Nailing Natural SUSY: Higgsino Parameter Determination at the ILC

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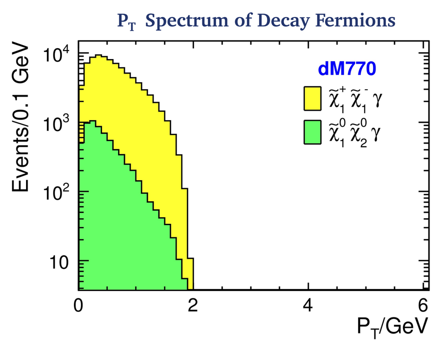
Natural SUSY

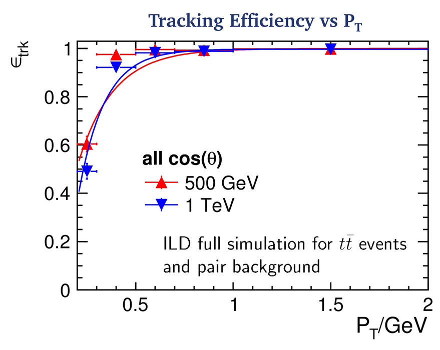
$$M_Z^2 = 2\frac{m_{H_u}^2 \tan^2\beta - m_{H_d}^2}{1-\tan^2\beta} - 2|\mu|^2$$

Naturalness requires μ parameter at the electroweak scale which arises light higgsinos

- The higgsinos are almost mass degenerate, mass differences between them are around a few GeV
- All other SUSY particles are heavy up to a few TeV
- Two production processes can be used to detect such light and degenerate higgsinos at the ILC
  - $e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$
  - $e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0$

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





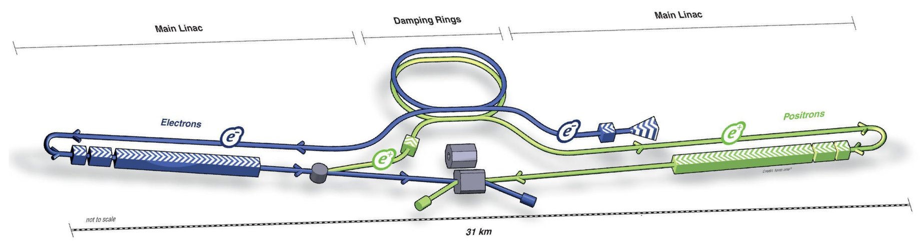
Signatures of the higgsinos

- A few soft visible particles (P_T <2 GeV)
- Lots of missing energy due to $\tilde{\chi}_1^0$
- This scenario is challenging for the LHC, since to resolve such degenerate particles is not easy
- However, it is possible to do this analysis at the ILC

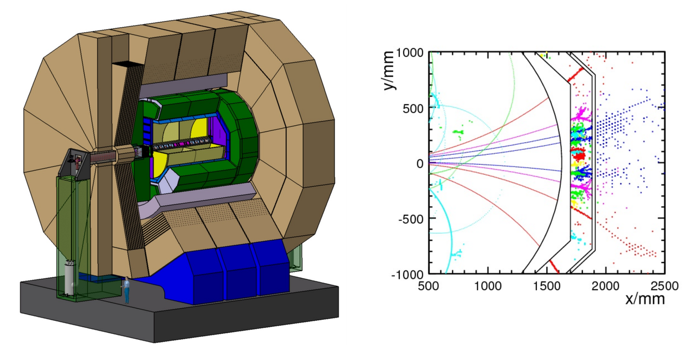
ILC
International Linear Collider

ILC is a planned electron-positron collider. Planned design properties:

- E_{CM} = 200 - 500 GeV (upgradable to 1 TeV)
- $\int \mathcal{L}dt/year = 250\ fb^{-1}$
- $P(e^-) = 80\%,\ P(e^+) = 30-60\%$



ILD
International Large Detector



- ILD has an excellent tracking and finely-grained calorimetry systems
- This gives ILD the ability to reconstruct the energy of individual particles [Particle Flow Approach]
- Samples run with ILD fast simulation (SGV)

