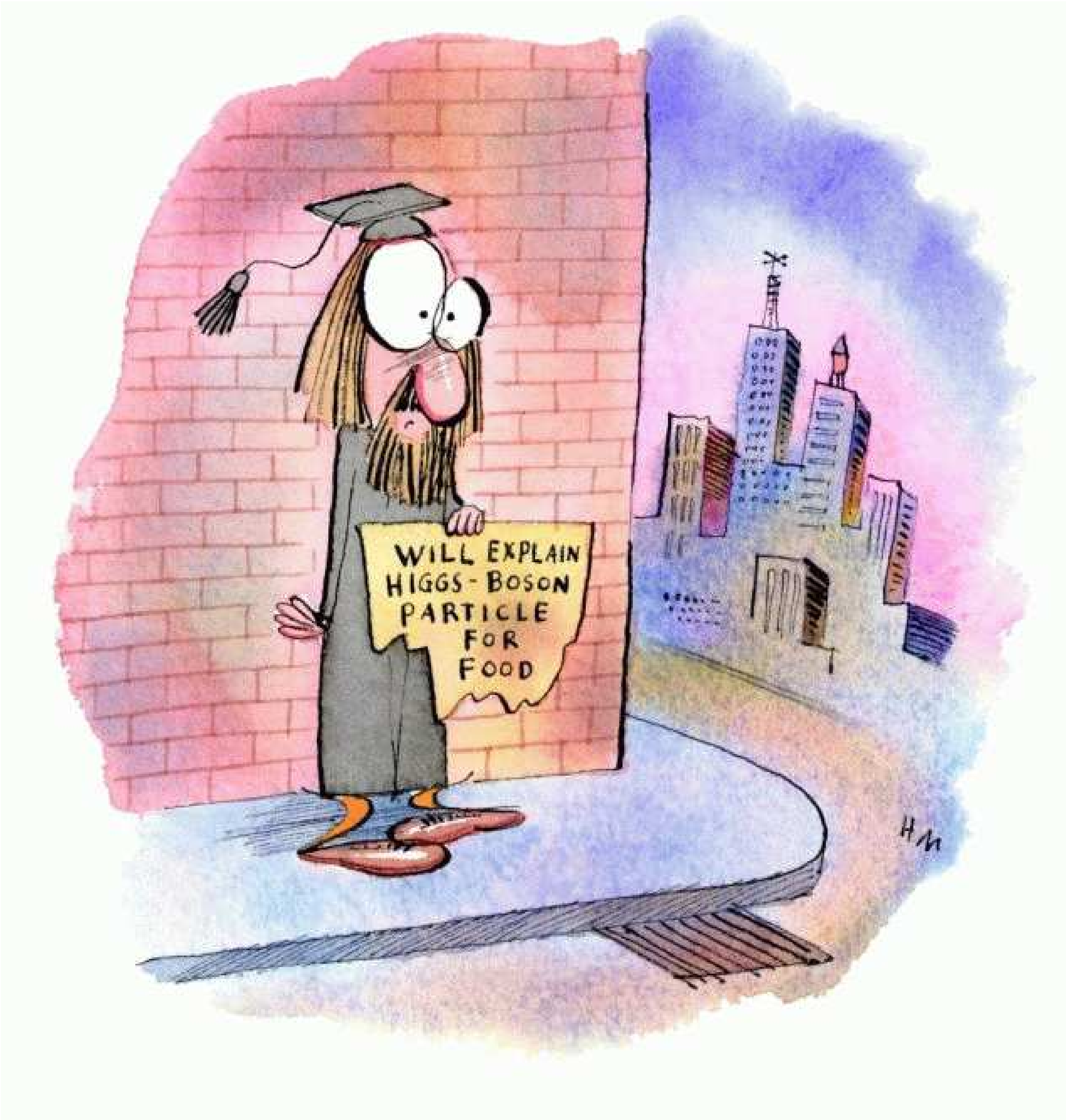
WILL EXPLAIN
HIGGS-BOSON
PARTICLE
FOR
FOOD

Higgs Physics

Sven Heinemeyer, IFCA (Santander)

Corfu, 09/2015

1. The Higgs in the Standard Model

2. The Higgs sector of the (N)MSSM

Higgs Physics

The Higgs in the Standard Model

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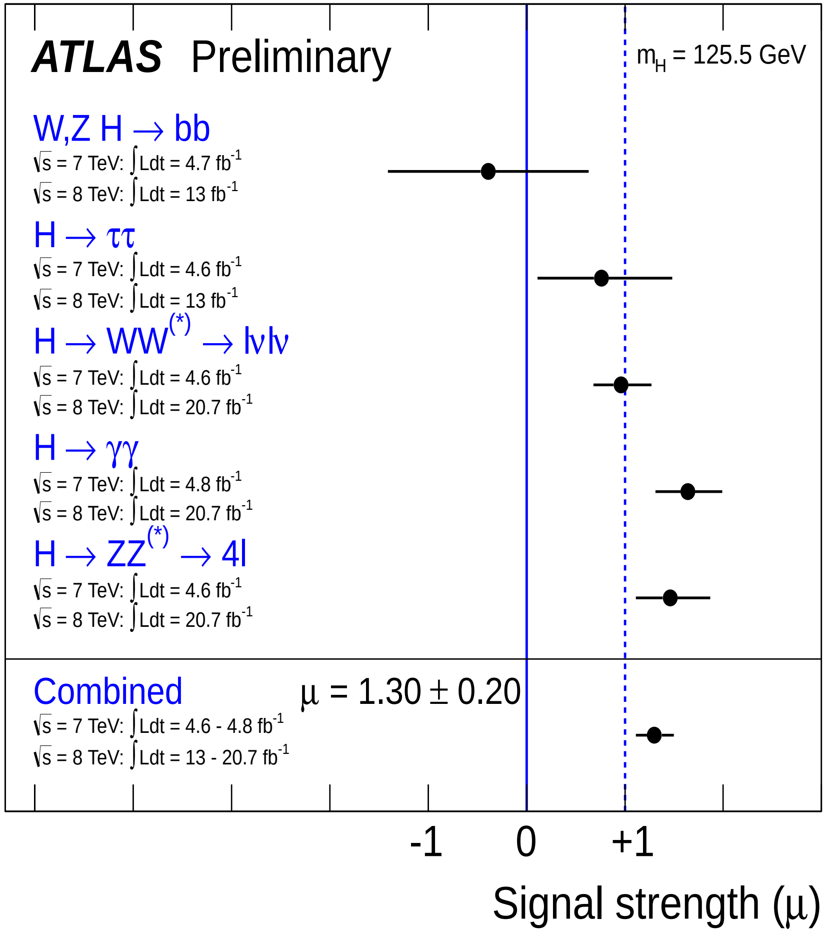
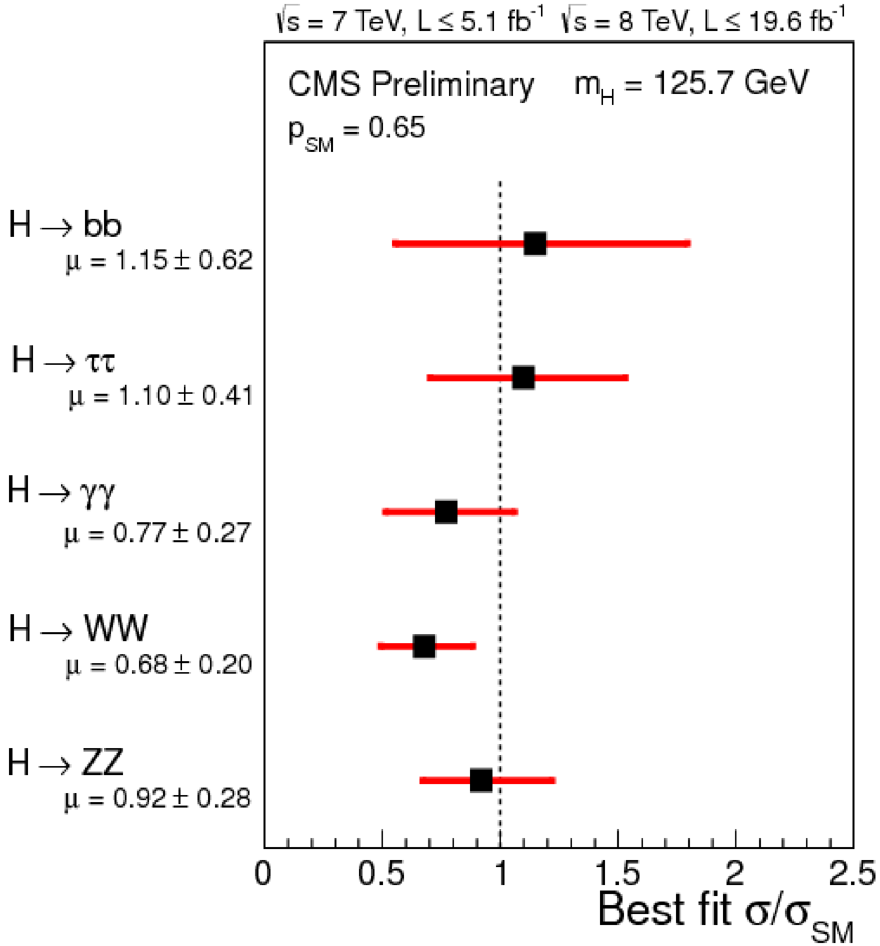
1. Foreword: The Higgs discovery
2. Why Higgs?
3. Predictions for the SM Higgs mass before discovery
4. Properties of the SM Higgs boson

1. Foreword: The Higgs discovery

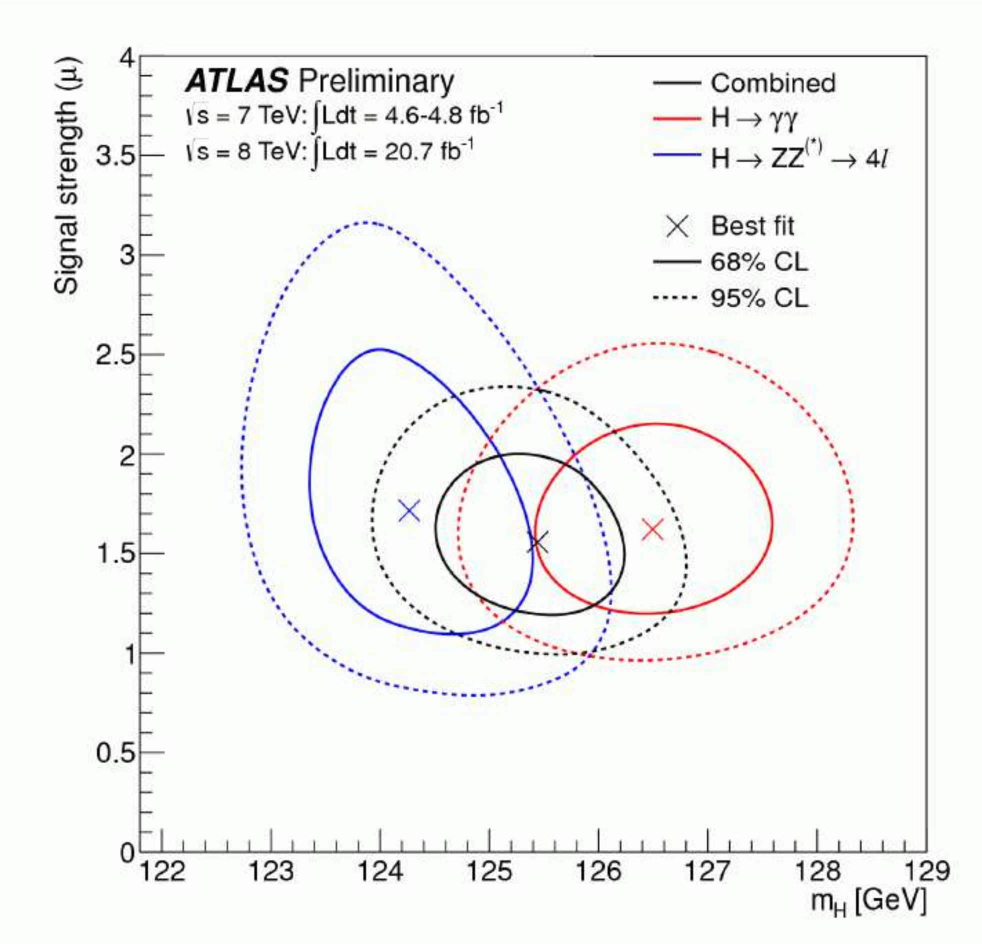
We have a discovery!



