Bounds on neutralino masses and mixings from cosmology and collider physics

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1 Outline

- Neutralinos in the Minimal Supersymmetric Standard Model
- Constraints on neutralino masses from collider physics:
  - $e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0$ at LEP2
  - $e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \gamma$ at LEP2
  - Meson decays
- Constraints on neutralino masses from Cosmology

2 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

3 Neutralinos in the MSSM

Gauge fields $s = 1$	Gauginos $s = \frac{1}{2}$
B field	Bino $\tilde{B}$
weak bosons W^a	Winos $\widetilde{W}^0$, $\widetilde{W}^\pm$
Higgs-fields $s = 0$	**Higgsinos $s = \frac{1}{2}$**
H_d	$\widetilde{H}_1 = (\widetilde{H}_d^0, \widetilde{H}_d^-)$
H_u	$\widetilde{H}_2 = (\widetilde{H}_u^+, \widetilde{H}_u^0)$

Fields with equal quantum numbers mix:

Charged fields $\widetilde{W}^-$, $\widetilde{H}_d^-$ and $\widetilde{W}^+$, $\widetilde{H}_u^+$: $\rightarrow$ Charginos

Neutral fields $\tilde{B}$, $\widetilde{W}^0$, $\widetilde{H}_d^0$, and $\widetilde{H}_u^0$: $\rightarrow$ Neutralinos

Physical states obtained by diagonalisation of the mixing matrices

3.1 The chargino mass matrix

Charginos are the SUSY partners of the charged gauge and Higgs fields ($\widetilde{W}^-$, $\widetilde{H}_d^-$ and $\widetilde{W}^+$, $\widetilde{H}_u^+$). Their mixing is described by the chargino mixing matrix X:

$$X = \begin{pmatrix} M_2 & \sqrt{2} m_W \sin(\beta) \\ \sqrt{2} m_W \cos(\beta) & \mu \end{pmatrix}$$

MSSM parameters: M_2, μ, $\tan\beta$

|eigenvalues| of X = chargino masses $m_{\tilde{\chi}^\pm_{1/2}}$

3.2 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 $m_{\tilde{\chi}_i^0}$, $i = 1, \ldots, 4$

4 Constraints on M_2, μ, and M_1

- M_2, μ determine chargino mass:
  LEP II: $m_{\tilde{\chi}_1^+} > 104\,\text{GeV}$ [Yao *et al.*, PDG, J. Phys. G **33** (2006) 1]
  $\Rightarrow M_2, |\mu| \gtrsim 100\,\text{GeV}$
  yields no bound for $m_{\tilde{\chi}_1^0}$ **without GUT relation** $M_1 = \frac{5}{3}\tan^2(\theta_w) M_2$

- M_1 can be chosen such that $m_{\tilde{\chi}_1^0} = 0$:

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

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

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

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

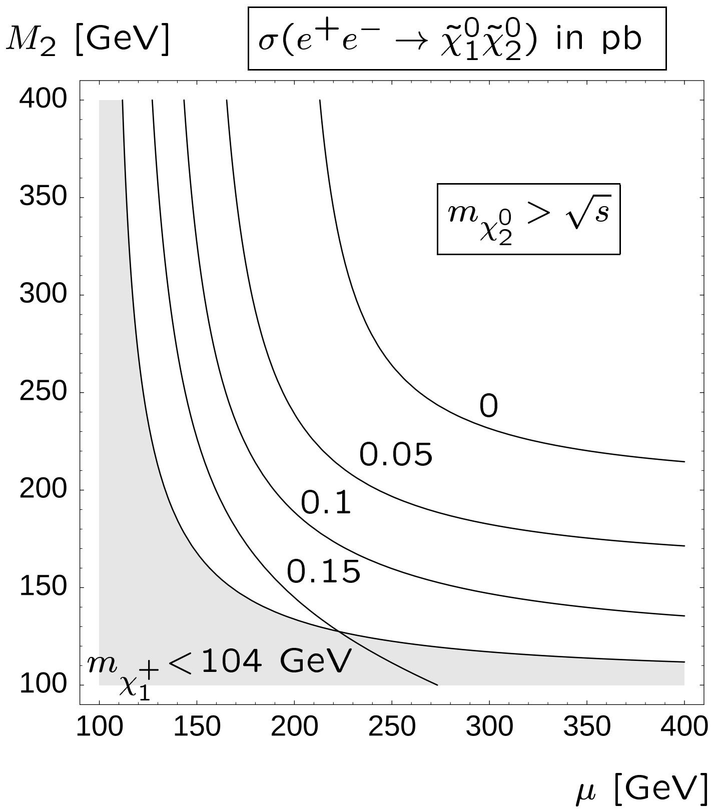
5 Light Neutralinos?

