Electroweak Precision Physics from LEP to ILC

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ILC PHYSICS IN FLORENCE

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Outline

- Electroweak precision observables – Standard Model
- Theory versus data
- Perspectives
- Extensions of the SM – Supersymmetry
- Outlook

Standard Model

- the symmetry group $SU(2) \times U(1) \times SU(3)_C$
- the principle of local gauge invariance
  $\longrightarrow$ fermion – vector boson interaction
  $\longrightarrow$ vector boson self-interaction
- Higgs mechanism and Yukawa interactions
  $\longrightarrow$ masses $M_W,\ M_Z,\ m_{\text{fermion}}$

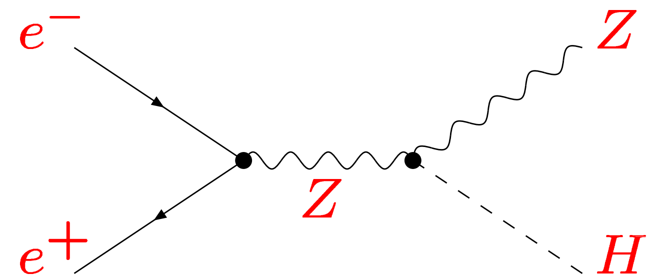
renormalizable quantum field theory

accurate theoretical predictions

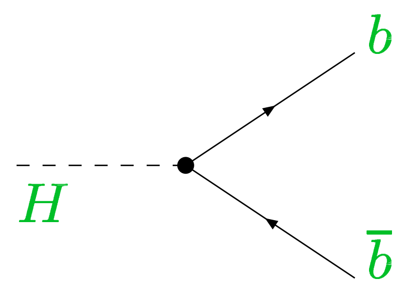
- detect deviations $\rightarrow$ “new physics” ?

Search for the Standard Model Higgs at LEP

Dominant production process: $e^+e^- \to ZH$



Dominant decay process: $H \to b\bar{b}$

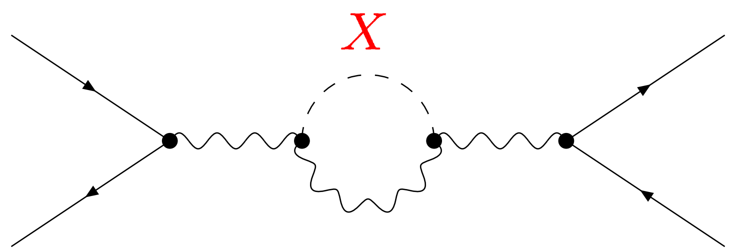


exclusion limit (95% C.L.): $M_{\mathrm{H}} > 114.4\ \mathrm{GeV}$

Precision observables – SM

Test of theory at quantum level:

Sensitivity to loop corrections

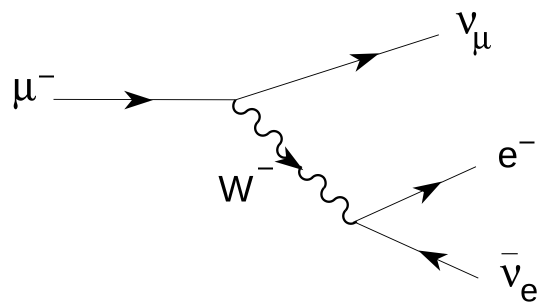


- μ lifetime: M_W, Δr, G_{F}
- Z observables: g_V, g_A, $\sin^2\theta_{\mathrm{eff}}$, Γ_Z, ...

sensitivity to heavy internal particles (X)

Standard Model: X = Higgs, top

$M_W - M_Z$ correlation



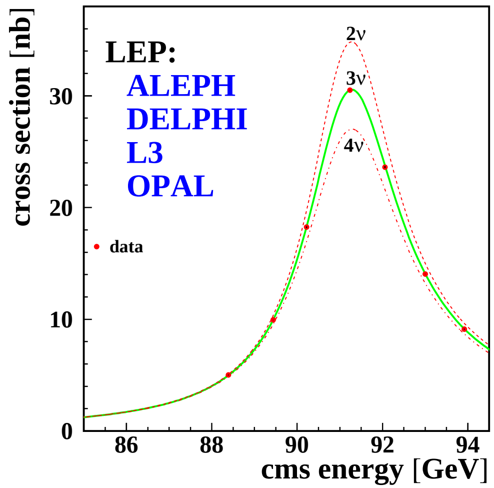
$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{M_W^2\left(1 - M_W^2/M_Z^2\right)}\left(1 + \Delta r\right)$$

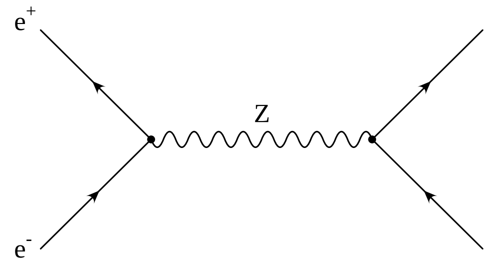
$\Delta r :$ quantum correction, $\Delta r = \Delta r(m_t, M_H)$

$\rightarrow$ $M_W = M_W(\alpha, G_F, M_Z, m_t, M_H)$

complete two-loop calculation available

Z resonance





- effective Z boson couplings with higher-order $\Delta g_{V,A}$

$$g_V^f \longrightarrow g_V^f + \Delta g_V^f, \qquad g_A^f \longrightarrow g_A^f + \Delta g_A^f$$

- effective ew mixing angle (for $f = e$):

$$\sin^2\theta_{\text{eff}} = \frac{1}{4}\left(1 - \text{Re}\,\frac{g_V^e}{g_A^e}\right) = \kappa \cdot \left(1 - \frac{M_W^2}{M_Z^2}\right)$$

EW 2-loop calculations for Δr

Freitas, Hollik, Walter, Weiglein

Awramik, Czakon

Onishchenko, Veretin

EW 2-loop calculations for $\sin^2\theta_{\text{eff}}$

Awramik, Czakon, Freitas, Weiglein

Awramik, Czakon, Freitas

Hollik, Meier, Uccirati

universal terms beyond 2-loop order (EW and QCD)

van der Bij, Chetyrkin, Faisst, Jikia, Seidensticker

Faisst, Kühn Seidensticker, Veretin

Boughezal, Tausk, van der Bij

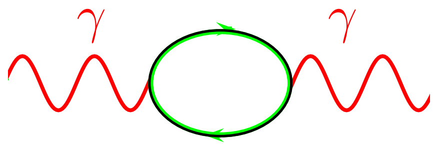
Schröder, Steinhauser

Chetyrkin, Faisst, Kühn *Chetyrkin, Faisst, Kühn, Maierhofer, Sturm*

Boughezal, Czakon

charge renormalization $e + \delta e$ **involves**

photon vacuum polarization



virtual pairs

$$\Pi^\gamma(M_Z^2) - \Pi^\gamma(0) \equiv \Delta\alpha \quad \rightarrow \quad \alpha(M_Z) = \frac{\alpha}{1 - \Delta\alpha}$$

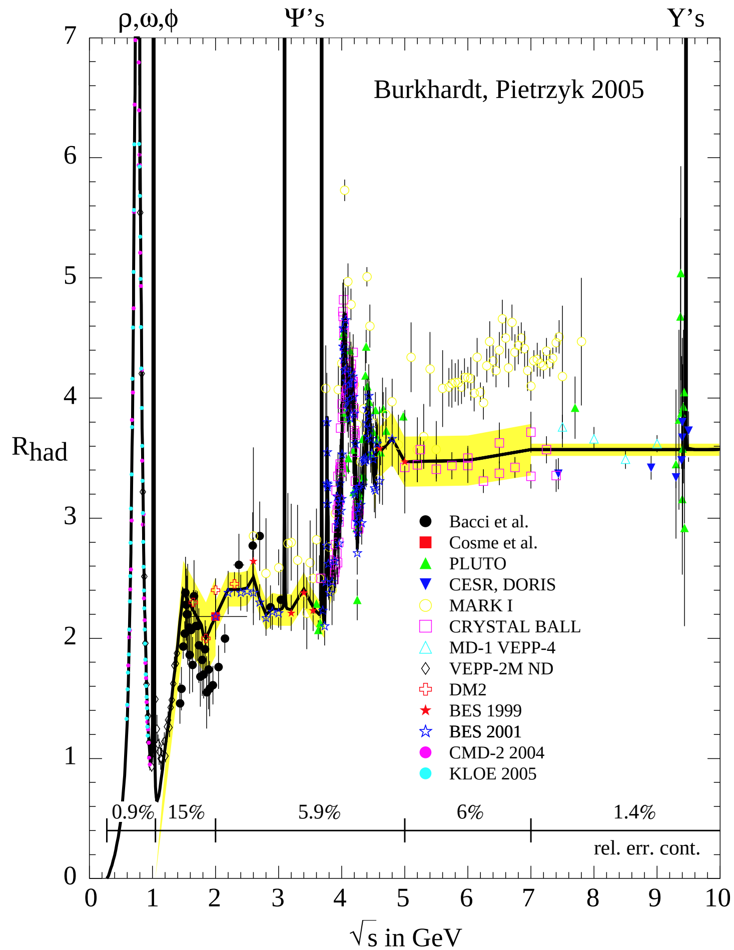
$$\Delta\alpha = \Delta\alpha_{\text{lept}} + \Delta\alpha_{\text{had}},$$

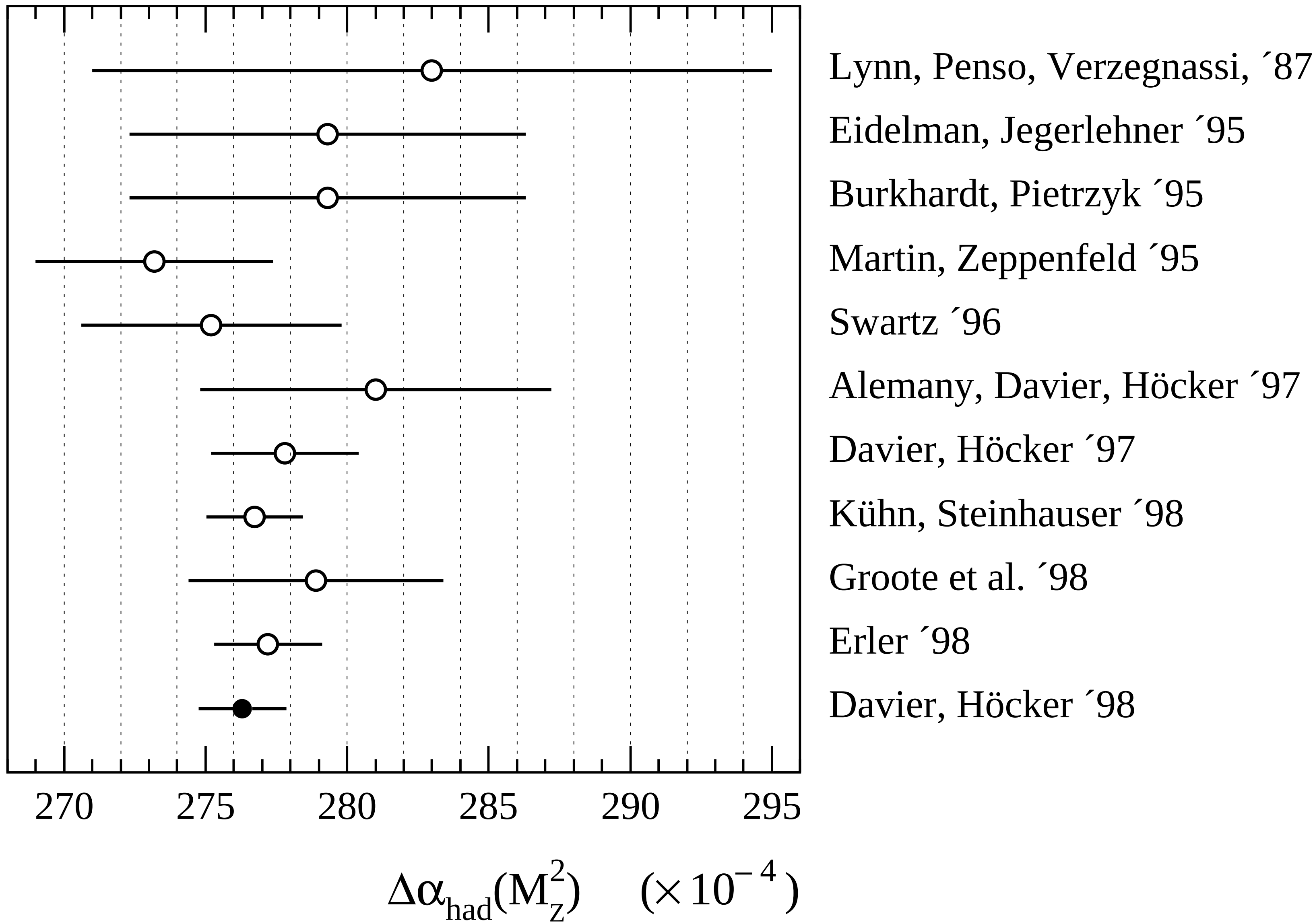
$$\Delta\alpha_{\text{lept}} = 0.031498 \quad (3 - \text{loop})$$

$$\Delta\alpha_{\text{had}} = 0.02758 \pm 0.00035$$

significant source of parametric uncertainty

$$\Delta\alpha_{\rm had} = -\frac{\alpha}{3\pi} M_Z^2 \ {\rm Re} \int_{4m_\pi^2}^{\infty} ds' \ \frac{R_{\rm had}(s')}{s'(s' - M_Z^2 - i\epsilon)}$$




Lynn, Penso, Verzegnassi, ´87
Eidelman, Jegerlehner ´95
Burkhardt, Pietrzyk ´95
Martin, Zeppenfeld ´95
Swartz ´96
Alemany, Davier, Höcker ´97
Davier, Höcker ´97
Kühn, Steinhauser ´98
Groote et al. ´98
Erler ´98
Davier, Höcker ´98
270
275
280
285
290
295
$\Delta\alpha_{had}(M_Z^2) \quad (\times 10^{-4})$

input from experiments

- LEP1/SLC: $e^+e^- \to Z \to f\bar{f}$
  LEP1: $\sim 4 \times 10^6$ events/experiment
  4 experiments $(1989 - 1995)$

