Polarization and Spin Effects in Neutralino Production and Decay

MSSM and Extended Models

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Sitges

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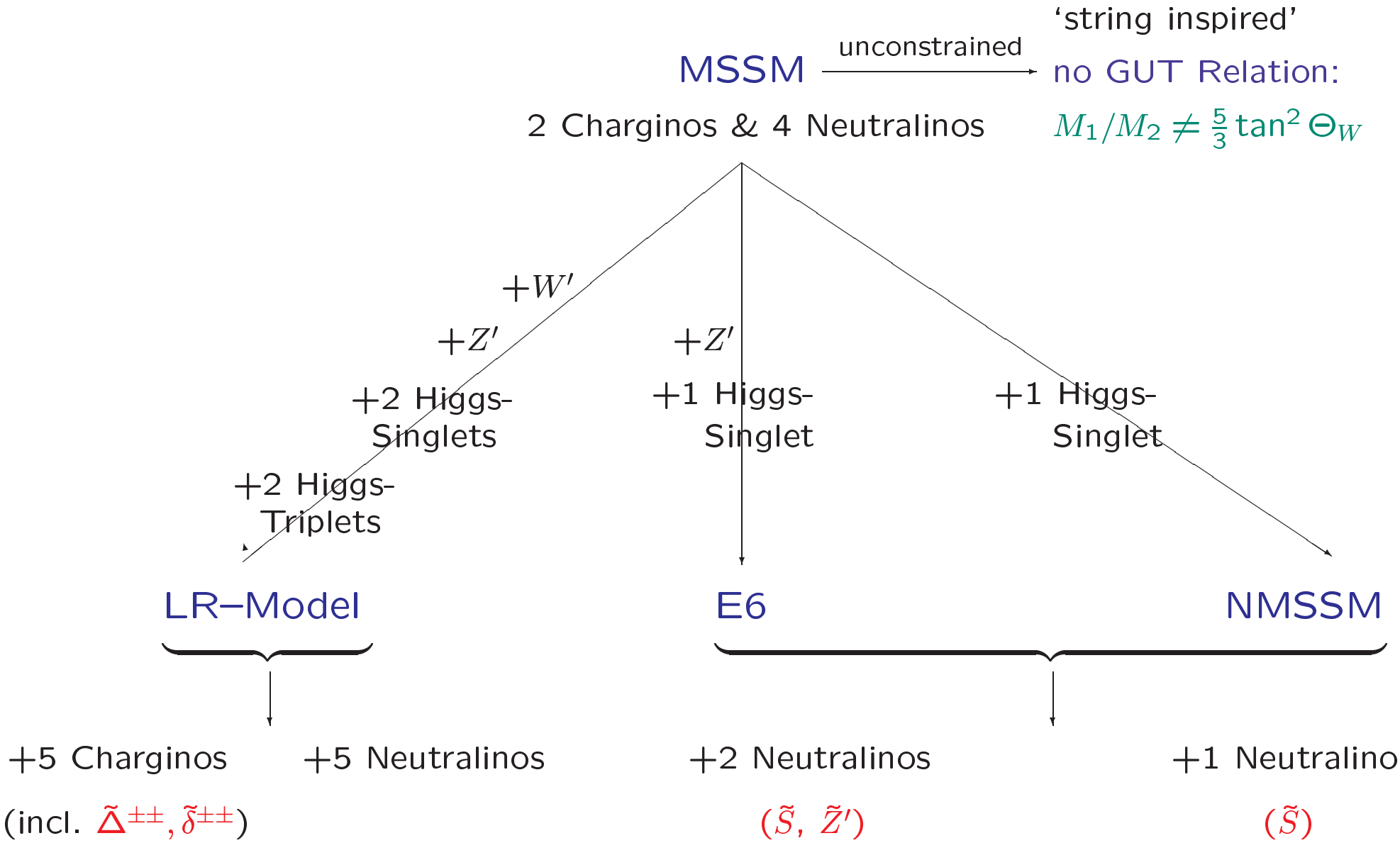


References

- MSSM without M_1/M_2 GUT Relation:
  Chen, Drees, Gunion ('95, '96); Feng et al. ('95, '97); Tsukamoto et al. ('95); Snowmass ('96); Kneur et al. ('98); Choi et al. ('98); M.-P. et al.('99);. . .

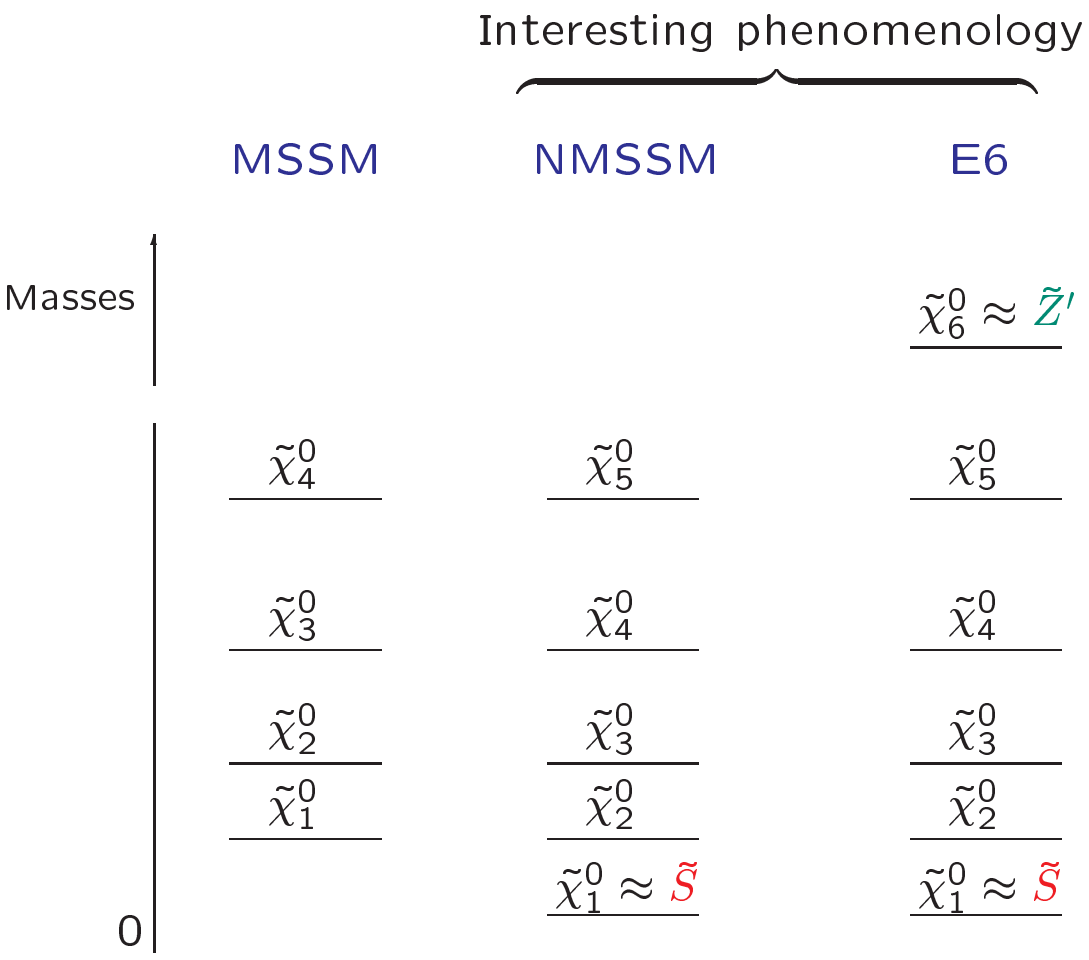
- NMSSM:
  Ellis et al. ('89); Kim, Oh, Stephan ('92, '93); Elliott, King, White ('93, '94); Franke ('94, '95, '96, '97); Ellwanger, Rausch de Trauenburg, Savoy ('93, '95, '97); Ellwanger, Hugonie ('97, '98, '99);. . .

- E6:
  Model: *Hewett, Rizzo ('89); Boyce, Domcheski, König ('97);. . .*
  Neutralinos: *Gunion, Roszoski, Haber ('88); Cvetic et al. ('97); Gherghetta, Kaeding, Kane ('98); Nandi ('97); Keith, Ma ('96, '97); de Carlos, Espinosa ('97); Hesselbach, Franke, Fraas ('97); Suematsu ('97, '98); Hesselbach ('99);. . .*

  Z'-Physics: *Belanger, Godfrey ('86); Choudhury, Cuypers, Leike ('94); Godfrey ('95, '96); S. Riemann ('96); Hewett ('97); Leike, S. Riemann ('97); Rizzo ('97); Cho, Hagiwara, Matsumoto ('98);. . .*

- SUSY–LR:
  Huitu, Maalampi, Raidal ('94); Aulakh, Melfo, Senjanovic ('96); Huitu et al. ('97); Raidal ('98); Raidal, Zerwas ('98); Huitu, Pandita, Puolamäki ('99);. . .

1.1 Neutralino Mass Spectra



- Lightest neutralino (LSP) $\tilde{\chi}_1^0 \approx$ Singlino $\tilde{S}$

NMSSM: Franke '94
E6: de Carlos '97
Hesselbach '97

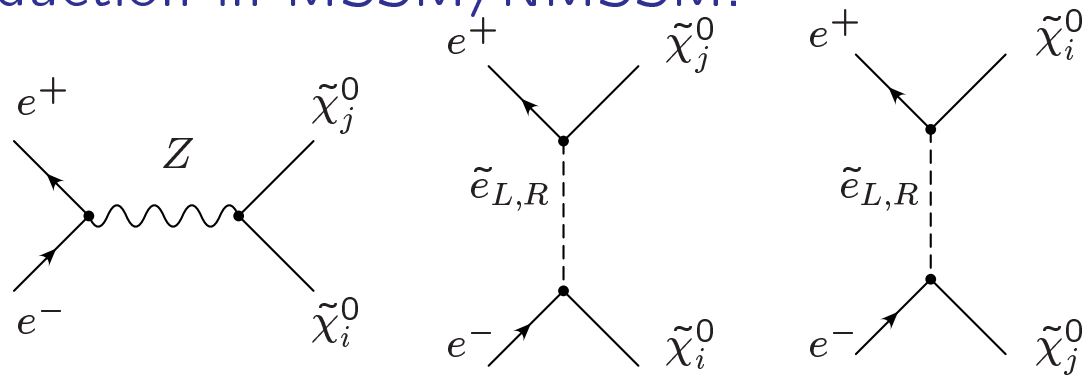
- $\tilde{S}$: direct search is difficult
  $\rightarrow$ produced in $\tilde{\chi}_2^0$–decay

1.2 Cross Sections

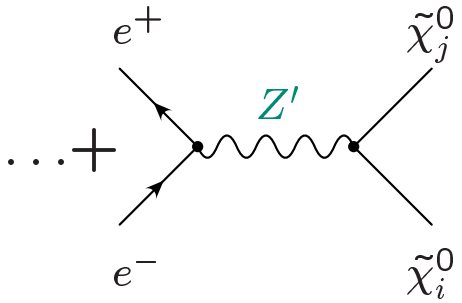
Feynman Diagrams

$$e^+e^- \to \tilde{\chi}_i^0\tilde{\chi}_j^0,\ \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 e^+e^-$$

