Determination of Dark Matter Mass at (Linear) Lepton Colliders

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Pheno 2012, Pittsburg, CA 94565

Outline

- Introduction: Background Info and Antler Definition
- Review of Kinematic Cusp
- Mass Measurement of Smuons
- Effects of Cuts on Cusps
- SM and MSSM Backgrounds
- Results
- Log Likelihood (Extra ?)

Introduction

- International Linear Collider (**if ever built**) may reveal the “dark side” of the universe
- Pair produced Dark Matter
  - Odd parity, even number of particles produced
  - If mass not too huge then producable
  - Pair of odd particles will cascade decay
- Hard to identify, Hard to measure !
- The cascade decay forms “antler” diagram

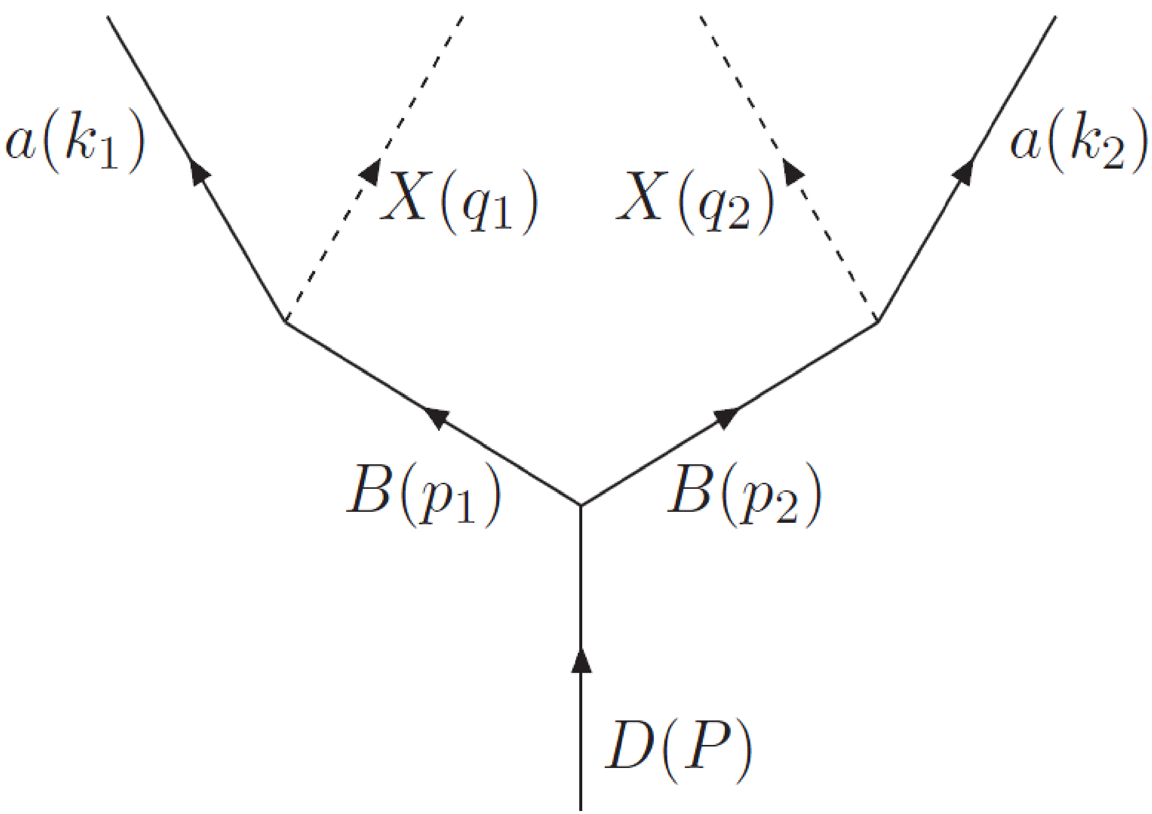
Intro. cont.

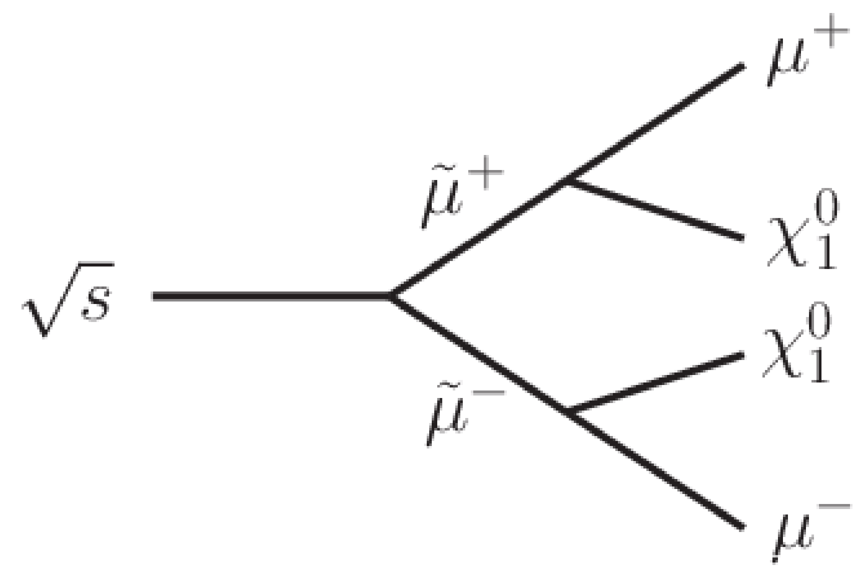
- Why linear lepton colliders?
  - Lab frame = Centre of Mass frame
  - Center of mass energy known → missing momentum known
  - Invariant missing mass constructable
  - Beams polarizable
- Let's concentrate on MSSM for now

$$e^+e^- \rightarrow \tilde{\mu}^+\tilde{\mu}^- \rightarrow \mu^+\mu^-\chi_1^0\chi_1^0$$

Antler Diagram ?

- It gives kinematic cusps and end points
- It looks like an antler .....





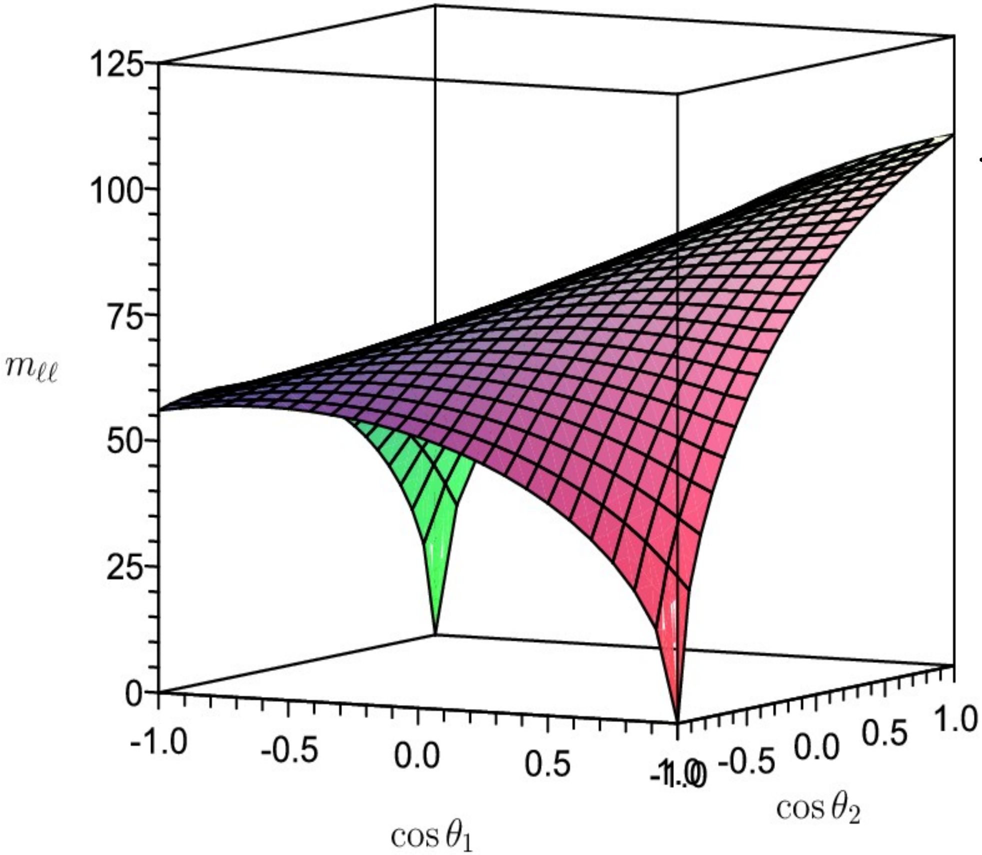
Review on Kinematic Cusps

- A heavy particle D decays to identical particles B_1 and B_2
- Followed by $B_1 \rightarrow a_1 X_1$ and $B_2 \rightarrow a_2 X_2$
- For notational simplicity, use rapidities (in each parent's rest frame)

$$\cosh \eta_B = \frac{m_D}{2m_B}, \quad \cosh \eta_a = \frac{m_B^2 + m_a^2 - m_X^2}{2m_a m_B}$$