Requirement of Hard ISR Photon

- Hard Initial State Radiation (ISR) photon is required to avoid similarity of the signal final state with some of the SM background
- It also makes it possible to use the recoil mass method for the mass measurement

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

Benchmark Point

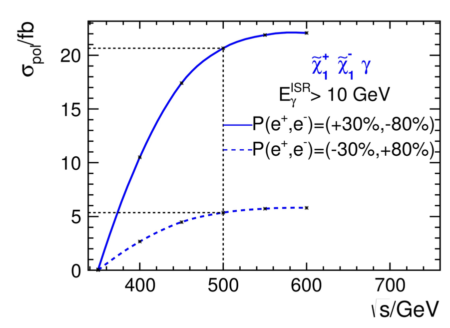
Input Parameters

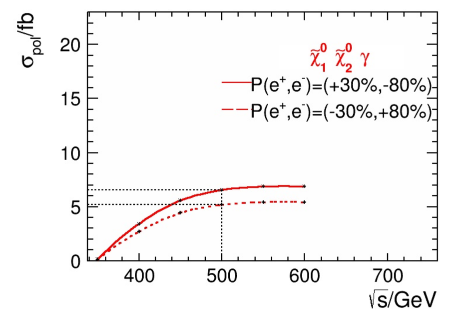
M_1 [TeV]	M_2 [TeV]	μ [GeV]	$\tan\beta$	$M_{\tilde{\chi}_1^\pm}$ [GeV]	$M_{\tilde{\chi}_2^0}$ [GeV]	$M_{\tilde{\chi}_1^0}$ [GeV]	m_h [GeV]
5.30	9.51	167.22	48	167.36	167.63	166.59	127

- $\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.77$ GeV
- $\Delta M(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 1.04$ GeV

Analysis Overview: Analysis is performed

- $E_{CM} = 500$ GeV
- $\int \mathcal{L}dt = 500\ fb^{-1}$
- Two different polarisation combinations are considered;
  - $P(e^+, e^-) = (+30\%, -80\%)$
  - $P(e^+, e^-) = (-30\%, +80\%)$
- Polarised cross sections can be seen from the right side





Event Selection

To suppress SM background pre-selection is applied;

Pre-selection:

- Hard ISR photon is required in each event
- High energetic electrons in the very forward region are excluded
- $E_{\text{decay products}} < 5$ GeV, $E_{miss} > 300$ GeV
- Both decay products and missing energy are required not to be in the very forward region

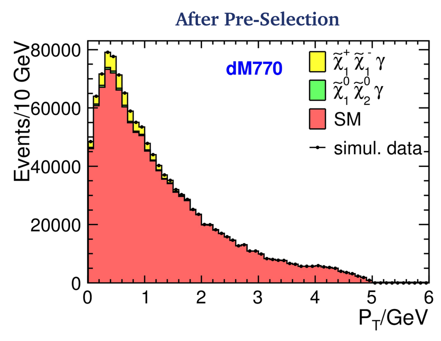
To separate signals exclusive decay modes are chosen;

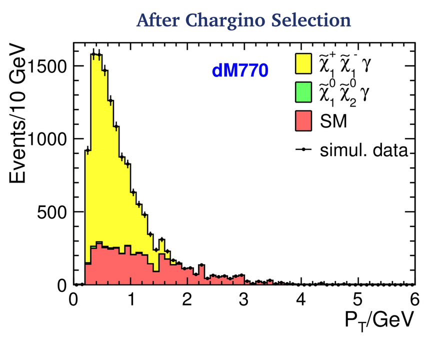
Chargino Selection:

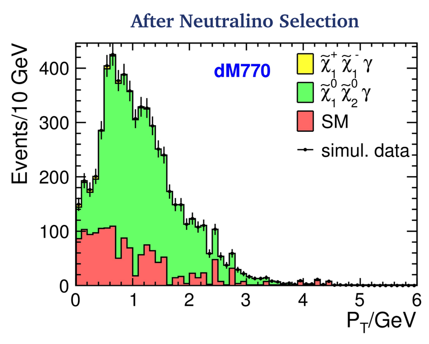
- Semileptonic final state ($\pi + e/\mu$)

