{\chi}_1^+$ & $\tilde{\chi}_2^0$

Recoil Mass:

$$M^2_{recoil} = s - 2\sqrt{s}E^\gamma$$

- $M_{recoil} = 2 \times M_{\tilde{\chi}}$ at the rest frame of $\tilde{\chi} = \tilde{\chi}_1^\pm$ or $\tilde{\chi}_2^0$.
- Fitting gives $M_{\tilde{\chi}}$.

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Recoil Mass:

$$M_{recoil}^2 = s - 2\sqrt{s}E^\gamma$$

- $M_{recoil} = 2 \times M_{\tilde{\chi}}$ at the rest frame of $\tilde{\chi} = \tilde{\chi}_1^\pm$ or $\tilde{\chi}_2^0$.
- Fitting gives $M_{\tilde{\chi}}$.

However; this method is an approximation, since

- formula is obtained only after some assumptions
- $\sqrt{s}$ is assumed 500 GeV

Hence,

- calibration is applied to the masses.

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Recoil Mass: $M^2_{recoil} = s - 2\sqrt{s}E^\gamma$

Mass Difference Measurement ($\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$):

- Boost decay products to the rest frame of $\tilde{\chi}_1^\pm$

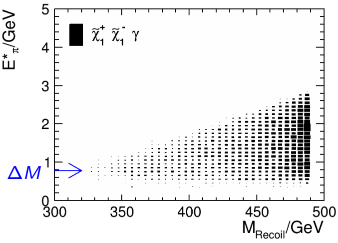
Boosted Energy:

$$E^*_\pi = \frac{(\sqrt{s} - E^\gamma)E^\pi + \mathbf{P}^\pi \cdot \mathbf{P}^\gamma}{2M_{\tilde{\chi}_1^\pm}}$$

At the rest frame of $\tilde{\chi}_1^\pm$;

- $\tilde{\chi}_1^0$ is produced at rest,

- $E^*_{decays} = \Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$



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Mass Difference Measurement ($\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$):

Boost decay products to the rest frame of $\tilde{\chi}_1^\pm$ ($E^*_{decays} = \Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$)

Boosted Energy: $E^*_\pi = \frac{(\sqrt{s}-E^\gamma)E^\pi + \mathbf{P}^\pi \cdot \mathbf{P}^\gamma}{2M_{\tilde{\chi}_1^\pm}}$

Polarized Cross Section Measurement ($\delta\sigma_{polarized}/\sigma_{polarized}$)

Statistical precision on polarized cross section

$$\frac{<\delta\sigma_{meas}>}{<\sigma_{meas}>} = \frac{1}{\sqrt{\epsilon \cdot \pi \cdot \int \mathcal{L}dt \cdot \sigma_{signal}}}$$

$$\sigma_{meas} = \sigma_{polarized} \times BR(\tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow 2\tilde{\chi}_1^0, \pi, e(\mu))$$

Estimated Precison is based on **efficiency** and **purity**

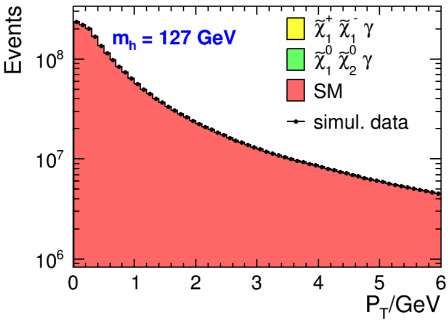
Event Selection

Signal:

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

Background:

- All SM backgrounds
  - $e^+e^- \to 2f, 4f, 6f$
  - $e^-\gamma - \gamma e^- \to 3f, 5f$
  - $\gamma\gamma \to 2f, 4f$

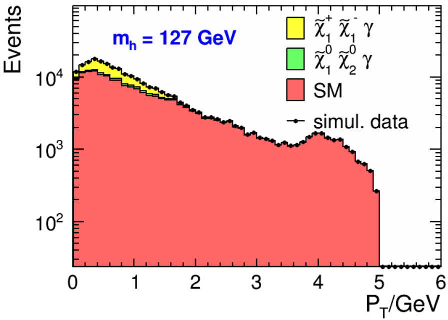


Before Any Selection

Event Selection

Preselection:

- $E_{beamcal} < 40$ GeV
- $N_{reconstructed\ \ particles} < 15$
- Require 1 photon with
  - $E_{\gamma}^{max} > 10$ GeV
  - $|\cos\theta_{\gamma}^{ISR}| < 0.993$
- $|\cos\theta_{soft}| < 0.9397$
- E_{soft} <5 GeV
- $E_{miss} > 300$ GeV
- $|\cos\theta_{miss}| < 0.992$

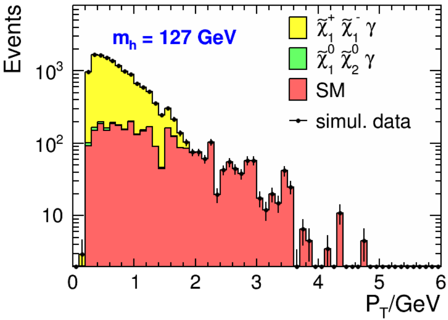


After PreSelection

Event Selection

Selection:

- $E_{beamcal} < 40$ GeV
- $N_{reconstructed\ \ particles} < 15$
- Require 1 photon with
  - $E_{\gamma}^{max} > 10$ GeV
  - $|\cos\theta_{\gamma}^{ISR}| < 0.993$
- $|\cos\theta_{soft}| < 0.9397$
- $E_{soft} < 5$ GeV
- $E_{miss} > 300$ GeV
- $|\cos\theta_{miss}| < 0.992$
- Select semi-leptonic decay modes
  - 1 π and (1 e or 1 μ)
- $E_{\pi}^{*} < 3$ GeV



After Chargino Selection

Event Selection

Selection:

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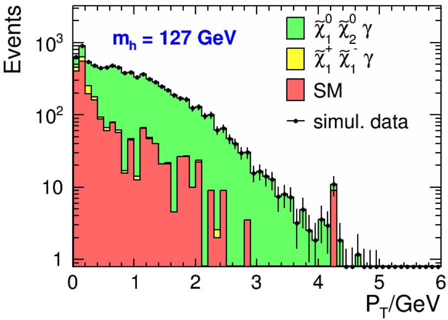
- Select semi-leptonic decay modes
  - 1 π and (1 e or 1 μ)
- $E_\pi^* < 3$ GeV
- Select photon decay mode
  - 1 γ

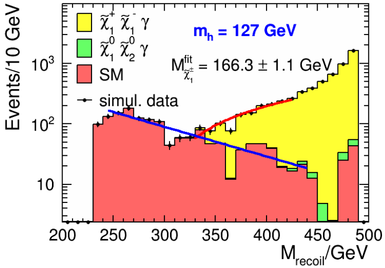


After Neutralino Selection

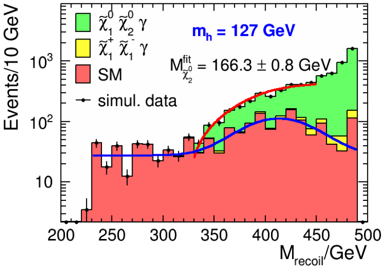
Mass Measurement Procedure

Fitting Procedure

- Fitting is done in the following order:
  - SM background is fitted with a convenient function assuming that we can precisely predict SM background.
  - SM background is fixed.
  - SM background + Signal are fitted using linear function for signal.



- SM Fit Function: Exponential
- Signal Fit Function: Linear

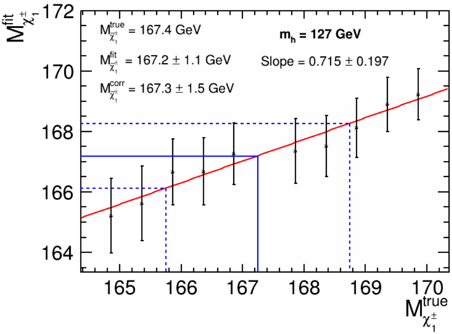


- SM Fit Function: Linear + Gaussian
- Signal Fit Function: Linear

Mass Measurement Procedure

Calibration Procedure

- Choose different true masses (X-axis)
- Apply measurement and get fitted masses (Y-axis)
- Obtain calibration curve



