Higgs and Electroweak Physics

Sven Heinemeyer, IFCA (Santander)

St. Andrews, 08/2009

1. The SM and the Higgs

2. The Higgs in Supersymmetry

3. Experimental facts and fiction (from a theorist's view)

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Higgs and Electroweak Physics (I):

The SM and the Higgs

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1. Higgs Theory

2. Electroweak Precision Observables

3. Properties of the SM Higgs boson

1. Higgs Theory

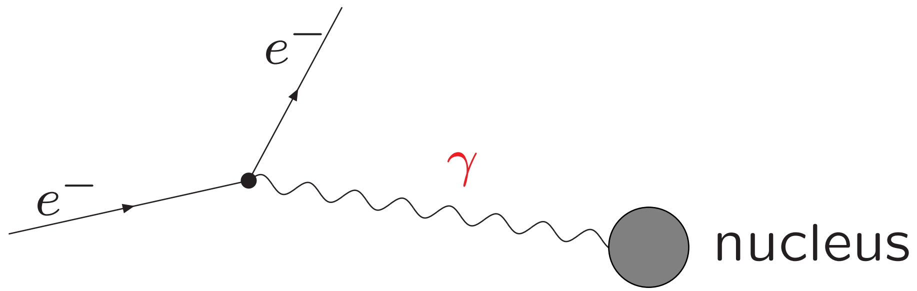
Standard Model (SM) of the electroweak and strong interaction

SM: Quantum field theory $\Rightarrow$ interaction: exchange of field quanta

Construction principle of the SM: gauge invariance

Example: Quantum electro-dynamics (QED)

field quanta: photon A_μ

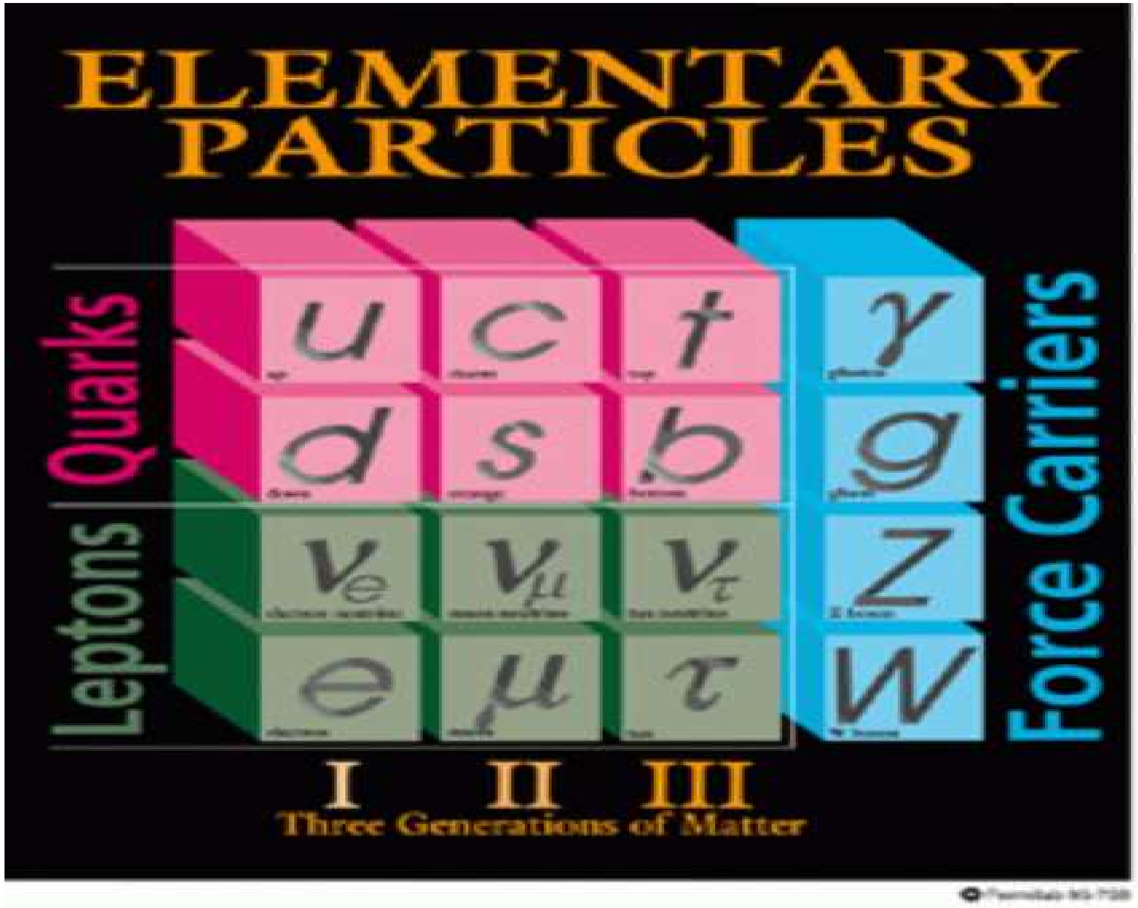


$\mathcal{L}_{\text{QED}}$ invariant under gauge transformation:

$\Psi \to e^{i\,e\,\lambda(x)}\Psi$, $A_\mu \to A_\mu + \partial_\mu \lambda(x)$

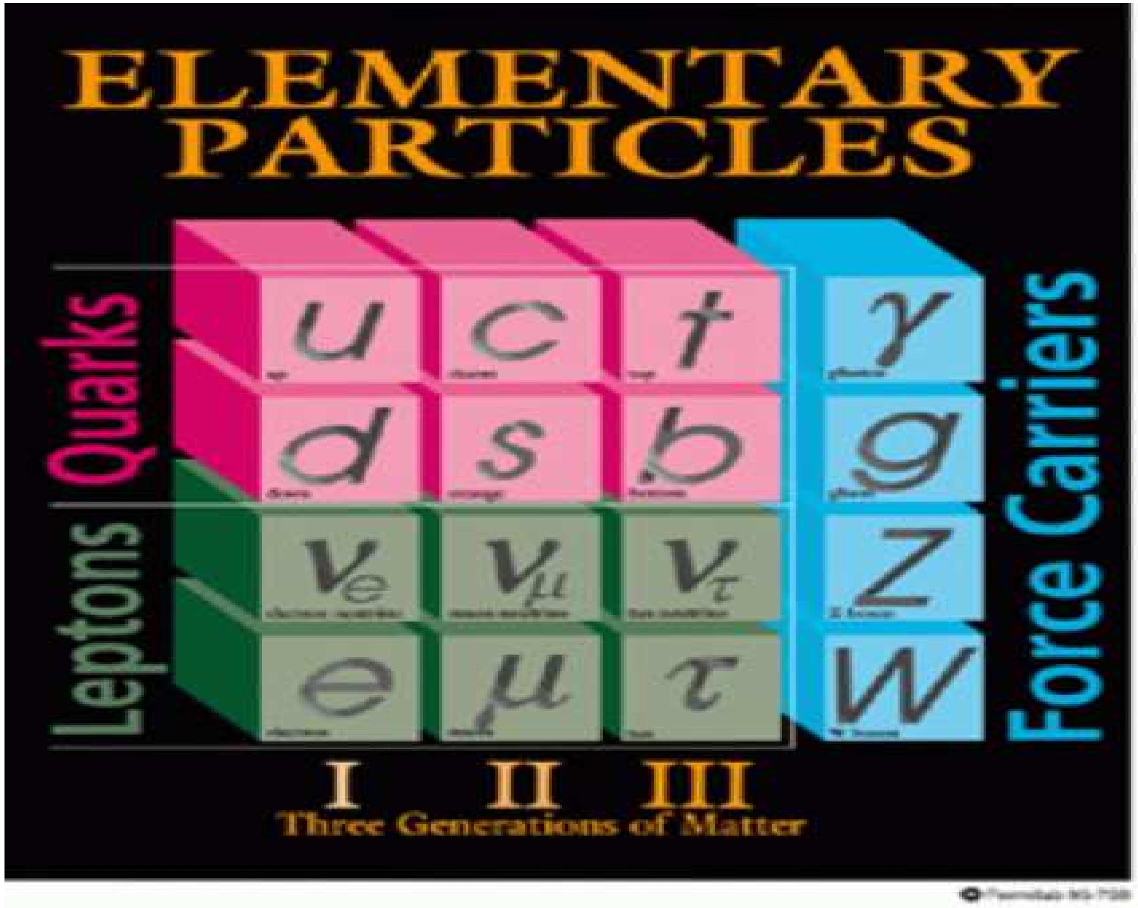
mass term for photon: $m^2 A^\mu A_\mu$ not gauge invariant
$\Rightarrow A_\mu$ is massless gauge field

Current status of knowledge: the Standard Model (SM)



⇒ all particles experimentally seen

Current status of knowledge: the Standard Model (SM)



⇒ all particles experimentally seen

⇒ but theory predicts massless gauge bosons . . .

