
HAVE YOU HEARD? THEY DISCOVERED THE GOD PARTI...
IT'S CALLED THE HIGGS BOSON!

Higgs Physics

Sven Heinemeyer, IFT/IFCA (CSIC, Madrid/Santander)

Dubna, 07/2018

1. Before the Higgs discovery

2. The Higgs sector of the SM

3. The Higgs sector of the (N)MSSM

4. Higgs boson(s) at the LHC

Higgs Physics

Before the Higgs Discovery

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1. Why Higgs?

2. Higgs mass predictions before the LHC

3. Electroweak Precision Observables (EWPO)

1. Why Higgs?

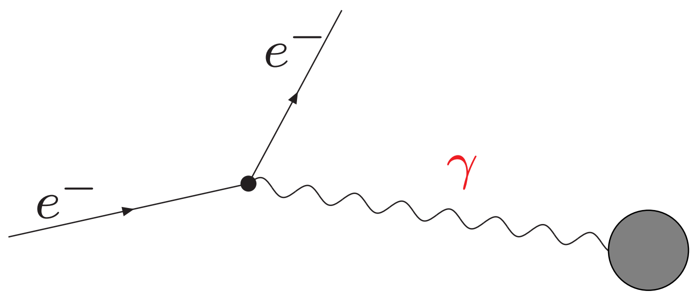
Standard Model (SM) of the electroweak and strong interaction

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



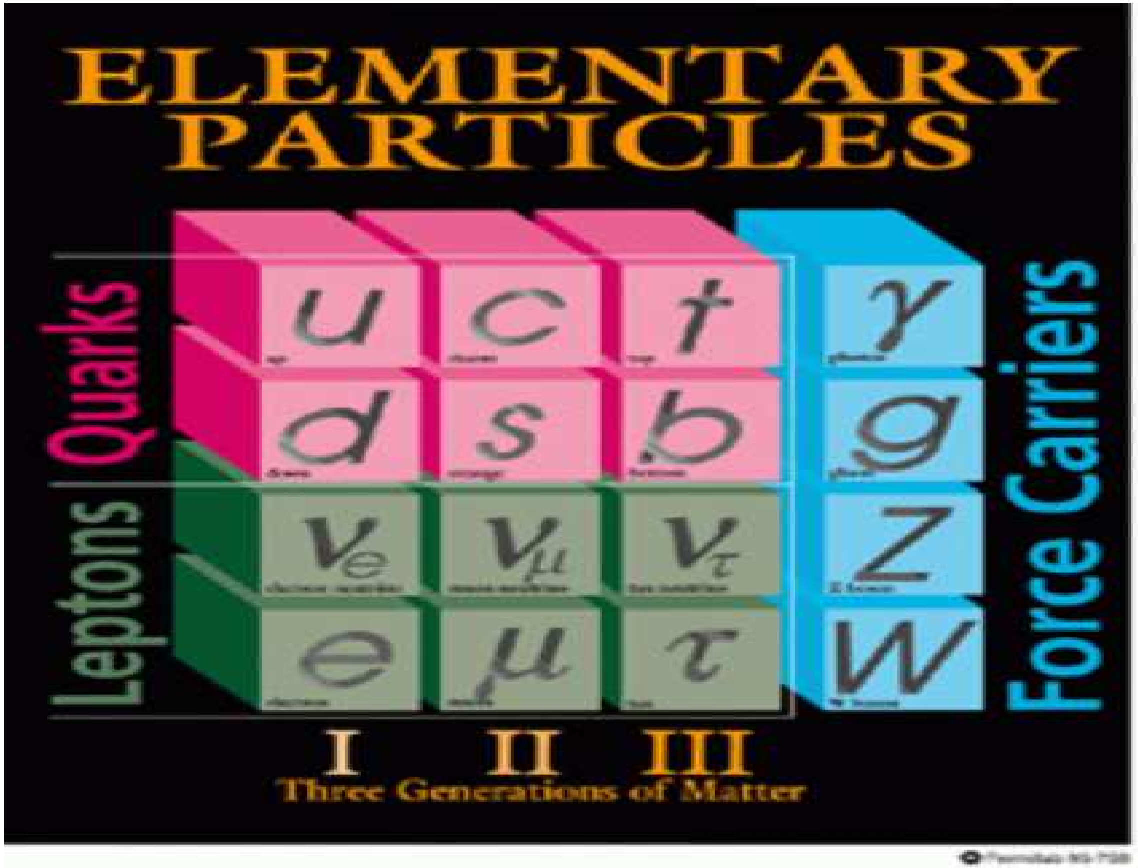
$\mathcal{L}_{\text{QED}}$ invariant under gauge transformation:

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

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

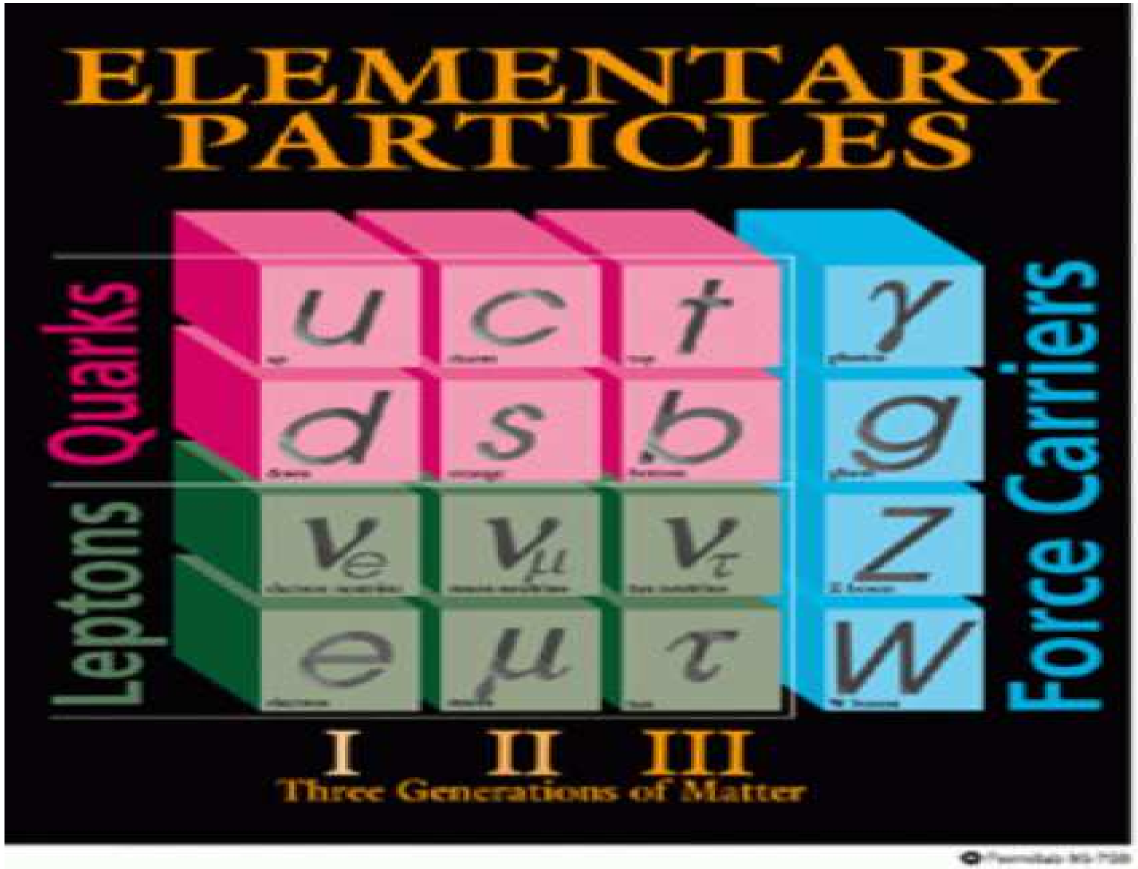
$\Rightarrow A_\mu$ is massless gauge field

Current status of knowledge: the Standard Model (SM)



⇒ all particles experimentally seen (as of 2011)

Current status of knowledge: the Standard Model (SM)



⇒ all particles experimentally seen (as of 2011)

⇒ but it 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:

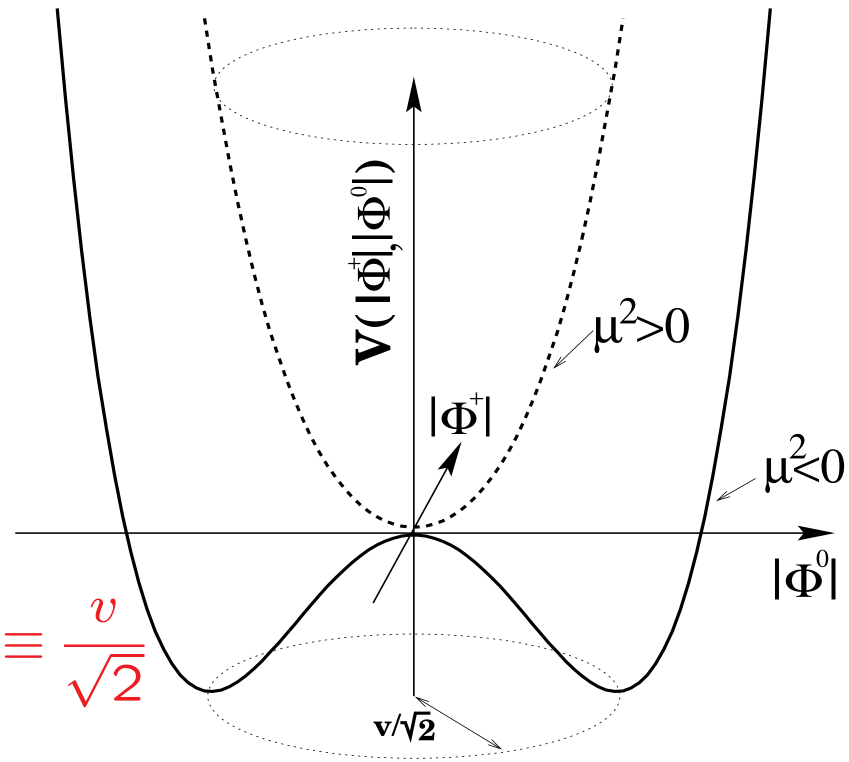
Scalar SU(2) doublet: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

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:

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

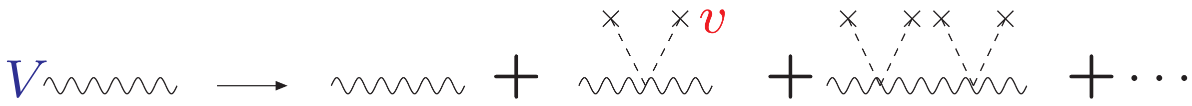
with

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

Gauge invariant coupling to gauge fields

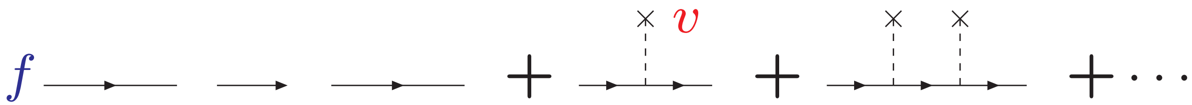
$\Rightarrow$ mass terms for gauge bosons and fermions

