The lightest neutralino in the Minimal Non-minimal Supersymmetric Standard Model

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based on

SH, D.J. Miller, G. Moortgat-Pick, R. Nevzorov, M. Trusov,

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Outline

- Introduction
  - Supersymmetry, MSSM, NMSSM
  - Minimal Non-minimal Supersymmetric Standard Model (MNSSM)
- MNSSM neutralino sector
- Upper bound on LSP mass
- Approximate solutions for LSP mass
- Neutralino production at ILC
- Conclusions and outlook

Supersymmetry (SUSY)

- Symmetry fermions $\leftrightarrow$ bosons
- "Standard" particles get superpartners with spin $\pm\frac{1}{2}$
- Supersymmetry is broken $\Rightarrow$ soft SUSY parameters
- Motivation: unification of gauge couplings, hierarchy problem

Minimal Supersymmetric Standard Model (MSSM)

- Minimal extension of Standard Model (SM)
- Minimal Higgs sector: 2 doublets
- μ term in superpotential: $W_\mu = \mu \hat{H}_d \hat{H}_u \leftrightarrow \mu$ problem
- Solution: extended Higgs sector

Introduction

Extended SUSY models

"Simplest" extension of MSSM $\longrightarrow$ add singlet/singlino superfield $\hat{S}$

$\longrightarrow$ extended Higgs sector: 2 doublets + 1 singlet

and neutralino sector: 5 neutralinos

Most common model:

Next-to-Minimal Supersymmetric Standard Model (NMSSM)

- Superpotential: $W = \lambda \hat{S} \hat{H}_d \hat{H}_u + \frac{\kappa}{3} \hat{S}^3 + W_{\text{MSSM}}(\mu = 0)$
- Solution of μ problem: $\mu \to \mu_{\text{eff}} = \lambda \langle S \rangle$
- Larger mass of lightest scalar Higgs possible $\Rightarrow$ less fine-tuning
- $\frac{\kappa}{3} \hat{S}^3$ breaks $U(1)_{\text{PQ}}$, $\mathbb{Z}_3$ symmetry remains
- Problem: spontaneous breaking of $\mathbb{Z}_3 \longleftrightarrow$ domain walls

[Vilenkin, '85; Abel, Sarkar, White, '95]

Introduction MNSSM

Minimal Non-minimal Supersymmetric Standard Model (MNSSM)

[Panagiotakopoulos, Tamvakis, ’99; Panagiotakopoulos, Pilaftsis, ’00]
[Dedes, Hugonie, Moretti, Tamvakis, ’00; Menon, Morrissey, Wagner, ’04]

- Superpotential: $W = \lambda \hat{S} \hat{H}_d \hat{H}_u + \xi \hat{S} + W_{\text{MSSM}}(\mu = 0)$ $(\xi \lesssim 1$ TeV)
- Gravity induced tadpole term $\xi \hat{S}$ breaks $U(1)_{PQ}$ and $\mathbb{Z}_3$
  $\longrightarrow$ no domain wall problem
- Solution of μ problem as in NMSSM ($\mu_{\text{eff}} = \lambda \langle S \rangle$)
- Neutralino sector $\leftrightarrow$ NMSSM with $\kappa = 0$
- Chargino sector: like MSSM with $\mu \to \mu_{\text{eff}}$

MNSSM Neutralino sector

- 5 Parameters (tree-level): M_1, M_2, μ_{eff}, λ, $\tan\beta$
- (5×5) mass matrix: (basis $\tilde{B}, \tilde{W}_3, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S}$)

$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z s_W c_\beta & M_Z s_W s_\beta & 0 \\ 0 & M_2 & M_Z c_W c_\beta & -M_Z c_W s_\beta & 0 \\ -M_Z s_W c_\beta & M_Z c_W c_\beta & 0 & -\mu_{\text{eff}} & -\frac{\lambda v}{\sqrt{2}} s_\beta \\ M_Z s_W s_\beta & -M_Z c_W s_\beta & -\mu_{\text{eff}} & 0 & -\frac{\lambda v}{\sqrt{2}} c_\beta \\ 0 & 0 & -\frac{\lambda v}{\sqrt{2}} s_\beta & -\frac{\lambda v}{\sqrt{2}} c_\beta & 0 \end{pmatrix}$$

