Measuring Dark Matter at Colliders

Andreas Birkedal
University of Florida
University of California, Santa Cruz

Outline of talk

- Cosmological Dark Matter <––––> LHC/LC Physics
- Why we need to measure Dark Matter at Colliders
  - The Importance of Being Correct
- A Model-Independent Approach
  - Seeing the Invisible
- Why knowing *all* of the masses is important
  - What You Don't Know *Will* Be Held Against You!
- Measuring Sleptons at the LHC
  - Knowing What We Don't Know
- Summary

Why Do We Care?

- Dark matter makes up most of the mass of the universe.
- Direct discovery of dark matter will tell us rather little.
  - Won't know how many dark matter candidates there are.
  - Won't know if dark matter is directly related to the weak scale and EWSB.
- These questions are best answered by colliders

Related Research

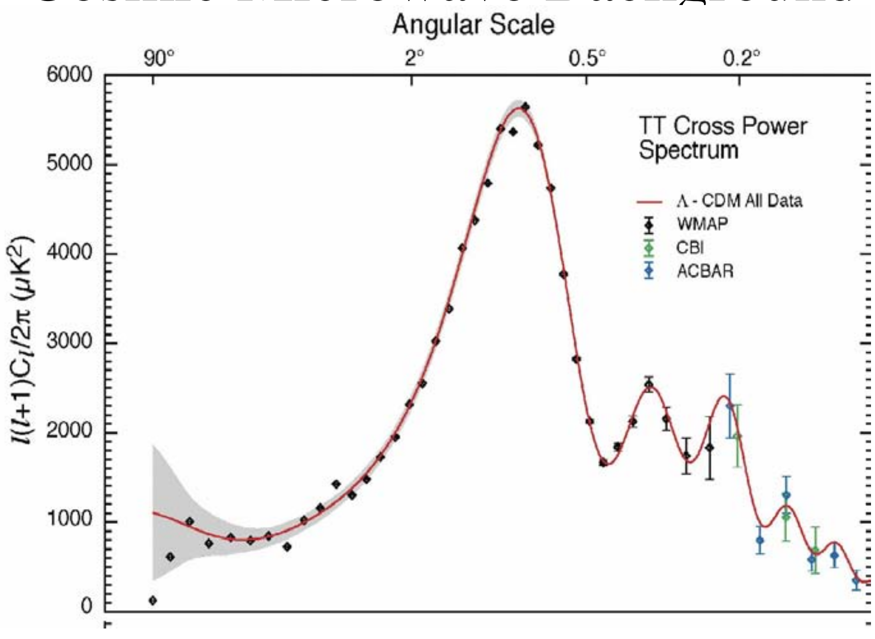
- H. Baer, and collaborators
- B. Dutta, and collaborators
- M. Battaglia, and collaborators
- J. Feng, and collaborators
- M. Peskin, and collaborators
- B.C. Allanach, G. Belanger, F. Boudjema, A. Pukhov
- W. de Boer, and collaborators
- T. Moroi, and collaborators
- *Many* others!

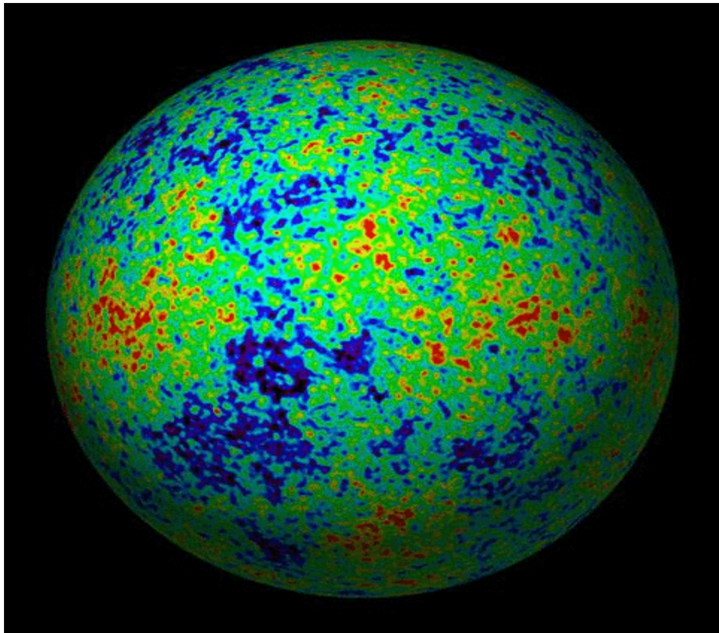
Dark Matter

- We know dark matter exists! (WMAP, Astrophys. J. Suppl. **148**, 175 (2003))

$$0.094 \leq \Omega_{dm} h^2 \leq 0.129$$

- Discovery – 1933 (Fritz Zwicky)
  - Galactic rotation
- WMAP – 2003 (Astrophys. J. Suppl. **148**, 175 (2003))
  - Cosmic Microwave Background



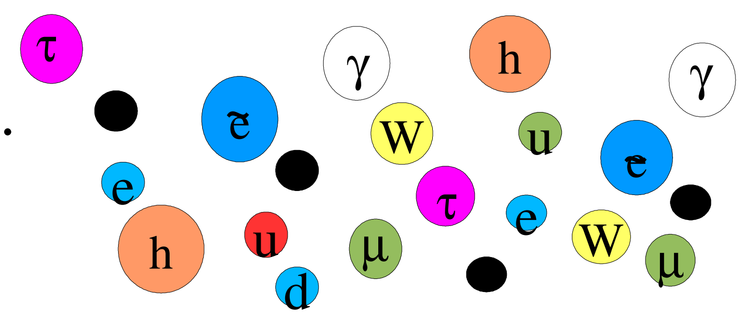


Dark Matter

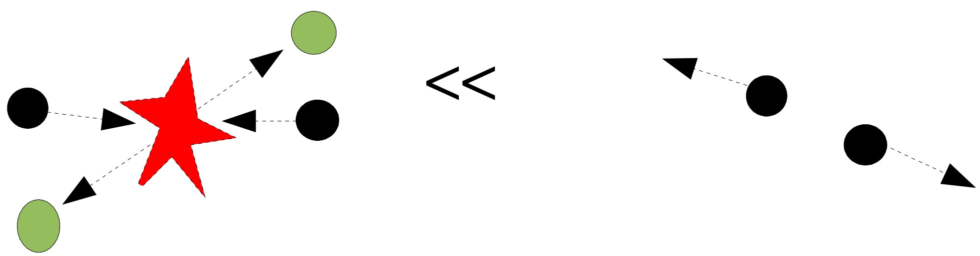
- We know dark matter exists! (WMAP, Astrophys. J. Suppl. **148**, 175 (2003))

$$0.094 \le \Omega_{dm} h^2 \le 0.129$$

- It's likely a particle (scales like matter with universal expansion)
  - Can't be protons, neutrons or electrons $\Omega_{matter} \simeq 0.3 \quad \Omega_{p,n,e} \simeq 0.05$
  - non-relativistic (from structure formation)
- We have a good idea how it got here:
  - A stable particle in the early universe...



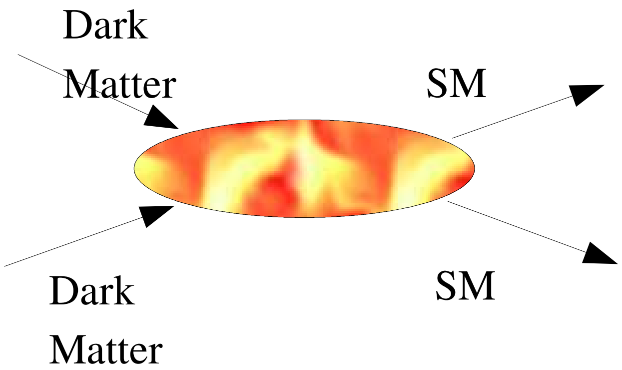
    - Very hot!
    - Everything in thermal equilibrium, $n_{DM}(T)$ is known.
      - Γ(DM DM -> SM SM) = Γ(SM SM -> DM DM)
    - T decreases, unstable particles decay

- $T < m_{DM}$, $n_{eq}(T) \sim e^{-m_{DM}/T}$
  - Equilibrium density decreases quickly!
- Interaction rate also drops, $\Gamma \sim n(T) \langle\sigma v\rangle$
- Dark matter drops out of thermal equlibrium.
  - Called "Freeze-out"
  - Details governed by Boltzmann equation:
  - $$\dot{n}+3Hn=-\langle\sigma v\rangle\left(n^2-n_{eq}^2\right)=-\Gamma n+\Gamma_{eq} n_{eq}$$
- Freeze-out: when interaction rate << universal expansion rate
- 
- After freeze-out, dark matter co-moving number density is fixed.

- Dark matter: interaction rate in early universe fixes present number density

Dark Matter

- Interaction Rate: just particle physics!

