Tackling Light Higgsinos at the ILC

Hale Sert

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DESY
Hamburg University

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Universität Hamburg
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Collaborative Research Centre 676
Particles, Strings, and the Early Universe
The Structure of Matter and Space-Time

Outline

- Introduction
  - Natural SUSY
- Model Properties
  - Light Higgsino Scenario
  - Production Processes and Decay Modes
  - Higgsino Signatures and Challenges
- Measurement Strategy
  - Mass of $\tilde{\chi}_1^{\pm}$ & $\tilde{\chi}_2^0$ Measurement
  - Mass difference Measurement
  - Polarized Cross Section Measurement
- Event Selection
- Analysis Results
- Parameter Determination
- Conclusion

Natural SUSY

Z boson mass in one-loop level is given as

$$m_Z^2 = 2\frac{(m_{H_u}^2 + \Sigma_u^u)\tan^2\beta - m_{H_d}^2 - \Sigma_d^d}{1 - \tan^2\beta} - 2|\mu|^2$$

[@ large $\tan\beta$]

$$m_Z^2 = -2(m_{H_u}^2 + \Sigma_u^u + |\mu|^2)$$

with H_u is a SM-like Higgs.

Naturalness requires to have higgsino mass parameter μ at the electroweak scale.

- $\mu^2 \sim m_Z^2/2$ GeV $\rightarrow$ Light Higgsinos
- In one-loop level $\Sigma(\tilde{t}_{1,2}) \sim m_Z^2/2$ GeV $\rightarrow$ Light Stops

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Light Higgsino Scenario

Scenario contains

- 3 light higgsinos: $\tilde{\chi}_1^\pm$ & $\tilde{\chi}_1^0$ & $\tilde{\chi}_2^0$
- 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 (sub) GeV
- All other supersymmetric particles are heavy up to a few TeV

Two benchmark points are considered:

dm1600

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

dm770

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

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Production Processes

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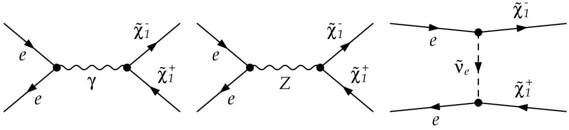
$$e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^-$$

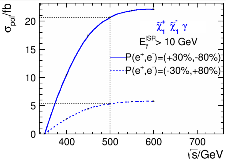
$$e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_2^0$$

Chargino Production Diagrams:



t-channel is suppressed / $Z-\gamma$ interference

Strong polarization dependence



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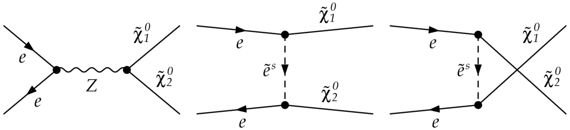

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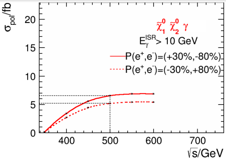
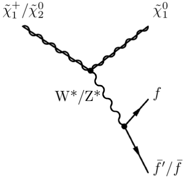
Weak polarization dependence

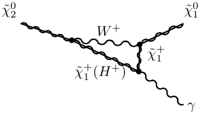


Decay Modes of the Higgsinos

Decay Modes

- $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 W^{\pm *}$
- $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z^{0*}$
- $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \gamma$



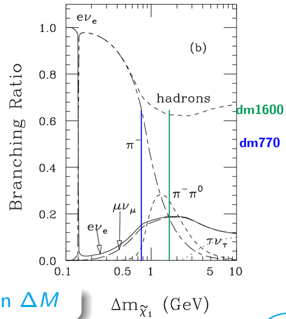


Separation of Signal Processes

Exclusive decay modes:

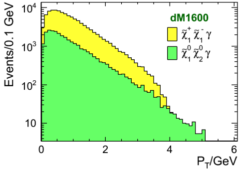
- $\tilde{\chi}_1^+\tilde{\chi}_1^+ \to 2\tilde{\chi}_1^0 \; W^{+*} \; W^{-*}$
  - semileptonic final state (30.5%, 35%)
- $\tilde{\chi}_1^0\tilde{\chi}_2^0 \to 2\tilde{\chi}_1^0 \; Z^{0*}/\gamma$
  - photonic final state (23.6%, 74%)

