Electroweak Precision Analyses

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SUSY02
DESY, June 2002

- Electroweak precision observables
  – theoretical basis

- Standard Model and precision data

- The MSSM and precision data

- The Higgs-boson mass m_{h^0}
  – a MSSM precision observable

- Conclusions

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 $M_W,\ M_Z,\ m_{\text{fermion}}$

> renormalizable quantum field theory
> accurate theoretical predictions

The (minimal) supersymmetric Standard Model (MSSM)

- same gauge symmetry

- Higgs mechanism with two scalar doublets,

- modified Yukawa interactions

- SUSY partners + SUSY interactions

Quantum Effects and Precision Tests

quantum effects: beyond Born approximation

loop diagrams

Theory $\overset{?}{\longleftrightarrow}$ Experiments

precise predictions

measurements with high accuracy

(expected) experimental precision

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

together with

$\delta M_Z = 2.1$ MeV (LEP)

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

High precision (theory) needed to

- extract parameters (masses, couplings) from e^+e^- processes, e.g.

  M_W, m_t, M_H, Yukawa couplings, SUSY(?), ...

- establish model-dependent relations between parameters, e.g.

$$
\begin{aligned}
M_W &\leftrightarrow m_t, M_H, \ldots \\
m_{\text{fermion}} &\leftrightarrow \text{Yukawa couplings} \\
\text{SUSY masses} &\leftrightarrow \text{SUSY couplings}
\end{aligned}
$$

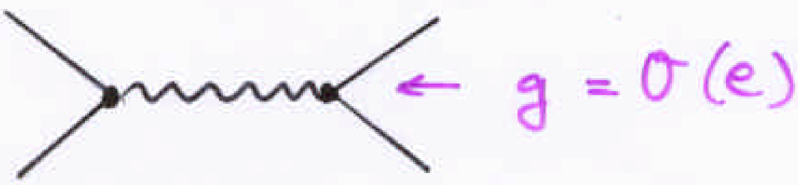
  specific model predictions

  precision tests of SM and beyond,
  especially SUSY models (MSSM)

Standard Model is renormalizable

→ quantum effects are calculable

- lowest order (Born approximation)



- next order (1-loop):

↑ all particles of the SM (virtual states)

top: $\sim m_t^2$, Higgs: $\sim \log M$

⇓ determination of top mass

⇓ constraints on Higgs-boson mas

mass renormalization

$$M_Z^2 \to M_Z^2 + \delta M_Z^2$$

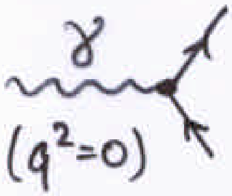
$$M_W^2 \to M_W^2 + \delta M_W^2$$

$$\sin^2\theta_W \to 1 - \frac{M_W^2 + \delta M_W^2}{M_Z^2 + \delta M_Z^2}$$

$$1 - \frac{M_W^2}{M_Z^2} + \frac{M_W^2}{M_Z^2}\left(\frac{\delta M_Z^2}{M_Z^2} - \frac{\delta M_W^2}{M_W^2}\right.$$

$\sim m_t^2$, $\sim \log M$

charge renormalization



$$\alpha = \frac{e^2}{4\pi} = \frac{1}{137.036\ldots}$$

$$e \to e + \delta e$$

$$\alpha \to \alpha + \delta\alpha$$

for electroweak processes:

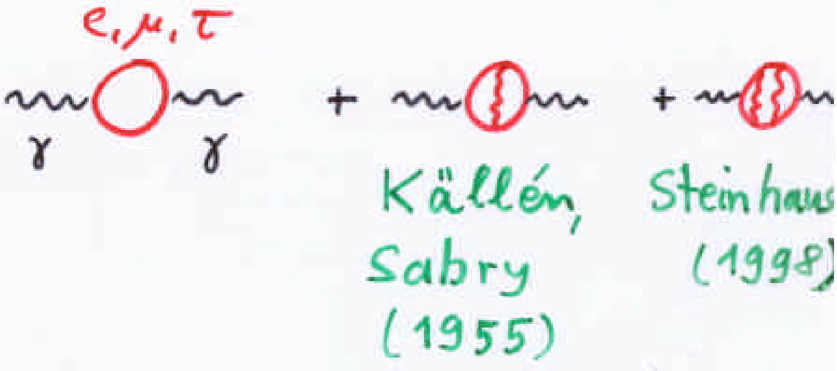
$$\Delta\alpha = \Pi^\gamma(0) - \Pi^\gamma(M_Z^2) \simeq 0.06$$

$$\alpha \to \frac{\alpha}{1-\Delta\alpha} = \alpha(M_Z)$$

effective e.m. α

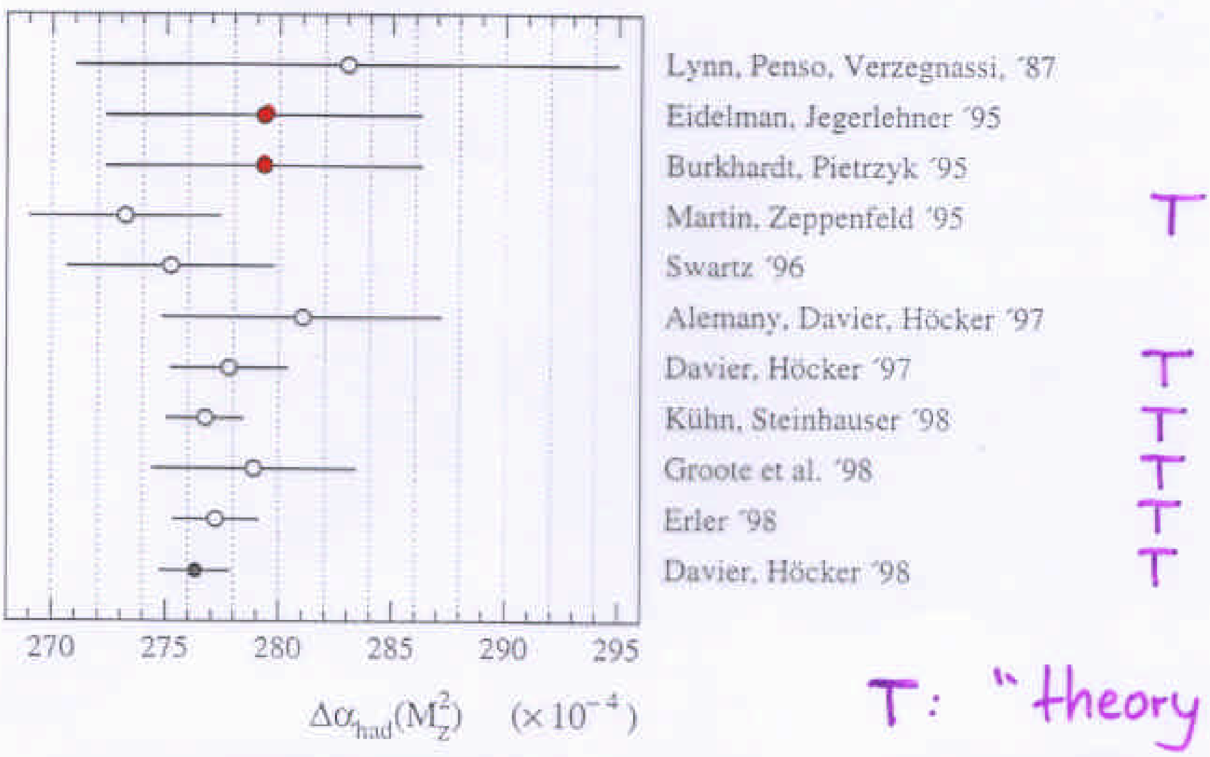
$$\Delta\alpha = (\Delta\alpha)_{lep} + (\Delta\alpha)^{(5)}_{had} + (\Delta\alpha)_{to\ldots}$$

$$(\Delta\alpha)_{lept} = \sum$$



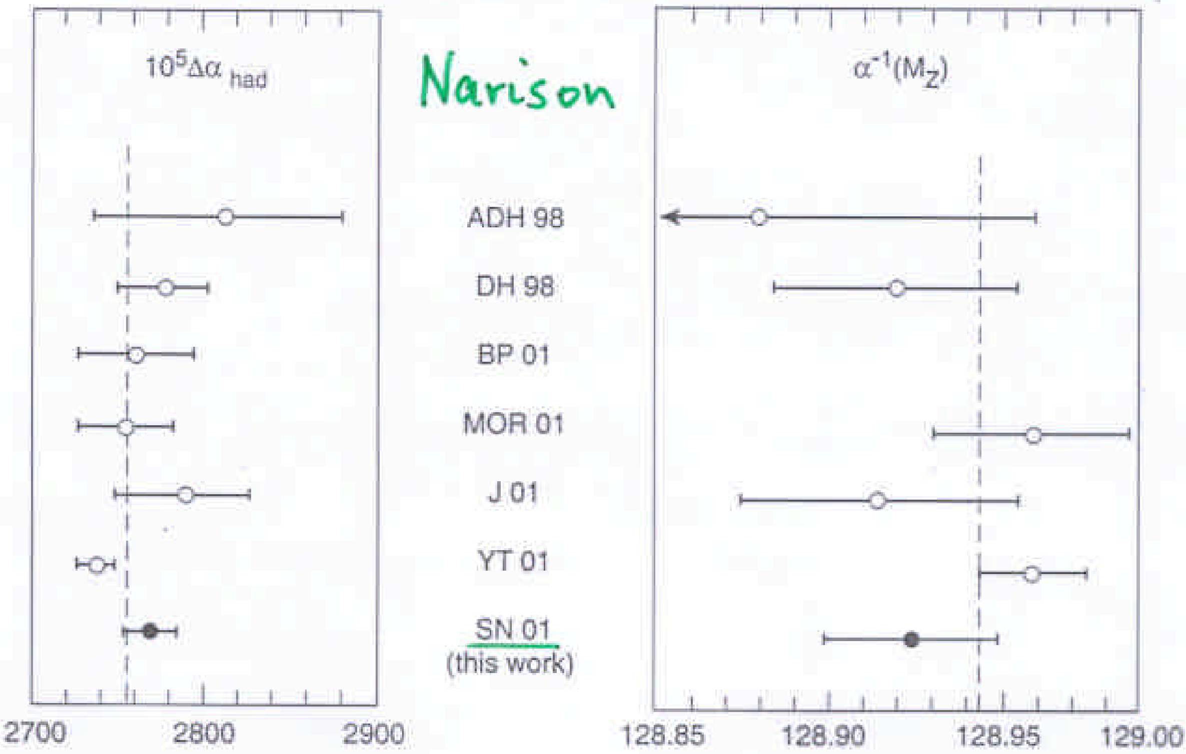
$$(\Delta\alpha)^{(5)}_{had} = -\frac{M_Z^2}{4\pi^2\alpha}\,\mathrm{Re}\int_{4m_\pi^2}^{\infty} ds\,\frac{\sigma(e^+e^-\to had)}{s-M_Z^2-i\varepsilon}$$

$$\alpha(M_Z) = \frac{\alpha}{1-\Delta\alpha} = \alpha\left[1+\Delta\alpha+\Delta\alpha^2+\cdots\right.$$



T: "theory driven…

(Oct. 2001)



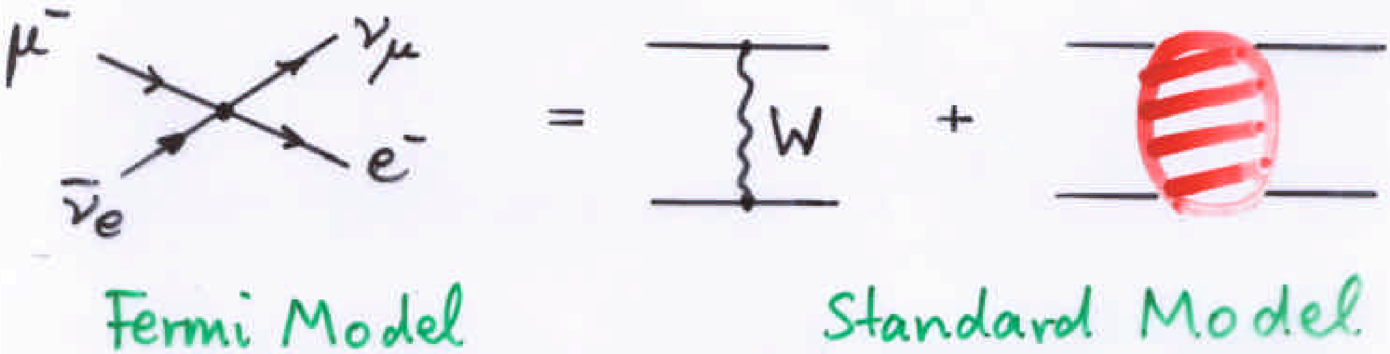
Narison
$10^5 \Delta\alpha_{had}$
$\alpha^{-1}(M_Z)$
ADH 98
DH 98
BP 01
MOR 01
J 01
YT 01
SN 01
(this work)
2700
2800
2900
128.85
128.90
128.95
129.00

Masses of W and Z bosons

correlated via muon lifetime $\leftrightarrow$ Fermi constant G_μ

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

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

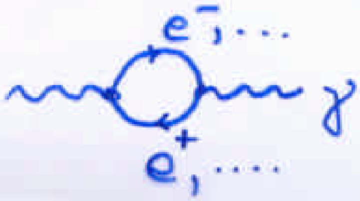


$$G_\mu = \frac{\pi}{\sqrt{2}}\cdot\frac{\alpha}{M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)}\cdot\frac{1}{1-\Delta r}$$

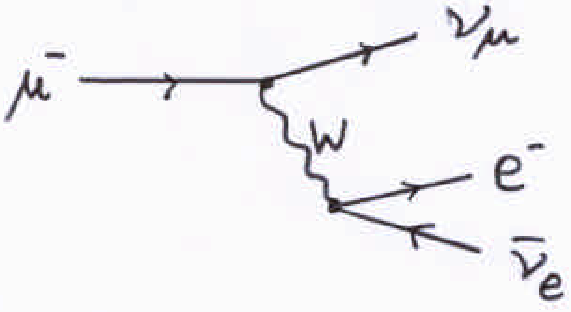
$$\Delta r = \Delta\alpha + \Delta r_W(m_t, M_H)$$

6%

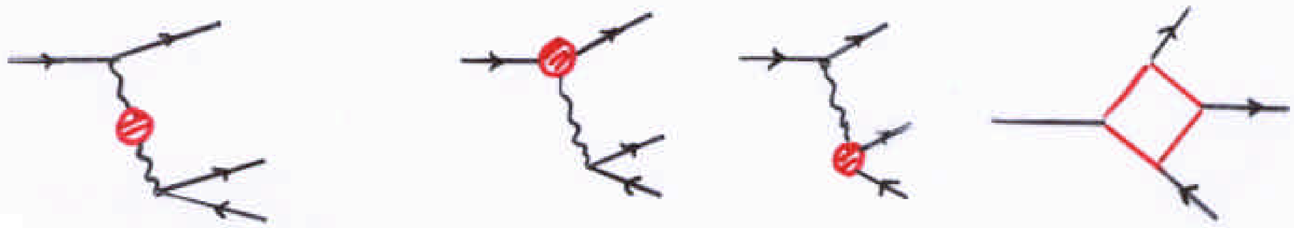
[QED]



μ decay



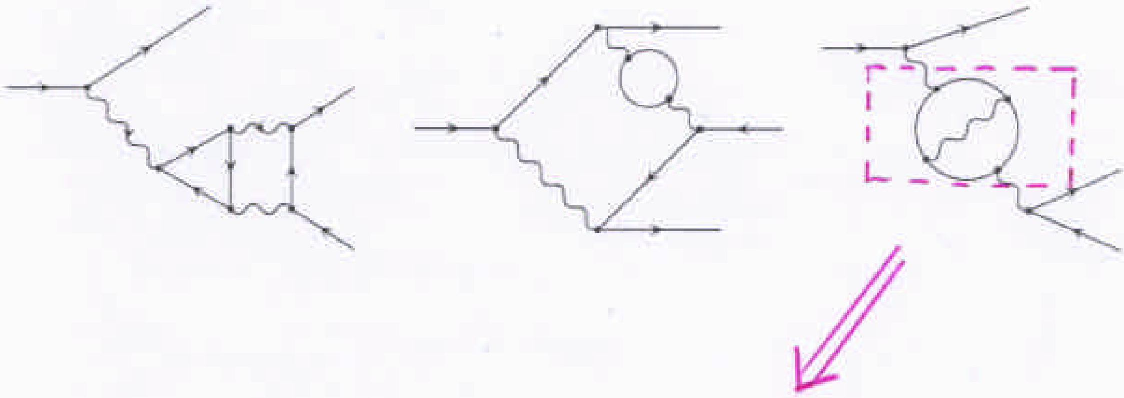
Born

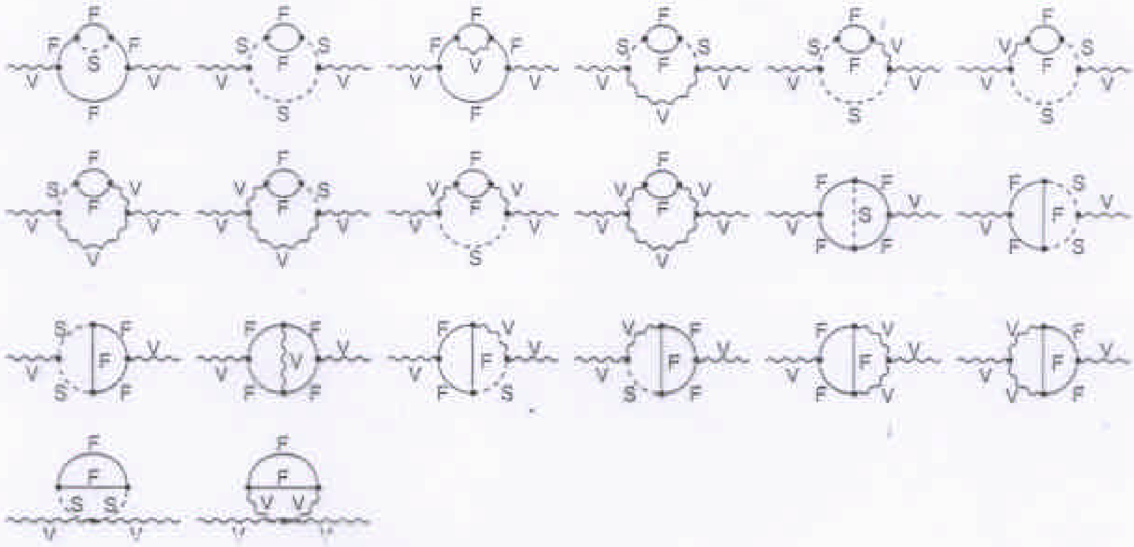


self energy　　vertex corrections　　box graph

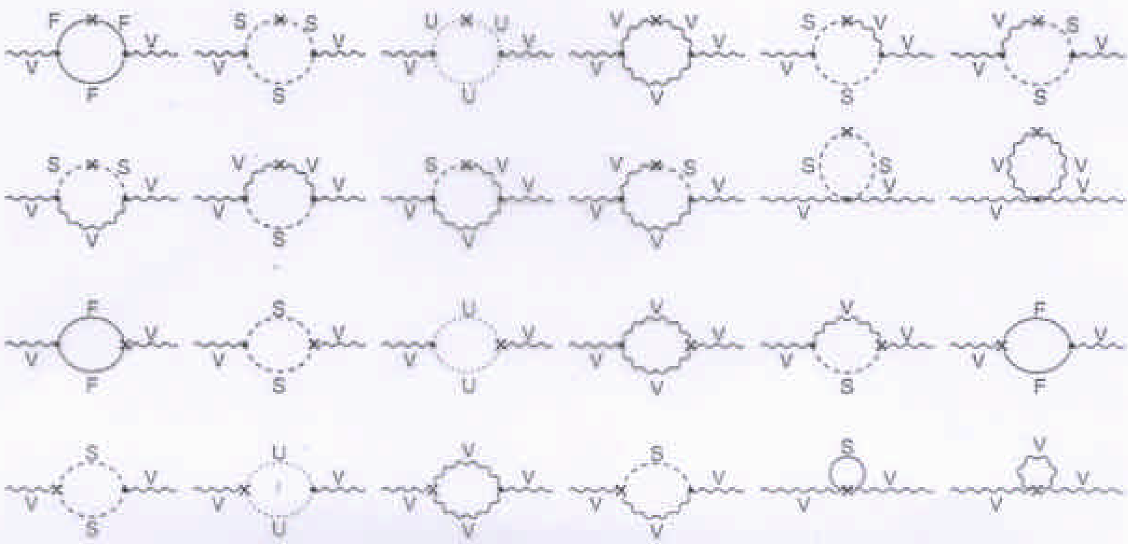
- 1-loop: complete [Sirlin, Marciano 1980
- 2-loop: QCD
  EW fermionic loops
  EW bosonic loops: missing
- 3-loop: leading QCD + EW
  (ρ-parameter)

