RHEINISCHE FRIEDRICH-WILHELMS-UNIVERSITÄT

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?

  Look at bounds from . . .
  - . . . neutralino production at LEP
  - . . . precision observables
  - . . . cosmology

- Summary and conclusions

1 Introduction

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

- solution to hierarchy problem
- window to gravity
- dark matter candidates

One solution is Supersymmetry (SUSY).

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

1 Introduction

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

- solution to hierarchy problem (SUSY masses $\mathcal{O}$(100 GeV))
- window to gravity (SUGRA-models)
- dark matter candidates (neutralino, gravitino, axino,...)

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

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

- Parameters:

M_2: wino mass, soft supersymmetry breaking

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 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

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

Motivation: Neutralino mass at LEP

- Colliders have searched for SUSY particles:

  No particles have been found, but limits on their masses are set.

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

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

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

  $\Rightarrow M_1 \gtrsim 50$ GeV

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

- What happens if we drop the GUT relation?

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:

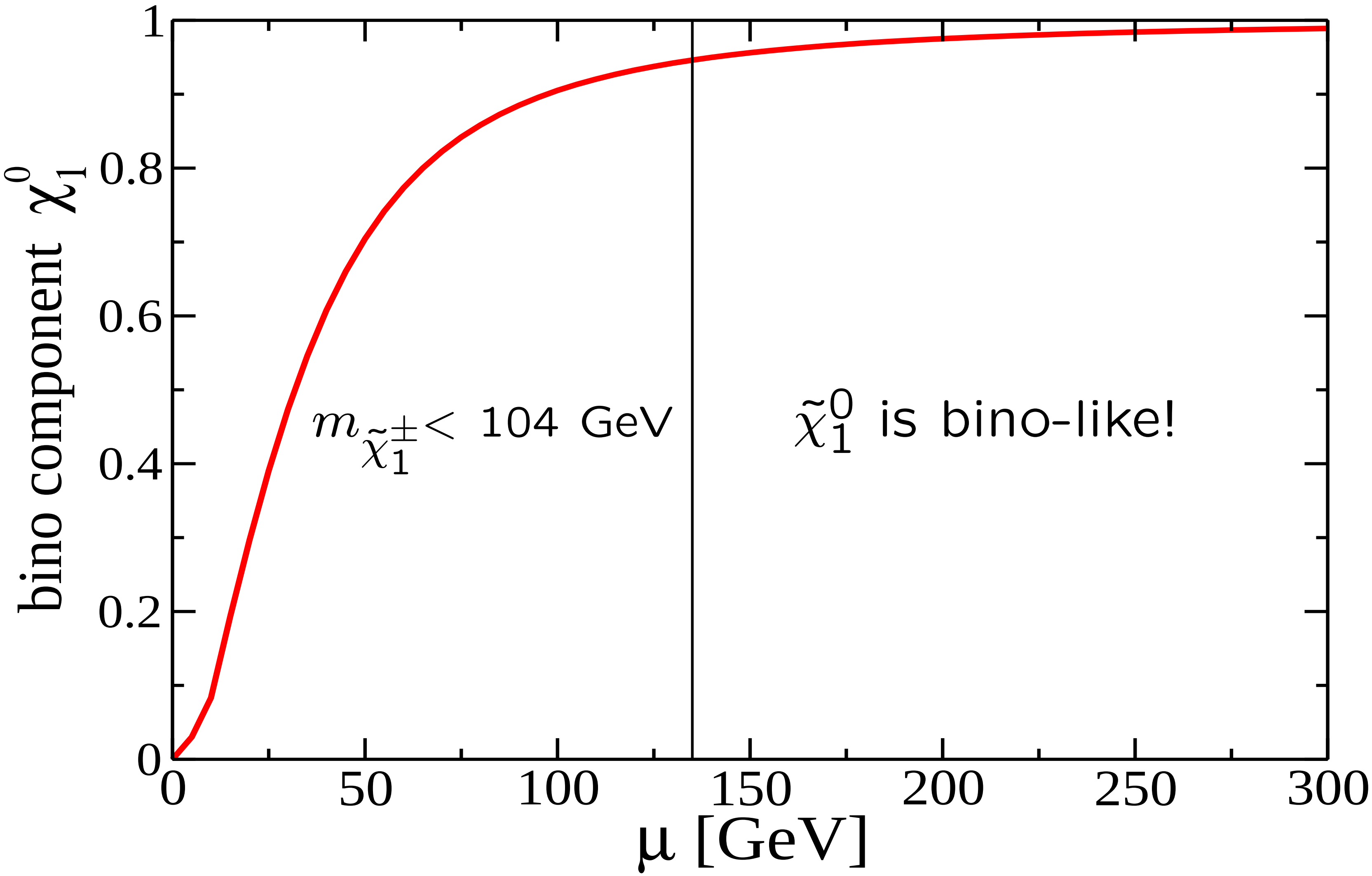
$$\det\left[\mathcal{M}_0(M_1, M_2, \mu, \tan\beta)\right] = 0$$

