Tackling Light Higgsinos at the ILC

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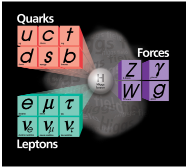
Outline

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

Standard Model (SM) and Beyond the SM

Standard Model

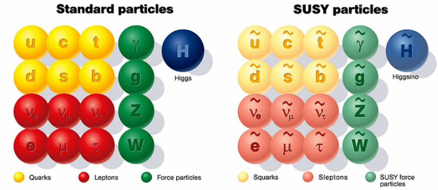


Standard Model problems

- Hierarchy problem
- Grand unification
- Dark Matter
- Baryon asymmetry
- CP violation

Supersymmetry is one of the theories proposed to solve the SM problems

- Each SM particles has their superpartners with 1/2 spin difference
- Superpartners couple like SM particles
- It is a **softly broken** symmetry [otherwise → $m_{\tilde{e}} = m_e$] **UNKNOWN**



In Minimal SUSY

Higgs Bosons: $h^0, H^0, A^0, H^\pm$

Higgsinos: $\tilde{h}^0, \tilde{H}^0, \tilde{A}^0, \tilde{H}^\pm$?

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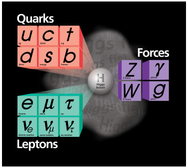

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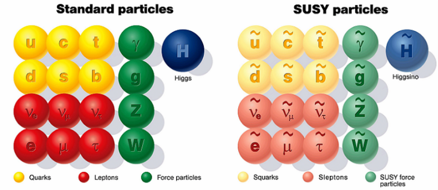

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Supersymmetric Particles of the SM bosons

SM(MSSM) Gauge Group: $SU(3)_C \times SU(2)_L \times U(1)_Y$

Electroweak Sector

Gauge Fields:

$B_\mu \rightarrow U(1)$
$W_\mu^i \rightarrow SU(2)$, $i = 1, 2, 3$

Higgs Doublets:

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$$

SM Bosons

$W^\pm \rightarrow W_\mu^1 \pm iW_\mu^2$

Z^0 & $\gamma \rightarrow W_\mu^3$ & B_μ

$h^0, H^0, A^0, H^\pm$

Electroweakino Sector

Gaugino Fields:

$\widetilde{B}_\mu \rightarrow U(1) \rightarrow$ *Bino*
$\widetilde{W}_\mu^i \rightarrow SU(2) \rightarrow$ *Wino* , $i = 1, 2, 3$

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Gaugino/Higgsino Mixing

Charginos ($\widetilde{\chi}_i^\pm$) $\rightarrow \left(\widetilde{W}^{+/-}, \widetilde{H}_{u/d}^{+/-}\right)$

Neutralinos ($\widetilde{\chi}_i^0$) $\rightarrow \left(\widetilde{B}_\mu^0, \widetilde{W}_\mu^3, \widetilde{H}_d^0, \widetilde{H}_u^0\right)$

with $\widetilde{W}^\pm \rightarrow \widetilde{W}_\mu^1 \pm i\widetilde{W}_\mu^2$

higgsino-like

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higgsino-like

Parameters of the Electroweakino Sector

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

Mass Parameters:

Soft SUSY Breaking Terms

- $M_1 \rightarrow$ Bino mass parameter
- $M_2 \rightarrow$ Wino mass parameter

Not related to the Soft SUSY Breaking

- $\mu \rightarrow$ Higgsino mass parameter

* It is allowed by unbroken SUSY
* It is the only dimensionful parameter in the MSSM

Other Parameter:

- $\tan\beta = \frac{<H_u^0>}{<H_d^0>} \rightarrow$ the ratio of Higgs vacuum expectation values

Higgino-like charginos and neutralinos

$$\text{if} \quad |\mu| << M_1, M_2$$

- $|\mu| \approx M_{\tilde{\chi}^0_{1,2}}, M_{\tilde{\chi}^\pm_1} \qquad M_1 \approx M_{\tilde{\chi}^0_{3/4}} \qquad M_2 \approx M_{\tilde{\chi}^\pm_2}, M_{\tilde{\chi}^0_{4/3}}$

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$\tilde{\chi}_1^0,\ \tilde{\chi}_2^0$ & $\tilde{\chi}_1^\pm$ are the interested Higgsinos

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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)

$$
\begin{aligned}
M_{\tilde{\chi}_1^\pm} &= |\mu| - \sin 2\beta\, sign(\mu) \cos^2\theta_W \frac{m_Z^2}{M_2} \\
M_{\tilde{\chi}_{1,2}^0} &= |\mu| \pm \frac{m_Z^2}{2}(1 \pm \sin 2\beta\, sign(\mu)) \left(\frac{\sin^2\theta_W}{M_1} + \frac{\cos^2\theta_W}{M_2} \right)
\end{aligned}
$$