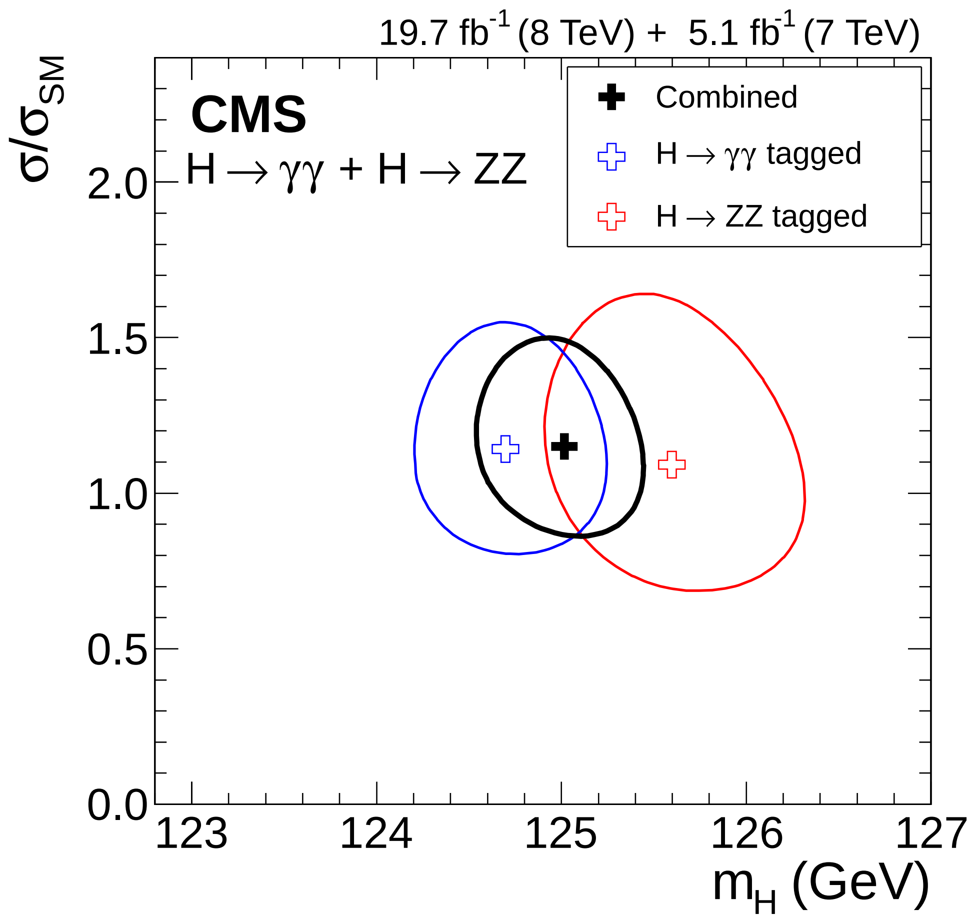


Mass measurement:

ATLAS



CMS



$M_H = 125.36 \pm 0.37 \pm 0.18$ GeV

$M_H = 125.03 \pm 0.27 \pm 0.15$ GeV

Combined: $M_H = 125.09 \pm 0.21 \pm 0.11$ GeV

We have a discovery!

But what is it?

Q: Is it a Higgs boson? $\Rightarrow$ yes according to CERN!

Q: Is it the Higgs boson (i.e. of the SM)?

Q: Is it an MSSM Higgs boson?

Q: Is it a Higgs boson of a different model?

Q: Is it an impostor? $\Rightarrow$ no according to CERN!

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How can we decide?

A: Measure all its characteristics

A: Compare to the predictions of the various models

We have a discovery!

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How can we decide?

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A: Compare to the predictions of the various models

⇒ Overview about implications/predictions in/for the SM and SUSY!

2. Why Higgs?

Current status of knowledge: the Standard Model (SM)

1. family: quarks: d, u leptons: e^-, ν_e (neutrino)

2. family: quarks: s, c leptons: μ^-, ν_μ (neutrino)

3. family: quarks: b, t leptons: τ^-, ν_τ (neutrino)

In total:

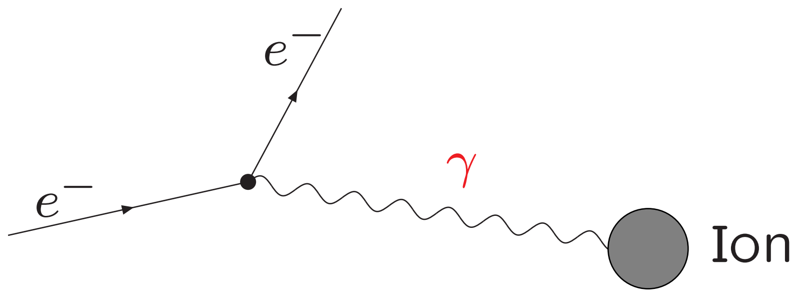
6 quarks and 6 leptons

The heavier particles (2. and 3. family) decay in very short time into the lighter particles (1. family)
Example:

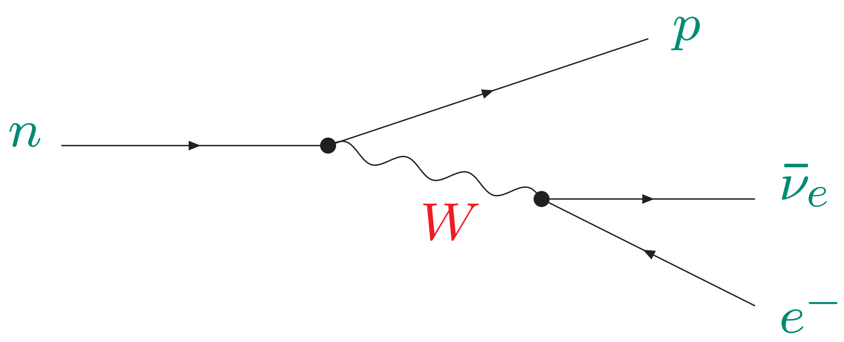
$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

Forces and force particles (I):

1. electromagnetic force: photon: γ

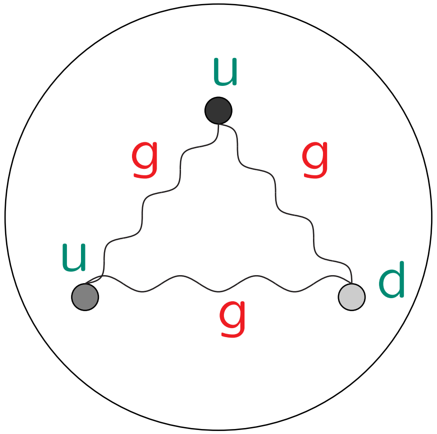


2. weak force: W^+, W^-, Z^0

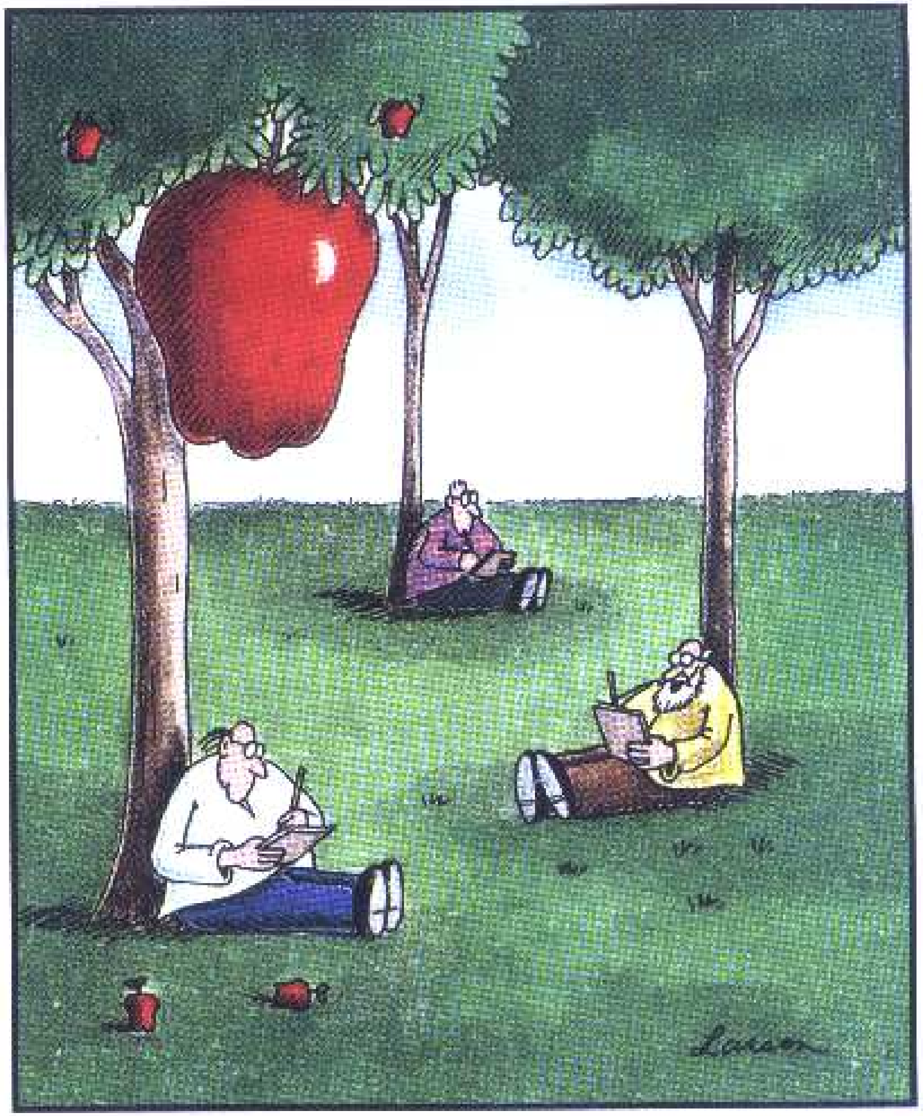


Forces and force particles (II):

3. strong force: gluon: g



4. gravitational force: graviton(?)



"Nothing yet. ... How about you, Newton?"

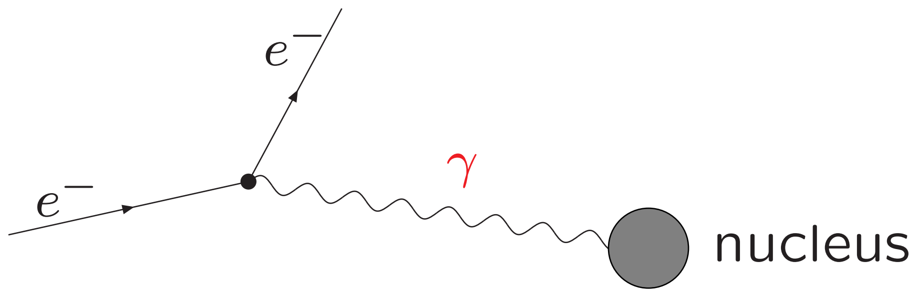
Standard Model (SM) of the electroweak and strong interaction

