Supersymmetry at the Linear Collider

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Chicago, 01/02

1. Introduction
2. Direct search/measurements
3. Indirect search/measurements
4. LC vs. LHC
5. Conclusions

1. Introduction

The Minimal Supersymmetric Standard Model (MSSM)

⇒ each SM multiplet is enlarged to its double size

⇒ number of particles are doubled in the MSSM

Superpartners for Standard Model particles

$[u, d, c, s, t, b]_{L,R}$ $[e, \mu, \tau]_{L,R}$ $[\nu_{e,\mu,\tau}]_L$ Spin $\frac{1}{2}$

$[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}]_{L,R}$ $[\tilde{e}, \tilde{\mu}, \tilde{\tau}]_{L,R}$ $[\tilde{\nu}_{e,\mu,\tau}]_L$ Spin 0

g $\underbrace{W^\pm, H^\pm}$ $\underbrace{\gamma, Z, H_1^0, H_2^0}$ Spin 1 / Spin 0

$\tilde{g}$ $\tilde{\chi}^\pm_{1,2}$ $\tilde{\chi}^0_{1,2,3,4}$ Spin $\frac{1}{2}$

Enlarged Higgs sector: Two Higgs doublets

physical states: $h^0, H^0, A^0, H^\pm$

goldstones: G^0, $G^\pm$

Supersymmetry: Motivation

The SM is in a pretty good shape. Why MSSM?

$\to$ 3 experimentally verified SUSY predictions

1.) Spontaneous symmetry breaking via Higgs mechanism is automatically achieved in mSUGRA theories $\to$ T

#1: $m_t = 150 - 200$ GeV

2.) Prediction for $\sin\theta_{W|M_{GUT}} = \frac{3}{8}$

low energy prediction via RGE $\to$ T

#2: $\sin^2\theta_{\text{eff}} \approx 0.232$

3.) Prediction of a light Higgs boson in the MSSM:

Tree level: $m_h < M_Z$

With loop corrections: $m_h \lesssim 135$ GeV

[*S.H., W. Hollik and G. Weiglein '98*]

Indirect search: Global fit to SM data:

[*LEPEWWG '01*]

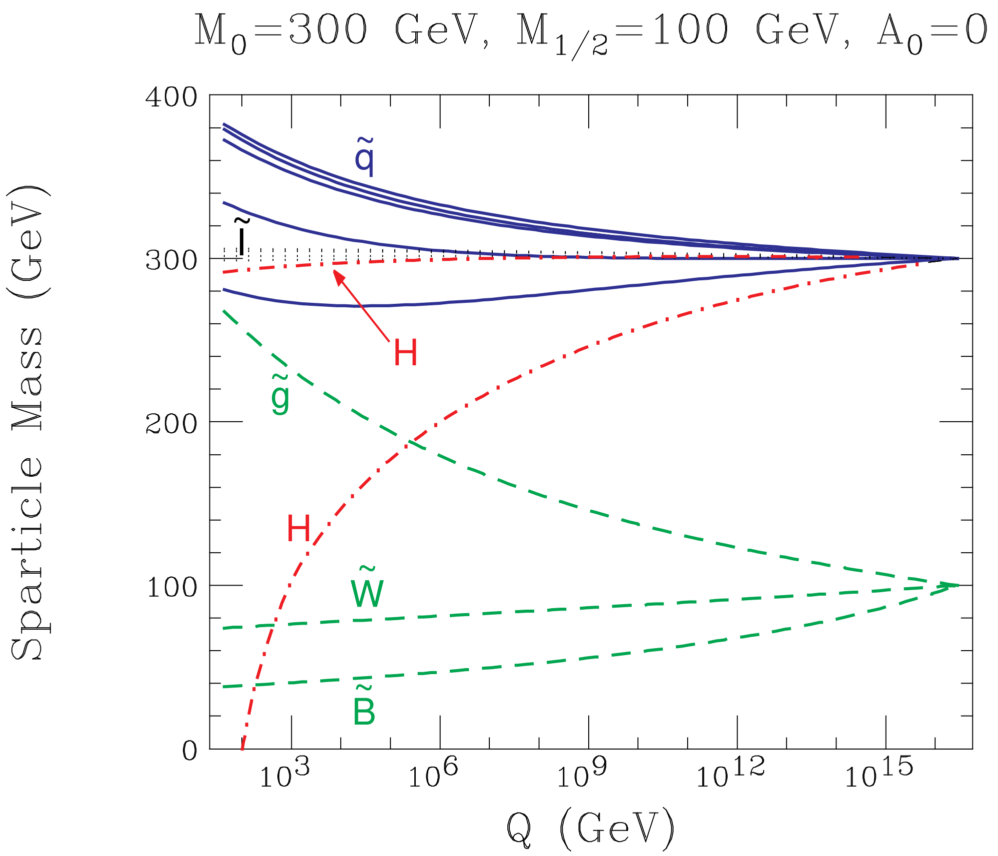
$\Rightarrow M_H \lesssim 200$ GeV, 95% C.L.

Direct search:

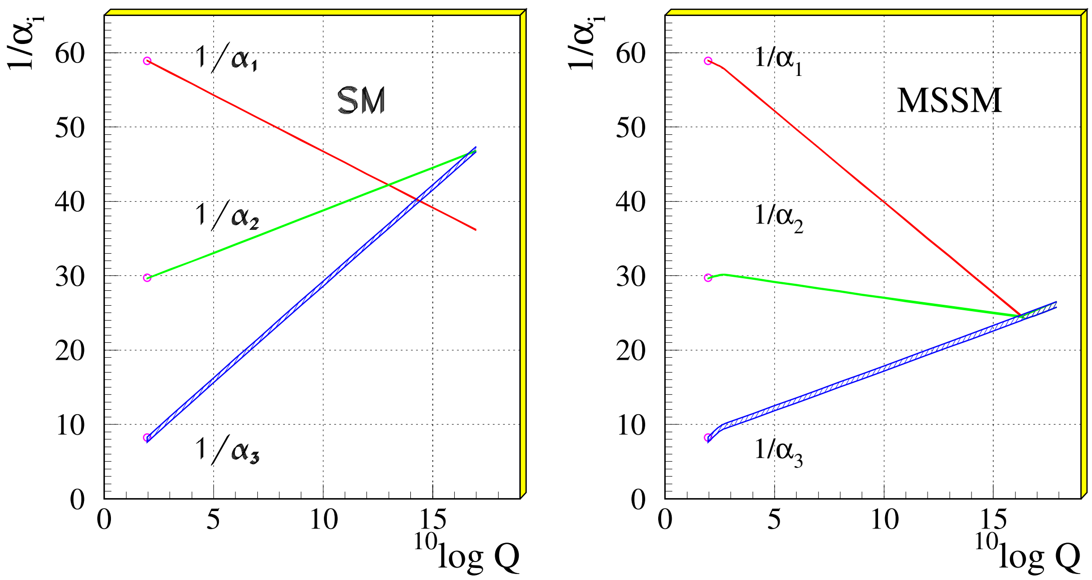
2.1σ indication of the Higgs boson at LEP:

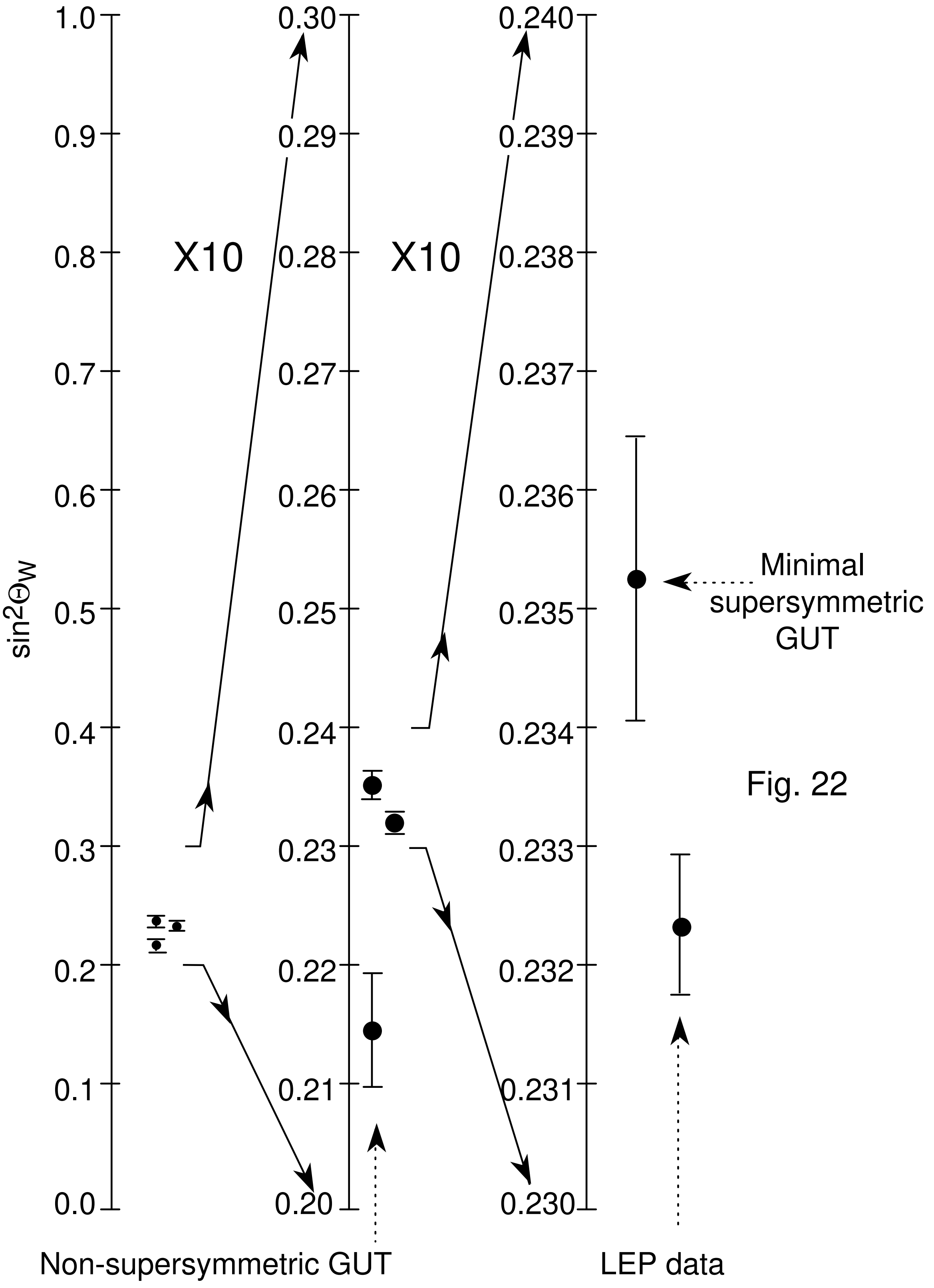
$m_h = 115.6 \pm 1$ GeV

#3: $m_h \lesssim 135$ GeV



Unification of the Coupling Constants
in the SM and the minimal MSSM





sin²Θ_W
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.30
0.29
0.28
0.27
0.26
0.25
0.24
0.23
0.22
0.21
0.20
0.240
0.239
0.238
0.237
0.236
0.235
0.234
0.233
0.232
0.231
0.230
X10
X10
Minimal
supersymmetric
GUT
Non-supersymmetric GUT
LEP data

Fig. 22

What should be demonstrated:

- every partner has its superpartner
- the quantum numbers are the same
- only the spin differs by 1/2
- SM and SUSY couplings are identical (up to higher-order corrections)
- SUSY masses etc. $\Rightarrow$ SUSY breaking ?

How can the LC contribute?

Precise measurements of:

- masses
- production XS, BRs
- angular distributions
- precision observables

Complementarity to Tevatron/LHC?

Example for SUSY masses: $\tilde{t}$ sector

(scalar partner of the top quark)

Mass matrix for $\tilde{t}_L, \tilde{t}_R$:

$$M_{\tilde{t}}^2 = \begin{pmatrix} M_{\tilde{t}_L}^2 + m_t^2 + DT_{1t} & m_t X_t \\ m_t X_t & M_{\tilde{t}_R}^2 + m_t^2 + DT_{2t} \end{pmatrix}$$

$$\Downarrow \leftarrow \text{Diagonalization}, \theta_{\tilde{t}}$$

$$\begin{pmatrix} m_{\tilde{t}_1}^2 & 0 \\ 0 & m_{\tilde{t}_2}^2 \end{pmatrix}$$

$X_t = A_t - \mu \cot \beta$

$\Rightarrow$ Physical parameters: $m_{\tilde{t}_1}$, $m_{\tilde{t}_2}$, $\theta_{\tilde{t}}$

Soft SUSY-breaking parameters: $M_{\tilde{t}_L}$, $M_{\tilde{t}_R}$, A_t

$\Rightarrow$ Soft SUSY-breaking parameters determine SUSY mass patterns

Problem: Pattern of SUSY-breaking

Uncontrained MSSM:

$\Rightarrow$ 105 new parameters
(masses, mixing angles, phases)

– hard to handle
– hard to believe

Constrained MSSM:

$\Rightarrow$ assume underlying theory

"Hidden sector": SUSY breaking	$\longrightarrow$	Visible sector: MSSM

$\Rightarrow$ large reduction of new parameters

Most prominent theories:

- mSUGRA
  minimal SUper GRAvity inspired SUSY break.
- GMSB
  Gauge Mediated Susy Breaking
- AMSB
  Anomaly Mediated Susy Breaking
- M$\tilde{g}$M
  Minimal $\tilde{g}$augino Mediation

Linear Collider

- linear e^+e^- collider
- energy: 350 GeV $\lesssim \sqrt{s} \lesssim$ 1000 GeV
- polarization: e^-: $\sim$ 80% , e^+: $\sim$ 60%
- low energy mode: GigaZ
  ($\sim 10^9$ Z bosons, $\sim 10^6$ $W^\pm$ pairs)
- other modes:

  $\left.\begin{array}{l}\gamma\,\gamma \text{ collider} \\ \gamma\, e^- \text{ collider}\end{array}\right\}$ not covered

References:

- TESLA TDR [*hep-ph/0106315*]
- NLC resource book for Snowmass
  [*hep-ex/0106056*]
- ACFA JLC report [*hep-ph/0109166*]

2. Direct search/measurements

Search for SUSY at the Tevatron, LHC, LC:

Benchmark scenarien (Snowmass consensus):

SPS: Snowmass Points and Slopes

→ Points and lines in the MSSM parameter space that exhibit certain MSSM characteristics

→ fulfil (partially) other constraints:
CDM, BR($b \to s\gamma$), $g_\mu - 2$, precision obs.