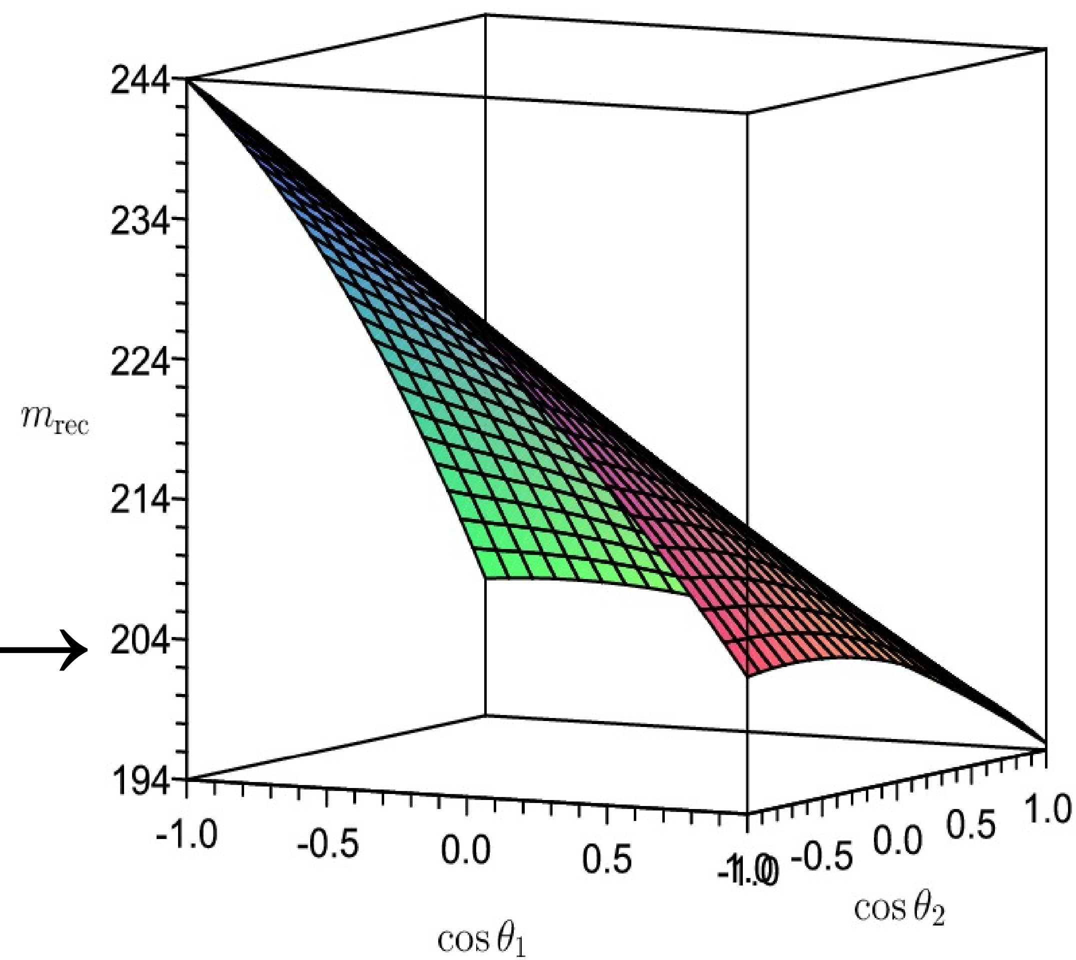
Review cont.

- Any observable can be expressed as a function of $\cos \Theta_1$ and $\cos \Theta_2$
- e.g. $M_{aa}(\cos \Theta_1, \cos \Theta_2)$, from symmetry it has 3 distinctive apexes $M_{aa}(\pm 1, \pm{-1})$, $M_{aa}(1,1)$ and $M_{aa}(-1,-1)$ which correspond to M^{min}, M^{max} and M^{cusp}
- If the observed particle is massless, the three positions are uniquely fixed by m_D, m_B and m_X
- $\mathcal{R}_1 : \eta_B < \frac{\eta_a}{2}, \quad \mathcal{R}_2 : \frac{\eta_a}{2} < \eta_B < \eta_a, \quad \mathcal{R}_3 : \eta_a < \eta_B$



← $M_{ll}(\cos\Theta_1, \cos\Theta_2)$

$M_{miss}(\cos\Theta_1, \cos\Theta_2)$ →



Review cont.

- Summary of the apexes

	$m_a \neq 0$			$m_a = 0$
	$\mathcal{R}_1: \ \eta_B < \frac{\eta_a}{2}$	$\mathcal{R}_2: \ \frac{\eta_a}{2} < \eta_B < \eta_a$	$\mathcal{R}_3: \ \eta_a < \eta_B$	
$m^{\min}$	$2m_a$		$2m_a \cosh(\eta_B - \eta_a)$	0
m^{cusp}	$2m_a \cosh(\eta_B - \eta_a)$	$2m_a \cosh \eta_B$		$2E_a^{(B)} e^{-\eta_B}$
$m^{\max}$	$2m_a \cosh(\eta_B + \eta_a)$			$2E_a^{(B)} e^{\eta_B}$

- Cusp in the angular distribution

$$|\cos\Theta|_{\max} = \tanh \eta_B = \sqrt{1 - \frac{4m_B^2}{m_D^2}}$$

$$\frac{d\Gamma}{d\cos\Theta} \propto \begin{cases} \sin^{-3}\Theta, & \text{if } |\cos\Theta| < \tanh \eta_B \\ 0, & \text{otherwise} . \end{cases}$$

Review cont.

- E_l has min and max at

$$E_\ell^{\mathrm{max,min}} = \frac{m_D}{4}\left(1 - \frac{m_X^2}{m_B^2}\right)\left(1 \pm \sqrt{1 - \frac{4m_B^2}{m_D^2}}\right)$$

- So, everything can be derived from m_D, m_B and m_X and vice versa

Mass Measurement of Smuons

- In MSSM

$$e^+e^- \to \tilde{\mu}^+_{R,L} + \tilde{\mu}^-_{R,L} \to \mu^+\tilde{\chi}^0_1 + \mu^-\tilde{\chi}^0_1$$

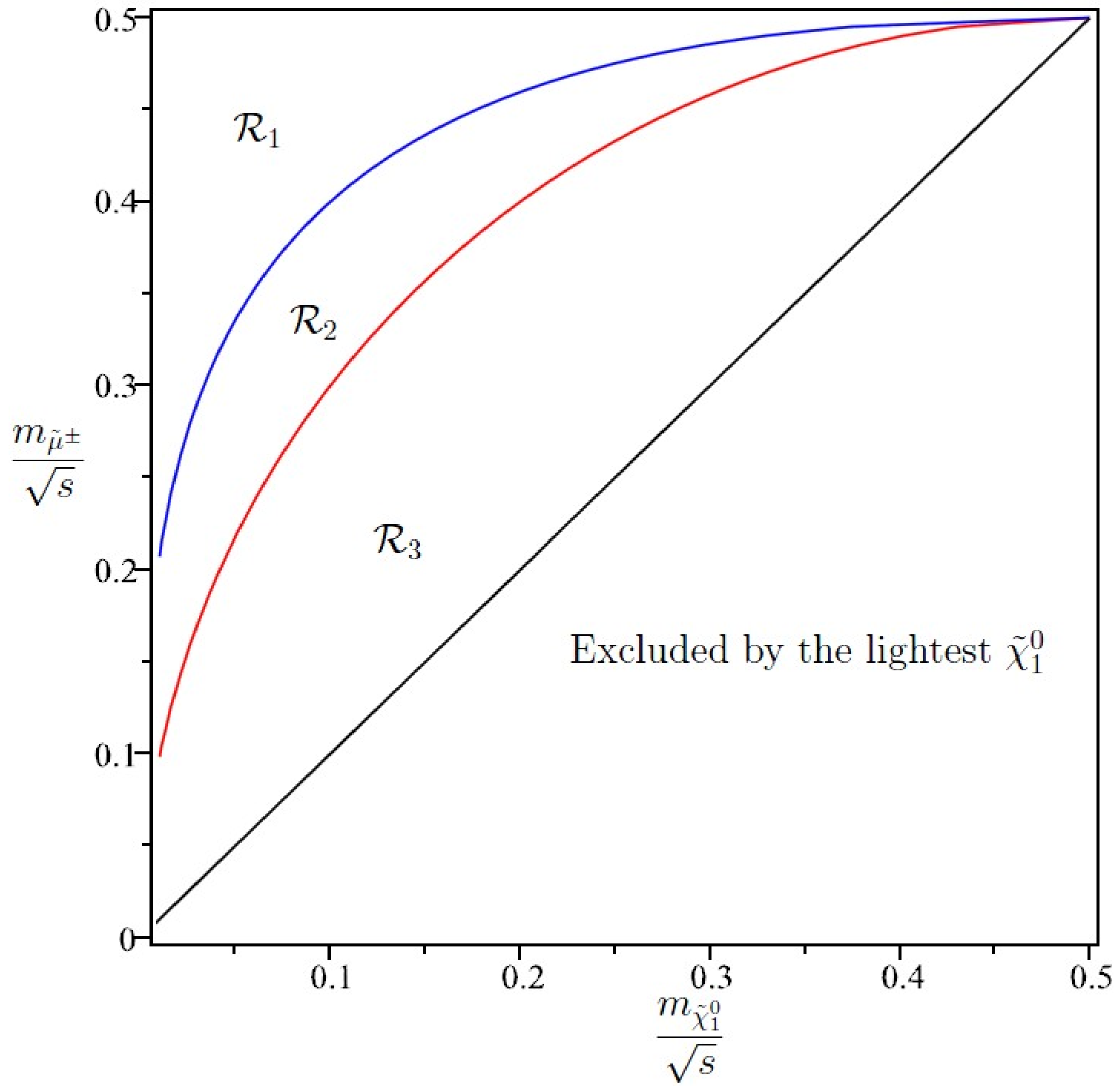
$$\cosh\eta_{\tilde{\mu}} = \frac{\sqrt{s}}{2m_{\tilde{\mu}}}, \quad \cosh\eta_{\tilde{\chi}^0_1} = \frac{m^2_{\tilde{\mu}} + m^2_{\tilde{\chi}^0_1}}{2m_{\tilde{\chi}^0_1}m_{\tilde{\mu}}}$$

- Invariant mass of missing particles

$$m^2_{\rm rec} \equiv m^2_{\tilde{\chi}^0_1\tilde{\chi}^0_1} = s + m^2_{\mu^+\mu^-} - 2\sqrt{s}(E_{\mu^+} + E_{\mu^-})$$

Mass Measurement cont.

