Electroweak Precision Physics from LEP to LHC and ILC

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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

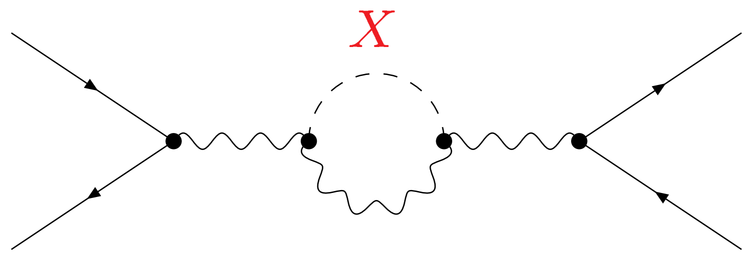
accurate theoretical predictions

- detect deviations $\rightarrow$ “new physics” ?
  precise predictions required

Outline

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

electroweak precision tests through quantum loops



sensitivity to unknown particles (X)

X = Higgs [+ non-standard]

precision observables

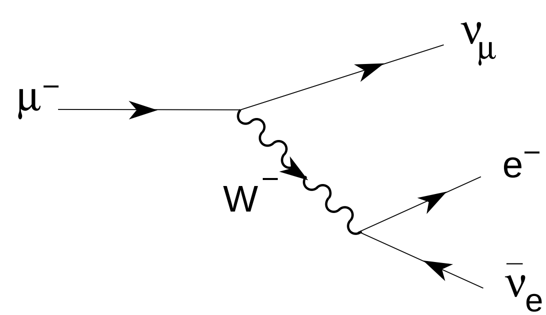
- μ lifetime: G_{F}
- Z observables: $M_Z,\, \Gamma_Z,\, g_V,\, g_A,\, \sin^2\theta_{\mathrm{eff}},\, \ldots$
- LEP 2, Tevatron: $M_W,\, m_t$
- low energies: $(g-2)_\mu$

$M_W - M_Z$ 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

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

Δr : quantum correction

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

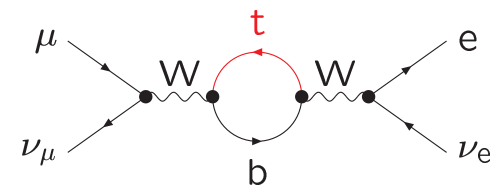
determines W mass

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

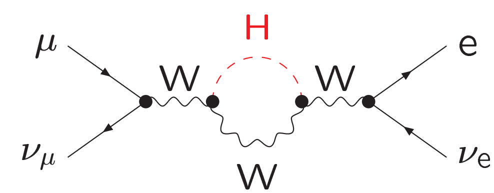
complete at 2-loop order

1-loop examples

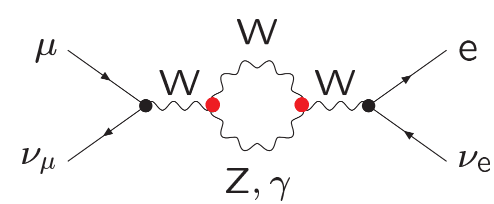
- top quark



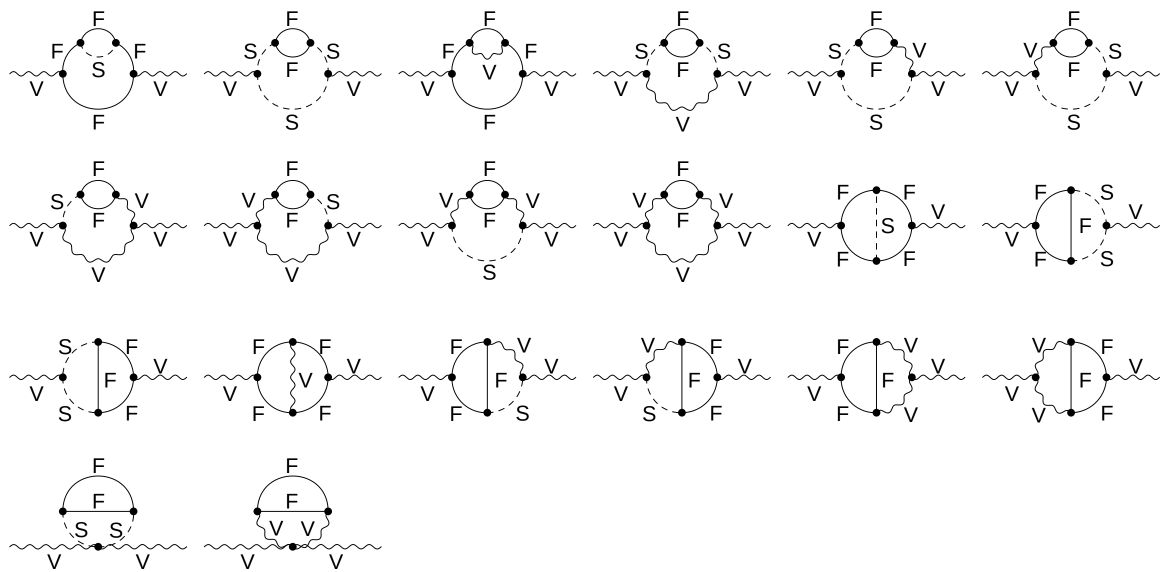
- Higgs boson

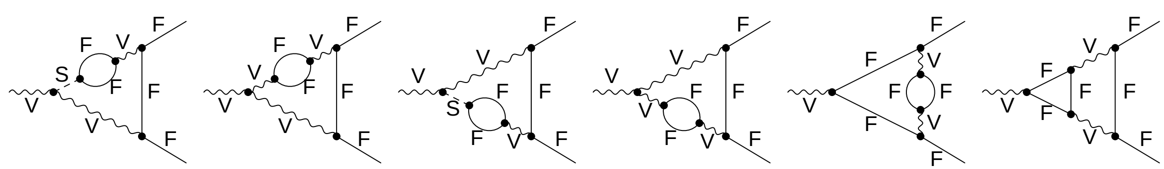


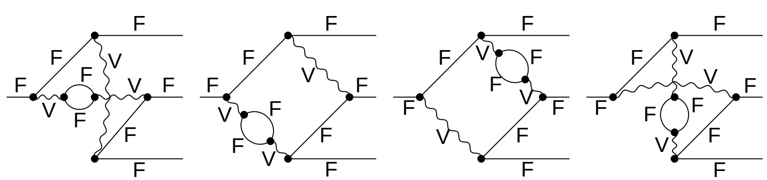
- gauge-boson self-couplings



full structure of SM

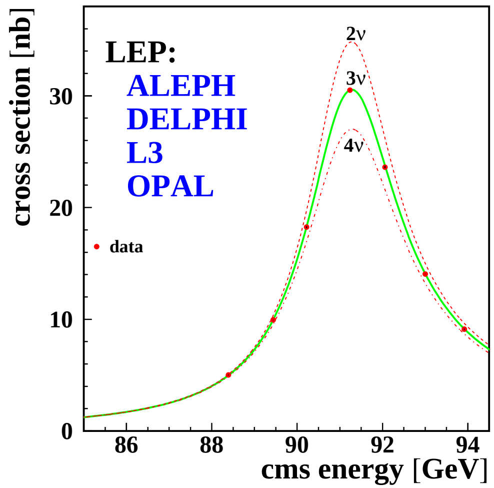


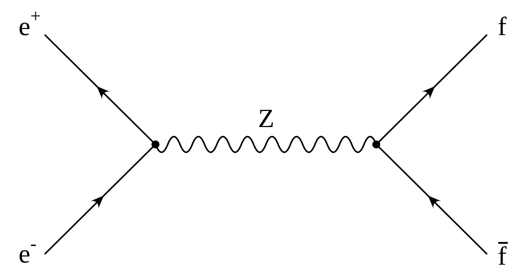




2-loop examples

Z resonance



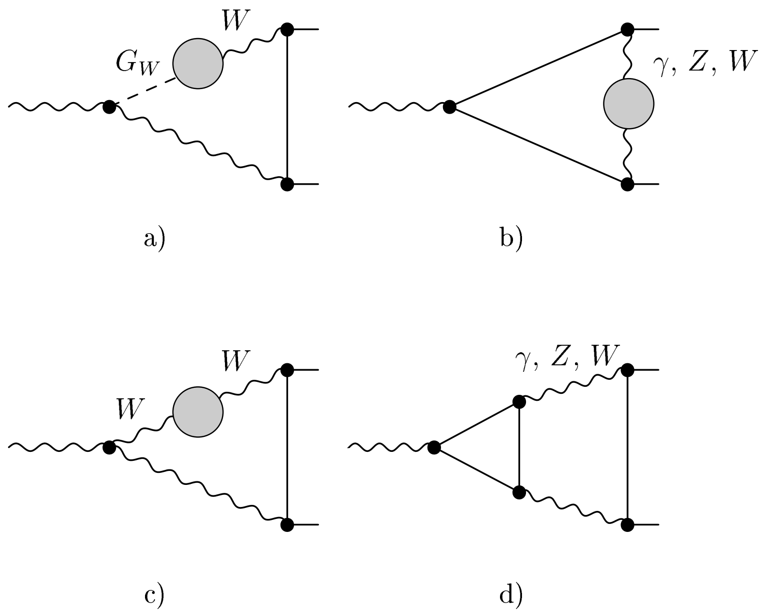


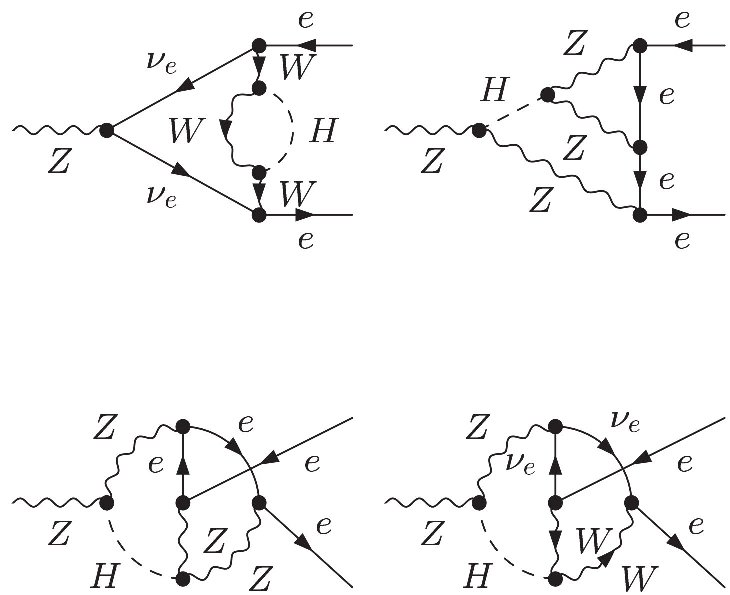
- effective Z boson couplings with higher-order $\Delta g_{V,A}$

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

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

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





2-loop examples for Z couplings

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

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

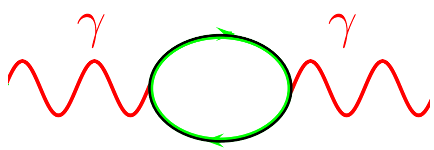
Schröder, Steinhauser

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

Boughezal, Czakon

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

photon vacuum polarization



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

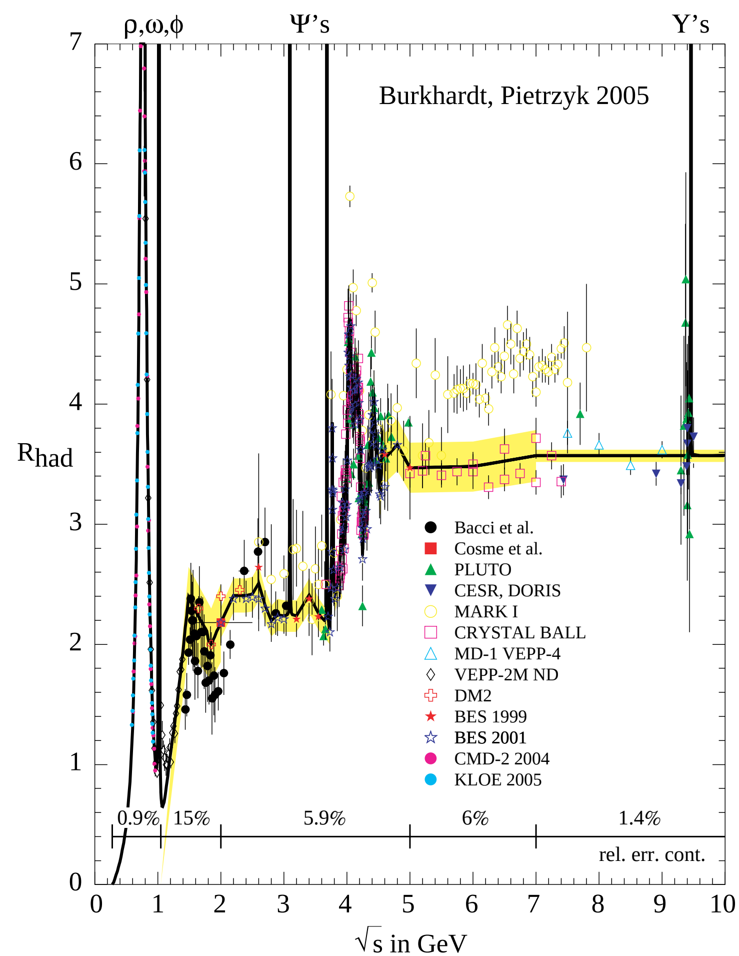
$$\begin{aligned} \Delta\alpha &= \Delta\alpha_{\rm lept} + \Delta\alpha_{\rm had}, \\ \Delta\alpha_{\rm lept} &= 0.031498 \quad (3 - {\rm loop}) \\ \Delta\alpha_{\rm had} &= 0.02758 \pm 0.00035 \end{aligned}$$

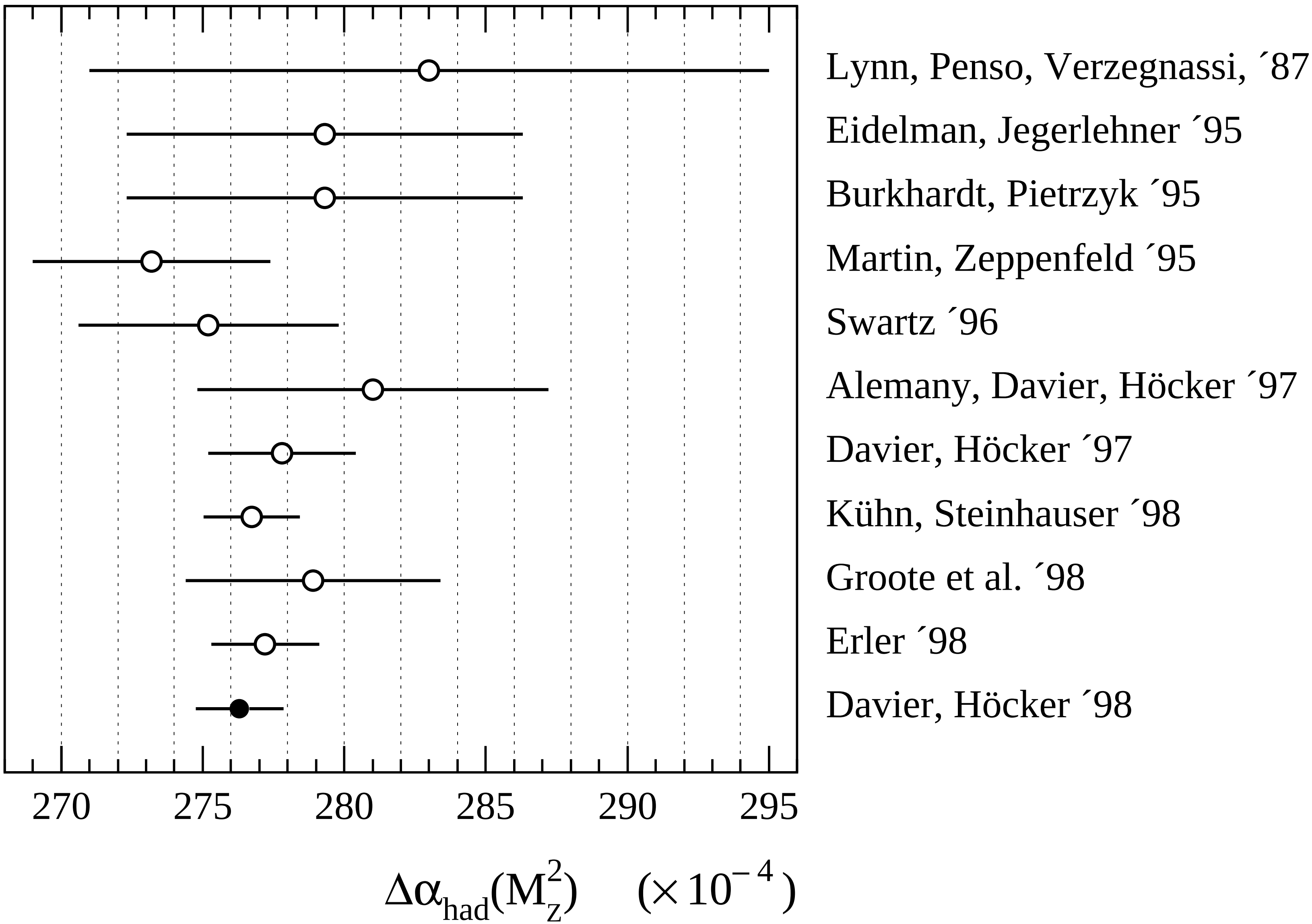
significant source of parametric uncertainty

$$\frac{\delta M_W}{M_W} \sim 0.23\ \delta\Delta\alpha, \qquad \frac{\delta \sin^2\theta}{\sin^2\theta} \sim 1.54\ \delta\Delta\alpha$$