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

$$
\begin{aligned}
M_{\tilde{\chi}_1^\pm} - M_{\tilde{\chi}_1^0} &= \frac{m_Z^2}{2} \left(\frac{\sin^2\theta_W}{M_1} + \frac{\cos^2\theta_W}{M_2} \right) + \mathcal{O}\left(\frac{\mu}{M_i^2}, \frac{1}{\tan\beta} \right) \\
M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0} &= m_Z^2 \left(\frac{\sin^2\theta_W}{M_1} + \frac{\cos^2\theta_W}{M_2} \right) + \mathcal{O}\left(\frac{\mu}{M_i^2} \right)
\end{aligned}
$$

- M_1 & M_2 determine $M_{\tilde{\chi}_2^0, \chi_1^\pm} - M_{\tilde{\chi}_1^0}$

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

Studied model contains **light higgsinos** but no other SUSY particles $<$ a TeV

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Light Higgsino Scenario

Motivated by naturalness which requires μ at the electroweak scale

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

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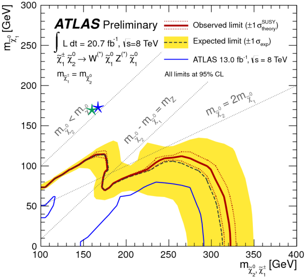
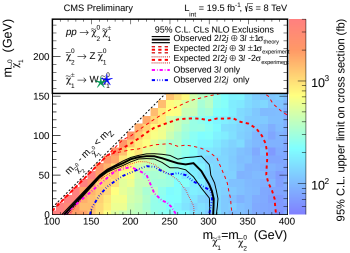
Due to small mass difference, it is a difficult scenario for LHC





Benchmark Points

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

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

light higgsinos

Input Model Parameters (dm1600)

Parameter	Value
μ	160 GeV
M_1	1.72 TeV
M_2	4.33 TeV
$\tan\beta$	43.81

Input Model Parameters (dm770)

Parameter	Value
μ	160 GeV
M_1	5.37 TeV
M_2	9.47 TeV
$\tan\beta$	47.66

$\mu << M_1 < M_2$

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

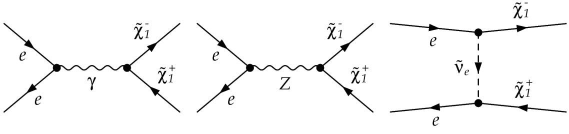
Production Processes

Production Processes:

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

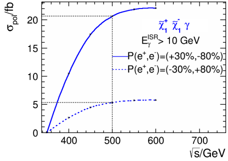
$$e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0$$

Chargino Production Diagrams:

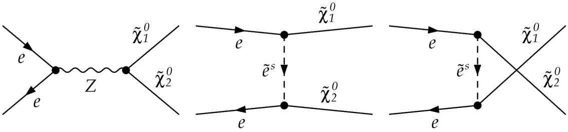


t-channel is suppressed / $Z-\gamma$ interference

Strong polarization dependence

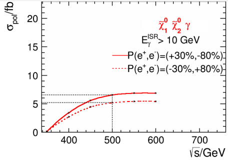


Neutralino Production Diagrams:



t-channels are suppressed / No $Z-\gamma$ interference

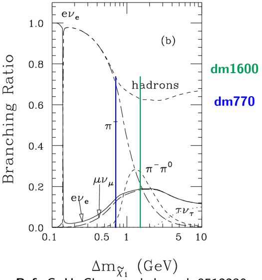
Weak polarization dependence



Decay Modes

Chargino Decay Modes

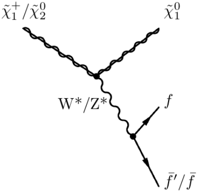
- $\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_1^0 W^{\pm *}$



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

Branching Ratios

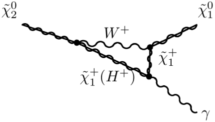
Mode	dm1600	dm770
$\pi^{\pm}$	16.5%	60.4%
$\pi^{\pm}\pi^0$	28.5%	7.3%
$e\nu$	17.3%	15.0%
$\mu\nu$	16.6%	13.7%



BRs depend crucially on ΔM

Neutralino Decay Modes

- $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z^{0*}$
- $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma$

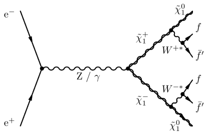


Branching Ratios

Mode	dm1600	dm770
γ	23.6%	74.0%
$\nu\bar{\nu}$	21.9%	9.7%
e^+e^-	3.7%	1.6%
$\mu^+\mu^-$	3.7%	1.5%
hadrons	44.9%	12.7%

Separation of the Processes

Chargino Process

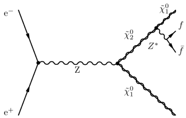


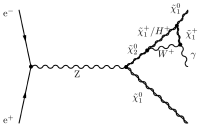
- $\tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow 2\tilde{\chi}_1^0 + W^{+*}W^{-*}$

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

dm1600	dm770
$e/\mu + \pi^{\pm}(\pi^0)$ $BR = 30.5\%$	$e/\mu + \pi^{\pm}$ $BR = 35\%$