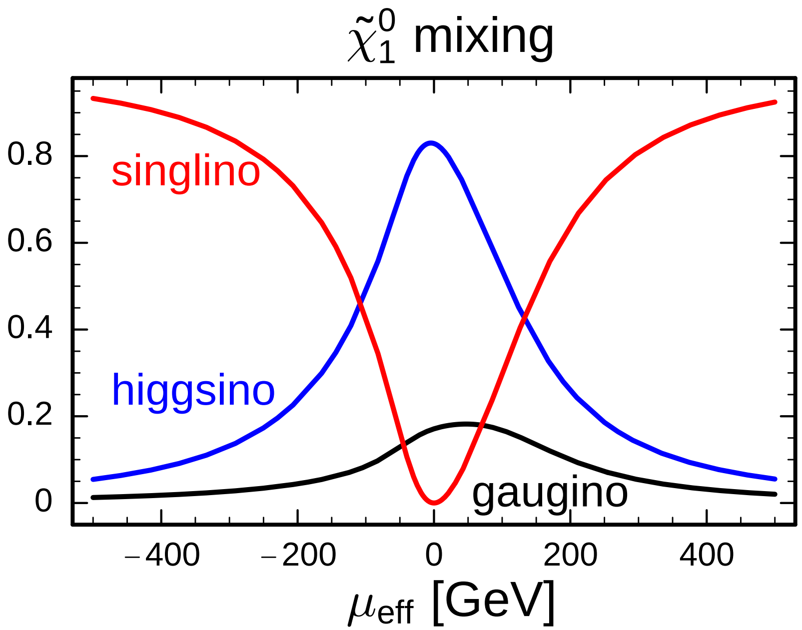
$s_\beta = \sin\beta$, $c_\beta = \cos\beta$, $s_W = \sin\theta_W$, $c_W = \cos\theta_W$

$\mu_{\text{eff}} = \lambda\langle S\rangle$, $\tan\beta = \frac{v_2}{v_1}$, $v^2 = v_1^2 + v_2^2$, $\frac{v_{1,2}}{\sqrt{2}} = \langle H_{d,u}\rangle$

[NMSSM: $(M_{\tilde{\chi}^0})_{55} = 2\kappa\langle S\rangle$]

MNSSM Neutralino sector

- Perturbativity up to the GUT scale $\Rightarrow$ $\lambda(M_Z) \lesssim 0.7$
- Limits from chargino search $\Rightarrow$ $|M_2|, |\mu_{\rm eff}| \gtrsim 100$ GeV
- GUT relation for gaugino masses $\Rightarrow$ $M_2 = 2M_1$
  (assumed in the following)
- $\tilde{\chi}_1^0$ singlino-like, $\tilde{\chi}_{2,3,4,5}^0$ MSSM-like



$\lambda = 0.7$
$\tan\beta = 5$
$M_2 = 200$ GeV
$M_1 = 100$ GeV

Upper bound on $\tilde{\chi}_1^0$ mass

- Consider $M_{\tilde{\chi}^0} M_{\tilde{\chi}^0}^\dagger$ with eigenvalues $|m_{\tilde{\chi}_i^0}|^2$
- In basis $(\tilde{B}, \tilde{W}_3, -\tilde{H}_d^0 s_\beta + \tilde{H}_u^0 c_\beta, \tilde{H}_d^0 c_\beta + \tilde{H}_u^0 s_\beta, \tilde{S})$
  $\longrightarrow$ bottom-right 2×2 block of $M_{\tilde{\chi}^0} M_{\tilde{\chi}^0}^\dagger$:

$$\begin{pmatrix} |\mu_{\text{eff}}|^2 + \sigma^2 & \nu^* \mu_{\text{eff}} \\ \nu \mu_{\text{eff}}^* & |\nu|^2 \end{pmatrix}$$

$$\nu = \frac{\lambda v}{\sqrt{2}}, \quad \sigma^2 = M_Z^2 \cos^2 2\beta + |\nu|^2 \sin^2 2\beta$$