Light neutralinos in the MSSM? Look at bounds from

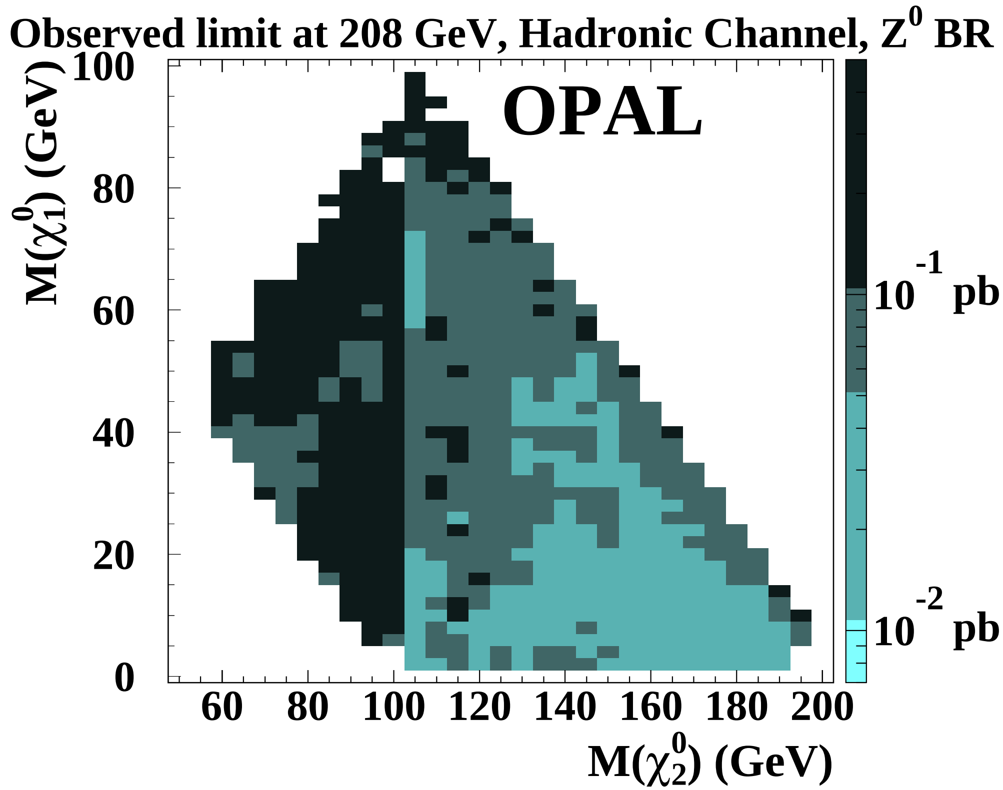
- Cosmology
  - Cowsik McClelland bound [Cowsik & McClelland, Phys. Rev. Lett. **29** 669]
  - Lee Weinberg bound [Lee & Weinberg, Phys. Rev. Lett. **39** (1977) 165]
  - full solution of the Boltzmann equation

    [Belanger et al.,Comput. Phys. Commun. **174** (2006) 577[arXiv:hep-ph/0405253]]
- neutralino production $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0$ at LEP
- radiative neutralino production at the linear collider