Neutralino Process





- $\tilde{\chi}_1^0\tilde{\chi}_2^0 \rightarrow 2\tilde{\chi}_1^0 + Z^{0*}$
- $\tilde{\chi}_1^0\tilde{\chi}_2^0 \rightarrow 2\tilde{\chi}_1^0 + \gamma$

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

dm1600	dm770
$BR(\gamma) = 23.6\%$	$BR(\gamma) = 74.0\%$

Higgsino Signatures and Challenges

In the Final State

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

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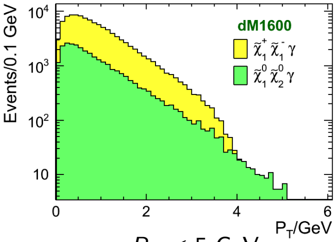
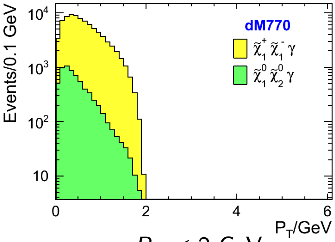


$P_T < 5$ GeV



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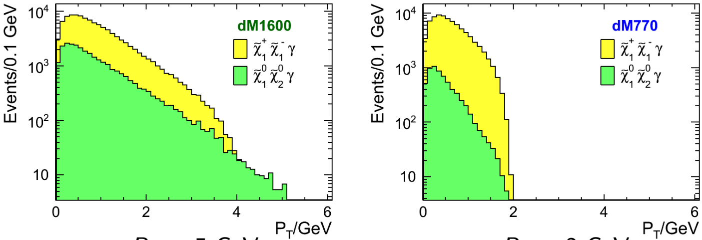

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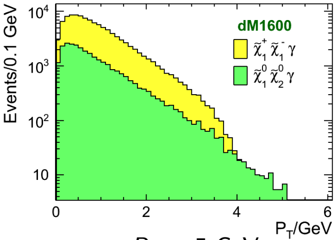

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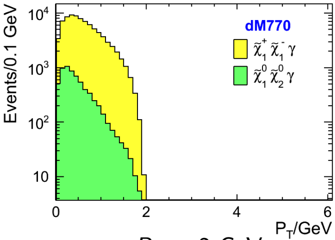


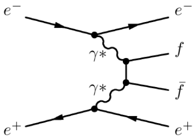
$P_T < 2$ GeV

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

It is also non-trivial for ILC

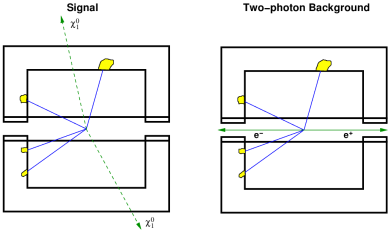
Standard Model Background: $\gamma\gamma \rightarrow f\bar{f}$

$\gamma\gamma \rightarrow 2f$



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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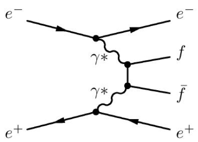

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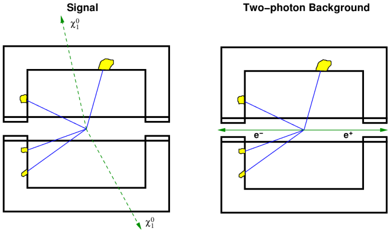

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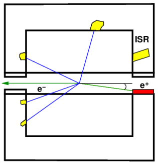
- We have required hard ISR photon,

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

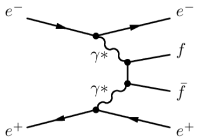
to avoid this similarity of the final states.

- Additional γ makes the beam electron visible in the detector.
- It also makes it possible to use the recoil mass method for the mass measurement



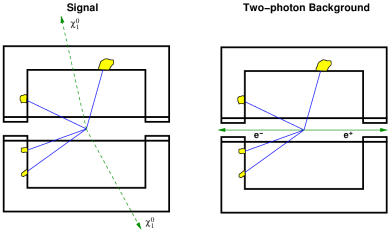
Standard Model Background: $\gamma\gamma \rightarrow f\bar{f}$

$\gamma\gamma \rightarrow 2f$



In the final state:

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



Ref: PhD thesis of C. Hensel

- We have required hard ISR photon,

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

to avoid this similarity of the final states.