Problem:

Gauge fields Z, W^+, W^- are massive

explicite mass terms in the Lagrangian $\Leftrightarrow$ breaking of gauge invariance

Solution: Higgs mechanism

scalar field postulated, mass terms from coupling to Higgs field

Higgs sector in the Standard Model:

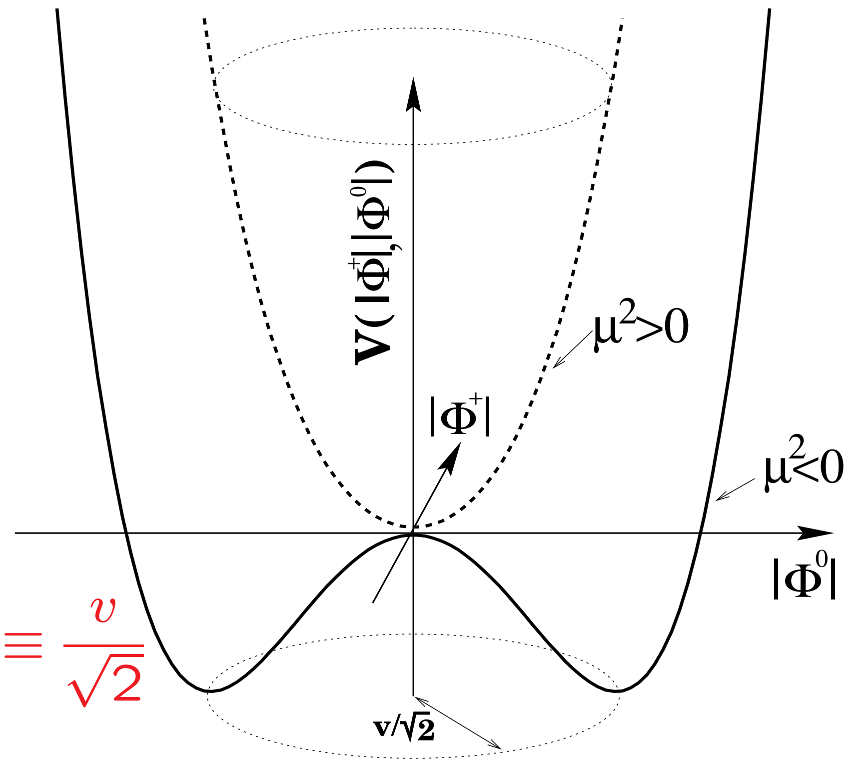
Scalar SU(2) doublet: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

Higgs potential:

$$V(\phi) = \mu^2 \left|\Phi^\dagger \Phi\right| + \lambda \left|\Phi^\dagger \Phi\right|^2, \quad \lambda > 0$$

$\mu^2 < 0$: Spontaneous symmetry breaking

minimum of potential at $|\langle \Phi_0 \rangle| = \sqrt{\frac{-\mu^2}{2\,\lambda}} \equiv \frac{v}{\sqrt{2}}$



$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix} \quad \text{(unitary gauge)}$$

H: elementary scalar field, Higgs boson

Lagrange density:

$$\begin{aligned} \mathcal{L}_{\text{Higgs}} = \quad & (D_\mu \Phi)^\dagger (D^\mu \Phi) \\ & - g_d \bar{Q}_L \Phi d_R \; - \; g_u \bar{Q}_L \Phi_c u_R \\ & - V(\Phi) \end{aligned}$$

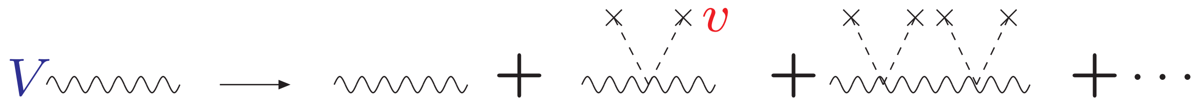
with

$$\begin{aligned} iD_\mu &= i\partial_\mu - g_2 \vec{I} \vec{W}_\mu - g_1 Y B_\mu \\ \Phi_c &= i\sigma_2 \Phi^\dagger \qquad\qquad Q_L \sim \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \; \Phi \sim \begin{pmatrix} 0 \\ v \end{pmatrix}, \; \Phi_c \sim \begin{pmatrix} v \\ 0 \end{pmatrix} \end{aligned}$$

Gauge invariant coupling to gauge fields

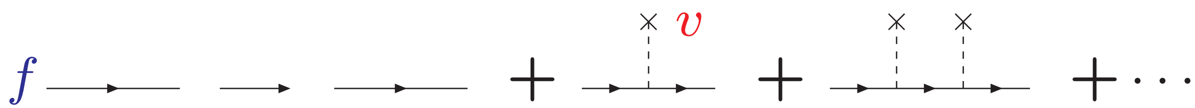
$\Rightarrow$ mass terms for gauge bosons and fermions

1.) $VV\Phi\Phi$ coupling:



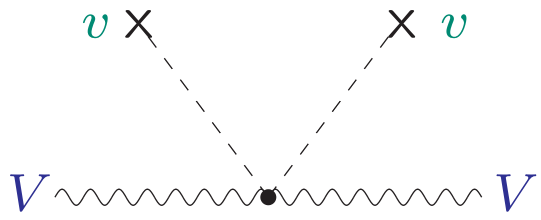
$$\frac{1}{q^2} \to \frac{1}{q^2} + \sum_j \frac{1}{q^2}\left[\left(\frac{gv}{\sqrt{2}}\right)^2 \frac{1}{q^2}\right]^j = \frac{1}{q^2 - M^2} \; : \; M^2 = g^2\frac{v^2}{2}$$

2.) fermion mass terms: Yukawa couplings:

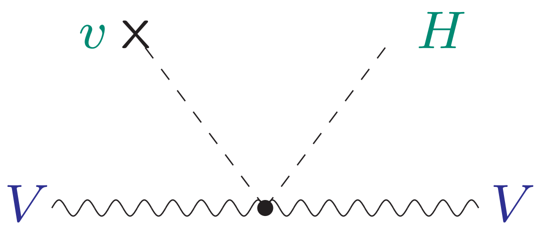


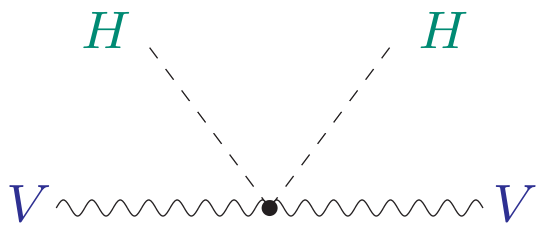
$$\frac{1}{\not{q}} \to \frac{1}{\not{q}} + \sum_j \frac{1}{\not{q}}\left[\frac{g_f v}{\sqrt{2}} \frac{1}{\not{q}}\right]^j = \frac{1}{\not{q} - m_f} \; : \; m_f = g_f\frac{v}{\sqrt{2}}$$

<u>1.) $VV\Phi\Phi$ coupling:</u>



⇒ VV mass terms: $g_2^2 v^2/2 \equiv M_W^2$, $(g_1^2 + g_2^2) v^2/2 \equiv M_Z^2$

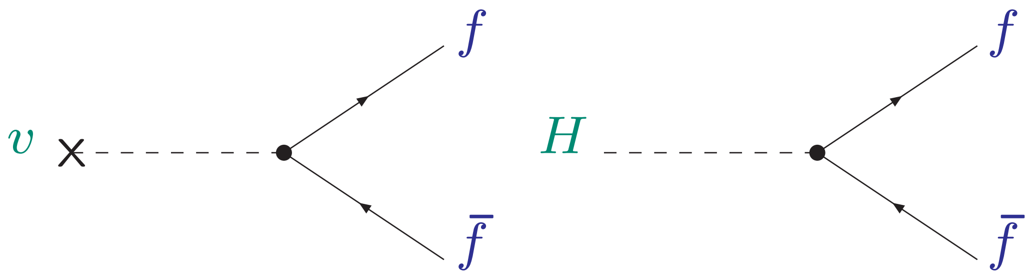




⇒ triple/quartic couplings to gauge bosons

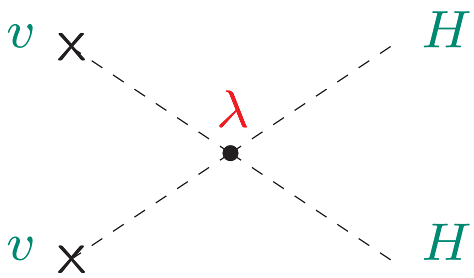
⇒ coupling $\propto$ masses

2.) fermion mass terms: Yukawa couplings



$m_f = v\, g_f \Rightarrow$ coupling $\propto$ masses

3.) mass of the Higgs boson: self coupling



. . .

$\lambda = M_H^2/v$

$M_H = v\sqrt{\lambda}$ free parameter

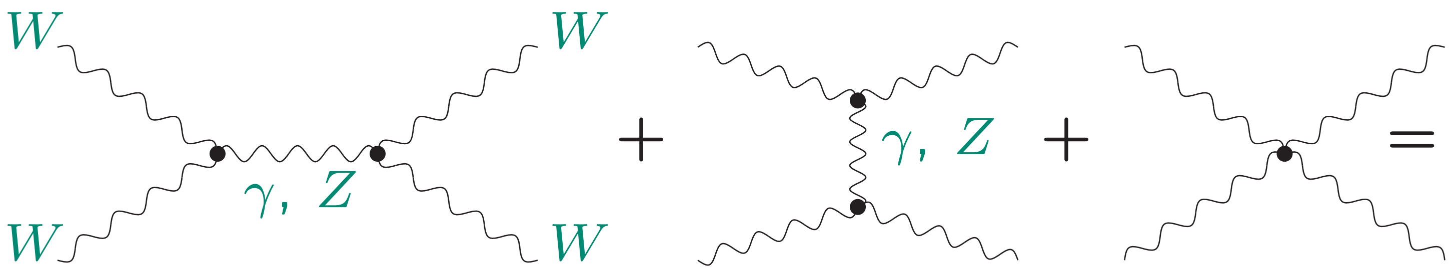
$\rightarrow$ last unknown parameter of the SM

$\Rightarrow$ establish Higgs mechanism $\equiv$ find the Higgs $\oplus$ measure its couplings

Another effect of the Higgs field:

Scattering of longitudinal W bosons: $W_L W_L \to W_L W_L$

$\mathcal{M}_V =$

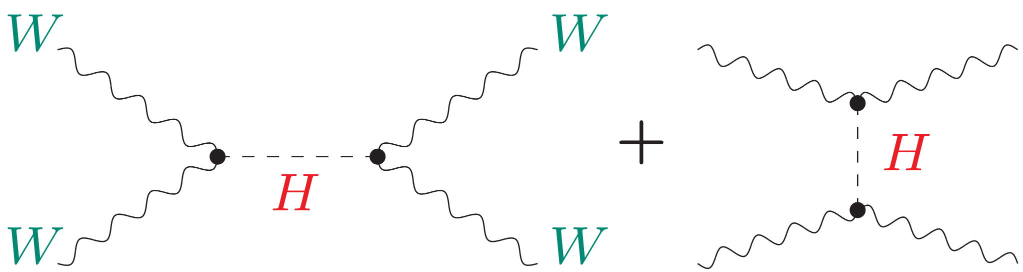


$= -g^2 \frac{E^2}{M_W^2} + \mathcal{O}(1)$ for $E \to \infty$

$\Rightarrow$ violation of unitarity

Contribution of a scalar particle with couplings prop. to the mass:

$\mathcal{M}_S =$



$= g_{WWH}^2 \frac{E^2}{M_W^4} + \mathcal{O}(1)$ for $E \to \infty$

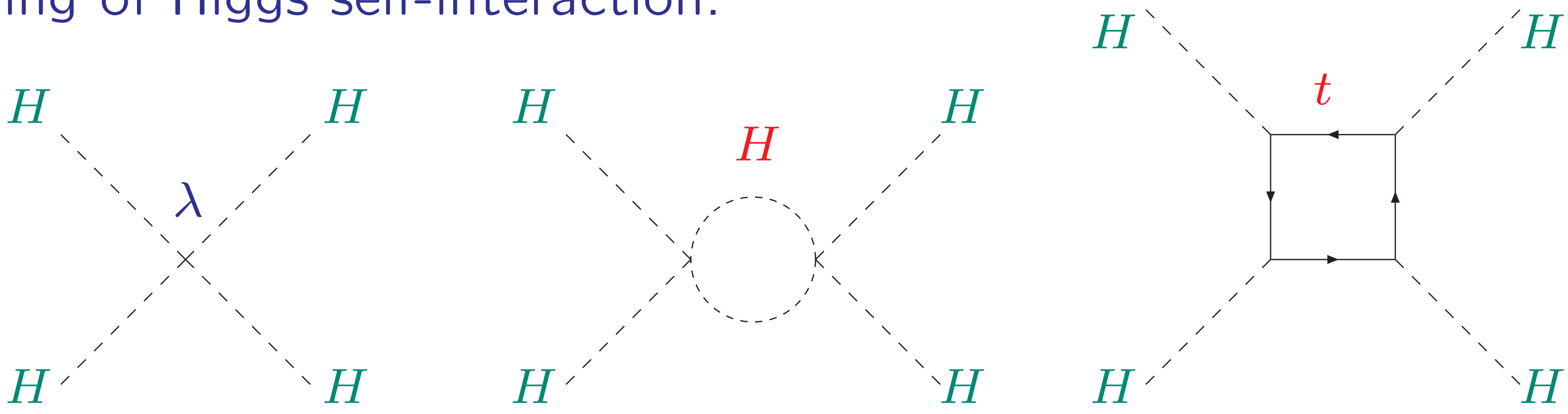
$$\mathcal{M}_{\text{tot}} = \mathcal{M}_V + \mathcal{M}_S = \frac{E^2}{M_W^4}\left(g_{WWH}^2 - g^2\, M_W^2\right) + \ldots$$

$\Rightarrow$ compensation of terms with bad high-energy behavior for

$$g_{WWH} = g\, M_W$$

What else do we know about the Higgs boson?

Running of Higgs self-interaction:



Renormalization group equation:

$$\frac{d\,\lambda}{d\,t} = \frac{3}{8\,\pi^2}\left[\lambda^2 + \lambda g_t^2 - g_t^4 + \frac{1}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right] \;, \quad t = \log\left(\frac{Q^2}{v^2}\right)$$

Two conditions:

1.) avoid Landau pole (for large $\lambda \sim M_H^2$)

2.) avoid vacuum instability (for small/negative λ)

1.) avoid Landau pole (for large $\lambda \sim M_H^2$)

$$\frac{d\,\lambda}{d\,t} = \frac{3}{8\,\pi^2}\left[\lambda^2\right]$$

$$\Rightarrow \qquad \lambda(Q^2) = \frac{\lambda(v^2)}{1 - \frac{3\lambda(v^2)}{8\,\pi^2}\log\left(\frac{Q^2}{v^2}\right)}$$

$$\lambda(\Lambda) < \infty \;\Rightarrow\; M_H^2 \leq \frac{8\,\pi^2\,v^2}{3\log\left(\frac{\Lambda^2}{v^2}\right)}$$: upper bound on M_H

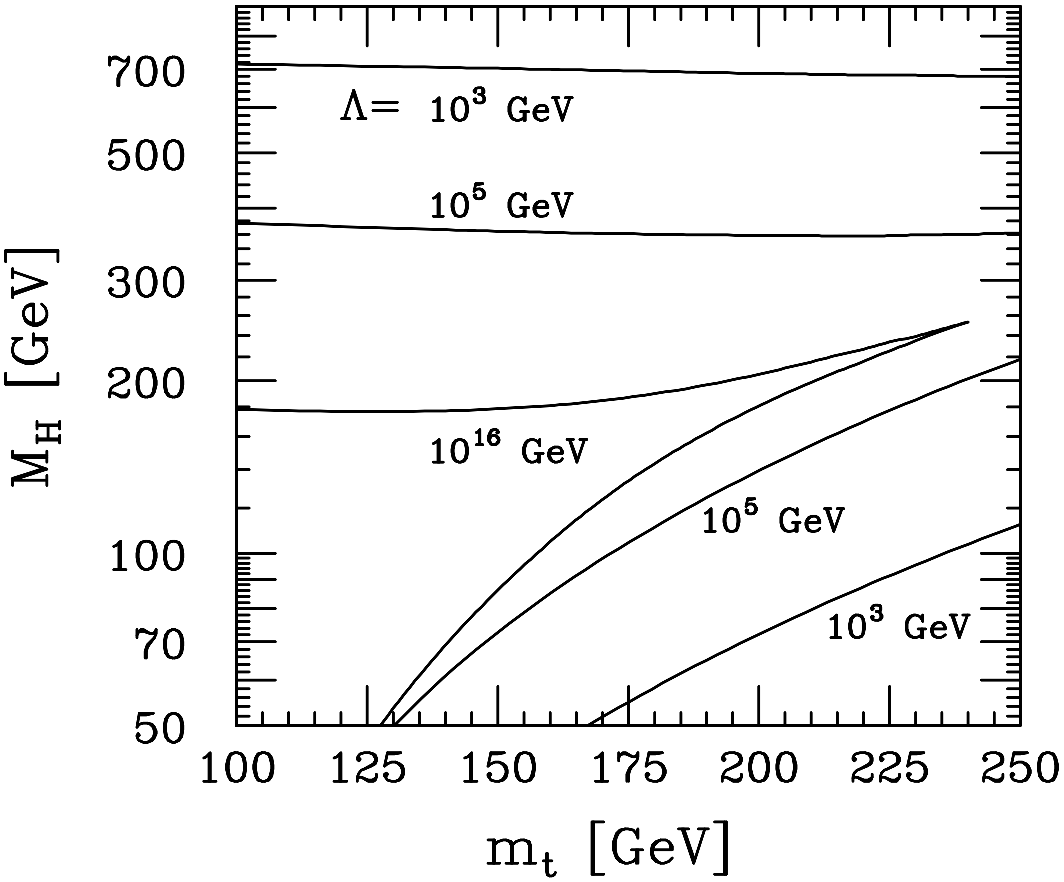
2.) avoid vacuum instability (for small/negative λ): $V(v) < V(0) \Rightarrow \lambda(\Lambda) > 0$

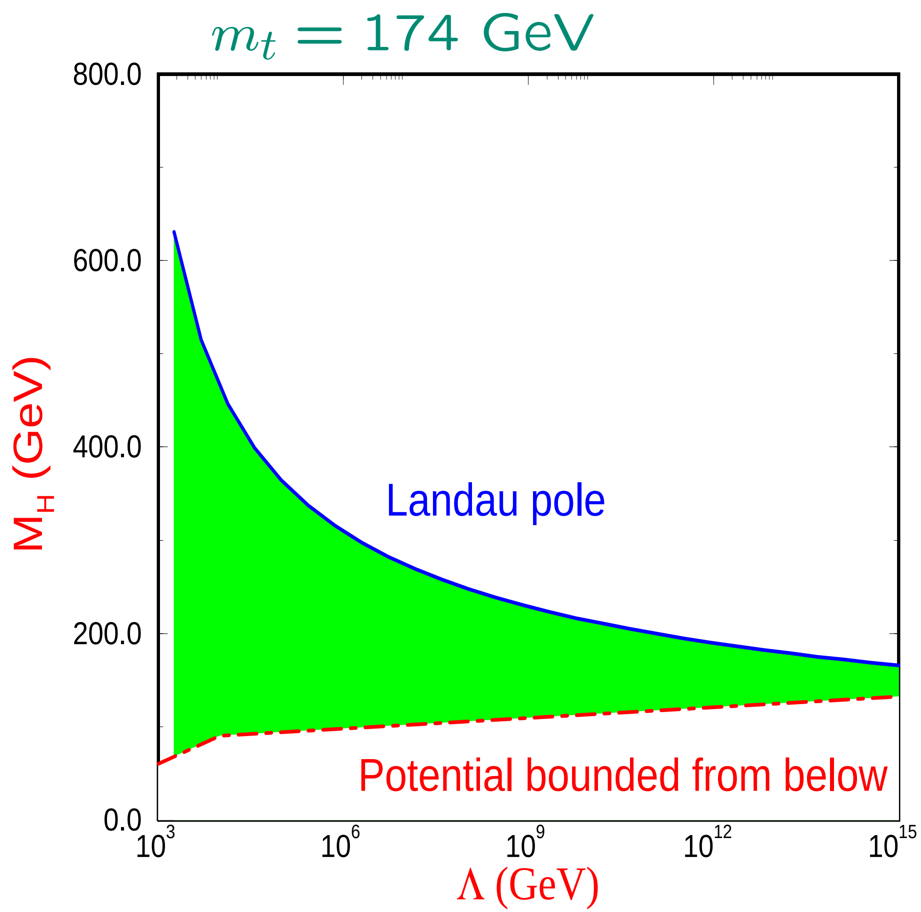
$$\frac{d\,\lambda}{d\,t} = \frac{3}{8\,\pi^2}\left[-g_t^4 + \frac{1}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]$$

$$\Rightarrow \qquad \lambda(Q^2) = \lambda(v^2)\frac{3}{8\,\pi^2}\left[-g_t^4 + \frac{1}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]\log\left(\frac{Q^2}{v^2}\right)$$

$$\lambda(\Lambda) > 0 \;\Rightarrow\; M_H^2 > \frac{v^2}{4\,\pi^2}\left[-g_t^4 + \frac{1}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]\log\left(\frac{\Lambda^2}{v^2}\right)$$: lower bound