6 LEP bounds on neutralino production $e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0$



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



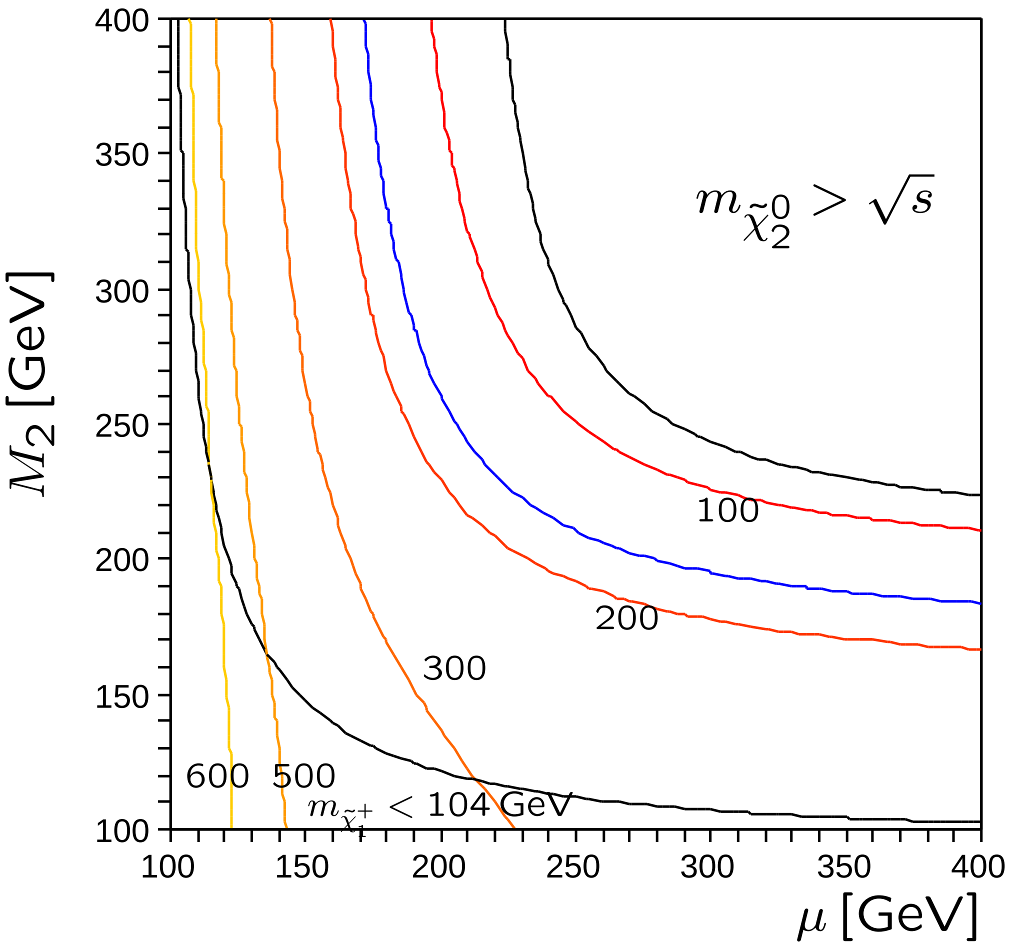
$\sqrt{s} = 208\,\text{GeV}$, $CL = 95\%$

[G. Abbiendi *et al.* [OPAL Collaboration], Eur. Phys. J. C **35** (2004) 1 [arXiv:hep-ex/0401026]]

From the OPAL plot, we read off:

$\sigma(e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2) \times \mathrm{BR}(\tilde{\chi}^0_2 \to Z\tilde{\chi}^0_1) \times \mathrm{Br}(Z \to q\bar{q}) < 70\,\mathrm{fb}$ $(\mathrm{Br}(\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 Z^0) = 1)$

this translates into mass bounds on the selectron mass

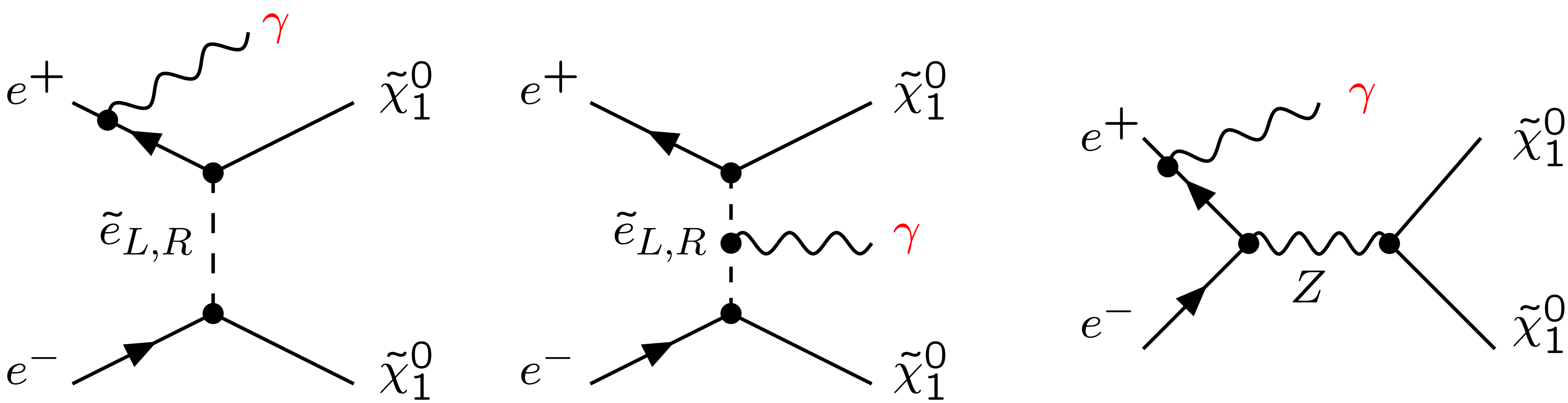


contour lines of minimal selectron masses that are compatible with OPAL data,

above the blue line:
$\tilde{\chi}^0_2$ heavier than $\tilde{e}_R$:
$\mathrm{Br}(\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 Z^0) \neq 1$

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

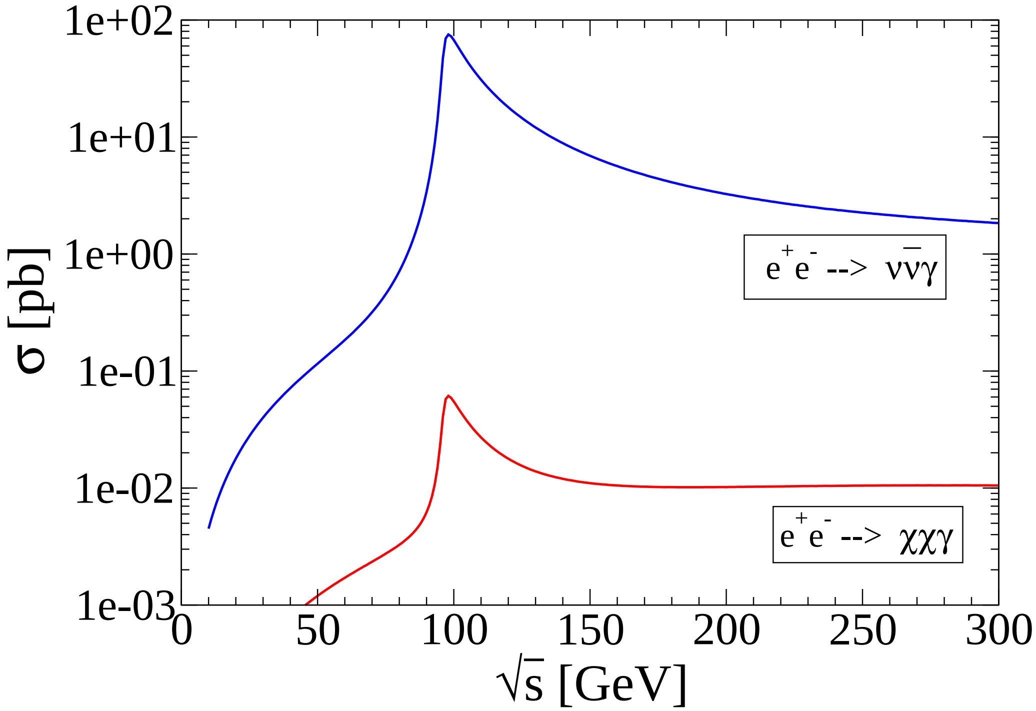
7.1 Diagrams of the process $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_1\gamma$:



7.2 Background

- Radiative neutrino production $e^+e^- \to \nu\bar{\nu}\gamma$

7.3 No bound from radiative neutralino production at LEP II



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

$M_2 = \mu = 200$ GeV

$\tan\beta = 10$

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

LEP II:

$\sqrt{s} = 200$ GeV

Luminosity $\mathcal{L} = 0.1\ \text{fb}^{-1}$

Significance $S = \frac{\sigma_{\text{Signal}}}{\sqrt{\sigma_{\text{Signal}} + \sigma_{\text{Background}}}}\sqrt{\mathcal{L}} < 0.1$

8 Meson decays

If neutralinos are light enough, mesons can decay into neutralino pairs.
Pseudoscalar mesons (psm): π, η, η'

$$\Gamma = C_{\mathrm{psm}} \frac{m_\chi^2 M_{psm}}{M_{\tilde{q}}^4} \sqrt{1 - \frac{4m_\chi^2}{M_{psm}^2}}$$
$$= \mathcal{O}(10^{-14\ldots-13}) \lll \Gamma_{\mathrm{exp}} \approx 10^{-7} \ldots 10^{-3}$$

Vector mesons (V): ρ, ω, ϕ, J/ψ, Υ

$$\Gamma = C_V \Gamma(V \to e^+ e^-) \frac{m_V^4}{M_{\tilde{q}}^4} \left(1 - \frac{4m_\chi^2}{M_V^2}\right)^{3/2}$$
$$= \mathcal{O}(10^{-16\ldots-10}) \lll \Gamma_{\mathrm{exp}} \approx 10^{-3}$$

Result: no bounds from meson decays

9 Cosmological bounds

9.1 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

Ingredients

- Robertson-Walker-metric: $\mathrm{d}s^2 = \mathrm{d}t^2 - R^2(t)\left(\frac{\mathrm{d}r^2}{1-kr^2} + r^2\mathrm{d}\theta^2 + r^2\sin^2\theta\mathrm{d}\phi^2\right)$
  with the Hubble parameter $H(t) = \dot{R}/R$
- CP conservation
- no chemical potential for the the particle species ψ

9.2 Cowsik-McClelland bound

If the $\tilde{\chi}_1^0$ is the lsp and stable, then $\tilde{\chi}_1^0$ is a dark matter candidate