- Additional γ makes the beam electron visible in the detector.
- It also makes it possible to use the recoil mass method for the mass measurement

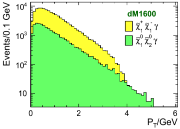
* This method is a well-known trick for $\gamma\gamma \rightarrow 2f$ background

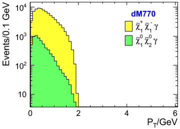
* In this study, it has been observed that this method doesn't work for $e\gamma \rightarrow 3f$ background

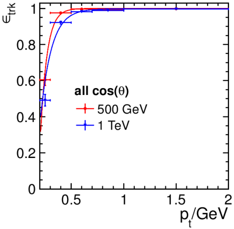
Analysis Overview

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 $\tan\beta$

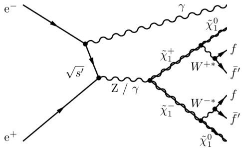
Measurement Strategy

$\tilde{\chi}_1^{\pm}$ & $\tilde{\chi}_2^0$ 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:

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



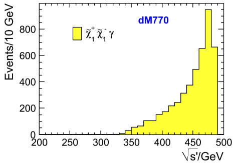
- $\sqrt{s'} = 2 \times M_{\tilde{\chi}}$ if 2 $\tilde{\chi}$ are produced at rest
- Fitting gives $M_{\tilde{\chi}}$.

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.



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:

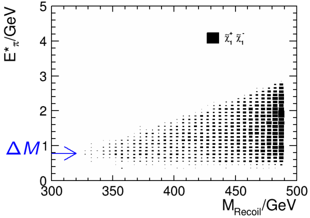
$$E_{\pi}^{*} = \frac{(\sqrt{s} - E^{\gamma})E^{\pi} + \mathbf{P}^{\pi} \cdot \mathbf{P}^{\gamma}}{2M_{\tilde{\chi}_1^{\pm}}}$$

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

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

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

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



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

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 $\tilde{\chi}_1^{+}$ & $\tilde{\chi}_2^0$

Reduced CM Energy: $s' = s - 2\sqrt{s}E^{\gamma}$

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

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

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

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

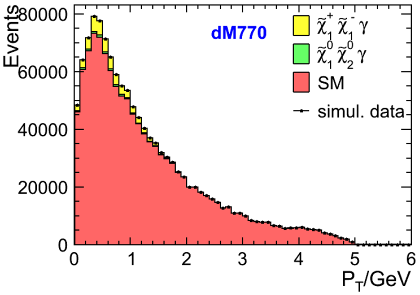
$$\sigma_{meas} = \sigma_{polarized} \times BR(\tilde{\chi}_1^{+}\tilde{\chi}_1^{-} \to 2\tilde{\chi}_1^0, \pi, e(\mu))$$

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

Event Selection

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

Event Selection

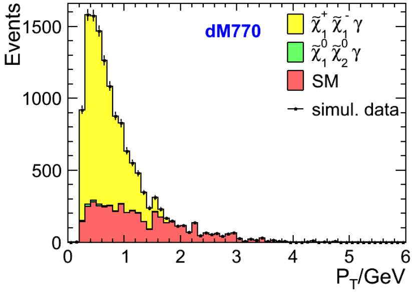
- Preselection is applied

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

Event Selection

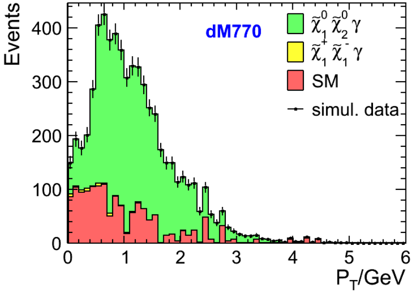
- Preselection is applied

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

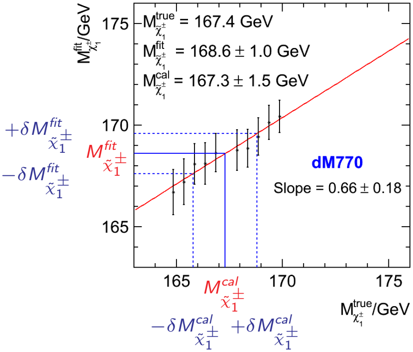
- Select photon decay modes
  - Only photons
- $|\cos\theta_{\gamma soft}| < 0.85$
- $E^*_{\gamma_{soft}} > 0.5$ GeV



