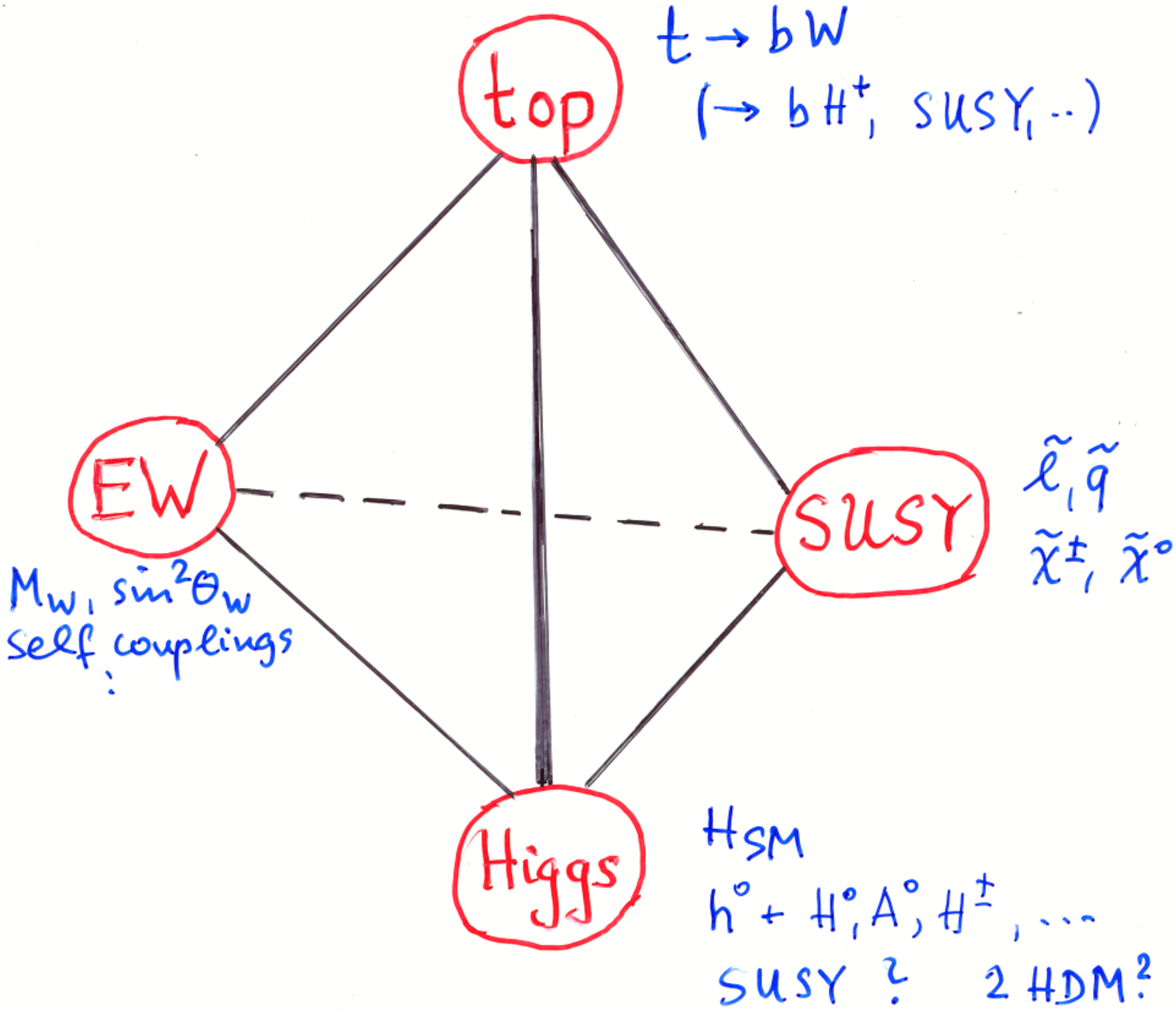
Linear Collider Physics Programme

W. Hollik, MPI München

ECFA-DESY
Amsterdam, 1 April 2003

- The known particles
  EW and top quark physics – the orthodoxy
- The almost known particles
  Higgs bosons
- The expected particles
  Supersymmetry – the new orthodoxy (?)
- Probing the ultra-high scale


top
t → bW
(→ bH+, SUSY, ..)
EW
Mw, sin²θw
self couplings
SUSY
l̃, q̃
χ̃±, χ̃°
Higgs
HSM
h° + H°, A°, H±, ...
SUSY ? 2 HDM?

Fundamental questions of particle physics:

constitutents of matter?

structure of fundamental interactions?

structure of vacuum?

structure of space time?

Current knowledge is based on the Standard Model

Try to understand

– origin of electroweak symmetry breaking

– further unification of forces

– link with gravity

→ find signals for physics "beyond the SM"

At a Linear Collider: precision experiments

definite initial state

tunable initial energy E_{CM}

beam polarization

This allows to

find signals of new physics in standard-particle processes

study quantum effects of standard and non-standard particles
$\rightarrow$ extrapolation to high energies

determine precisely direct signals (non-standard Higgs, SUSY, ...)
$\rightarrow$ study symmetry breaking mechanisms

e^+e^- with options:

e^-e^-

$e^-\gamma$

$\gamma\gamma$

The Standard Model

- the symmetry group $SU(2)_L \times U(1) \times SU(3)_C$

- the principle of local gauge invariance
  $\longrightarrow$ fermion – vector boson interaction
  $\longrightarrow$ vector boson – vector boson interaction

- Higgs mechanism and Yukawa interactions
  $\longrightarrow$ masses $M_W,\ M_Z,\ m_{\mathrm{fermion}}$

> renormalizable quantum field theory
>
> accurate theoretical predictions

Beyond the Standard Model

- further unification of forces

- hierarchy of interactions

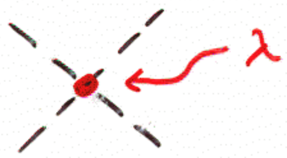
- hierarchy of fermion masses

- concept of Supersymmetry

- **Higgs bosons:** quanta of H field

  neutral, spin 0

  mass: $M_H = v \cdot \sqrt{\lambda}$



self-coupling

$\lambda \sim M_H^2$

M_H : free parameter

exp: $M_H > 114$ GeV LEP

[95% C.L.]

$M_H = 115$ GeV ? LEP

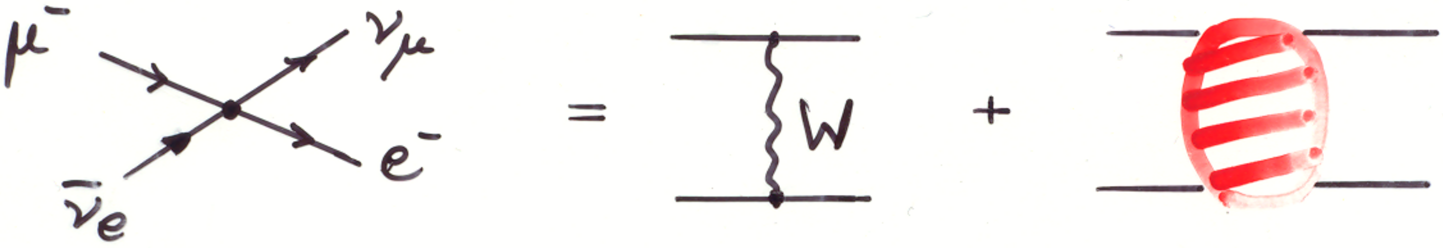
Nov. 2000

Masses of W and Z bosons

correlated via muon lifetime $\leftrightarrow$ Fermi constant G_μ

$$\frac{1}{\tau_\mu} = \frac{G_\mu^2 m_\mu^5}{192\pi^3}\left(1 - \frac{8m_e^2}{m_\mu^2}\right)\cdot(1+\delta_{\rm QED})$$

$$G_\mu = 1.16637(1)\cdot 10^{-5}\ \mathsf{GeV}^{-2}$$



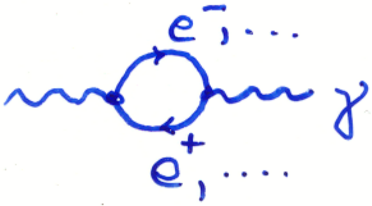
Fermi Model   Standard Model

$$G_\mu = \frac{\pi}{\sqrt{2}}\cdot\frac{\alpha}{M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)}\cdot\frac{1}{1-\Delta r}$$

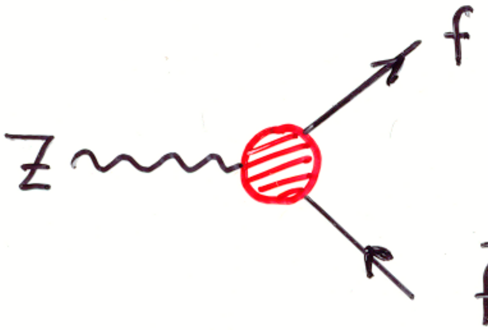
$$\Delta r = \Delta\alpha + \Delta r_W(m_t, M_H)$$

6%

[QED]



Effective Z couplings



$$g_A = \sqrt{\rho_f}\, I_3^f$$

$$g_V = \sqrt{\rho_f}\left(I_3^f - 2Q_f \sin^2\Theta_f\right)$$

$\rho = \rho(m_t, M_H, \dots)$

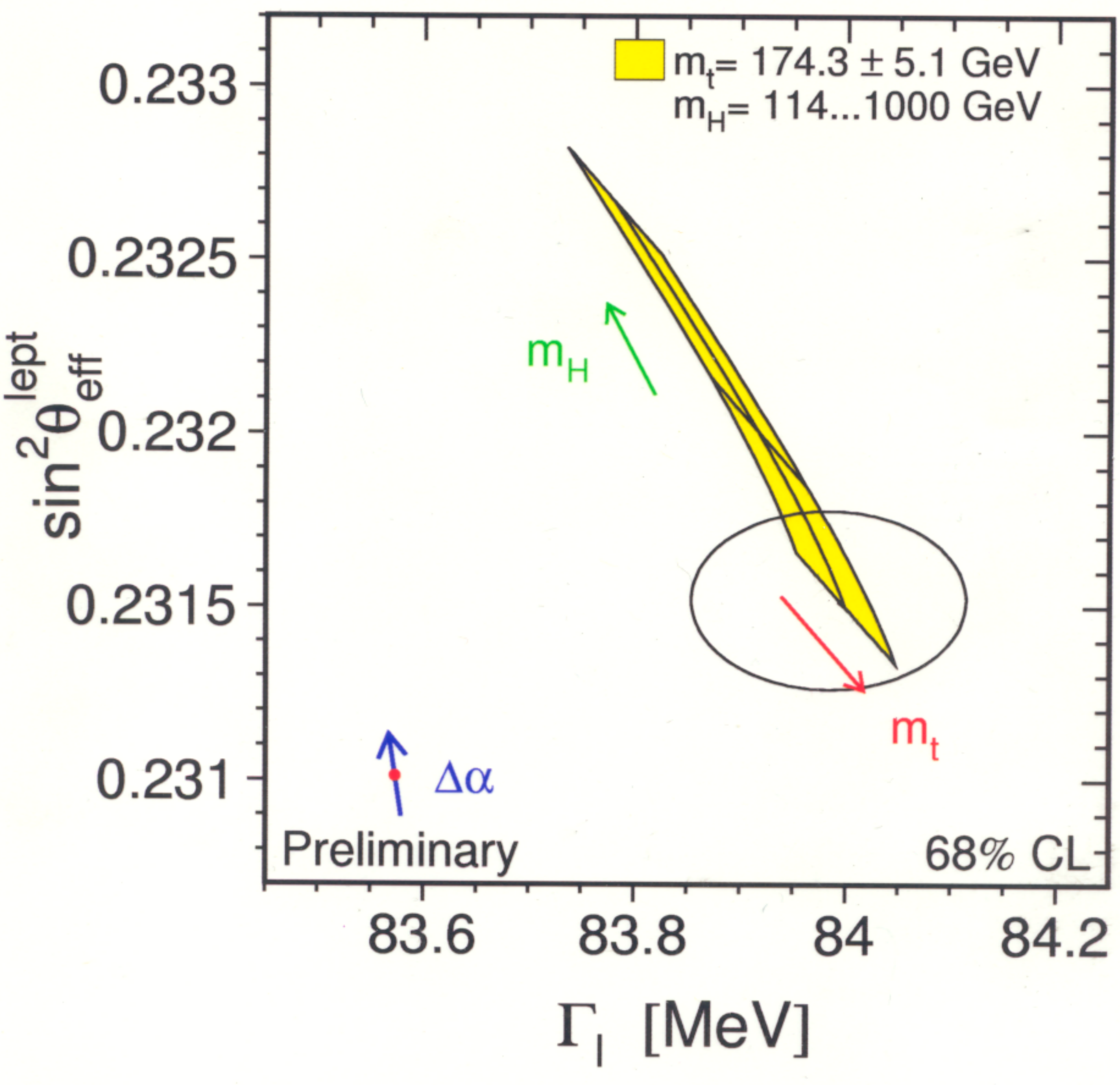
$\sin^2\Theta_f = \sin^2\Theta_f(m_t, M_H, \dots)$

$f =$ lepton: $\sin^2\Theta_{eff}$

complete at 1-loop

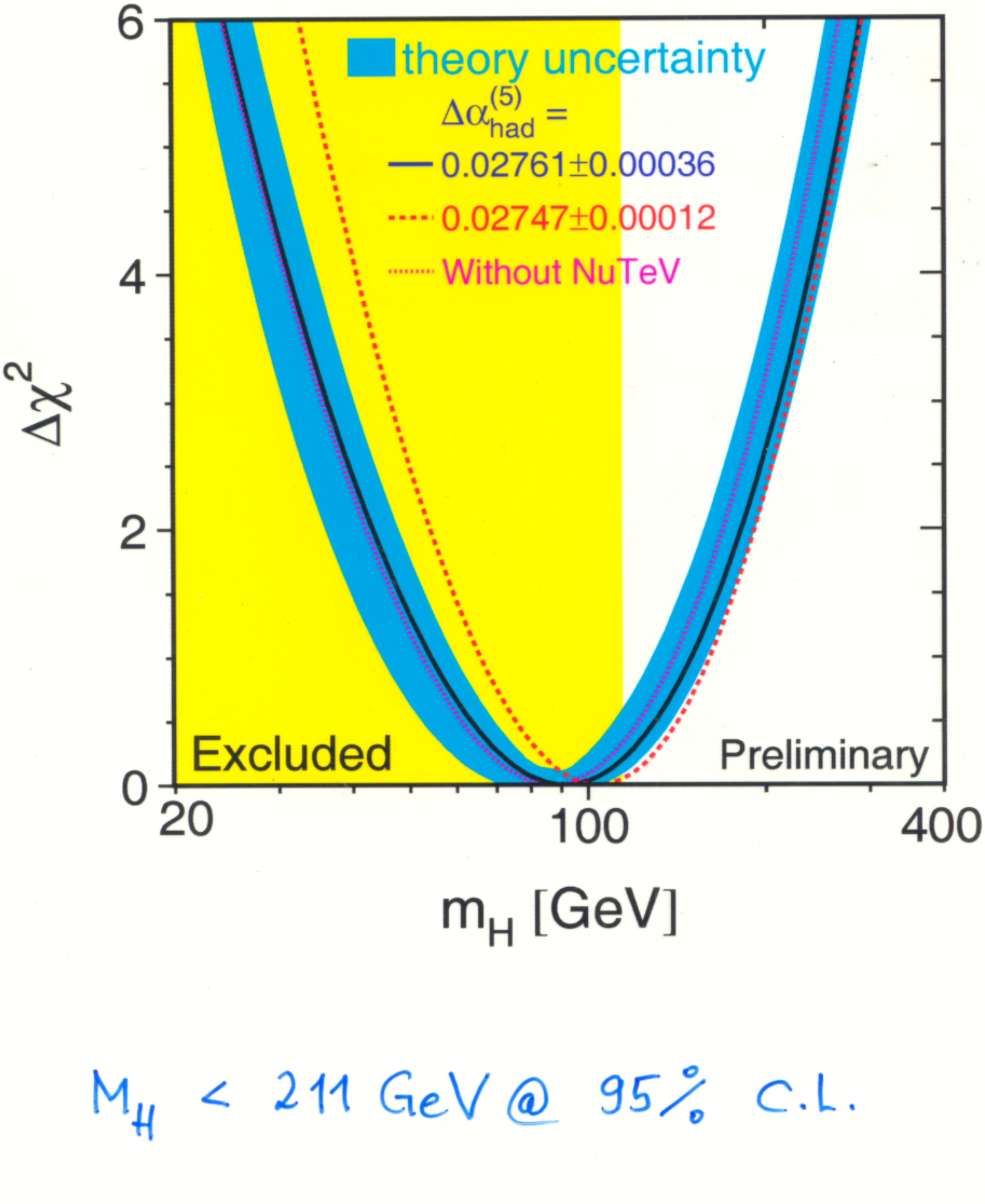
+ 2-loop m_t^4, m_t^2 terms

↑ Degrassi, Gambino, Sirlin



m_t= 174.3 ± 5.1 GeV
m_H= 114...1000 GeV
0.233
0.2325
0.232
0.2315
0.231
$\sin^2\theta_{eff}^{lept}$
m_H
m_t
$\Delta\alpha$
Preliminary
68% CL
83.6
83.8
84
84.2
Γ_l [MeV]

LEPEWWG [M. Grünewald, 2003]



M_H < 211 GeV @ 95% C.L.

