Measuring a light neutralino mass at the ILC

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Outline

1. Motivation
2. The measurement
3. Conclusions and outlook

The PDG bound

$$M_{\chi_1^0} > 46\,\mathrm{GeV}\,.$$

Origin of this bound

- Chargino searches set lower bound on M_2 and μ.
- SUSY GUT relation $M_1 = \frac{5}{3}\tan^2\theta_\mathrm{w} M_2$ is assumed.
- LEP Higgs search limits $\tan\beta \gtrsim 2$.
- Scan over allowed parameter space yields above bound.

Abandoning SUSY GUT assumption dramatically relaxes bound!

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Direct bounds on light neutralinos

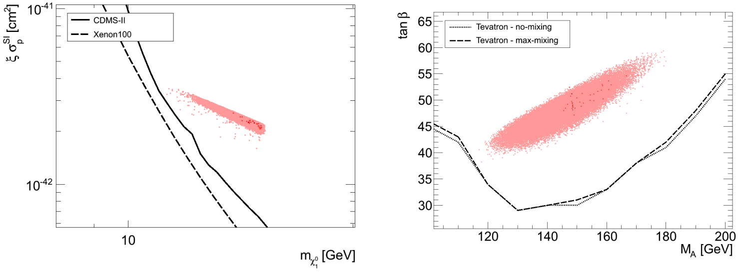
How light can the neutralino be? [Dreiner et. al. '09]

- If M_1 and M_2 allowed to vary independently, neutralino mass matrix can have small or even zero eigenvalues.
- Even a massless neutralino can pass all direct laboratory and astrophysical bounds.

Direct bounds on a very light neutralino

- Supernova cooling
- Rare meson decays
- Monojets
- Many precision EW observables
- Dark matter (Cowsik-McClelland/Lee-Weinberg)

Can a light neutralino be realized in the MSSM?



Maybe not: in MSSM, $m_{\chi_1^0} > 28$ GeV. [Vasquez et. al. '10]

MCMC exploration of parameter space finds no models with light neutralinos that pass $B_S \to \mu\mu$ + (Tevatron *or* direct detection)

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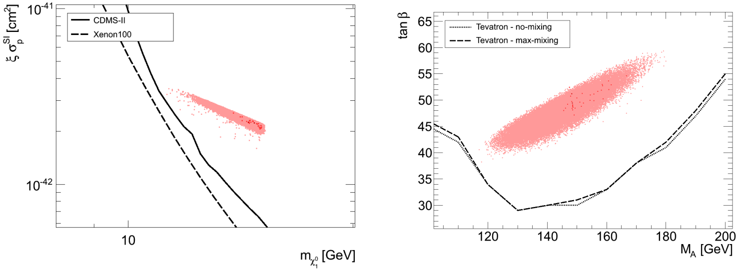

Light neutralinos in non-minimal models still viable

e.g. NMSSM a possibility, and scattering cross sections possibly high enough to explain DM detection hints.

Hints from the sky for light dark matter?

The DAMA/LIBRA, CoGeNT, and CDMS experiments have each provided hints for a light dark matter particle.

Problems with this interpretation

- Null result of XENON 100
- Cross section needed for DAMA/LIBRA incompatible with results from CDMS and CoGeNT?
- However: clever model-building and uncertainties may render the experiments compatible

- Crucial to check evidence from the sky with a collider measurement of the DM mass.
- Light neutralino mass at ILC $\Longrightarrow$ non-minimal SUSY or non-standard cosmology?

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Methods

Methods for measuring $m_{\chi_1^0}$

- $e^+e^- \to \tilde{\ell}^-\tilde{\ell}^+ \to \ell^-\ell^+ + 2\chi_1^0$
  Slepton pair production $\to$ lepton energy distribution
  [Martyn ‘04, Freitas et. al. ’04, Moortgat-Pick ’08]
- $e^+e^- \to \chi_2^0\chi_2^0 \to (\chi_1^0\ell_1^+\ell_1^-)\,(\chi_1^0\ell_2^+\ell_2^-)$
  χ_2^0 pair production $\to$ dilepton inv. mass and energy
  [TESLA TDR ‘01, ILC RDR ‘07]
- Threshold scans can fix masses of other SUSY particles involved.