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

$$R_{\rm had} = \frac{\sigma(e^+e^- \to \gamma^* \to \text{hadrons})}{\sigma(e^+e^- \to \gamma^* \to \mu^+\mu^-)}$$




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

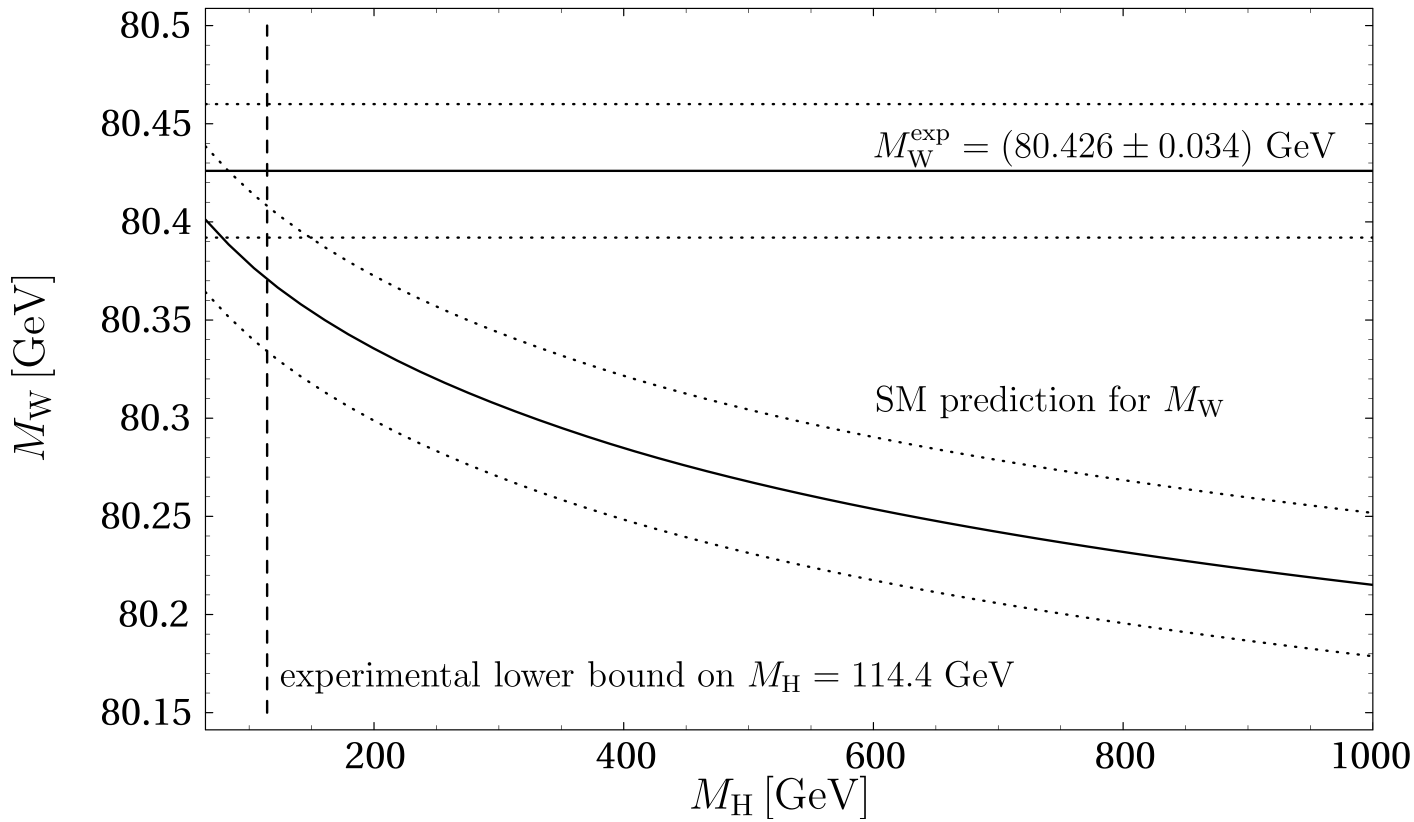
- low-energy experiments (μ decay, νN scattering, νe scattering, atomic parity violation, ...)

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%
$\sin^2\theta_{\rm eff}^{\rm lept}$	$= 0.23148 \pm 0.00017$	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

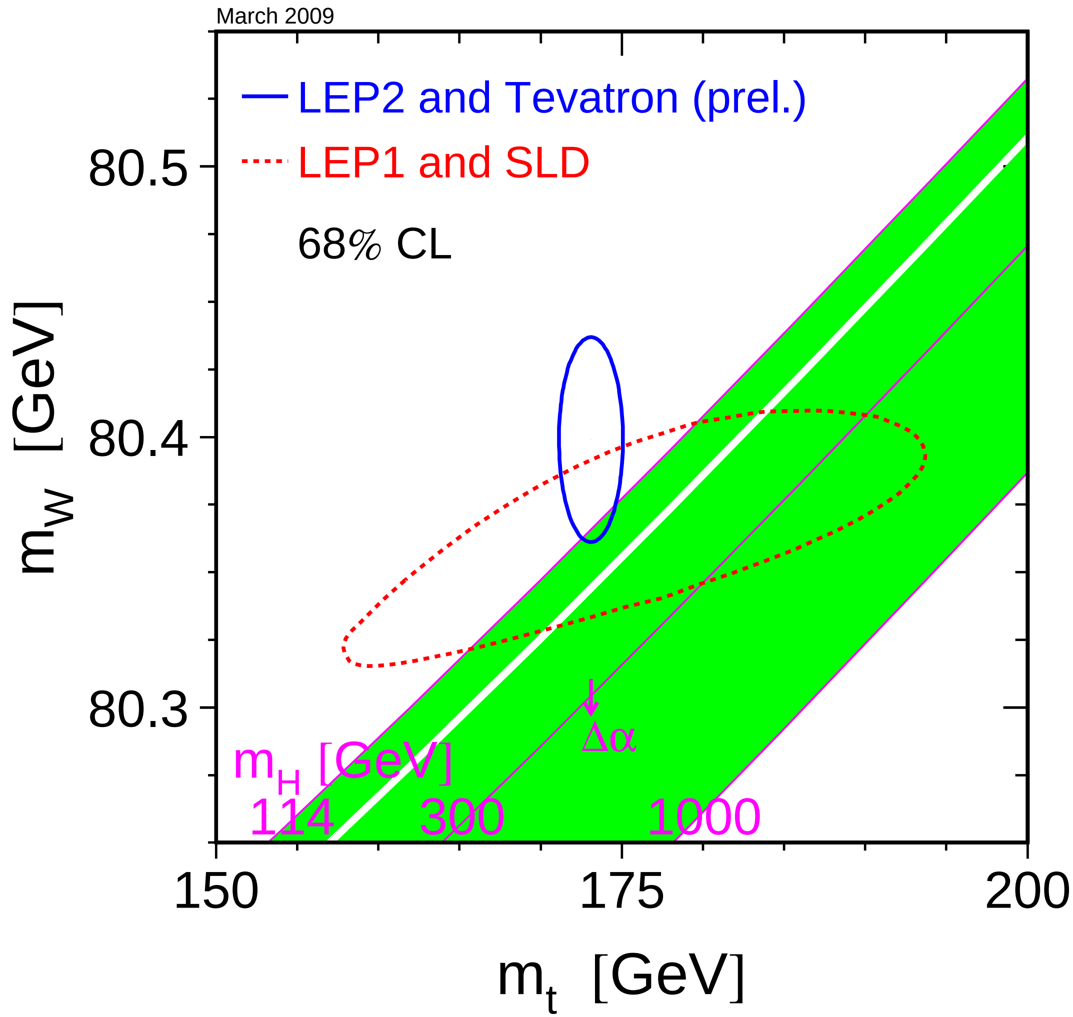


[Awramik, Czakon, Freitas, Weiglein] $m_t = 174.3 \pm 5.1$ GeV

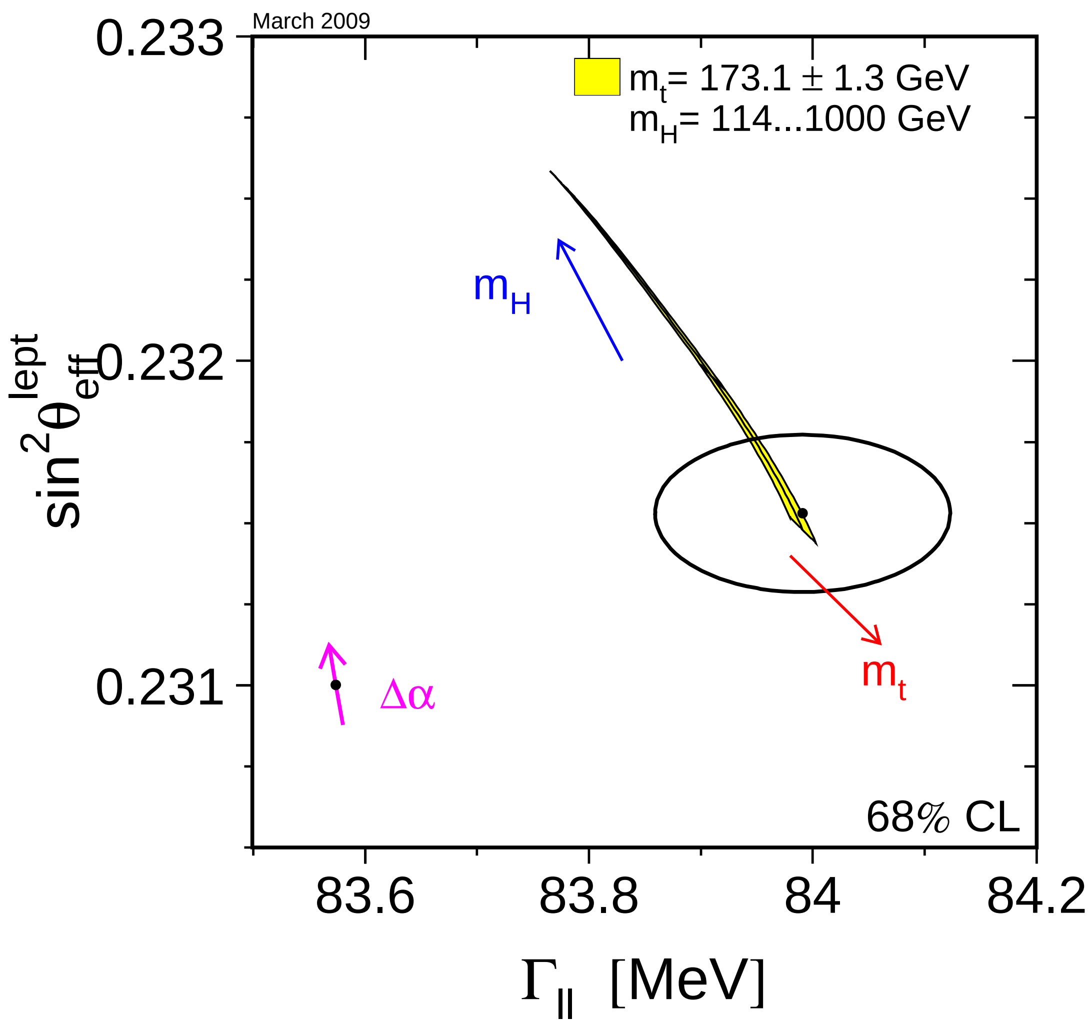
$$\delta M_W^{\text{theo}} \simeq 4\,\text{MeV}$$