Exact two-loop corrections to Δr with fermionic loops



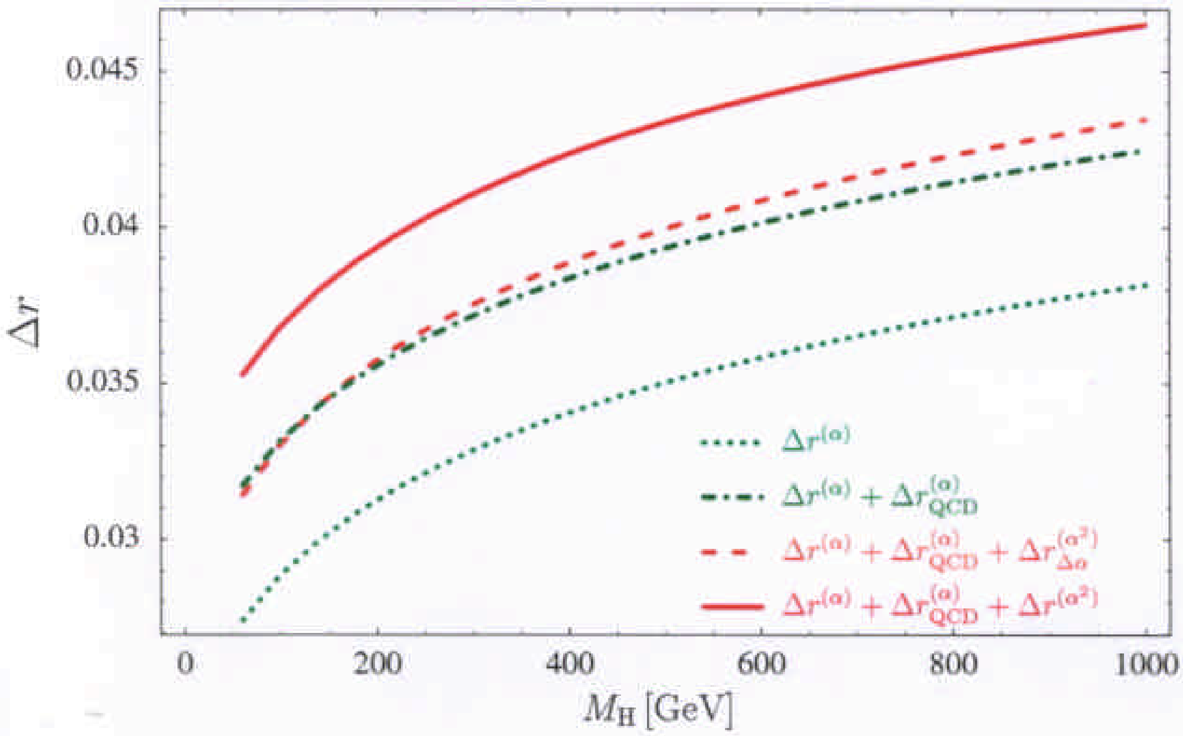


Counter term insertions (1-loop)



+ 2-loop counter-terms

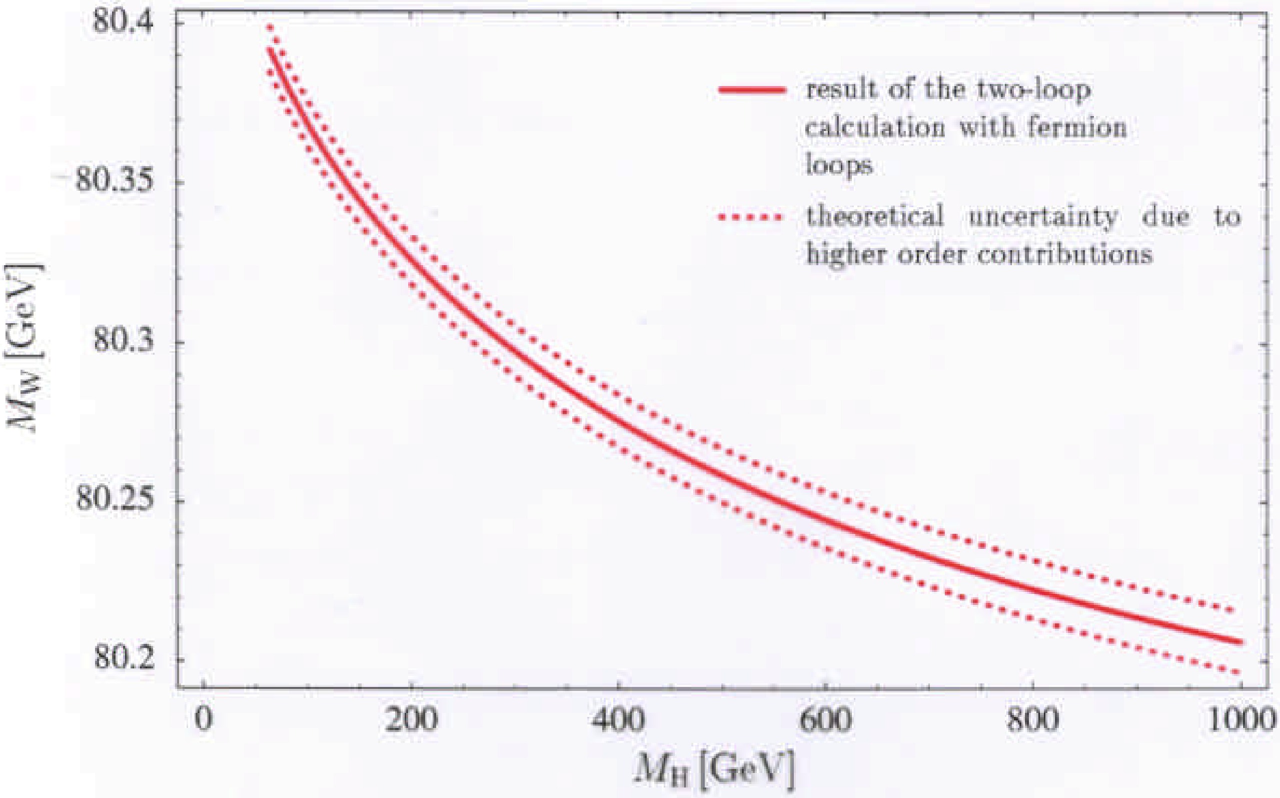
[Freitas, WH, Walter, Weiglein]



Uncertainty from experimental error of input parameters: $\delta m_{\rm t} = \pm 5.1$ GeV $\Rightarrow$ $\delta M_{\rm W} \approx \pm 31$ MeV

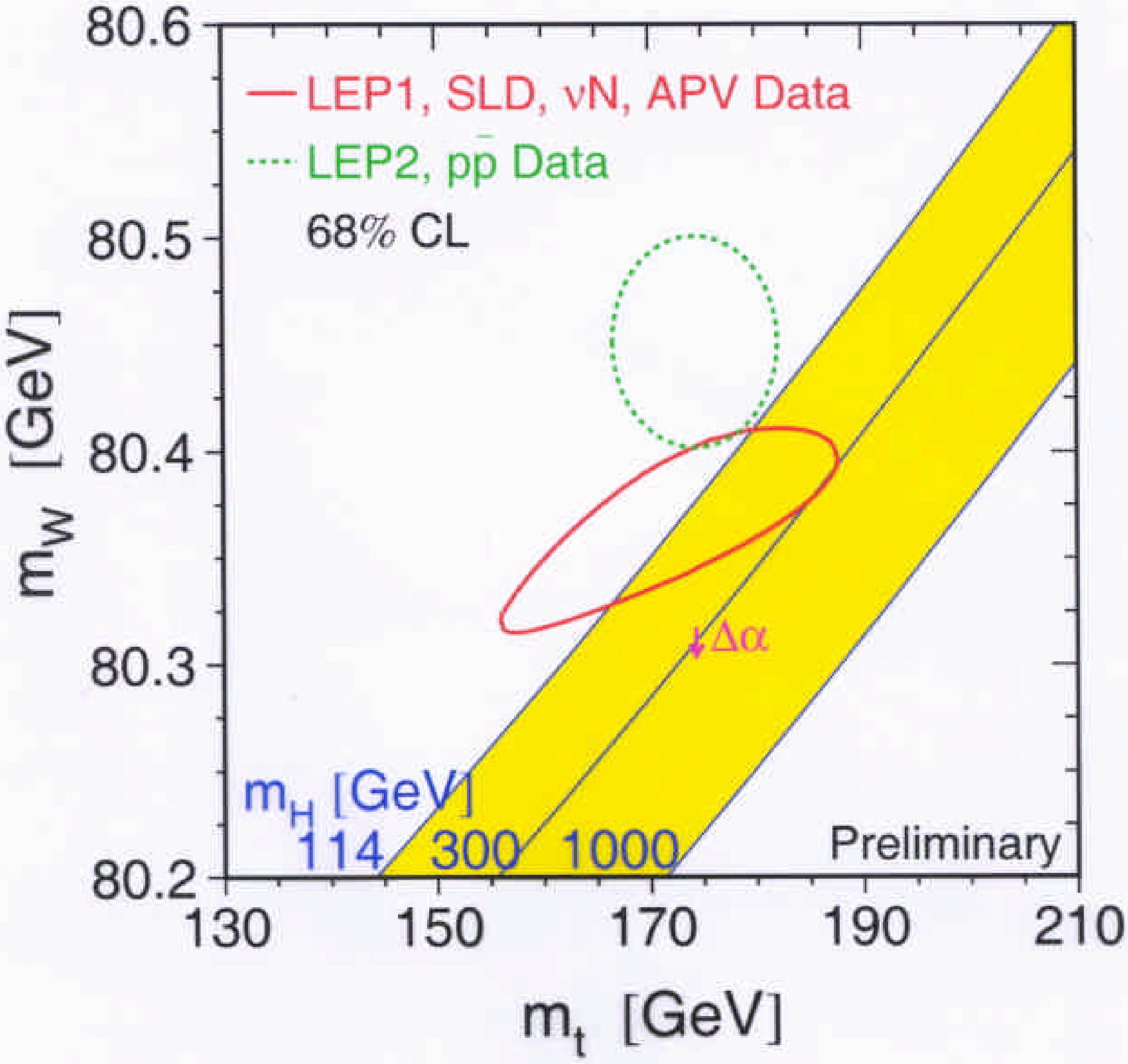
Estimate of theoretical uncertainty from unknown higher-order corrections:

- Purely bosonic $\mathcal{O}(\alpha^2)$ electroweak corrections
- Higher-order electroweak corrections: $\mathcal{O}(\alpha^3)$
- Higher-order QCD corrections: $\mathcal{O}(\alpha\alpha_s^3)$, $\mathcal{O}(\alpha^2\alpha_s)$



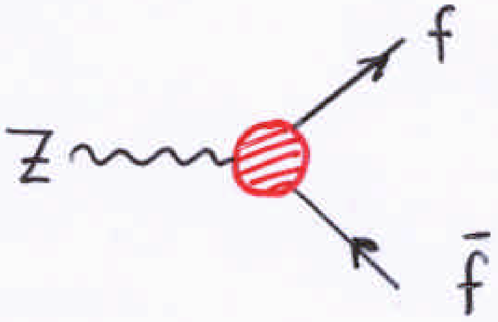
For light Higgs masses:

$$\Delta M_{\rm W}^{\rm theo} \approx \pm 6\,\text{MeV}$$



LEP1, SLD, νN, APV Data
LEP2, pp̄ Data
68% CL
Δα
m_H [GeV]
114
300
1000
Preliminary
80.6
80.5
80.4
80.3
80.2
m_W [GeV]
130
150
170
190
210
m_t [GeV]

Effective Z couplings



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

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

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

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

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

complete at 1-loop

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

Prediction for $\sin^2\theta_{eff}$:

$$\sin^2\theta_{eff} = \left(1 - \frac{M_W^2}{M_Z^2}\right) \cdot \kappa(m_t, M_H, \alpha_s)$$

↑ complete 2-loop fermionic EW contribution not know

$$\left.\begin{matrix} \delta M_W \\ \delta \kappa \end{matrix}\right\} \Rightarrow \delta \sin^2\theta_{eff}$$

uncertainty of $M_W \rightarrow 8 \cdot 10^{-5}$

compensation (partially) through κ expected

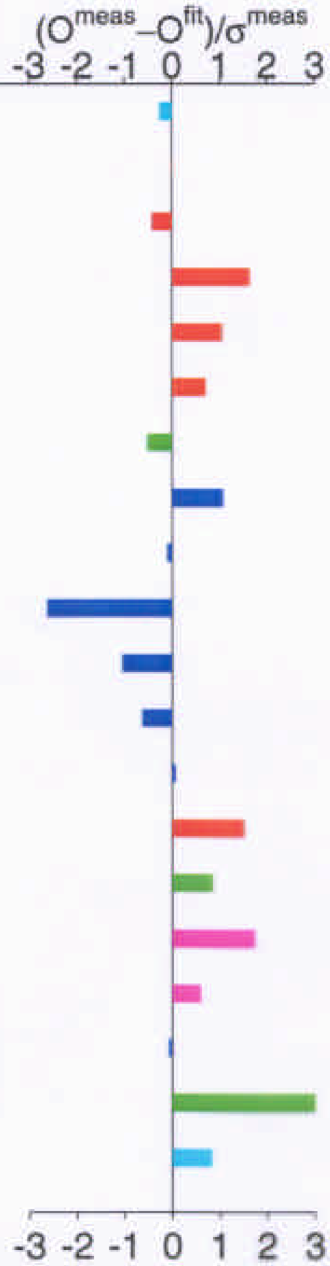
$\Rightarrow$ κ is needed

fermionic + bosonic 2-loop terms

- complete EW 2-loop calculation for Δr and $\sin^2\theta_{eff}$ necessary for LC / GigaZ

Winter 2002

	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-.27
m_Z [GeV]	91.1875 ± 0.0021	.01
Γ_Z [GeV]	2.4952 ± 0.0023	-.42
σ^0_{had} [nb]	41.540 ± 0.037	1.63
R_l	20.767 ± 0.025	1.05
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.70
$A_l(P_\tau)$	0.1465 ± 0.0033	-.53
R_b	0.21646 ± 0.00065	1.06
R_c	0.1719 ± 0.0031	-.11
$A^{0,b}_{fb}$	0.0994 ± 0.0017	-2.64
$A^{0,c}_{fb}$	0.0707 ± 0.0034	-1.05
A_b	0.922 ± 0.020	-.64
A_c	0.670 ± 0.026	.06
A_l(SLD)	0.1513 ± 0.0021	1.50
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	.86
m_W [GeV]	80.451 ± 0.033	1.73
Γ_W [GeV]	2.134 ± 0.069	.59
m_t [GeV]	174.3 ± 5.1	-.08
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	3.00
Q_W(Cs)	-72.39 ± 0.59	.84



$$M_H = 85(81)\ \text{GeV},\ M_H < 196\ \text{GeV at 95\% CL}$$

χ^2/d.o.f.=28.8/15 (19.6/14) $\Rightarrow$ prob=1.7(14)%.

isoscalar targets (# neutrons = # protons)

⇒ Llewellyn-Smith relations:

$$R_\nu = \frac{\sigma_{NC}^{\nu}}{\sigma_{CC}^{\nu}} = \frac{1 - 2 s_W^2 + \frac{10}{9}(1+r)\, s_W^2}{2 c_W^2} \cdot \left(\frac{M_W}{M_Z}\right)^4$$

$$R_{\bar\nu} = \frac{\sigma_{NC}^{\bar\nu}}{\sigma_{CC}^{\bar\nu}} = \frac{1 - 2 s_W^2 + \frac{10}{9}\left(1+\frac{1}{r}\right) s_W^2}{2 c_w} \cdot \left(\frac{M_W}{M_Z}\right)^4$$

$$r = \frac{\sigma_{CC}^{\bar\nu}}{\sigma_{CC}^{\nu}} = 0.39 \pm 0.01 \leftarrow \text{measured}$$

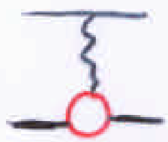
electroweak higher order corrections:

M^2

$\rightarrow M^2 + \delta M^2 - \Sigma(0)$

$\simeq M^2$ (+ small)