Points:
→ detailed analyses

Slopes:
→ variation in parameter space
→ reach of a collider

⇒ should be used for future studies!
⇒ comparable results from different groups

SPS:

- mSUGRA : 6 scenarios
  - typical $\to$ T
  - focus point
  - coannihilation region
  - light Higgses
  - light scalar top
  - no gaugino mass unification
- GMSB : 2 scenarios
  - $\tilde{\tau}$ NLSP $\to$ T
  - $\tilde{\chi}$ NLSP
- AMSB : 1 scenario $\to$ T
- not covered:
  - M$\tilde{g}$M
  - NMSSM
  - CPV MSSM
  - RPV MSSM
  - string inspired MSSM
  - ...

obtainable at wwwhephy.oeaw.ac.at/susy/lcws.html

[Snowmass Proceedings '01]

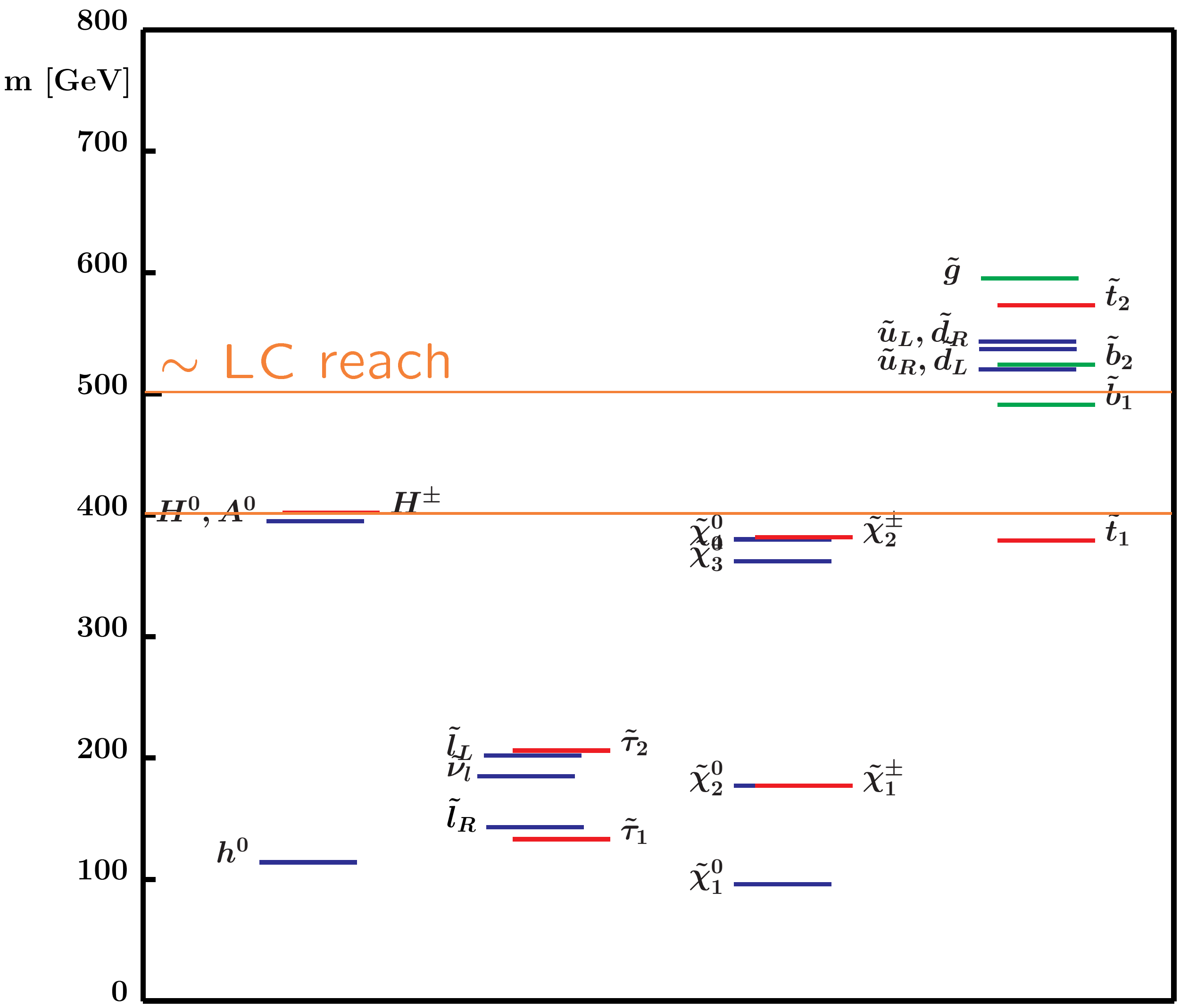
SPS1: "typical" mSUGRA scenario

Point:

$$m_0 = 100 \text{ GeV}, \quad m_{1/2} = 250 \text{ GeV}$$
$$A_0 = -100 \text{ GeV}, \quad \tan\beta = 10, \quad \mu > 0$$

Slope:

$$m_0 = -A_0 = 0.4\, m_{1/2}, \quad m_{1/2} \text{ varies}$$



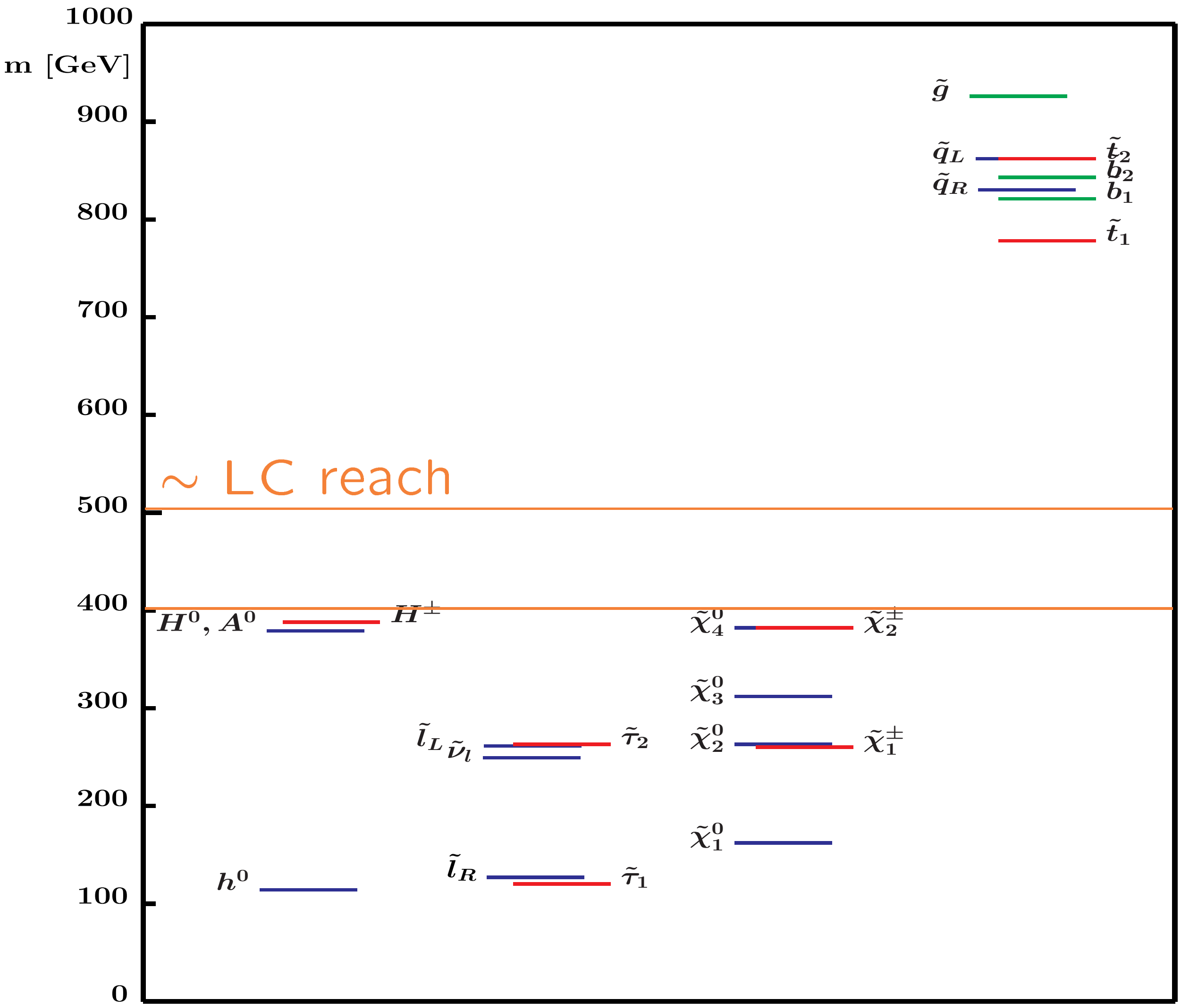
SPS7: GMSB with $\tilde{\tau}$ NLSP

Point:

$$\Lambda = 40 \text{ TeV}, \quad M_{\text{mess}} = 80 \text{ TeV}$$
$$N_{\text{mess}} = 3, \quad \tan\beta = 15, \quad \mu > 0$$

Slope:

$$M_{\text{mess}}/\Lambda = 2, \quad \Lambda \text{ varies}$$



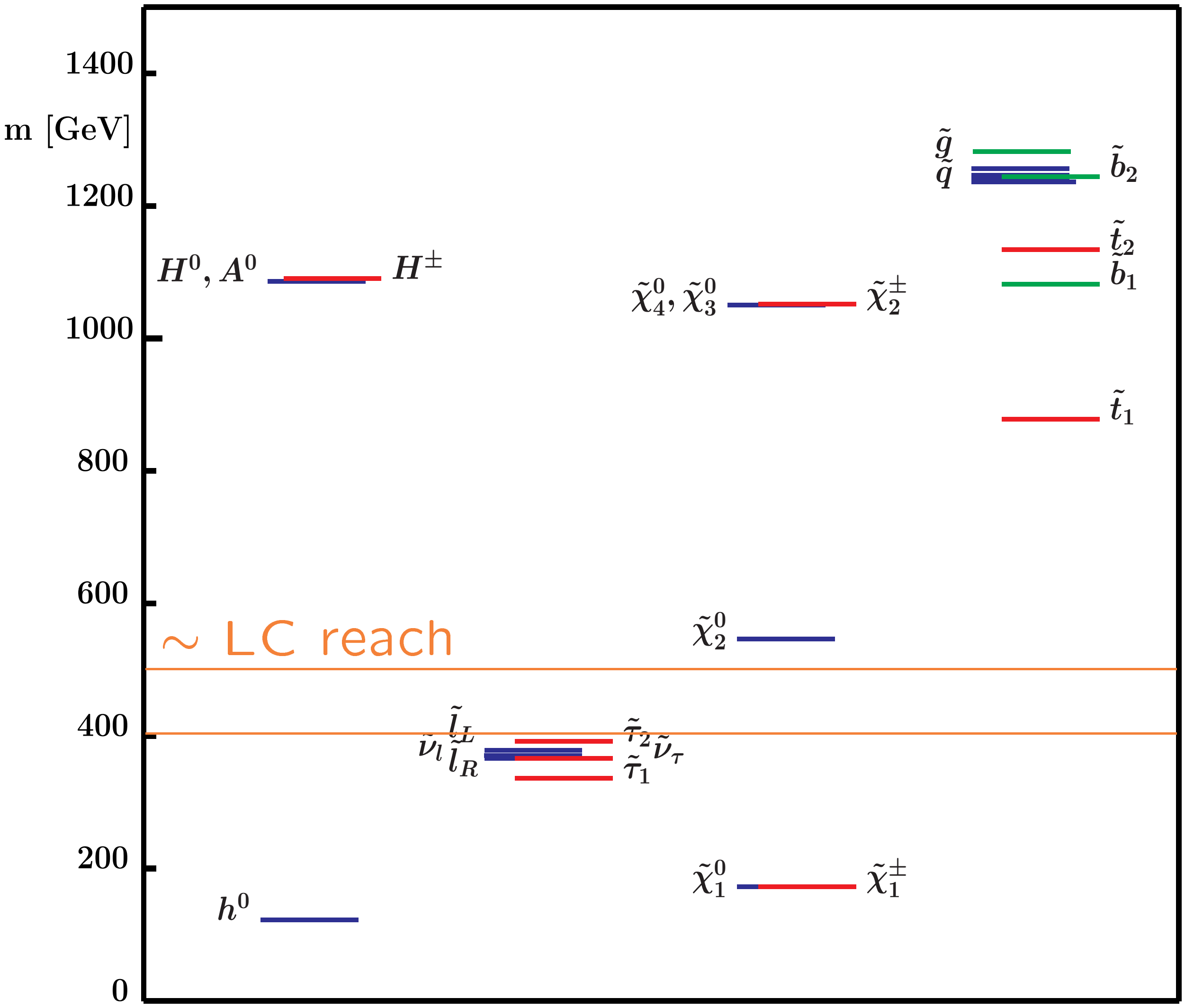
SPS9: "typical" AMSB scenario

Point:

$$m_0 = 450 \text{ GeV}, \quad m_{\text{aux}} = 60 \text{ TeV}$$
$$\tan\beta = 10, \quad \mu > 0$$