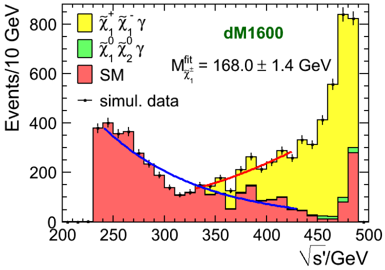
After Neutralino Selection

Calibration Procedure

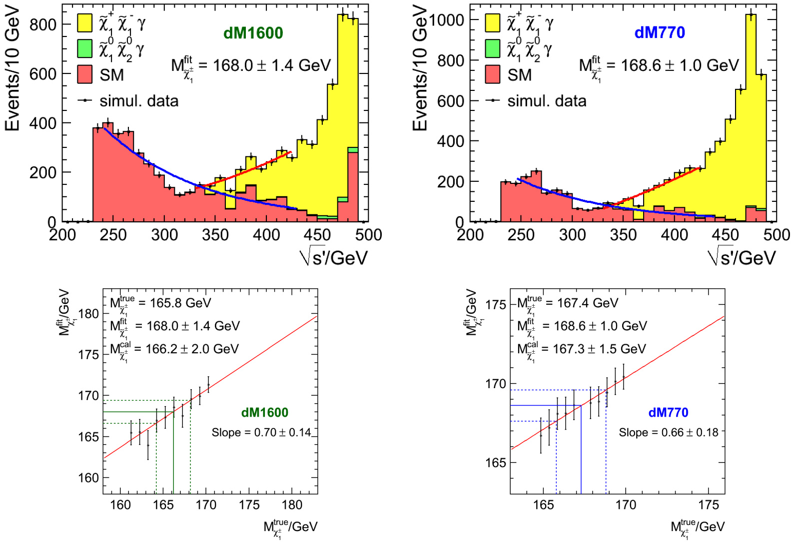
- Choose different true masses (X-axis)
- Apply measurement and get fitted masses (Y-axis)
- Obtain calibration curve



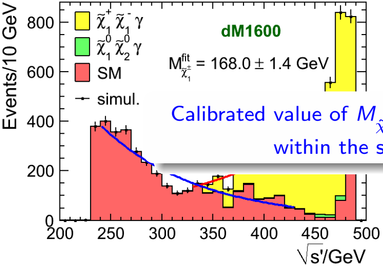
$\tilde{\chi}_1^+$ Mass Measurement & Calibration

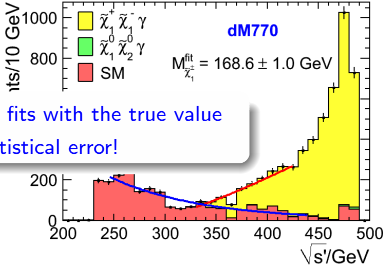


$\tilde{\chi}_1^+$ Mass Measurement & Calibration

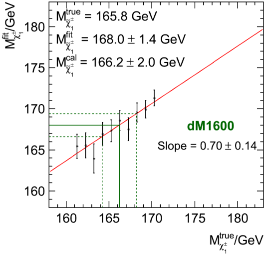


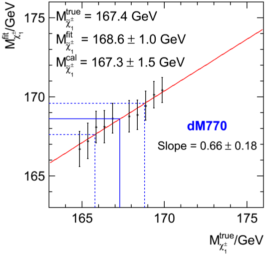
$\tilde{\chi}_1^+$ Mass Measurement & Calibration



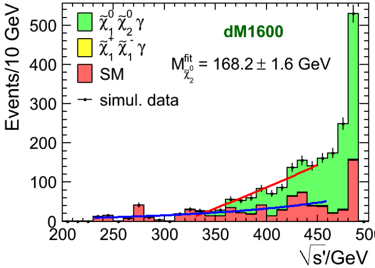


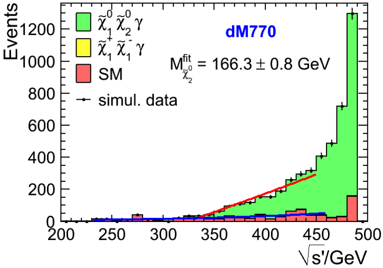
Calibrated value of $M_{\tilde{\chi}_1^\pm}$ fits with the true value within the statistical error!



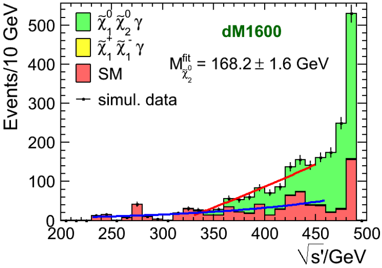


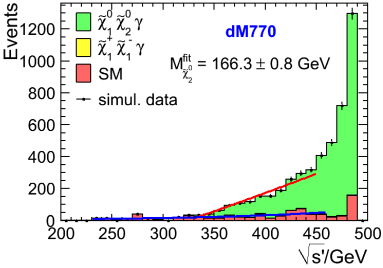
$\tilde{\chi}_2^0$ Mass Measurement & Calibration