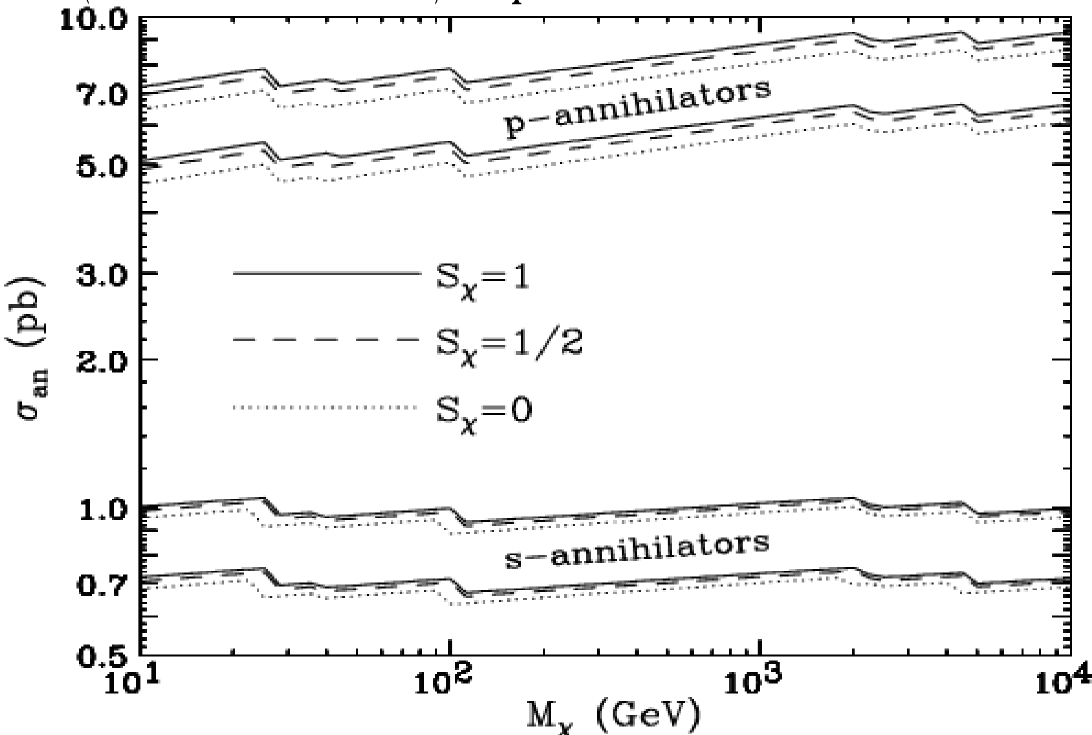


- To get $0.094 \le \Omega_{dm} h^2 \le 0.129$, we need $\sigma(DM\,DM \rightarrow SM\,SM) \simeq 1\,pb$

This is just the Weak Scale, so

$$\sigma(DM\,DM \rightarrow SM\,SM) \sim \alpha_{EW}^2 / M_{EW}^2$$

- WIMP!

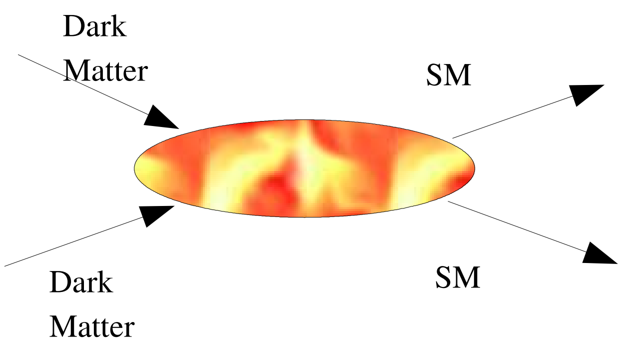


(A.B., K. Matchev and M. Perelstein, PRD 70:077701, 2004)

Connections between DM and LHC/LC Physics

- We know dark matter exists!

$$0.094 \le \Omega_{dm} h^2 \le 0.129$$



- Correct answer for ρ_{DM}

$$\sigma(DM\,DM \to SM\,SM) \simeq weak\ scale$$

- WIMP!

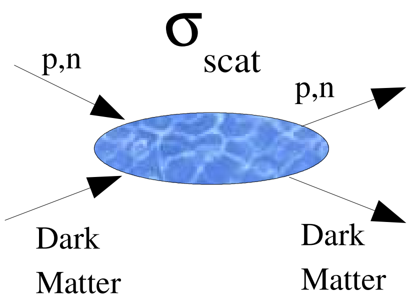
- Explanations of the weak scale (SUSY, Ex. Dim., little Higgs, etc.) –> left-over symmetries
  - leaves stable weak-scale particle
  - perfect DM candidate!

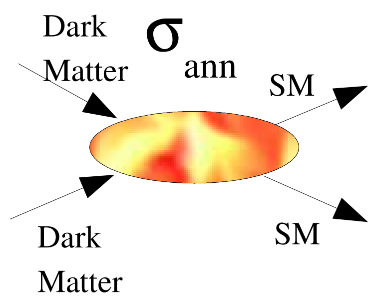
Dark Matter and LHC/LC physics...

made for each other!

The Importance of Being Correct

- Imagine CDMS II sees something, what do we know?
  - All of the dark matter?
    - Astrophysical Uncertainties
      - Halo model? Caustics?
    - Turning σ_{scat} into σ_{ann} (then $\Omega_{DM}h^2$) ?



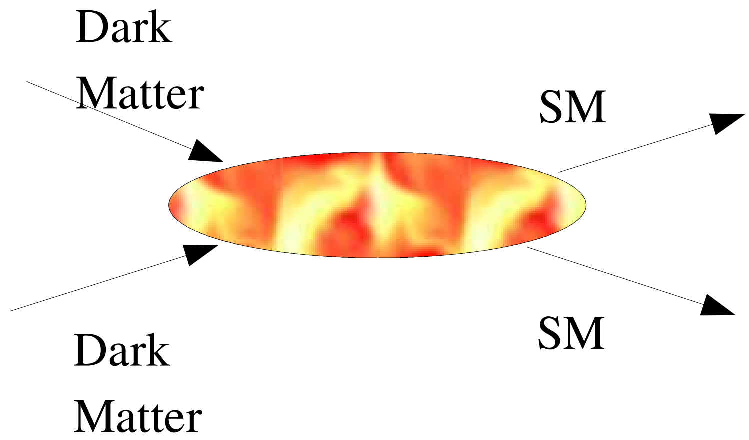


- To *know* that we have the dark matter particle:
  - enough measurements to calculate annihilation cross section
    - Direct detection –> not nearly enough
  - Making and measuring dark matter at colliders
    - Absolutely essential

Seeing the Invisible

- Cosmology: $\Omega_{DM} h^2$

$$\Omega_{DM} h^2 \simeq \frac{1}{\langle \sigma v \rangle}$$



- Collider signature?
  - Build a DM collider?
  - No! Crossing symmetry:

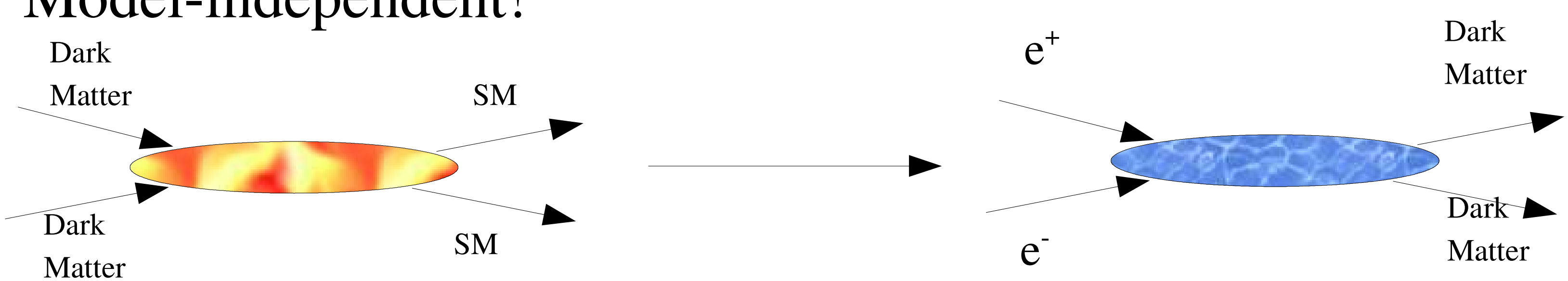
$$\frac{\sigma\left(DM\, DM \to X \bar{X}\right)}{\sigma\left(X \bar{X} \to DM\, DM\right)} = 2 \frac{v_X^2 \left(2 S_X + 1\right)^2}{v_{DM}^2 \left(2 S_{DM} + 1\right)^2}$$

- But we don't collide 'SM+SM'
  - we *can* collide 'e^++e^-'

$$\kappa_e = \frac{\langle \sigma\left(DM\, DM \to e^+ e^-\right) v \rangle}{\langle \sigma\left(DM\, DM \to SM\, SM\right) v \rangle}$$

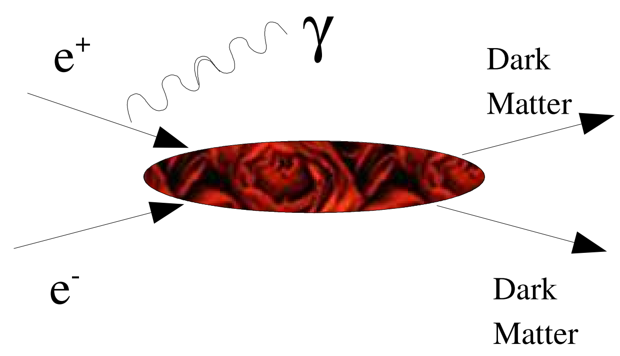
- Model-independent!