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

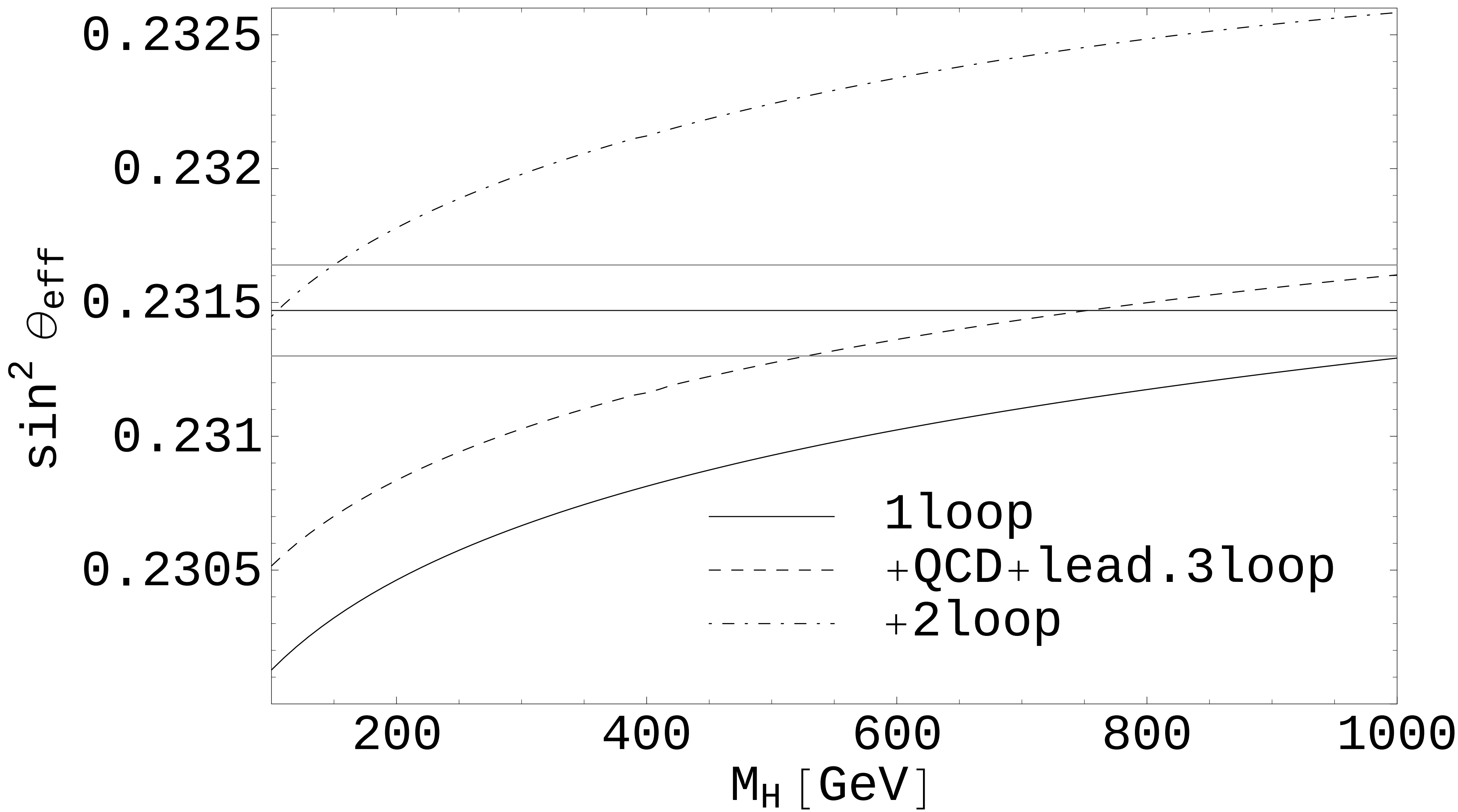
LEP Electroweak Working Group



LEP Electroweak Working Group



importance of two-loop calculations



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Z PHYSICS AT LEP 1

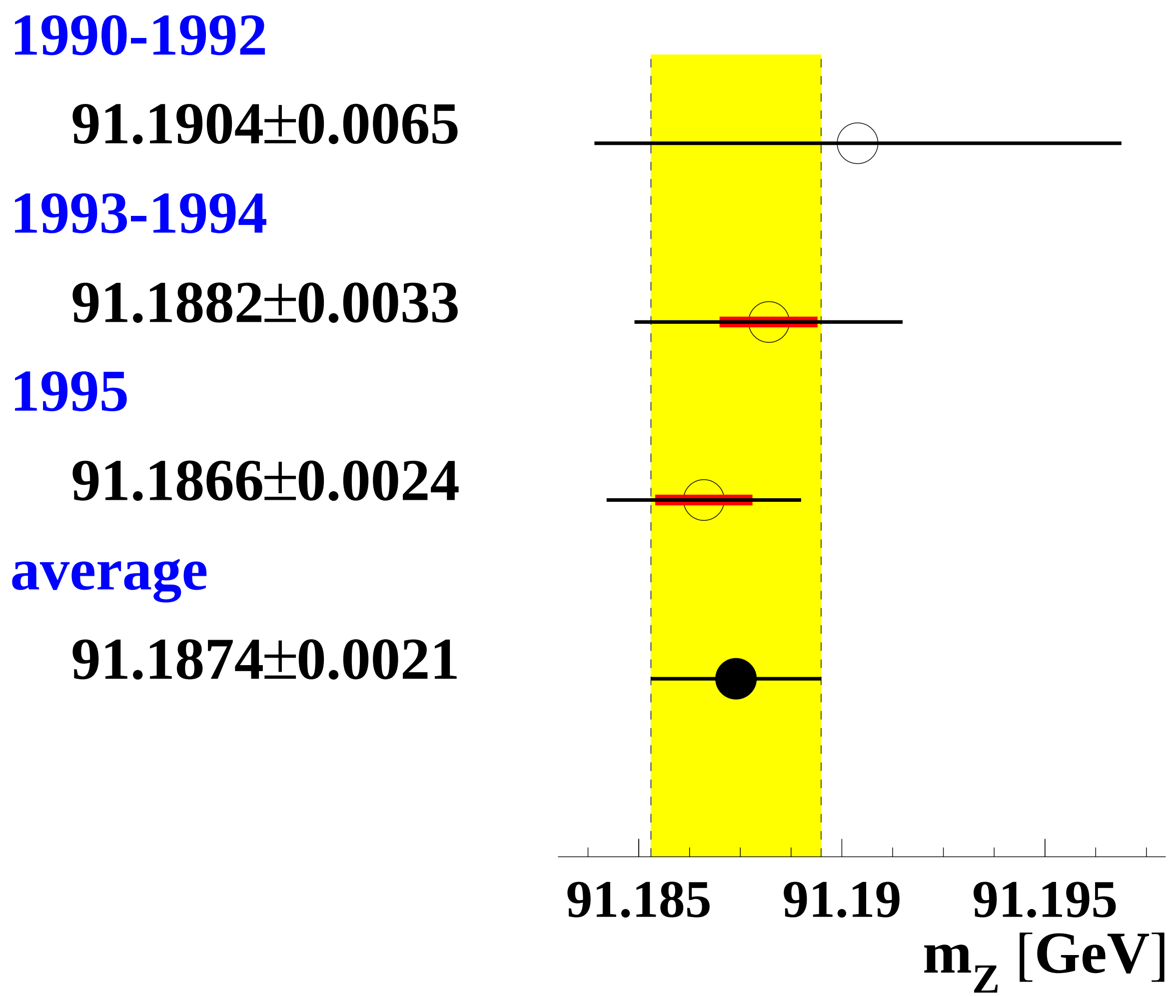
Edited by
Guido Altarelli, Ronald Kleiss and Claudio Verzegnassi

Volume 1: STANDARD PHYSICS

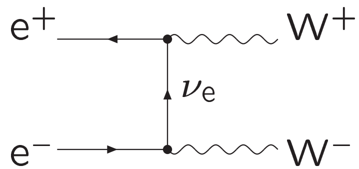
Co-ordinated and supervised by G. Altarelli

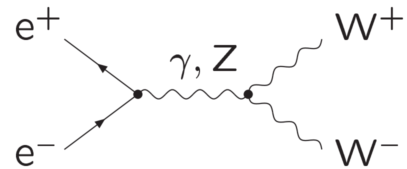
GENEVA
1989

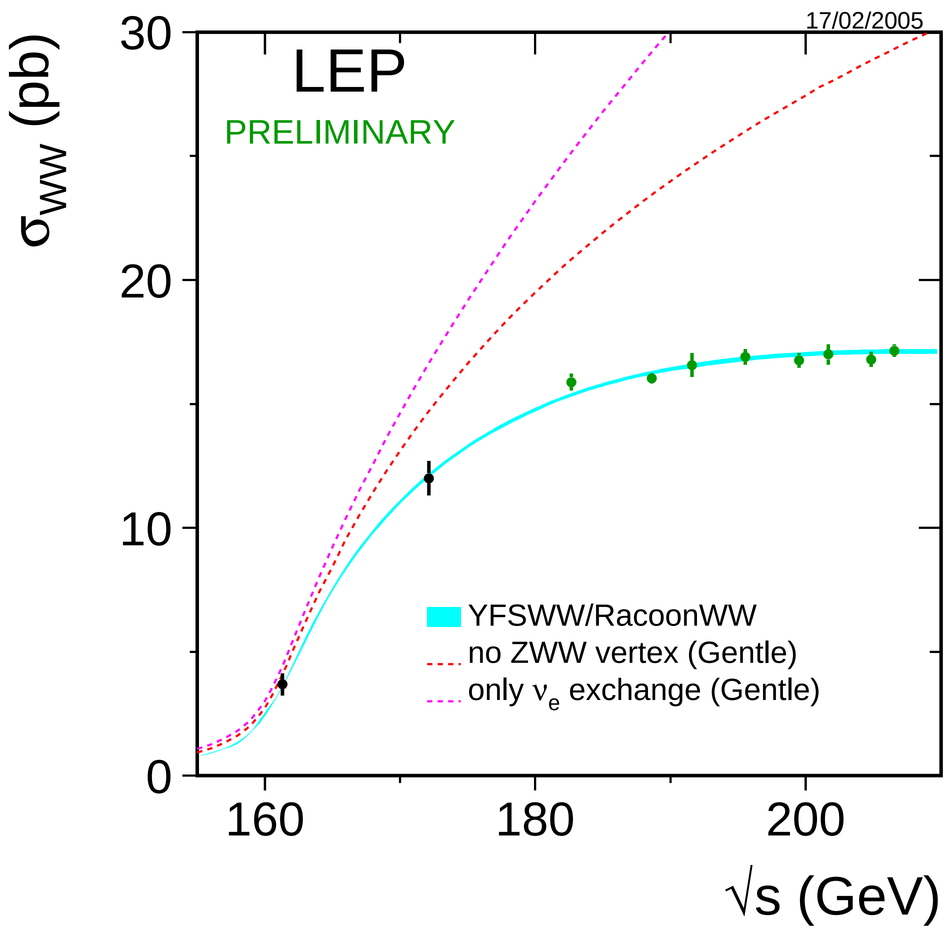
development of precision

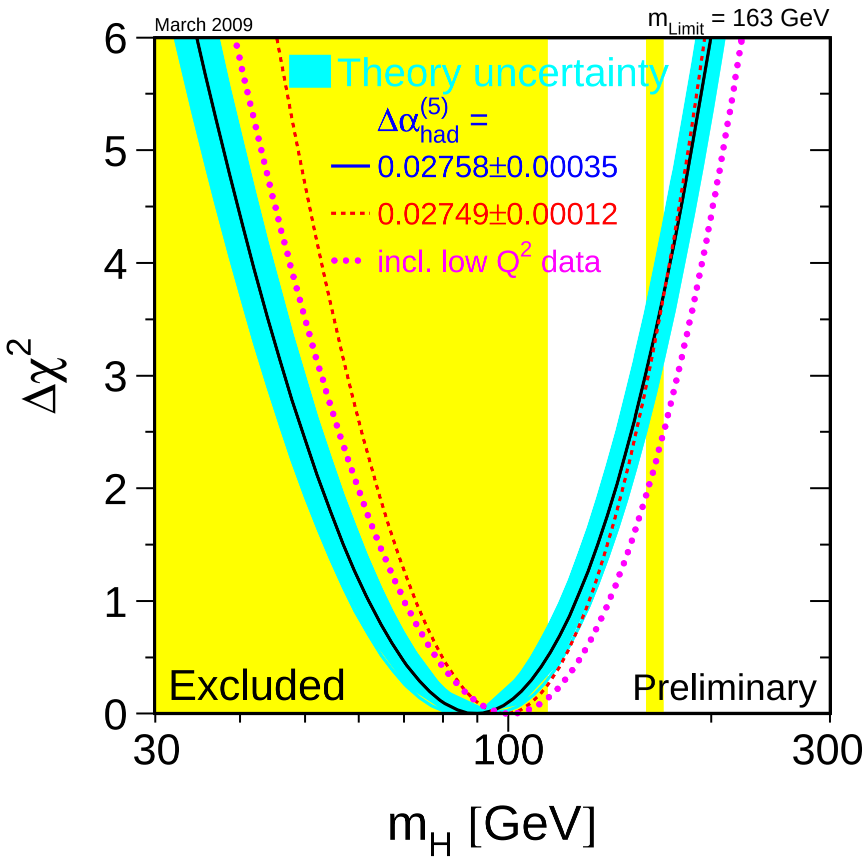


W-pair production









blueband: theory uncertainty

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

[Bardin, Hollik, Passarino (eds.)]

$$M_{\mathrm{H}} < 163\ \mathrm{GeV} \quad (95\%\mathrm{C.L.})$$

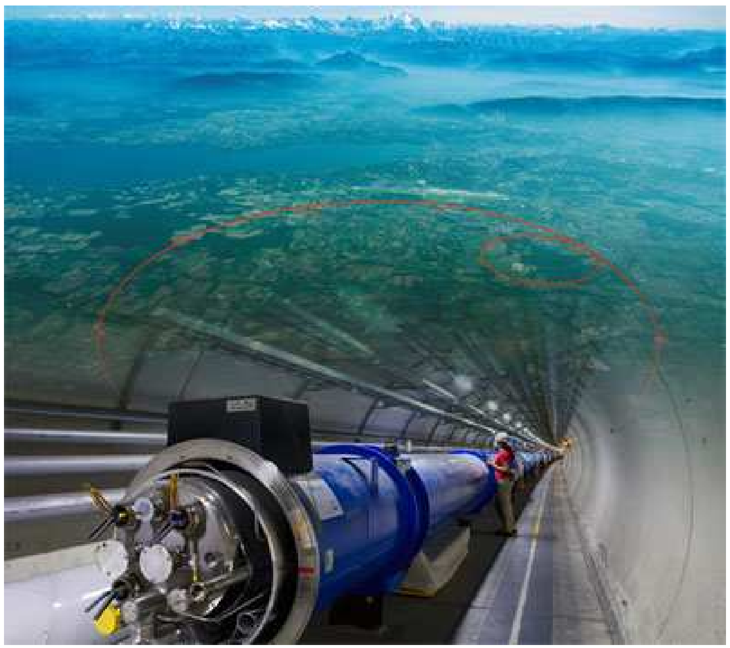
with renormalized probability for $M_{\mathrm{H}} > 114$ GeV:

$$M_{\mathrm{H}} < 191\ \mathrm{GeV} \quad (95\%\mathrm{C.L.})$$

Perspectives

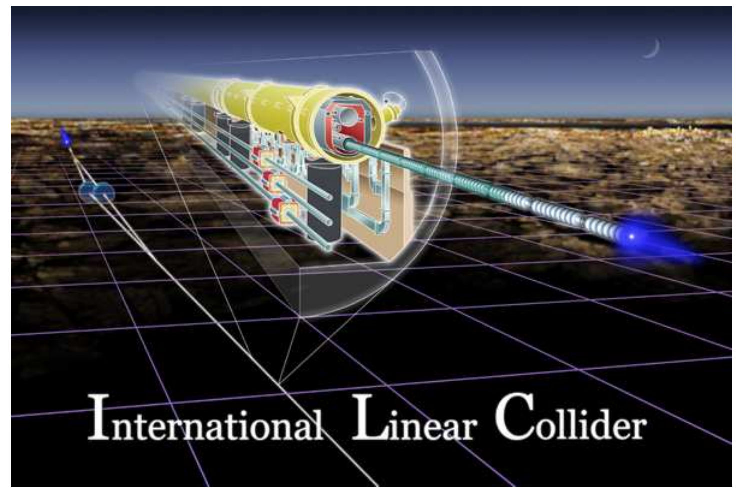
2008:

The Large Hadron Collider



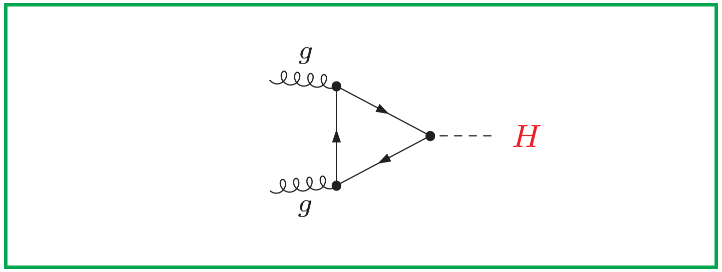
Future:

e^+e^- Linear Collider

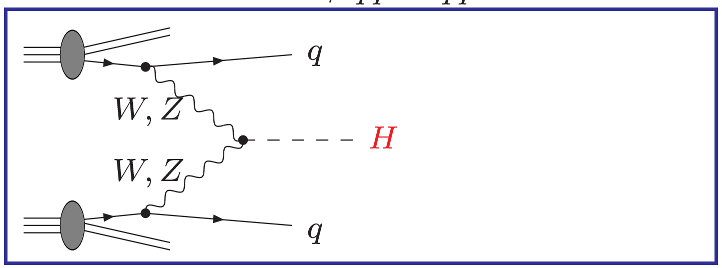


Higgs production at the LHC

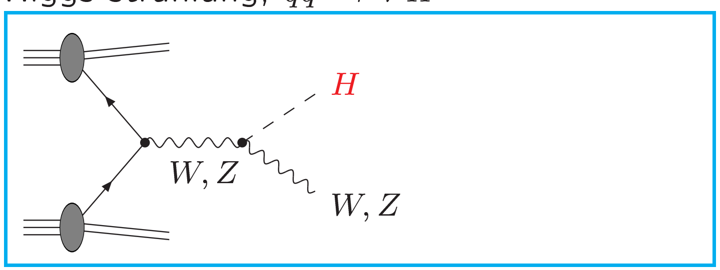
- gluon fusion, $gg \to H$



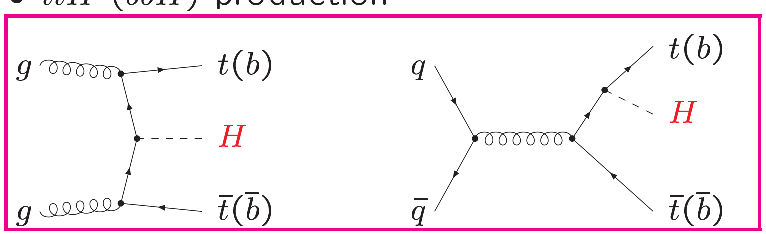
- vector boson fusion, $qq \to qqH$

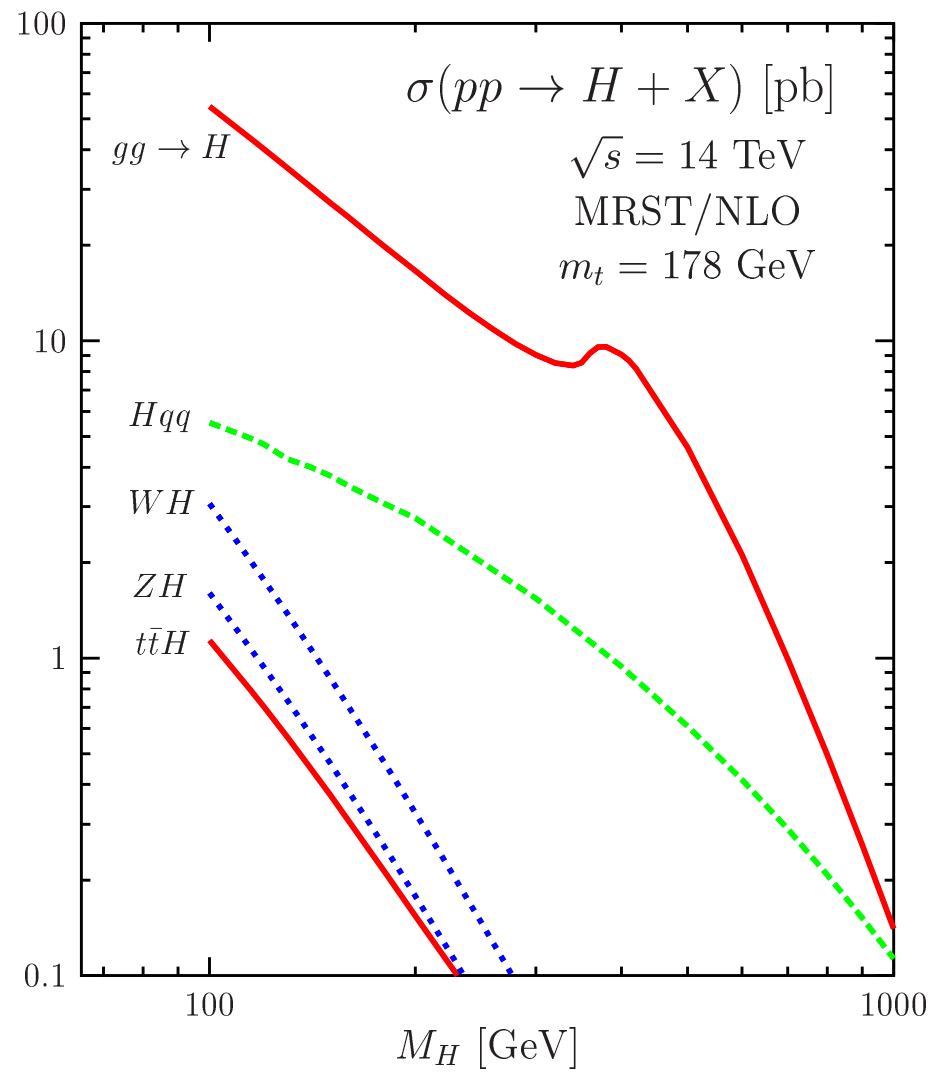


- Higgs strahlung, $q\bar{q}' \to VH$



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





(expected) experimental precision

error for	LEP/Tev	Tev/LHC	LC	LC/GigaZ
$M_W\,[\mathrm{MeV}]$	25	15	15	7
$\sin^2\theta_{\mathrm{eff}}$	0.00017	0.00021		0.000013
$m_{\mathrm{top}}\,[\mathrm{GeV}]$	1.3	1	0.2	0.13
$M_{\mathrm{Higgs}}\,[\mathrm{GeV}]$	–	0.1	0.05	0.05