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



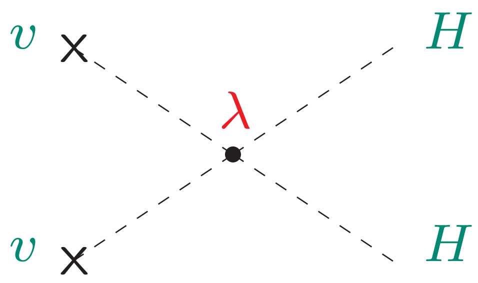
$$\frac{1}{q^2} \to \frac{1}{q^2} + \sum_j \frac{1}{q^2}\left[\left(\frac{gv}{\sqrt{2}}\right)^2 \frac{1}{q^2}\right]^j = \frac{1}{q^2 - M^2} \; : \; M^2 = g^2\frac{v^2}{2} \qquad \Rightarrow M \propto g$$

<u>2.) fermion mass terms: Yukawa couplings:</u>



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

3.) mass of the Higgs boson: self coupling



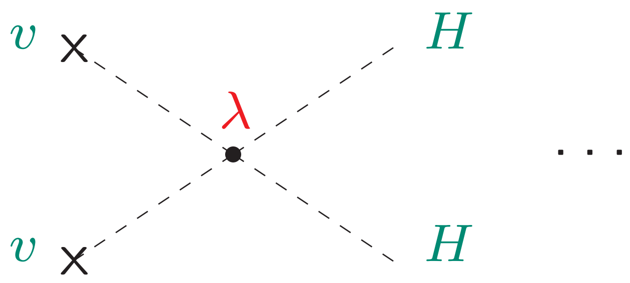
. . .

$$\lambda = M_H^2/v^2$$

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

→ last unknown (now measured) parameter of the SM

3.) mass of the Higgs boson: self coupling



$$\lambda = M_H^2/v^2$$

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

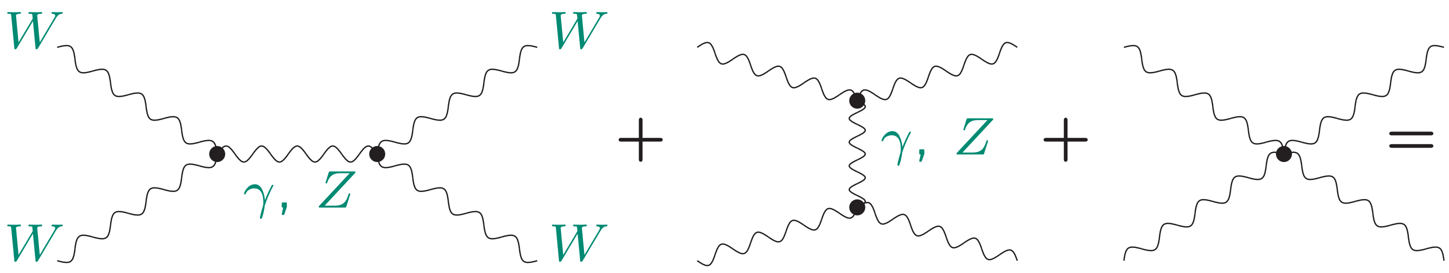
→ last unknown (now measured) parameter of the SM

⇒ establish Higgs mechanism ≡ find the Higgs ⊕ measure its couplings

Another effect of the Higgs field:

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

$\mathcal{M}_V =$

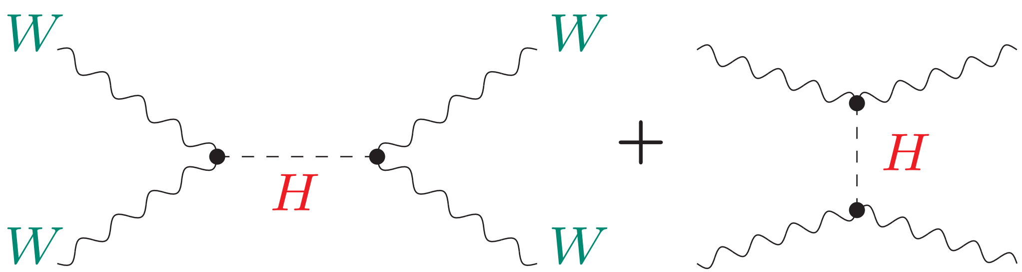


$= -g^2 \frac{E^2}{M_W^2} + \mathcal{O}(1)$ for $E \to \infty$

$\Rightarrow$ 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 $E \to \infty$

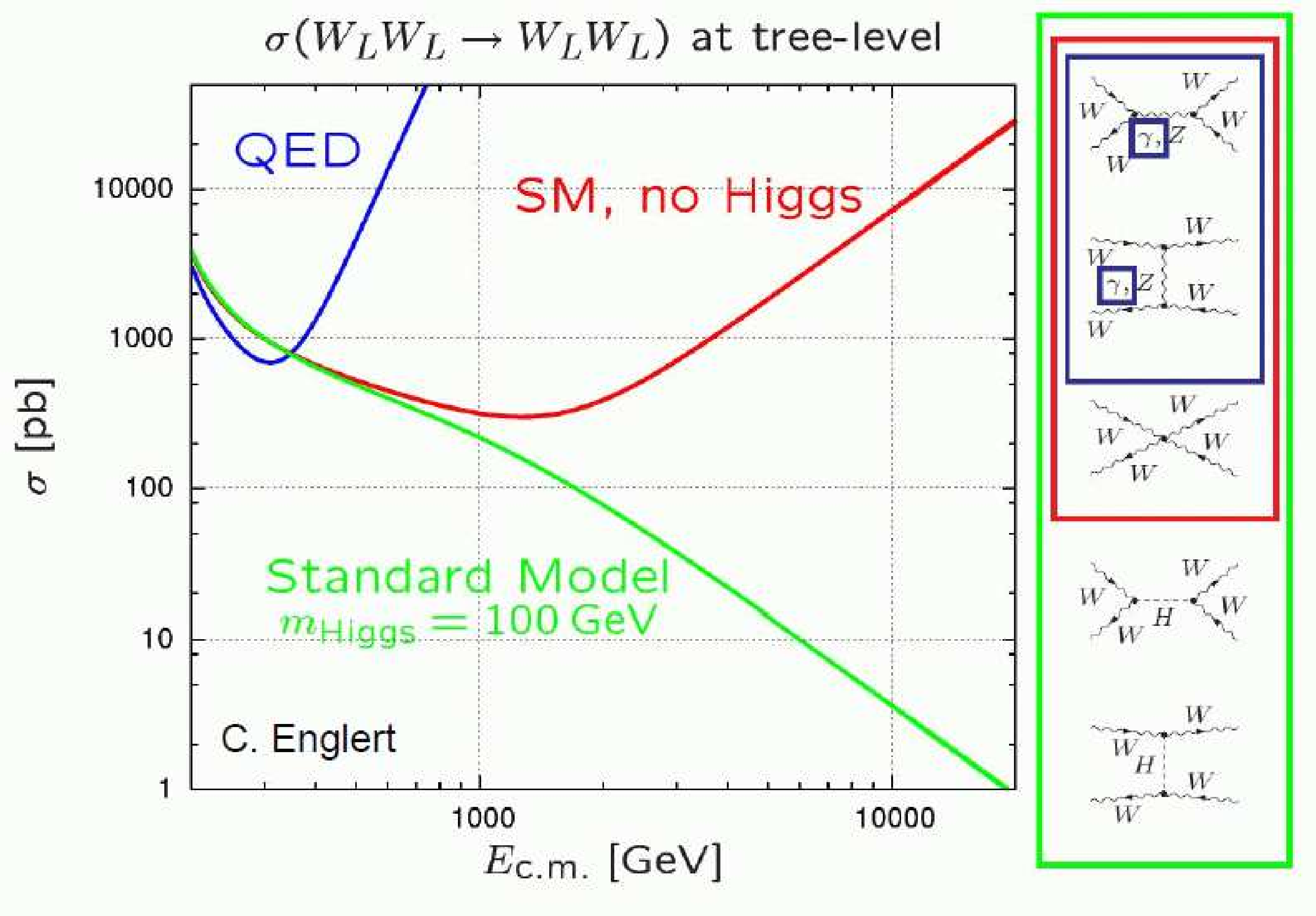
$$\mathcal{M}_{\rm tot} = \mathcal{M}_V + \mathcal{M}_S = \frac{E^2}{M_W^4}\left(g_{WWH}^2 - g^2\, M_W^2\right) + \ldots$$

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

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

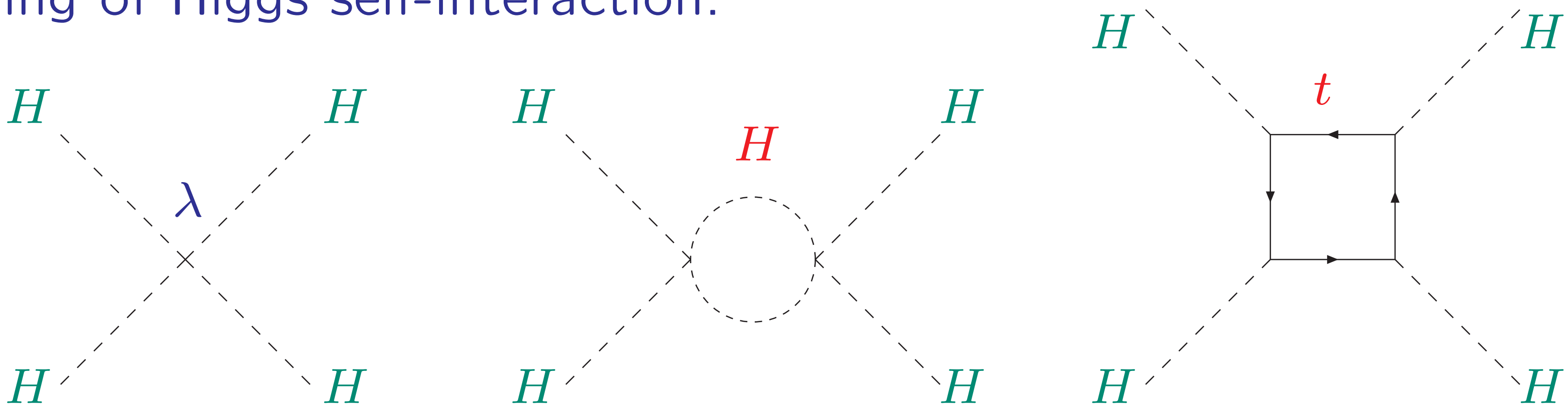
Cross section with/without the Higgs:

[*taken from M. Schumacher '12 / C. Englert*]



2. Higgs mass predictions before the LHC

Running of Higgs self-interaction:



Renormalization group equation:

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

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 $\lambda \sim M_H^2$)

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

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

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

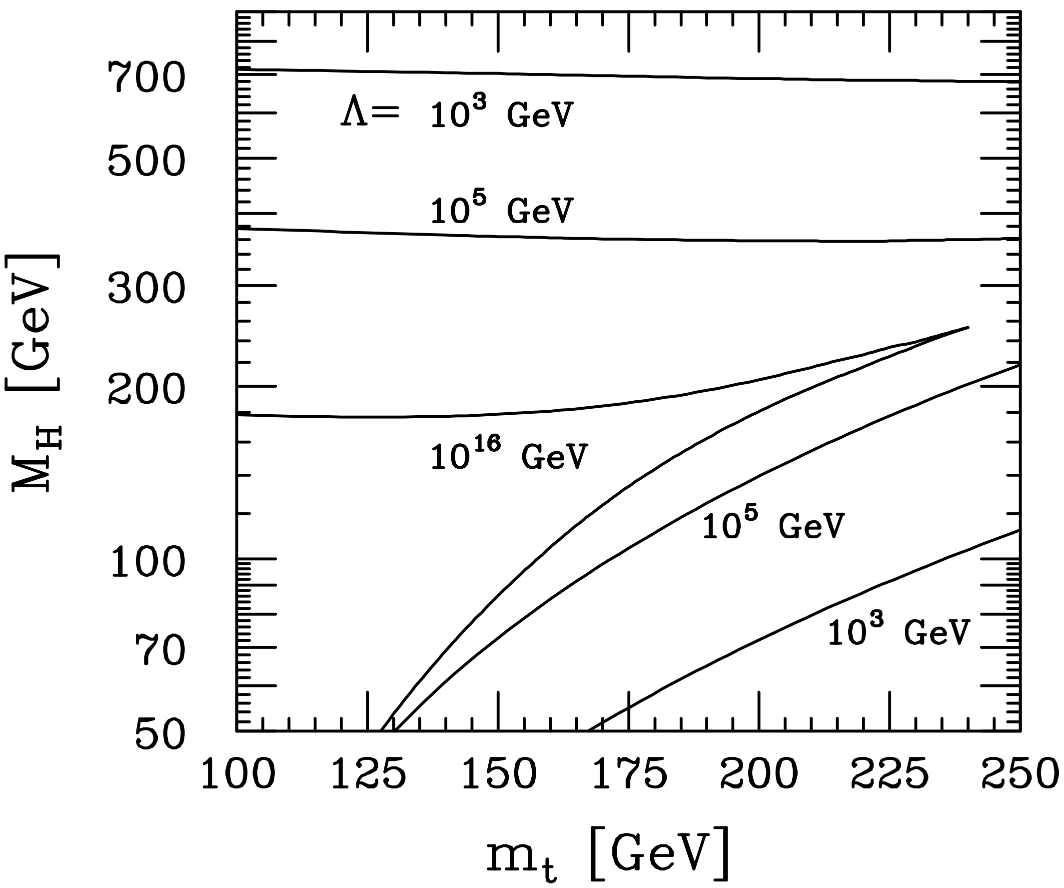
2.) avoid vacuum instability (for small/negative λ): $V(v) < V(0) \Rightarrow \lambda(\Lambda) > 0$

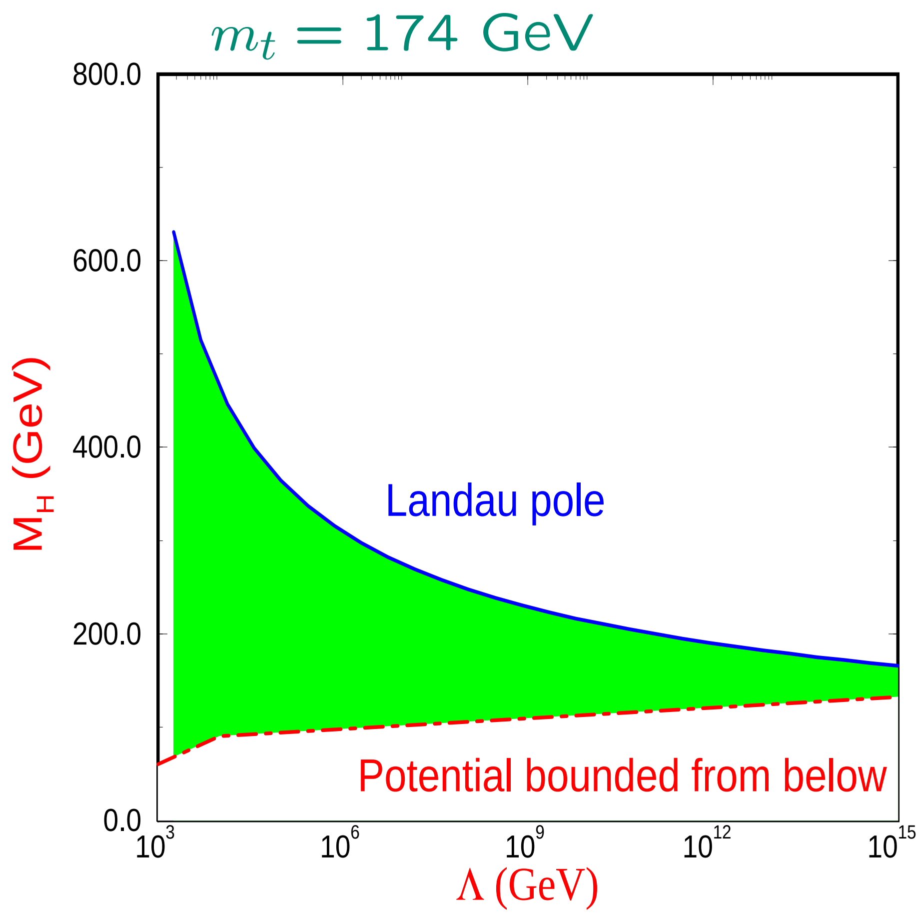
$$\frac{d\lambda}{dt} = \frac{3}{8\pi^2}\left[-g_t^4 + \frac{1}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]$$

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

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

Both limits combined:



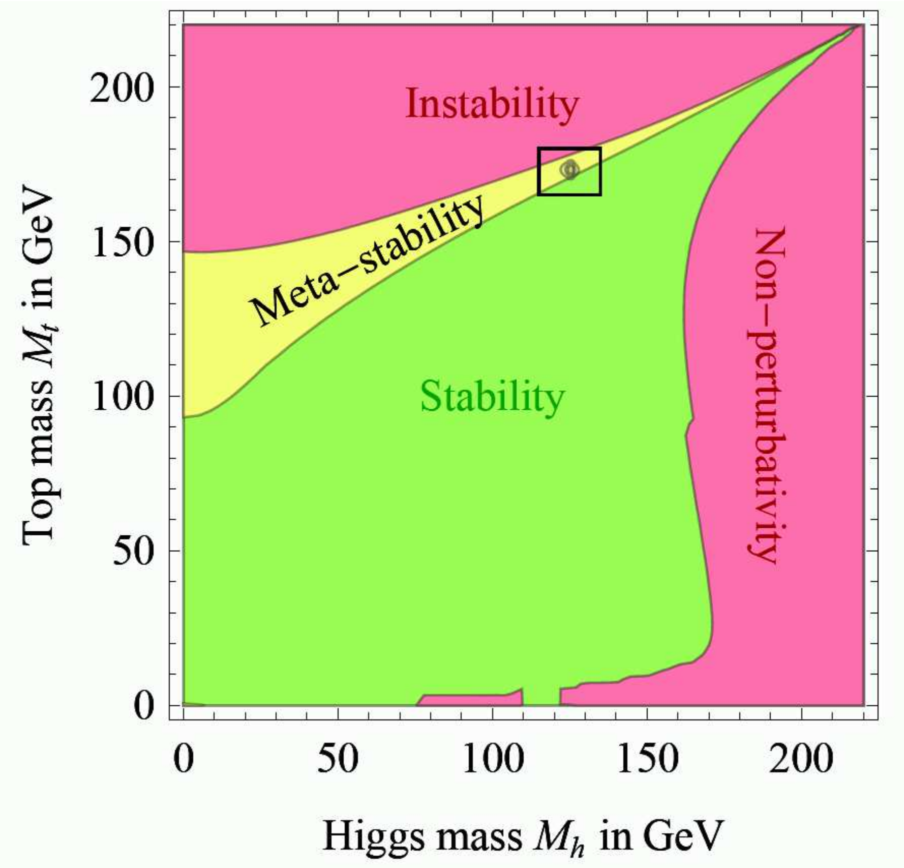


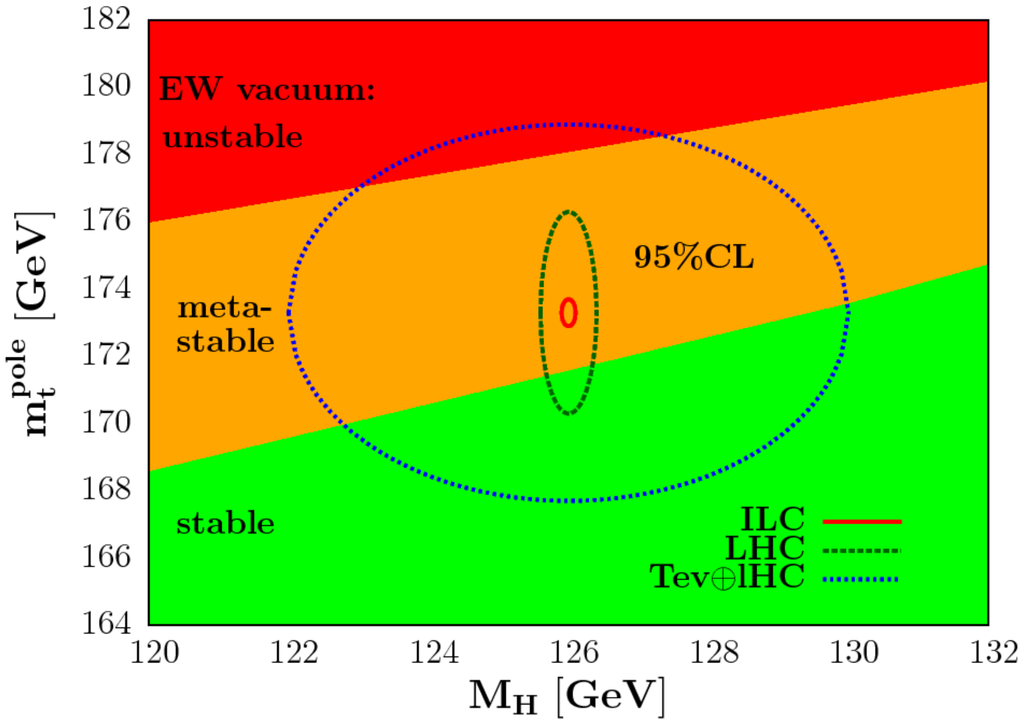
Λ: scale up to which the SM is valid

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

$M_H = 125$ GeV $\Rightarrow$ we live in a meta-stable vacuum!

