How light can the lightest neutralino be?

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all work in progress, in collaboration with:

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Outline

- Introduction and motivation

- A light neutralino in the MSSM – How light can it be?

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1 Introduction

The Standard Model (SM) has been tested to high precision.

However we need ...

- solution to hierarchy problem
- window to gravity
- dark matter candidate, CP-phases for baryon asymmetry, ...

One solution is Supersymmetry (SUSY).

- symmetry between bosons and fermions
- minimal SUSY extension of SM $\rightarrow$ MSSM

The chargino mass matrix $\mathcal{M}_{\pm}$

- Charginos $\tilde{\chi}_i^{\pm}$ are a mixture of charged winos $\tilde{W}^{\pm}$ and higgsinos $\tilde{H}^{\pm}$.

$$\mathcal{M}_{\pm} = \begin{pmatrix} M_2 & \sqrt{2} M_W \sin(\beta) \\ \sqrt{2} M_W \sin(\beta) & \mu \end{pmatrix}$$

- Parameters:

  M_2: wino mass, soft supersymmetry breaking parameter

  μ: Higgs mixing parameter

  $\tan\beta$: ratio of vacuum expectation values of the two neutral, CP-even Higgs fields

- |eigenvalues| of $\mathcal{M}_{\pm}$ = chargino masses $m_{\tilde{\chi}^{\pm}_{i=1,2}}$

The neutralino mass matrix $\mathcal{M}_0$

- Neutralinos $\tilde{\chi}_i^0$ are a mixture of the neutral gauginos ($\tilde{B}$, $\tilde{W}^3$) and higgsinos ($\tilde{H}_u$, $\tilde{H}_d$).

$$\mathcal{M}_0 = \begin{pmatrix} M_1 & 0 & -m_Z \sin(\theta_W)\cos(\beta) & m_Z \sin(\theta_W)\sin(\beta) \\ 0 & M_2 & m_Z \cos(\theta_W)\cos(\beta) & -m_Z \cos(\theta_W)\sin(\beta) \\ -m_Z \sin(\theta_W)\cos(\beta) & m_Z \cos(\theta_W)\cos(\beta) & 0 & -\mu \\ m_Z \sin(\theta_W)\sin(\beta) & -m_Z \cos(\theta_W)\sin(\beta) & -\mu & 0 \end{pmatrix}$$

- M_1: bino mass, soft supersymmetry breaking parameter

- |eigenvalues| of $\mathcal{M}_0$ = neutralino masses $m_{\tilde{\chi}^0_{i=1,2,3,4}}$

Motivation: Neutralino mass at LEP

- Experimental search for charginos $\tilde{\chi}_1^{\pm}$ at LEP:

  chargino mass limit: $m_{\tilde{\chi}_1^{\pm}} > 104$ GeV $\quad \Rightarrow M_2, \mu \gtrsim 100\,\text{GeV}$

- Assume SUSY Grand Unified Theory (GUT): $\quad M_1 = \frac{5}{3}\tan^2(\theta_w)\, M_2$

  $\Rightarrow M_1 \gtrsim 50$ GeV

  $\Rightarrow$ Neutralino mass constrained to: $\quad m_{\tilde{\chi}_1^0} \gtrsim 50$ GeV

- What happens if the GUT relation is dropped?

Consider the neutralino mass matrix $\mathcal{M}_0$:

- M_1 is now a free parameter! Can have $m_{\tilde{\chi}_1^0} = 0$!

- Calculate the determinant:

$$\det\left[\mathcal{M}_0(M_1, M_2, \mu, \tan\beta)\right] = 0$$

$$\Rightarrow M_1 = \frac{m_Z^2 M_2 \sin^2\theta_w \sin(2\beta)}{\mu\, M_2 - m_Z^2 \cos^2\theta_w \sin(2\beta)} \approx 0.05 \frac{m_Z^2}{\mu} = \mathcal{O}(1\,\mathrm{GeV})$$

$$\Rightarrow M_1 \ll M_2$$

$$\Rightarrow \tilde{\chi}_1^0 \;\; \text{bino} - \text{like!}$$

- For $\tilde{\chi}_1^0 =$ bino, the $Z\tilde{\chi}_1^0\tilde{\chi}_1^0$ coupling vanishes at tree-level.
  $\Rightarrow$ No significant contribution to the Z-width!!

What about CP phases in the neutralino sector?

- In general, M_1 and μ can be complex

- CP phases φ_{M_1} and φ_μ constrained by electric dipole moments
  $\rightarrow$ not constrained in certain models (flavor violation,cancellations,...)