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



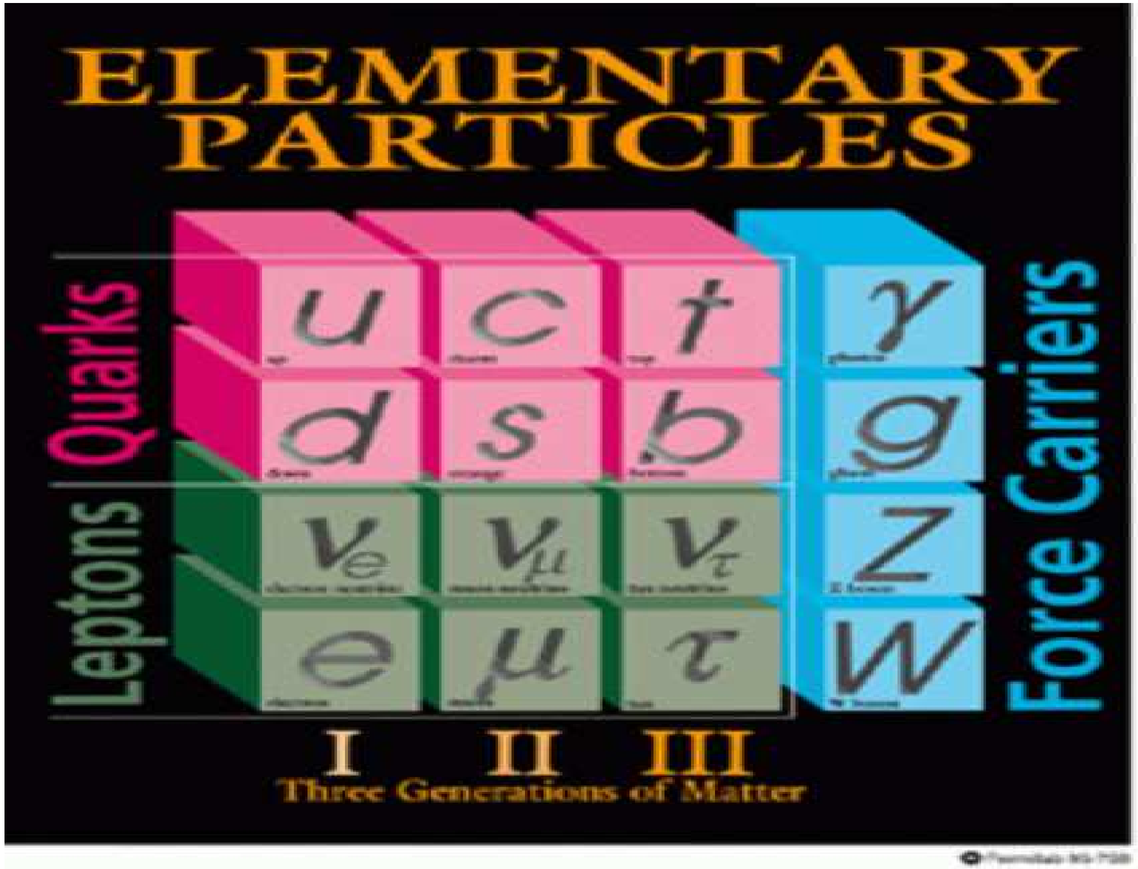
$\mathcal{L}_{\text{QED}}$ invariant under gauge transformation:

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

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

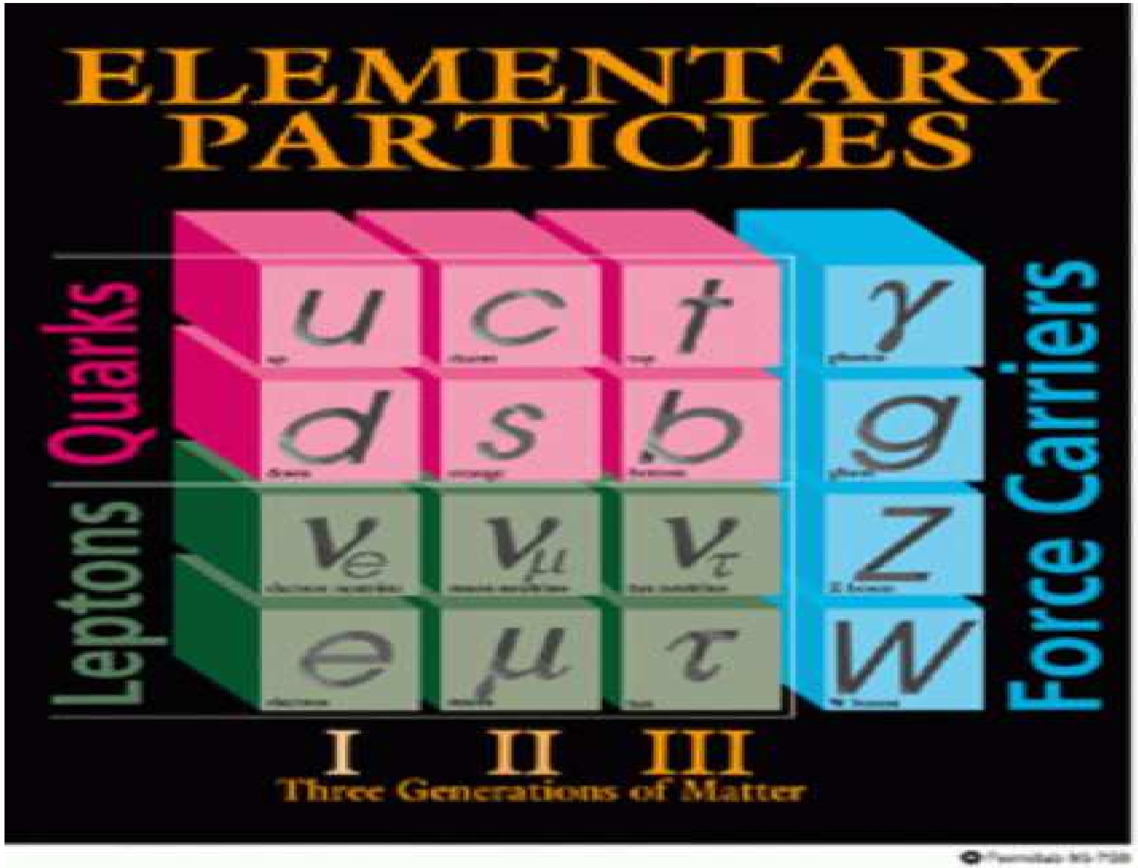
$\Rightarrow A_\mu$ is massless gauge field

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 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:

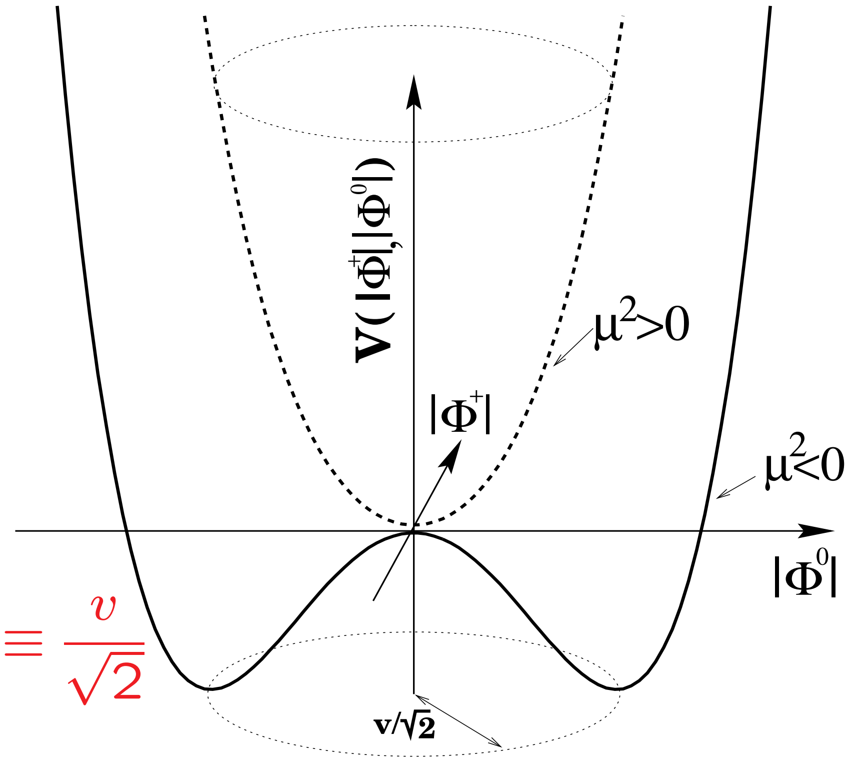
Scalar SU(2) doublet: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

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

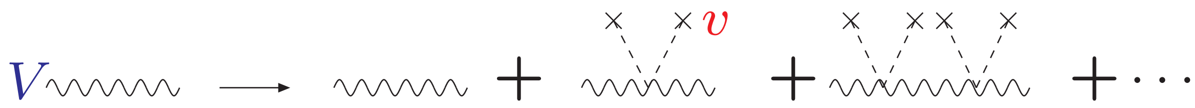
$$iD_\mu = i\partial_\mu - g_2 \vec{I}\vec{W}_\mu - g_1 Y B_\mu$$

$$\Phi_c = i\sigma_2 \Phi^* \qquad Q_L \sim \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \ \Phi \sim \begin{pmatrix} 0 \\ v \end{pmatrix}, \ \Phi_c \sim \begin{pmatrix} v \\ 0 \end{pmatrix}$$

Gauge invariant coupling to gauge fields

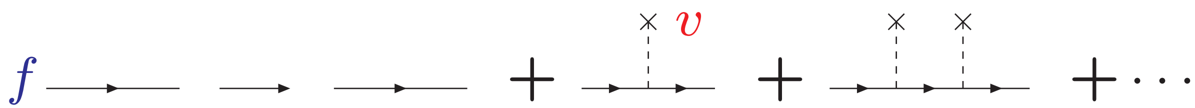
$\Rightarrow$ mass terms for gauge bosons and fermions

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



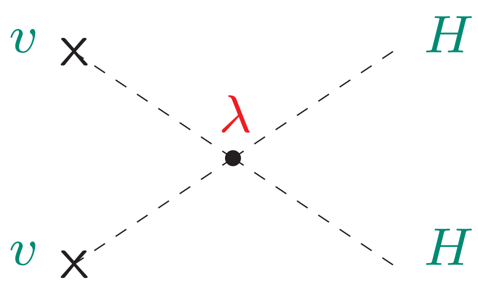
$$\frac{1}{q^2} \to \frac{1}{q^2} + \sum_j \frac{1}{q^2} \left[\left(\frac{gv}{\sqrt{2}} \right)^2 \frac{1}{q^2} \right]^j = \frac{1}{q^2 - M^2} \; : \; M^2 = g^2 \frac{v^2}{2} \qquad \Rightarrow M \propto g$$

2.) fermion mass terms: Yukawa couplings:



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

3.) mass of the Higgs boson: self coupling



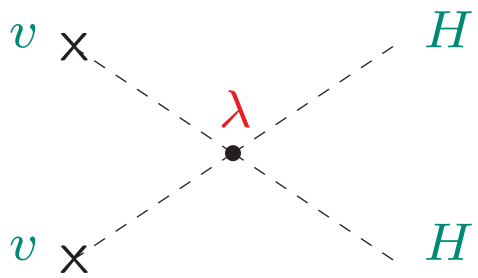
$\ldots$

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

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

$\rightarrow$ last unknown parameter of the SM

3.) mass of the Higgs boson: self coupling



. . .

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

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

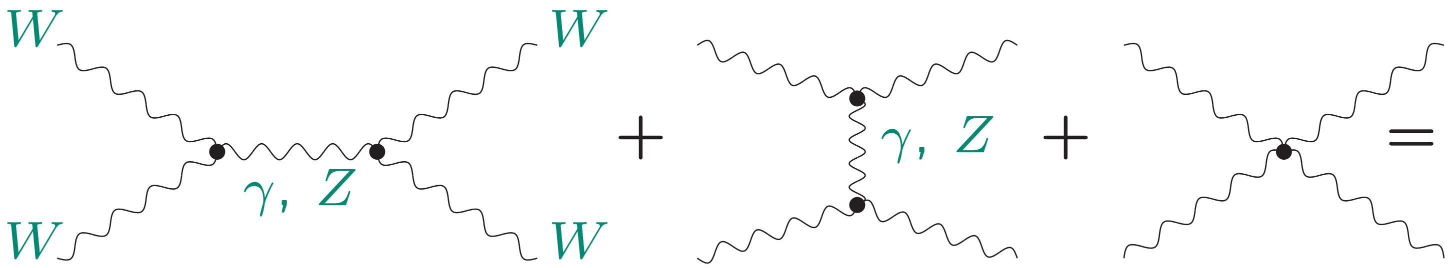
$\rightarrow$ last unknown parameter of the SM

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

Another effect of the Higgs field:

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

$\mathcal{M}_V =$

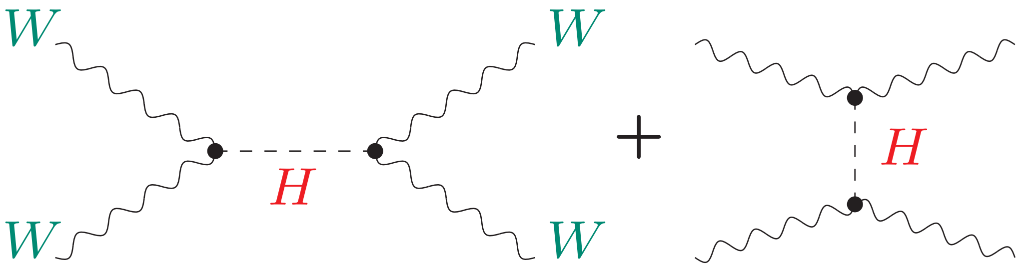


$= -g^2 \frac{E^2}{M_W^2} + \mathcal{O}(1)$ for $E \to \infty$

$\Rightarrow$ 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 $E \to \infty$

