Supersymmetry at the Linear Collider

S. Heinemeyer, BNL

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)

$\Rightarrow$ each SM multiplet is enlarged to its double size

$\Rightarrow$ 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?

$\rightarrow$ 3 experimentally verified SUSY predictions

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

#1: $m_t = 150 - 200$ GeV

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

low energy prediction via RGE $\rightarrow$ T

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

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*]

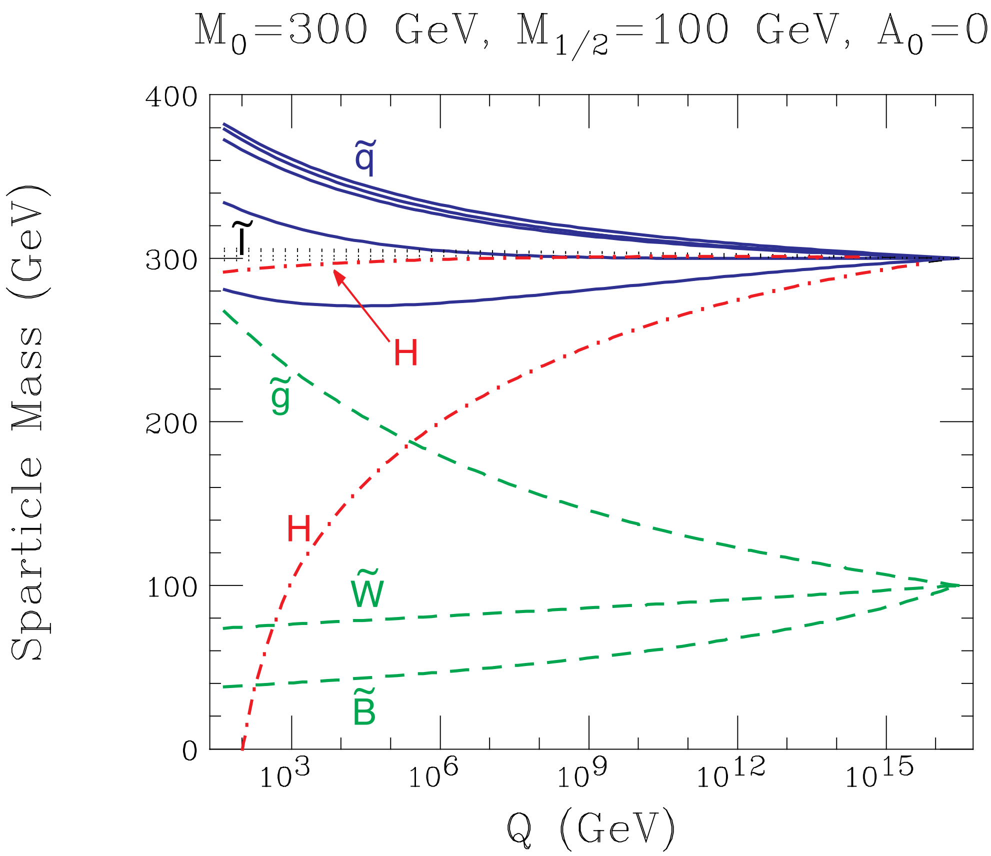
$\Rightarrow M_H \lesssim 200$ GeV, 95% C.L.

Direct search:

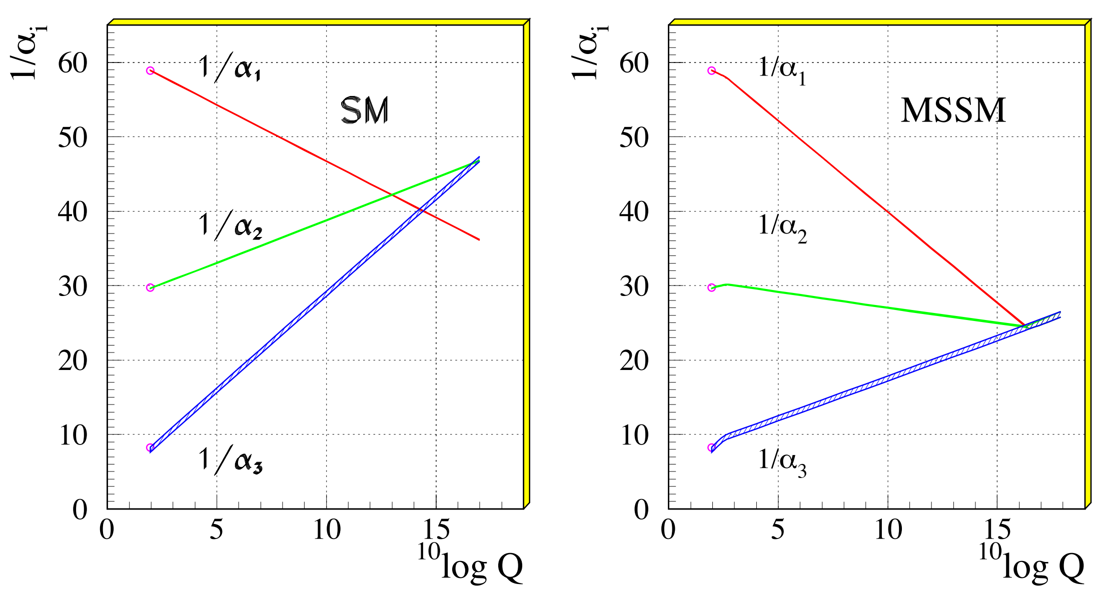
2.1σ indication of the Higgs boson at LEP:

$m_h = 115.6 \pm 1$ GeV

#3: $m_h \lesssim 135$ GeV



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



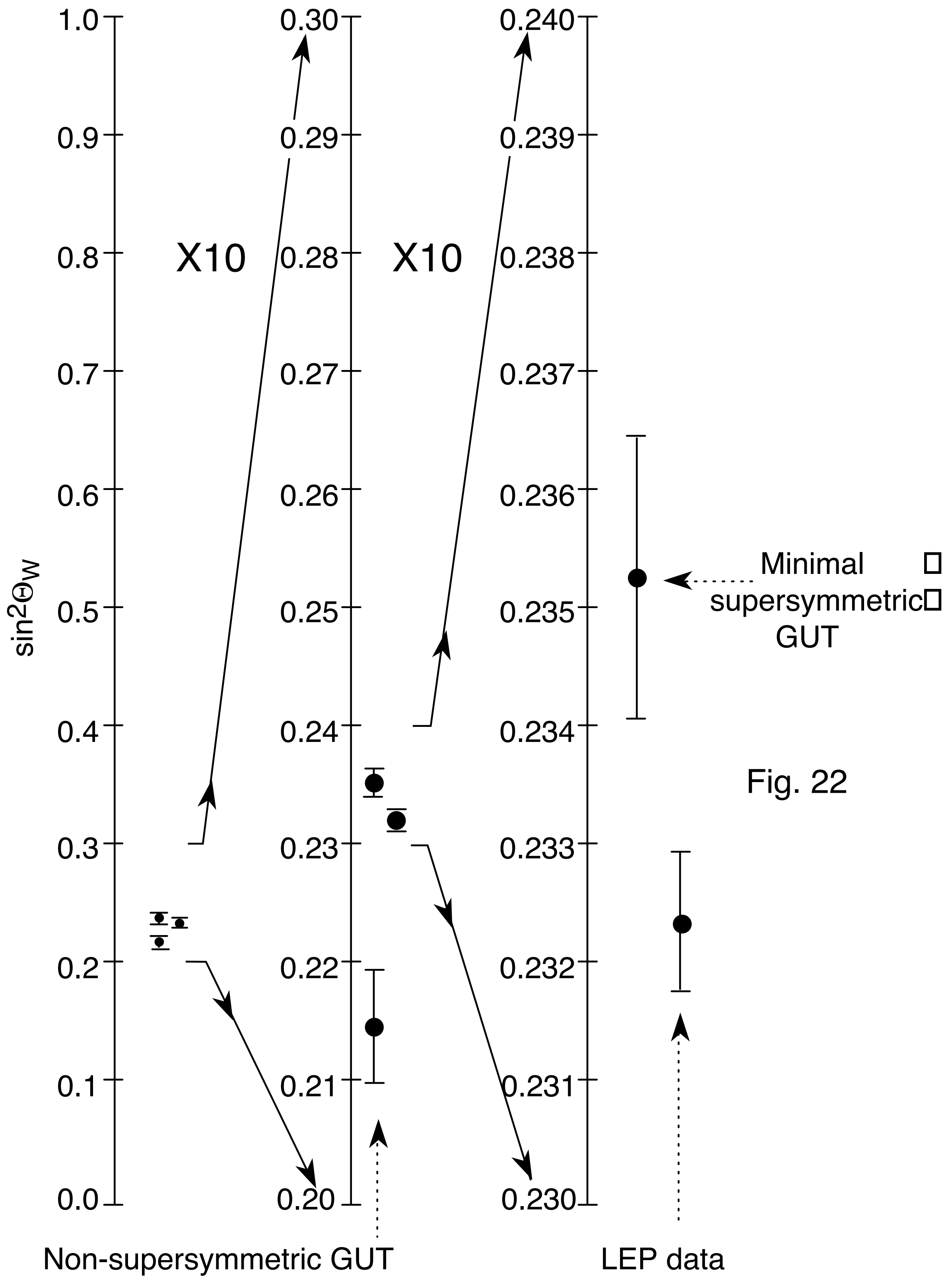

1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
$\sin^2\Theta_W$
X10
0.30
0.29
0.28
0.27
0.26
0.25
0.24
0.23
0.22
0.21
0.20
X10
0.240
0.239
0.238
0.237
0.236
0.235
0.234
0.233
0.232
0.231
0.230
Minimal
supersymmetric
GUT
Non-supersymmetric GUT
LEP data

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 $\tilde{t}_L, \tilde{t}_R$:

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

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

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

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

$\Rightarrow$ 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:

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

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

$\to$ Points and lines in the MSSM parameter space that exhibit certain MSSM characteristics

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

Points:
$\to$ detailed analyses

Slopes:
$\to$ variation in parameter space
$\to$ reach of a collider

$\Rightarrow$ should be used for future studies!
$\Rightarrow$ comparable results from different groups

SPS:

- mSUGRA : 6 scenarios
  - typical $\rightarrow$ T
  - focus point
  - coannihilation region
  - light Higgses
  - light scalar top
  - no gaugino mass unification
- GMSB : 2 scenarios
  - $\tilde{\tau}$ NLSP $\rightarrow$ T
  - $\tilde{\chi}$ NLSP
- AMSB : 1 scenario $\rightarrow$ 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*]