- Immediately obvious: $\boxed{|m_{\tilde{\chi}_1^0}| \leq |\nu| = \frac{\lambda v}{\sqrt{2}}}$

  (minimal eigenvalue is smaller than smallest diagonal entry)

- $|m_{\tilde{\chi}_1^0}| \longrightarrow 0$ for $\lambda \longrightarrow 0$

Upper bound on $\tilde{\chi}_1^0$ mass

- Improvement:

  $|m_{\tilde{\chi}_1^0}|^2$ also smaller than smallest eigenvalue of sub-matrix:

$$|m_{\chi_1^0}|^2 \leq \frac{1}{2}\left(|\mu_{\text{eff}}|^2 + \sigma^2 + |\nu|^2 - \sqrt{\left(|\mu_{\text{eff}}|^2 + \sigma^2 + |\nu|^2\right)^2 - 4|\nu|^2\sigma^2}\right)$$

- Upper bound decreasing for increasing $|\mu_{\text{eff}}|$

  $\longrightarrow$ for minimal $|\mu_{\text{eff}}|$ and maximal λ: $m_{\chi_1^0} \lesssim 80$ GeV

- For large $|\mu_{\text{eff}}| \gg M_Z$: $|m_{\chi_1^0}|^2 \lesssim \dfrac{|\nu|^2\sigma^2}{\left(|\mu_{\text{eff}}|^2 + \sigma^2 + |\nu|^2\right)}$

Approximate solution for $\tilde{\chi}_1^0$ mass

- Characteristic equation ($\varkappa$: eigenvalues of $M_{\tilde{\chi}^0} \leftrightarrow m_{\tilde{\chi}_i^0}$)

$$\det\left(M_{\tilde{\chi}^0} - \varkappa I\right) =$$

$$\left(M_1 M_2 - (M_1 + M_2)\varkappa + \varkappa^2\right)\left(\varkappa^3 - (\mu_{\text{eff}}^2 + \nu^2)\varkappa + +\nu^2\mu_{\text{eff}}\sin 2\beta\right)$$

$$+ M_Z^2\left(\tilde{M} - \varkappa\right)\left(\varkappa^2 + \mu_{\text{eff}}\sin 2\beta\varkappa - \nu^2\right) = 0$$

$$\tilde{M} = M_1 c_W^2 + M_2 s_W^2$$

- If $|m_{\tilde{\chi}_1^0}| \ll |m_{\tilde{\chi}_2^0}| \longrightarrow$ ignore $\varkappa^3$, $\varkappa^4$, $\varkappa^5$ terms

$$\Rightarrow \det\left(M_{\tilde{\chi}^0} - \varkappa I\right) \approx \varkappa^2 - B\varkappa + C = 0$$

with

$$B = \frac{M_1 M_2}{M_1 + M_2} + \left(\frac{\nu^2}{\mu_{\text{eff}}^2 + \nu^2} - \frac{M_Z^2}{\mu_{\text{eff}}^2 + \nu^2}\frac{\tilde{M}}{M_1 + M_2}\right)\mu_{\text{eff}}\sin 2\beta - \frac{M_Z^2\nu^2}{(M_1 + M_2)(\mu_{\text{eff}}^2 + \nu^2)}$$

$$C = \frac{\nu^2}{\mu_{\text{eff}}^2 + \nu^2}\left(\frac{M_1 M_2}{M_1 + M_2}\mu_{\text{eff}}\sin 2\beta - \frac{\tilde{M}}{M_1 + M_2}M_Z^2\right)$$

Approximate solution for $\tilde{\chi}_1^0$ mass

- Approximate solution

$$|m_{\chi_1^0}| = \text{Min}\left\{\frac{1}{2}\left|B - \sqrt{B^2 - 4C}\right|, \frac{1}{2}\left|B + \sqrt{B^2 - 4C}\right|\right\}$$