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



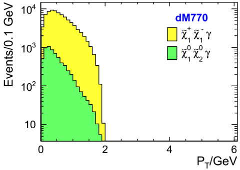
BRs depend crucially on ΔM

Higgsino Signatures and Challenges



In the Final State

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



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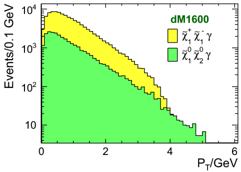

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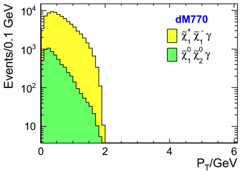
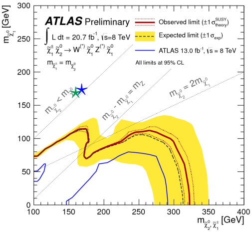
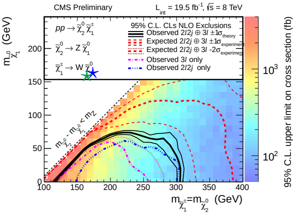


It is extremely challenging for LHC to observe or resolve such low energetic and degenerate particles



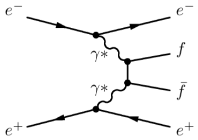
Ref: ATLAS-CONF-2013-035



Ref: CMS-PAS-SUS-13-006

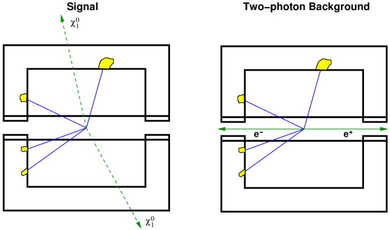
Standard Model Backgrounds

$\gamma\gamma \rightarrow 2f$



In the final state:

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



Ref: PhD thesis of C. Hensel

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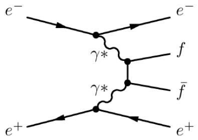

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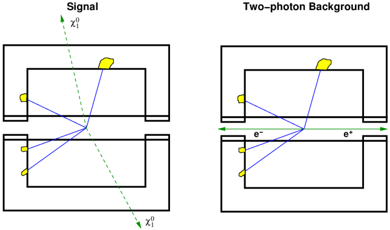

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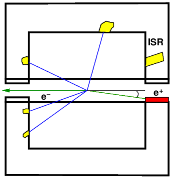
- We have required hard ISR photon,

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

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

to avoid this similarity of the final states.

- Additional γ makes the beam electron visible in the detector.



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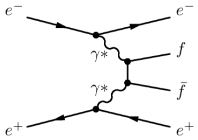

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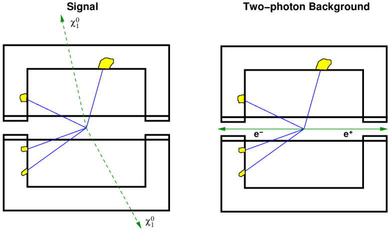

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to avoid this similarity of the final states.

- Additional γ makes the beam electron visible in the detector.

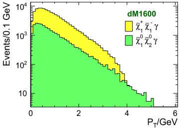
* This method is a well-known trick for $\gamma\gamma \to 2f$ background

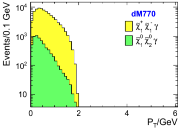
* In this study, it has been observed that this method doesn't work for $e\gamma \to 3f$ background

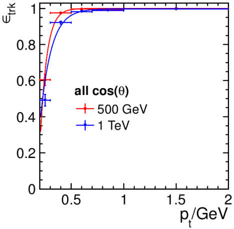
Analysis Overview

Software:

- Signal events are generated 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 is applied for low P_t
  - Signals
  - Dominating SM backgrounds







From full simulation including $t\bar{t}$ events and pair background

Analysis Overview

Data Set:

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

Aim of the Study:

To measure

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

To check

- if the measurements are good enough to determine μ, M_1, M_2 and $\tan\beta$

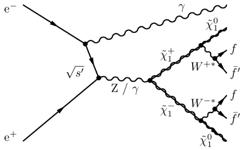
Measurement Strategy

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

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

Reduced CM Energy:

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



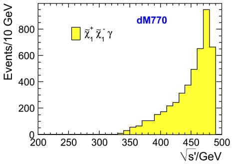
- $\sqrt{s'} = 2 \times M_{\tilde{\chi}}$ if 2 $\tilde{\chi}$ are produced at rest
- Fitting gives $M_{\tilde{\chi}}$.