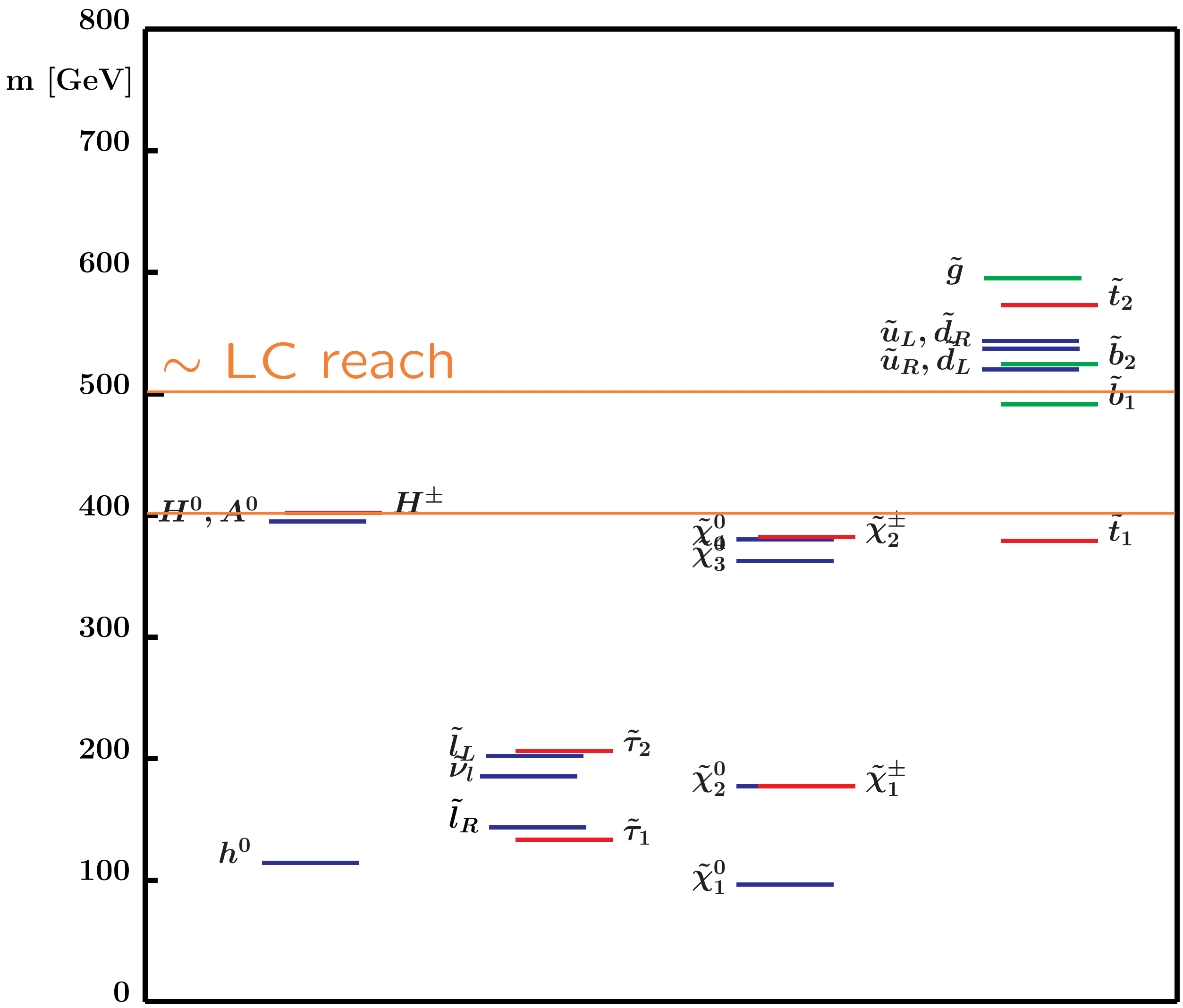
SPS1: "typical" mSUGRA scenario

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:

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



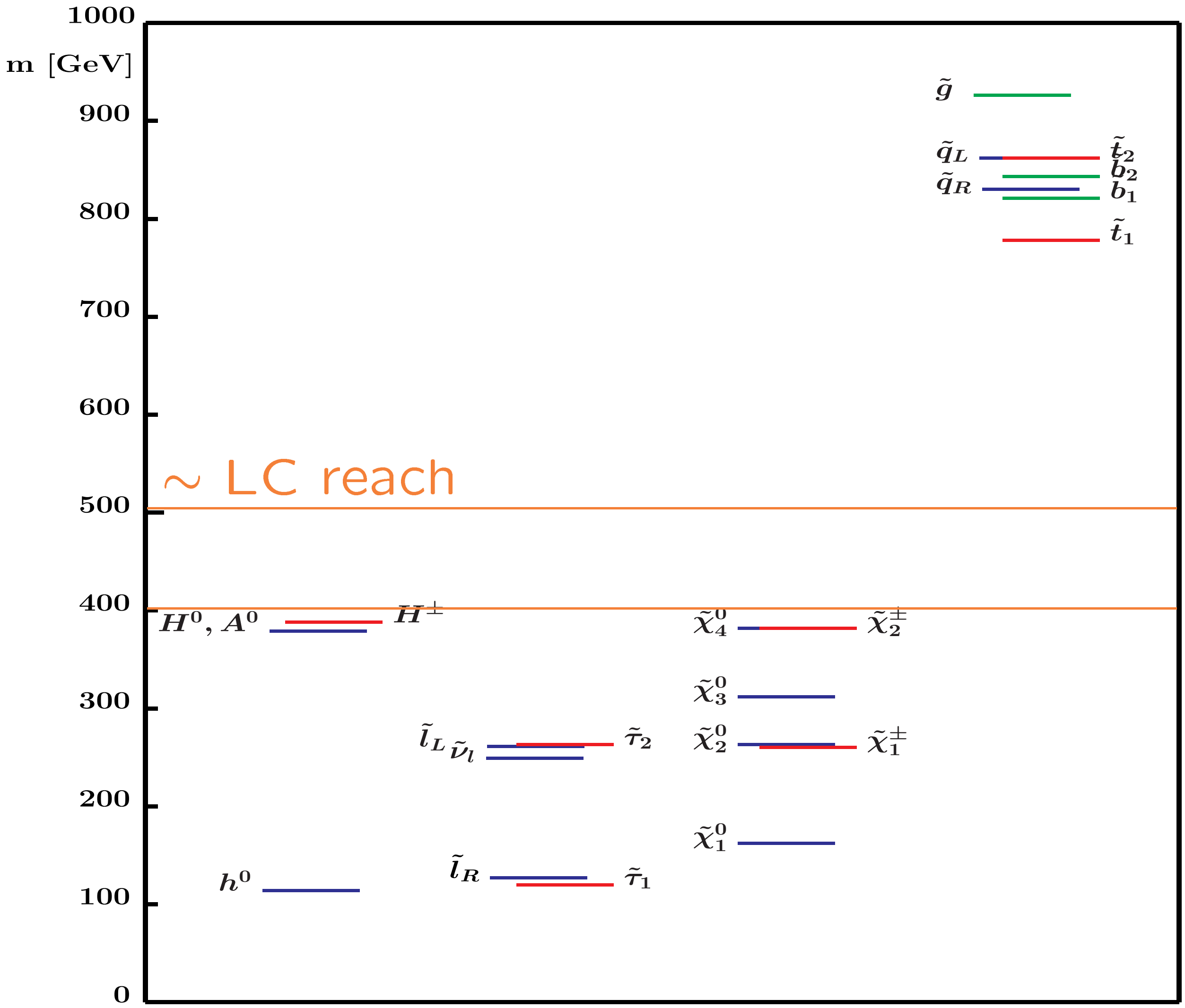
SPS7: GMSB with $\tilde{\tau}$ NLSP

Point:

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

Slope:

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



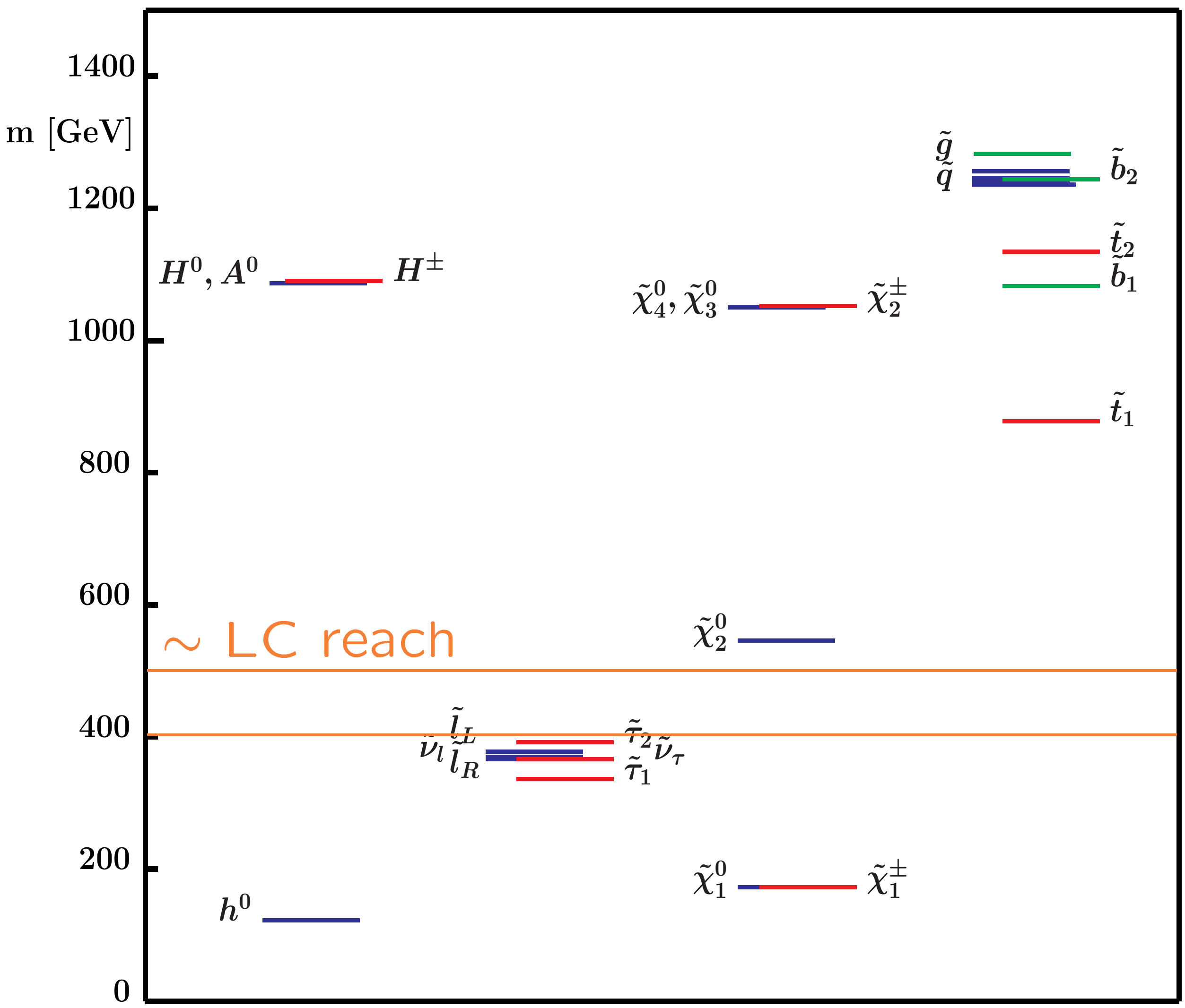
SPS9: "typical" AMSB scenario

Point:

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

Slope:

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



Production of sfermions

(studies exist for sleptons and stops)

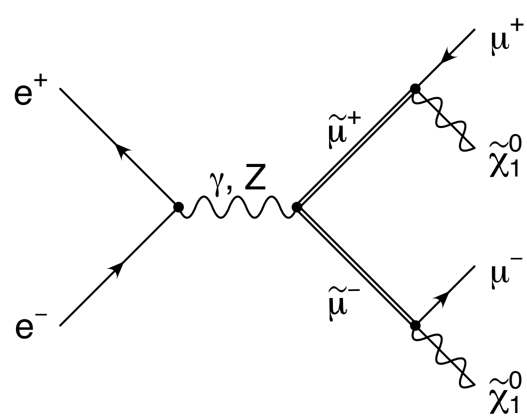
$$e^+e^- \quad \to \quad \tilde{f}_R\tilde{f}_R, \quad \tilde{f}_R\tilde{f}_L, \quad \tilde{f}_L\tilde{f}_L$$

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*]

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

   $\to$ 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

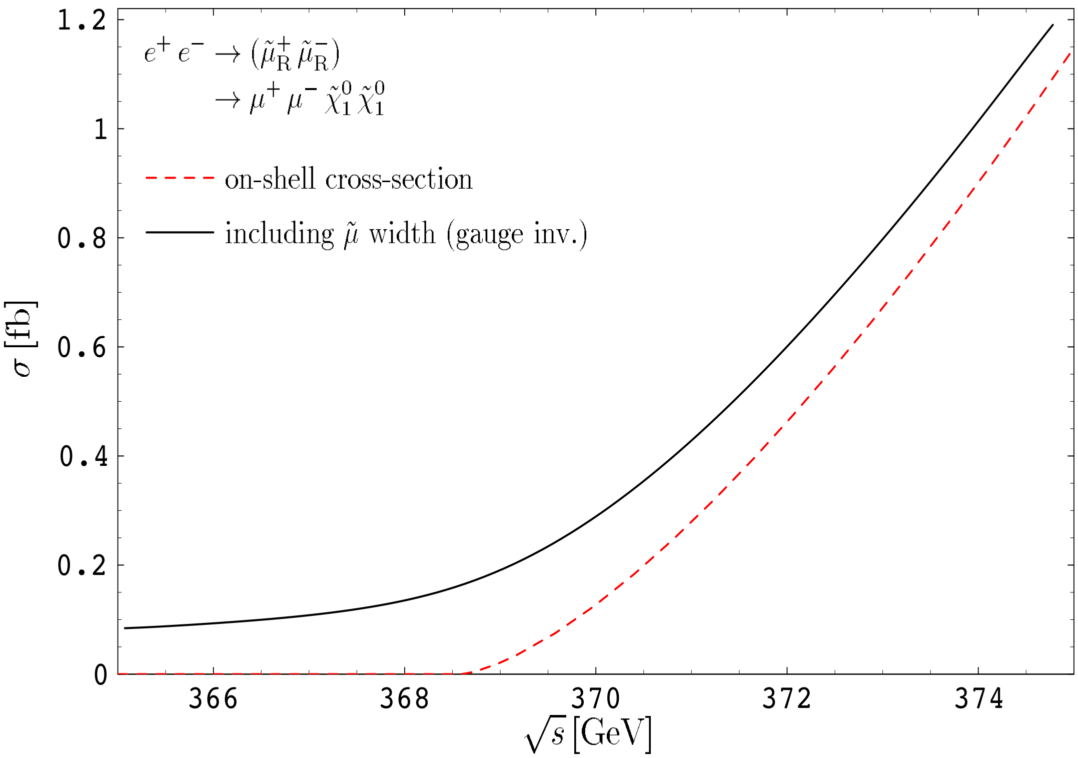
$$\begin{array}{lcll} e_L^+e_R^- / e_R^+e_L^- & \to & \tilde{e}_L^+\tilde{e}_L^-\,,\,\tilde{e}_R^+\tilde{e}_R^- & [\gamma, Z;\, \tilde{\chi}^0] \text{ [P]} \\ e_L^+e_L^- / e_R^+e_R^- & \to & \tilde{e}_R^+\tilde{e}_L^- / \tilde{e}_L^+\tilde{e}_R^- & [\tilde{\chi}^0] \quad \text{[S]} \\ e_L^-e_R^- / e_R^-e_L^-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

$\to$ T

$\Rightarrow$ polarized beams needed

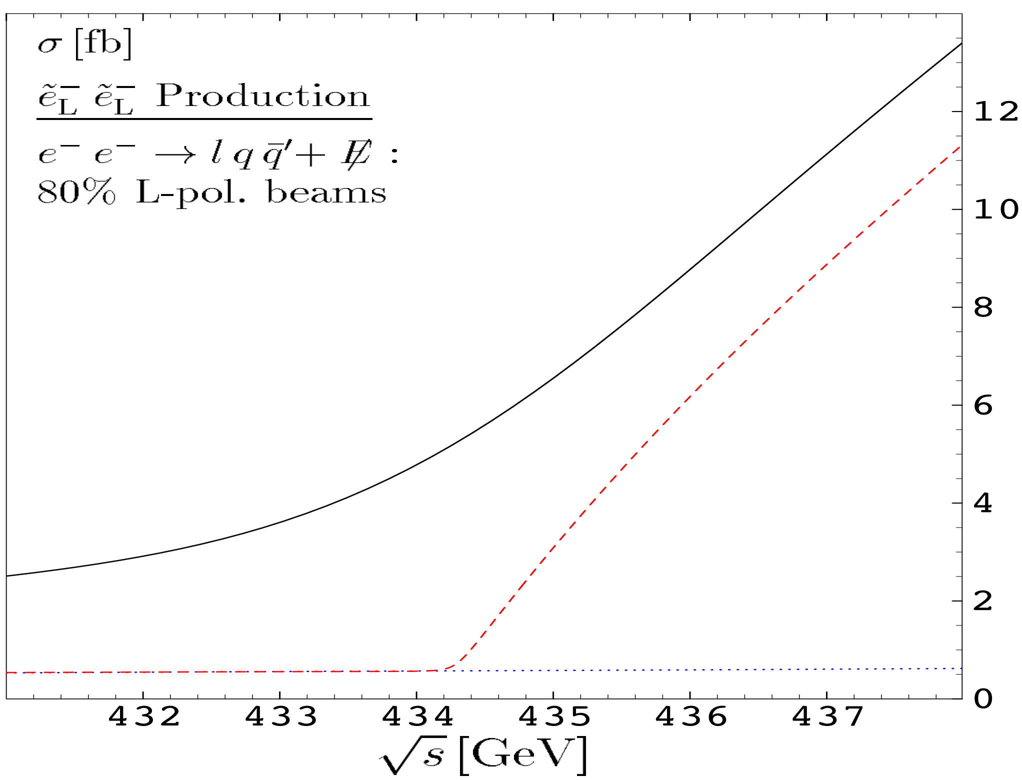
$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-$ [P]

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



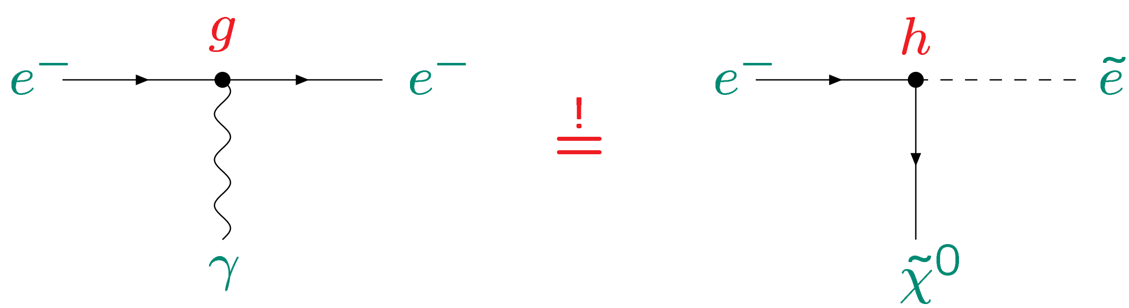
$e_L^- e_L^- \,/\, e_R^- e_R^- \to \tilde{e}_L^- \tilde{e}_L^- \,/\, \tilde{e}_R^- \tilde{e}_R^-$ [S]

[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)

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

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*]

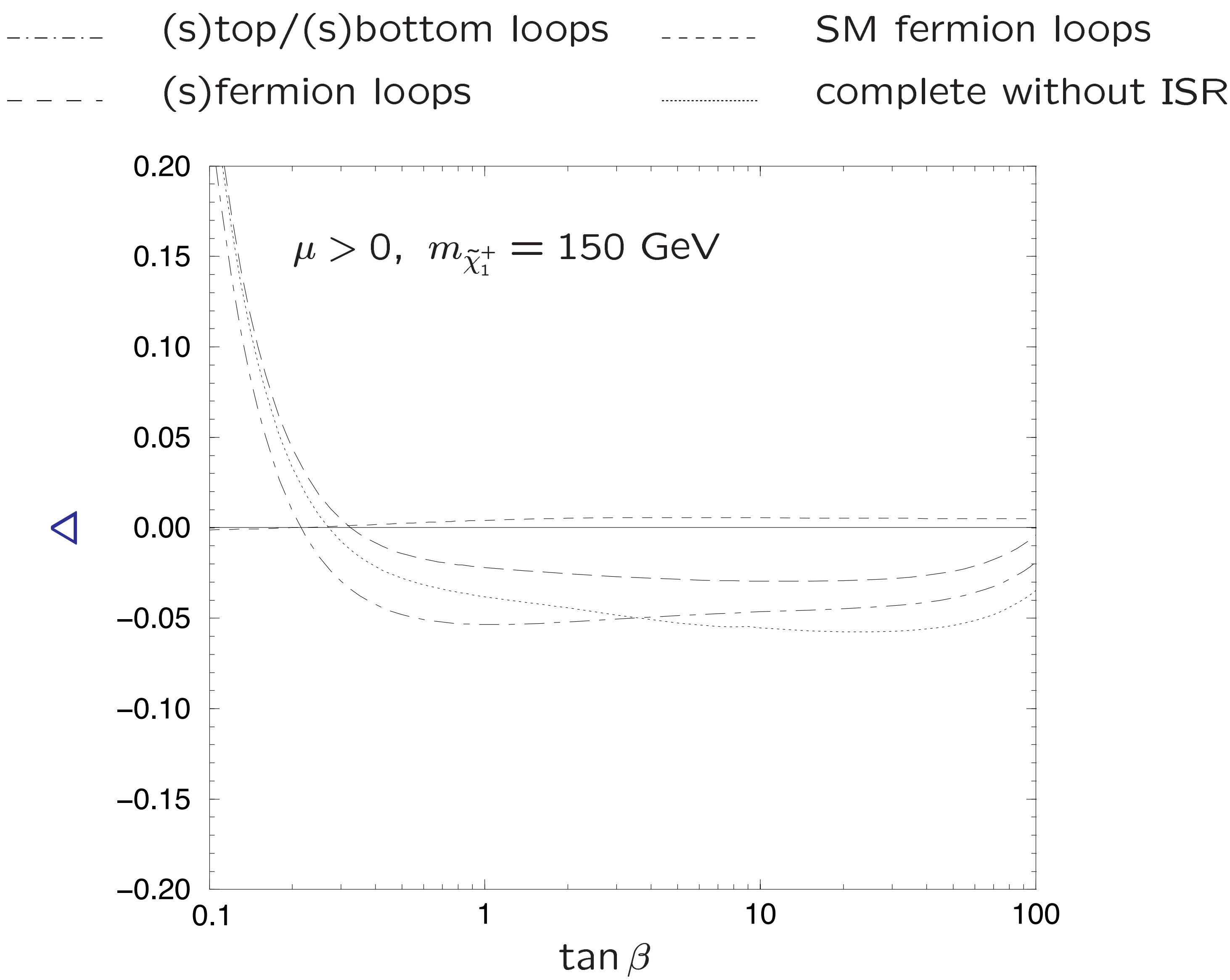
$$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_2^+ \to \tilde{\chi}_1^+\tilde{\chi}_1^+ Z \to \tilde{\chi}_1^+\tilde{\chi}_1^+ q\bar{q}$$