- Decoupling limit
  - $\mu_{\text{eff}} \gg M_Z$ or $M_1, M_2 \gg M_Z$, small $\tan\beta \longrightarrow B^2 \gg C$

$$\Rightarrow \quad |m_{\chi_1^0}| \simeq \frac{C}{B} \simeq \frac{|\mu_{\text{eff}}|\nu^2 \sin 2\beta}{\mu_{\text{eff}}^2 + \nu^2}$$

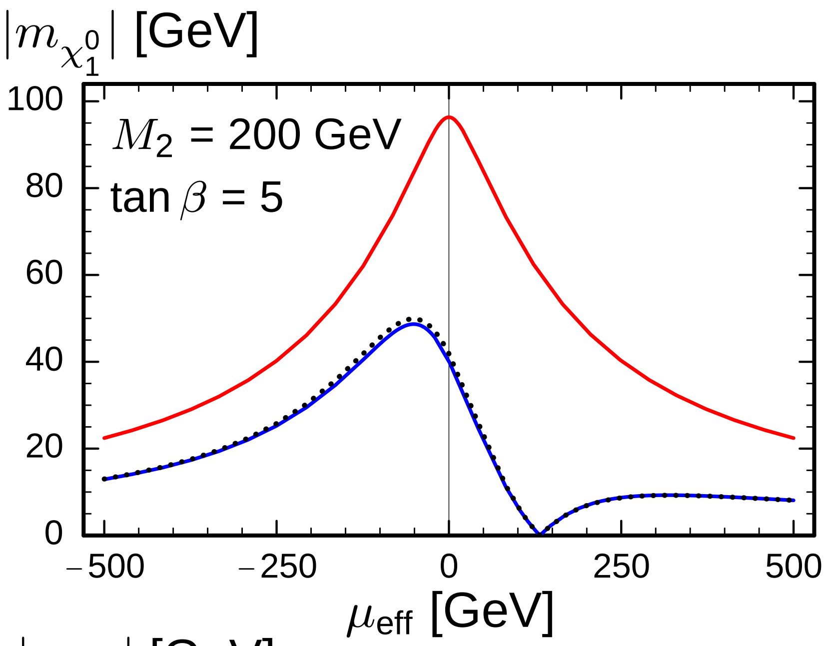
  - $\mu_{\text{eff}}, M_1, M_2 \gg M_Z$, large $\tan\beta$

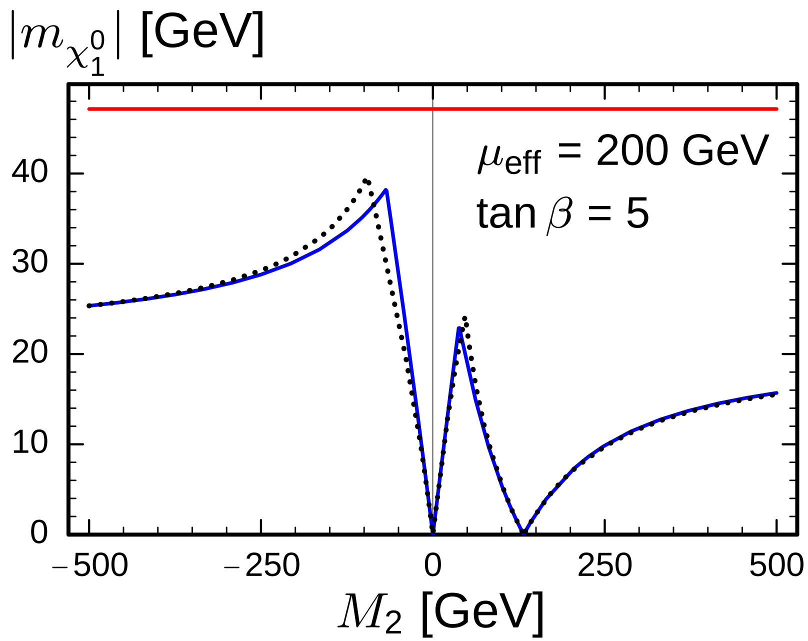
$$\Rightarrow \quad |m_{\chi_1^0}| \to \frac{\nu^2 M_Z^2}{\mu_{\text{eff}}^2 + \nu^2}\left|\frac{\tilde{M}}{M_1 M_2}\right|$$