κ_e X



Seeing the Invisible

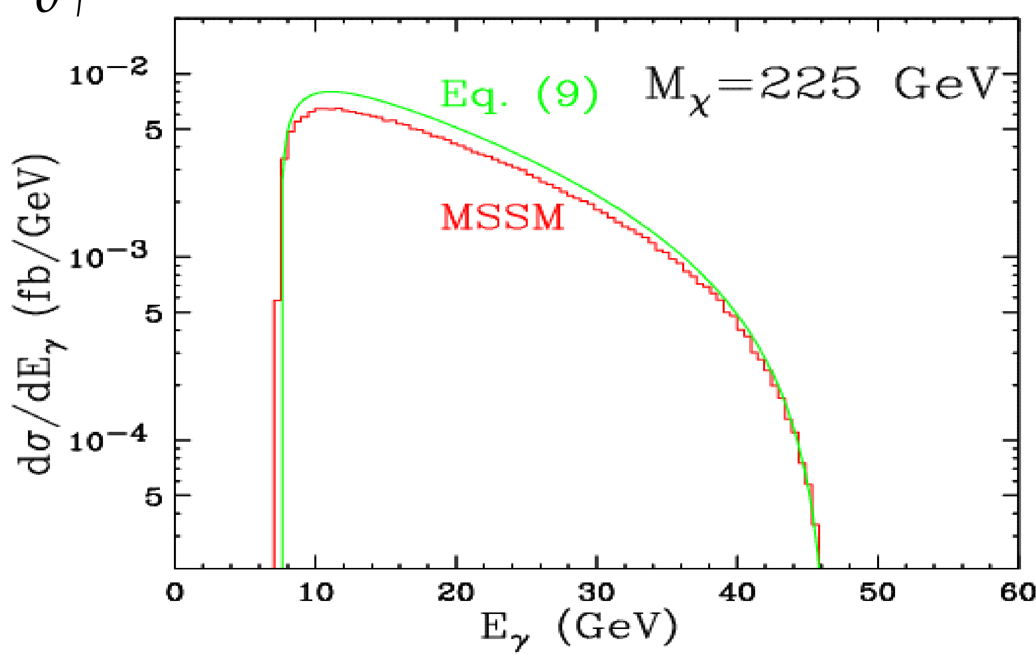
- Hmm... $e^+ e^-$ –> *nothing* might be hard to detect!
- Add a photon!
  - Soft or Collinear – SM calculable!
    - (A.B., K. Matchev and M. Perelstein, PRD 70:077701, 2004)
  - Collinear works best



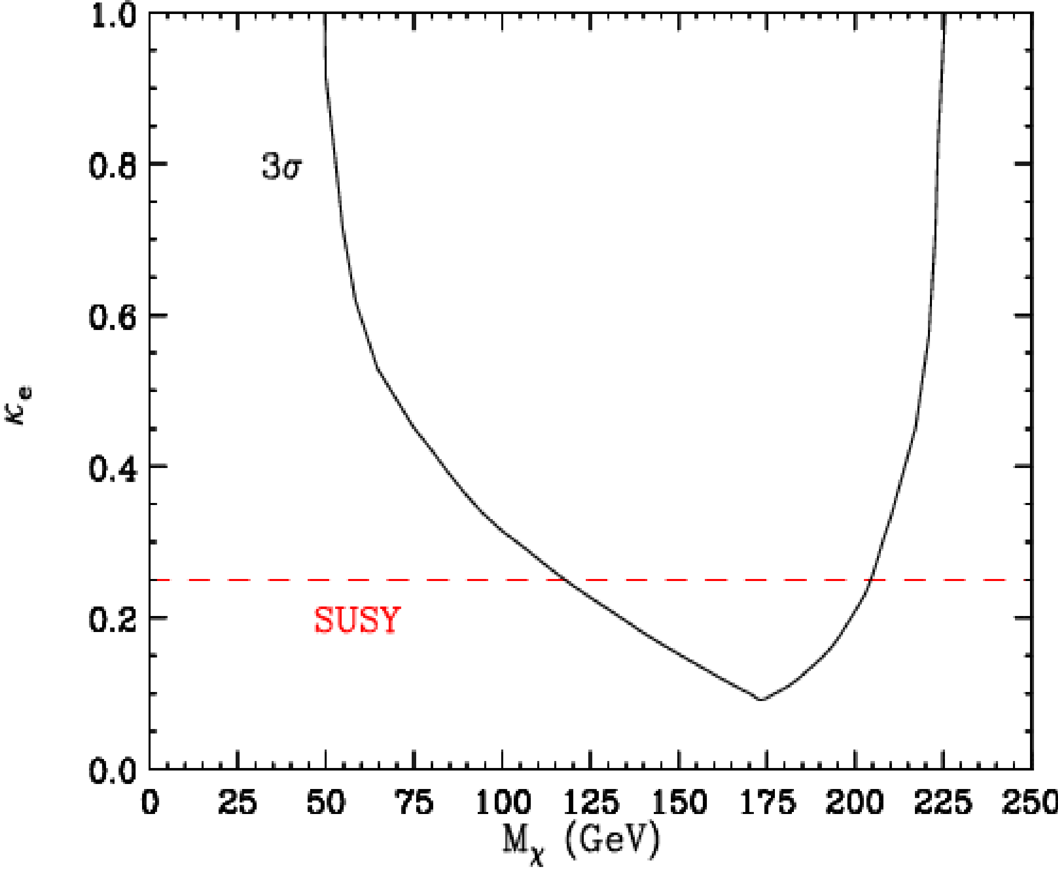
$$\frac{d\sigma\left(e^+ e^- \to 2\,DM + \gamma\right)}{dx\, d\cos\theta} \approx \left(\frac{\alpha}{\pi}\ \frac{1+\left(1-x\right)^2}{x}\ \frac{1}{\sin^2\theta}\right)\hat{\sigma}\left(e^+ e^- \to 2\,DM\right)$$

Here $x = 2E_\gamma/\sqrt{s}$

Universal SM factor



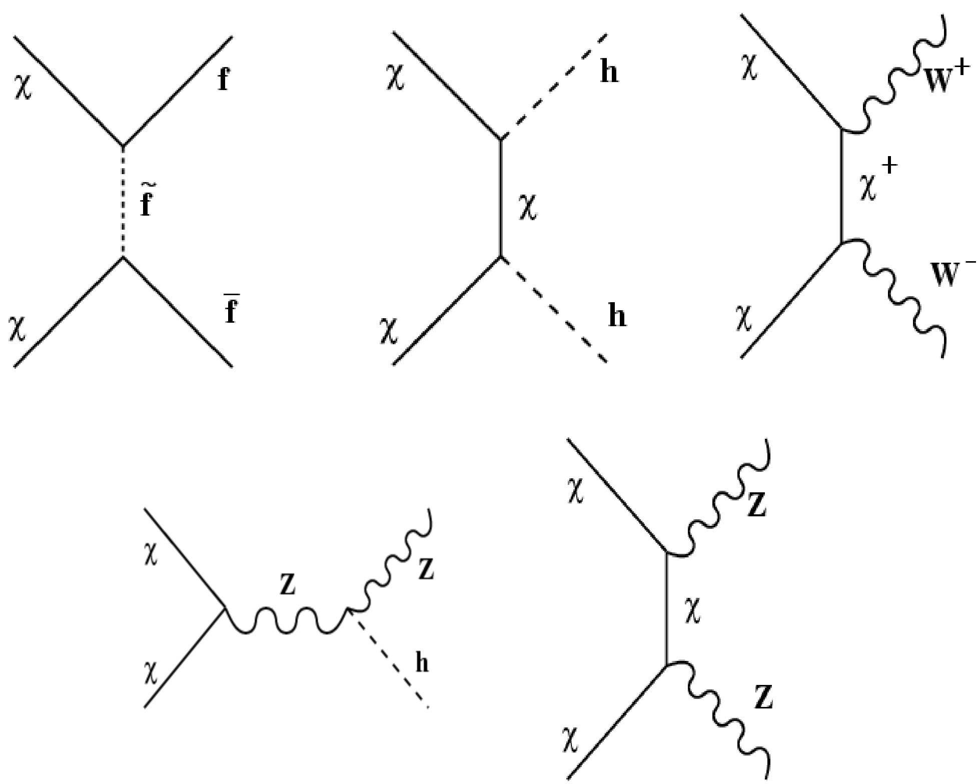
- 500 GeV LC, 500 fb^{-1}
- Cuts
  - sin θ> 0.1
    - detector acceptance
  - $p_{T,}$ > 7.5 GeV
    - eliminates Bhahba
  - $$\frac{\sqrt{s}}{2}\left(1-\frac{8M_\chi^2}{s}\right)\leq E_\gamma \leq \frac{\sqrt{s}}{2}\left(1-\frac{4M_\chi^2}{s}\right)$$
  - Systematics?
  - Polarization?