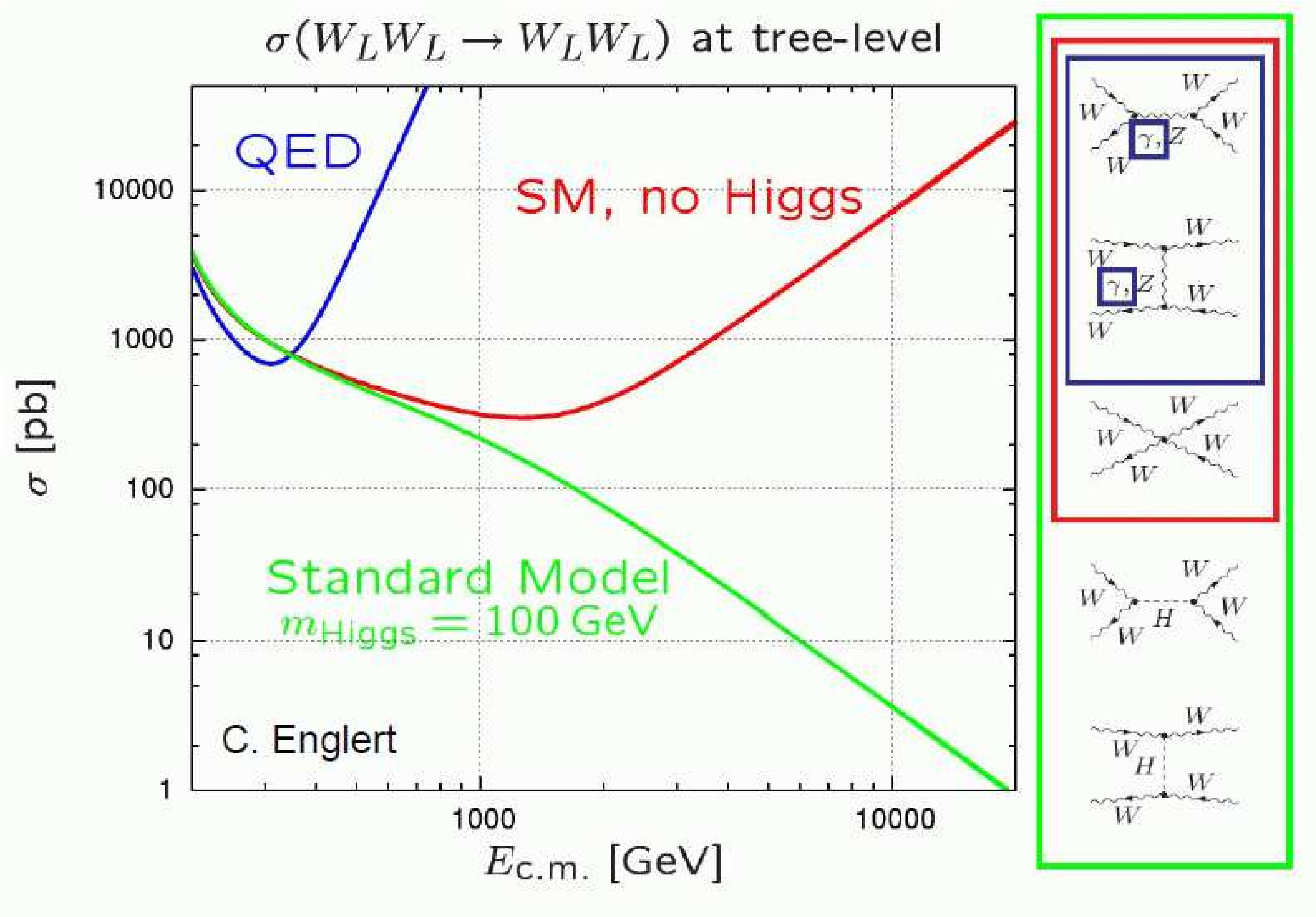
$$\mathcal{M}_{\text{tot}} = \mathcal{M}_V + \mathcal{M}_S = \frac{E^2}{M_W^4}\left(g_{WWH}^2 - g^2 M_W^2\right) + \ldots$$

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

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

Cross section with/without the Higgs:

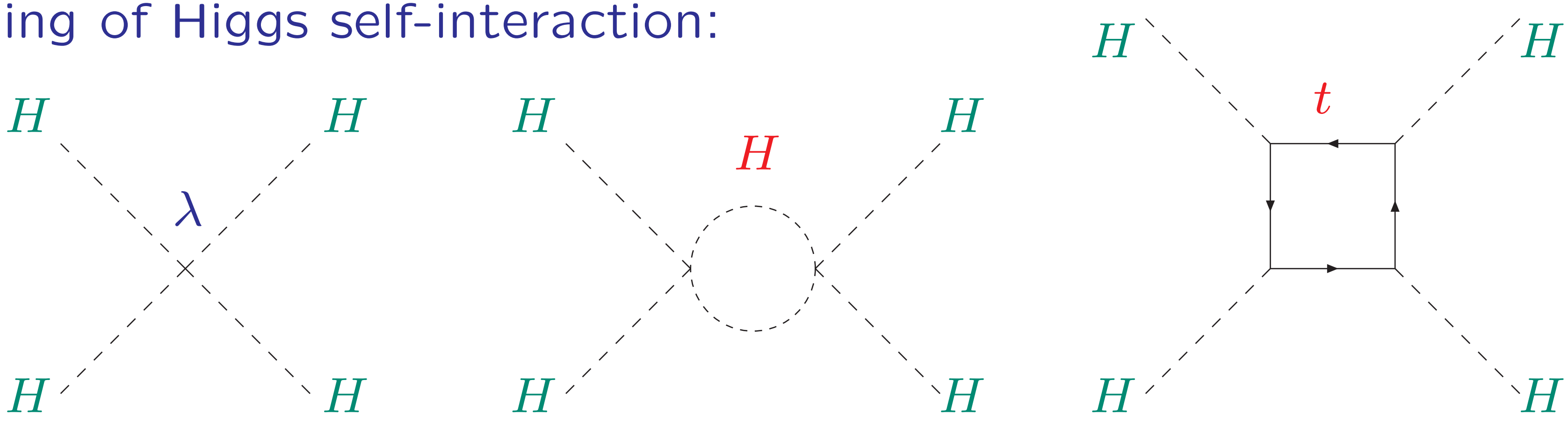
[*taken from M. Schumacher '12 / C. Englert*]



3. Predictions for the SM Higgs mass before discovery

What else do we know about the Higgs boson?

Running of Higgs self-interaction:



Renormalization group equation:

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

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 $\lambda \sim M_H^2$)

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

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

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

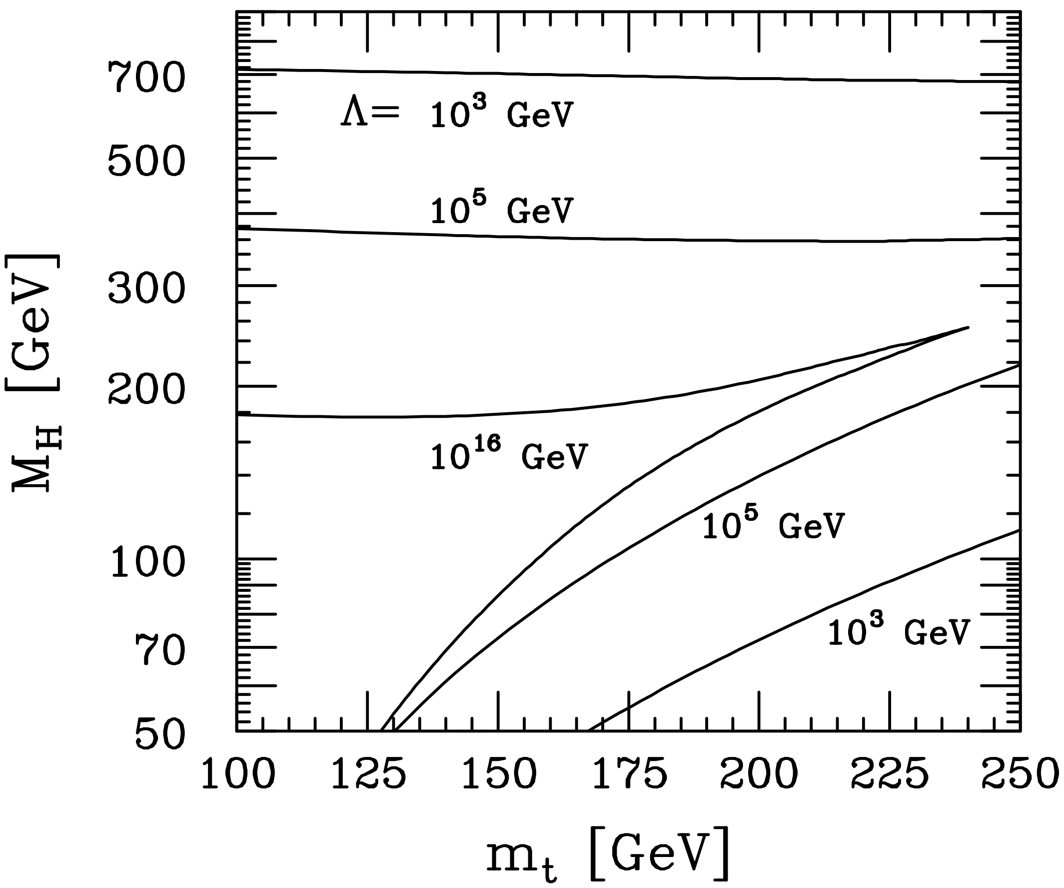
2.) avoid vacuum instability (for small/negative λ): $V(v) < V(0) \Rightarrow \lambda(\Lambda) > 0$

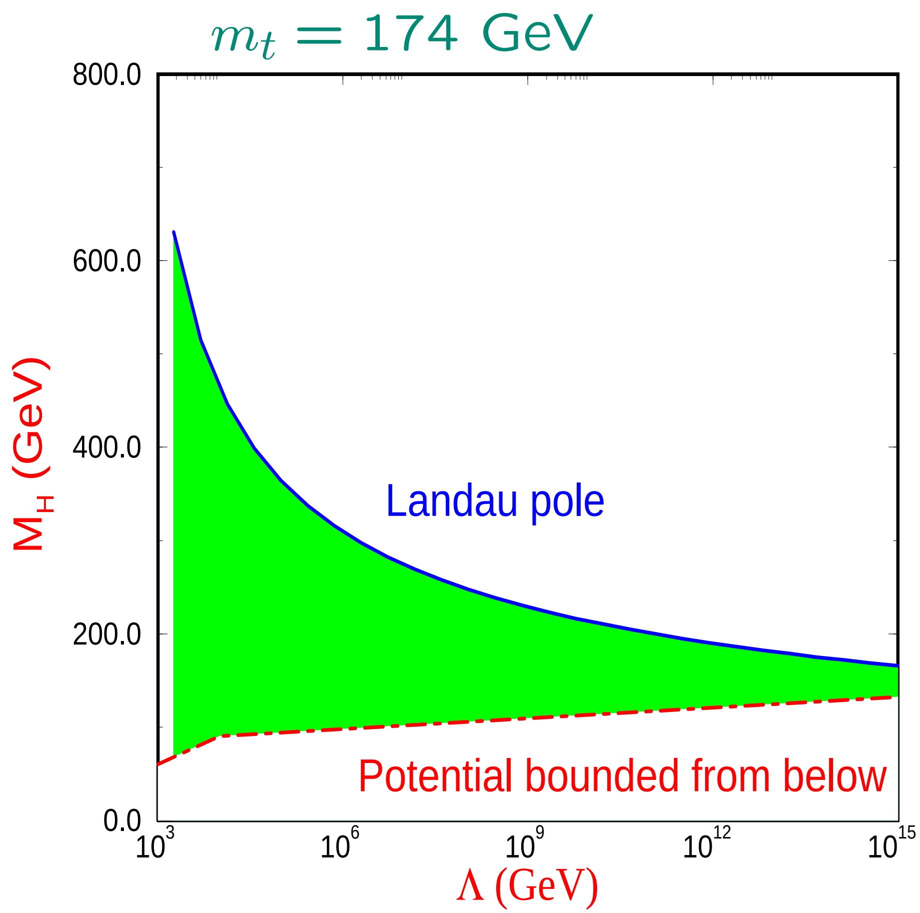
$$\frac{d\lambda}{dt} = \frac{3}{8\pi^2}\left[-g_t^4 + \frac{1}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]$$