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.



DESY

Measurement Strategy

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:

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

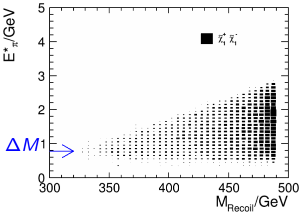
At the rest frame of $\tilde{\chi}_1^\pm$;

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

$$E_\pi^* = \frac{(M_{\tilde{\chi}_1^\pm} - M_{\tilde{\chi}_1^0})(M_{\tilde{\chi}_1^\pm} + M_{\tilde{\chi}_1^0}) + m_\pi^2}{2M_{\tilde{\chi}_1^\pm}}$$

$$E_\pi^* = \frac{1}{1/\Delta M + 1/\sum M} + \frac{m_\pi^2}{2M_{\tilde{\chi}_1^\pm}}$$

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



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

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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

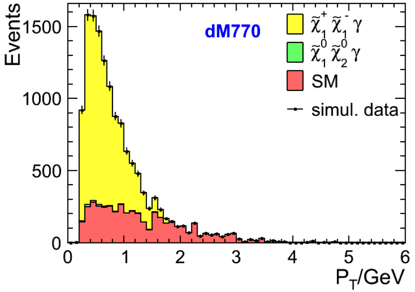
- Preselection is applied to suppress the SM background

Chargino Selection

- Select semi-leptonic decay modes
  - 1 π and (1 e or 1 μ)
- $E^*_\pi < 3$ GeV
- $\Phi_{acop} < 2$ or $\sqrt{s'} < 480$ GeV

Neutralino Selection

- Select photon decay modes
  - Only photons
- $|\cos\theta_{\gamma soft}| < 0.85$
- $E^*_{\gamma_{soft}} > 0.5$ GeV



After Chargino Selection

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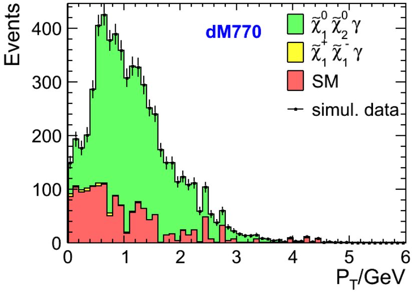
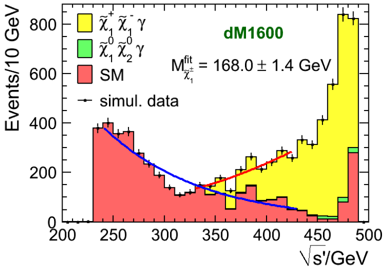
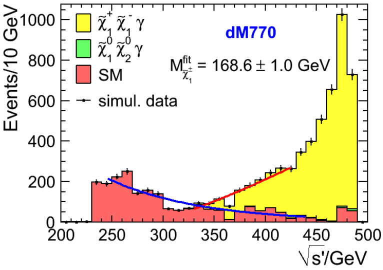


After Neutralino Selection

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





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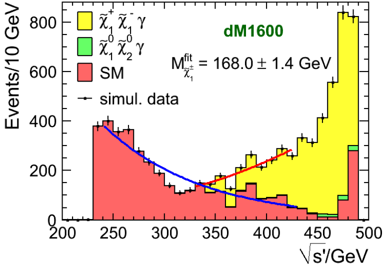