[Degrassi et al. '12] *[Alehkin et al. '12]*





...if there is nothing else than the SM up to the Planck scale!

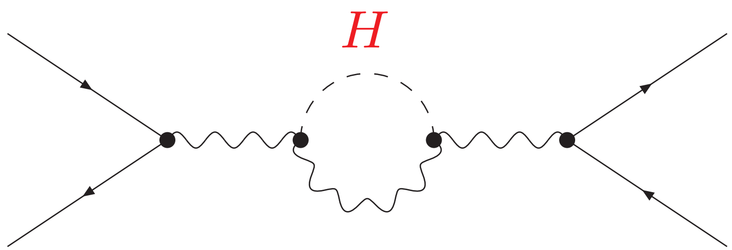
3. Electroweak Precision Observables (EWPO) and the Higgs mass:

Comparison of electro-weak precision observables with theory:

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

$\Downarrow$

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



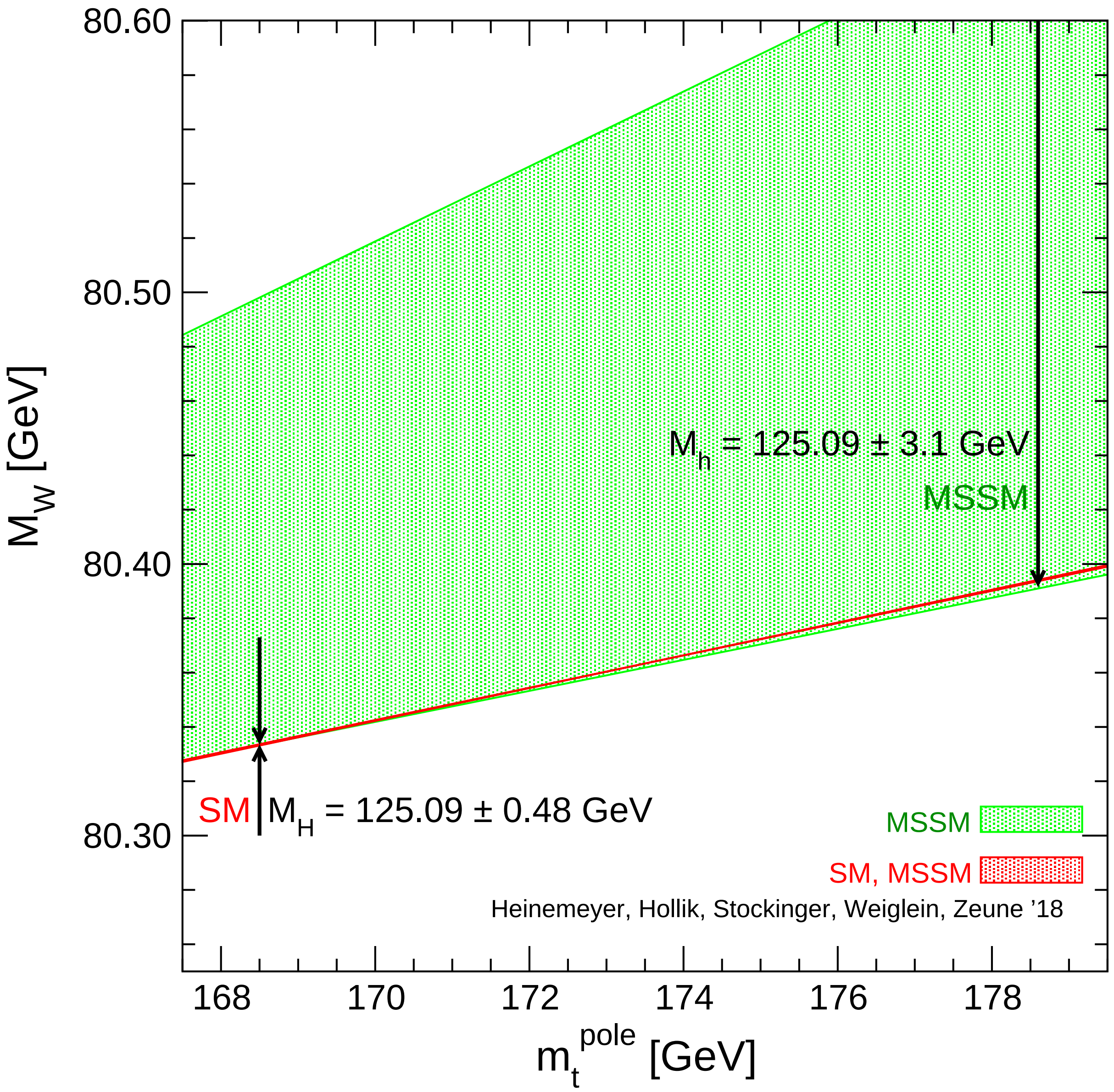
$\Downarrow$

SM: limits on M_H

Very high accuracy of measurements and theoretical predictions needed

Example: Prediction for M_W in the SM and the MSSM :

[S.H., W. Hollik, D. Stockinger, G. Weiglein, L. Zeune '13]



MSSM band:
scan over
SUSY masses

overlap:
SM is MSSM-like
MSSM is SM-like

SM band:
variation of M_H^{SM}

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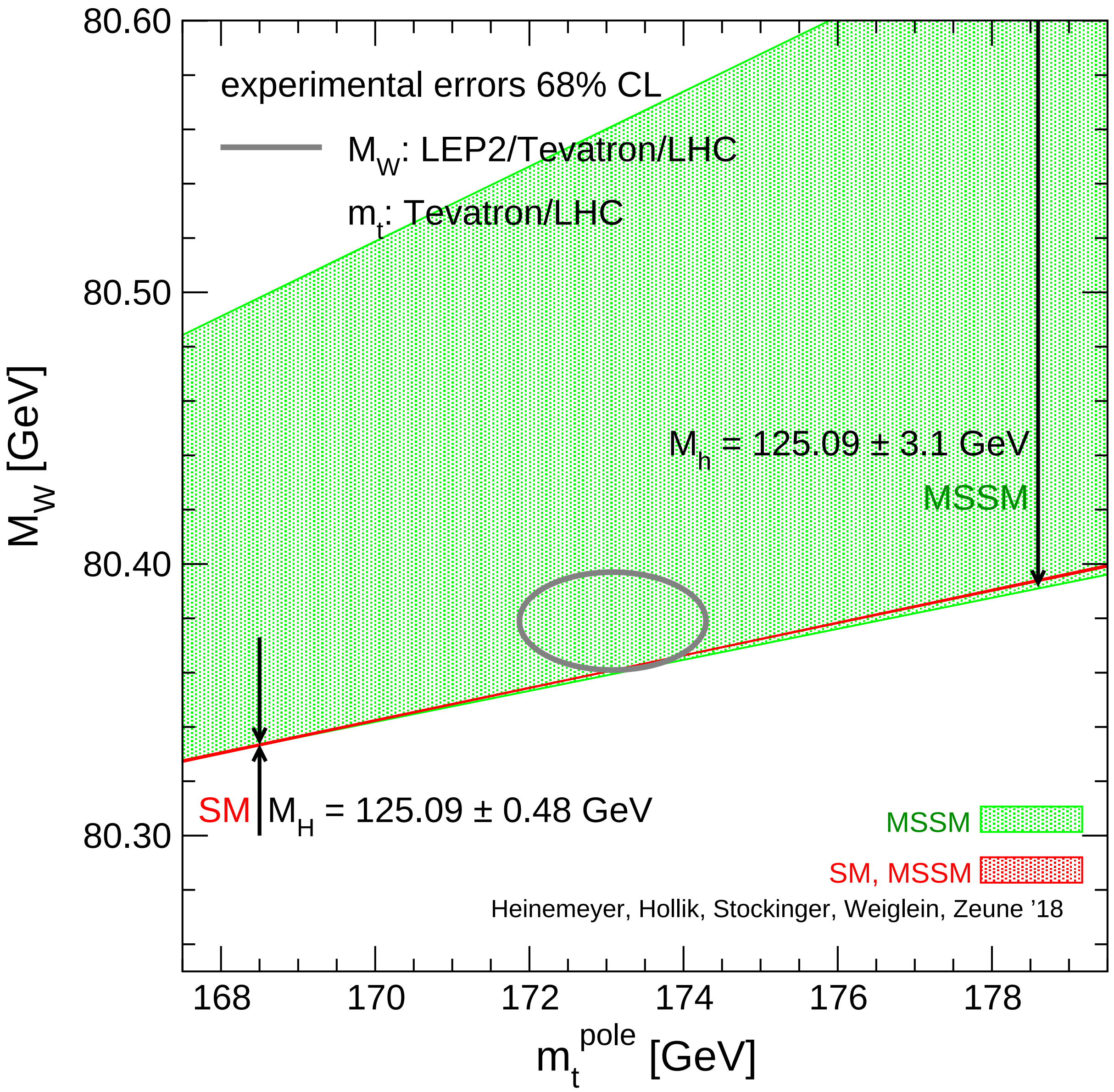

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What about the **UNCERTAINTIES?**

Three different types of uncertainties:

Experimental error:

– current error

– future expectations

⇒ sets the scale, has to be matched by other errors

Theory uncertainty:

⇒ uncertainty due to missing higher order corrections

– only estimates possible

– even more complicated for the future

Parametric uncertainty:

uncertainty in the prediction due to error in the input parameters

– m_t, α_s, PDFs, . . .

– future expectations?

⇒ derive information about (unknown) SUSY parameters
(SUSY parametric uncertainties highly model dependent)

Precision observables in the SM and the MSSM

M_W, $\sin^2\theta_{\rm eff}$, M_h, $(g-2)_\mu$, b physics, . . .

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*]

$$\Delta r_{1-\rm loop} = \Delta\alpha - \frac{c_{\rm W}^2}{s_{\rm W}^2}\Delta\rho + \Delta r_{\rm rem}(M_H)$$

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

Precision observables in the SM and the MSSM

M_W, $\sin^2\theta_{\text{eff}}$, M_h, $(g-2)_\mu$, b physics, ...