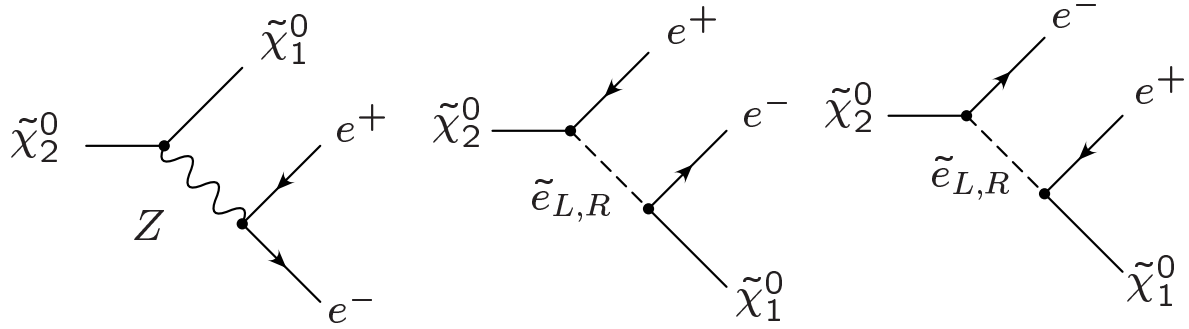
Production in MSSM/NMSSM:



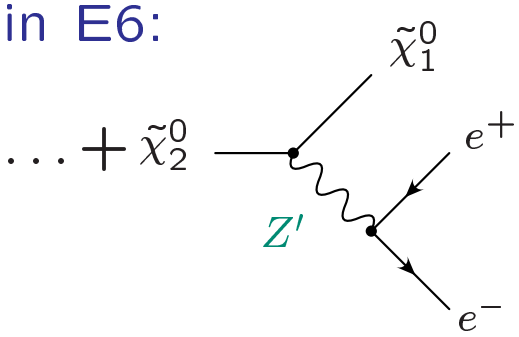
in E6:



Decay in MSSM/NMSSM:



in E6:



Numerical Results

For this study:

- Gaugino-like light Neutralinos
- Neutralino masses: $m_{\tilde{\chi}_1^0} = 72$ GeV, $m_{\tilde{\chi}_2^0} = 130$ GeV
  $\rightarrow$ same kinematics in all models
- Slepton masses: $m_{\tilde{e}_L} = 197$ GeV, $m_{\tilde{e}_R} = 160$ GeV
- NMSSM, E6: $\tilde{\chi}_1^0 \approx \tilde{S}$ (=LSP)
- Polarization of **both** beams:
  $P_{e^-} = \pm 85\%$, $P_{e^+} = \pm 60\%$
  Notation: $(\mathrm{sgn}(P_{e^-})\mathrm{sgn}(P_{e^+}))$, left–handed: $-$, right-handed: $+$
- High Luminosity $\mathcal{L}^h = 500$ fb^{-1}
  Low Luminosity $\mathcal{L}^l = 50$ fb^{-1}

Comparison of MSSM, NMSSM, E6:

- Production Cross Section $\sigma(\sqrt{s})$
- Decay Angular Distribution and
  Forward–Backward–Asymmetry A_{FB}
  in the lab–system

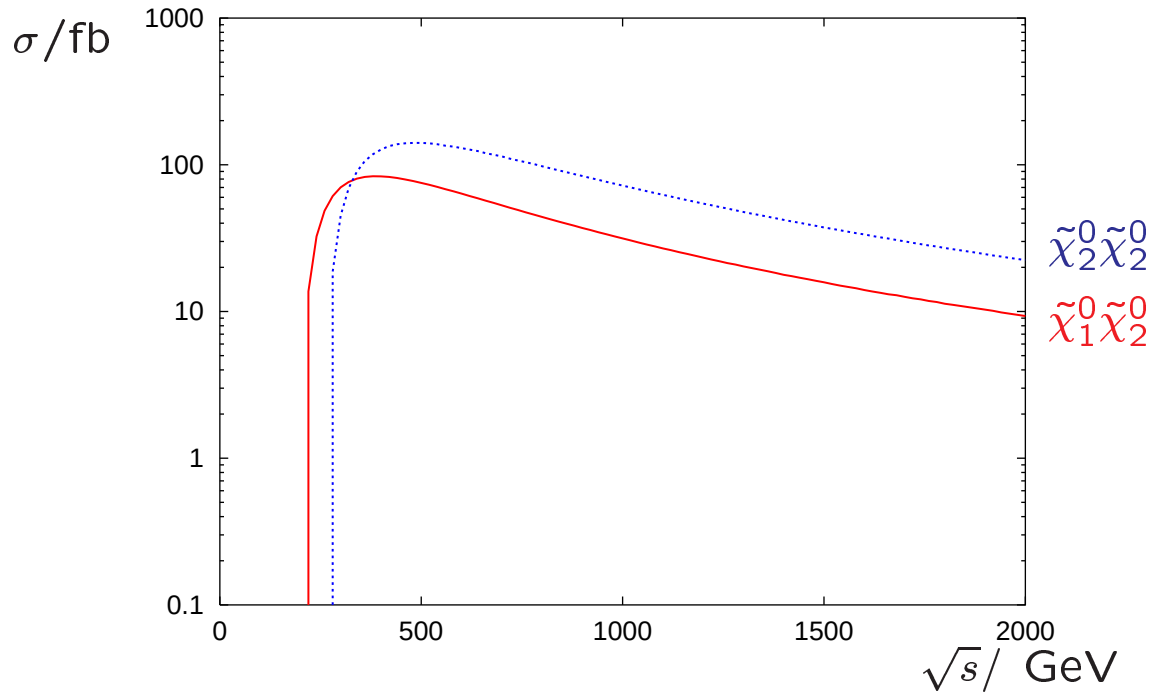
1.2.1 Neutralino Production in MSSM

gaugino–like:
([mass]=GeV)

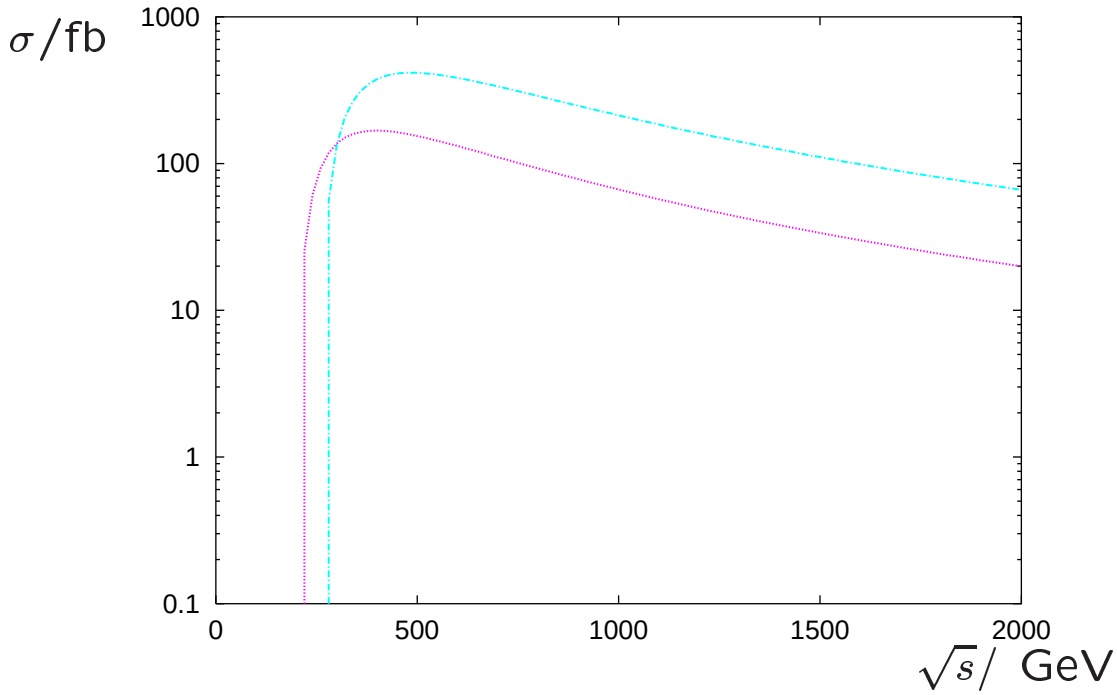
M_2	μ	$\tan\beta$
152	316	3

(Ambrosanio, Blair, Zerwas '98)

$\sigma = \sigma(e^+e^- \to \tilde{\chi}_i^0\tilde{\chi}_j^0)$ for (00)



and $(-+)$:



$(-+)$

$(-+)$

- highest σ for $(-+)$
- $\sigma(-+)/\sigma(00) \sim 2-3$

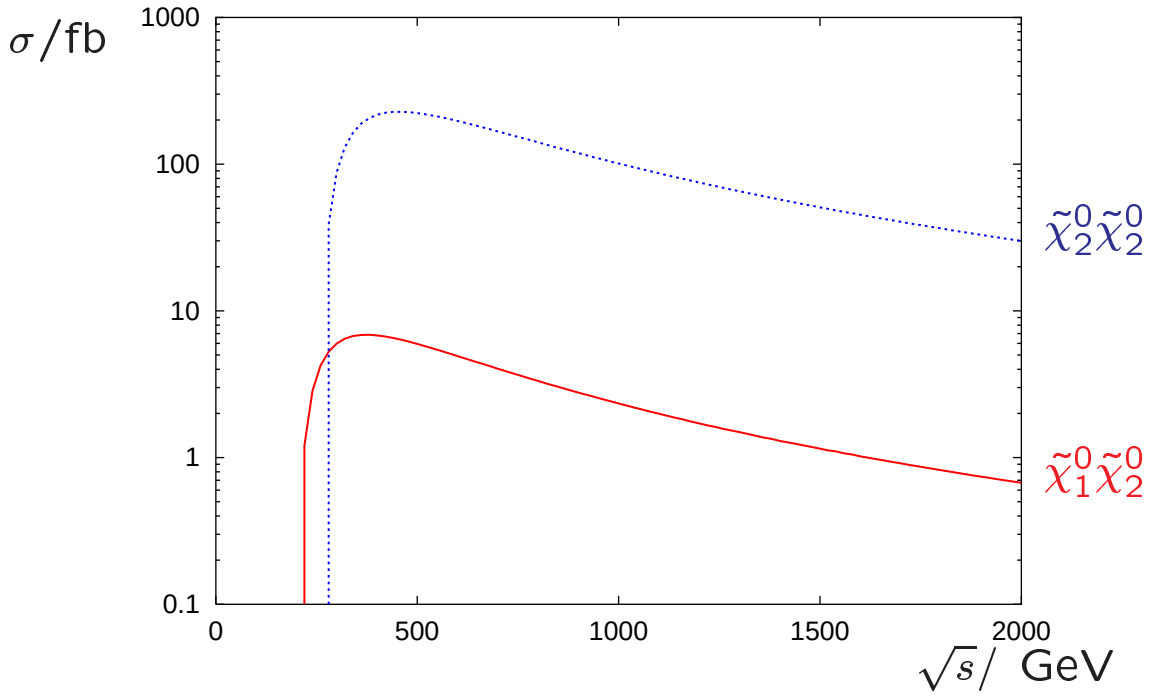
1.2.2 Neutralino Production in NMSSM

NMSSM parameters ($\lambda v_3 \widehat{=} \mu$):

