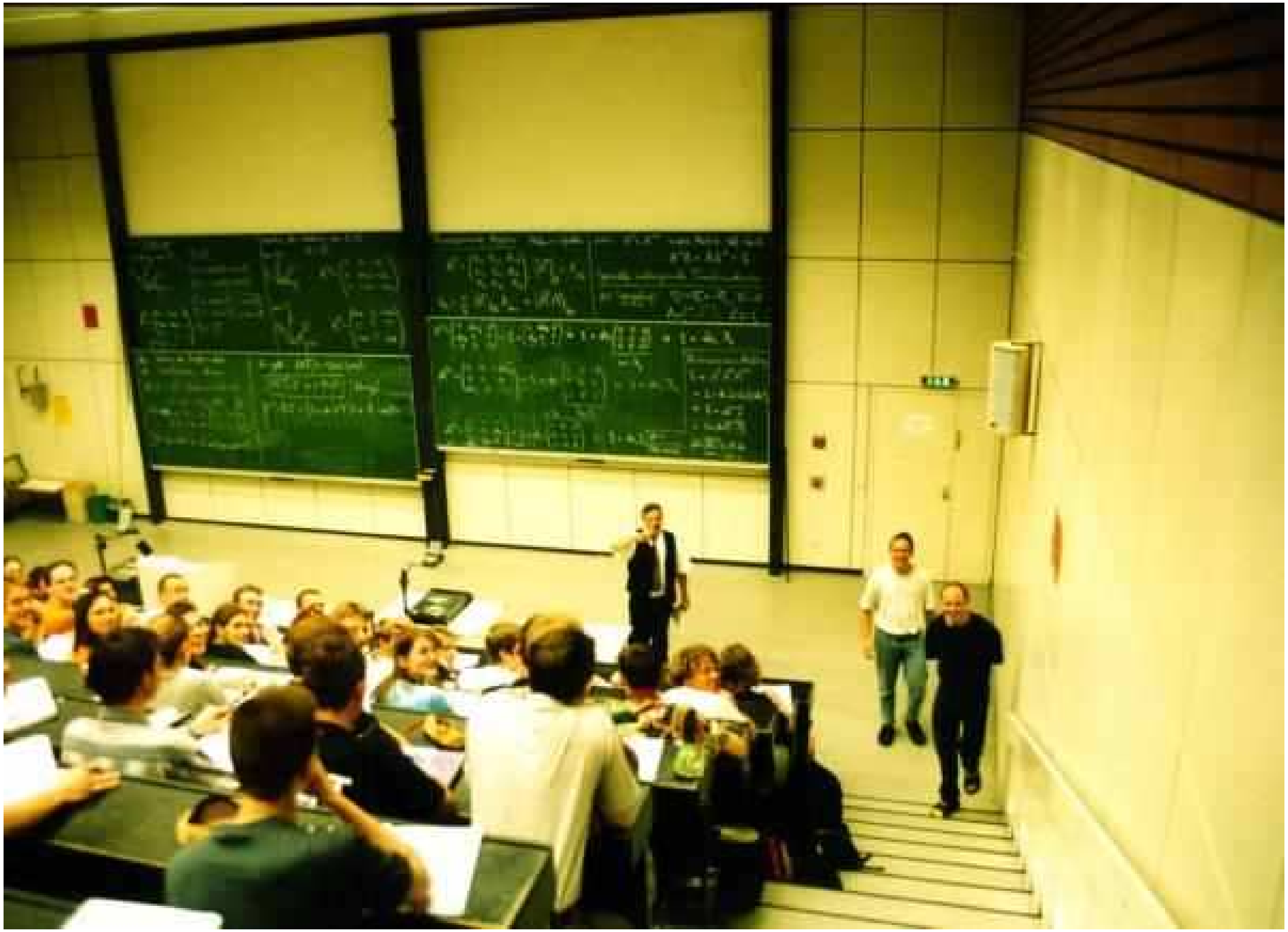
Electroweak Precision Physics from LEP to LHC and ILC

50th Anniversary

Particle and Nuclear Physics at KIT

W. Hollik

Max-Planck-Institut für Physik, München



Fundamental questions of particle physics:

- constituents of matter?
- structure of fundamental interactions?
- structure of vacuum?

Current knowledge is based on the Standard Model

Outline

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

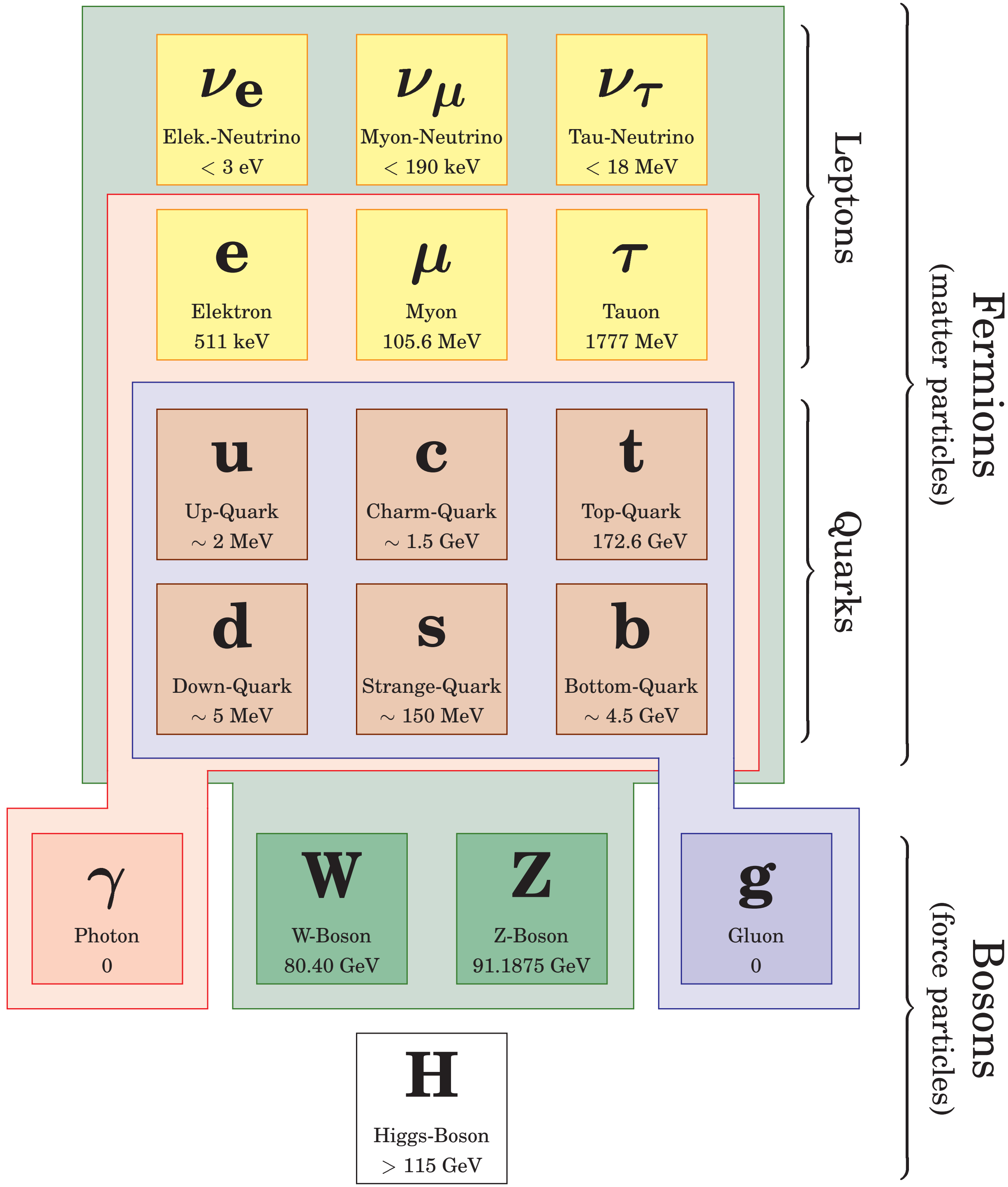
Standard Model

- 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” ?
  precise predictions required

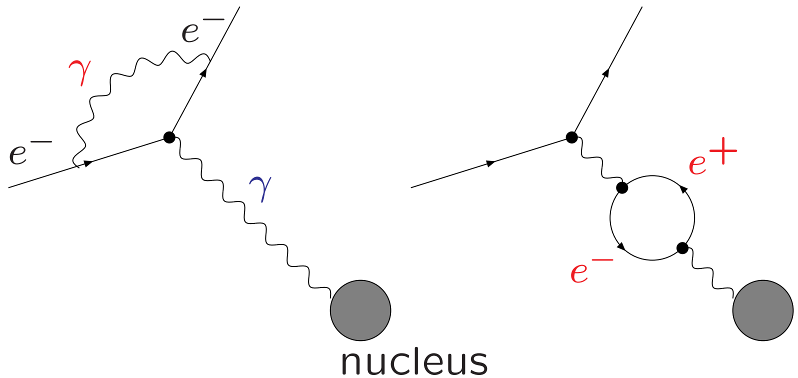


ν_e
Elek.-Neutrino
< 3 eV
ν_μ
Myon-Neutrino
< 190 keV
ν_τ
Tau-Neutrino
< 18 MeV
e
Elektron
511 keV
μ
Myon
105.6 MeV
τ
Tauon
1777 MeV
u
Up-Quark
~ 2 MeV
c
Charm-Quark
~ 1.5 GeV
t
Top-Quark
172.6 GeV
d
Down-Quark
~ 5 MeV
s
Strange-Quark
~ 150 MeV
b
Bottom-Quark
~ 4.5 GeV
γ
Photon
0
W
W-Boson
80.40 GeV
Z
Z-Boson
91.1875 GeV
g
Gluon
0
H
Higgs-Boson
> 115 GeV
Leptons
Quarks
Fermions
(matter particles)
Bosons
(force particles)

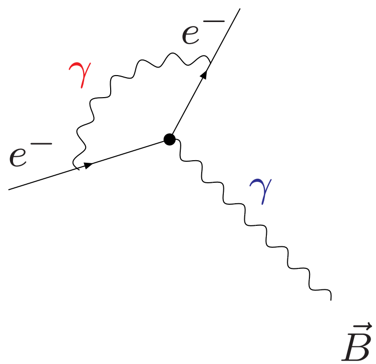
precision tests of a theory at the quantum level

example: QED

Lamb shift:



$g-2$:



$$a = \frac{1}{2}(g-2)$$

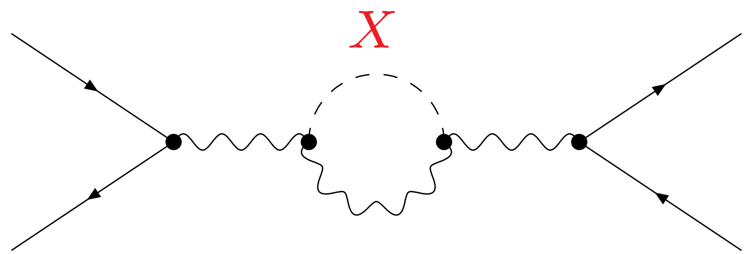
$$a_{\text{exp}} = 1\,159\,652\,180(\pm 1)\times 10^{-12}$$

$$a_{\text{theo}} = 1\,159\,652\,183(\pm 8)\times 10^{-12}$$

requirement:

- precise measurements
- precise predictions – loop calculations

precision tests of the Standard Model through quantum loops



sensitivity to heavy internal particles (X)

Standard Model: X = Higgs, top

precision observables

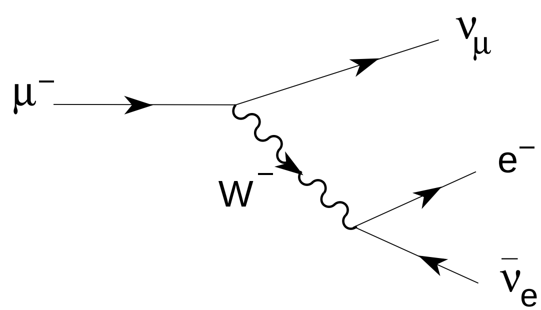
- μ lifetime: G_{F}
- Z observables: $M_Z, \Gamma_Z, g_V, g_A, \sin^2\theta_{\mathrm{eff}}, \ldots$
- LEP 2, Tevatron, LHC: M_W, m_t

$M_W - M_Z$ correlation

Definition of Fermi constant G_F via muon lifetime:

$$\tau_\mu^{-1} = \frac{G_F^2 m_\mu^5}{192\pi^3} F\left(\frac{m_e^2}{m_\mu^2}\right)\left(1 + \frac{3}{5}\frac{m_\mu^2}{M_W^2}\right)(1 + \Delta q)$$