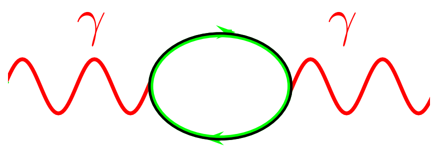
theory uncertainty:

$$\Delta M_W = 4\ \mathrm{MeV}, \quad \Delta \sin^2\theta_{\mathrm{eff}} = 5\cdot 10^{-5}$$

crucial parametric uncertainties for PO from

m_{top} and $\alpha_{\mathrm{em}}(M_Z)$

photon vacuum polarization



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

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

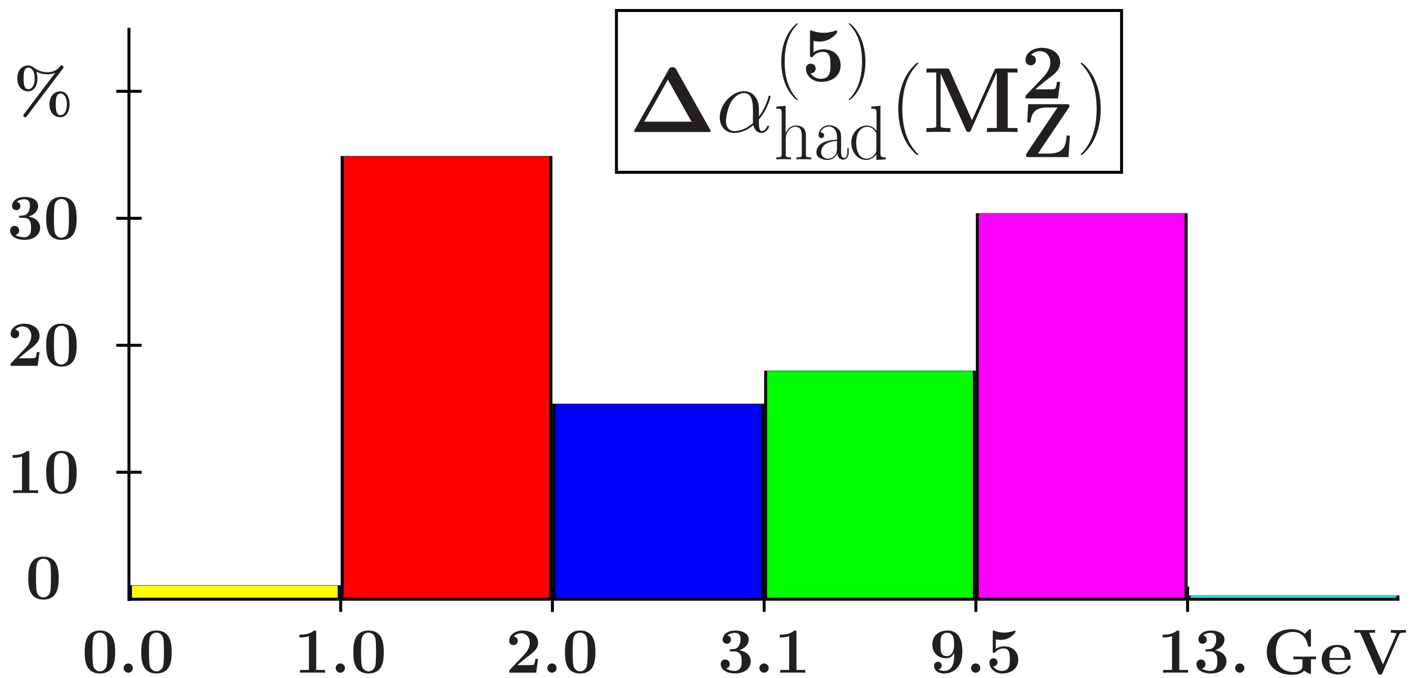
$$0.02749 \pm 0.00012 \quad \text{(QCD based)}$$

significant source of parametric uncertainty

$\frac{\delta M_W}{M_W} \sim 0.23\ \delta\Delta\alpha,$	$\frac{\delta \sin^2\theta}{\sin^2\theta} \sim 1.54\ \delta\Delta\alpha$
$\delta M_W = 6\,\text{MeV}$	$\delta \sin^2\theta = 0.00012$
$\delta M_W = 2\,\text{MeV}$	$\delta \sin^2\theta = 0.00004 \quad \text{(QCD based)}$

required for GigaZ precision: $\delta\Delta\alpha = 5 \cdot 10^{-5}$

distribution of uncertainties



[Jegerlehner]

M_W from Drell-Yan at the LHC

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

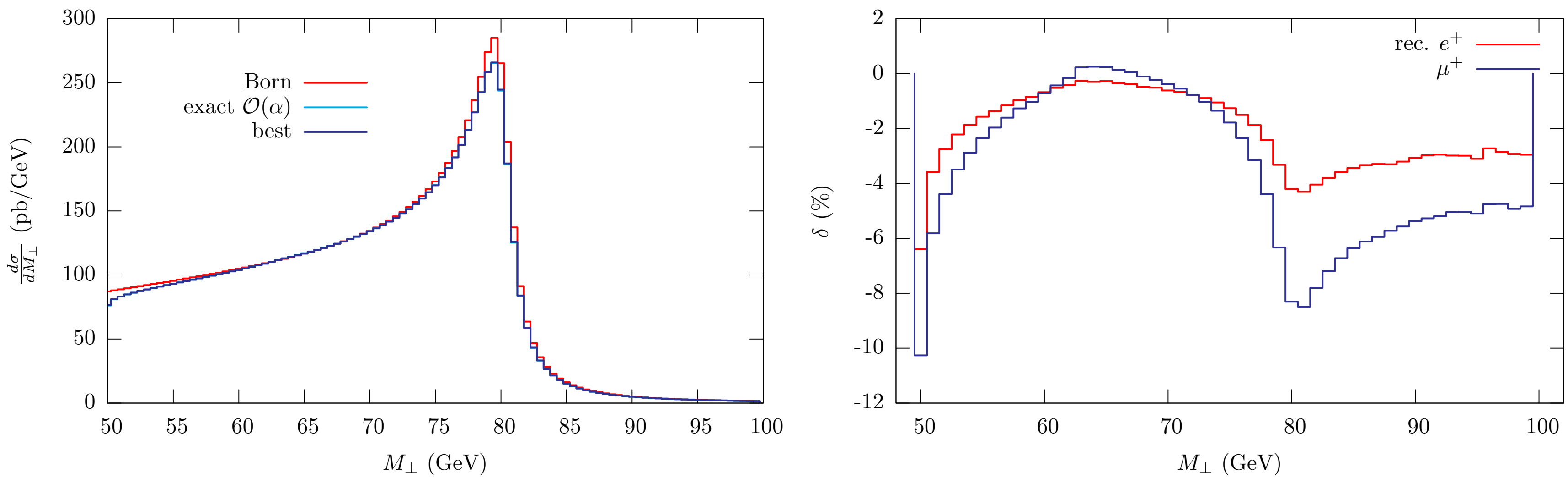


Fig. 1. Transverse mass distribution and $\mathcal{O}(\alpha)$ relative correction.

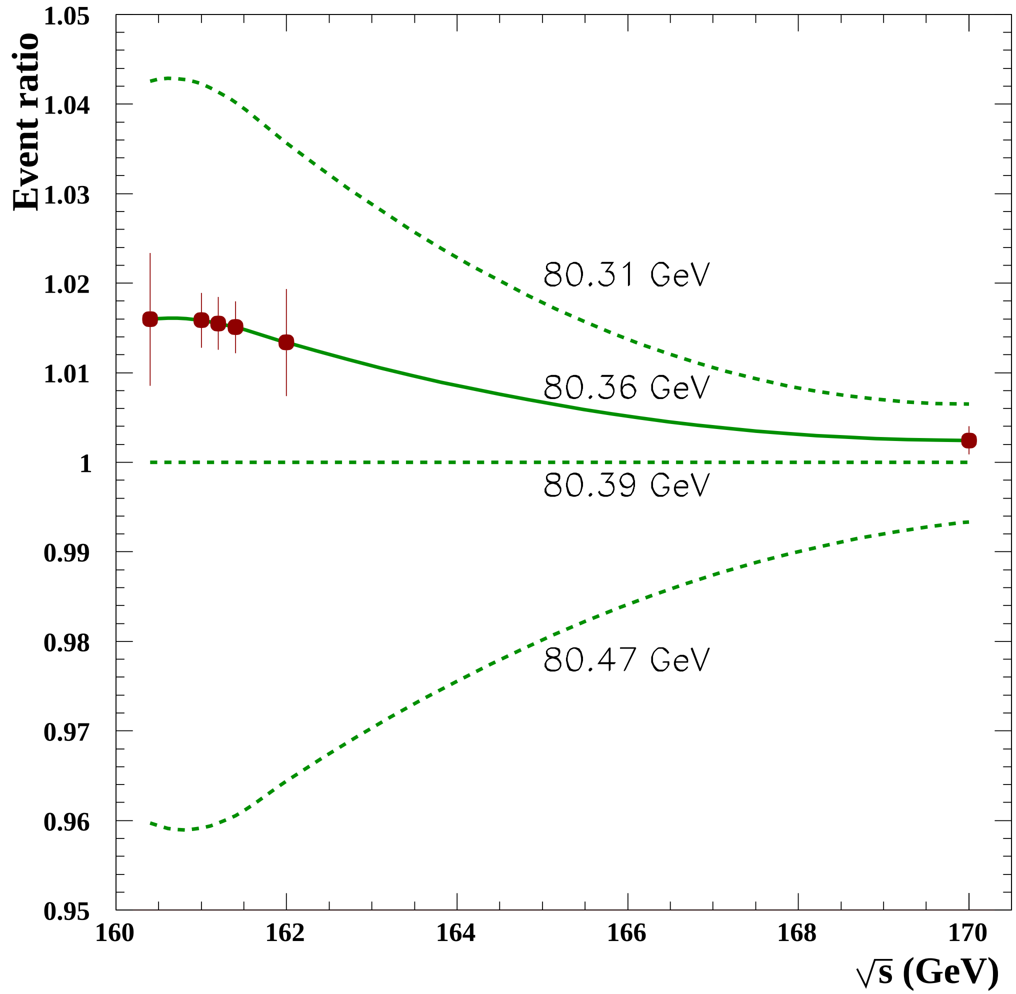
[Carloni Calame et al.]

[Baur, Wackeroth]

[Dittmaier, Krämer]

[Arbuzov et al.]

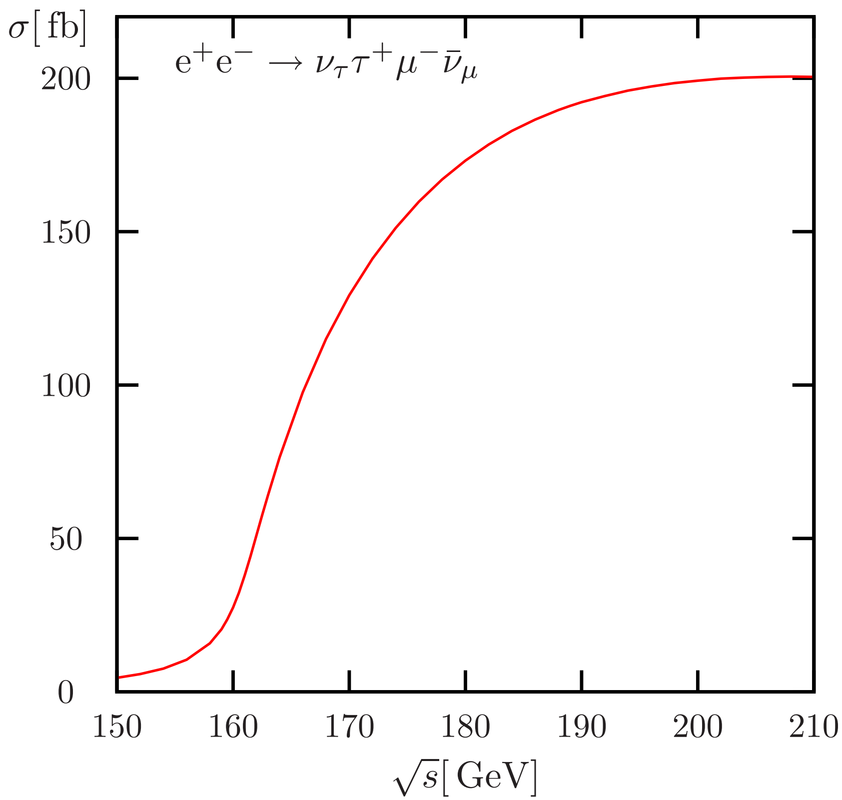
M_W from threshold scan in e^+e^- annihilation

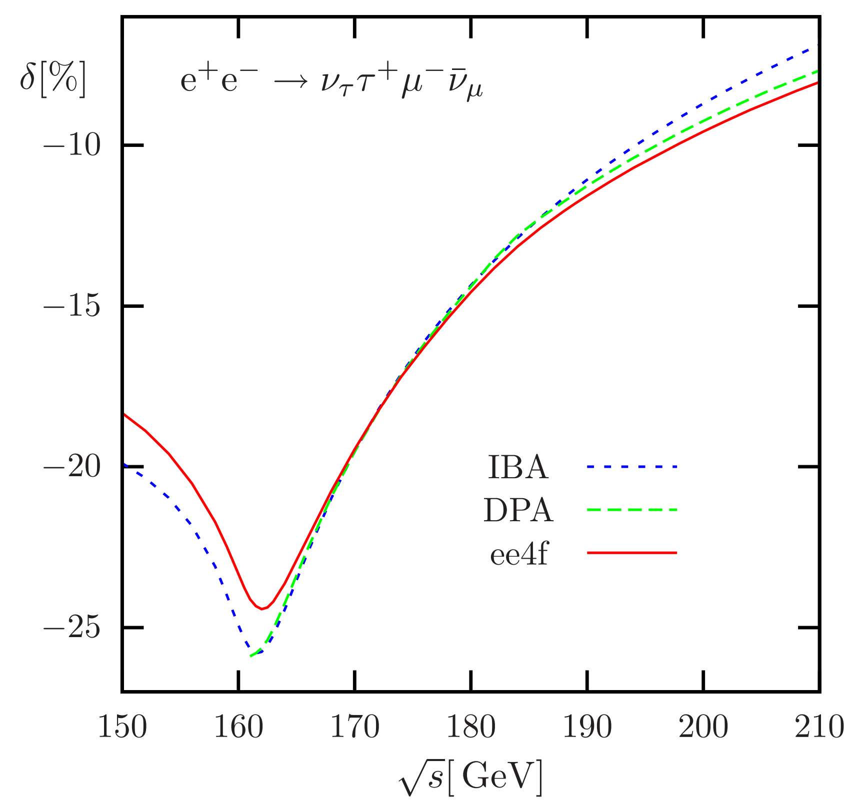


TESLA Technical Design Report (DESY 2001)