Experimentally challenging, but not out of the question!

What you don't know *WILL* be held against you!

- $\Omega_{DM}h^2$ depends on any particle involved in $\chi\,\chi \to$ SM SM

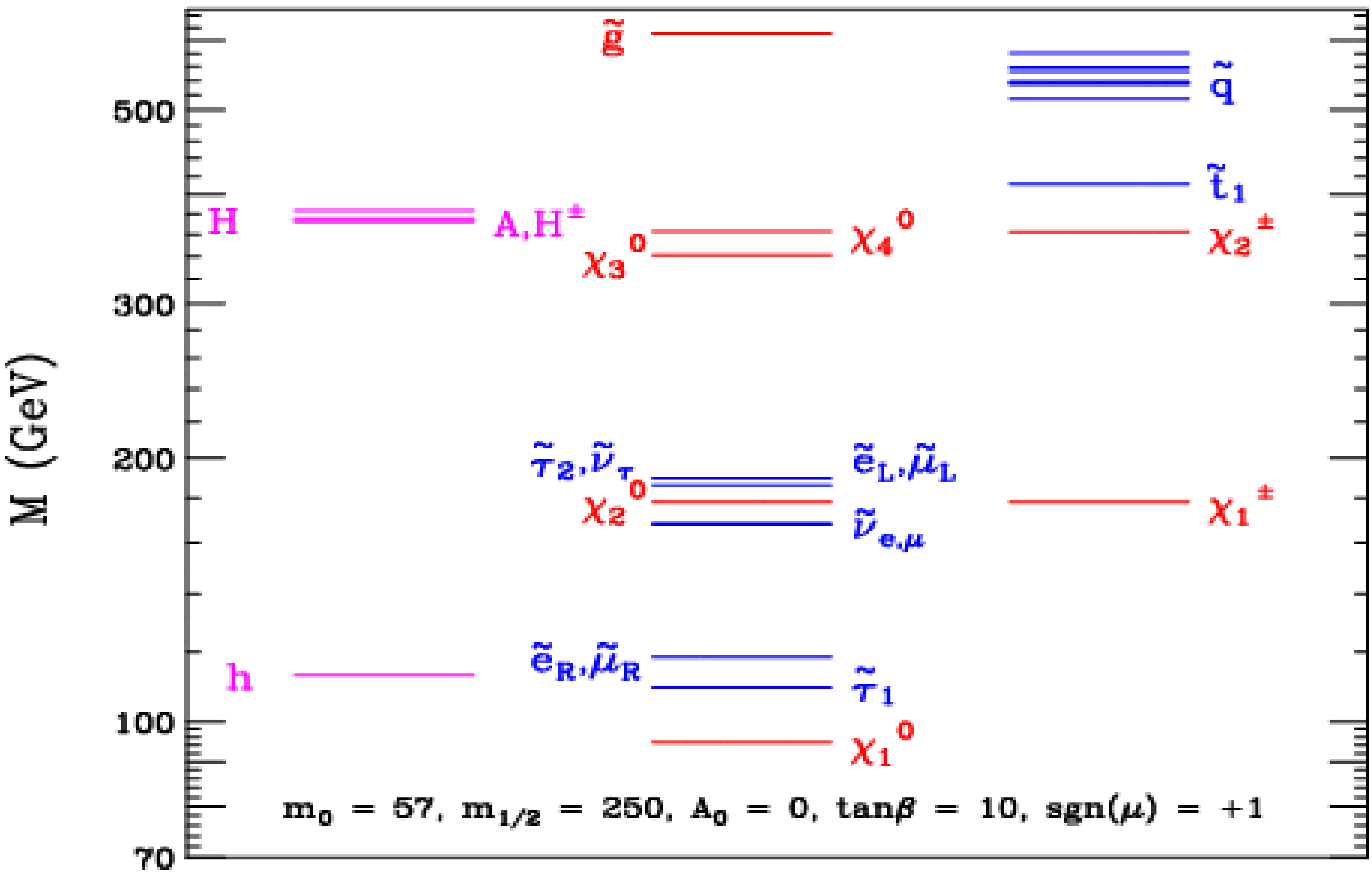


- Hope to measure them all?
- Coannihilation?
- Maybe only a few are important?
- mSUGRA
  - 5 parameters:

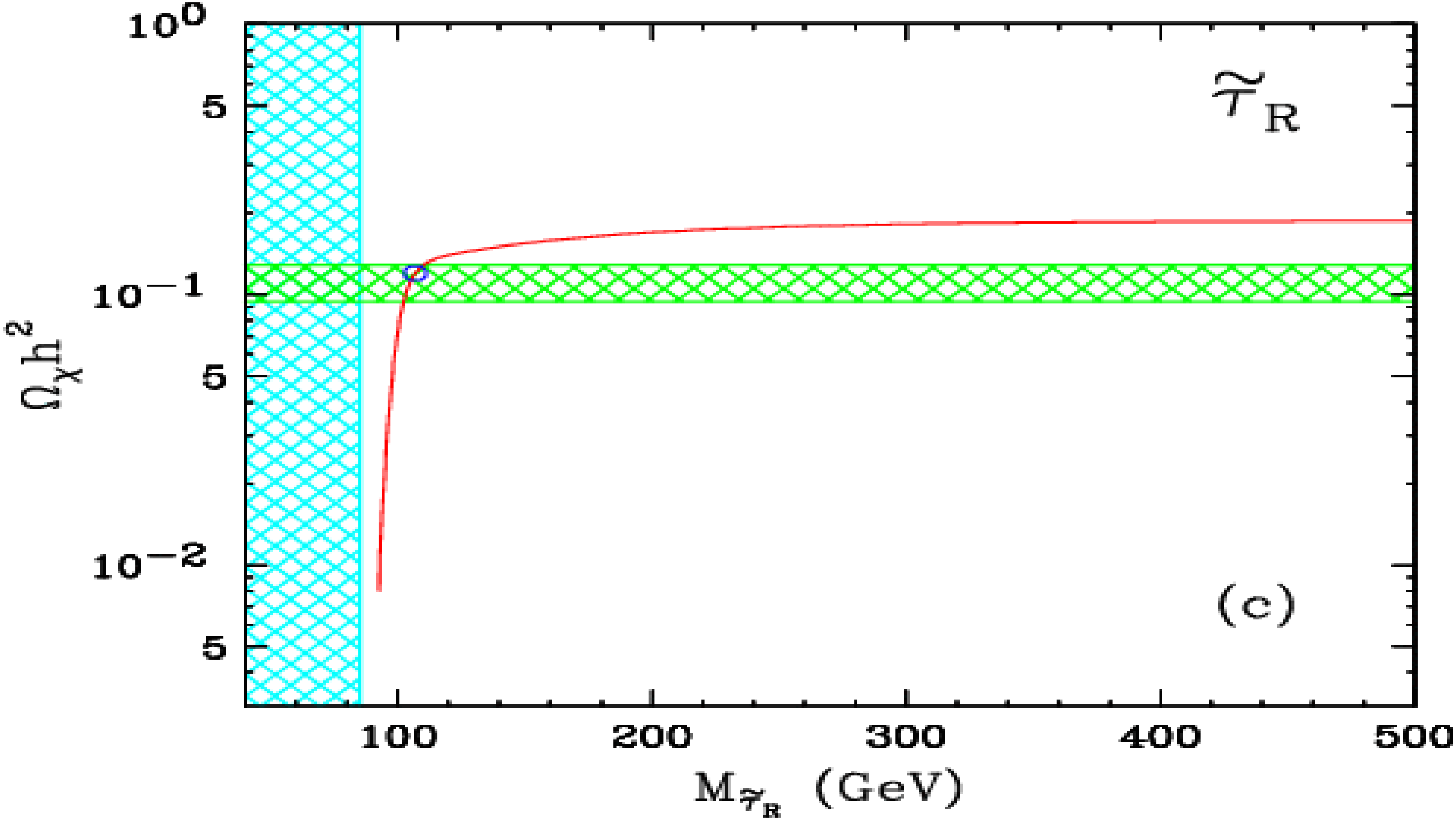
$$\left(M_0, M_{1/2}, A_0, \tan\left(\beta\right), sgn\left(\mu\right)\right)$$

