Testing Focus Point Cosmology at the NLC

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Work in progress, with experimental collaborators from Cornell (Jim Alexander, Karl M. Ecklund, Laura Fields, **Richard Gray**, Dan Hertz, Chris Jones, Surik Mehrabyan and Jim Pivarski) and Konstantin Matchev (Florida).

The Big Goal

This talk investigates the following question:

- Assume: LHC has run, ’discovered’ SUSY, made the expected measurements

- Now assume: linear collider has run, made expected measurements
- What will be the theoretical uncertainty in $\Omega_{dm}h^2$ (the neutralino relic density) post-NLC?

Today: A report[1] on our progress.

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[1] More detail can be found during **Richard Gray**’s talk later today!

Last year at ALCPG04, results from a ’bulk point’:

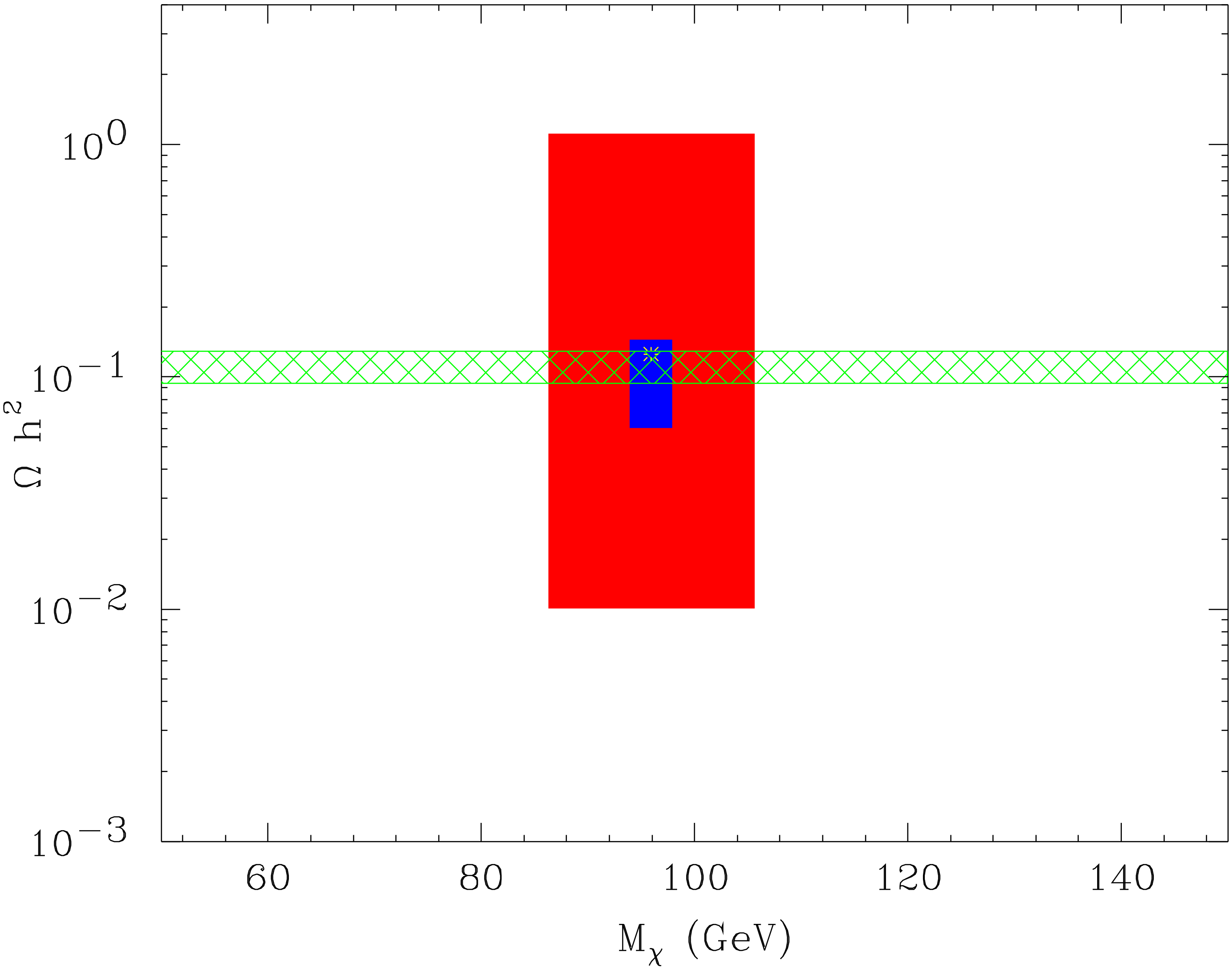

Figure 1: **Dark Matter Power of the Linear Collider** For the mSUGRA point $m_0 = 57$ GeV, $m_{1/2} = 250$ GeV, $\tan\beta = 10$, $sgn(\mu) = +1$, $A_0 = 0$.

A. Birkedal and K. Matchev, 2004

Today, first results regarding a focus point.

Outline[2]

- The Big Goal
- Dark Matter and Supersymmetry
- Discovering Dark Matter at a Collider
- The Linear Collider
- Conclusions

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[2] All RGEs have been run using ISAJET 7.69, physical spectra and relic densities have been calculated using DarkSUSY, except where otherwise noted.

Dark Matter and Supersymmetry

Dark Matter → WMAP constraints:

$$0.094 \leq \Omega_{dm} h^2 \leq 0.129 \text{ (at } 2\sigma)$$

Simplest: neutral particle, stable on cosmological timescales.

In practice:

$$\Omega_{dm} h^2 = \frac{\rho_{dm}}{\rho_{crit}} h^2 = \frac{m_{dm}\, n_{dm}}{\rho_{crit}} h^2 \sim 0.1 \frac{\langle \sigma v \rangle_{EW}}{\langle \sigma v \rangle} \qquad (1)$$

WIMP (weakly interacting massive particle) is good!