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:

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

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:

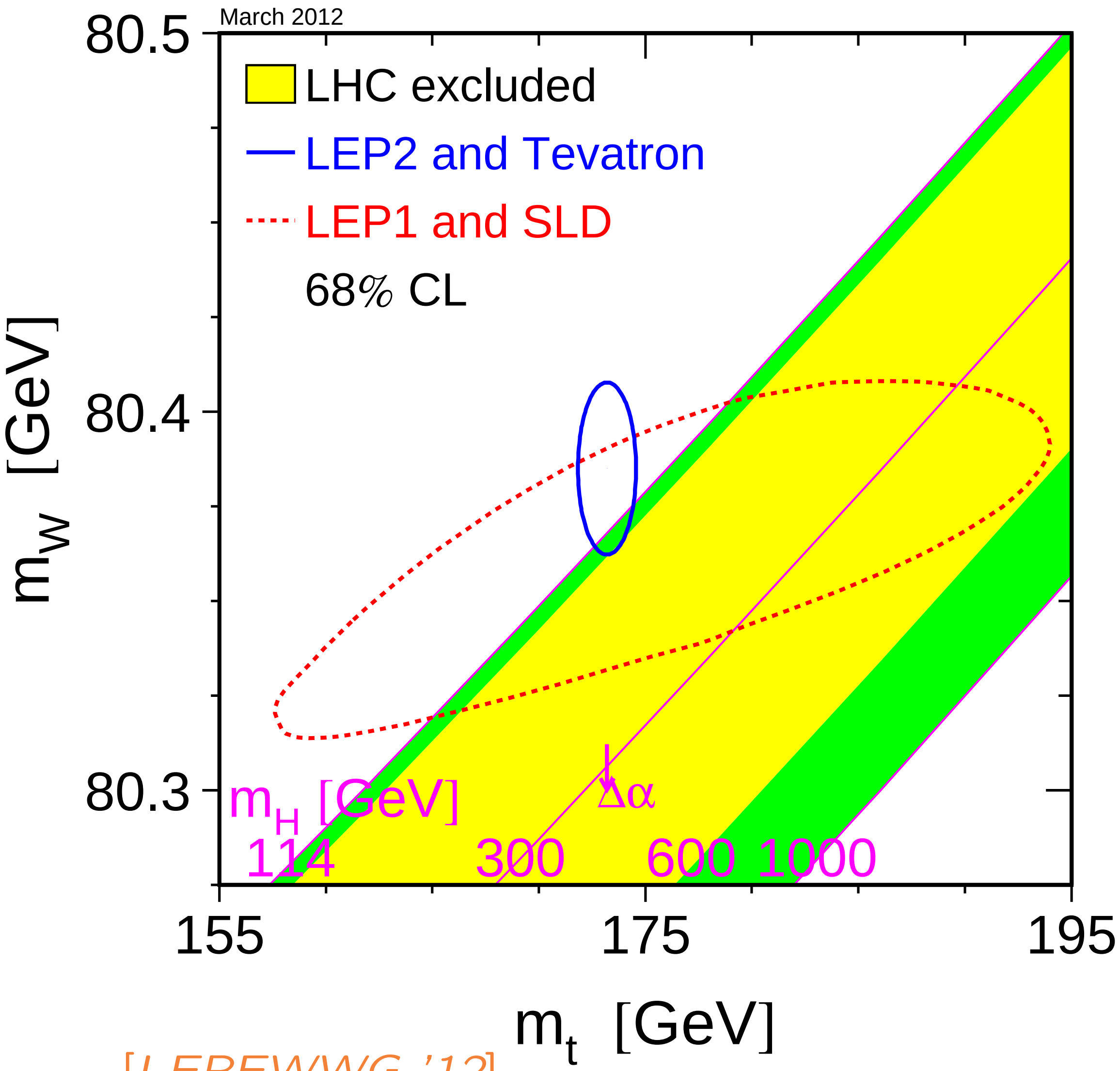
$$\Delta r = -\frac{11 g_2^2}{96\,\pi^2}\frac{s_W^2}{c_W^2}\log\left(\frac{M_H}{M_W}\right)$$

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



[LEPEWWG '12]

⇒ light Higgs boson preferred

Corrections to M_W, $\sin^2\theta_{\text{eff}}$ → approximation via the ρ-parameter:

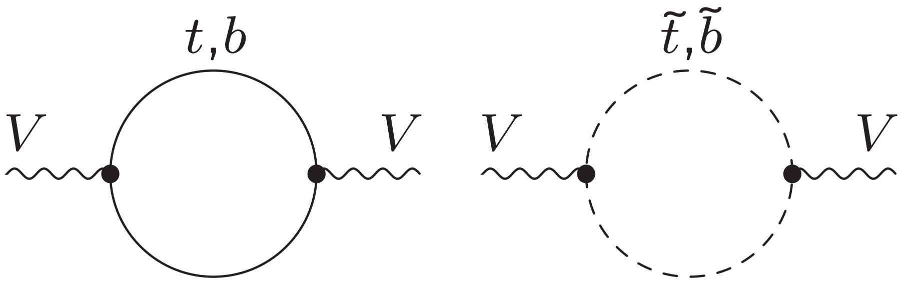
ρ measures the relative strength between neutral current interaction and charged current interaction

$$\rho = \frac{1}{1 - \Delta\rho} \qquad \Delta\rho = \frac{\Sigma_Z(0)}{M_Z^2} - \frac{\Sigma_W(0)}{M_W^2}$$

(leading, process independent terms)

$\Delta\rho$ gives the main contribution to EW observables:

$$\Delta M_W \approx \frac{M_W}{2} \frac{c_{\text{W}}^2}{c_{\text{W}}^2 - s_{\text{W}}^2} \Delta\rho, \qquad \Delta \sin^2\theta_W^{\text{eff}} \approx -\frac{c_{\text{W}}^2 s_{\text{W}}^2}{c_{\text{W}}^2 - s_{\text{W}}^2} \Delta\rho$$



$\Delta\rho^{\text{SUSY}}$ from $\tilde{t}/\tilde{b}$ loops > 0 $\quad \Rightarrow M_W^{\text{SUSY}} \gtrsim M_W^{\text{SM}}$

$\Delta\rho^{\text{SUSY}}$ from $\tilde{t}/\tilde{b}$ loops > 0 $\Rightarrow M_W^{\text{SUSY}} \gtrsim M_W^{\text{SM}}$, $\sin^2\theta_{\text{eff}}^{\text{SUSY}} \lesssim \sin^2\theta_{\text{eff}}^{\text{SM}}$

SM result for M_W and $\sin^2\theta_{\text{eff}}$:

– full one-loop
– full two-loop
– leading 3-loop via $\Delta\rho$
– leading 4-loop via $\Delta\rho$

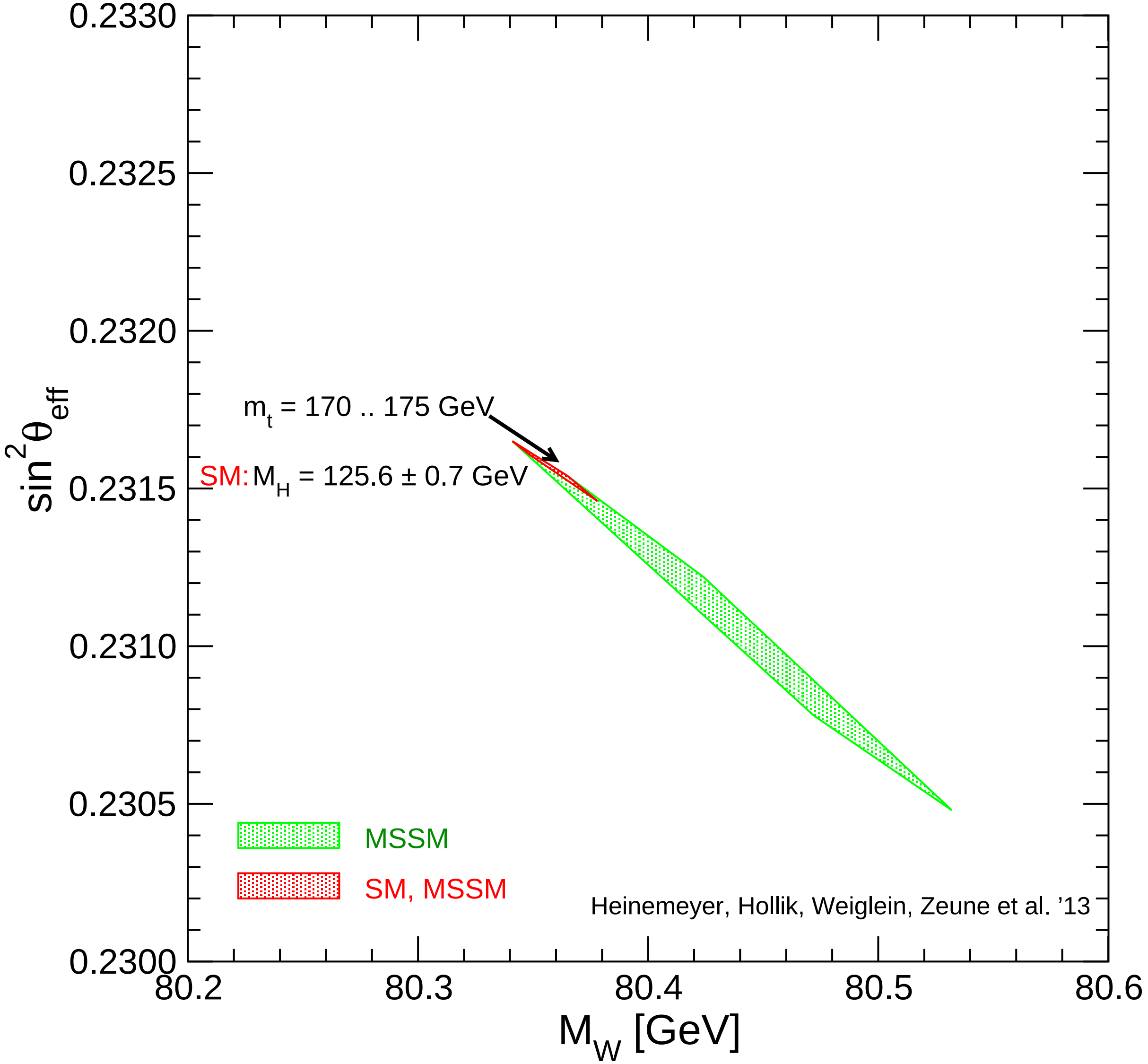
Our MSSM result for M_W and $\sin^2\theta_{\text{eff}}$:

– full SM result (via fit formel)
– full MSSM one-loop (incl. complex phases)
– all existing two-loop $\Delta\rho$ contributions

$\Rightarrow$ non-$\Delta\rho$ one-loop and $\Delta\rho$ two-loop contributions sometimes non-negligible!