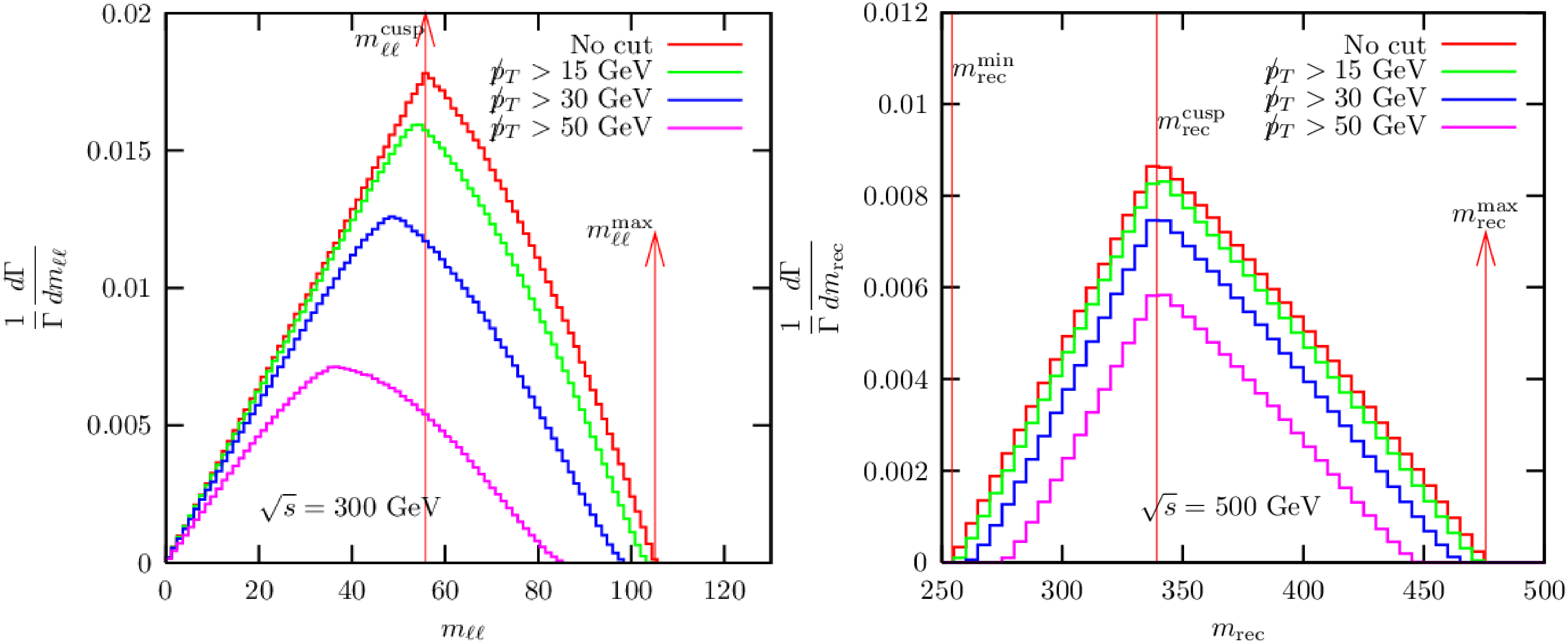
- Characteristic features of R_1, R_2 *and* R_3



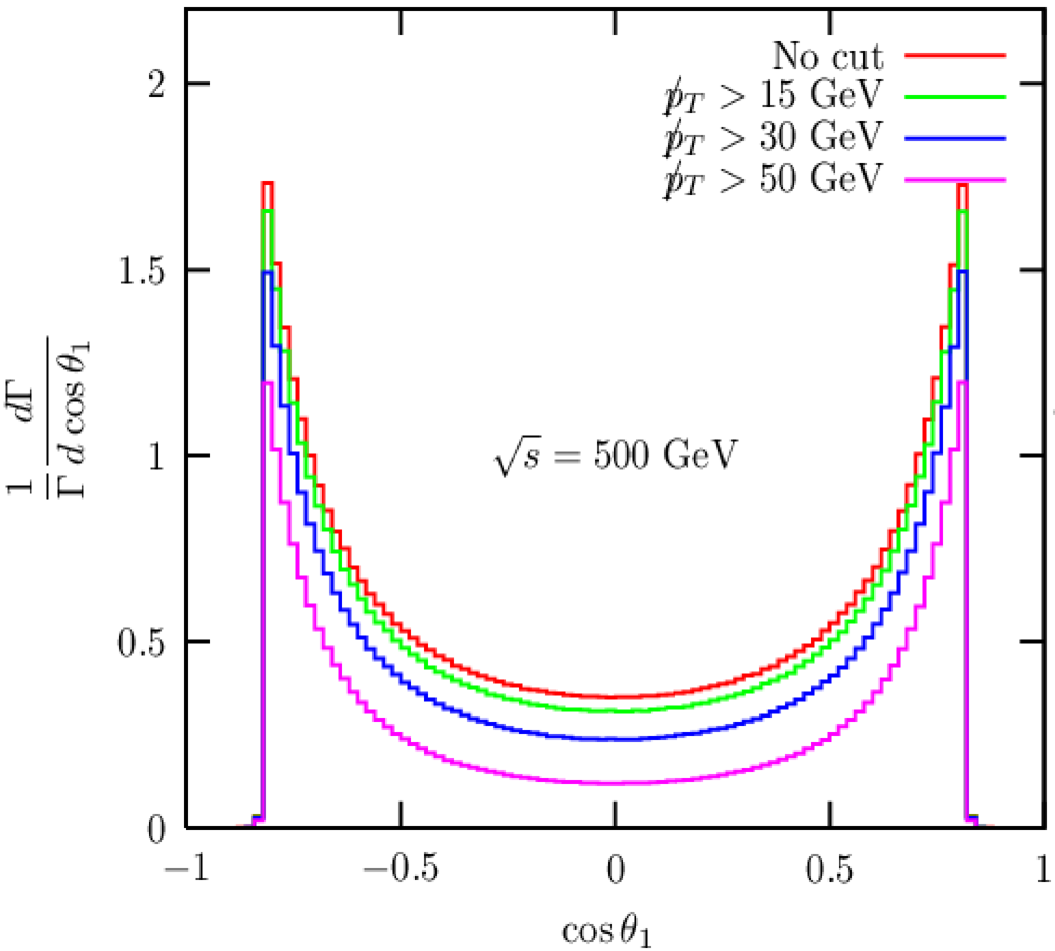
Effects of Cuts on Cusps

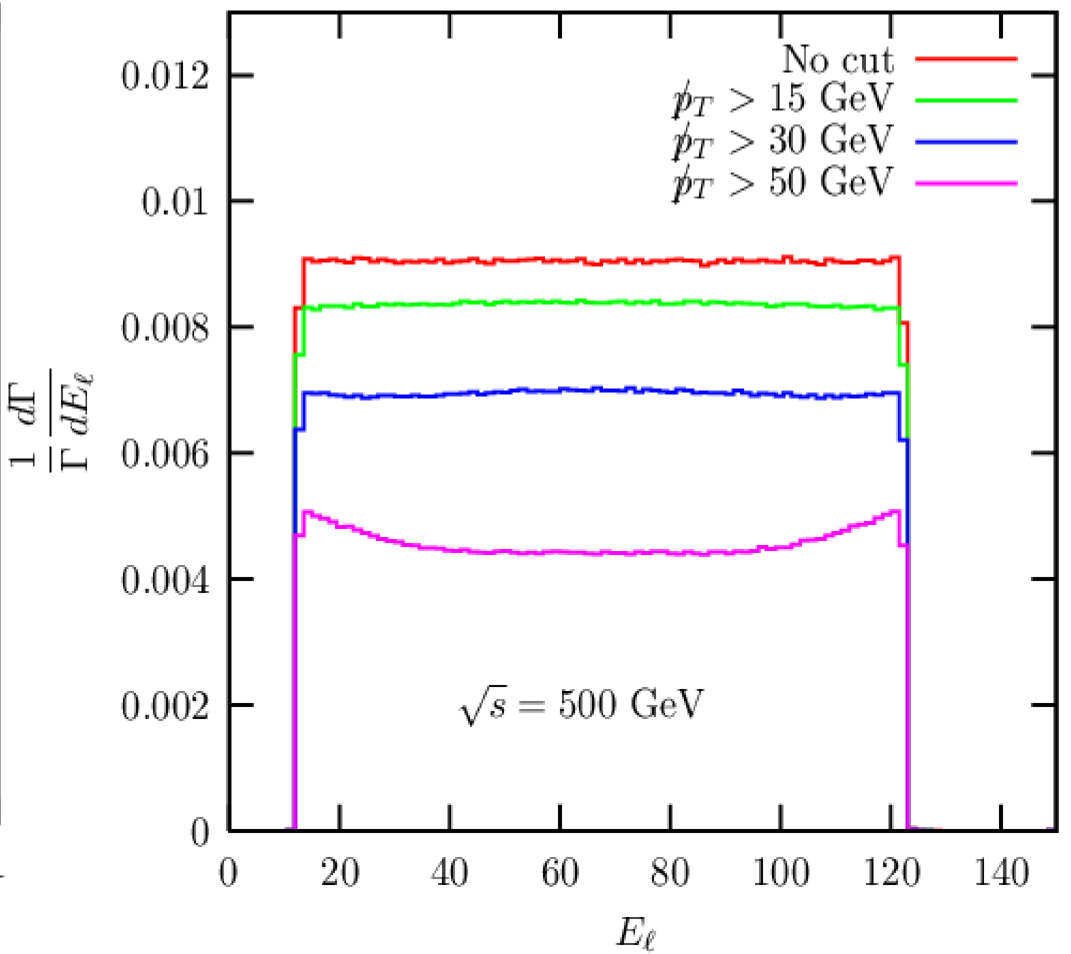
- Cuts due to detector design (and also purposeful cuts)
  - Distorts distribution
- End points of cos Θ_1 and E_l distributions remain intact
- M_{ll} and M_{rec} are distorted, giving wrong values for masses

Effects cont.