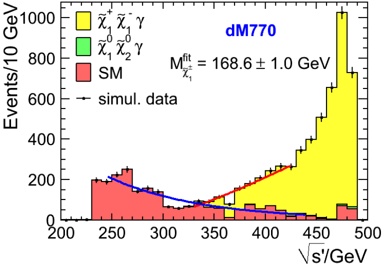

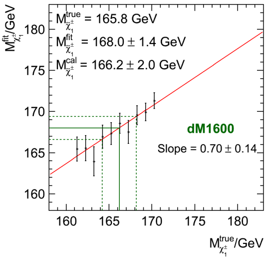

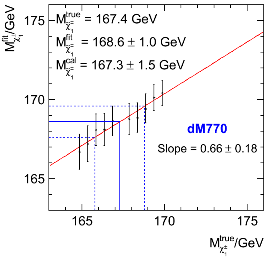

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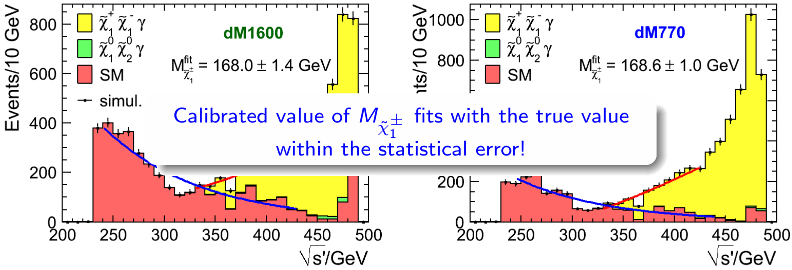
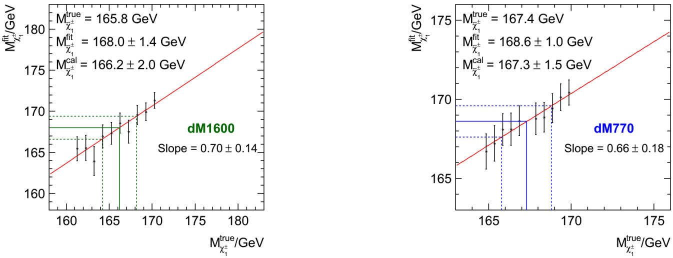
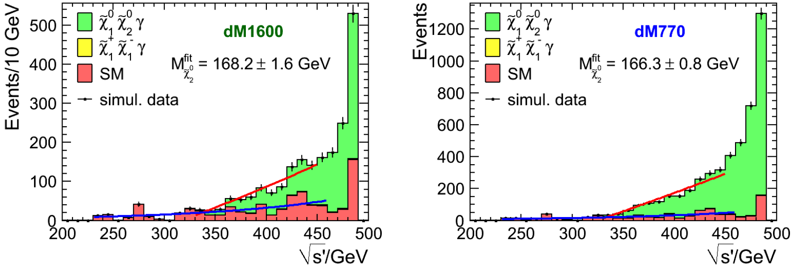


Calibrated value of $M_{\tilde{\chi}_1^\pm}$ fits with the true value within the statistical error!



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



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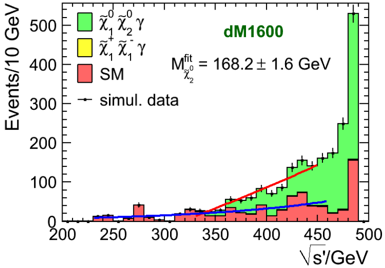
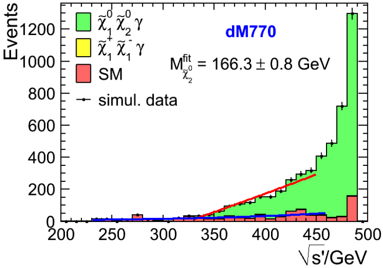
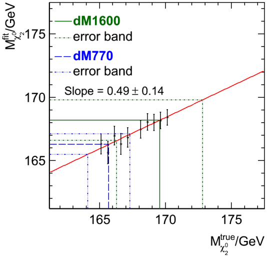
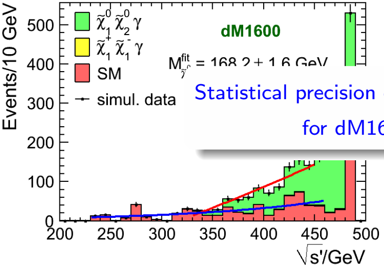


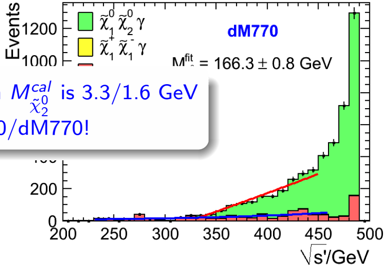




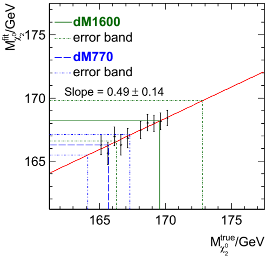
dM1600	dM770
$M^{true}_{\tilde{\chi}_2^0}$ = 166.9 GeV	$M^{true}_{\tilde{\chi}_2^0}$ = 167.6 GeV
$M^{fit}_{\tilde{\chi}_2^0}$ = 168.2 ± 1.6 GeV	$M^{fit}_{\tilde{\chi}_2^0}$ = 166.3 ± 0.8 GeV
$M^{cal}_{\tilde{\chi}_2^0}$ = 169.6 ± 3.3 GeV	$M^{cal}_{\tilde{\chi}_2^0}$ = 165.7 ± 1.6 GeV