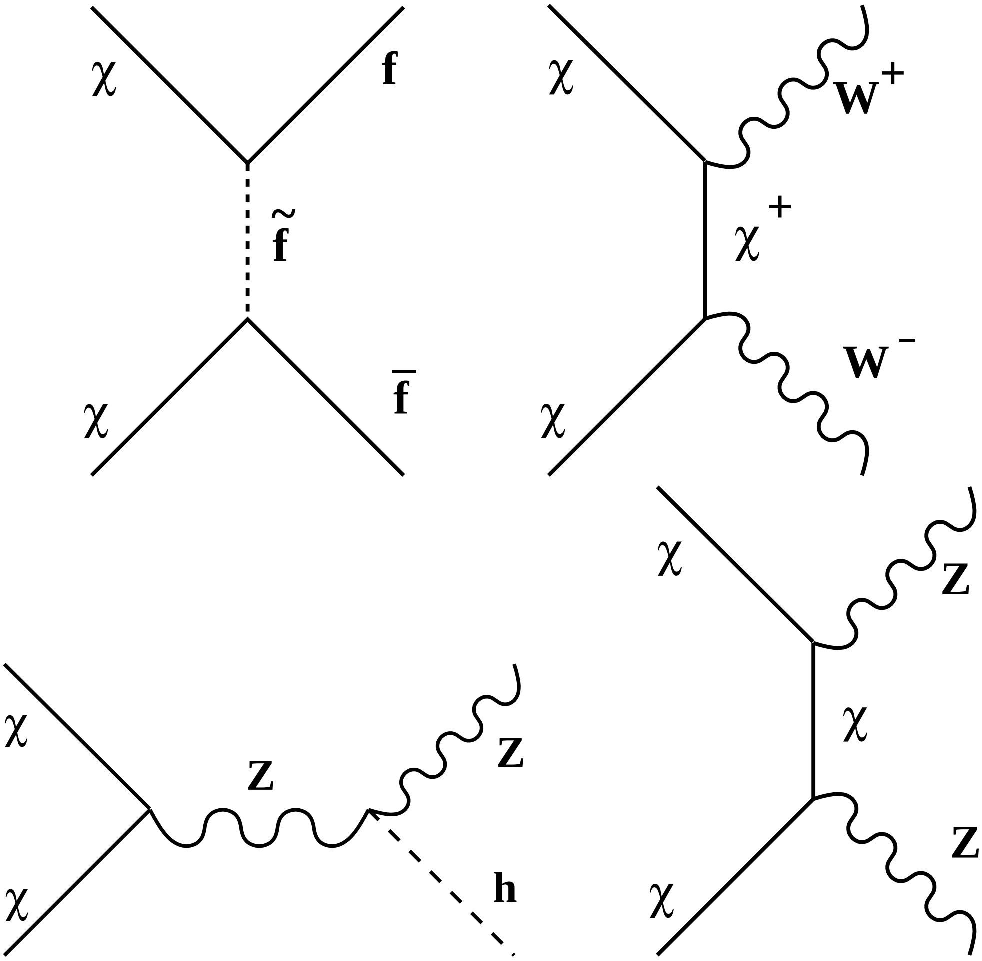
SUSY theories:

- contains WIMPS: spin-1/2 partners of the photon, Z, and two Higgses (neutralinos).
- LSP (lightest superpartner) is stable from R-parity.
- Often the LSP is the lightest neutralino.

Discovering Dark Matter at a Collider

If a collider measures some masses of a broken SUSY theory, how well can we determine the relic density, $\Omega_{dm}h^2$?

- generic set of annihilation diagrams → many masses → try to measure every input into the relic density calculation → dead end



As a start:

- Hope that the world exists at a point in SUSY parameter space where not **all** of the masses are important.
  Then hope to measure a few masses accurately enough to bound the relic density.

As an illustrative example, take a focus point in mSUGRA: $\tan\beta = 10$, $sgn(\mu) = +1$, $m_0 = 3280$, $m_{1/2} = 300$, $A_0 = 0$.