Slope:

$$m_0 = 0.0075\, m_{\text{aux}}, \quad m_{\text{aux}} \text{ varies}$$



Production of sfermions

(studies exist for sleptons and stops)

$$e^+e^- \quad \to \quad \tilde{f}_R\tilde{f}_R, \quad \tilde{f}_R\tilde{f}_L, \quad \tilde{f}_L\tilde{f}_L$$

LC precision requires more:

- full 1-loop correction for production/decay

  $\to$ available for stops

  [*Vienna SUSY group '96-'00*]

  [*W. Beenakker, R. Höpker, P. Zerwas '95*]

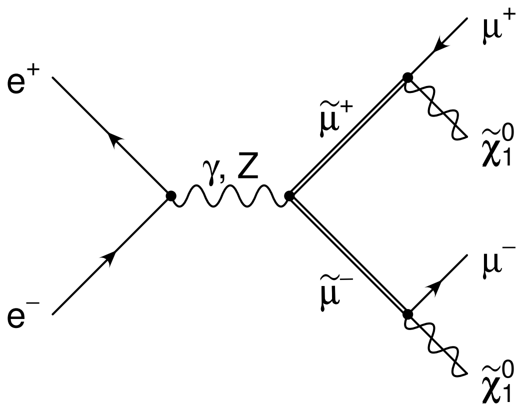
  [*K. Hikasa, J. Hisano '96*]

  $\to$ to be completed for sleptons

- finite width effects

  [*A. Freitas, D. Miller, P. Zerwas '01*]

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



Mass determinations:

1. kinematical endpoints (continuum)

   [J. Feng, D Finnel '93]

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

   $\to$ energy spectrum of μs

2. threshold scan:

   (more precise)

   $\Rightarrow$ finite width effects important

$$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^- \;:\sim \beta^3 \text{ [P]}$$

$\to$ T

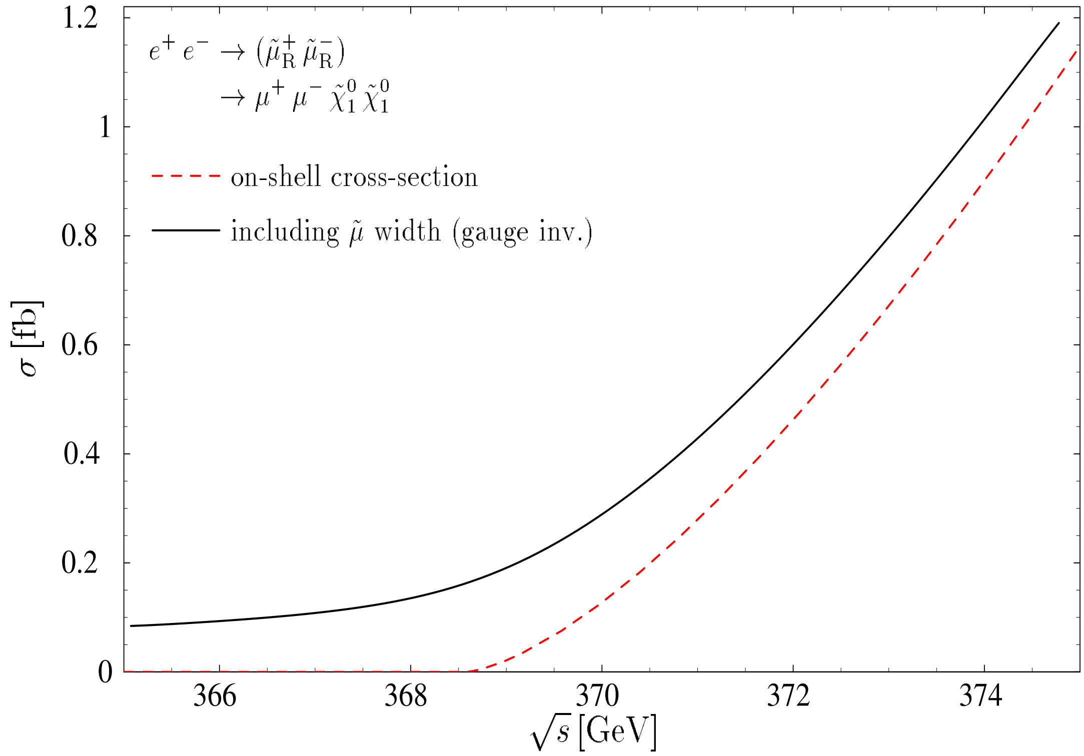
$$\begin{array}{lcllr}
e^+_L e^-_R \,/\, e^+_R e^-_L & \to & \tilde{e}^+_L \tilde{e}^-_L \,,\, \tilde{e}^+_R \tilde{e}^-_R & [\gamma, Z;\, \tilde{\chi}^0] & \text{[P]} \\
e^+_L e^-_L \,/\, e^+_R e^-_R & \to & \tilde{e}^+_R \tilde{e}^-_L \,/\, \tilde{e}^+_L \tilde{e}^-_R & [\tilde{\chi}^0] & \text{[S]} \\
e^-_L e^-_R \,/\, e^-_R e^-_L & \to & \tilde{e}^-_L \tilde{e}^-_R & [\tilde{\chi}^0] & \text{[P]} \\
e^-_L e^-_L \,/\, e^-_R e^-_R & \to & \tilde{e}^-_L \tilde{e}^-_L \,/\, \tilde{e}^-_R \tilde{e}^-_R & [\tilde{\chi}^0] & \text{[S]}
\end{array}$$

$\to$ T

$\Rightarrow$ polarized beams needed

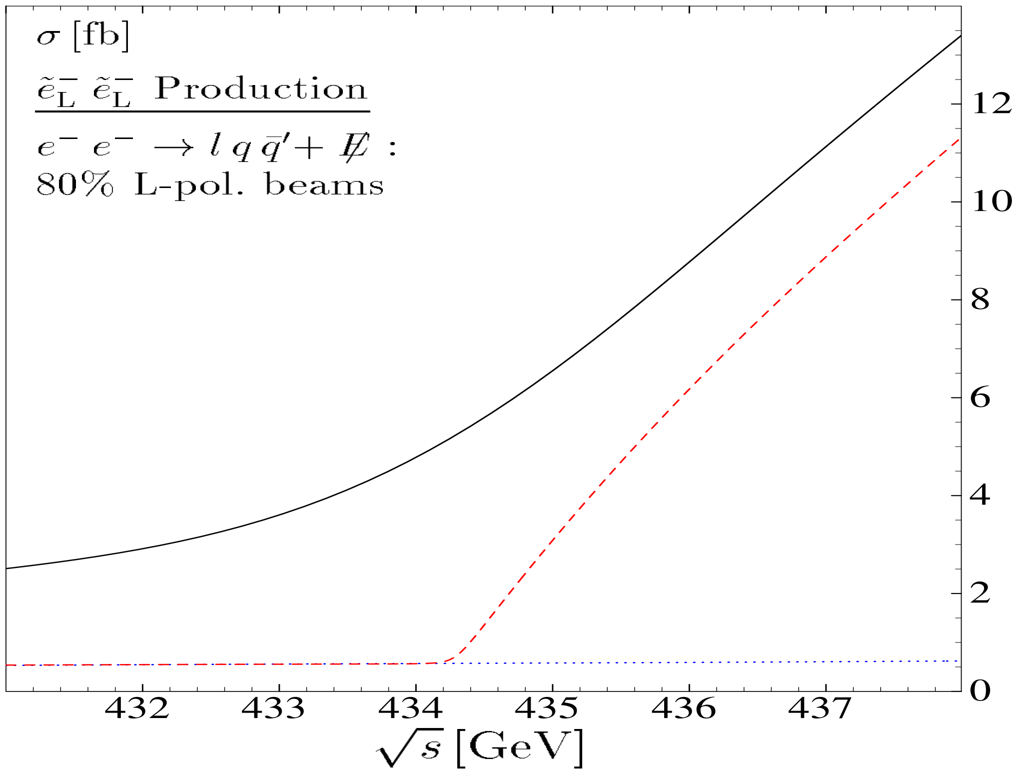
$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-$ [P]

[A. Freitas, D. Miller, P. Zerwas '01]



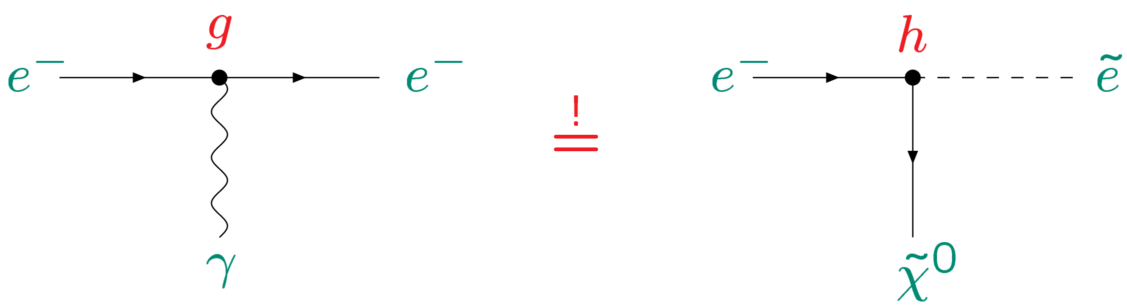
$e^-_L e^-_L \,/\, e^-_R e^-_R \to \tilde{e}^-_L \tilde{e}^-_L \,/\, \tilde{e}^-_R \tilde{e}^-_R$ [S]

[A. Freitas, D. Miller, P. Zerwas '01]



Tests of SUSY

SUSY predicts equality of couplings:



Super-oblique corrections:

Non-decoupling effects of heavy particles

$$\tilde{U} = \frac{h}{g} - 1 \approx \frac{g^2}{16\,\pi^2}\,\Delta b\,\log\frac{M}{m}$$

Δb : one-loop β function of g
M : heavy mass scale
m : light (electroweak) scale

$\Rightarrow \mathcal{O}\,(1\%)\ \times \log M/m$ effect
Access to heavy scales?

Analogous ideas for g_1, g_2, α_s

However . . .

- Up to now only vertex corrections investigated

- At the LC: only XS measurement

  (incl. boxes, . . .)

- Separation of scales not always possible

  (usually more complex situation)

Necessary: full XS calculation

$\rightarrow$ comparison with measured XS

$\Rightarrow$ Test of SUSY

(equality of couplings)

$\Rightarrow$ access to high(er) scales ?

$\Rightarrow$ much work to do

(precision at the 1% level)

Production of gauginos

(studies exist for neutralinos and charginos)

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

LC precision requires more:

- (s)fermion corrections for production
  [*M. Diaz, S. King, D. Ross '98*]
  [*S. Kiyoura, M. Nojiri, D. Pierce, Y. Yamada '98*]
  full 1-loop correction for production
  [*T. Blank, W. Hollik, '00*] $\to$ T

- (s)fermion corrections for decay
  [*H. Eberl, M. Kincel, W. Majerotto, Y. Yamada '01*]
  (some work to do)

- finite width effects
  [*A. Freitas, D. Miller, P. Zerwas '01*]