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

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

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

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

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

$g_{\text{eff}} = 3/4 \times$number of rel. degrees of freedom $= 3/2$

$g_{*S}(T) = \sum g_b (T_b/T)^3 + \frac{7}{8} \sum g_f (T_f/T)^3 = 12.5$

9.3 Lee-Weinberg bound

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

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

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

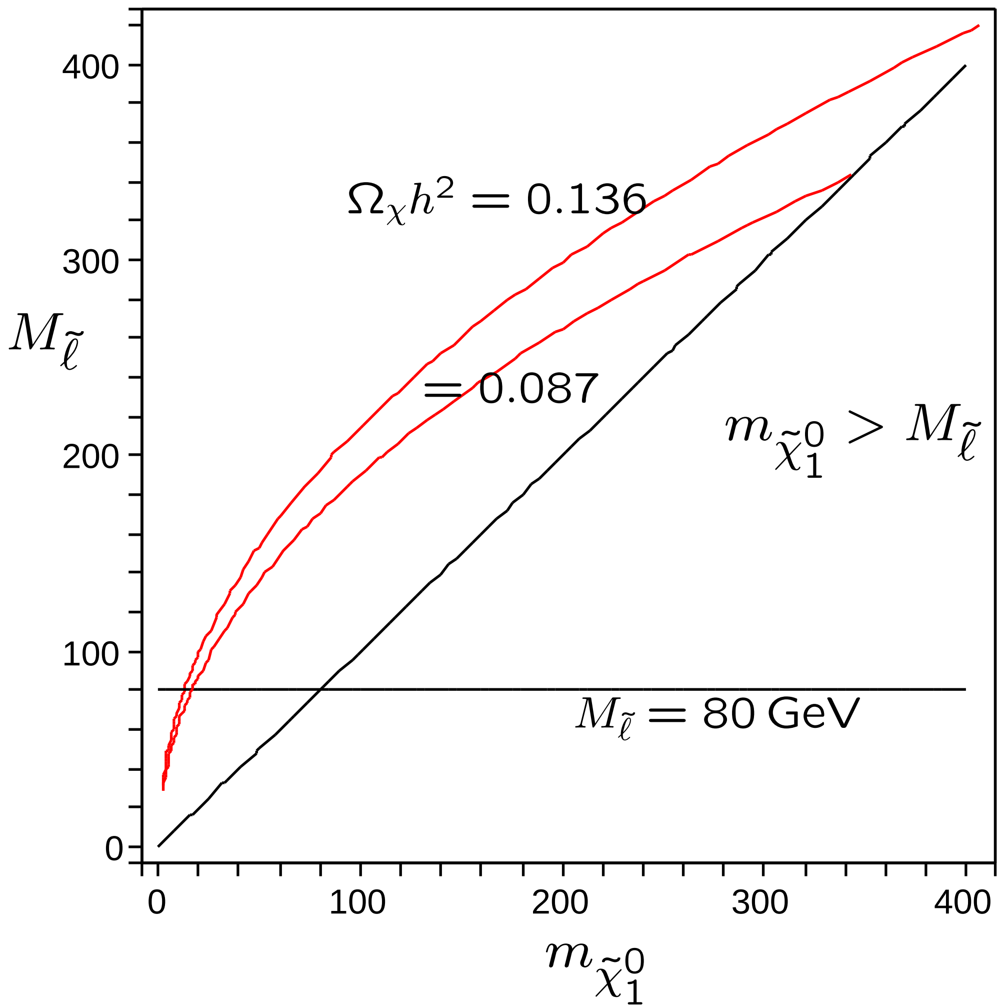
$$\Omega_\chi h^2 \ \approx\ \frac{2.14\times 10^9 (m_\chi/T_f)^2}{(g_{*S}/g_*^{1/2}) m_{\text{Pl}}\sigma_0}\ \ \text{GeV}^{-1}$$

T_f: freeze out temperature, $\approx \frac{m_\chi}{25}\ldots\frac{m_\chi}{20}$

σ_0: cross section

m_{Pl}: Planck mass

Result:



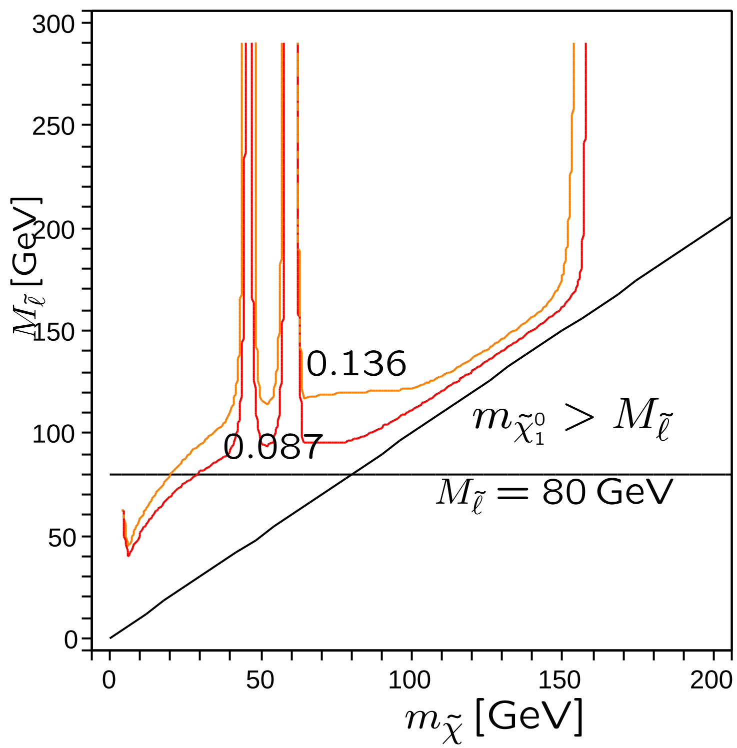
contours of constant relic density for $\Omega_\chi h^2 \pm 3\sigma$

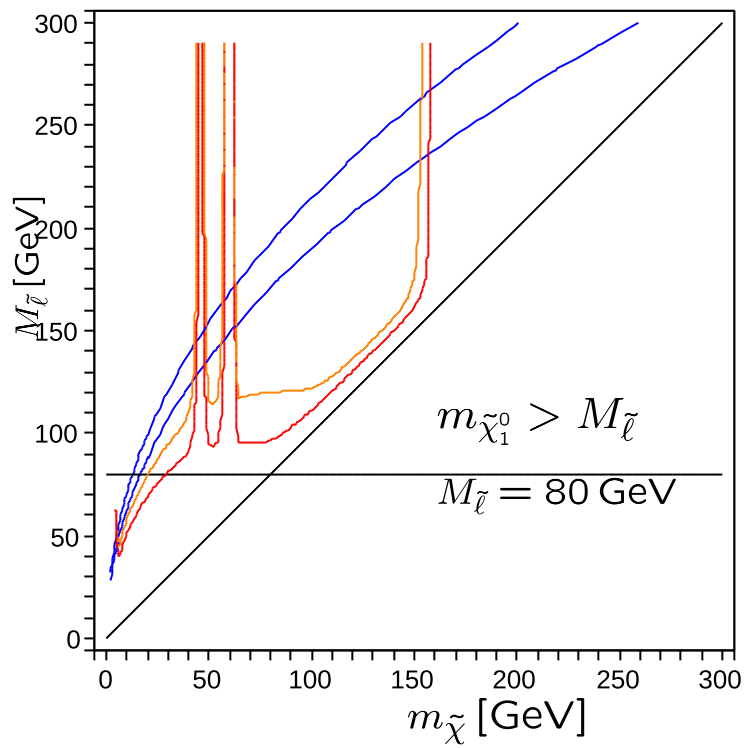
$= 0.112 \pm 3 \times 0.008$

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

$\Rightarrow 15$ GeV $\leq m_{\tilde{\chi}_1^0} \leq 400$ GeV

9.4 Full solution of the Boltzmann equation





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

$$M_{\tilde{\ell}} > 80\,\text{GeV} \quad \Rightarrow m_{\tilde{\chi}} \gtrsim 10 - 15\,\text{GeV}$$

10 Summary

- 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
- no bounds from meson decays
- Cosmological bounds:
  - Cowsik -McClelland bound for rel. $\tilde{\chi}_1^0$: $m_{\tilde{\chi}_1^0} \lesssim 1\,\text{eV}$
  - Lee-Weinberg bound for non-rel. $\tilde{\chi}_1^0$: $m_{\tilde{\chi}_1^0} \gtrsim 15\,\text{GeV}$