Δq: QED corrections in Fermi Model,



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

with loop contributions

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

Δr : quantum correction

$\Delta r = \Delta r(m_t, M_H)$

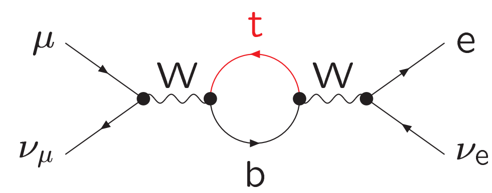
determines W mass

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

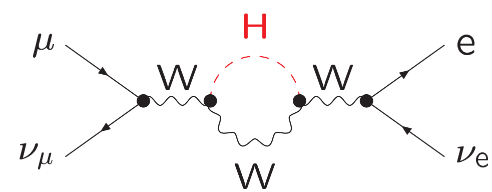
complete at 2-loop order

1-loop examples

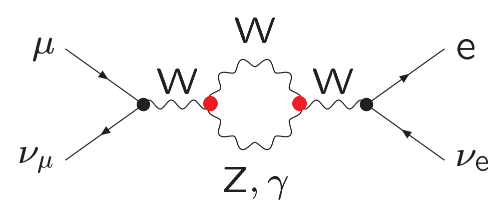
- top quark



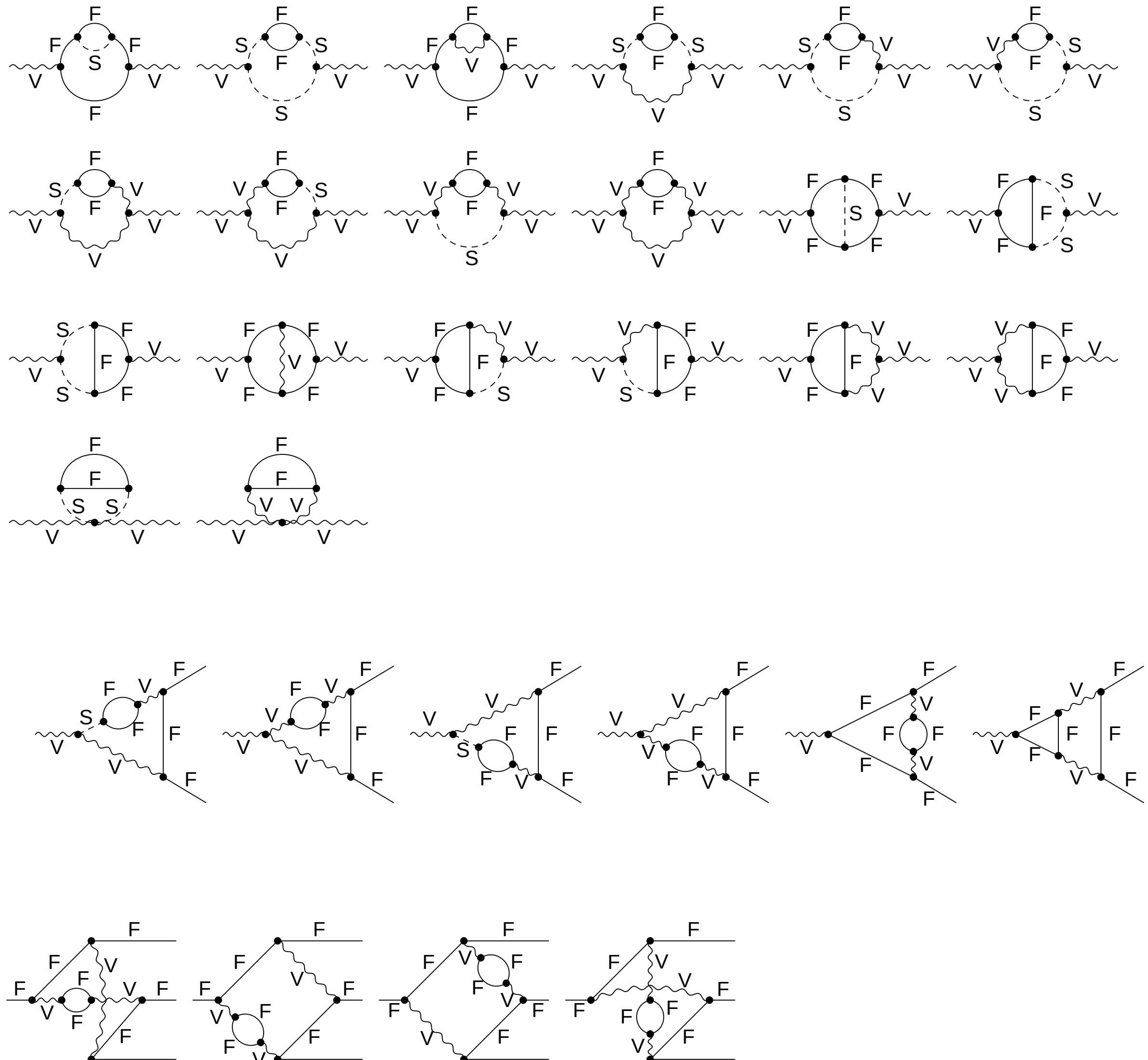
- Higgs boson



- gauge-boson self-couplings

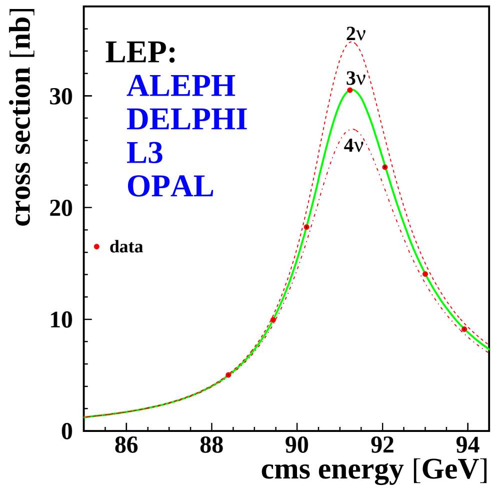


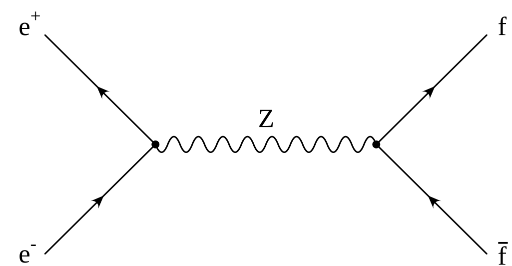
full structure of SM



2-loop examples

Z resonance



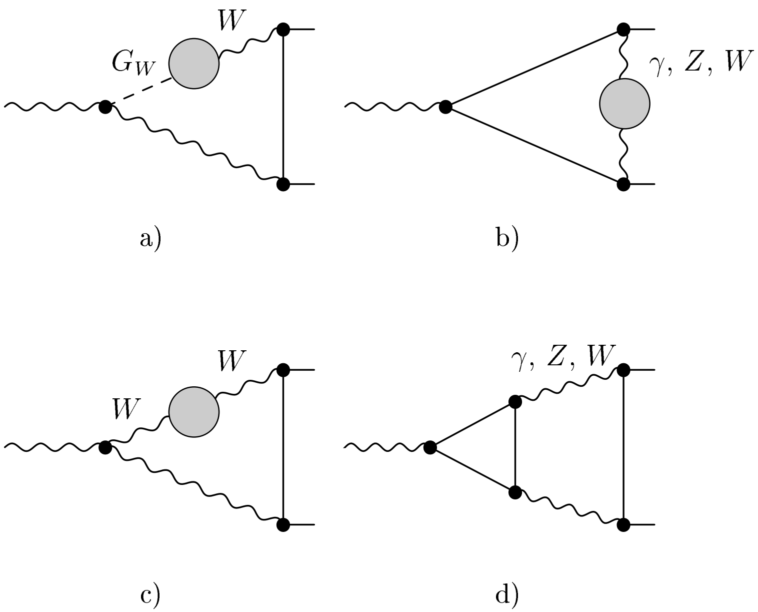


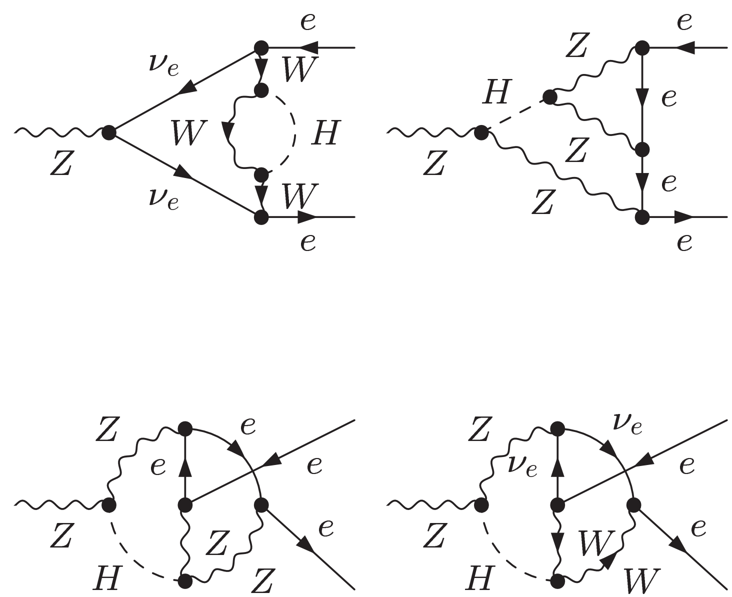
- effective Z boson couplings with higher-order $\Delta g_{V,A}$

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

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

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





2-loop examples for Z couplings

complete 2-loop calculation available for $\sin^2\theta_{\text{eff}}$

EW 2-loop calculations for Δr

Freitas, Hollik, Walter, Weiglein

Awramik, Czakon

Onishchenko, Veretin

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

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

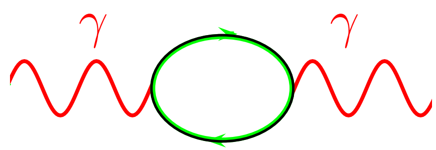
Schröder, Steinhauser

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

Boughezal, Czakon

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

photon vacuum polarization



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

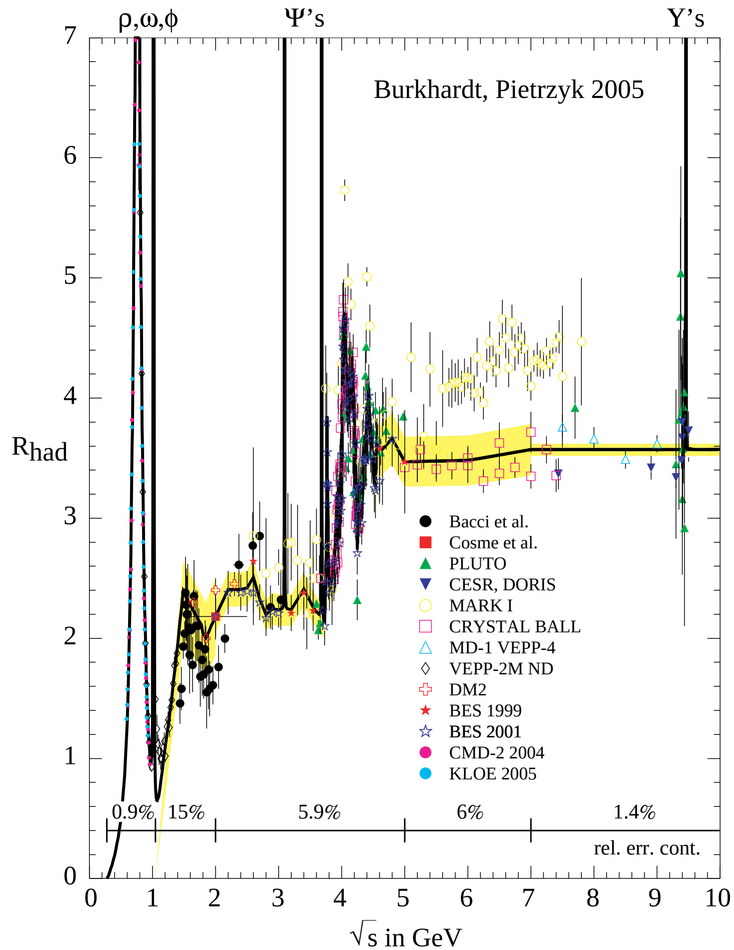
$$\Delta\alpha = \Delta\alpha_{\rm lept} + \Delta\alpha_{\rm had},$$

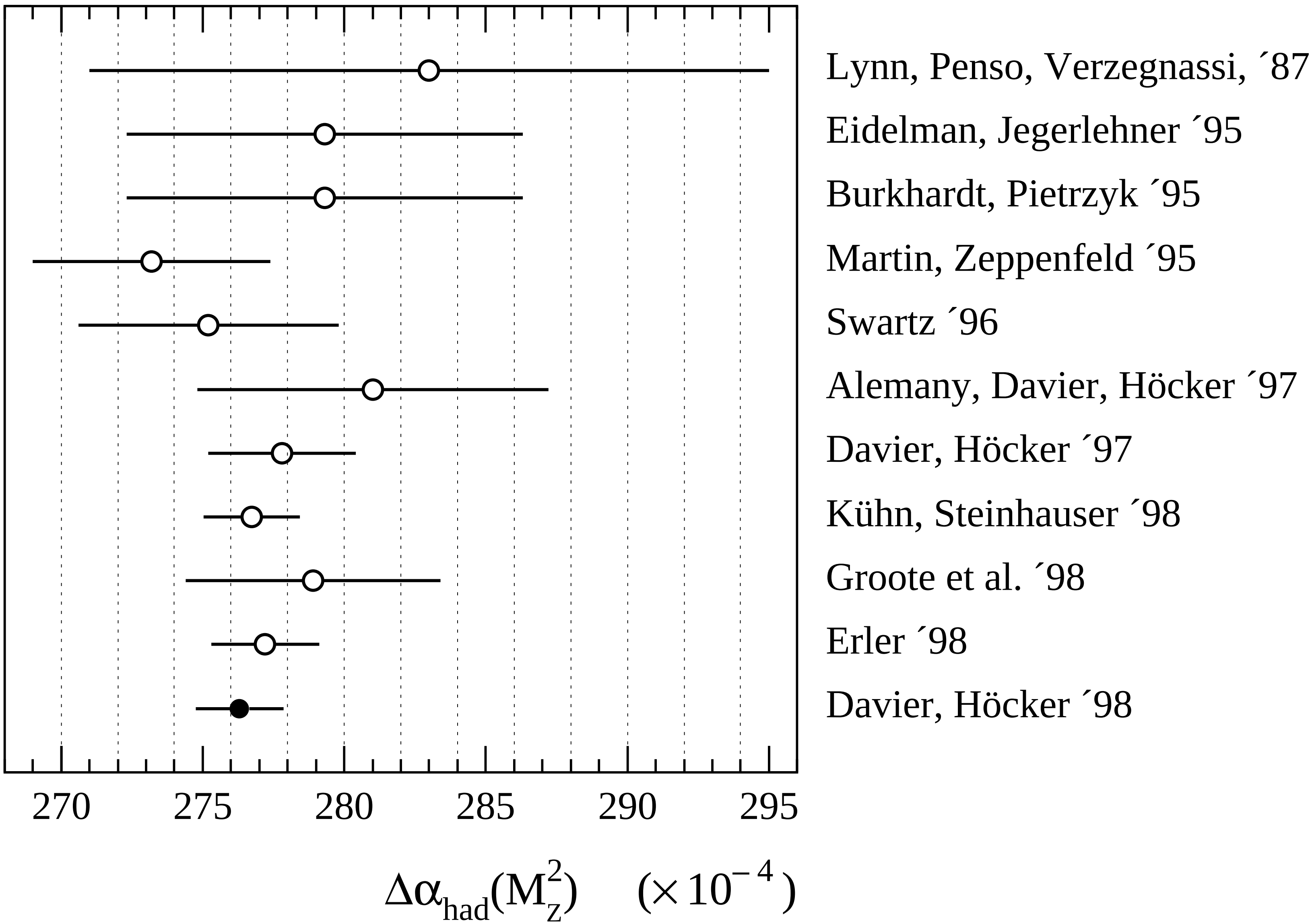
$$\Delta\alpha_{\rm lept} = 0.031498 \quad (3-\text{loop}) \quad [\text{Steinhauser}]$$

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

significant source of parametric uncertainty

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




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
$\Delta\alpha_{had}(M_Z^2)$ $(\times 10^{-4})$

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, ...)

