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

Higgs and BSM Phenomenology

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

Cosener's house, 07/2019

1. Basics of the Higgs

2. BSM Higgs physics (theory)

3. Higgs boson(s) at the LHC

4. Further BSM phenomenology

Higgs and BSM Phenomenology

Basics of the Higgs

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1. Why Higgs?

2. Higgs mass predictions before the LHC

3. Properties of the SM Higgs boson

4. Higgs Production and Decay at the LHC

5. Higgs BRs with uncertainties

1. Why Higgs?

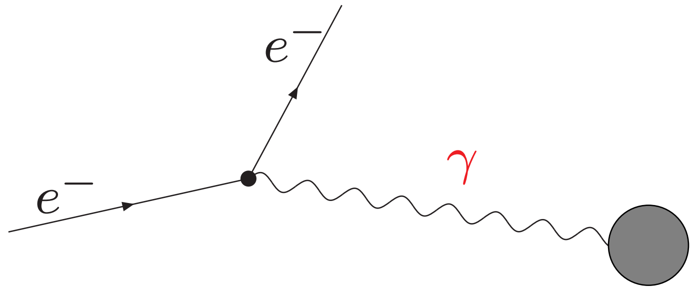
Standard Model (SM) of the electroweak and strong interaction

SM: Quantum field theory ⇒ interaction: exchange of field quanta

Construction principle of the SM: gauge invariance

Example: Quantum electro-dynamics (QED)

field quanta: photon A_μ

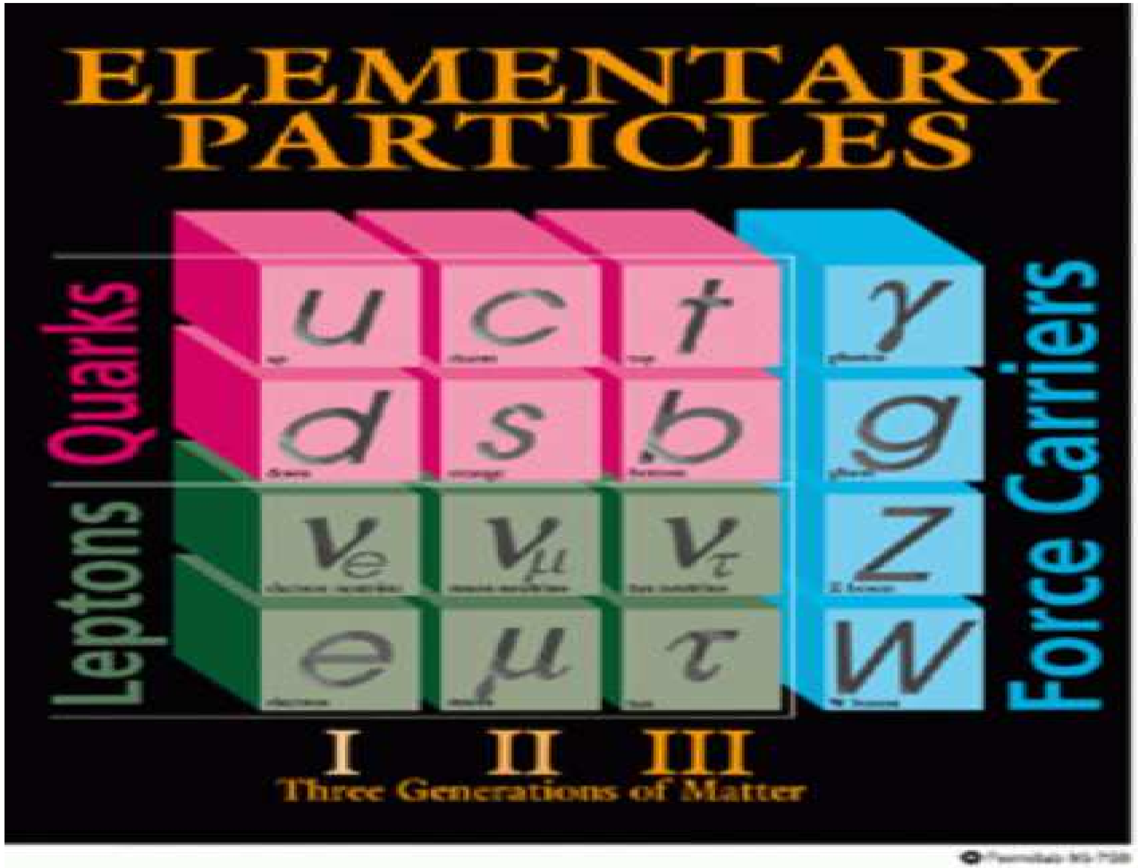


$\mathcal{L}_{\text{QED}}$ invariant under gauge transformation:

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

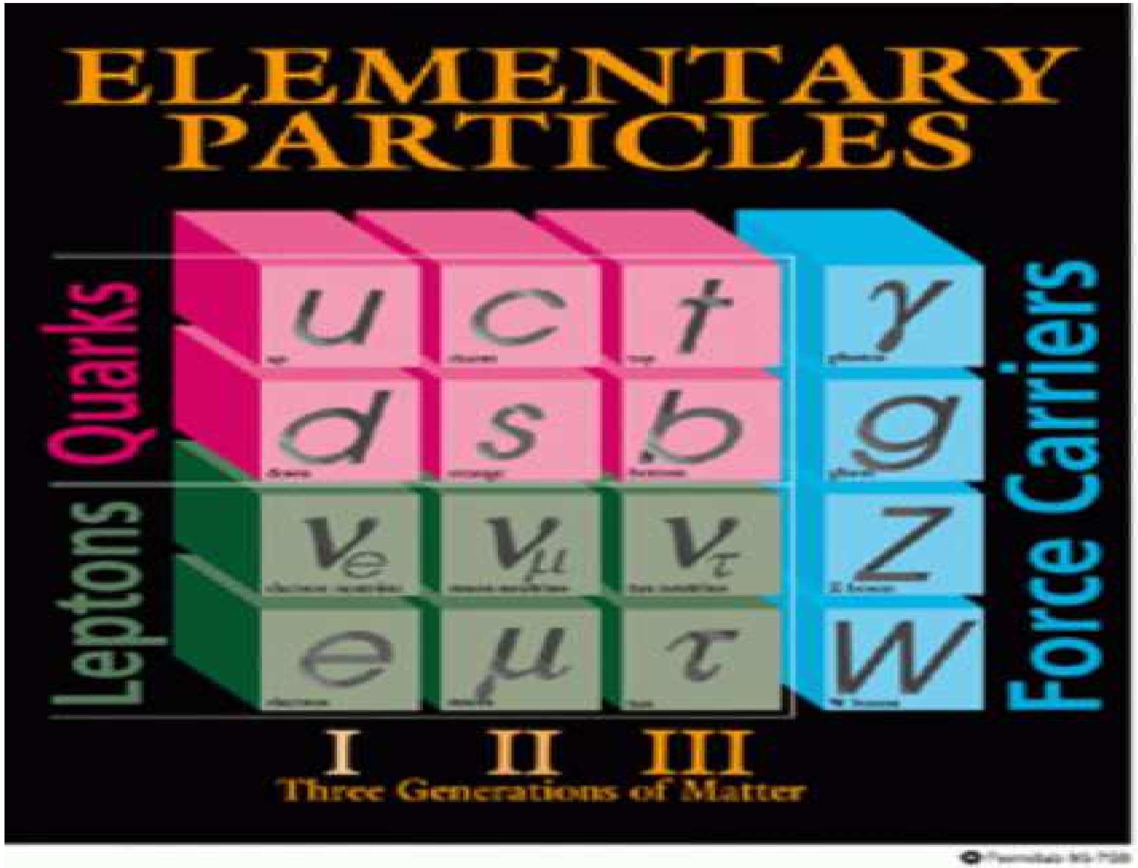
mass term for photon: $m^2 A^\mu A_\mu$ not gauge invariant
⇒ A_μ is massless gauge field

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:

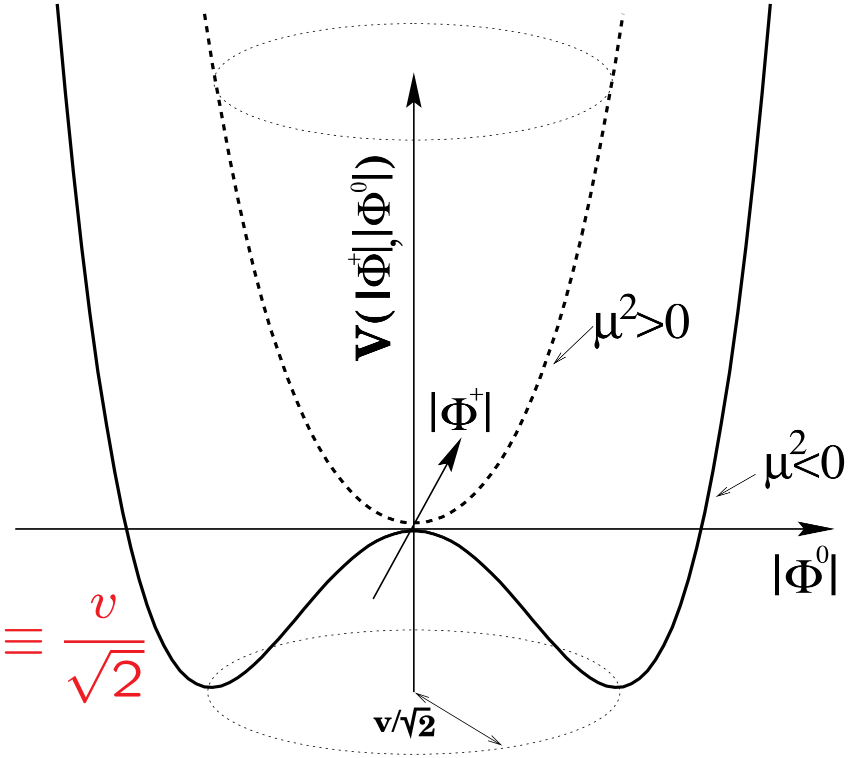
Scalar SU(2) doublet: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

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:

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

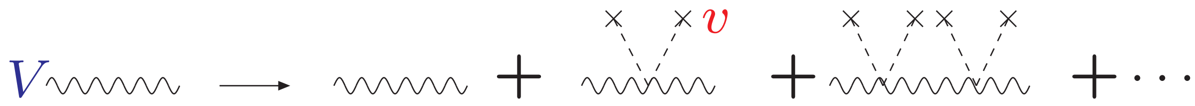
with

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

Gauge invariant coupling to gauge fields

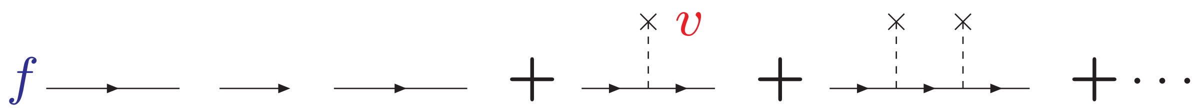
$\Rightarrow$ mass terms for gauge bosons and fermions

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



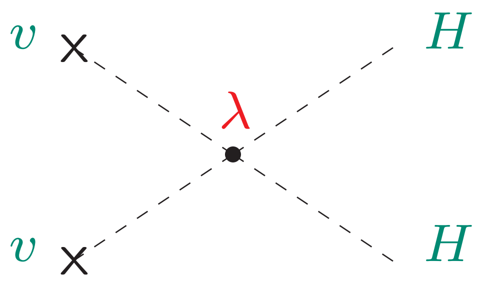
$$\frac{1}{q^2} \to \frac{1}{q^2} + \sum_j \frac{1}{q^2}\left[\left(\frac{gv}{\sqrt{2}}\right)^2 \frac{1}{q^2}\right]^j = \frac{1}{q^2 - M^2} \ : \ M^2 = g^2\frac{v^2}{2} \qquad \Rightarrow M \propto g$$

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



. . .