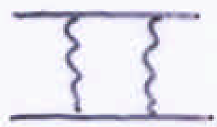
no m_t^2



s_W^2

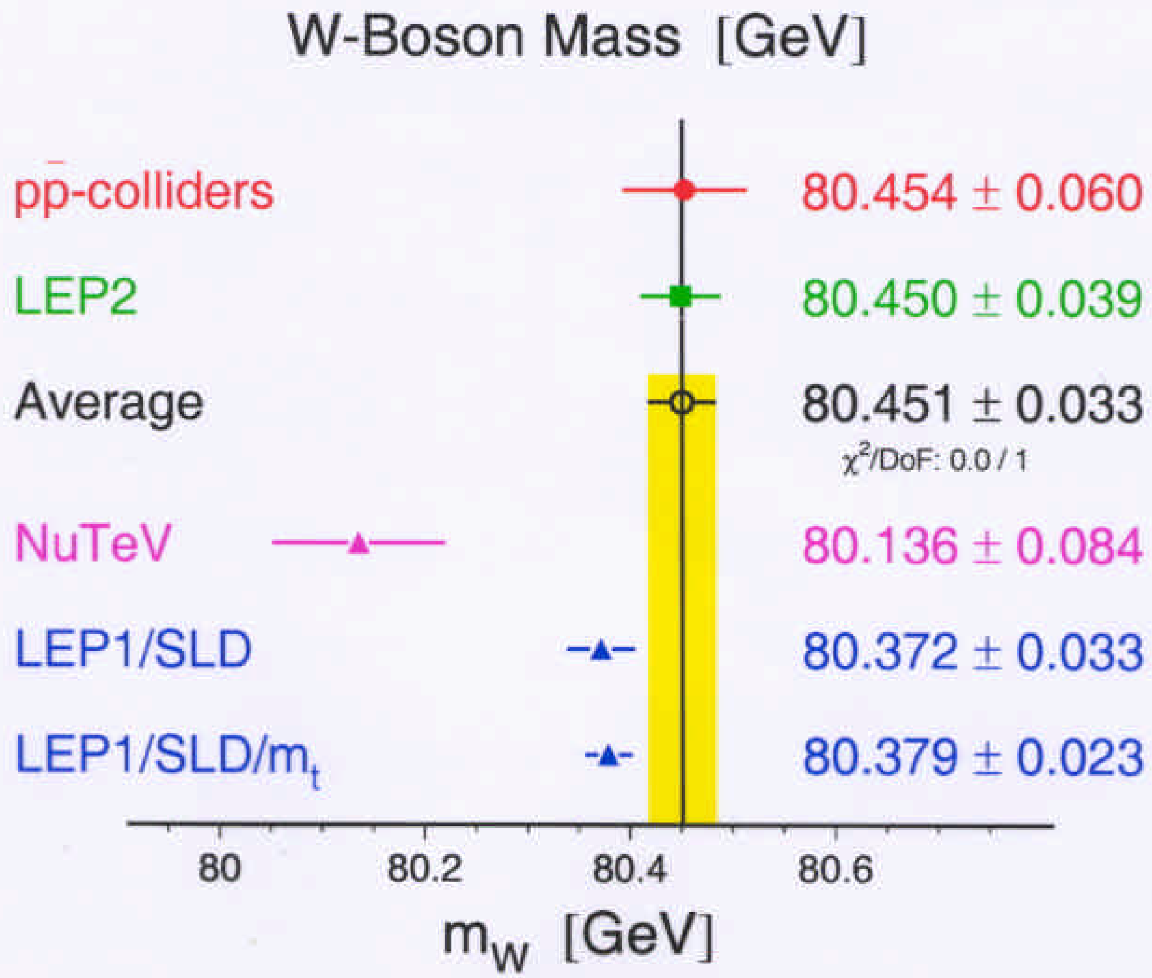
$\rightarrow s_W^2 + \Delta s_W^2$

↑ $\sim m_t^2$

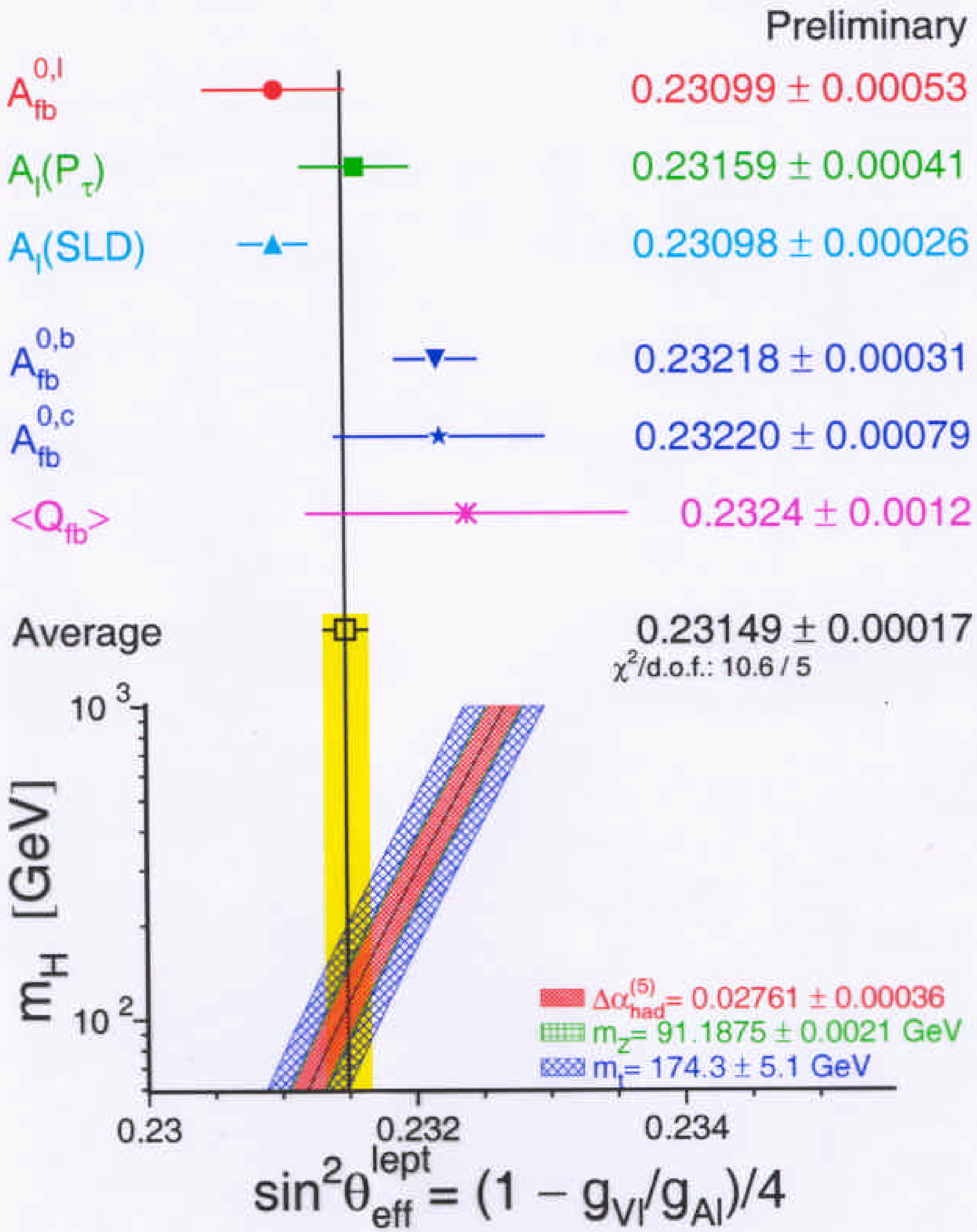


small, no m_t^2

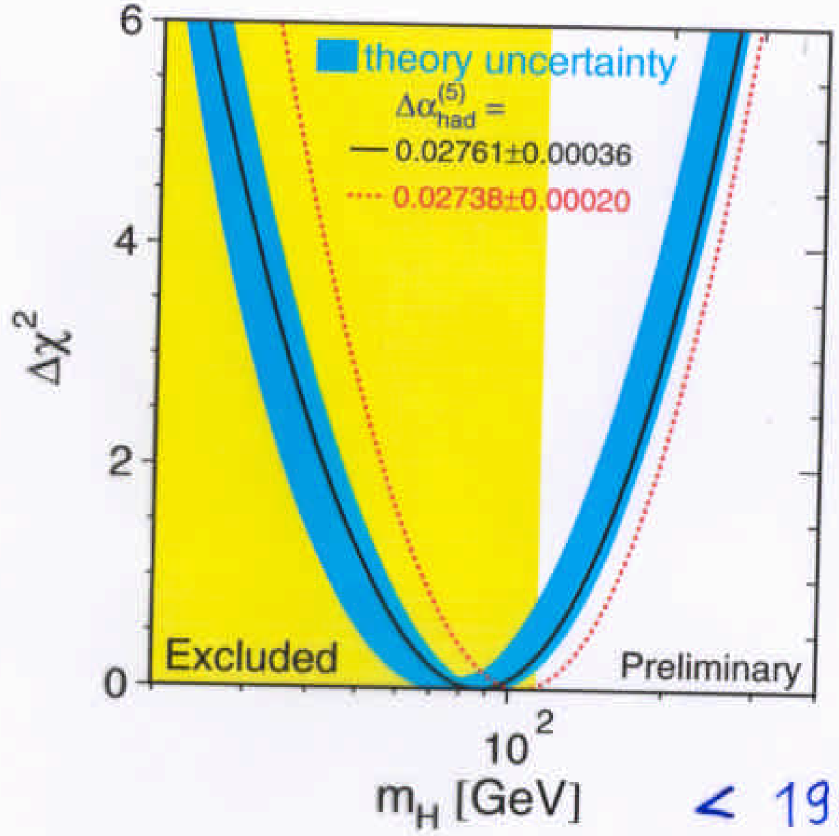
$$R \simeq \left(\frac{M_W}{M_Z}\right)^4 \cdot P(s_W^2 + \Delta s_W^2)$$

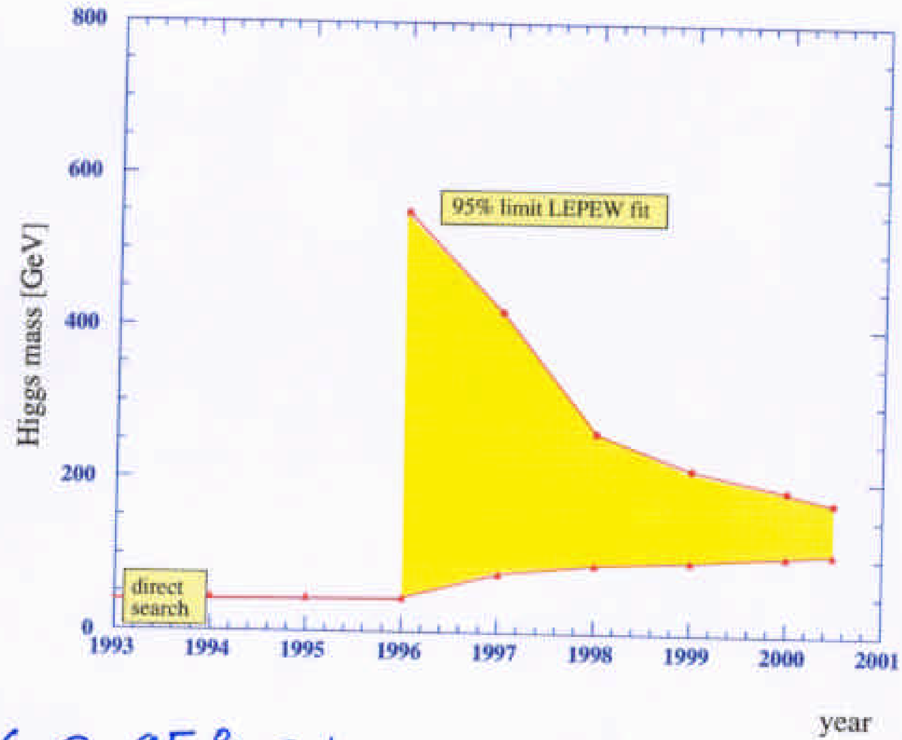


W-Boson Mass [GeV]
p$\bar{p}$-colliders
80.454 ± 0.060
LEP2
80.450 ± 0.039
Average
80.451 ± 0.033
χ^2/DoF: 0.0 / 1
NuTeV
80.136 ± 0.084
LEP1/SLD
80.372 ± 0.033
LEP1/SLD/m_t
80.379 ± 0.023
80
80.2
80.4
80.6
m_W [GeV]



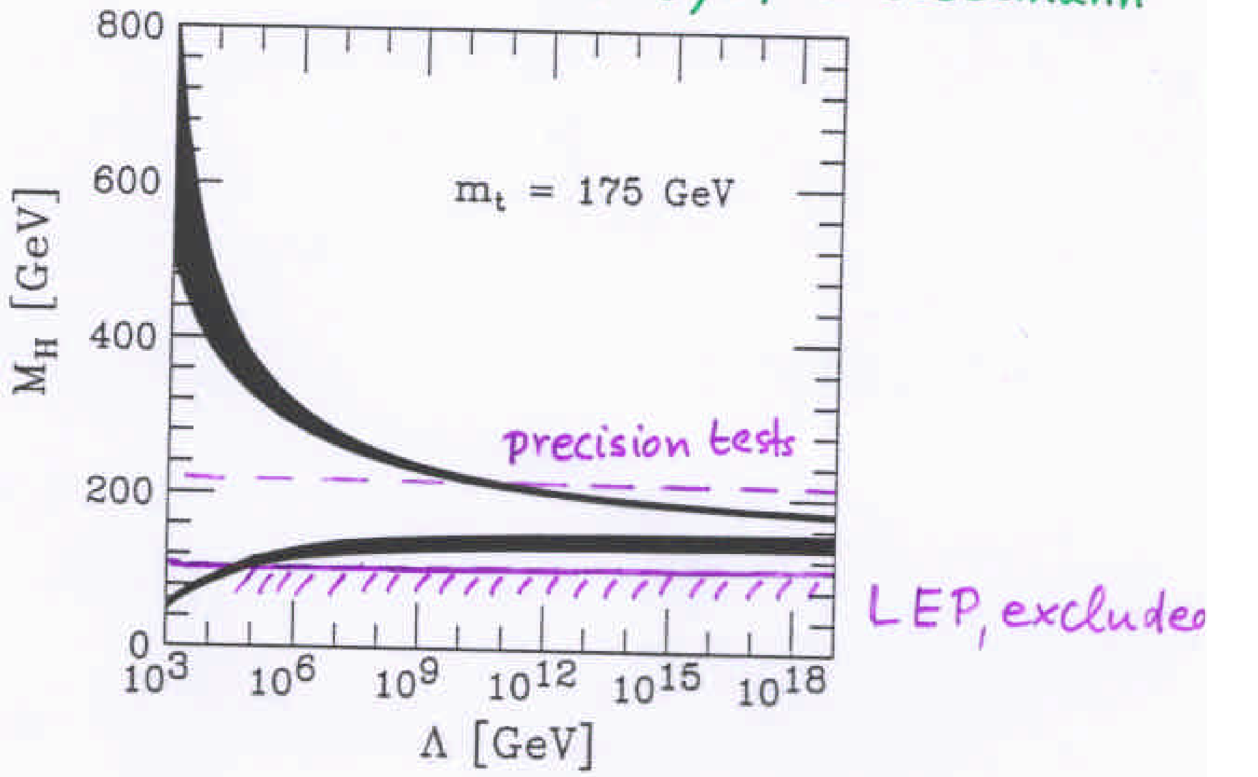
Preliminary
A_fb^0,l 0.23099 ± 0.00053
A_l(P_τ) 0.23159 ± 0.00041
A_l(SLD) 0.23098 ± 0.00026
A_fb^0,b 0.23218 ± 0.00031
A_fb^0,c 0.23220 ± 0.00079
<Q_fb> 0.2324 ± 0.0012
Average 0.23149 ± 0.00017
χ²/d.o.f.: 10.6 / 5
m_H [GeV]
10^3
10^2
Δα_had^(5)= 0.02761 ± 0.00036
m_Z= 91.1875 ± 0.0021 GeV
m_t= 174.3 ± 5.1 GeV
0.23
0.232
0.234
sin²θ_eff^lept = (1 − g_Vl/g_Al)/4

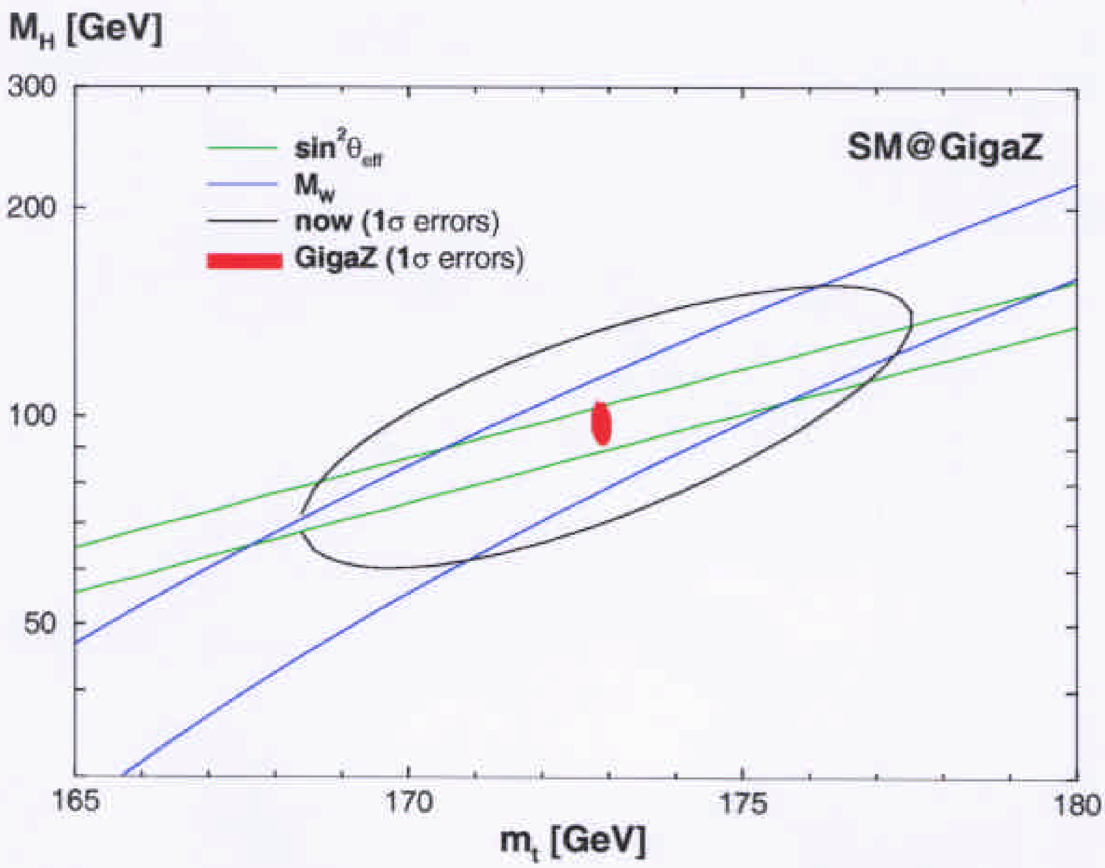

theory uncertainty
$\Delta\alpha^{(5)}_{had}$ =
0.02761±0.00036
0.02738±0.00020
Excluded
Preliminary
$\Delta\chi^2$
m_H [GeV]
6
4
2
0
10^2


95% limit LEPEW fit
direct search
Higgs mass [GeV]
year
800
600
400
200
0
1993
1994
1995
1996
1997
1998
1999
2000
2001

< 196 @ 95% C.L.

Hambye, Riesselmann

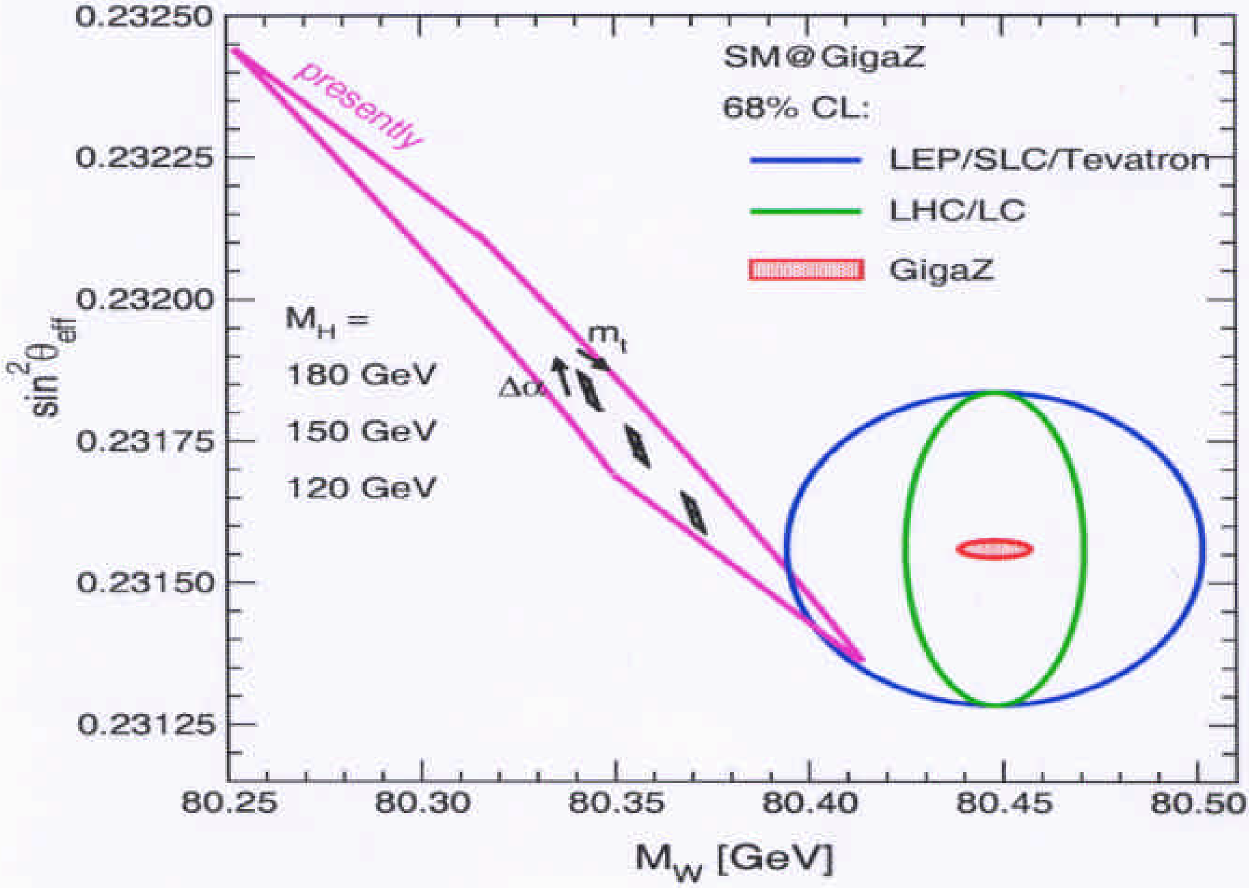




[Erler, Heinemeyer, WH, Weiglein, Zerwas]

$\delta M_H / M_H \sim 7\%$

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



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, $G^{\pm}$

Systematic studies of higher-order terms in the MSSM required for

- Indirect tests of the MSSM
  → virtual SUSY effects in precision observables
- Precision studies for SUSY particles
  → determination of masses & couplings
  → reconstruction of model parameters
- Direct versus indirect tests
  → precision observables for precisely measured SUSY parameters
  → consistency check

Processes with external

(i) standard particles

(ii) Higgs bosons, especially light Higgs h^0

(iii) SUSY particles

Higher-order calculations

- **dimReg** | **dimRed**

dimReg	dimRed
D dimensions for momenta and fields (A_μ)	D dimensions for momenta, 4 dimensions for A_μ
↯ SUSY	math. problems
correct results after adding (finite) CTs	correct results at 1-loop order

proof: SUSY ST-Identities

[WH, Kraus, Stöckinger]

- MSSM renormalization on the basis of symmetry relations (ST-Identities, ...)