mSUGRA: Bulk Point

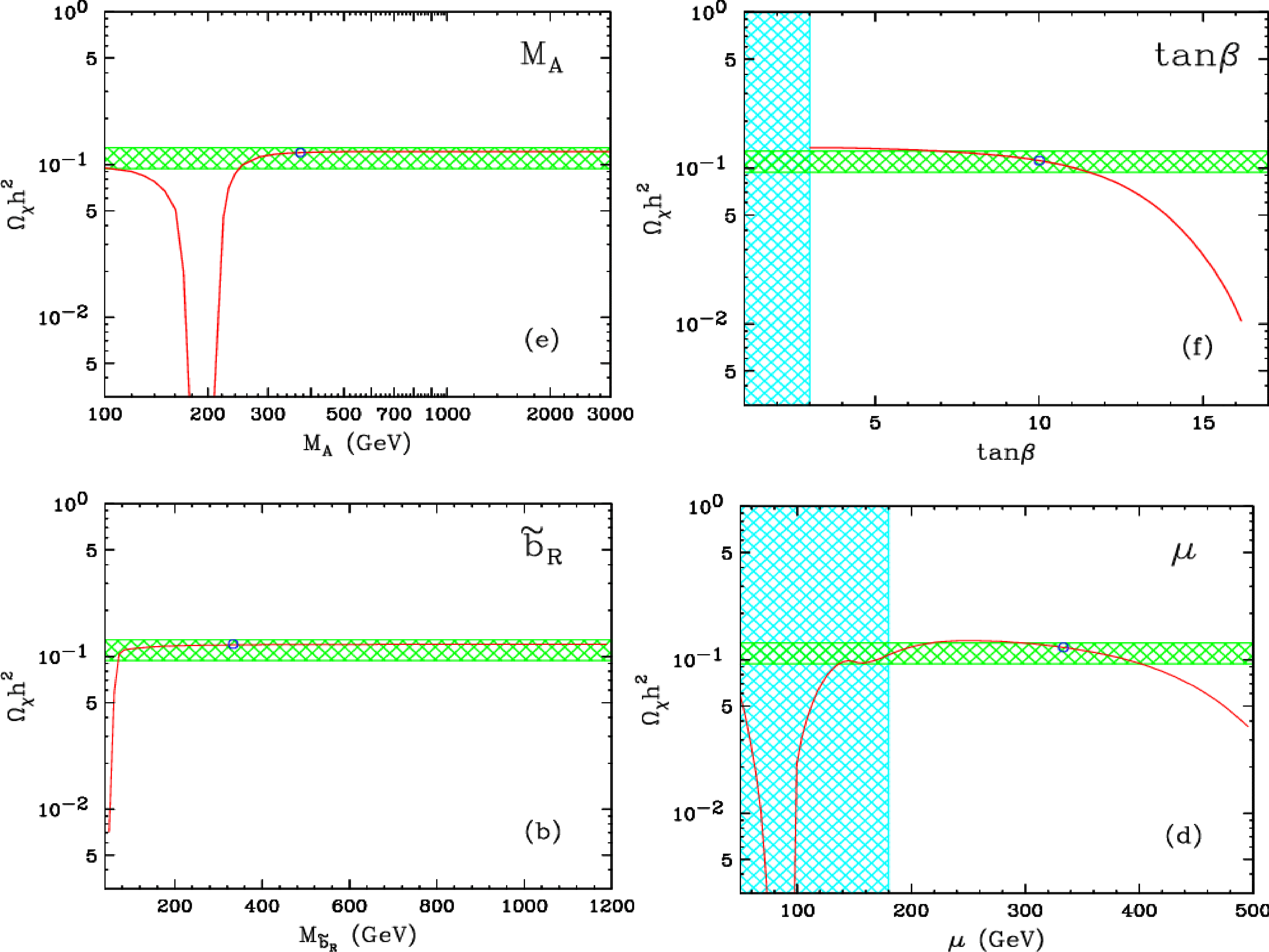
(from A.B., talk at ALCPG 04, SLAC, R. Gray et. al. hep-ph/0507008, and A. B. et. al. hep-ph/0507214)



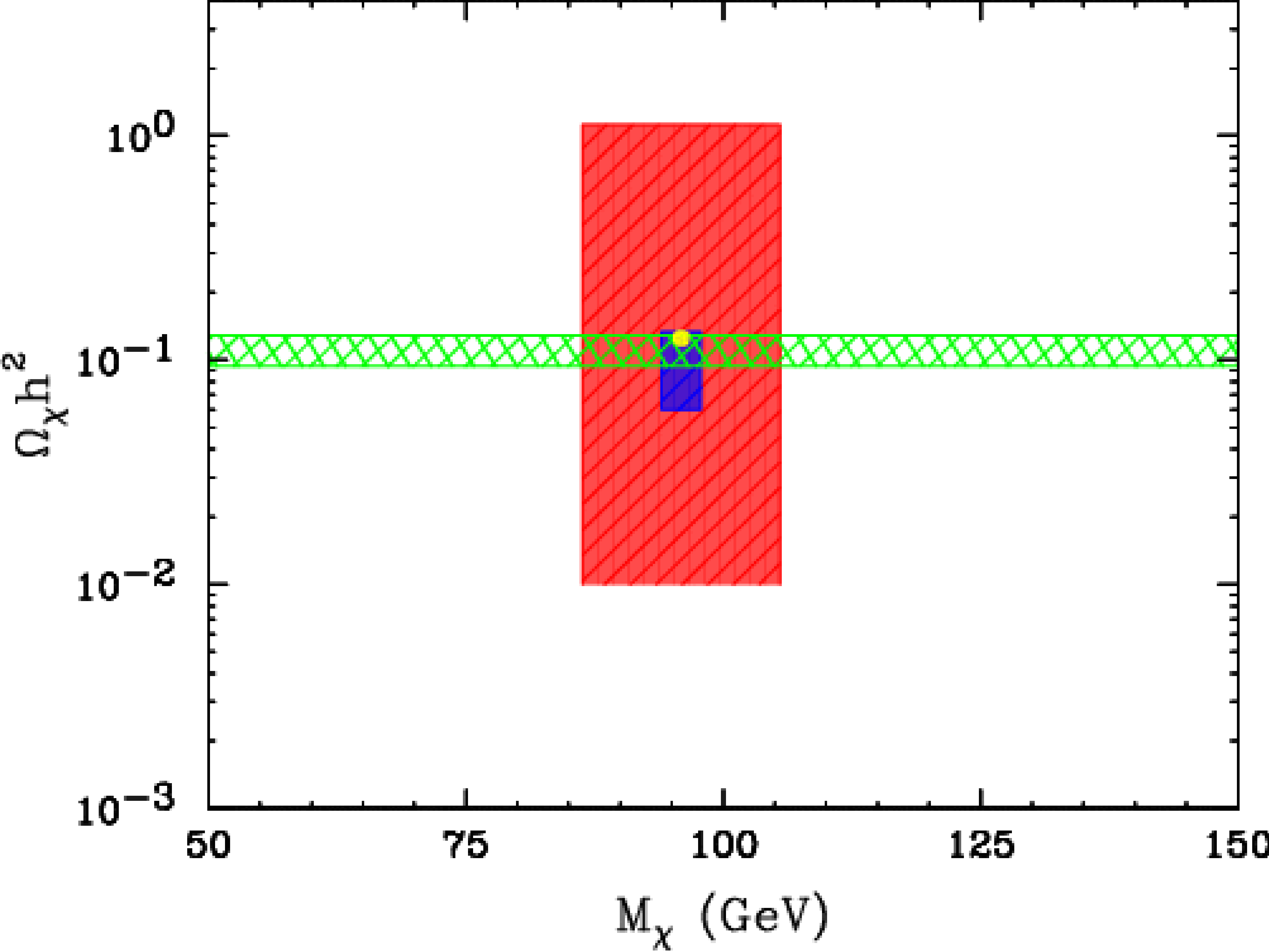
- 3 light sleptons and lightest neutralino
  - What else is important? Let's see...