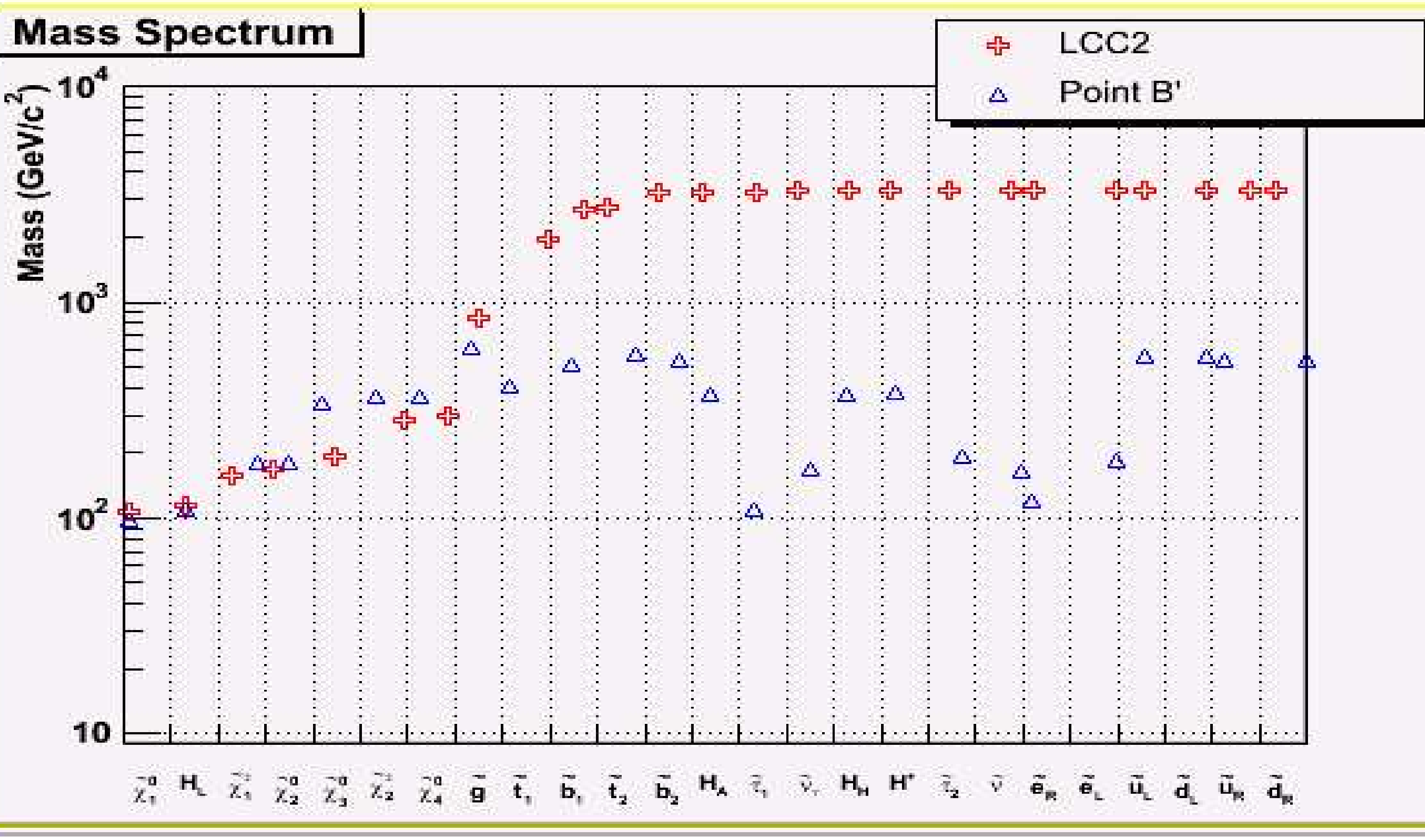


Figure 2: From R.C. Group and B. Scurlock.

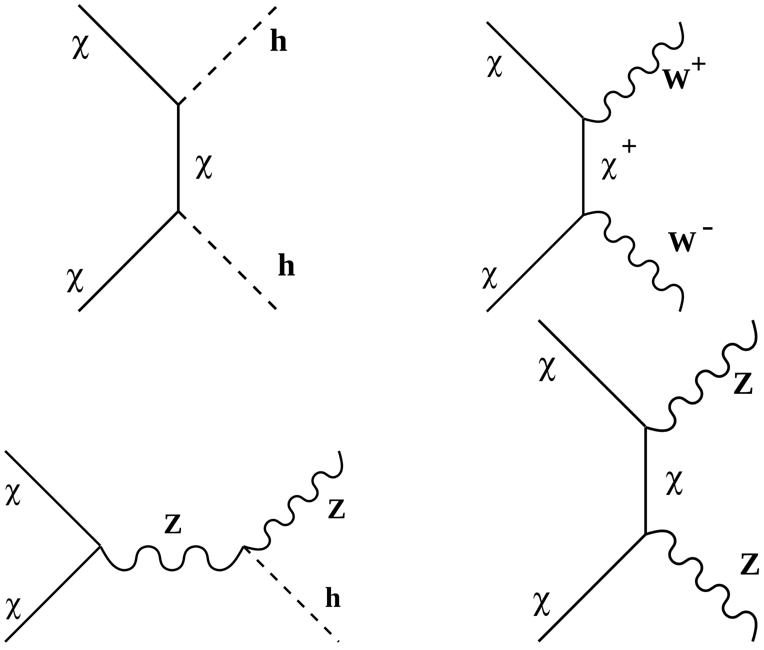
Nice! The -inos are relatively light (in GeV):

$m_{\chi_1^0} = -107.7$, $m_{\chi_2^0} = -166.3$, $m_{\chi_3^0} = +190.0$,
$m_{\chi_4^0} = -294.2$, $m_{\chi_1^\pm} = -159.4$, $m_{\chi_2^\pm} = -286.6$

- all of the sleptons are above 3200 GeV
- all of the squarks are above 1950 GeV
- the gluino weighs in at 850 GeV

Another reason to like this point:

- dominant diagrams for dark matter → SM gauge boson, neutralino and chargino exchange.



So, we can hope to see the most important -inos and thereby determine the relic density.

What are the key soft parameters in determining the relic density? Let's see...

Very little effect from sleptons or squarks.
What about the -ino sector parameters?

Neutralinos:

$$\begin{pmatrix} M_1 & 0 & -s_W c_\beta M_Z & s_W s_\beta M_Z \\ 0 & M_2 & c_W c_\beta M_Z & -c_W s_\beta M_Z \\ -s_W c_\beta M_Z & c_W c_\beta M_Z & 0 & -\mu \\ s_W s_\beta M_Z & -c_W s_\beta M_Z & -\mu & 0 \end{pmatrix} \tag{2}$$

Charginos:

$$\begin{pmatrix} M_2 & \sqrt{2} s_\beta M_W \\ \sqrt{2} c_\beta M_W & \mu \end{pmatrix} \tag{3}$$