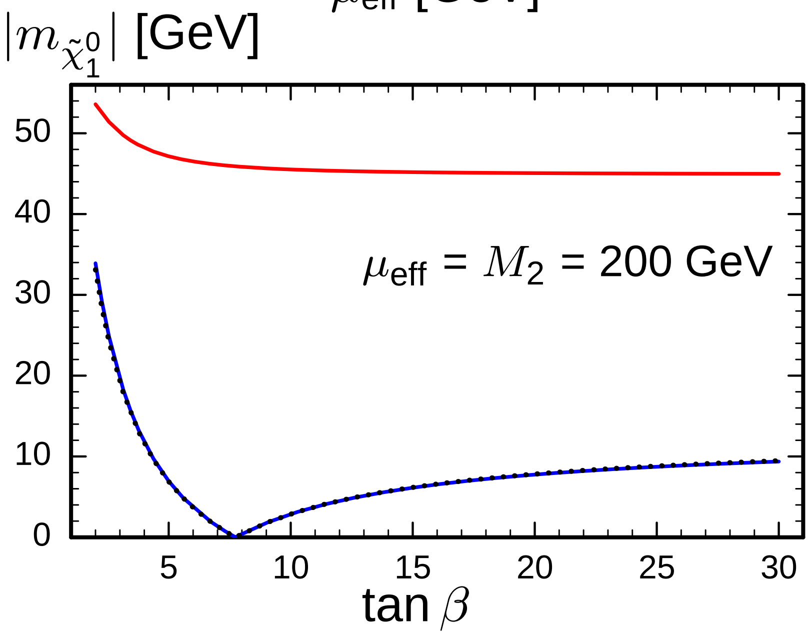
$\longrightarrow |m_{\chi_1^0}|$ decreases with increasing $\mu_{\text{eff}}, M_1, M_2$

$\longrightarrow |m_{\chi_1^0}| \sim \nu^2 \sim \lambda^2$ for $\lambda \to 0$ and $\mu_{\text{eff}} = \lambda\langle S\rangle = \text{const}$