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

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

$\rightarrow$ last unknown (now measured) parameter of the SM

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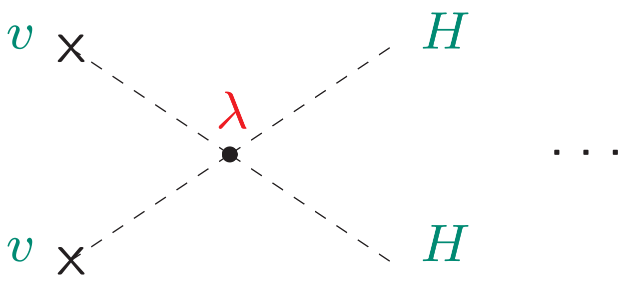

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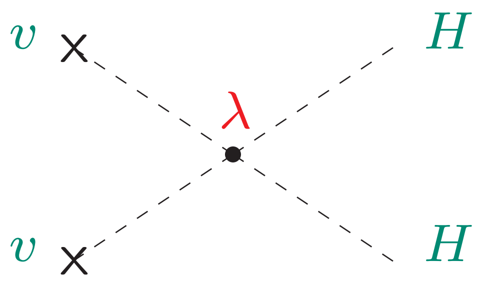

$\cdots$

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

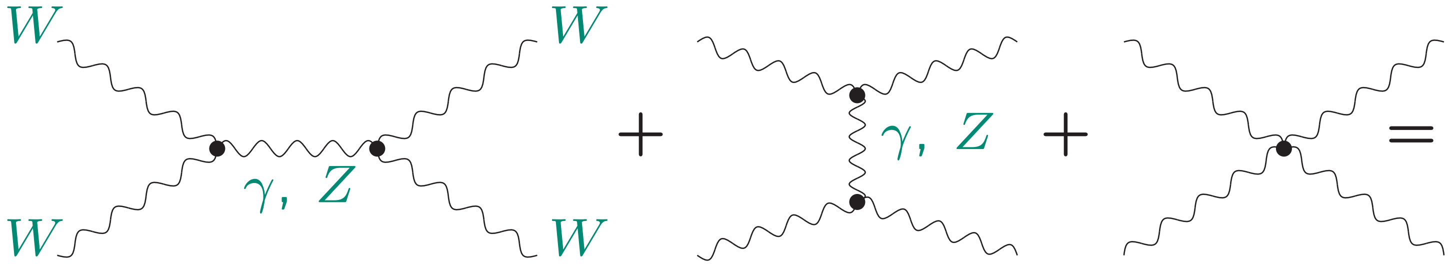
Q1: How can one measure couplings (in general)?

Q2: What else should be measured?

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 $E \to \infty$

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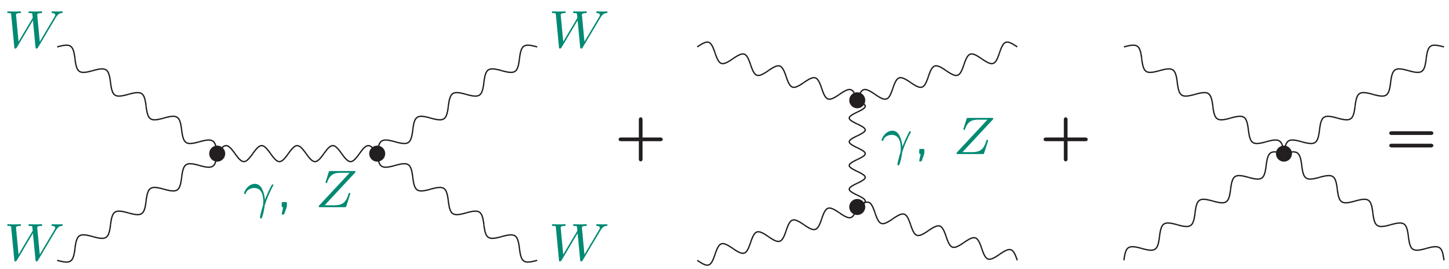

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Q: Why is this dangerous?