A successful decade of precision tests

Standard Model as a Quantum Field Theory

quantum effects are established

indirect versus direct determination of $m_{\rm top}$

constraints on $M_{\rm Higgs}$ $\rightarrow$ light Higgs-boson

gauge-boson self-interactions

not yet *directly* **tested:**

existence of the Higgs boson

Higgs-boson self interaction $\rightarrow$ Higgs potential

Yukawa interaction

$\longrightarrow$ **future experiments**

(expected) experimental precision

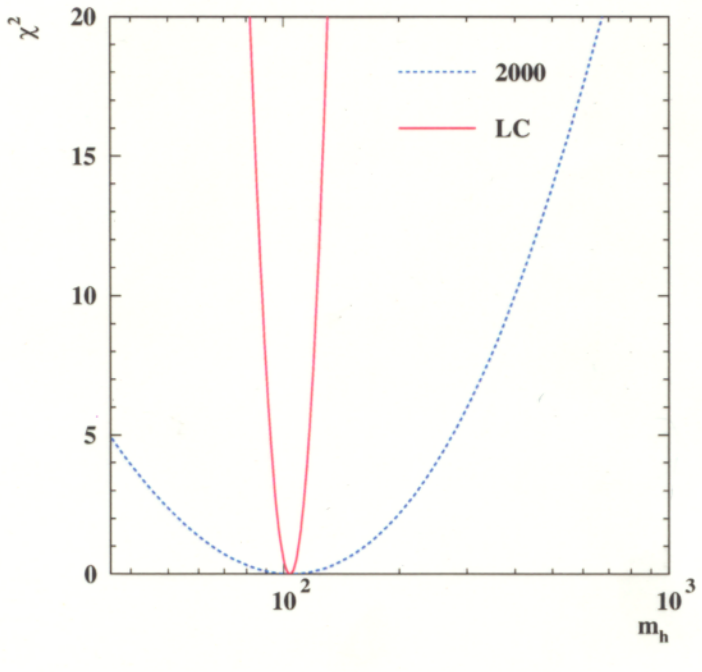
error for	LEP/Tev	Tev/LHC	LC	GigaZ
M_W [MeV]	33	15	15	6
$\sin^2\theta_{\rm eff}$	0.00017 LEP + SLC	0.00021		0.000013
$m_{\rm top}$ [GeV]	5.1	2	0.2	0.13
$M_{\rm Higgs}$ [GeV]	–	0.1	0.05	0.05

together with

$\delta M_Z = 2.1$ MeV (LEP)

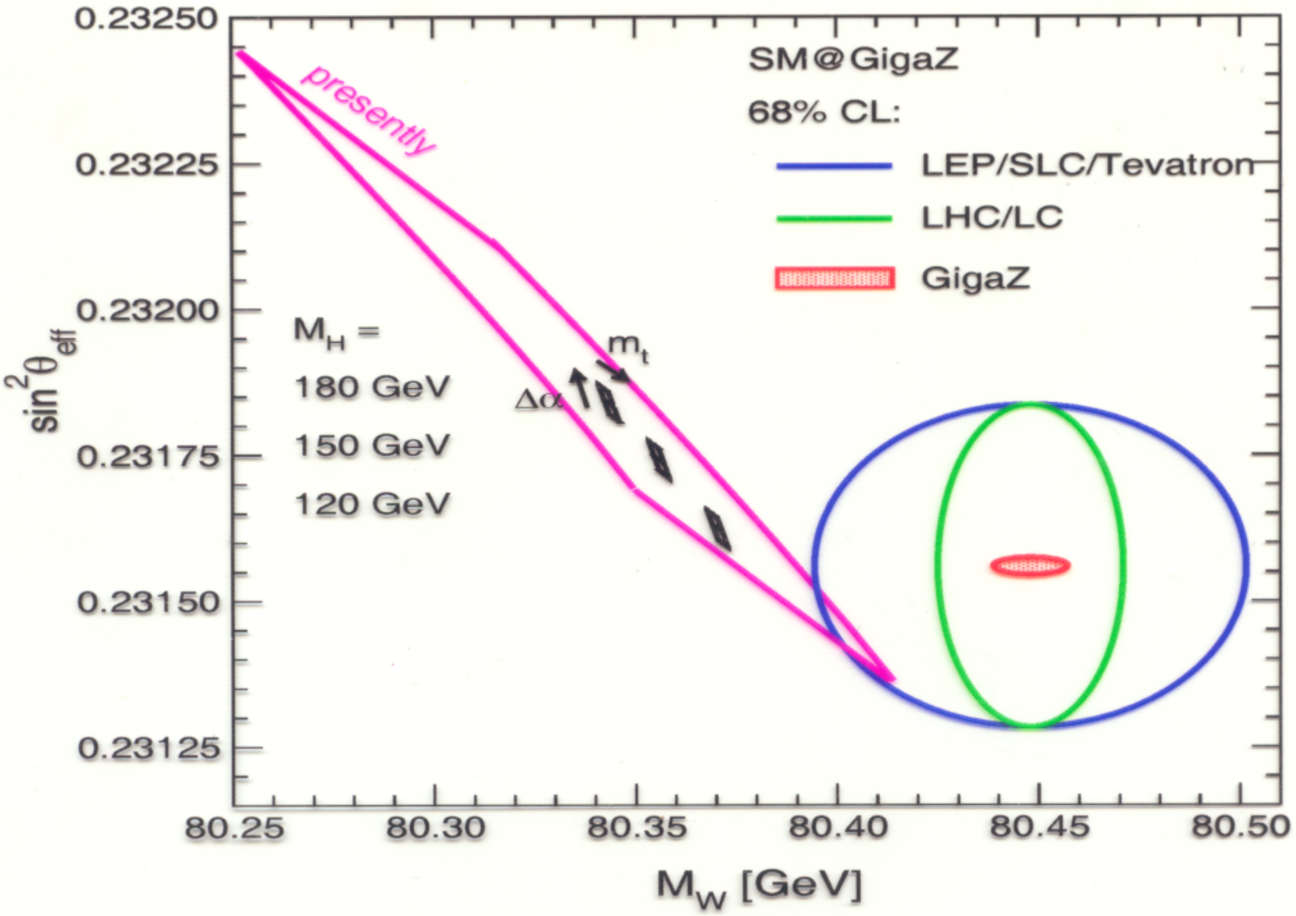
$\delta G_{\rm F}/G_{\rm F} = 1 \cdot 10^{-5}$ (μ lifetime)

	LEP/SLC/Tev [19]	TESLA
$\sin^2\theta^{\ell}_{\rm eff}$	0.23146 ± 0.00017	± 0.000013
lineshape observables:		
M_Z	91.1875 ± 0.0021 GeV	± 0.0021 GeV
$\alpha_s(M_Z^2)$	0.1183 ± 0.0027	± 0.0009
$\Delta\rho_\ell$	$(0.55 \pm 0.10) \cdot 10^{-2}$	$\pm 0.05 \cdot 10^{-2}$
N_ν	2.984 ± 0.008	± 0.004
heavy flavours:		
$\mathcal{A}_{\rm b}$	0.898 ± 0.015	± 0.001
$R^0_{\rm b}$	0.21653 ± 0.00069	± 0.00014
M_W	80.436 ± 0.036 GeV	± 0.006 GeV



$\frac{\delta M_H}{M_H} \sim 7\%$

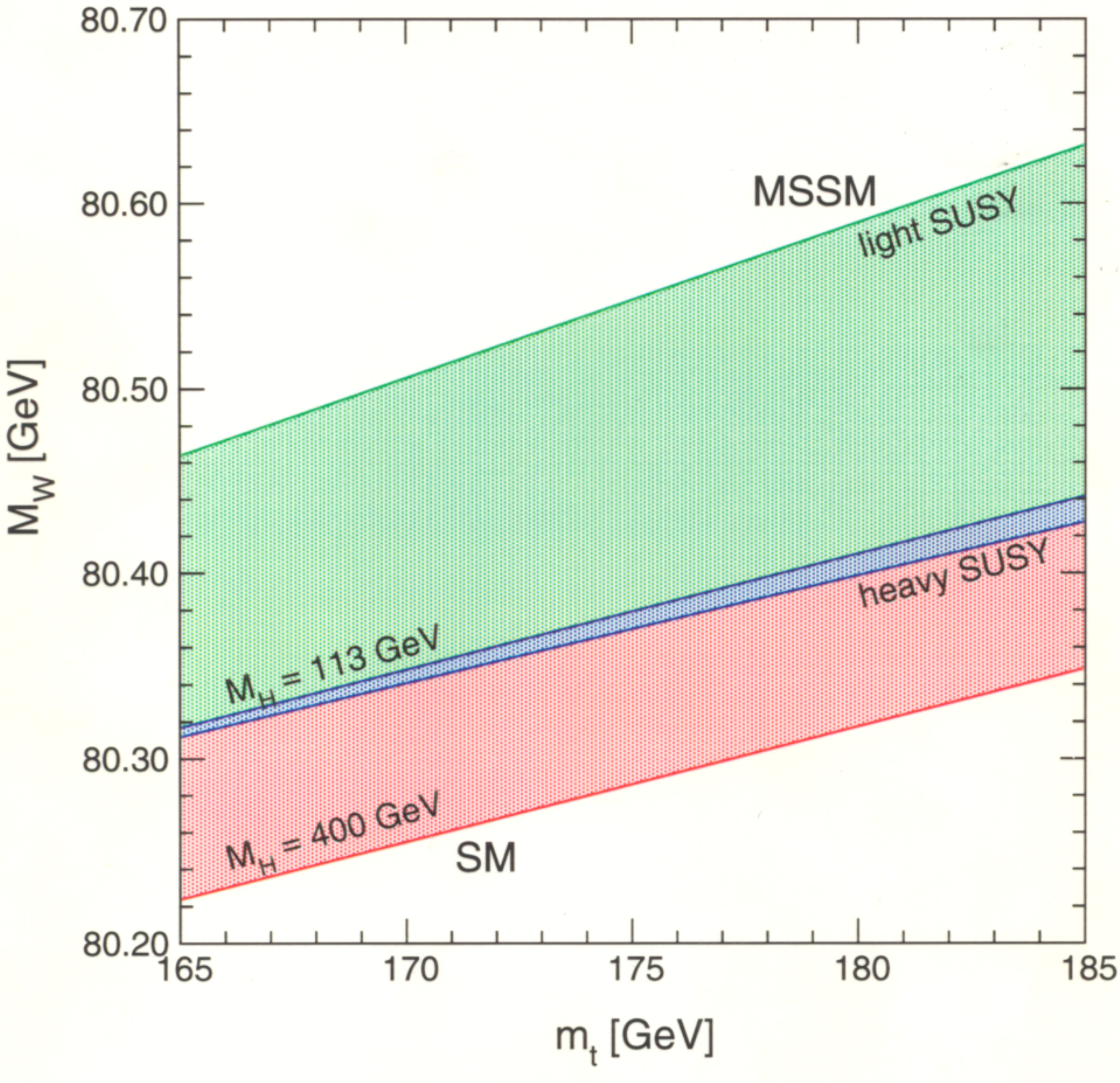
[J. Erler, S. Heinemeyer, W. H., G.Weiglein, P. Zerwas '00]



Prediction for M_W in the SM and the MSSM:

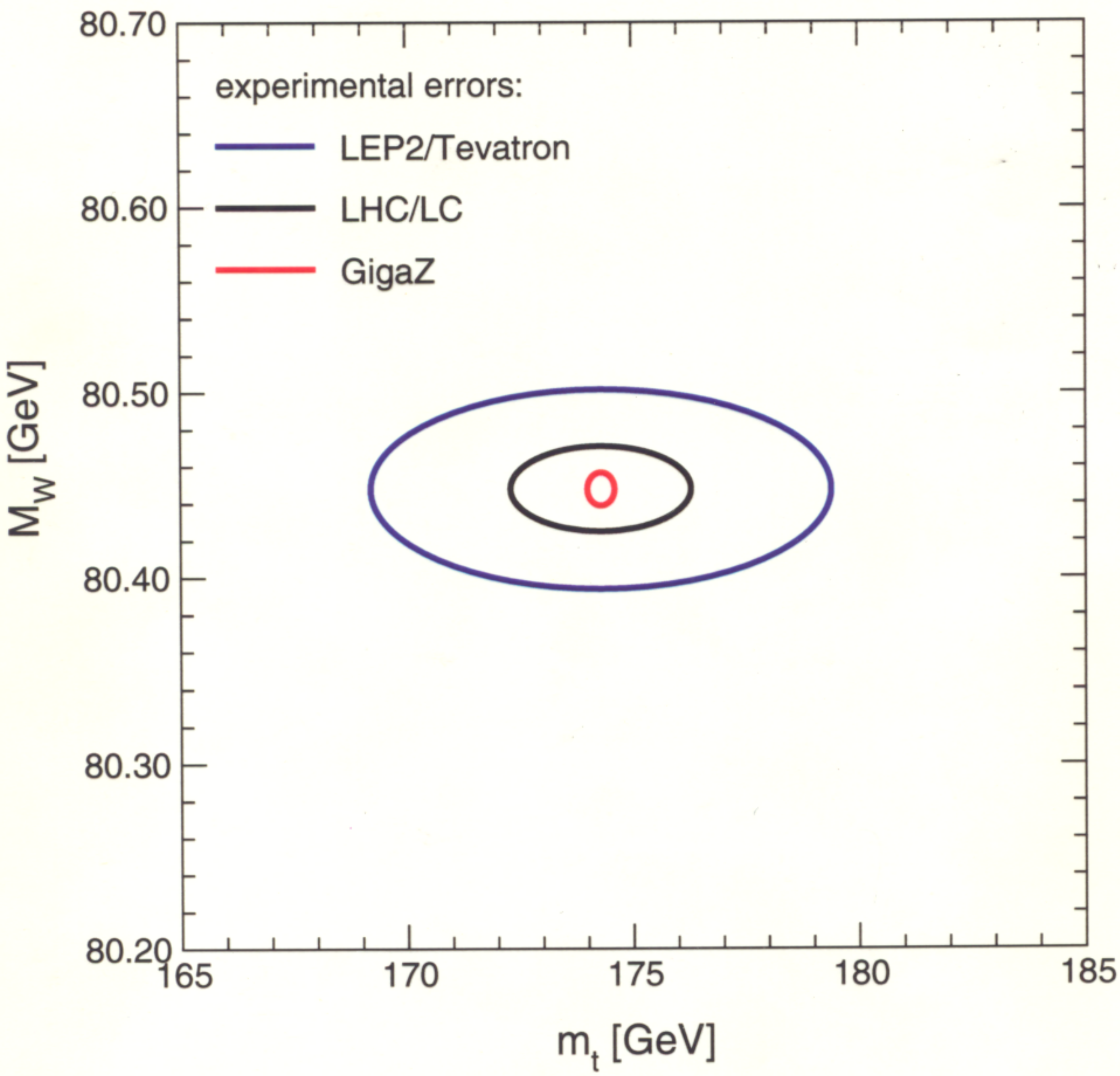
[A. Djouadi, P. Gambino, S. Heinemeyer,
W. Hollik, C. Jünger, G. Weiglein '97]

[S. Heinemeyer, W. Hollik, G. Weiglein '98]



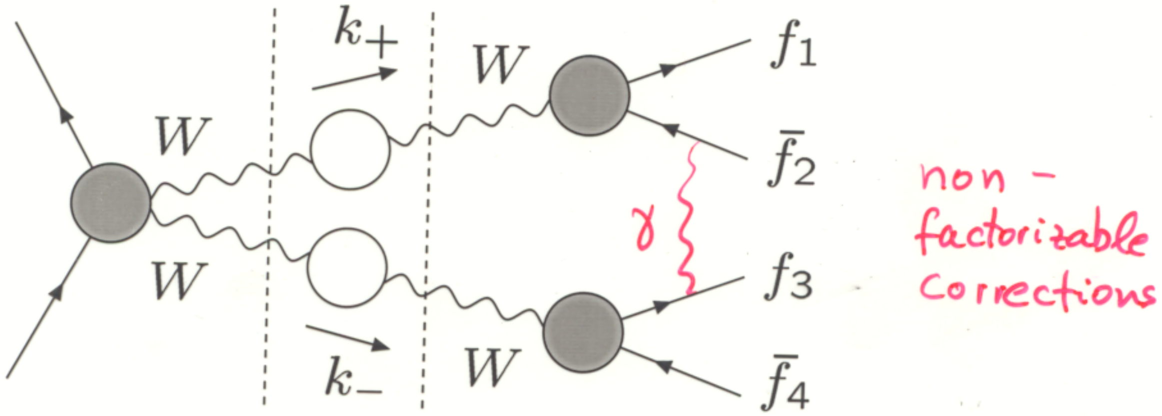
SM: M_H varied

MSSM: SUSY parameters varied



experimental errors:
LEP2/Tevatron
LHC/LC
GigaZ
80.70
80.60
80.50
80.40
80.30
80.20
165
170
175
180
185
M_W [GeV]
m_t [GeV]

$e^+e^- \to W^+W^-$

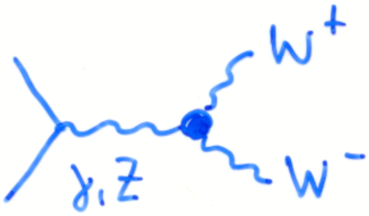


+ radiation of photons

+ background processes

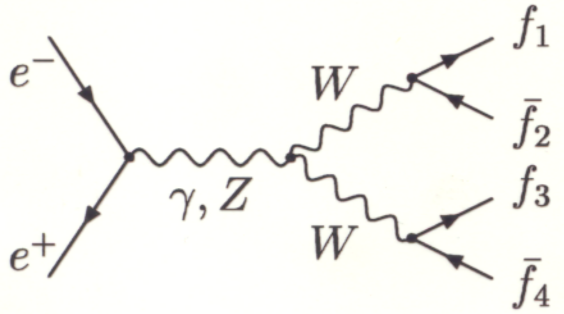
* determination of M_W
  - from reconstruction (continuum) $\delta M_W = 15\,\text{MeV}$
  - from threshold $\delta M_W \simeq 6\,\text{MeV}$

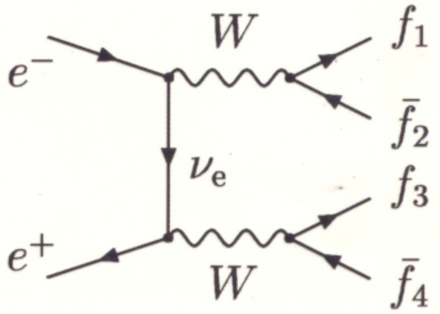
* measurement of triple-gauge couplings



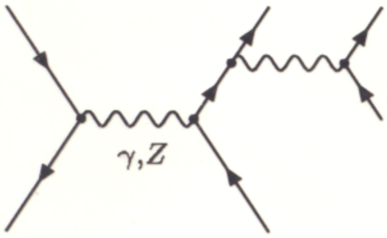
Lowest-order four-fermion cross section

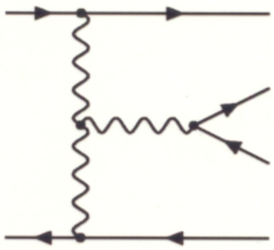
Signal diagrams: two resonant W bosons

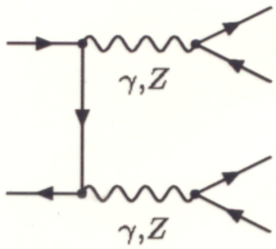




Background diagrams: at most one resonant W





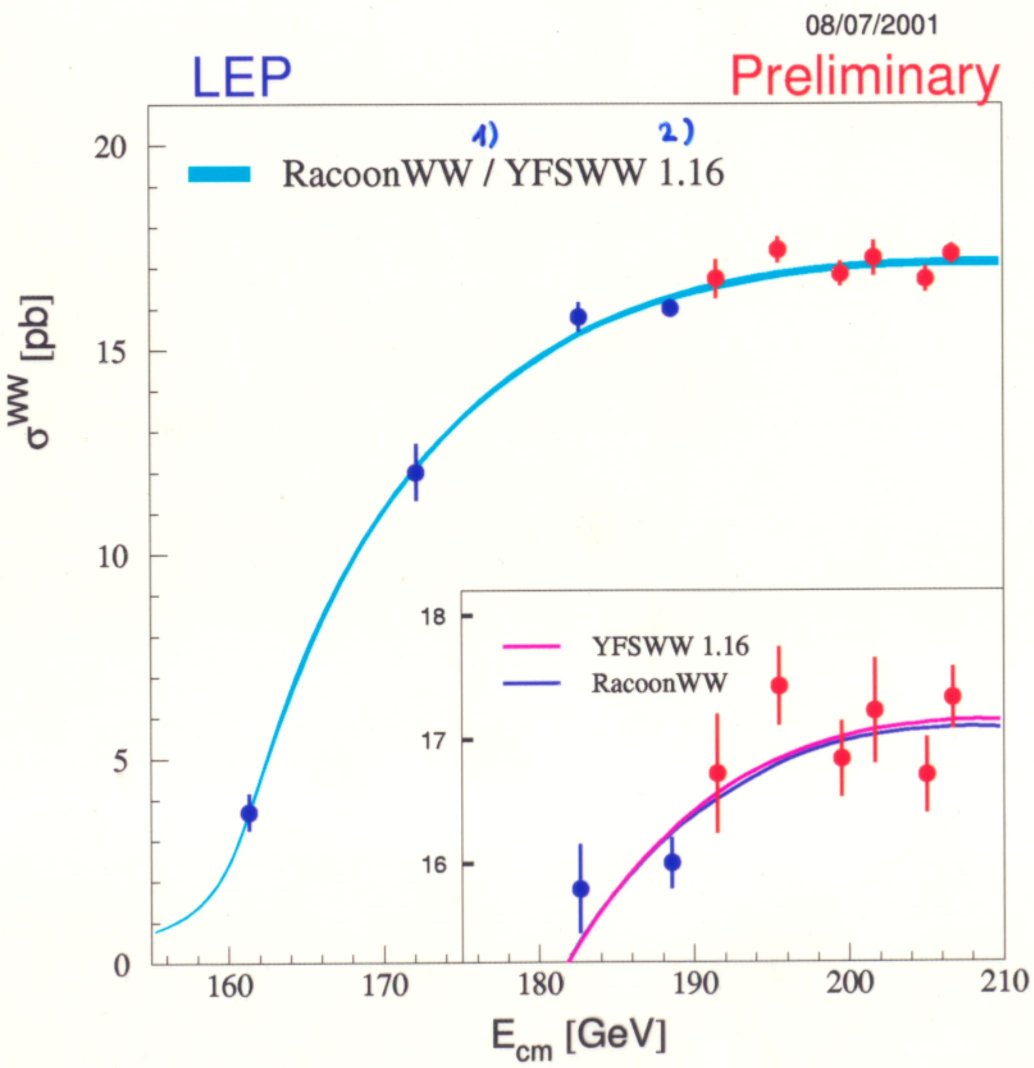


etc.