- Calculate the determinant:

$$\det\left[\mathcal{M}_0(M_1, M_2, \mu, \tan\beta)\right] = 0$$

$$\Rightarrow M_1 \approx \frac{m_Z^2 \sin^2\theta_w \sin(2\beta)}{\mu\cos(\varphi_\mu + \varphi_{M_1})} \quad \text{and} \quad M_2 = \frac{m_Z^2 \cos^2\theta_w \cos(2\beta)\sin(\varphi_{M_1})}{\mu\sin(\varphi_\mu + \varphi_{M_1})}$$

- Zero mass neutralino still possible, however even more fine-tuning.

2 A light neutralino in the MSSM – How light can it be?

Look at bounds from . . .

- . . . cosmology
- . . . precision observables
- . . . colliders (LEP)

Bounds on neutralino mass from cosmology

- Dark matter density: MSSM with non-universal gaugino masses:

  $\Rightarrow m_{\tilde{\chi}_1^0} > 6\,\text{GeV}$ [e.g. Bottino et al., hep-ph/0304080] [Belanger et al., hep-ph/0310037]

  depends on the cosmological standard model

- Supernova cooling:

  $m_{\tilde{\chi}_1^0} \gtrsim 0.2\,\text{GeV}$ for $m_{\tilde{e}} \approx 500\,\text{GeV}$ [Dreiner et al., hep-ph/0304289]

  depends on selectron mass $m_{\tilde{e}}$, and on the explosion mechanism

- Red giant cooling? What if neutralinos are hot dark matter?

However:
Look at bounds, which are independent of cosmological models.

Bounds on neutralino mass from precision observables

Assuming $m_{\tilde{\chi}_1^0} = 0$, we have checked values of:

- $\sin^2(\theta_w)$
- M_W, Γ_W
- $(g-2)_\mu$

$\rightarrow$ No constraints for $m_{\tilde{\chi}_1^0} = 0$!

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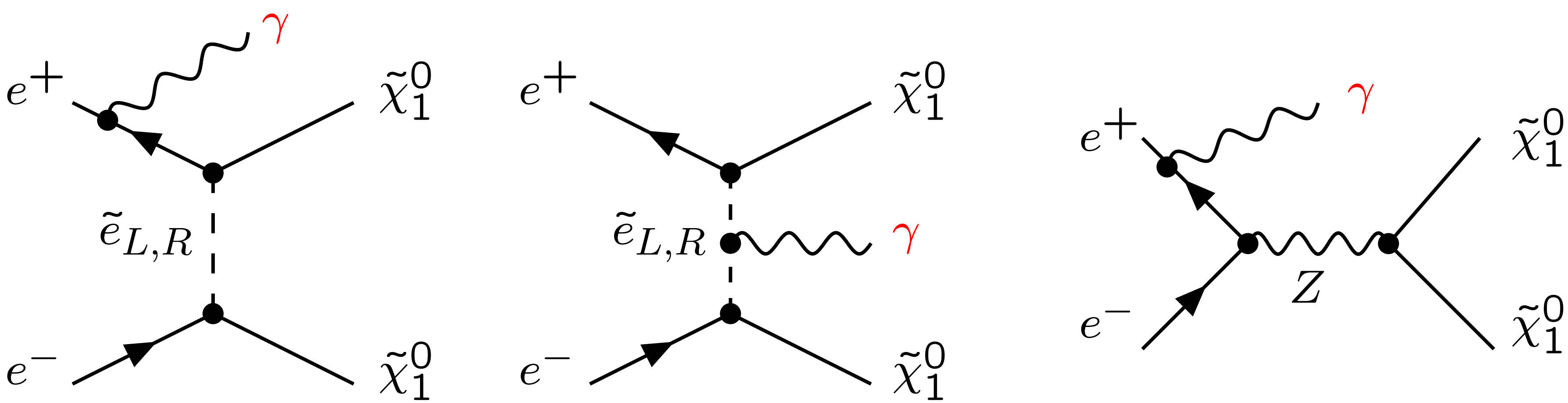
In addition: have to look at rare decays, e.g., $b \rightarrow s\gamma$,
$\Upsilon(1s) \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$ [McElrath, hep-ph/0506151]
$B \rightarrow K^{(*)} +$ invisible, or $K \rightarrow \pi + \tilde{\chi}_1^0 \tilde{\chi}_1^0$

Bounds on neutralino mass from measurements at LEP

- neutralino pair production (direct): $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_i^0$
- radiative production (indirect): $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0\gamma$