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

[S.H., W. Hollik, G. Weiglein, L. Zeune et al. '13]



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SM band:
variation of M_H^{SM}

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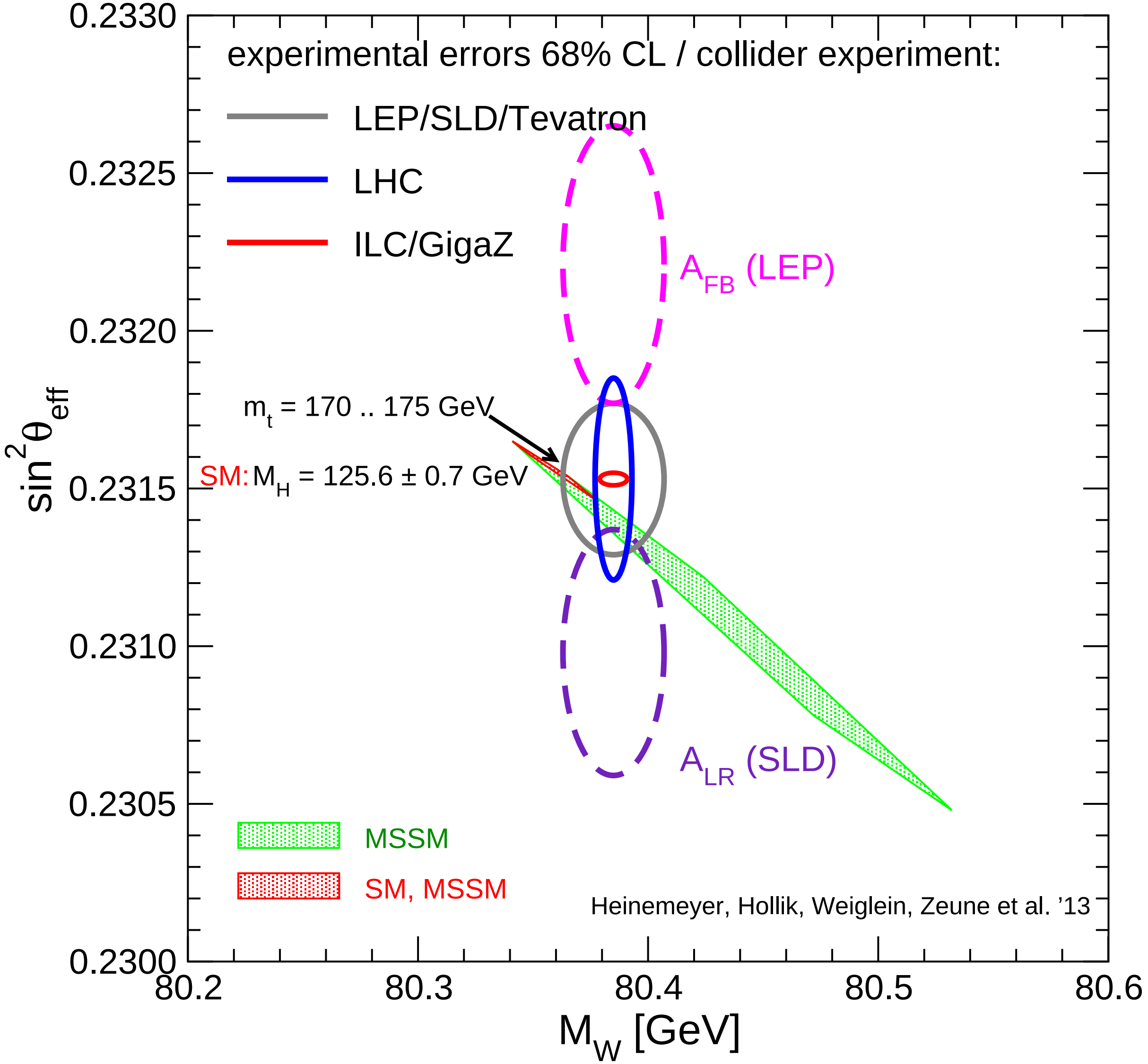

MSSM band:
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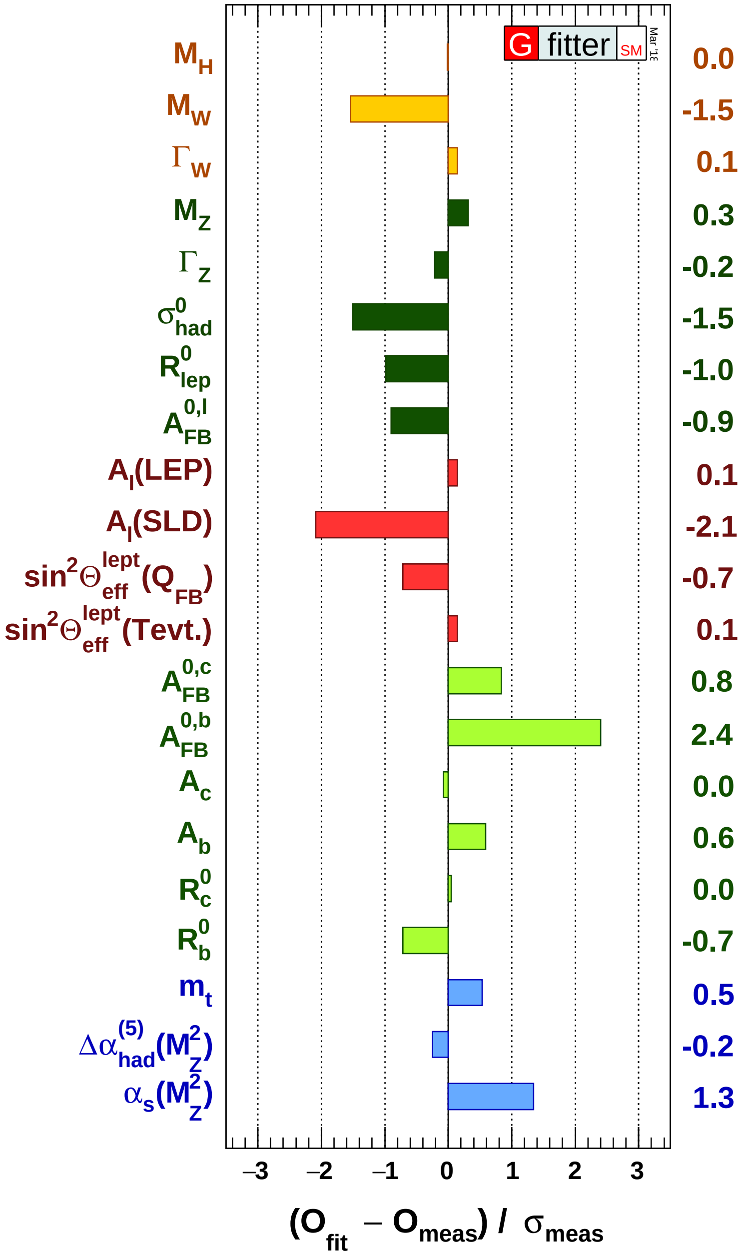
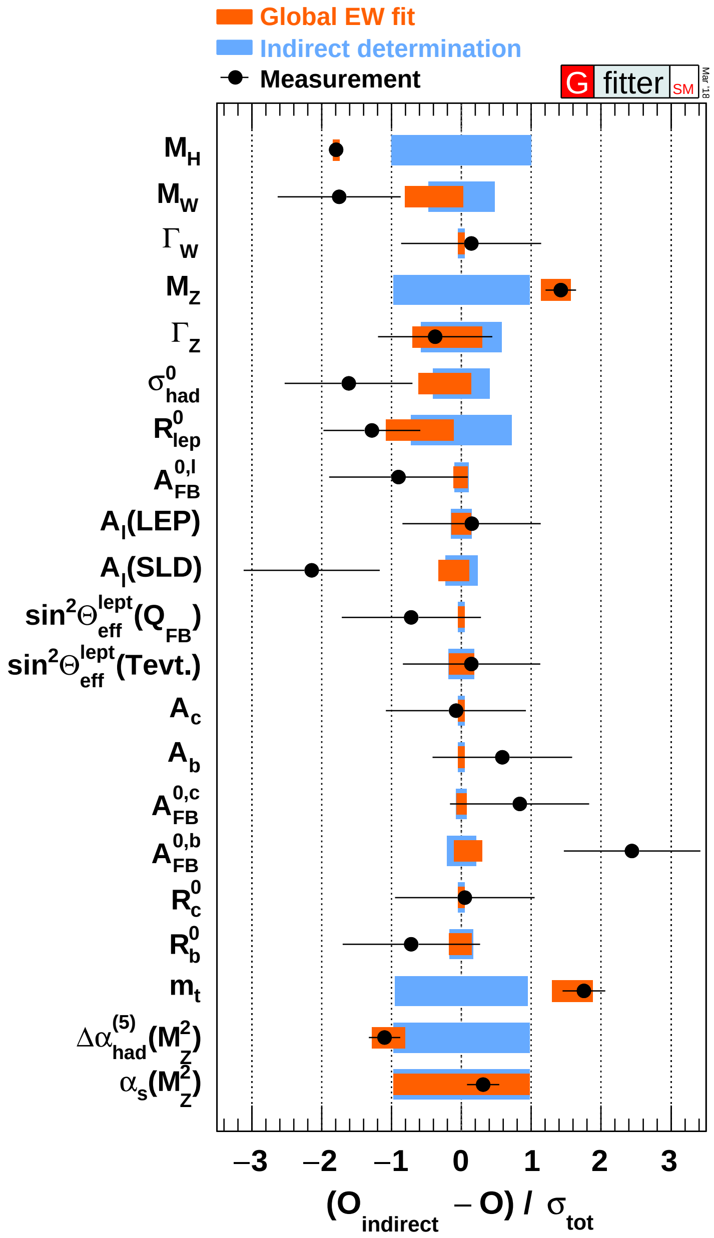
SM band:
variation of $M_H^{\rm SM}$