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

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

Both limits combined:



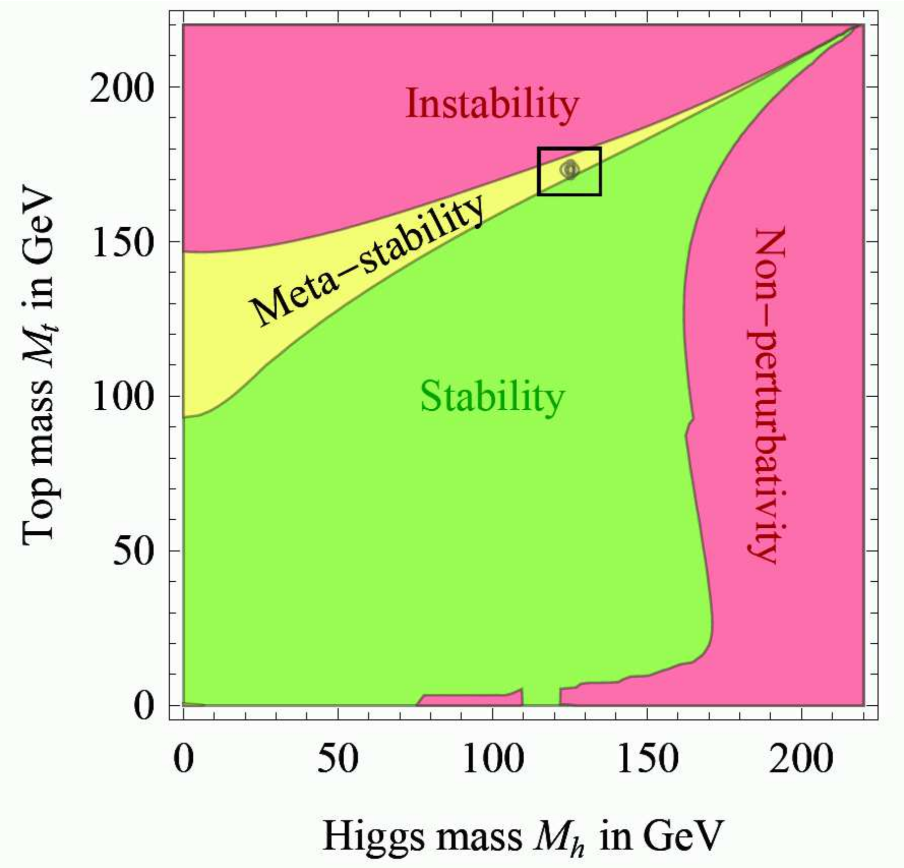


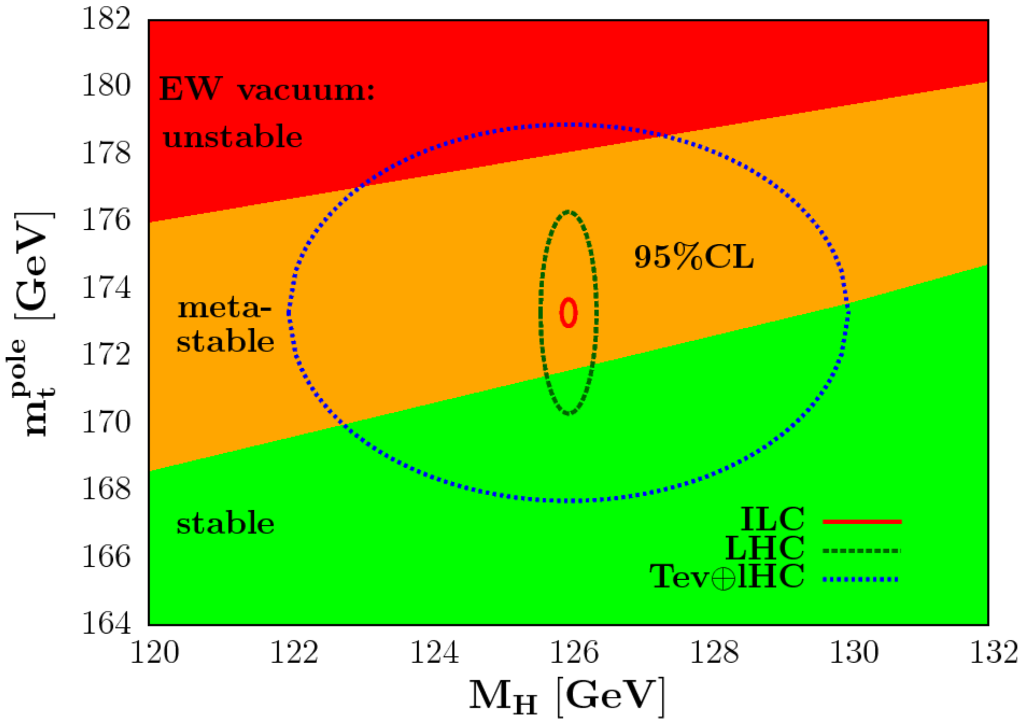
Λ: scale up to which the SM is valid

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

$M_H = 125$ 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!

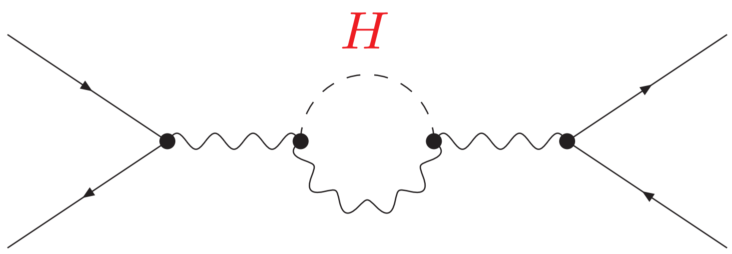
Electroweak Precision Observables (EWPO):

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

Precision observables in the SM:

M_W, $\sin^2\theta_{\rm eff}$, $(g-2)_\mu$, 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*]

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

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

Precision observables in the SM:

M_W, $\sin^2\theta_{\text{eff}}$, $(g-2)_\mu$, 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:

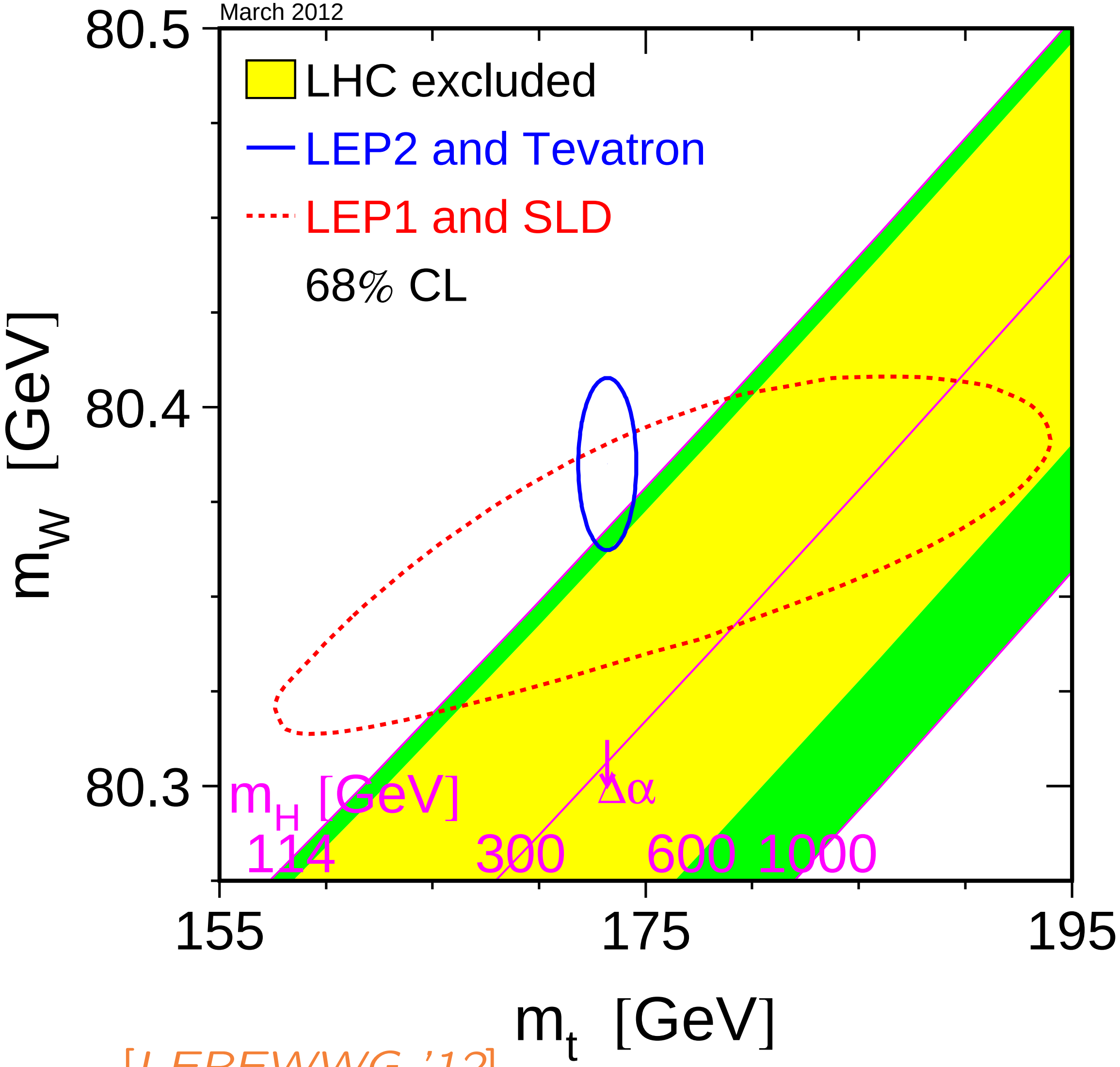
$$\Delta r = -\frac{11 g_2^2}{96\,\pi^2}\frac{s_W^2}{c_W^2}\log\left(\frac{M_H}{M_W}\right)$$

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

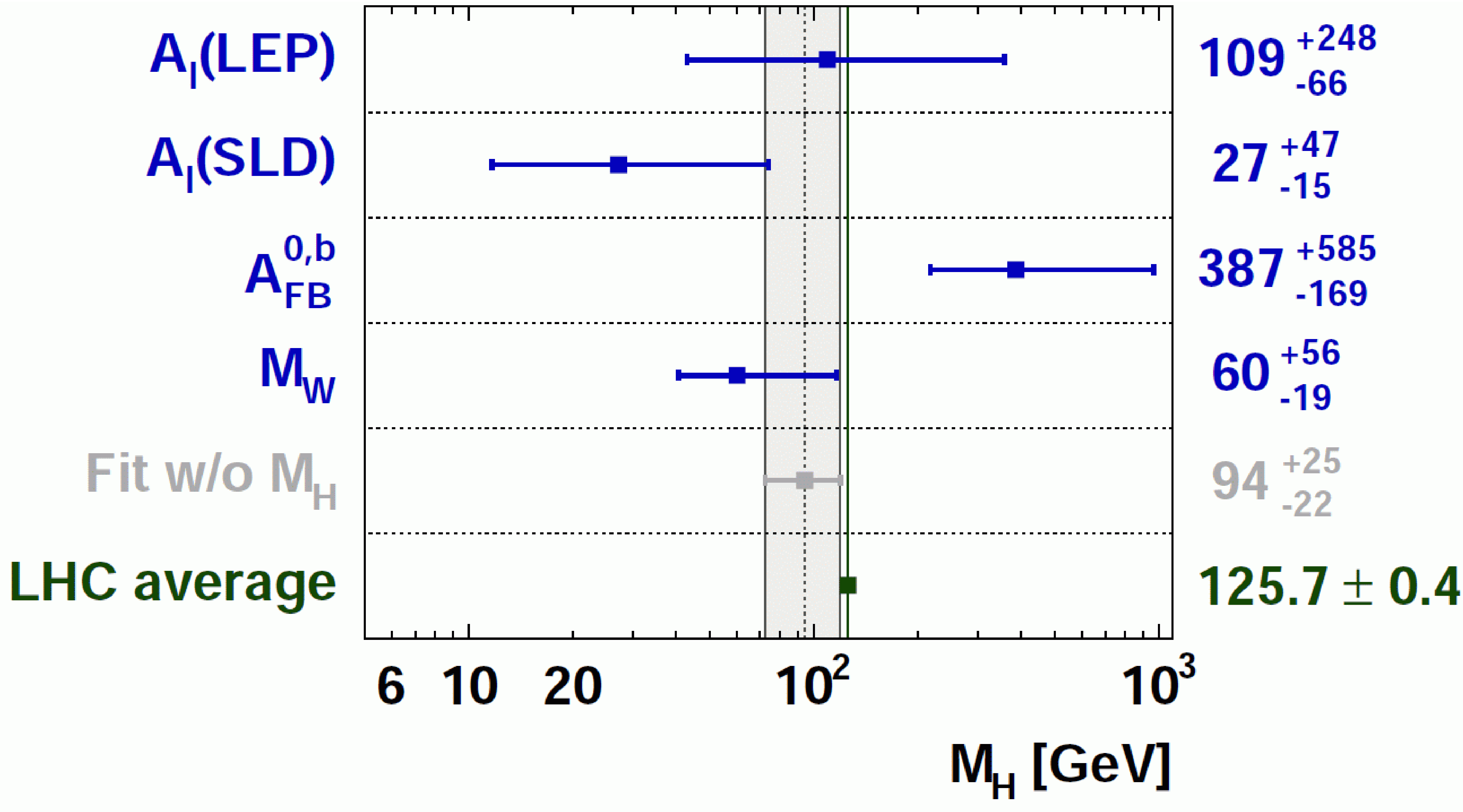


[LEPEWWG '12]