Effects cont.





SM and MSSM Background

- Our signal

$$e^+e^- \rightarrow \mu^+\mu^- + \text{ missing energy}$$

- SM background

$$e^+e^- \;\rightarrow\; W^+ + W^- \;\rightarrow\; \mu^+\nu_\mu + \mu^-\bar{\nu}_\mu$$
$$e^+e^- \;\rightarrow\; Z + Z \;\rightarrow\; \mu^+\mu^- + \nu\bar{\nu}$$

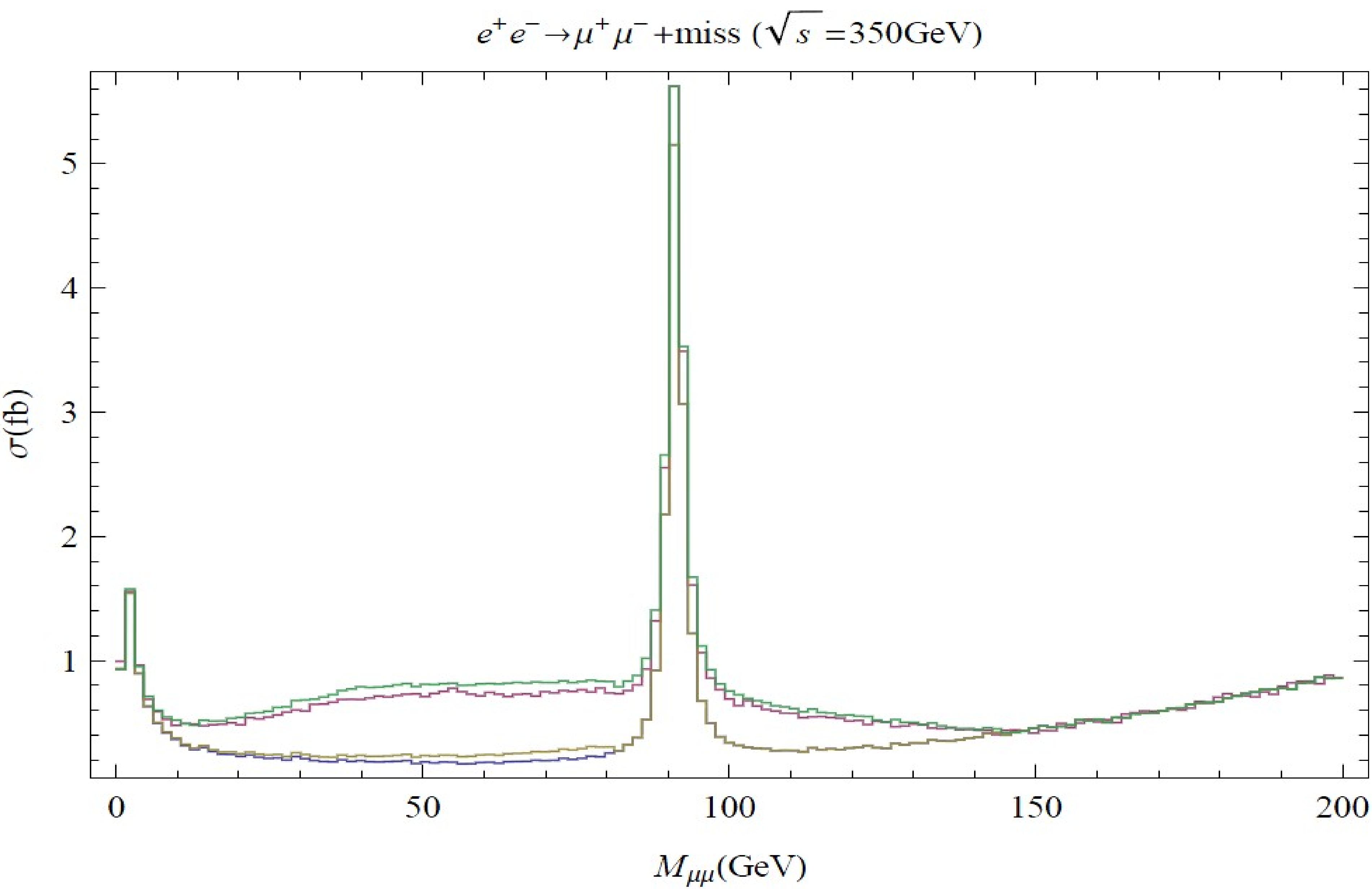
- Dominant SUSY background

$$\tilde{\chi}^0_{j\geq 2} \rightarrow \mu^+\mu^-\tilde{\chi}^0_1$$

Basic Cuts

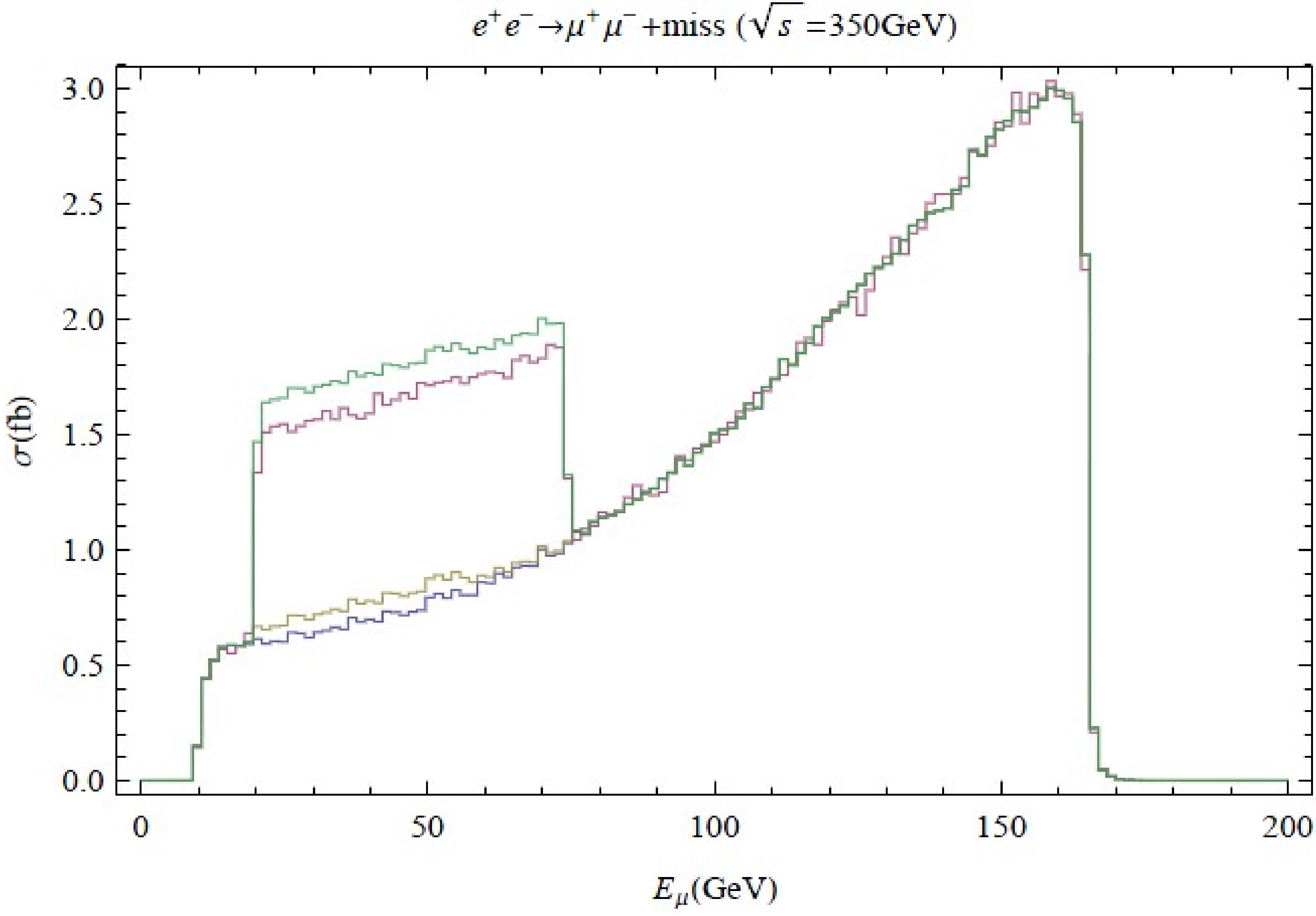
- For 350 GeV c.m. Energy
  - 350 GeV removes Left Smuon production
- $E_{\mu} \geq 10$ GeV, $|\cos \Theta_{\mu}| \leq 0.9962$, $M_{\mu\mu} \geq 1$ GeV, $M_{miss} \geq 1$ GeV, $p_T \geq 10$ GeV
- Observed muon lie at least 5^{o} from beam pipe