M_2	$\tan\beta$	λ	v_3	κ
262	3	0.9	1000	0.0295

([mass]=GeV)

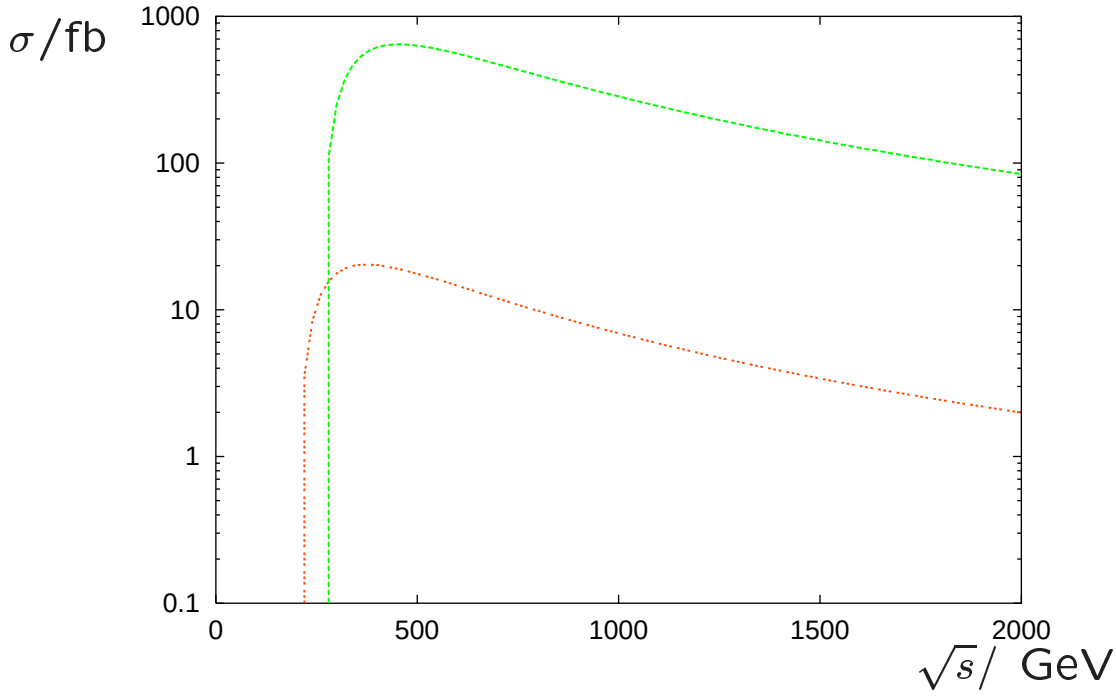
$\sigma = \sigma(e^+e^- \to \tilde{\chi}_i^0 \tilde{\chi}_j^0)$ for (00)



- $\tilde{\chi}_1^0 \approx \tilde{S}$ couples very weakly $\to$ small σ
- if , $_{\tilde{\chi}_2^0} < 10^{-12}$ GeV $\Rightarrow$ displaced vertices
  if , $_{\tilde{\chi}_2^0} < 10^{-16}$ GeV $\Rightarrow$ escapes detection

Hugonie et al. '98

and $(+-)$:



$(+-)$

$(+-)$

- highest σ for $(+-)$ $\rightarrow$ contrary to MSSM!
- $\sigma(+-)/\sigma(00) \sim 3$

1.2.3 Neutralino Production in E6

E6 parameters ($\lambda v_3 = \mu$):

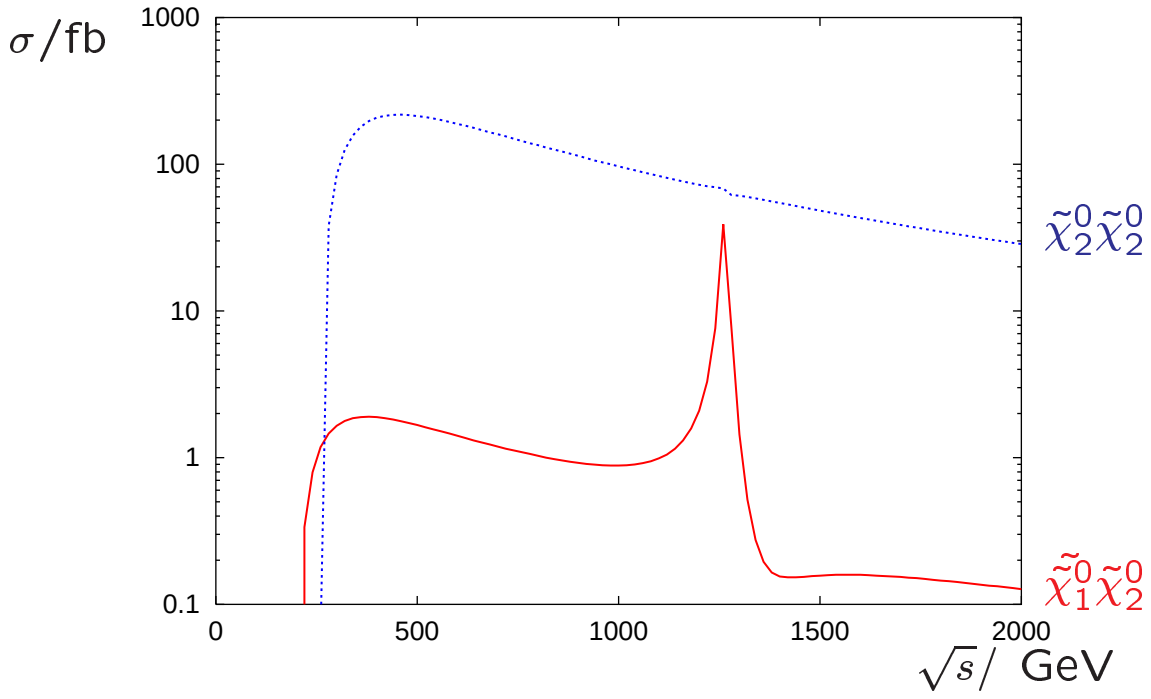
M_2	$\tan\beta$	M'	λ	v_3
270	3	22300	0.15	3000

([mass]=GeV)

$m_{Z'}$=1264 GeV

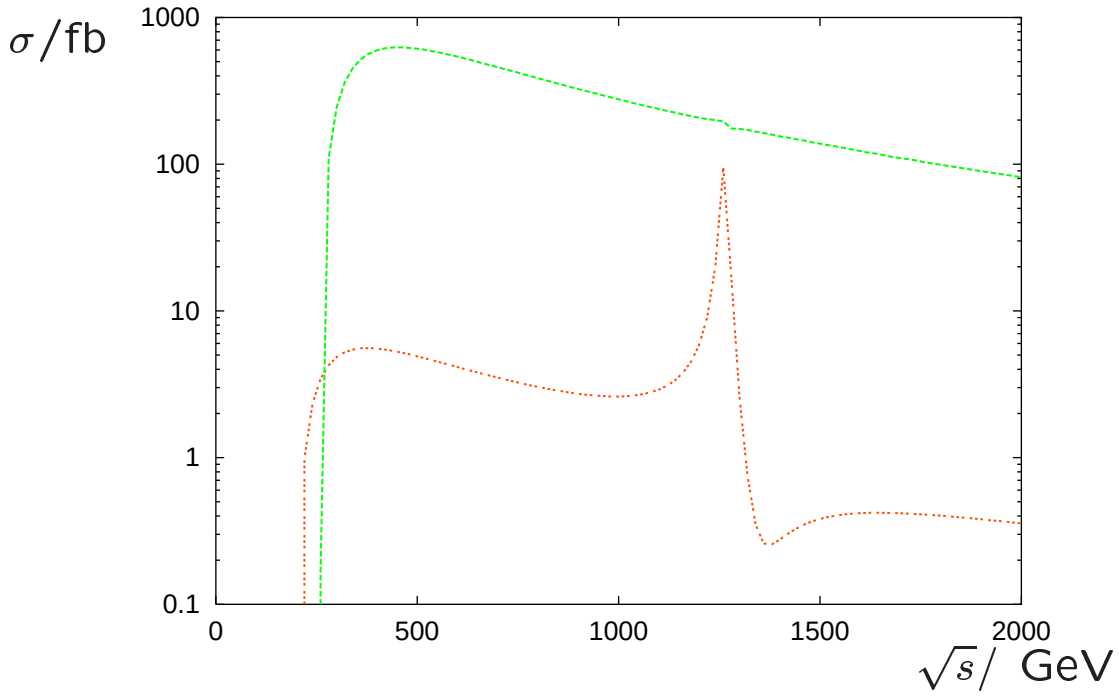
$\Gamma_{Z'} = 0.014 m_{Z'}$ Gherghetta et al.'98

$\sigma = \sigma(e^+e^- \to \tilde{\chi}_i^0 \tilde{\chi}_j^0)$ for (00)



- $\tilde{\chi}_1^0 \approx \tilde{S}$ couples to $Z' \to$ peak at $\approx \sqrt{s} = 1264$ GeV
- $\tilde{\chi}_2^0$ (gaugino–like): very small coupling to Z'
  $\to$ almost no Z' peak
- displaced vertices also possible Hesselbach '99

and $(+-)$:



$(+-)$

$(+-)$

- highest σ for $(+-)$: contrary to MSSM!
- $\sigma(+-)/\sigma(00) \sim 3$

1.3 Decay Angular Distribution of e^- in the Laboratory System

Neutralino production and leptonic decay:

$$e^+ + e^- \to \tilde{\chi}_i^0 + \tilde{\chi}_j^0$$
$$\Big| \quad \tilde{\chi}_1^0 + e^+ + e^-$$

$\Rightarrow$ Including complete spin correlations between production and decay!