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

  For this value of M_1 we have $m_{\tilde{\chi}_1^0} = 0$.

- $M_1 \ll M_2, \mu \Rightarrow$ neutralino $\tilde{\chi}_1^0$ is bino-like!
- $\Rightarrow$ No significant contribution to the Z-width $\Gamma(Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0)$!!
  (For $\tilde{\chi}_1^0 =$ bino, the $Z\tilde{\chi}_1^0\tilde{\chi}_1^0$ coupling vanishes at tree-level.)

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



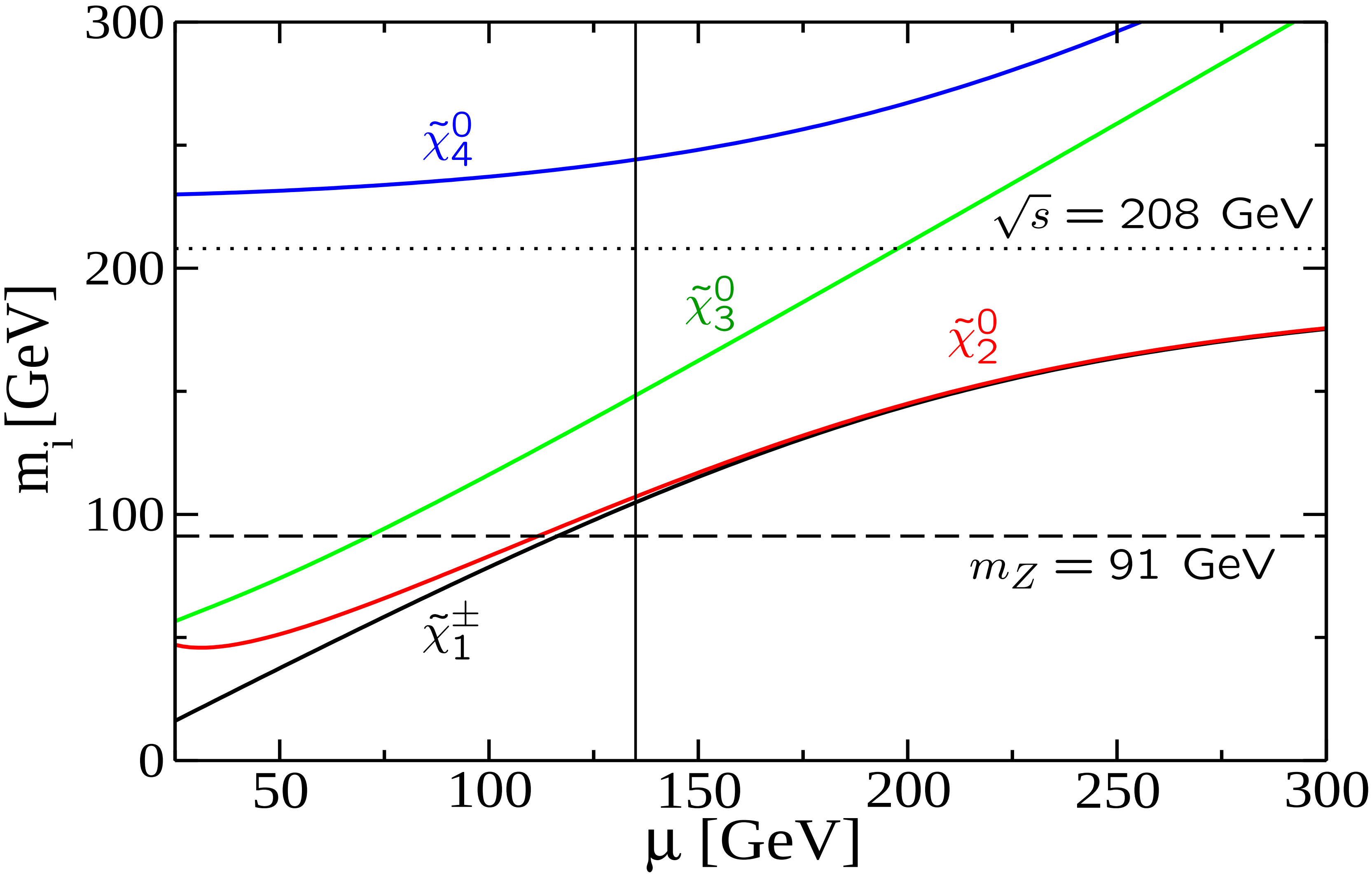