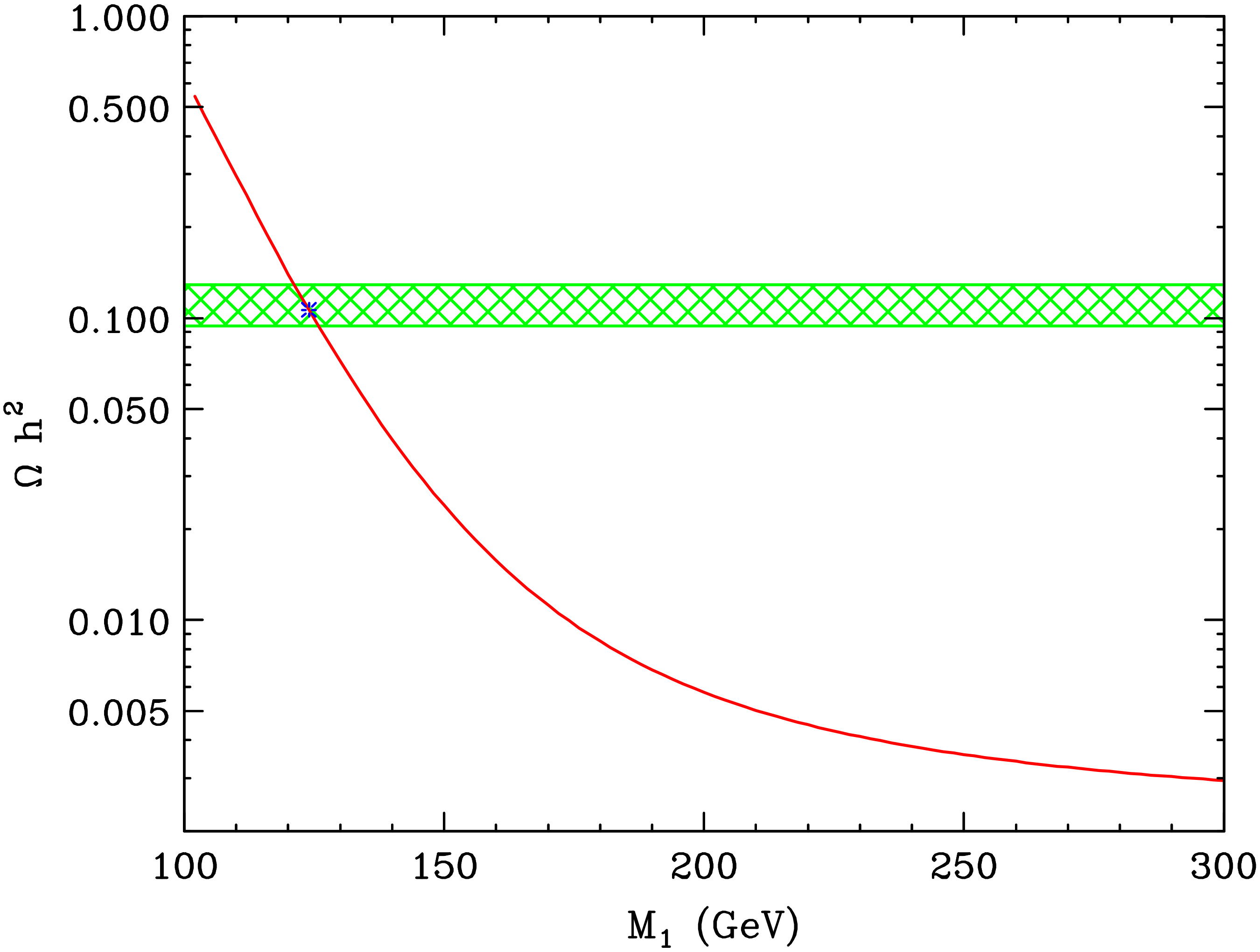


Figure 3: **Effect on Relic Density of Varying M_1.** The actual mSUGRA point is in blue. The green lines denote the 2-σ WMAP limits on the dark matter density. The red line shows what happens to the relic density as a function of M_1.

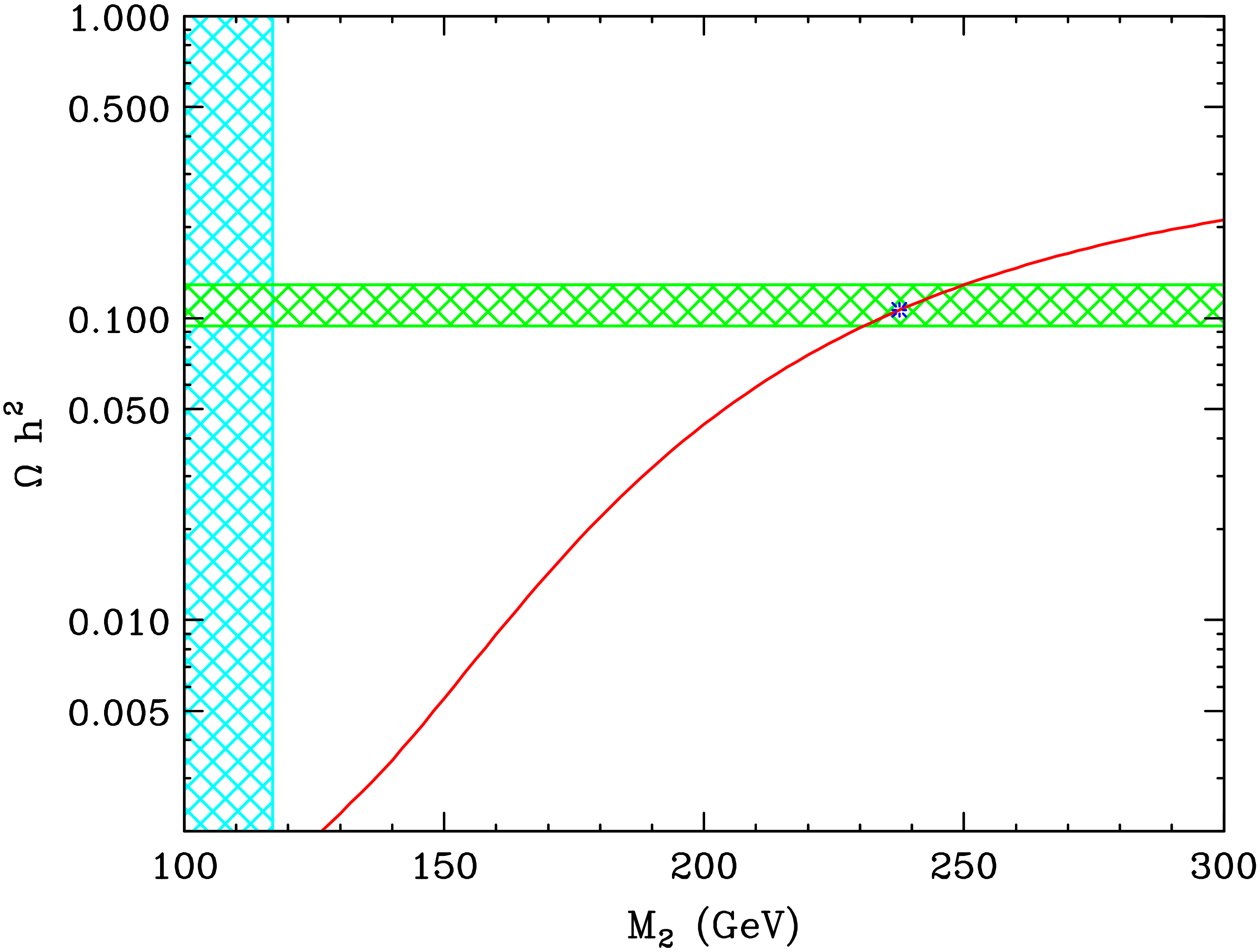


Figure 4: **Effect on Relic Density of Varying M_2.** The actual mSUGRA point is in blue. The green lines denote the 2-σ WMAP limits on the dark matter density. The red line shows what happens to the relic density as a function of M_2.