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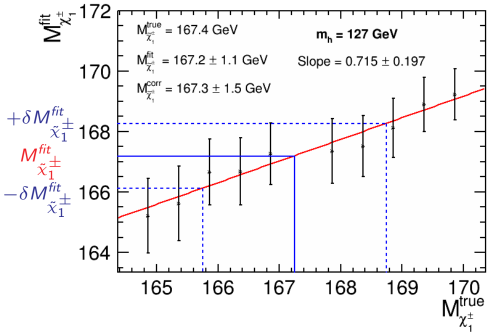
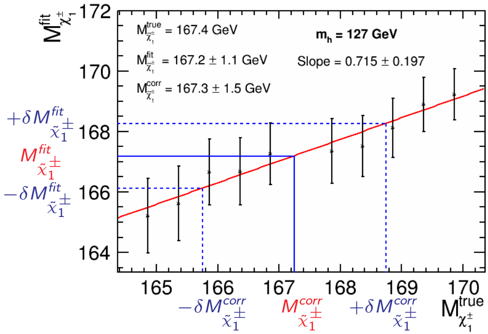


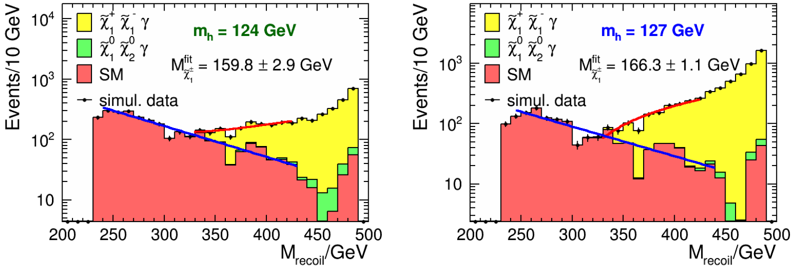
Mass Measurement Procedure

Calibration Procedure

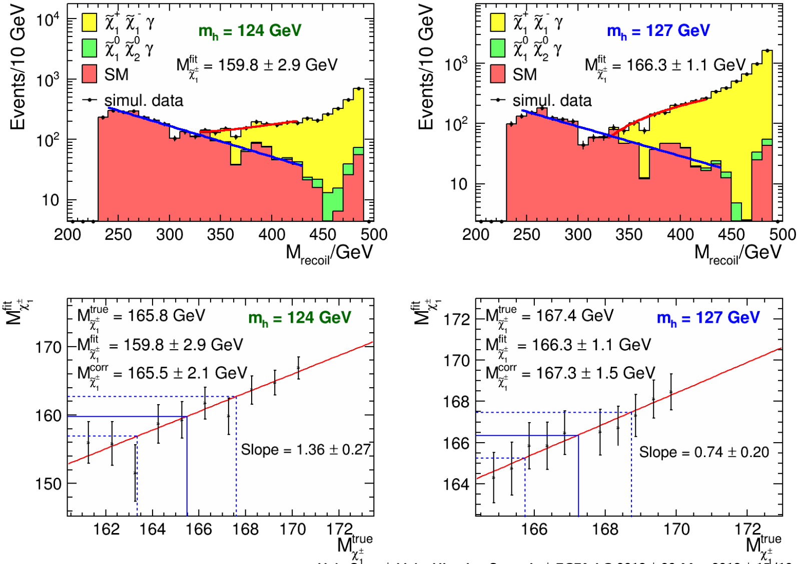
- Choose different true masses (X-axis)
- Apply measurement and get fitted masses (Y-axis)
- Obtain calibration curve



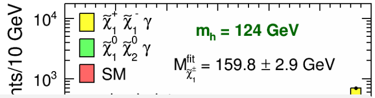
$\tilde{\chi}_1^+$ Mass Measurement & Calibration

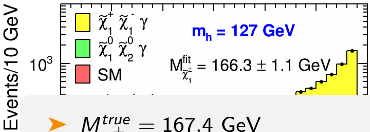


$\tilde{\chi}_1^+$ Mass Measurement & Calibration



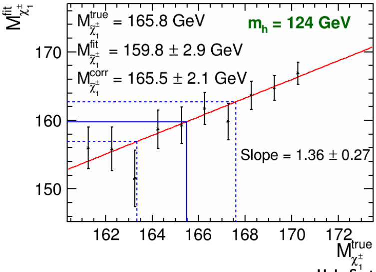
$\tilde{\chi}_1^+$ Mass Measurement & Calibration