Both limits combined:





Λ: scale up to which the SM is valid

$\Lambda = M_{\text{GUT}} \Rightarrow 130 \text{ GeV} \lesssim M_H \lesssim 180 \text{ GeV}$

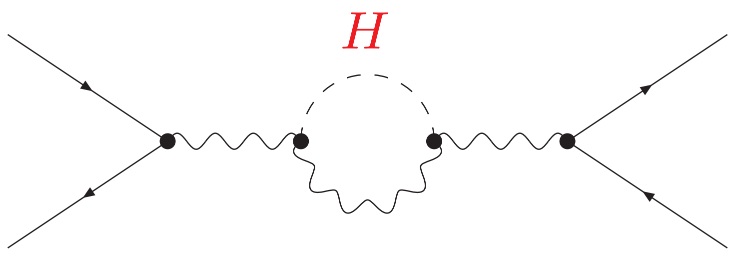
2. Electroweak Precision Observables (EWPO):

Comparison of electro-weak precision observables with theory:

EW Precision data:		Theory:
$M_W, \sin^2\theta_{\mathrm{eff}}, a_\mu$	$\leftrightarrow$	SM, MSSM , . . .

$\Downarrow$

Test of theory at quantum level: Sensitivity to loop corrections, e.g. H



$\Downarrow$

SM: limits on M_H

Very high accuracy of measurements and theoretical predictions needed

Example: prediction of M_W, $\sin^2\theta_{\rm eff}$

A) Theoretical prediction for M_W in terms

of $M_Z, \alpha, G_\mu, \Delta r$:

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

$\Updownarrow$

loop corrections

Evaluate Δr from μ decay $\Rightarrow M_W$

One-loop result for M_W in the SM:

[*A. Sirlin '80*] , [*W. Marciano, A. Sirlin '80*]

$$\Delta r_{1-\text{loop}} = \Delta\alpha - \frac{c_W^2}{s_W^2}\Delta\rho + \Delta r_{\text{rem}}(M_H)$$

$\sim \log\frac{M_Z}{m_f}$	$\sim m_t^2$	$\log(M_H/M_W)$
$\sim 6\%$	$\sim 3.3\%$	$\sim 1\%$

Example: prediction of M_W, $\sin^2\theta_{\rm eff}$

A) Theoretical prediction for M_W in terms

of $M_Z, \alpha, G_\mu, \Delta r$:

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

$\Updownarrow$

loop corrections

B) Effective mixing angle:

$$\sin^2\theta_{\rm eff} = \frac{1}{4\,|Q_f|}\left(1 - \frac{\mathrm{Re}\,g_V^f}{\mathrm{Re}\,g_A^f}\right)$$

Higher order contributions:

$$g_V^f \to g_V^f + \Delta g_V^f, \quad g_A^f \to g_A^f + \Delta g_A^f$$

Comparison of SM prediction of M_W with direct measurements:

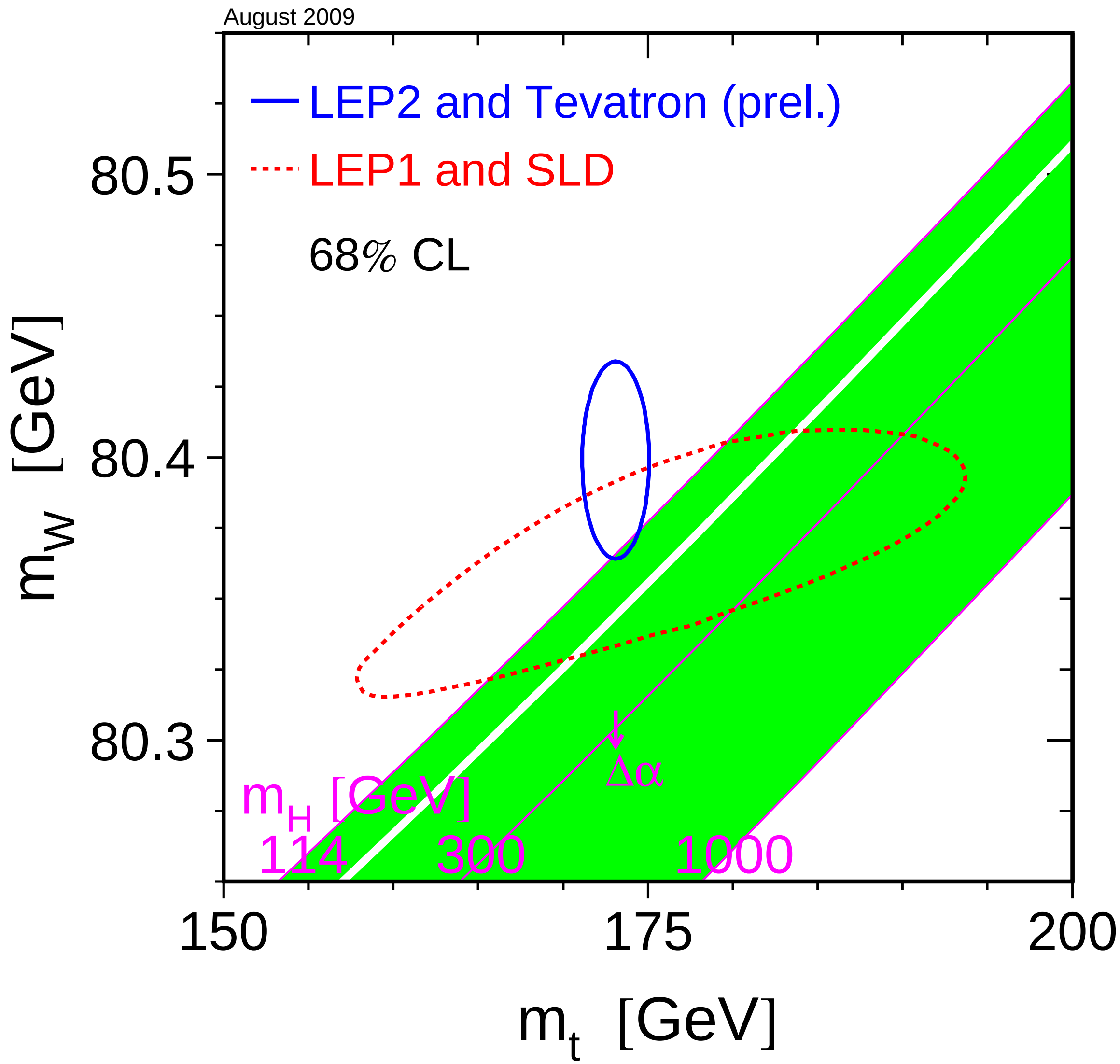
$$\Delta r = -\frac{11 g_2^2}{96\,\pi^2}\frac{s_W^2}{c_W^2} \log\left(\frac{M_H}{M_W}\right)$$

general for EWPO:

$$\Delta \sim g_2^2 \left[\log\left(\frac{M_H}{M_W}\right) + g_2^2 \frac{M_H^2}{M_W^2} \right]$$

leading term: $\log(M_H)$

first term $\sim M_H^2$ with g_2^4



⇒ light Higgs boson preferred

[*LEPEWWG '09*]

Results for M_H from other EWPO:

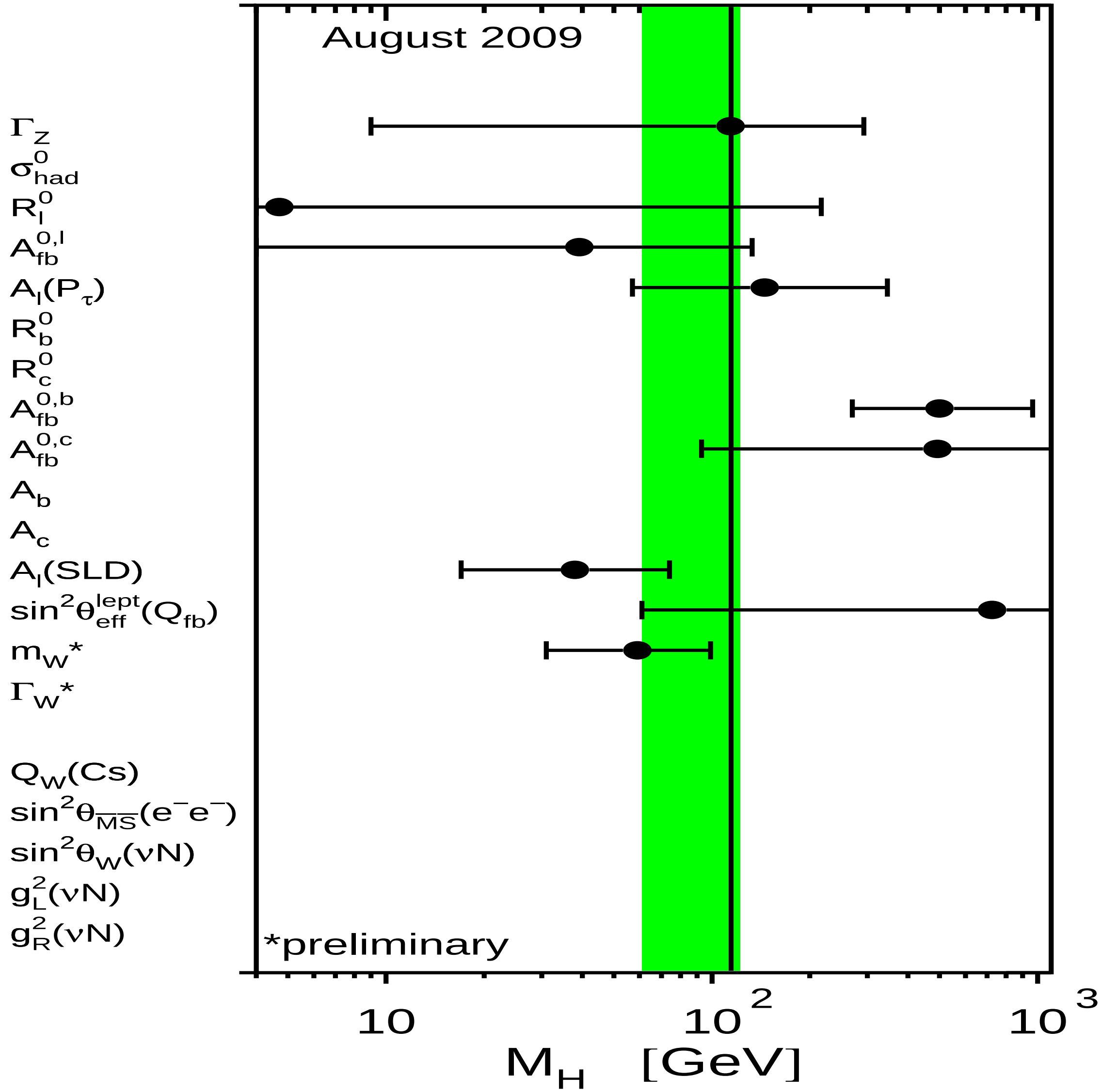
light Higgs preferred by:

M_W, A_l^{LR} (SLD)

heavier Higgs preferred by:

A_b^{FB} (LEP)

⇒ keeps SM alive



[LEPEWWG '09]

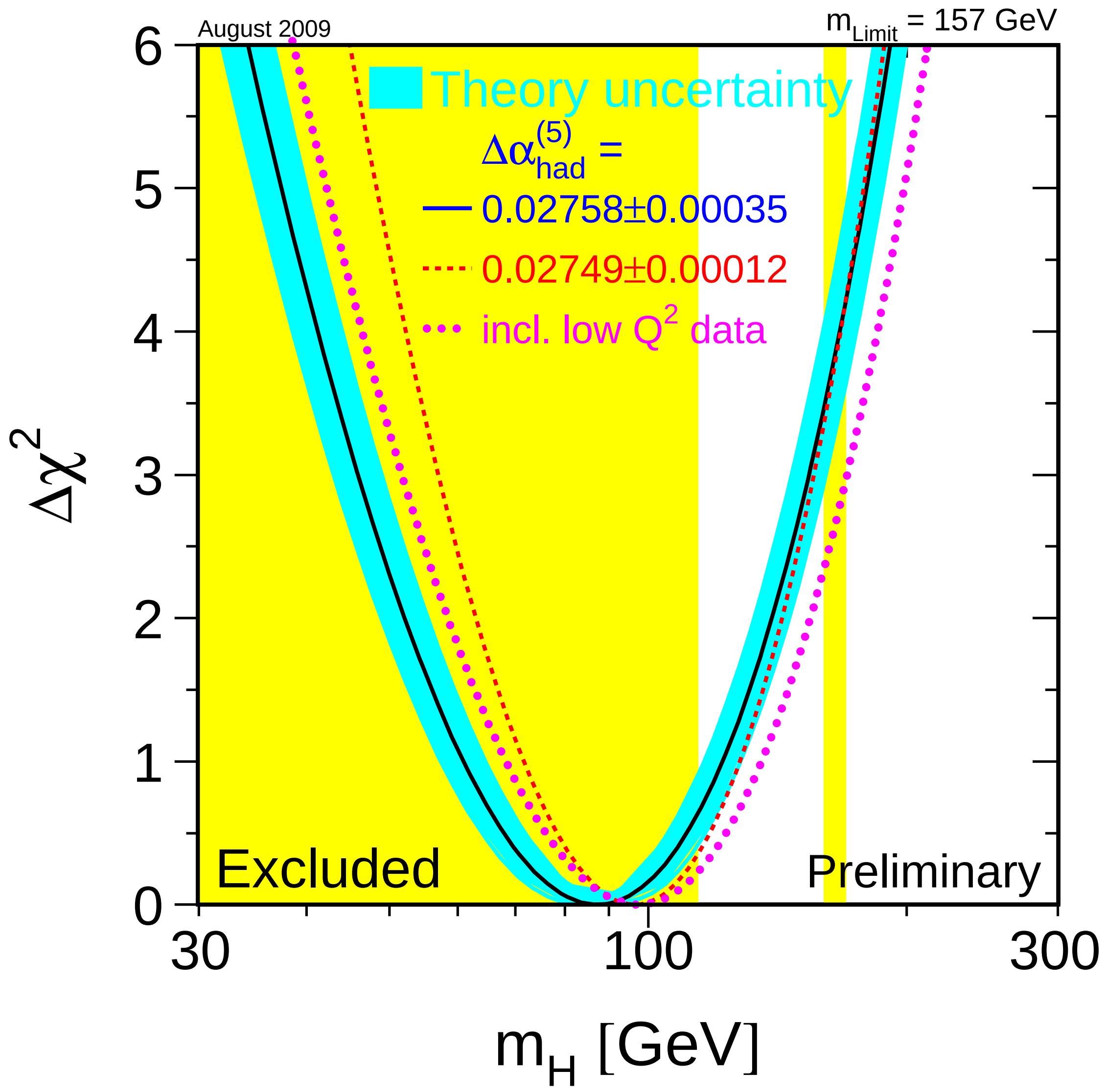
⇒ light Higgs boson preferred

Global fit to all SM data:

[*LEPEWWG '09*]

$\Rightarrow M_H = 87^{+35}_{-26}$ GeV

$M_H < 157$ GeV, 95% C.L.



Assumption for the fit:
SM incl. Higgs boson

$\Rightarrow$ no confirmation of Higgs mechanism

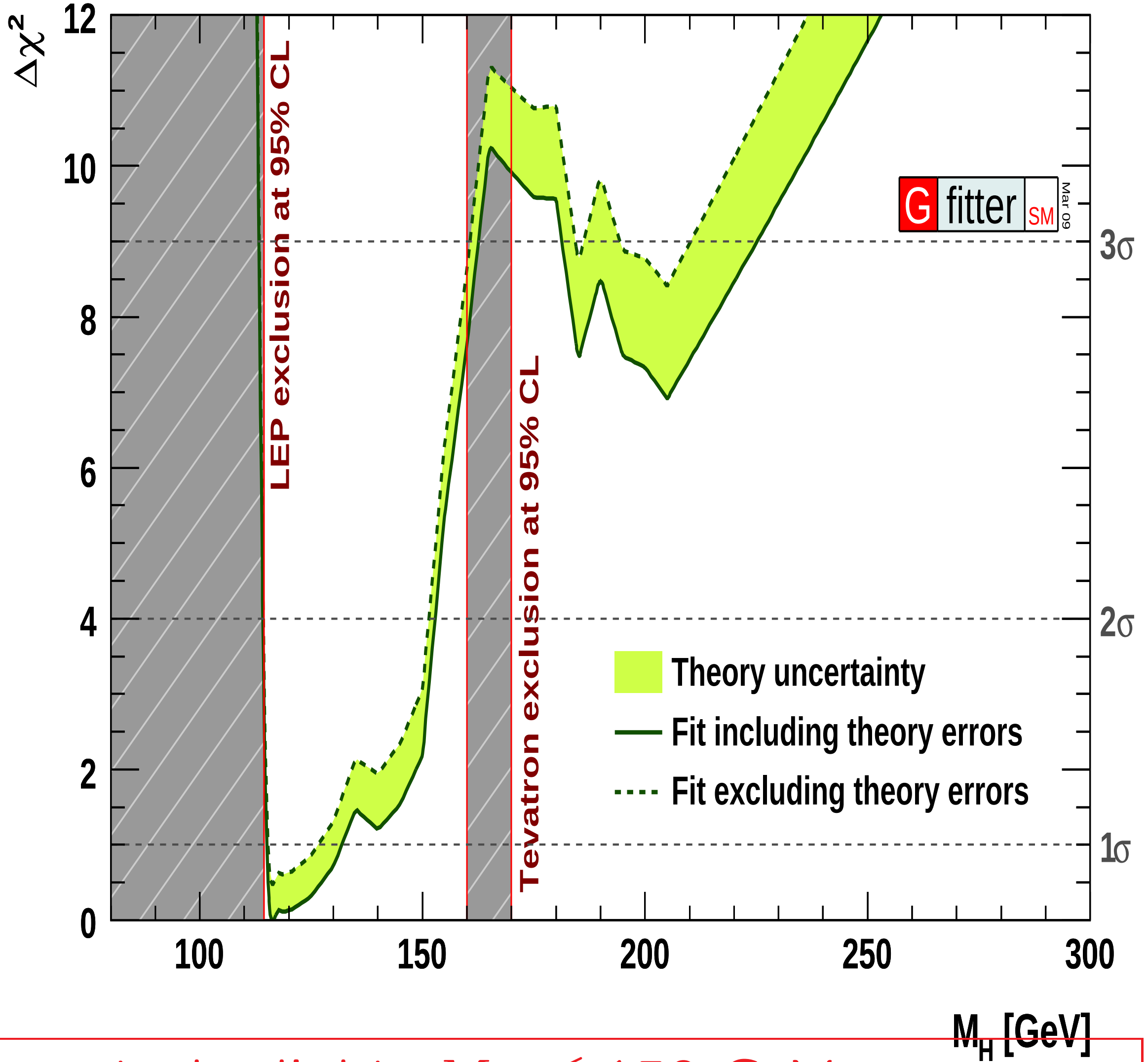
$\Rightarrow$ Higgs boson seems to be light, $M_H \lesssim 160$ GeV

Global fit to all SM data incl. direct searches:

[*GFitter '09*]

$\Rightarrow M_H = 116.4^{+18.3}_{-1.4}$ GeV

$M_H < 152$ GeV, 95% C.L.