Typical size $\approx \frac{\Gamma_W}{M_W} \approx 2.5\%$

W-pair-production cross section

LEPEWWG '01



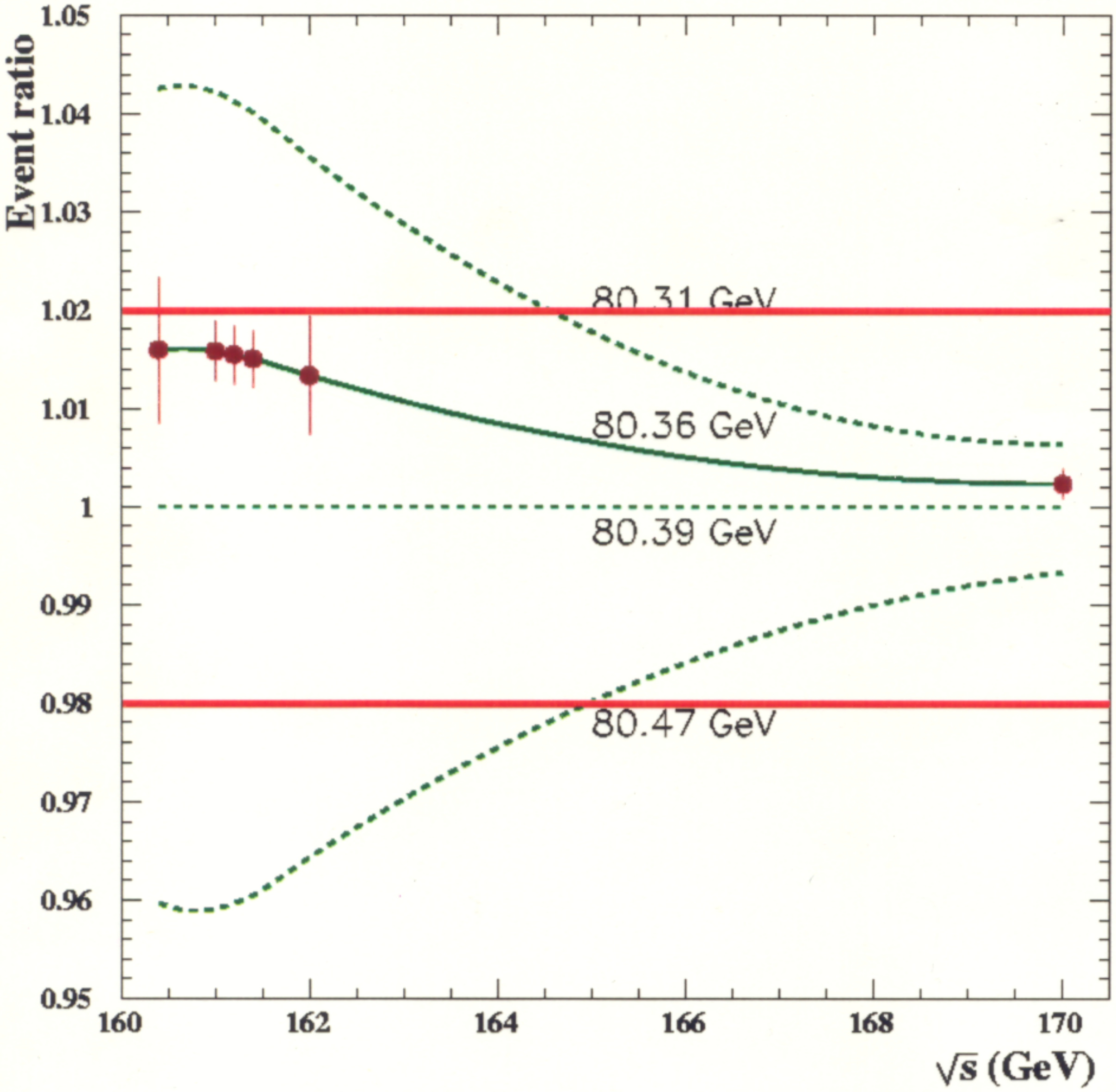
agreement confirms
non-universal
electroweak corrections
(2%)

1) Denner et al. 2) Jadach et al.

M_W measurement from threshold scan:

Experimental sensitivity: $\Delta M_W(\text{exp}) \sim 6\,\text{MeV}$

TESLA-TDR '01



— $\pm 2\%$ TU on cross section (no better estimate available)

$\Rightarrow$ Precise prediction of threshold slope necessary (with reliable TU)

WWγ/Z triple couplings

$$\mathcal{L}_{WW\gamma/Z} =$$

$$e \Big\{ (\partial_\mu W_\nu^+ - \partial_\nu W_\mu^+) W^{-\mu} A^\nu$$

$$+ \kappa_\gamma W_\mu^+ W_\nu^- F^{\mu\nu}$$

$$+ \frac{\lambda_\gamma}{M_W^2} W^+_{\rho\mu} W^{-\mu}{}_\nu F^{\rho\nu} \quad + \quad h.c. \Big\}$$

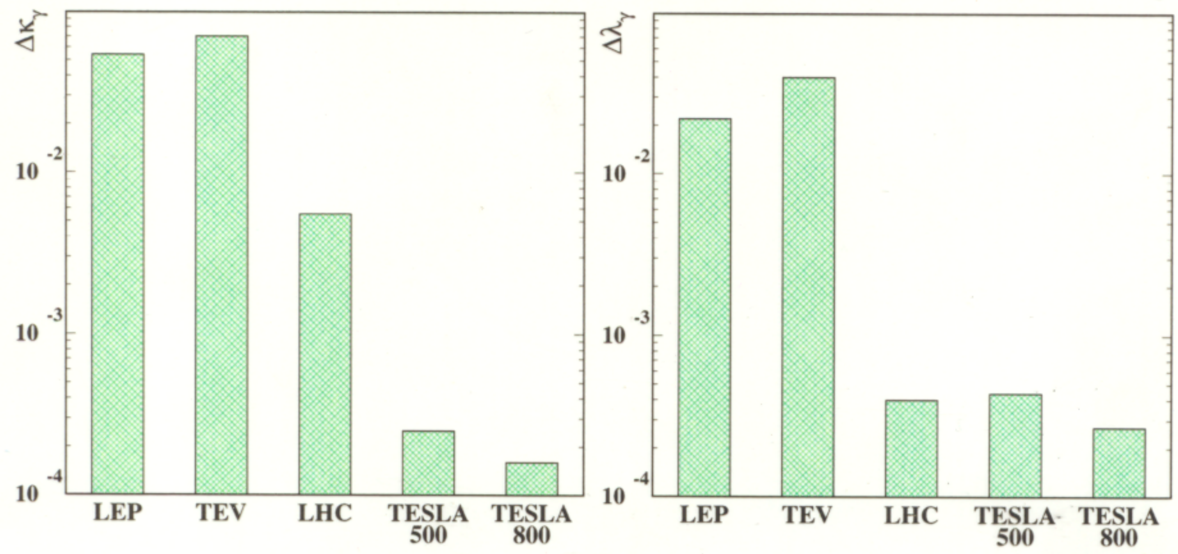
$$+ e \cot\theta_W \Big\{ (\partial_\mu W_\nu^+ - \partial_\nu W_\mu^+) W^{-\mu} Z^\nu$$

$$+ \kappa_Z W_\mu^+ W_\nu^- Z^{\mu\nu}$$

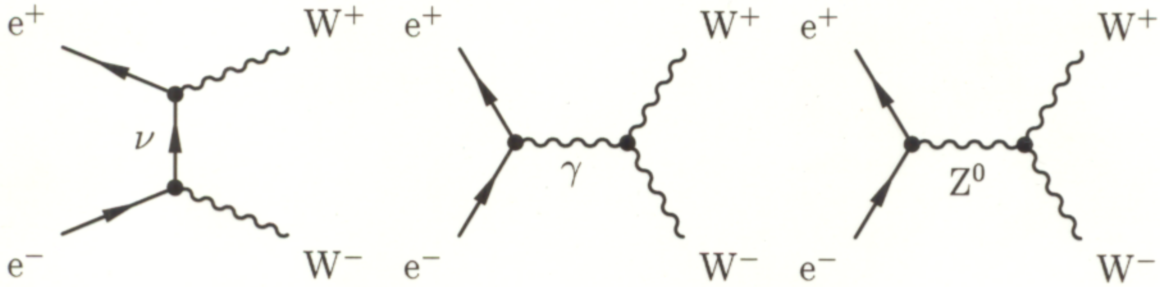
$$+ \frac{\lambda_Z}{M_W^2} W^+_{\rho\mu} W^{-\mu}{}_\nu Z^{\rho\nu} \quad + h.c. \Big\}$$

Standard Model : $\kappa_\gamma = \kappa_Z = 1$

$\lambda_\gamma = \lambda_Z = 0$



Δκ_γ
10^-2
10^-3
10^-4
LEP
TEV
LHC
TESLA 500
TESLA 800
Δλ_γ
10^-2
10^-3
10^-4
LEP
TEV
LHC
TESLA 500
TESLA 800



e+
W+
ν
e−
W−
e+
W+
γ
e−
W−
e+
W+
Z0
e−
W−

Effective Lagrangian for EWSB

$$\mathcal{L}_{eff} = \mathcal{L}_{SM}^{no-Higgs} + \sum_i L_i$$

$$L_1 = \frac{\alpha_1}{16\pi^2}\frac{gg'}{2}B_{\mu\nu}\,\mathrm{tr}\left(\sigma_3 W^{\mu\nu}\right)$$
$$L_2 = \frac{\alpha_2}{16\pi^2}\mathrm{i}g' B_{\mu\nu}\,\mathrm{tr}\left(\sigma_3 V^\mu V^\nu\right)$$
$$L_3 = \frac{\alpha_3}{16\pi^2}2\mathrm{i}g\,\mathrm{tr}\left(W_{\mu\nu} V^\mu V^\nu\right)$$

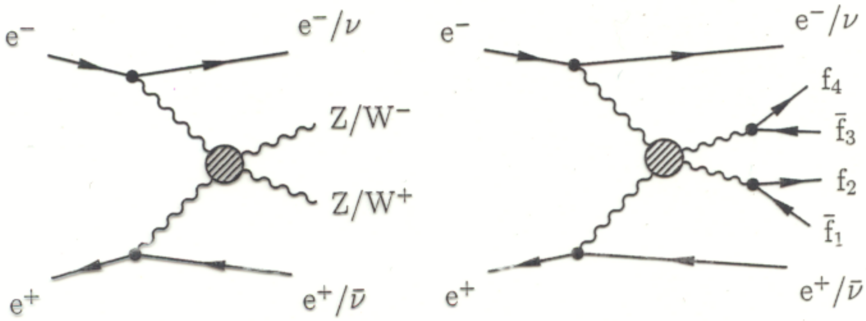
L_1, L_2, L_3 → TGCs, QGCs

$$L_4 = \frac{\alpha_4}{16\pi^2}\mathrm{tr}\left(V_\mu V_\nu\right)\mathrm{tr}\left(V^\mu V^\nu\right)$$
$$L_5 = \frac{\alpha_5}{16\pi^2}\mathrm{tr}\left(V_\mu V^\mu\right)\mathrm{tr}\left(V_\nu V^\nu\right)$$

L_4, L_5 → QGCs

$$\frac{\alpha_i}{16\pi^2} = \left(\frac{v}{\Lambda_i^*}\right)^2$$

TGC $\Rightarrow \Lambda_i^* \simeq 5$ TeV



QGC:

$\sqrt{s}$	800 GeV, $P_{e^-} = 80\%$, $P_{e^+} = 40\%$	
$\int \mathcal{L} dt$	$1000\,\mathrm{fb}^{-1}$	$2000\,\mathrm{fb}^{-1}$
α_4	$-1.8\ \ldots\ +1.5$	$-1.3\ \ldots\ +1.1$
α_5	$-0.9\ \ldots\ +1.0$	$-0.6\ \ldots\ +0.7$
Λ_4^*	2.3 TeV	2.7 TeV
Λ_5^*	3.1 TeV	3.7 TeV

68% C.L.

Top quark

- measure precisely

– top quark mass m_t ($\delta m_t \sim 100$ MeV)
$\sigma_{t\bar{t}}$, momentum spectrum

– top quark width

– non-standard decays (¿)
$t \to H^+ b, \cdots$

– top-quark parameters
$g^Z_{V,A}$, μ_t, electric dipole moment, ...
anomalous couplings (?)

- multi-parameter fit to tt threshold

observables: $\sigma_{t\bar{t}}$, $\frac{d\sigma}{dp_t}$, A_{FB}

fit parameters: $m_t, \Gamma_t, y_t, (\alpha_s)$ [$\alpha_s = 0.118 \pm 0.001$ fixed]

$$\Rightarrow \quad \delta m_t = 30 \text{ MeV}$$

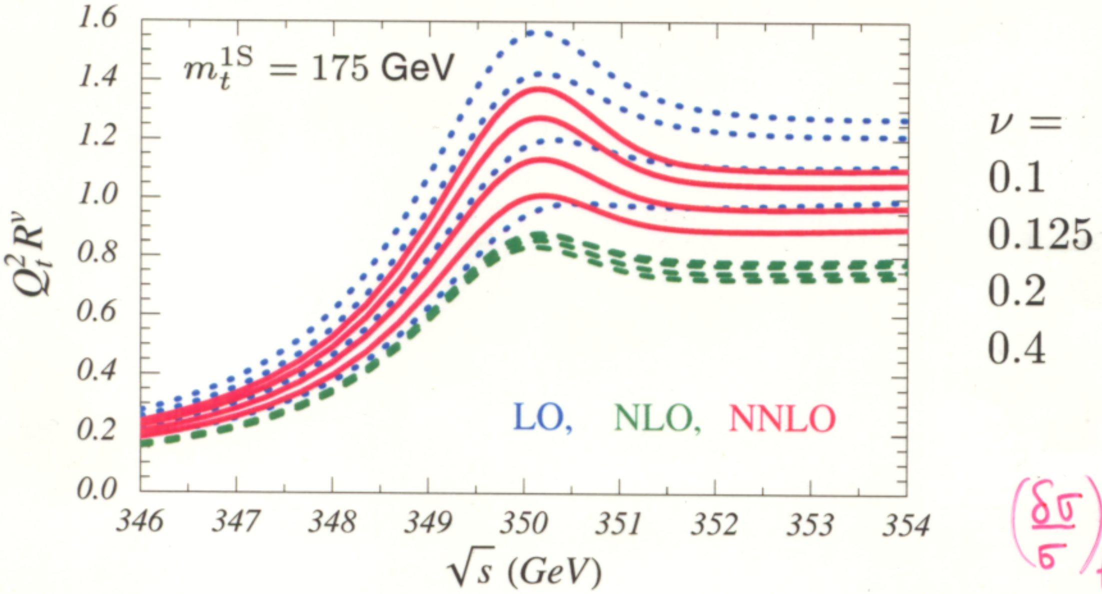
$$\delta \Gamma_t = 33 \text{ MeV}$$

$$\frac{\delta y_t}{y_t} = \begin{cases} +0.33 \\ -0.57 \end{cases}$$

[Martinez et al]

near threshold
perturb. theory
in α_s ↯

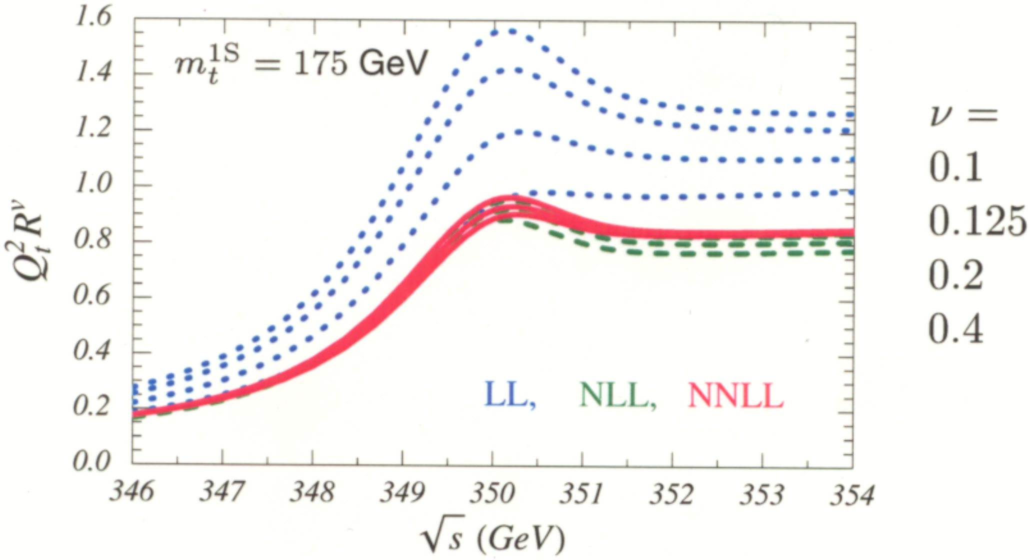
Hoang, Teubner, Melnikov, Yelkhovsky, Beneke, Signer, Smirnov, Sumino, Nagano, Ota, Yakovlev, Manohar, Stewart