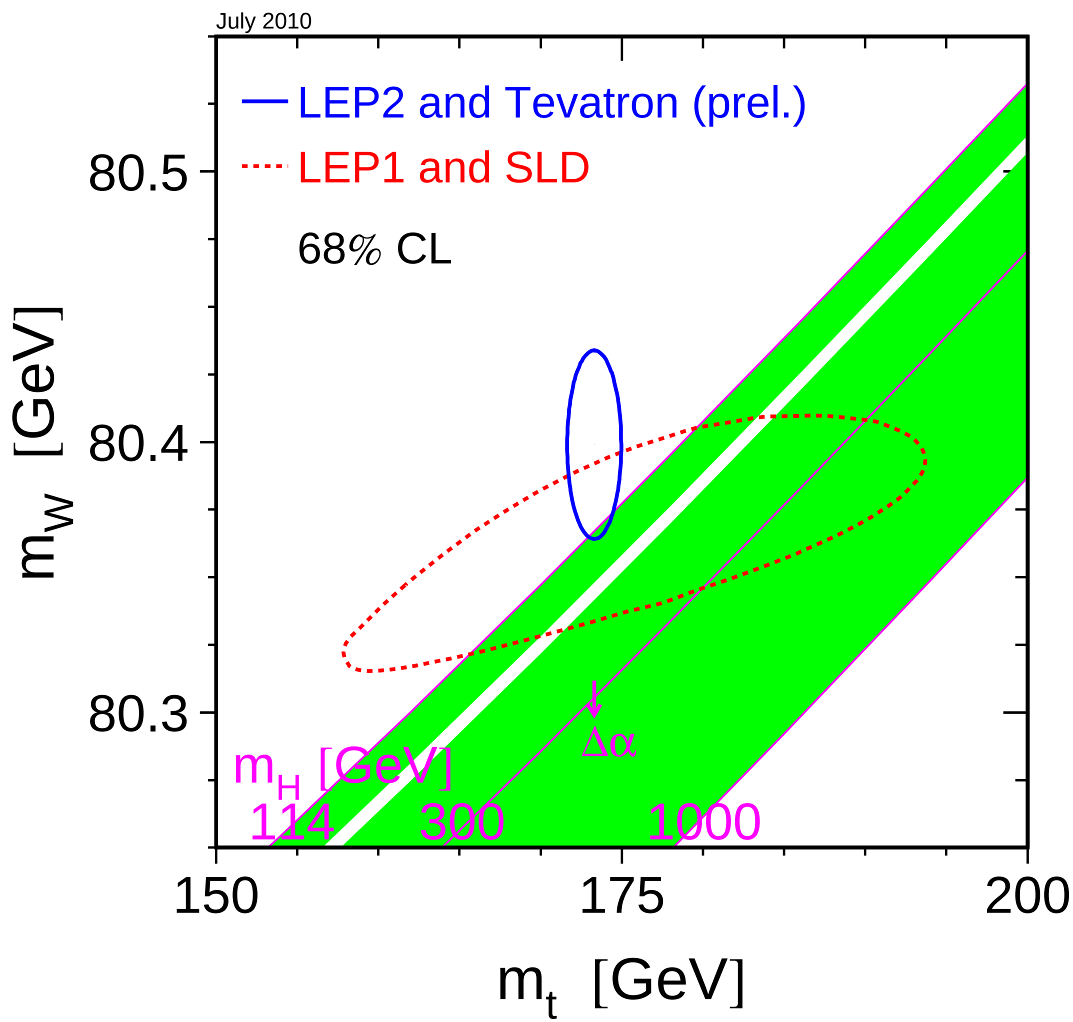
Theory versus Data

experimental results (selection)

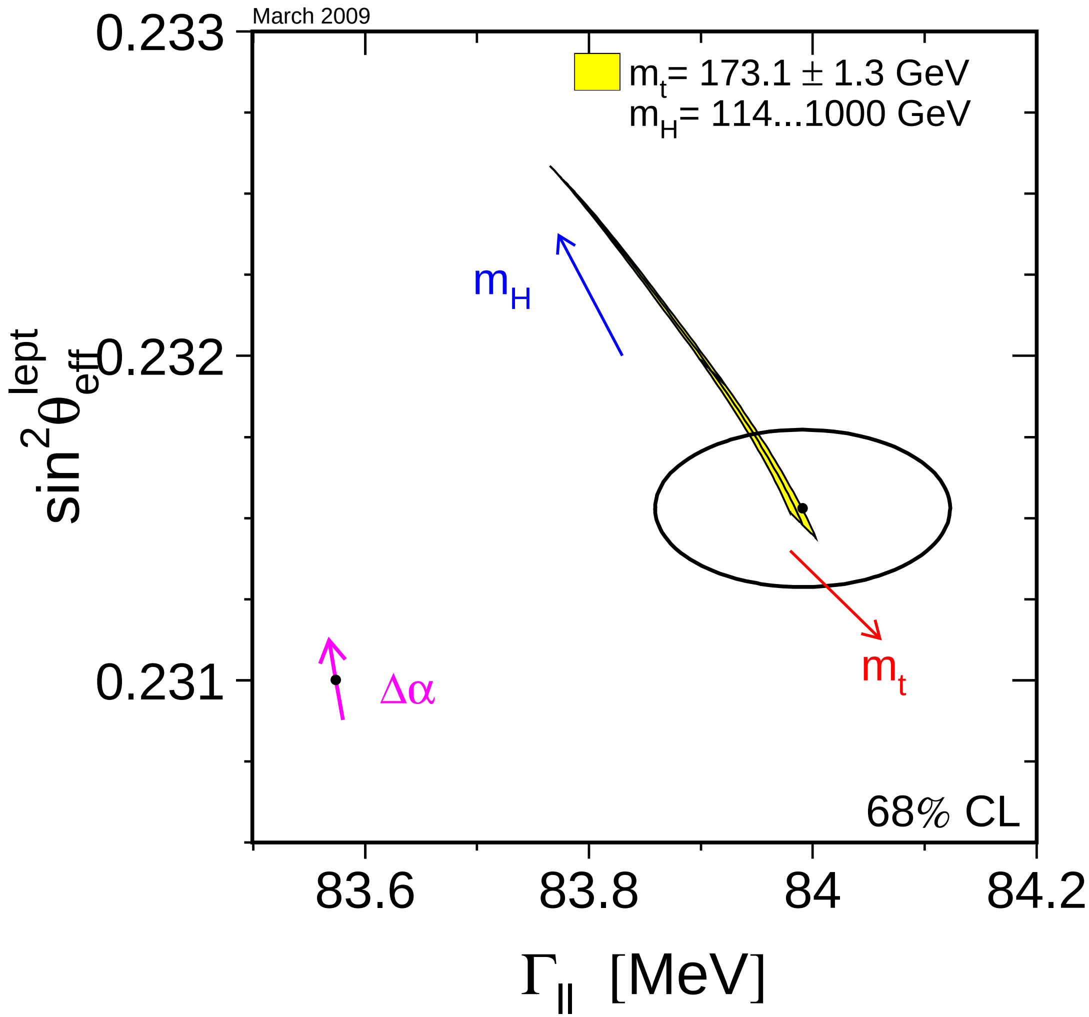
M_{Z} [GeV]	$= 91.1875 \pm 0.0021$	0.002%
Γ_{Z}[GeV]	$= 2.4952 \pm 0.0023$	0.09%
$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$	$= 0.23148 \pm 0.00017$	0.07%
M_{W} [GeV]	$= 80.398 \pm 0.025$	0.04%
m_{t} [GeV]	$= 173.1 \pm 1.3$	0.75%
G_{F} [GeV^{-2}]	$= 1.16637(1)10^{-5}$	0.001%

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

LEP Electroweak Working Group



LEP Electroweak Working Group



CERN 89-08
Volume 1
21 September 1989

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Z PHYSICS AT LEP 1

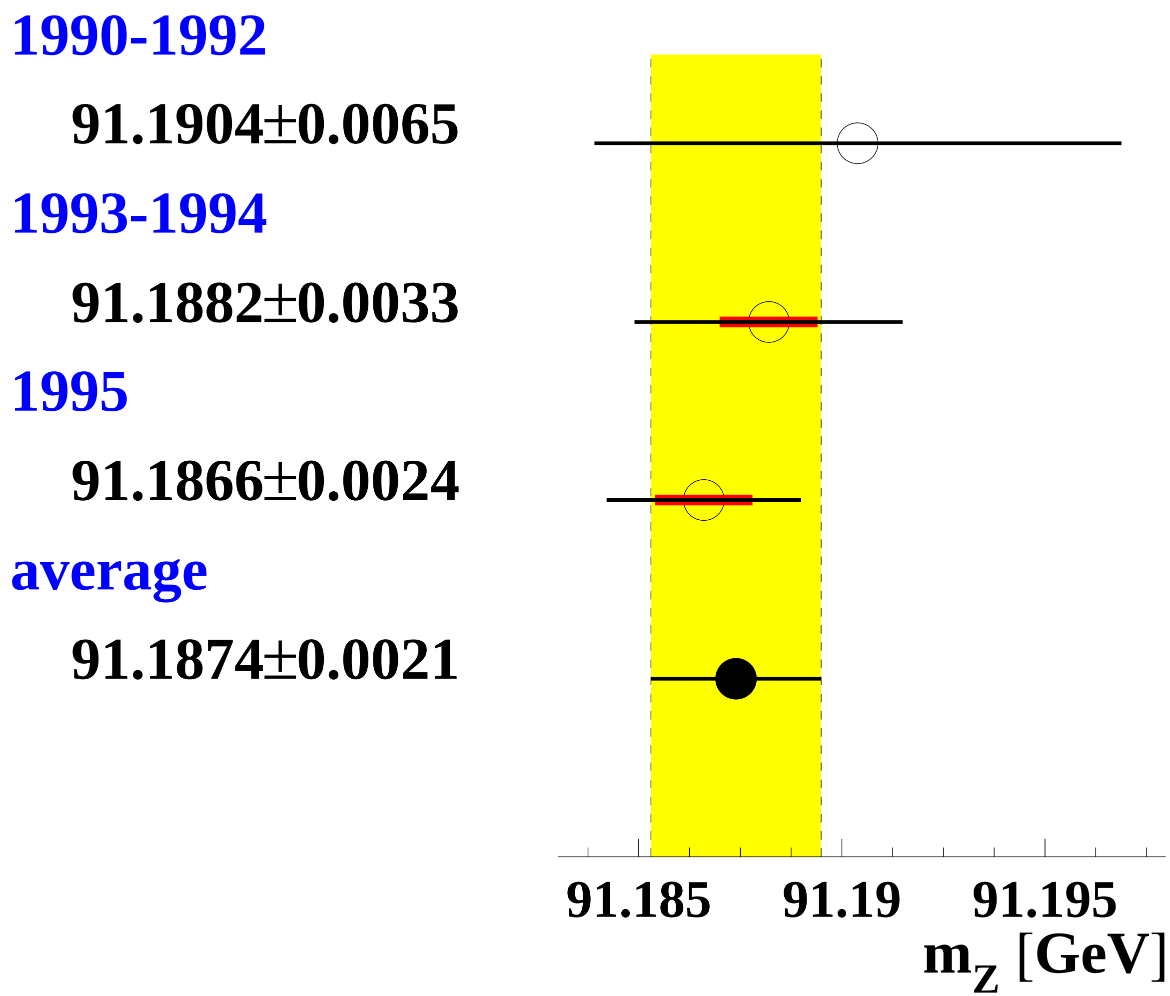
Edited by
Guido Altarelli, Ronald Kleiss and Claudio Verzegnassi

Volume 1: STANDARD PHYSICS

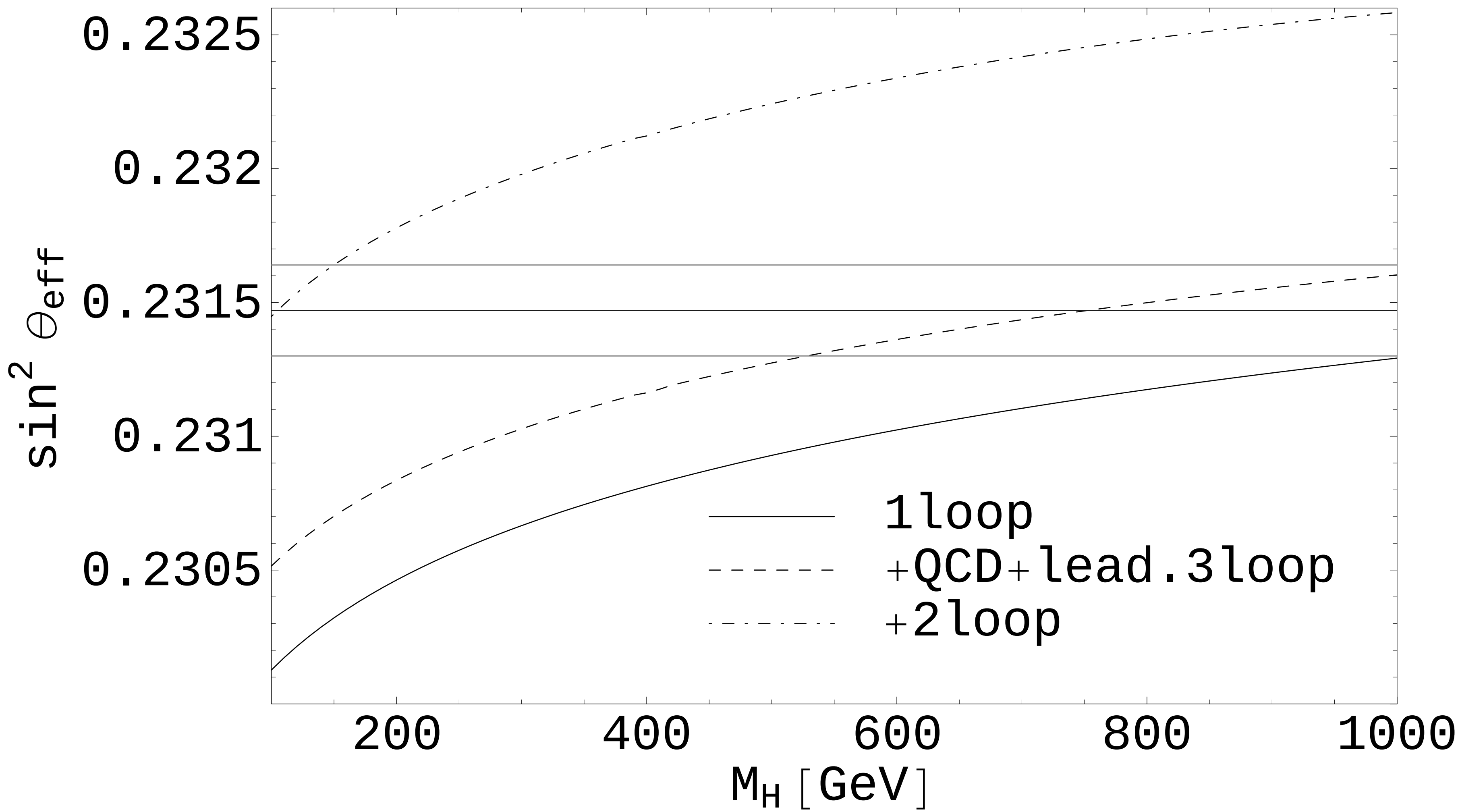
Co-ordinated and supervised by G. Altarelli