$\to$ T

(much work to do)

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

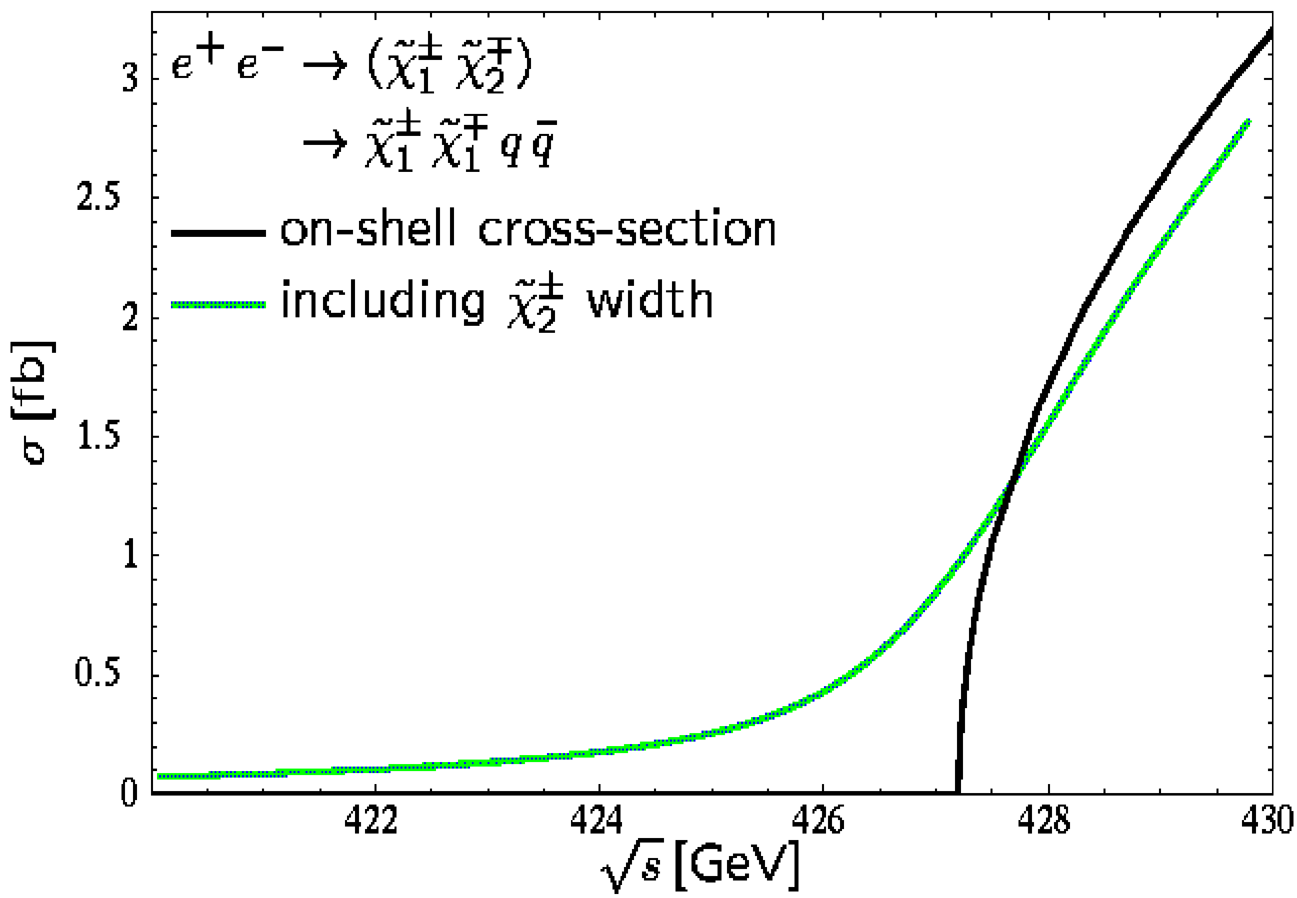
[*T. Blank, W. Hollik, '00*]



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

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

[*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 $\to$ T

$\Rightarrow$ ϕ_L and ϕ_R can be reconstructed

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

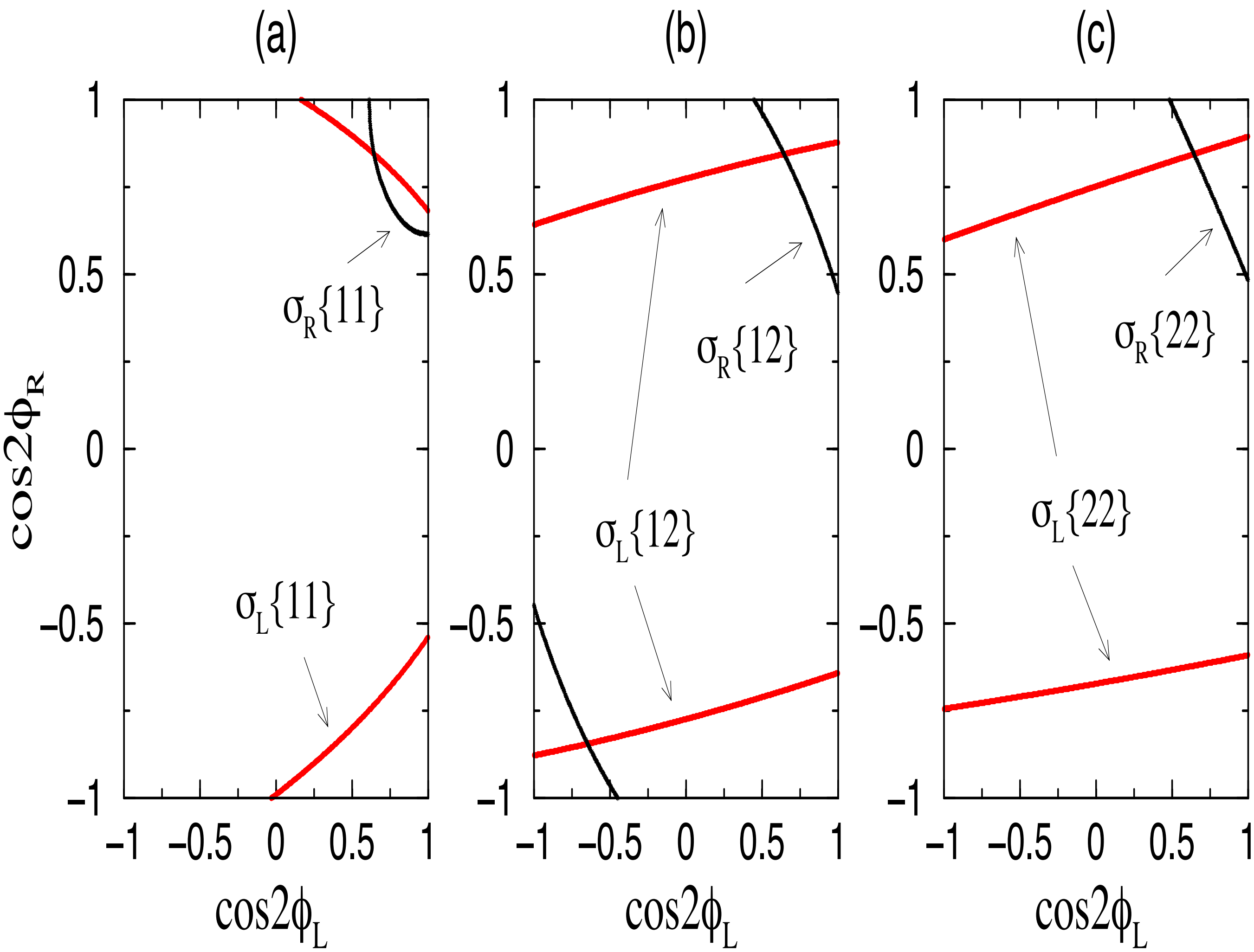
However . . .

– 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

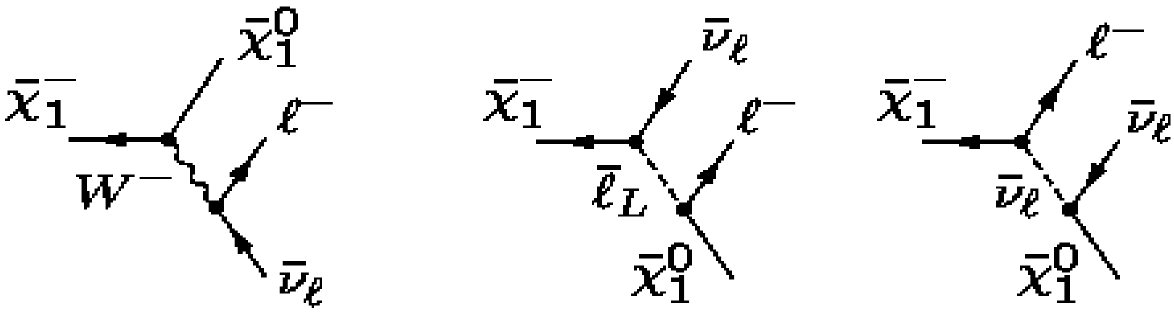
[S. Choi, A. Djouadi, M. Guchait, J. Kalinowski, K. Song, P. Zerwas '00]



$\Rightarrow$ 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 $\qquad \to$ T