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

Denner, Dittmaier, Roth, Wieders '05

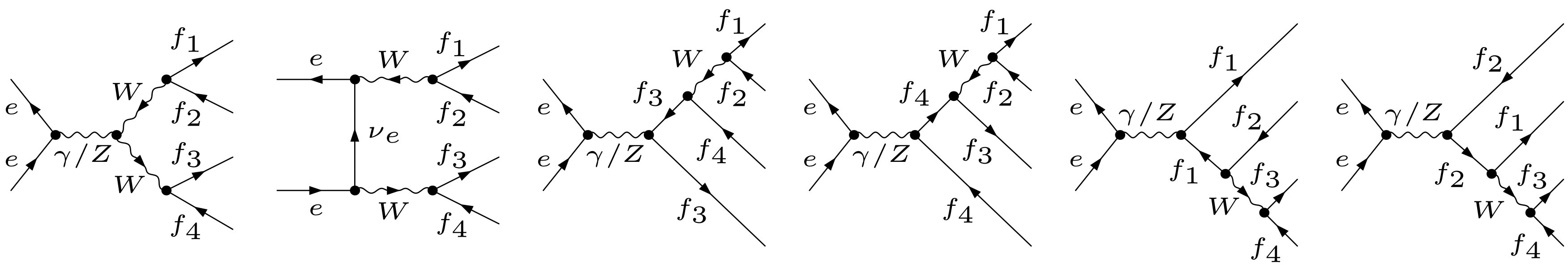




M_W from threshold $e^+e^- \to WW \to 4\,f$

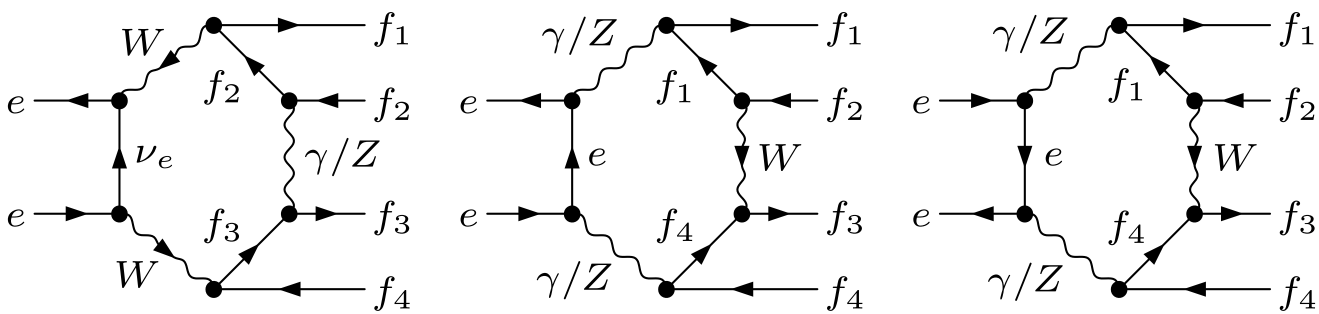
Some Feynman diagrams...

...for LO:



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

40 hexagons

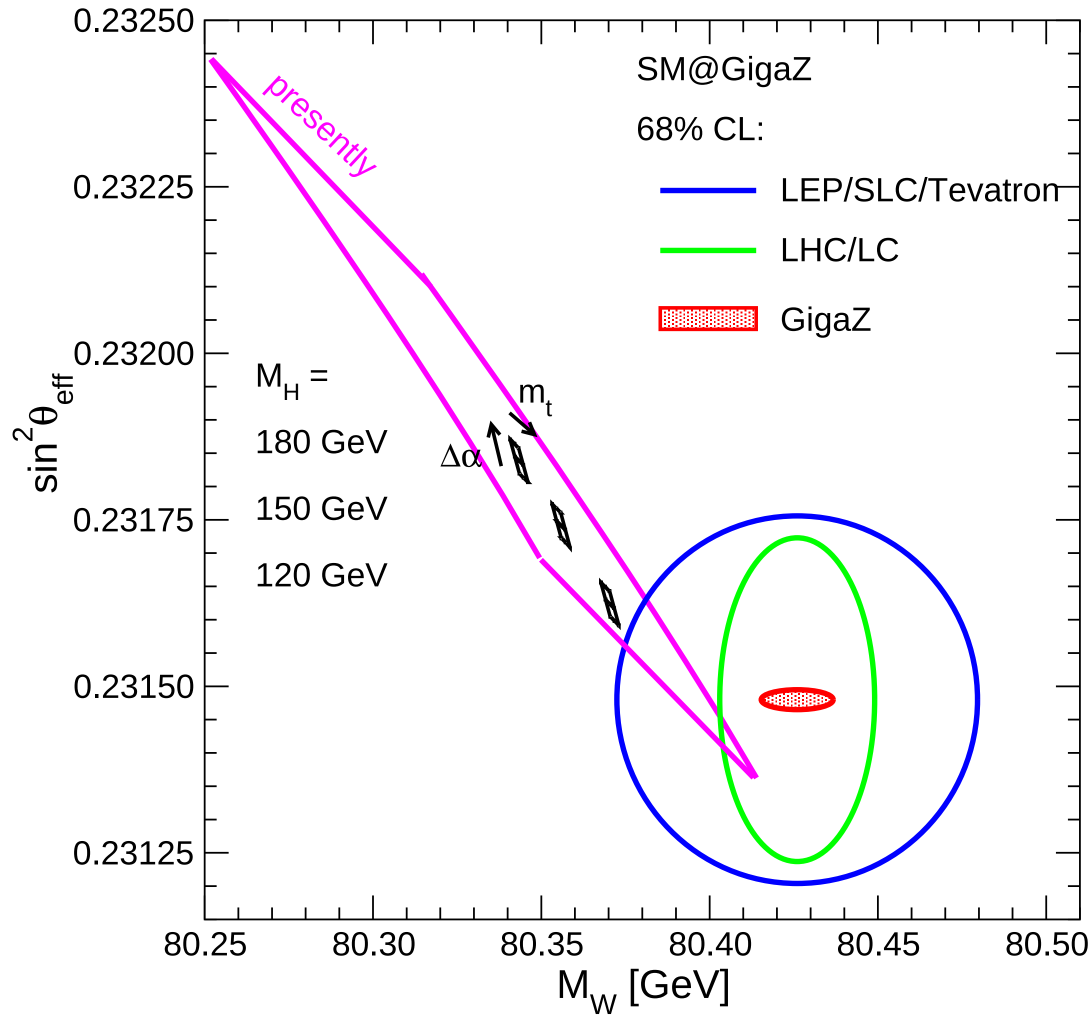


+ graphs with reversed fermion-number flow in final state

+ 112 pentagons

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

[Erler, Heinemeyer, Hollik, Weiglein, Zerwas]

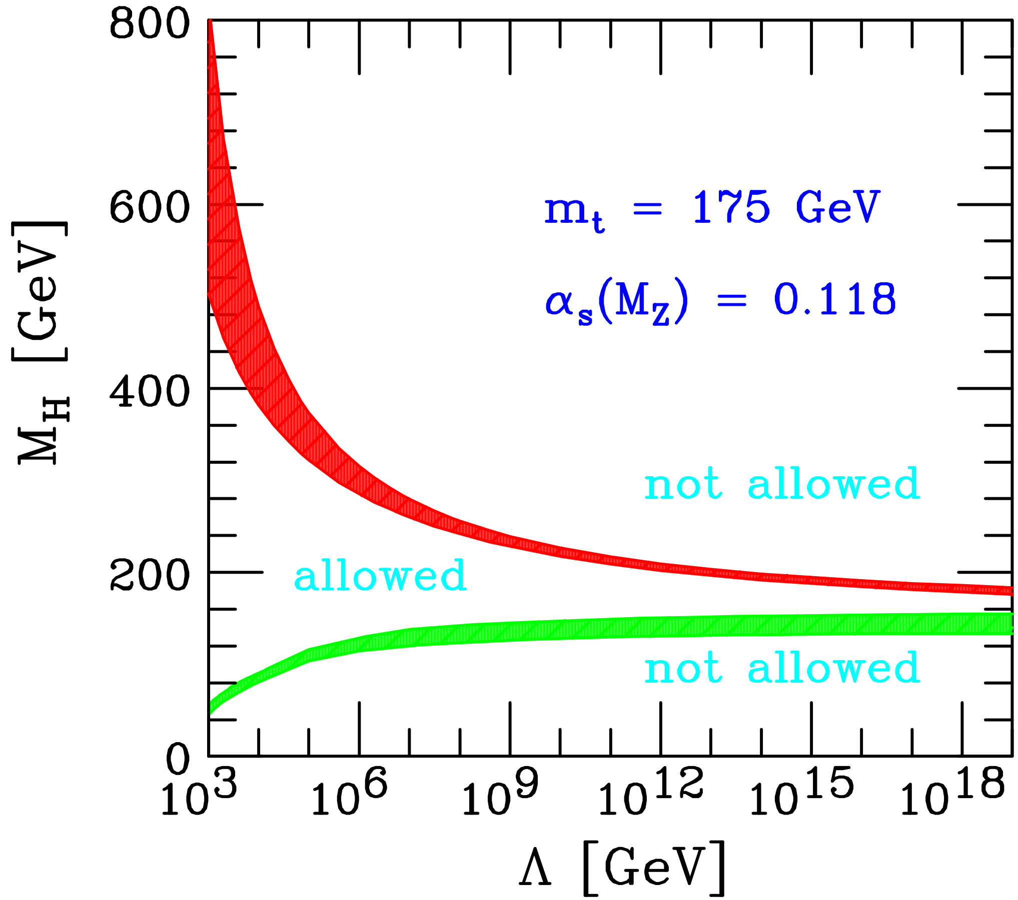


Theoretical bounds on Higgs boson mass from

- 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:

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

SUSY Standard Model 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

MSSM Higgs potential contains two Higgs doublets:

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

gauge couplings, in contrast to SM

Five physical states: $h^0, H^0, A^0, H^\pm$

Input parameters: $\tan\beta = \frac{v_2}{v_1}$, M_A

$\Rightarrow m_\mathrm{h}$, m_H, mixing angle α, $m_{\mathrm{H}^\pm}$: no free parameters coupling to vector bosons $V = W, Z$:

$$[h^0, H^0]VV = [\sin(\alpha - \beta), \cos(\alpha - \beta)] \cdot [\mathrm{SM}]$$

coupling to fermions $(u \to H_2,\ d \to H_1)$:

$$[h^0, H^0]bb = [\frac{\sin\alpha}{\cos\beta},\ \frac{\cos\alpha}{\cos\beta}][\mathrm{SM}], \quad [h^0, H^0]tt = [\frac{\cos\alpha}{\sin\beta},\ \frac{\sin\alpha}{\sin\beta}][\mathrm{SM}]$$

$$A\,bb = \tan\beta\,[\mathrm{SM}] \qquad A\,tt = \cot\beta\,[\mathrm{SM}]$$

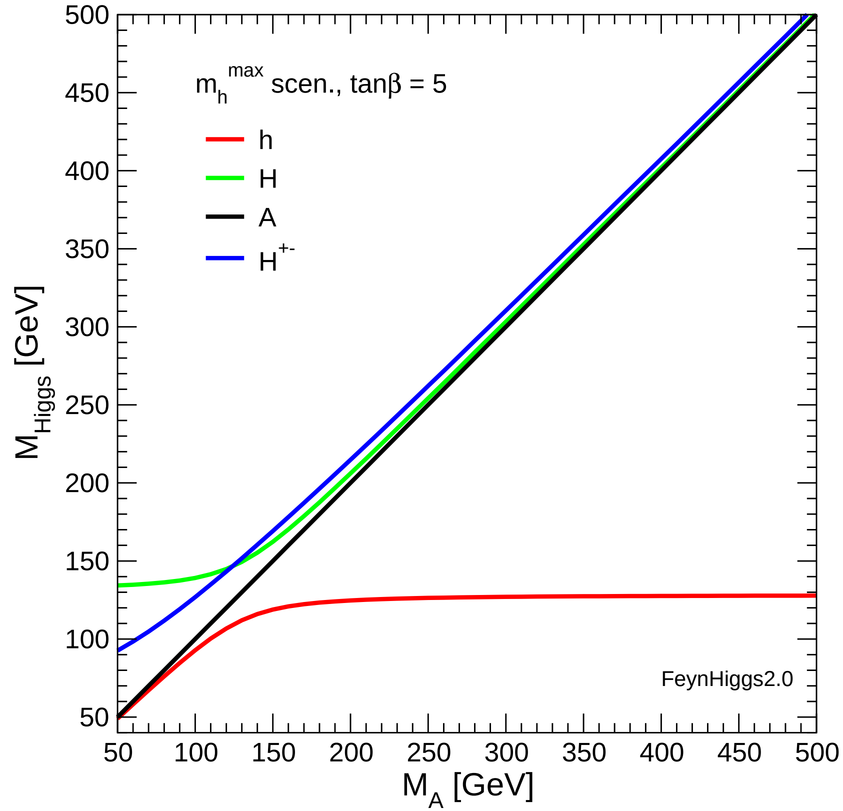
large M_A: h^0 is SM-like

H^0, A^0 have non-standard couplings

$m_H \sim m_A \sim m_{H^\pm} \gg m_Z,\ \alpha \to \beta - \frac{\pi}{2}$: 'decoupling regime'

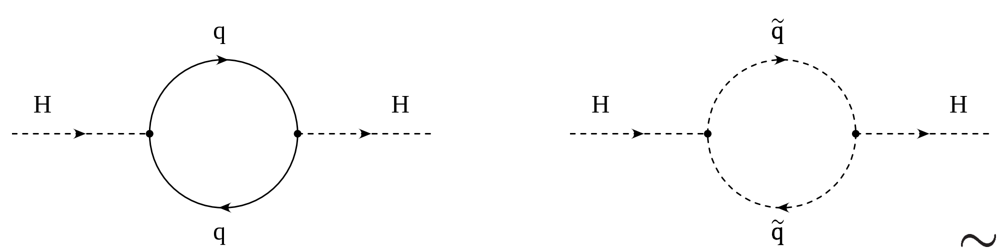
$m_h \to M_Z + \Delta m_h$ with large loop contributions Δm_h

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 $\sim \alpha_s\alpha_t,\ \alpha_s\alpha_b$

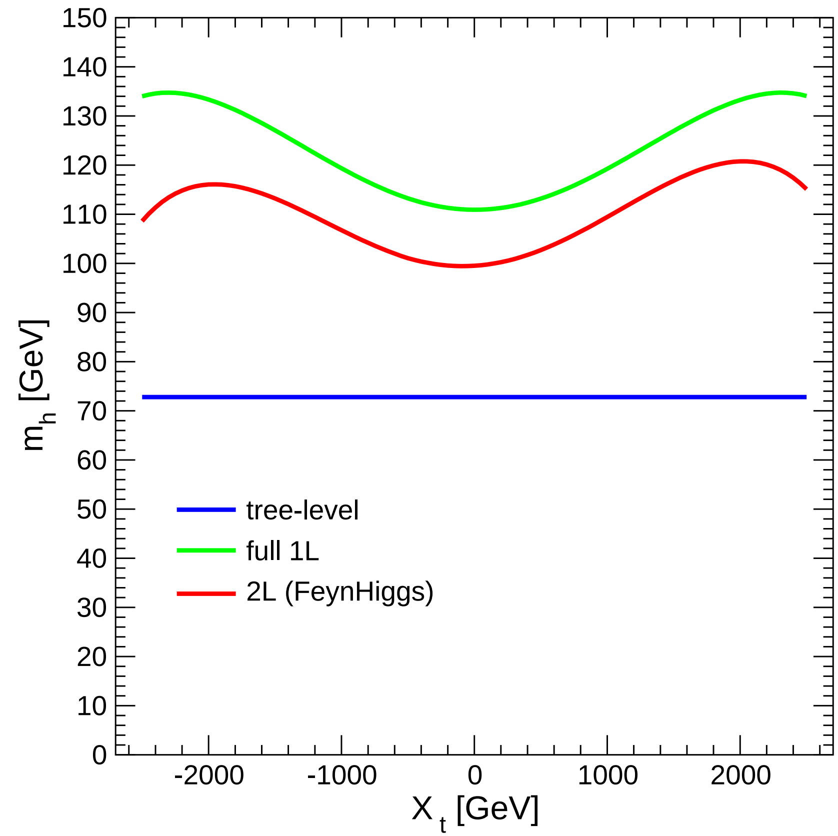
– Yukawa corrections $\sim \alpha_t^2$

theoretical uncertainty:

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

[Degrassi, Heinemeyer, WH, Slavich, Weiglein]