⇒ light Higgs boson preferred

Comparison for single observables:

[*GFitter '12*]

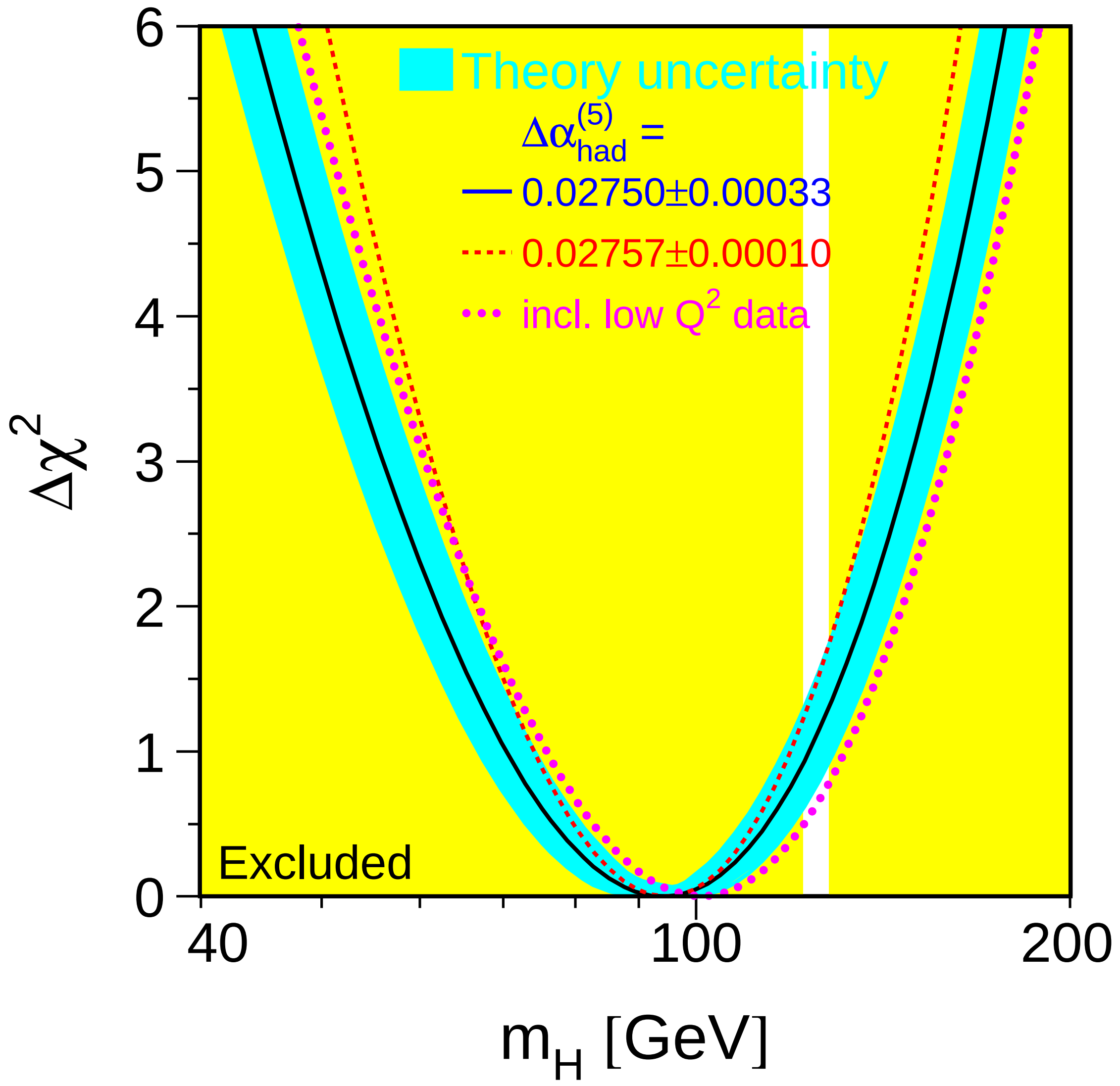


Global fit to all SM data:

[*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

4. 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 ($M_H > 2M_V$):

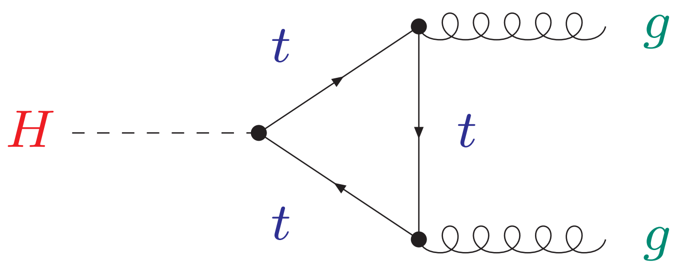
$$\Gamma(H \to VV) = \delta_V \frac{G_\mu M_H^3}{16\sqrt{2}\,\pi} \left(1 - 4\frac{M_V^2}{M_H^2} + 12\frac{M_V^4}{M_H^4}\right) \left(1 - 4\frac{M_V^2}{M_H^2}\right)^{1/2}$$