$M_2 = 200$ GeV, $\tan\beta = 10$

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

Look at bounds from . . .

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

Neutralino and chargino masses for $m_{\tilde{\chi}_1^0} = 0$ GeV



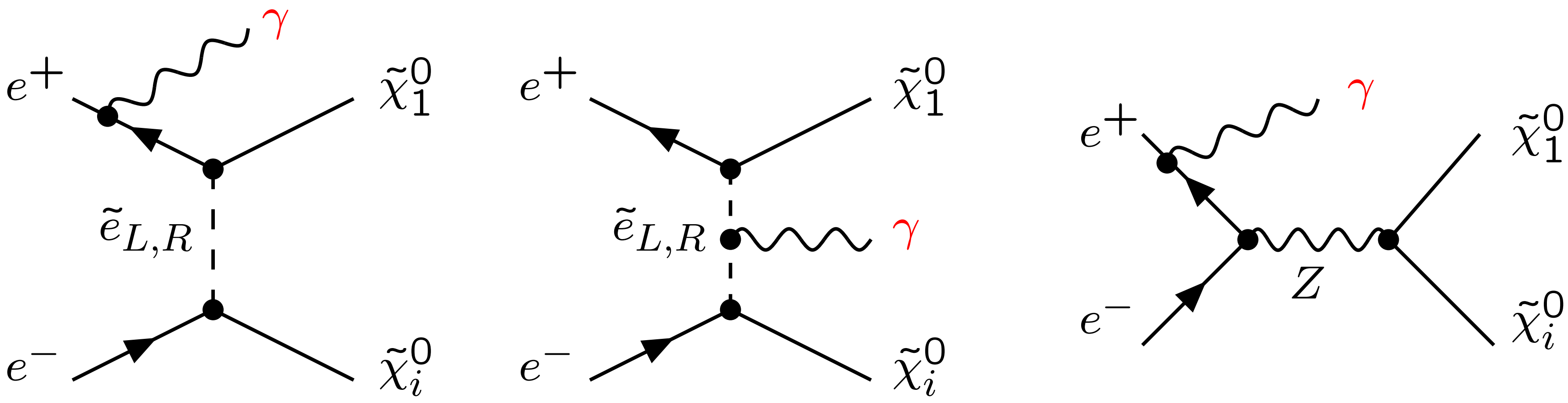
$M_2 = 200$ GeV, $\tan\beta = 10$

Bounds on neutralino mass from measurements at LEP

LEP II: center of mass energy $\sqrt{s} = 208$ GeV, luminosity $\mathcal{L} \approx 100$ pb^{-1}

consider a bino-like, massless neutralino $\tilde{\chi}_1^0$:

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



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

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

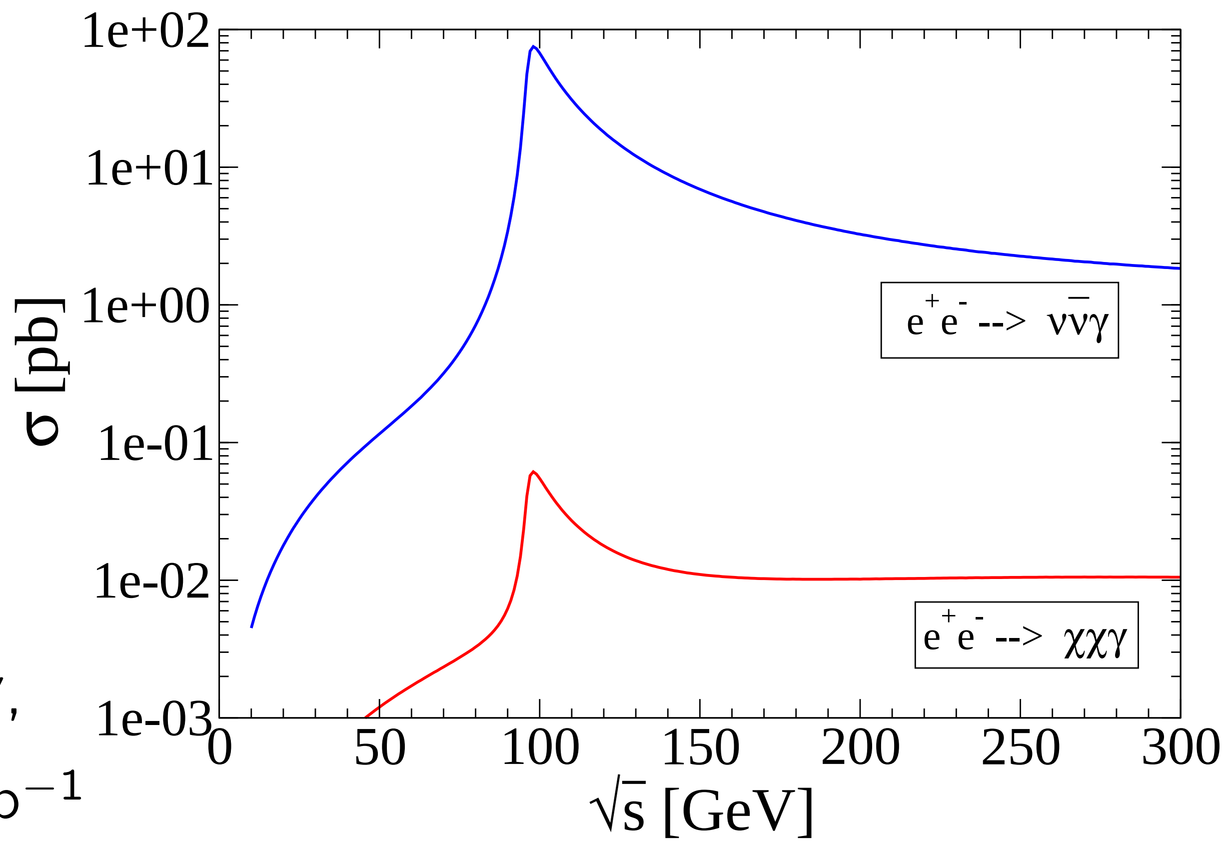
$M_2 = \mu = 200\,\mathrm{GeV}$

$\tan\beta = 10$

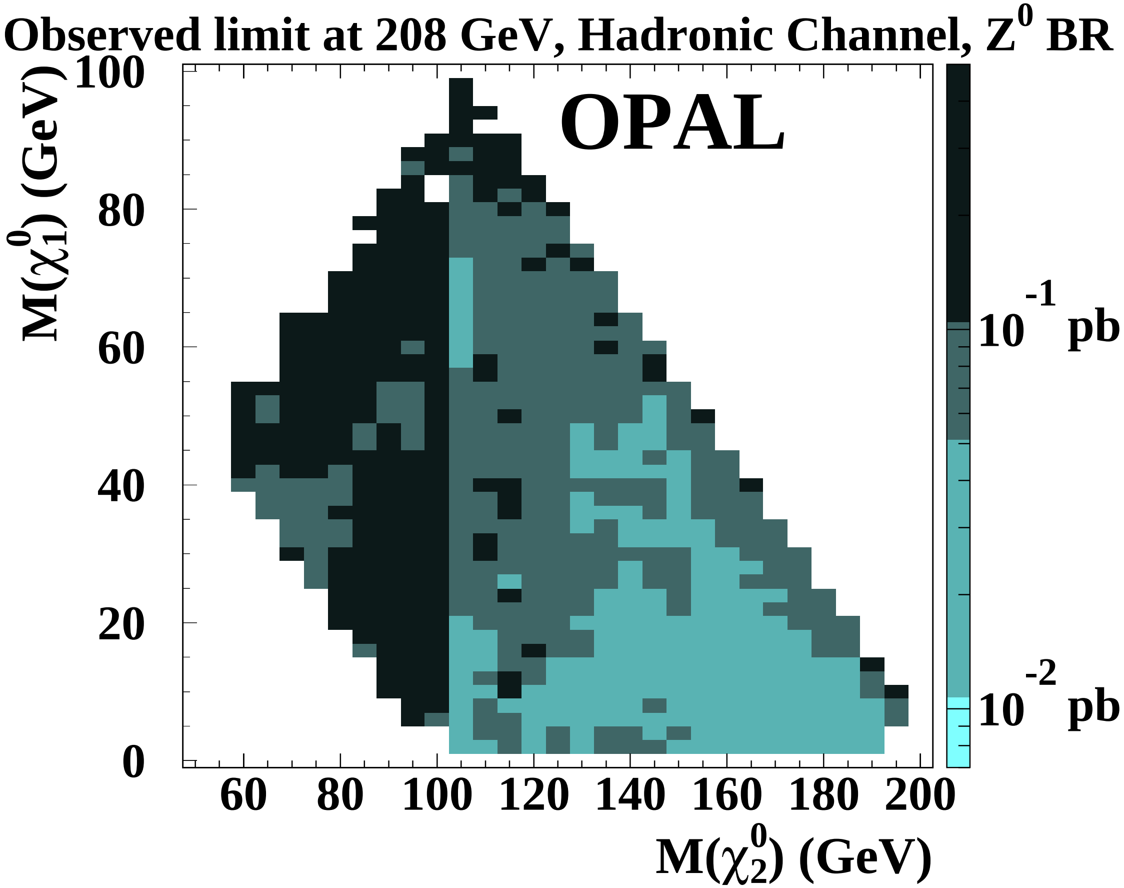
$m_{\tilde{\chi}_1^0} = 0\,\mathrm{GeV}$