Assumption for the fit:
SM incl. Higgs boson

$\Rightarrow$ no confirmation of
Higgs mechanism

$\Rightarrow$ Higgs boson seems to be light, $M_H \lesssim 150$ GeV

Experimental errors of the precision observables:

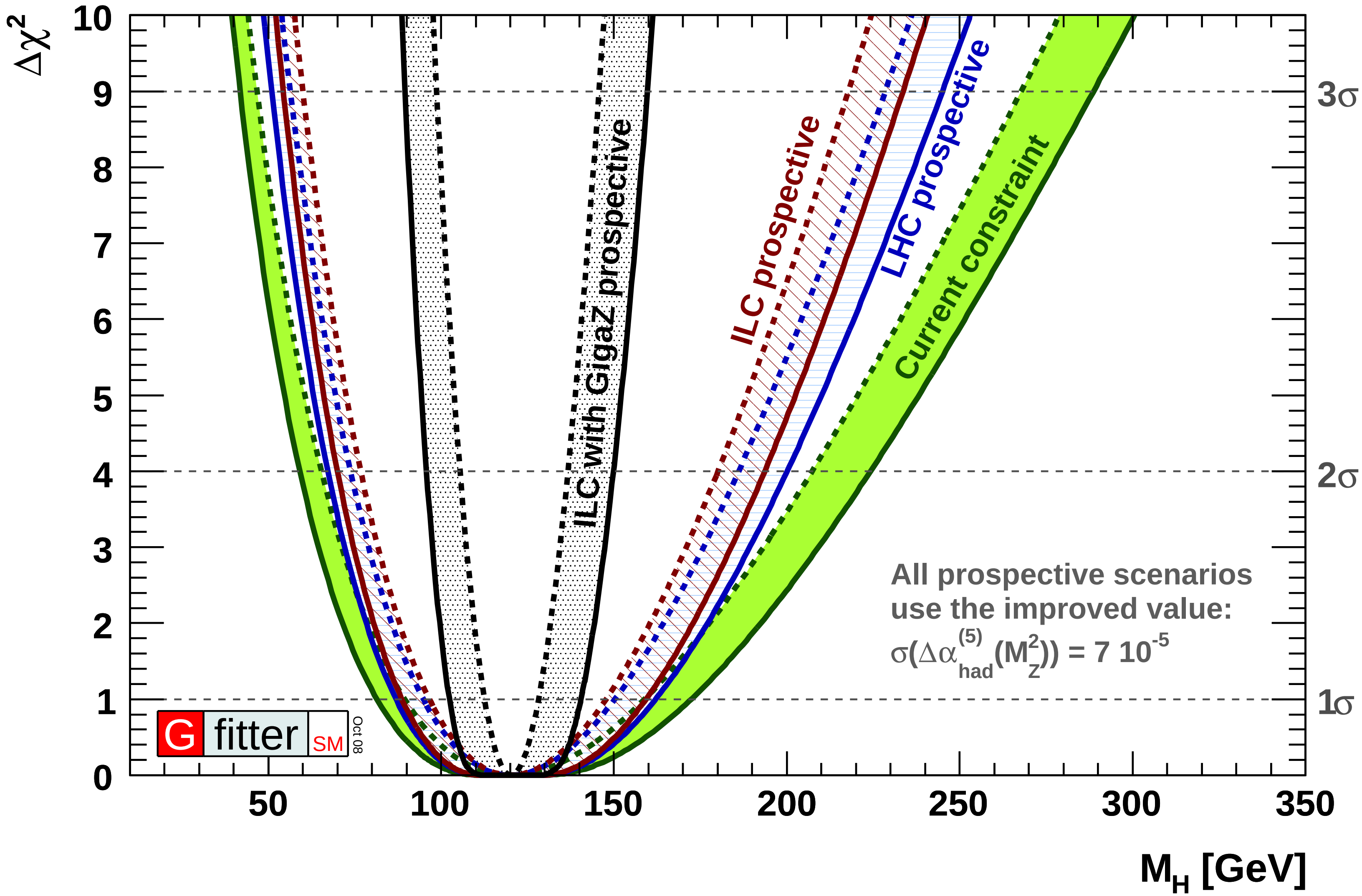
	today	Tev./LHC	ILC	GigaZ
$\delta \sin^2\theta_{\mathrm{eff}} (\times 10^5)$	16	16	–	1.3
δM_W [MeV]	25 (23)	15	10	7
δm_t [GeV]	1.3	1-2	0.2	0.1

Relevant SM parametric errors: $\delta(\Delta\alpha_{\mathrm{had}}) = 5 \times 10^{-5}$, $\delta M_Z = 2.1$ MeV

	$\delta m_t = 2$	$\delta m_t = 1$	$\delta m_t = 0.1$	$\delta(\Delta\alpha_{\mathrm{had}})$	δM_Z
$\delta \sin^2\theta_{\mathrm{eff}}$ $[10^{-5}]$	6	3	0.3	1.8	1.4
ΔM_W [MeV]	12	6	1	1	2.5

Improvement in the Blue Band plot:

[*GFitter '09*]

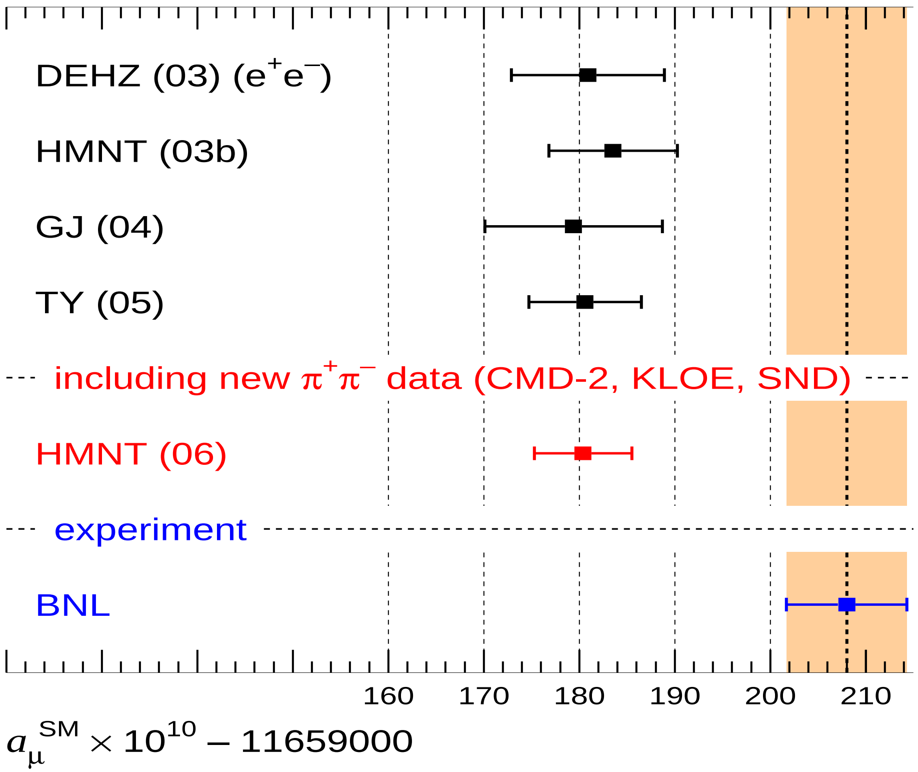


(note: artificially $M_H^{\text{SM}} = 120$ GeV)

