Bounds on light Neutralinos from Cosmology and Collider experiments

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1 Introduction

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

2 Light Neutralinos?

A very light neutralino in the MSSM? Look at bounds from

- Cosmology
  - Cowsig McClelland bound
  - Lee Weinberg bound
  - full calculation
- neutralino production $e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0$ at LEP
- radiative neutralino production at the linear collider

3 The neutralino mass matrix

Neutralinos are the SUSY partners of the neutral gauge ($\tilde{B}$, $\tilde{W}^3$) and CP-even Higgs bosons ($\tilde{H}_u$, $\tilde{H}_d$). These states mix, and the mass eigenstates are the eigenvectors of the matrix:

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

MSSM parameters: M_1, M_2, μ, $\tan\beta$

|eigenvalues| of M = neutralino masses $m_{\chi_i^0}$, $i = 1, \ldots, 4$

4 Constraints on M_2, μ, and M_1

- M_2, μ determine chargino mass:
  LEP II: $m_{\chi_1^+} > 104\,\text{GeV} \Rightarrow M_2, \mu \gtrsim 100\,\text{GeV}$
  yields no bound for $m_{\chi_1^0}$ **without GUT relation** $M_1 = \frac{5}{3}\tan^2(\theta_w) M_2$

- M_1 can be chosen such that $m_{\chi_1^0} = 0$:

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

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

$$\Rightarrow M_1 \ll M_2 \quad \Rightarrow \tilde{\chi}_1^0 \ \text{bino-like} \quad \Rightarrow Z^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0 \ \text{is suppressed}$$

$$\Rightarrow Z^0 \ \text{invisible width o.k.}$$

5 Cosmological bounds

5.1 The Boltzmann equation

The Boltzmann equation describes the evolution of a particles species in the thermal bath of the universe:

$$\frac{\mathrm{d}n_\psi}{\mathrm{d}t} = -3Hn_\psi - \langle\sigma|v|\rangle[n_\psi^2 - (n_\psi^2)_{\mathrm{EQ}}].$$

the first rhs term describes dilution of the species by expansion of the universe

the second term accounts for the decrease by annihilation into or coannihilation with other particles

5.2 Cowsig-McClelland bound

If the χ_1^0 is the lsp and stabile, then χ_1^0 is a dark matter candidate

if $m_\chi = \mathcal{O}(1\,\text{eV}) \Rightarrow \tilde{\chi}_1^0$ is relativistic

behaves like a neutrino $\rightarrow$ Cowsig-McClelland bound is applicable

$$\Omega_\chi \;\equiv\; \frac{\rho_\chi}{\rho_c} = \frac{43}{11}\frac{\zeta(3)}{\pi^2}\frac{8\pi G}{3H_0^2}\frac{g_{\text{eff}}}{g_{*S}(T)}T^3\, m_\chi \overset{!}{\leq} \Omega_\nu$$

$$\Rightarrow m_\chi \;\leq\; 0.7/h^2\,\text{eV} \;\text{ with }\; \Omega_\nu h^2 \approx 0.007 \;\text{ (WMAP 2003)}$$

$$\text{for comparison: } \sum m_\nu \leq 2\,\text{eV} \;\text{ (WMAP)}$$

H_0: Hubble constant today, G: Newton's constant

$g_{\text{eff}} = g$ for bosons, $g_{\text{eff}} = 3/4g$ for fermions with $g =$ number of rel. degrees of freedoms

$g_{*S}(T) = \sum g_b (T_b/T)^3 + \frac{7}{8}\sum g_f (T_f/T)^3$

5.3 Lee-Weinberg bound

if $m_\chi > \mathcal{O}(1 - 10 \;\; \text{GeV})$, $\rightarrow$ then $\tilde{\chi}_1^0$ is non-relativistic

for simplicity, consider the processes ($\tilde{\chi}_1^0 = \tilde{B}$)

$$\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \ell\bar{\ell}, \;\; \ell = e, \mu, \tau \quad m_\ell = 0, \;\; M_{\tilde{\ell}} = M_{\tilde{e},\tilde{\mu},\tilde{\tau}}$$