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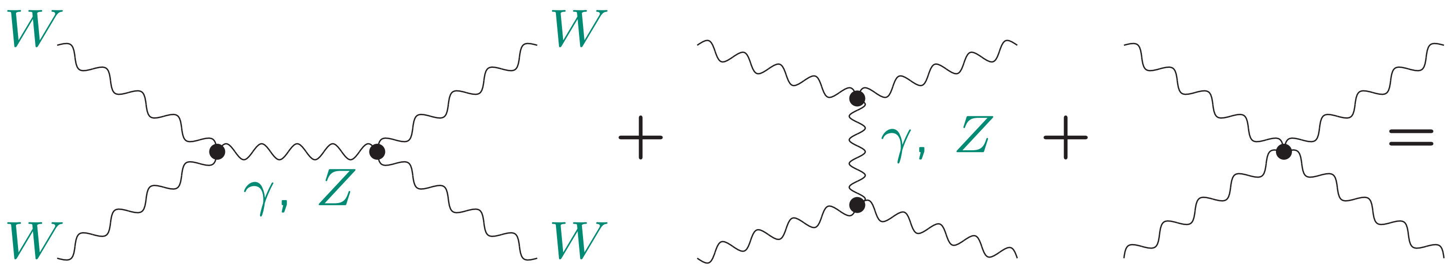
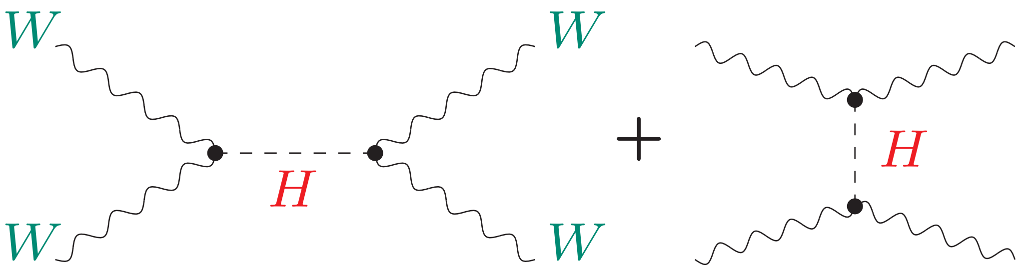


$= -g^2 \frac{E^2}{M_W^2} + \mathcal{O}(1)$ for $E \to \infty$

$\Rightarrow$ 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 $E \to \infty$

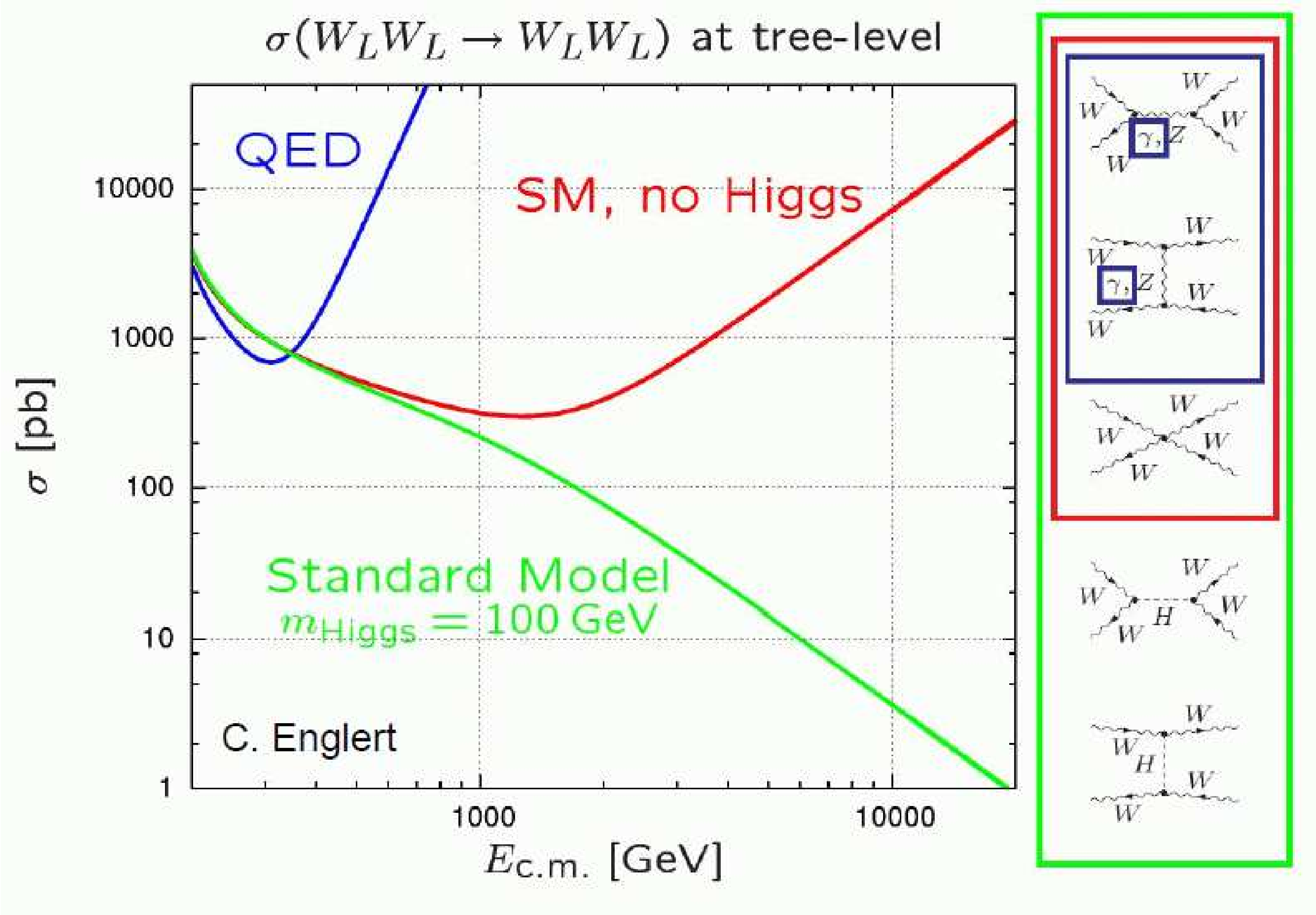
$$\mathcal{M}_{\text{tot}} = \mathcal{M}_V + \mathcal{M}_S = \frac{E^2}{M_W^4}\left(g_{WWH}^2 - g^2 M_W^2\right) + \ldots$$