$\left(\frac{\delta\sigma}{\sigma}\right)_{th} \simeq 20\%$

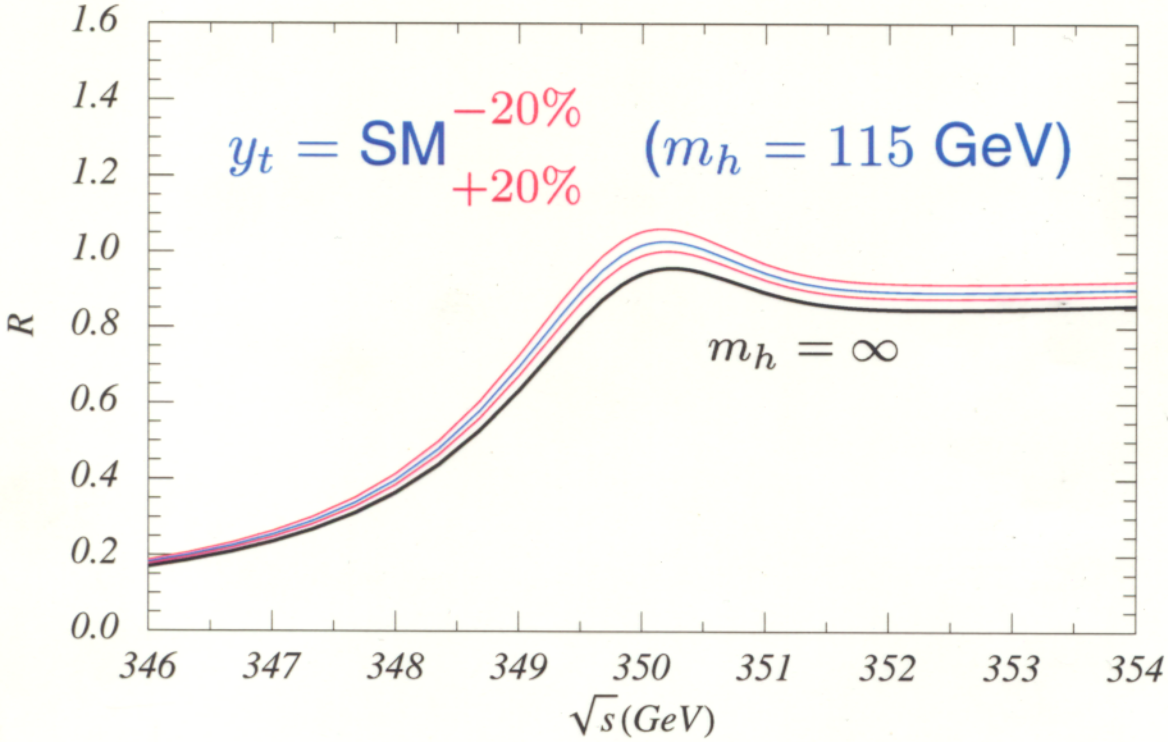
1S mass - with running

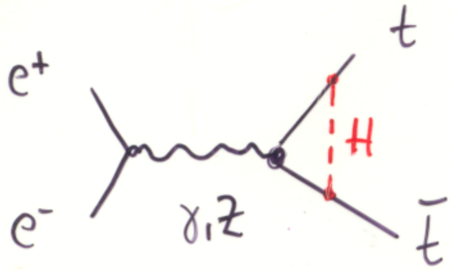
[redacted], Manohar, Stewart, Teubner
Hoang,



$\left(\frac{\delta\sigma}{\sigma}\right)_{th} \lesssim 3\%$

indirect: Yukawa coupling

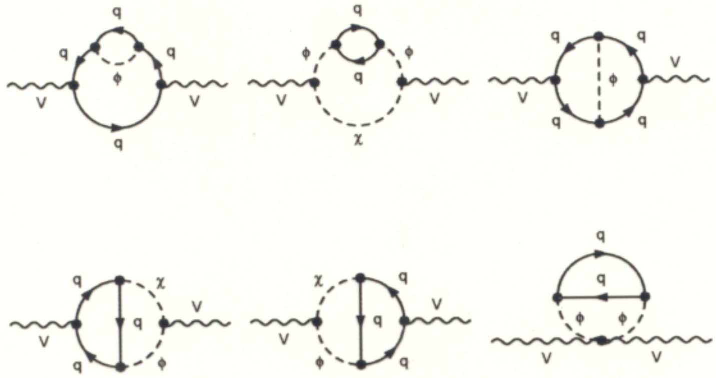




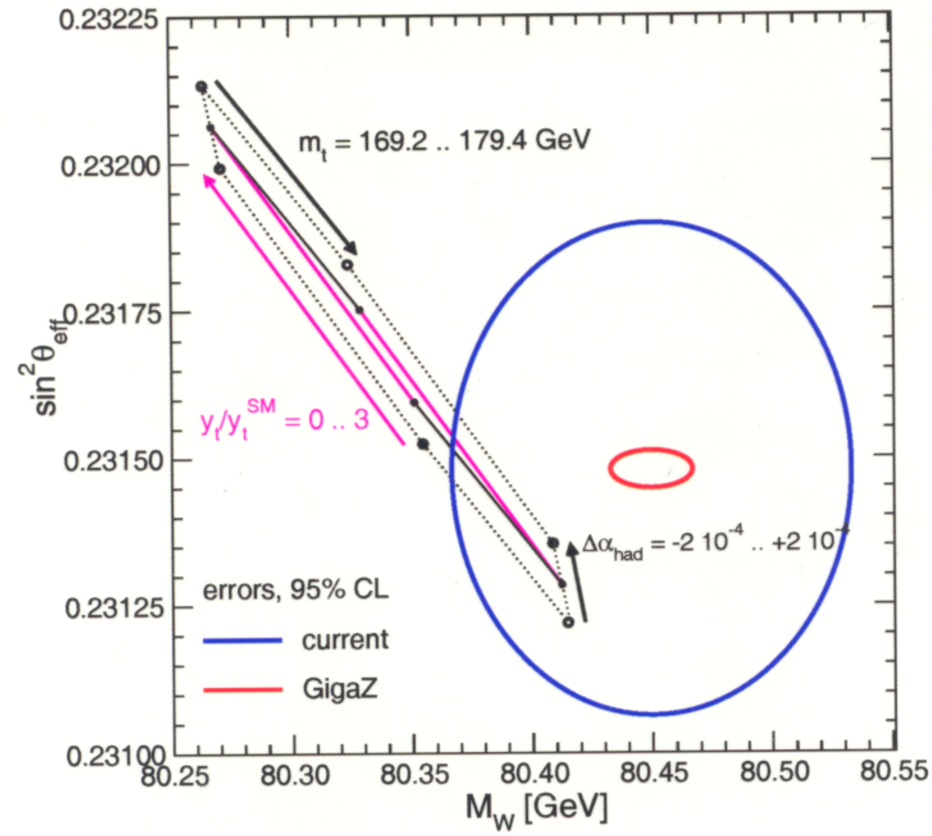
non-rel. Yukawa pot.

$$V_{Yuk} \sim y_t^2 \, e^{-r M_H}$$

$y_t \xrightarrow{\text{2-loop}} \Delta g \rightarrow$ precision observables



SM with $M_H = 114.1$ GeV, $y_t = x\, y_t^{\text{SM}}$:
Predictions for M_W, $\sin^2\theta_{\text{eff}}$ vs. experimental result

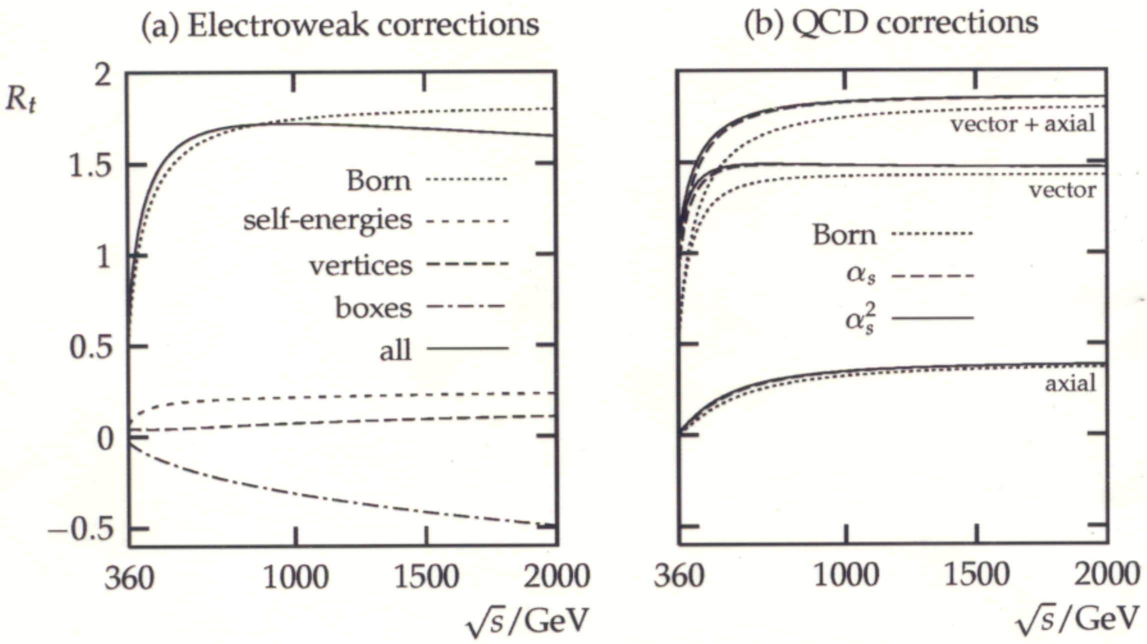


Heinemeyer, Weiglein

$\Rightarrow$ for $m_t = 174.3$ GeV: $y_t < 1.3\, y_t^{\text{SM}}$ at 95% C.L.

$\Rightarrow$ for $m_t = 179.4$ GeV: $y_t < 2.2\, y_t^{\text{SM}}$ at 95% C.L.

$$\sigma(e^+e^- \to t\bar{t}) = R_t \cdot \sigma_0, \qquad \sigma_0 = \frac{4\pi\alpha^2}{3s}$$



[Kühn, Hahn, Harlander]

approximative treatment of $O(\alpha\alpha_s)$,
complete $O(\alpha\alpha_s)$ contribution missing

threshold region $\longrightarrow$ m_t and α_s
discussion at $O(\alpha_s^2)$ [Hoang et al.]

top quarks unstable
$t\bar{t} \to (bW^+)(\bar{b}W^-) \to$ 6 fermions
$e^+e^- \to$ 6 fermion background required

Higgs boson(s)

- questions to be answered:

– numbers of Higgs particles

– masses and quantum numbers
(spin, partity, charges, CP, . . .)

– couplings to fermions / gauge bosons $g_i \sim M_i$

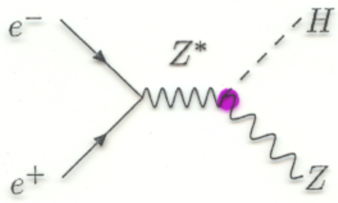
– self couplings → Higgs potential

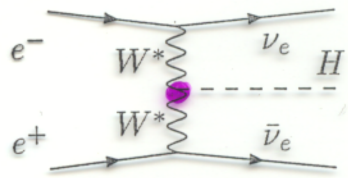
- needs precise determination of mass(es) and coupling constants

– production cross sections

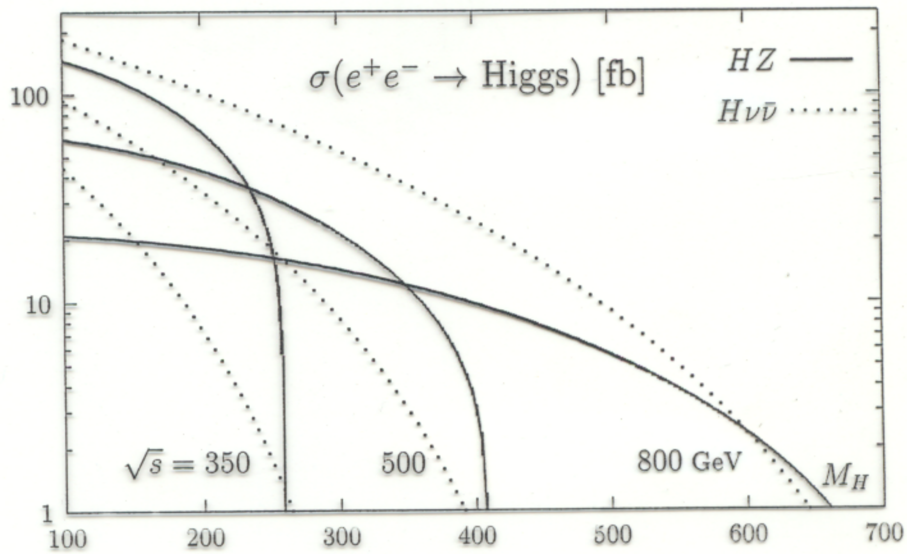
– decay rates/ branching ratios

– inclusion of higher-order effects





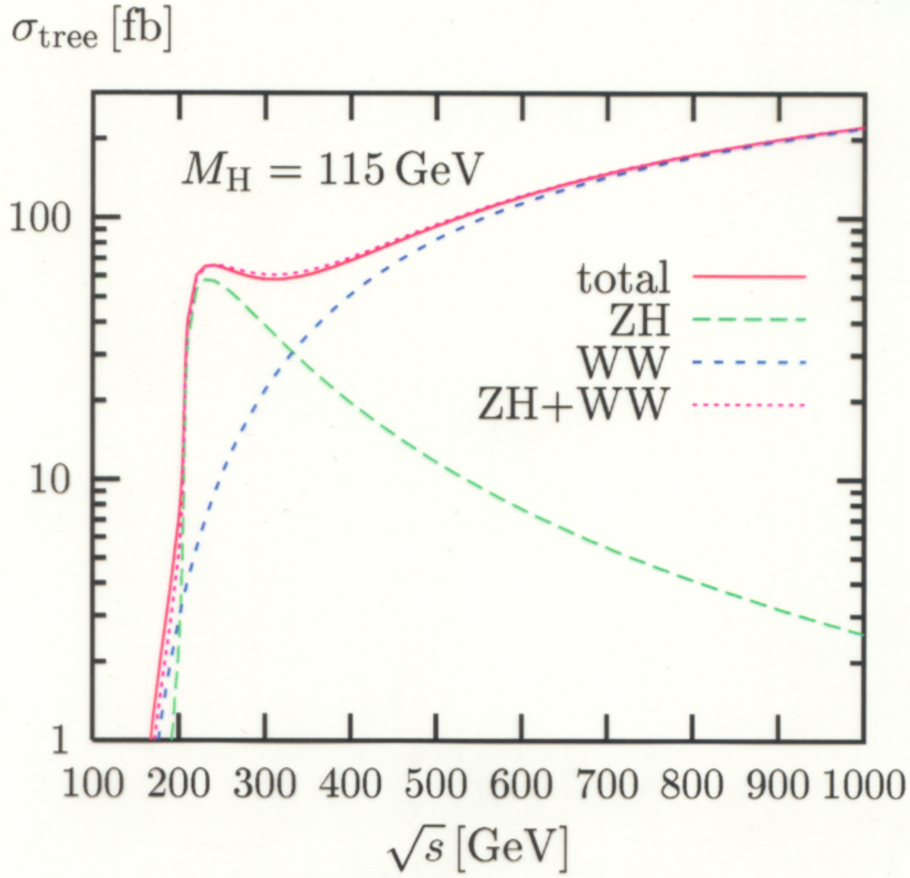
$\sigma \sim g_{ZZH}^2 \, \frac{\beta}{s}$ $\sigma \sim g_{WWH}^2 \log \frac{s}{M_H^2}$

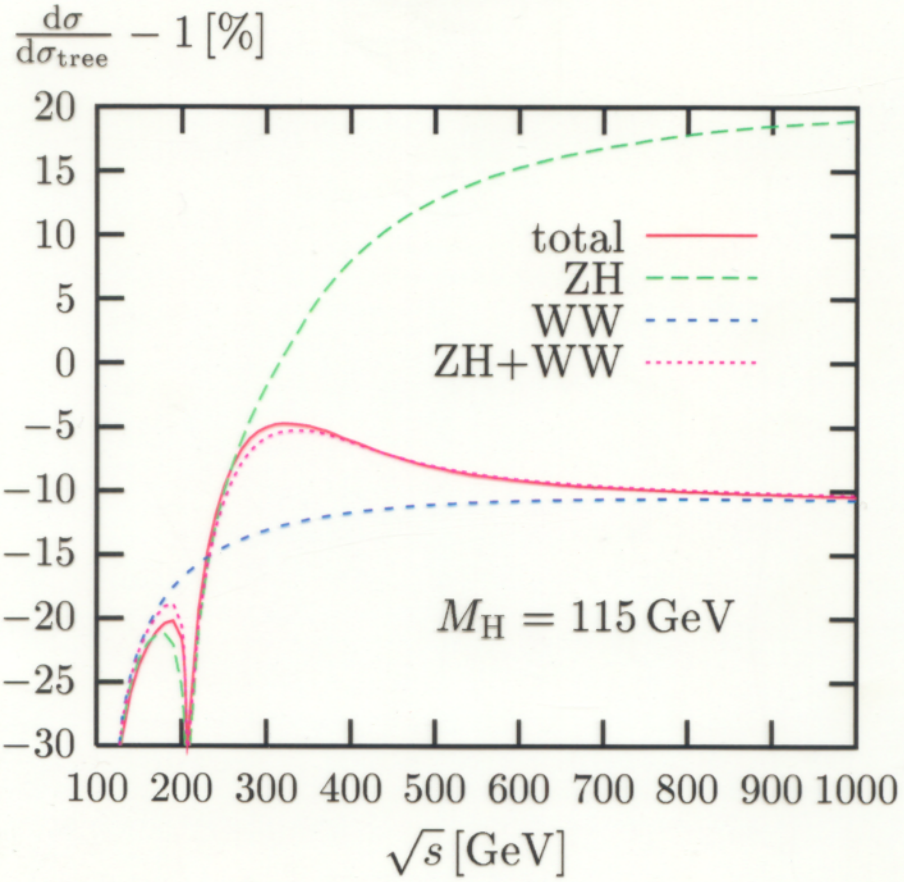


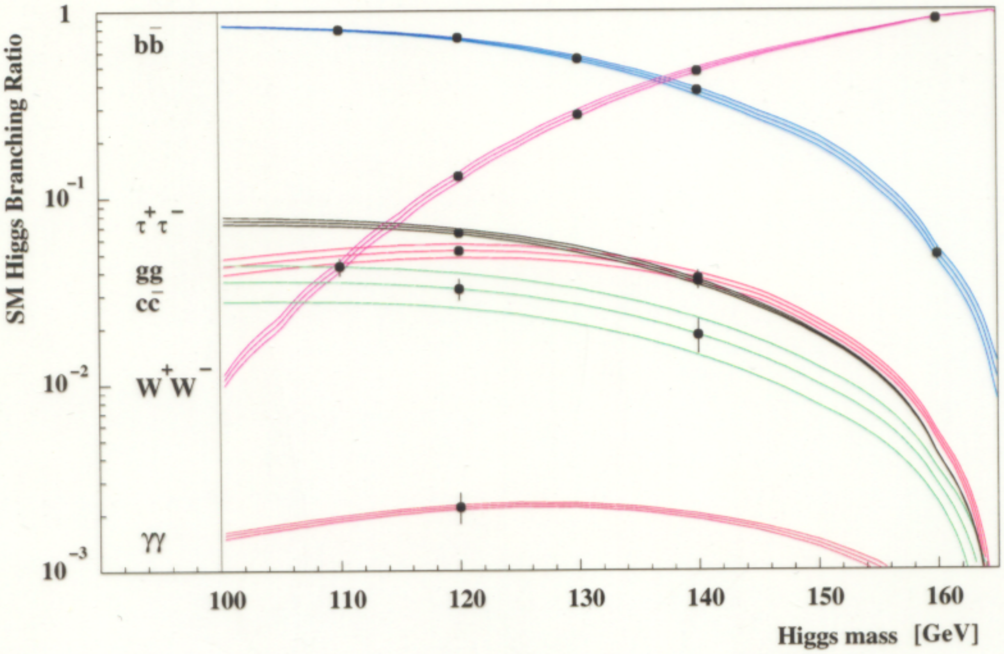
$\delta M_H \simeq 50\,\text{MeV}$ @ 350 GeV $[M_H = 120\,\text{GeV}]$