- LEP2: $e^+e^- \to W^+W^-$
  $\mathcal{O}(10^4)$ W pairs $(1996 - 2000)$

- Tevatron: $q\bar{q}' \to W \to l\nu, q\bar{q}'$
  $(p\bar{p})$ $q\bar{q}' \to t\bar{t},\ t \to W^+b \to \ldots$

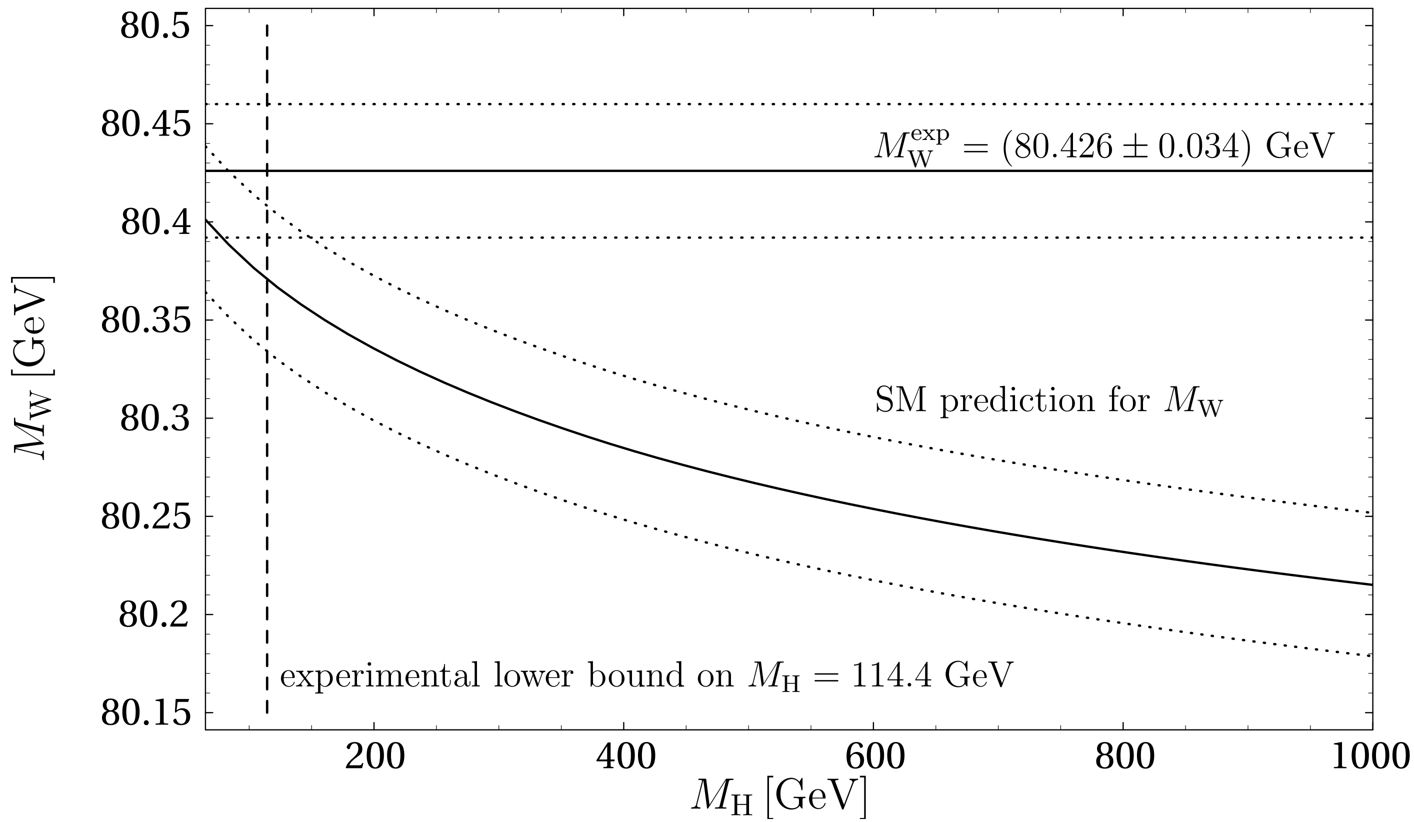
- low-energy experiments (μ decay, νN scattering, νe scattering, atomic parity violation, ...)

Theory versus Data

experimental results (selection)

M_{Z} [GeV]	$= 91.1875 \pm 0.0021$	0.002%
Γ_{Z}[GeV]	$= 2.4952 \pm 0.0023$	0.09%
$\sin^2\theta_{\mathsf{eff}}^{\mathsf{lept}}$	$= 0.23148 \pm 0.00017$	0.07%
M_{W} [GeV]	$= 80.392 \pm 0.029$	0.04%
m_{t} [GeV]	$= 170.9 \pm 1.8$	1.05%
G_{F} [GeV^{-2}]	$= 1.16637(1)10^{-5}$	0.001%

quantum effects at least one order of magnitude larger than experimental uncertainties

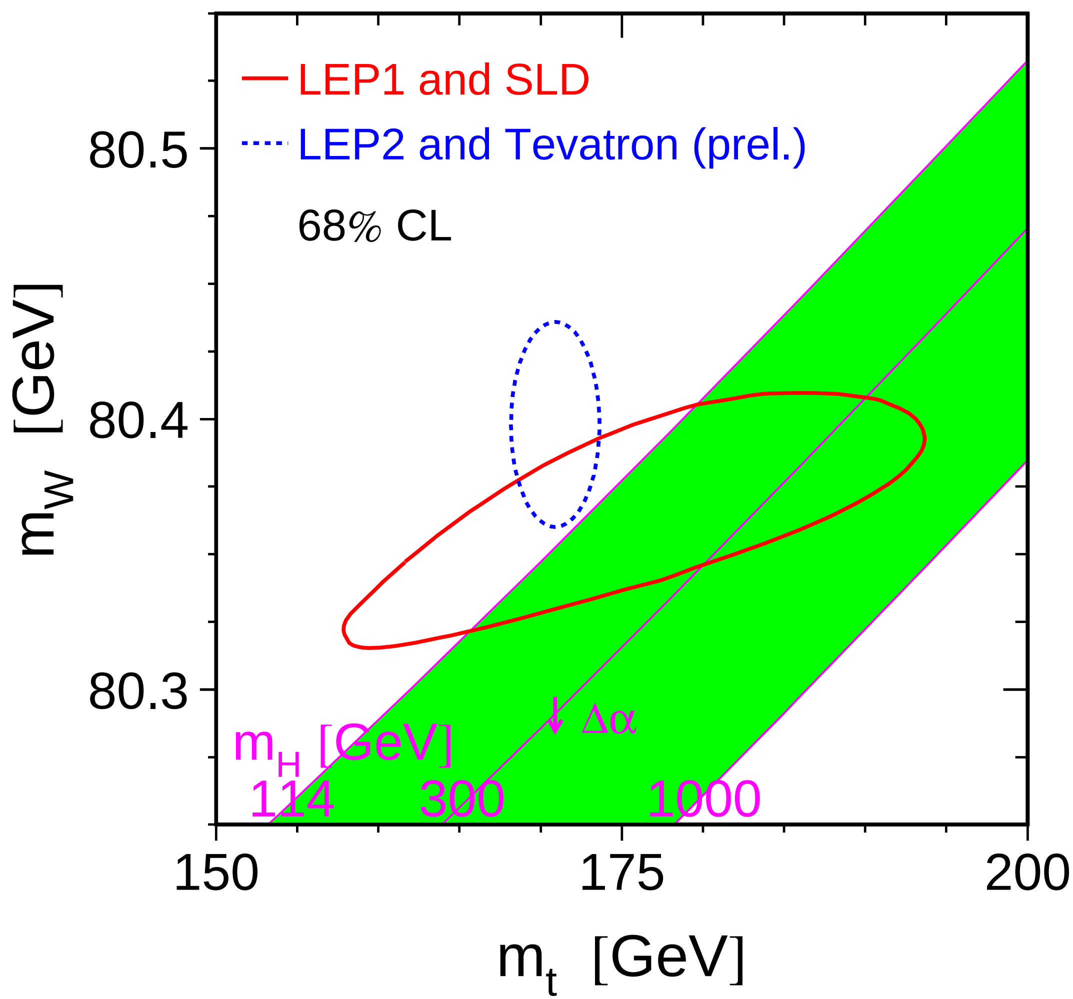


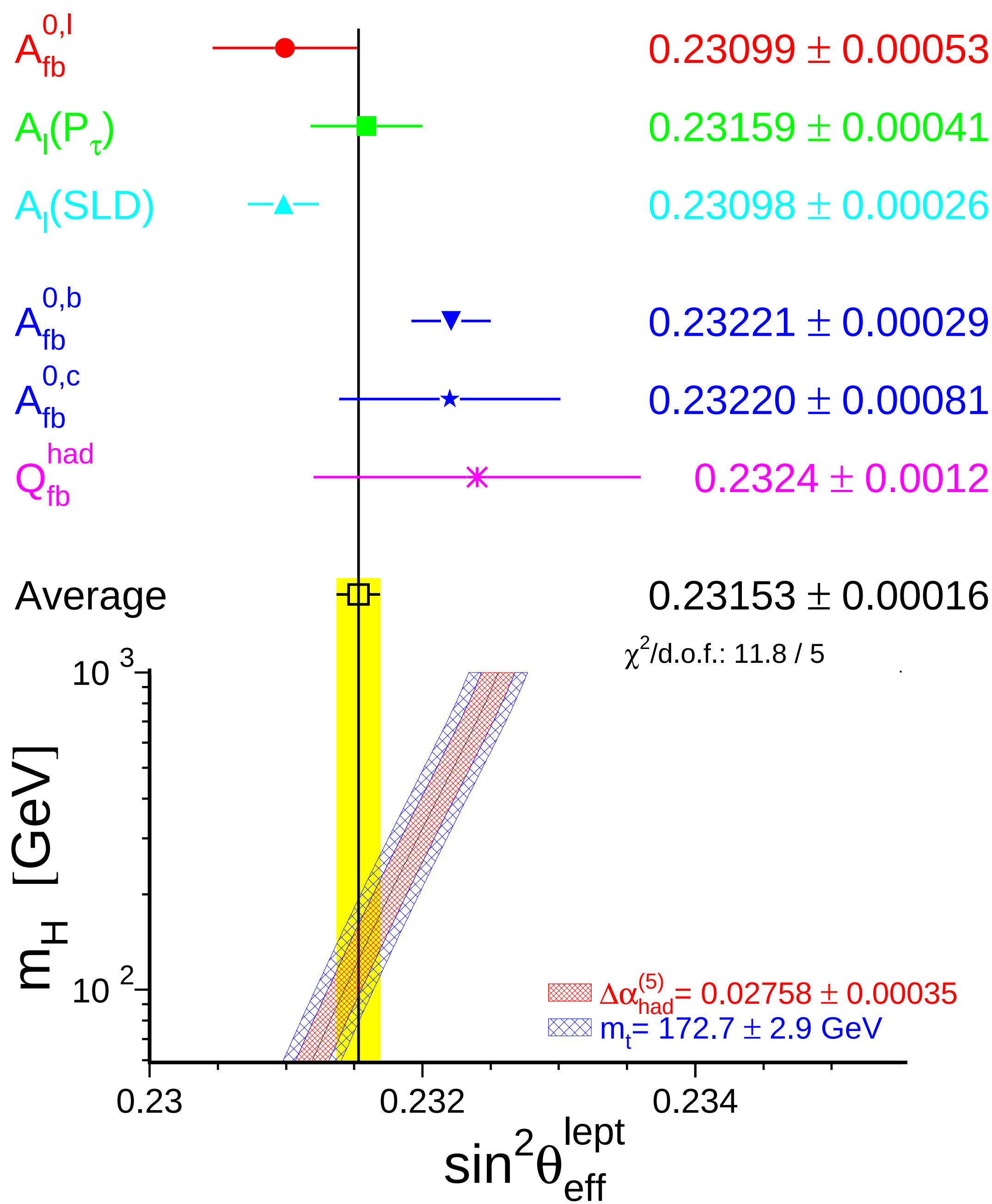
[Awramik, Czakon, Freitas, Weiglein] $m_t = 174.3 \pm 5.1$ GeV

$$\delta M_W^{\text{theo}} \simeq 4\,\text{MeV}$$

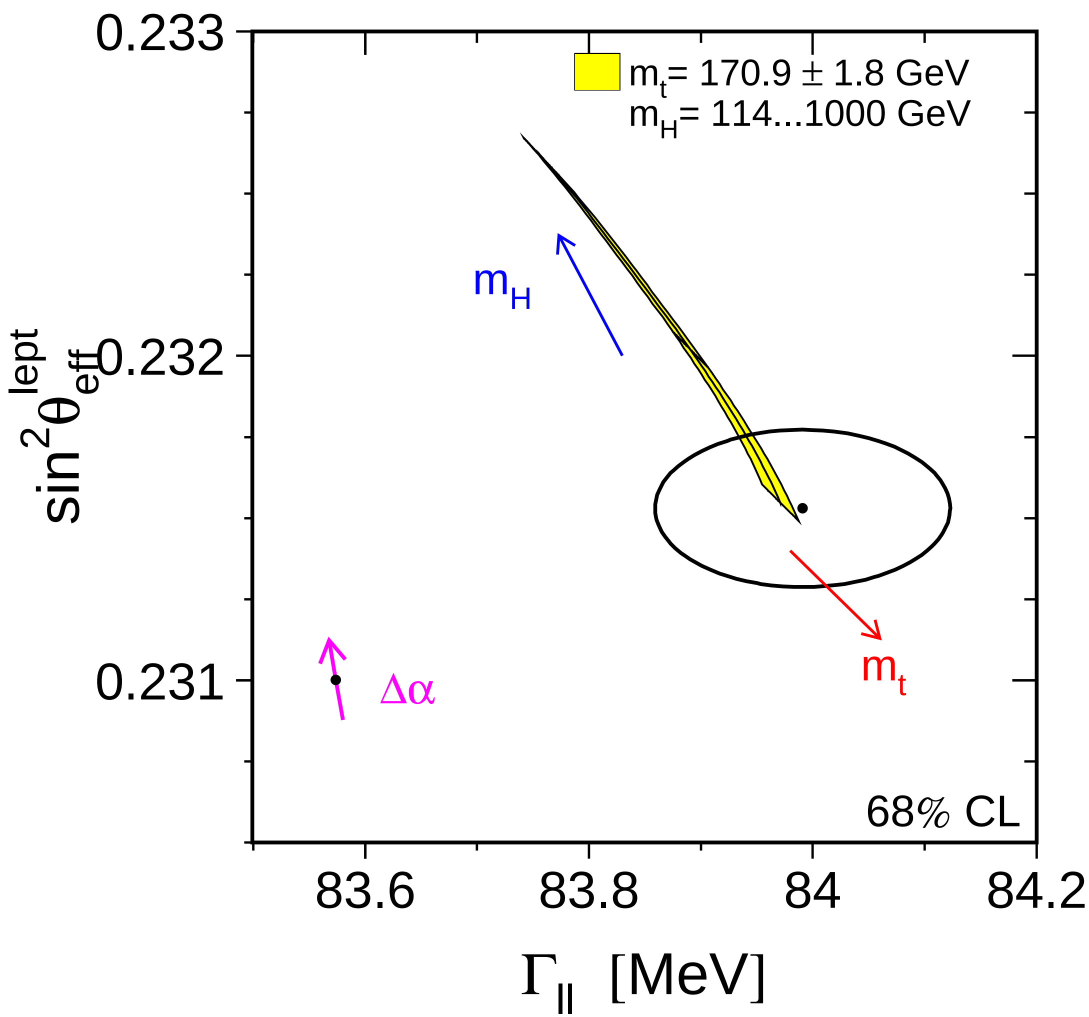
$$\delta \sin^2\theta_{\text{eff}}^{\text{theo}} \simeq 5 \cdot 10^{-5}$$