M.-P. et al. '97, '99

Amplitude squared of production $\times$ decay:

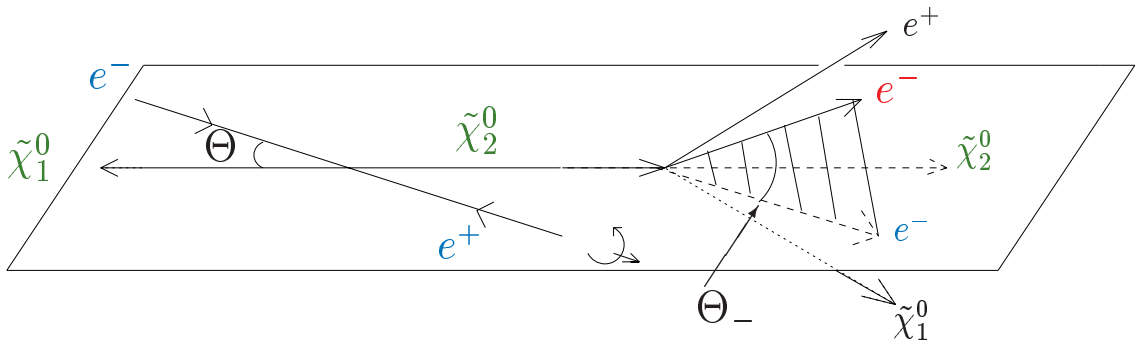
$$|T|^2 \sim \mathcal{P}(p_j, \overbrace{s_j, p_i, \underbrace{s_i}}^{\text{spin correlations}}) \otimes \mathcal{D}(p_i, s_i \underbrace{)}_{\text{spin correlations}} \otimes \mathcal{D}(p_j, s_j)$$

$$\sim \left(\begin{array}{ll} P_{ij} \cdot D_i \cdot D_j & \to \text{no correlations} \\ +S_j^P(s_j) \otimes S_j^D(s_j) \cdot D_i & \\ +S_i^P(s_i) \otimes S_i^D(s_i) \cdot D_j & \\ +S_{ij}^P(s_i, s_j) \otimes S_i^D(s_i) \otimes S_j^D(s_j) & \end{array} \right\} = 0 \text{ if } \tilde{\chi}_i^0 = \tilde{\chi}_1^0$$

$\mathcal{P}(p_i, s_i, p_j, s_j) = P_{ij} + S_i^P(s_i) + S_j^P(s_j) + S_{ij}^P(s_i, s_j)$
$\mathcal{D}(p_i, s_i) = D_i + S_i^D(s_i)$
$\mathcal{D}(p_j, s_j) = D_j + S_j^D(s_j)$ ($s_i(s_j)$: spin vector of $\tilde{\chi}_i^0(\tilde{\chi}_j^0)$)

Decay Angular Distribution of e^- in the Laboratory System

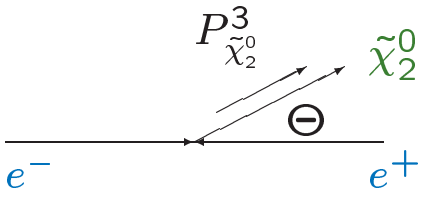
$$e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0,\ \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 e^+e^-$$

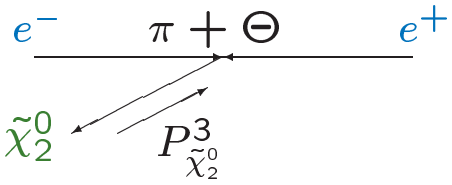


- Production:
  No forward-backward asymmetry!
  (Majorana fermions!)

- Production $\times$ Decay:

  Decay angular distribution of e^- depends on polarization of $\tilde{\chi}_2^0$, e.g. $P^3_{\tilde{\chi}_2^0} \sim \cos\Theta$





$P^3_{\tilde{\chi}_2^0} > 0$ $\qquad$ $P^3_{\tilde{\chi}_2^0} < 0$

$\Rightarrow$ Spin correlations between production and decay

$\Rightarrow$ Large forward-backward-asymmetry of decay e^- possible: $A_{FB} = \frac{\sigma(\cos\Theta_- > 0) - \sigma(\cos\Theta_- < 0)}{\sigma(\cos\Theta_- > 0) + \sigma(\cos\Theta_- < 0)}$

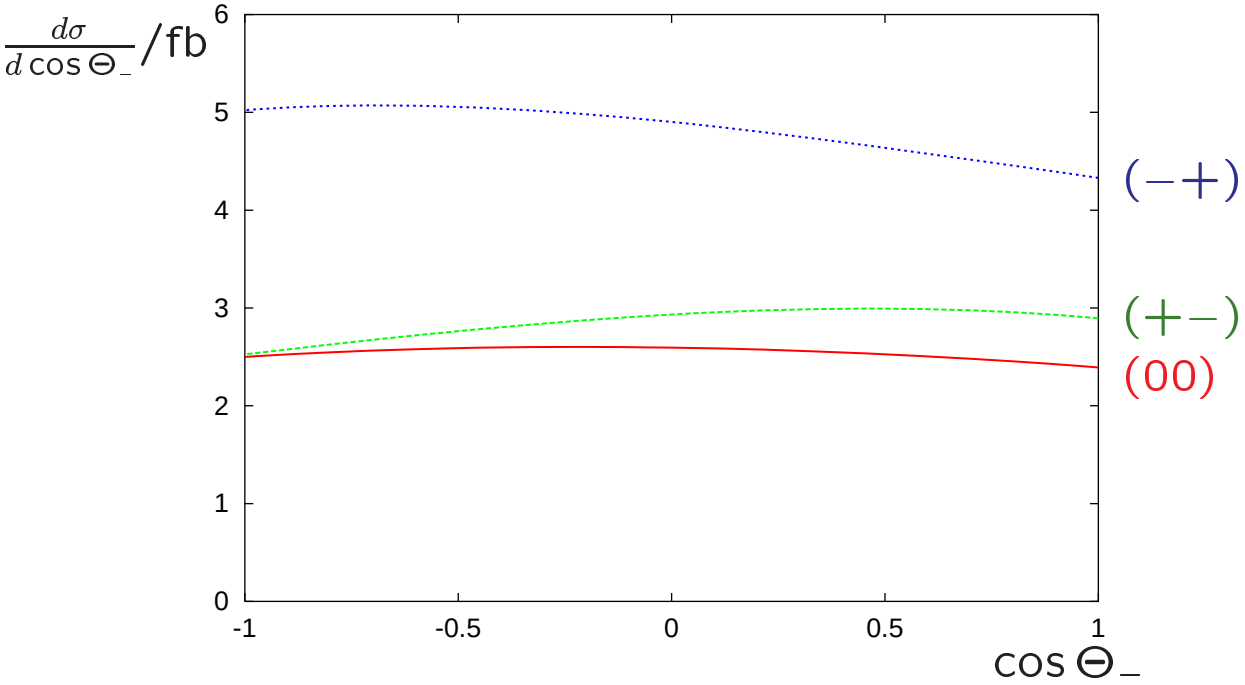
- Cross Section: $\sigma_e = \sigma \times BR = \int \frac{d\sigma}{d\cos\Theta_-} d\cos\Theta_-$

1.3.1 Decay Angular Distribution in MSSM

gaugino-like:
([mass]=GeV)

M_2	μ	$\tan\beta$
152	316	3

$$\sqrt{s} = m_{\tilde{\chi}_1^0} + m_{\tilde{\chi}_2^0} + 50 \text{ GeV}$$



	$A_{FB}(\mathcal{L}^h)$ /%	$A_{FB}(\mathcal{L}^l)$ /%	$\sigma_e(\mathcal{L}^h)$ /fb	$\sigma_e(\mathcal{L}^l)$ /fb
(00)	-1.2 ± 1.9	-1.2 ± 6.3	5.1 ± 0.1	5.1 ± 0.3
(−+)	-4.1 ± 1.4	-4.1 ± 4.5	9.7 ± 0.1	9.7 ± 0.4
(+−)	$+3.8 \pm 1.8$	$+3.8 \pm 5.9$	5.7 ± 0.1	5.7 ± 0.3

- Strong influence of spin correlations
  $\rightarrow$ result without spin correlations: $A_{FB} = 0.1\%$!
- Beam polarization *changes* angular distribution!
- other gaugino scenarios: larger A_{FB} up to 15%

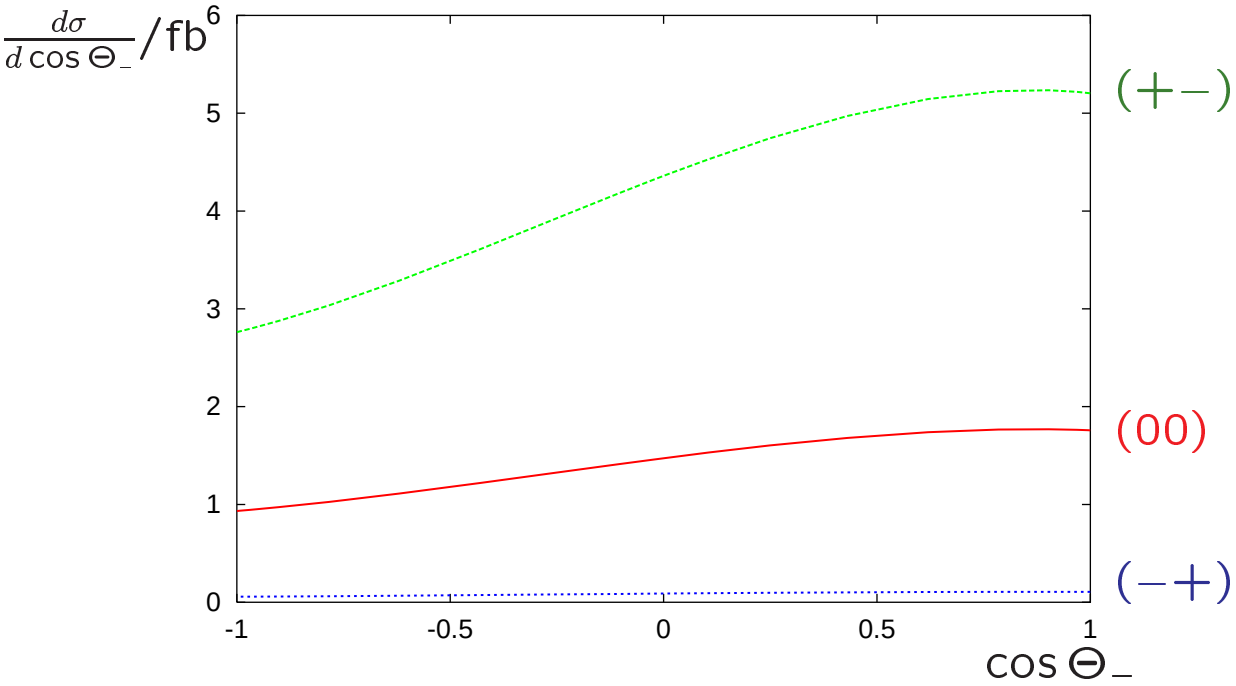
M.-P. '97,'98

1.3.2 Decay Angular Distribution in NMSSM

M_2	$\tan\beta$	λ	v_3	κ
262	3	0.9	1000	0.0295

([mass]=GeV)

$$\sqrt{s} = m_{\tilde{\chi}_1^0} + m_{\tilde{\chi}_2^0} + 50 \text{ GeV}$$



	$A_{FB}(\mathcal{L}^h)$ /%	$A_{FB}(\mathcal{L}^l)$ /%	$\sigma_e(\mathcal{L}^h)$/fb	$\sigma_e(\mathcal{L}^l)$/fb
(00)	$+17.1 \pm 2.6$	$+17.1 \pm 8.2$	$2.9 \pm < 0.1$	2.9 ± 0.2
$(-+)$	$+16.9 \pm 10.7$	$+16.9 \pm 33.8$	$0.17 \pm < 0.1$	0.17 ± 0.1
$(+-)$	$+17.1 \pm 1.5$	$+17.1 \pm 4.8$	8.5 ± 0.1	8.5 ± 0.4