LEP II: center of mass energy $\sqrt{s} = 200$ GeV, luminosity $\mathcal{L} = 100$ pb^{-1}



No LEP bounds from radiative production $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0\gamma$

$M_{\tilde{e}_{L,R}} = 200$ GeV

$M_2 = \mu = 200$ GeV

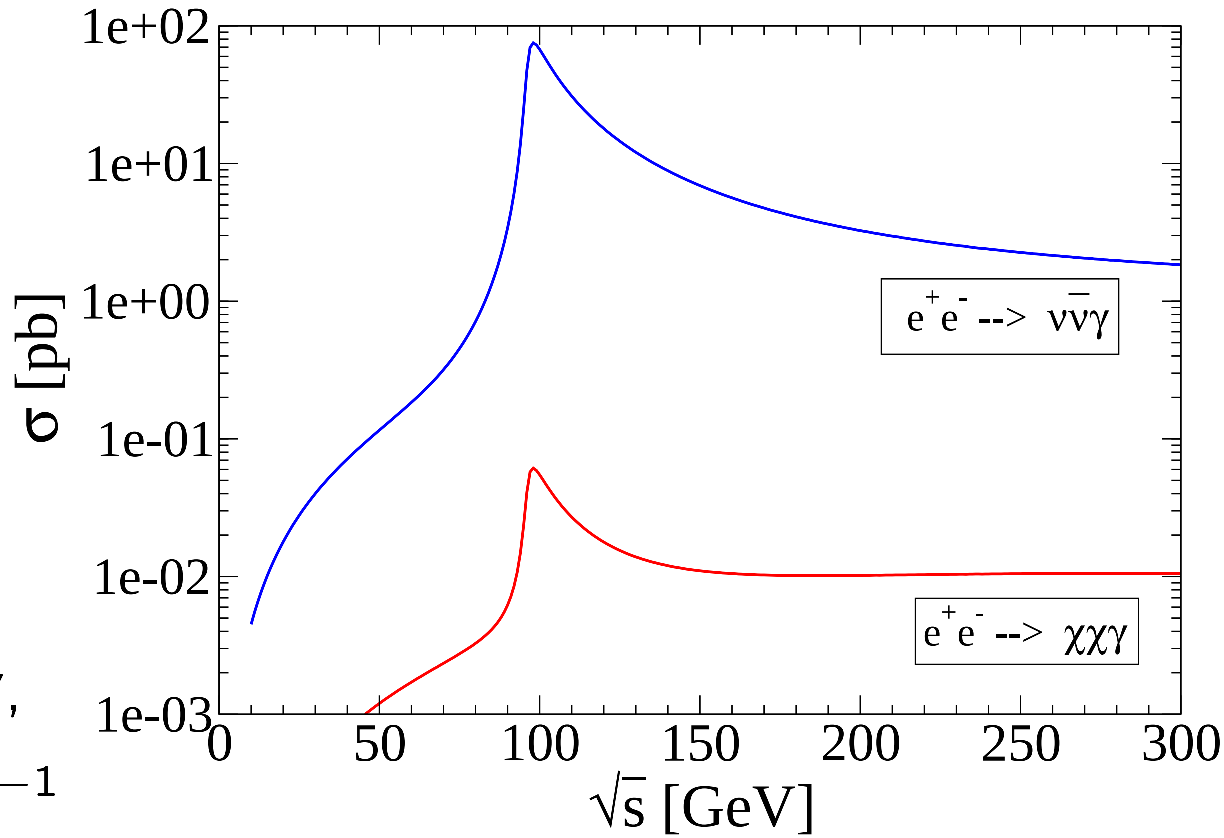
$\tan\beta = 10$

$m_{\tilde{\chi}_1^0} = 0$ GeV

LEP II: $\sqrt{s} = 200$ GeV,

luminosity $\mathcal{L} = 100$ pb^{-1}

Significance: $\frac{S}{\sqrt{B}} < 0.1$



3 Note on radiative neutralino production at the ILC

- Radiative neutralino production
  $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0\gamma$
  can not be mesured at LEP.

- However, good prospects at at the ILC,
  due to high luminosity, e.g., $\mathcal{L} = 500$ fb^{-1}.