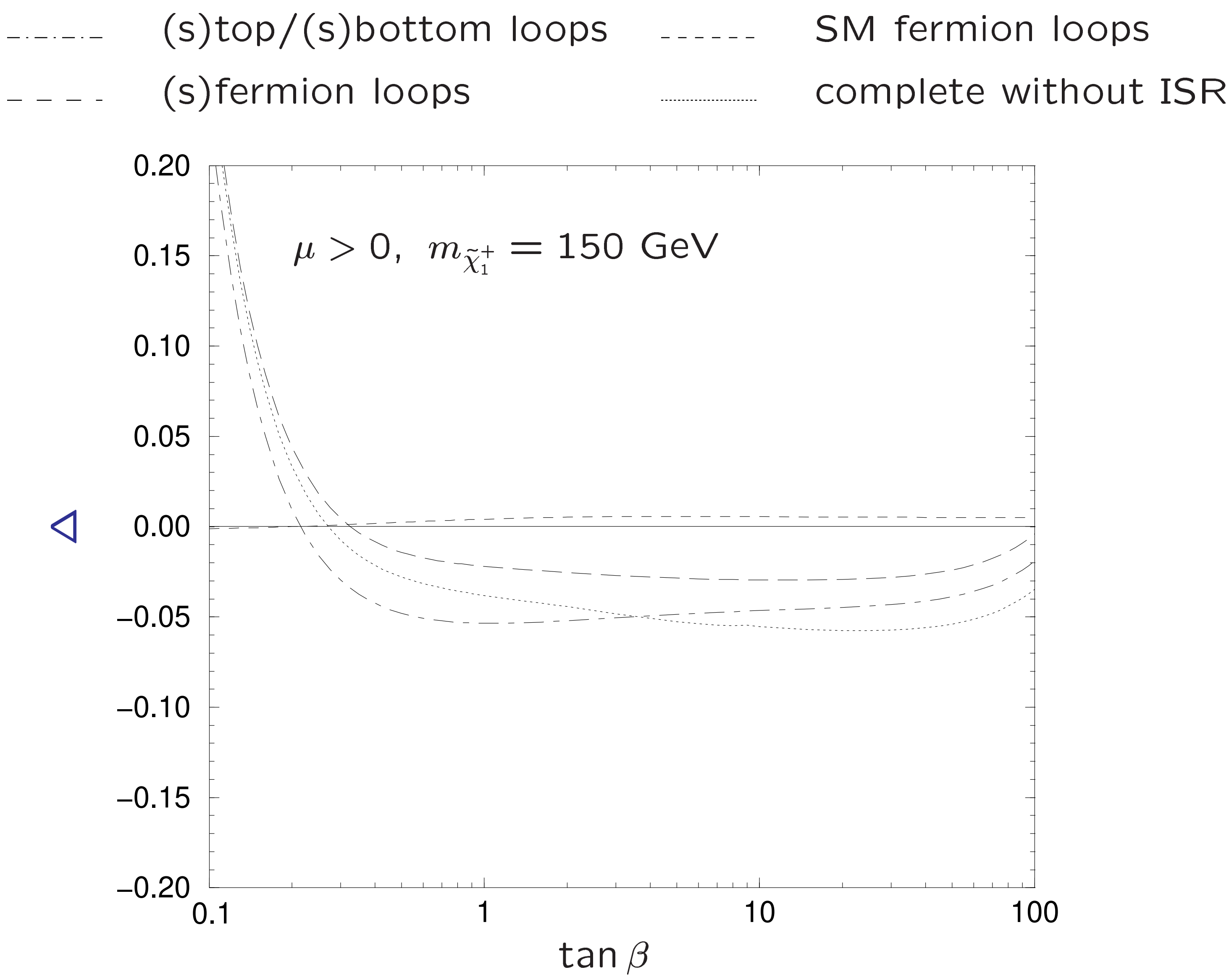
$$e^+e^- \to \tilde{\chi}^+_1 \tilde{\chi}^+_2 \to \tilde{\chi}^+_1 \tilde{\chi}^+_1 Z \to \tilde{\chi}^+_1 \tilde{\chi}^+_1 q\bar{q}$$

$\to$ T

(much work to do)

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

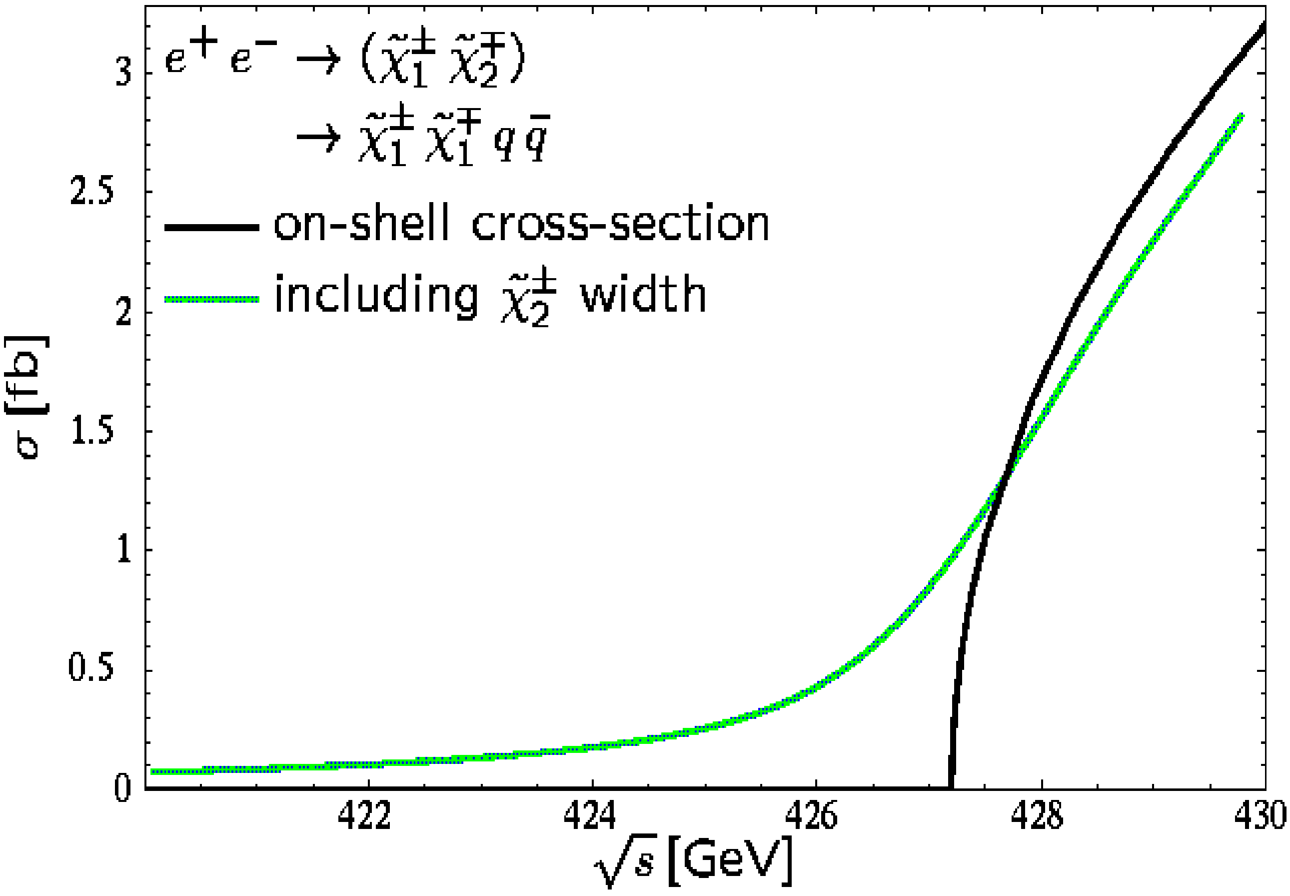
[T. Blank, W. Hollik, '00]



$$\Delta = (\sigma - \sigma_0)/\sigma_0$$

$e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^+ q\bar{q}$

[*A. Freitas, D. Miller, P. Zerwas '01*]



Reconstruction of fundamental parameters

Example: Chargino sector

mass matrix:

$$M_C = \begin{pmatrix} M_2 & \sqrt{2}M_W \cos\beta \\ \sqrt{2}M_W \sin\beta & \mu \end{pmatrix}$$

$\to$ 2 angles: ϕ_L, ϕ_R

$\tilde{\chi}_1^+\tilde{\chi}_1^+$ and $\tilde{\chi}_1^+\tilde{\chi}_2^+$ accessible
$\Rightarrow m_{\tilde{\chi}_1^+}, m_{\tilde{\chi}_2^+}$ and production XSs

$\to$ measurement in the $\phi_L - \phi_R$ plane $\qquad \to$ T

$\Rightarrow$ ϕ_L and ϕ_R can be reconstructed

$\Rightarrow$ M_2 and μ can be reconstructed
(moderate sensitivity to $\tan\beta$)

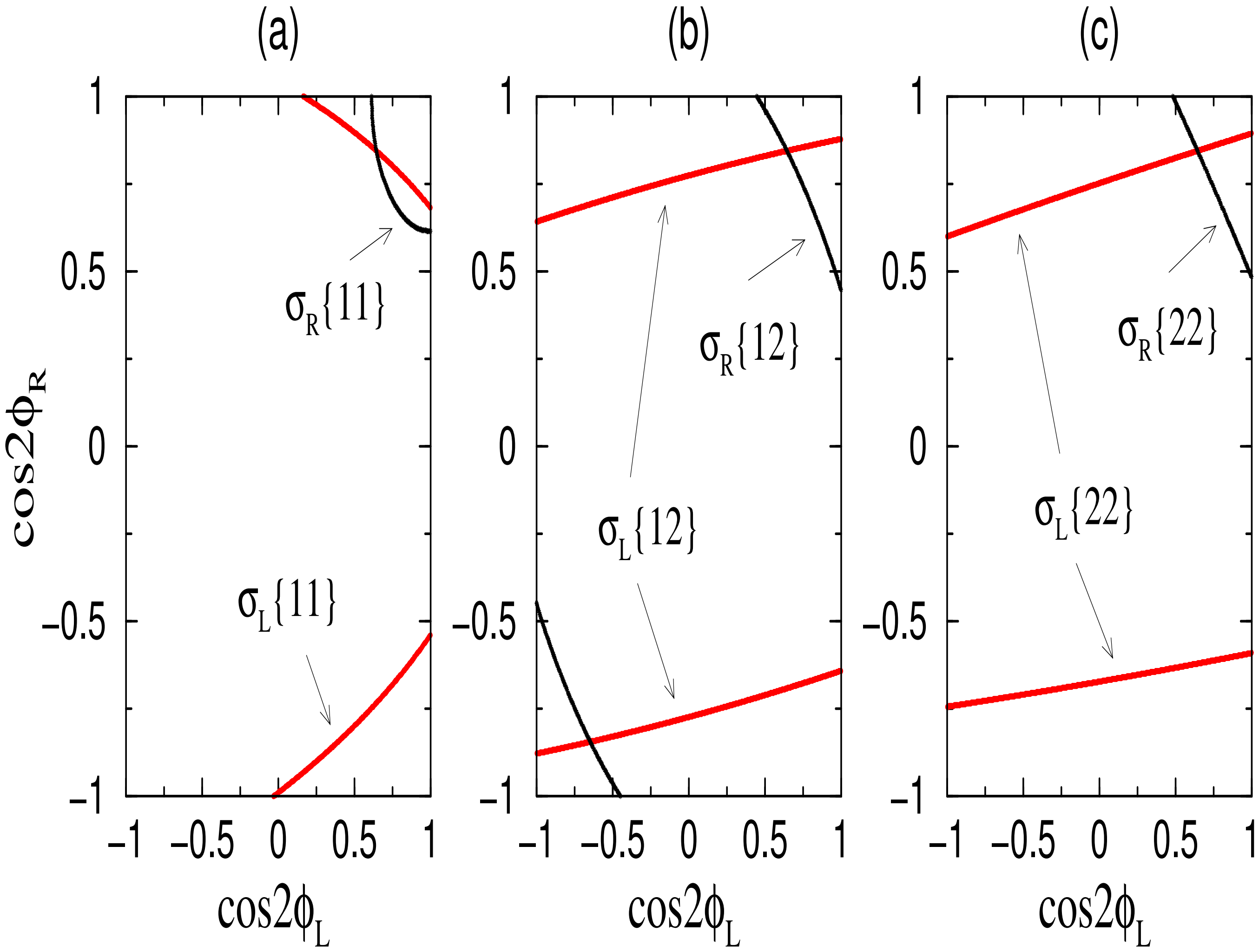
However . . .

– 100% polarization assumed
– no higher-order corrections

$\Rightarrow$ much work to do

Iso-contours of $\sigma_L ij$, $\sigma_R ij$ in the $\phi_L - \phi_R$ plane

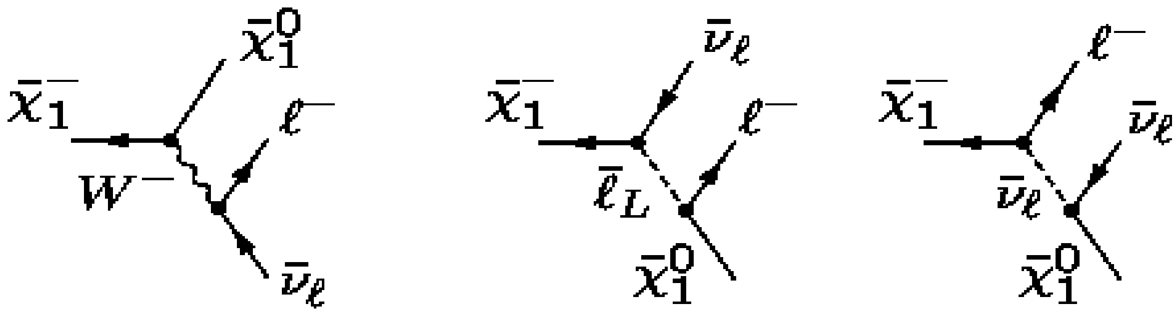
[S. Choi, A. Djouadi, M. Guchait, J. Kalinowski, K. Song, P. Zerwas '00]



$\Rightarrow$ ϕ_L and ϕ_R can be reconstructed

Spin correlations / Asymmetries:

$e^+e^- \;\to\; \tilde{\chi}_1^+\tilde{\chi}_1^- \;\to\; \tilde{\chi}_1^+\tilde{\chi}_1^0\,\bar{\nu}e^-$