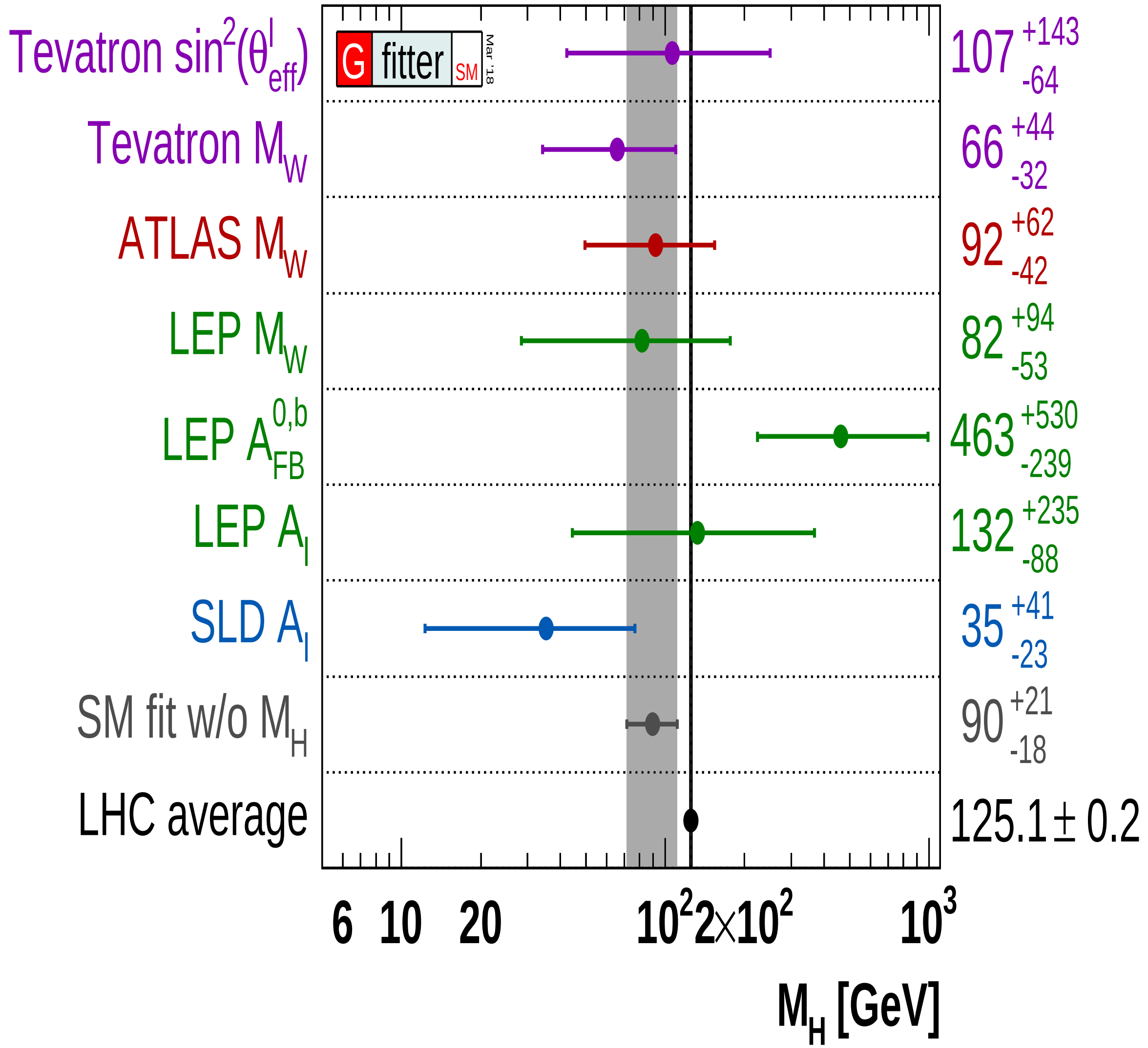
Overview about all EWPO:

[GFitter '18]





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

⇒ light Higgs boson preferred

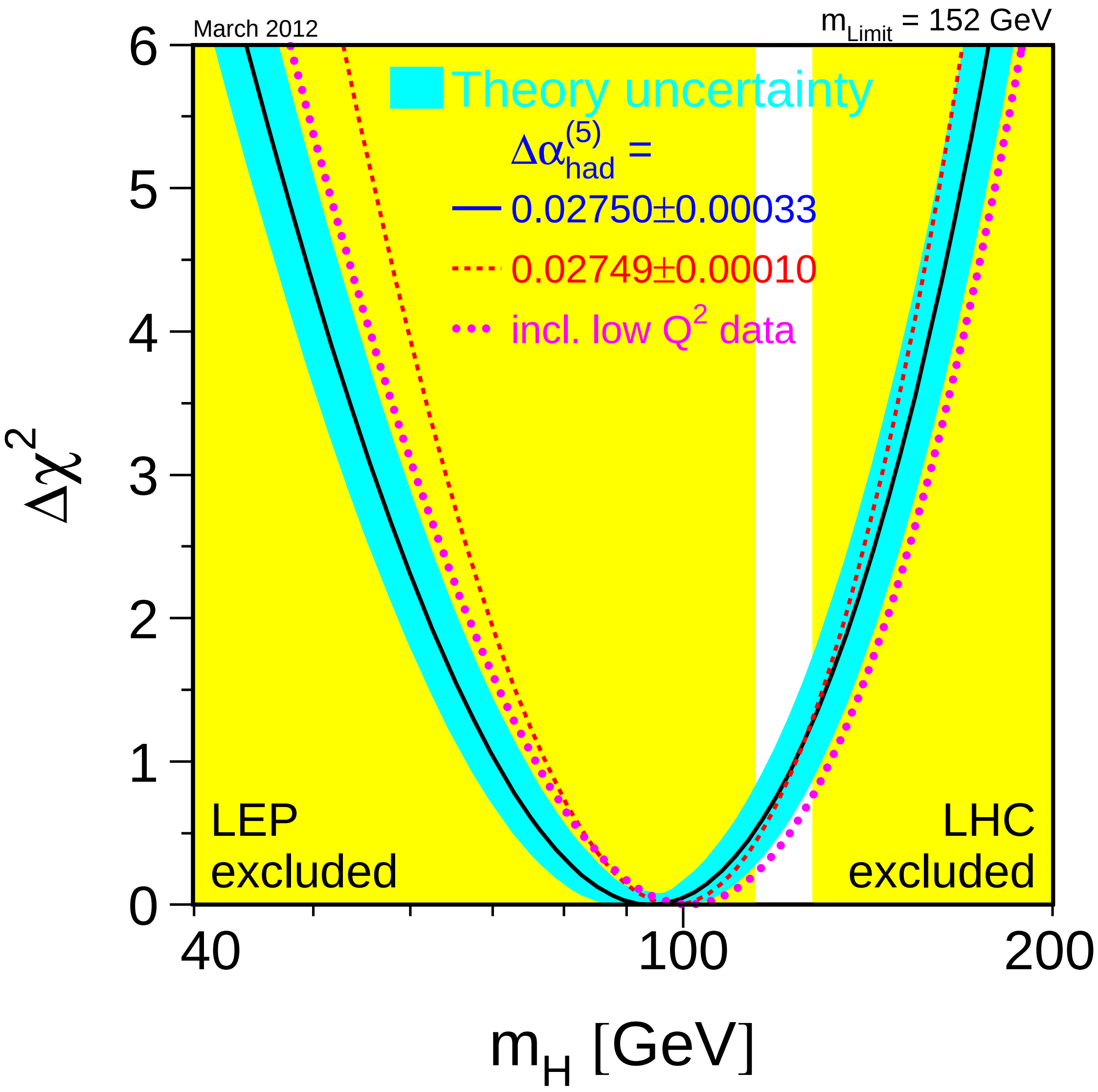
[GFitter '18]

Global fit to all SM data:

[*LEPEWWG '12*]

$\Rightarrow M_H = 94^{+29}_{-24}$ GeV

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



Assumption for the fit:
SM incl. Higgs boson

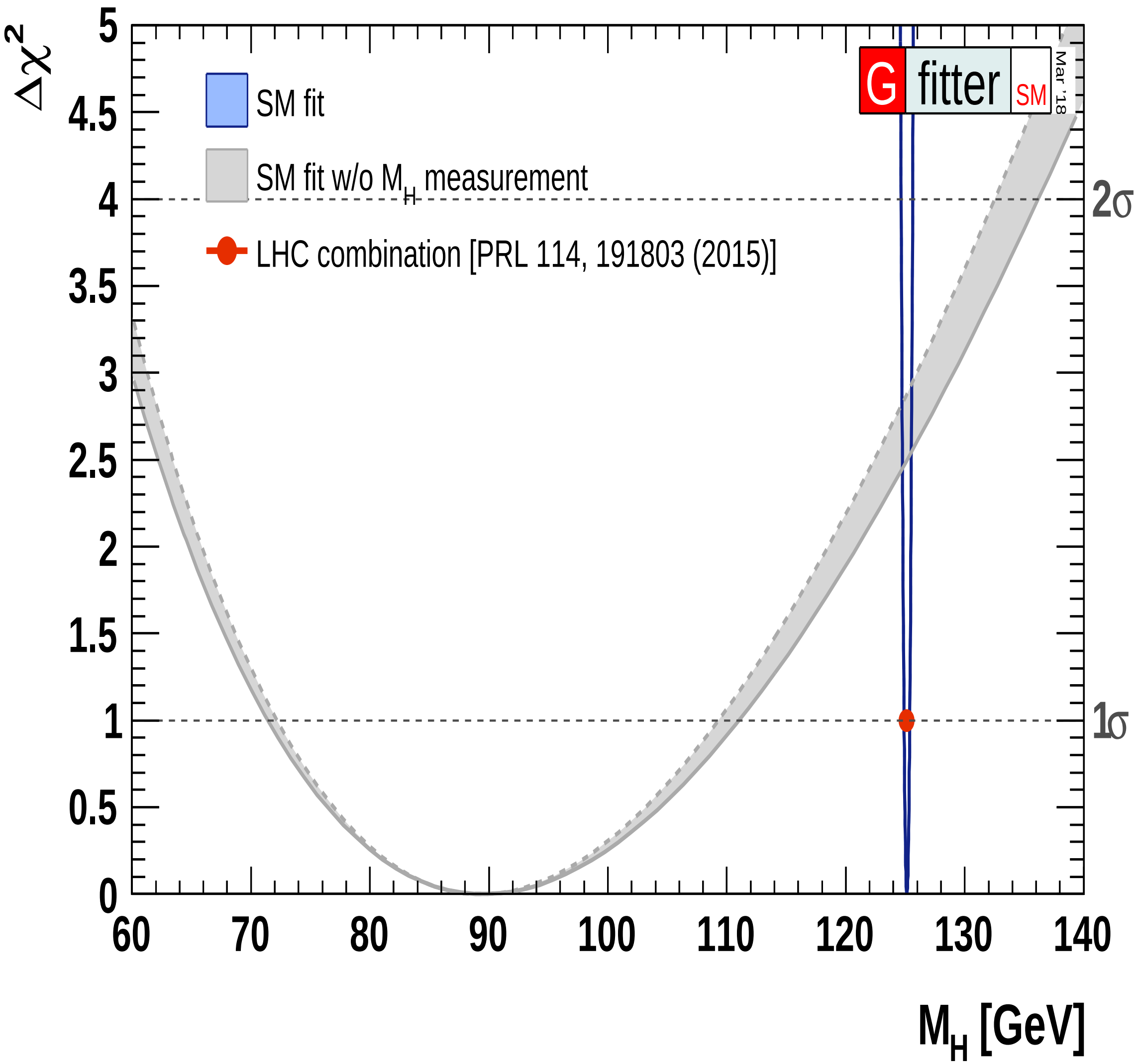
$\Rightarrow$ no confirmation of Higgs mechanism

$\Rightarrow$ Prediction before discovery: in the SM: $M_H \lesssim 160$ GeV

Latest global fit to all SM data:
[*GFitter '18*]

$\Rightarrow M_H = 90^{+21}_{-18}$ GeV

"agreement" at $1.8\,\sigma$



Assumption for the fit:
SM incl. Higgs boson

$\Rightarrow$ no confirmation of
Higgs mechanism

$\Rightarrow$ slightly rising "tension" over the last years . . .