LEP Electroweak Working Group




$A_{fb}^{0,l}$ 0.23099 ± 0.00053
$A_l(P_\tau)$ 0.23159 ± 0.00041
A_l(SLD) 0.23098 ± 0.00026
$A_{fb}^{0,b}$ 0.23221 ± 0.00029
$A_{fb}^{0,c}$ 0.23220 ± 0.00081
Q_{fb}^{had} 0.2324 ± 0.0012
Average 0.23153 ± 0.00016
χ^2/d.o.f.: 11.8 / 5
10^3
10^2
m_H [GeV]
$\Delta\alpha_{had}^{(5)} = 0.02758 \pm 0.00035$
$m_t = 172.7 \pm 2.9$ GeV
0.23
0.232
0.234
$\sin^2\theta_{eff}^{lept}$

LEP Electroweak Working Group



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CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Z PHYSICS AT LEP 1

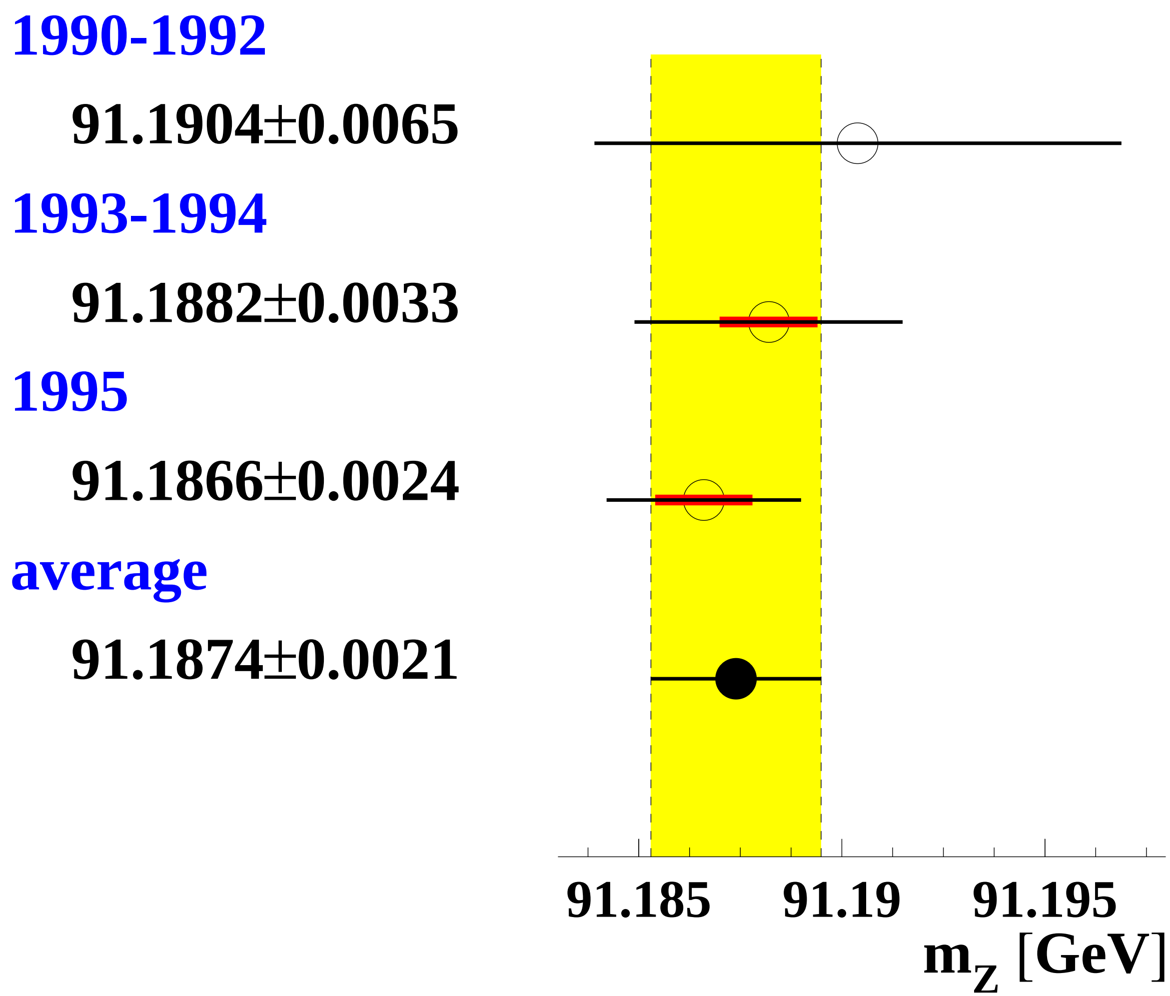
Edited by
Guido Altarelli, Ronald Kleiss and Claudio Verzegnassi

Volume 1: STANDARD PHYSICS

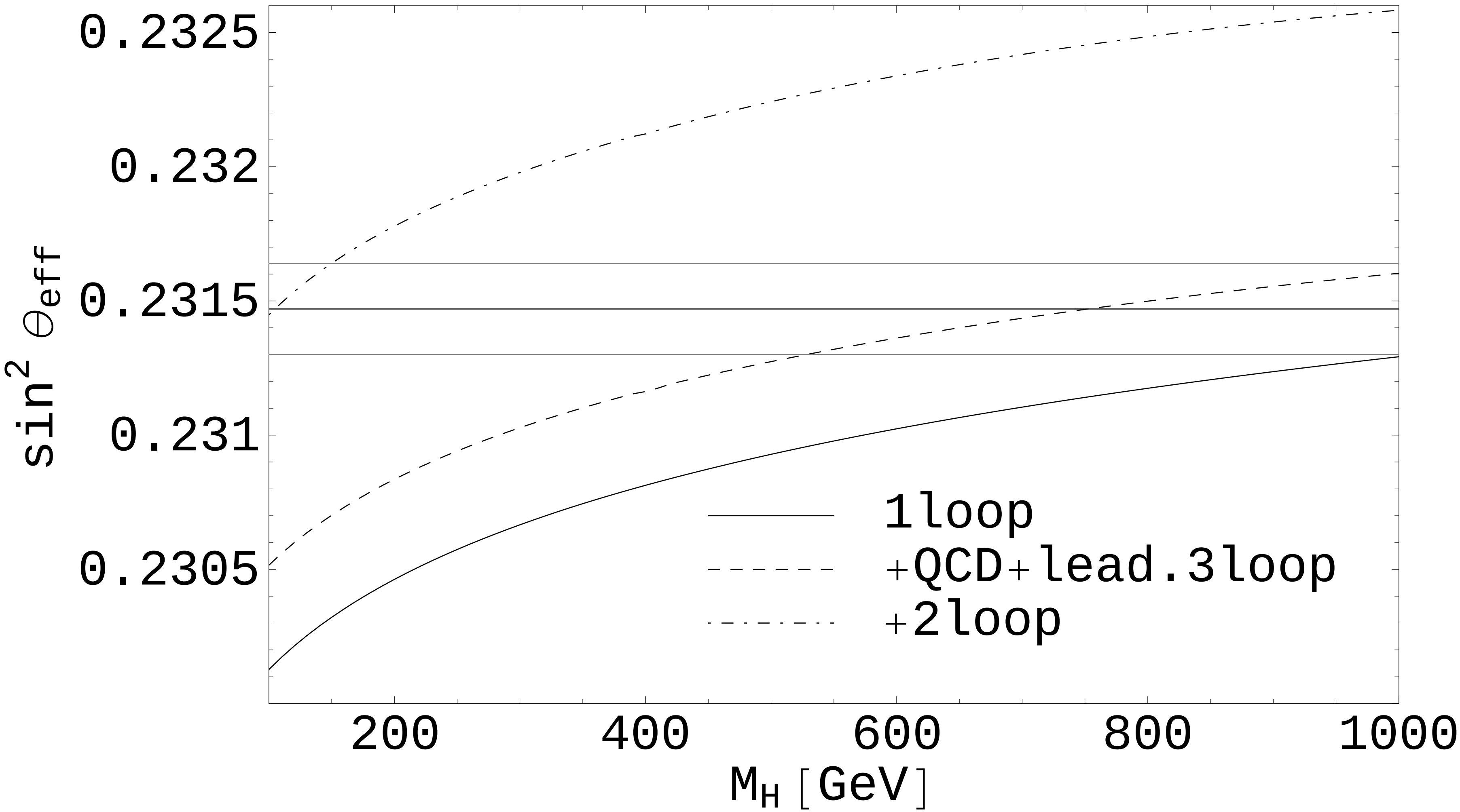
Co-ordinated and supervised by G. Altarelli

GENEVA
1989

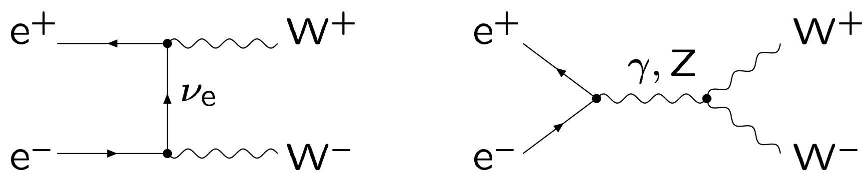
development of precision

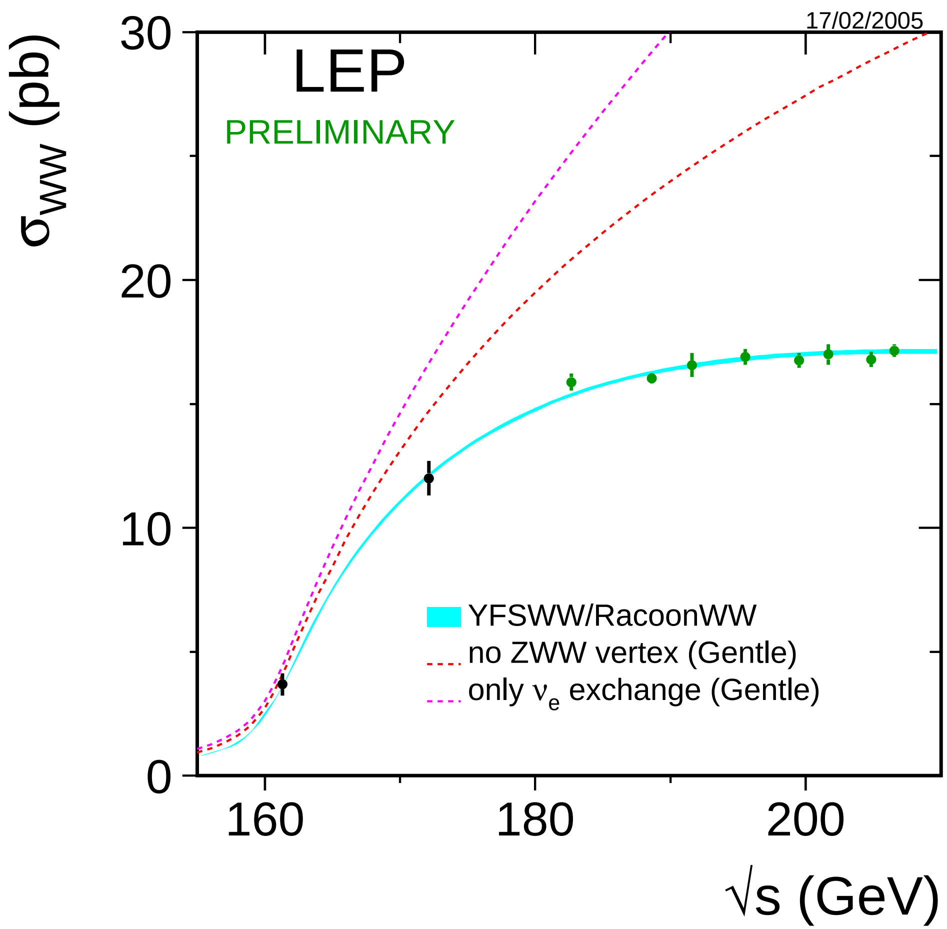


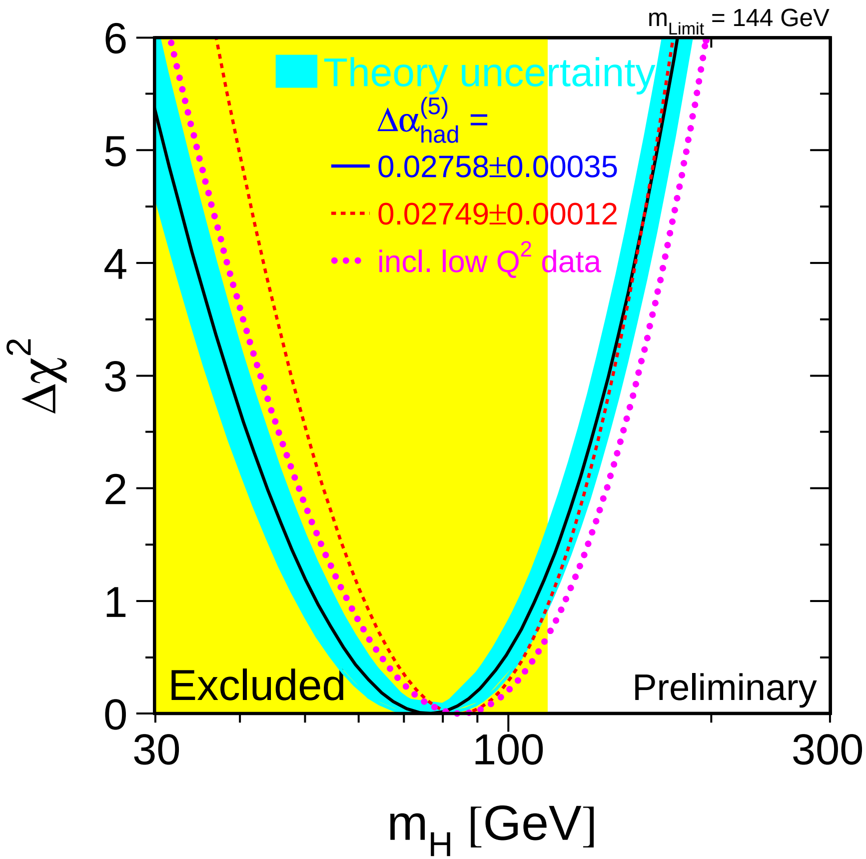
importance of two-loop calculations



W-pair production







blueband: theory uncertainty

“Precision Calculations

at the Z Resonance”