Neutralino Selection:

- Photonic final state (γ)







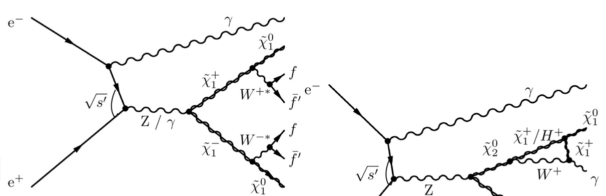
Measurement Procedure

$\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ Mass Measurement

Recoil mass of hard ISR photon is used to calculate mass of the higgsinos

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

where $\sqrt{s'}$ is the reduced center of mass energy after the ISR photon is emitted
At the rest frame of the higgsinos, $\sqrt{s'} = 2 \times M_{\tilde{\chi}}$



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

To measure the mass difference, the boosted energy of decay products of the W boson into the rest frame of the chargino is used. Because at the rest frame of the chargino, the neutralino is also produced at rest and mass difference between them gives the energy of decay products of the W boson

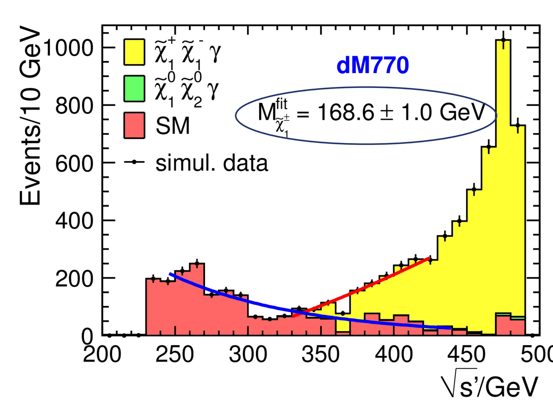
- $E_\pi^* = \frac{(\sqrt{s} - E^\gamma)E^\pi + \mathbf{P}^\pi \cdot \mathbf{P}^\gamma}{\sqrt{s'}}$ $\quad \left[E_\pi^* = \frac{(M_{\tilde{\chi}_1}^\pm - M_{\tilde{\chi}_1}^0)(M_{\tilde{\chi}_1}^\pm + M_{\tilde{\chi}_1}^0) + m_\pi^2}{2M_{\tilde{\chi}_1}^\pm} = \frac{1}{1/\Delta M + 1/\Sigma M} + \frac{m_\pi^2}{2M_{\tilde{\chi}_1}^\pm}, \quad E_\pi^* \approx \Delta M\right]$

Precision on Polarised Cross Section

The below formula is used to calculate statistical error on the cross section. As seen estimated precision is based on the efficiency and purity

- $\frac{\langle\delta\sigma_{meas}\rangle}{\langle\sigma_{meas}\rangle} = \frac{1}{\sqrt{\epsilon \cdot \pi \cdot \int \mathcal{L}dt \cdot \sigma_{signal}}}$

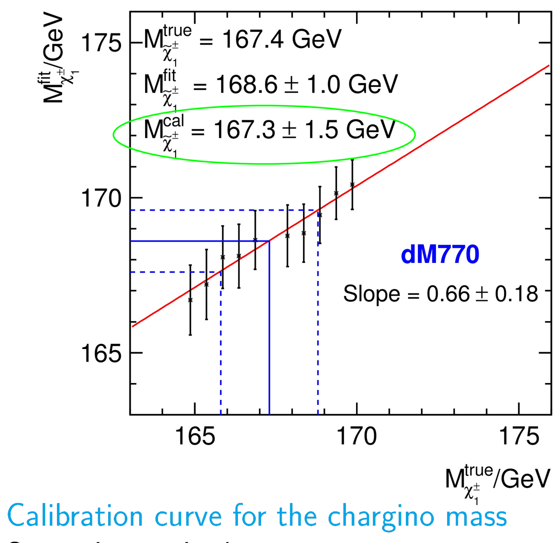
$\tilde{\chi}_1^\pm$ Mass Measurement



Reduced CM energy distribution for the chargino mass

Fitting is done in the following order:

- SM is fitted with an exponential function assuming that SM background is known precisely
- SM background is fixed
- SM + signals are fitted using linear function for signal

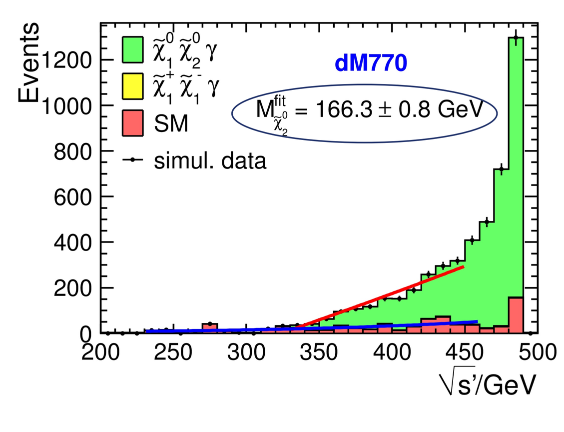


Calibration curve for the chargino mass

Since the method is an approximation in some sense, the fitted higgsino masses have been calibrated

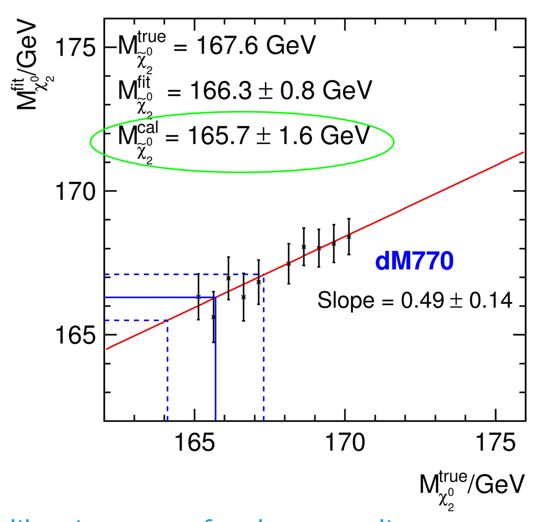
- The chargino mass can be measured with 1.5 GeV statistical uncertainty

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



Reduced CM energy distribution for the neutralino mass

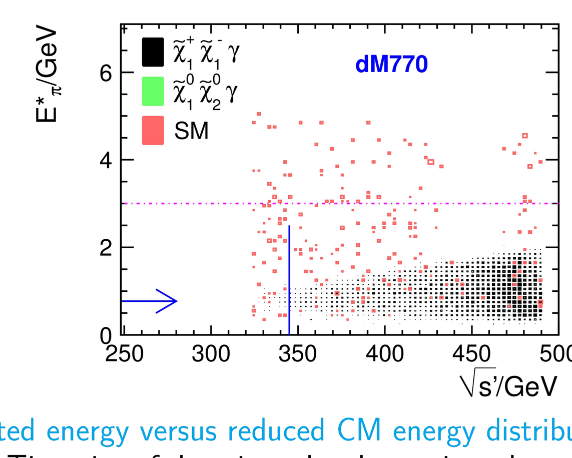
- The same fitting procedure with the chargino case is applied.



Calibration curve for the neutralino mass

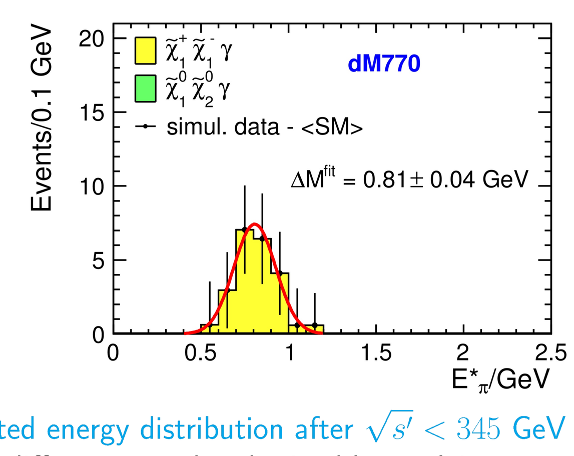
- The neutralino mass can be measured with 1.6 GeV statistical uncertainty