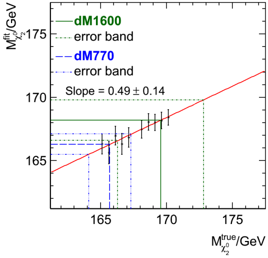




$\tilde{\chi}_2^0$ Mass Measurement & Calibration

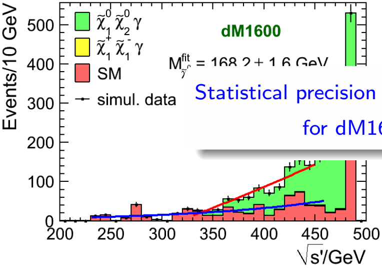


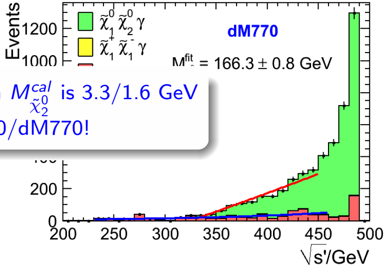




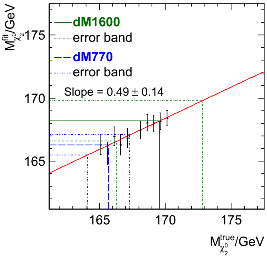
dM1600	**dM770**
$M^{true}_{\tilde{\chi}_2^0}$ = 166.9 GeV	$M^{true}_{\tilde{\chi}_2^0}$ = 167.6 GeV
$M^{fit}_{\tilde{\chi}_2^0}$ = 168.2 ± 1.6 GeV	$M^{fit}_{\tilde{\chi}_2^0}$ = 166.3 ± 0.8 GeV
$M^{cal}_{\tilde{\chi}_2^0}$ = 169.6 ± 3.3 GeV	$M^{cal}_{\tilde{\chi}_2^0}$ = 165.7 ± 1.6 GeV

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



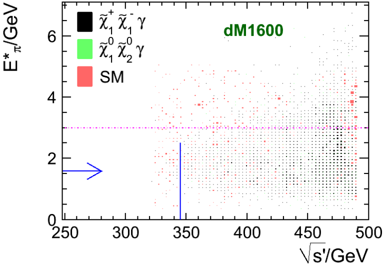


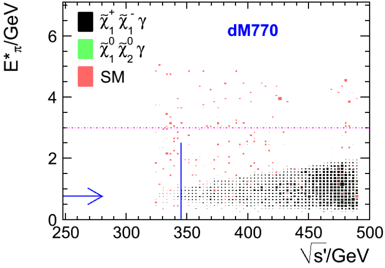
Statistical precision on $M^{cal}_{\tilde{\chi}_2^0}$ is 3.3/1.6 GeV for dM1600/dM770!



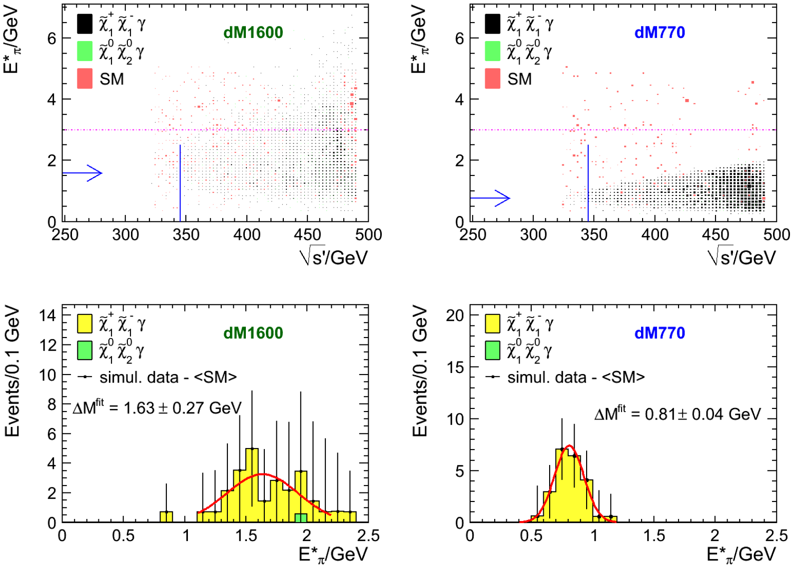
dM1600	dM770
$M^{true}_{\tilde{\chi}_2^0}$ = 166.9 GeV	$M^{true}_{\tilde{\chi}_2^0}$ = 167.6 GeV
$M^{fit}_{\tilde{\chi}_2^0}$ = 168.2 ± 1.6 GeV	$M^{fit}_{\tilde{\chi}_2^0}$ = 166.3 ± 0.8 GeV
$M^{cal}_{\tilde{\chi}_2^0}$ = 169.6 ± 3.3 GeV	$M^{cal}_{\tilde{\chi}_2^0}$ = 165.7 ± 1.6 GeV

Mass Difference Measurement

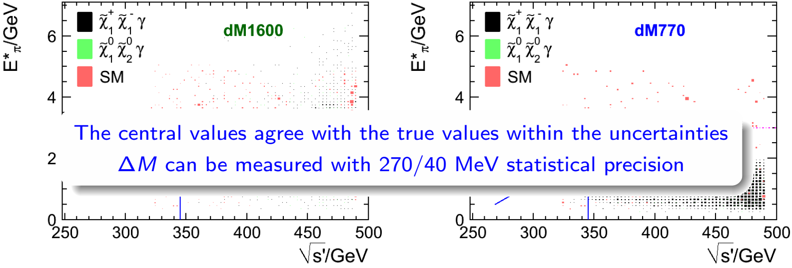




Mass Difference Measurement

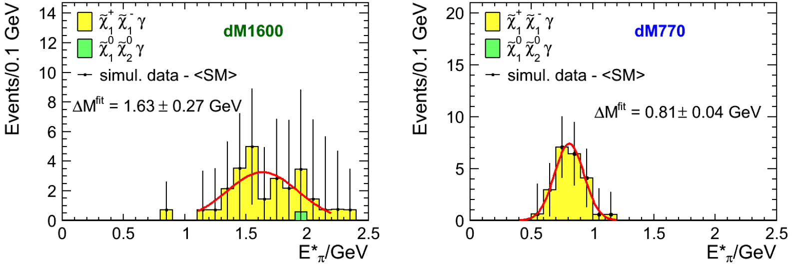


Mass Difference Measurement



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

μ, M_1 & M_2 can be determined using the result of the analysis.