- Strong influence of spin correlations
  $\Rightarrow$ large A_{FB}
- Small $\sigma_e \Rightarrow \mathcal{L}^h$ essential

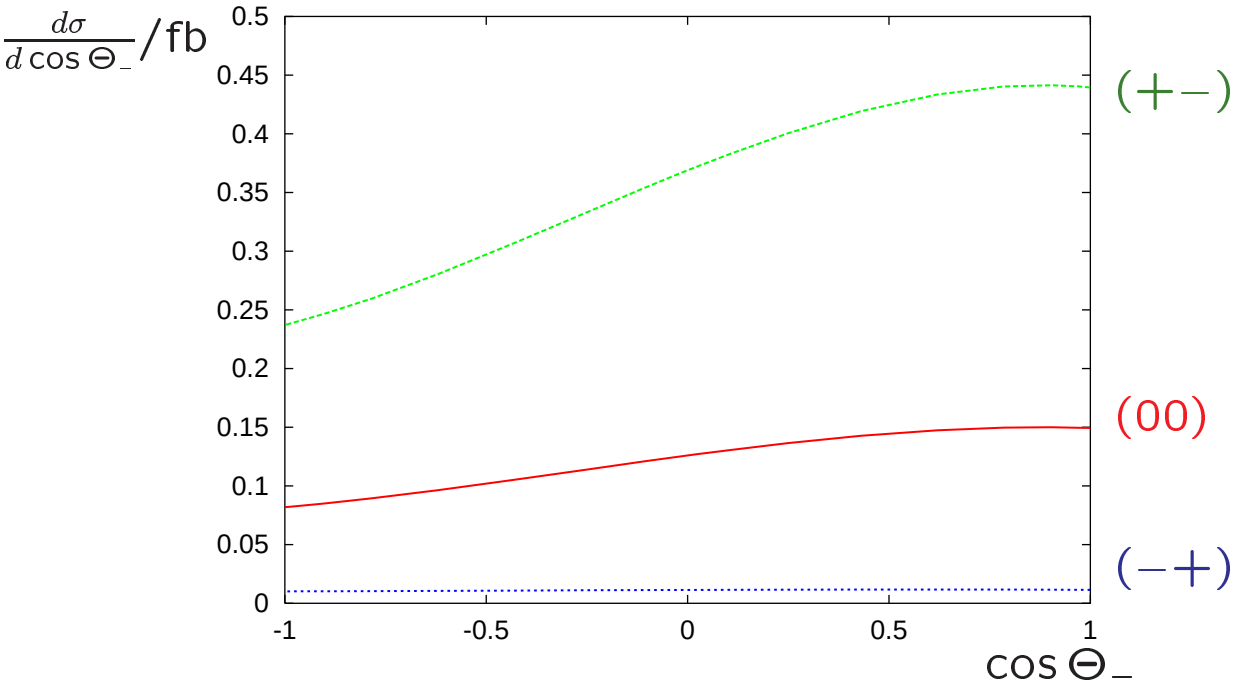
1.3.3 Decay Angular Distribution in E6

gaugino-like:

M_2	λ	v_3	M'	$\tan\beta$
-270	0.15	3000	22300	3

([mass]=GeV)

$$\sqrt{s} = m_{\tilde{\chi}_1^0} + m_{\tilde{\chi}_2^0} + 50 \text{ GeV}$$

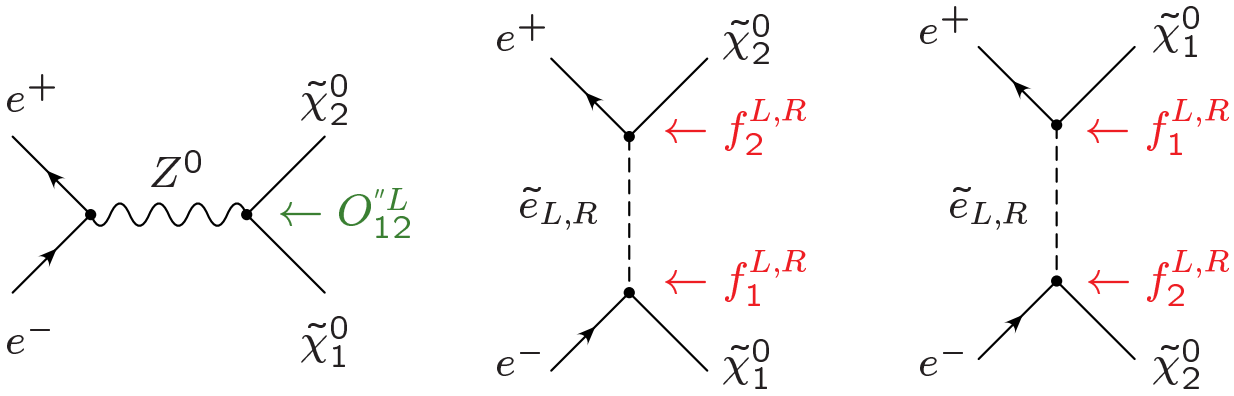


	$A_{FB}(\mathcal{L}^h)$ /%	$A_{FB}(\mathcal{L}^l)$ /%	$\sigma_e(\mathcal{L}^h)$/fb	$\sigma_e(\mathcal{L}^l)$/fb
(00)	$+16.2 \pm 8.8$	$+16.2 \pm 27.9$	0.25 ± 0.02	0.25 ± 0.07
(−+)	+3.9	+3.9	0.02	0.02
(+−)	$+16.6 \pm 5.2$	$+16.6 \pm 16.4$	0.72 ± 0.04	0.72 ± 0.12

- Here: angular dependence similar to NMSSM
- very small σ_e $\Rightarrow$ highest $\mathcal{L}^h$ necessary
- Polarization of *both* beams useful

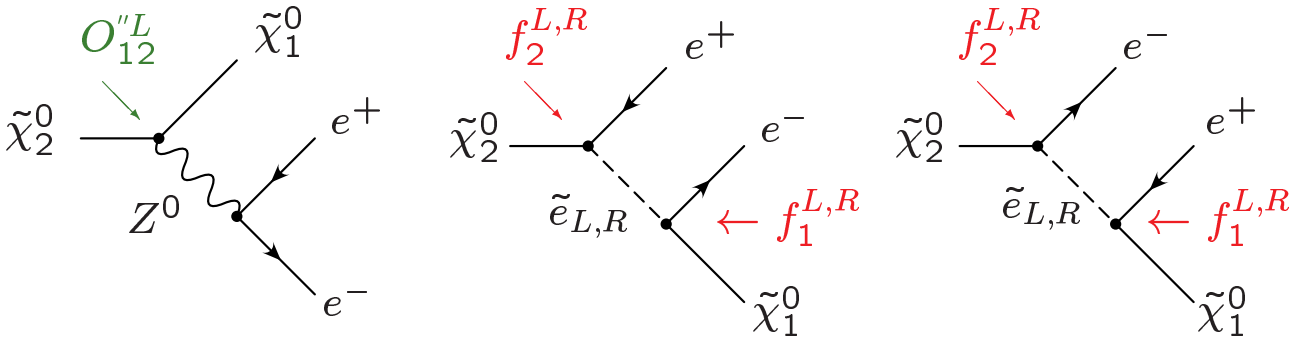
2. MSSM without M_1/M_2 GUT-Relation Feynman Diagrams

Production:



Z^0 and left and right selectron exchange

Decay:



Z^0 and left and right selectron exchange

$$M_1 \Rightarrow \begin{cases} \text{couplings:} & f_1^L f_2^L, f_1^R f_2^R, O''^L_{12} \\ \text{neutralino masses:} & m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0} \end{cases}$$

2.1 M_1 Dependence on Masses and Couplings

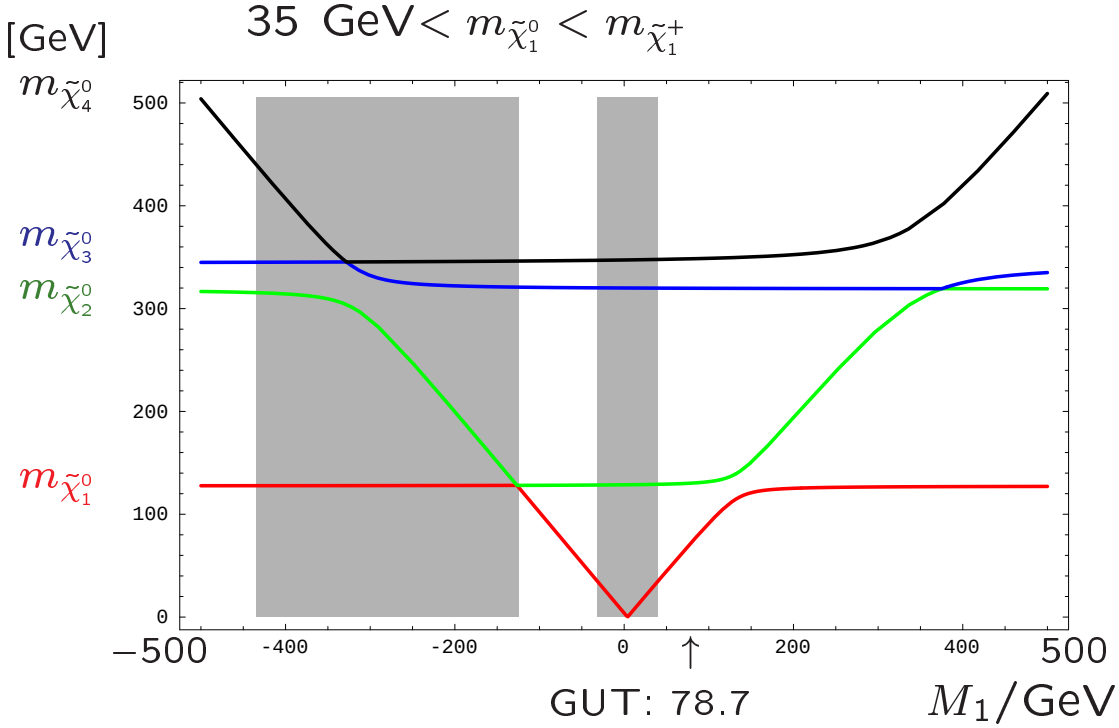
2.1.1 Neutralino Masses

gaugino-like:

([mass]=GeV)

M_2	μ	$\tan\beta$	$m_{\tilde{\chi}_1^\pm}$
152	316	3	128

Neutralino mass spectrum:



→ $|M_1| < 150$ GeV: strong influence on $m_{\tilde{\chi}_1^0}$

→ $150 < M_1 < 380$ GeV: strong influence on $m_{\tilde{\chi}_2^0}$

$m_{\tilde{\chi}_2^0} > m_{\tilde{e}_{L,R}}$: two-body decays

→ degeneracy possible: $m_{\tilde{\chi}_1^0} \approx m_{\tilde{\chi}_1^\pm}$, $m_{\tilde{\chi}_1^0} \approx m_{\tilde{\chi}_2^0}$,