Mass Difference Measurement



Boosted energy versus reduced CM energy distribution

- Tip point of the triangular shape gives the mass difference. Blue arrow shows the true mass difference
- A cut on the reduced CM energy is applied to examine the region around tip, which is shown with blue line



Boosted energy distribution after $\sqrt{s'} < 345$ GeV cut

Mass difference can be obtained by applying a gaussian fit to this distribution

- The mass difference can be measured with 40 MeV statistical uncertainty

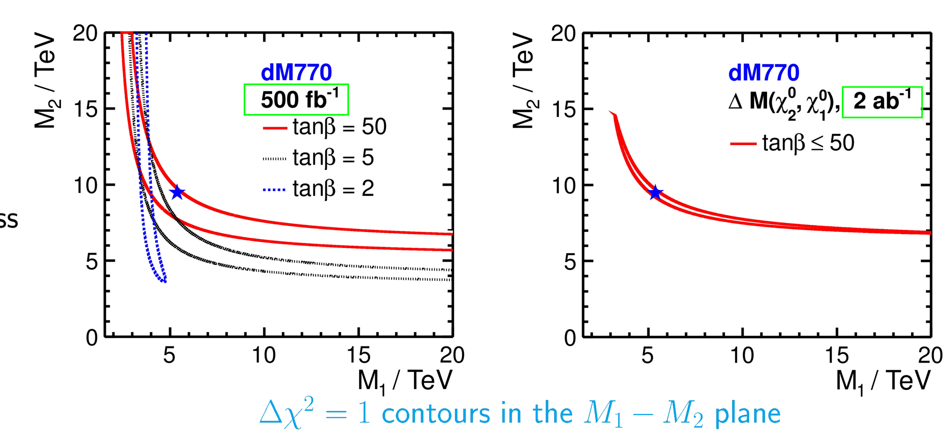
Statistical Precision on Polarised Cross Sections

Polarisations	$P(e^+,e^-) = (+30\%, -80\%)$		$P(e^+,e^-) = (-30\%, -80\%)$	
Processes	$\tilde{\chi}_1^+\tilde{\chi}_1^-\gamma$	$\tilde{\chi}_1^0\tilde{\chi}_2^0\gamma$	$\tilde{\chi}_1^+\tilde{\chi}_1^-\gamma$	$\tilde{\chi}_1^0\tilde{\chi}_2^0\gamma$
Efficiency($\epsilon \times BR$)	34.9	23.2	34.9	23.2
Purity(π)	85.3	85.8	56.1	82.5
$\frac{\langle\delta\sigma_{meas}\rangle}{\sigma_{meas}}$	1.6	1.7	3.8	1.9

- Efficiencies are same for both polarisations
- Huge difference between purities for both polarizations in the chargino processes are due to the difference between polarised cross sections
- In terms of the precision on cross sections, cross sections can be measured more precisely using the first polarisation

Parameter Determination-Conclusion

- The light higgsinos which are well motivated by naturalness can be observed at the ILC
- They can be resolved inspite of small mass differences
- Measurement of the higgsino masses and cross sections can be done with very good statistical precision



$\Delta\chi^2 = 1$ contours in the $M_1 - M_2$ plane

- 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 2.5 GeV statistical precision, 1 σ allowed range for μ is [164.8, 167.8] GeV

References:
[1] T. Behnke, et. al. (Editors) "The ILC Technical Design Report - Volume 4 : Detectors" arXiv: 1306.6329 [physics.ins-det]
[2] M. Berggen, et. al. "Trackling light higgsinos at the ILC" arXiv: 1307.3566 [hep-ph, hep-ex]

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