GENEVA
1989

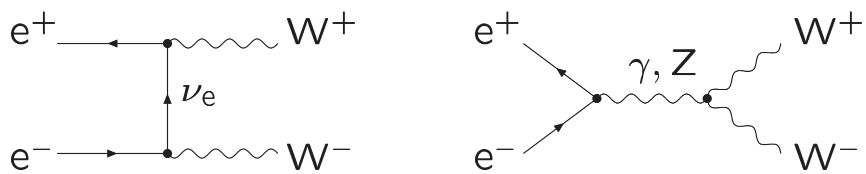
development of precision

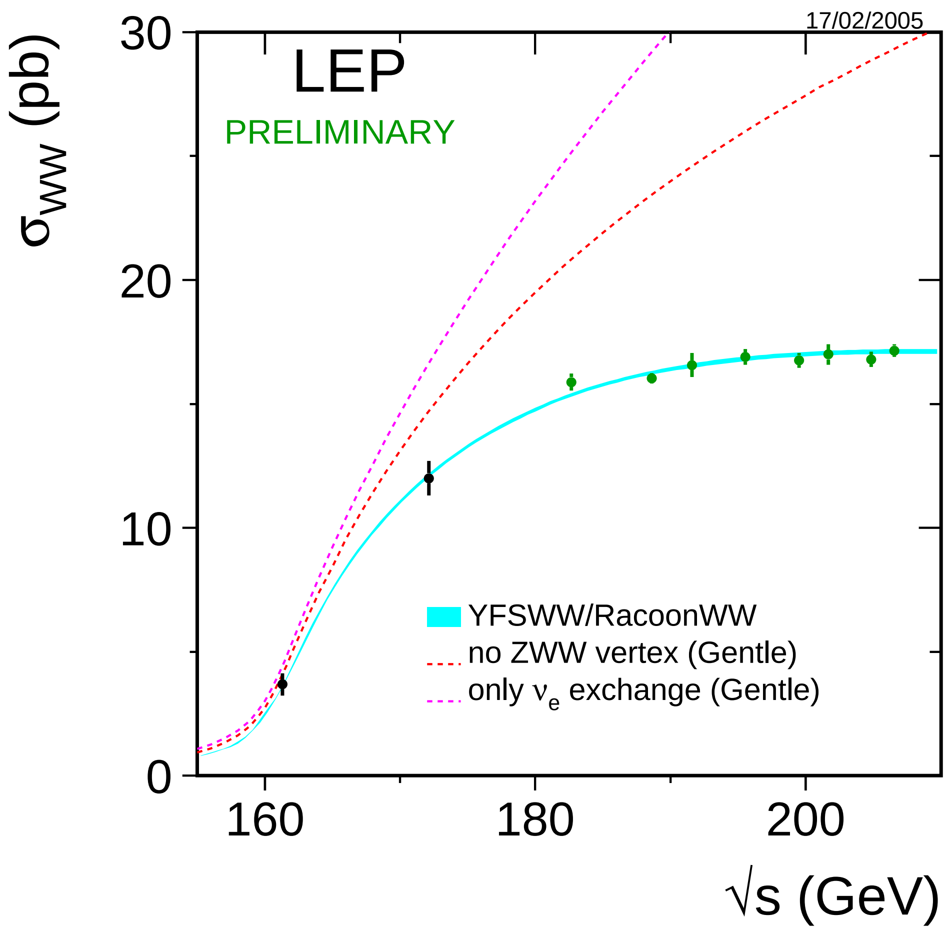


importance of two-loop calculations

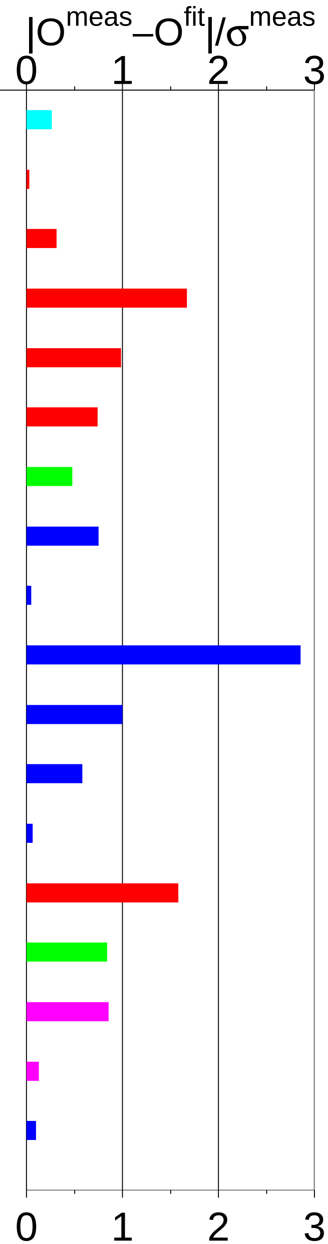


W-pair production

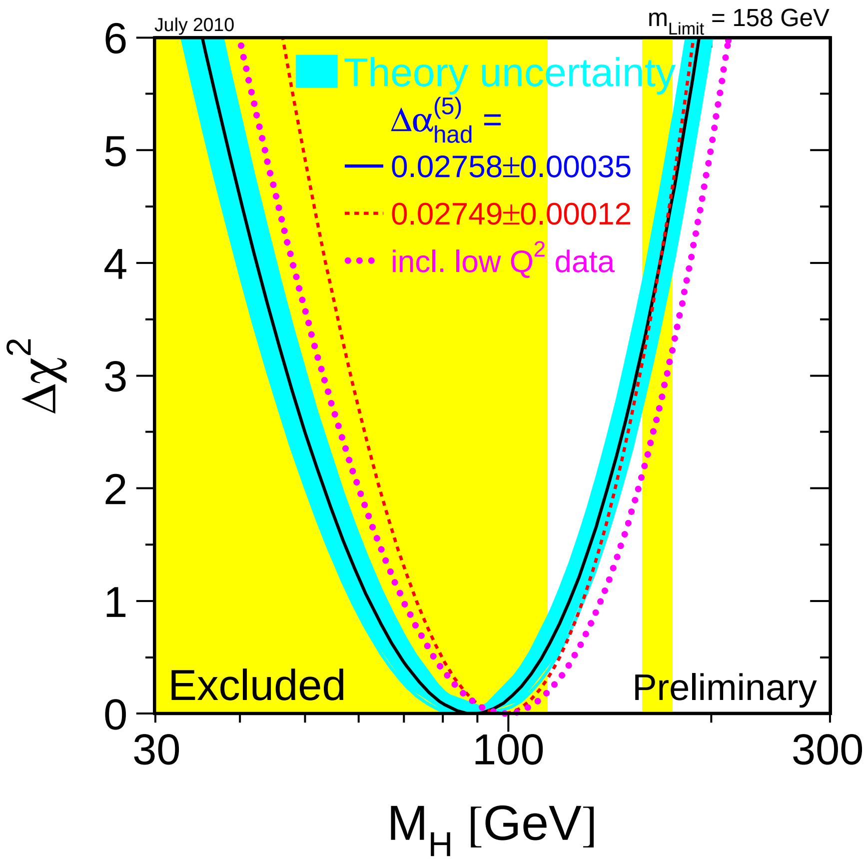




	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	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	0.1480
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.025	80.378
Γ_W [GeV]	2.098 ± 0.048	2.092
m_t [GeV]	173.1 ± 1.3	173.2



March 2009



blueband: theory uncertainty

"Precision Calculations at the Z Resonance"
CERN 95-03

[Bardin, Hollik, Passarino (eds.)]

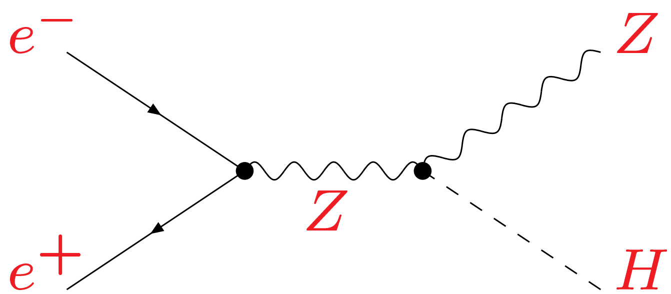
$$M_{\rm H} < 157\ {\rm GeV} \quad (95\%{\rm C.L.})$$

with direct search $M_{\rm H} > 114$ GeV:

$$M_{\rm H} < 186\ {\rm GeV} \quad (95\%{\rm C.L.})$$

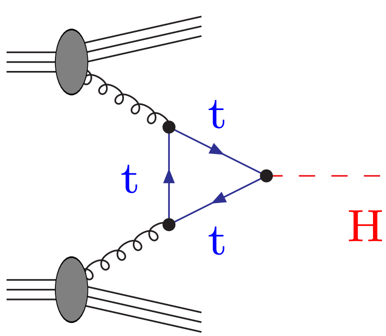
experimental search

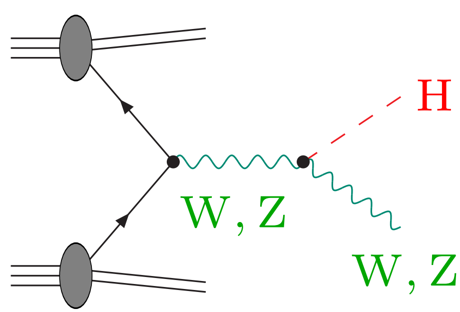
LEP:

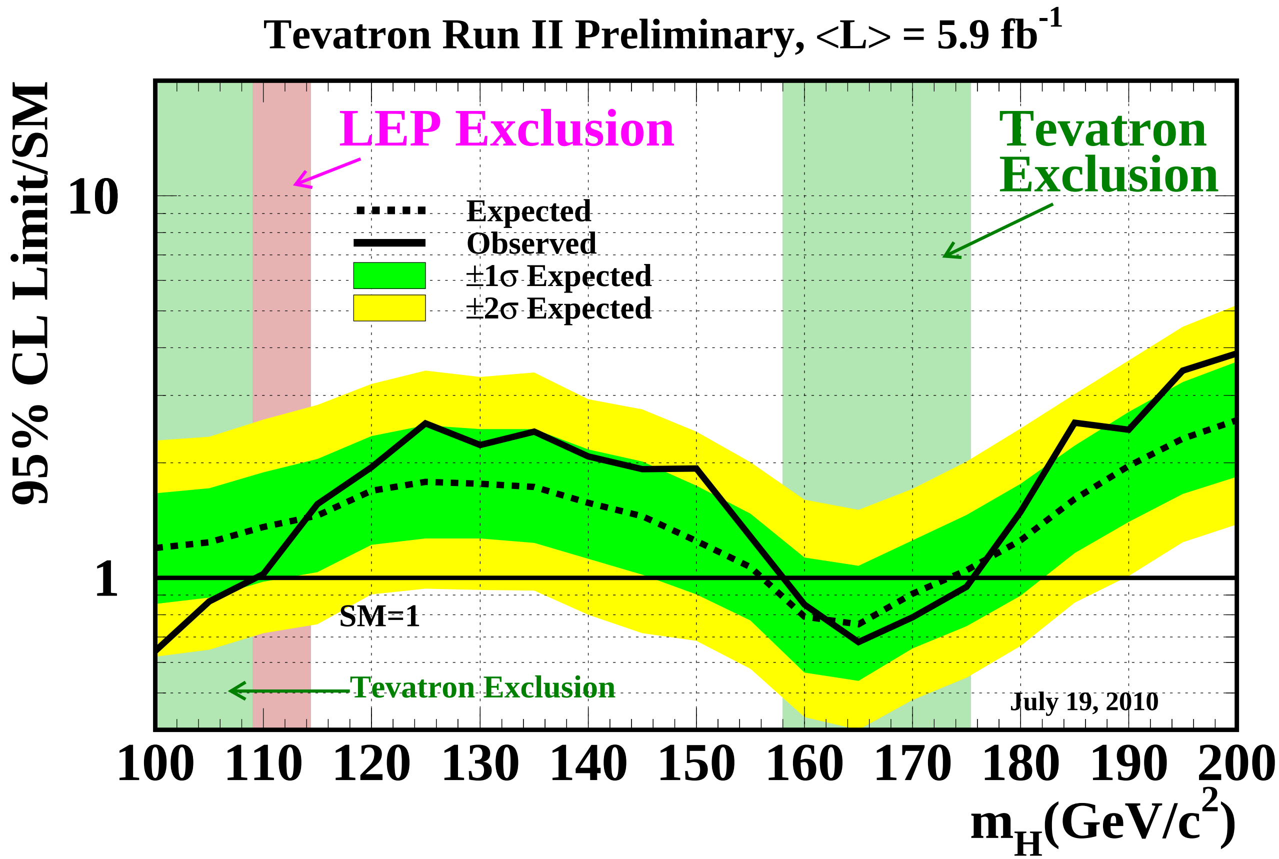


excluded $M_H < 114\,\mathrm{GeV}$

Tevatron:





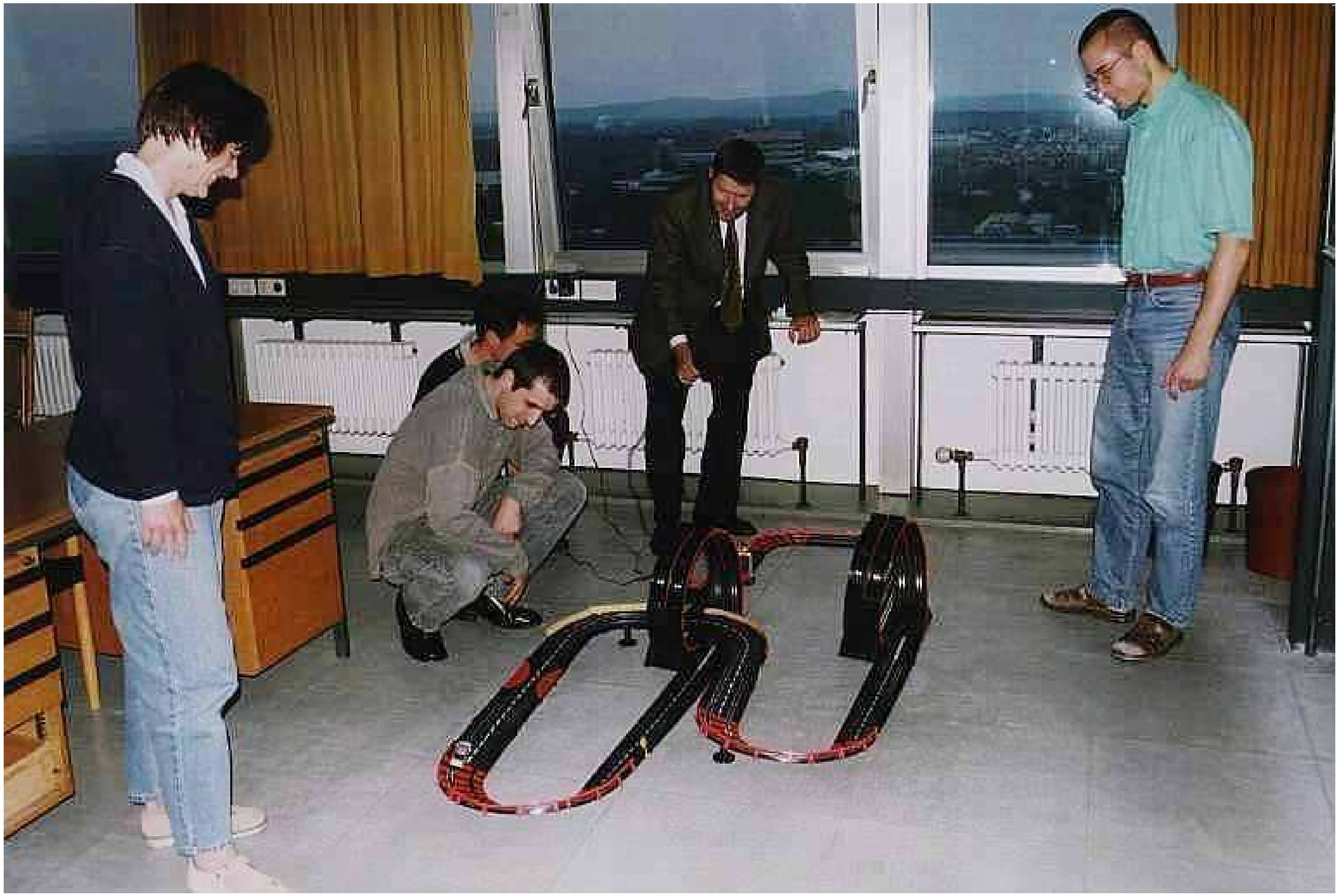


– high mass 95% CL exclusion: $158 < m_H < 175$ GeV
dominated by $gg \to H \to WW$ channel

– low mass sensitivity mainly by $qq \to WH \to \ell\nu\, b\bar{b}$

Next experiments at high energy accelerators

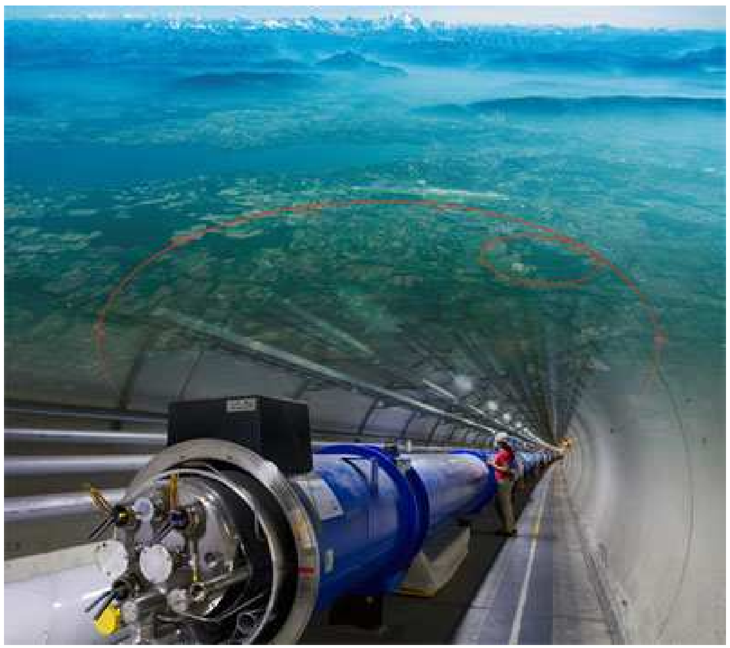
Next experiments at high energy accelerators