  [WH, Kraus, Roth, Rupp, Sibold]

  → talk, M. Roth

- Wess-Zumino gauge

  fewest unphysical degrees of freedom

Precision observables in the MSSM:

In order to treat MSSM at same level of accuracy as SM

⇒ Include higher-order corrections

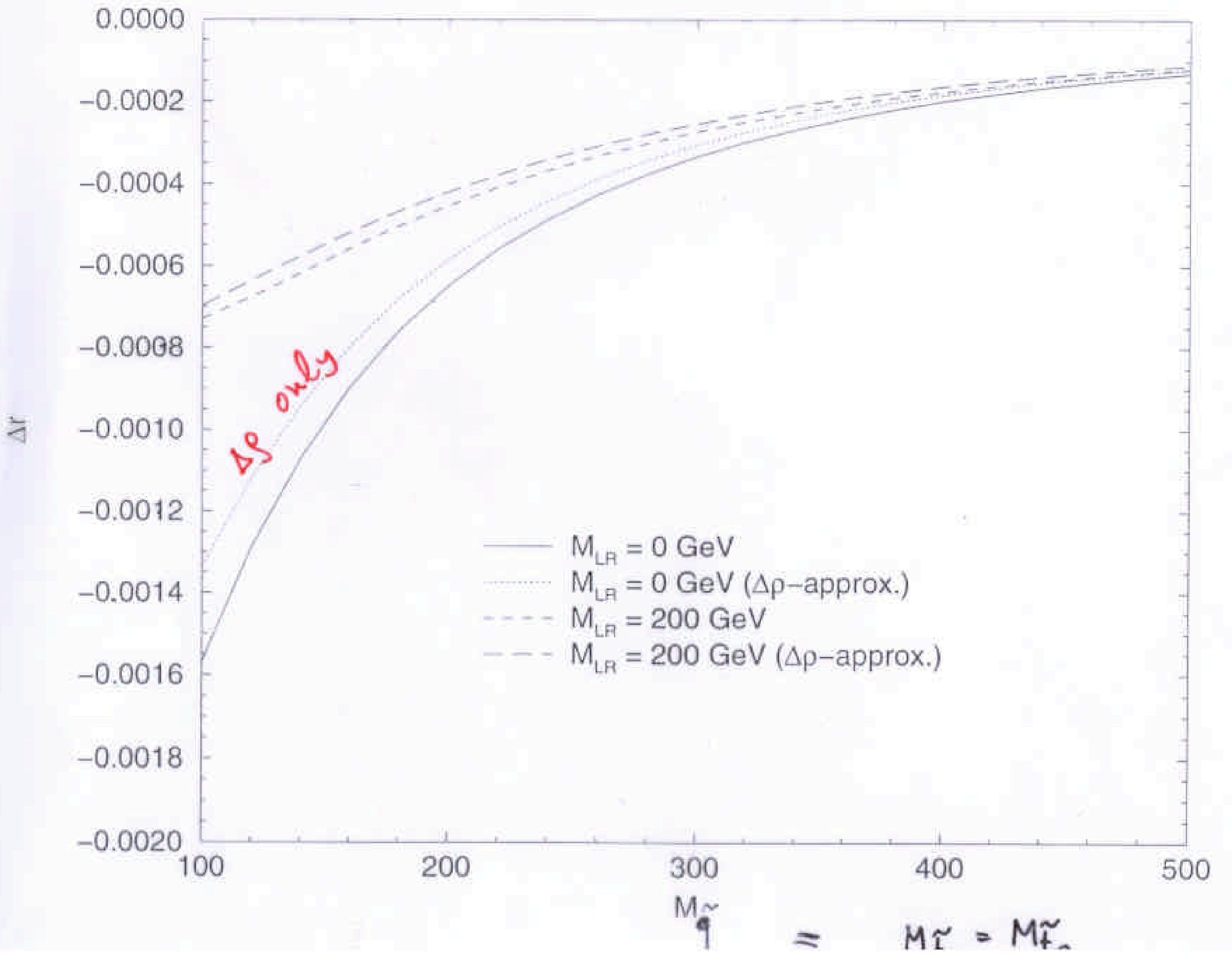
Prediction for M_W, $\sin^2\theta_{\rm eff}$ in the MSSM:

- Complete 1-loop results
  [P. Chankowski, A. Dabelstein, W. Hollik, W. Mösle, S. Pokorski, J. Rosiek '94]
  [D. Garcia, J. Solà '94]
  [D. Garcia, R. Jiménez, J. Solà '95]
  [A. Dabelstein, W. Hollik, W. Mösle '95]
  [P. Chankowski, S. Pokorski '96]

- Leading 2-loop $\mathcal{O}(\alpha\alpha_s)$ corrections
  [A. Djouadi, P. Gambino, S. Heinemeyer, W. Hollik, C. Jünger, G. Weiglein '97]
  [S. Heinemeyer, W. Hollik, G. Weiglein '98]

- Leading 2-loop $\mathcal{O}(\alpha^2)$ corrections
  [S. Heinemeyer, G. Weiglein '01]

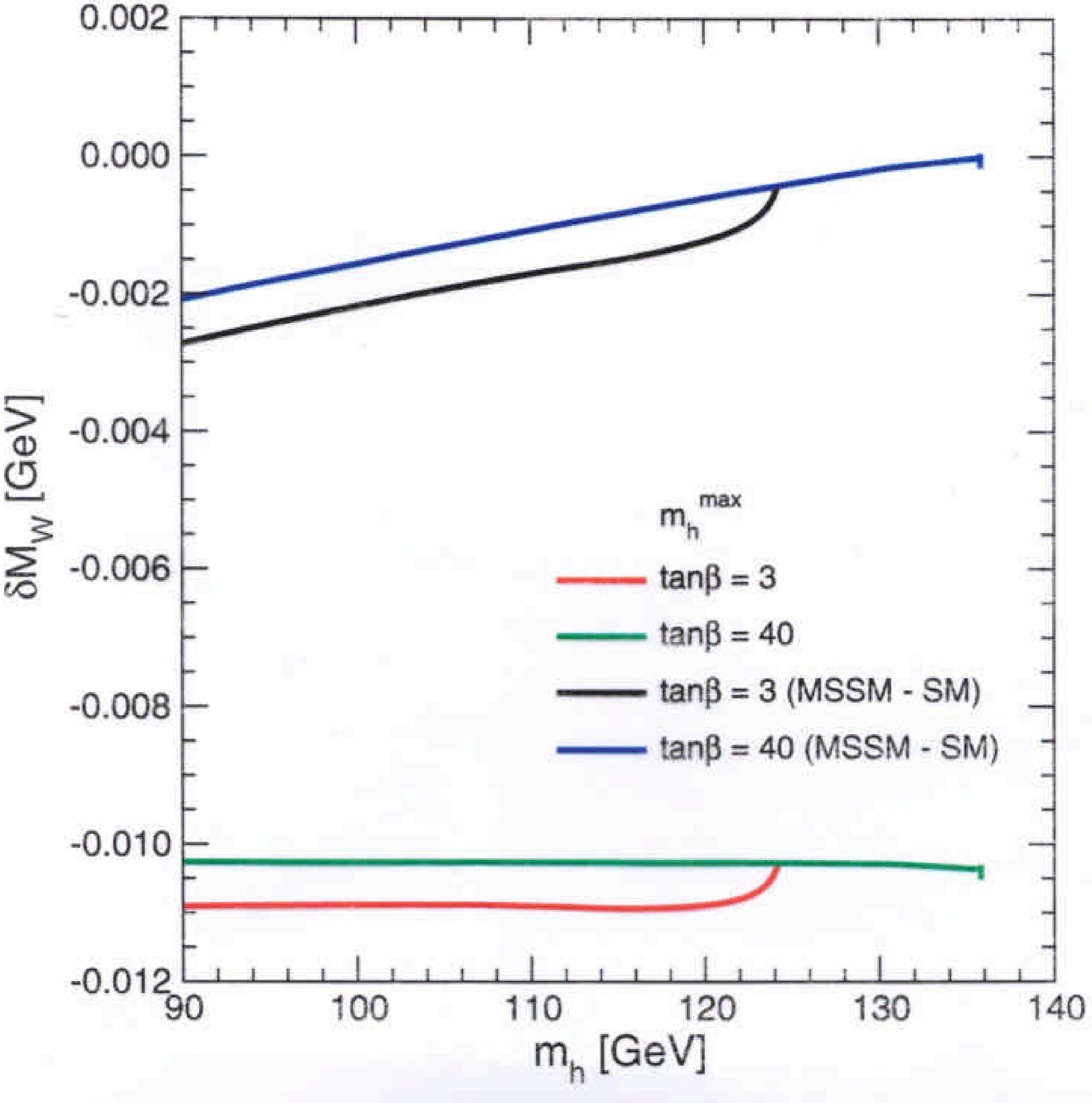
Δr (Gluon)



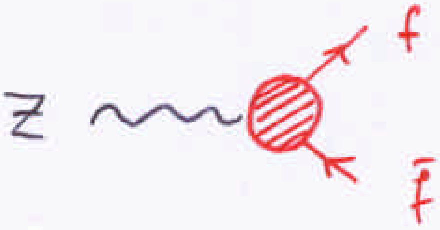
shift in M_W:

$\Delta M_W \lesssim 20$ MeV

[talk → G. Weiglein]



- Effective Z boson couplings:



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

$\rho_f\,(m_t, \alpha_s, M_A, \tan\beta,$ SUSY-parameters

$\sin^2\theta_f\,(m_t, \alpha_s, M_A, \tan\beta,$ SUSY-parameters)

- $M_W - M_Z$ correlation:

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

$\Delta r = \Delta r\,(m_t, \alpha_s, M_A, \tan\beta,$ SUSY-par.)

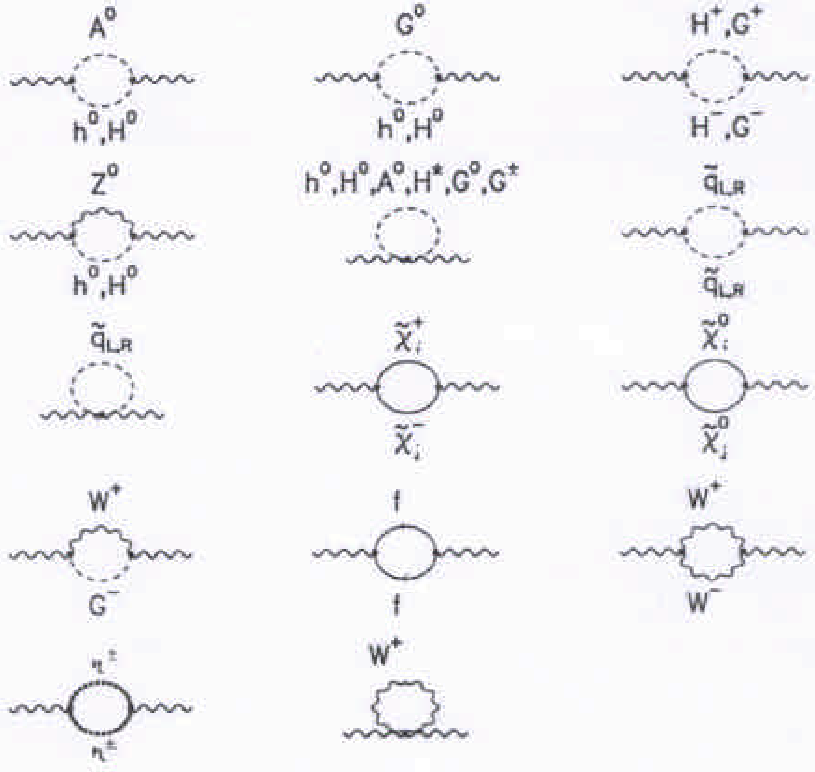


Abbildung 2: Z^0-Selbstenergie

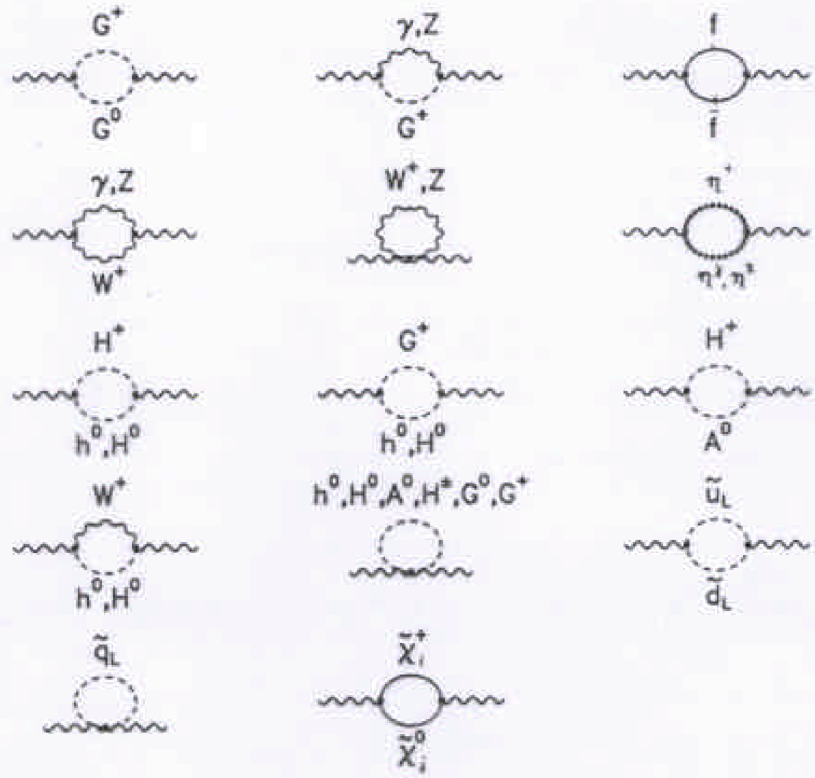
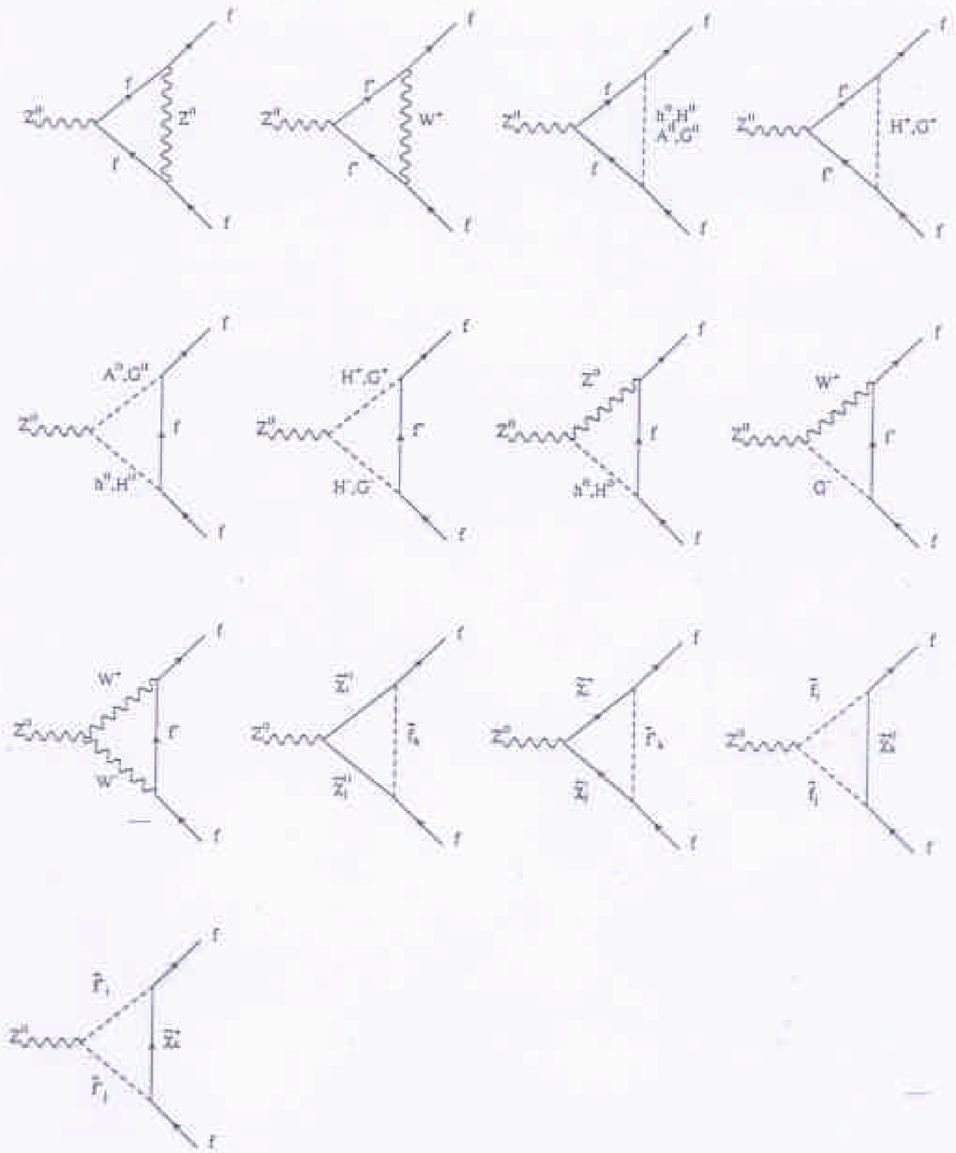
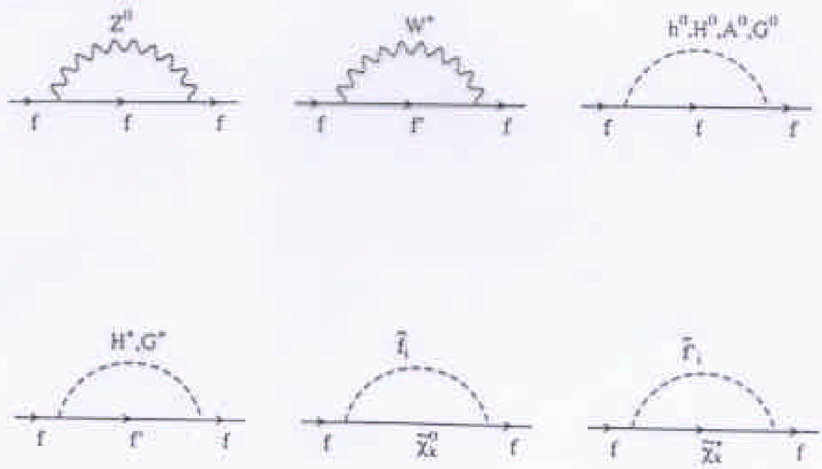


Abbildung 3: $W^{\pm}$-Selbstenergie

Zff vertex corr.

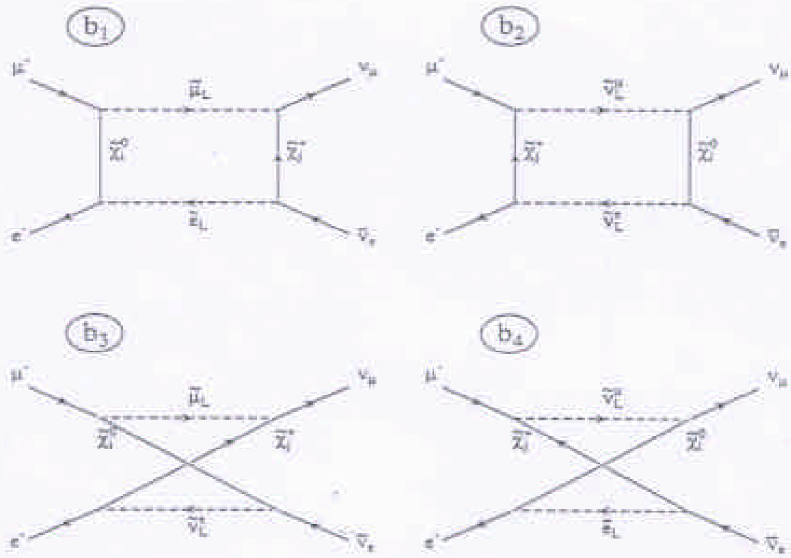


fermion self-energies → wave function renorm.

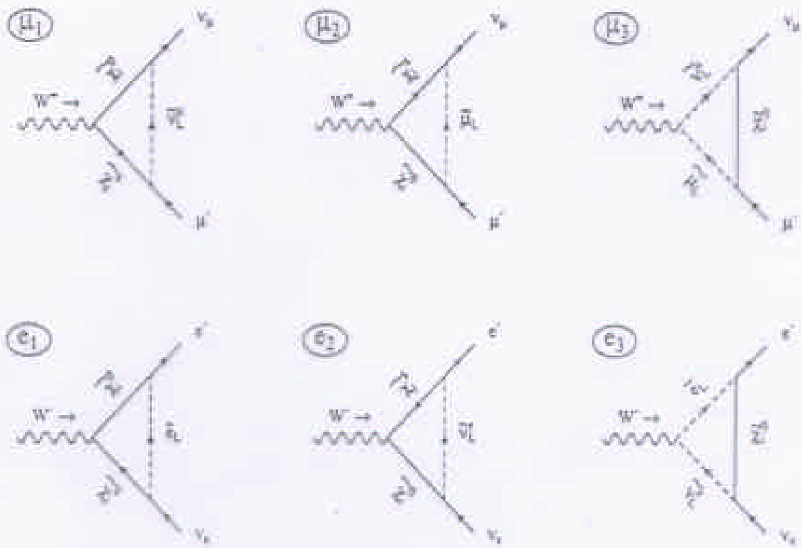


μ- decay → Δr

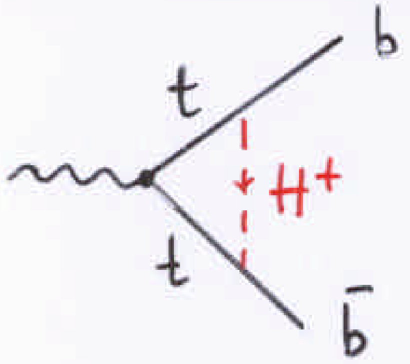
box diagrams

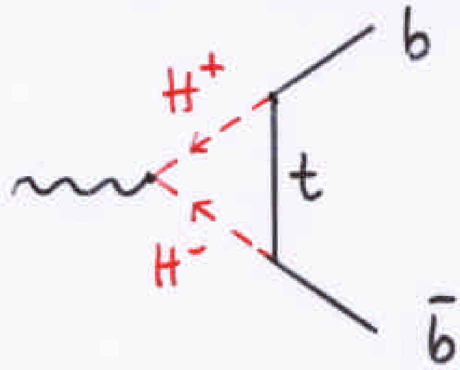


CC vertex corr.