Plots for $\tilde{\tau}_L$, $\tilde{e}_R$, $\tilde{\mu}_R$ are similar

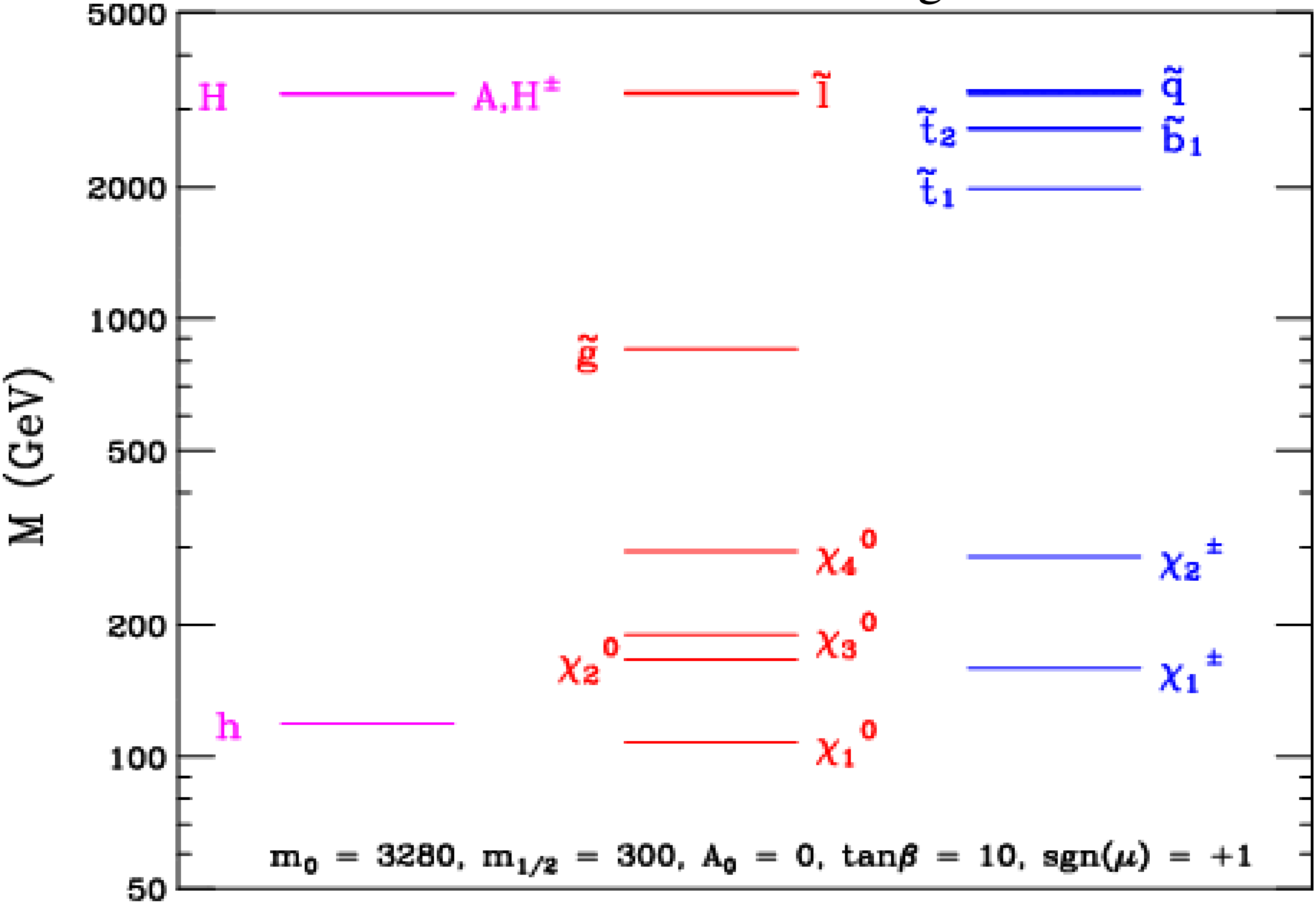


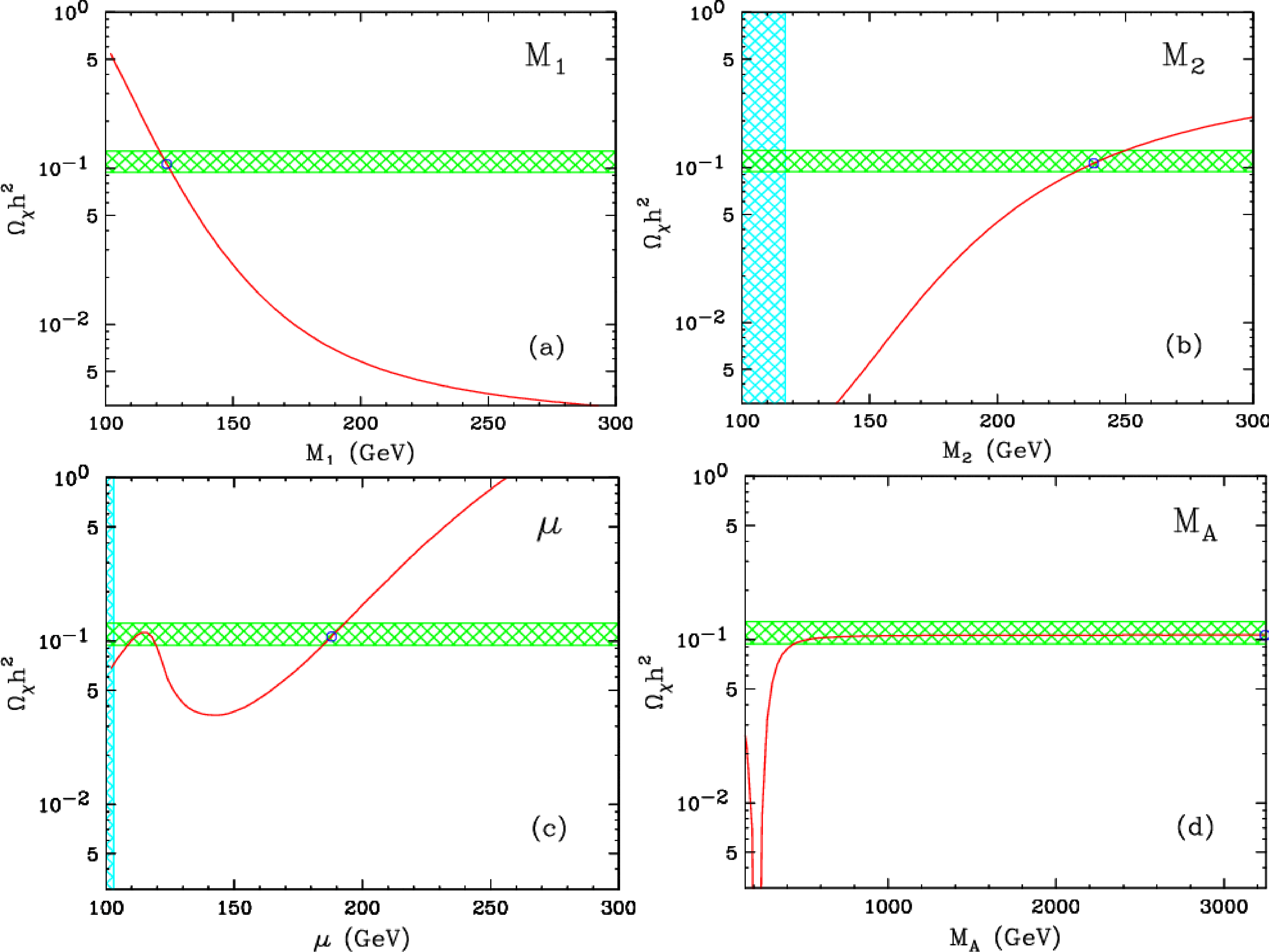
M_A
(e)
Ω_χh²
10⁰
5
10⁻¹
5
10⁻²
5
100
200
300
500
700
1000
2000
3000
M_A (GeV)
tanβ
(f)
Ω_χh²
10⁰
5
10⁻¹
5
10⁻²
5
5
10
15
tanβ
b̃_R
(b)
Ω_χh²
10⁰
5
10⁻¹
5
10⁻²
5
200
400
600
800
1000
1200
M_b̃R (GeV)
μ
(d)
Ω_χh²
10⁰
5
10⁻¹
5
10⁻²
5
100
200
300
400
500
μ (GeV)



10^0
10^{-1}
10^{-2}
10^{-3}
$\Omega_\chi h^2$
50
75
100
125
150
M_χ (GeV)

mSUGRA: Focus Point Region





M1
(a)
M1 (GeV)
M2
(b)
M2 (GeV)
μ
(c)
μ (GeV)
MA
(d)
MA (GeV)
Ωχh²

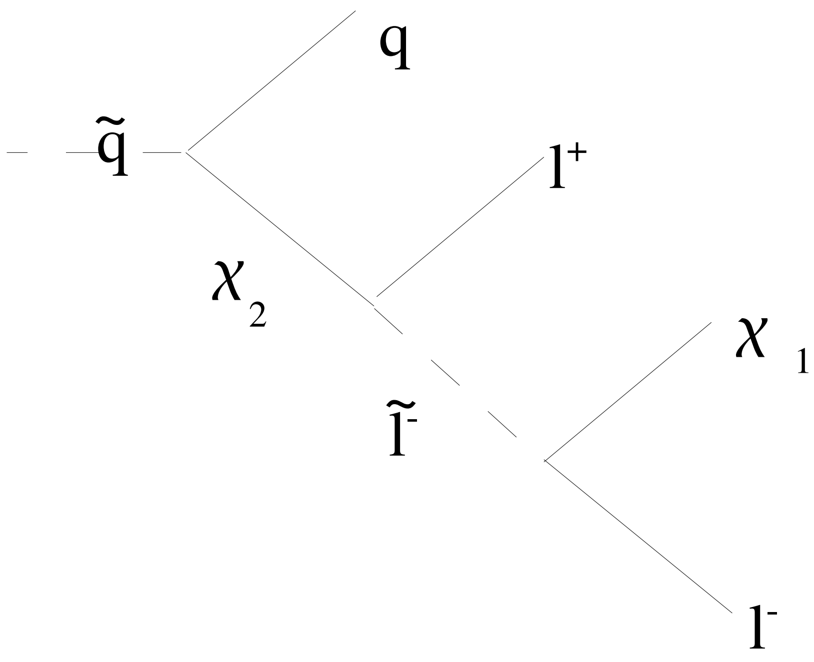
- Focus Point – lightest neutralino is dark matter, scalars very heavy
  - Relic density –> –ino sector, *nothing else*
    - -ino masses and couplings
      - $\Delta m_{\chi_1^0} \leq 1.6\,GeV \qquad \Delta(m_{\chi_2^0} - m_{\chi_1^0}) \leq 0.3\,GeV \qquad \Delta(m_{\chi_3^0} - m_{\chi_1^0}) \leq 0.5\,GeV$
      - 500 GeV LC (J. Alexander, *et. al.*, preliminary)
    - Lower bound on scalar masses (~500 GeV)
      - How? (LHC?)
    - Limit on $\Omega_{DM}h^2$? Not yet for focus point...