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



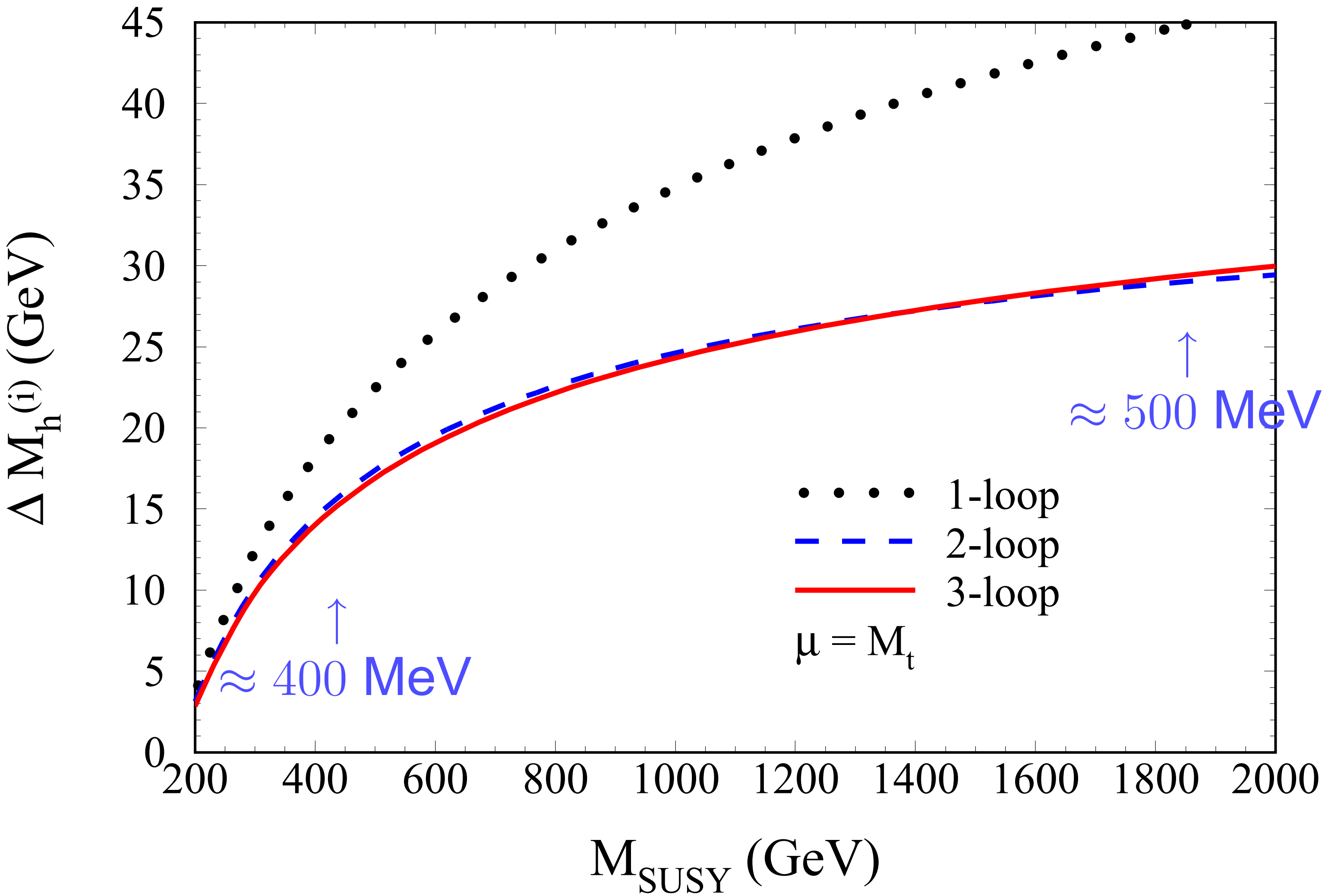
$\tan\beta = 3, \quad M_{\tilde{Q}} = M_A = 1$ TeV, $\quad m_{\tilde{g}} = 800$ GeV

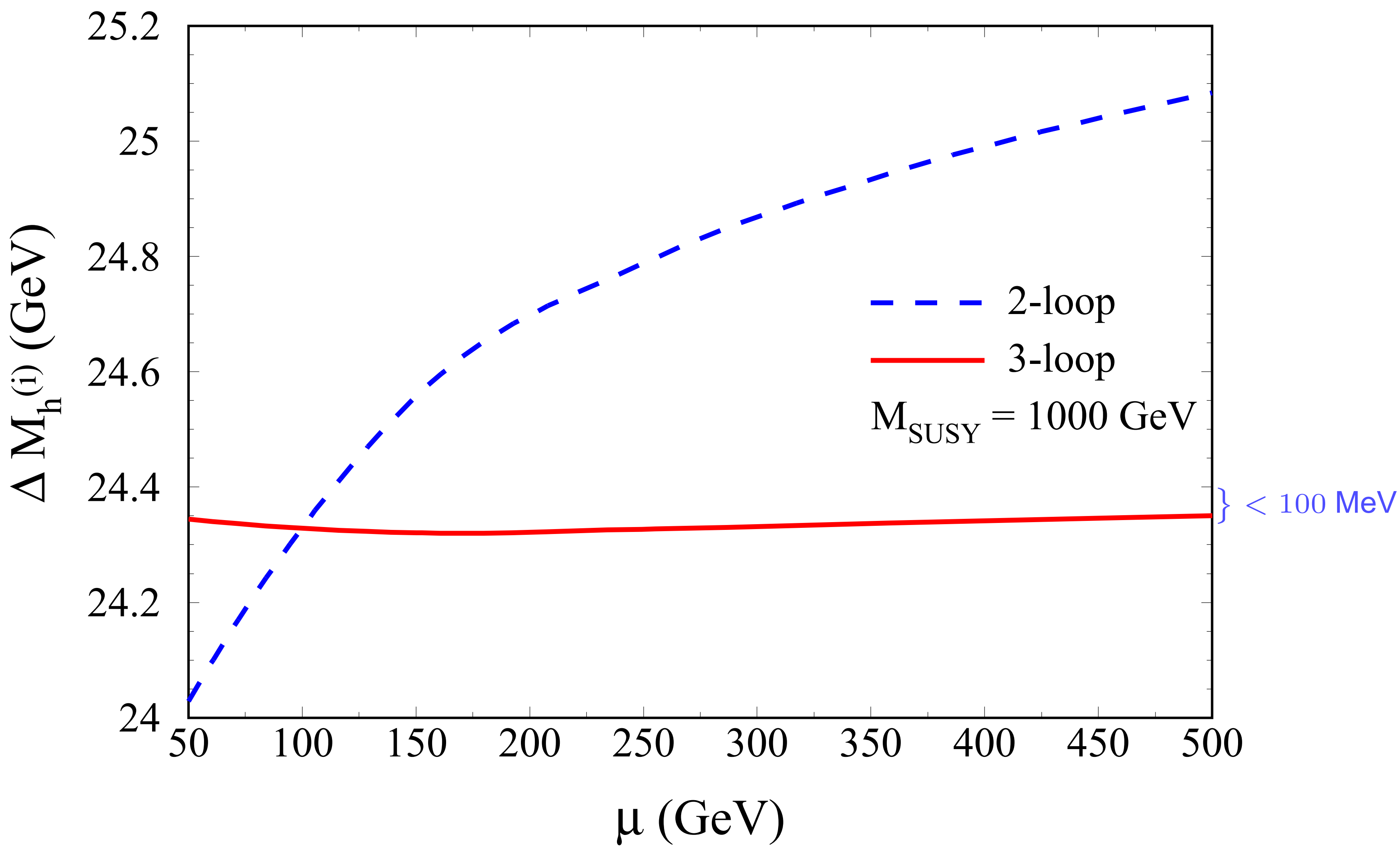
X_t : top-squark mixing parameter

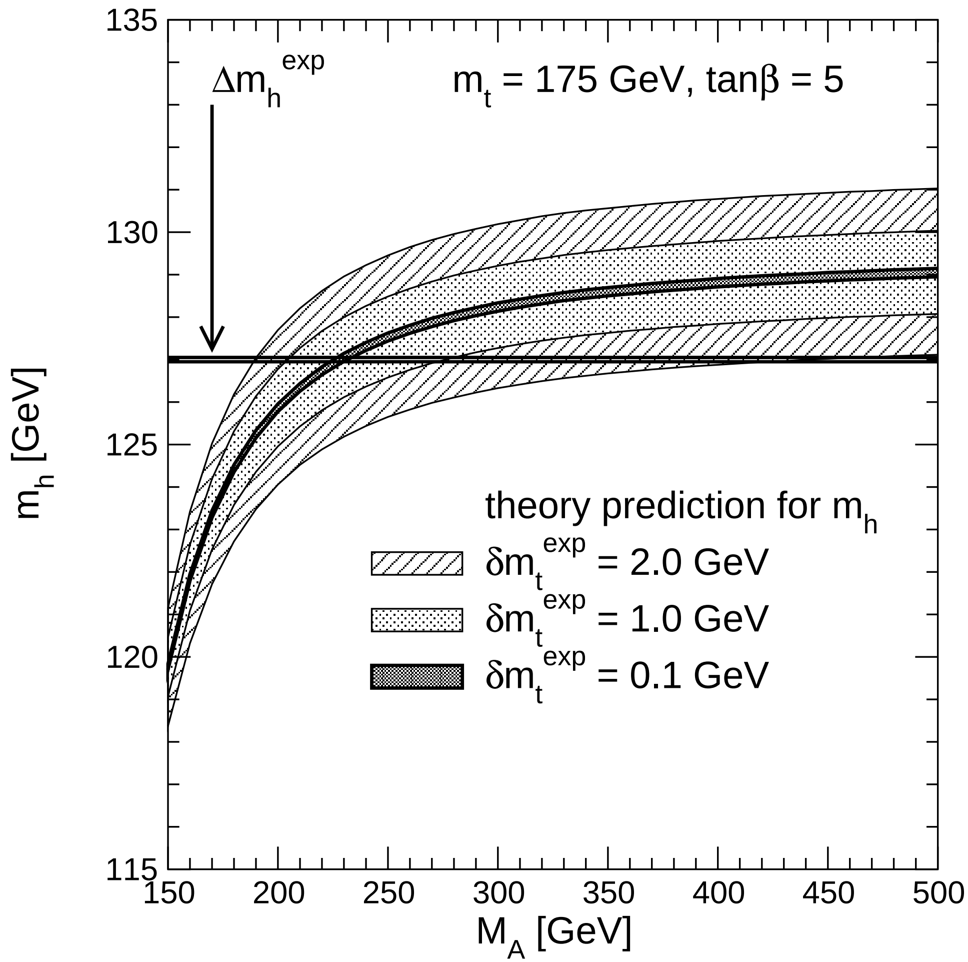
$$\mathrm{X_t} = \mathrm{A_t} - \mu \cot\beta$$

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

[Harlander, Kant, Mihaila, Steinhauser]




25.2
25
24.8
24.6
24.4
24.2
24
50
100
150
200
250
300
350
400
450
500
$\Delta M_h^{(i)}$ (GeV)
μ (GeV)
2-loop
3-loop
M_{SUSY} = 1000 GeV
} < 100 MeV



[Kraml et al.]

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

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 $\tilde{f}$
  $\longrightarrow$ L-R sfermion mixing
- supersymmetric Higgsino mass parameter: μ
- Higgs sector parameters: $M_A, \ \tan\beta = v_2/v_1$

Benchmark scenarios

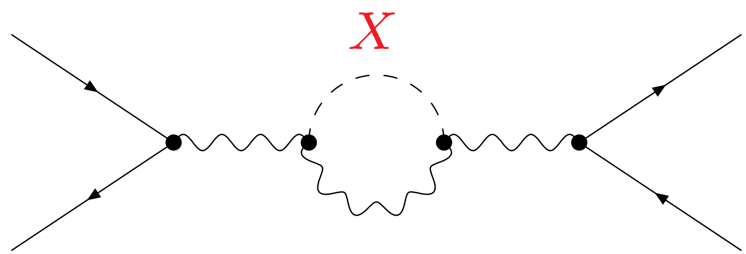
"Snowmass points and slopes" (SPS), hep-ph/0202233

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, $A_0 = 0$, $\tan\beta = 30$, $\mu > 0$.

indirect access to SUSY particles through quantum loops



X = Higgs bosons, SUSY particles

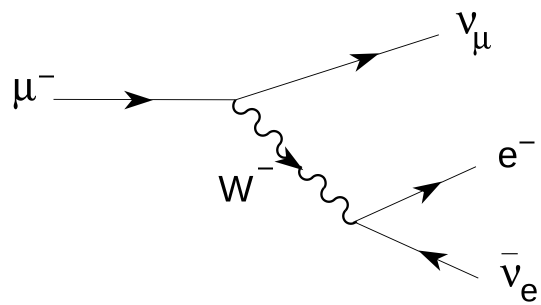
- μ lifetime: $M_W \leftrightarrow M_Z, G_\mathrm{F}$
- Z observables: $g_V, g_A, \sin^2\theta_\mathrm{eff}, \Gamma_Z, M_Z, \ldots$

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

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



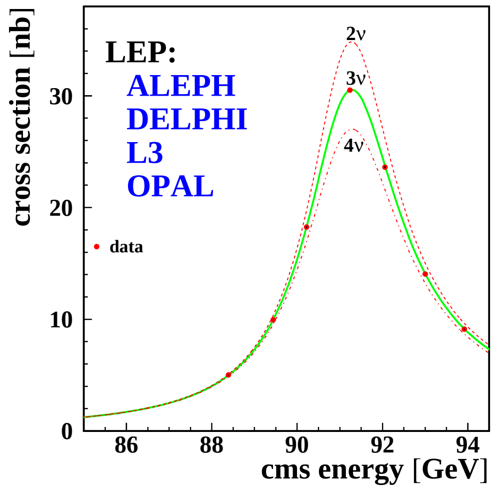
$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{M_W^2\left(1 - M_W^2/M_Z^2\right)}\,(1 + \Delta r)$$

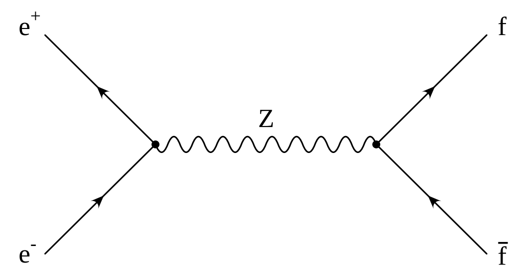
Δr : quantum correction, $\Delta r = \Delta r(m_t, X_{\rm SUSY})$