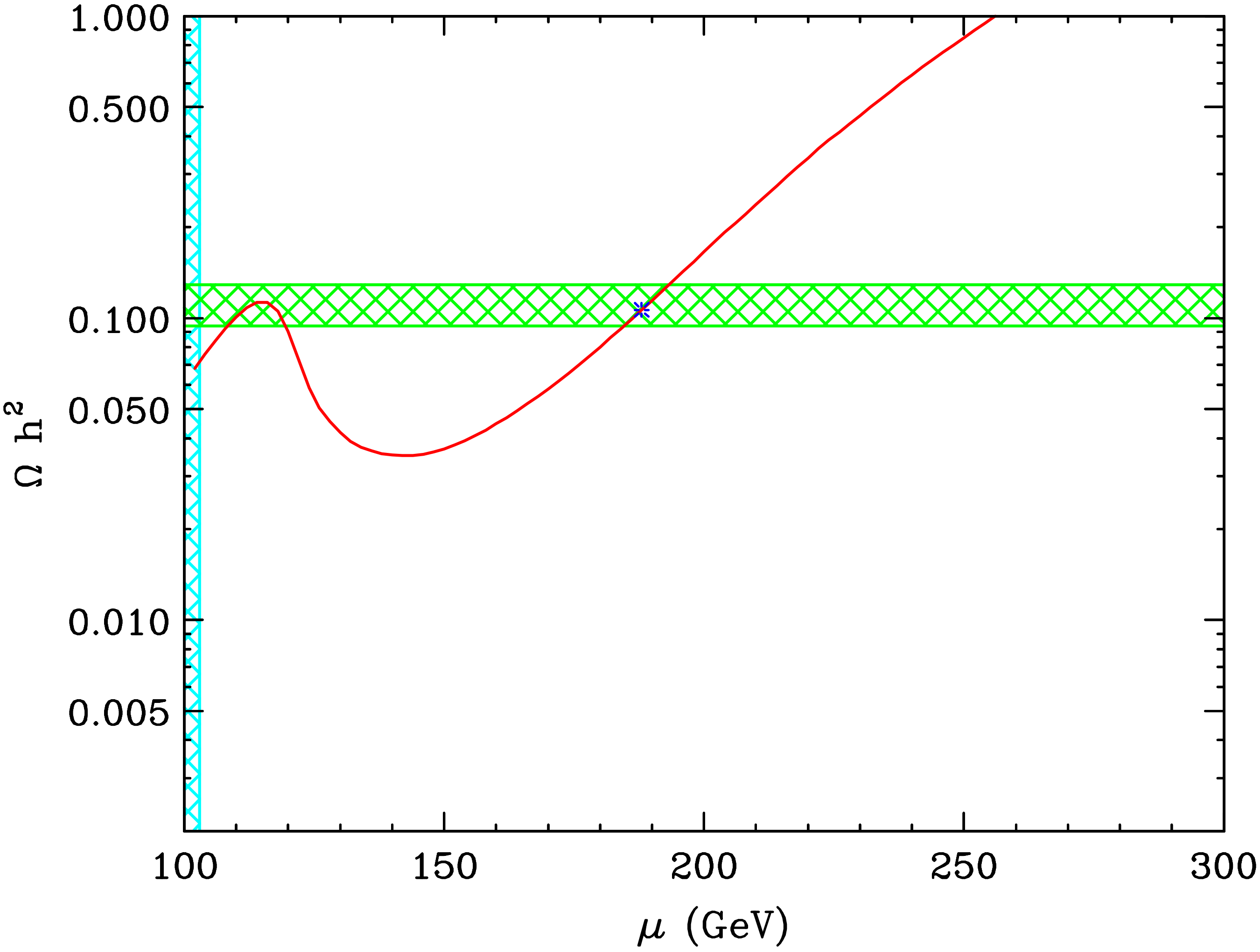


Figure 5: **Effect on Relic Density of Varying μ.** The actual mSUGRA point is in blue. The green lines denote the 2-σ WMAP limits on the dark matter density. The red line shows what happens to the relic density as a function of μ.