Perspectives

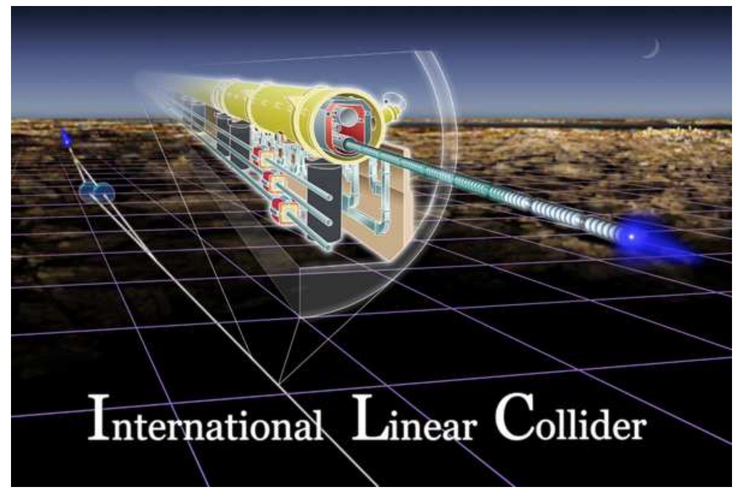
2009:

The Large Hadron Collider



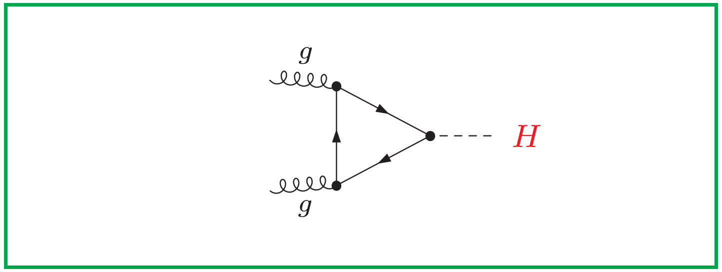
Future:

e^+e^- **Linear Collider**

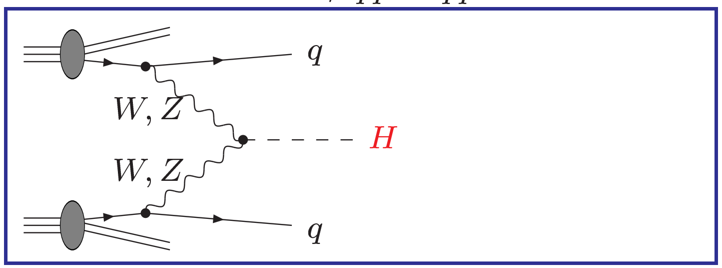


Higgs production at the LHC

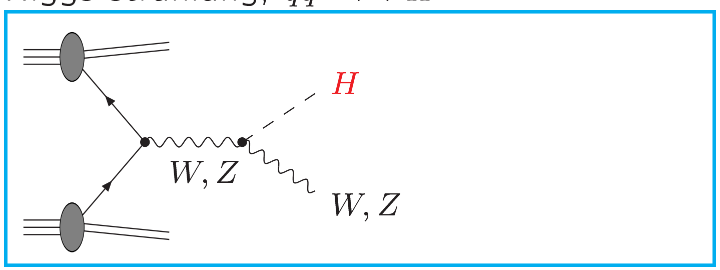
- gluon fusion, $gg \to H$



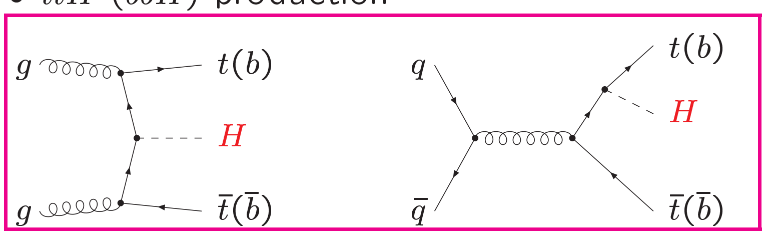
- vector boson fusion, $qq \to qqH$

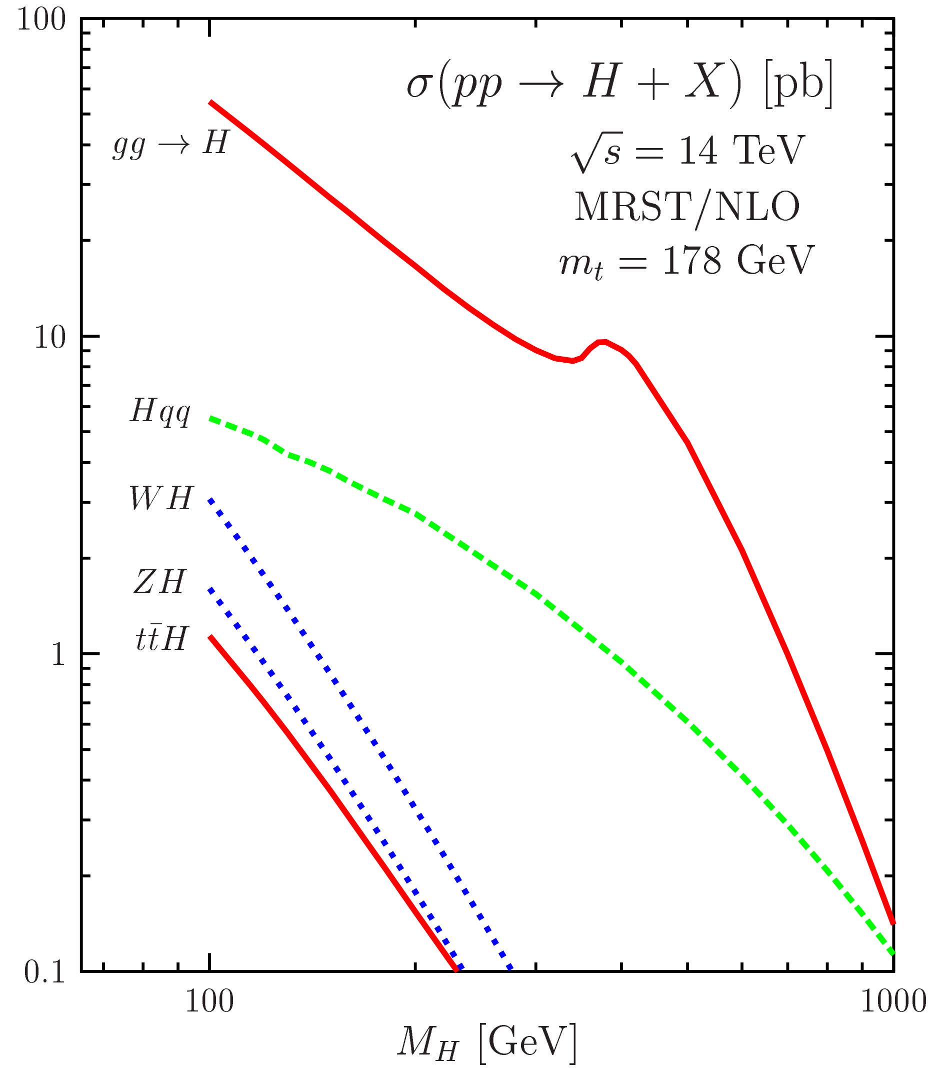


- Higgs strahlung, $q\bar{q}' \to VH$



- $t\bar{t}H$ ($b\bar{b}H$) production





Higgs production at the LHC

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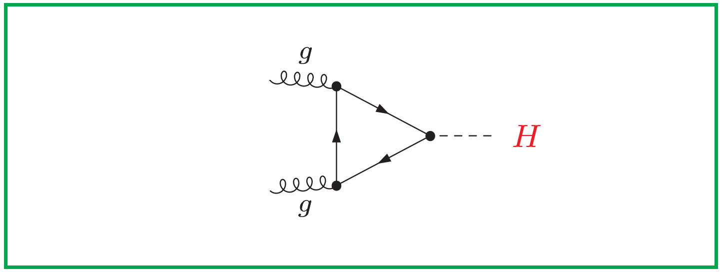

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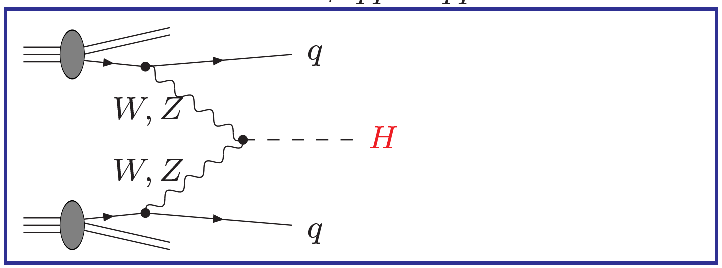
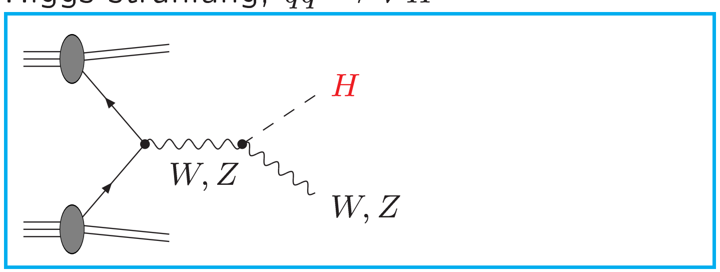
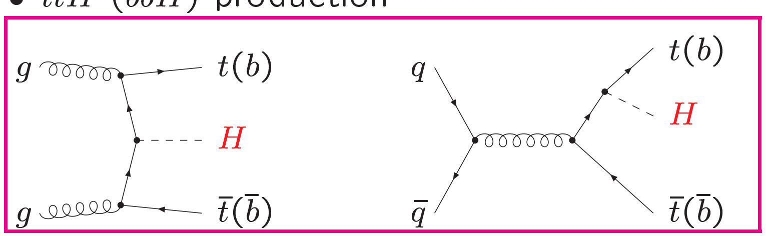


- Higgs strahlung, $q\bar{q}' \to VH$



- $t\bar{t}H$ ($b\bar{b}H$) production



- gluon-gluon fusion:
  NNLO QCD *[Harlander, Kilgore]*
  NL EW *[Degrassi, Maltoni]*

- WW (ZZ) fusion:
  NLO QCD
  [Figy, Oleari, Zeppenfeld]

- Higgs-strahlung processes:
  NNLO QCD + NLO EW
  [Brein et al.]

- radiation from heavy quarks:
  NLO QCD *[Beenakker et al., Dawson et al.]*
  NLO EW *[Denner et al.]*

expected precision

error for	LEP/Tev	Tev/LHC	ILC	ILC/GigaZ
$M_W\,[\mathrm{MeV}]$	25	15	15	7
$\sin^2\theta_{\mathrm{eff}}$	0.00017	0.00021		0.000013
$m_{\mathrm{top}}\,[\mathrm{GeV}]$	1.2	1	0.2	0.13
$M_{\mathrm{Higgs}}\,[\mathrm{GeV}]$	–	0.1	0.05	0.05

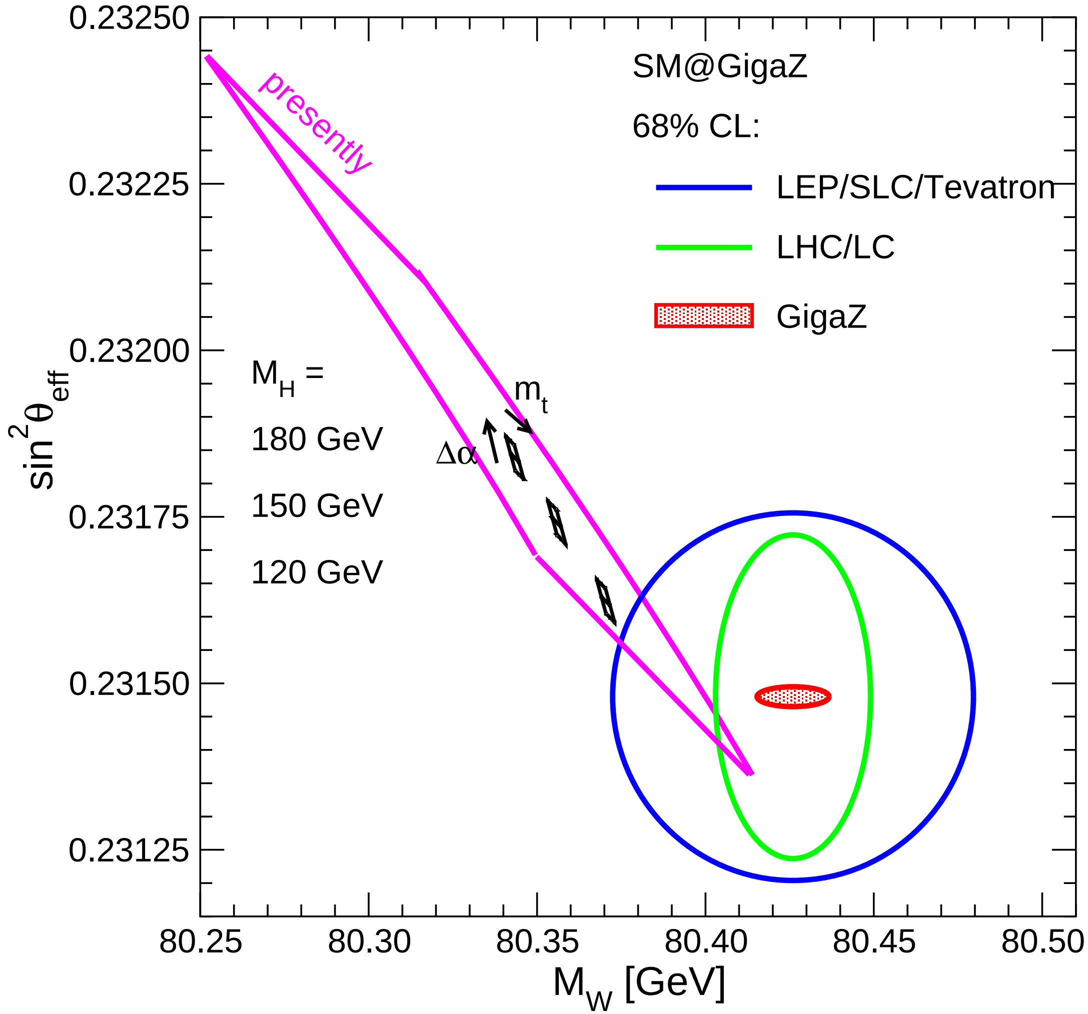
$\delta M_Z = 2.1\,\mathrm{MeV}$ (LEP)