$m_{\tilde{\nu}_l} = m_{\tilde{l}_L} + M_Z^2 \cos 2\beta\,(1 - s_w^2)$

$\Rightarrow$ $m_{\tilde{\nu}_l}$ only new parameter

$\to$ Study of A_{FB} of the decay electron $\quad\to$ T

$\Rightarrow$ sensitivity to $m_{\tilde{\nu}_l}$ far beyond kinematic reach

Example: $A_{FB} = 26\% \pm 0.5\%$

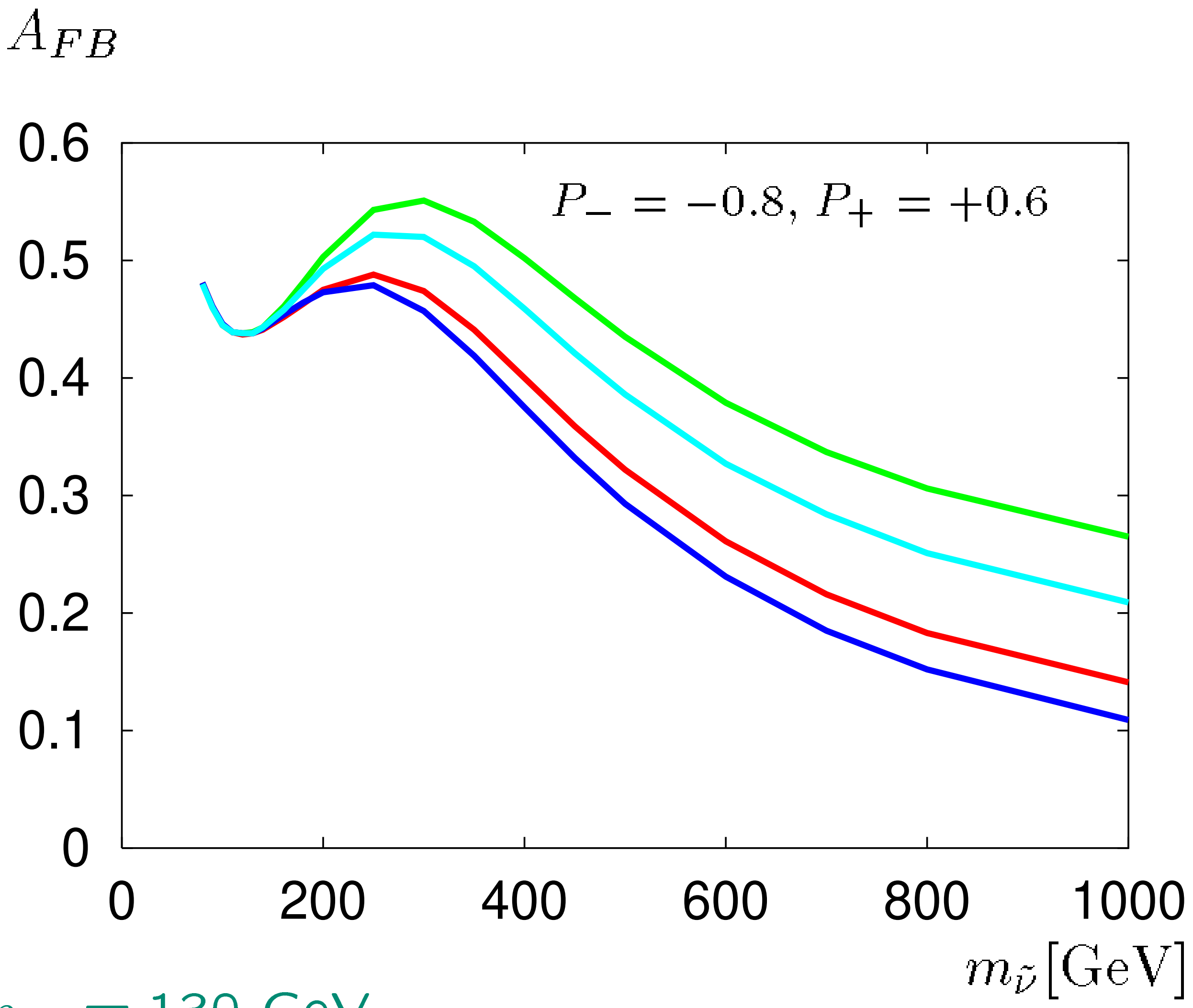
$m_{\tilde{e}_L} = 200$ GeV $\Rightarrow$ 590 GeV $\lesssim m_{\tilde{\nu}} \lesssim$ 610 GeV

$m_{\tilde{e}_L} > 250$ GeV $\Rightarrow$ 540 GeV $\lesssim m_{\tilde{\nu}} \lesssim$ 580 GeV

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

$\to$ Study of A_{FB} of the decay electron

[G. Moortgat-Pick, A. Bartl, H. Fraas, W. Majerotto, '00]



$m_{\tilde{e}_L} = 130$ GeV

$m_{\tilde{e}_L} = 150$ GeV

$m_{\tilde{e}_L} = 200$ GeV

$m^2_{\tilde{e}_L} = m^2_{\tilde{\nu}} - M^2_W \cos 2\beta$

$\sqrt{s} = 500$ GeV

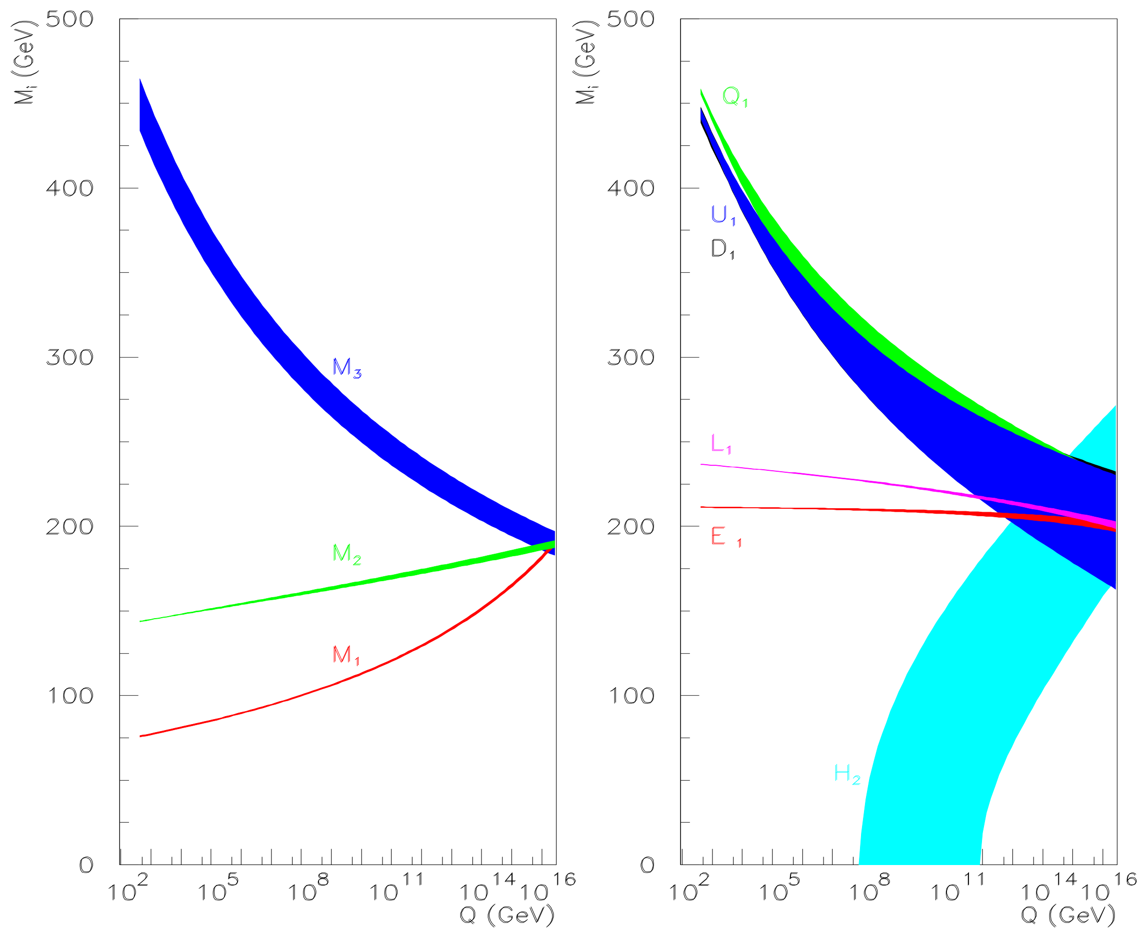
$\Rightarrow e^+$ polarization needed

Extrapolation to the GUT scale

use "low energy" mass measurements from
– LHC
– LC (complementary, see below)
$\Rightarrow$ extrapolate to high scales

[*G. Blair, W. Porod, P. Zerwas '00*]

mSUGRA example:



$\Rightarrow$ test of GUT models
reconstruction of m_0, $m_{1/2}$, A_0, $\tan\beta$, sign(μ)

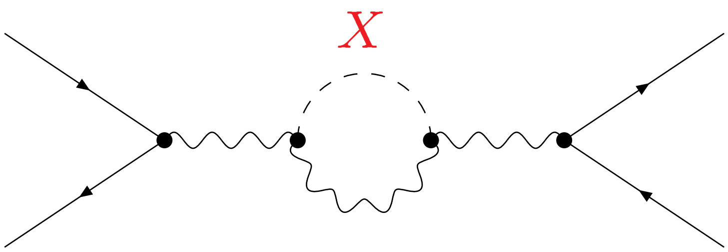
3. Indirect search/measurements

Comparison of precision observables with theory:

Precision observables:		Theory:
$g_\mu - 2$ BR$(b \to s\gamma)$ $M_W, \sin^2\theta_{\mathrm{eff}}$	$\leftrightarrow$	SM, MSSM , . . .