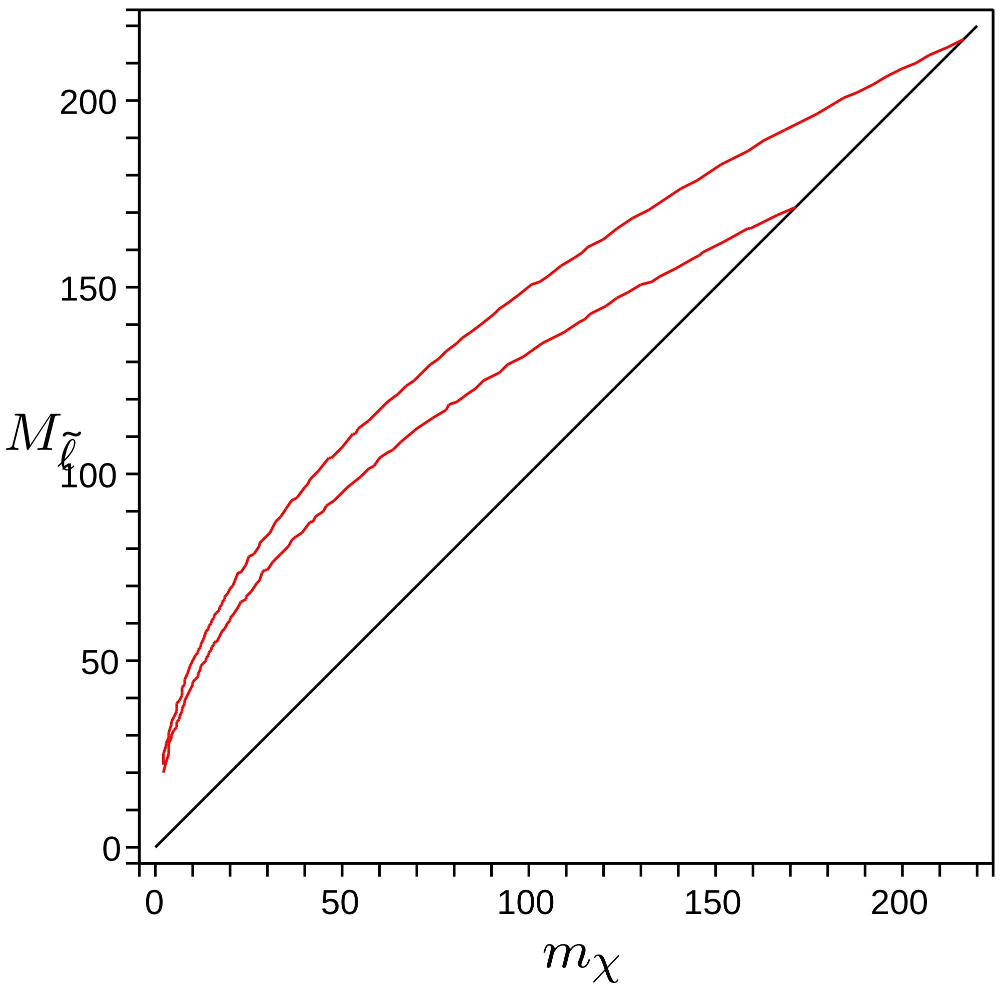
$$\Omega_\chi h^2 \;\approx\; \frac{2.14 \times 10^9 (m_\chi/T_f)^2}{(g_{*S}/g_*^{1/2}) m_{\mathrm{Pl}} \sigma_0} \quad \text{GeV}^{-1}$$

T_f: freeze out temperature, $\approx m_\chi/25 \ldots m_\chi/20$

σ_0: cross section

m_{Pl}: Planck mass

Result:

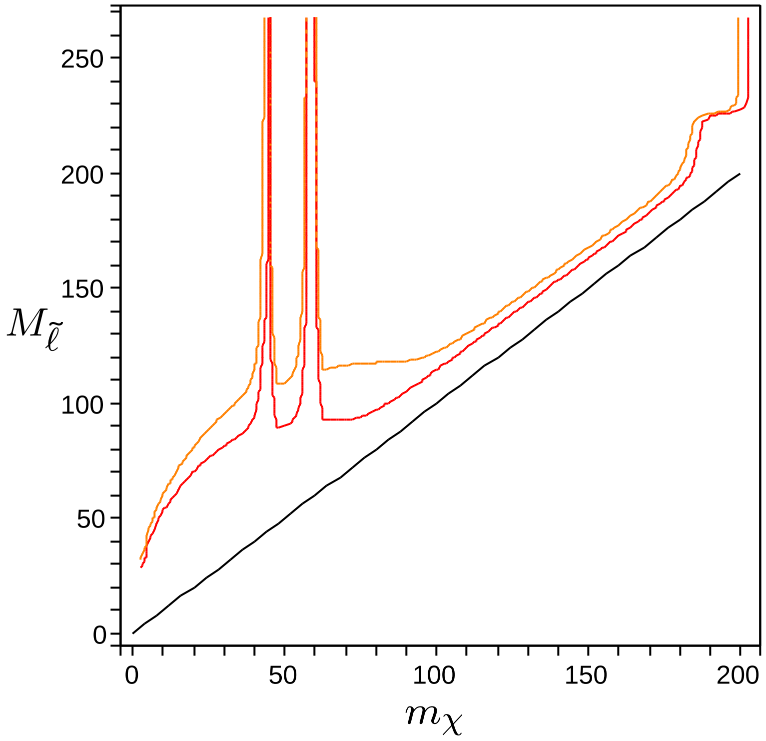


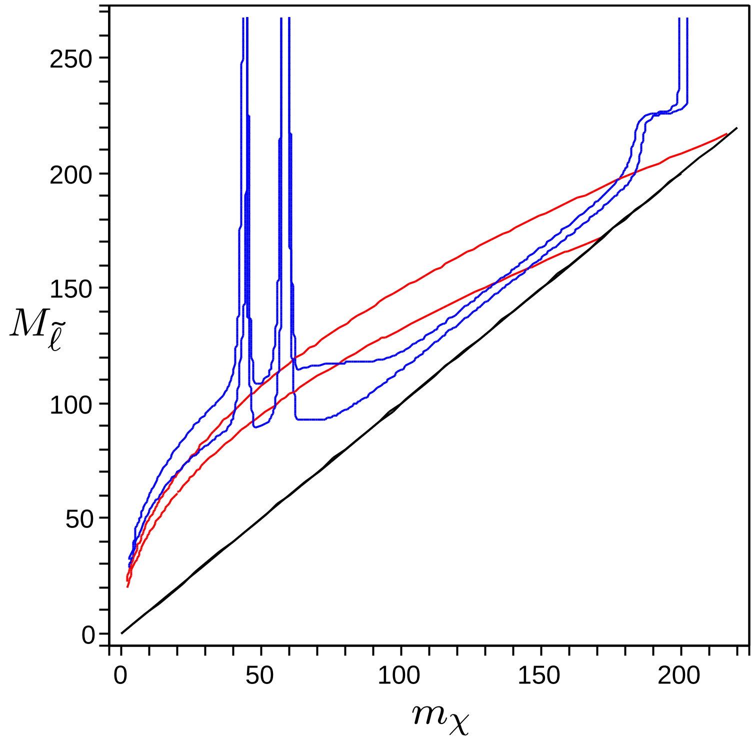
contours of constant relic density for $\Omega_\chi h^2 \pm 3\sigma$