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

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

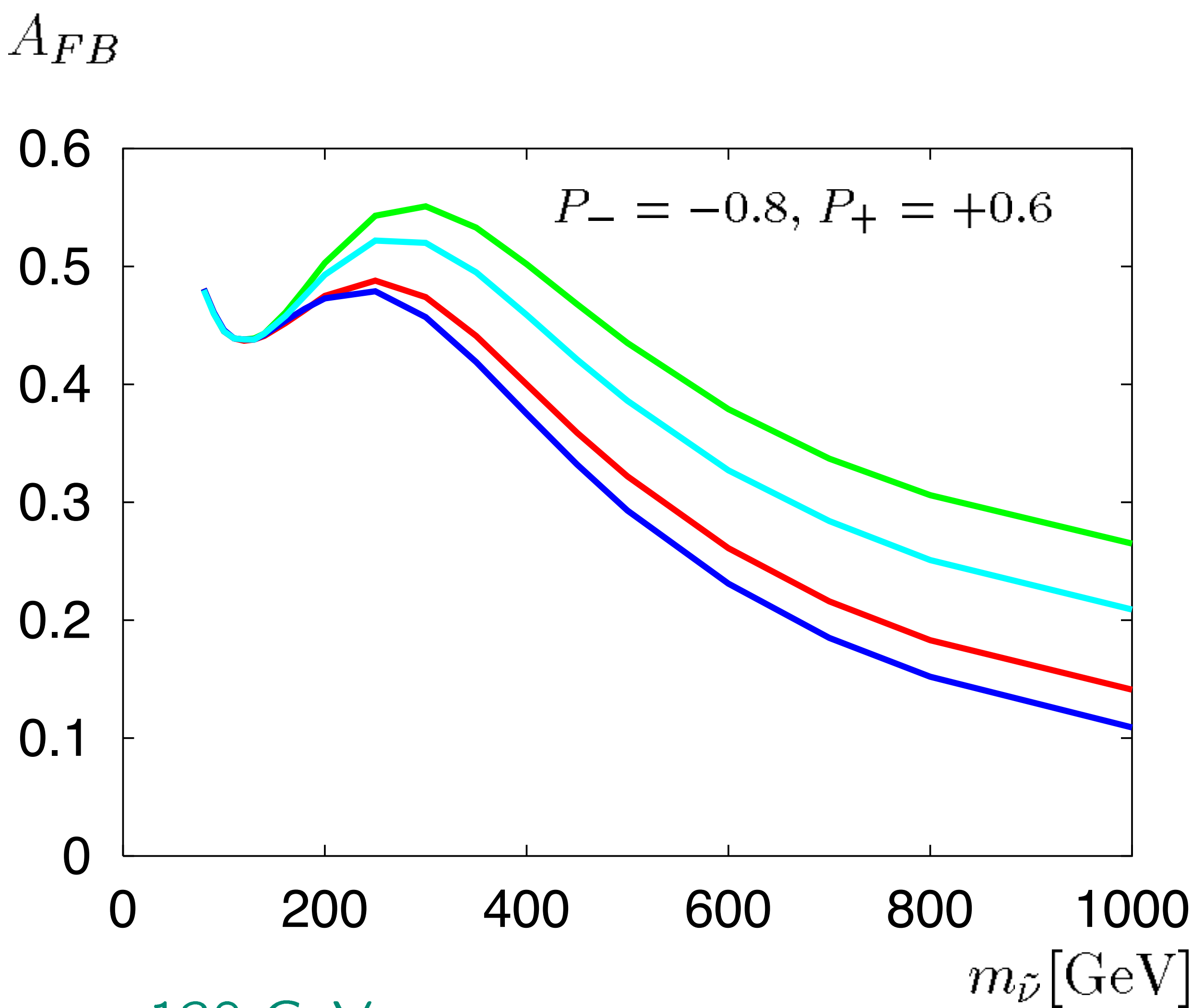
$m_{\tilde{e}_L} = 200$ GeV $\Rightarrow$ 590 GeV $\lesssim m_{\tilde{\nu}} \lesssim$ 610 GeV

$m_{\tilde{e}_L} > 250$ 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

$m_{\tilde{e}_L}^2 = m_{\tilde{\nu}}^2 - M_W^2 \cos 2\beta$

$\sqrt{s} = 500$ GeV

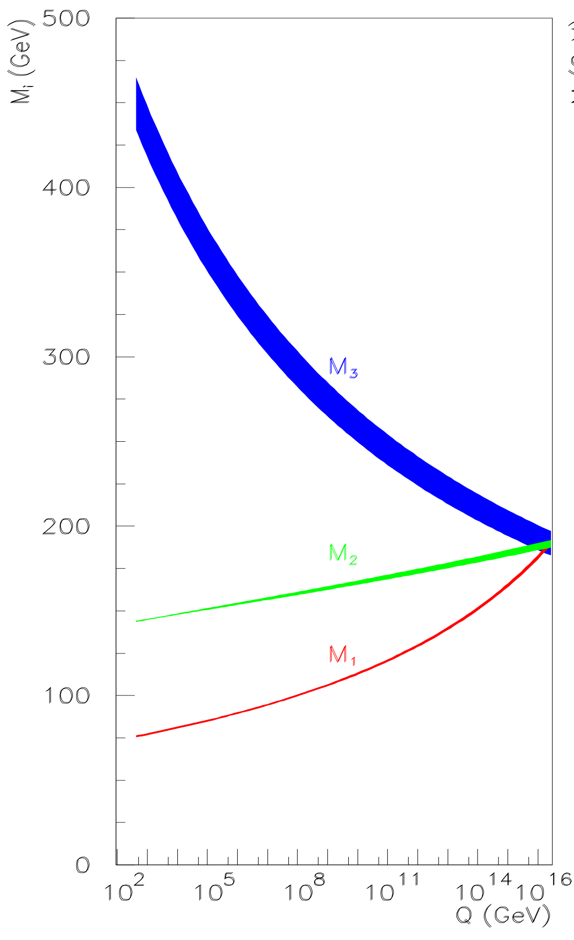
$\Rightarrow e^+$ polarization needed

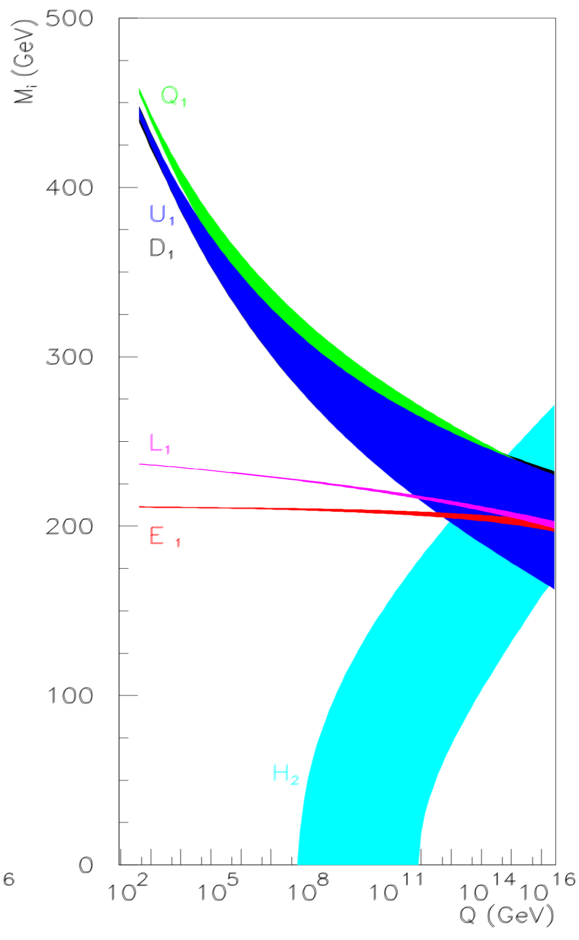
Extrapolation to the GUT scale

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

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

mSUGRA example:





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

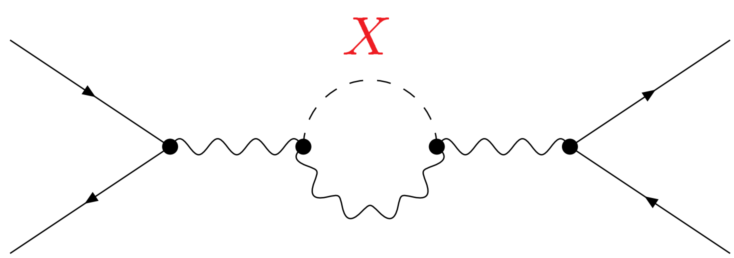
3. Indirect search/measurements

Comparison of precision observables with theory:

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

$\Downarrow$

Sensitivity to loop corrections



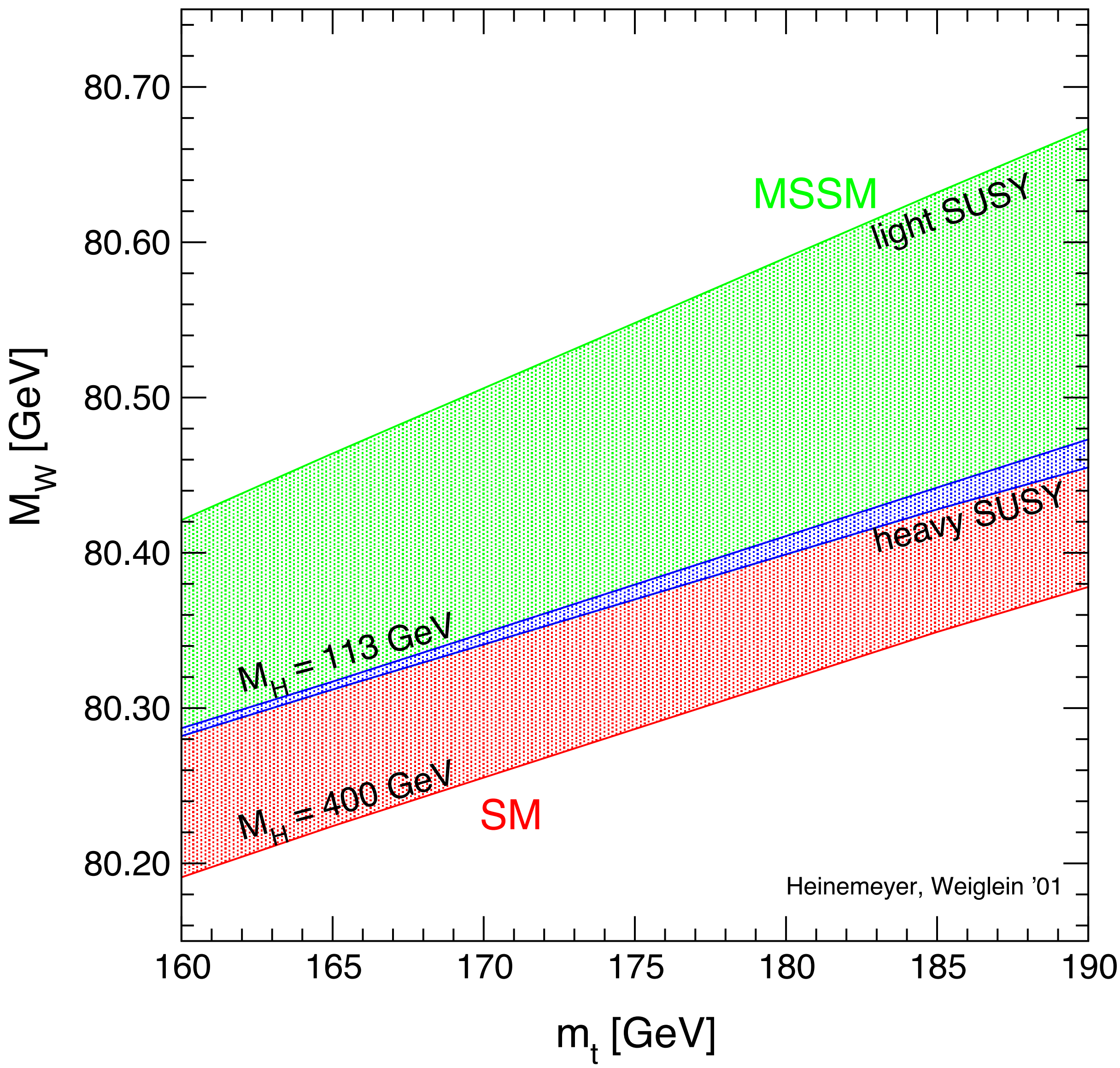
$\Downarrow$

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

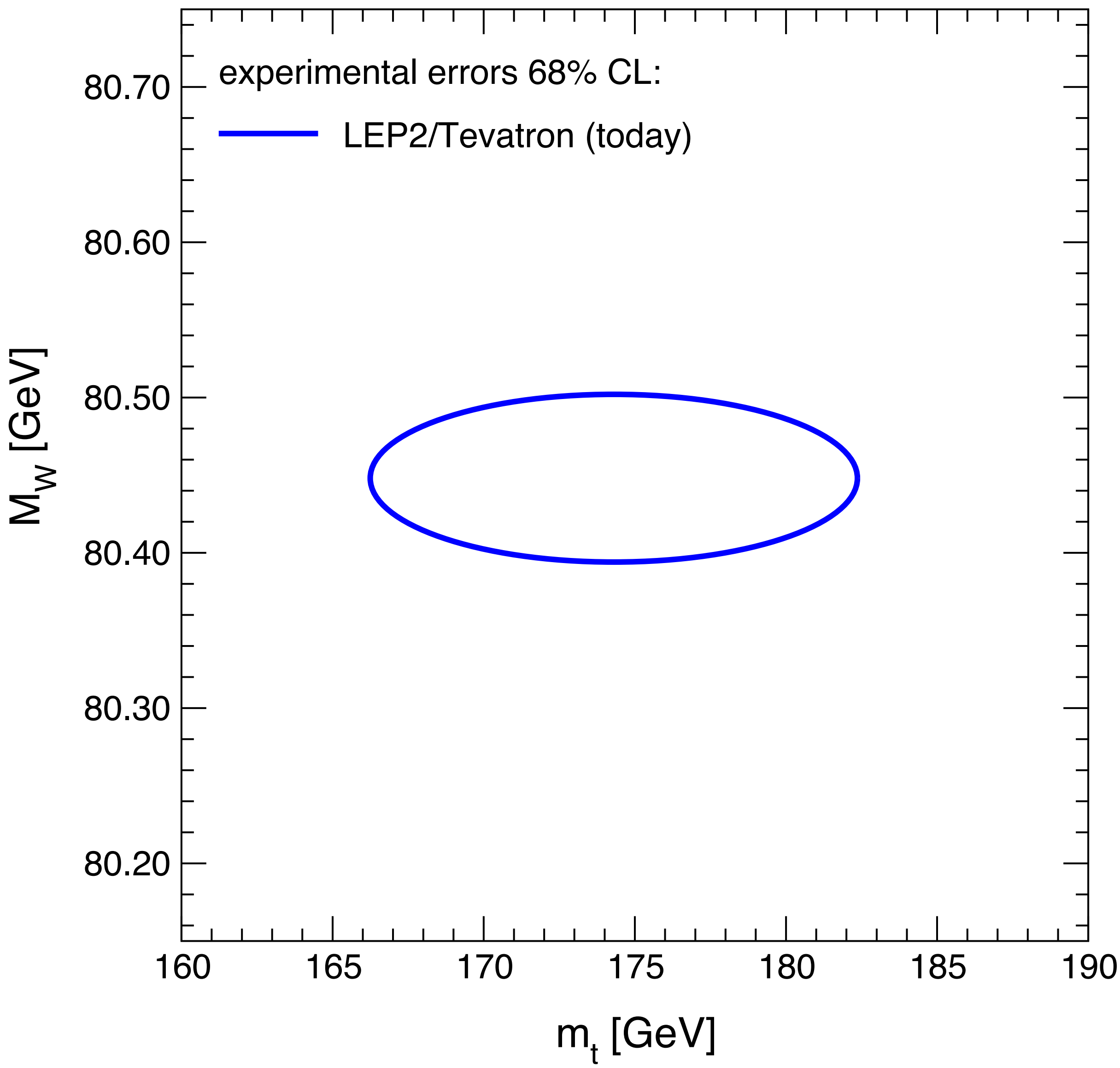
Example I: SM vs. MSSM



$\Rightarrow$ 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: $\frac{e\, m_t}{2 M_W s_w}, \frac{e\, m_t^2}{M_W s_w}, \ldots$

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, $\quad \delta m_h^{\text{theo,fut}} \approx 0.5$ 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*]

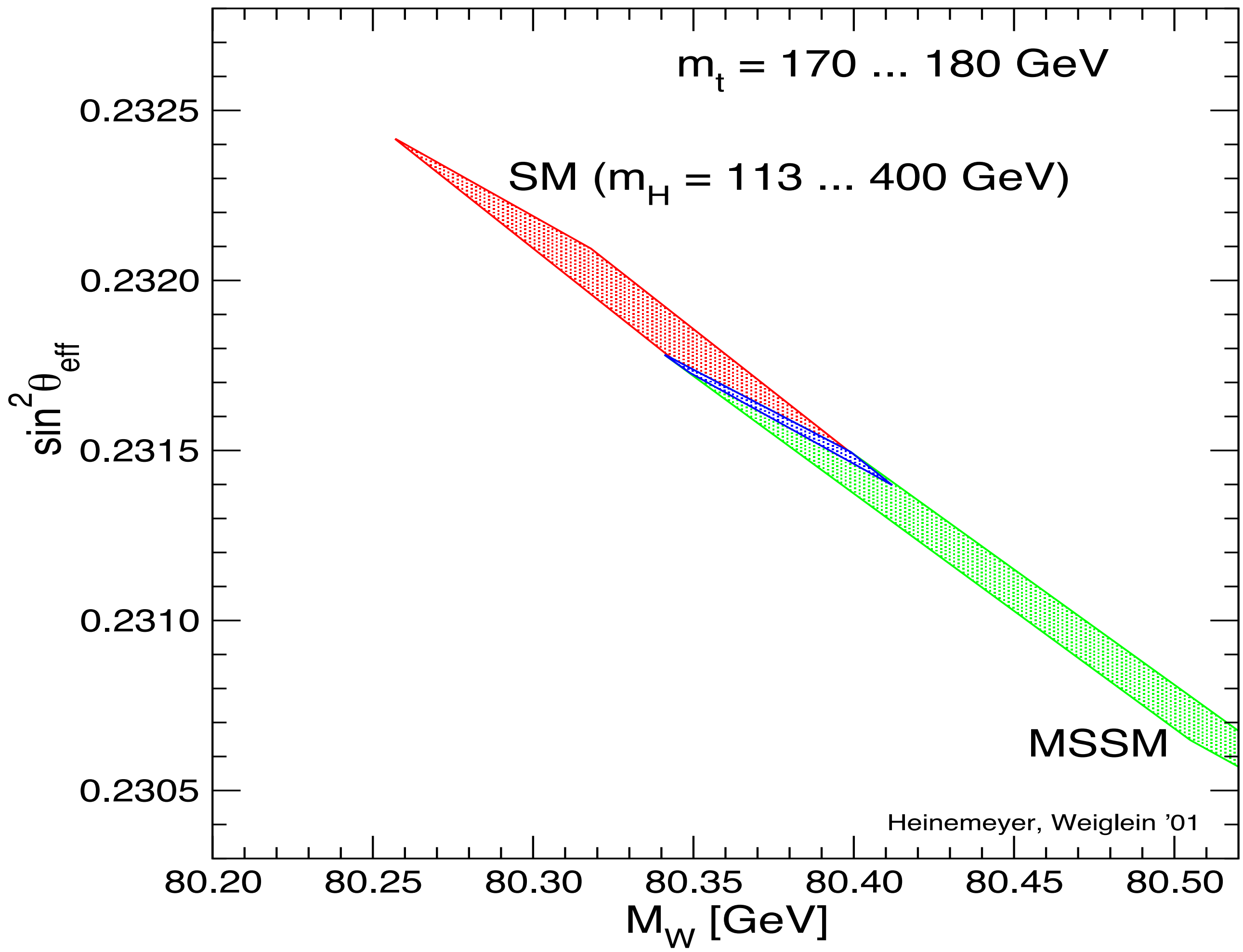
. . . obtained in EP, RGiEP and FD approach

MSSM consistency check:

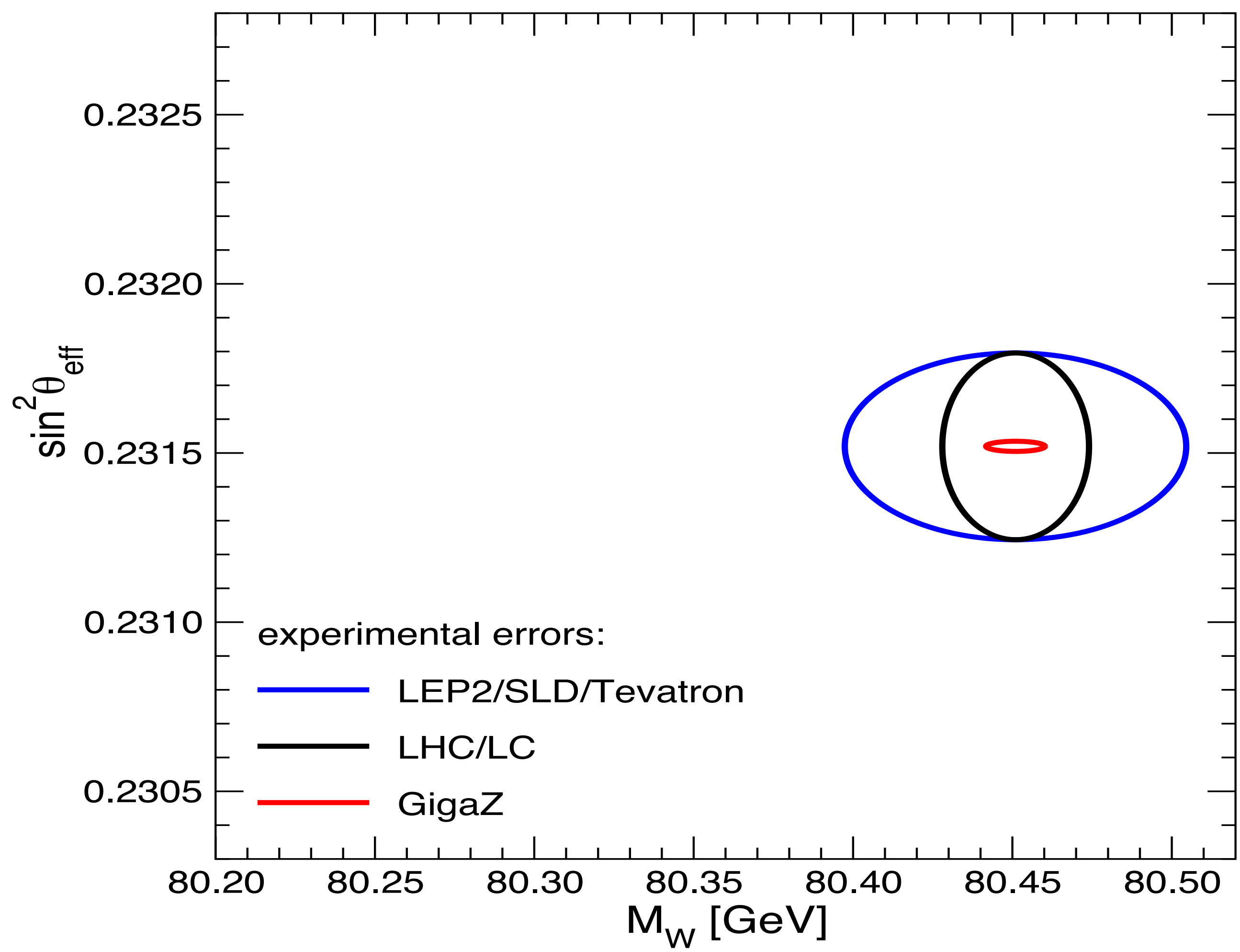
Prediction for M_W, $\sin^2\theta_{\rm eff}$ in the SM and MSSM

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, $\tan\beta$, ...

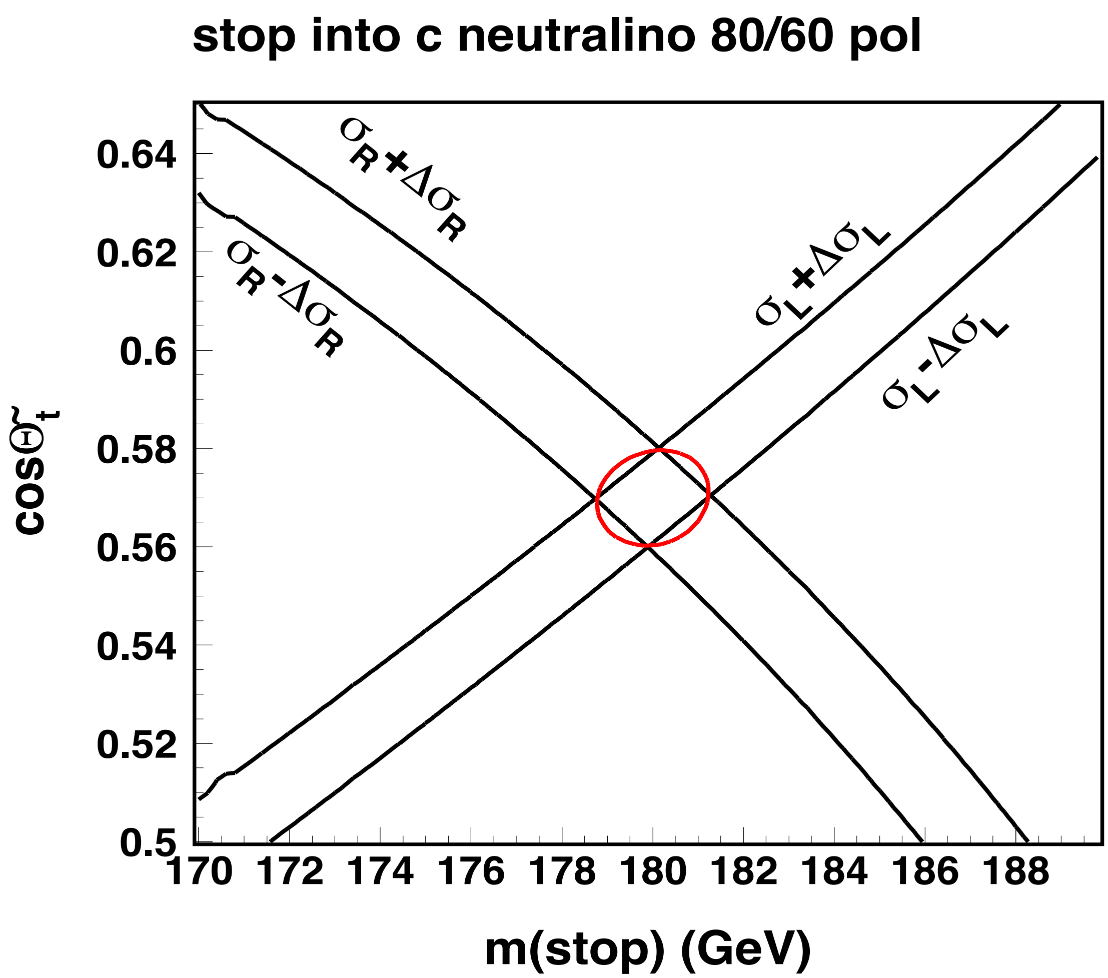
Combination of direct and indirect
information on $\tilde{t}$ sector parameters

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*]

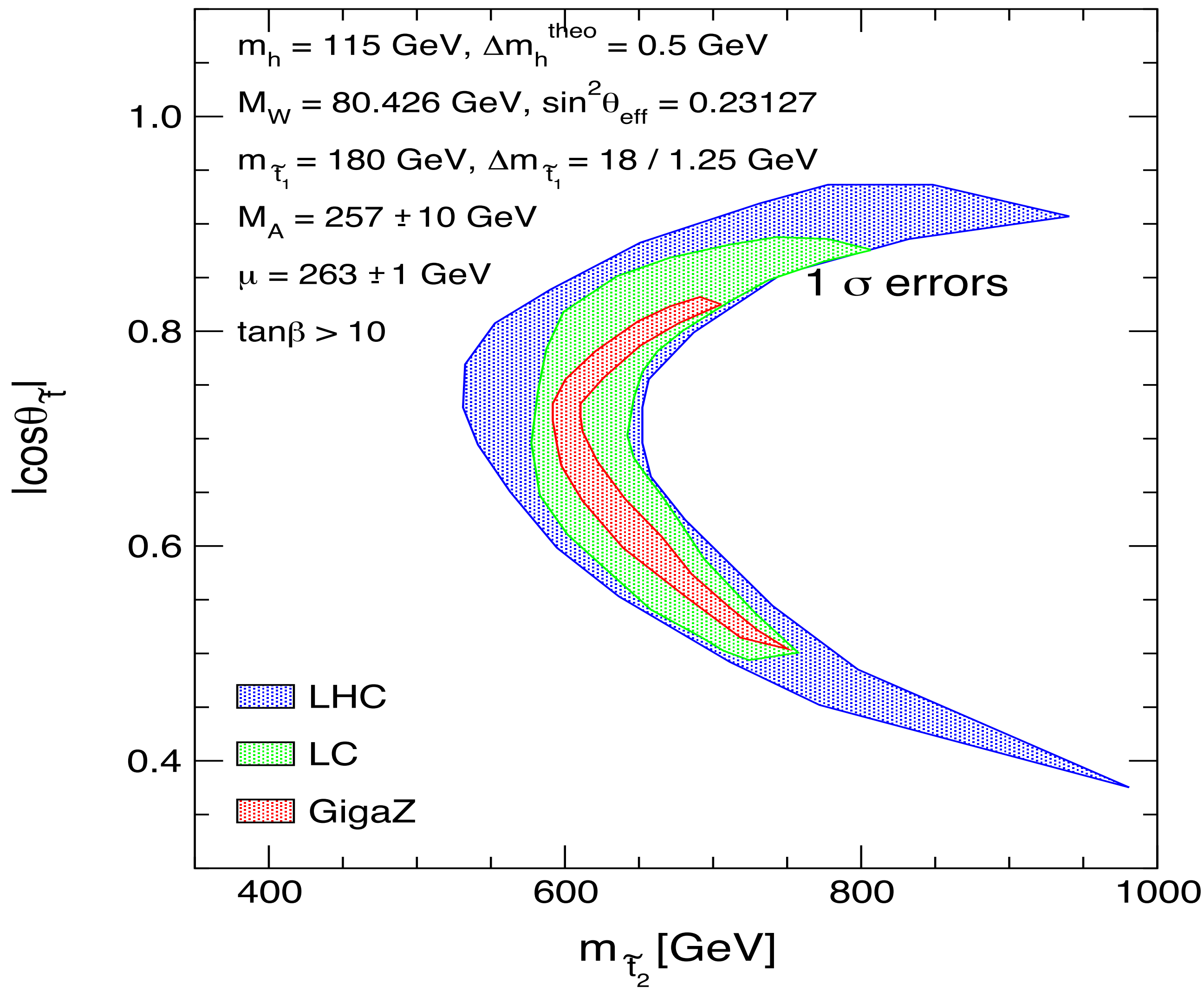


$\Rightarrow$ Precise determination of $m_{\tilde{t}_1}$, $\theta_{\tilde{t}}$

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 :