Experimental errors of the precision observables:

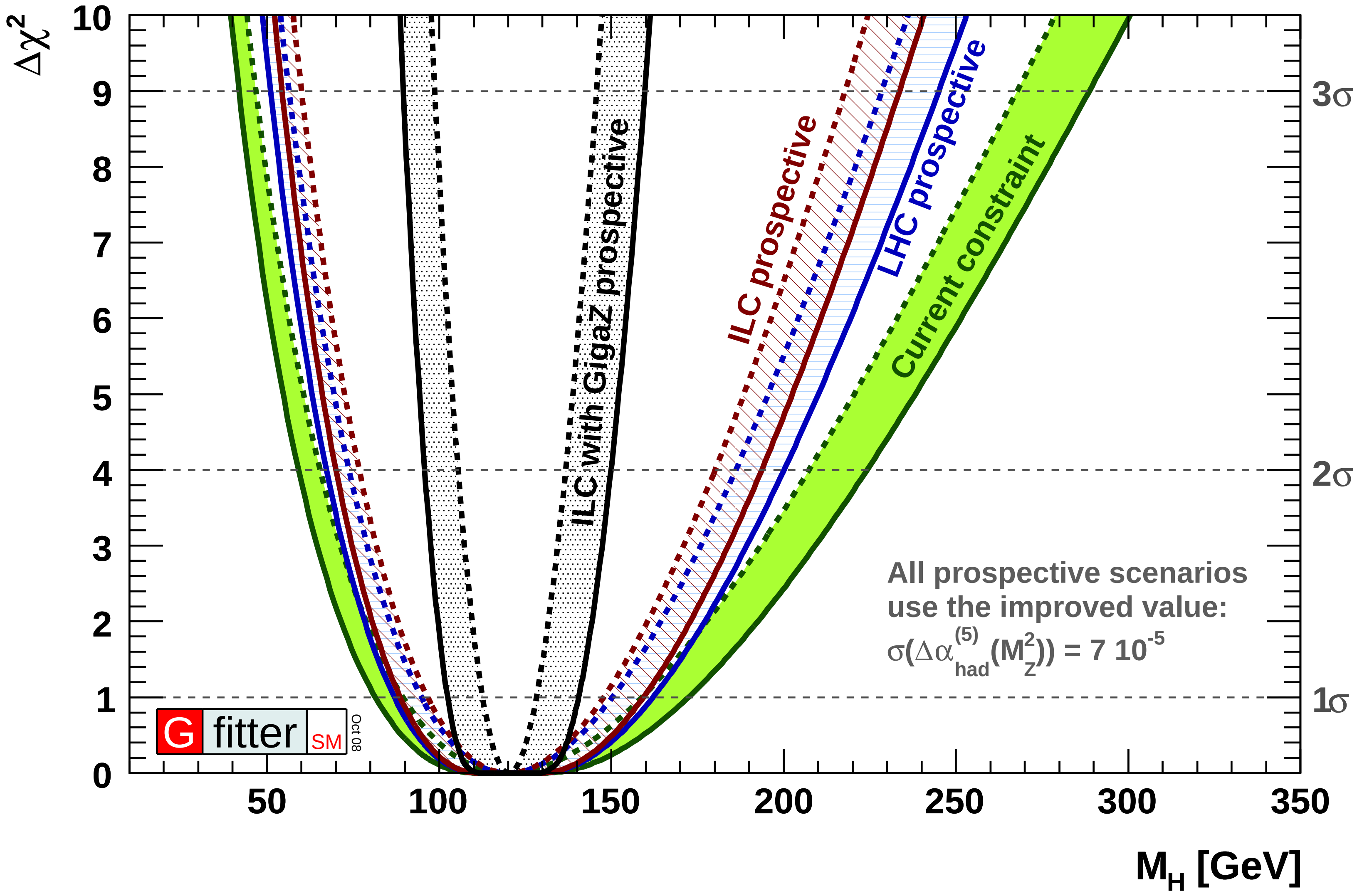
	today	Tev./LHC	LC	GigaZ
$\delta\sin^2\theta_{\rm eff}(\times 10^5)$	16	16	–	1.3
δM_W [MeV]	15	$\leq$15	3-4	3-4
δm_t [GeV]	0.8	$\leq$1	0.1	0.1

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

	$\delta m_t = 2$	$\delta m_t = 1$	$\delta m_t = 0.1$	$\delta(\Delta\alpha_{\rm had})$	δM_Z
$\delta\sin^2\theta_{\rm eff}$ [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:

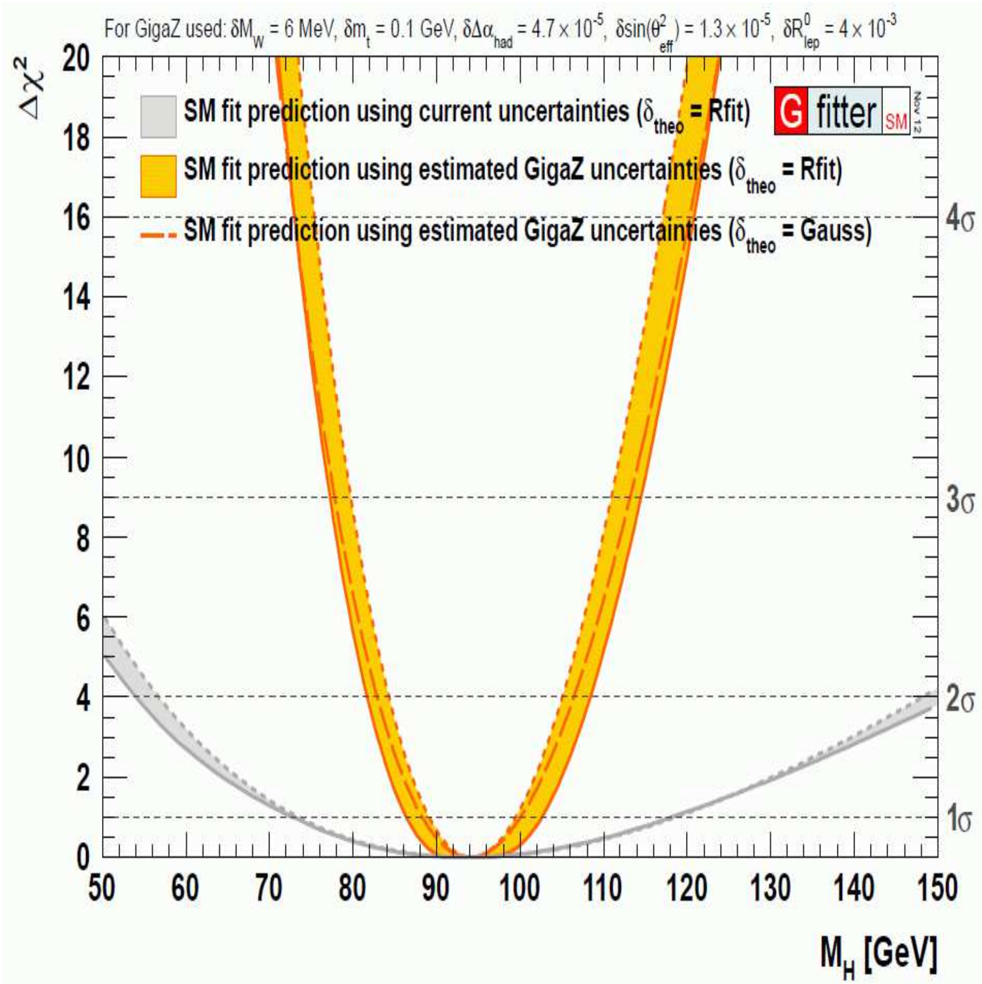
[GFitter '09]

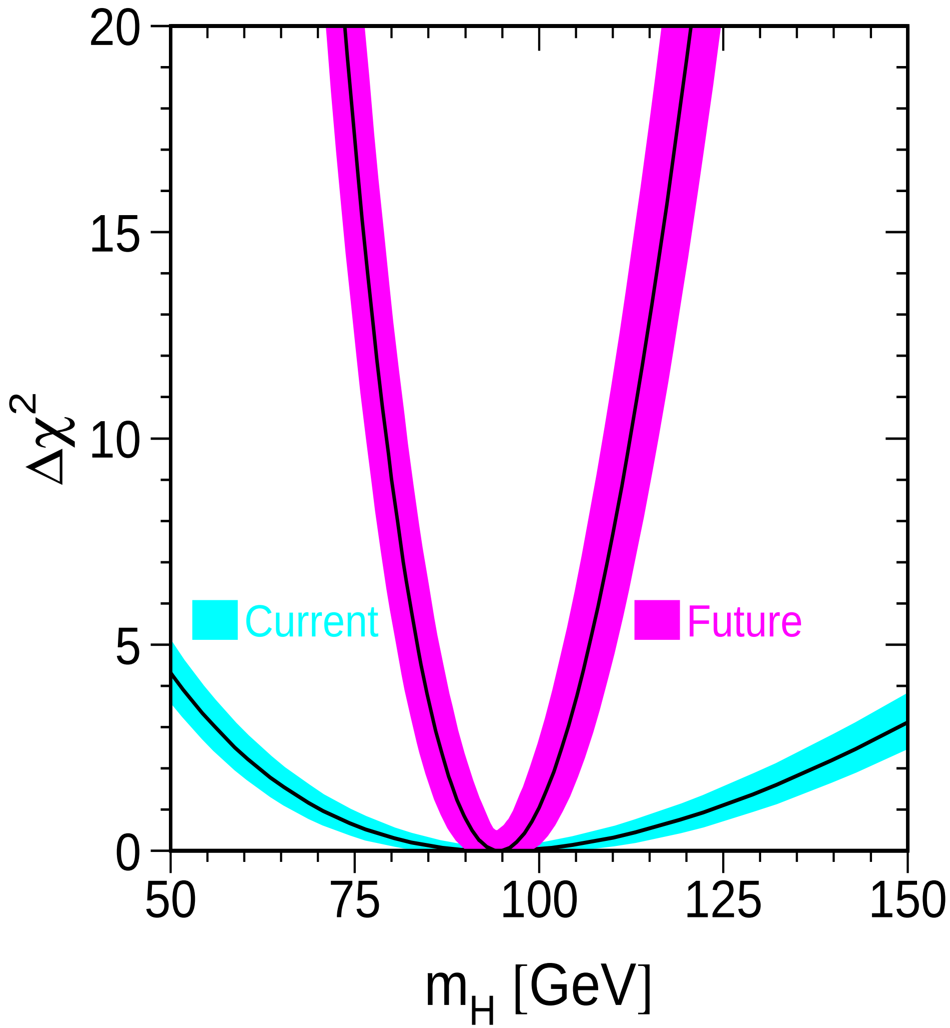


(note: artificially $M_H^{\text{SM}} = 120$ GeV)

Most precise M_H test with the ILC:

[GFitter '13] [LEPEWWG '13]





$\Rightarrow \delta M_H^{\text{ind}} \lesssim \pm 6$ GeV

$\Rightarrow$ extremely sensitive test of SM (and BSM) possible