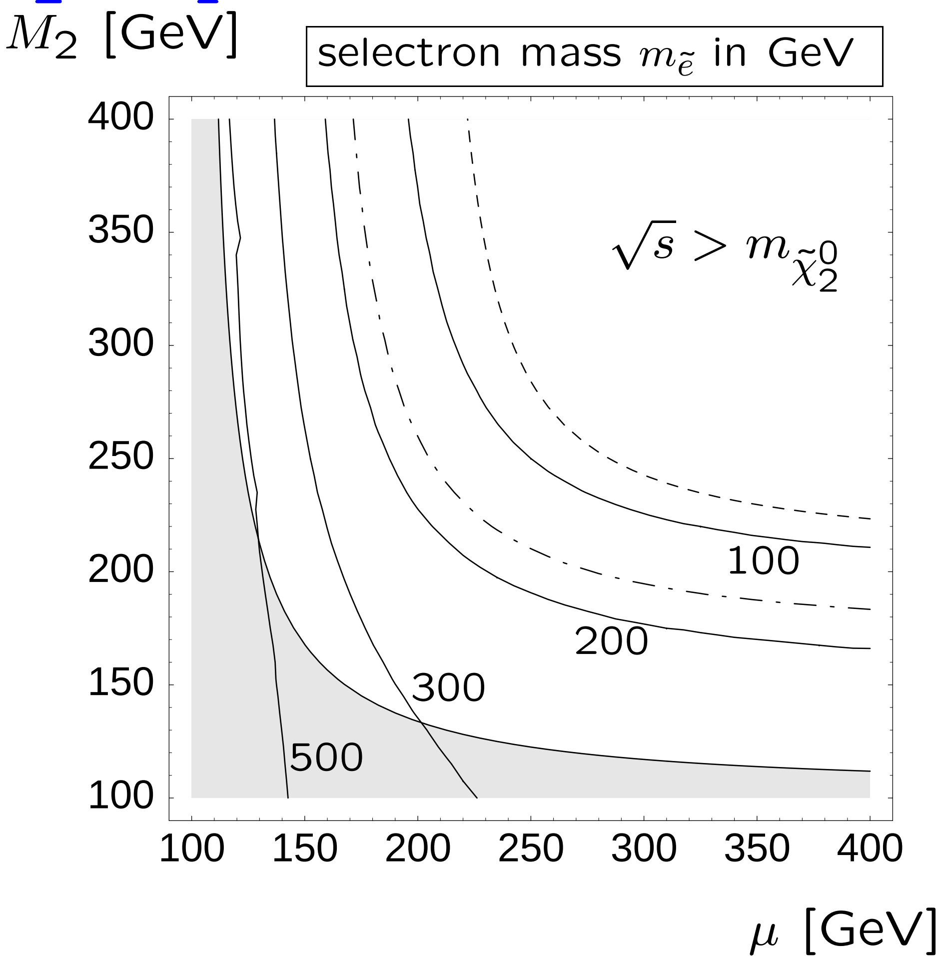
LEP II: $\sqrt{s} = 200$ GeV,

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



LEP bounds on $\sigma(e^+e^-\to\tilde\chi^0_1\tilde\chi^0_2)\times\mathrm{BR}(\tilde\chi^0_2\to\tilde\chi^0_1 Z)\times\mathrm{BR}(Z\to q\bar q)$





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

$\Rightarrow \sigma(e^+e^-\to\tilde\chi^0_1\tilde\chi^0_2) < 70$ fb

$\tan\beta = 10$, dot-dashed: $m_{\tilde\chi^0_2} = m_{\tilde e}$

$m_{\tilde\chi^0_1} = 0$ GeV, dashed: $m_{\tilde\chi^0_2} = \sqrt{s}$

Bounds on neutralino mass from precision observables

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

- $\sin^2(\theta_w)$
- M_Z, Γ_Z and M_W, Γ_W
- $(g-2)_\mu$
- EDMs of n, e, Hg
- $b \to s\gamma$

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

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Invisible Z width: $\Gamma_{\text{inv}} = \Gamma(Z \to \nu\bar{\nu}) + \Gamma(Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0)$ at $\mathcal{O}(\alpha)$

$\Gamma_{\text{inv}}^{\text{exp}} = 499.0 \pm 1.5$ MeV

$\delta\Gamma = \Gamma_{\text{inv}} - \Gamma_{\text{inv}}^{\text{exp}}$

note: $\delta\Gamma^{\text{SM}} = 1\sigma$!