$\delta M_H \simeq 200\,\text{MeV}$ @ 500 GeV $[M_H = 240\,\text{GeV}]$

Denner, Dittmaier, Roth, Weber





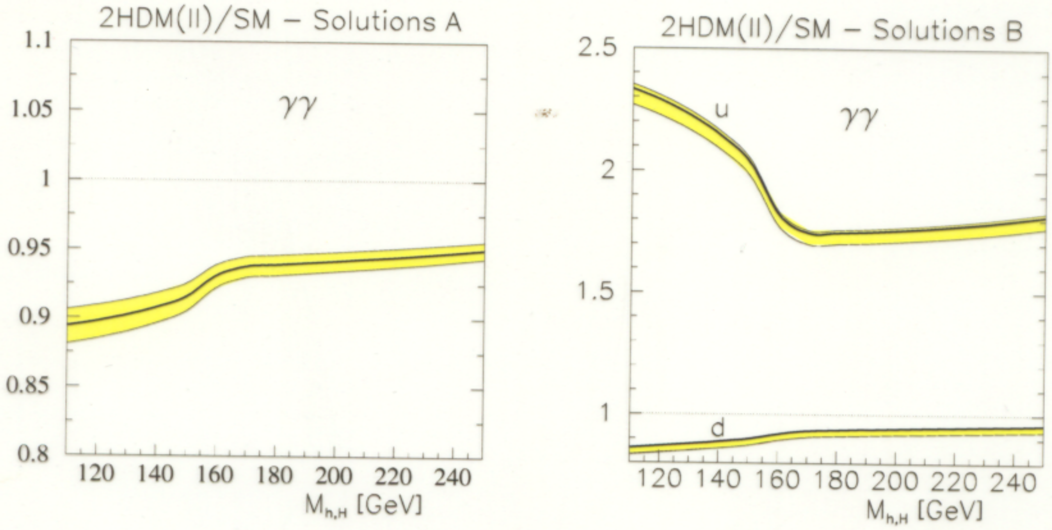


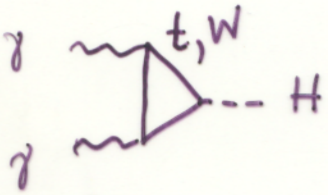
decay mode	SM precision
$h \to b\bar{b}$	1.5%
$h \to \tau^+\tau^-$	4.5%
$h \to c\bar{c}$	6%
$h \to gg$	4%
$h \to WW^*$	3%

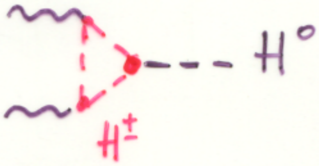
$h \to \gamma\gamma$ 21%

2% @ $\gamma\gamma$ Collider

Ginzburg, Krawczyk, Osland

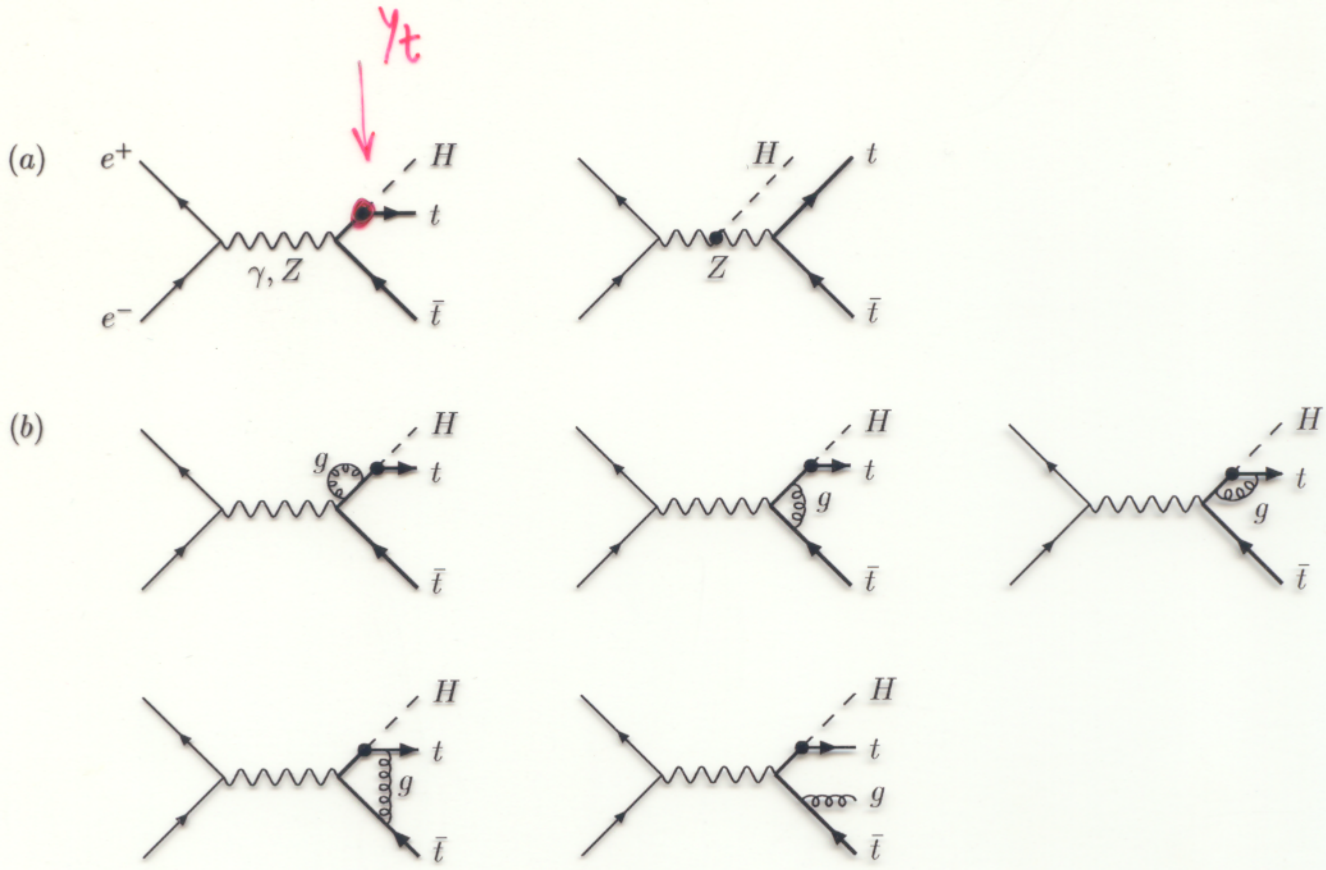






non-decoupling

SUSY, ...



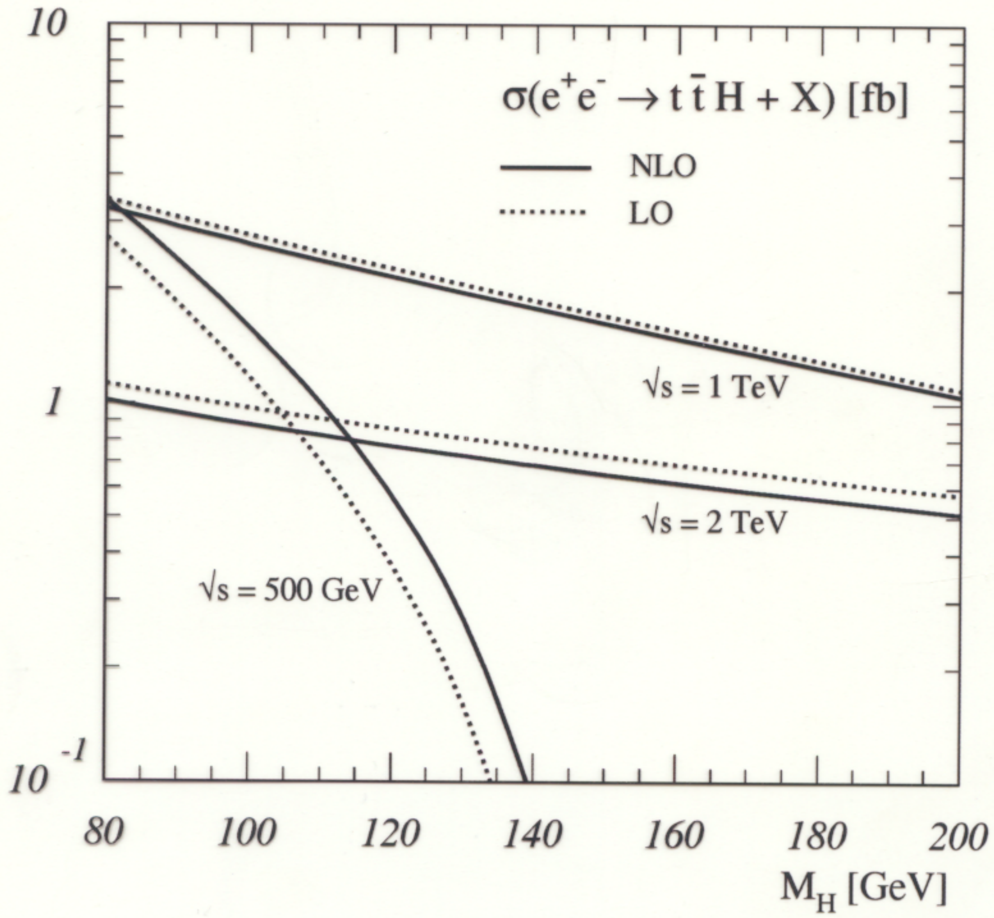
Yukawa coupling: $\frac{\delta y_t}{y_t} \sim 7\%$

[E.Gross, Jeju]

Measurement of the top–Higgs Yukawa coupling

$$e^+e^- \rightarrow t\bar{t}H$$

Effect of QCD corrections:

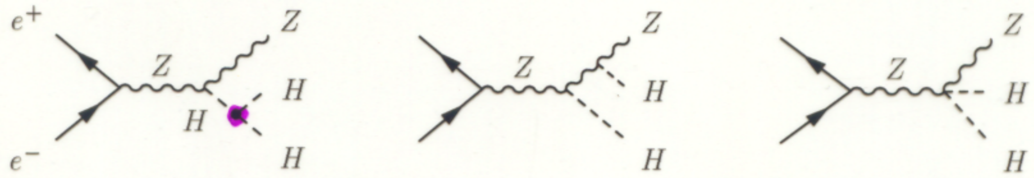


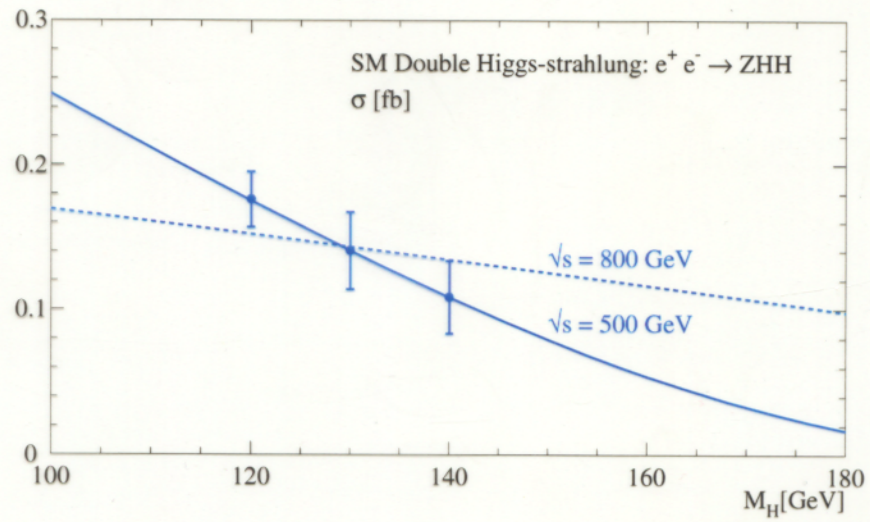
[Dittmaier, Krämer, Liao, Spira, Zerwas]

[Dawson, Reina]

Higgs potential $\longleftrightarrow$ self interaction

$$V = \lambda v^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4$$





$$\frac{\delta\lambda}{\lambda} \simeq 20\% \qquad [M_H = 120\,\text{GeV} @ 500\,\text{GeV}]$$

(Battaglia)

Higgs sector of the MSSM:

MSSM: Enlarged Higgs sector:

Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

Higgs potential:

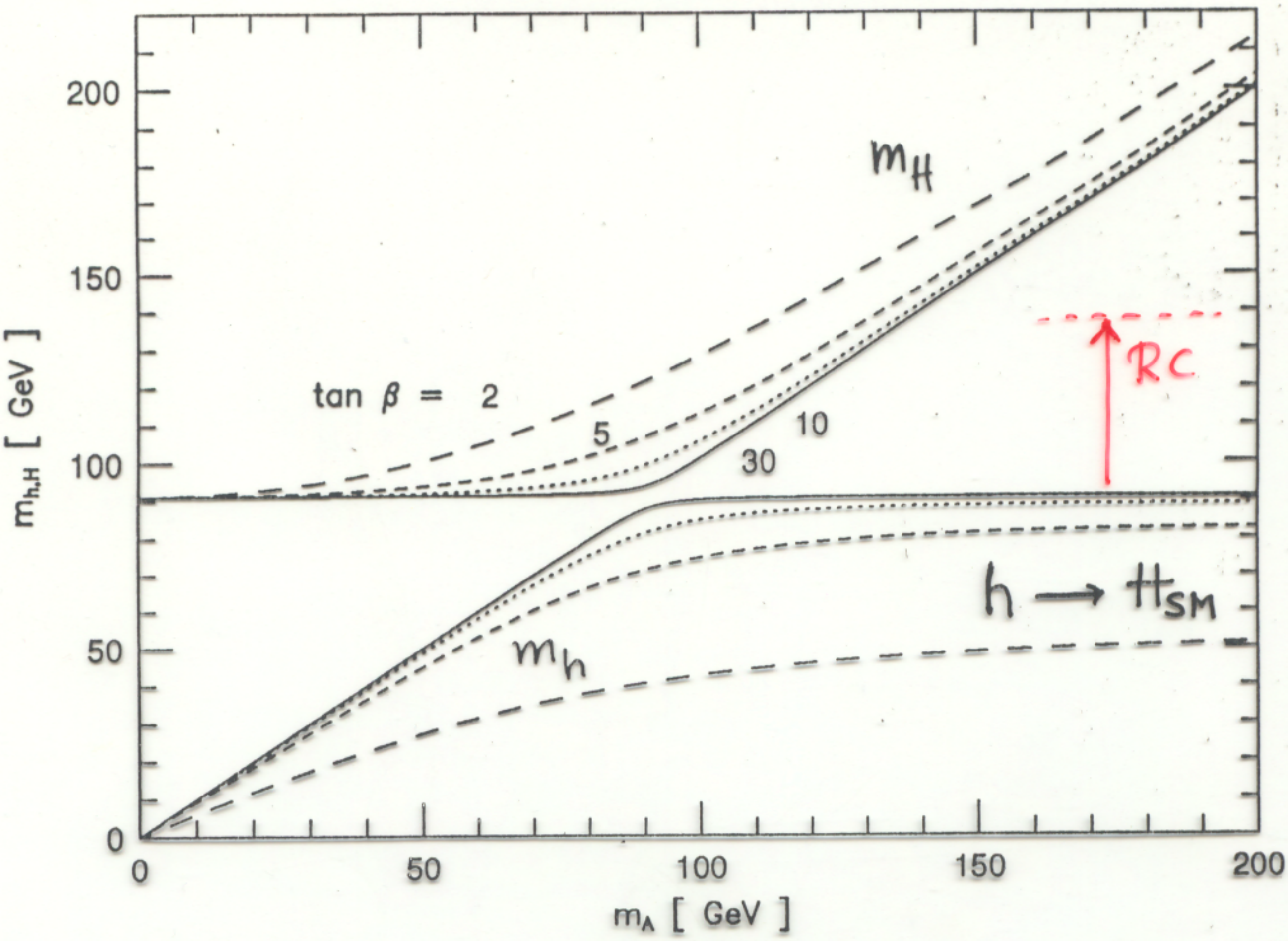
$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2(\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) + \frac{g'^2 + g^2}{8}(H_1\bar{H}_1 - H_2\bar{H}_2)^2 + \frac{g^2}{2}|H_1\bar{H}_2|^2$$

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

Input parameters:

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_A^2 = -m_{12}^2(\tan\beta + \cot\beta)$$

light and heavy scalar Higgs mass



<u>lowest order</u>

$$m_h < m_Z$$

$$m_h < m_A$$

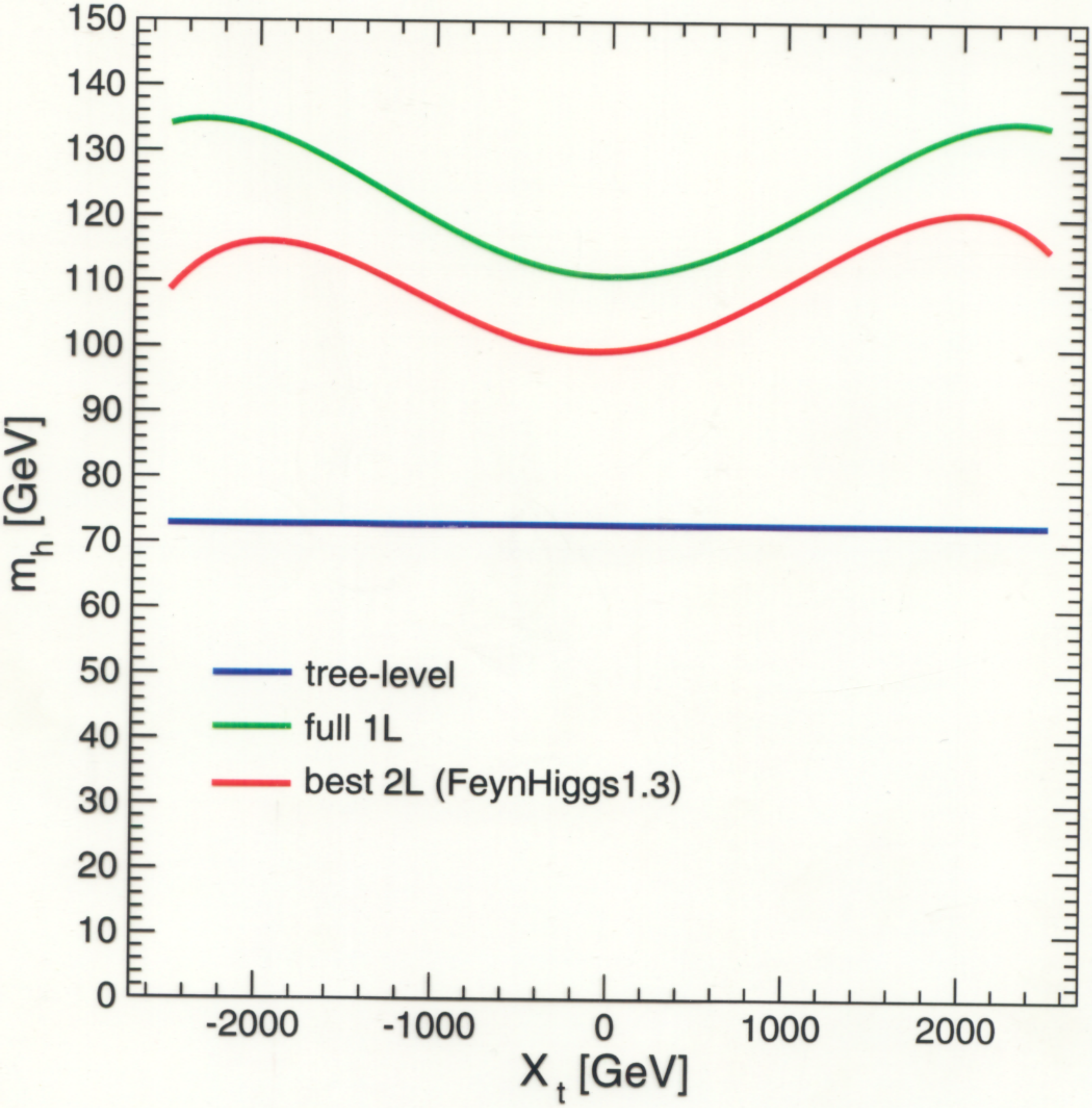
- Maximum value of m_h :

$$m_A \rightarrow \infty$$

$$\tan\beta \rightarrow \infty$$

- large radiative corrections

m_{h^0} prediction at different levels of accuracy:



$\tan\beta = 3, \quad M_{\tilde{Q}} = M_A = 1$ TeV, $\quad m_{\tilde{g}} = 800$ GeV

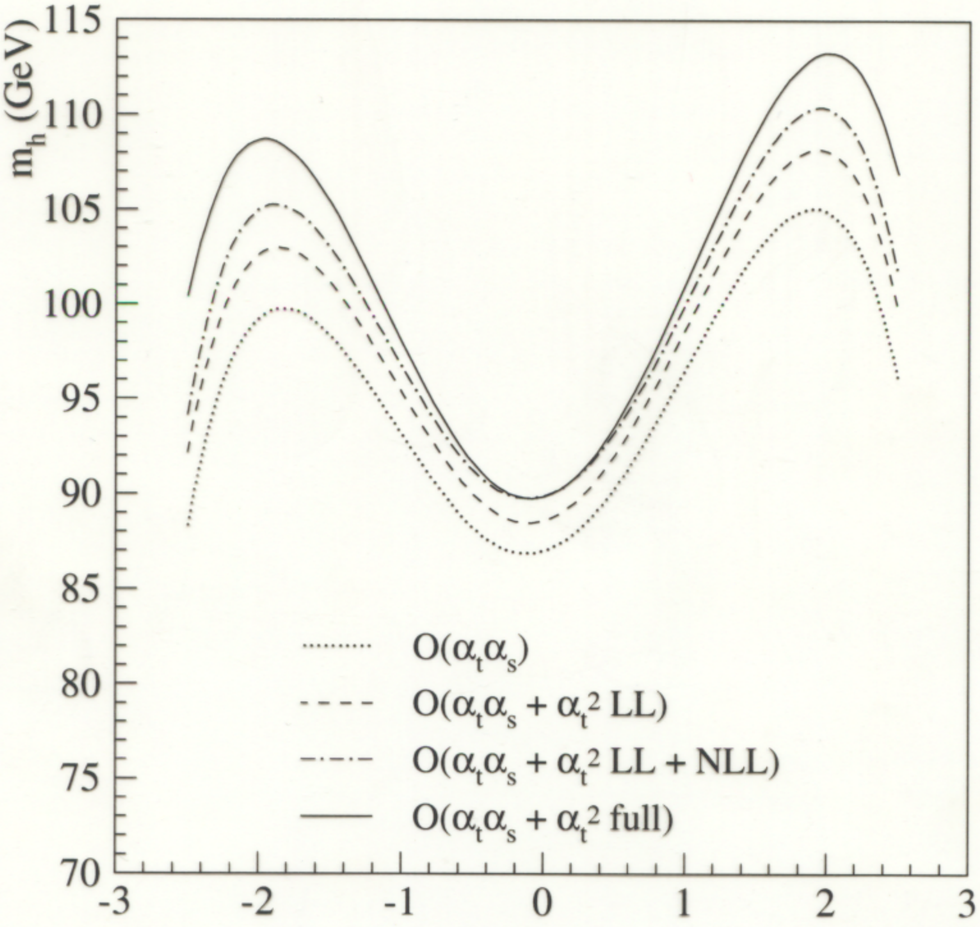
X_t : top-squark mixing parameter

$$\begin{pmatrix} M_{\tilde{Q}}^2 & m_t X_t \\ m_t X_t & M_{\tilde{Q}}^2 \end{pmatrix} \xrightarrow{\theta_{\tilde{t}}} \begin{pmatrix} m_{\tilde{t}_1}^2 & 0 \\ 0 & m_{\tilde{t}_2}^2 \end{pmatrix}$$

The h mass at the two-loop level

combined strong and top-Yukawa terms

[Degrassi, Heinemeyer, WH, Slavich, Weiglein]



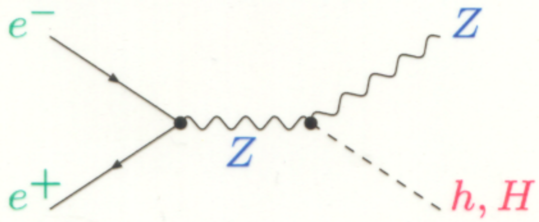
$= A_t - \mu \cot\beta$

$\tan\beta = 3, \quad M_{\tilde{Q}} = M_A = 1\ \text{TeV}, \quad m_{\tilde{g}} = 800\ \text{GeV}$

$$A \log^2 \frac{M_{\tilde{Q}}}{m_t} + B \log \frac{M_{\tilde{Q}}}{m_t} + C$$

A ↑ RG 1-loop; B ↑ RG 2-loop; C ↑ only diagram.

Higgs-strahlung process, $e^+e^- \to Zh, ZH$

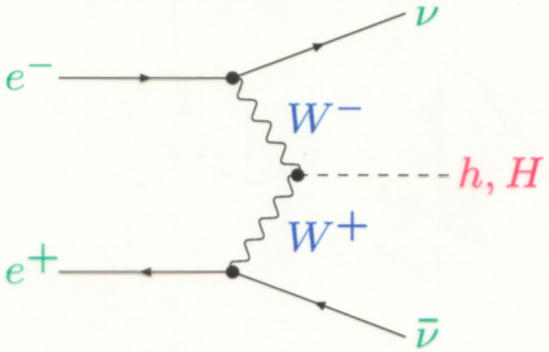


$$\sigma_{\mathrm{hZ}} \sim \sin^2(\beta-\alpha)\sigma^{\mathrm{SM}}_{\mathrm{HZ}}$$

$$\sigma_{\mathrm{HZ}} \sim \cos^2(\beta-\alpha)\sigma^{\mathrm{SM}}_{\mathrm{HZ}}$$

Dominates at low energies

Vector-boson fusion process, $e^+e^- \to \bar{\nu}_e\nu_e\{h, H\}$

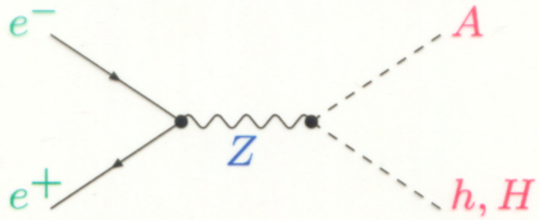


$$\sigma_{\bar{\nu}\nu\mathrm{h}} \sim \sin^2(\beta-\alpha)\sigma^{\mathrm{SM}}_{\bar{\nu}\nu\mathrm{H}}$$

$$\sigma_{\bar{\nu}\nu\mathrm{H}} \sim \cos^2(\beta-\alpha)\sigma^{\mathrm{SM}}_{\bar{\nu}\nu\mathrm{H}}$$

Dominates at high energies

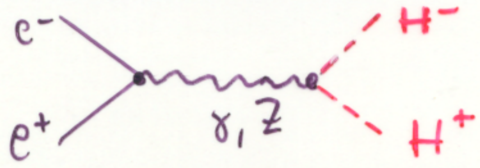
Higgs boson pair production, $e^+e^- \to Ah, AH$



$$\sigma_{\mathrm{hA}} \sim \cos^2(\beta-\alpha)\sigma^{\mathrm{SM}}_{\mathrm{HZ}}$$

$$\sigma_{\mathrm{HA}} \sim \sin^2(\beta-\alpha)\sigma^{\mathrm{SM}}_{\mathrm{HZ}}$$

$e^+e^- \to H^+H^-$



Higgs couplings, tree level:

$$g_{\text{hVV}} = \sin(\beta - \alpha)\; g^{\text{SM}}_{\text{HVV}}, \quad V = W^{\pm}, Z$$
$$g_{\text{HVV}} = \cos(\beta - \alpha)\; g^{\text{SM}}_{\text{HVV}}$$
$$g_{\text{hAZ}} \sim \cos(\beta - \alpha)$$
$$g_{\text{HAZ}} \sim \cos(\beta - \alpha)$$

In decoupling limit, $M_A \gg M_Z$:

$\sin^2(\beta - \alpha) \to 1, \quad \cos^2(\beta - \alpha) \to 0, \quad m_H \approx M_A$

⇒ h couples to vector bosons with SM strength

H decouples from vector bosons

production of heavy neutral Higgs bosons in e^+e^- mode only via HA pair production

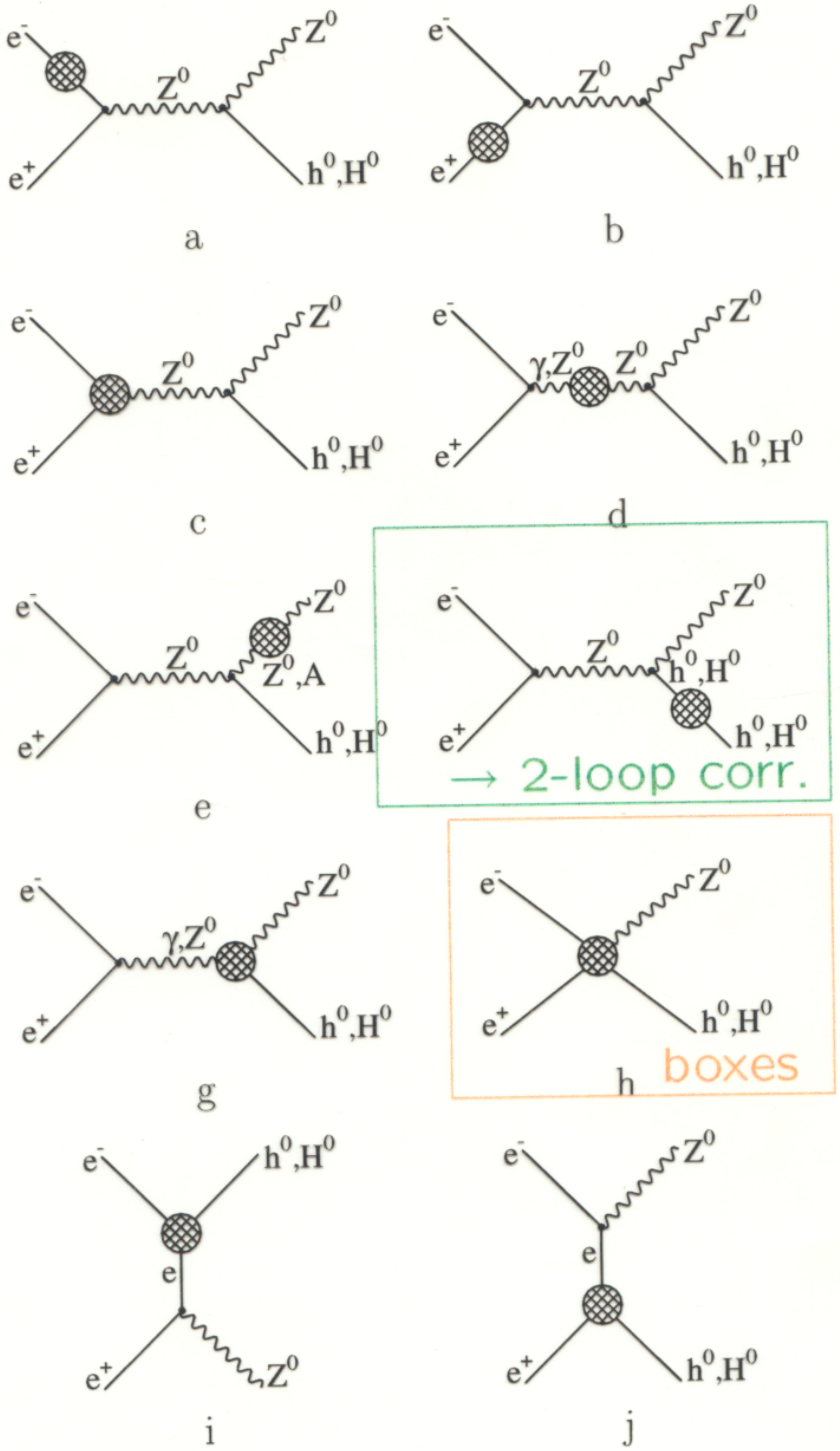
kinematical limit: $m_H, M_A \lesssim \sqrt{s}/2$

loop effects are important !

Higgs production at a LC: $e^+e^- \to hZ$

Complete Feynman-diagrammatic one-loop result +
dominant two-loop corrections (*FeynHiggs*)

[*S. Heinemeyer, W. Hollik, J. Rosiek, G. Weiglein '01*]

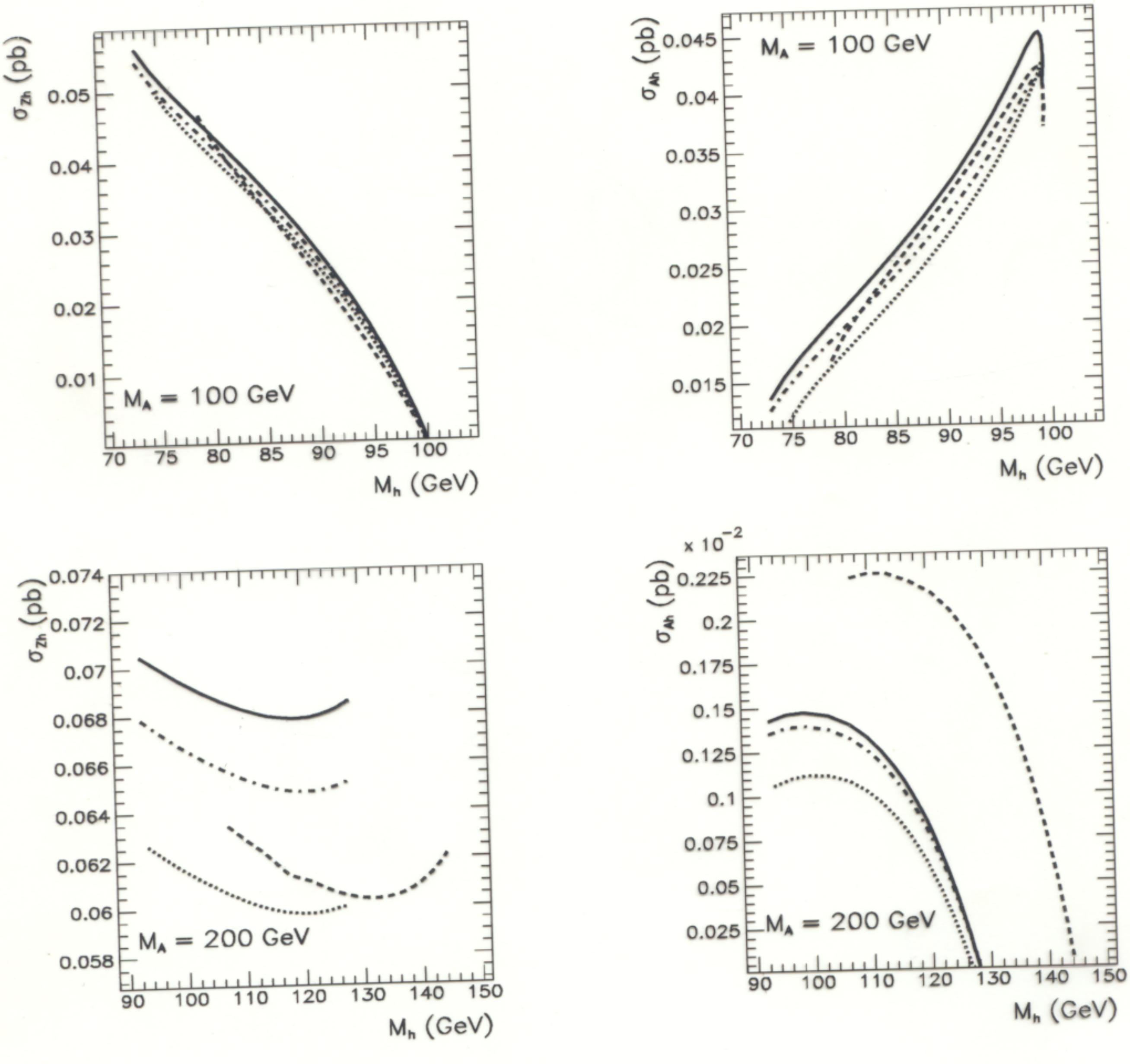


$e^+e^- \to hZ, hA$, $\sqrt{s} = 500$ GeV, maximal $\tilde{t}$ mixing:

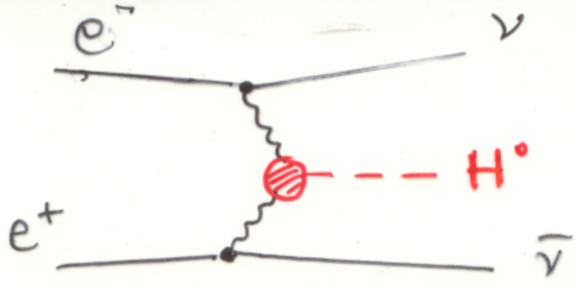
$M_{\tilde{q}} = 1$ TeV, $M_{\tilde{l}} = 300$ GeV, $M_2 = \mu = 200$ GeV