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

GigaZ $\sim 10^9$ Z bosons

MegaW $\sim 10^6$ W bosons

after the Higgs boson mass is measured



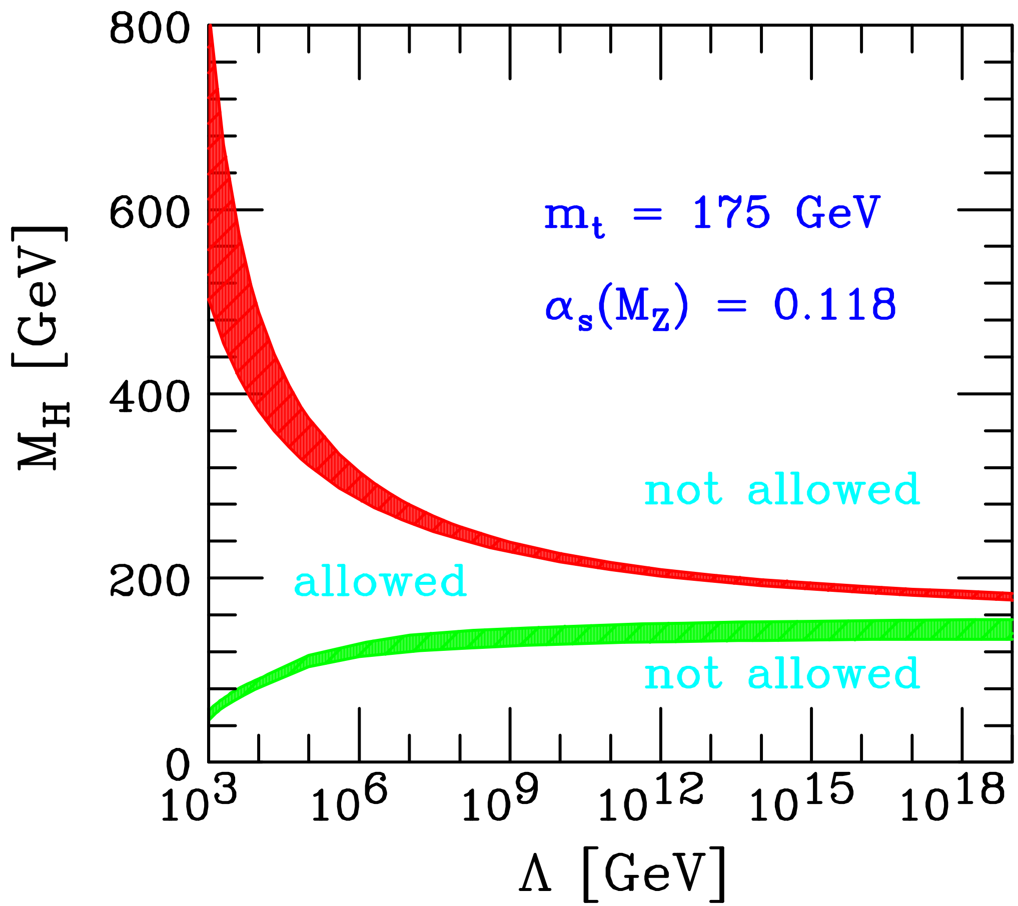
[Erler, Heinemeyer, Hollik, Weiglein, Zerwas]

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:

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



Standard Model Higgs:

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

the question for New Physics

Beyond the Standard Model

further substructure	elementary fundamental fields
effects from new strong interaction	interactions remain weak
	Grand Unified Theories
new strong dynamics at high enery scale	new symmetry supersymmetry

supersymmetry in particle physics

Julius Wess

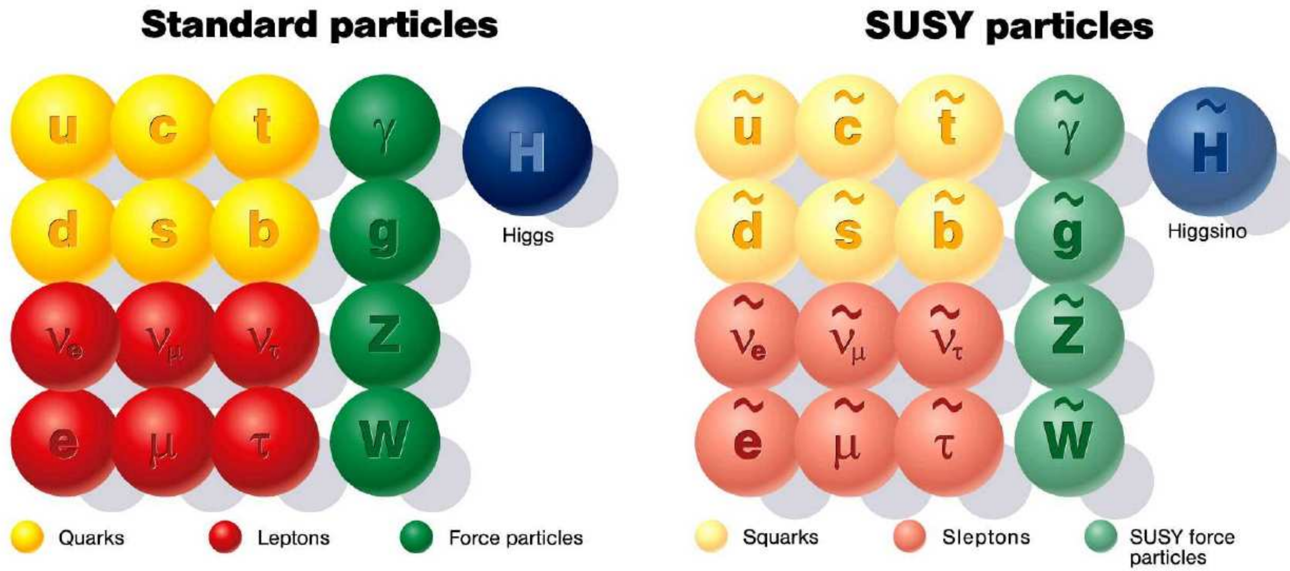
Institut für Theoretische Physik

Karlsruhe, 1968 – 1990

supersymmetric relativistic QFT

Wess, Zumino 1974

$\longrightarrow$ **SUSY Standard Model**



- gauge coupling unification
- stabilization of the electroweak scale
- dark matter candidate (lightest SUSY particle)
- lightest Higgs boson h^0 $< 135\,$GeV

  physical Higgs bosons: $h^0,\ H^0,\ A^0,\ H^\pm$

Standard Model Higgs: $V = -\mu^2\,\Phi^2 + \lambda\,\Phi^4, \quad \Phi = v + H$

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

SUSY Standard Model: light Higgs is natural

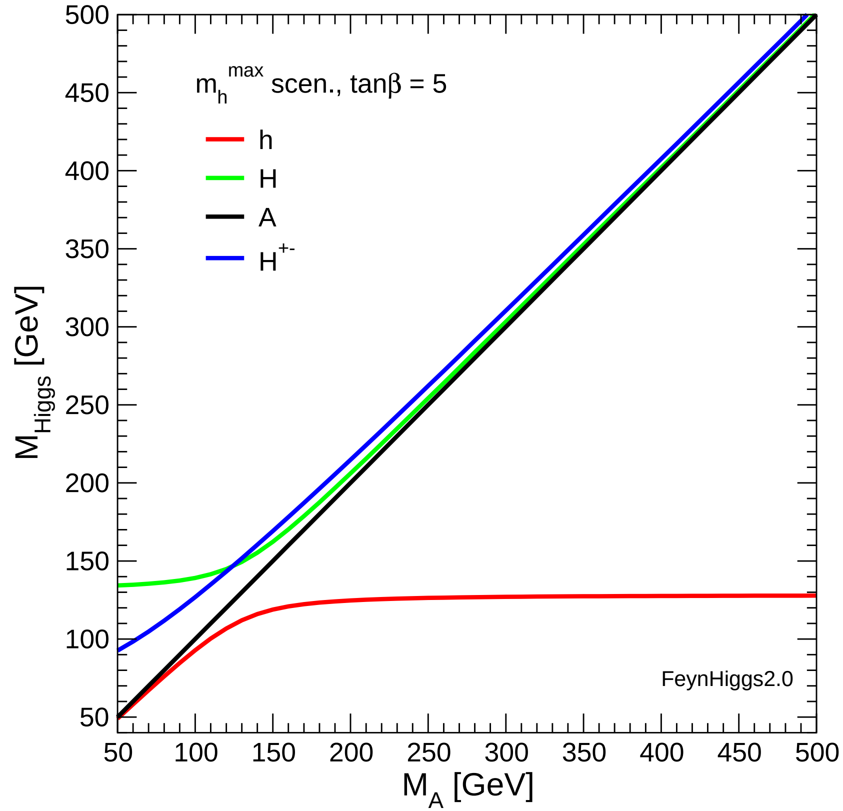
$$H_2 = \begin{pmatrix} H_2^+ \\ v_2 + H_2^0 \end{pmatrix}, \qquad H_1 = \begin{pmatrix} v_1 + H_1^0 \\ H_1^- \end{pmatrix}$$

couples to u couples to d

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

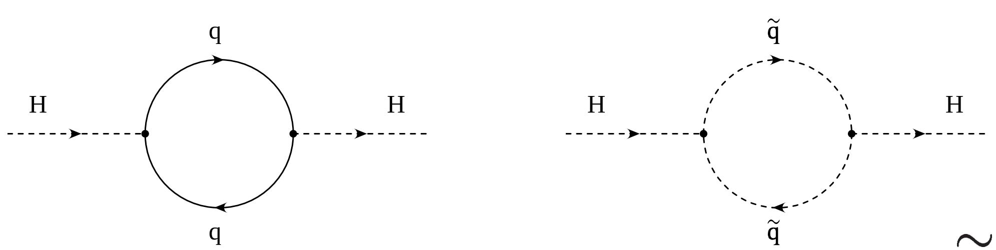
2 doublets: minimal model, MSSM

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 $\sim \alpha^2_{t,b}$

theoretical uncertainty:

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

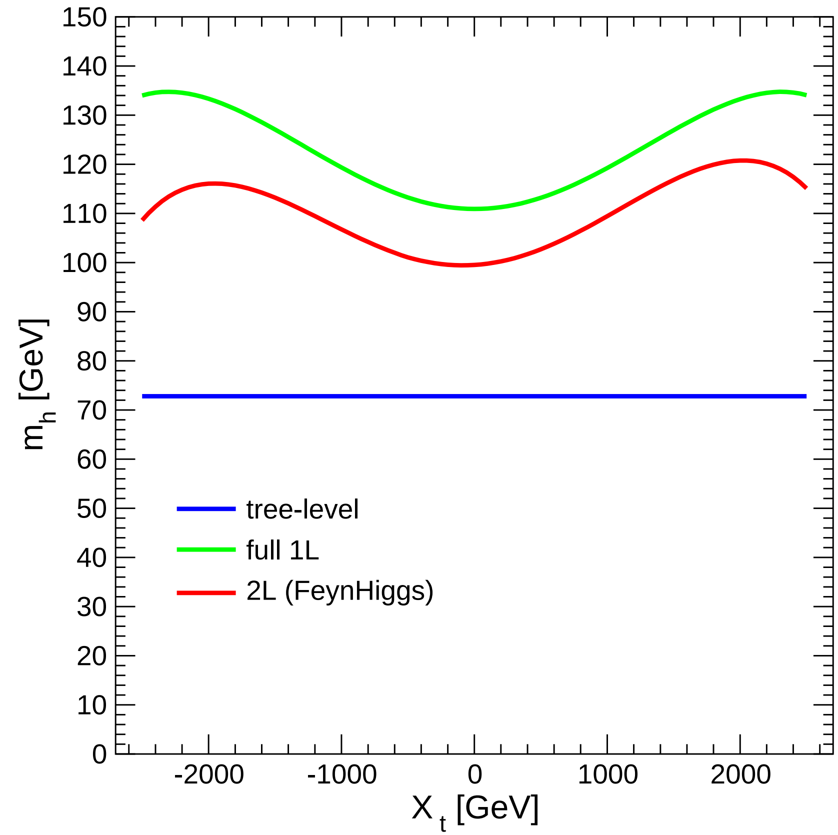
public code `FeynHiggs`

latest version:

`FeynHiggs2.7`

arXiv:1007.0956

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



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

X_t : top-squark mixing parameter

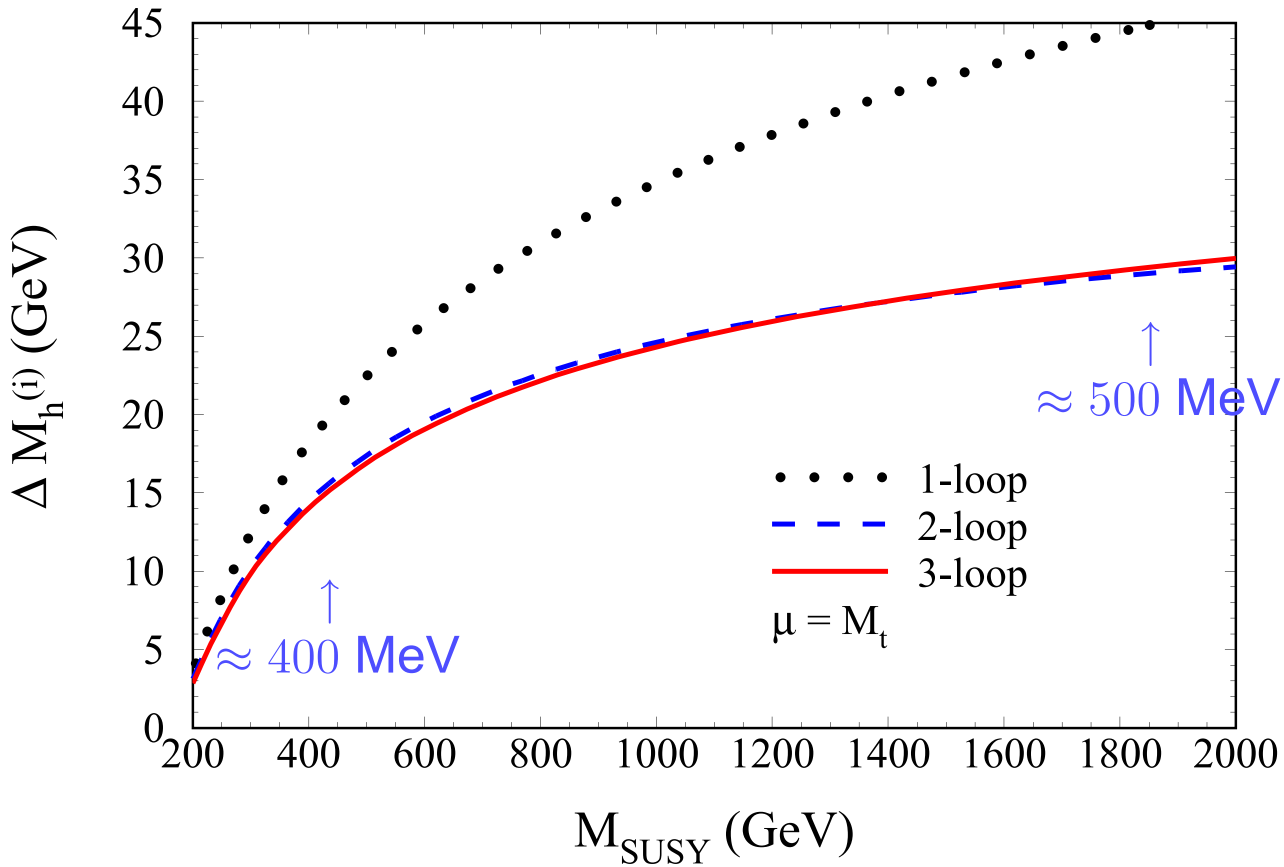
$$\mathrm{X_t} = \mathrm{A_t} - \mu \cot\beta$$