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



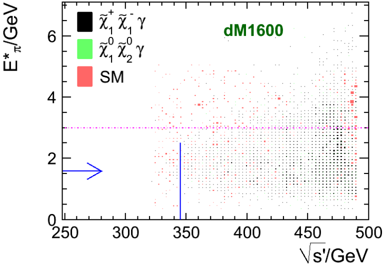


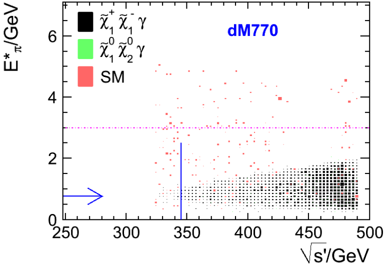
Statistical precision on $M^{cal}_{\tilde{\chi}_2^0}$ is 3.3/1.6 GeV for dM1600/dM770!



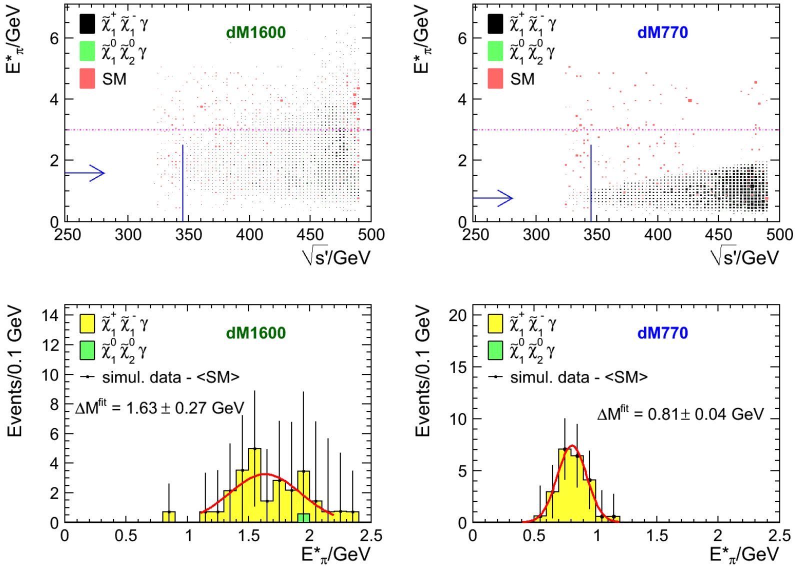
	dM1600	dM770
$M^{true}_{\tilde{\chi}_2^0}$	166.9 GeV	167.6 GeV
$M^{fit}_{\tilde{\chi}_2^0}$	168.2 ± 1.6 GeV	166.3 ± 0.8 GeV
$M^{cal}_{\tilde{\chi}_2^0}$	169.6 ± 3.3 GeV	165.7 ± 1.6 GeV

Mass Difference Measurement

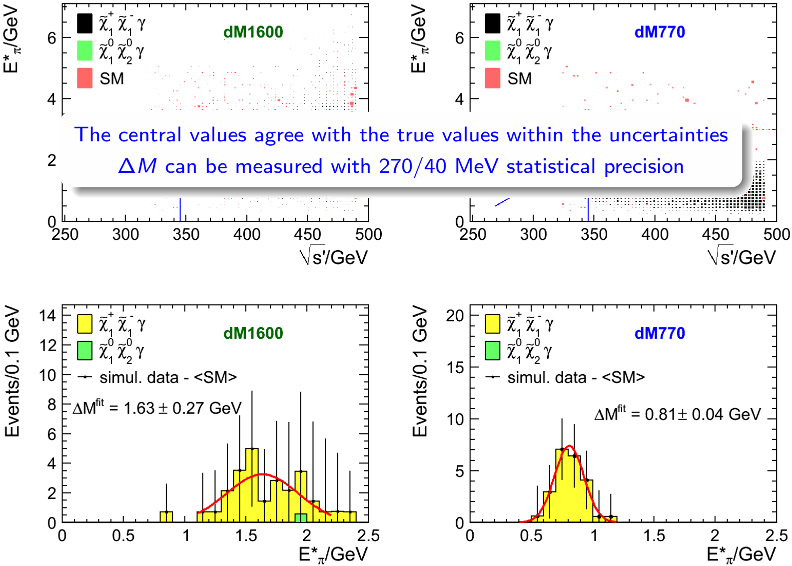




Mass Difference Measurement



Mass Difference Measurement



The central values agree with the true values within the uncertainties

ΔM can be measured with 270/40 MeV statistical precision

Polarized Cross Section Measurement

Efficiency, Purity and Precison on Polarized Cross Sections:

Polarizations	$P(e^+, e^-) = (+30\%, -80\%)$		$P(e^+, e^-) = (-30\%, +80\%)$	
Processes	$\tilde{\chi}_1^+\tilde{\chi}_1^-\gamma$	$\tilde{\chi}_2^0\tilde{\chi}_1^0\gamma$	$\tilde{\chi}_1^+\tilde{\chi}_1^-\gamma$	$\tilde{\chi}_2^0\tilde{\chi}_1^0\gamma$
dm1600				
BR of selected mode	30.5 %	23.6 %	30.5 %	23.6 %
Efficiency(ϵ)	9.9 %	5.8 %	9.5 %	6.0 %
Purity(π)	70.1%	67.4 %	36.4 %	62.3 %
$\frac{\langle \delta\sigma_{meas}\rangle}{\langle \sigma_{meas}\rangle}$	**1.9 %**	**3.2 %**	**5.3 %**	**3.7 %**
dm770				
BR of selected mode	34.7 %	74.0 %	34.7 %	74.0 %
Efficiency(ϵ)	12.1 %	17.1 %	12.2 %	17.2%
Purity(π)	85.3 %	85.8 %	56.1 %	82.5 %
$\frac{\langle \delta\sigma_{meas}\rangle}{\langle \sigma_{meas}\rangle}$	**1.6 %**	**1.7 %**	**3.8 %**	**1.9 %**

- Efficiencies are almost same for both polarizations
- Huge difference between purities for both polarizations in the chargino processes are due to the strong polarization dependence
- Cross sections can be measured more precisely using the polarisation with $e_R^+ e_L^-$

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

$$\sigma_{meas} = \sigma_{polarized} \times BR$$

Parameter Determination

Parameters related to chargino and neutralino sector:

$$M_1, \quad M_2, \quad \mu, \quad \tan\beta$$

Used parameters for the fit

- $M_{\tilde{\chi}_1^\pm}$, $M_{\tilde{\chi}_2^0}$, $\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$
- Statistical precision on the cross sections ($\delta\sigma/\sigma$)

Fit Procedure

- $\tan\beta$ is fixed in the range [1,60]
- Fit the mass parameters; μ, M_1 and M_2.

Parameter determination @ High Luminosity

- Luminosity is increased to $\int Ldt = 2\ ab^{-1}$ for each polarization
- It is assumed that experimental errors would be reduced by a factor 2
- The measurement of the $\Delta M(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ is also included (not measured in this analysis)

Electroweakino parameters & experimental observables

Relation between electroweakino parameters and experimental observables

Tree level masses in the case that M_1 & M_2 are large ($\theta_W \rightarrow$ Weinberg angle)

$$M_{\tilde{\chi}_1^\pm} = |\mu| - \sin 2\beta sign(\mu) \cos^2\theta_W \frac{m_Z^2}{M_2}$$

$$M_{\tilde{\chi}_{1,2}^0} = |\mu| \pm \frac{m_Z^2}{2}(1 \pm \sin 2\beta sign(\mu)) \left(\frac{\sin^2\theta_W}{M_1} + \frac{\cos^2\theta_W}{M_2}\right)$$

- They are **weakly** dependent on $\tan\beta$
- μ determines $M_{\tilde{\chi}_2^0}$ & $M_{\tilde{\chi}_1^\pm}$

$$M_{\tilde{\chi}_1^\pm} - M_{\tilde{\chi}_1^0} = \frac{m_Z^2}{2}\left(\frac{\sin^2\theta_W}{M_1} + \frac{\cos^2\theta_W}{M_2}\right) + \mathcal{O}\left(\frac{\mu}{M_i^2}, \frac{1}{\tan\beta}\right)$$