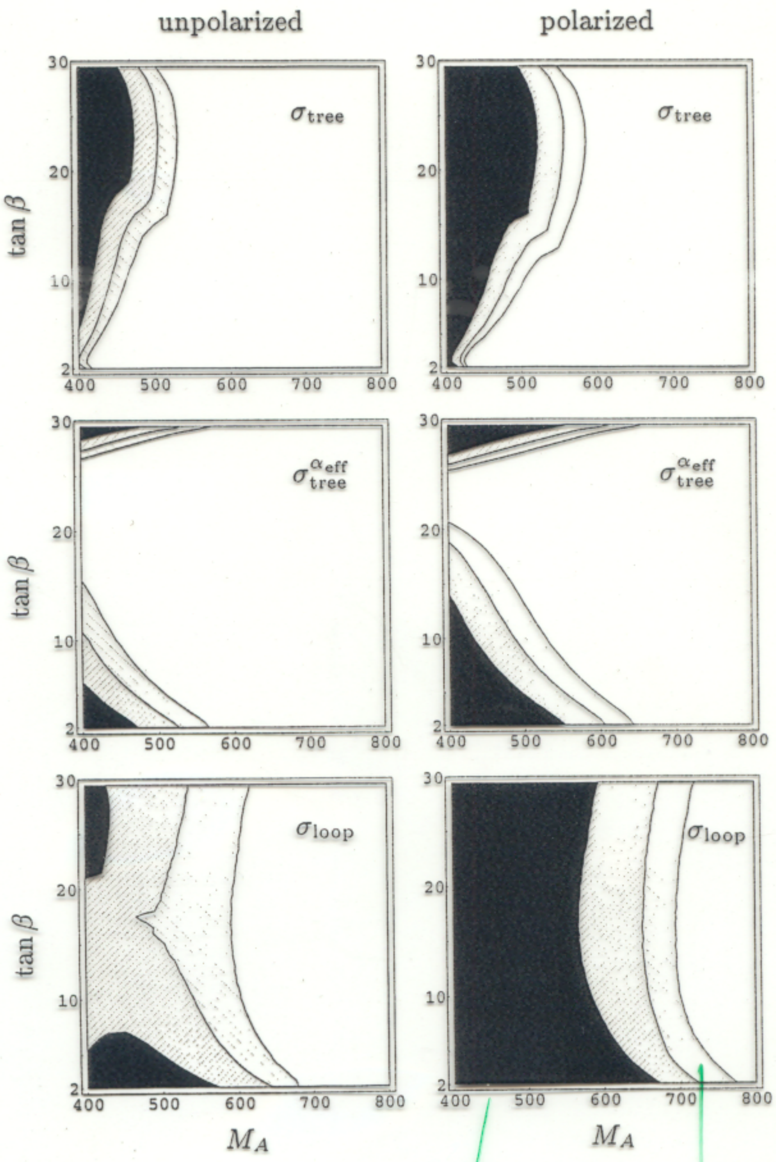
solid: FD 2L (with box), dot-dashed: FD 2L (no box)

dashed: FD 1L, dotted: $\alpha_{\rm eff}$ RG approximation



Diff. FD 2L − $\alpha_{\rm eff}$ RG: $\sigma_{Zh} \approx$ 10–15%, $\sigma_{Ah} \approx$ 25%





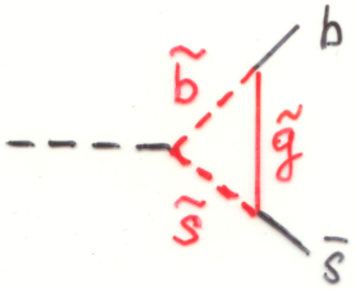
Heinemeyer, Hahn, Weiglein

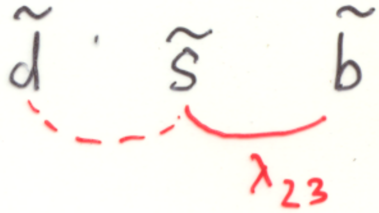
(1 TeV)

σ > 0.05 fb

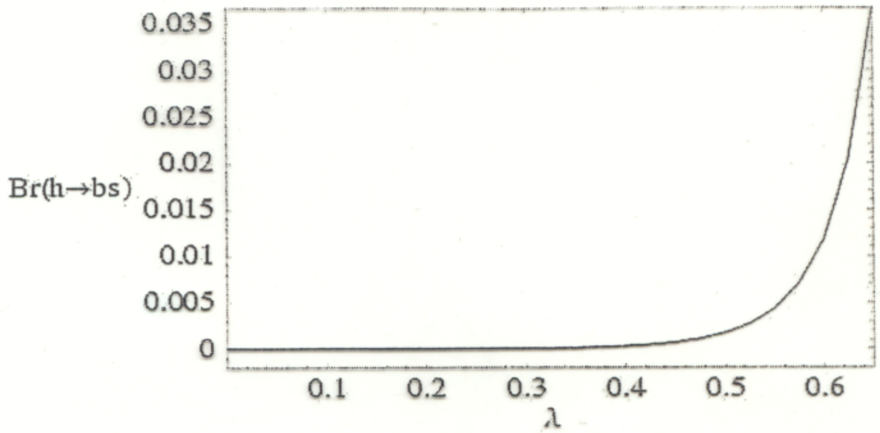
σ > 0.01 fb

FCNC Higgs decays

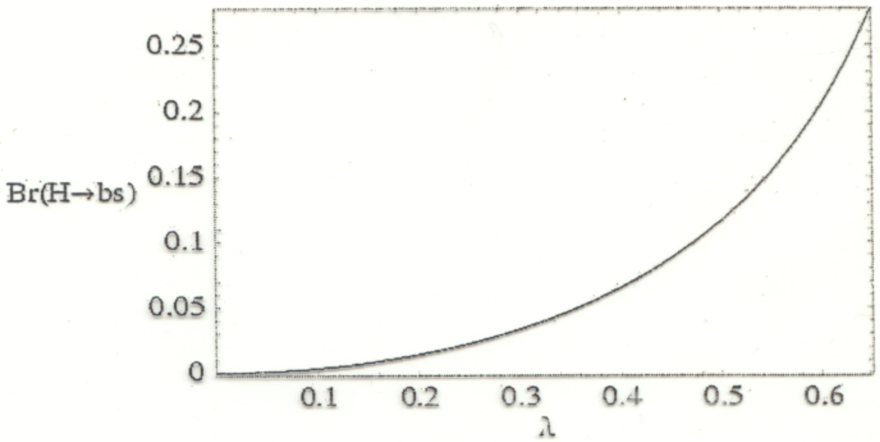




$\tilde{q}$ family mixing



$\lambda = \lambda_{23}$



Curiel, Herrero, Temes

remains also for heavy SUSY

* non-decoupling *

Possible scenarios

- a single light Higgs boson
  - SM Higgs boson?
  - SUSY light Higgs boson?
    with H, A, $H^{\pm}$ heavy (decoupling scenario)
    $h \sim H_{\text{SM}}$
- a light Higgs boson + more $(H, A, H^{\pm})$
  - SUSY Higgs?
  - non-SUSY 2-Higgs-Doublet model?
- a single heavy Higgs boson ($\gg 200$ GeV)
  - SUSY ruled out
  - SM + (?)   strong interaction?
- no Higgs boson
  - strongly interacting weak interaction
    new strong force $\sim$ TeV scale

MSSM Minimal Supersymmetric Standard Model

SM		Spin	SUSY		Spin
leptons	$\ell,\ \nu_\ell$	$\frac{1}{2}$	sleptons	$\tilde{\ell},\ \tilde{\nu}_\ell$	0
quarks	q	$\frac{1}{2}$	squarks	$\tilde{q}$	0
gluons	g	1	gluinos	$\tilde{g}$	$\frac{1}{2}$
EW bosons	γ, Z, W	1 }	{ charginos	$\tilde{\chi}^\pm_{1,2}$	$\frac{1}{2}$
Higgs	$h, H, A, H^\pm$	0 }	{ neutralinos	$\tilde{\chi}^0_{1,2,3,4}$	$\frac{1}{2}$

lightest SUSY particle stable   LSP $= \tilde{\chi}^0_1$

to prove SUSY demonstrate that
- every SM particle has a superpartner
- with spins different by 1/2
- identical gauge quantum numbers
- identical couplings

needs accurate measurements

mass spectra, branching ratios, cross sections, angular distributions, polarization asymmetries, ...

Achievable precisions:

particles		$\Delta m/m$
sleptons	$\tilde{\ell},\ \tilde{\nu}_\ell$	0.05–0.5 %
charginos	$\tilde{\chi}^\pm_i$	0.03–0.1 %
neutralinos	$\tilde{\chi}^0_i$	0.05–0.1 %

Parameters:

M_1, M_2, M_3	gaugino masses
μ	Higgsino mass
$M_{\tilde{f}_{L,R}}$	sfermion masses
$A_{\tilde{f}}$	trilinear couplings $\rightarrow \tilde{f}_{L-R}$ mixing

Threshold scan

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

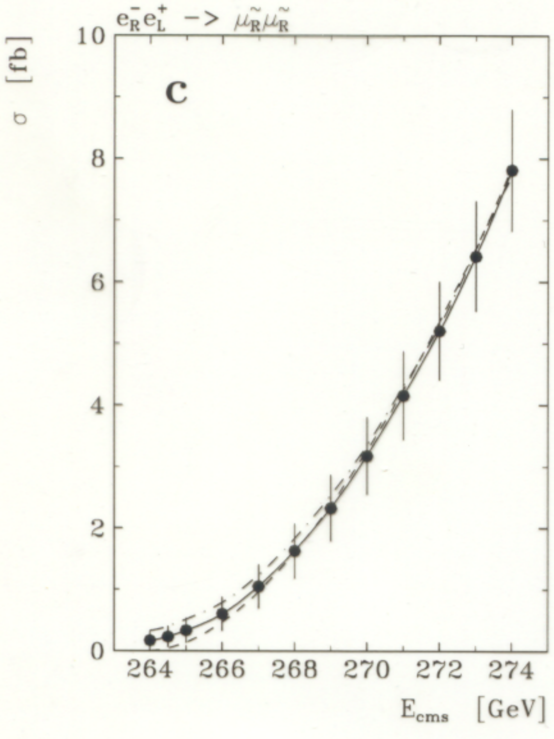
$\rightarrow \tilde{\chi}^+ \tilde{\chi}^-$

...

$\rightarrow$ { masses, spin }

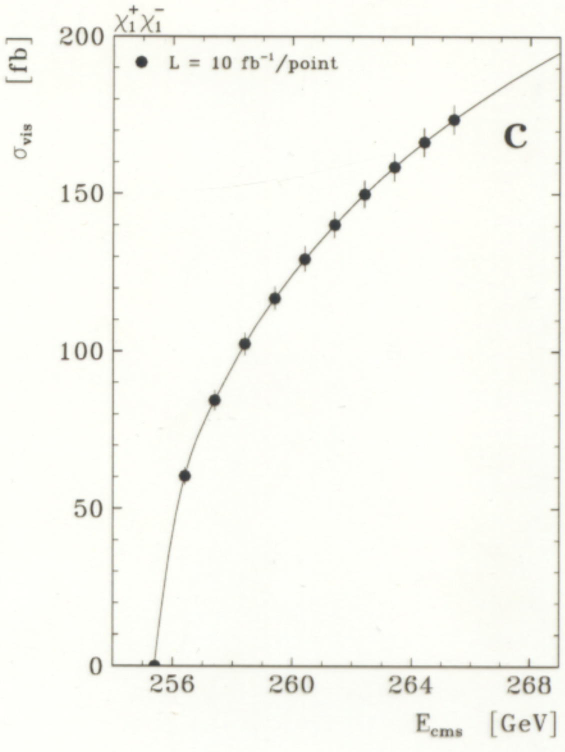
Spin = 0

$\sigma \sim \beta^3$



Spin = $\frac{1}{2}$

$\sigma \sim \beta$

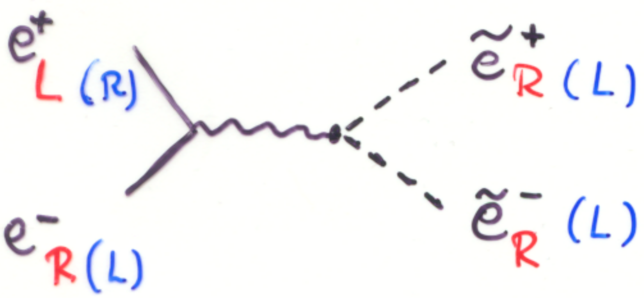


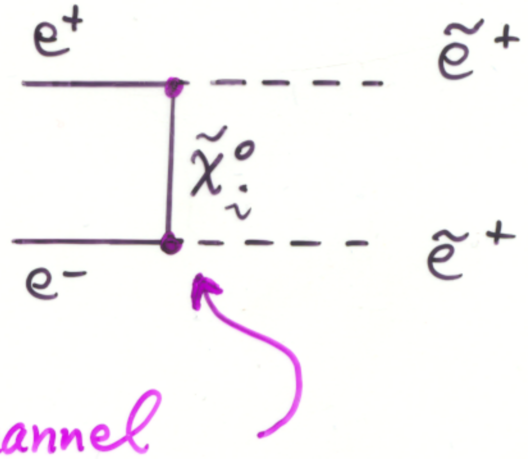
$e^+e^- \to \tilde{\mu}^+\mu^-$

polarization separates $\tilde{\mu}_R / \tilde{\mu}_L$

- $\tilde{\mu} \to \mu \tilde{\chi}^0_1$ $\quad \mu + \not{E}$ $\quad \to$ mass $m_{\tilde{\mu}}$
- $\frac{d\sigma}{d\Omega} \sim \sin^2\Theta$ $\quad \to$ spin 0

$e^+e^- \to \tilde{e}\tilde{e}$





$e^+_L e^-_L$: no s-channel

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

$\tilde{\chi}^\pm_1 \to \tilde{\chi}^0_1 W^\pm$

$\tilde{\chi}^0_i \to \chi^0_1 Z$

complete reconstruction
+ CP violation

M_1, M_2, μ
$\mathrm{Arg}(\mu)$

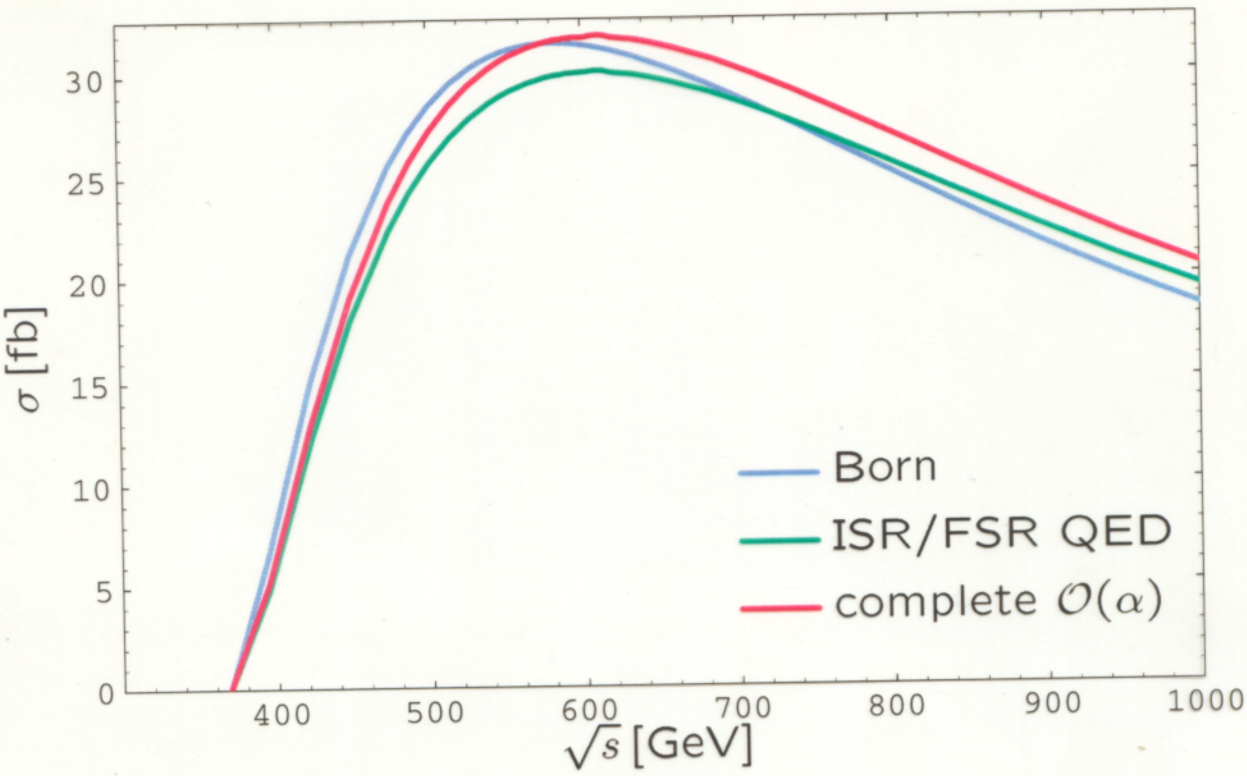
Numerical results

A. Freitas et al.

Inclusive treatment of real photon emission contributions

TESLA TDR reference scenario RR2:

$M_1 = 78$ GeV, $M_2 = 150$ GeV, $\mu = 263$ GeV,
$\tan\beta = 30$, $M_{\mathrm{A}} = 257$ GeV,
$m_{\tilde{\mu}_{\mathrm{R}}} = 184$ GeV, $m_{\tilde{l}} \sim 200$ GeV,
$m_{\tilde{q}} \sim 450$ GeV.