Numerical results







$\lambda = 0.7$, $M_1 = 0.5 M_2$

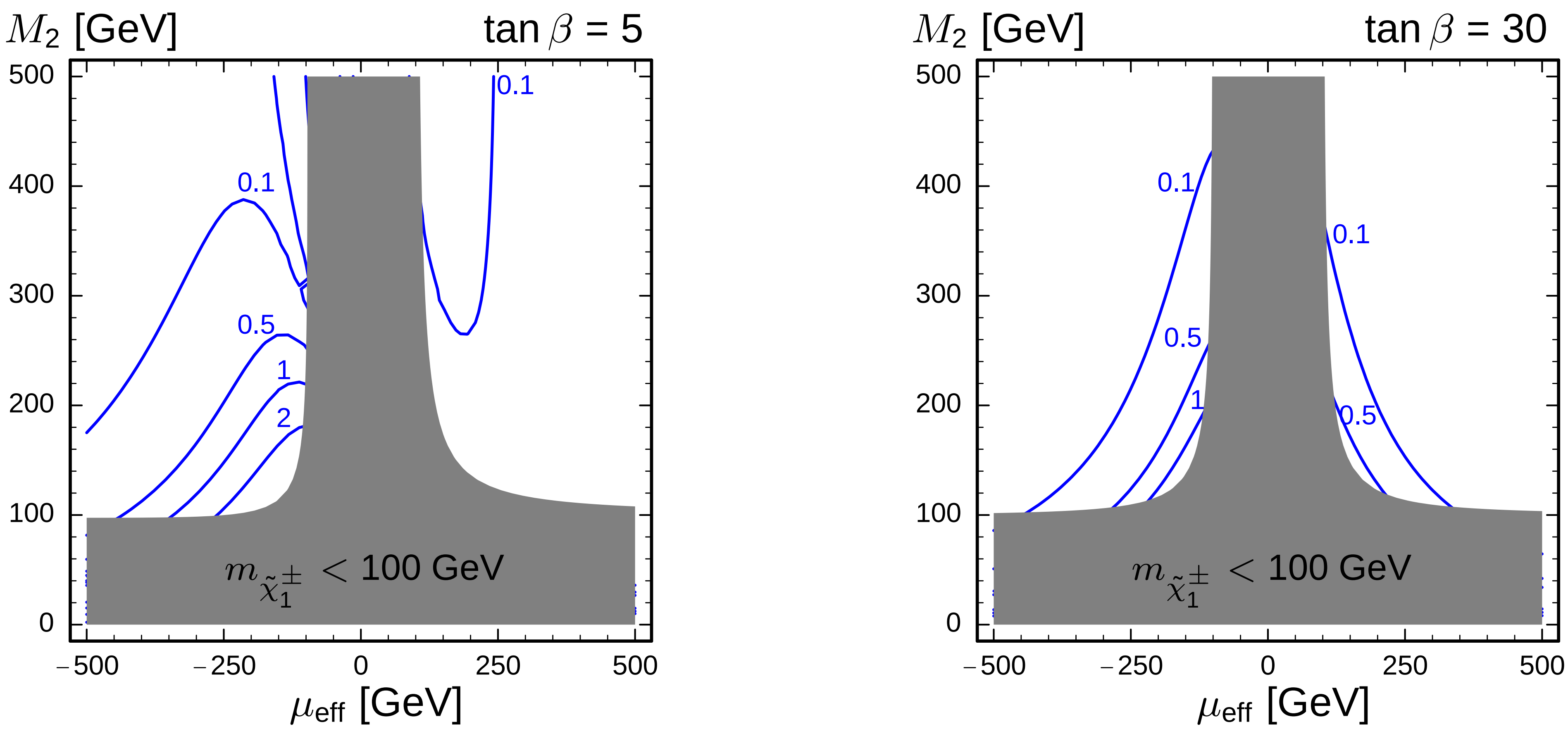
red: upper bound

dotted: approximate solution

blue: exact $|m_{\chi_1^0}|$

Numerical results

Contours of difference between approximate and exact solution [GeV]



λ = 0.7, M_1 = 0.5M_2

$\longrightarrow$ difference $<$ 1 GeV in most of allowed parameter space

Production of $\tilde{\chi}_1^0$ at ILC

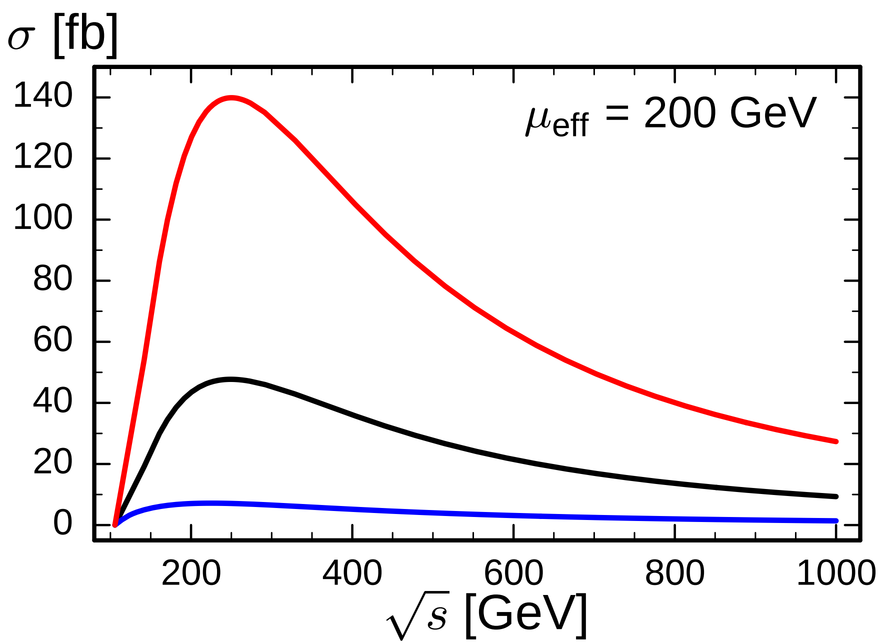
- Singlino-like neutralinos visible at ILC up to high purity $\sim$ 99%