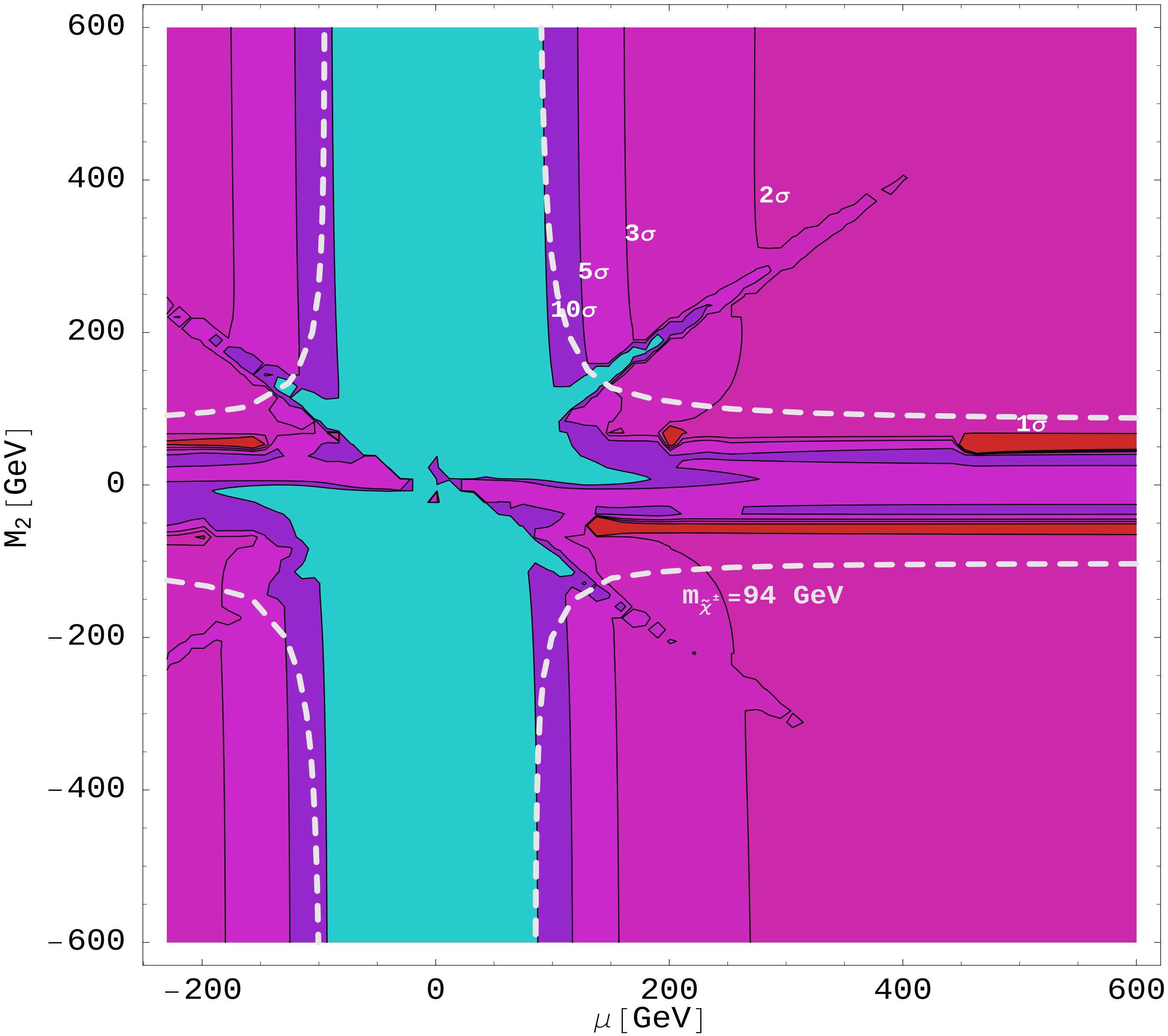
$m_{\tilde{\chi}_1^0} = 0\,\text{GeV}$

$\tan\beta = 10$

$A_\tau = A_t = A_b = m_{\tilde{g}} =$

$= M_A = 2M_{\tilde{f}} = 500$ GeV

[A. Weber]