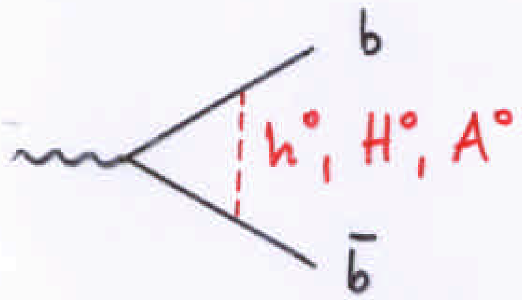
Special corrections to $Zb\bar{b}$:

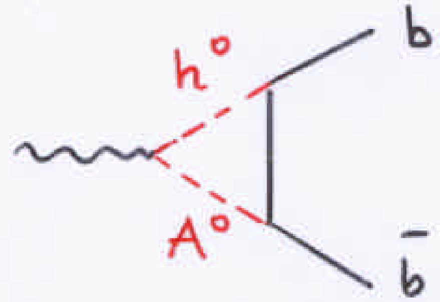




$\sim m_t^2 \cot^2\beta, \quad m_b^2 \tan^2\beta$

$\Delta\Gamma_b < 0$

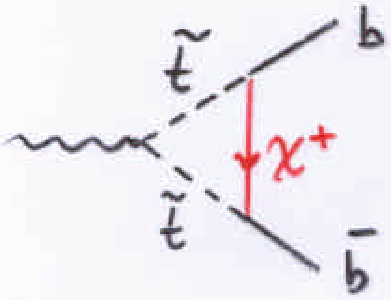


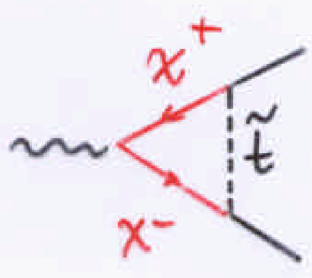


$\sim m_b^2 \tan^2\beta$

$\Delta\Gamma_b > 0$

$M_{h^0} \simeq M_A$ < 100 Ge





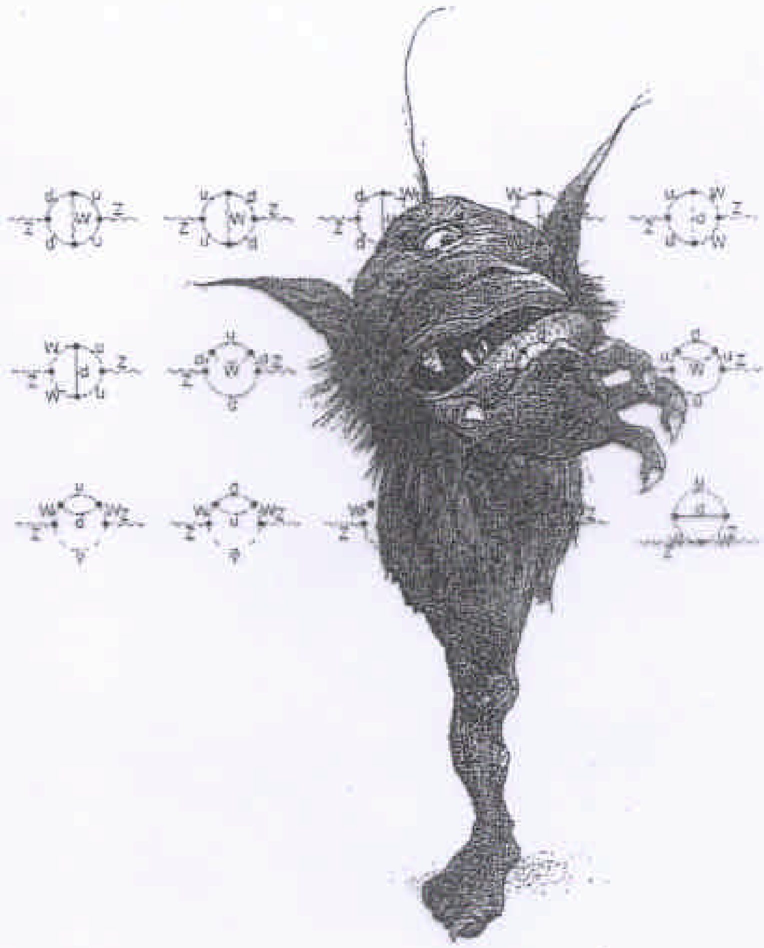
$\Delta\Gamma_b > 0$

$m_{\chi^+}, m_{\tilde{t}_R}$

~ 100 GeV

Minimal Supersymmetric Standard Model
(MSSM)

- renormalizable quantum field theory,
  precision calculations possible → FeynArts
- predictions ⟷ experiments



FeynArts 3 User's Guide

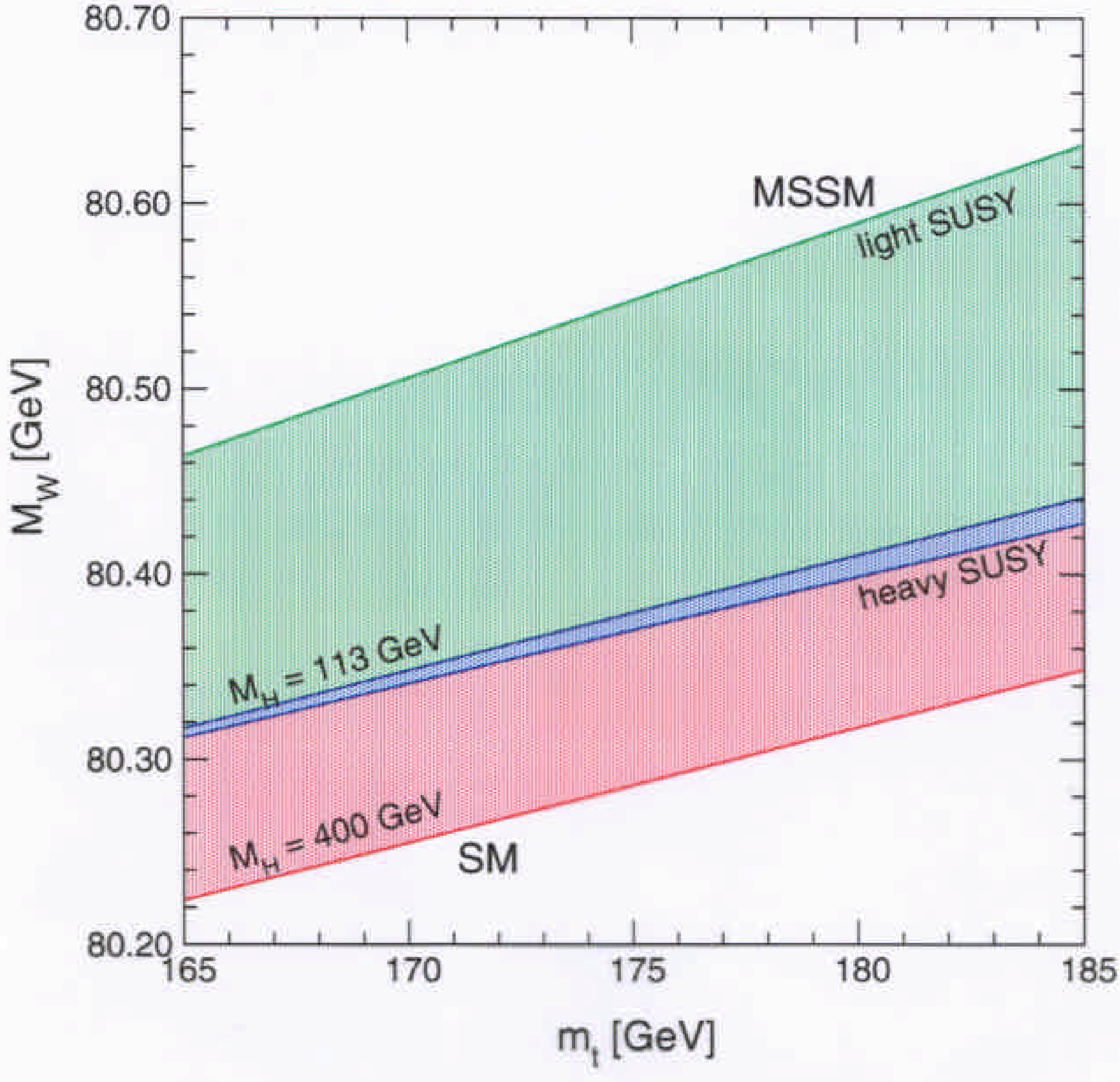
September 23, 2001 Thomas Hahn

http://www.feynarts.de

Prediction for M_W in the SM and the MSSM:

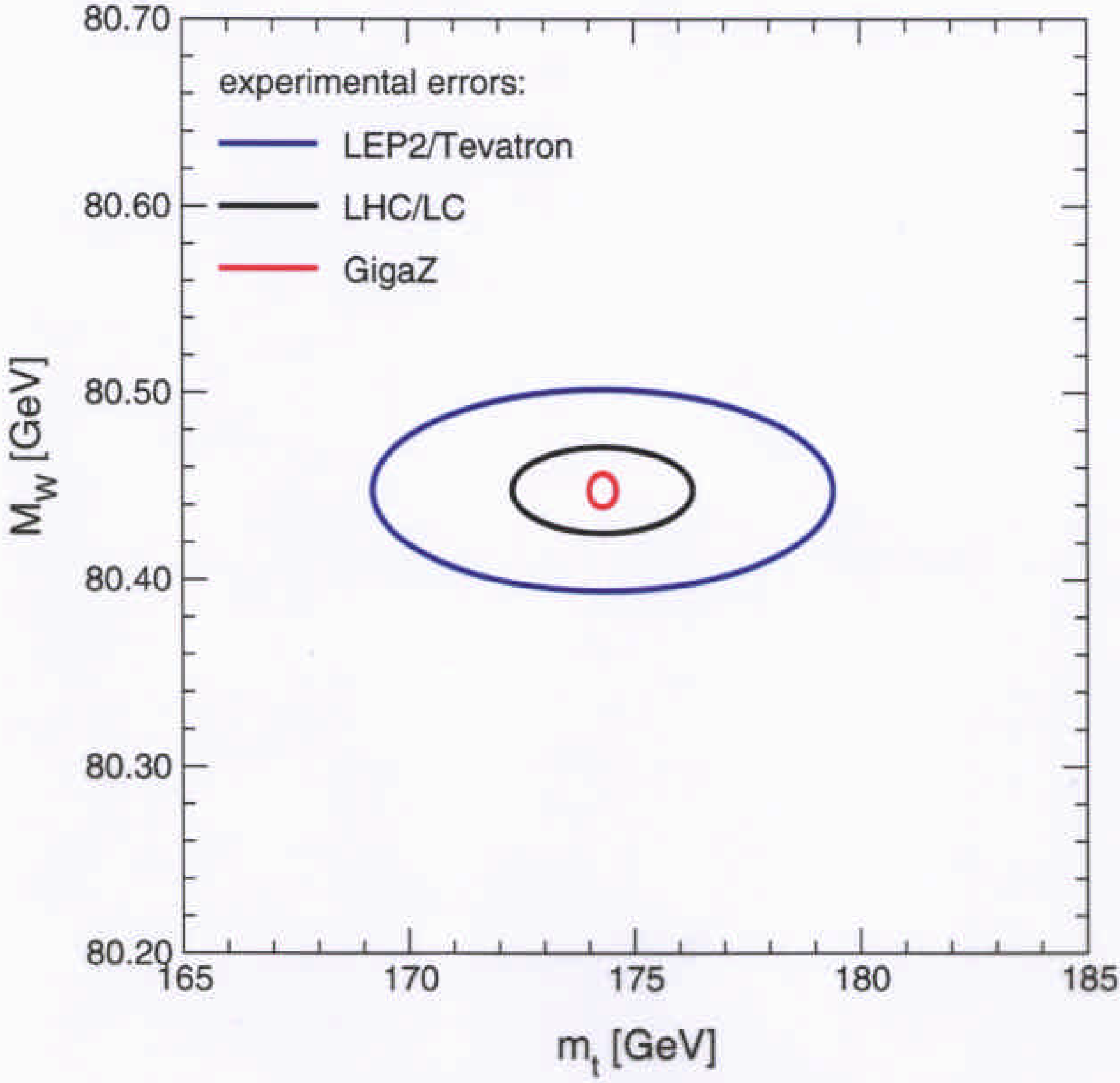
[A. Djouadi, P. Gambino, S. Heinemeyer,
W. Hollik, C. Jünger, G. Weiglein '97]

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



SM: M_H varied

MSSM: SUSY parameters varied



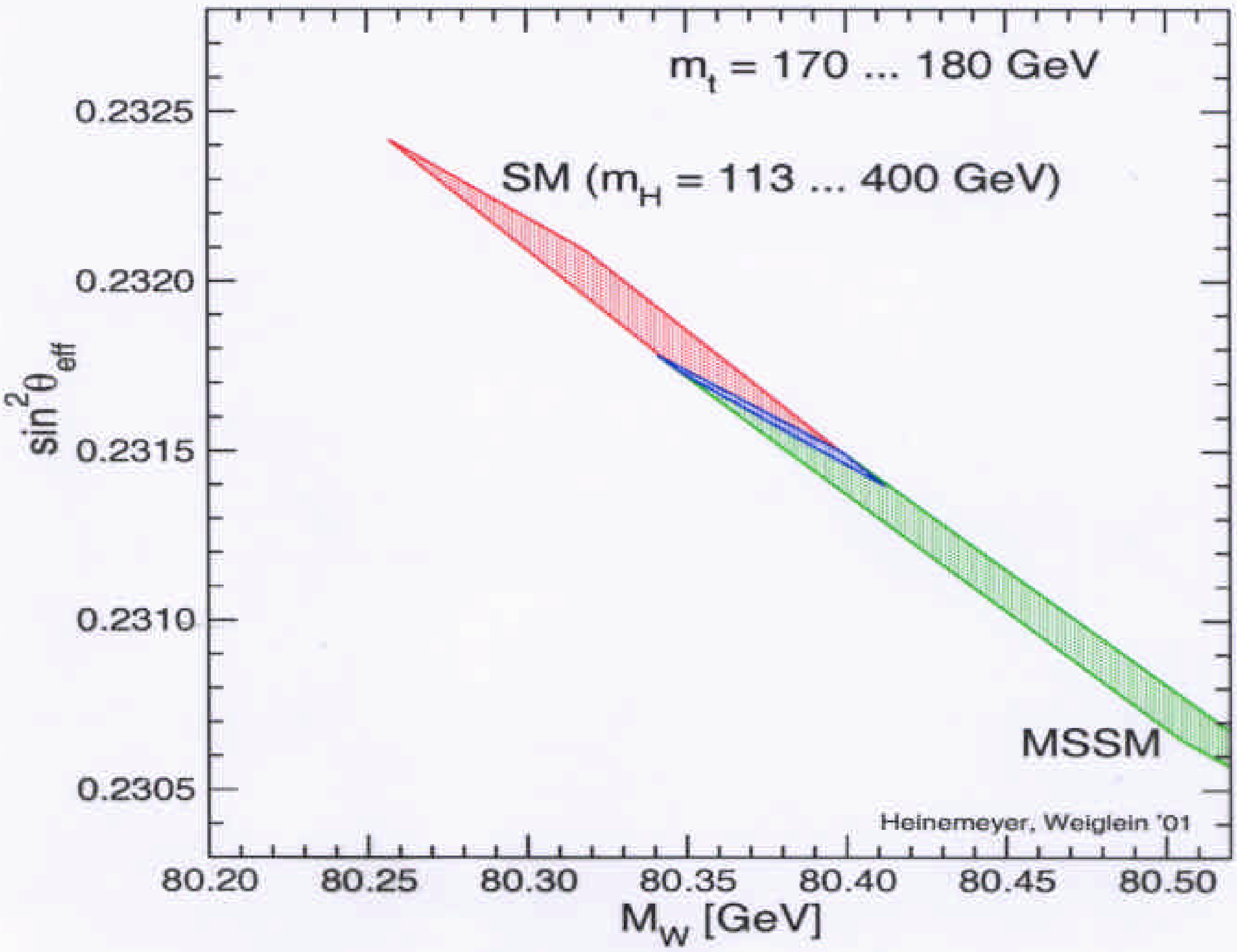
experimental errors:
LEP2/Tevatron
LHC/LC
GigaZ
80.70
80.60
80.50
80.40
80.30
80.20
165
170
175
180
185
M_W [GeV]
m_t [GeV]

MSSM consistency check:

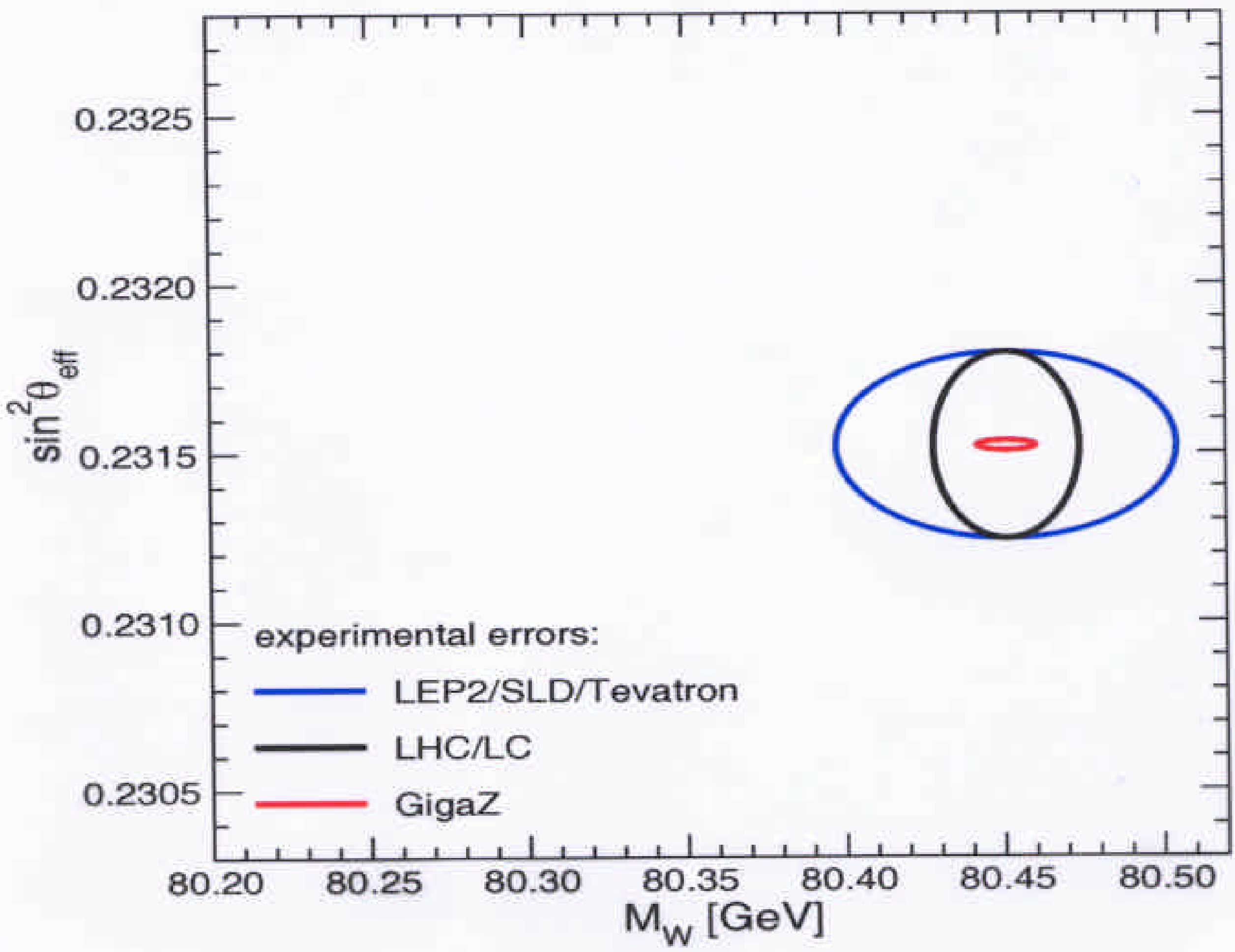
Prediction for M_W, $\sin^2\theta_{\text{eff}}$ in the SM and MSSM

vs. prospective accuracies at

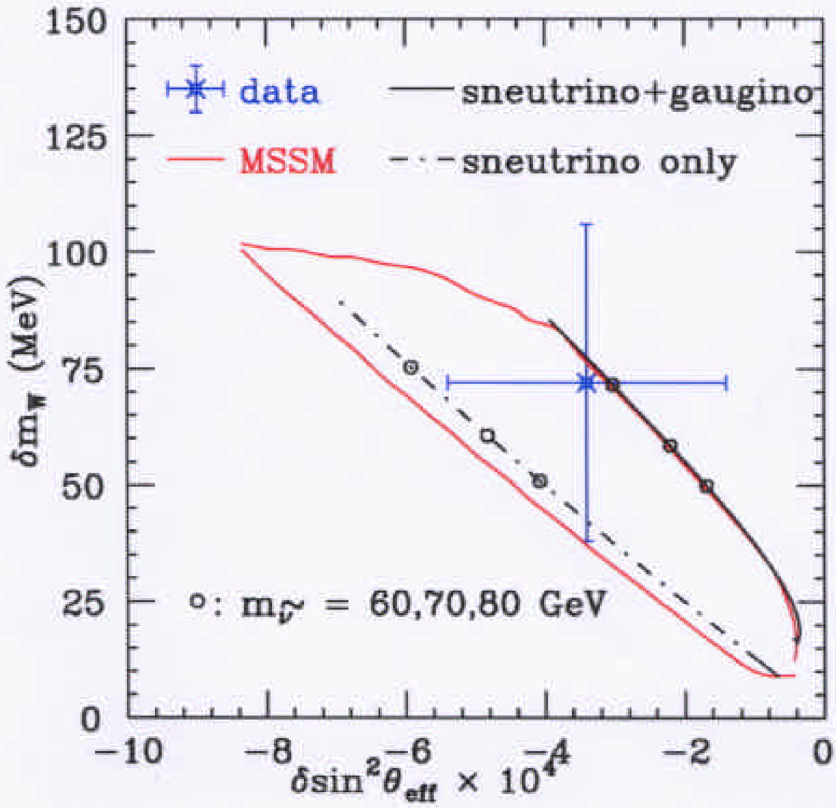
LEP2/SLD/Tevatron , LHC/LC, GigaZ:

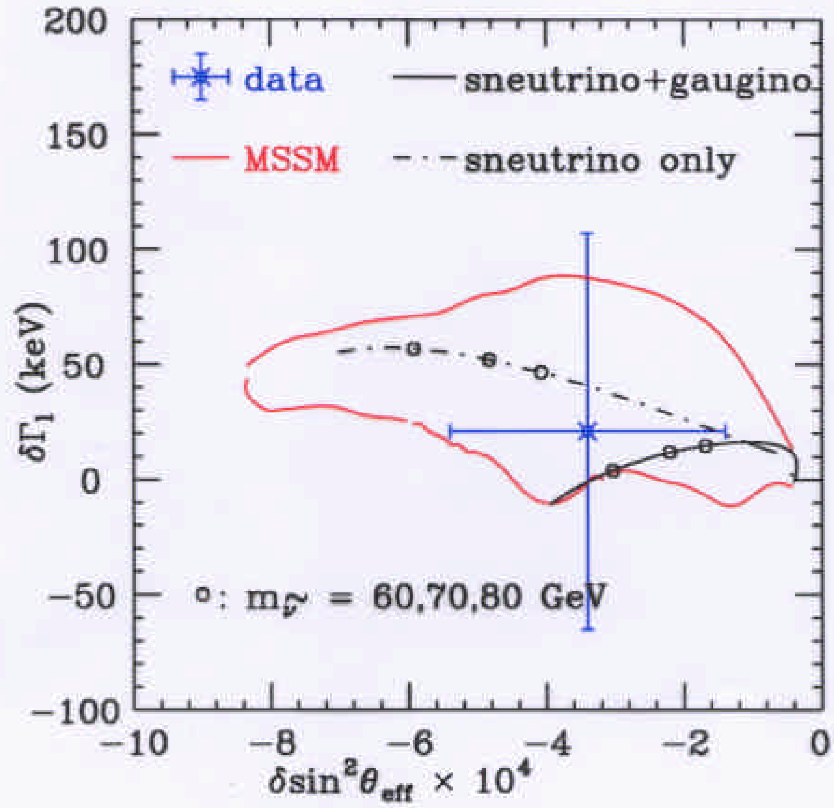


$\Rightarrow$ Highly non-trivial check of the MSSM with GigaZ


0.2325
0.2320
0.2315
0.2310
0.2305
sin²θ_eff
experimental errors:
LEP2/SLD/Tevatron
LHC/LC
GigaZ
80.20
80.25
80.30
80.35
80.40
80.45
80.50
M_W [GeV]

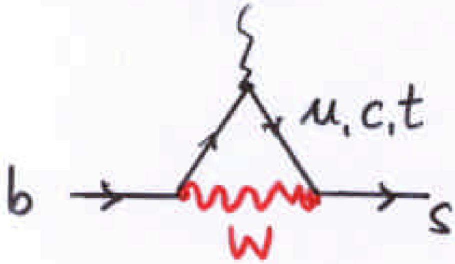
[Altarelli, Caravaglios, Gambino, Giudice, Ridolfi]

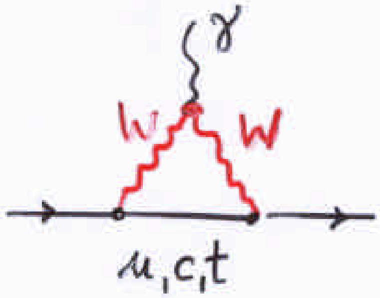




Low energy observables

$B \to X_s \gamma$





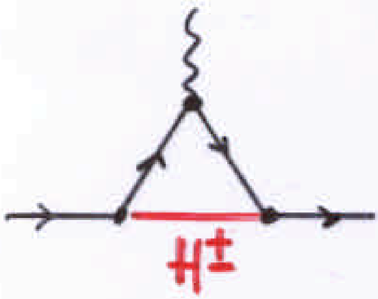
SM

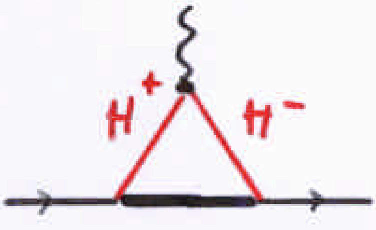
exp: $(3.23 \pm 0.41) \cdot 10^{-4}$ BR

theo: $(3.73 \pm 0.30) \cdot 10^{-4}$

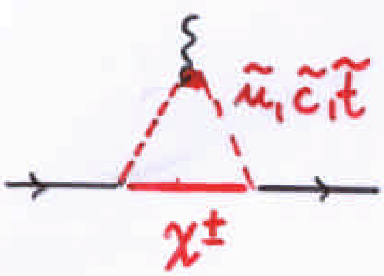
[including h.o. QCD + EW]

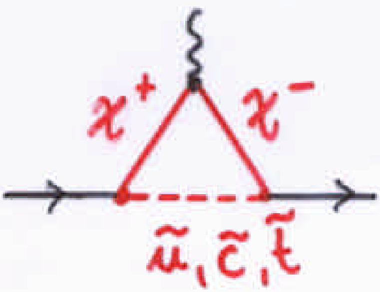
→ talk M. Neubert





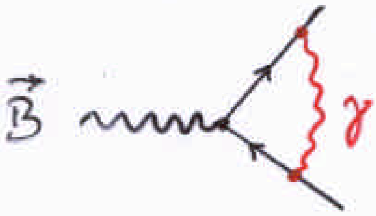
SUSY (MSSM)





Anomalous g-factor of the Muon

- Dirac Theory: $g = 2$
- QED, 1-loop-order: $g = 2 + \frac{\alpha}{\pi}$



- Theory prediction 2001:

  Electroweak: 2-loop
  QED part: 4-loop (5-loop estimate)

- **Experiment 2001:**
  Brookhaven E821
  Phys. Rev. Lett. 86 (2001) 2227

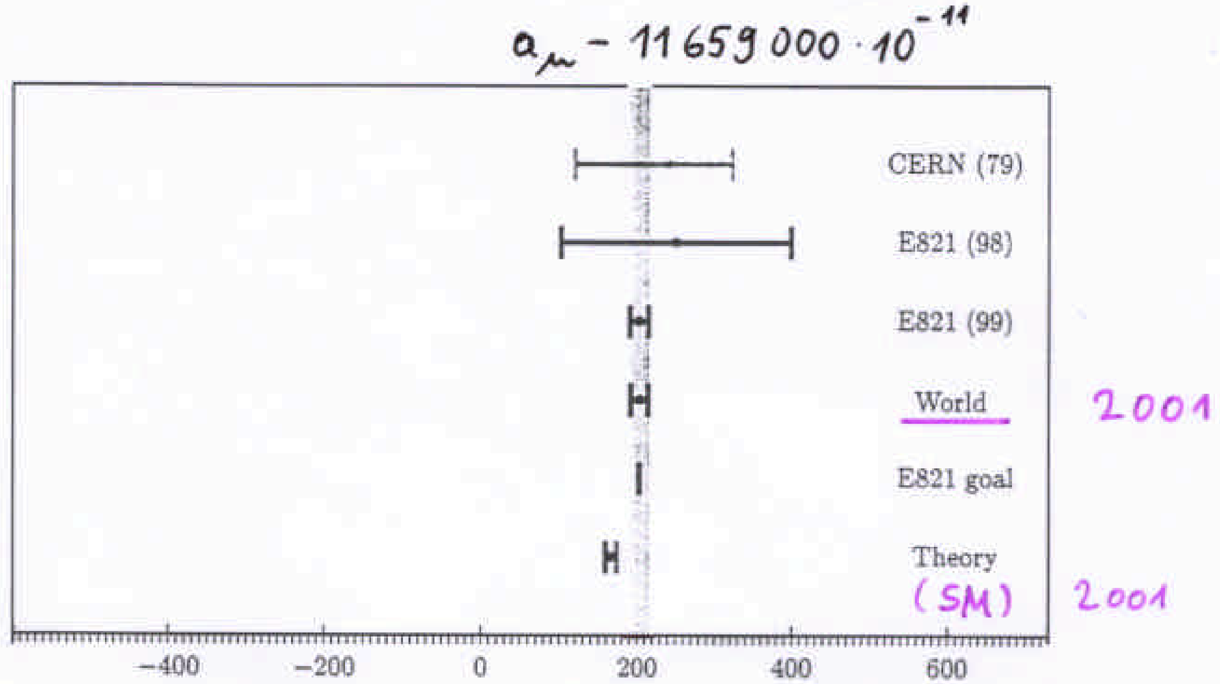
theory < experiment

2 - 2.5 σ (2001)

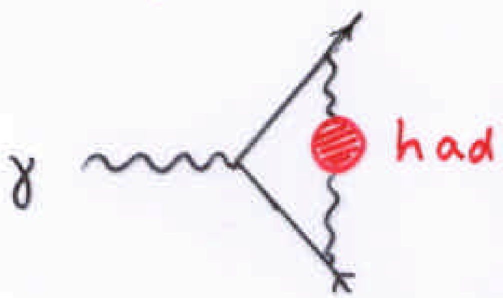
1 - 1.5 σ (2002)

g − 2 for muons

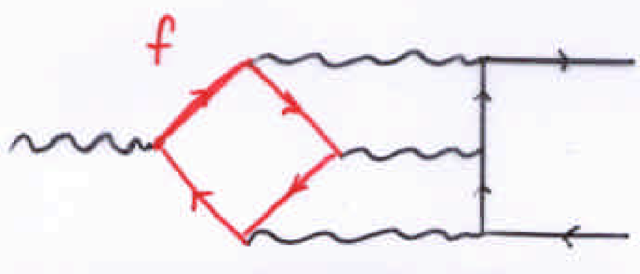
$$a_\mu = \frac{g-2}{2}$$



main uncertainties in the SM prediction:



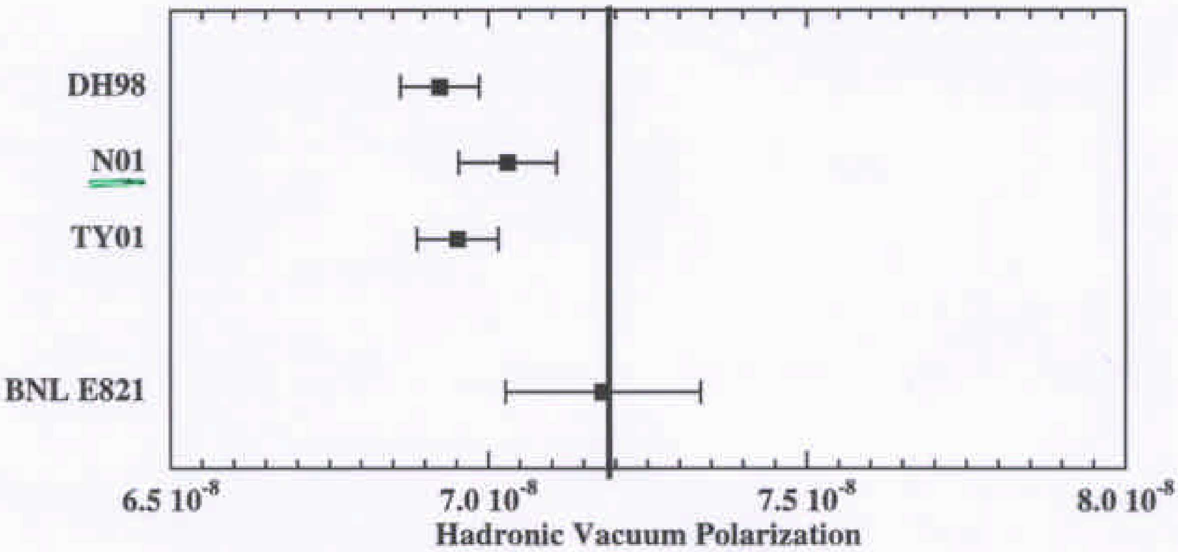
hadronic vacuum pol



light-by-light scattering

quark loops

Narison


DH98
N01
TY01
BNL E821
6.5 10^-8
7.0 10^-8
7.5 10^-8
8.0 10^-8
Hadronic Vacuum Polarization

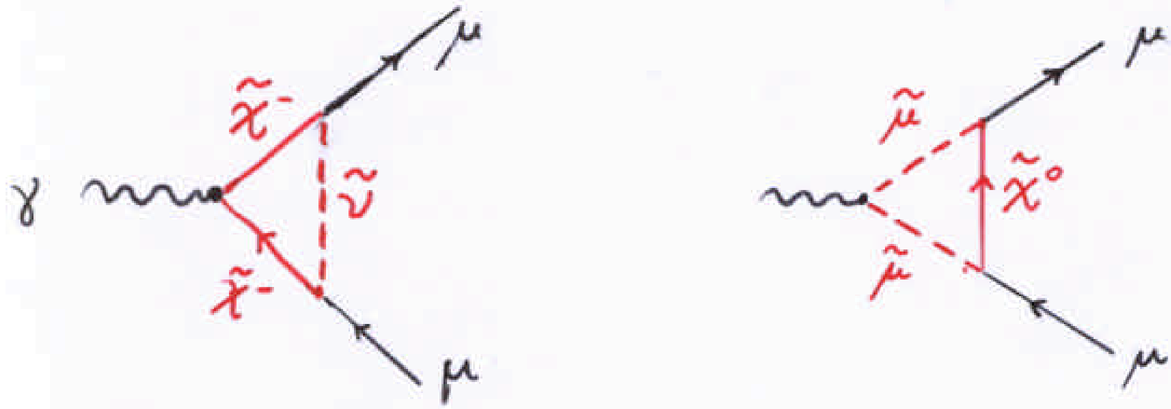
$$g = 2(1 + \Delta a_\mu)$$

Δa_μ	contribution [10^{-11}]	± error [10^{-11}]
QED	116 584 705.7	2.9
had. VP(1)	6924[a]	62
	6988[b]	111
	7021[c]	76
had. VP(2)	-100	6
light-light	+ 85	25
EW (1+2 loop)	152	4
SM prediction	116 591 864	80
⟨exp⟩	116 592 023	151
⟨goal⟩		40

a) Davier, Höcker (1998)
b) Jegerlehner (2001)
c) Narison (2001)

$\langle a_\mu^{exp} \rangle - \langle a_\mu^{SM} \rangle$	159	(170)	0.946
	256	(165)	1.65

SUSY: positive contribution to a_μ for large $\tan\beta$, "light" $\tilde{\mu}$, $\tilde{\chi}^{+}$,



- simple model : $m_{\tilde{\chi}} \simeq m_{\tilde{\mu}} = \tilde{m}$

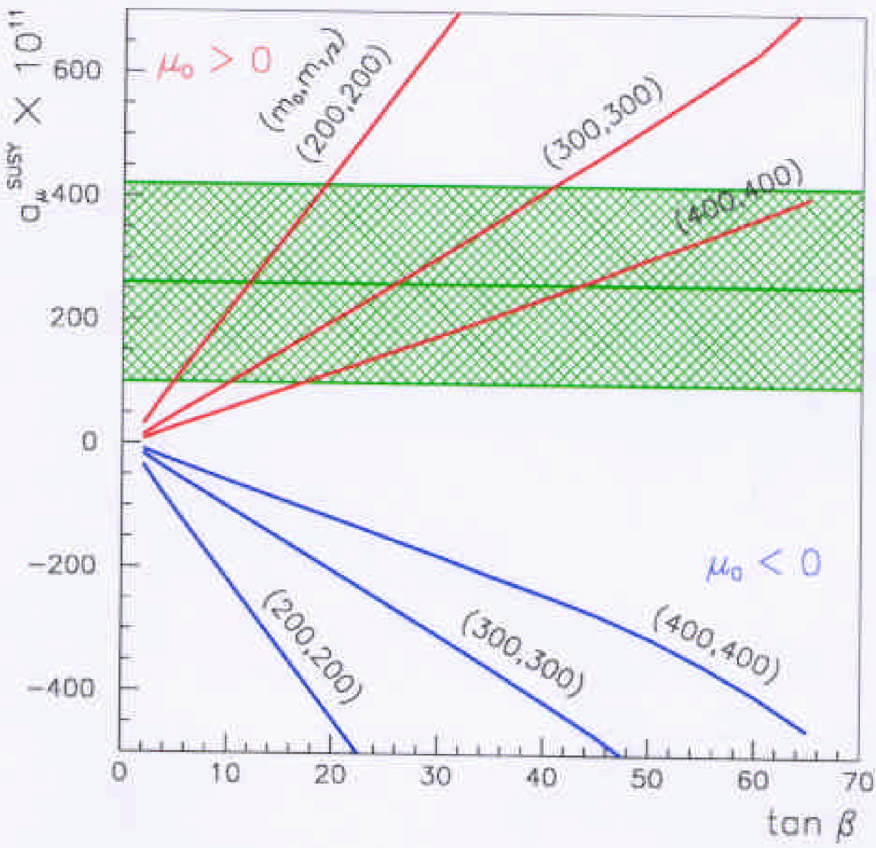
$$(\Delta a_\mu)^{SUSY} \simeq 130 \cdot 10^{-11} \tan\beta \left(\frac{100\text{ GeV}}{\tilde{m}} \right)$$

[Czarnecki, Marciano]

$200\text{ GeV} < \tilde{m} < 500\text{ GeV}$ if $\langle a_\mu^{exp} \rangle - a_\mu^{SM}$ entirely SUSY

- More detailed study:

Baer et al, hep-ph/0103280



[de Boer, Sander]

Global fits in the MSSM

fit program → precision observables

MSSMFITTER

[de Boer, Dabelstein, WH, Mösle, Schwickerath]