Fit Procedure

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

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 ($\delta\sigma/\sigma$)
- $\delta\sigma/\sigma$ at $\sqrt{s}$ =350 GeV are also added after scaling errors by the ratio of the production cross section, $\sqrt{30}$.

Relation between measured and fitted parameters

- $\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ is the crucial parameter for determination of M_1 and M_2
- $M_{\tilde{\chi}_1^\pm}$, $M_{\tilde{\chi}_2^0}$ and $\delta\sigma/\sigma$ are used for the determination of the μ parameter

Parameter Determination

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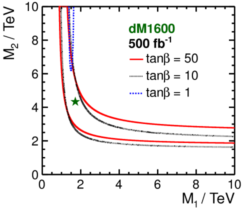
Relation between measured and fitted parameters

- $\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ is the crucial parameter for determination of M_1 and M_2
- $M_{\tilde{\chi}_1^\pm}$, $M_{\tilde{\chi}_2^0}$ and $\delta\sigma/\sigma$ are used for the determination of the μ parameter

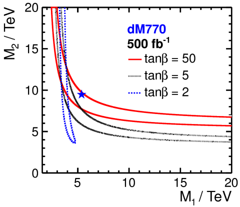
Parameter Determination

Results

- Lower limits and allowed regions for M_1 and M_2 can be obtained from the correlation between M_1 and M_2
- μ parameter can be determined with 6.8(2.5) GeV statistical precision for dM1600(dM770) scenario.



dM1600 @ 500 fb^{-1}	input	$\sqrt{s} = 500$ GeV lower	$\sqrt{s} = 500$ GeV upper	$\sqrt{s} = 350\&500$ GeV lower	$\sqrt{s} = 350\&500$ GeV upper
M_1	1.7	~ 0.8	no	~ 0.8	no
M_2	4.4	~ 1.5	no	~ 1.5	no
μ	165.7	165.2	172.5	165.4	170.2



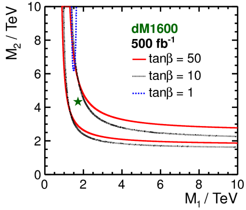
dM770 @ 500 fb^{-1}	input	$\sqrt{s} = 500$ GeV lower	$\sqrt{s} = 500$ GeV upper	$\sqrt{s} = 350\&500$ GeV lower	$\sqrt{s} = 350\&500$ GeV upper
M_1	5.3	~ 2	no	~ 2	no
M_2	9.5	~ 3	no	~ 3	no
μ	167.2	164.8	167.8	165.2	167.7

- Inclusion of $\delta\sigma/\sigma$ at 350 GeV only effects the determination of the μ parameter

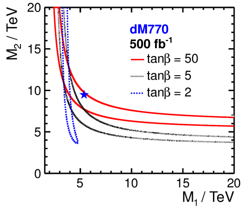
Parameter Determination

Results

- Lower limits and allowed regions for M_1 and M_2 can be obtained from the correlation between M_1 and M_2
- μ parameter can be determined with 6.8(2.5) GeV statistical precision for dM1600(dM770) scenario.



dM1600		$\sqrt{s} = 500$ GeV		$\sqrt{s} = 350\&500$ GeV	
@ 500 fb^{-1}	input	lower	upper	lower	upper
M_1	1.7	~ 0.8	no	~ 0.8	no
M_2	4.4	~ 1.5	no	~ 1.5	no
μ	165.7	165.2	172.5	165.4	170.2



dM770		$\sqrt{s} = 500$ GeV		$\sqrt{s} = 350\&500$ GeV	
@ 500 fb^{-1}	input	lower	upper	lower	upper
M_1	5.3	~ 2	no	~ 2	no
M_2	9.5	~ 3	no	~ 3	no
μ	167.2	164.8	167.8	165.2	167.7

- Inclusion of $\delta\sigma/\sigma$ at 350 GeV only effects the determination of the μ parameter

350 GeV is not sufficient to measure the masses and mass difference, larger statistics are needed. So, analysis should be done at 500 GeV