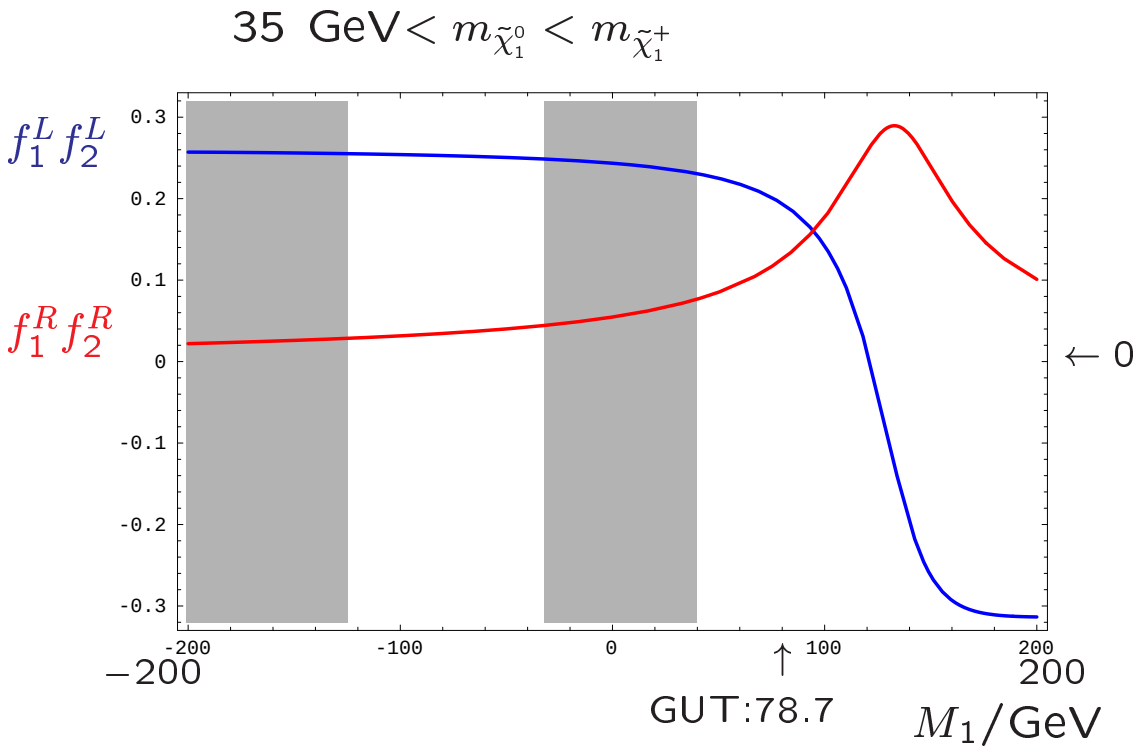
⇒ soft decay lepton spectrum Drees et al. '95, '96

2.1.2 M_1 Dependence of $\tilde{\chi}_i^0 \tilde{e} e$-couplings

gaugino-like:

M_2	μ	$\tan\beta$	$m_{\tilde{\chi}_1^\pm}$
152	316	3	128

([mass]=GeV)



- $f_1^R f_2^R > 0$: maximum at $M_1 \approx 140$ GeV
- $f_1^L f_2^L$: changes sign at $M_1 \approx 120$ GeV!

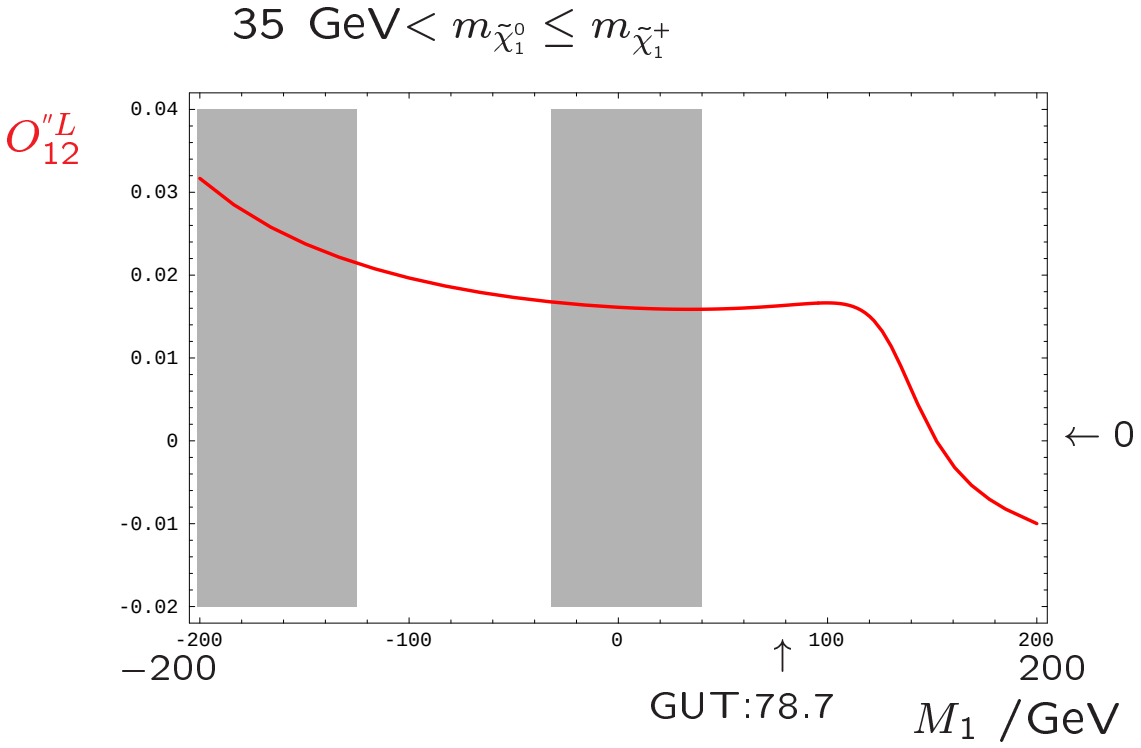
$\Rightarrow$ Studied range for $M_1 = [40, 160]$ GeV

2.1.3 M_1 Dependence of $\tilde{\chi}_i^0\tilde{\chi}_j^0 e$-couplings

gaugino-like:

M_2	μ	$\tan\beta$	$m_{\tilde{\chi}_1^\pm}$
152	316	3	128

([mass]=GeV)



- $M_1 < 115$ GeV: O''^L_{12} ≈const. and small
- $M_1 > 115$ GeV: O''^L_{12} decreases

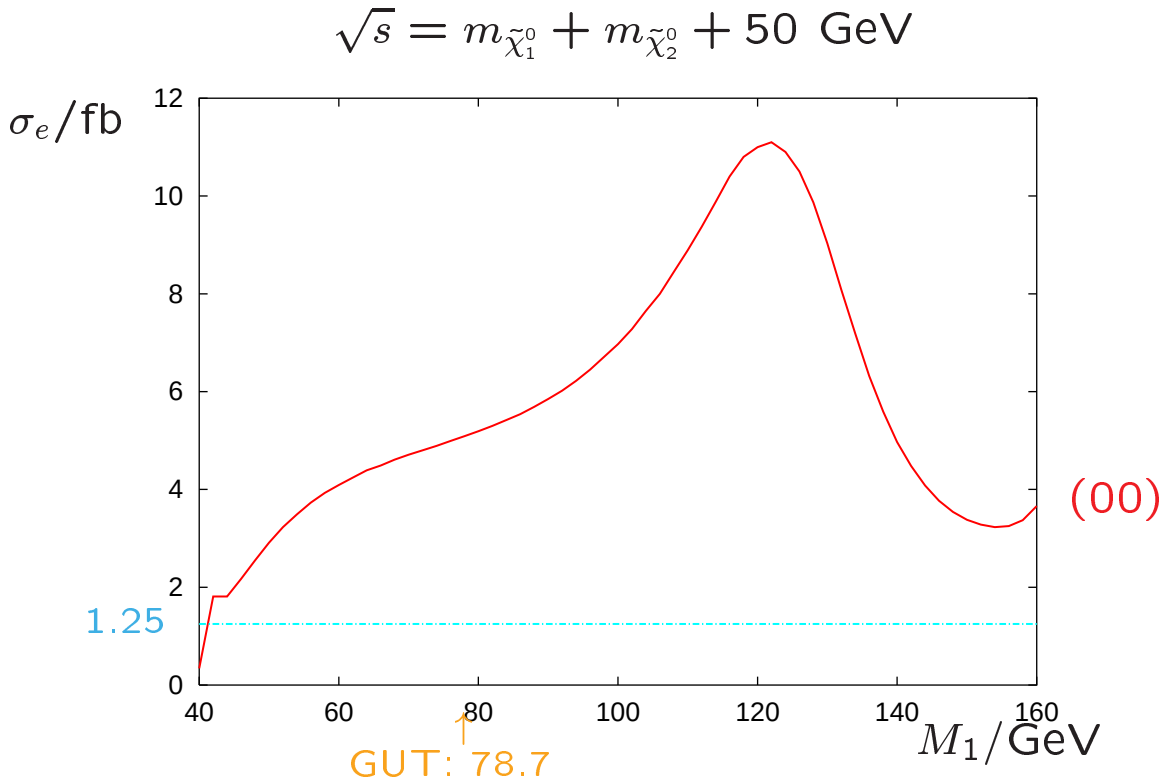
$\Rightarrow$ $M_1 = [40, 160]$ GeV: small influence of Z^0-exchange

2.2.1 M_1 Dependence of σ_e

M_2	μ	$\tan\beta$	$m_{\tilde{e}_L}$	$m_{\tilde{e}_R}$
152	316	3	197	160

[mass]=GeV

Cross sections for (00)



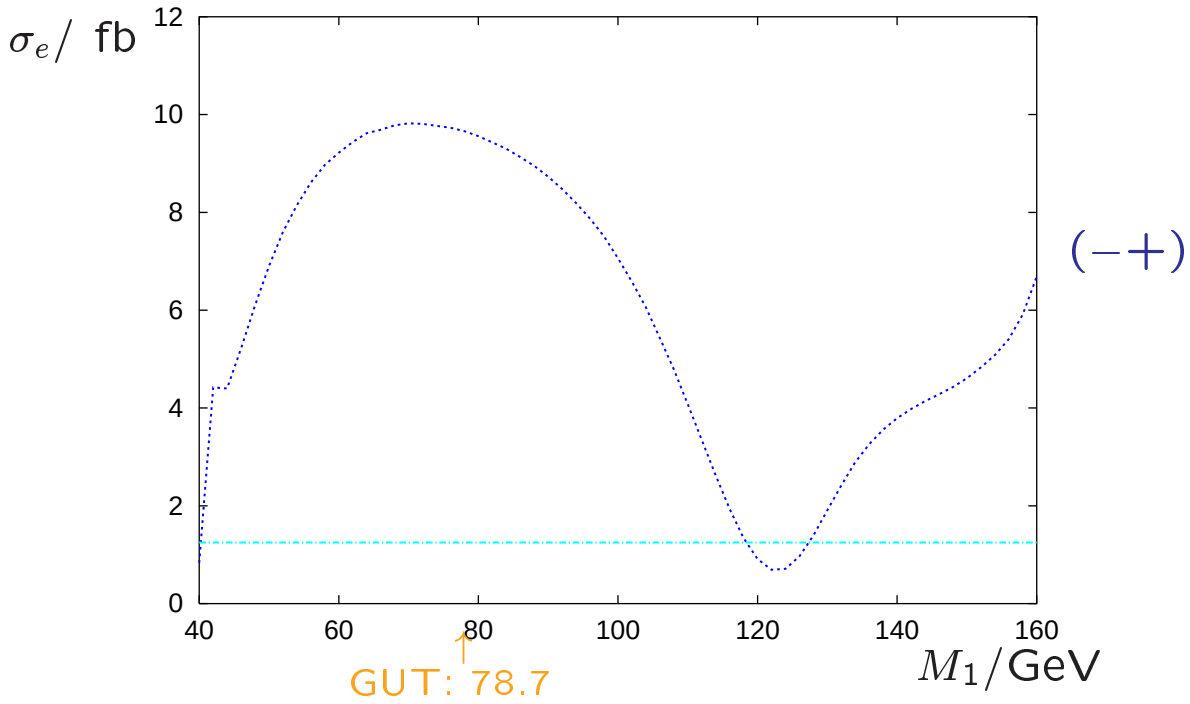
- strong M_1 dependence
  $\rightarrow$ influence of slepton couplings
- for Asymmetries $\geq 4\%$ (up to '1 σ'):

  for $\mathcal{L}^h$: $\sigma_e \geq 1.25$ fb

  for $\mathcal{L}^l$: $\sigma_e \geq 12.5$ fb (not reached!)