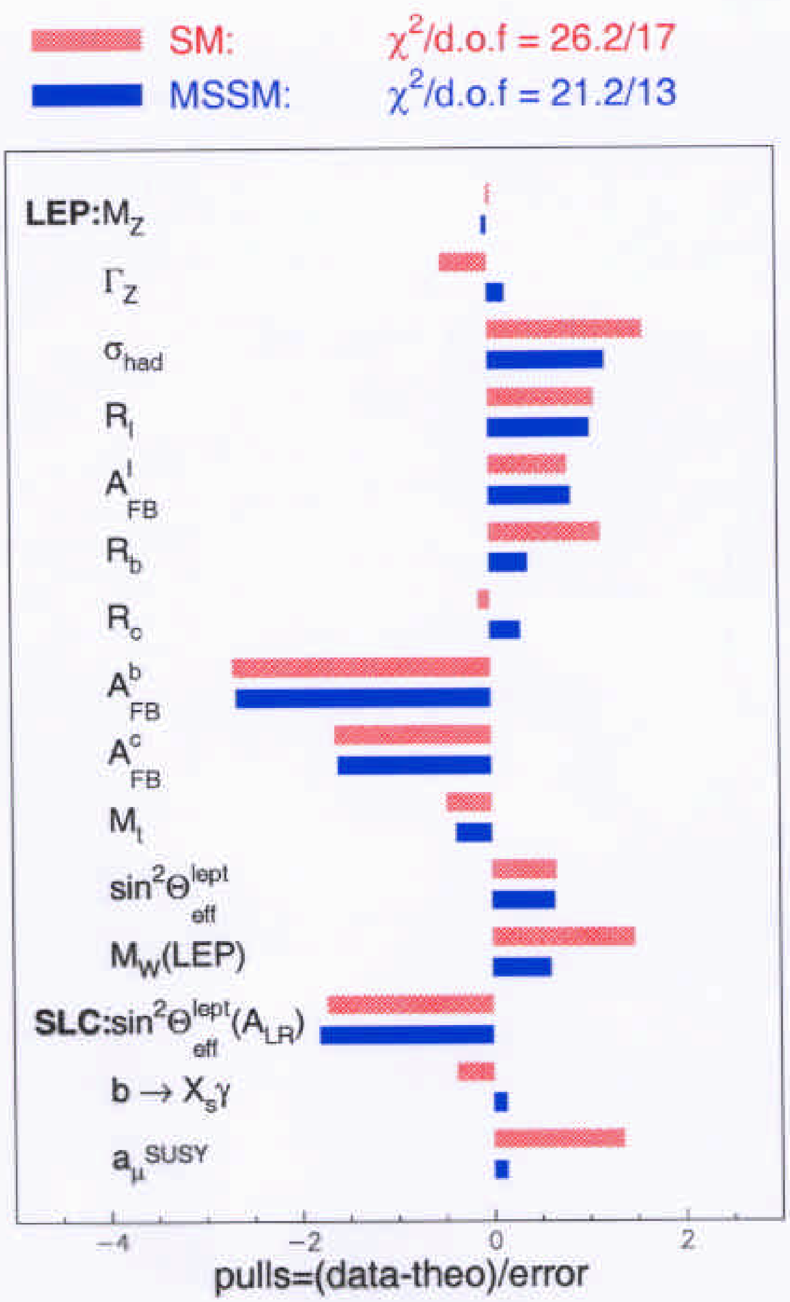
update: de Boer, Sander [→ talk]

M_W, Z observables, $B \to X_s \gamma$, a_μ

best fit parameters

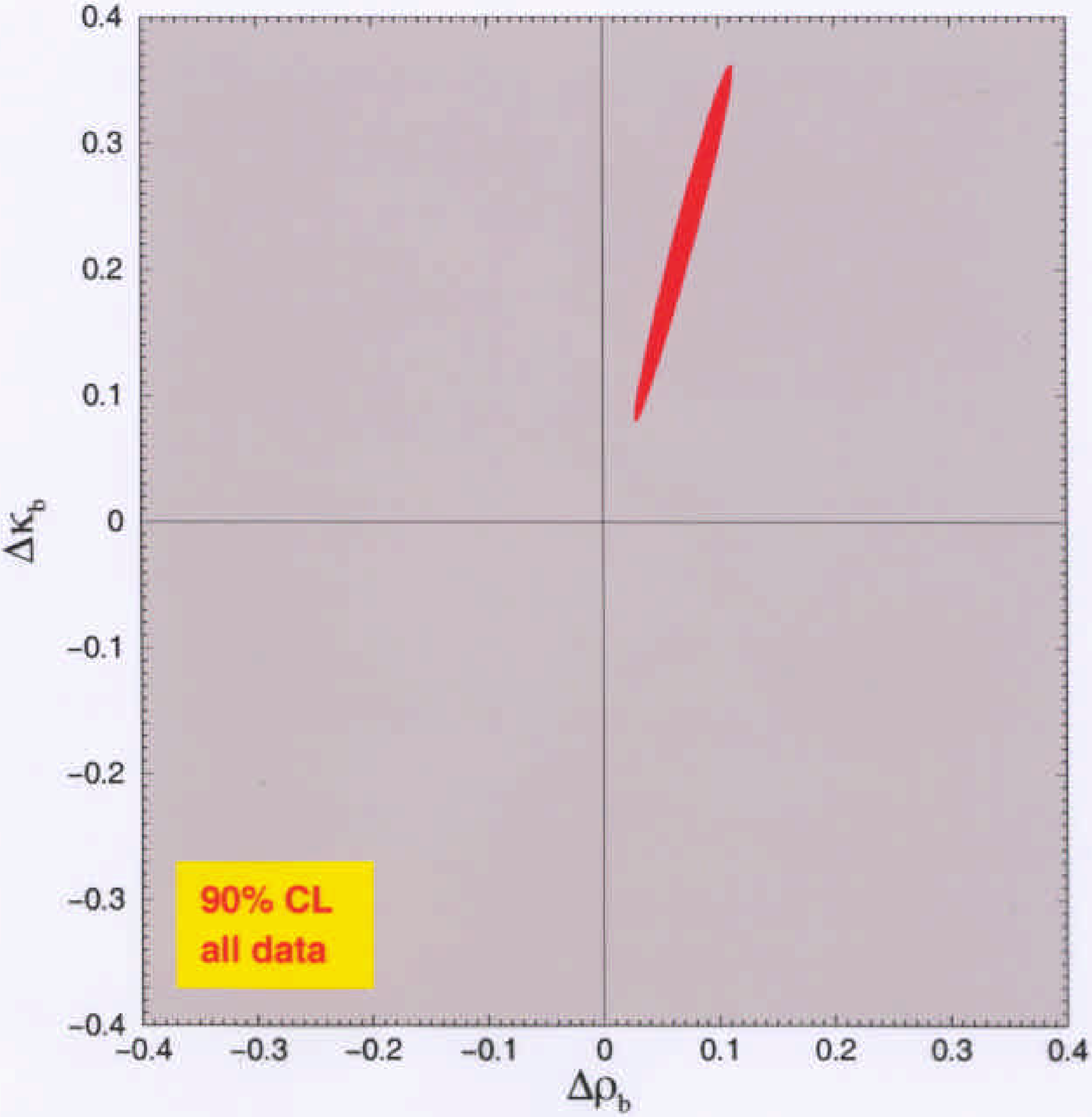
[de Boer, Sander → de Boer talk]

SUSY Parameters						
				rescaled		
Symbol	$\tan\beta = 20$	$\tan\beta = 35$	$\tan\beta = 50$	$\tan\beta = 20$	$\tan\beta = 35$	$\tan\beta = 50$
m_t[GeV]	175.4	176.2	176.4	175.0	176.1	177.4
α_s	0.1182	0.1181	0.1176	0.1179	0.1181	0.1181
μ[GeV]	130	132	133	130	132	133
$m_{\tilde{t}_1}$[GeV]	563	623	680	463	632	681
$m_{\tilde{t}_2}$[GeV]	355	261	262	322	270	263
$m_{\tilde{b}_1}$[GeV]	542	605	666	439	614	666
$m_{\tilde{b}_2}$[GeV]	404	440	496	366	440	496
$m_{\tilde{q}}$[GeV]	542	605	666	439	614	666
$m_{\tilde{l}}$[GeV]	459	792	784	457	797	782
$m_{\tilde{\chi}_1^\pm}$[GeV]	219	220	221	219	220	221
$m_{\tilde{\chi}_2^\pm}$[GeV]	104	104	104	104	104	104
M_W[GeV]	80.426	80.426	80.426	80.430	80.425	80.432
$\sin^2\theta_{\rm eff}^{\rm lept}$	0.23143	0.23145	0.23145	0.23140	0.23146	0.23143
χ^2/d.o.f.	22.1/13	21.2/13	22.2/13	14.0/13	13.3/13	14.1/13
Probability	5.4%	6.8%	5.2%	37.1%	42.3%	36.9%



SM: χ^2/d.o.f = 26.2/17
MSSM: χ^2/d.o.f = 21.2/13
LEP:M_Z
Γ_Z
σ_{had}
R_l
A^l_{FB}
R_b
R_c
A^b_{FB}
A^c_{FB}
M_t
$\sin^2\Theta^{lept}_{eff}$
M_W(LEP)
SLC:$\sin^2\Theta^{lept}_{eff}(A_{LR})$
$b \rightarrow X_s\gamma$
a_μ^{SUSY}
−4
−2
0
2
pulls=(data-theo)/error

Erler, Langacker



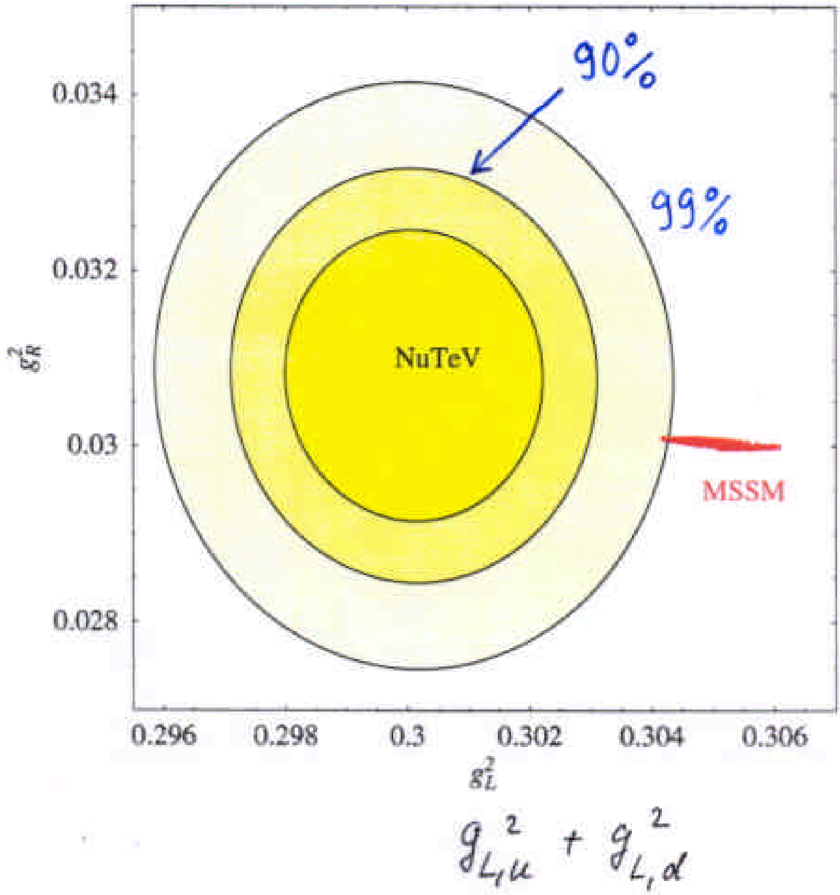
$$g_A^b = \sqrt{\rho_b} \cdot I_3^b$$

$$\sin^2\Theta_b = \kappa_b \, s_W^2$$

$$\uparrow$$

$$1 - \frac{M_W^2}{M_Z^2}$$

[Davidson, Forte, Gambino, Rius, Strumia]



Higgs bosons in the MSSM

MSSM parameters ⟶ m_{h^0}

precise prediction

higher orders are needed

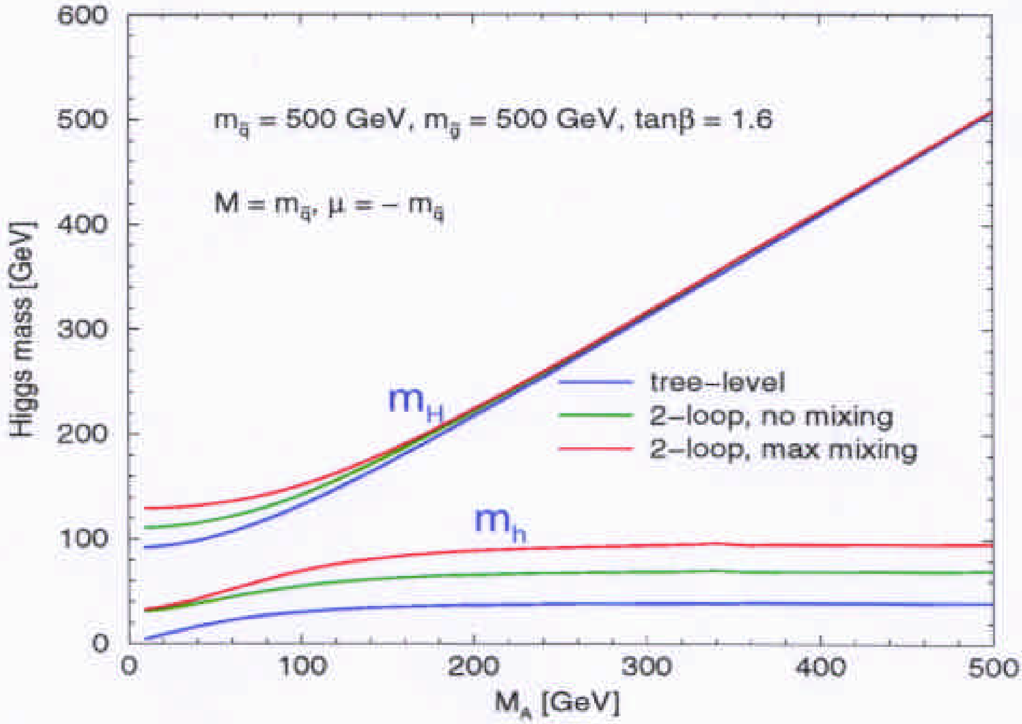
exp. constraints on m_{h^0} ⟶ constraints on MSSM parameters

EW Presision Observables ↔ MSSM parameters ↔ m_{h^0}

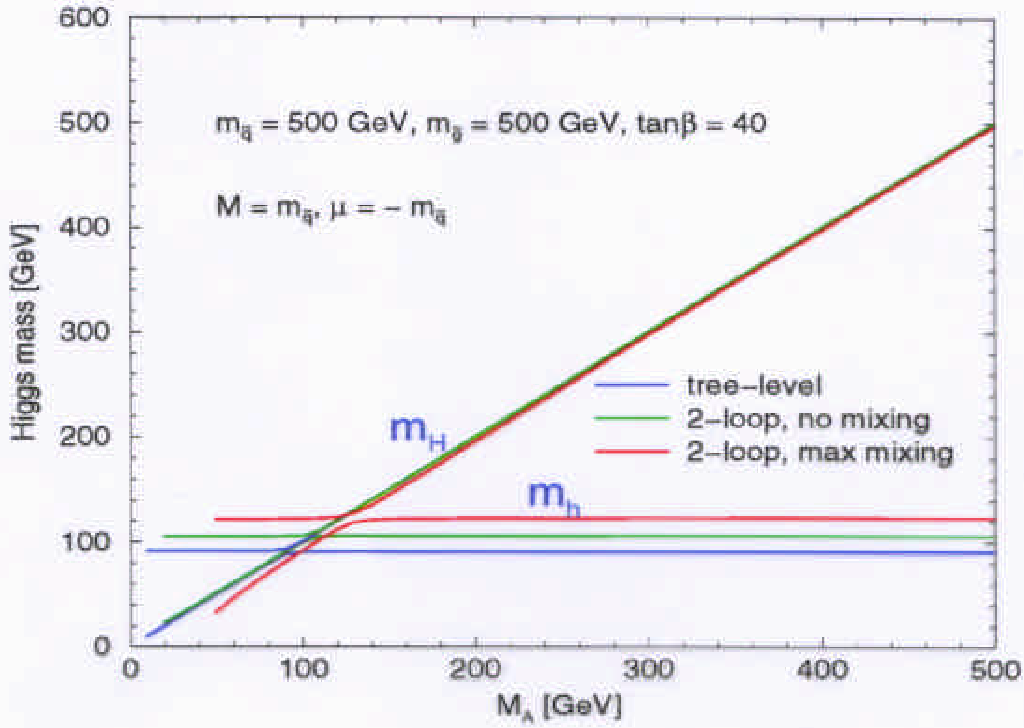
complementary in special regions

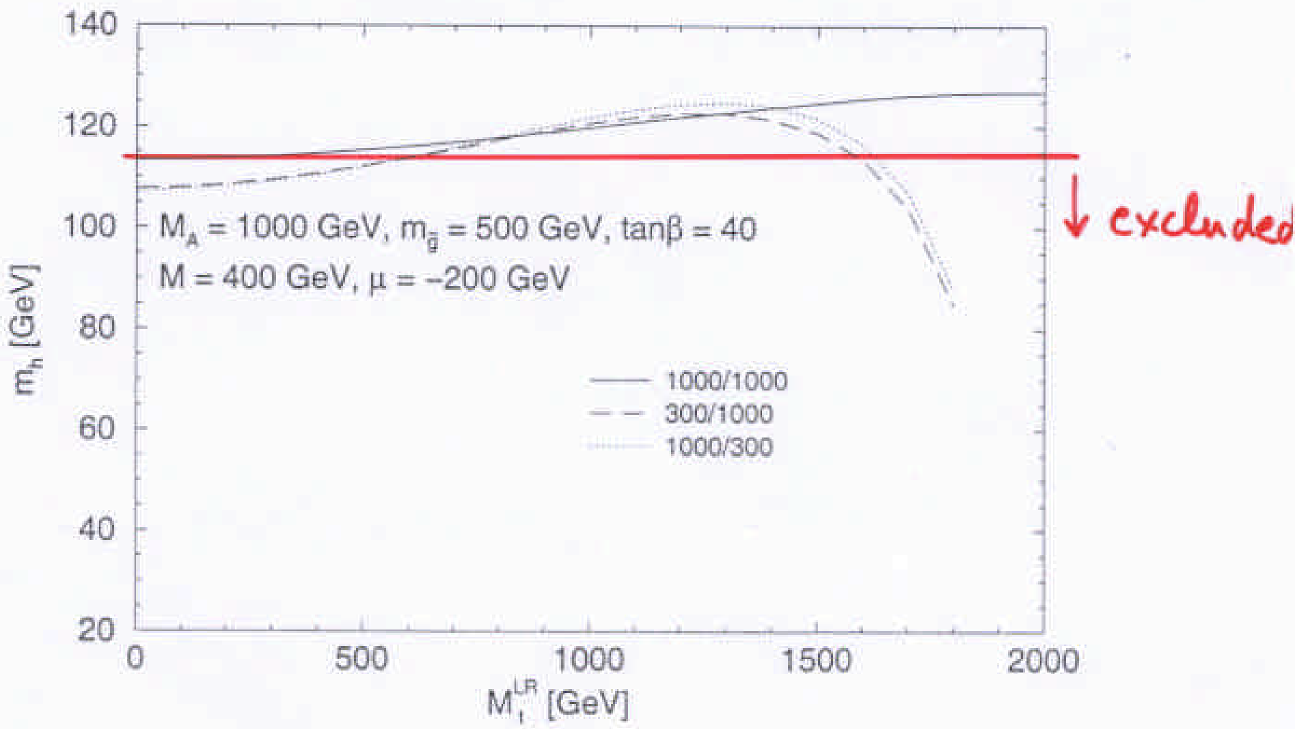
Dependence of m_h, m_H on M_A :