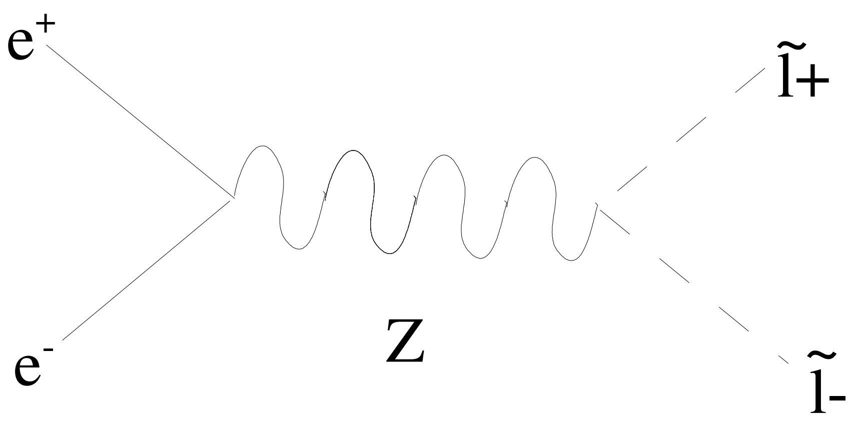
Knowing what We Don't Know

- Rough idea of particle masses is essential for $\Omega_{DM}h^2$
  - lower bounds just as crucial as mass measurements
- Heavy Sleptons (above LC reach): how do we tell mass?
- If we can't, we only know: LC $< m < \infty$
- Sleptons at the LHC? Can that be done?
  - Let's see...

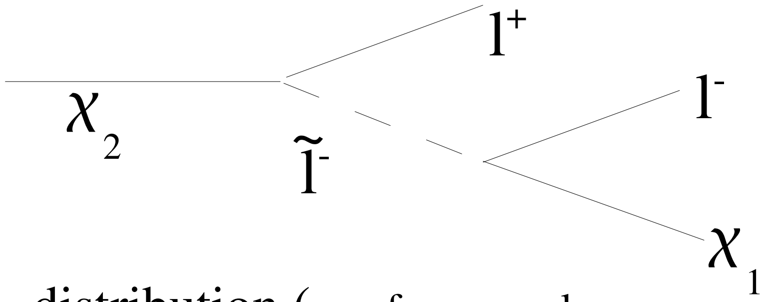
Sleptons at the LHC and LC

- LHC – We'll mainly make squarks and gluinos. Sleptons will be made through cascade decays mostly.
- LC – Sleptons can be made directly!



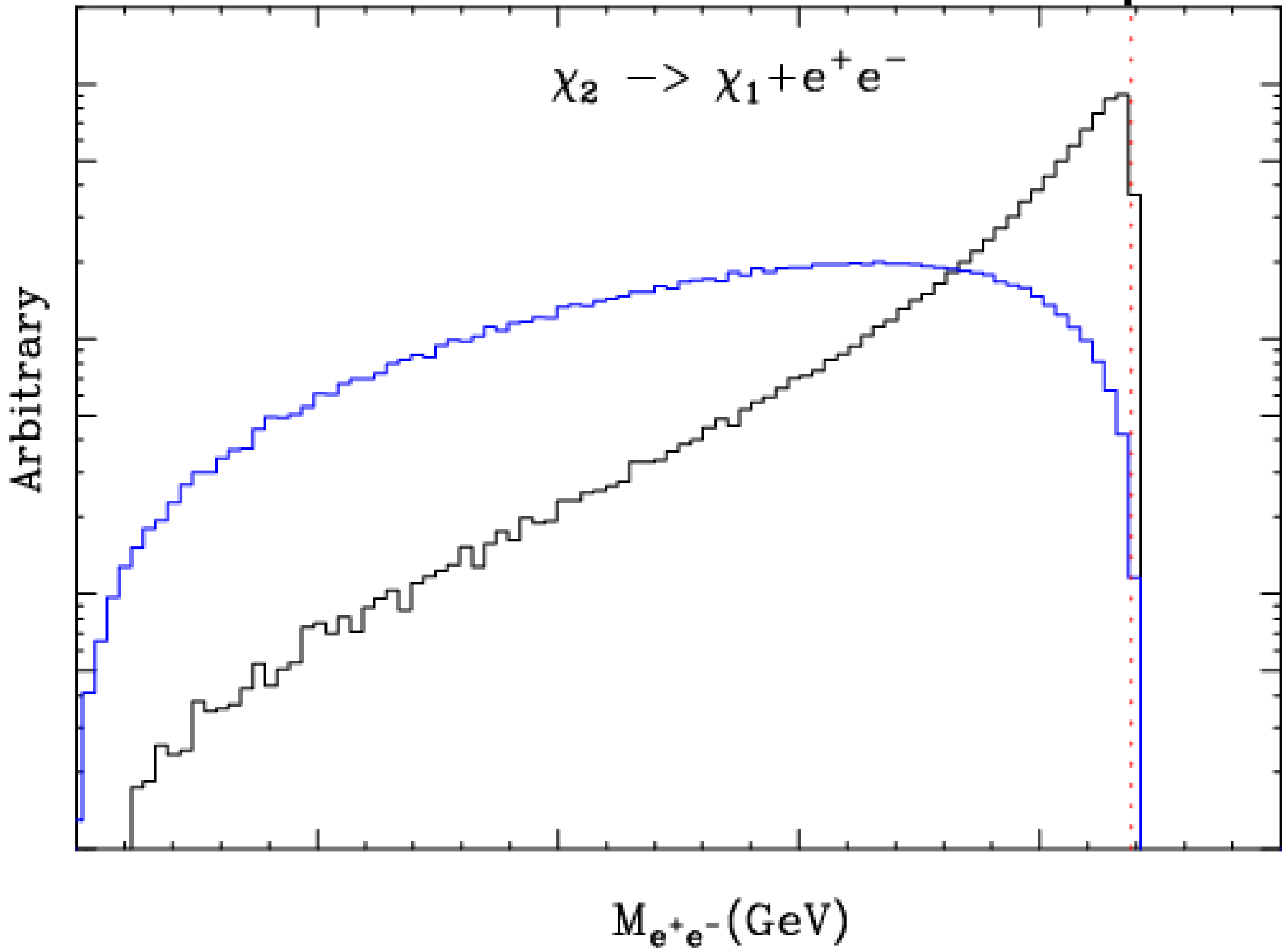


Slepton masses at the LHC through χ_2 decay.



- Sleptons - cascade decays at the LHC
- Useful information - from the endpoint of the m_{ll} distribution (see, for example, I. Hinchliffe and F. Paige, PRD 61:095011, 2001):
  - 3-body decays (virtual slepton/Z): kinematic endpoint of m_{ll} gives $(m_{\chi 2} - m_{\chi 1})$
  - 2-body decays: kinematic endpoint of m_{ll} gives: $((m_{\chi 2}{}^2 - m_{slep}{}^2)(m_{slep}{}^2 - m_{\chi 1}{}^2)/m_{slep}{}^2)^{1/2}$
- Just the endpoints? What about the shape of the distribution? Can that tell us anything?
  - Yes, can discriminate between 3-body and 2-body decay.
  - Can even measure slepton masses!