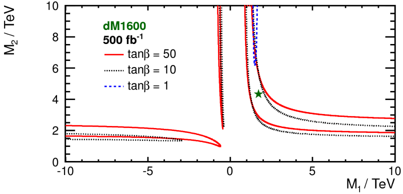
$$M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0} = m_Z^2\left(\frac{\sin^2\theta_W}{M_1} + \frac{\cos^2\theta_W}{M_2}\right) + \mathcal{O}\left(\frac{\mu}{M_i^2}\right)$$

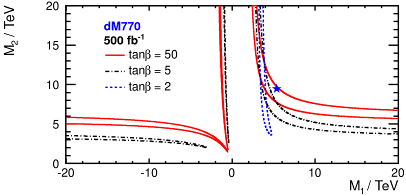
- M_1 & M_2 determine $\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ & $\Delta M(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$

Parameter Determination

Results

- Lower limits and allowed regions for M_1 and M_2 can be obtained from the correlation between M_1 and M_2
- For $M_1 < 0$, low values of $\tan\beta$ are excluded
- When $M_1 \sim$-500 GeV, direct production of $\tilde{\chi}^0_3$ could be possible at 1 TeV





- μ parameter can be determined with 6.8(2.5) GeV statistical precision for dM1600(dM770) scenario.

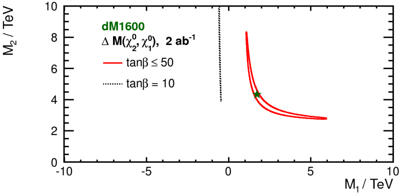
@ 500 fb^{-1}	input	lower	upper
$\|M_1\|$ [TeV]	1.7	$\sim$ 0.8(-0.4)	no
M_2 [TeV]	4.4	$\sim$ 1.5(1.0)	no
μ [GeV]	165.7	165.2	172.5

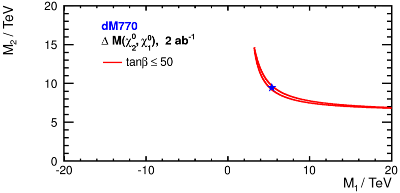
@ 500 fb^{-1}	input	lower	upper
$\|M_1\|$ [TeV]	5.3	$\sim$ 2(-0.3)	no
M_2 [TeV]	9.5	$\sim$ 3(1.2)	no
μ [GeV]	167.2	164.8	167.8

Parameter Determination at High Luminosity

Results:

- Inclusion of $\Delta M(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ breaks the dependency of M_1 & M_2 on the low $\tan\beta$ region
- In dM1600 scenario, if $M_1 < 0$ it gets very small values for moderate $\tan\beta$
- dM770 scenario has valid solutions only for $M_1 > 0$





- Increased luminosity narrows the allowed region for μ parameter

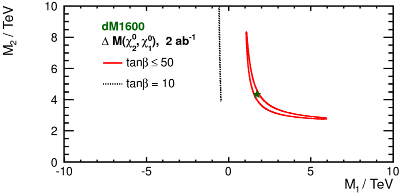
@ 2 ab^{-1}	input	lower	upper
M_1 [TeV]	1.7	∼ 1.0 (-0.4)	∼ 6.0
M_2 [TeV]	4.4	∼ 2.5 (3.5)	∼ 8.5
μ [GeV]	165.7	166.2	170.1

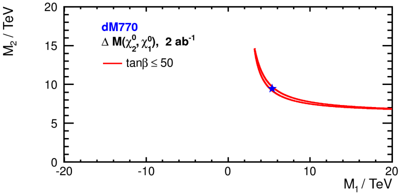
@ 2 ab^{-1}	input	lower	upper
M_1 [TeV]	5.3	∼ 3	no
M_2 [TeV]	9.5	∼ 7	∼ 15
μ [GeV]	167.2	165.2	167.4

Parameter Determination at High Luminosity

Results:

- Inclusion of $\Delta M(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ breaks the dependency of M_1 & M_2 on the low $\tan\beta$ region
- In dM1600 scenario, if $M_1 < 0$ it gets very small values for moderate $\tan\beta$
- dM770 scenario has valid solutions only for $M_1 > 0$





- Increase ... er

$\Delta M(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ has an important parameter for the fit!