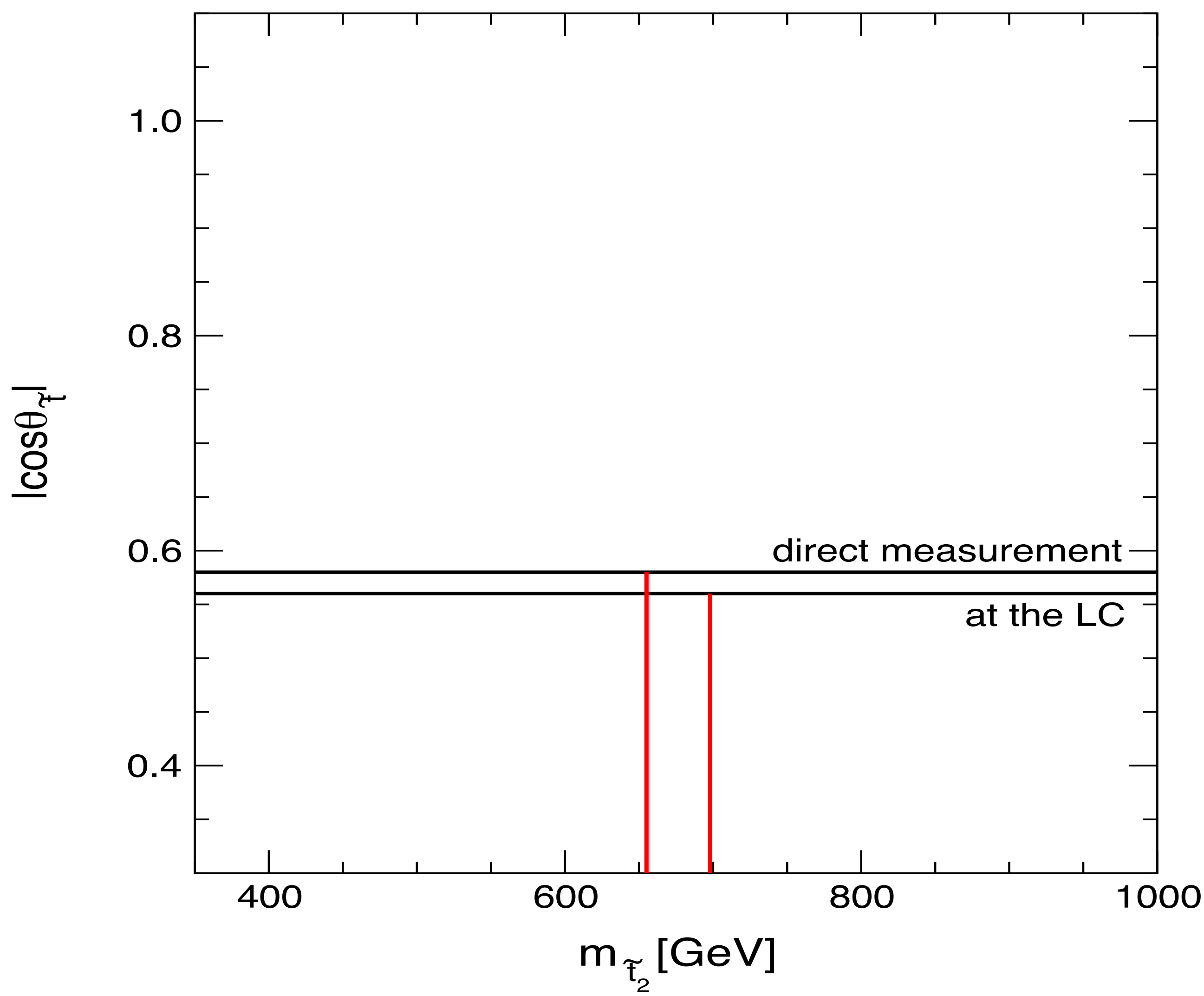
$$\begin{aligned} \delta M_W &= 7 \text{ MeV} \\ \delta \sin^2\theta_{\mathrm{eff}} &= 1 \times 10^{-5} \\ \delta m_h^{\mathrm{theo}} &= 0.5 \text{ GeV} \end{aligned}$$

Allowed region in $m_{\tilde{t}_2}$–$\theta_{\tilde{t}}$ plane ($m_h = 115$ GeV):
[S.H., G. Weiglein '00]



$\Rightarrow$ Direct/indirect information is complementary

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



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

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 $\delta m_h^{\text{theo}} \approx 0.2\text{–}0.5$ 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 !!

$$\boxed{\text{Theoretical calculations should be viewed as an essential part of all future High Energy Physics programs}}$$

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	$\sim 10\%$	$\lesssim 1\%$

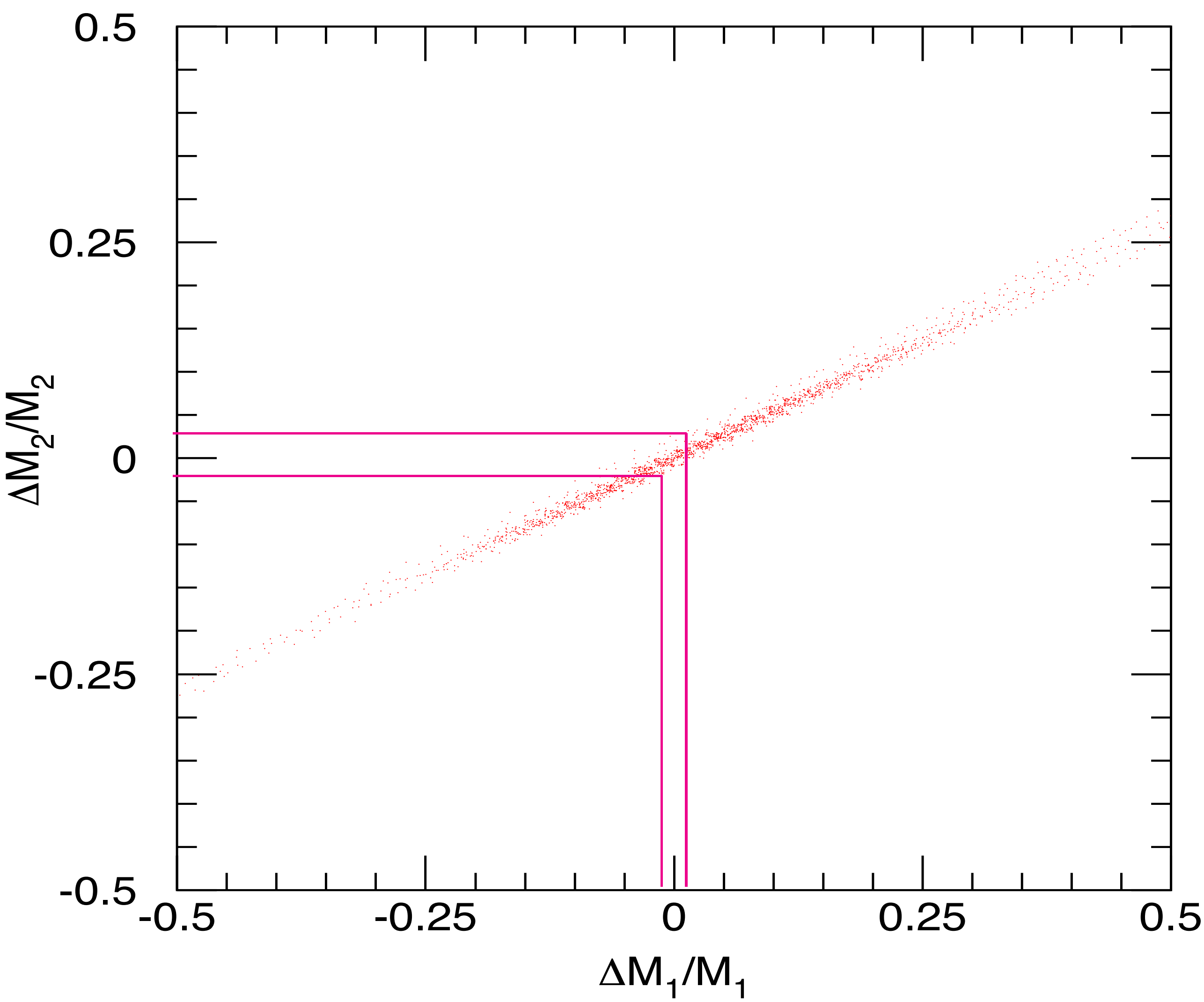
$\Rightarrow$ LC much better

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

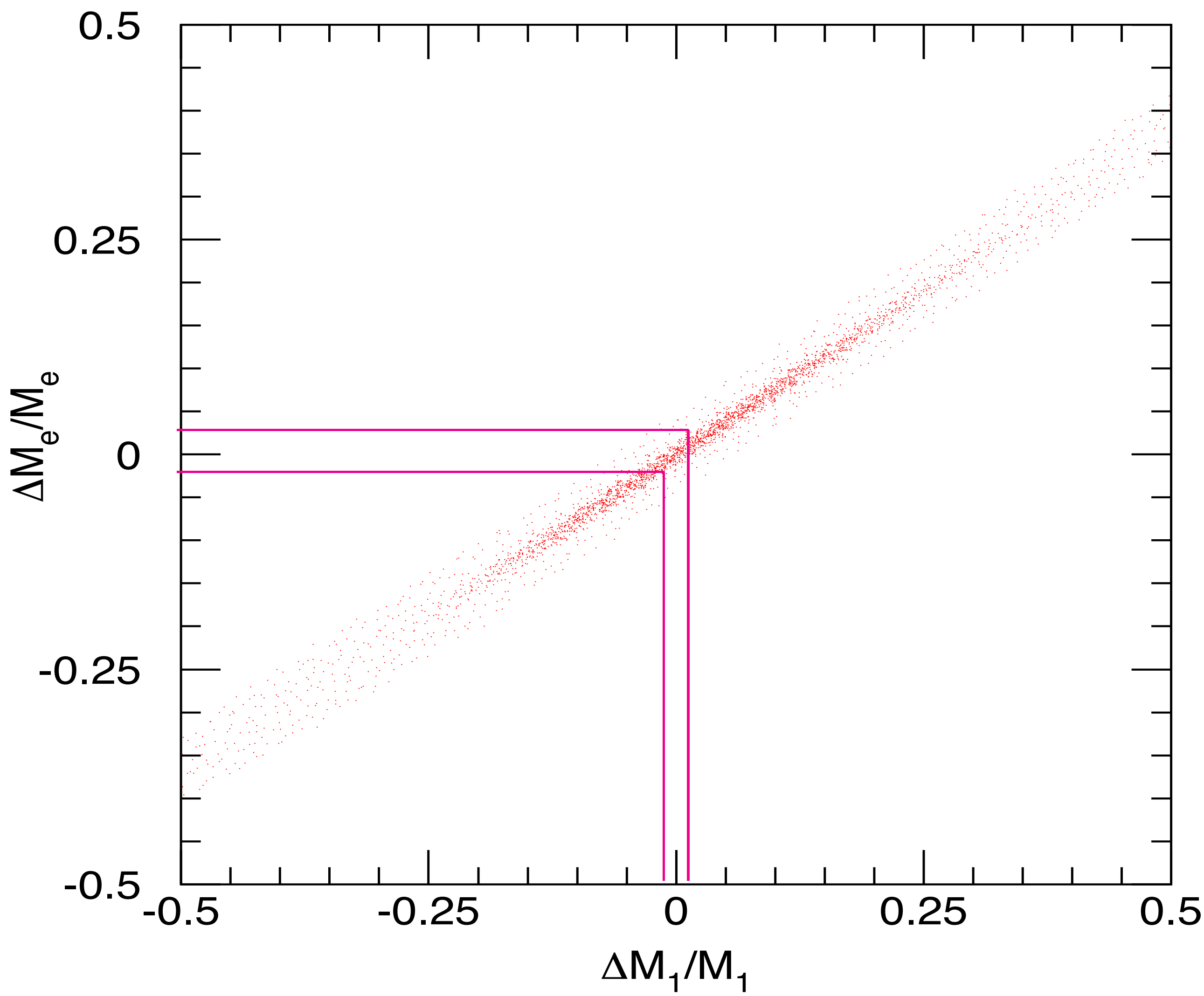
Example I: $m_{\tilde{\chi}_2^0}$



[*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 !!