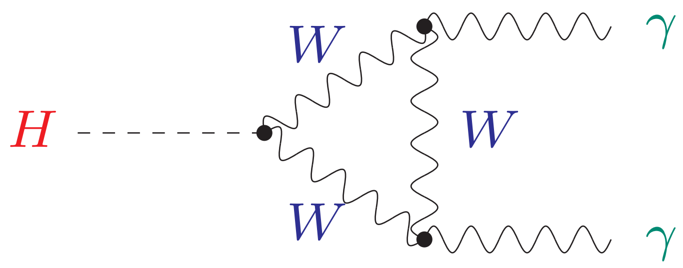
with $\delta_{W,Z} = 2, 1$

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

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

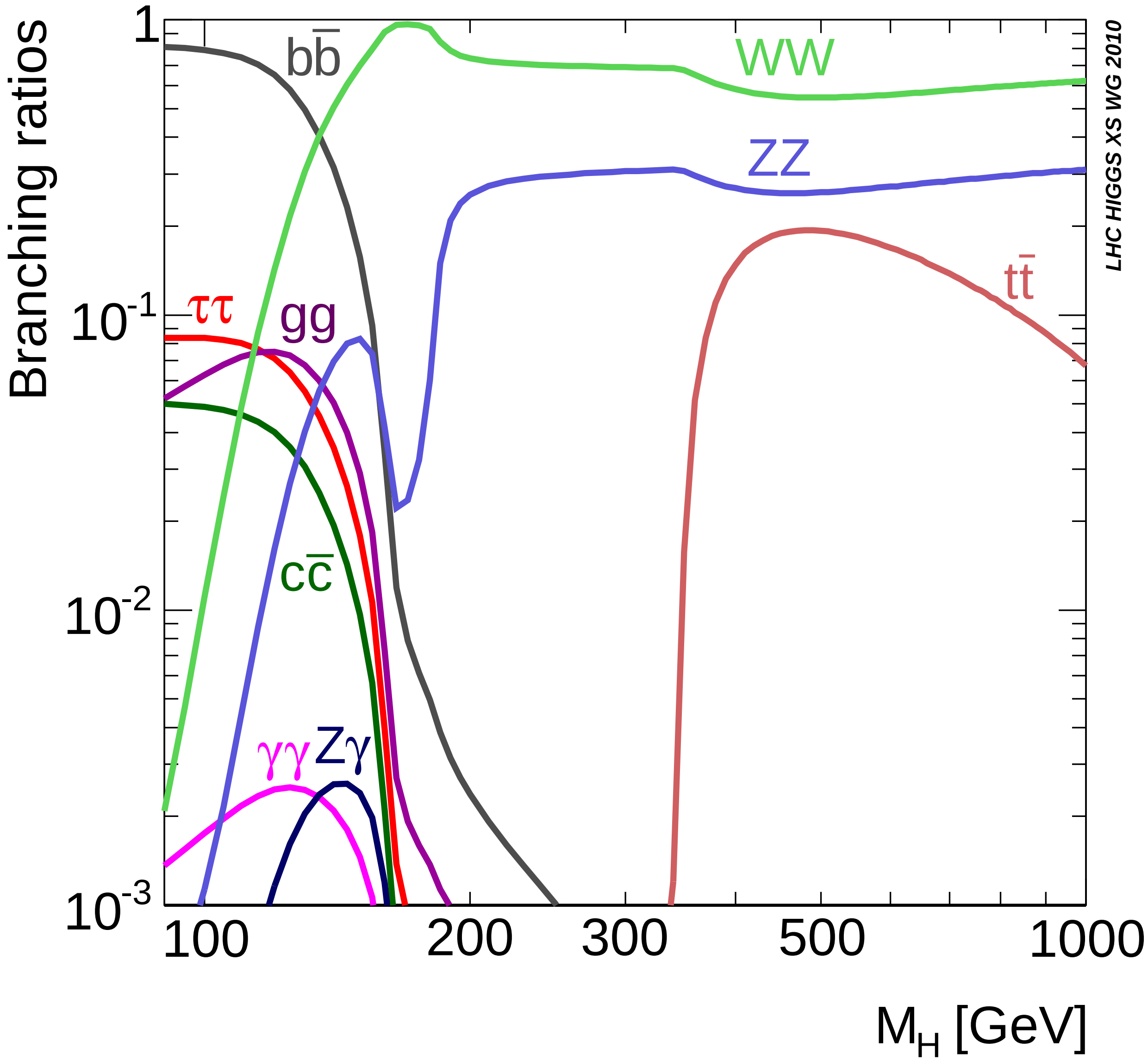
$\Rightarrow$ huge QCD corrections

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

via the top quark and W boson loop

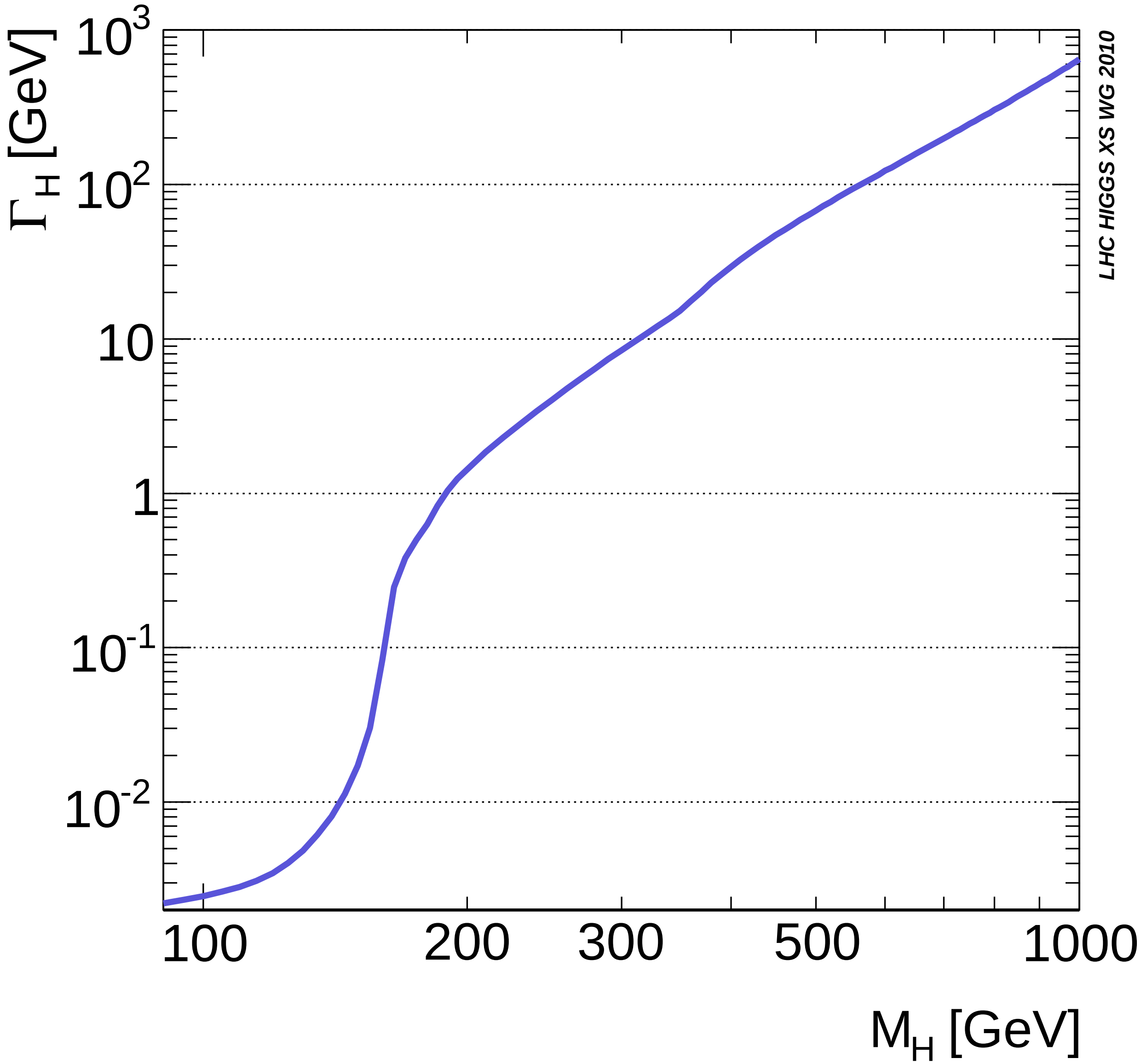
Latest theory predictions for the SM Higgs: branching ratios

[*LHC Higgs XS WG '10*]



Latest theory predictions for the SM Higgs: total width

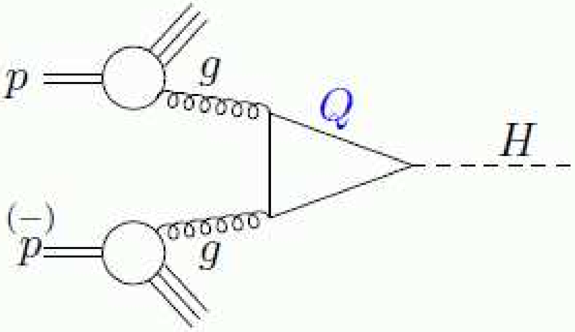
[*LHC Higgs XS WG '10*]



Higgs production modes at the LHC:

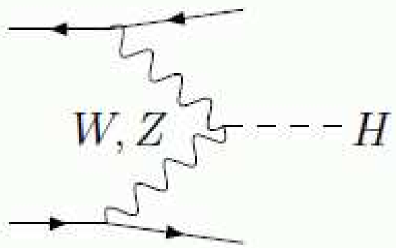
- **Gluon Gluon Fusion**

$pp \to gg \to H$



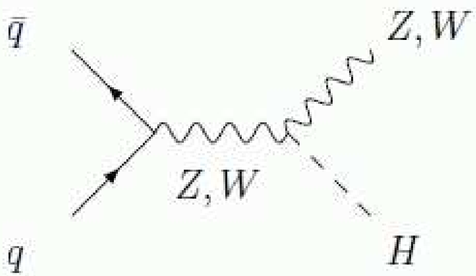
- **W/Z Fusion**

$pp \to qq \to qq + WW/ZZ \to qq + H$



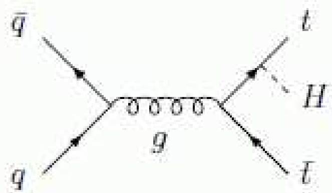
- **Higgs-strahlung**

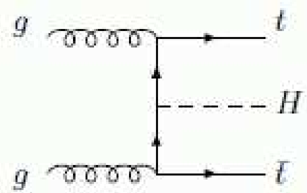
$pp \to W^*/Z^* \to W/Z + H$



- **Associated production with $t\bar{t}$**

$pp \to t\bar{t} + H$

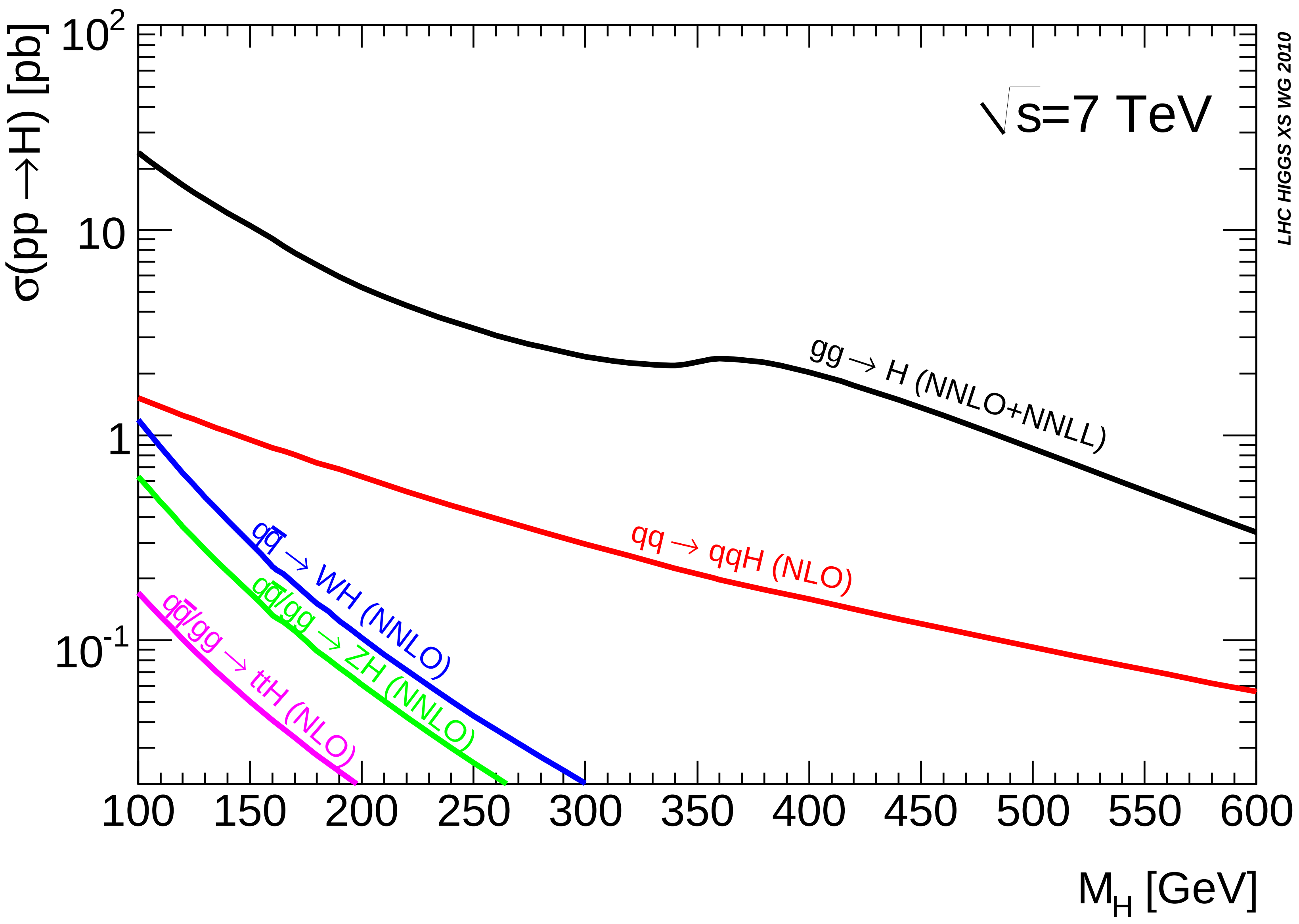




dominant

Latest theory predictions for the SM Higgs: LHC production XS

[LHC Higgs XS WG '10]



Do never forget 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:

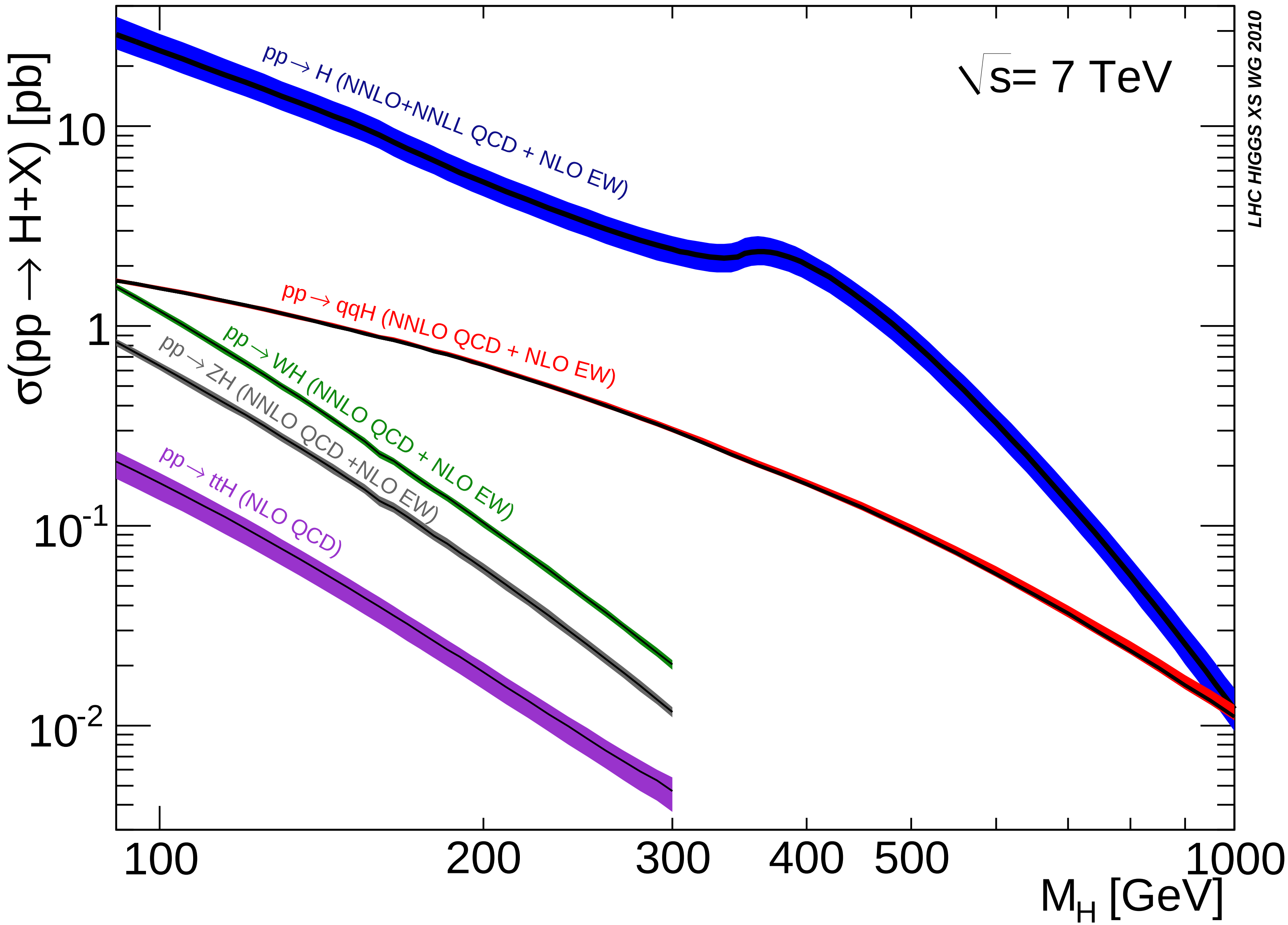
uncertainty in the prediction due to error in the input parameters

– m_t, α_s, PDFs, . . .