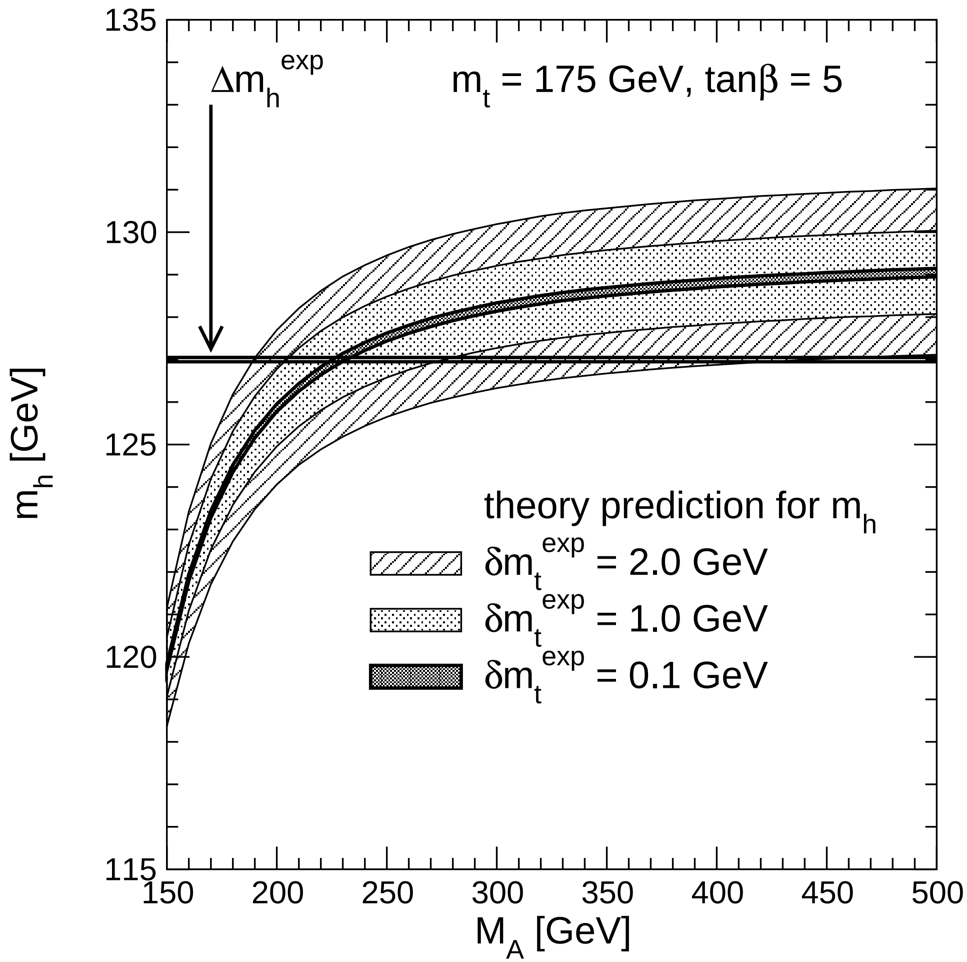
FeynHiggs – the Swiss Army Knife for Higgs Physics

T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak, G. Weiglein

3-loop contributions $\sim \alpha_s^2\,\alpha_t$

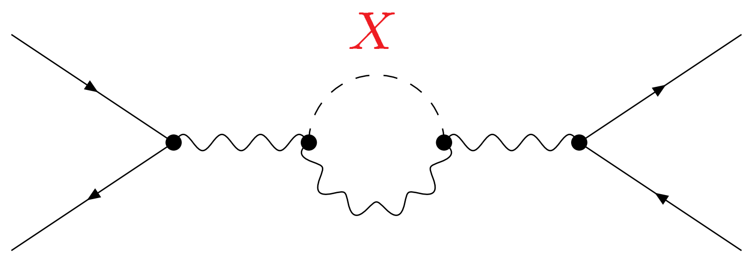
[Harlander, Kant, Mihaila, Steinhauser]





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

indirect access to SUSY particles through quantum loops



X = Higgs bosons, SUSY particles

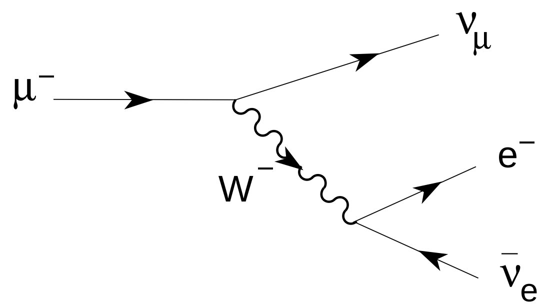
- μ lifetime: $M_W \leftrightarrow M_Z, G_\mathrm{F}$
- Z observables: $g_V, g_A, \sin^2\theta_\mathrm{eff}, \Gamma_Z, M_Z, \ \ldots$

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

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

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

$M_W - M_Z$ correlation



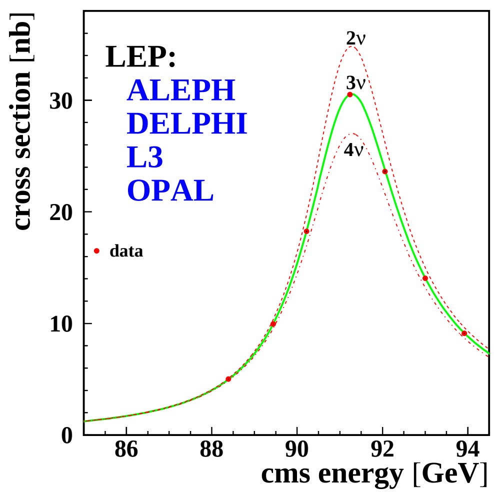
$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{M_W^2\left(1 - M_W^2/M_Z^2\right)}\left(1 + \Delta r\right)$$

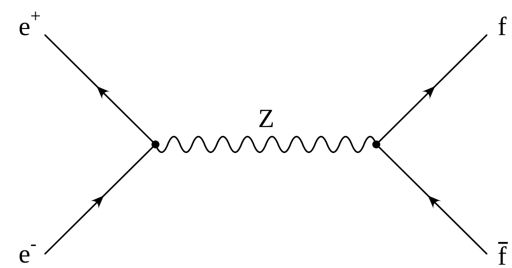
Δr : quantum correction, $\Delta r = \Delta r(m_t, X_{\text{SUSY}})$

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

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

Z resonance



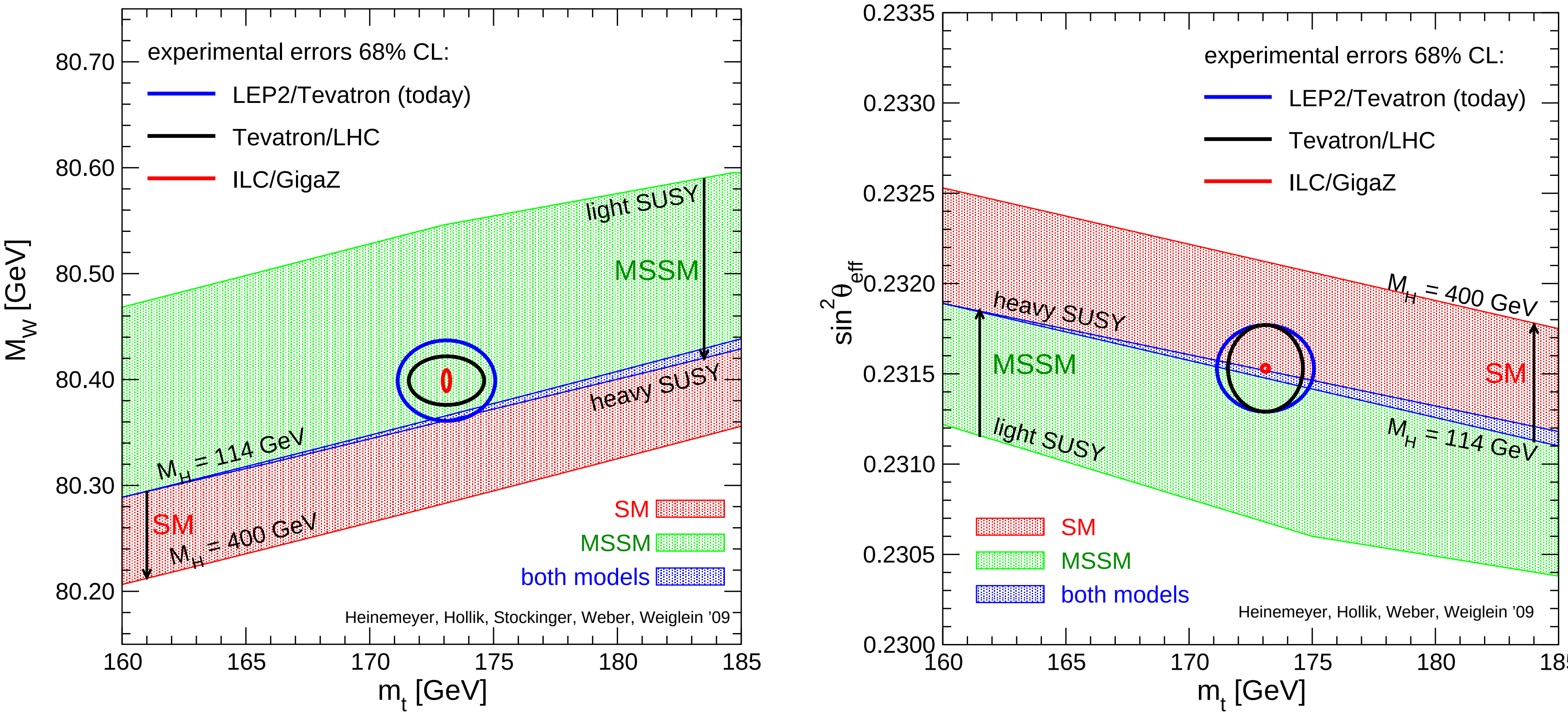


effective Z boson couplings

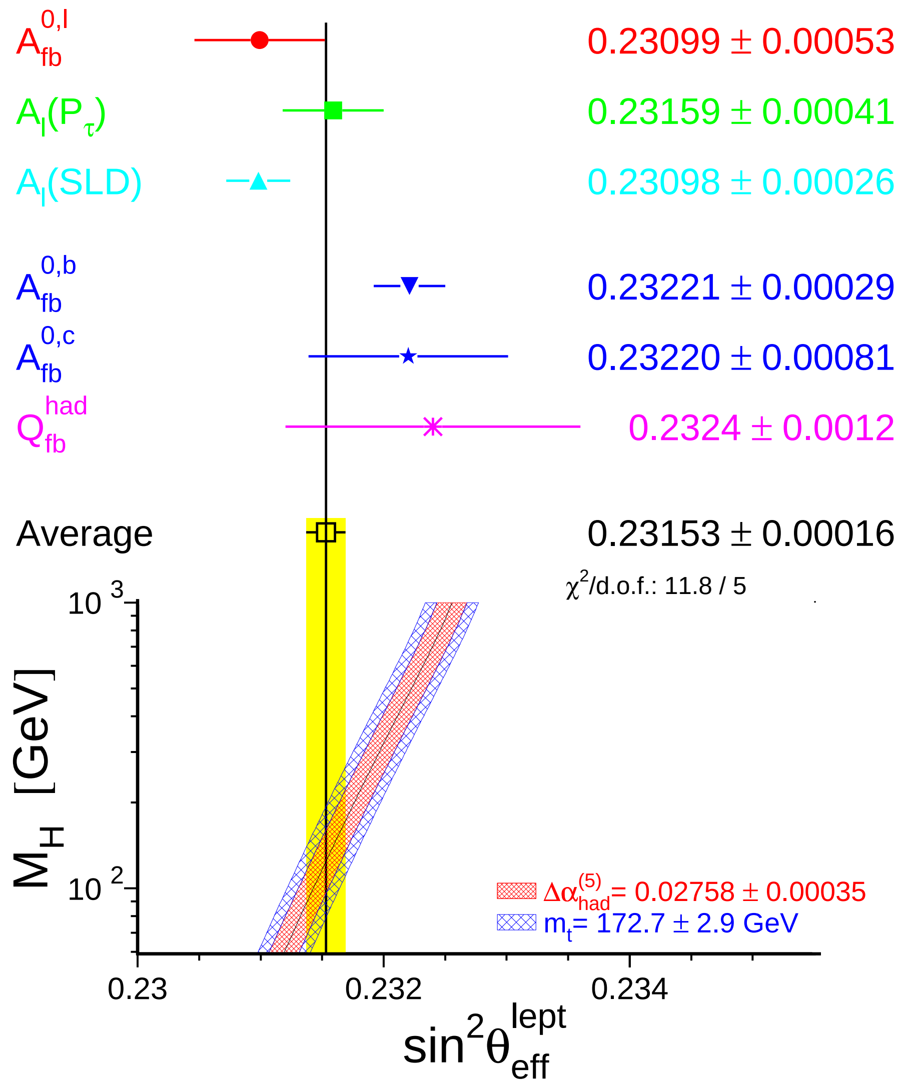
$$g_V^f \longrightarrow g_V^f + \Delta g_V^f, \qquad g_A^f \longrightarrow g_A^f + \Delta g_A^f$$

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

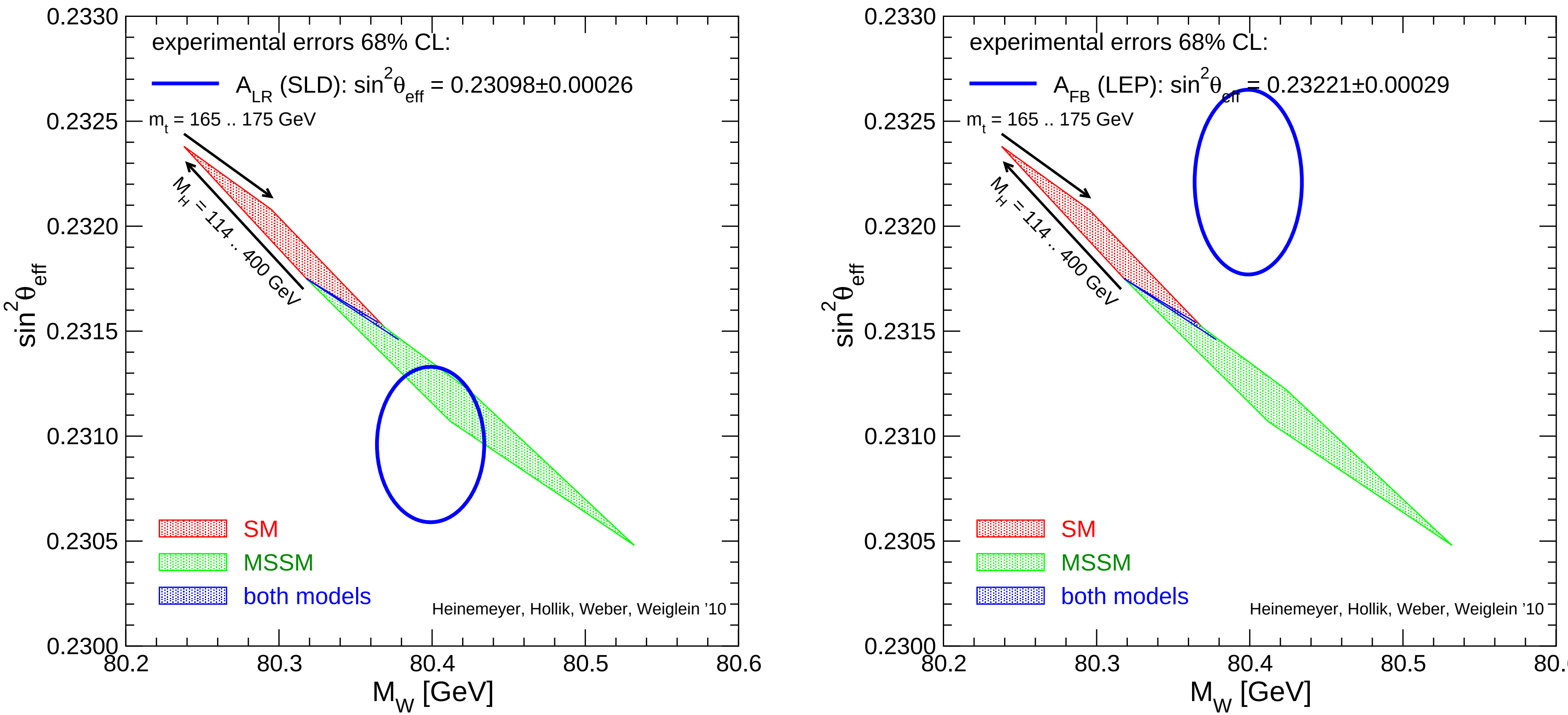
$$\sin^2\theta_{\mathrm{eff}} = \frac{1}{4}\left(1 - \mathrm{Re}\,\frac{g_V^e}{g_A^e}\right) = \kappa \cdot \left(1 - \frac{M_W^2}{M_Z^2}\right)$$



experimental errors 68% CL:
LEP2/Tevatron (today)
Tevatron/LHC
ILC/GigaZ
light SUSY
MSSM
heavy SUSY
M_H = 114 GeV
M_H = 400 GeV
SM
both models
Heinemeyer, Hollik, Stockinger, Weber, Weiglein '09
M_W [GeV]
m_t [GeV]
80.70
80.60
80.50
80.40
80.30
80.20
160
165
170
175
180
185
experimental errors 68% CL:
LEP2/Tevatron (today)
Tevatron/LHC
ILC/GigaZ
heavy SUSY
MSSM
light SUSY
M_H = 400 GeV
M_H = 114 GeV
SM
both models
Heinemeyer, Hollik, Weber, Weiglein '09
sin^2θ_eff
m_t [GeV]
0.2335
0.2330
0.2325
0.2320
0.2315
0.2310
0.2305
0.2300