@ 2 ab^{-1}	input	lower	upper
M_1 [TeV]	1.7	∼ 1.0 (-0.4)	∼ 6.0
M_2 [TeV]	4.4	∼ 2.5 (3.5)	∼ 8.5
μ [GeV]	165.7	166.2	170.1

@ 2 ab^{-1}	input	lower	upper
M_1 [TeV]	5.3	∼ 3	no
M_2 [TeV]	9.5	∼ 7	∼ 15
μ [GeV]	167.2	165.2	167.4

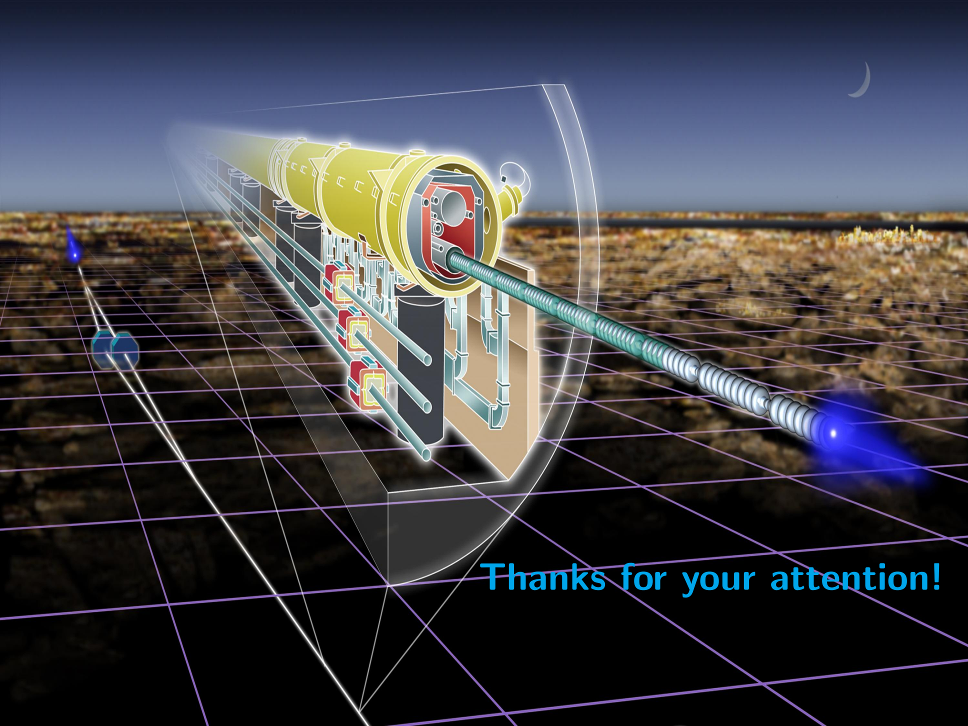
Conclusion

Summary

- Naturalness leads to have light higgsinos
- Studied extreme case of no other sparticles accessible at the ILC
- Separation of Higgsinos at the reconstructed level is possible at the ILC
- $\delta M_{\tilde{\chi}_1^\pm}(M_{\tilde{\chi}_2^0})$, $\delta\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$, and $\delta(\sigma \times BR)$ are small
- Precision is sufficent
  - to determine μ to a few percent
  - to constrain M_1, M_2 to narrow band, especially after adding $\Delta M(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$

Outlook

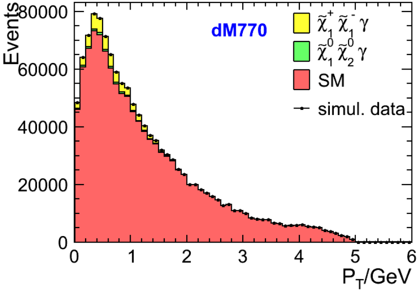
- Do the analysis with full simulation
- Measure neutralino mass difference, $\Delta M(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$


Thanks for your attention!

Backup

Preselection:

- Require 1 photon
  - with $E_\gamma^{max} > 10$ GeV
  - within the acceptance of TPC
- No significant activity in the BeamCal
- Less than 15 reconstructed particles
- $E_{\text{decay products}} < 5$ GeV
- $E_{miss} > 300$ GeV
- Both soft decay products and missing particles are required not to be in the forward region

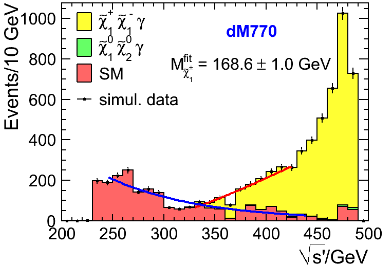


After PreSelection

Mass Measurement Procedure

Fitting Procedure

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



Calibration Procedure

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