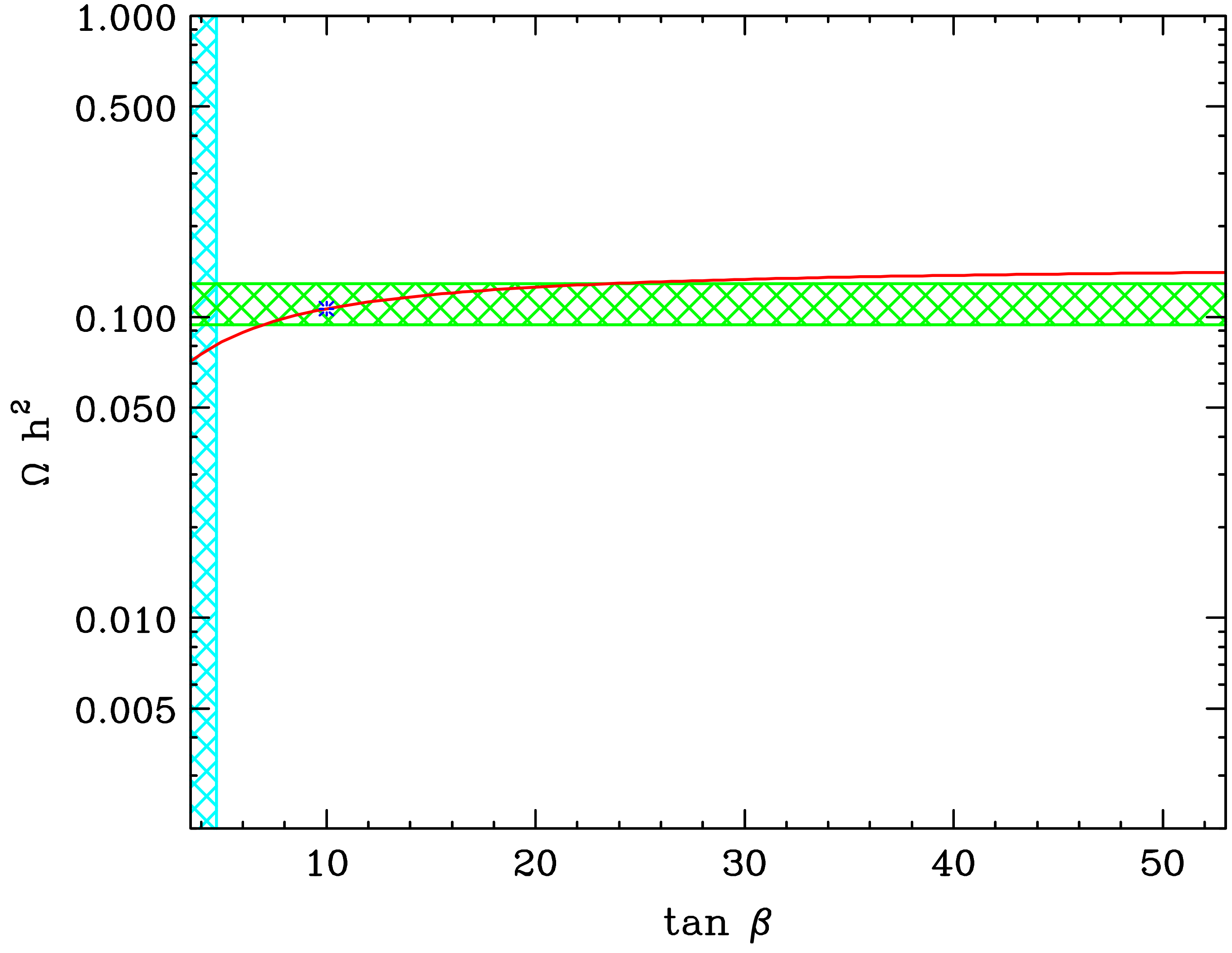


Figure 6: **Effect on Relic Density of Varying** $\tan\beta$. The actual mSUGRA point is in blue. The green lines denote the 2-σ WMAP limits on the dark matter density. The red line shows what happens to the relic density as a function of $\tan\beta$.

And how much varying m_A changes the relic density:

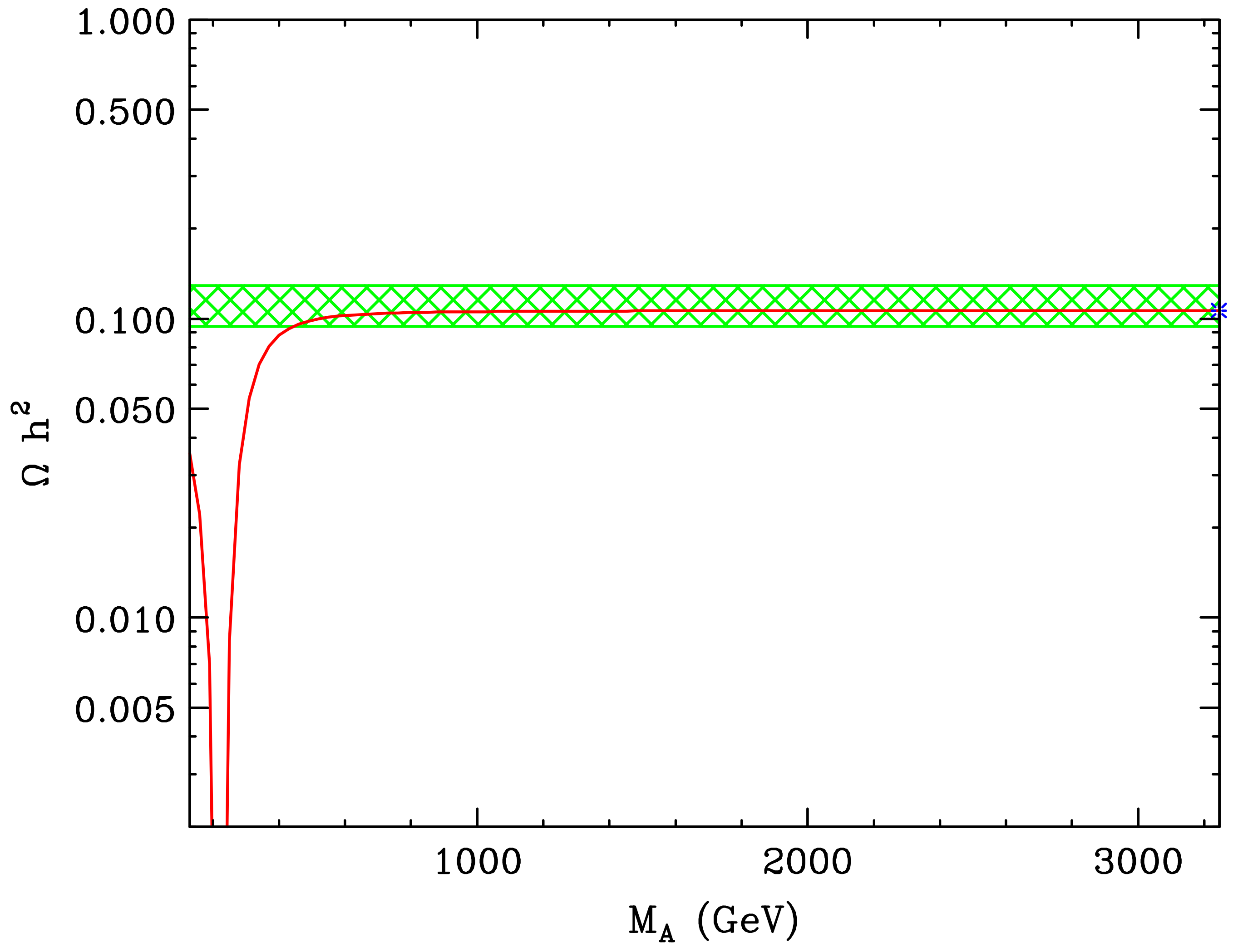


Figure 7: **Effect on Relic Density of Varying m_A.** The actual mSUGRA point is in blue. The green lines denote the 2-σ WMAP limits on the dark matter density. The red line shows what happens to the relic density as a function of m_A.

The Linear Collider

What can we measure with a 500 GeV linear collider?

Lots!

But, how well can we pin down M_1, M_2, μ and $\tan\beta$?

- h, χ_1^0, χ_2^0, χ_3^0, $\chi_1^\pm$, $\chi_2^\pm$ should be visible
- we can tell that all other sparticles have masses above 250 GeV (at least)
- M_1, M_2, μ and $\tan\beta$ from accurate measurement of the decays of χ^0's and $\chi^\pm$'s.
- We are investigating production and decay of $\chi_1^+\chi_2^-$, $\chi_1^+\chi_1^-$, $\chi_1^0\chi_3^0$ and $\chi_2^0\chi_3^0$ using $500 fb^{-1}$ of 90% polarized e^+e^- data ($250 fb^{-1}$ left-polarized and $250 fb^{-1}$ right-polarized) simulated for a 500 GeV linear collider.