Parameter Determination at High Luminosity

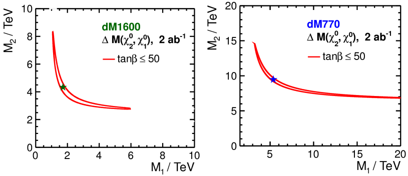
- Luminosity is increased to $\int Ldt = 2\ ab^{-1}$ for each polarization
- It is assumed that experimental errors would be reduced by a factor 2
- The measurement of the $\Delta M(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ is also included (not measured in this analysis)

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
- Increased luminosity narrows the allowed region for μ parameter

@ 2 ab^{-1}	input	lower	upper
M_1	5.3	~ 3	no
M_2	9.5	~ 7	~ 15
μ	167.2	165.2	167.4

@ 500 fb^{-1}	input	lower	upper
M_1	5.3	~ 2	no
M_2	9.5	~ 3	no
μ	167.2	164.8	167.8



Parameter Determination at High Luminosity

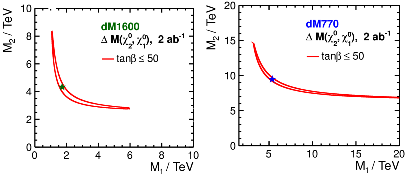
- Luminosity is increased to $\int Ldt = 2\ ab^{-1}$ for each polarization
- It is assumed that experimental errors would be reduced by a factor 2
- The measurement of the $\Delta M(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ is also included (not measured in this analysis)

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
- Increased luminosity narrows the allowed region for μ parameter

@ 2 ab^{-1}	input	lower	upper
M_1	5.3	~ 3	no
M_2	9.5	~ 7	~ 15
μ	167.2	165.2	167.4

@ 500 fb^{-1}	input	lower	upper
M_1	5.3	~ 2	no
M_2	9.5	~ 3	no
μ	167.2	164.8	



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

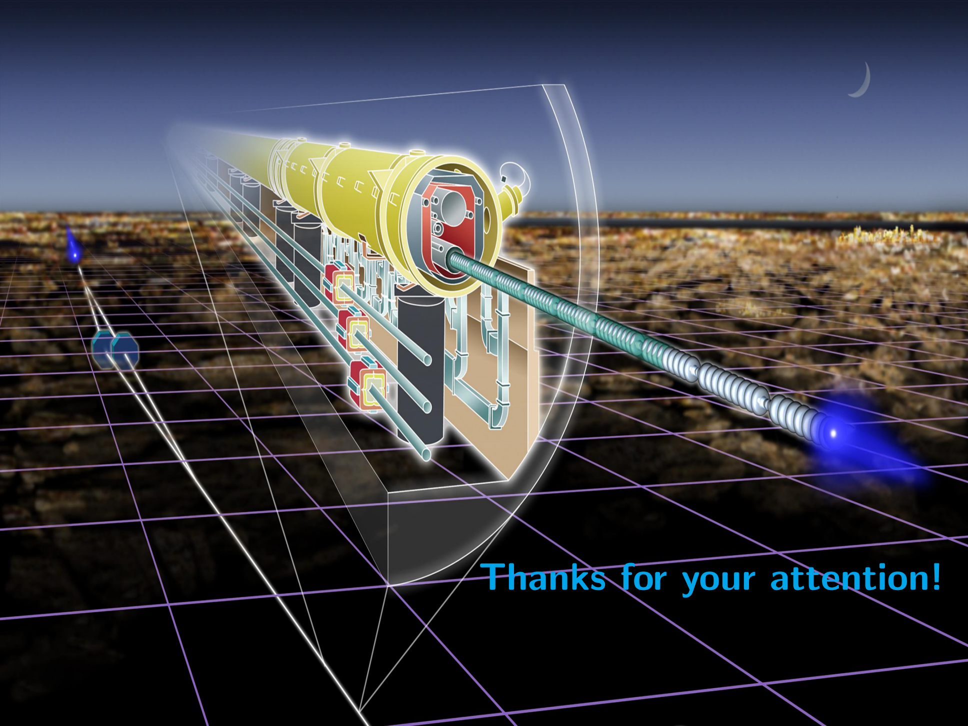
Conclusion

Summary

- Naturalness leads to have light higgsinos
- Studied extreme case of no other sparticles accessible 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
- 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 in multi-TeV regime

Outlook

- Do the analysis with full simulation
- Add neutralino mass difference measurement


Thanks for your attention!

Backup

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
dm1600						
nocut	38672	24250	1.09×10^9	9817	19071	1.07×10^9
semi-lep sel	3813	897	4016	930	77	3969
photon sel	19	1395	764	3	1134	762
dm770						
nocut	38130	23940	1.09×10^9	9792	18773	1.07×10^9
semi-lep sel	4600	36	2199	1190	32	2416
photon sel	22	4095	764	3	3230	762

Efficiency, Purity and Precison on Polarized Cross Sections:

Polarizations	$\mathbf{P(e^+, e^-) = (+30\%, -80\%)}$		$\mathbf{P(e^+, e^-) = (-30\%, +80\%)}$	
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 %	17.21%
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 %**

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.