Another EWPO: the anomalous magnetic moment of the muon

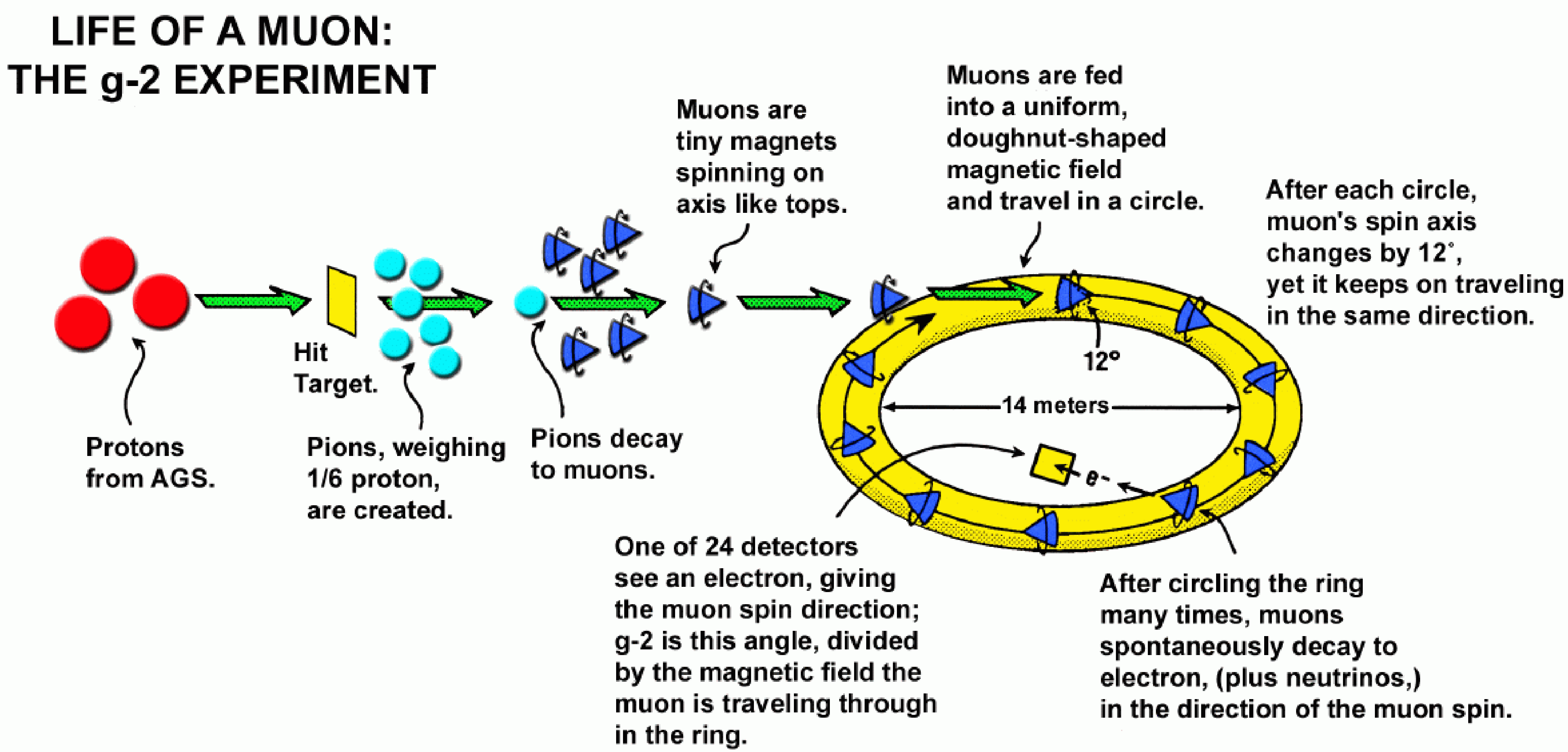
$$a_\mu \equiv (g-2)_\mu/2$$

Overview about the current experimental and SM (theory) result:
[*g-2 Collaboration, hep-ex/0602035*] $\rightarrow$ T



$$a_\mu^{\rm exp} - a_\mu^{\rm theo,SM} \approx (28 \pm 8) \times 10^{-10} \quad : \; 3.4\,\sigma$$

The $(g-2)_\mu$ experiment:



Coupling of muon to magnetic field : $\mu - \mu - \gamma$ coupling

$$\bar{u}(p') \left[\gamma^\mu F_1(q^2) + \frac{i}{2m_\mu} \sigma^{\mu\nu} q_\nu F_2(q^2) \right] u(p) A_\mu \qquad F_2(0) = a_\mu$$

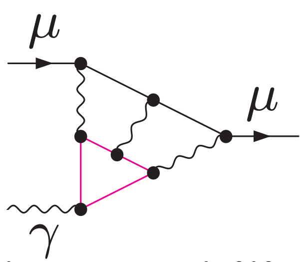
Current status of $(g-2)_\mu$:

Experiment:

– 2001 - 2006: very stable development
– final error: 6×10^{-10} , still statistically dominated

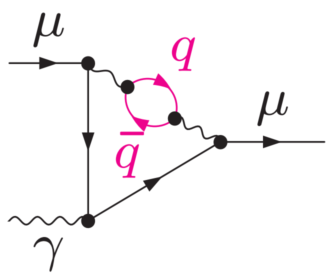
Theory:

– the light-by-light contribution:



2002: sign error discovered; since then stabilized

– the hadronic vacuum contribution:



problems with the τ data $\Rightarrow$ hardly used anymore (status 06/2009)
new 'direct' e^+e^- data from CMD-II and SND
$\Rightarrow$ agrees well (also with old e^+e^- data)
new radiative return data from KLOE and B-factories
$\Rightarrow$ agrees well with e^+e^- data

new SM evaluations, based on new exp data for a_μ^{had} :

$$a_\mu(\text{Exp-SM}) = \left\{ \begin{array}{ll} \text{[HMNT '06]} & 28(8) \\ \text{[DEHZ '06]} & 28(8) \\ \text{[FJ '07]} & 29(9) \\ \text{[MRR '07]} & 29(9) \end{array} \right\} \times 10^{-10}$$

better agreement between evaluations, more precise,

larger deviation from exp than ever before

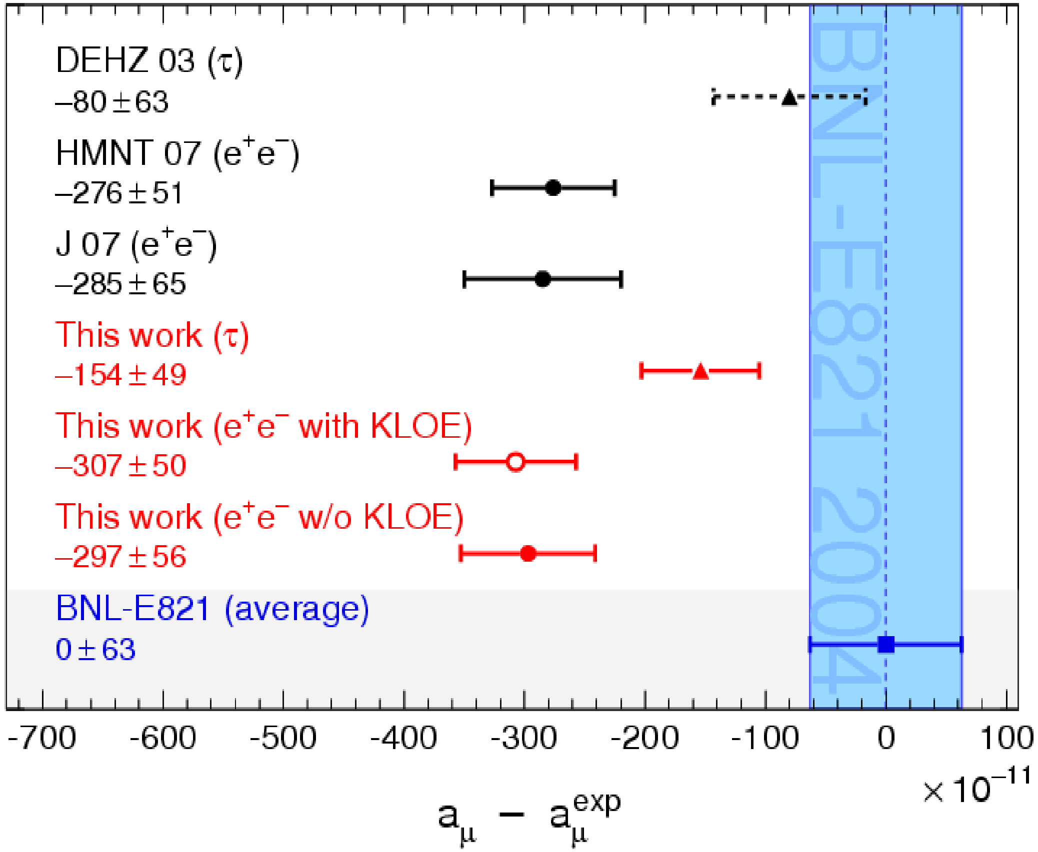
$\Downarrow$

3σ deviation has now been definitely established

New development for τ data:

[*M. Davier, A. Höcker et al. '09*]

Re-evaluation of τ data: improved evaluation of iso-spin breaking effects
$\Rightarrow$ shift in τ data :