require $M_{\tilde{\ell}} > 80$ GeV

$\Rightarrow 35$ GeV $\leq m_\chi \leq 200$ GeV

5.4 Full calculation

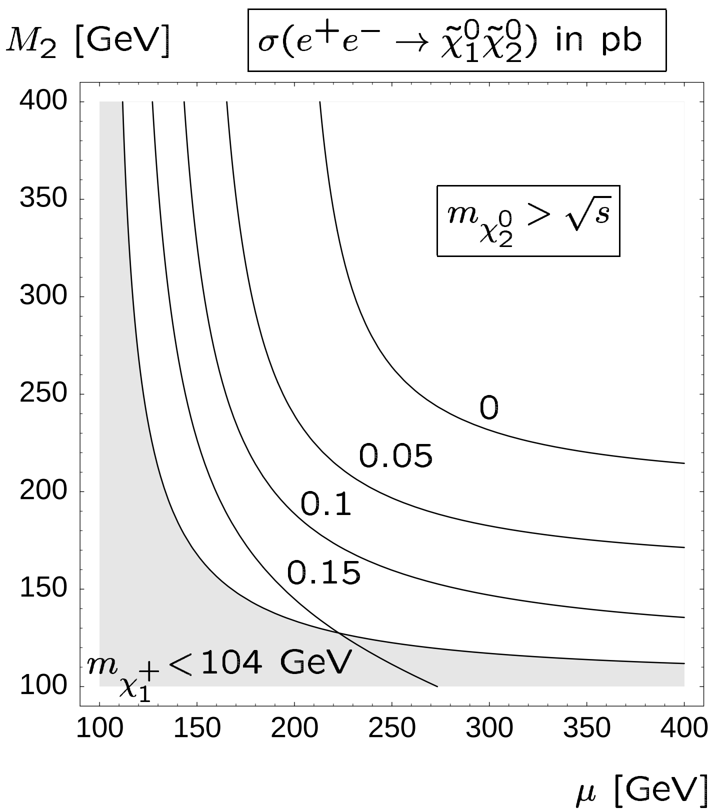


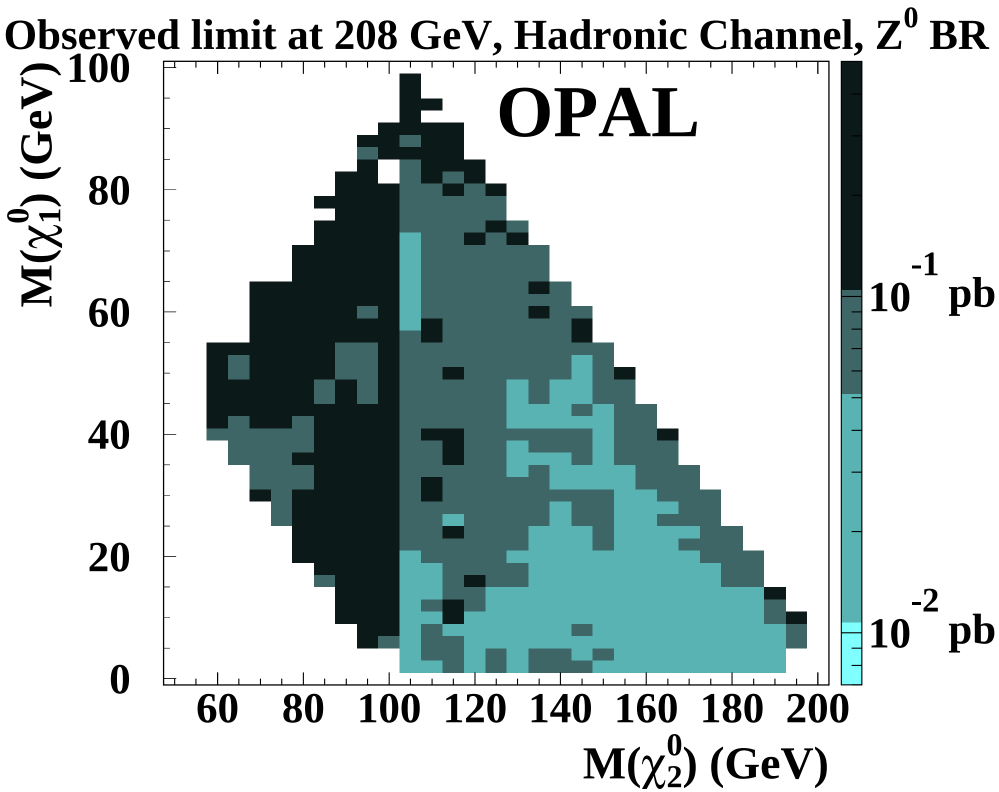


$M_2 = 193$ GeV, $\mu = 350$ GeV,
$M_{\tilde{q}} = 1000$ GeV, $\tan\beta = 10$