Results

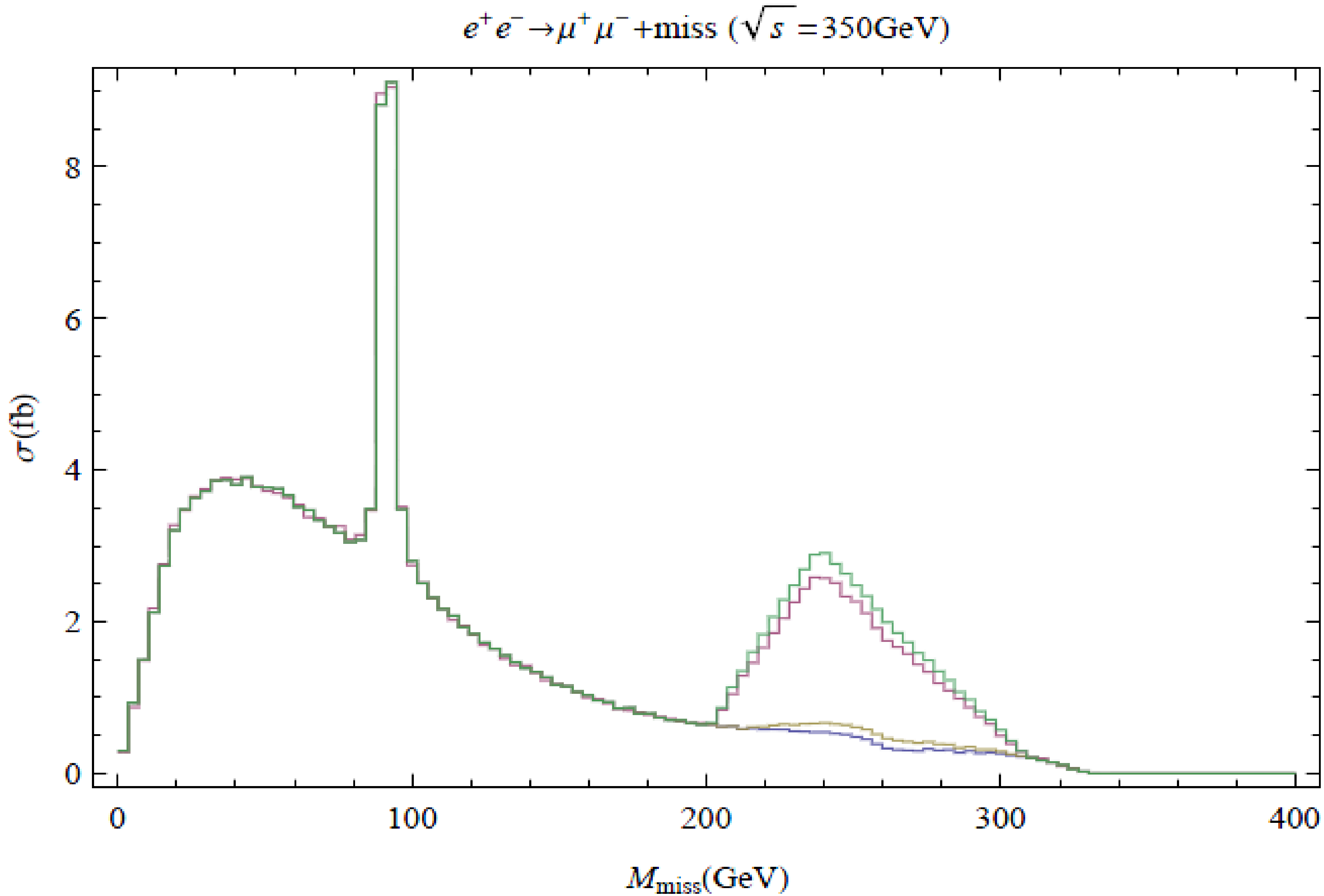


$e^+e^- \to \mu^+\mu^-$+miss ($\sqrt{s}$ =350GeV)
σ(fb)
$M_{\mu\mu}$(GeV)
0
50
100
150
200
1
2
3
4
5

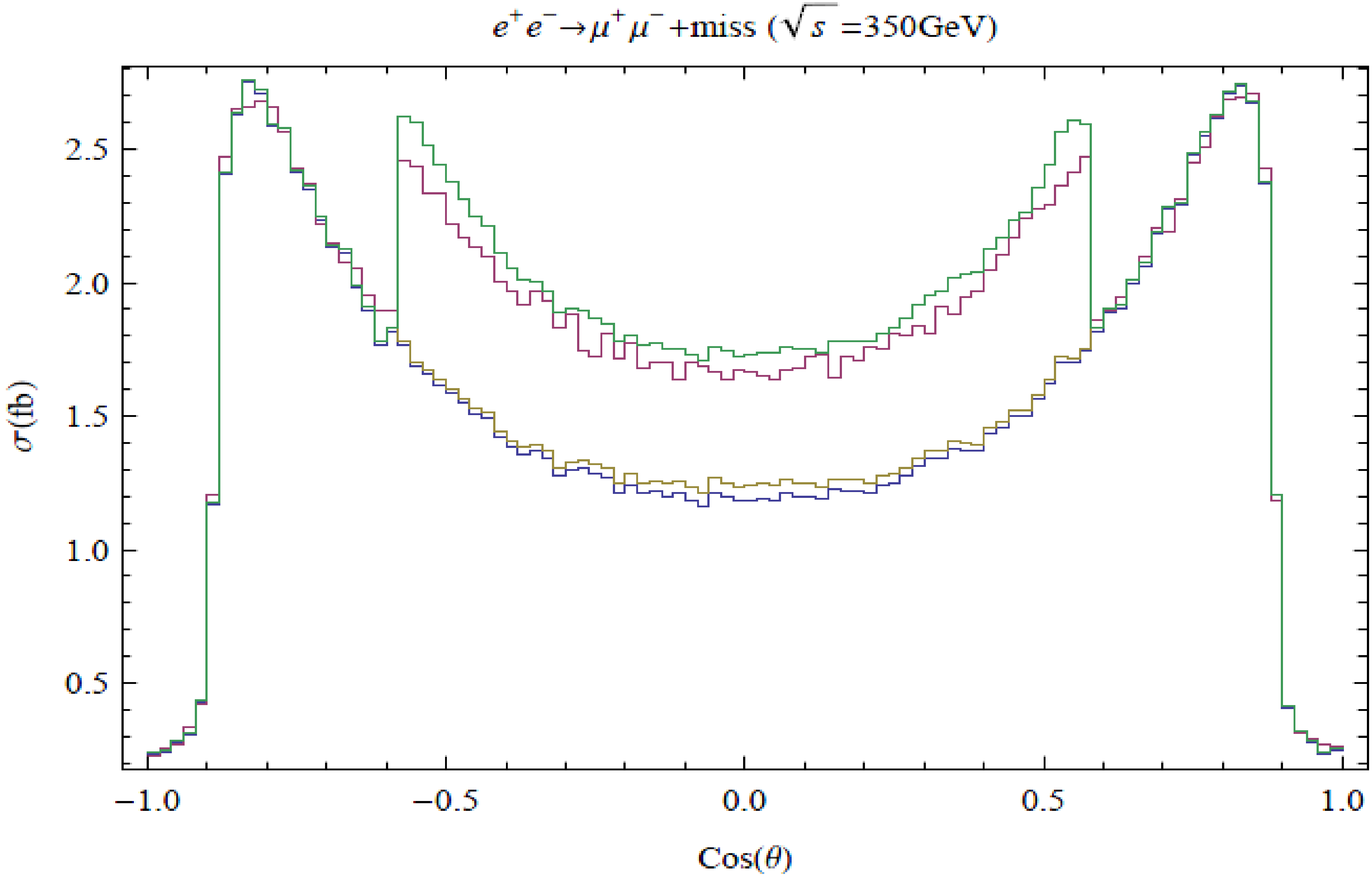
Results cont.



Results cont.



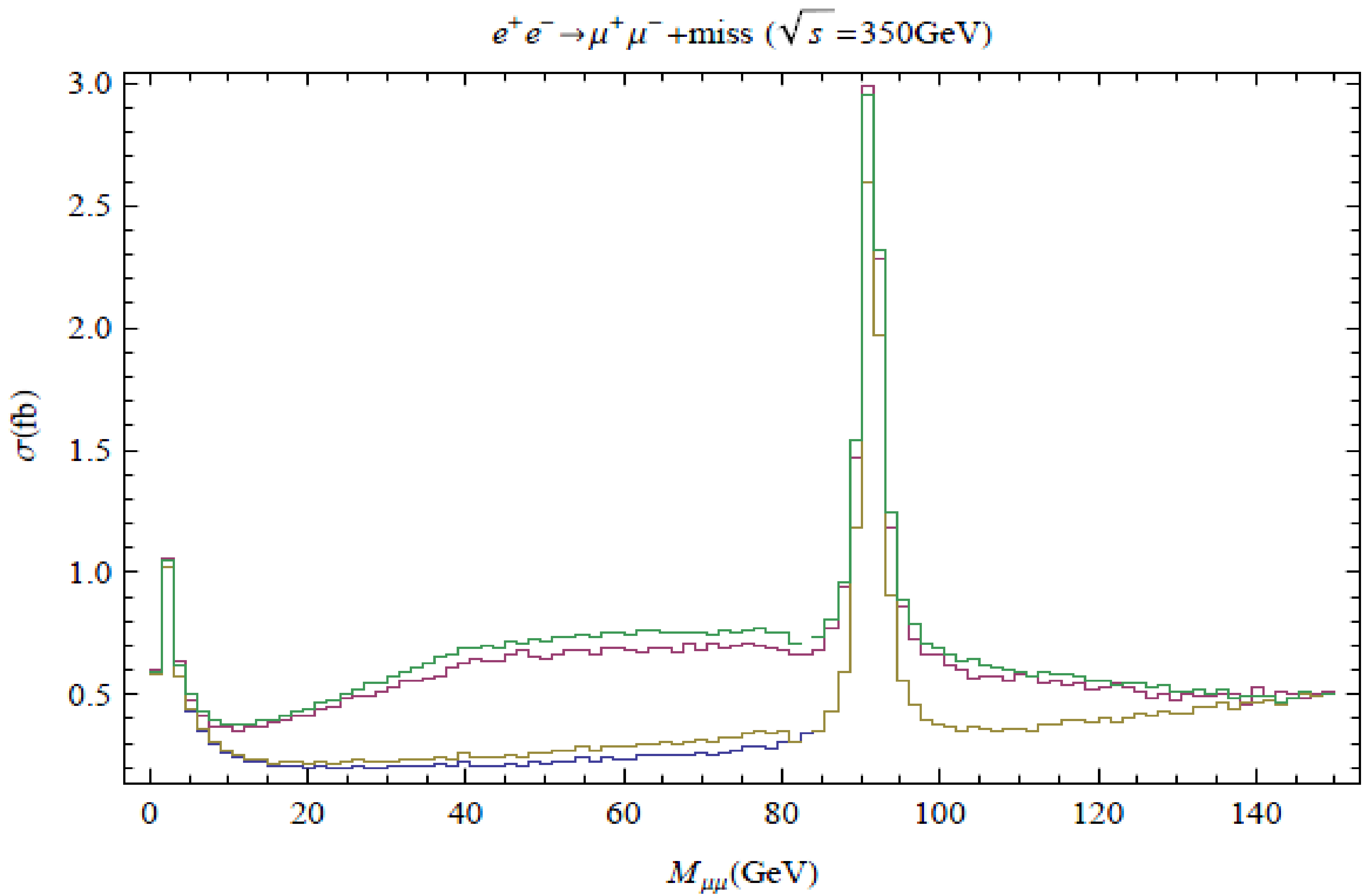
Results cont.