Radiative neutralino production at the ILC

Consider e.g. the SPS 1a scenario ('typical' SUSY point):

$\tan\beta = 10$	$\mu = 352$ GeV	$M_2 = 193$ GeV	$m_0 = 100$ GeV
$m_{\chi_1^0} = 94$ GeV	$m_{\chi_1^\pm} = 178$ GeV	$m_{\tilde{e}_R} = 143$ GeV	$m_{\tilde{e}_L} = 204$ GeV

At $\sqrt{s} = 500$ GeV with $\mathcal{L} = 500$ fb^{-1},
and beam polarizations $P_{e^-} = 80\%$, $P_{e^+} = 60\%$ we find:

- signal: $\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0\gamma) = 70$ fb

  background: $\sigma(e^+e^- \to \nu\bar{\nu}\gamma) = 330$ fb

- Signal to background ratio: $\frac{N_S}{N_B} = \frac{1}{5}$, Significance: $\frac{N_S}{\sqrt{N_B}} = 80$

[Dreiner, O.K., Langenfeld: hep-ph/0610020]

4 Summary and conclusions

Zero mass neutralino is allowed!

- no constraints from electroweak precision data and rare decays

- no constraints from $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_i^0$

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

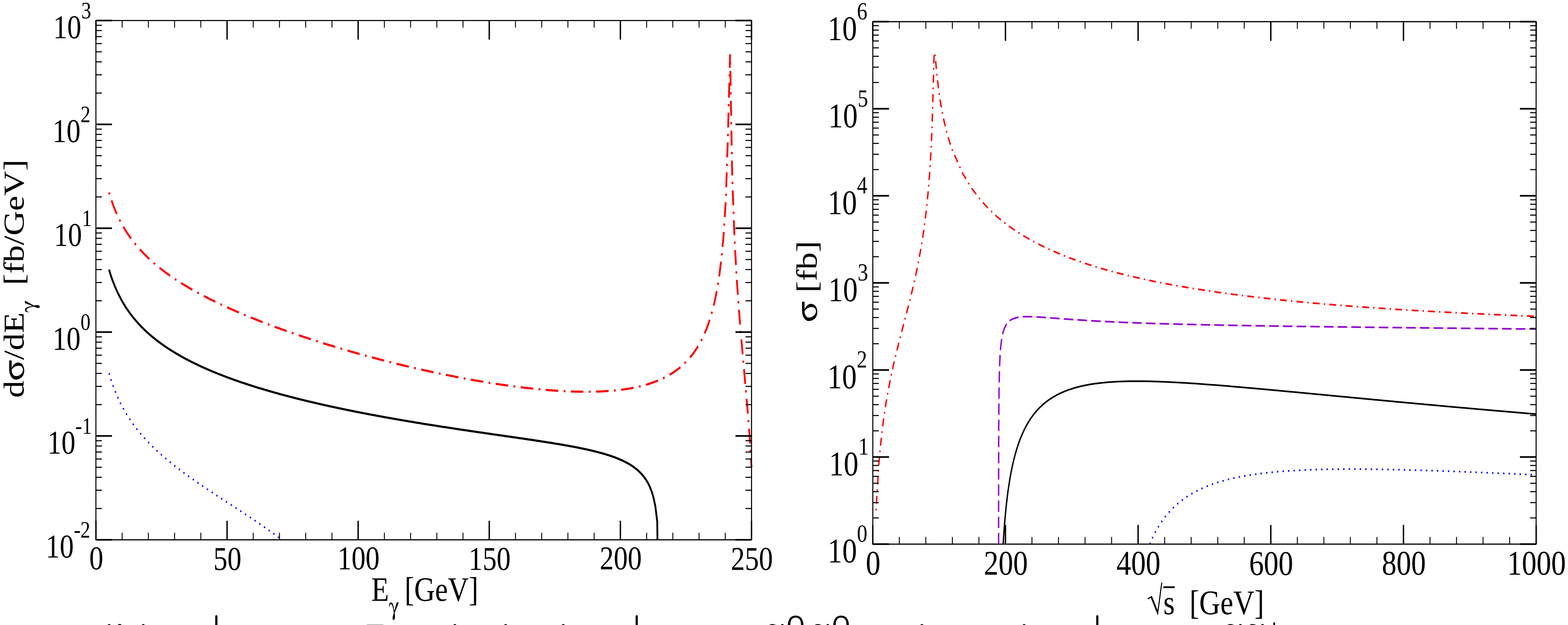
Summary and conclusions: Part II

Radiative production of neutralinos $e^{+}e^{-} \to \tilde{\chi}_1^0\tilde{\chi}_1^0\gamma$

- LEP: due to small luminosity (order 100 pb^{-1}) significance $S < 0.1$

- ILC:
  - $\mathcal{L} = 500$ fb^{-1} $\to$ significance $S = 80$ for SPS 1a
  - polarized beams enhance signal and reduce background
    $\longrightarrow$ talk in polarization session
  - $\chi_1^0\tilde{\chi}_1^0\gamma$ could be the lightest SUSY state to be observed!