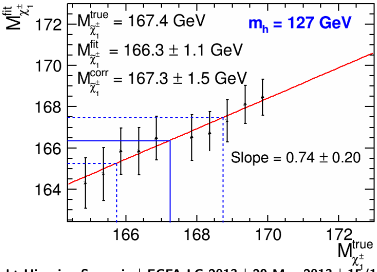




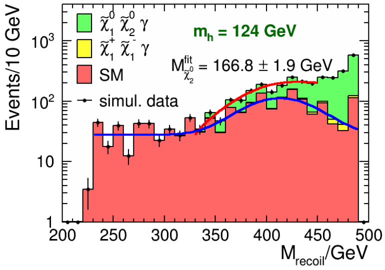
- $M^{true}_{\tilde{\chi}_1^\pm} = 165.8$ GeV
- $M^{fit}_{\tilde{\chi}_1^\pm} = 159.8 \pm 2.9$ (stat.) GeV
- $M^{corr}_{\tilde{\chi}_1^\pm} = 165.5 \pm 2.1$ (stat.) GeV

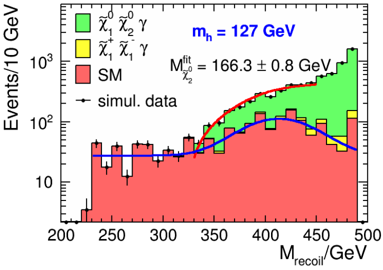
- $M^{true}_{\tilde{\chi}_1^\pm} = 167.4$ GeV
- $M^{fit}_{\tilde{\chi}_1^\pm} = 166.3 \pm 1.1$ (stat.) GeV
- $M^{corr}_{\tilde{\chi}_1^\pm} = 167.3 \pm 1.5$ (stat.) GeV



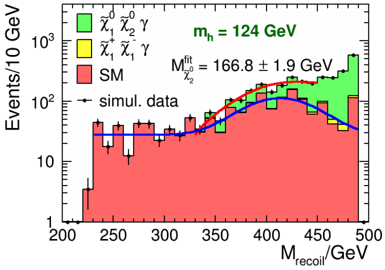


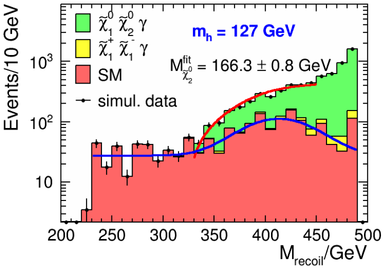
$\tilde{\chi}^0_2$ Mass Measurement & Calibration

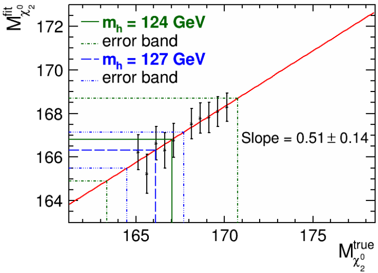




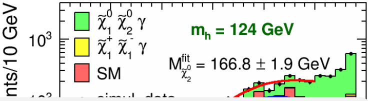
$\tilde{\chi}_2^0$ Mass Measurement & Calibration



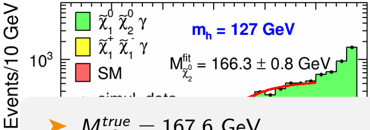




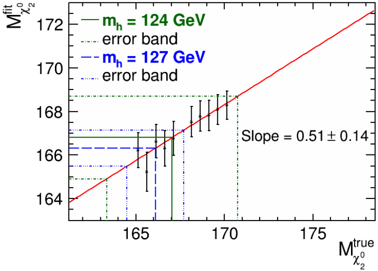
$\tilde{\chi}_2^0$ Mass Measurement & Calibration



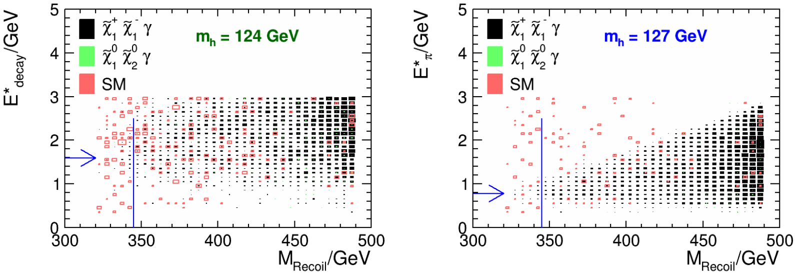
- $M^{true}_{\tilde{\chi}_2^0} = 166.9$ GeV
- $M^{fit}_{\tilde{\chi}_2^0} = 166.8 \pm 1.9$ (stat.) GeV
- $M^{corr}_{\tilde{\chi}_2^0} = 167.1 \pm 3.7$ (stat.) GeV