CERN 95-03

[Bardin, Hollik, Passarino (eds.)]

$$M_{\rm H} < 144\ {\rm GeV} \quad (95\%{\rm C.L.})$$

with renormalized probability for $M_{\rm H} > 114$ GeV:

$$M_{\rm H} < 182\ {\rm GeV} \quad (95\%{\rm C.L.})$$

Future perspectives

error for	LEP/Tev	Tev/LHC	LC	LC/GigaZ
$M_W\,[\mathrm{MeV}]$	29	15	15	7
$\sin^2\theta_{\mathrm{eff}}$	0.00017	0.00021		0.000013
$m_{\mathrm{top}}\,[\mathrm{GeV}]$	1.8	1 - 1.5	0.2	0.13
$M_{\mathrm{Higgs}}\,[\mathrm{GeV}]$	–	0.1	0.05	0.05

$\delta M_Z = 2.1\,\mathrm{MeV}$ (LEP)

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

GigaZ $\sim 10^9$ Z bosons

MegaW $\sim 10^6$ W bosons

M_W from Drell-Yan at the LHC

$$q\bar{q}' \to W^+ \to \ell^+ \nu_\ell$$

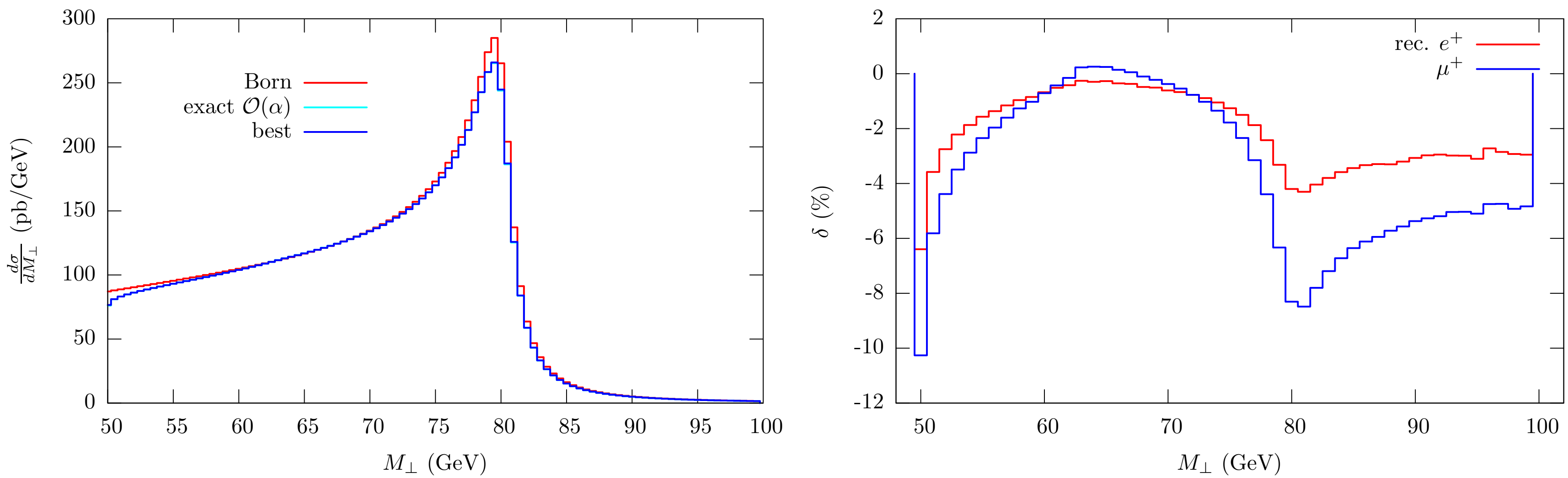


Fig. 1. Transverse mass distribution and $\mathcal{O}(\alpha)$ relative correction.

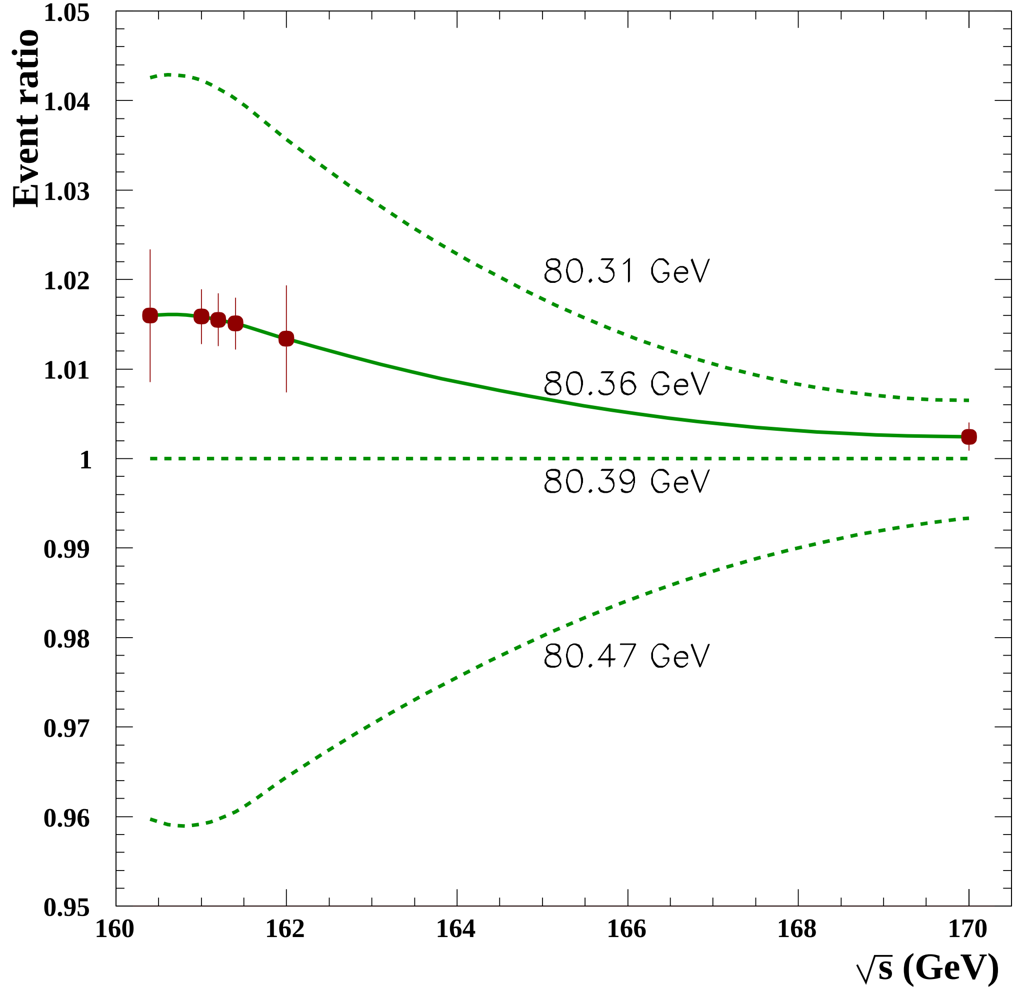
[Carloni Calame et al.]

[Baur, Wackeroth]

[Dittmaier, Krämer]

[Arbuzov et al.]

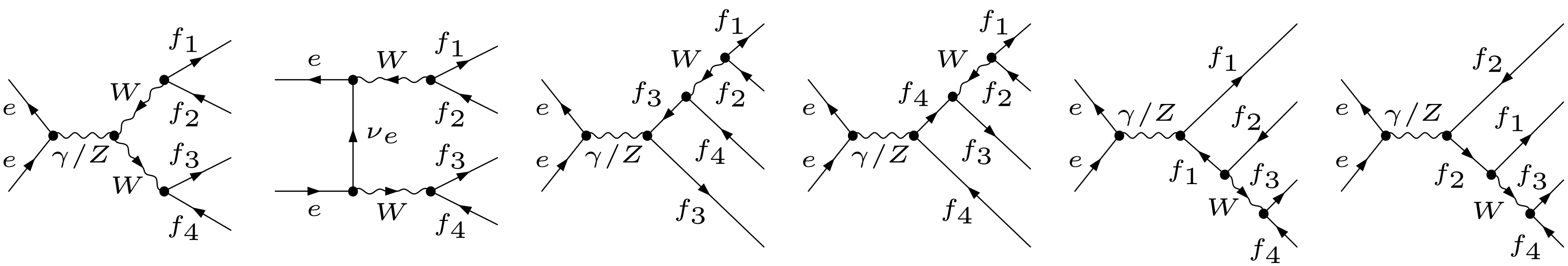
M_W from threshold scan in e^+e^- annihilation



M_W from threshold $e^+e^- \rightarrow WW \rightarrow 4\,f$

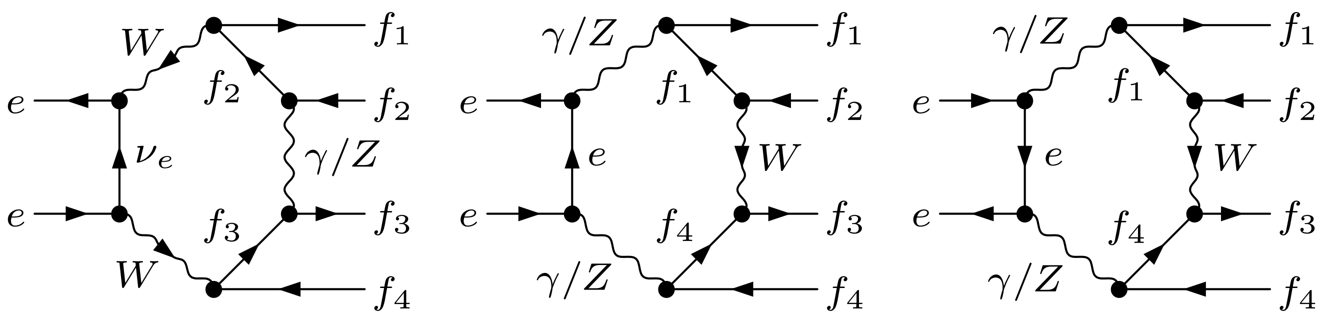
Some Feynman diagrams...

...for LO:



...for NLO: total number $= \mathcal{O}(1200)$

40 hexagons



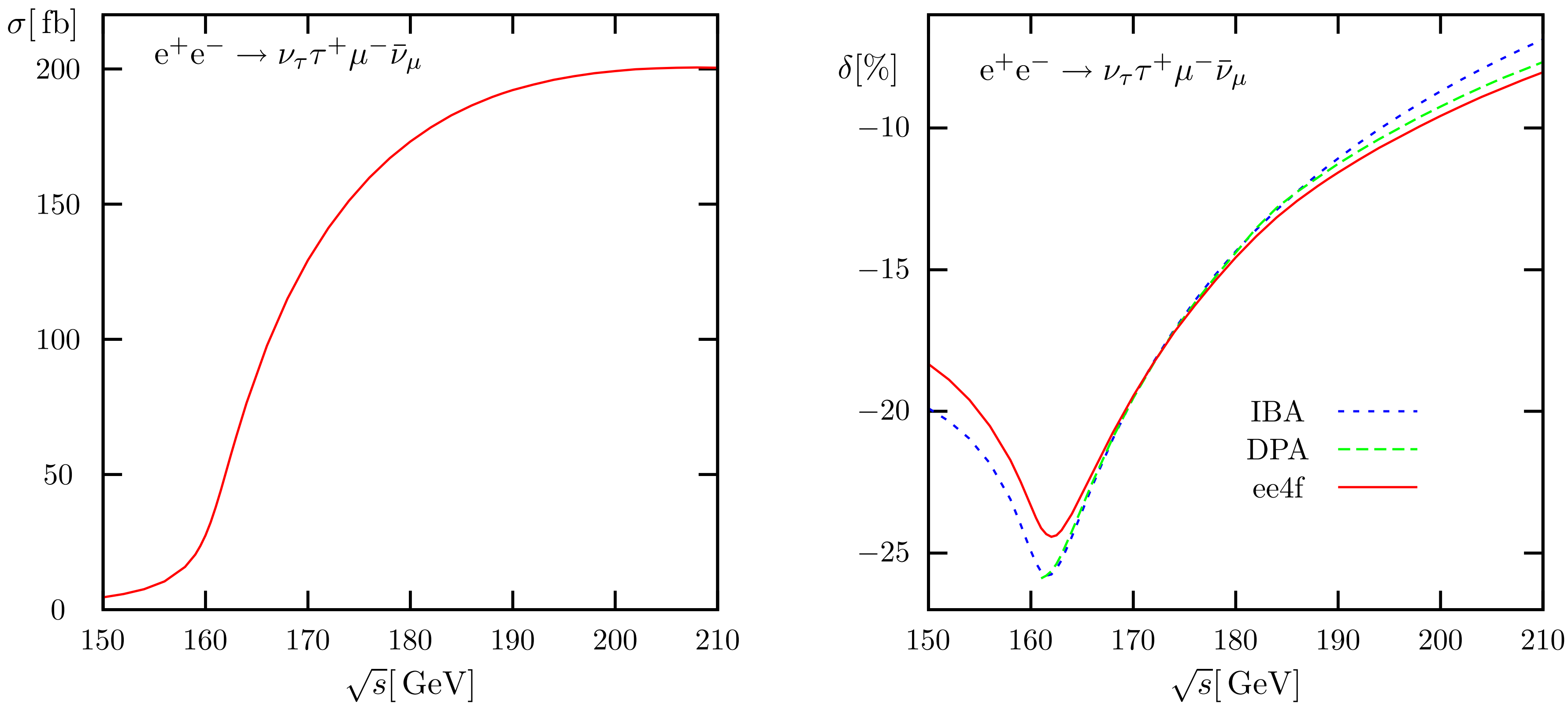
+ graphs with reversed fermion-number flow in final state