– future expectations?

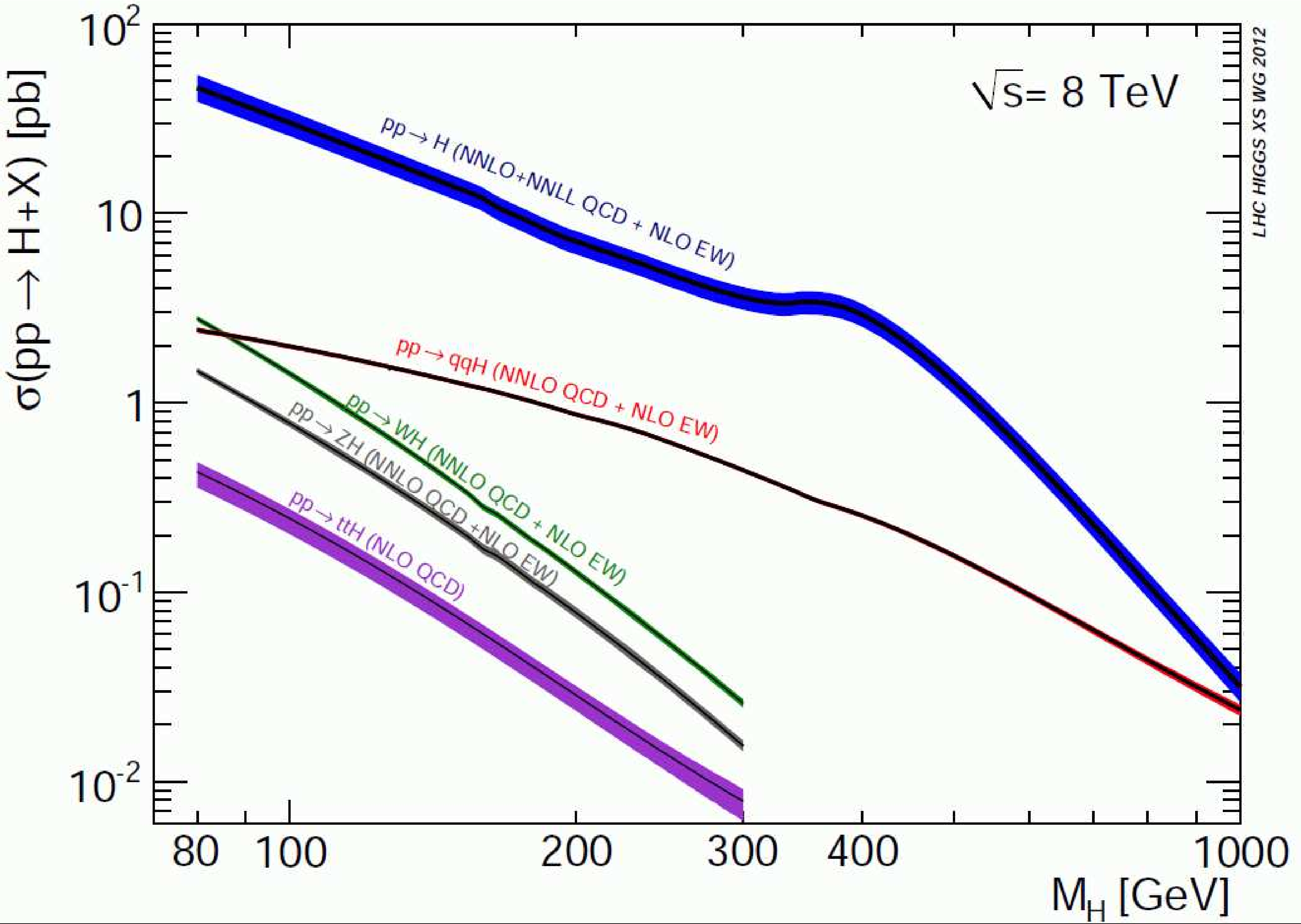
Latest theory predictions for the SM Higgs: LHC production XS

[*LHC Higgs XS WG '10*]



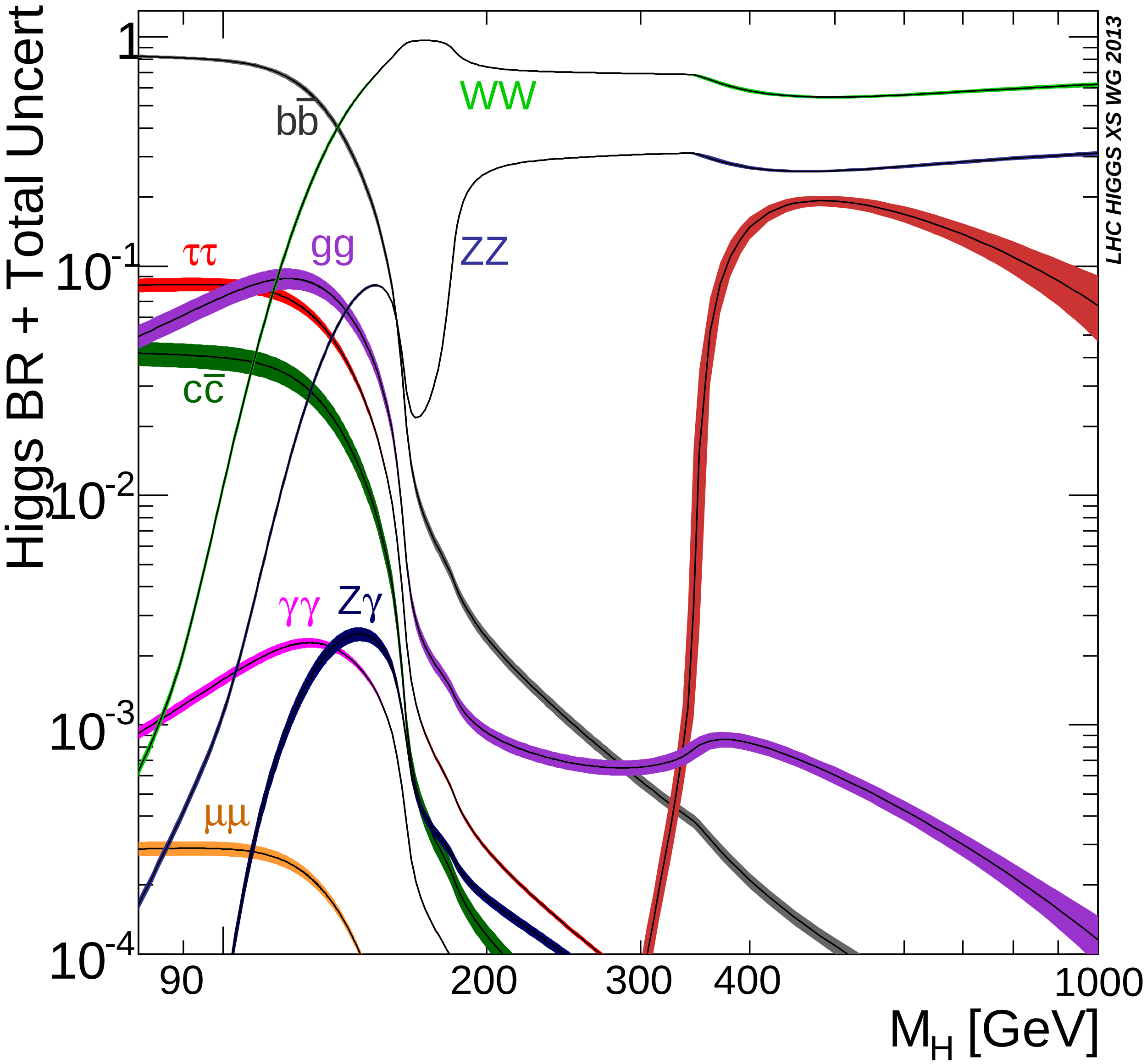
Latest theory predictions for the SM Higgs: LHC production XS

[*LHC Higgs XS WG '12*]



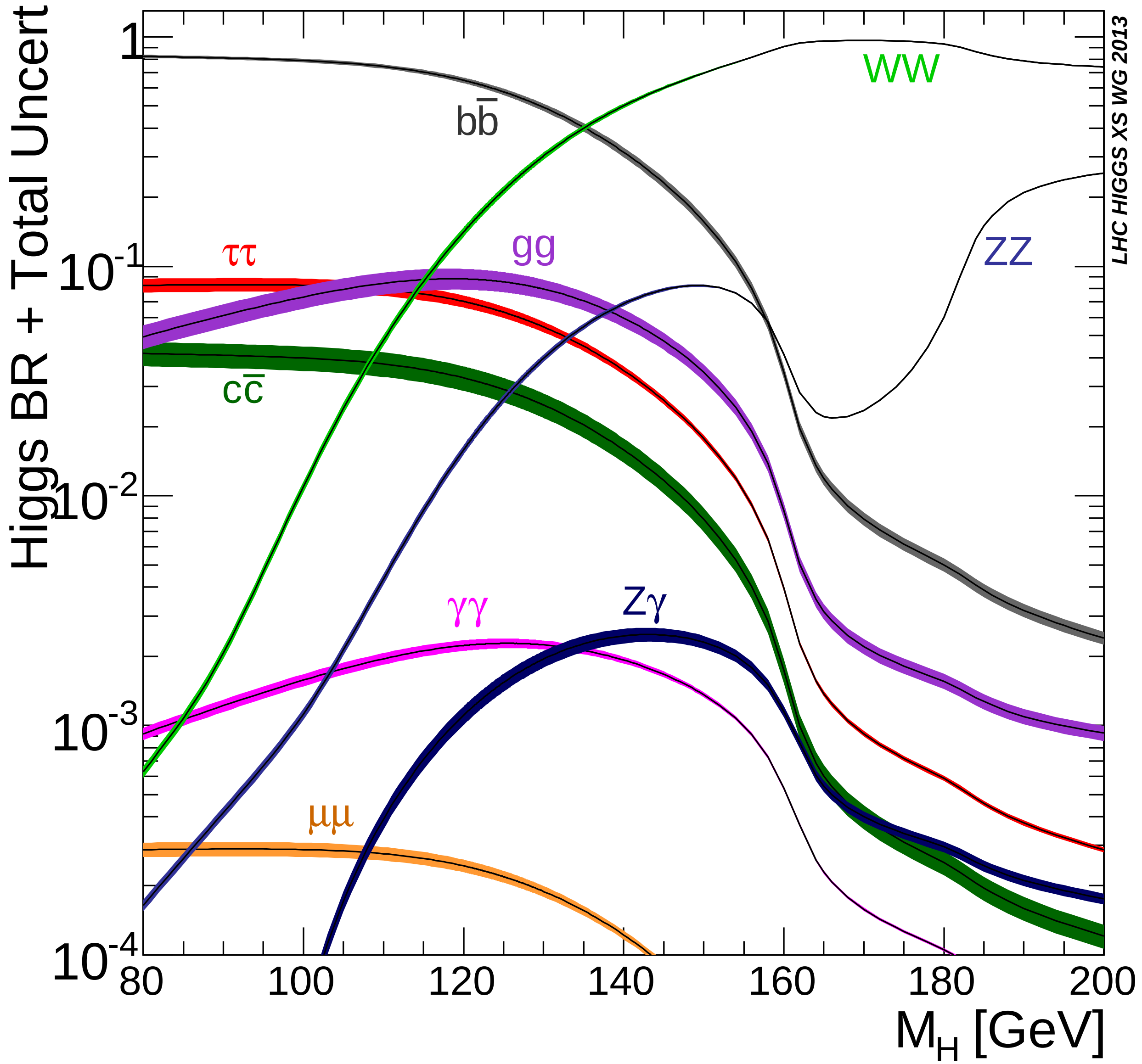
Latest theory predictions for the SM Higgs: branching ratios

[*LHC Higgs XS WG '13*]



Latest theory predictions for the SM Higgs: branching ratios

[*LHC Higgs XS WG '13*]



LHC Higgs Cross Section Working Group

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

- Mixed group of ATLAS/CMS experimentalists and theorists (crucial!)
- Subgroups for each LHC Higgs production cross section or BRs
- Goal: obtain best theory predictions to facilitate
  - "best" Higgs boson search
  - "best" combination of ATLAS and CMS
  - "best" extraction of parameters
- Much to do for theorists:
  - improve cross section/BR calculation
  - calculation of distributions
  - extract/fit Higgs couplings
  - ...
- $\Rightarrow$ more workforce always appreciated!