and $(-+)$:

$$\sqrt{s} = m_{\tilde{\chi}_1^0} + m_{\tilde{\chi}_2^0} + 50 \text{ GeV}$$



- M_1 dependence of σ_e changes strongly
  $\rightarrow$ influence of beam polarization

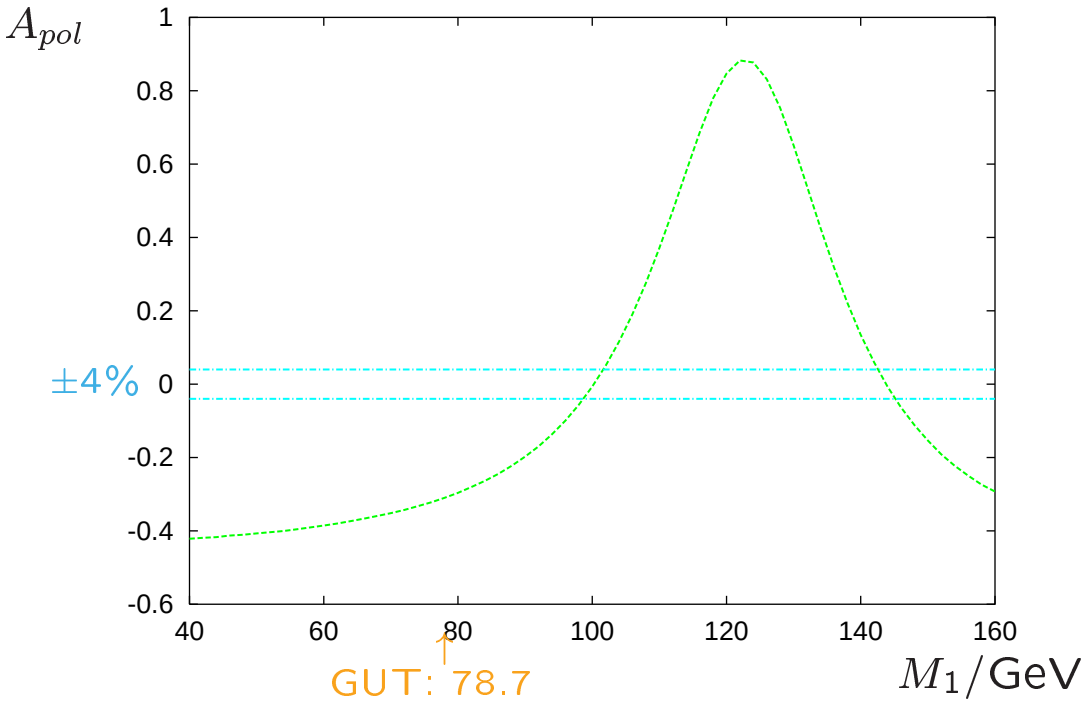
2.2.2 M_1 Dependence of Polarization Asymmetry

M_2	μ	$\tan\beta$	$m_{\tilde{e}_L}$	$m_{\tilde{e}_R}$
152	316	3	197	160

[mass]=GeV

$$A_{pol} := [\sigma_e(00) - \sigma_e(-+)]/[\sigma_e(00) + \sigma_e(-+)]$$

$$\sqrt{s} = m_{\tilde{\chi}_1^0} + m_{\tilde{\chi}_2^0} + 50 \text{ GeV}$$



- strong M_1 dependence
- for $\mathcal{L}^h$: $A_{pol} \geq 4\%$ in almost the whole region
- for high slepton mass splitting

  $\Rightarrow$ weak M_1 dependence

M.-P. '99

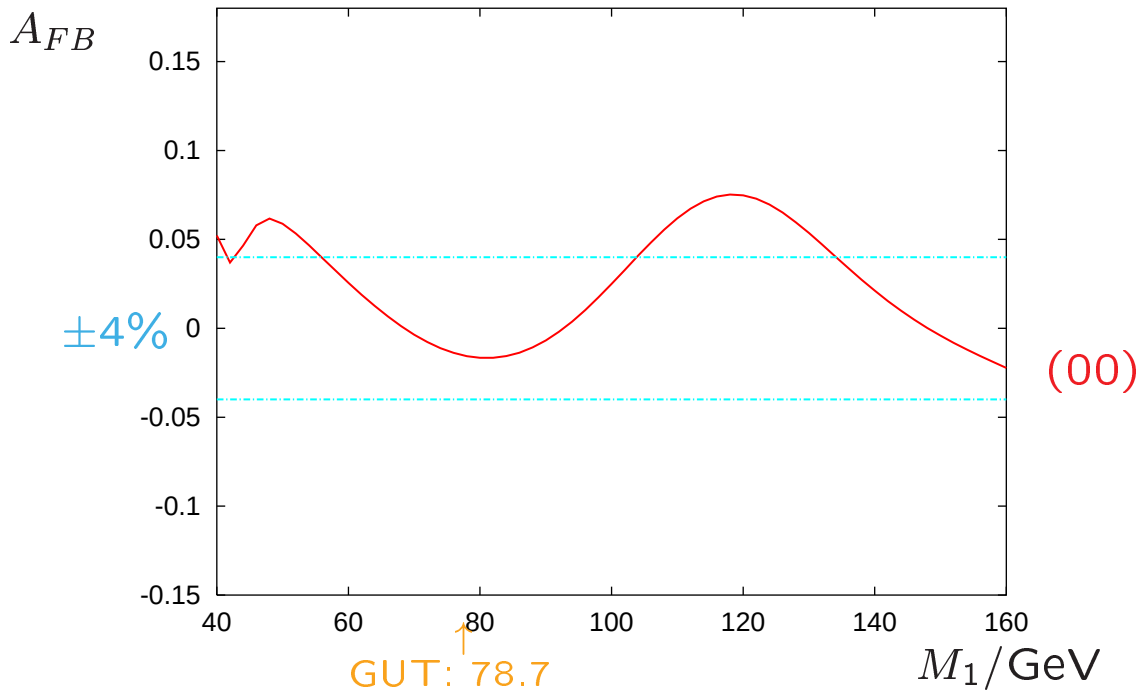
2.2.3 M_1 Dependence of A_{FB} in Lab-system

M_2	μ	$\tan\beta$	$m_{\tilde{e}_L}$	$m_{\tilde{e}_R}$
152	316	3	197	160

[mass]=GeV

A_{FB} for (00)

$$\sqrt{s} = m_{\tilde{\chi}_1^0} + m_{\tilde{\chi}_2^0} + 50 \text{ GeV}$$

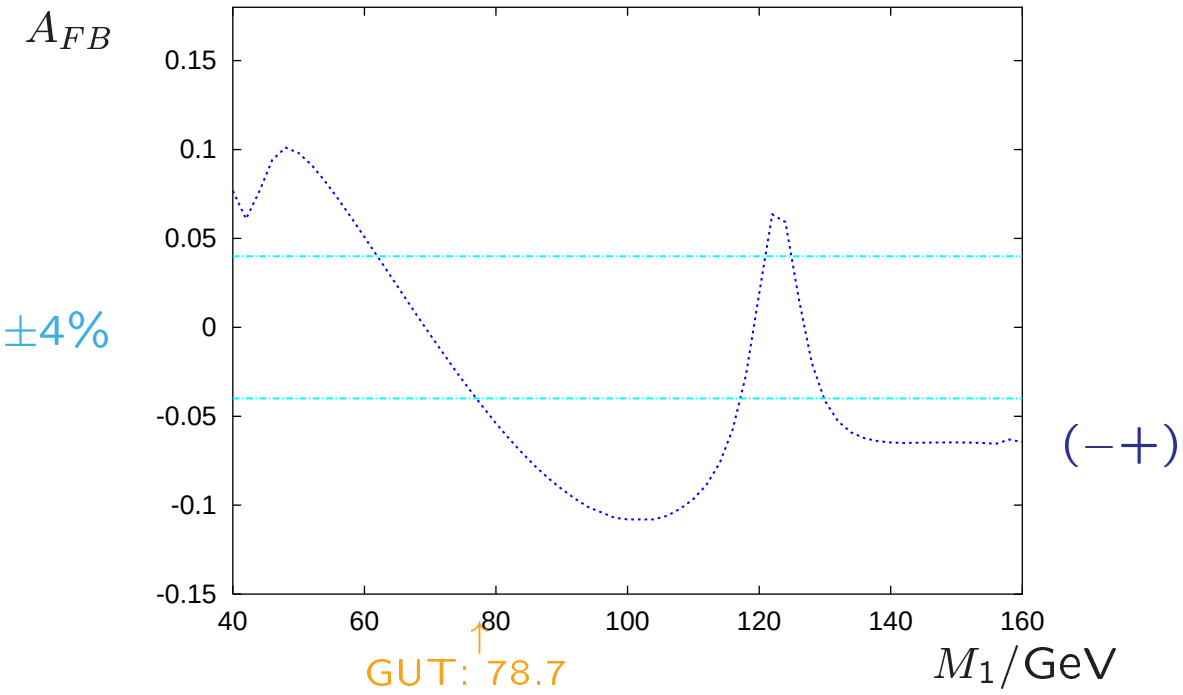


- complex interplay between production and decay ($\rightarrow$ spin correlations)
- A_{FB} depends strongly on M_1
- for $\mathcal{L}^h$: in $M_1 < 58$ GeV and $M_1 = [105, 135]$ GeV

  $\Rightarrow A_{FB} \geq 4\%$

and $(-+)$:

$$\sqrt{s} = m_{\tilde{\chi}_1^0} + m_{\tilde{\chi}_2^0} + 50 \text{ GeV}$$



- strong dependence on beam polarization
- for $\mathcal{L}^h$: information from $A_{FB} \geq 4\%$
  where $A_{pol} \leq 4\%$!