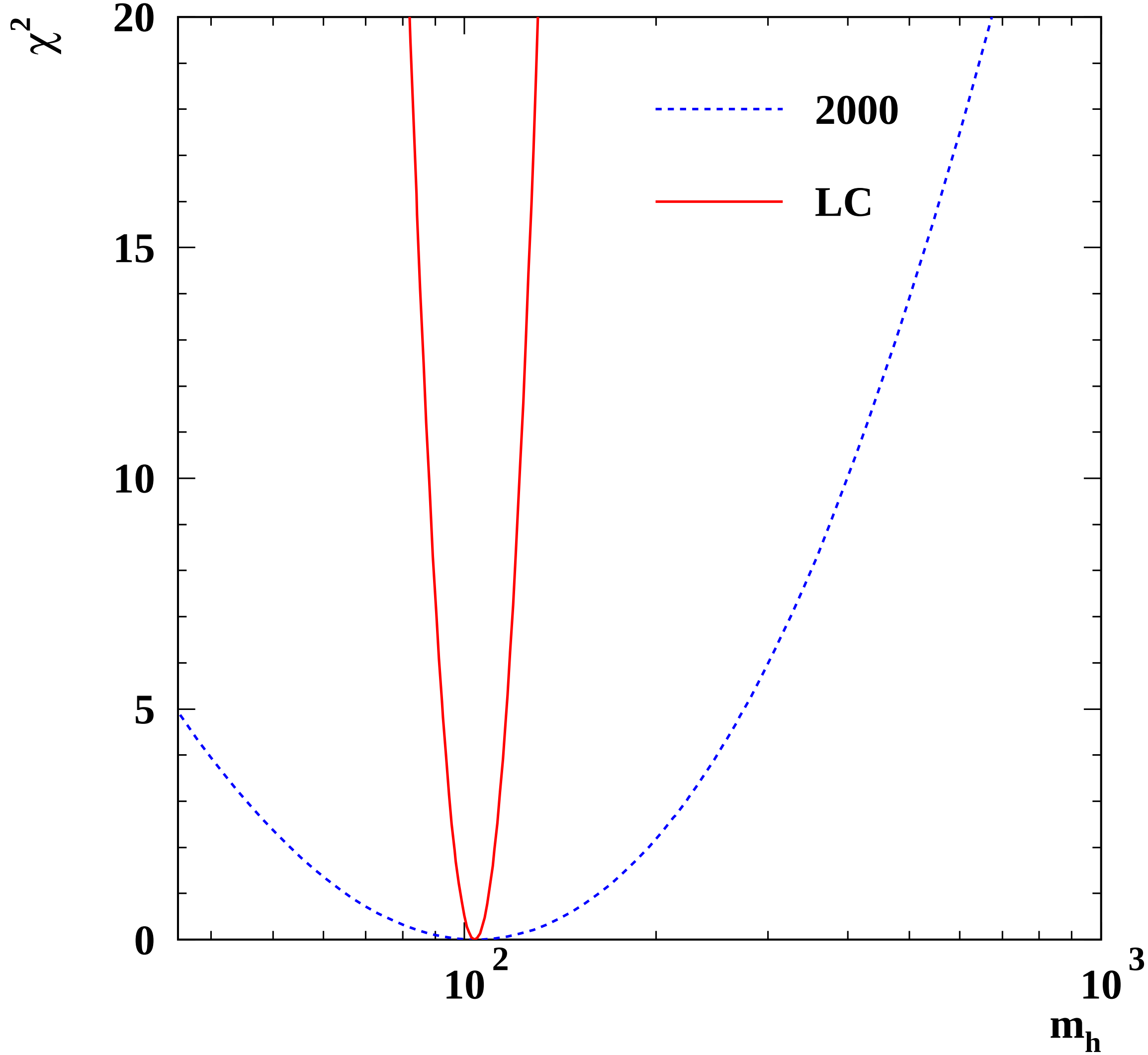
+ 112 pentagons

+ 227 boxes ('tHF gauge) + many vertex and self-energy corrections

M_W from threshold $e^+e^- \to WW \to 4\,f$

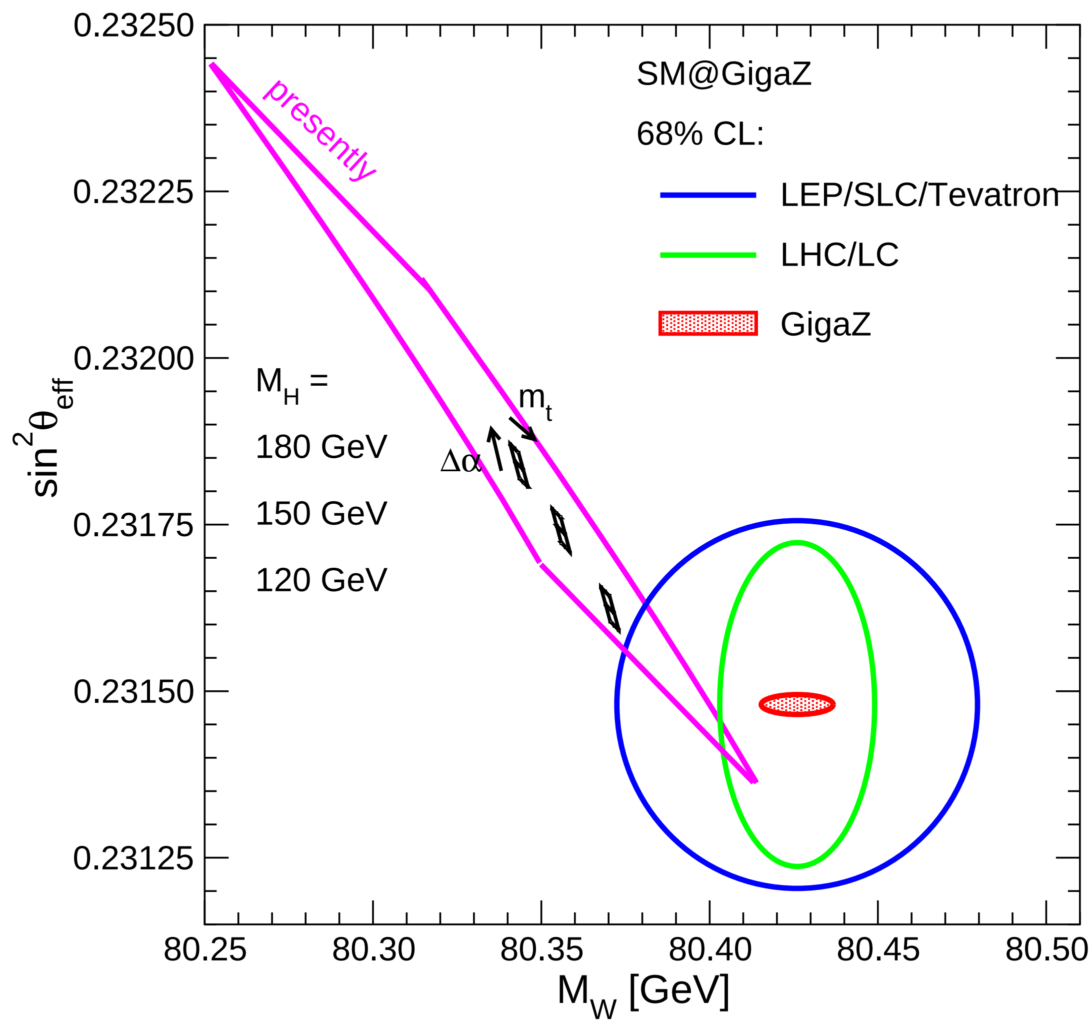
Denner, Dittmaier, Roth, Wieders '05





χ^2
20
15
10
5
0
2000
LC
10^2
10^3
m_h

[Erler, Heinemeyer, Hollik, Weiglein, Zerwas]

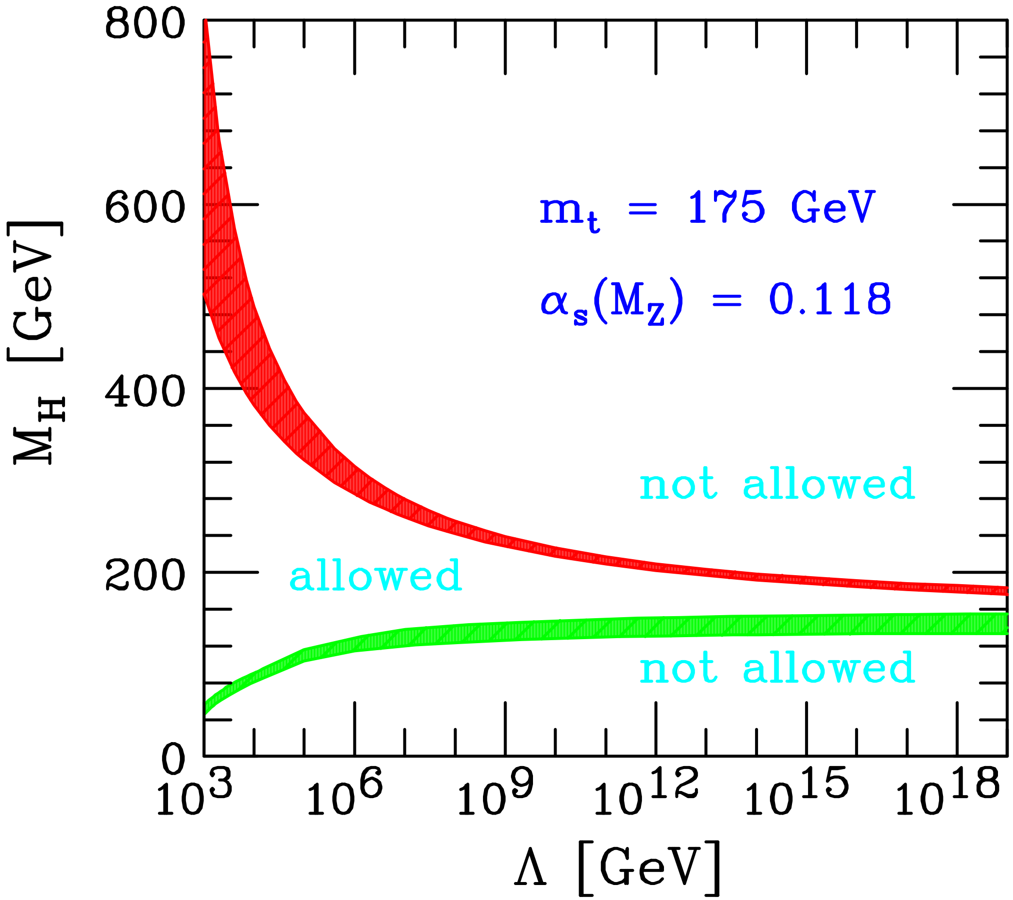


Theoretical bounds on Higgs boson mass from

- perturbativity $\longrightarrow$ upper bound
- unitarity $\longrightarrow$ upper bound
- triviality (Landau pole) $\longrightarrow$ upper bound
- vacuum stability $\longrightarrow$ lower bound

combined effects, RGE in two-loop order:

$$\frac{d\lambda}{dt} = \frac{1}{16\pi^2} \left(12\lambda^2 - 3\, g_t^4 + 6\, \lambda\, g_t^2\, + \cdots \right)$$



SM Higgs:

- λH^4 term ad hoc
- Higgs boson mass: free parameter $\sim \sqrt{\lambda}$
- no a-priori reason for a light Higgs boson

SUSY Standard Model avoids these questions

$$H_2 = \begin{pmatrix} H_2^+ \\ v_2 + H_2^0 \end{pmatrix}, \qquad H_1 = \begin{pmatrix} v_1 + H_1^0 \\ H_1^- \end{pmatrix}$$

$$\text{couples to } u \qquad\qquad \text{couples to } d$$

• SUSY gauge interaction $\rightarrow$ H^4 terms
• self coupling remains weak

Minimal Supersymmetric SM

Superpartners for Standard Model particles:

$$\left[u, d, c, s, t, b\right]_{L,R} \quad \left[e, \mu, \tau\right]_{L,R} \quad \left[\nu_{e,\mu,\tau}\right]_L \qquad \text{Spin } \tfrac{1}{2}$$

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

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

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

Enlarged Higgs sector: two Higgs doublets, physical states: $h^0, H^0, A^0, H^{\pm}$

masses and mixing of SUSY particles through soft-breaking

model parameters

- gaugino masses: M_1, M_2, M_3
- sfermion masses: $M_L, M_{\tilde{u}_R}, M_{\tilde{d}_R}$
  for each doublet of squarks and sleptons
- trilinear coupling: $A_{\tilde{f}}$ for each $\tilde{f}$
  $\rightarrow$ L-R sfermion mixing
- supersymmetric Higgsino mass parameter: μ
- Higgs sector parameters: $M_A, \ \tan\beta = v_2/v_1$

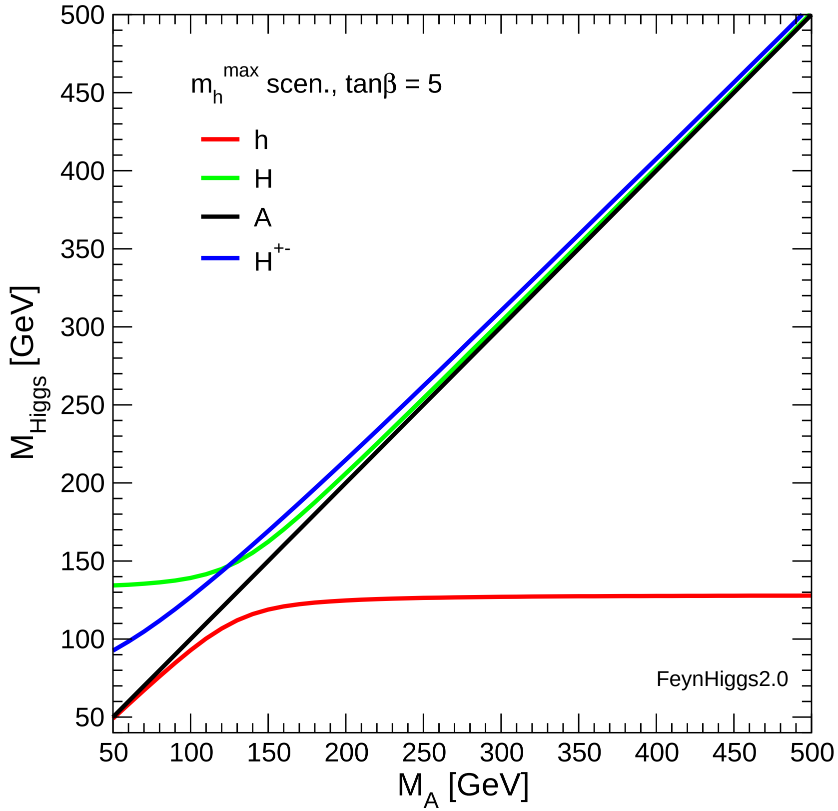
Benchmark scenarios
"Snowmass points and slopes" (SPS), hep-ph/0202233

examples (mSUGRA):

- SPS1a: $m_0 = 100$ GeV, $m_{1/2} = 250$ GeV, $A_0 = -100$, $\tan\beta = 10$, $\mu > 0$.