$$\Downarrow$$

Sensitivity to loop corrections



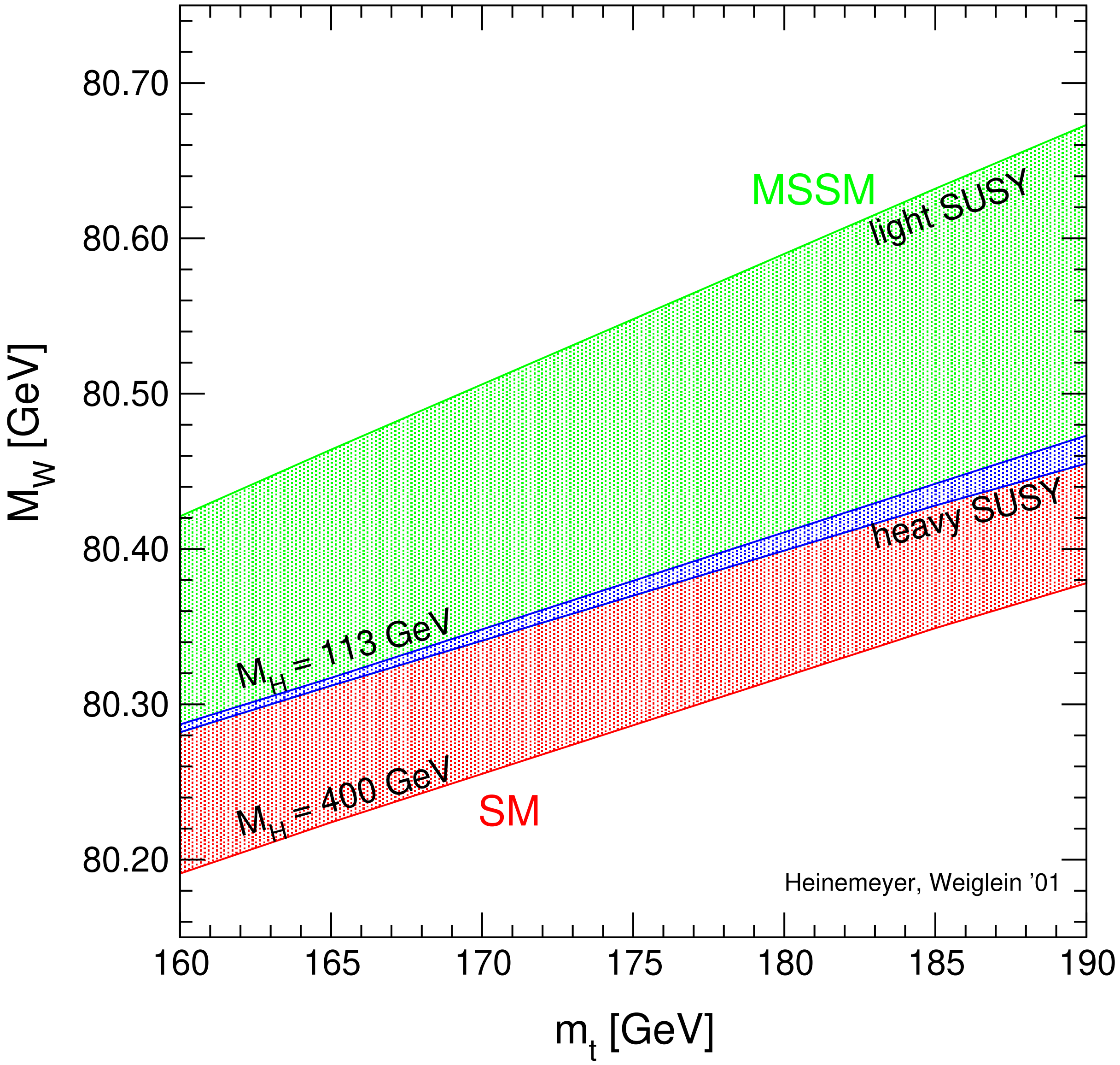
$$\Downarrow$$

Improve indirect constraints on unknown parameters: $m_{\tilde{t}}, \ldots$

Comparison of direct/indirect data: consistency check

Very high accuracy of measurements and theoretical predictions needed

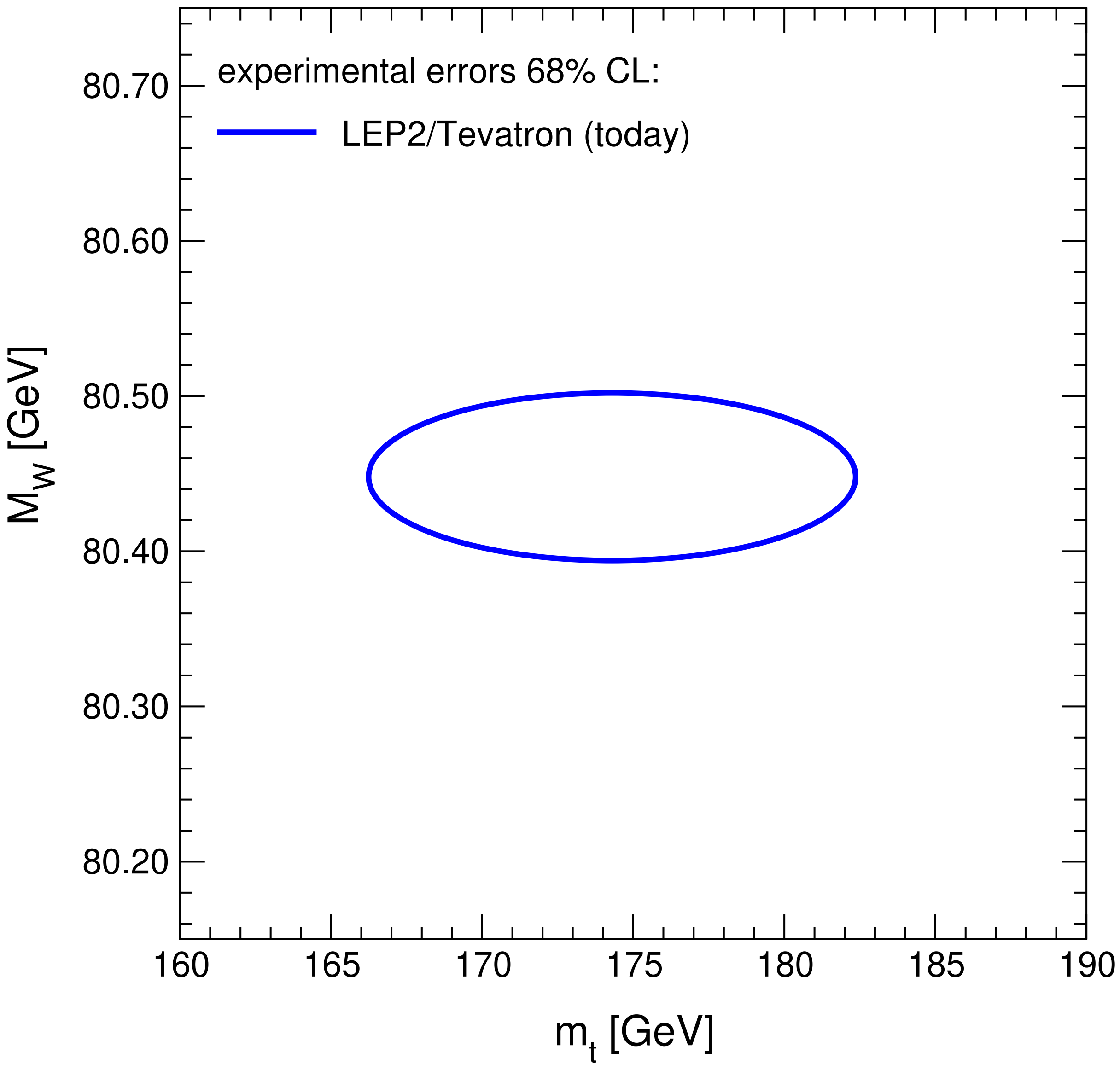
Example I: SM vs. MSSM



$\Rightarrow$ not an LC issue

Example II: (SUSY assumed)

$$\left.\begin{array}{l} g_\mu - 2 \\ \mathrm{BR}(b \to s\gamma) \end{array}\right\} \mu \times M_2 > 0,\ A_t \times \mu < 0 \text{ preferred}$$



experimental errors 68% CL:
LEP2/Tevatron (today)
80.70
80.60
80.50
80.40
80.30
80.20
M_W [GeV]
160
165
170
175
180
185
190
m_t [GeV]

Best SUSY precision observable:

the mass of the lightest Higgs boson: m_h

Tree level: $m_h < M_Z$

Yukawa couplings: $\frac{\mathrm{e}\, m_t}{2 M_W s_w}, \; \frac{\mathrm{e}\, m_t^2}{M_W s_w}, \; \ldots$

Dominant corrections to m_h from $t - \tilde{t}$-sector :

$$\Delta m_h^2 \;\sim\; \frac{m_t^4}{M_W^2} \log\left(\frac{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}{m_t^4}\right)$$

$$\approx\; \frac{m_t^4}{M_W^2} \log\left(\frac{(M_{\mathrm{SUSY}}^2 + m_t^2)^2 - m_t^2 X_t^2}{m_t^4}\right)$$

$$(M_{\mathrm{SUSY}} = M_{\tilde{t}_L} = M_{\tilde{t}_R})$$

Two-loop calculation $\Rightarrow m_h \lesssim 135$ GeV
($M_{\mathrm{SUSY}} \leq 1000$ GeV, $m_t = 175$ GeV)
[S.H., W. Hollik, G. Weiglein '98]

Measurement of Higgs masses and couplings:

$\Rightarrow$ Information about soft SUSY-breaking parameters / $\tilde{t}$ parameters

Expectations from the LC/GigaZ:

	now	LC	GigaZ
M_W [MeV]	33	10	7
$\sin^2\theta_{\text{eff}}$ [$\times 10^{-5}$]	17	?	1.3
m_h [MeV]	$---$	50	$---$
M_{SUSY}	$---$	$\mathcal{O}(1\%)$	$---$
m_t [GeV]	5.1	0.2	0.13

- M_W:
  LC: δM_W in the continuum
  [K. Mönig, A. Tonazzo '00]
  GigaZ: δM_W from threshold scan
  $\Rightarrow e^+$ polarization needed
  [G. Wilson '99] [U. Baur et al. '01]
- $\sin^2\theta_{\text{eff}}$:
  measurement of doubly pol. cross sections
  2$\Rightarrow e^+$ polarization needed
  [R. Hawkings, K. Mönig '99]
- m_h:
  experimental error dominated by theory error
  $\delta m_h^{\text{theo,curr}} \approx 3$ GeV, $\delta m_h^{\text{theo,fut}} \approx 0.5$ GeV
  [M. Frank, S.H., W. Hollik, G. Weiglein '01]
- M_{SUSY}:
  outside kin. reach: LHC uncertainty: $\sim \mathcal{O}(10\%)$
- m_t: better at GigaZ due to better α_s meas.

Status of calculations in the MSSM:

- MSSM, Δr: full one-loop corrections
  [*P. Chankowski, A. Dabelstein, W. Hollik, W. Mösle, S. Pokorski, J. Rosiek '94*]
  [*D. Garcia, J. Solà '94*]
- MSSM: Z-boson observables, one-loop
  [*D. Garcia, R. Jiménez, J. Solà '95*]
  [*D. Garcia, J. Solà '95*]
  [*A. Dabelstein, W. Hollik, W. Mösle '95*]
  [*P. Chankowski, S. Pokorski '96*]
- MSSM, $\Delta\rho$: leading $\mathcal{O}(\alpha\alpha_s)$ corrections
  [*A. Djouadi, P. Gambino, S.H., W. Hollik, C. Jünger, G. Weiglein '97*]
  [*S.H., W. Hollik, G. Weiglein '98*]
- MSSM, Δr: leading gluonic $\mathcal{O}(\alpha\alpha_s)$ corr.
  [*S.H. '98*]
- MSSM, $\Delta\rho$: leading $\mathcal{O}\left(G_F^2 m_t^4\right)$ corrections ($M_{\text{SUSY}} \to \infty$)
  [*S.H., G. Weiglein '01*]

Missing:

- MSSM, $\Delta\rho$: leading $\mathcal{O}\left(G_F^2 m_t^4\right)$ corrections ($M_{\text{SUSY}} \neq \infty$)
- MSSM, Δr, $\sin^2\theta_{\text{eff}}$: subleading $\mathcal{O}\left(G_F^2 m_t^2\right)$

Status of m_h prediction in the MSSM:

- Complete one-loop result:
  $\delta m_h \lesssim$ 50 – 100 GeV
  [*P. Chankowski, S. Pokorski, J. Rosiek '94*]
  [*A. Dabelstein '95*]

- Leading logs at two-loop, $\mathcal{O}(\alpha\alpha_s)$:
  $\delta m_h \lesssim$ 10 – 20 GeV
  [*J. Casas, J. Espinosa, M. Quirós, A. Riotto '95*]
  [*M. Carena, M. Quirós, C. Wagner '95*]
  [*H. Haber, R. Hempfling, A. Hoang '97*]
  [*S.H., W. Hollik, G. Weiglein '98*]

- Leading non-log corrections at $\mathcal{O}(\alpha\alpha_s)$:
  $\delta m_h \lesssim\ \sim 5$ GeV
  [*S.H., W. Hollik, G. Weiglein '98*]

- Leading $\mathcal{O}\left(G_F^2 m_t^6\right)$ terms:
  $\delta m_h \lesssim\ \sim 3$ GeV
  [*M. Carena, M. Quirós, C. Wagner '95*]
  [*H. Haber, R. Hempfling, A. Hoang '97*]

- Subleading $\mathcal{O}\left(G_F^2 m_t^6\right)$ terms:
  $\delta m_h \lesssim\ \sim 3$ GeV
  [*J. Espinosa, R. Zhang '00*]
  [*A. Brignole, G. Degrassi, P. Slavitch, F. Zwirner '01*]

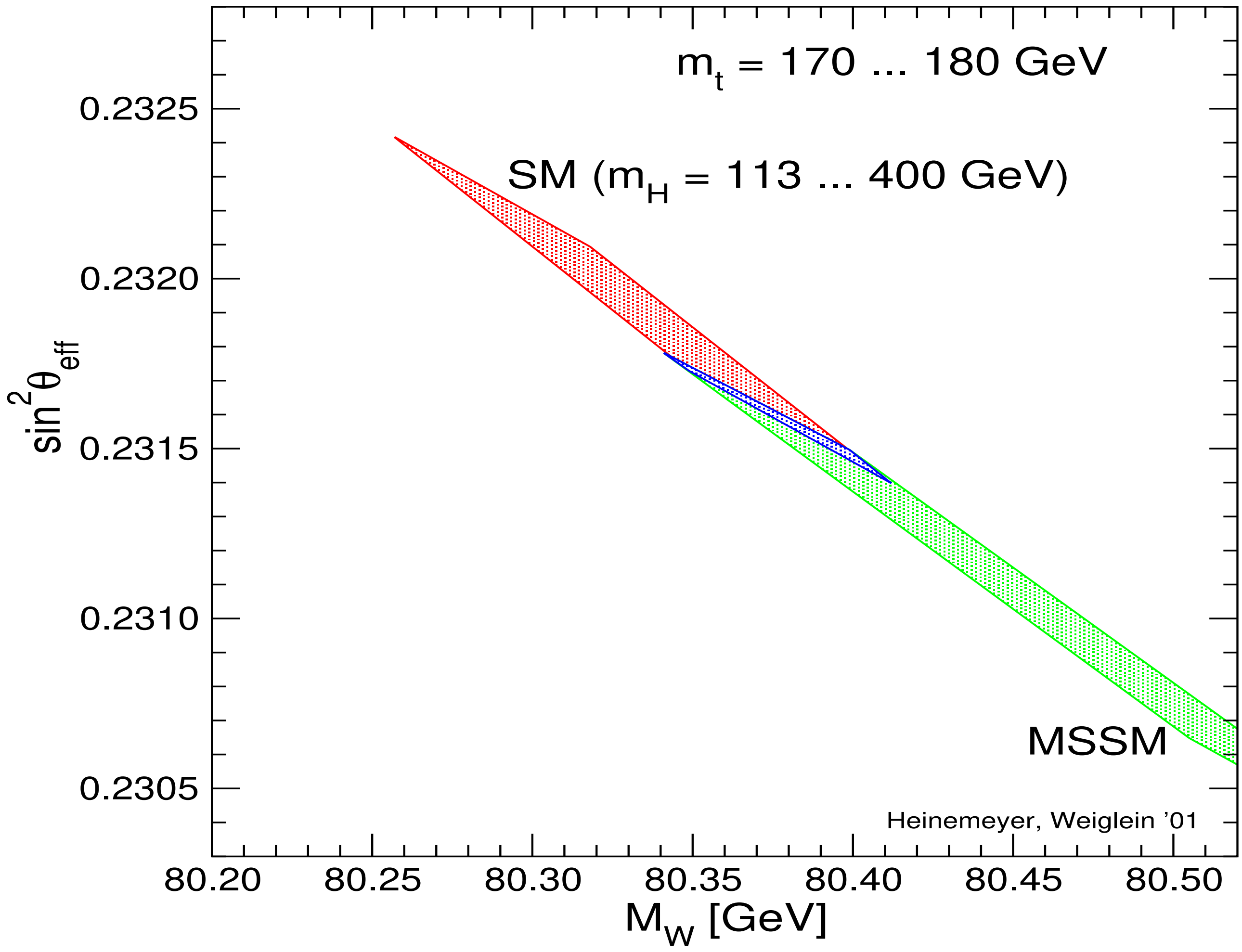
...obtained in EP, RGiEP and FD approach

MSSM consistency check:

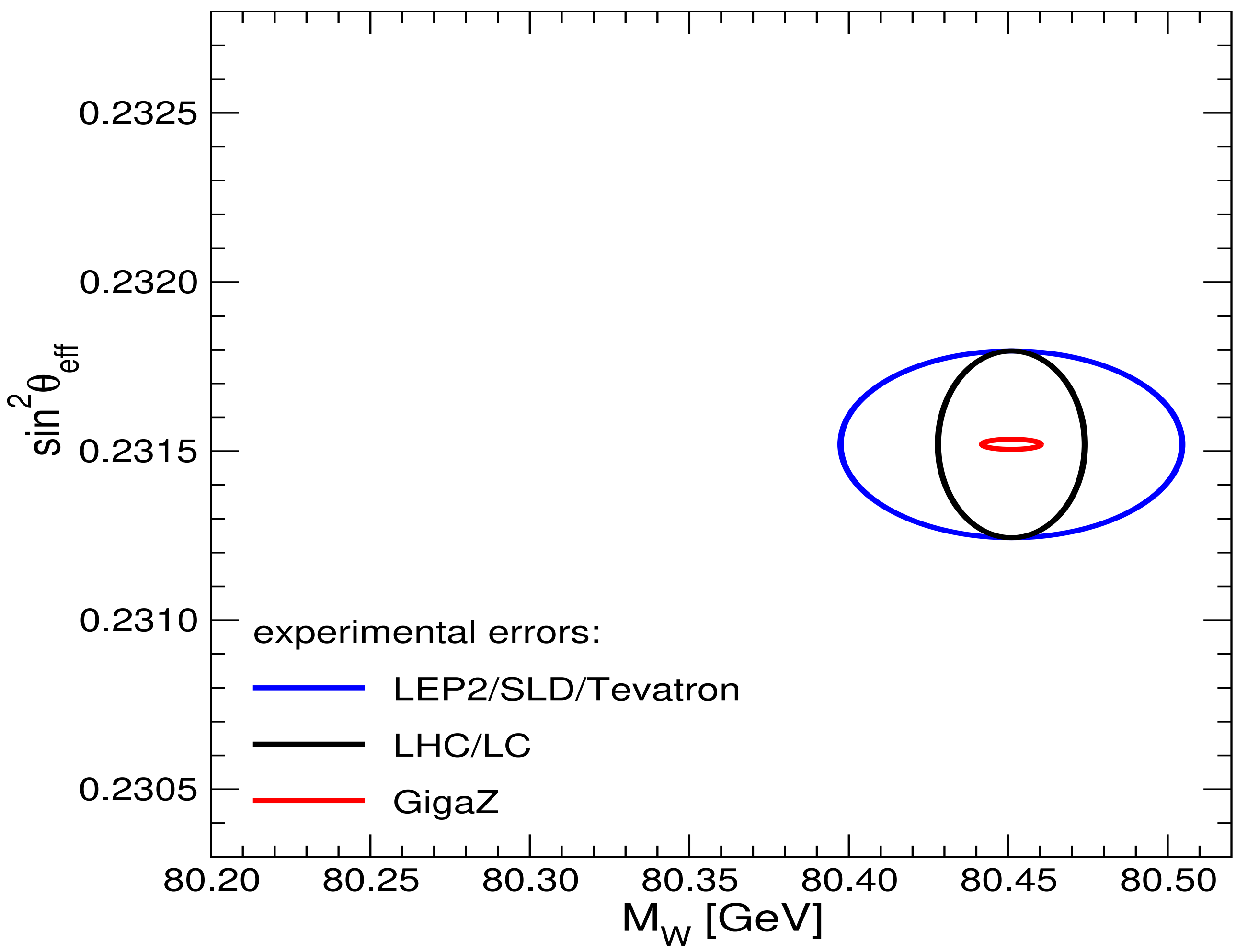
Prediction for M_W, $\sin^2\theta_{\mathrm{eff}}$ in the SM and MSSM

vs. prospective accuracies at

LEP2/SLD/Tevatron , LHC/LC, GigaZ:



$\Rightarrow$ Highly non-trivial check of the MSSM with GigaZ


0.2325
0.2320
0.2315
0.2310
0.2305
$\sin^2\theta_{eff}$
80.20
80.25
80.30
80.35
80.40
80.45
80.50
M_W [GeV]
experimental errors:
LEP2/SLD/Tevatron
LHC/LC
GigaZ

m_h as precision observable

$\Rightarrow$ Constraints on $m_{\tilde{t}_1}$, $m_{\tilde{t}_2}$, $\theta_{\tilde{t}}$, M_A, $\tan\beta$, ...

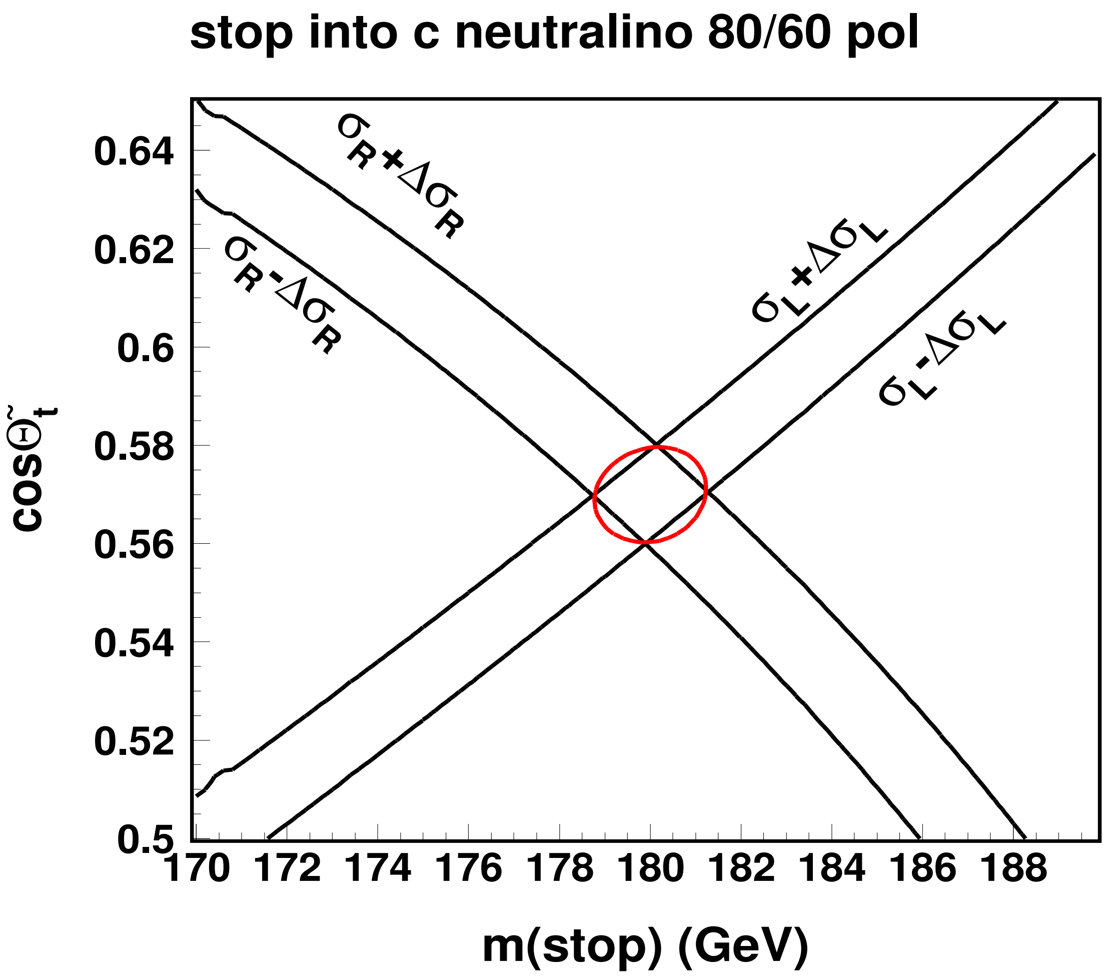
Combination of direct and indirect
information on $\tilde{t}$ sector parameters

Direct information:

$e^+e^- \to \tilde{t}_1\tilde{t}_1$ at LC, $\sqrt{s} = 500$ GeV, $\mathcal{L} = 500$ fb^{-1}

80% pol. e^- beam, 60% pol. e^+ beam

[*R. Keränen, H. Nowak, A. Sopczak '00*]



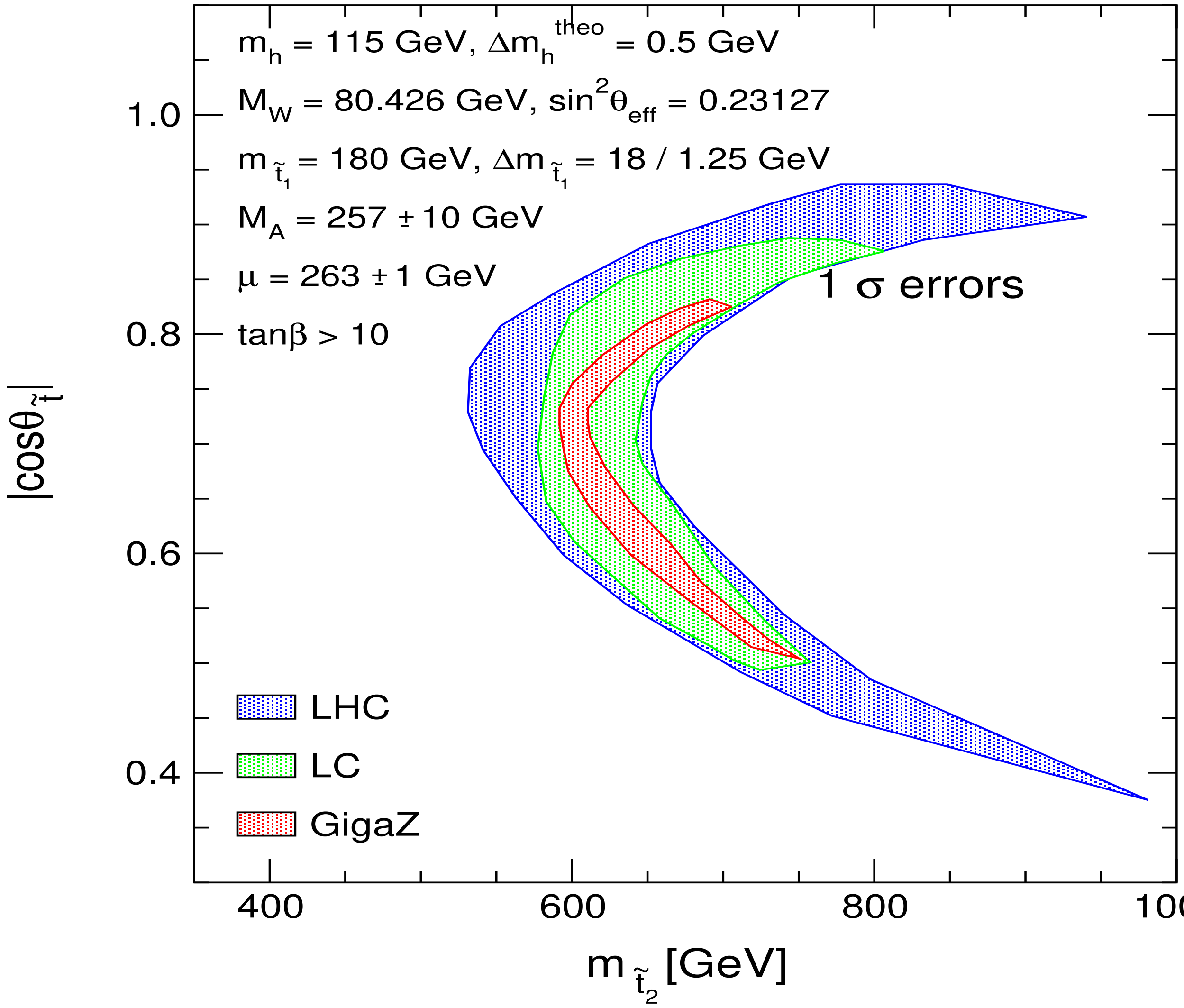
$\Rightarrow$ Precise determination of $m_{\tilde{t}_1}$, $\theta_{\tilde{t}}$

Indirect constraints on $m_{\tilde{t}_2}$, $\theta_{\tilde{t}}$ from precise measurement of m_h, M_W, $\sin^2\theta_{\mathrm{eff}}$ at LC/GigaZ :

$$\delta M_W = 7 \text{ MeV}$$
$$\delta \sin^2\theta_{\mathrm{eff}} = 1 \times 10^{-5}$$
$$\delta m_h^{\mathrm{theo}} = 0.5 \text{ GeV}$$