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

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

Z resonance





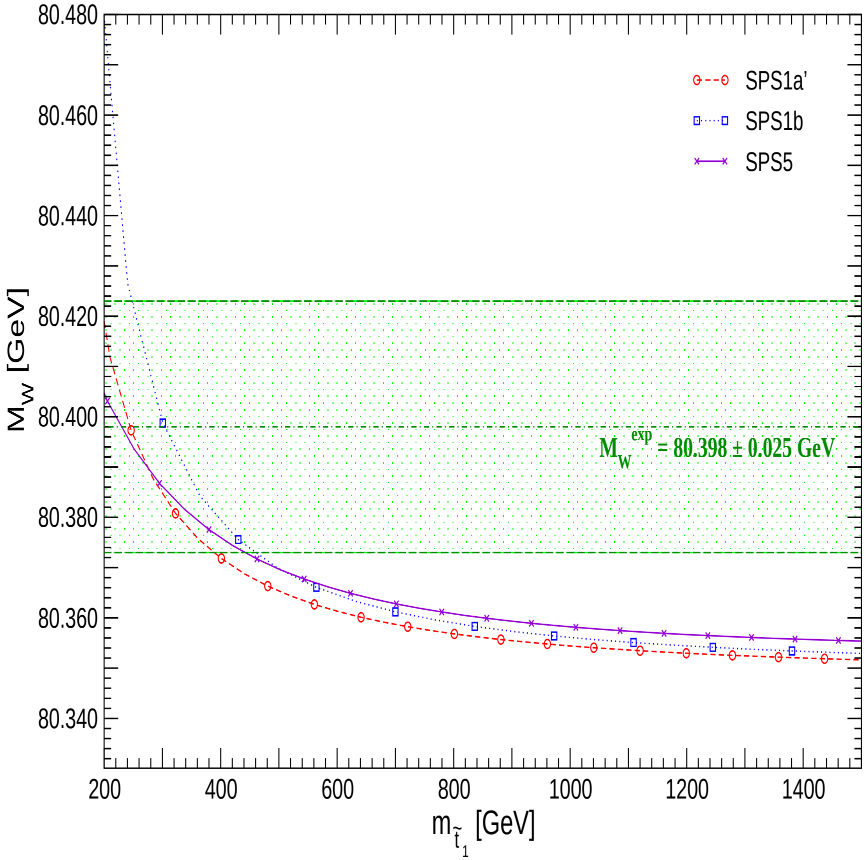
effective Z boson couplings

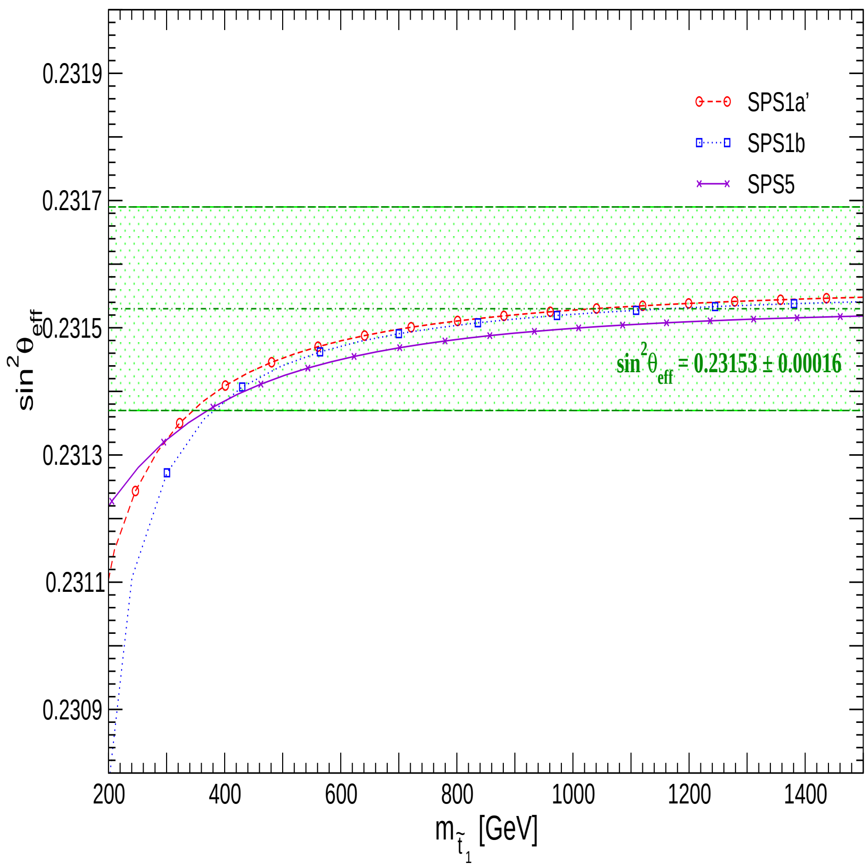
$$g_V^f \longrightarrow g_V^f + \Delta g_V^f, \qquad g_A^f \longrightarrow g_A^f + \Delta g_A^f$$

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

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

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



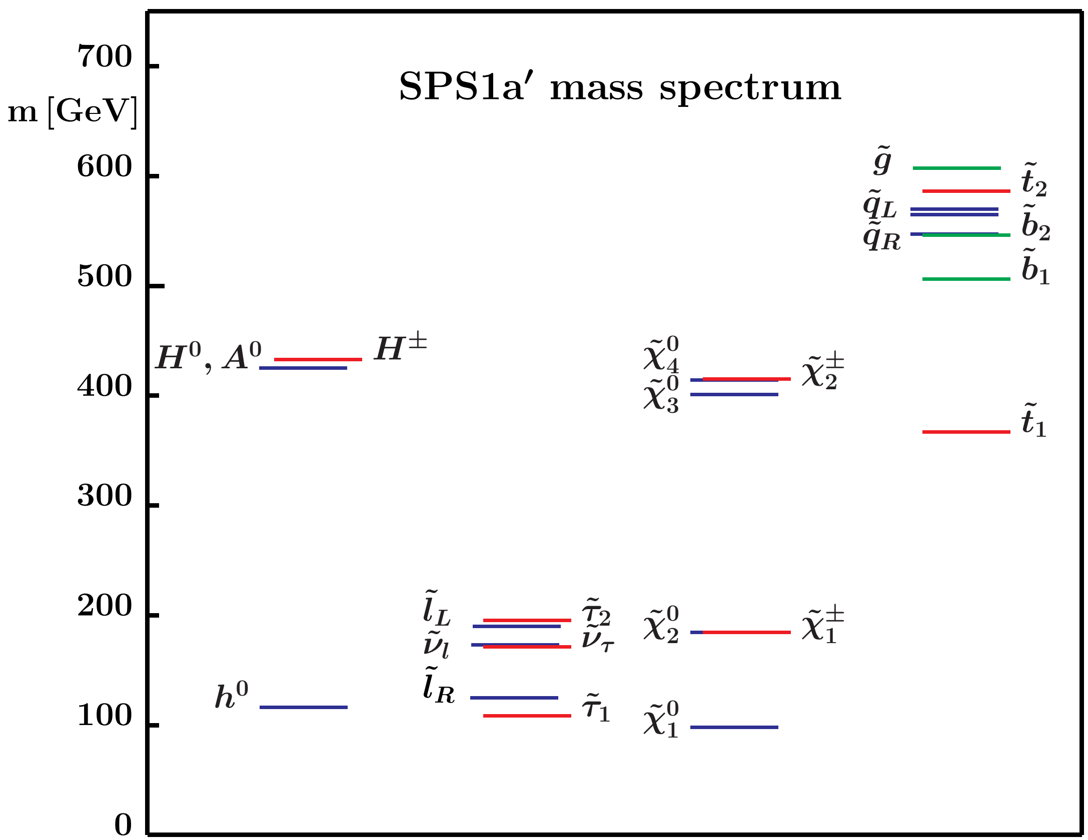


Fortran Code SUSYPOPE *[A. Weber, PhD thesis, Munich 2008]*

also used in recent fits by *AbdusSalam, Allanach, Quevedo, Feroz, Hobson, arxiv:0904.2548*

SPS1a′ scenario

$M_{1/2}$	$=$	250 GeV	sign(μ)	$= +1$
M_0	$=$	70 GeV	$\tan\beta(\tilde{M})$	$= 10$
A_0	$=$	-300 GeV		



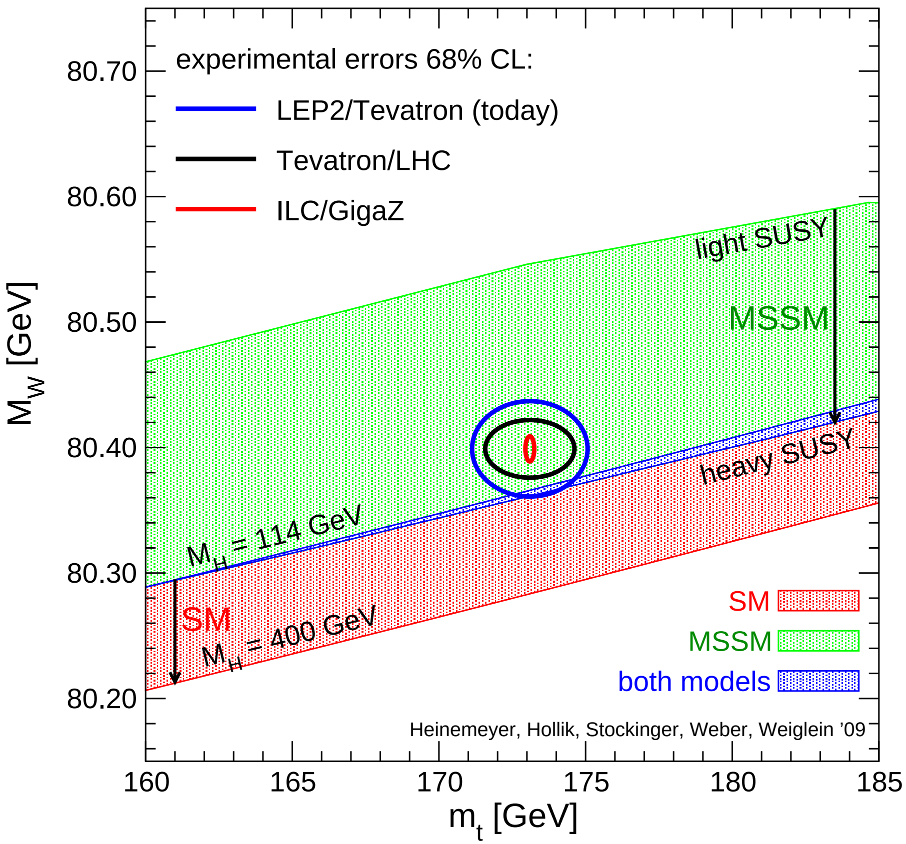
Scatter plots for M_W & $\sin^2\theta_{\rm eff}$

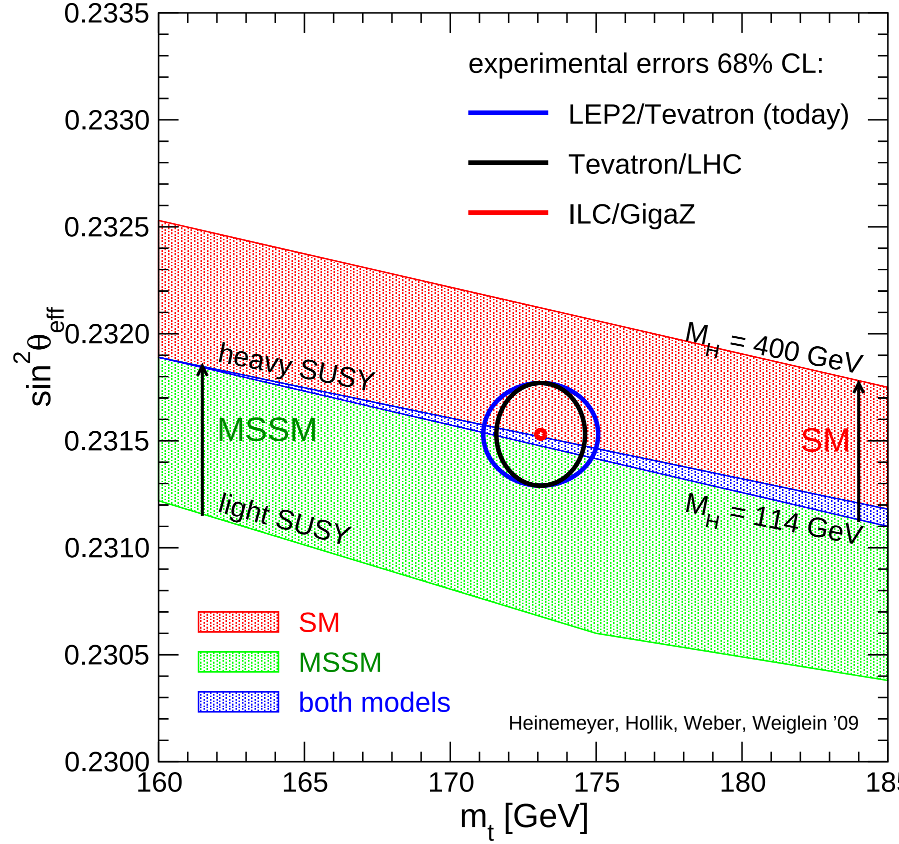
- SUSY parameters:

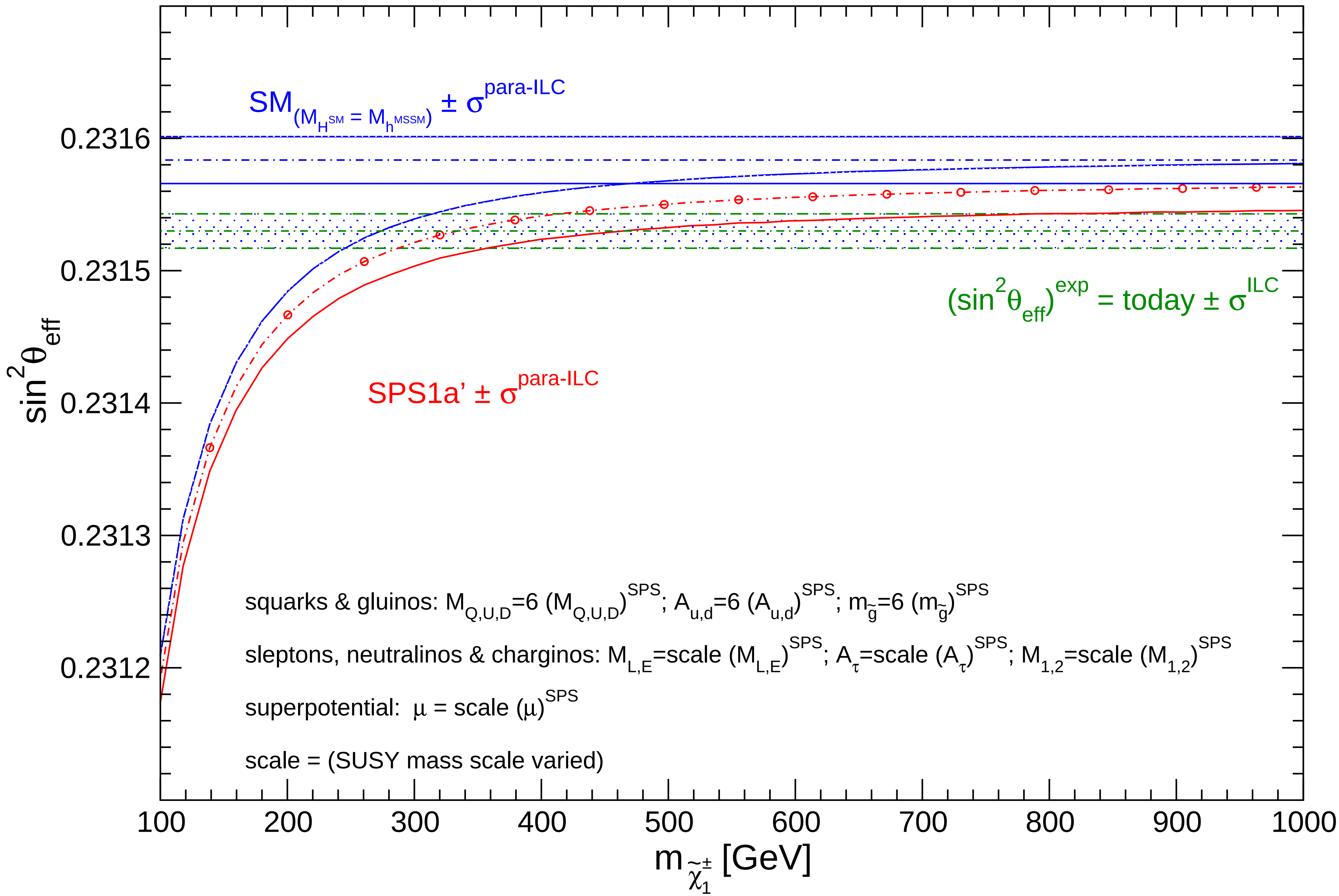
$$\begin{aligned}
\text{sleptons} &: \quad M_{\tilde{F},\tilde{F}'} = 100\ldots2000 \text{ GeV} \\
\text{light squarks} &: \quad M_{\tilde{F},\tilde{F}'_{\text{up/down}}} = 100\ldots2000 \text{ GeV} \\
\tilde{t}/\tilde{b} \ \text{doublet} &: \quad M_{\tilde{F},\tilde{F}'_{\text{up/down}}} = 100\ldots2000 \text{ GeV} \\
& \quad A_{t,b} = -2000\ldots2000 \text{ GeV} \\
\text{gauginos} &: \quad M_{1,2} = 100\ldots2000 \text{ GeV} \\
& \quad m_{\tilde{g}} = 195\ldots1500 \text{ GeV} \\
& \quad \mu = -2000\ldots2000 \text{ GeV} \\
\text{Higgs} &: \quad M_A = 90 - 1000 \text{ GeV} \\
& \quad \tan\beta = 1.1\ldots60
\end{aligned}$$

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

[Heinemeyer, Hollik, Stöckinger, Weber, Weiglein]