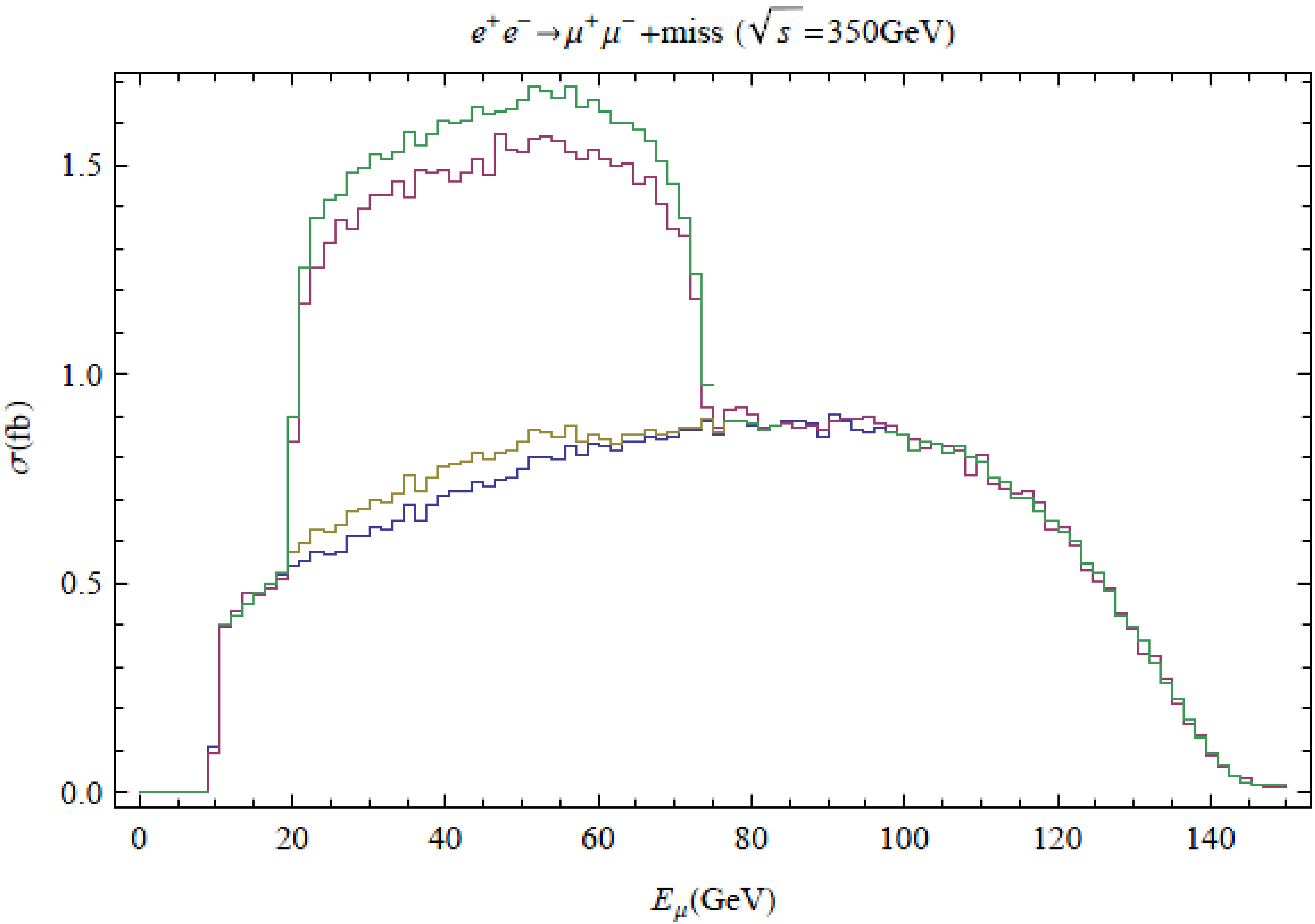
Optimal Cuts + Other Effects

- Added polarizations
  - P_{e-} = +80% and P_{e+} = -60%
  - $M_{miss} \geq 120$ GeV
  - ISR and Beamstrahlung
  - Detector smearing

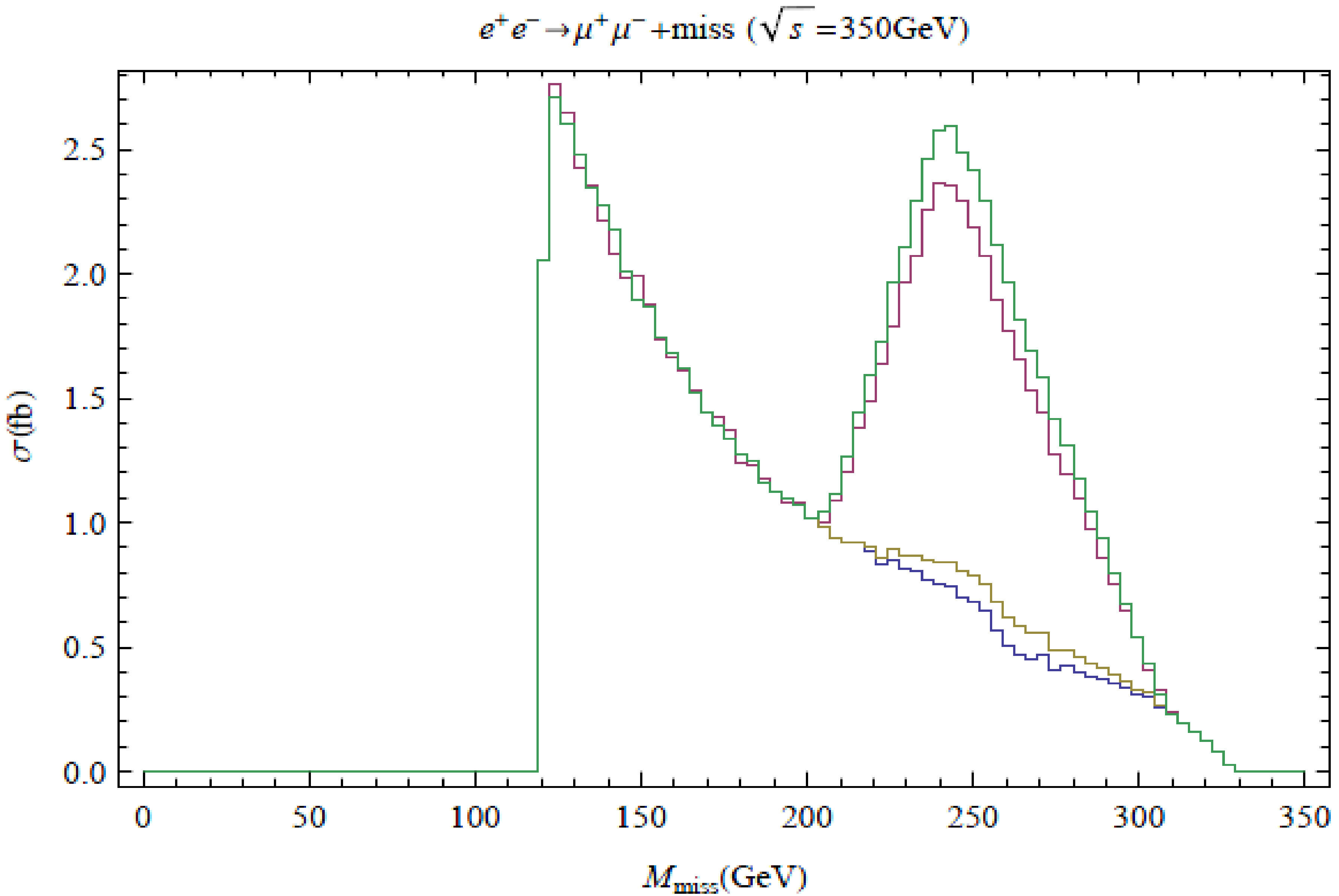
Optimal Cuts cont.