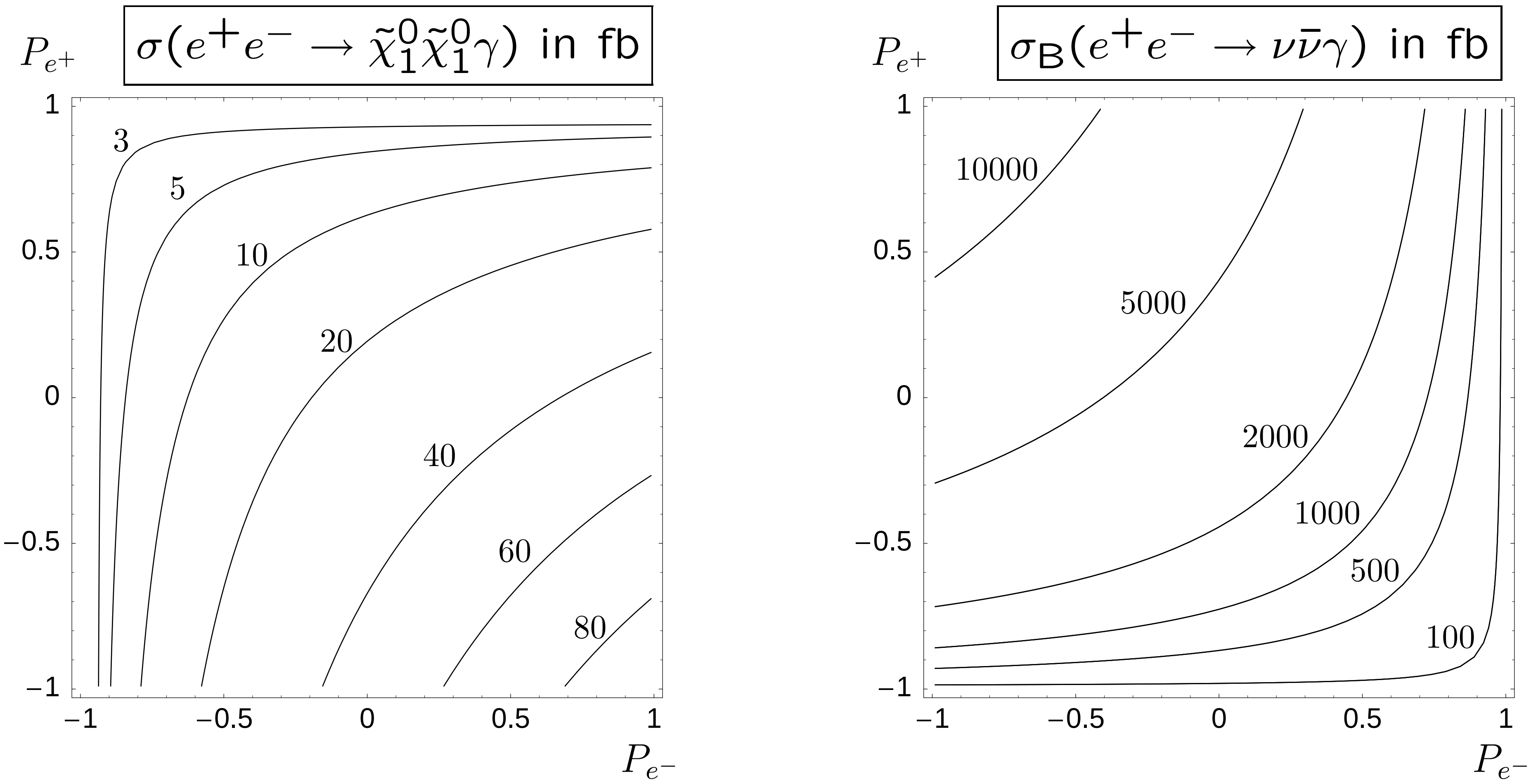
Energy distribution and $\sqrt{s}$ dependence



solid: $e^+e^- \to \nu\bar{\nu}\gamma$, dashed: $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0\gamma$, dotted: $e^+e^- \to \tilde{\nu}\tilde{\nu}^*\gamma$

beam polarization: $(P_{e^-}, P_{e^+}) = (0.8, -0.6)$

Beam polarization dependence



$\sqrt{s} = 500$ GeV, for SPS1 scenario:

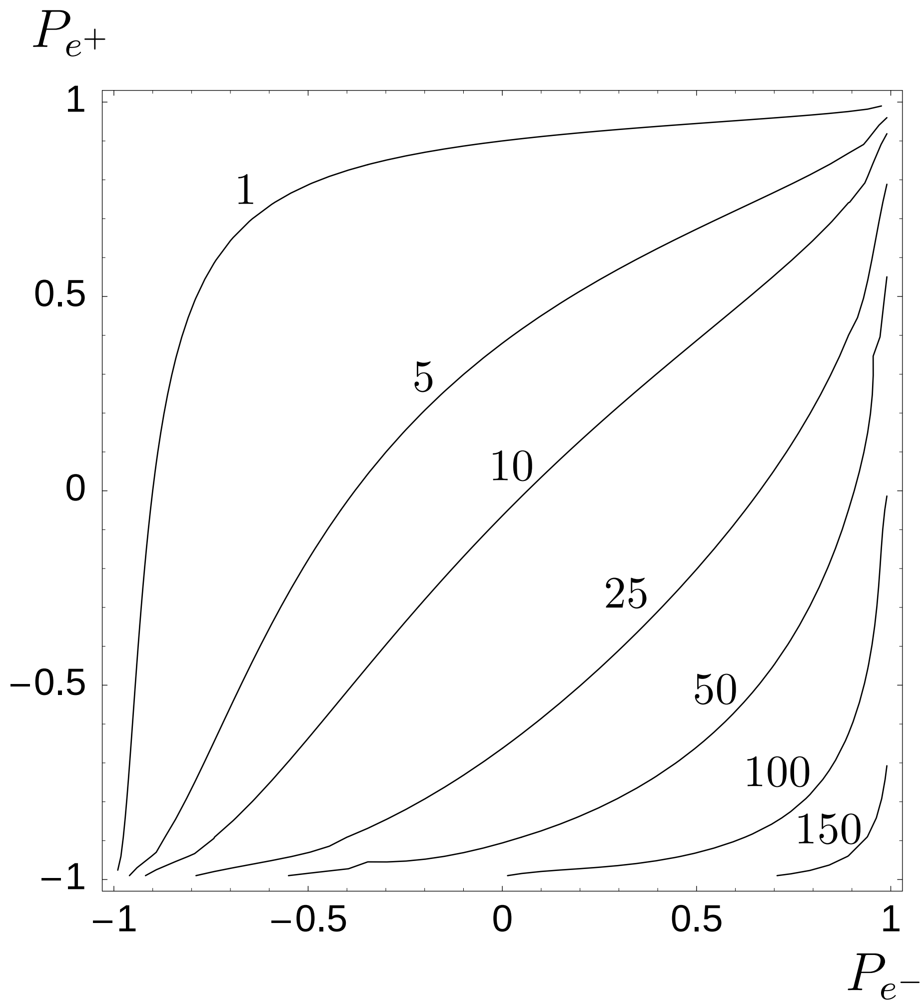
$\mu = 352$ GeV, $M_2 = 193$ GeV, $\tan\beta = 10$, $m_0 = 100$ GeV