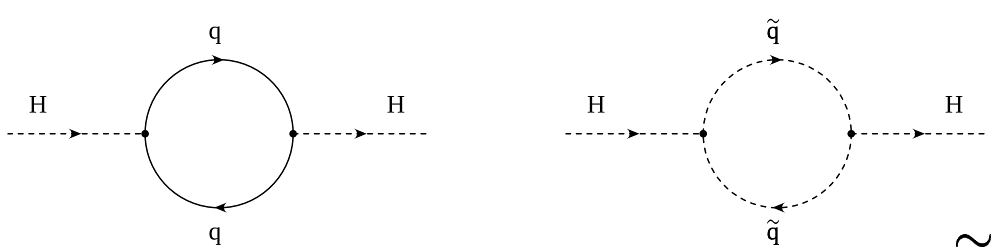
- SPS1b: $m_0 = 200$ GeV, $m_{1/2} = 400$ GeV, $A_0 = 0$, $\tan\beta = 30$, $\mu > 0$.

Spectrum of Higgs bosons in the MSSM (example)



large M_A: h^0 like SM Higgs boson $\sim$ decoupling regime

m_h^0 strongly influenced by quantum effects, *e.g.*



$\sim \alpha_t$

1-loop: complete

2-loop:

– QCD corrections $\sim \alpha_s \alpha_t,\ \alpha_s \alpha_b$

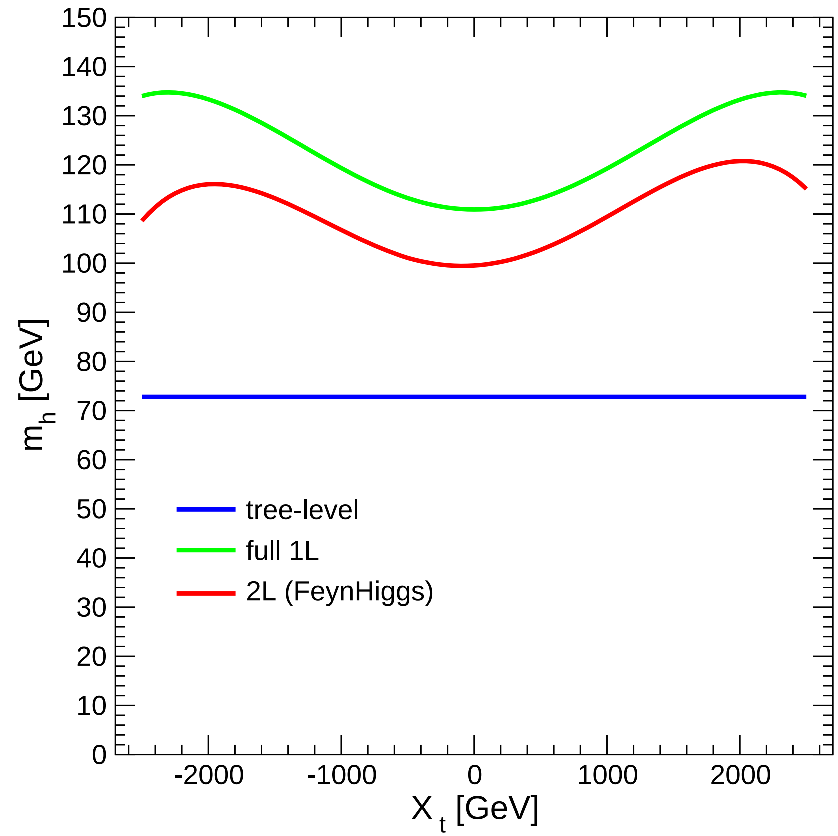
– Yukawa corrections $\sim \alpha_t^2$

present theoretical uncertainty:

$\boldsymbol{\delta m_h} \simeq$ 3-4 GeV

[Degrassi, Heinemeyer, WH, Slavich, Weiglein]

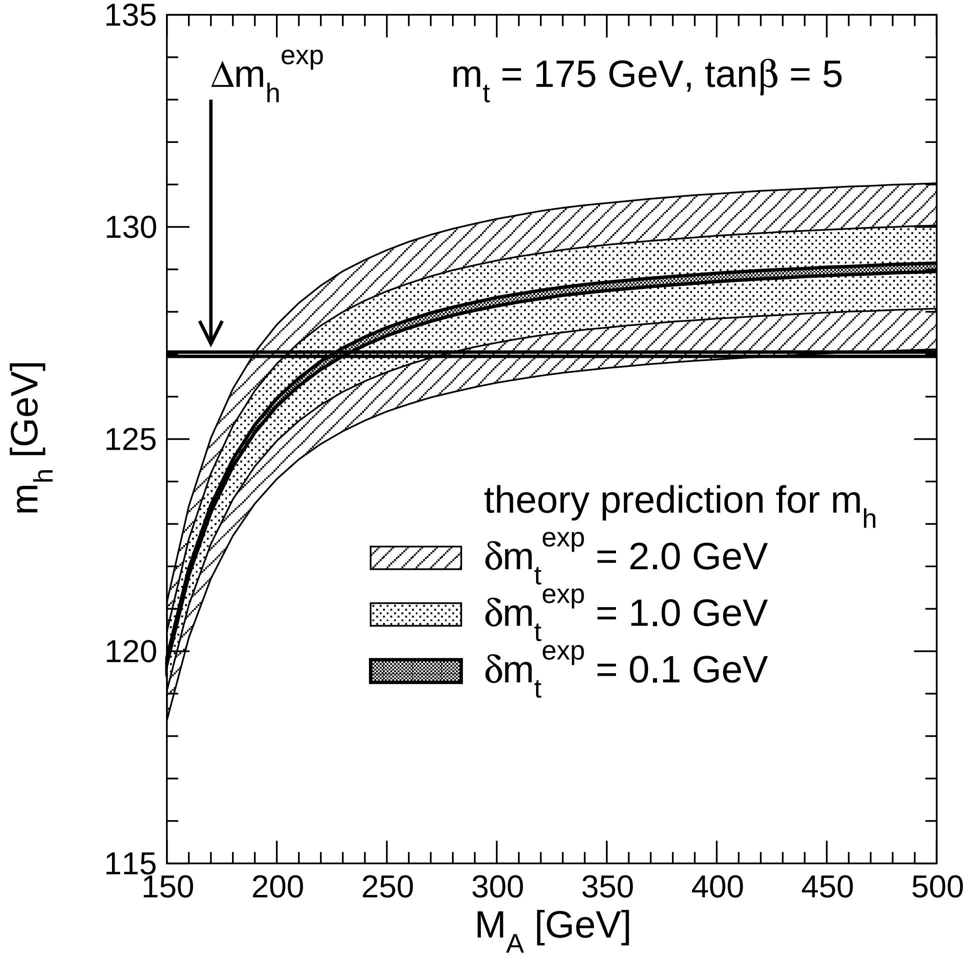
m_{h^0} prediction at different levels of accuracy:



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

X_t : top-squark mixing parameter

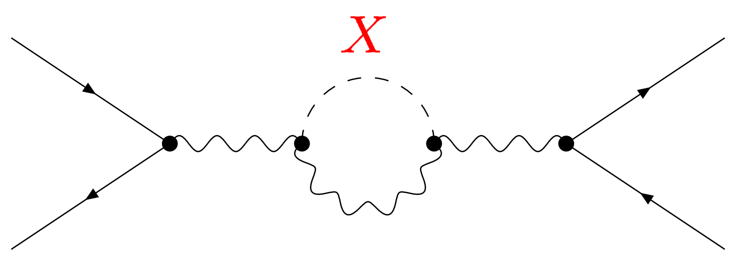
$$\mathrm{X_t} = \mathrm{A_t} - \mu \cot\beta$$



dependent on all SUSY particles and masses/mixings through Higgs self-energies

Test of theory at quantum level:

Sensitivity to loop corrections



X = Higgs bosons, SUSY particles

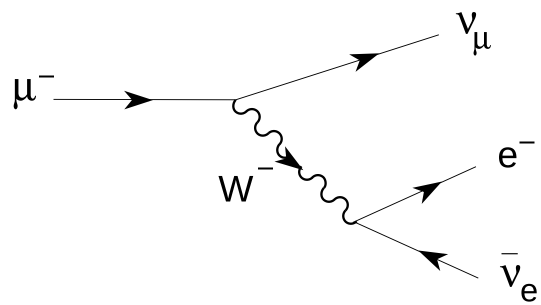
- μ lifetime: $M_W, \Delta r, G_\mathrm{F}$
- Z observables: $g_V, g_A, \sin^2\theta_\mathrm{eff}, \Gamma_Z, \ldots$

[Heinemeyer, WH, Weiglein, Phys. Rep. 425 (2006) 265]

new: 2-loop improvements $\mathcal{O}(\alpha\alpha_s,\ \alpha_t^2,\ \alpha_b^2,\ \alpha_t\alpha_b)$
and complex parameters

[Heinemeyer, WH, Stöckinger, A. Weber, Weiglein 06]
[Heinemeyer, WH, A. Weber, Weiglein 07]

$M_W - M_Z$ correlation



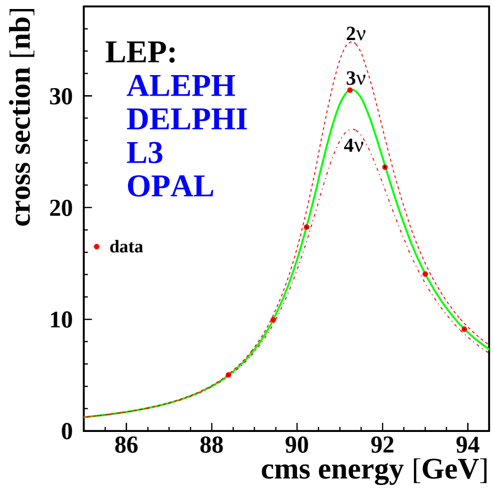
$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{M_W^2\left(1 - M_W^2/M_Z^2\right)}\left(1 + \Delta r\right)$$

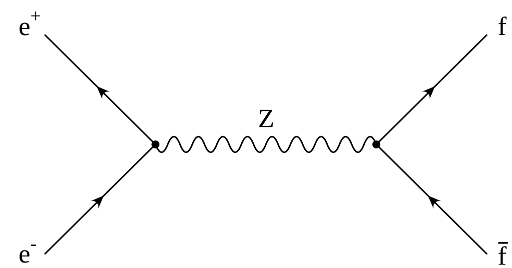
$\Delta r :$ quantum correction, $\Delta r = \Delta r(m_t, X_{\mathrm{SUSY}})$