more detailed analyses are done f. e. by Hooper et al. (2002),

6 LEP bounds on neutralino production $e^+e^- \to \tilde\chi_1^0\tilde\chi_2^0$

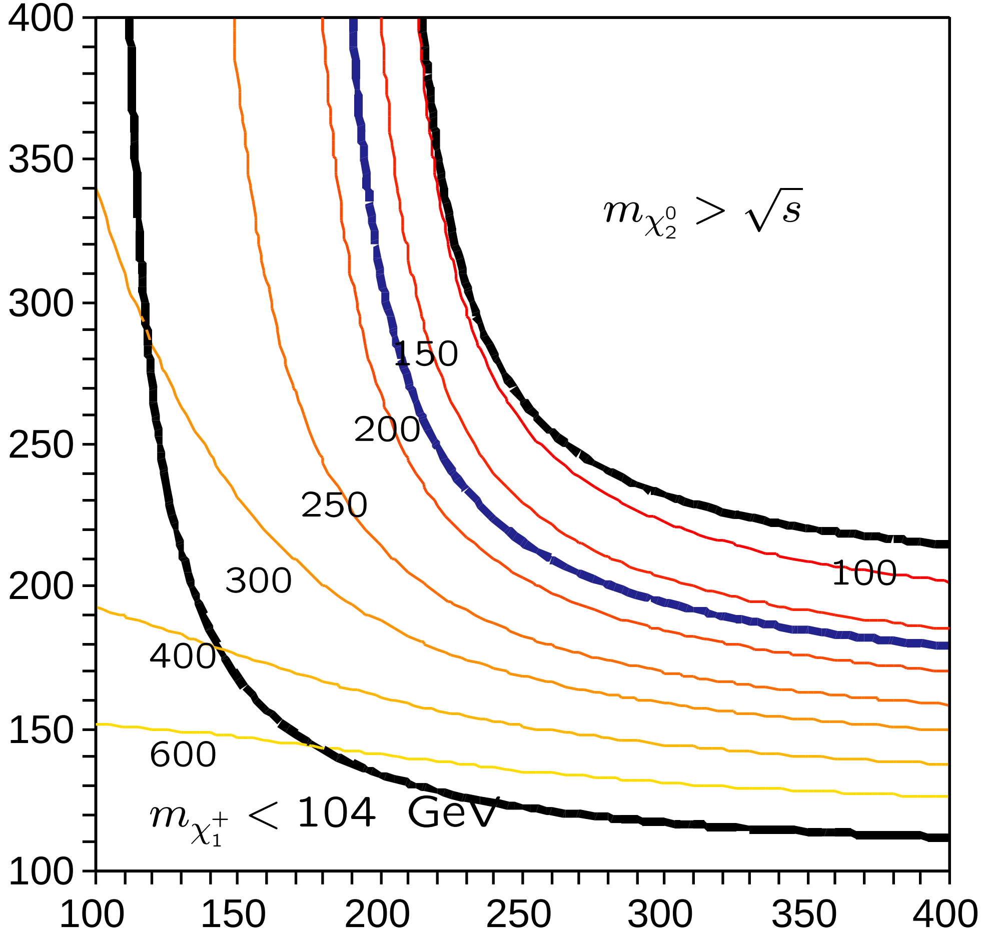




$\sqrt{s} = 200$ GeV, $M_{\tilde e} = 200$ GeV,
$\tan\beta = 10$, $m_{\chi_1^0} = 0$ GeV