Invariant Mass Distributions and the Slepton Mass



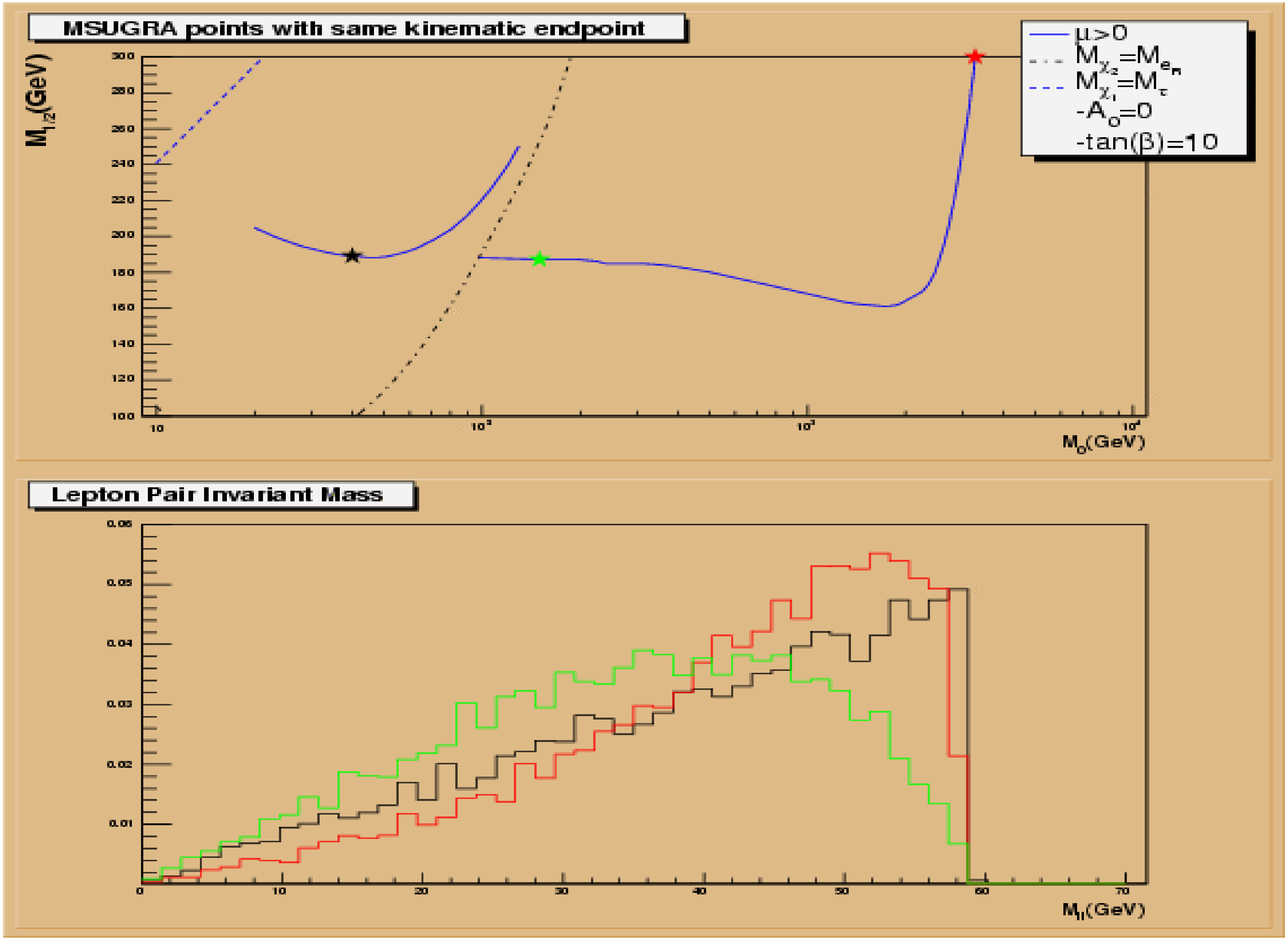
Slepton mass values: black - infinite, blue – 300 GeV

Aha! The shapes are quite different, even for the same endpoint value!

(from A.B., R.C. Group and K. Matchev, hep-ph/0507002)

Distribution Shapes in mSUGRA

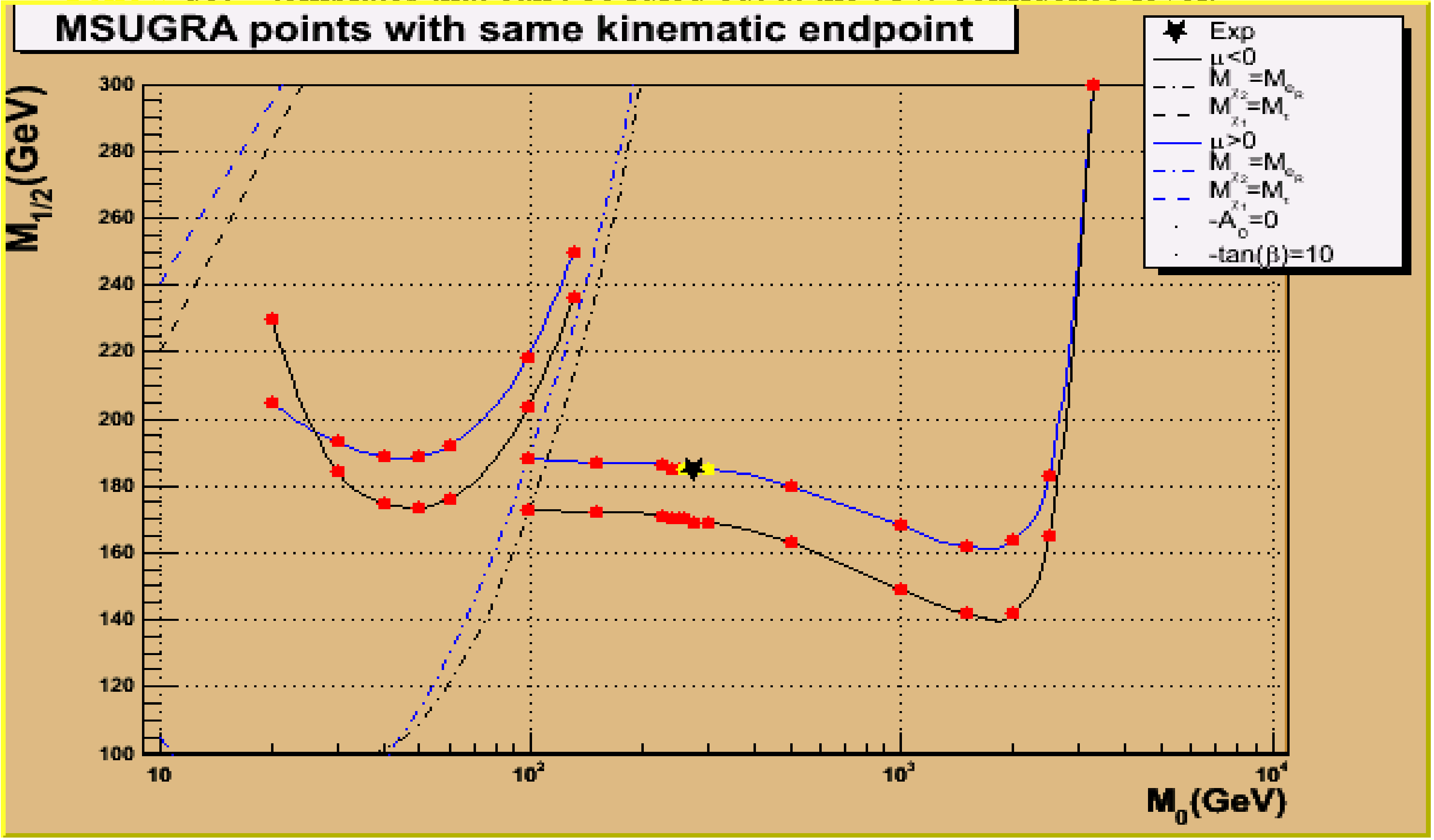
- For a fixed endpoint value of 59 GeV, we get line segments in the $(M_0, M_{1/2})$ plane:



(from A.B., R.C. Group and K. Matchev, hep-ph/0507002)

Kolmogorov-Smirnov in mSUGRA (point with M_0 ~ 300 GeV)

- Black star – taken to be experimental result.
- Red dot – templates that can be ruled out at the 95% confidence level.
- Yellow dot – templates that can't be ruled out at the 95% confidence level.



(from A.B., R.C. Group and K. Matchev, hep-ph/0507002)

What can we learn from this?

- High-mass points (M_0 > 1 TeV) can often be distinguished from low-mass points, and a lower limit on the value of M_0 can be determined.
- For low-mass 3-body decay points, the M_0 value can be bracketed (sometimes quite nicely).
- For 2-body decay points (with a real slepton), the value of M_0 can be bracketed, and they can be clearly distinguished from 3-body decay points.

Summary

- Dark Matter and LHC/LC physics: Intimately connected?
  - Great reason to be *very* excited if you are a particle/astro physicist!
- Cosmological dark matter predicts model-independent collider signature
  - Certainly possible for SUSY and UED (challenging!)
- A convincing case for specific dark matter particle
  - Requires verifying $\Omega_{DM}h^2$ through collider measurements
  - The irrelevant becomes relevant (heavy sleptons, for instance)
  - Cosmological precision on $\Omega_{DM}h^2$ possible in mSUGRA bulk region
    - work ongoing in the focus point

Summary

- Slepton mass determinations are possible at the LHC through neutralino decays, even for heavy virtual sleptons.
  - Needs backgrounds and cuts (currently in progress).
  - These shape analyses will also undoubtably be useful in making measurements at a future linear collider.
- Lots of *exciting*, **relevant** work to be done!

Thanks to Norman Graf for the cool logo!