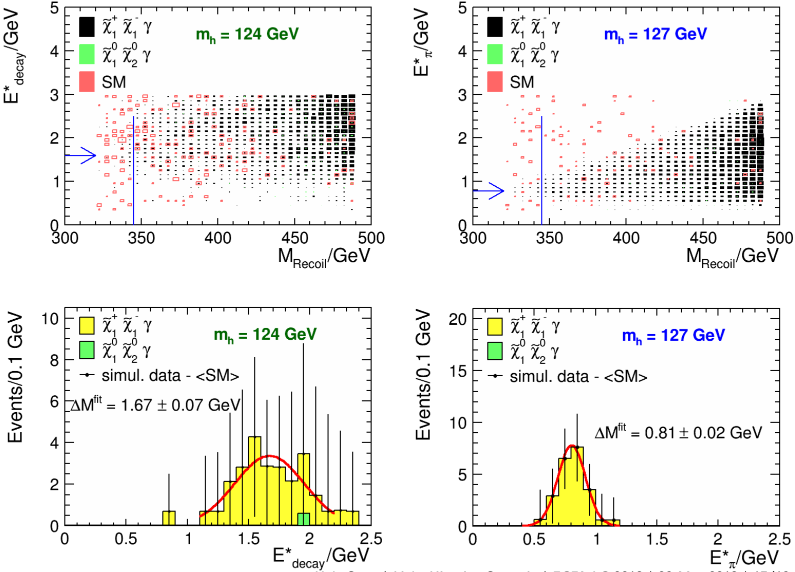
- $M^{true}_{\tilde{\chi}_2^0} = 167.6$ GeV
- $M^{fit}_{\tilde{\chi}_2^0} = 166.3 \pm 0.8$ (stat.) GeV
- $M^{corr}_{\tilde{\chi}_2^0} = 166.1 \pm 1.6$ (stat.) GeV



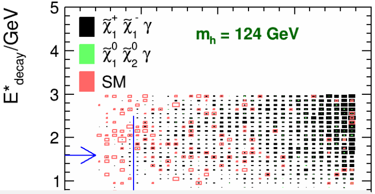
Mass Difference Measurement

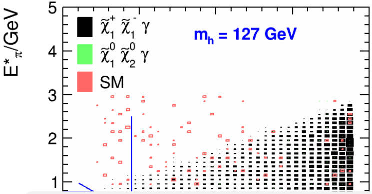


Mass Difference Measurement



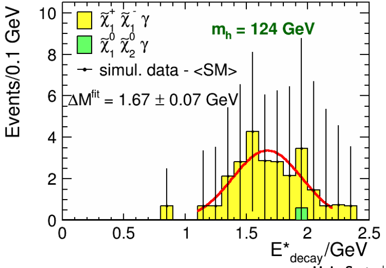
Mass Difference Measurement

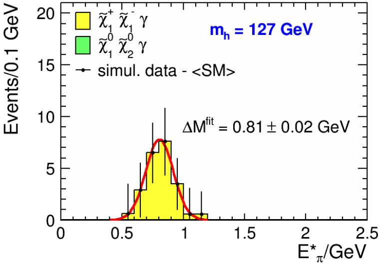




- $\Delta M^{true} = 1.59$ GeV
- $\Delta M^{fit} = 1.64 \pm 0.07$ GeV

- $\Delta M^{true} = 0.77$ GeV
- $\Delta M^{fit} = 0.81 \pm 0.02$ GeV



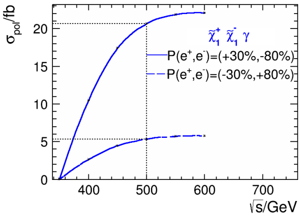


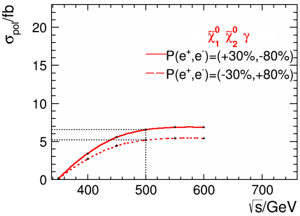
Polarized Cross Section Measurement

Efficiency, Purity and Precison on Polarized Cross Sections:

Polarizations	$P(e^+, e^-) = (+30\%, -80\%)$		$P(e^+, e^-) = (-30\%, +80\%)$	
Processes	$\tilde{\chi}_1^+ \tilde{\chi}_1^- \gamma$	$\tilde{\chi}_2^0 \tilde{\chi}_1^0 \gamma$	$\tilde{\chi}_1^+ \tilde{\chi}_1^- \gamma$	$\tilde{\chi}_2^0 \tilde{\chi}_1^0 \gamma$
m_h=124 GeV				
Efficiency($\epsilon \times BR$)	24.1 %	28.8 %	24.1 %	28.8 %
Purity(π)	62.8 %	50.9 %	32.4 %	49.6 %
$\frac{\langle \delta\sigma_{meas} \rangle}{\langle \sigma_{meas} \rangle}$	**2.3 %**	**3.4 %**	**6.5 %**	**3.8 %**
m_h=127 GeV				
Efficiency($\epsilon \times BR$)	41.4 %	29.7 %	41.4 %	29.7 %
Purity(π)	90.7 %	74.7 %	67.9 %	73.9 %
$\frac{\langle \delta\sigma_{meas} \rangle}{\langle \sigma_{meas} \rangle}$	**1.4 %**	**1.6 %**	**3.2 %**	**1.8 %**

Polarized Cross Sections:





Conclusion

- Light Higgsinos are well motivated by naturalness
- It is a challenging scenario for LHC
- Separation of Higgsinos at the reconstructed level is possible at the ILC
- Assumed
  - $\sqrt{s} = 500$ GeV
  - $\int \mathcal{L}dt = 500\ fb^{-1}$ with $P(e^+, e^-) = (+30\%, -80\%)$ and $P(e^+, e^-) = (-30\%, +80\%)$ each
- Statistical uncertainities for $P(e^+, e^-) = (+30\%, -80\%)$

$\mathbf{m_h}$=124 GeV

- $\delta(\sigma \times BR) \approx 3\ \%$ $\delta M_{\tilde{\chi}_1^\pm}(M_{\tilde{\chi}_2^0}) \approx 2.1(3.7)$ GeV $\delta\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 70$ MeV

$\mathbf{m_h}$=127 GeV

- $\delta(\sigma \times BR) \approx 1.5\ \%$ $\delta M_{\tilde{\chi}_1^\pm}(M_{\tilde{\chi}_2^0}) \approx 1.5(1.6)$ GeV $\delta\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 20$ MeV

Conclusion

- Light Higgsinos are well motivated by naturalness
- It is a challenging scenario for LHC
- Separation of Higgsinos at the reconstructed level is possible at the ILC
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  - $\sqrt{s} = 500$ GeV
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m_h=124 GeV

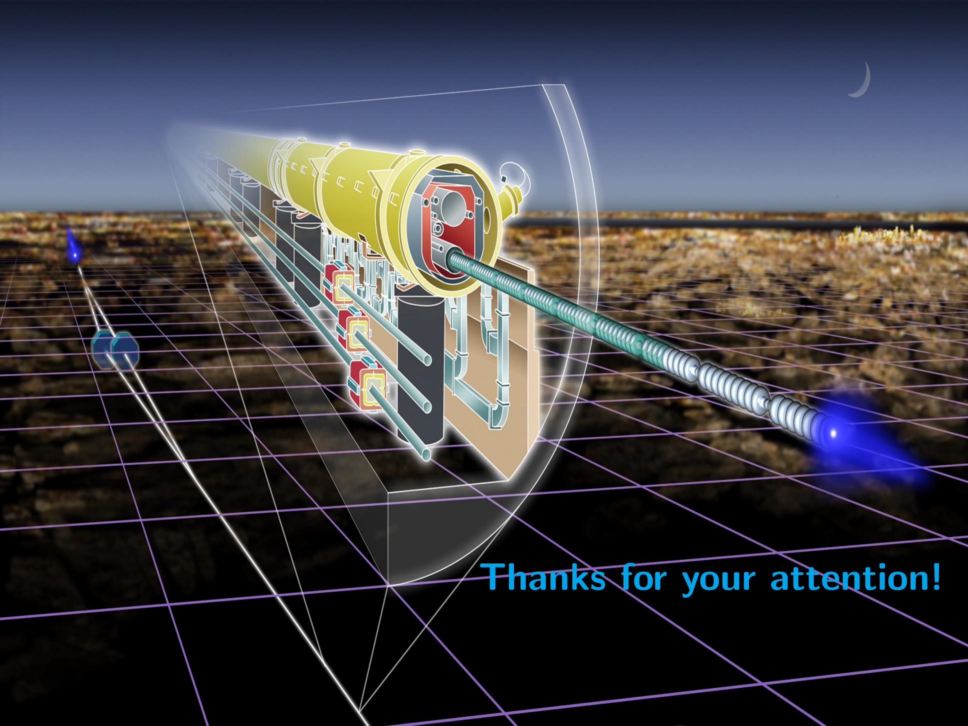
- $\delta(\sigma \times BR) \approx 3\ \%$ $\delta M_{\tilde{\chi}_1^\pm}(M_{\tilde{\chi}_2^0}) \approx 2.1(3.7)$ GeV $\delta\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 70$ MeV