2.3 Influence of Slepton Masses: $m_{\tilde{e}_L} < m_{\tilde{e}_R}$

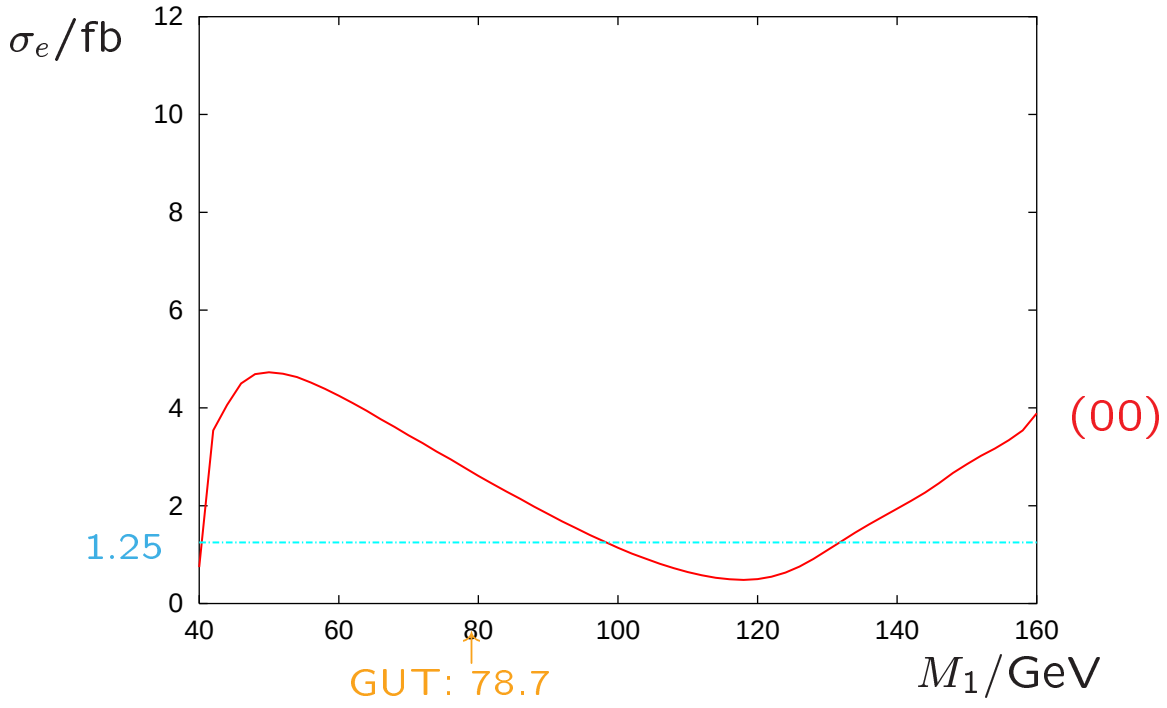
M_1 Dependence of σ_e

M_2	μ	$\tan\beta$	$m_{\tilde{e}_L}$	$m_{\tilde{e}_R}$
152	316	3	160	197

[mass]=GeV

Cross sections for (00):

$$\sqrt{s} = m_{\tilde{\chi}_1^0} + m_{\tilde{\chi}_2^0} + 50 \text{ GeV}$$



- σ_e strongly influenced by slepton masses
- M_1 Dependence changes completely

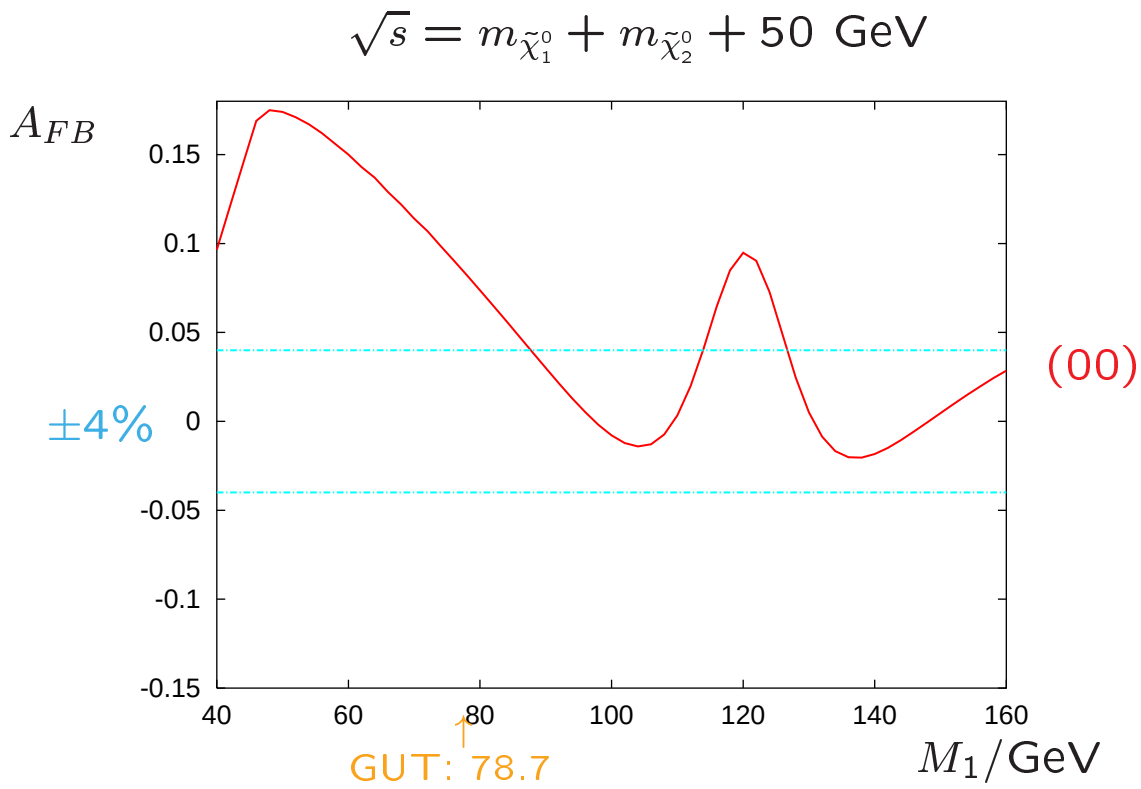
  $\Rightarrow$ Strong differences for $\begin{pmatrix} m_{\tilde{e}_L}=197\ GeV \\ m_{\tilde{e}_R}=160\ GeV \end{pmatrix} \leftrightarrow \begin{pmatrix} m_{\tilde{e}_L}=160\ GeV \\ m_{\tilde{e}_R}=197\ GeV \end{pmatrix}$

M_1 Dependence of A_{FB} in lab-system

M_2	μ	$\tan\beta$	$m_{\tilde{e}_L}$	$m_{\tilde{e}_R}$
152	316	3	160	197

[mass]=GeV

A_{FB} with (00):



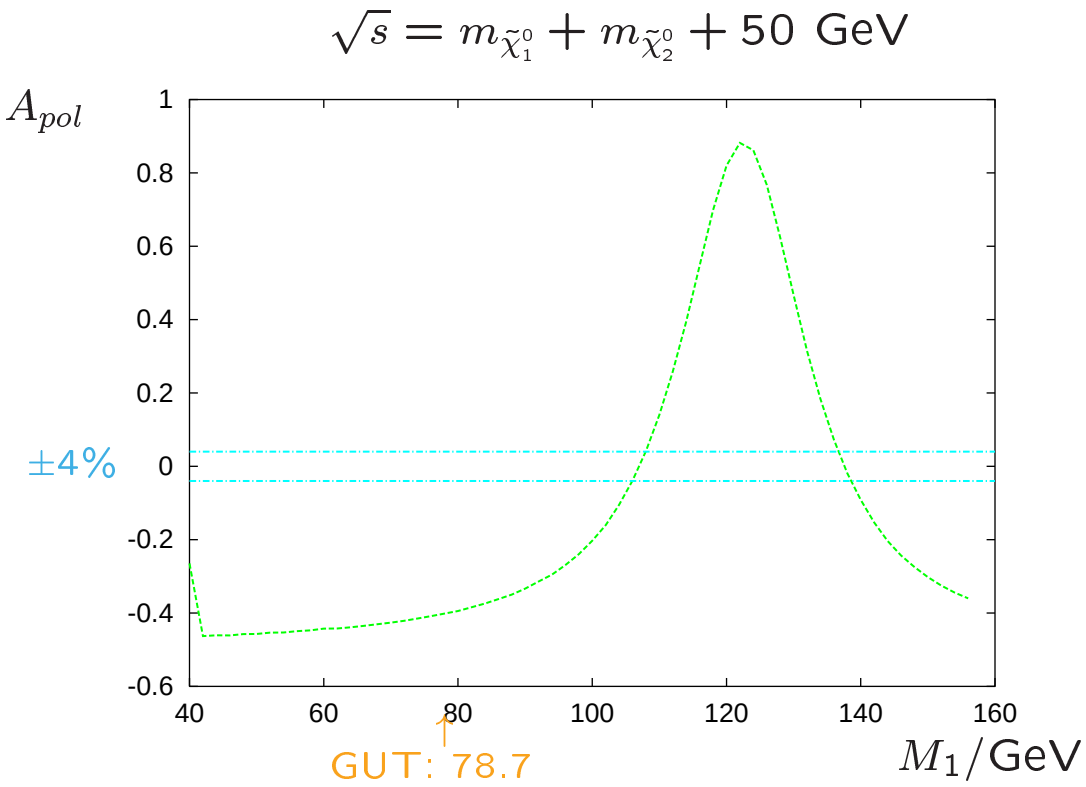
- A_{FB} strongly influenced by slepton masses
  $\Rightarrow$ larger A_{FB} possible
- M_1 Dependence of A_{FB} changes
  $\Rightarrow$ Strong differences for $\binom{m_{\tilde{e}_L}=197\ GeV}{m_{\tilde{e}_R}=160\ GeV} \leftrightarrow \binom{m_{\tilde{e}_L}=160\ GeV}{m_{\tilde{e}_R}=197\ GeV}$

M_1 Dependence of Polarization Asymmetry

M_2	μ	$\tan\beta$	$m_{\tilde{e}_L}$	$m_{\tilde{e}_R}$
152	316	3	160	197

[mass]=GeV

$$A_{pol} := [\sigma_e(00) - \sigma_e(-+)]/[\sigma_e(00) + \sigma_e(-+)]$$



- A_{pol} less influenced by slepton masses
  (but dependent on slepton mass splitting!)

3. Conclusions

- Comparison of Extended Models
  → polarization effects completely different from MSSM ($\Rightarrow$*different couplings!*)
  → strong influence of spin correlations for gauginos
  → A_{FB} of decay leptons different from MSSM
  → polarization of *both* beams useful
  → if light $\tilde{S}$: high luminosity essential

- M_1 Dependence in MSSM
  σ_e, A_{pol} and A_{FB}:
  → show strong M_1 Dependence due to influence on couplings and masses
  → Test of M_1/M_2 GUT Relation

  strongly influenced by:
  → beam polarization
  → slepton masses