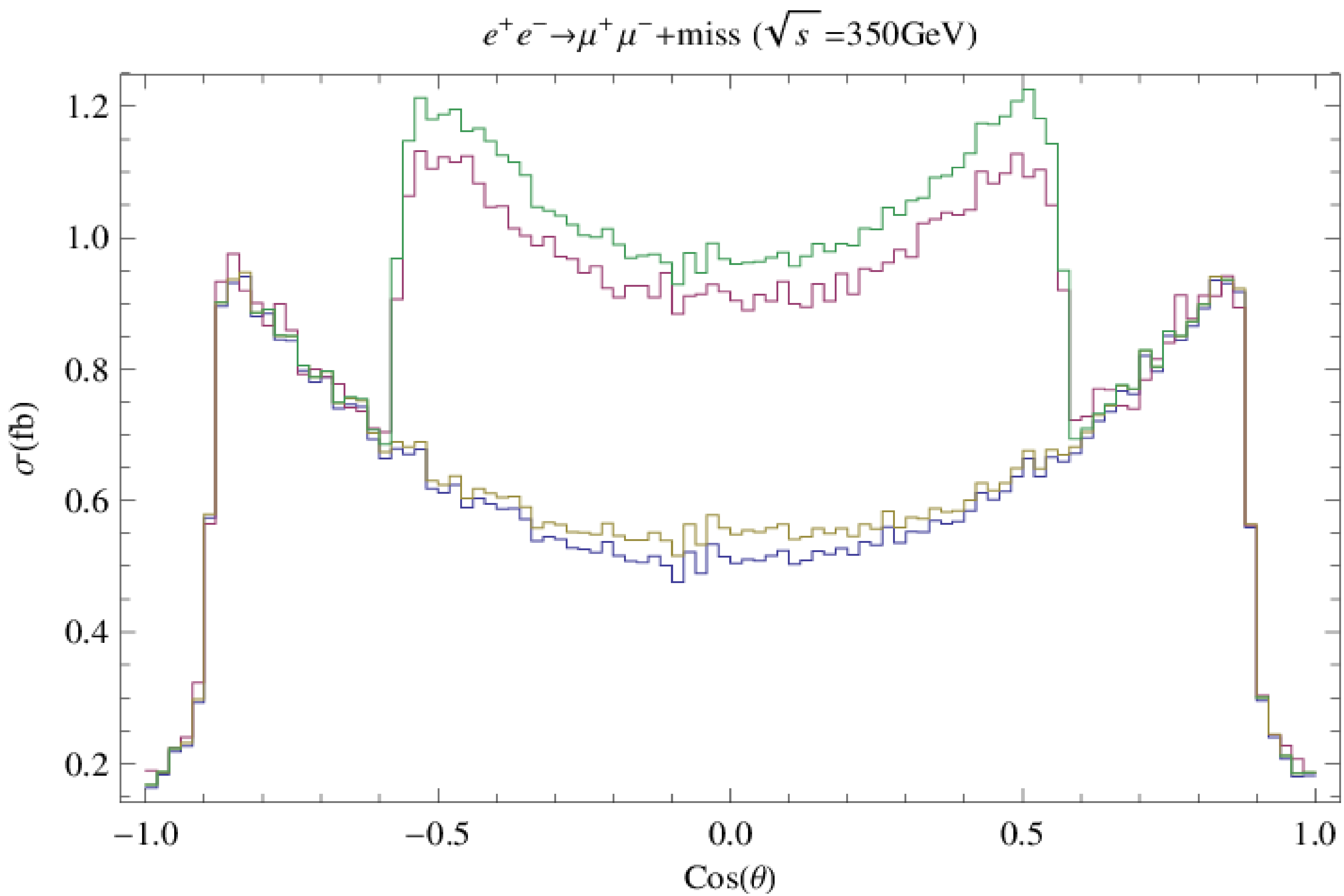
Optimal Cuts cont.



Optimal Cuts cont.

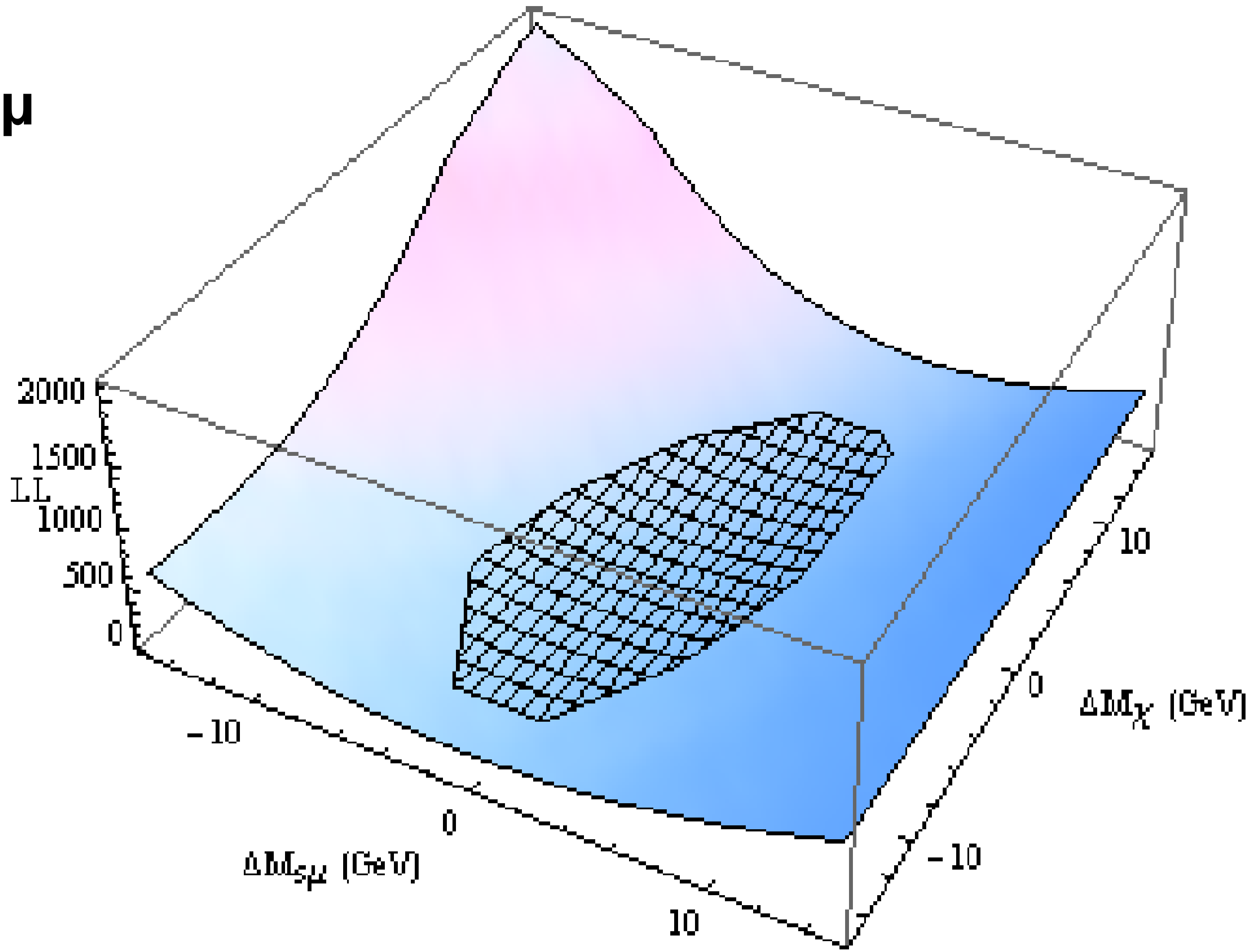


Optimal Cuts cont.