$\rightarrow \quad M_W = M_W(\alpha, G_F, M_Z, m_t, X_{\mathrm{SUSY}})$

$X_{\mathrm{SUSY}} =$ set of non-standard model parameters

Z resonance





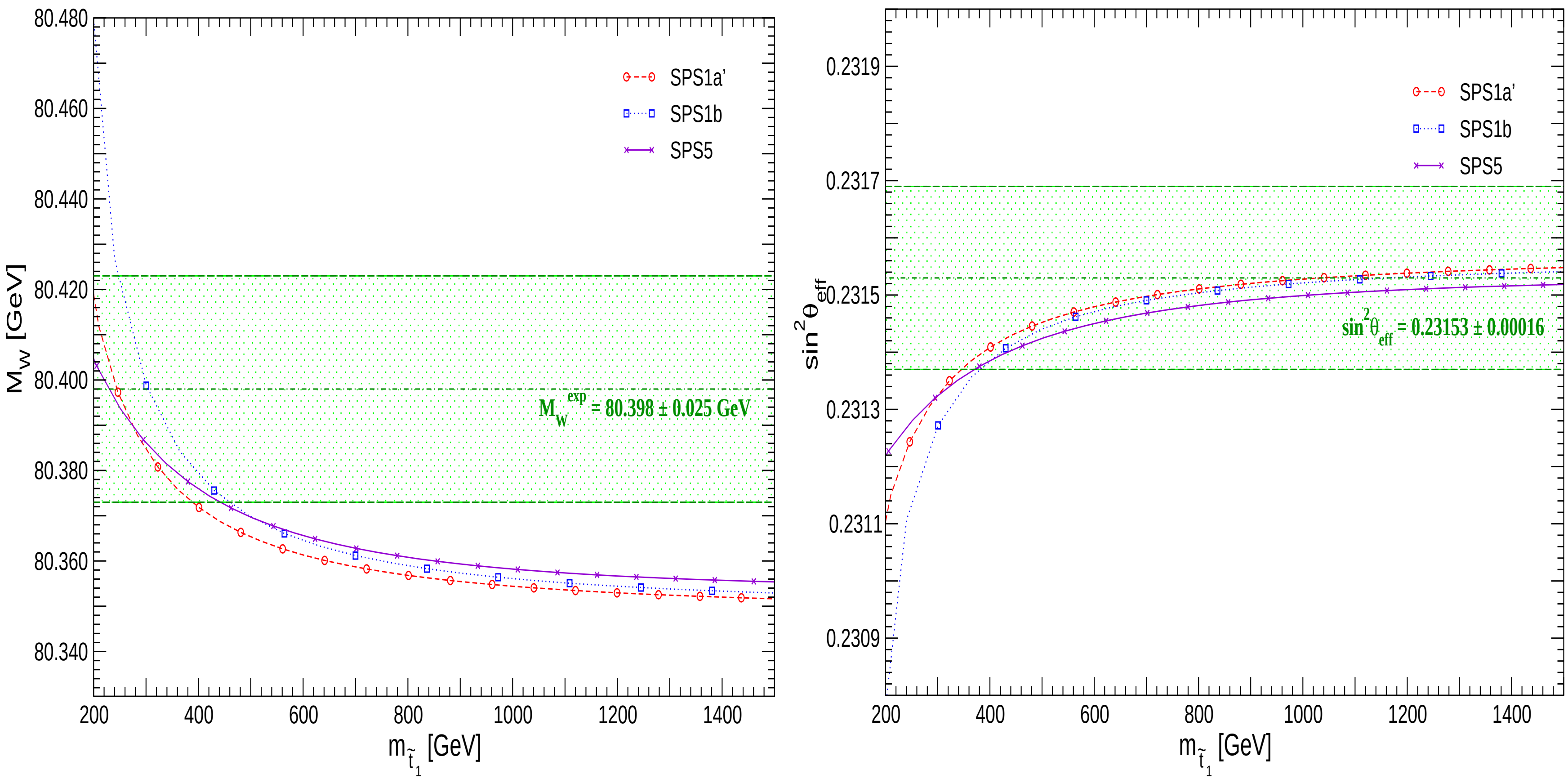
effective Z boson couplings

$$g_V^f \longrightarrow g_V^f + \Delta g_V^f, \qquad g_A^f \longrightarrow g_A^f + \Delta g_A^f$$

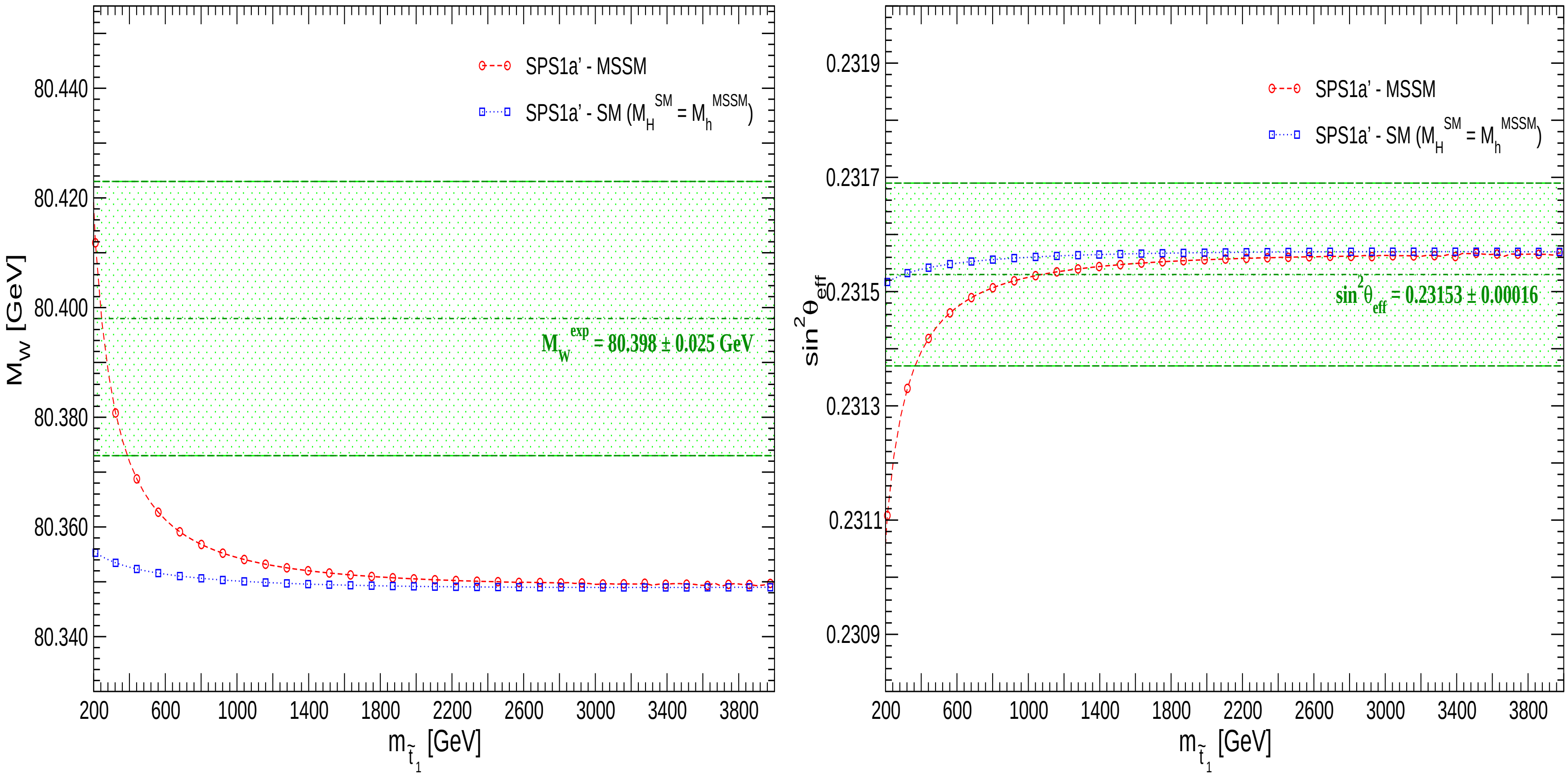
with higher order contributions $\Delta g_{V,A}^f\,(m_t, X_{\text{SUSY}})$

$$\sin^2\theta_{\text{eff}} = \frac{1}{4}\left(1 - \text{Re}\,\frac{g_V^e}{g_A^e}\right) = \kappa \cdot \left(1 - \frac{M_W^2}{M_Z^2}\right)$$

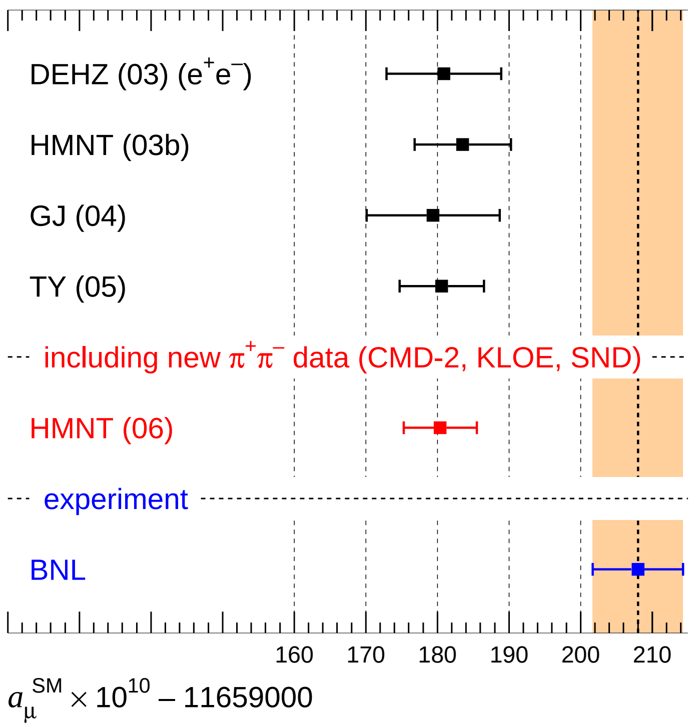
M_W and $\sin^2\theta_{\mathrm{eff}}$ for varied SUSY-scale



M_W and $\sin^2\theta_{\text{eff}}$ for varied SUSY-scale



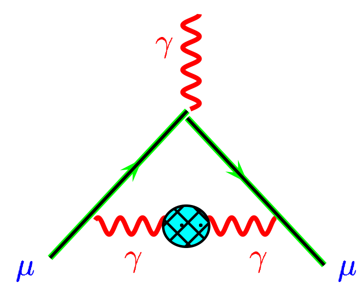
Anomalous g-factor of the muon



Hagiwara,Martin,Nomura,Teubner

e^+e^- data based SM prediction: 3.4 σ below exp. value

theory uncertainty from hadronic vacuum polarization



$g-2$ with supersymmetry

new contributions from virtual SUSY partners of $\mu,\ \nu_\mu$
and of $W^\pm,\ Z$

extra terms

$$+\quad \frac{\alpha}{\pi}\,\frac{m_\mu^2}{M_{\rm SUSY}^2}\cdot\frac{v_2}{v_1}$$

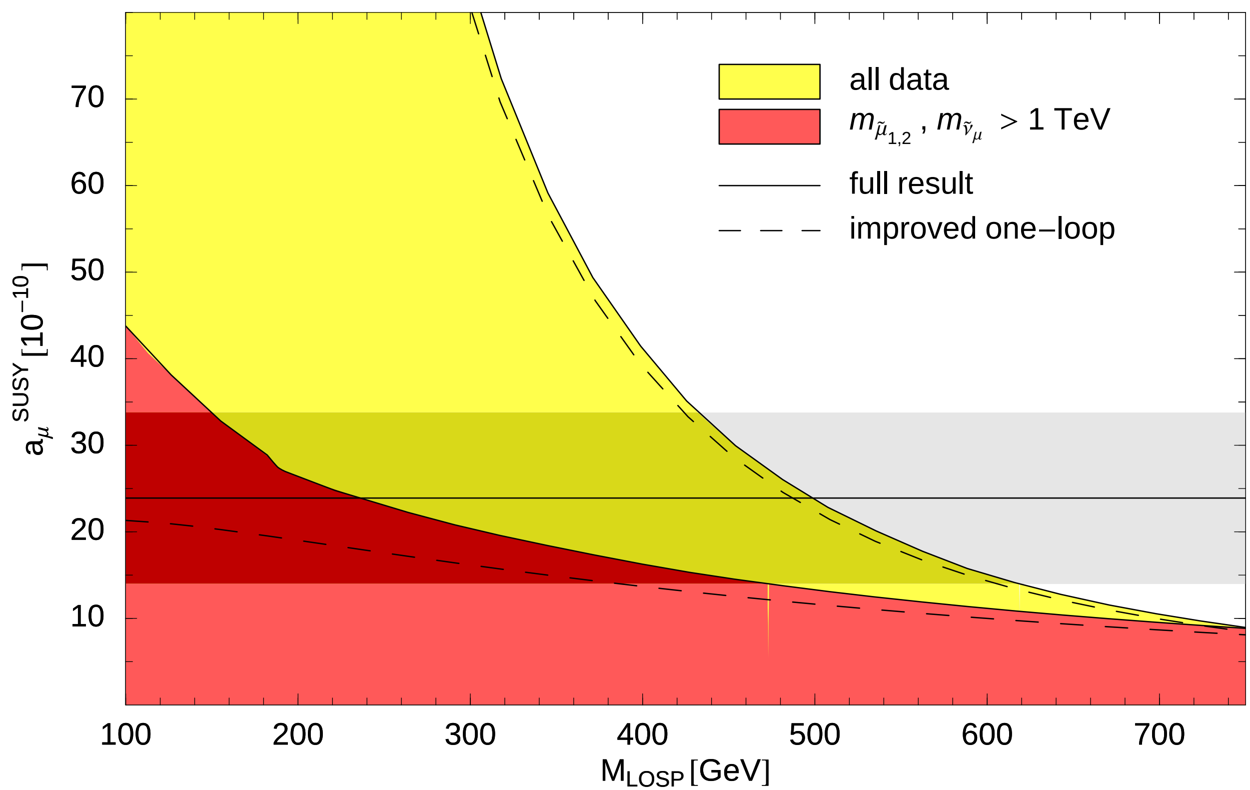
can provide missing contribution for

$$M_{\rm SUSY} = 200 - 600\,\mathrm{GeV}$$

2-loop calculation *[Heinemeyer, Stöckinger, ...]*

scan over SUSY parameters compatible with EW and $b \to s\gamma$ constraints $(\tan\beta = 50)$

[Stöckinger]