Significance

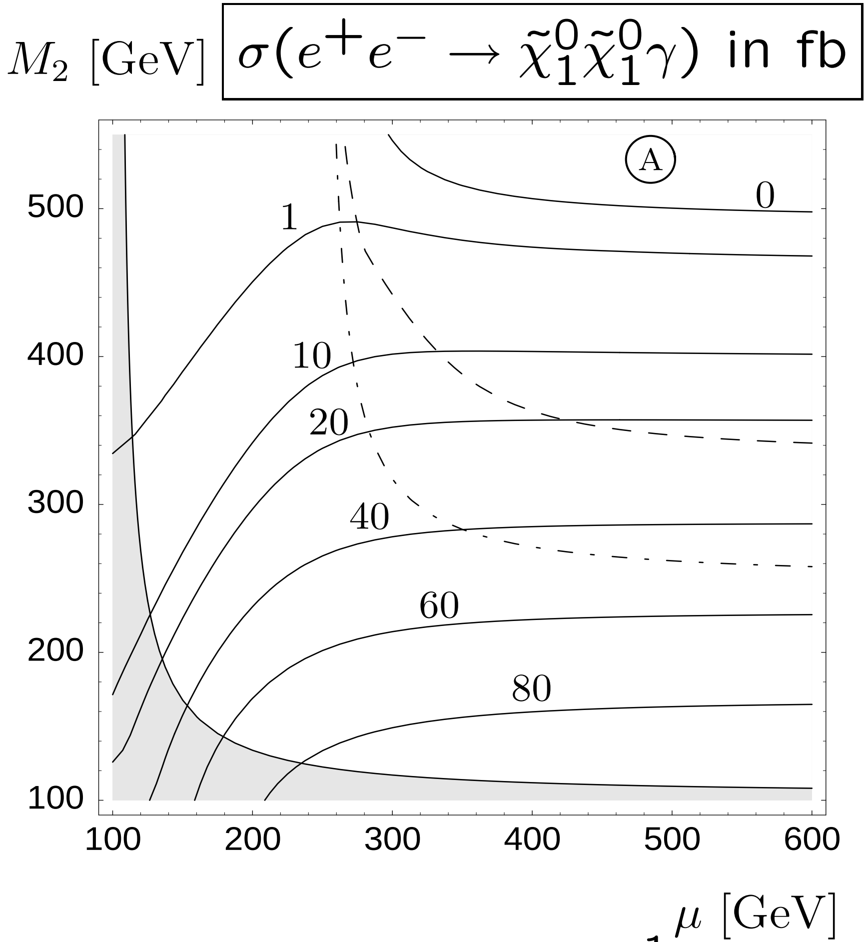
$$S = \frac{N}{\sqrt{N+N_B}}$$

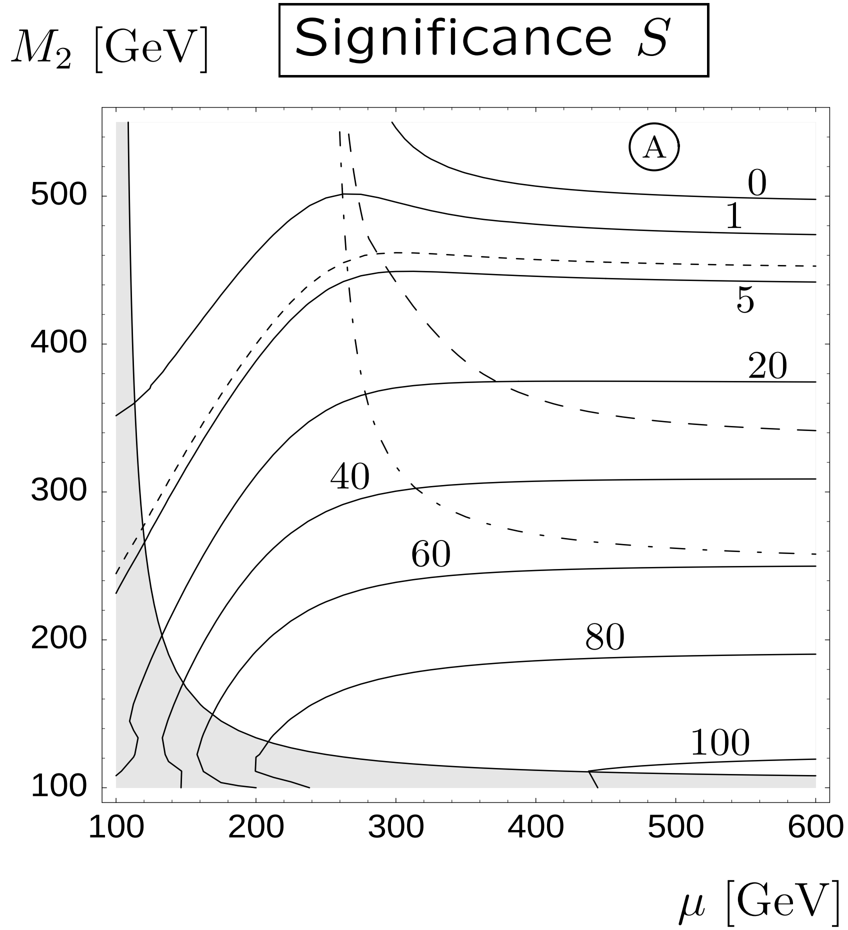
$$N = \mathcal{L} \times \sigma$$

$$\Rightarrow S = \frac{\sigma}{\sqrt{\sigma+\sigma_{\mathrm{B}}}}\sqrt{\mathcal{L}}$$