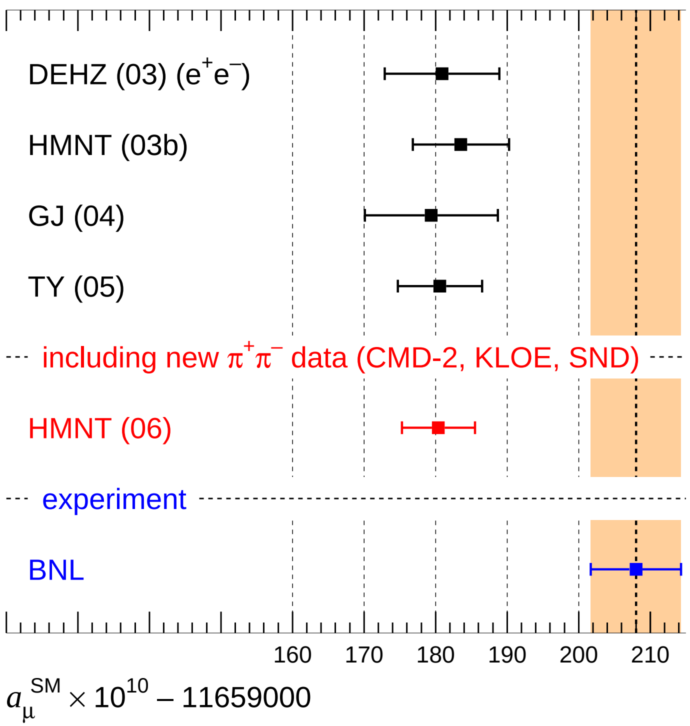






$\mathrm{SM}_{(M_{H^{SM}} = M_{h^{MSSM}})} \pm \sigma^{\text{para-ILC}}$
$(\sin^2\theta_{\text{eff}})^{\text{exp}}$ = today $\pm\ \sigma^{\text{ILC}}$
SPS1a' $\pm\ \sigma^{\text{para-ILC}}$
squarks & gluinos: $M_{Q,U,D}$=6 $(M_{Q,U,D})^{SPS}$; $A_{u,d}$=6 $(A_{u,d})^{SPS}$; $m_{\tilde{g}}$=6 $(m_{\tilde{g}})^{SPS}$
sleptons, neutralinos & charginos: $M_{L,E}$=scale $(M_{L,E})^{SPS}$; A_τ=scale $(A_\tau)^{SPS}$; $M_{1,2}$=scale $(M_{1,2})^{SPS}$
superpotential: μ = scale $(\mu)^{SPS}$
scale = (SUSY mass scale varied)
$\sin^2\theta_{\text{eff}}$
0.2316
0.2315
0.2314
0.2313
0.2312
100
200
300
400
500
600
700
800
900
1000
$m_{\tilde{\chi}_1^\pm}$ [GeV]

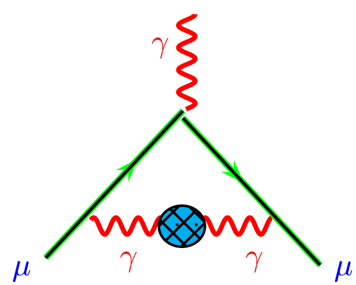
Anomalous g-factor of the muon



Hagiwara,Martin,Nomura,Teubner

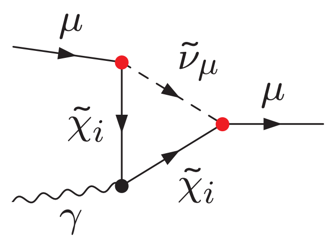
e^+e^- data based SM prediction: 3.4 σ below exp. value

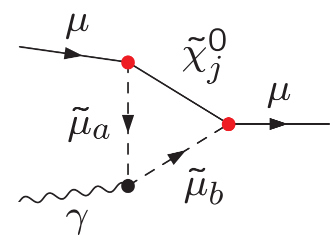
theory uncertainty from hadronic vacuum polarization



$g-2$ with supersymmetry

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





extra terms

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

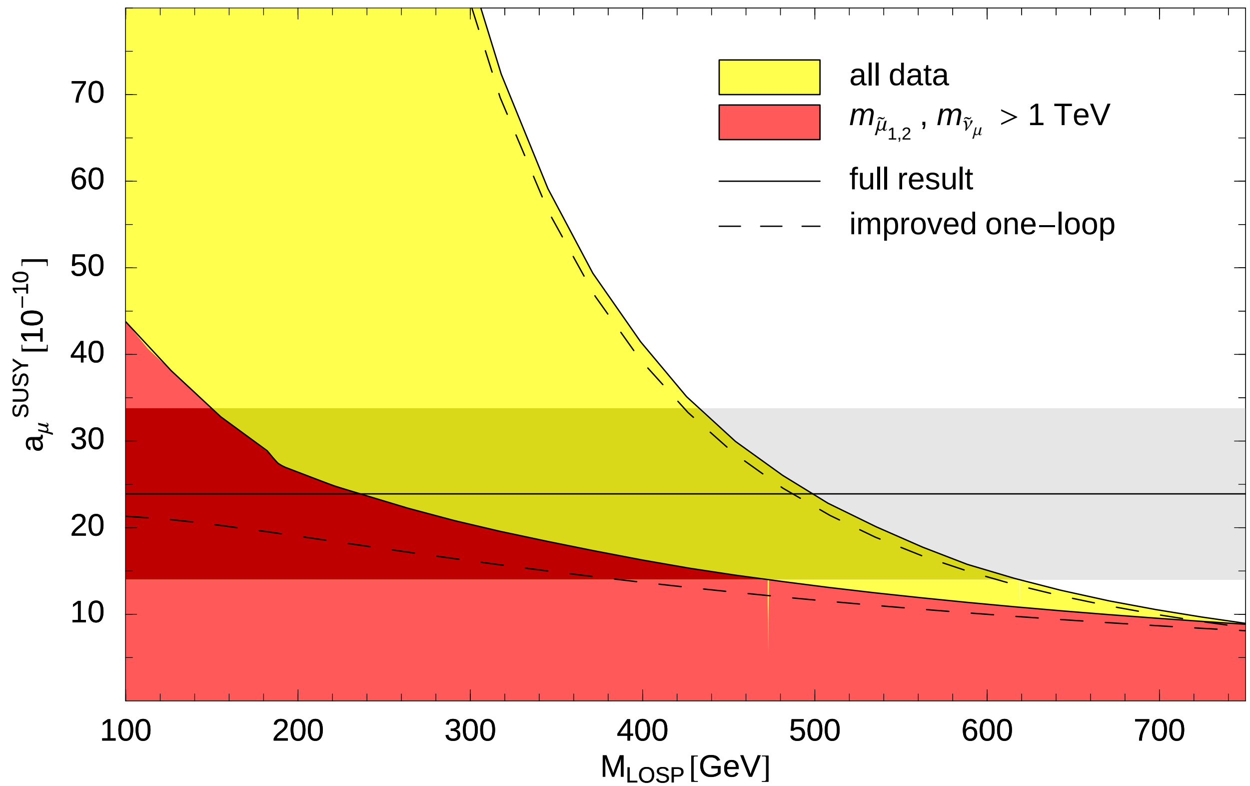
can provide missing contribution for

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

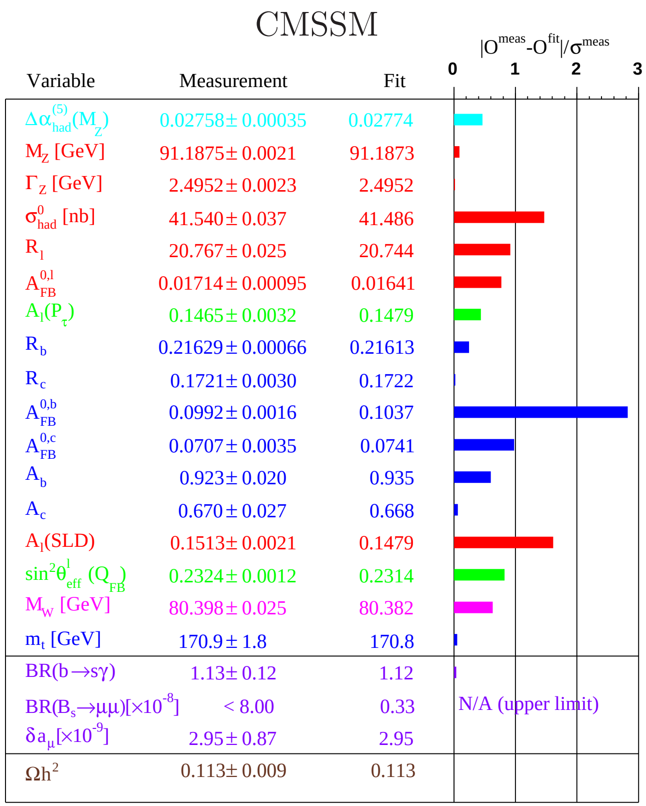
2-loop calculation *[Heinemeyer, Stöckinger, ...]*

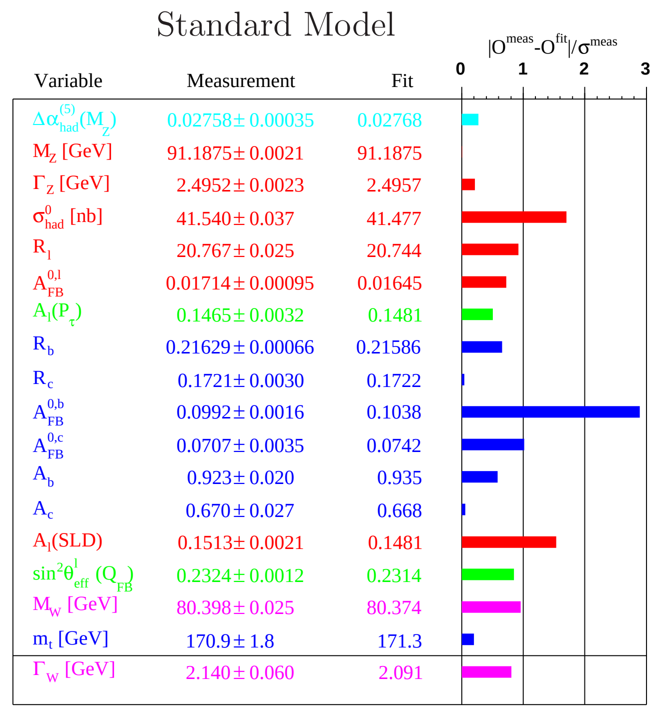
scan over SUSY parameters compatible with EW and $b \to s\gamma$ constraints $(\tan\beta = 50)$

[Stöckinger]



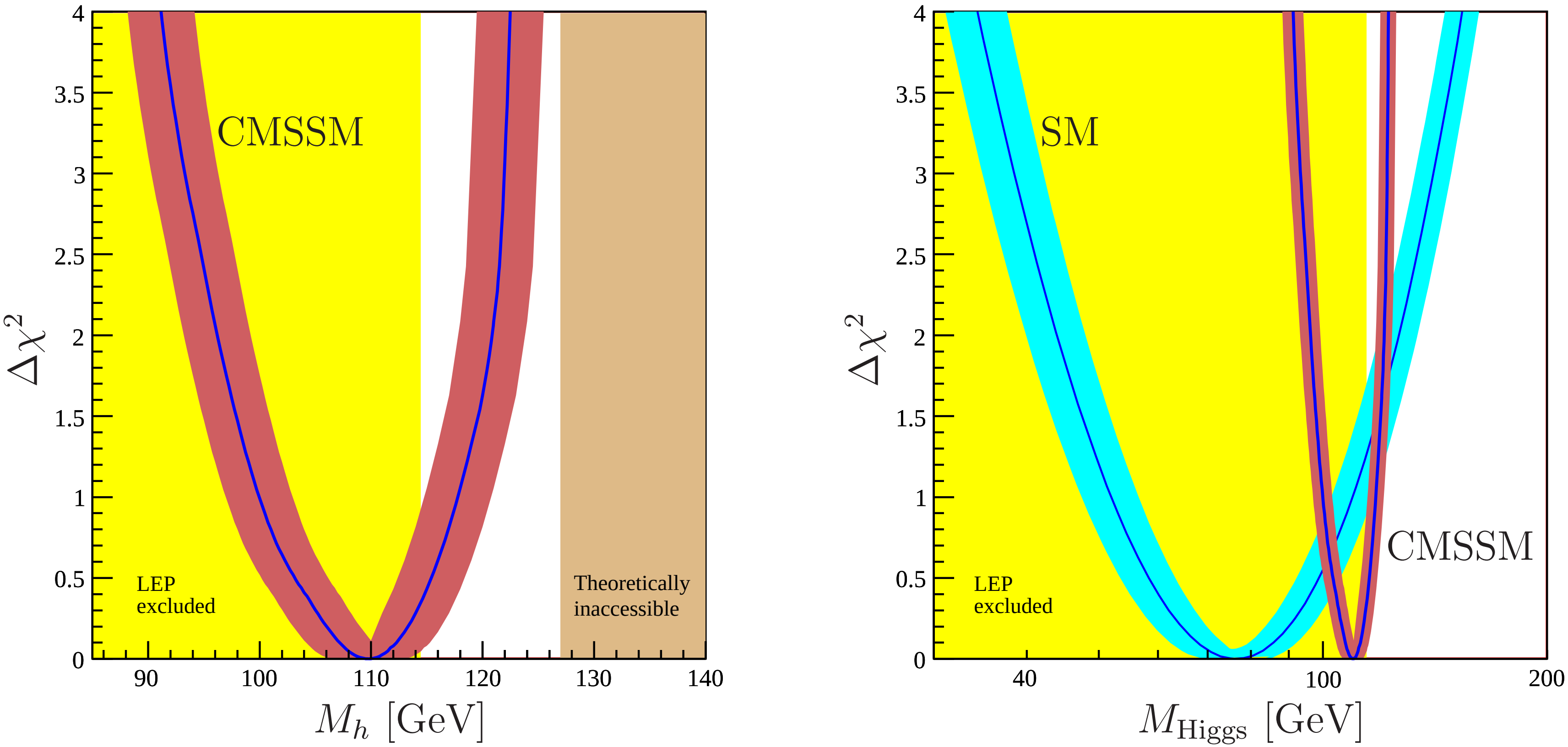
LOSP = lightest observable SUSY particle ($\chi_1^\pm, \chi_2^0, \cdots$)



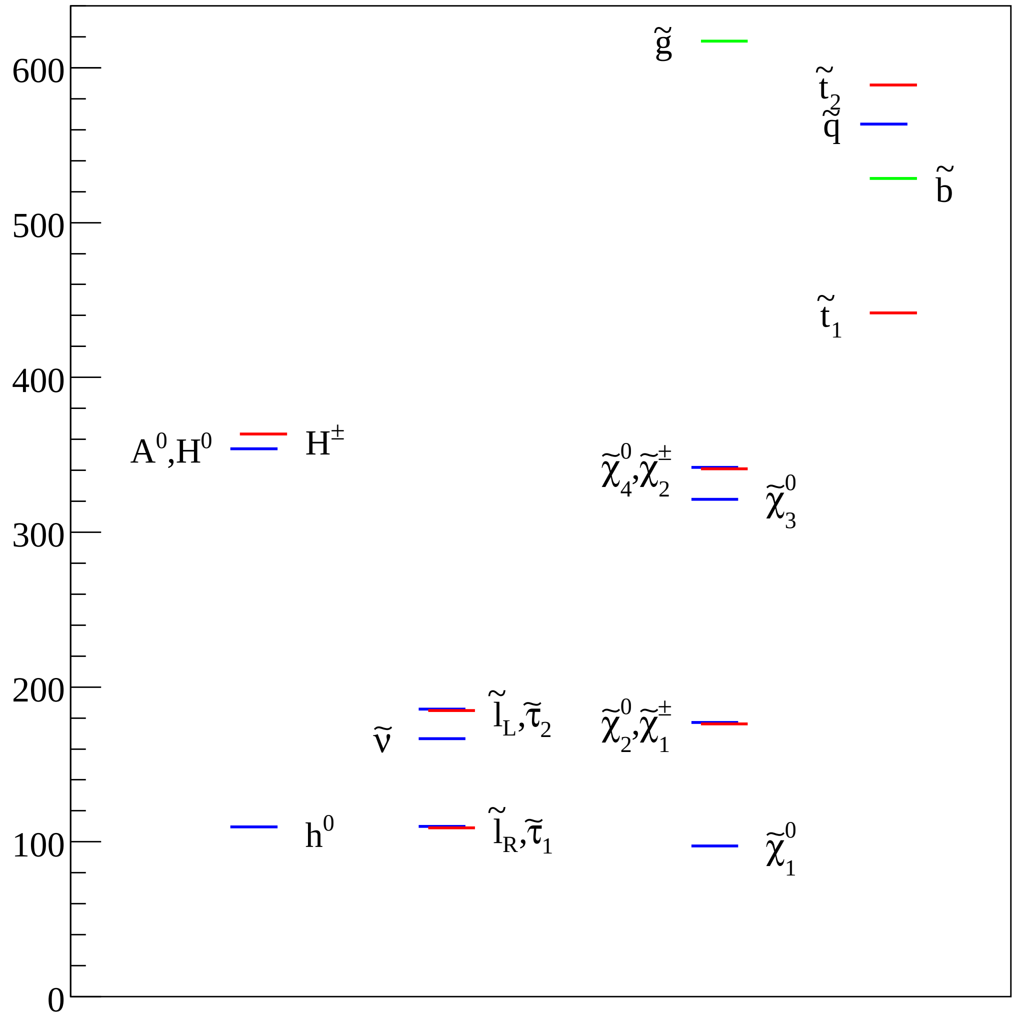


global fit in the constrained MSSM including data from $g-2$, B physics, and cosmic relic density

[O. Buchmueller, . . . , Weber, Weiglein]



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



best fit particle spectrum

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