- Each decay (such as $\chi_2^+ \rightarrow \chi_1^0 W^* \rightarrow \chi_1^0 f f'$) has a dilepton (or possible dijet) invariant mass distribution such as:

$$\frac{d\Gamma_{\chi_1^+}}{dm_{ff'}} \propto \frac{m_{ff'}\sqrt{\left(m_2^2-m_1^2\right)^2-2m_{ff'}^2\left(m_2^2+m_1^2\right)+m_{ff'}^4}}{\left(m_{ff'}^2-m_W^2\right)^2}$$

$$\times \ \left(\left(m_1^4+m_2^4+m_{ff'}^2 m_2^2-2m_{ff'}^4+m_1^2\left(m_{ff'}^2-2m_2^2\right)\right)\right.$$

$$\left. - \ 6\,\zeta\,\epsilon_1\epsilon_2\,m_{ff'}^2\,m_1 m_2\right). \tag{4}$$

where $\zeta = \frac{|C_V^{\chi_1^+\chi_1^0 W^-}|^2-|C_A^{\chi_1^+\chi_1^0 W^-}|^2}{|C_V^{\chi_1^+\chi_1^0 W^-}|^2+|C_A^{\chi_1^+\chi_1^0 W^-}|^2}$

- Even easier – kinematic endpoints determine $m_{ff',max} = m_2 - m_1$ (Here for $2 \rightarrow 1ff'$), so we can find kinematic endpoints and then fit to both distributions *and* endpoints.
- Additional information is needed to find m_2 and m_1 separately. This is supplied by also looking at the distribution of the dilepton energy, $E_{ff'}$.
- The upper and lower limits of $E_{ff'}$ depend on $m_{ff'}$, this relationship is given by:

$$m_{ff'}\left(E_{ff'}\right) = \sqrt{E_{ff'}^2-\left(p_2-\sqrt{\left(E_2-E_{ff'}\right)^2-m_1^2}\right)^2} \tag{5}$$

- Given enough statistics, it is even possible to fit to this 2-d distribution:

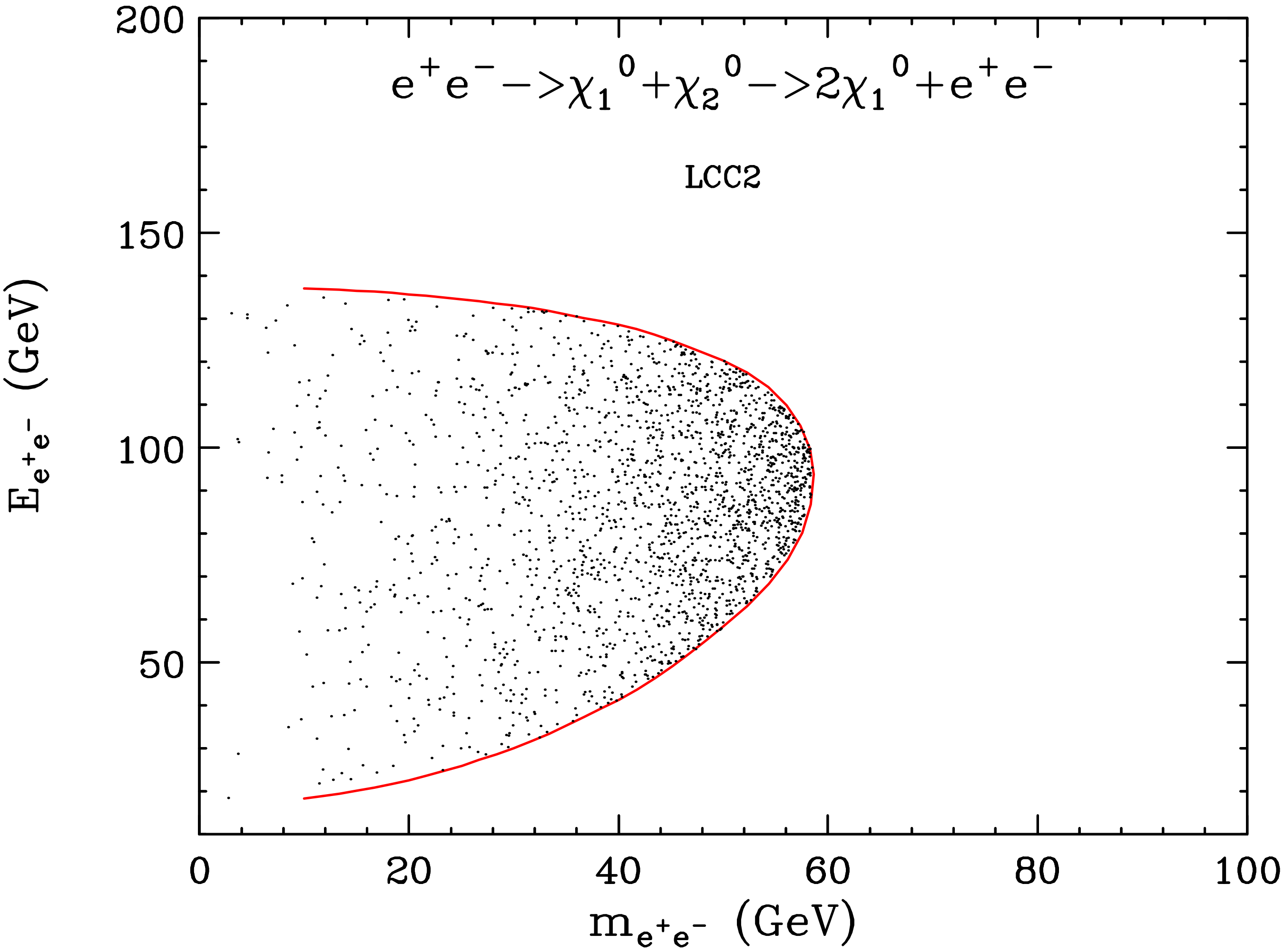


Figure 8: **2-d distribution of $m_{e^+e^-}$ vs. $E_{e^+e^-}$.** The red line shows the envelope function.