m_h=127 GeV

- $\delta(\sigma \times BR) \approx 1.5\ \%$ $\delta M_{\tilde{\chi}_1^\pm}(M_{\tilde{\chi}_2^0}) \approx 1.5(1.6)$ GeV $\delta\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 20$ MeV

Can this scenario be used to calculate μ parameter and predict M_1 & M_2?

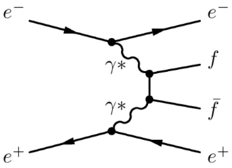
Krzysztof's talk


Thanks for your attention!

Backup

$\gamma\gamma \to \mathrm{f\bar{f}}$ SM background

$\gamma\gamma \to f\bar{f}$ SM background



- Outgoing particles go in the direction of the beampipe. So,

In the final state:

- 2 fermions with low energy, which is very similar to the signal

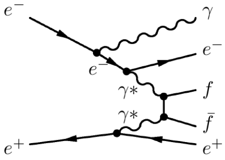
➤ We have required hard ISR photon,

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

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

to avoid this similarity of the final states.

➤ For $\gamma\gamma \to f\bar{f}$ SM background



additional γ makes the beam electron visible in the detector.

Polarized Cross Section Measurement

Number of events for two signals and all SM background:

Polarizations	$P(e^+, e^-) = (+30\%, -80\%)$			$P(e^+, e^-) = (-30\%, +80\%)$		
Processes	$\tilde{\chi}_1^+ \tilde{\chi}_1^- \gamma$	$\tilde{\chi}_2^0 \tilde{\chi}_1^0 \gamma$	All SM Bkg	$\tilde{\chi}_1^+ \tilde{\chi}_1^- \gamma$	$\tilde{\chi}_2^0 \tilde{\chi}_1^0 \gamma$	All SM Bkg
m_h=124 GeV						
nocut	38672	24250	1.37×10^8	9817	19071	1.05×10^8
semi-lep sel	2872	82	906	712	62	893
photon sel	53	1733	1616	11	1414	1423
m_h=127 GeV						
nocut	38130	23940	1.37×10^8	9792	18773	1.05×10^8
semi-lep sel	5489	38	525	1408	32	634
photon sel	155	5224	1616	44	4128	1423

Measurement Results for Efficiency, Purity and Polarized Cross Sections:

Polarizations	$P_{e^+} = +30\%, P_{e^-} = -80\%$		$P_{e^+} = -30\%, P_{e^-} = +80\%$	
Processes	$\tilde{\chi}_1^+ \tilde{\chi}_1^- \gamma$	$\tilde{\chi}_2^0 \tilde{\chi}_1^0 \gamma$	$\tilde{\chi}_1^+ \tilde{\chi}_1^- \gamma$	$\tilde{\chi}_2^0 \tilde{\chi}_1^0 \gamma$
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Efficiency($\epsilon \times BR$)	24.1 %	28.8 %	24.1 %	28.8 %
Purity(π)	62.8 %	50.9 %	32.4 %	49.6 %
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$\frac{\langle \delta\sigma_{meas} \rangle}{\langle \sigma_{meas} \rangle}$	1.4 %	1.6 %	3.2 %	1.8 %