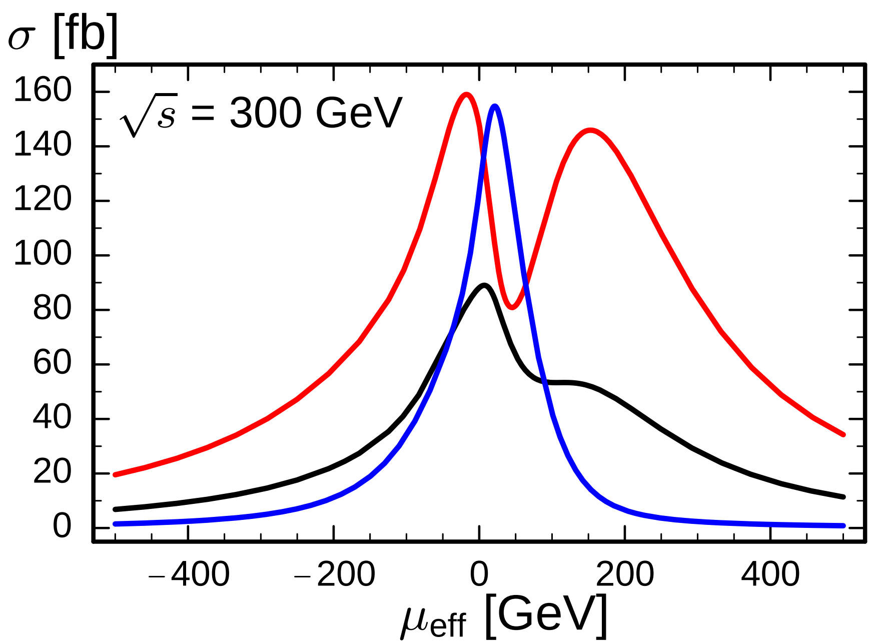
  [Franke, SH, '01, '02]

- $\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0)$ in MNSSM

  for λ = 0.7, tan β = 5, M_2 = 200 GeV, M_1 = 100 GeV, $m_{\tilde{e}_L}$ = 200 GeV, $m_{\tilde{e}_R}$ = 150 GeV

  beam polarizations (P_{e^-}, P_{e^+}) = (0, 0), (90%, −60%), (−90%, 60%)





Conclusions and outlook

- Lightest neutralino $\tilde{\chi}_1^0$ in MNSSM
  $\longrightarrow$ predominantly singlino in most of allowed parameter space
- Upper bound and approximate solution for $m_{\tilde{\chi}_1^0}$ in MNSSM
  - $|m_{\tilde{\chi}_1^0}| \lesssim 80$ GeV (for large $\lambda \sim 0.7$ and small M_1, M_2, μ_{eff}, $\tan\beta$)
  - $|m_{\tilde{\chi}_1^0}|$ decreasing with increasing M_1, M_2, μ_{eff} or decreasing λ
- Visible at ILC in large regions of parameter space
- Cosmological implications
  - Correct relic density through Z and (singlet) Higgs exchange
    [Menon, Morrissey, Wagner, '04]
  - Analogue singlino dark matter in NMSSM
    [e.g. Bélanger, Boudjema, Hugonie, Pukhov, Semenov, '05]