No bounds on neutralino mass from rare meson decays

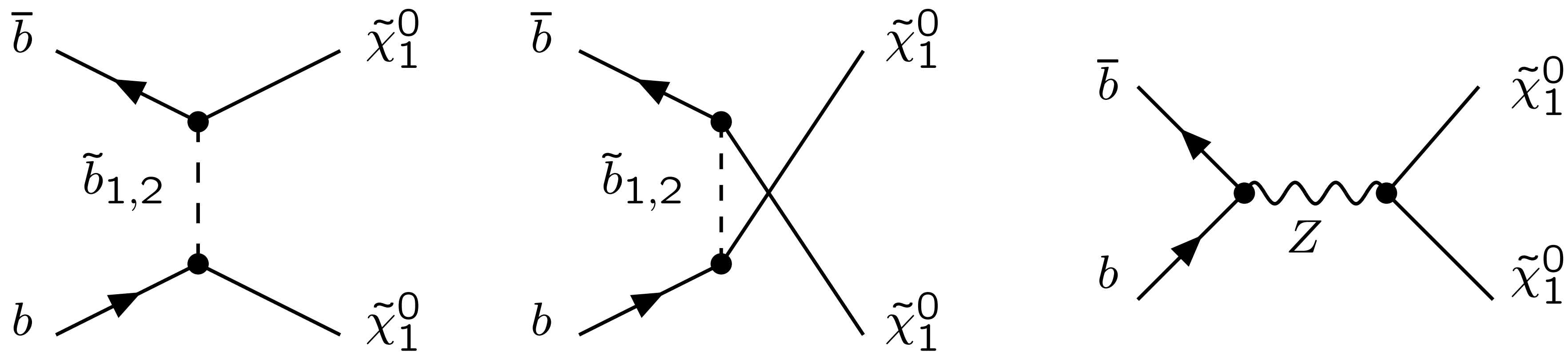
- At B-factories: BR($\Upsilon(1S) \to$ invis.) $\lesssim 10^{-4}$ exp. (10^{-5} SM)

  neutralino contribution: BR($\Upsilon(1S) \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$) $\approx 10^{-8}$ MSSM

- And similar: $J/\Psi[B^0] \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$, or $K[D,B]^+ \to \pi^+ \tilde{\chi}_1^0 \tilde{\chi}_1^0, ...$

- Finally: various meson decays $\rho, \pi, \phi, \omega, \eta, ... \to$ invis.

Υ:



see e.g. [McElrath, hep-ph/0506151]

Bounds on neutralino mass from cosmology/astrophysics

- Cold dark matter: Thermal relic density of neutralinos

  $$\Rightarrow m_{\tilde{\chi}_1^0} > 6\,\text{GeV}$$

  [Hooper, Plehn, hep-ph/021226]
  [Bottino et al., hep-ph/0304080]
  [Belanger et al., hep-ph/0310037]

- Hot dark matter: (Cowsik-McClelland bound)

  $$\Rightarrow m_{\tilde{\chi}_1^0} \lesssim 0.7/h^2\ \text{eV}$$

  [Langenfeld, PhD thesis]

- Supernova cooling:

  $m_{\tilde{\chi}_1^0} \gtrapprox 0.2\,\text{GeV}$ 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)

- also: cooling of other objects (red giants), Big Bang nucleosynthesis, cosmic rays,...?

Summary and conclusions

How light can the lightest neutralino be?

- no constraints from electroweak precision data and rare decays
- constraints from LEP:

  $\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0) < 70$ fb $\Rightarrow$ bounds on $\tilde{e}$ mass: $m_{\tilde{e}} < 100...500$ GeV

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

  Neutralino cold dark matter: $m_{\tilde{\chi}_1^0} > 6$ GeV

  Neutralino hot dark matter: $m_{\tilde{\chi}_1^0} \lesssim 1$ eV

Zero mass neutralino is allowed!

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 are 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.