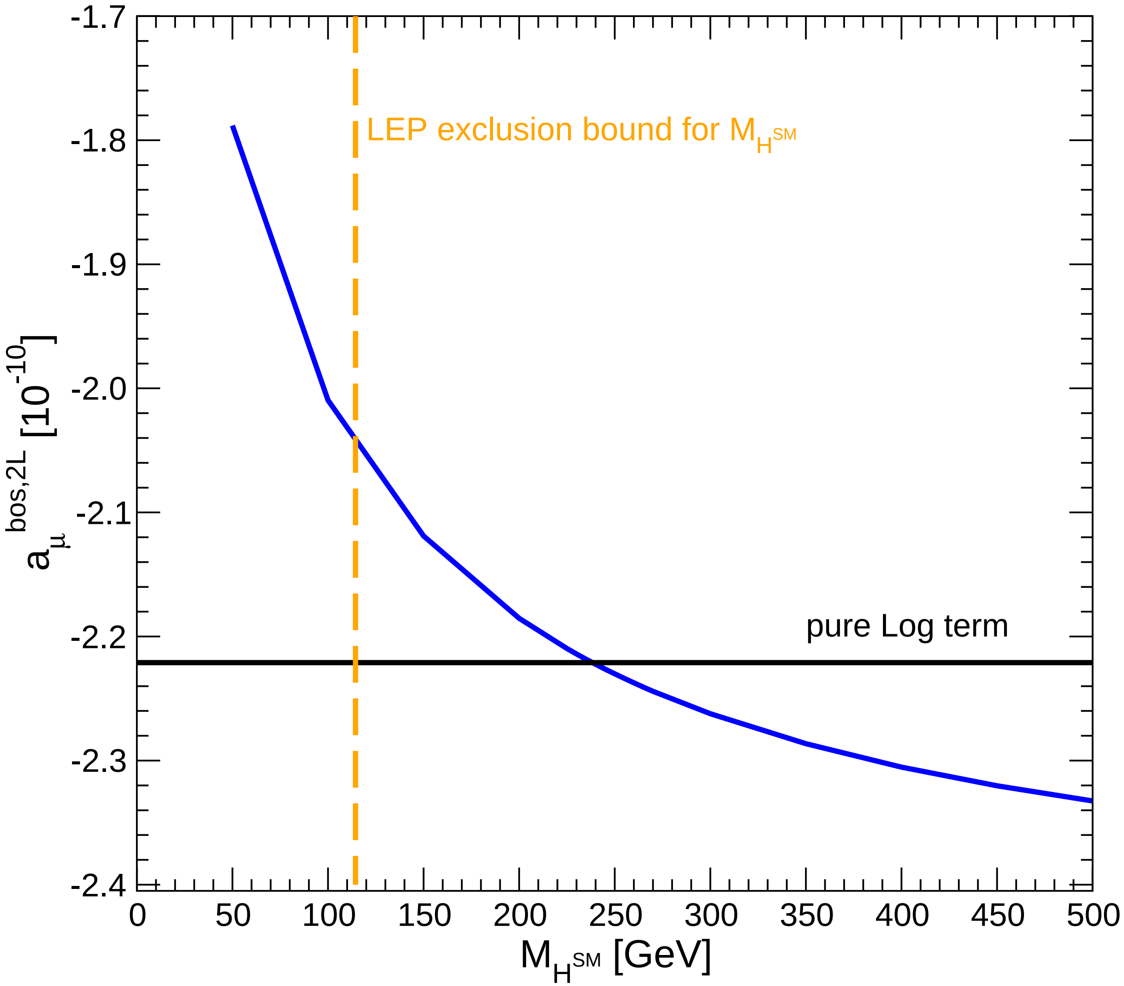
Now: 1.9 σ deviation! $\Rightarrow$ still tbc!
If correct: $\Rightarrow$ new average of all data possible . . .

Restrictions on M_H from a_μ?

$\Rightarrow$ Higgs enters only at the two-loop level

Example for M_H dependence:

[*S.H., D. Stöckinger, G. Weiglein '04*]



$\Rightarrow$ no restrictions on M_H (but wait for tomorrow! :-)

3. Properties of the SM Higgs boson

1.) Decay to fermions:

coupling:

$$g_{f\bar{f}H} = \left[\sqrt{2}\,G_\mu\right]^{1/2} m_f$$

decay width:

$$\Gamma(H \to f\bar{f}) = N_c \frac{G_\mu\, M_H}{4\sqrt{2}\,\pi} m_f^2(M_H^2) \left(1 - 4\frac{m_f^2}{M_H^2}\right)^{3/2}$$

with N_c = number of colors

Bulk of QCD corrections for decays to quarks are mapped into

$$m_q^2(\text{pole}) \to m_q^2(M_H^2)$$

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

2.) Decay to heavy gauge bosons ($V = W, Z$):

coupling:

$$g_{VVH} = 2\left[\sqrt{2}\,G_\mu\right]^{1/2} M_V^2$$

on-shell decay width ($M_H > 2M_V$):

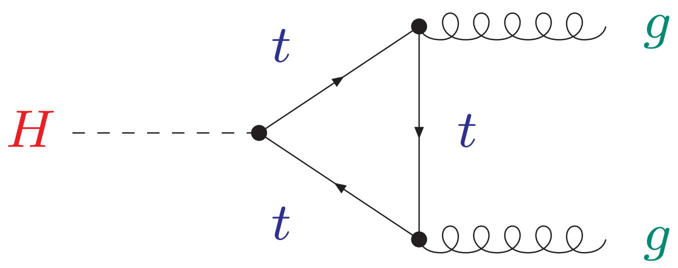
$$\Gamma(H \to VV) = \delta_V \frac{G_\mu M_H^3}{16\sqrt{2}\,\pi}\left(1 - 4\frac{M_V^2}{M_H^2} + 12\frac{M_V^4}{M_H^4}\right)\left(1 - 4\frac{M_V^2}{M_H^2}\right)^{1/2}$$

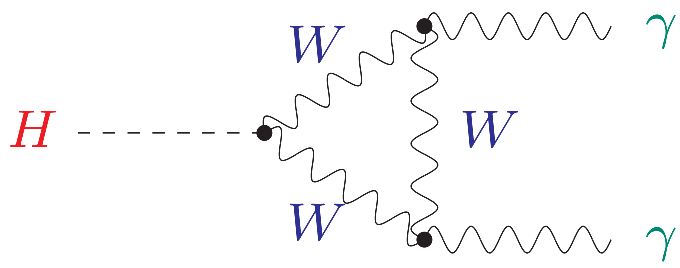
with $\delta_{W,Z} = 2, 1$

off-shell decay width ($M_H < 2M_V$):

$$\Gamma(H \to VV^*) = \delta'_V \frac{3G_\mu^2 M_H}{16\,\pi^3} M_V^4 \times \text{Integral}$$

3.) Decay to massless gauge bosons (gg, $\gamma\gamma$):





$$\Gamma(H \to gg) \;=\; \frac{G_\mu\, \alpha_s^2(M_H^2)\, M_H^3}{36\,\sqrt{2}\,\pi^3}\left[1 + C\frac{\alpha_s(\mu)}{\pi}\right]$$

via the top quark loop with

$$C = \frac{215}{12} - \frac{23}{6}\log\left(\frac{\mu^2}{M_H^2}\right) + \mathcal{O}(\alpha_s)$$

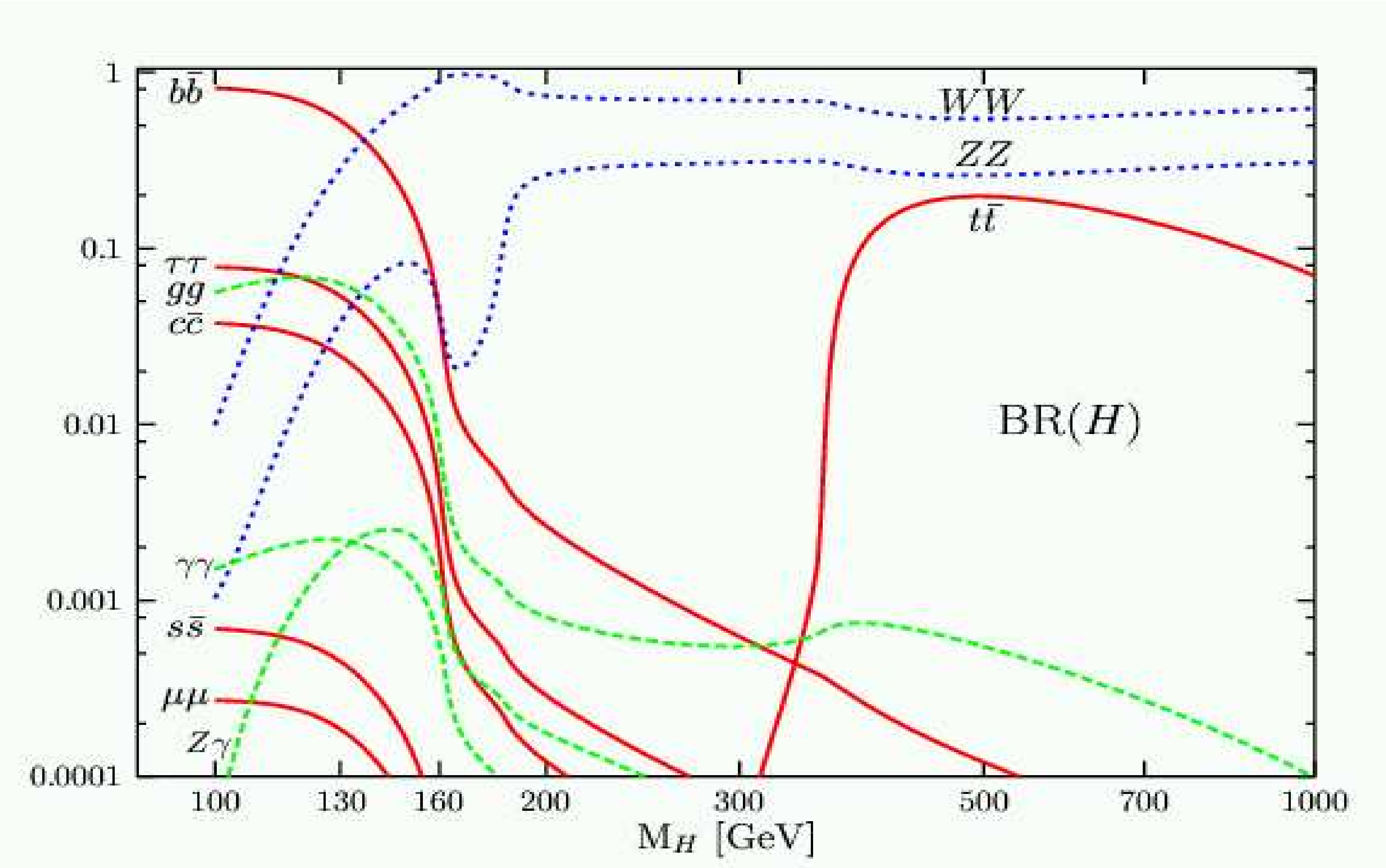
⇒ huge QCD corrections

$$\Gamma(H \to \gamma\gamma) \;=\; \frac{G_\mu\, \alpha^2\, M_H^3}{128\,\sqrt{2}\,\pi^3}\left|\frac{4}{3}e_t^2 - 7\right|^2$$

via the top quark and W boson loop

Overview of the branching ratios:

[*taken from hep-ph/0503172*]



The total SM Higgs boson width:

[*taken from hep-ph/0503172*]