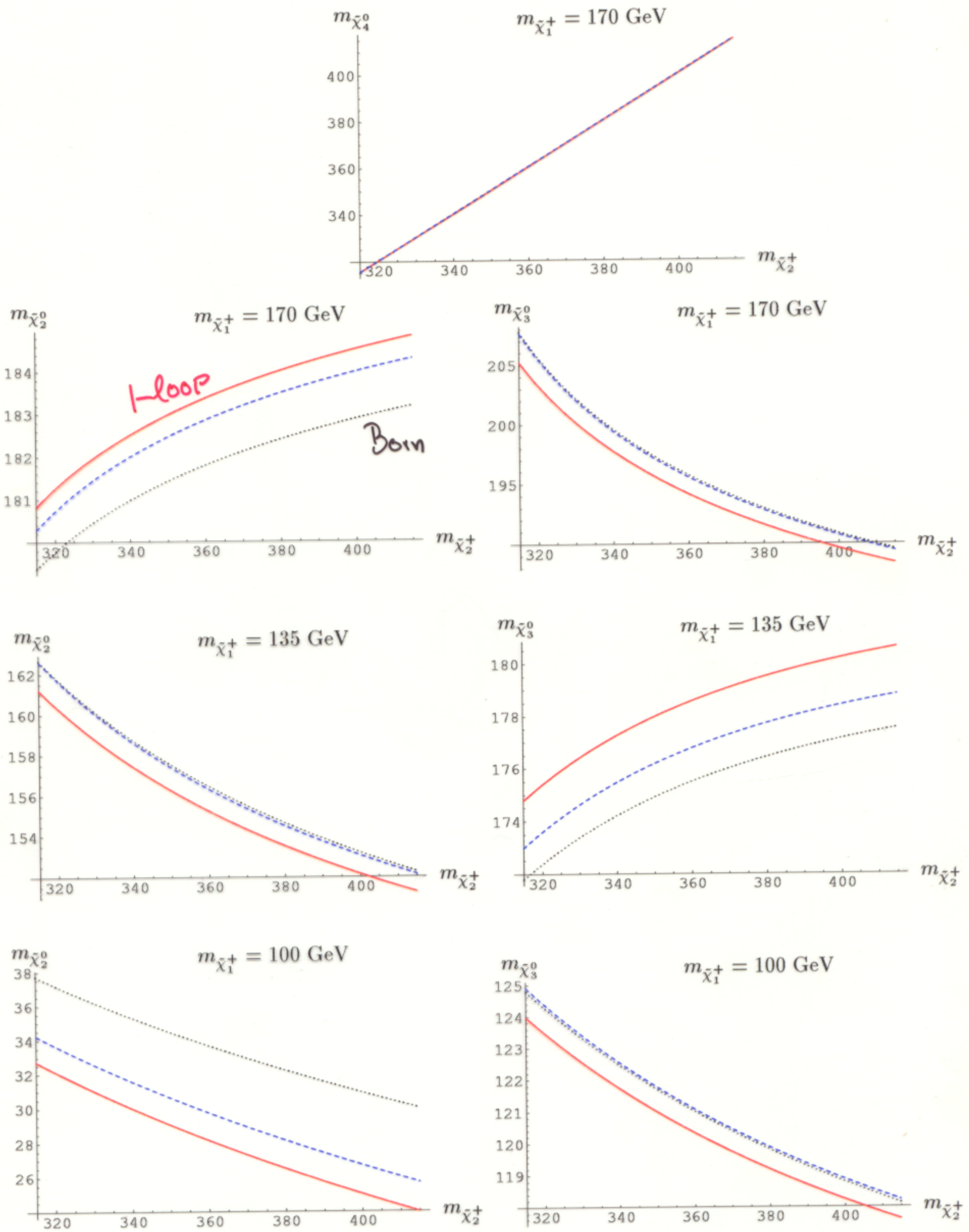


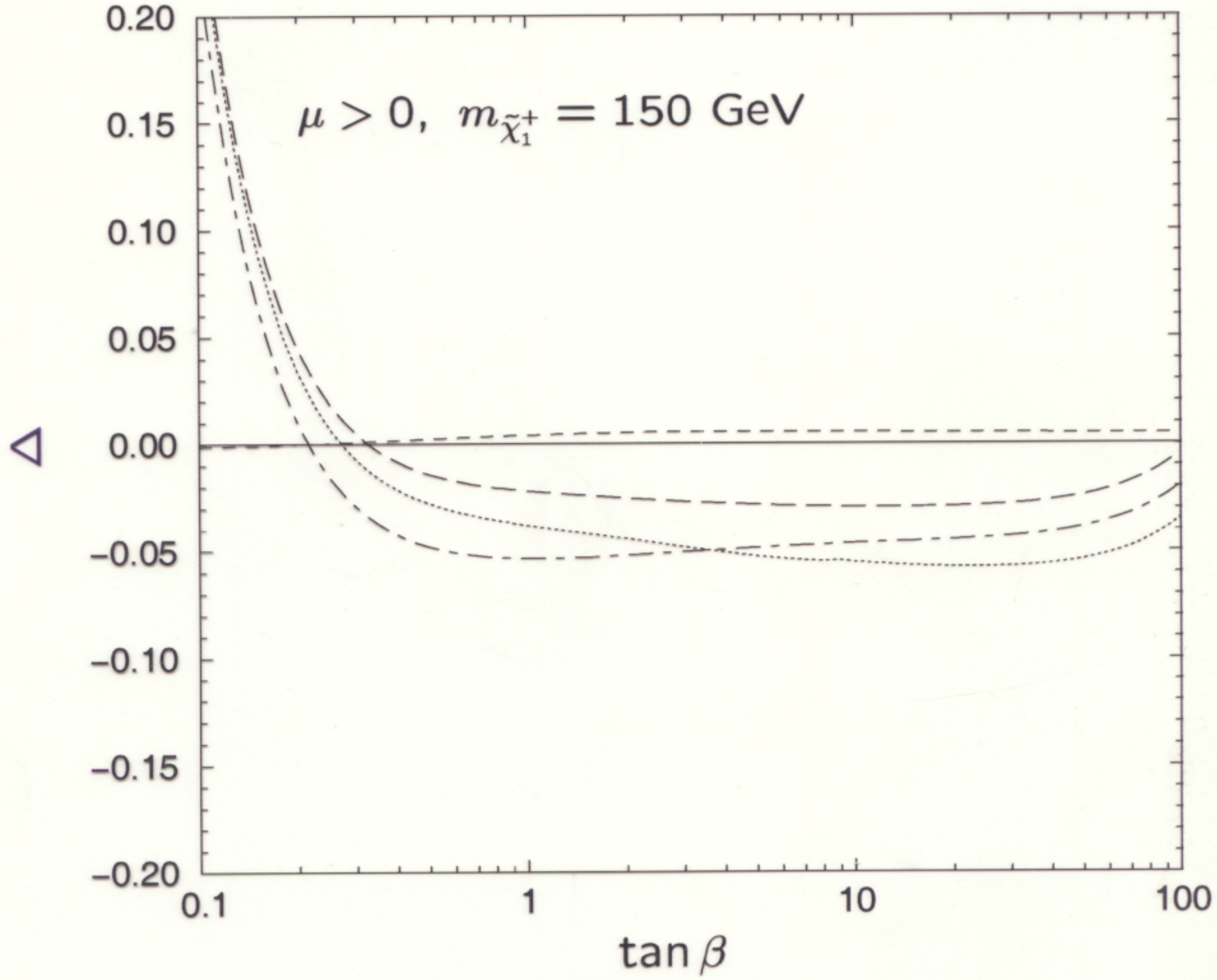
Figure 1: Dependence of the calculated neutralino masses (in GeV) on the chargino masses $m_{\tilde{\chi}_1^+}$ and $m_{\tilde{\chi}_2^+}$, in Born approximation (dotted, black), including loop corrections with (s)fermions only (dashed, blue), and with the complete one-loop contributions (solid, red). The input neutralino mass is chosen as $m_{\tilde{\chi}_1^0} = 110$ GeV throughout all diagrams. The plots for $m_{\tilde{\chi}_4^0}$ neutralino would look very much alike the one shown for all three different values of $m_{\tilde{\chi}_1^+}$.

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

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

-.-.-.- (s)top/(s)bottom loops ------ SM fermion loops

- - - - (s)fermion loops .... complete 1loop



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

Models of SUSY breaking

generic MSSM: 105 parameters (masses, mixing angles, phases)

reduced to few parameters in specific models

mSUGRA: m_0, $m_{1/2}$, A_0, $\tan\beta$, $\text{sign}(\mu)$

GMSB: M_{mess}, N_{mess}, $\tan\beta$, $\text{sign}(\mu)$

AMSB: m_{aux}, m_0, $\tan\beta$, $\text{sign}(\mu)$

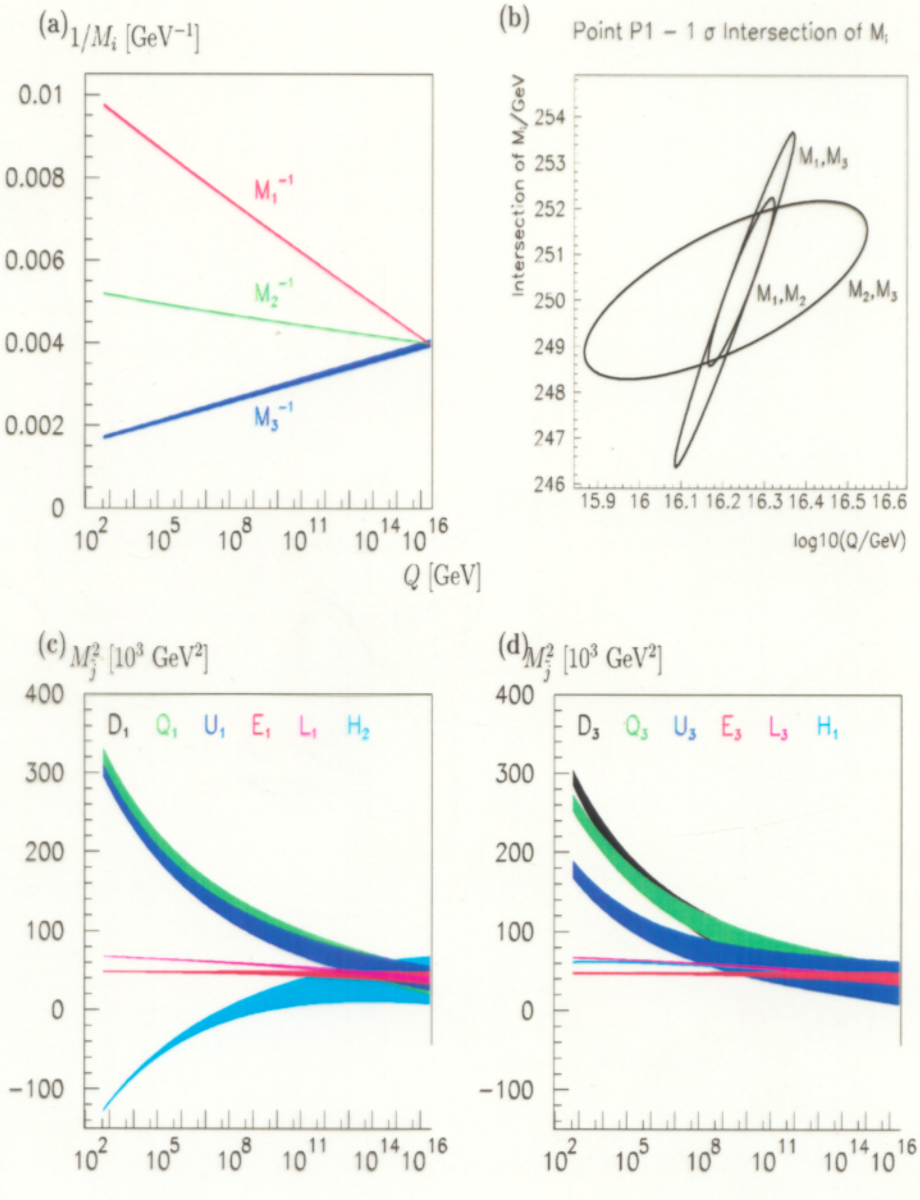
$\rightarrow$ mass parameters at the electroweak scale
$(M_1, M_2, M_3, \mu, M_{\tilde{f}_{L,R}}, \ldots)$

Precise determination of mass parameters of SUSY particles essential

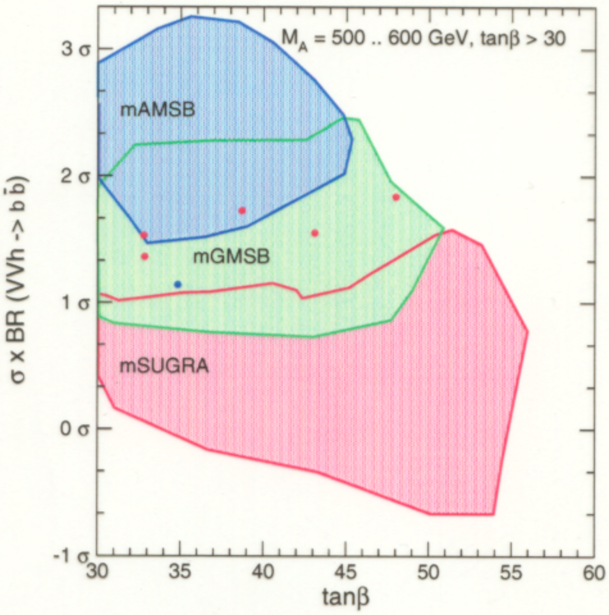
- distinction between SUSY-breaking models
- extrapolation to unification scale
- determination of unification scale

[Blair, Porod, Zerwas]

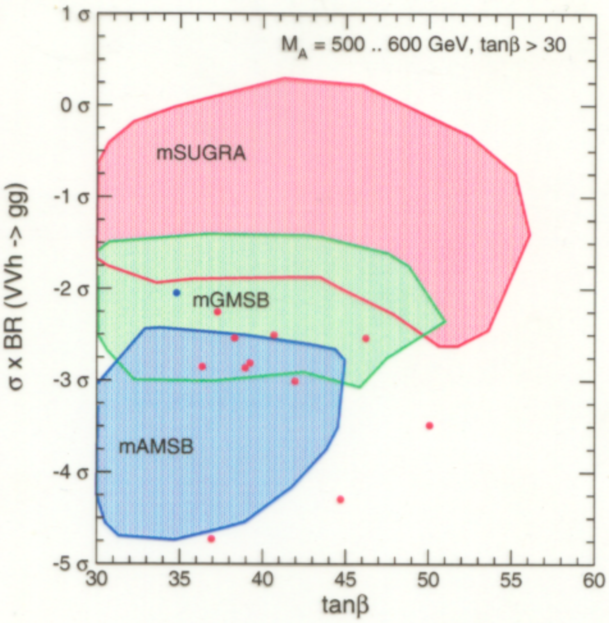
mSUGRA:



[Dedes et al.]



M_A = 500 .. 600 GeV, tanβ > 30
mAMSB
mGMSB
mSUGRA
σ x BR (VVh -> b b̄)
3 σ
2 σ
1 σ
0 σ
-1 σ
30
35
40
45
50
55
60
tanβ



M_A = 500 .. 600 GeV, tanβ > 30
mSUGRA
mGMSB
mAMSB
σ x BR (VVh -> gg)
1 σ
0 σ
-1 σ
-2 σ
-3 σ
-4 σ
-5 σ
30
35
40
45
50
55
60
tanβ

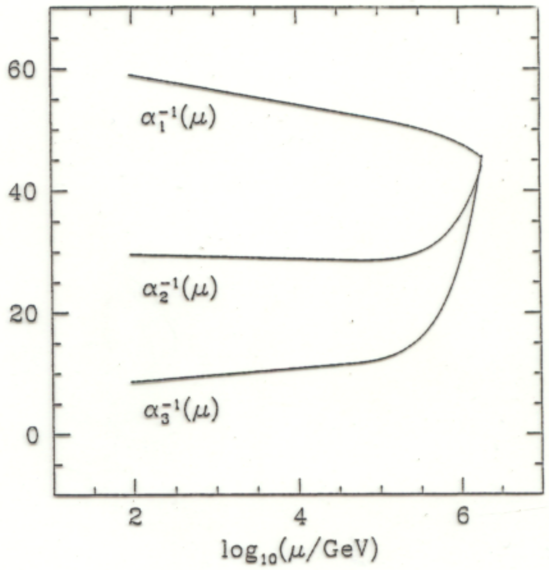
Large extra dimensions

if extra dimensions $\gg 1/M_{Planck}$

$\Rightarrow$ scale of gravity close to EW scale

$$F(r) = \frac{m_1 \cdot m_2}{M_D^{2+\delta}} \cdot \frac{1}{r^{2+\delta}} \quad \text{for} \quad r < R$$

$$M_{Pl}^2 = M_D^{2+\delta} R^\delta$$



$\delta = 1$

$M_D = 1\,\mathrm{TeV}$

[Dienes et al.]

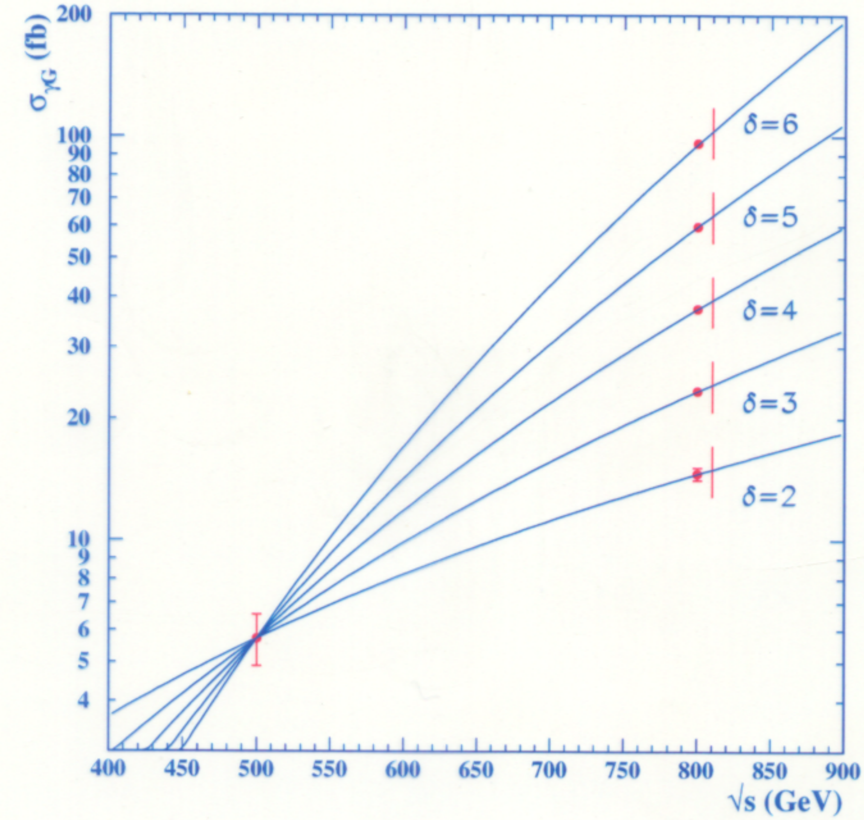
Possible collider signals:

- $e^+e^- \to \gamma G$ graviton emission
- $e^+e^- \to f\bar{f}$ with virtual graviton exchange

  interference with SM processes
  (sensitivity $M_D \sim 8$ TeV)

  graviton resonances in specific models
  (Randall-Sundrum, 1 extra dim.)

$$\sigma(\gamma G) \sim \frac{\alpha}{M_D^2}\left(\frac{\sqrt{s}}{M_D}\right)^{\delta}$$



Randall-Sundrum:

$$ds^2 = e^{-2k|y|} \underbrace{\eta_{\mu\nu} dx^\mu dx^\nu}_{\text{4-dim}} - \underbrace{b^2 dy^2}_{\text{1 extra}}$$

$\eta_{\mu\nu}$ → gravitons

$b^2 dy^2$ → radion → mixing with Higgs

Non-commutative space-time:

$$[X_\mu, X_\nu] \sim \frac{1}{\Lambda^2_{NC}} \neq 0$$

→ new vertices $\gamma\gamma\gamma, \ldots$

new gauge bosons

Conclusions

- Finding and understanding dynamics of EW symmetry breaking of basic importance for particle physics $\to$ next step

- Linear Collider with high luminosity and higher energies $\to$ high-precision experiments

  verify SM or identify signals from "beyond the SM"

- Specific ideas beyond the SM (SUSY, GUT, extra dimensions) accessible

  – indirect: test precision observables
  – Higgs sector: identify origin of Higgs bosons
  – SUSY particles: reconstruct breaking parameters

- theoretical effort for high-precision calculations, new complexity of calculations:

  $2 \to 2$ processes at 2-loop + leading 3-loop
  $2 \to 4\,(6)$ processes at complete 1-loop

- future improved studies possible based on new theoretical tools and improved predictions