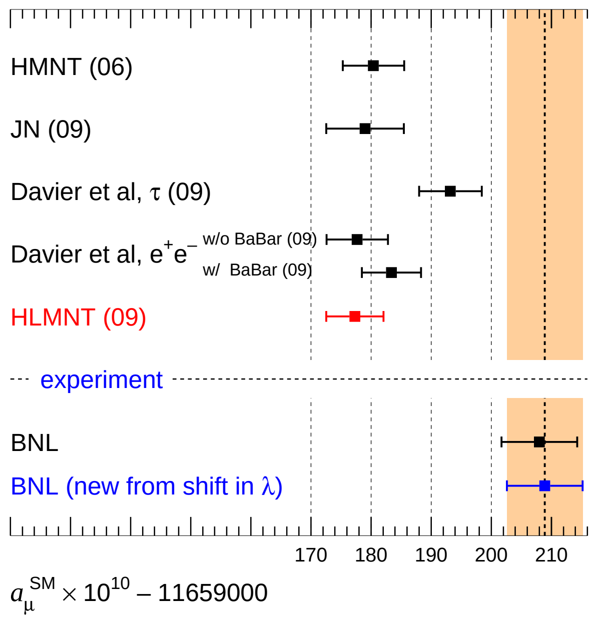


$A_{fb}^{0,l}$
0.23099 ± 0.00053
$A_l(P_\tau)$
0.23159 ± 0.00041
A_l(SLD)
0.23098 ± 0.00026
$A_{fb}^{0,b}$
0.23221 ± 0.00029
$A_{fb}^{0,c}$
0.23220 ± 0.00081
Q_{fb}^{had}
0.2324 ± 0.0012
Average
0.23153 ± 0.00016
χ^2/d.o.f.: 11.8 / 5
10^3
10^2
M_H [GeV]
$\Delta\alpha_{had}^{(5)}$ = 0.02758 ± 0.00035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



experimental errors 68% CL:
A_{LR} (SLD): $\sin^2\theta_{eff}$ = 0.23098±0.00026
m_t = 165 .. 175 GeV
M_H = 114 .. 400 GeV
SM
MSSM
both models
Heinemeyer, Hollik, Weber, Weiglein '10
$\sin^2\theta_{eff}$
M_W [GeV]
experimental errors 68% CL:
A_{FB} (LEP): $\sin^2\theta_{eff}$ = 0.23221±0.00029
m_t = 165 .. 175 GeV
M_H = 114 .. 400 GeV
SM
MSSM
both models
Heinemeyer, Hollik, Weber, Weiglein '10
$\sin^2\theta_{eff}$
M_W [GeV]

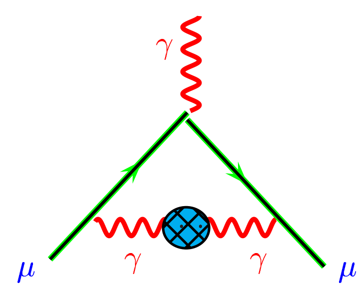
Anomalous g-factor of the muon



Hagiwara,Martin,Nomura,Teubner 2010

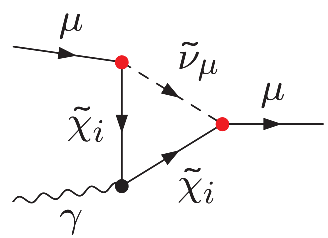
e^+e^- data based SM prediction: almost 4 σ below exp. value

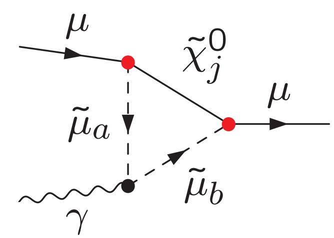
theory uncertainty from hadronic vacuum polarization



$g-2$ with supersymmetry

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





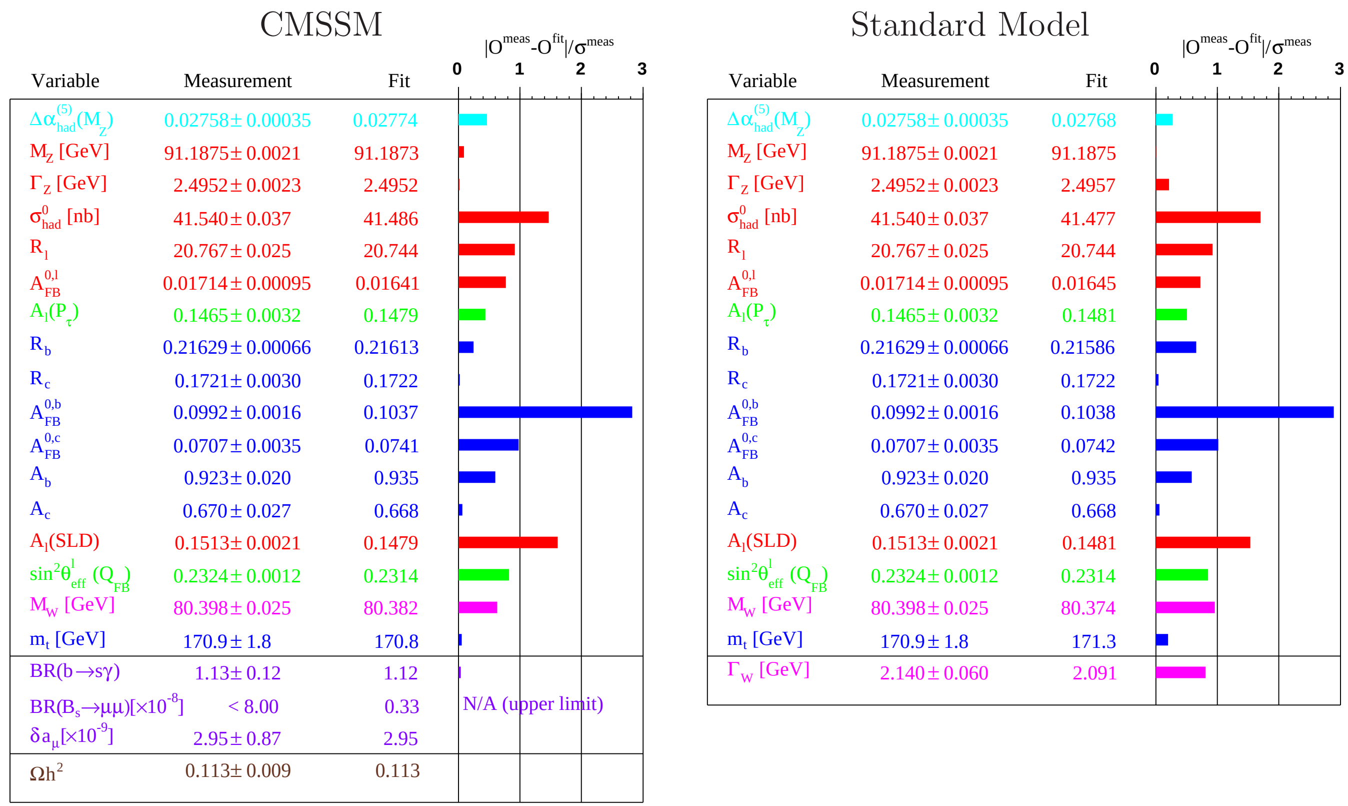
extra terms

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

can provide missing contribution for

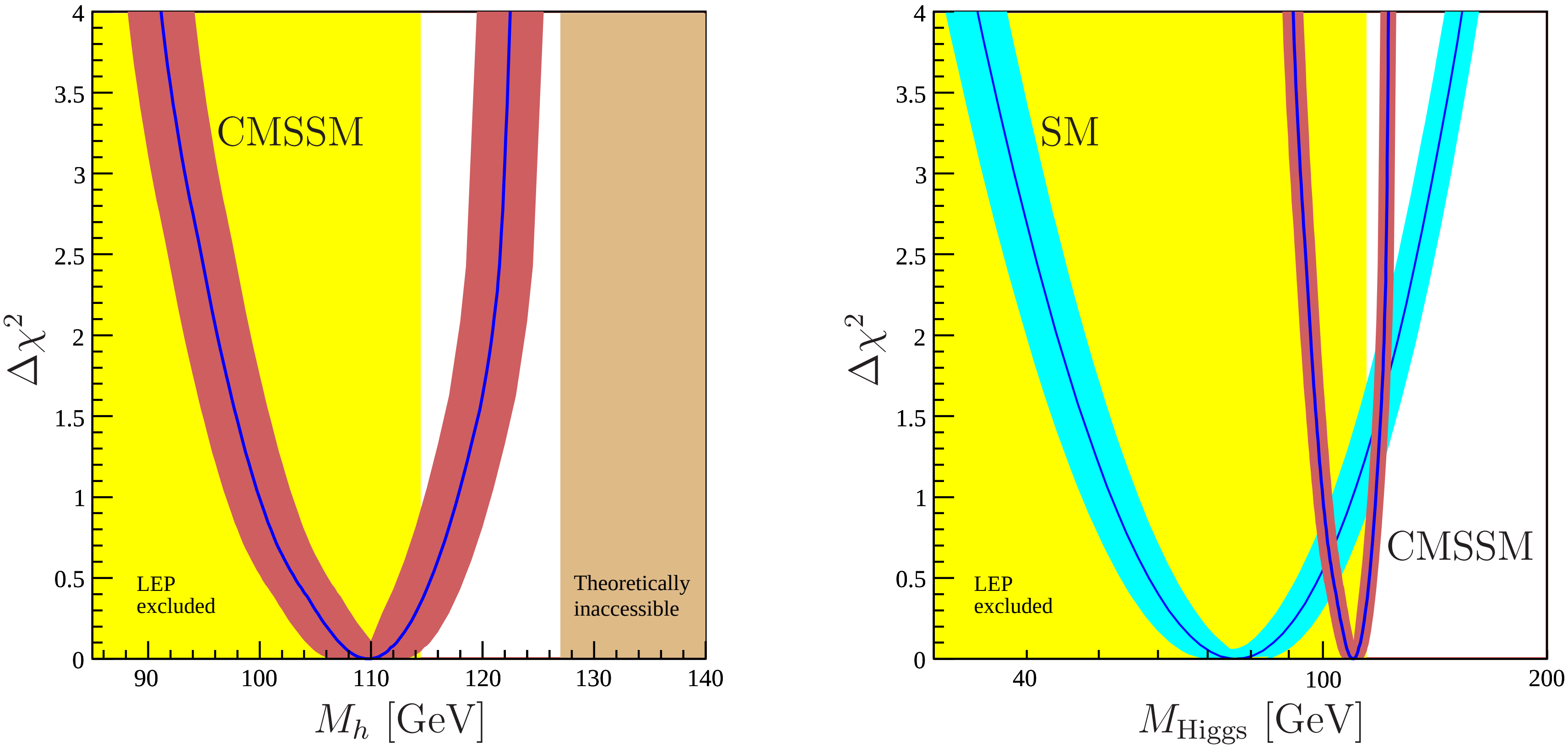
$$M_{\rm SUSY} = 200 - 600\,{\rm GeV}$$

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

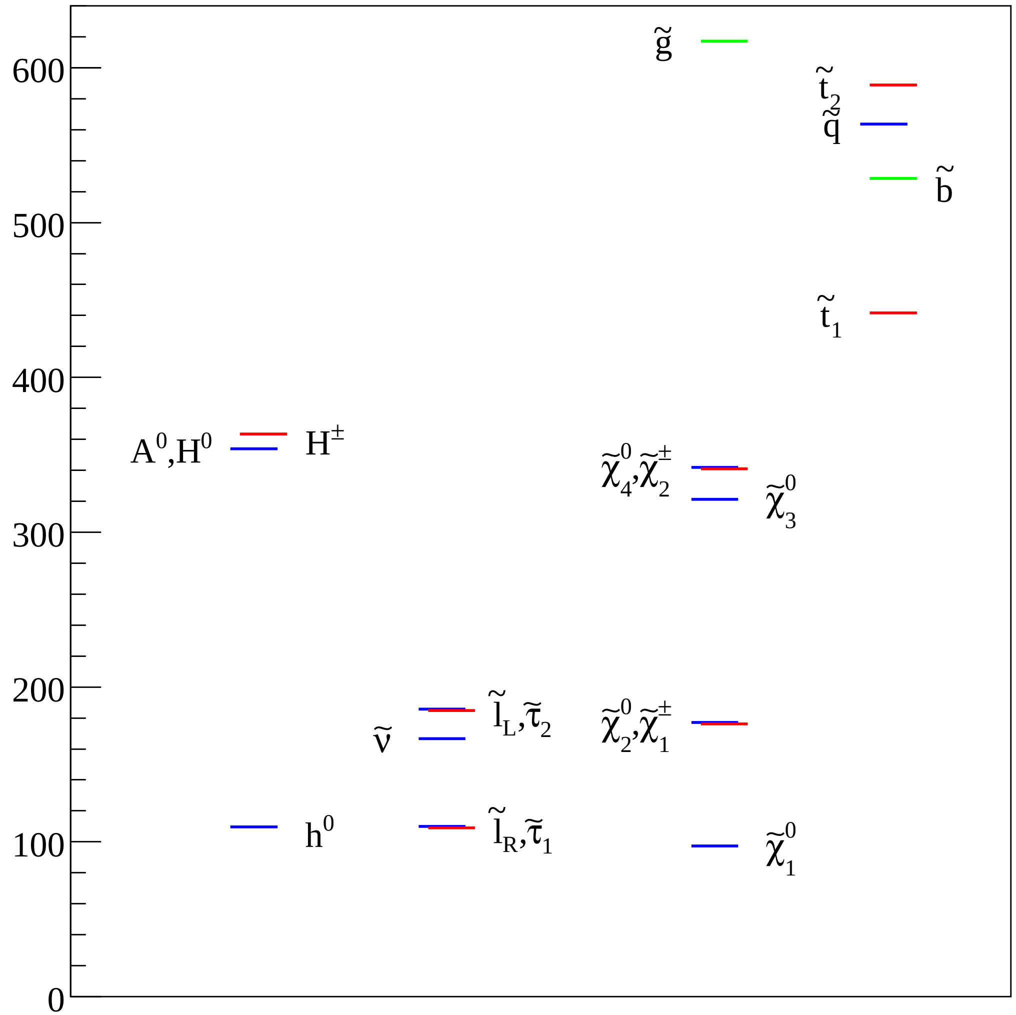


global fit in the constrained MSSM including data from $g-2$, B physics, and cosmic relic density

[O. Buchmueller, . . . , Weber, Weiglein, arXiv:0707.3447]



$$M_h = 110^{+8}_{-10}\ \text{GeV}$$



best fit particle spectrum

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