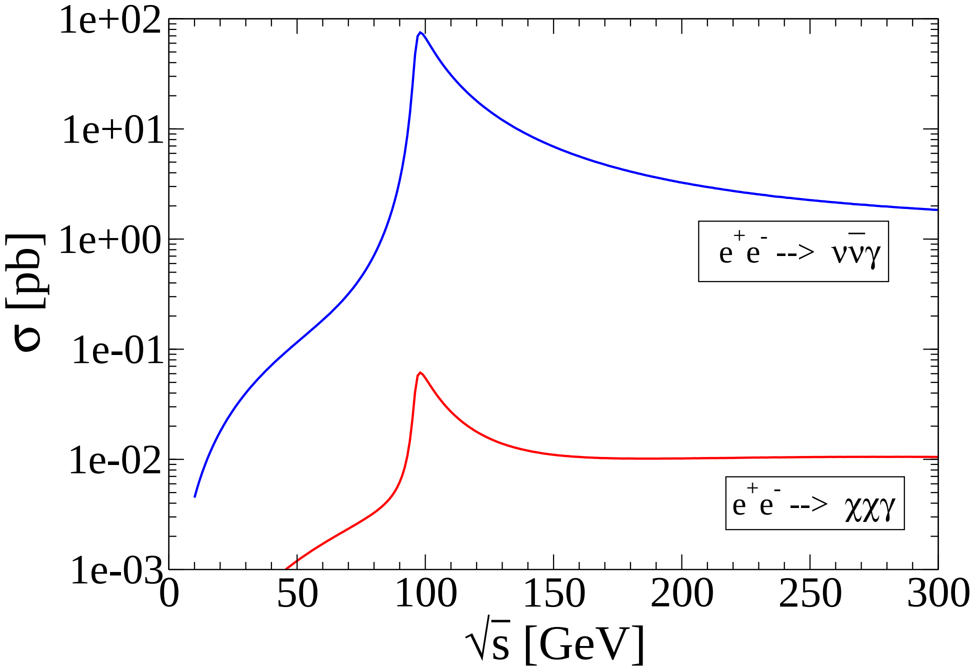
$\sqrt{s} = 208$ GeV, $CL = 95\%$

From the OPAL plot: require, that $\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0) < 50$ fb this translates into mass bound on the selectron mass if BR$(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z^0 = 100\%)$



contour lines of minimal selectron masses that are compatible with OPAL data

7 No bound from radiative neutralino production $e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \gamma$



$M_{\tilde{e}} = 200$ GeV

$M_2 = \mu = 200$ GeV

$\tan \beta = 10$

$m_{\chi_1^0} = 0$ GeV

8 Summary

- Cosmological bounds:
  - Cowsig -McClelland bound for rel. $\tilde{\chi}_1^0$: $m_{\tilde{\chi}_1^0} \leq 1\,\text{eV}$
  - Lee-Weinberg bound for non-rel. $\tilde{\chi}_1^0$: $m_{\tilde{\chi}_1^0} \approx \mathcal{O}(10 - 100)$ GeV
  - Lee-Weinberg bound can be problematic, $\tilde{\chi}_1^0$ is embedded in complex particle spectrum

- bounds on $\tilde{\chi}_1^0\tilde{\chi}_2^0$-production at LEP translate into selectron mass bounds if $\tilde{\chi}_1^0$ is massless

- no bounds from radiative neutralino production at LEP