We will concentrate on slepton pair production.

Kinematics of slepton pair production

- θ_0: angle between $\vec{p}(e)$ in slepton rest–frame and $\vec{p}(\tilde{e})$
- $E_e = \frac{\sqrt{s}}{4}\left(1 - \frac{m^2_{\chi^0_1}}{m^2_{\tilde{e}}}\right)(1 + \beta_{\tilde{e}}\cos\theta_0)$, where $\beta_{\tilde{e}} = \sqrt{1 - \frac{4m^2_{\tilde{e}}}{s}}$
- Electron energy has flat distribution between endpoints $E_\pm$ for $\cos\theta_0 = \pm 1$
- Solve for the SUSY masses:

$$m_{\tilde{e}} = \sqrt{s}\frac{\sqrt{E_+ E_-}}{E_+ + E_-}, \qquad m_{\chi^0_1} = m_{\tilde{e}}\sqrt{1 - \frac{E_+ + E_-}{\sqrt{s}/2}}$$

- Measure E_+ and E_-: thus determine $m_{\chi^0_1}$

Measurement for SPS1a

- In SPS1a, $m_{\tilde{e}_R} = 143$ and $m_{\chi_1^0} = 96$ GeV.
- [Martyn '04] event generation, fast detector simulation, and background subtraction.
- $\sqrt{s} = 500\ \mathrm{GeV}, \quad \mathcal{L} = 200\ \mathrm{fb}^{-1}, \quad \mathcal{P}_{e^-} = 0.8,\ \mathcal{P}_{e^+} = -0.6$
- $\implies$ endpoint energy measurements:

$$E_- = 16.528 \pm 0.020, \qquad E_+ = 93.34 \pm 0.11\ \mathrm{GeV}\,.$$

- $\implies$ mass measurements:

$$m_{\tilde{e}_R} = 142.99 \pm 0.08, \qquad m_{\chi_1^0} = 96.05 \pm 0.1\ \mathrm{GeV}\,.$$

The trouble with light neutralinos

For very light neutralinos, we can write:

$$\delta M_{\chi_1^0} \simeq \frac{M_{\tilde{\ell}}^2}{M_{\chi_1^0}\sqrt{s}}\sqrt{\delta E_+^2 + \delta E_-^2}$$

- For $M_{\tilde{\ell}} = 200\ \mathrm{GeV}$, $M_{\chi_1^0} = 1\ \mathrm{GeV}$, and $\sqrt{s} = 500\ \mathrm{GeV}$, coefficient is 80!
- This means that if δE's are the same as for SPS1a, $\delta M_{\chi_1^0} \simeq 9\ \mathrm{GeV}$
- We should be helped somewhat by higher $\tilde{e}$ pair production, due to t-channel exchange of light neutralino.

Our simulation

Simple kinematics allows simple simulation

- Throw random lepton energies from flat distribution
- Include beamstrahlung: $\sqrt{s'} < \sqrt{s}$
- Smear according to minimum of ECAL and tracker resolution:

$$\Delta\left(\frac{1}{p_T}\right) = 1 \cdot 10^{-4}\ \mathrm{GeV}^{-1} \qquad \text{(tracker)}$$

$$\frac{\Delta E}{E} = \frac{0.166}{\sqrt{E/\mathrm{GeV}}} \oplus 0.011 \qquad \text{(ECAL)}$$

- Calculate polarized $[(\mathcal{P}_{e^-}, \mathcal{P}_{e^+}) = (+80\%, -60\%)]$ cross sections with SPheno [Porod '03]

Scenarios

First we compare with Martyn for SPS1a, and find $\sim$30% agreement

Light neutralino scenarios

- $\sqrt{s} = 500$ GeV and $\mathcal{L} = 250\ \mathrm{fb}^{-1}$; beam pol. $(+80\%, -60\%)$
- Fix slepton mass at 200 and 100 GeV and scan neutralino mass (MSSM)
- $\tilde{e}_R$ production dominates the fit

Future work?