LOSP = lightest observable SUSY particle $(\chi_1^\pm, \chi_2^0, \cdots)$

CMSSM

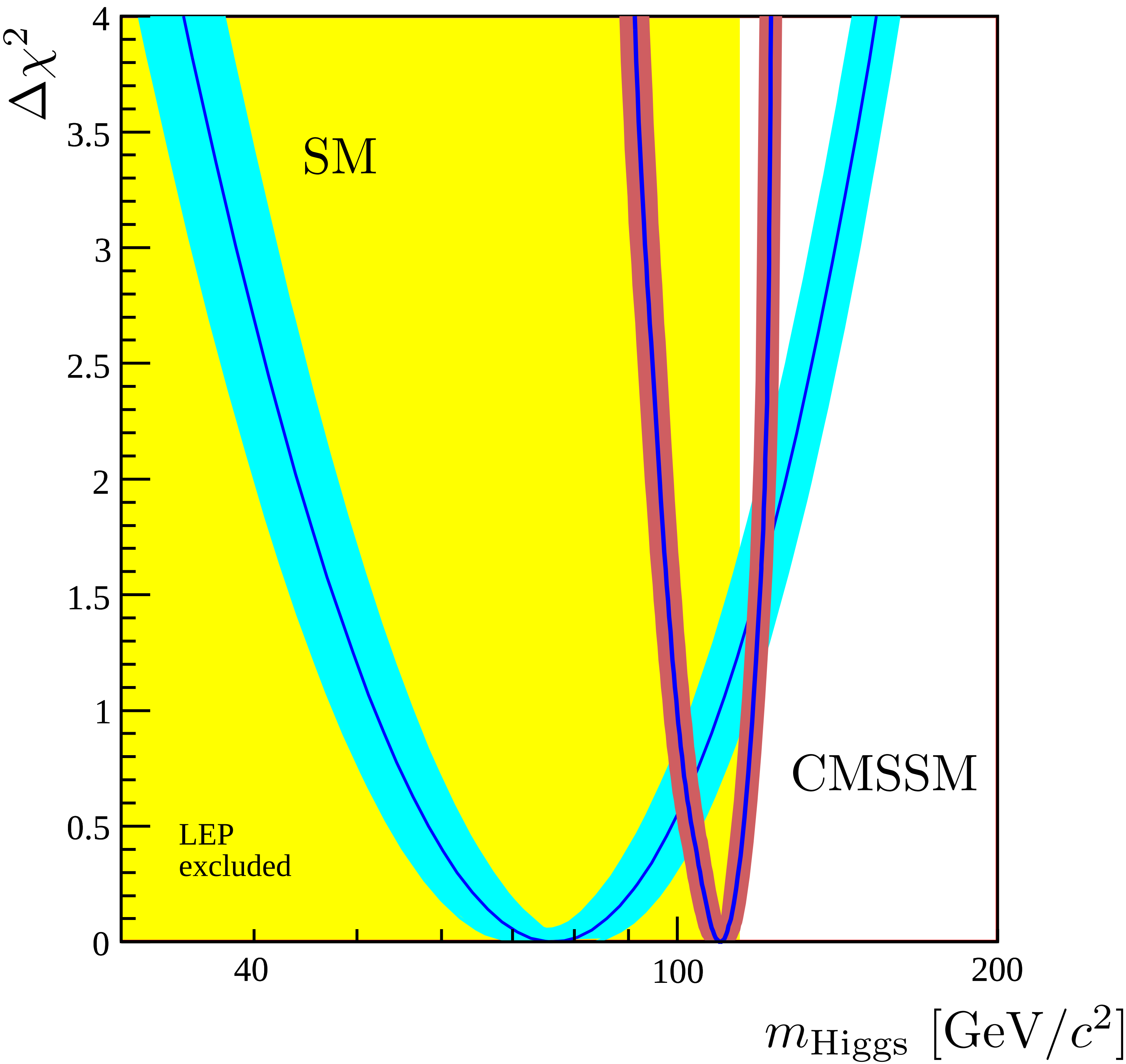
Variable	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02774	
m_Z [GeV]	91.1875 ± 0.0021	91.1873	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4952	
σ^0_{had} [nb]	41.540 ± 0.037	41.486	
R_l	20.767 ± 0.025	20.744	
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01641	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479	
R_b	0.21629 ± 0.00066	0.21613	
R_c	0.1721 ± 0.0030	0.1722	
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037	
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0741	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1479	
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.398 ± 0.025	80.382	
m_t [GeV]	170.9 ± 1.8	170.8	
$R(b\to s\gamma)$	1.13 ± 0.12	1.12	
$B_s\to\mu\mu$ [$\times 10^{-8}$]	< 8.00	0.33	N/A (upper limit)
Δa_μ [$\times 10^{-9}$]	2.95 ± 0.87	2.95	
Ωh^2	0.113 ± 0.009	0.113	

Standard Model

Variable	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768	
m_Z [GeV]	91.1875 ± 0.0021	91.1875	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957	
σ^0_{had} [nb]	41.540 ± 0.037	41.477	
R_l	20.767 ± 0.025	20.744	
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481	
R_b	0.21629 ± 0.00066	0.21586	
R_c	0.1721 ± 0.0030	0.1722	
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038	
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1481	
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.398 ± 0.025	80.374	
m_t [GeV]	170.9 ± 1.8	171.3	
Γ_W [GeV]	2.140 ± 0.060	2.091	

global fit in the constrained MSSM including data from $g-2$, B physics, and cosmic relic density

[O. Buchmueller et al., arXiv:0707.3447]



$\Delta\chi^2$
4
3.5
3
2.5
2
1.5
1
0.5
0
SM
LEP
excluded
CMSSM
40
100
200
m_{Higgs} [GeV/c^2]

Scatter plots for M_W & $\sin^2\theta_{\rm eff}$

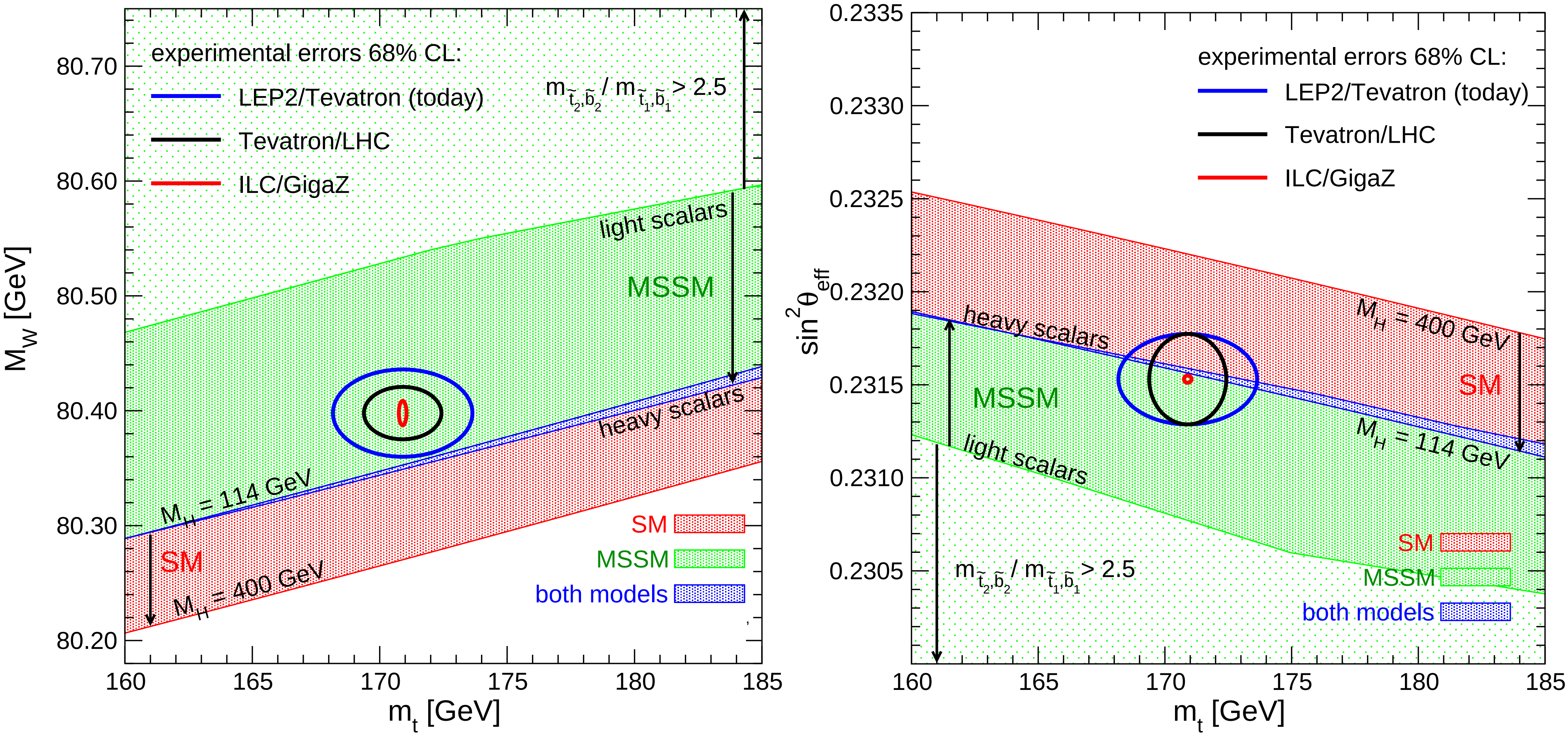
- SUSY parameters:

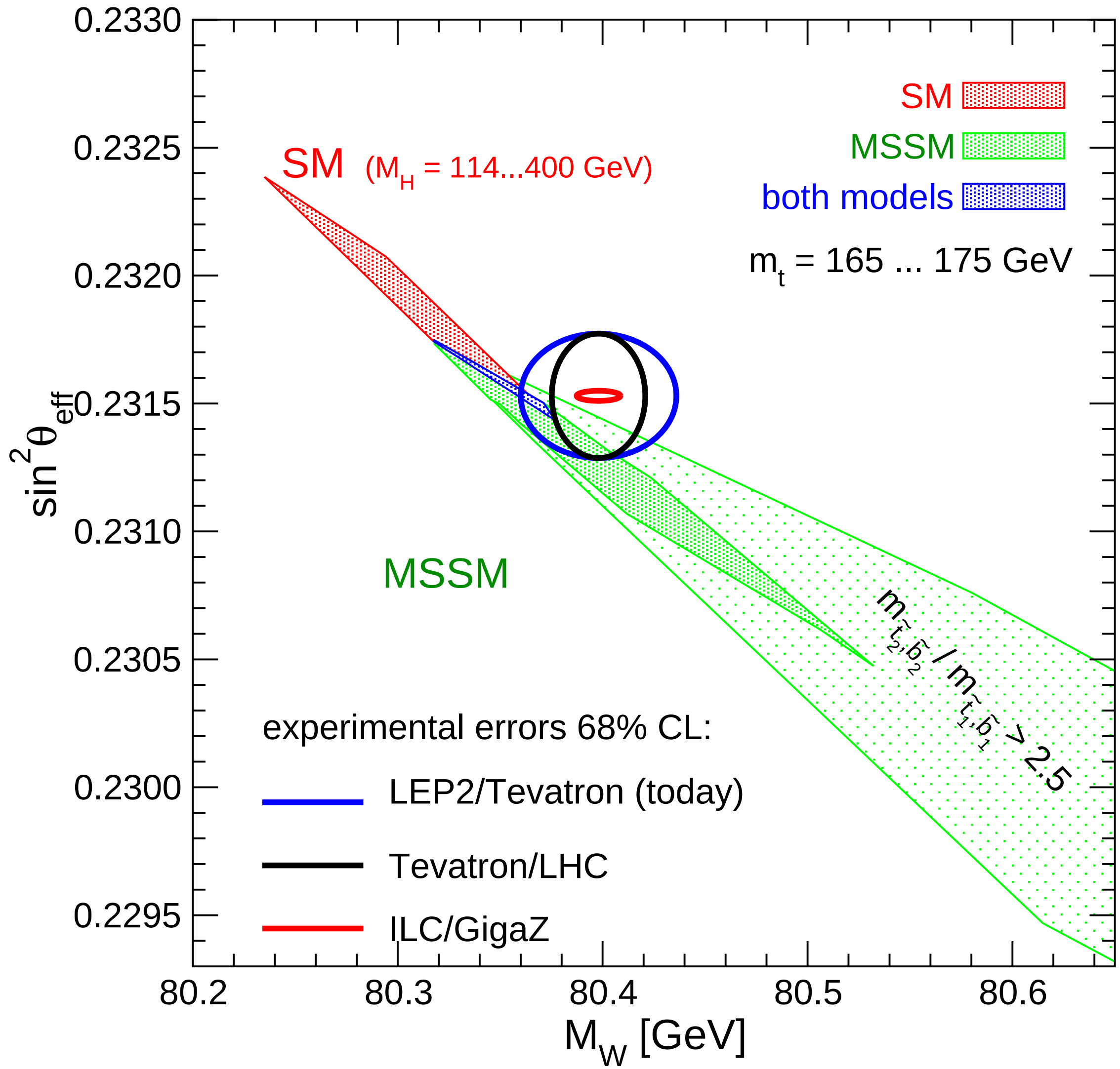
$$
\begin{aligned}
\text{sleptons} &: \quad M_{\tilde F,\tilde F'} = 100\ldots 2000\ \text{GeV} \\
\text{light squarks} &: \quad M_{\tilde F,\tilde F'_{\text{up/down}}} = 100\ldots 2000\ \text{GeV} \\
\tilde t/\tilde b\ \ \text{doublet} &: \quad M_{\tilde F,\tilde F'_{\text{up/down}}} = 100\ldots 2000\ \text{GeV} \\
 & \quad\ \ A_{t,b} = -2000\ldots 2000\ \text{GeV} \\
\text{gauginos} &: \quad M_{1,2} = 100\ldots 2000\ \text{GeV} \\
 & \quad\ \ m_{\tilde g} = 195\ldots 1500\ \text{GeV} \\
 & \quad\ \ \mu = -2000\ldots 2000\ \text{GeV} \\
\text{Higgs} &: \quad M_A = 90 - 1000\ \text{GeV} \\
 & \quad\ \ \tan\beta = 1.1\ldots 60
\end{aligned}
$$

- Unconstrained scan, only Higgs mass required to be in agreement with LEP data.

[Heinemeyer, Hollik, Stöckinger, Weber, Weiglein]

$M_W(m_t)$ and $\sin^2\theta_{\text{eff}}(m_t)$ in the MSSM





SM
MSSM
both models
m_t = 165 ... 175 GeV
SM (M_H = 114...400 GeV)
MSSM
$m_{\tilde{t}_2,\tilde{b}_2} / m_{\tilde{t}_1,\tilde{b}_1} > 2.5$
experimental errors 68% CL:
LEP2/Tevatron (today)
Tevatron/LHC
ILC/GigaZ
$\sin^2\theta_{eff}$
M_W [GeV]
0.2330
0.2325
0.2320
0.2315
0.2310
0.2305
0.2300
0.2295
80.2
80.3
80.4
80.5
80.6

Outlook –Possible scenarios

- a single light Higgs boson
  – SM Higgs boson?
  – SUSY light Higgs boson?
  $H,\ A,\ H^{\pm}$ heavy (decoupling scenario) $h \sim H_{\rm SM}$
- 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

Conclusions

- Electroweak precision physics
  $\longrightarrow$ sensitive to quantum structure
  $\longrightarrow$ constraints on unknown parameters
- precision tests of the Standard Model have established the SM as a quantum field theory
- MSSM is competitive to the SM
  – global fits of similar quality (even better)
  – natural: light Higgs boson h^0
- future experiments at colliders
  – discovery of Higgs and SUSY at LHC (?)
  – precision studies at e^+e^- Linear Collider