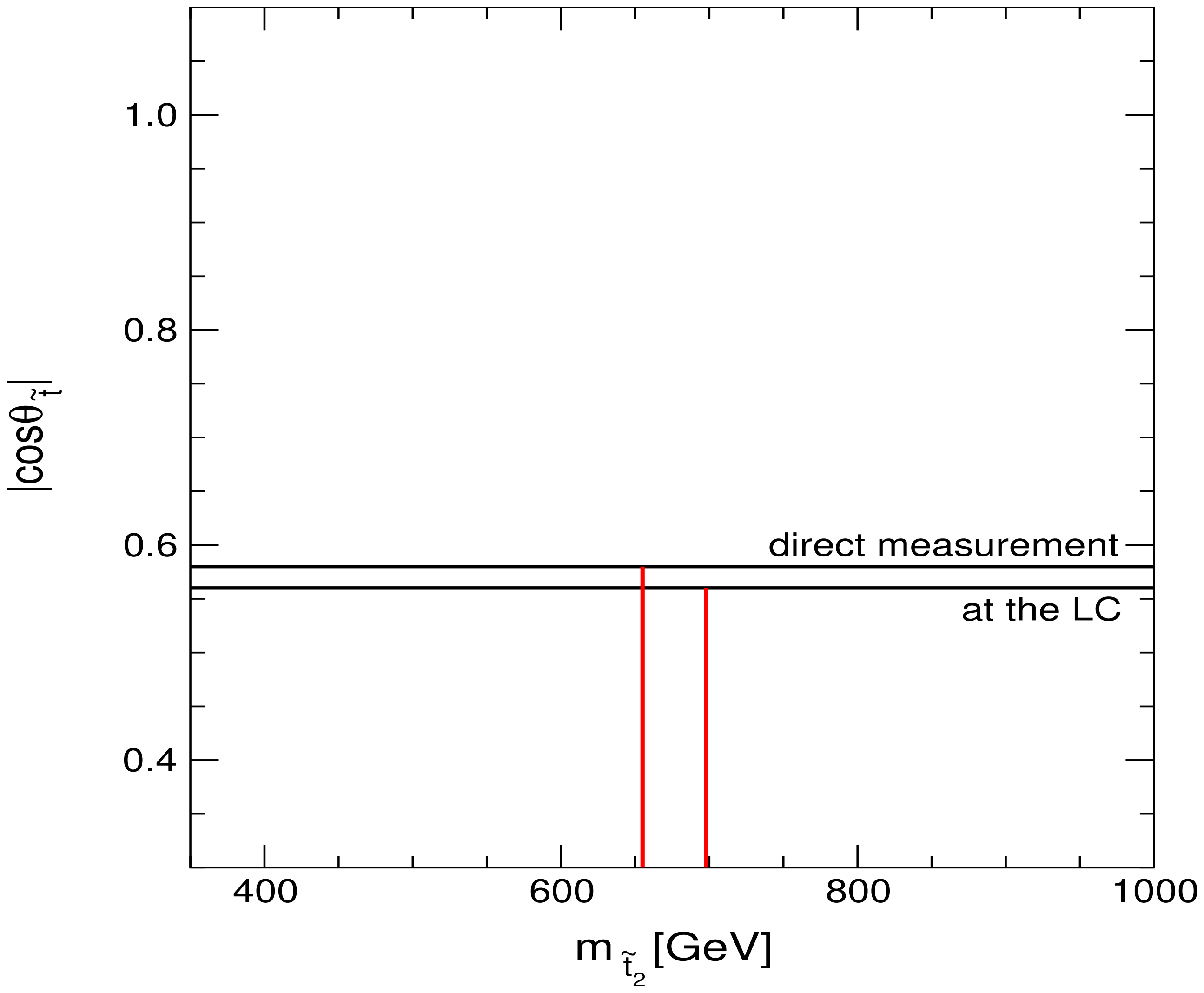
Allowed region in $m_{\tilde{t}_2}$–$\theta_{\tilde{t}}$ plane ($m_h = 115$ GeV):

[S.H., G. Weiglein '00]



⇒ Direct/indirect information is complementary

Indirect determination of $m_{\tilde{t}_2}$ with high precision



direct measurement
at the LC
$|\cos\theta_{\tilde{t}}|$
$m_{\tilde{t}_2}$ [GeV]
1.0
0.8
0.6
0.4
400
600
800
1000

SUSY particles/light Higgs boson:

LC provides high accuracy measurements

But . . .

meaningful only if matched with theoretical prediction at the same level of accuracy

Necessary:

– SUSY mass predictions to $\mathcal{O}(1\%)$

– SUSY production prediction to the 1% level

– Higgs mass prediction to $\delta m_h^{\text{theo}} \approx 0.2$–$0.5$ GeV

$\Rightarrow$ Need more than factor 3-10 improvement in uncertainty from unknown higher-order corrections

Much calculational effort needed

Have to start now to be ready at LC start !!

Theoretical calculations should be viewed as an essential part of all future High Energy Physics programs

4. LC vs. LHC

Mass reach:

	LHC	LC
Squarks [GeV]	~ 2500	~ 500
Gluinos [GeV]	~ 2500	??
Sleptons [GeV]	~ 350	~ 500
Gauginos [GeV]	~ 200	~ 500

$\Rightarrow$ LC and LHC are complementary

Precision in mass measurement:

	LHC	LC
Squarks	$\sim 10\%$	$\lesssim 1\%$
Gluinos	$\sim 10\%$	??
Sleptons	$\sim 10\%$	$\lesssim 1\%$
Gauginos	$\sim 10\%$	$\lesssim 1\%$

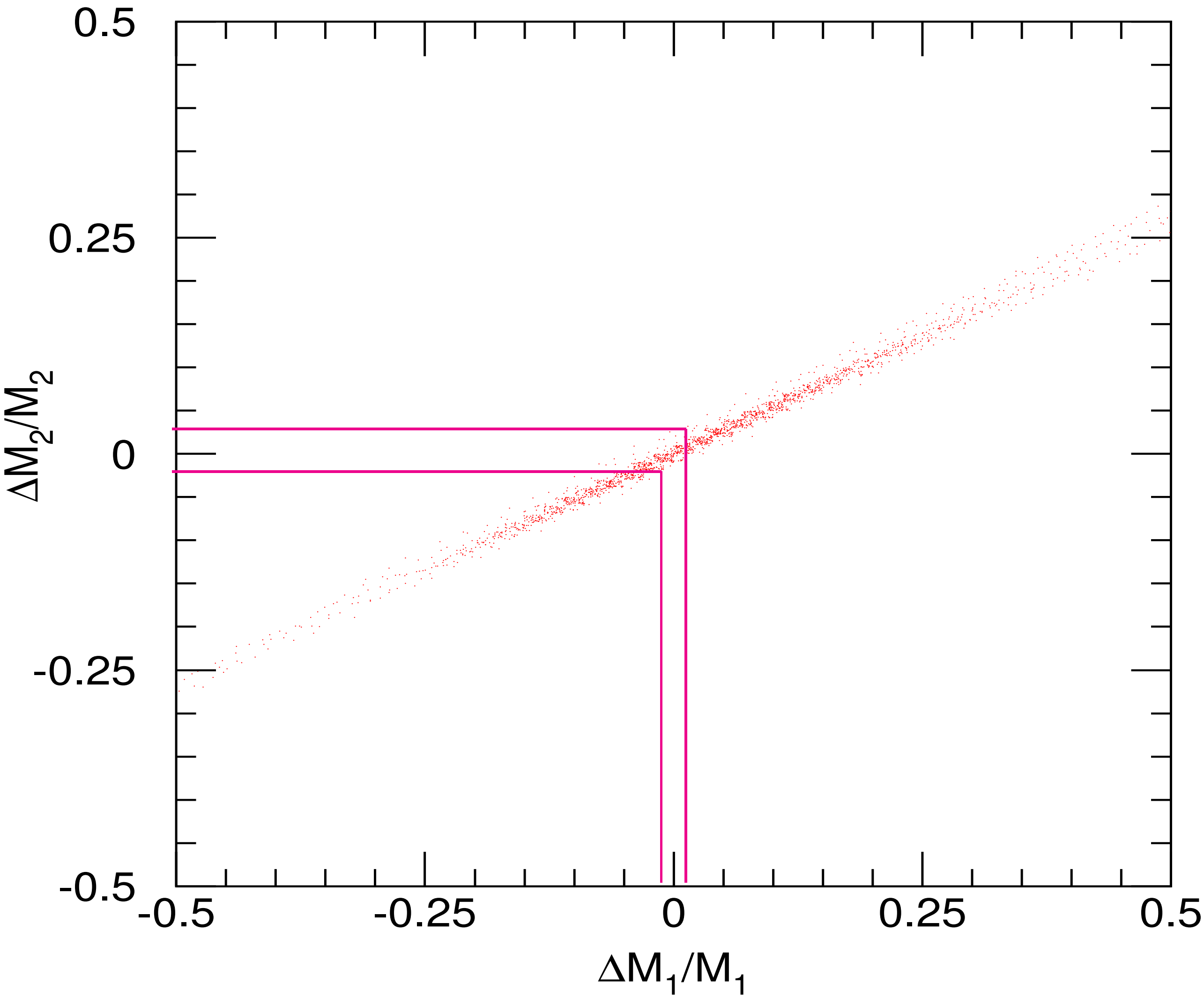
$\Rightarrow$ LC much better

LC can decrease LHC uncertainties:

Main source for LHC uncertainty: $\delta m_{\tilde{\chi}_1^0}$

LC uncertainty: $\delta m_{\tilde{\chi}_1^0} = 0.1 - 1$ GeV

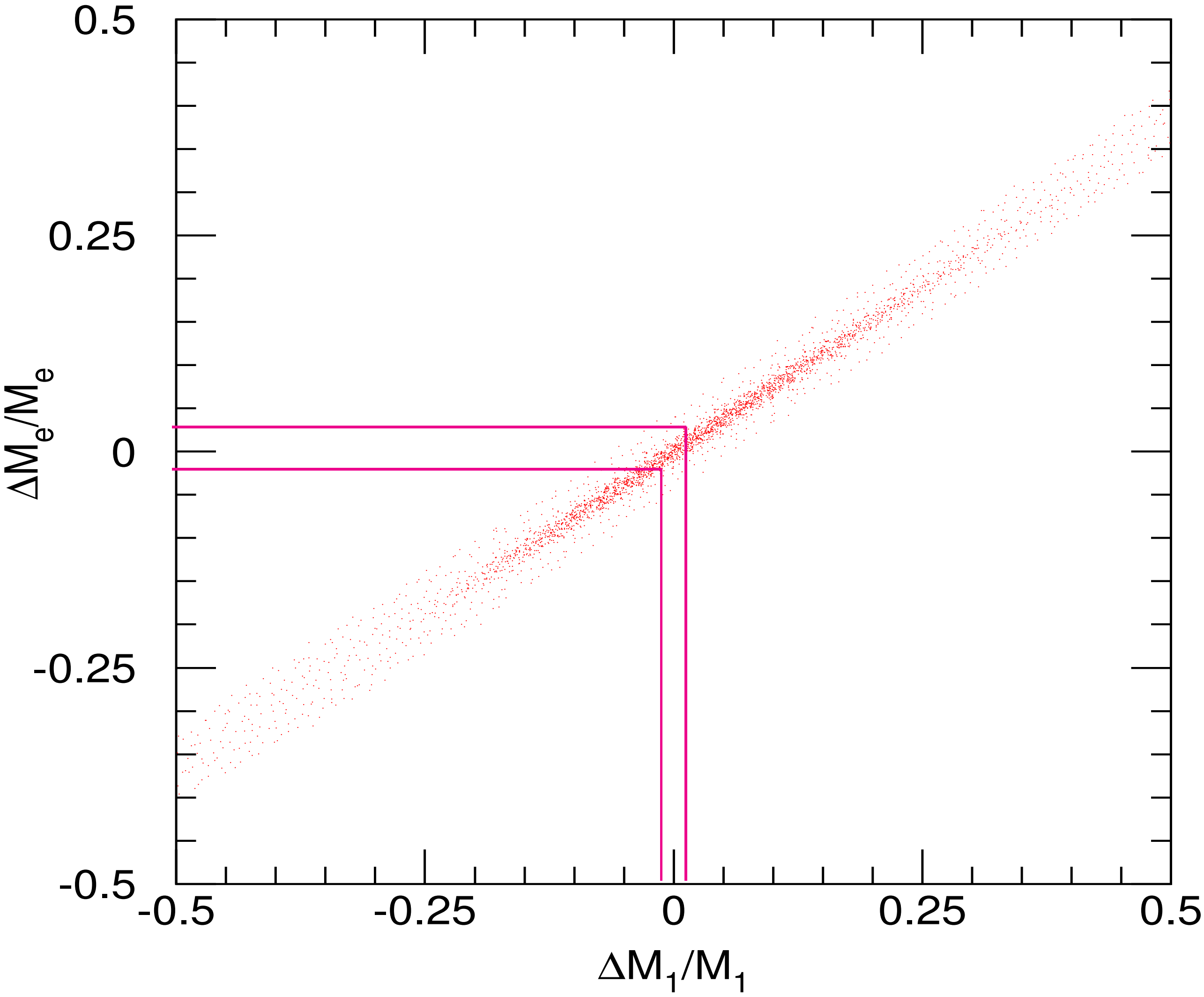
Example I: $m_{\tilde{\chi}_2^0}$



[*ATLAS TDR*]

$\Rightarrow$ $\delta m_{\tilde{\chi}_2^0} \approx 2\%$ possible

Example II: $m_{\tilde{e}}$



[*ATLAS TDR*]

$\Rightarrow$ $\delta m_{\tilde{e}} \approx 2\%$ possible

$\Rightarrow$ applicable to all LHC mass determinations
(not worked out yet)

$\Rightarrow$ topic at next european LC workshop 04/02

What the LC does (much) better:

(if particles are in the kinematic reach)

- determination of spin and quantum numbers
- measurement of $\mathcal{CP}$ violating phases
- measurement of sfermion mixing angles
- determination of mixing parameters of gauginos
- better model independent determination of SUSY parameters
- distinguish between $\tilde{l}_L$ and $\tilde{l}_R$
  $\Rightarrow$ polarized beams necessary
- measurement of branching ratios of SUSY particles
- determination of $\tan\beta$

5. Conclusinos

- task: establish SUSY
  (masses, quantum numbers, ...)
- SPS: Snowmass points and slopes

  new benchmark scenarios for SUSY search

  (6 mSUGRA, 2 GMSB, 1 AMSB + ...)
- Sfermion production:
  - full 1-loop corrections
  - finite width effects

  Pattern of SUSY breaking
- Gaugino production:
  - full 1-loop corrections
  - finite width effects

  Reconstruction of fundamental parameters
- Reconstruction of GUT scale

  $\to$ LC precision necessary
- Indirect SUSY:

  $\to$ m_h best precision observable

  $\to$ sensitivity to $m_{\tilde{t}_2}$ with GigaZ precision
- LC complementary to LHC

  $\Rightarrow$ improved mass det. at LHC possible
- $\Rightarrow$ much work to do !!