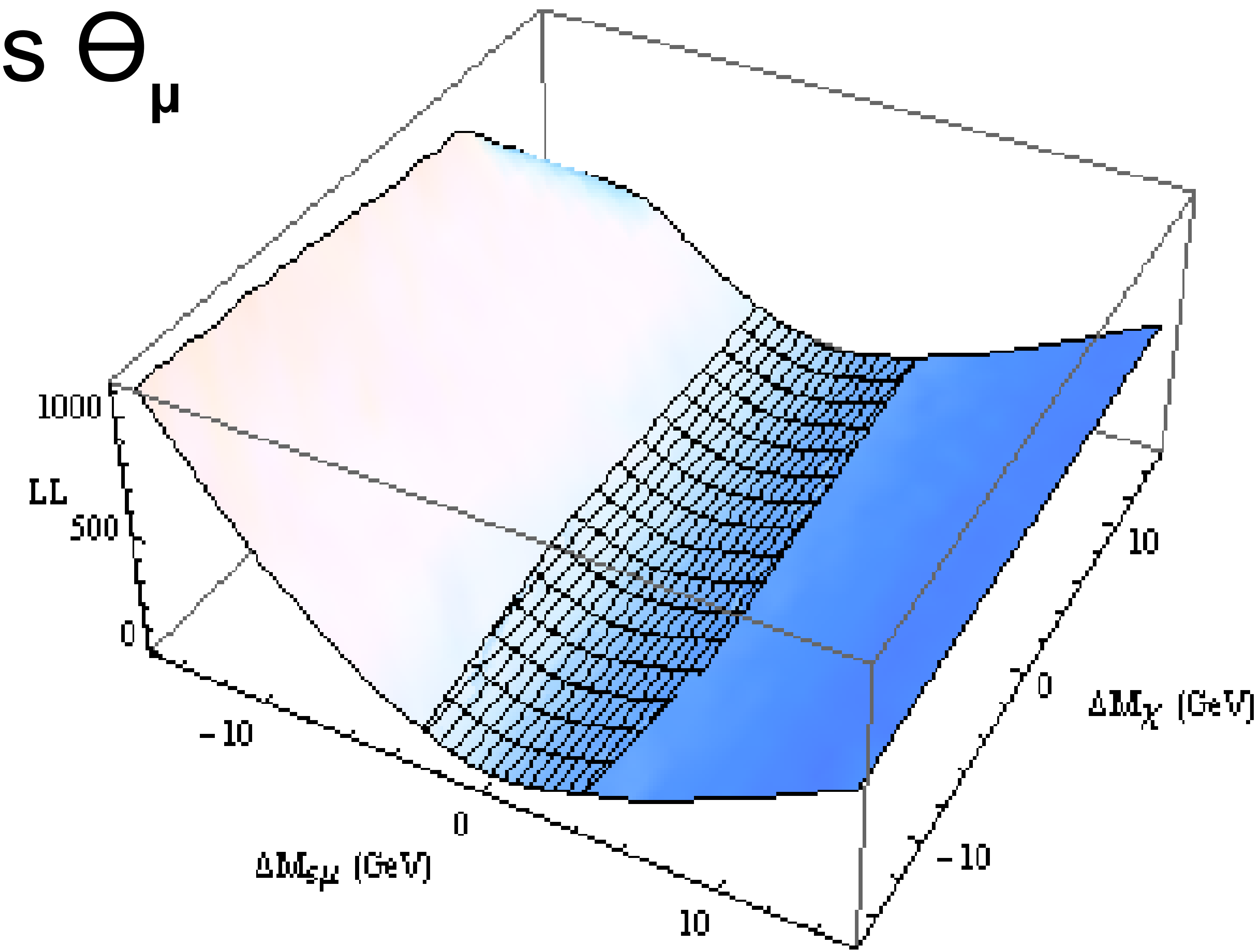
Log Likelihood Analysis

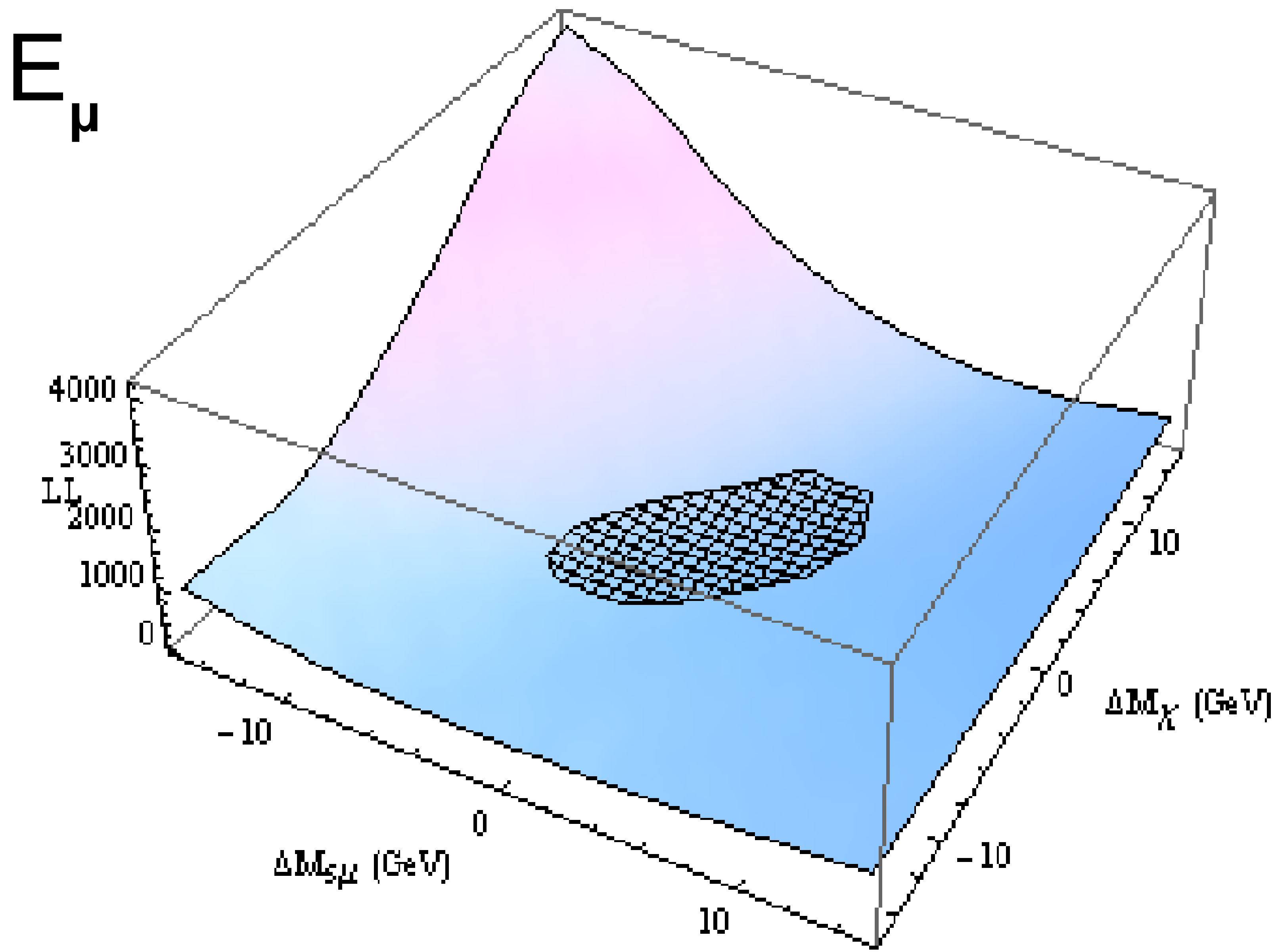
$M_{\mu\mu}$



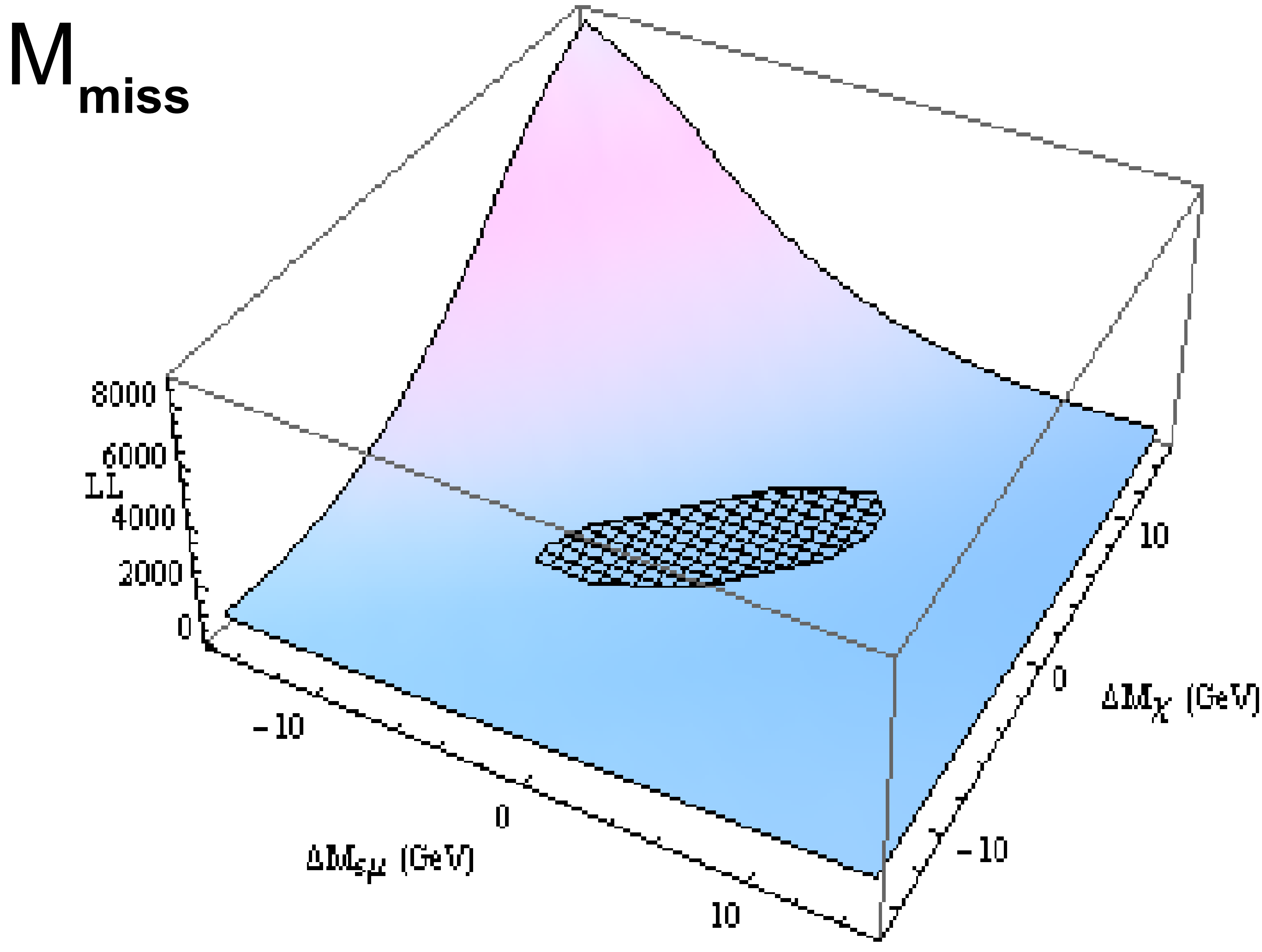
$$|\cos\Theta|_{\max} = \tanh\eta_B = \sqrt{1 - \frac{4m_B^2}{m_D^2}}$$

cos Θ$_\mu$





E$_\mu$
4000
3000
LL
2000
1000
0
−10
0
10
ΔM$_{s\mu}$ (GeV)
10
0
−10
ΔM$_\chi$ (GeV)



M_miss
8000
6000
LL
4000
2000
0
−10
0
ΔM_{eμ} (GeV)
10
10
0
ΔM_χ (GeV)
−10

Conclusion

- Odd parity “Darkened” Matter can be produced in pairs in linear lepton colliders
- Clean production environment
- Cusps easier to identify than end points
- Log likelihood analysis shows that the ambiguity in dark matter masses is quite small
- Spin of particles can be determined as well (to be discussed at Pheno 2013 ?)