- Is *WW* background still negligible for light neutralinos?
- Redo for other scenarios, e.g. NMSSM

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Fitting the endpoints

- We fit measured endpoint shapes to parametrizations:

$$f_-(E) = \begin{cases} \frac{1}{2}\left[\mathrm{erf}\left(\frac{E-\hat{E}_-}{\sqrt{2}\sigma_1^-}\right)+1\right] & : \quad E < \hat{E}_- \\ \frac{1}{2}\left[\mathrm{erf}\left(\frac{E-\hat{E}_-}{\sqrt{2}\sigma_2^-}\right)+1\right] & : \quad E \geq \hat{E}_- \end{cases}$$

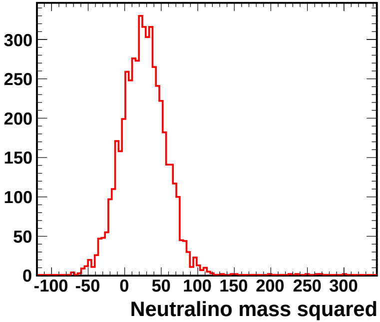
  for E_- and

$$f_+(E) = \begin{cases} \frac{1}{2}\mathrm{erfc}\left(\frac{E-\hat{E}_+}{\sqrt{2}\sigma_1^+}\right) & : \quad E < \hat{E}_+ \\ \frac{1}{2}\mathrm{erfc}\left(\frac{E-\hat{E}_+}{\sqrt{2}\sigma_2^+}\right) & : \quad E \geq \hat{E}_+ \end{cases}$$

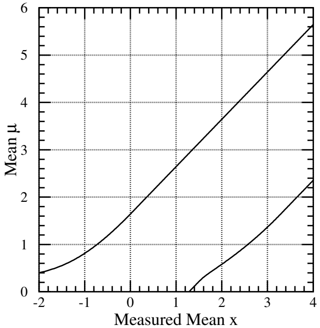
- $\sigma_1 \neq \sigma_2$ because beamstrahlung is asymmetric.

Toy datasets and distributions

- For a given neutralino mass, we simulate many toy datasets
- For each toy dataset, we fit the endpoints and compute the neutralino mass
- We take the spread of $M^2_{\chi^0_1}$ values as a measure of uncertainty



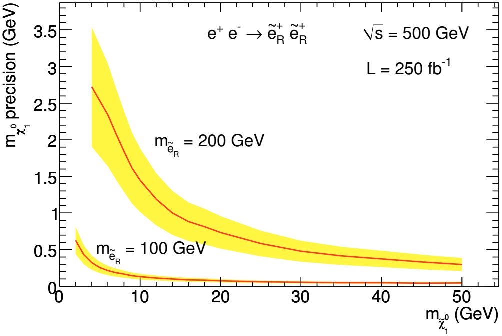
Negative mass-squared and Feldman-Cousins



[Feldman and Cousins ’97]

- For small $M_{\chi_1^0}$, M^2 distribution extends below zero
- Feldman-Cousins method gives confidence intervals with correct coverage in this case
- Smooth transition from mass measurement to upper bound

Results



- Upper bound only is possible if $M_{\chi_1^0} \lesssim 2(4)\ \mathrm{GeV}$ for a 100(200) GeV $\tilde{e}_R$
- For $M_{\chi_1^0} = 1\ \mathrm{GeV}$, upper bound is 2.5(7.6) GeV for a 100(200) GeV $\tilde{e}_R$

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Conclusions

- Light neutralinos are of phenomenological interest.
- Depending on the slepton masses, the neutralino mass can be measured accurately at the ILC down to $M_{\chi_1^0} =$ few – several GeV.
- For even lighter neutralinos, only an upper bound on the mass can be set.
- Measuring such a light neutralino mass could have striking theoretical consequences!