Summary of Backgrounds and Cuts

- $e^+e^- \to \chi_1^+\chi_1^- \to jjl + \not{E}$

  Require one isolated lepton

  Main background is W^+W^- pair production

  $|\cos\theta_j| < 0.8, \not{E} > 300$ GeV, $m_{jj} < 70$ GeV, $E_l > 15$ GeV, $N_{tracks} > 10$.
- $e^+e^- \to \chi_1^0\chi_3^0, \chi_2^0\chi_3^0 \to jj + \not{E}$

  Main backgrounds: W^+W^-, ZZ and $\chi_1^+\chi_1^-$

  $|\cos\theta_j| < 0.9, \not{E} > 350$ GeV, $p_T > 50$ GeV

  Must also include a b-tag for left polarized electrons.
- $e^+e^- \to \chi_1^0\chi_3^0, \chi_2^0\chi_3^0 \to ll + \not{E}$

  Require two oppositely charged leptons

  Main backgrounds: W^+W^-, ZZ and $\chi_1^+\chi_1^-$

  $|\cos\theta_j| < 0.9, \not{E} > 350$ GeV

  For left polarized, we must require $\cos\theta_{l+} > \cos\theta_{l-}$ to cut W^+W^-.
- $e^+e^- \to \chi_2^0\chi_3^0 \to jjll + \not{E}$

  Require two oppositely charged same flavor leptons and 2 or 3 (gluon emission) jets

  Main backgrounds: tt, ZZ and $\chi_1^+\chi_2^-$

  $|\cos\theta_j| < 0.95$, $E_{l,j} < 110$ GeV, $p_T > 10$ GeV,$\not{E} > 275$ GeV

  We also need an anti b-tagging cut to reduce tt further.

$\chi_2^0\chi_3^0 \to jj(j)ll + \not{E}$

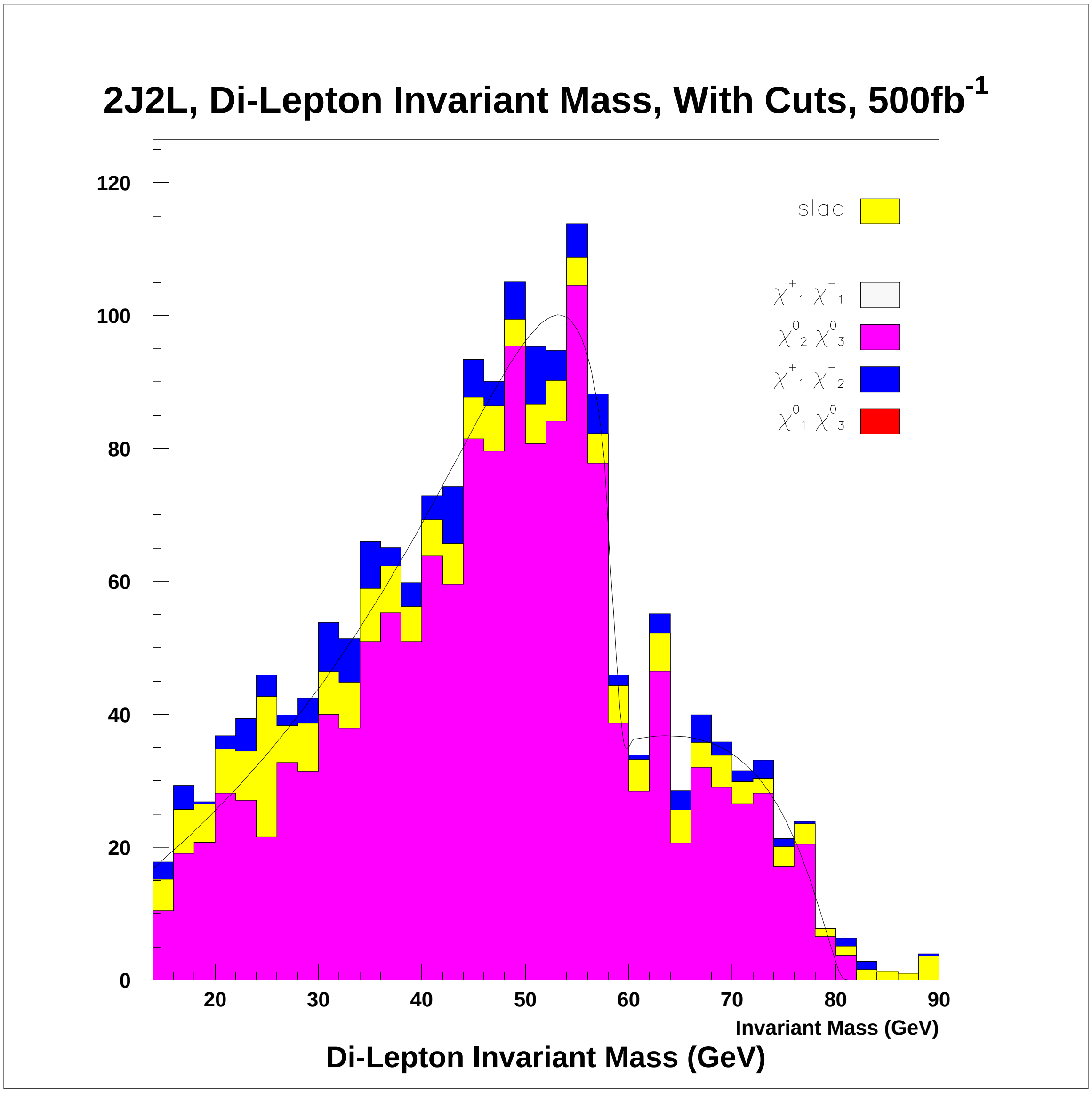


Figure 9: **Dilepton invariant mass distribution for** $\chi_2^0\chi_3^0 \to 2(or3)j2l$.

Sample Preliminary Results

- $m_{\chi_1^0} = 107.5^{+0.5}_{-1.1}$ GeV (Input value is 107.7 GeV)
- $m_{\chi_2^0} - m_{\chi_1^0} = 58.7^{+0.2}_{-0.1}$ GeV (Input value is 58.6 GeV)
- $m_{\chi_3^0} - m_{\chi_1^0} = 82.0^{+0.4}_{-0.1}$ GeV (Input value is 82.3 GeV)

Current and Future Tasks

- Cross-check with the SLAC sample of SM background (thanks T. Barklow and company!).
- Finish analyses on all channels
- Convert measurements of $\chi^{0,\pm}$ masses and σs into M_1, M_2, μ, $\tan\beta$
- Determine lower limits on $\tilde{l}$, $\tilde{q}$, H and A masses
- Determination the accuracy of LC measurement of $\Omega_{DM}h^2$

Finally, a big 'Thanks!'[3] to T. Barklow, J. Feng, R.C. Group, M. Peskin, B. Scurlock and many others for continued support and suggestions thus far.

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[3] 'Thanks' in more modern language is a 'shout-out.'