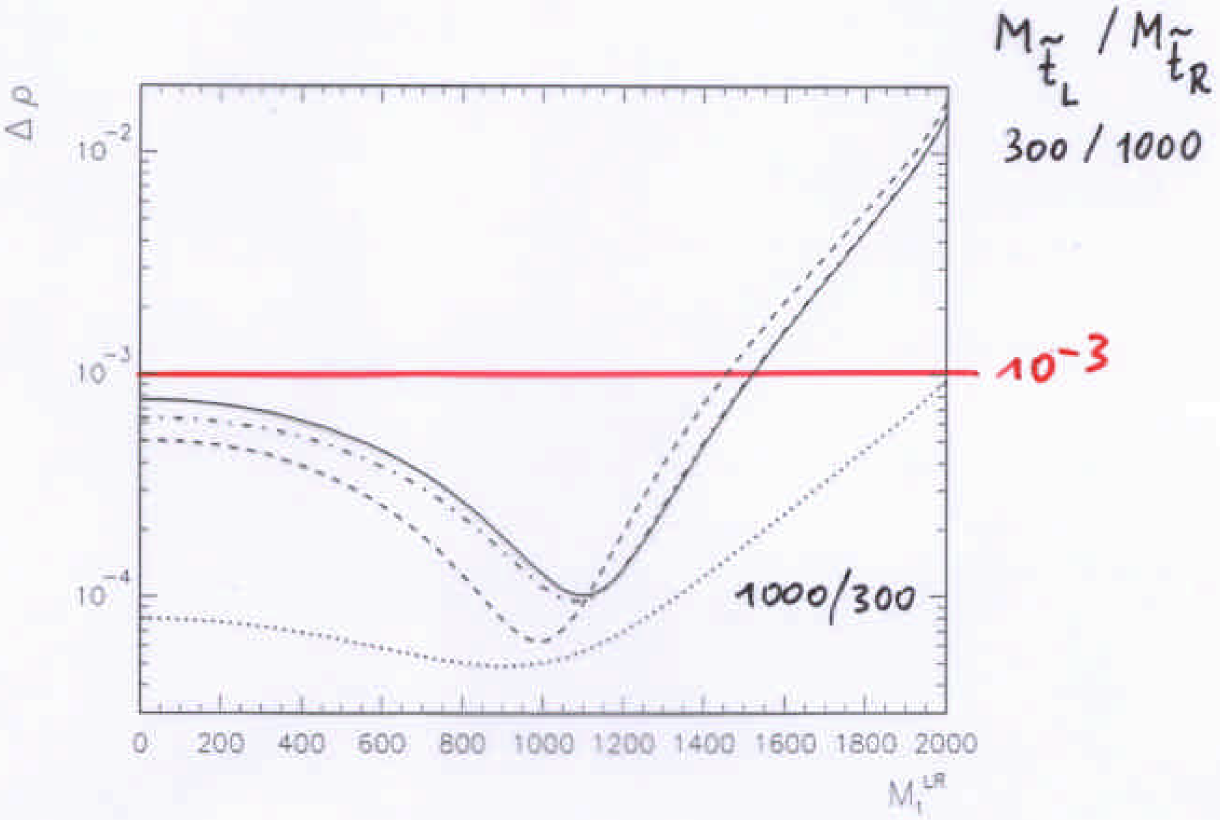
For $\tan\beta = 1.6$:



For $\tan\beta = 40$:

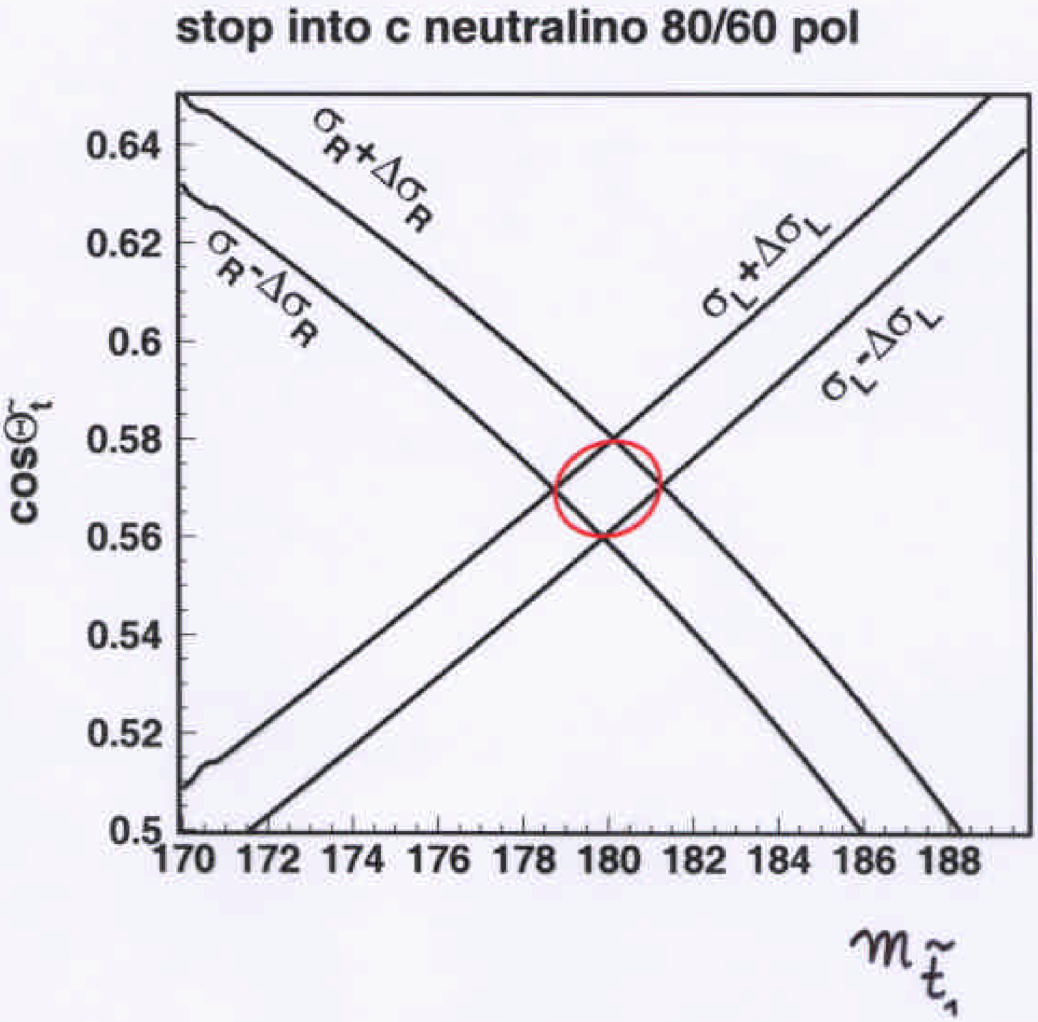






$$M_t^{LR} = A_t - \mu \cot\beta$$

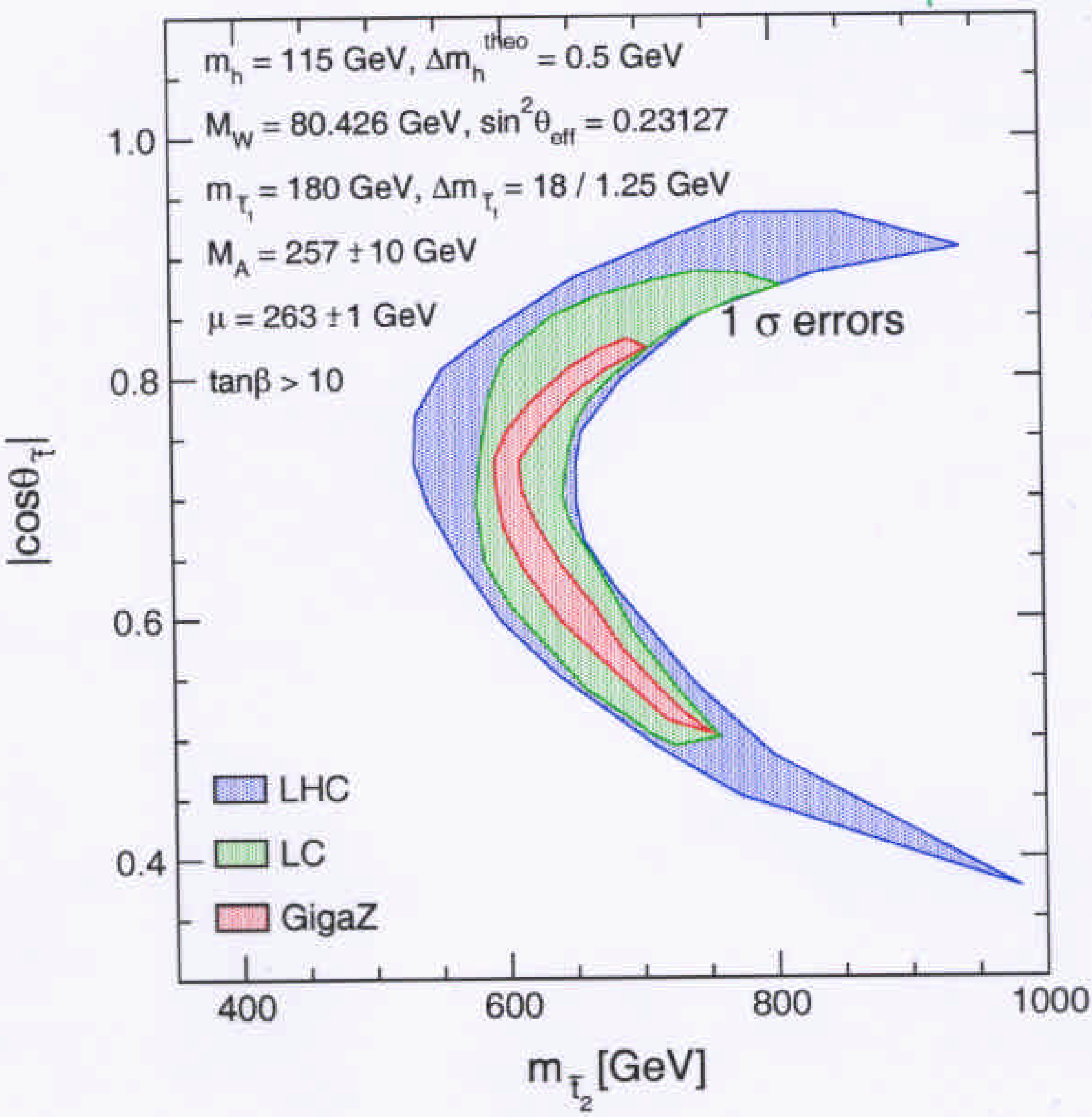
[Keränen, Nowak, Sopczak]

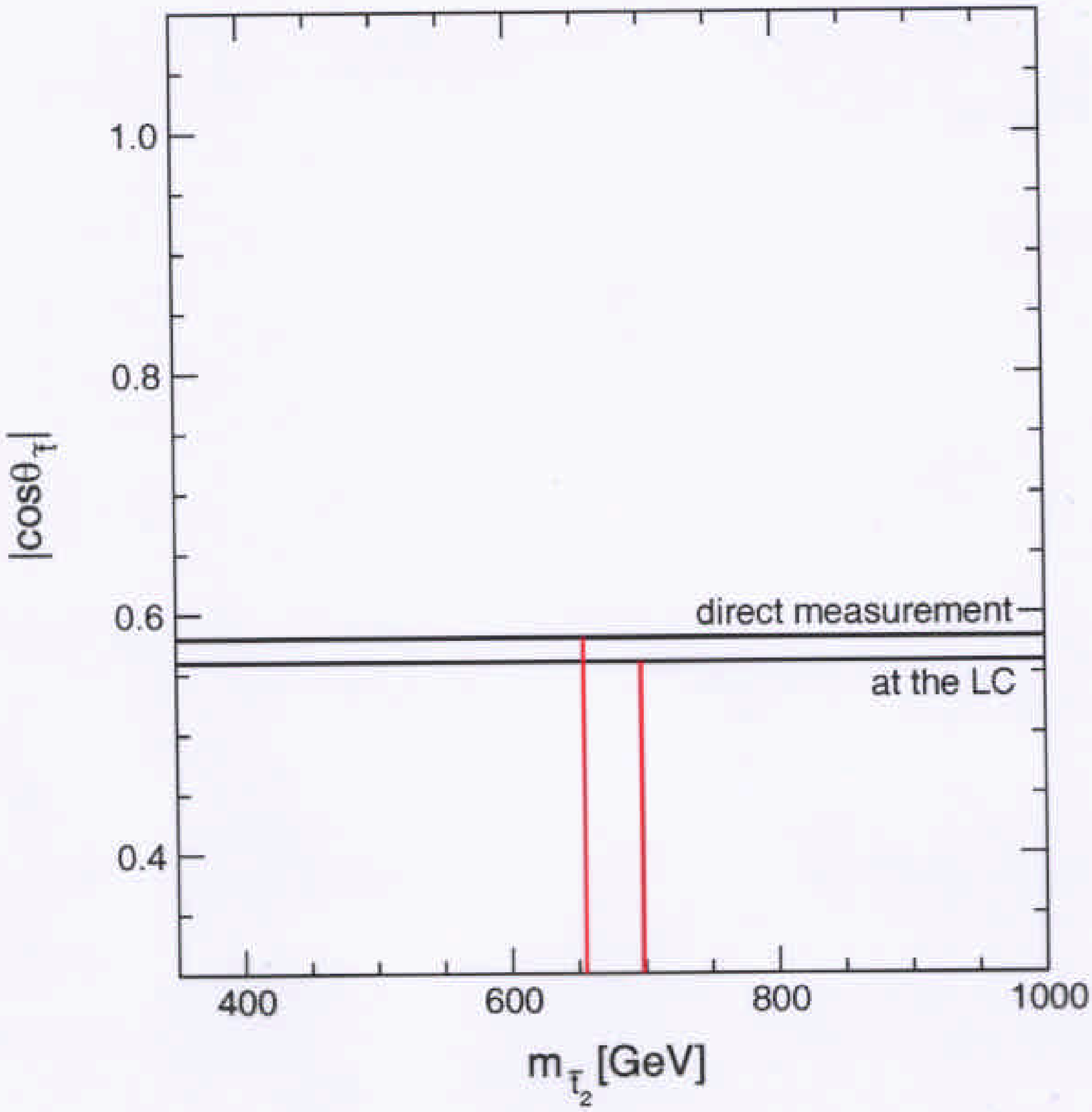


$\tilde{t}_L, \tilde{t}_R \xrightarrow{\Theta_{\tilde{t}}} \tilde{t}_1, \tilde{t}_2$

$\tilde{t}_1$: light, $\tilde{t}_2$: heavy

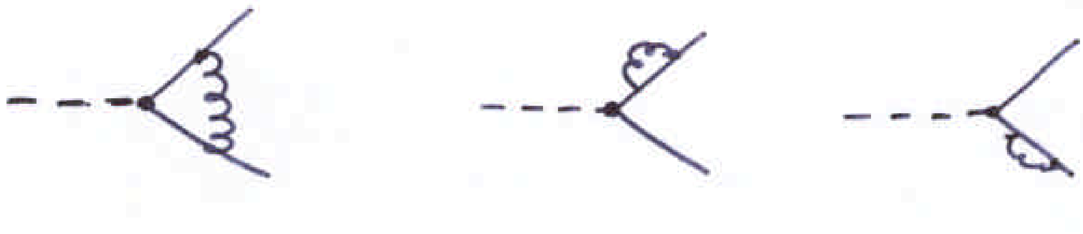
Heinemeyer, Weiglein





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

QCD corrections [$g \to \gamma$: QED corrections]



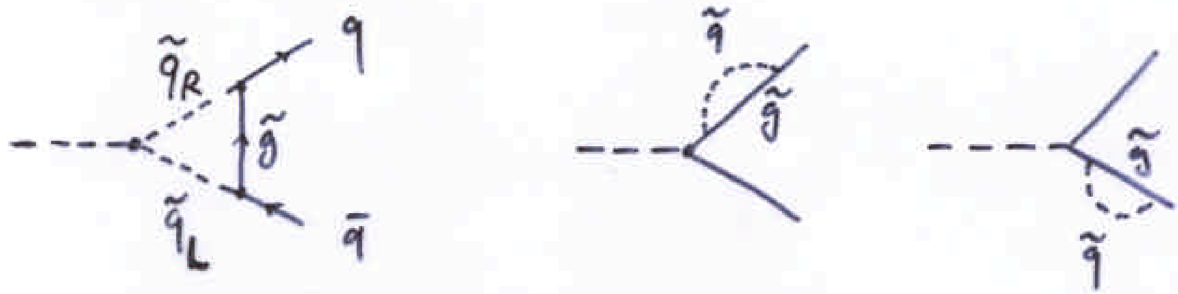
Drees, Hikasa
⋮

dominant : $m_{pole} \to \overline{m}(M_{h/H})$

large effects (− 40%)

QED corrections are small (< 0.4% for $b\bar{b}$)

SUSY-QCD corrections:



large effects $\sim m_{\tilde{g}} \, \mu \tan\beta \cdot \alpha_s$

Dabelstein

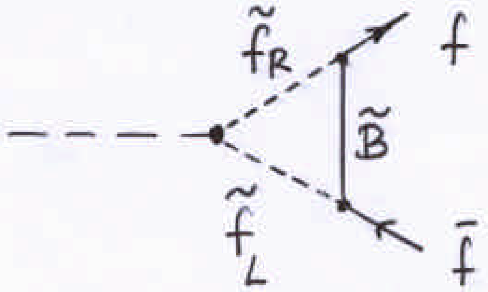
Coarasa, Jiménez, Solà

Haber et al.

non-universal $[b] \neq [\tau]$

electroweak corrections

large effects $\sim M_1 \mu \tan\beta \cdot (Y_{\tilde{f}_L} Y_{\tilde{f}_R})$



non-universal

$[b] \neq [\tau]$

Resummation of leading α_s and EW contributi
for large $\tan\beta$,

absorption into effective tree-level couplin

$$m_f \to \overline{m}_f (M_h) \cdot [1 + \Delta_f]$$

Carena, Mrenna, Wagner

Carena, Garcia, Nierste, Wagner

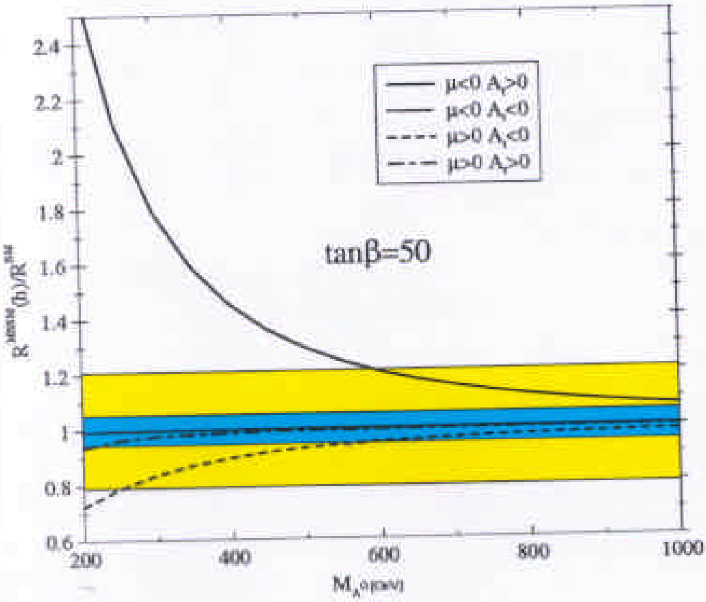
Eberl, Hidaka, Kraml, Majerotto, Yamada

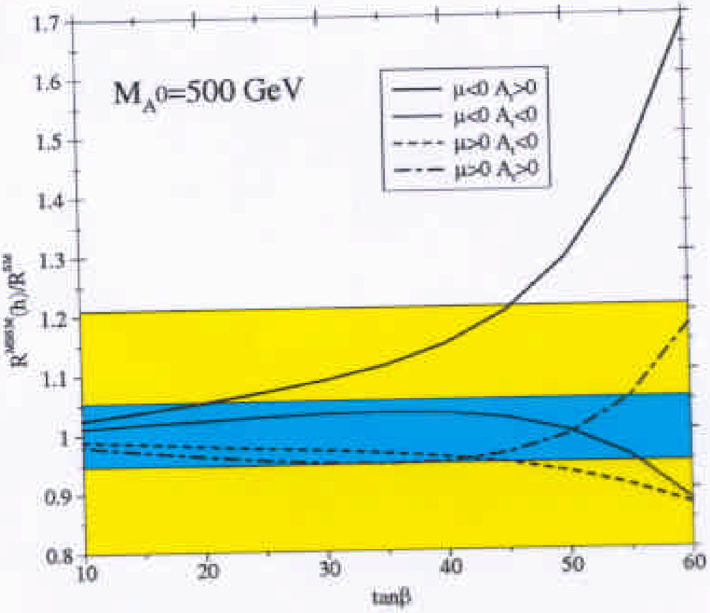
- For fixed M_A: SUSY non-decoupling

$$\Delta_b \simeq \tan\beta \left\{ \frac{\alpha_s}{3\pi} - \frac{\alpha_2}{16\pi} \left(3 + \frac{7}{9} \frac{s_W^2}{c_W^2}\right) \right\}$$

$$\Delta_\tau \simeq - \tan\beta \cdot \frac{\alpha_2}{16\pi} \left(1 + \frac{s_W^2}{c_W^2}\right)$$

$$R = \frac{\Gamma(h \to b\bar{b})}{\Gamma(h \to \tau^+\tau^-)}$$





[Guasch, WH, S. Peñaranda]

SUSY masses ~ 1.5 TeV

Conclusions

- Era of electroweak precision physics:
  - quantum effects have been established
  - Higgs boson is awaiting its discovery
  - anomalies with A^b_{FB}, $\sin^2\theta_W(\nu N)$?
- The MSSM is competitive to the SM
  - global fits of similar quality
  - better agreement for a_μ, M_W, $\sin^2\theta_\ell$, R_b
    but not for A^b_{FB} , $\sin^2\theta_W(\nu N)$

  natural: light Higgs boson
- Even if a Higgs boson will be disocvered:

  → standard Higgs boson?

  → SUSY?

  → $\cdots$?