μ and M_2 dependence



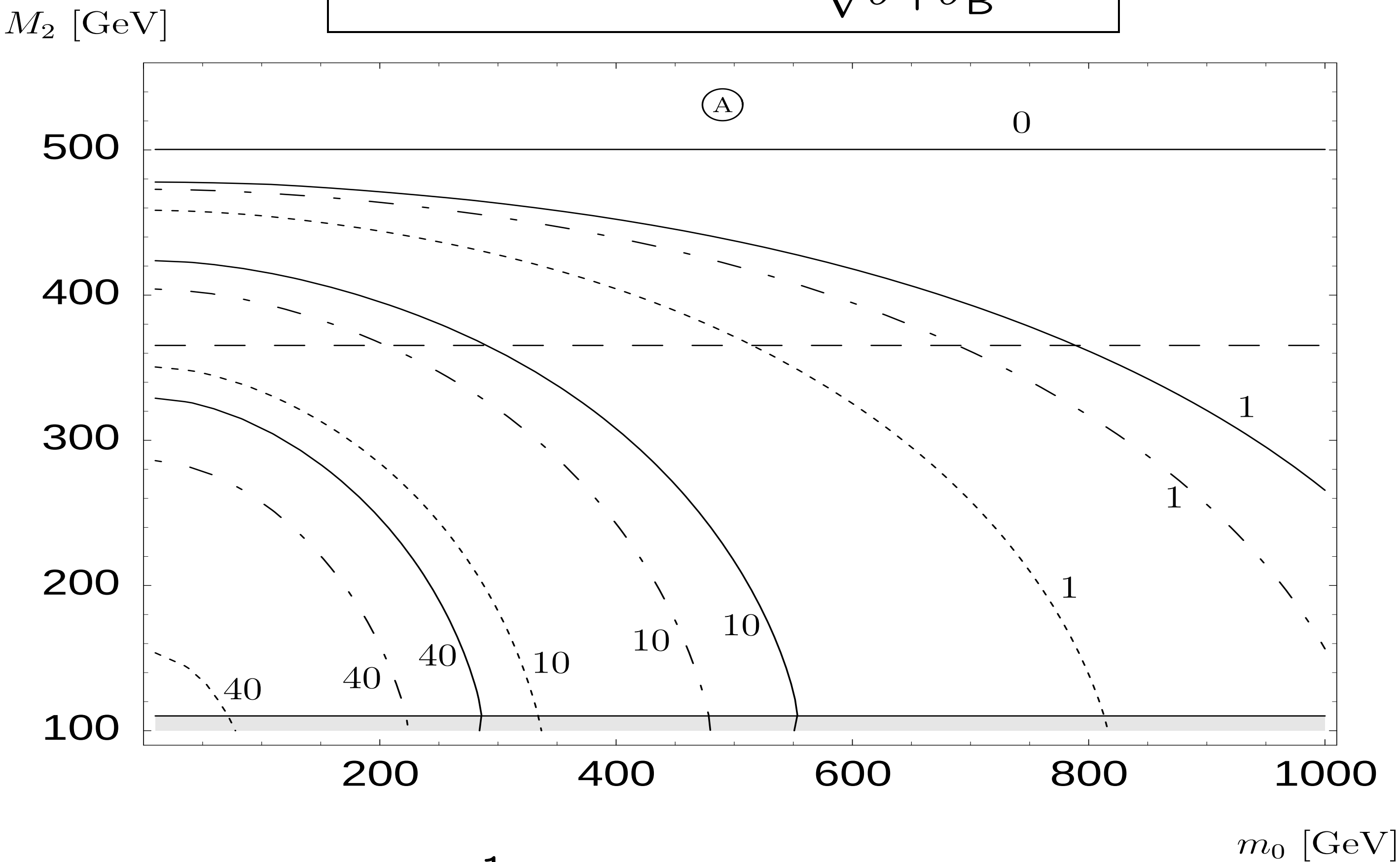


$\sqrt{s} = 500$ GeV, $\mathcal{L} = 500$ fb^{-1}; $(P_{e^-}, P_{e^+}) = (0.8, -0.6)$

kinematical limits: $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0$(dashed); $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-$(dot-dashed)

selectron mass dependence for different sets of beam polarizations

Significance $S = \frac{\sigma}{\sqrt{\sigma + \sigma_B}} \sqrt{\mathcal{L}}$



$\sqrt{s} = 500$ GeV, $\mathcal{L} = 500$ fb^{-1}; $\mu = 500$ GeV, $\tan\beta = 10$

solid: $(P_{e^-}, P_{e^+}) = (0, 0)$; dot-dashed: $(0.8, 0)$; dotted: $(0.8, -0.6)$