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

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

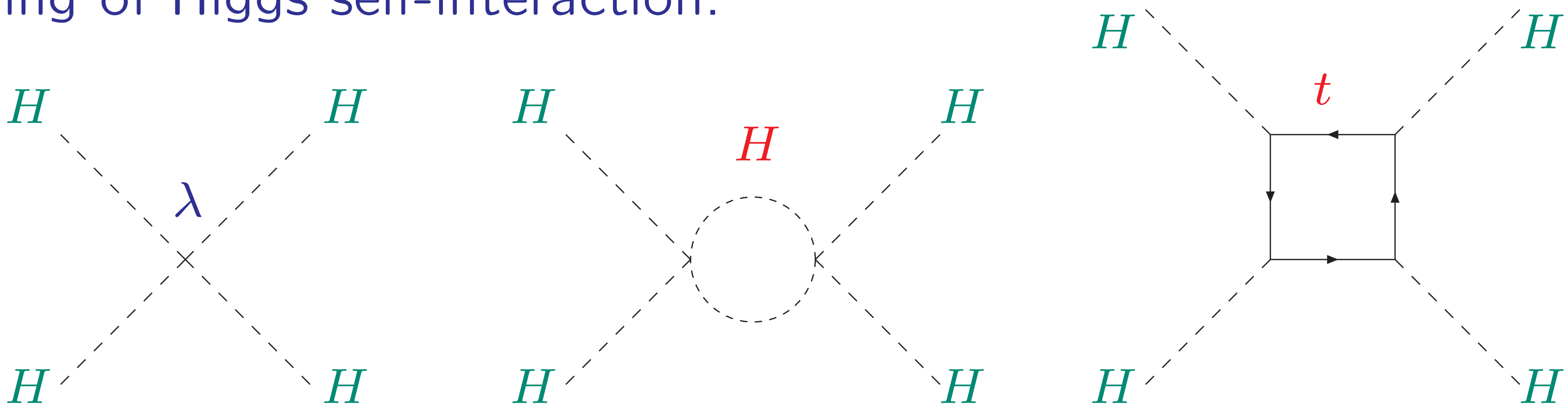
Cross section with/without the Higgs:

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



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 $\lambda \sim M_H^2$)

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

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

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

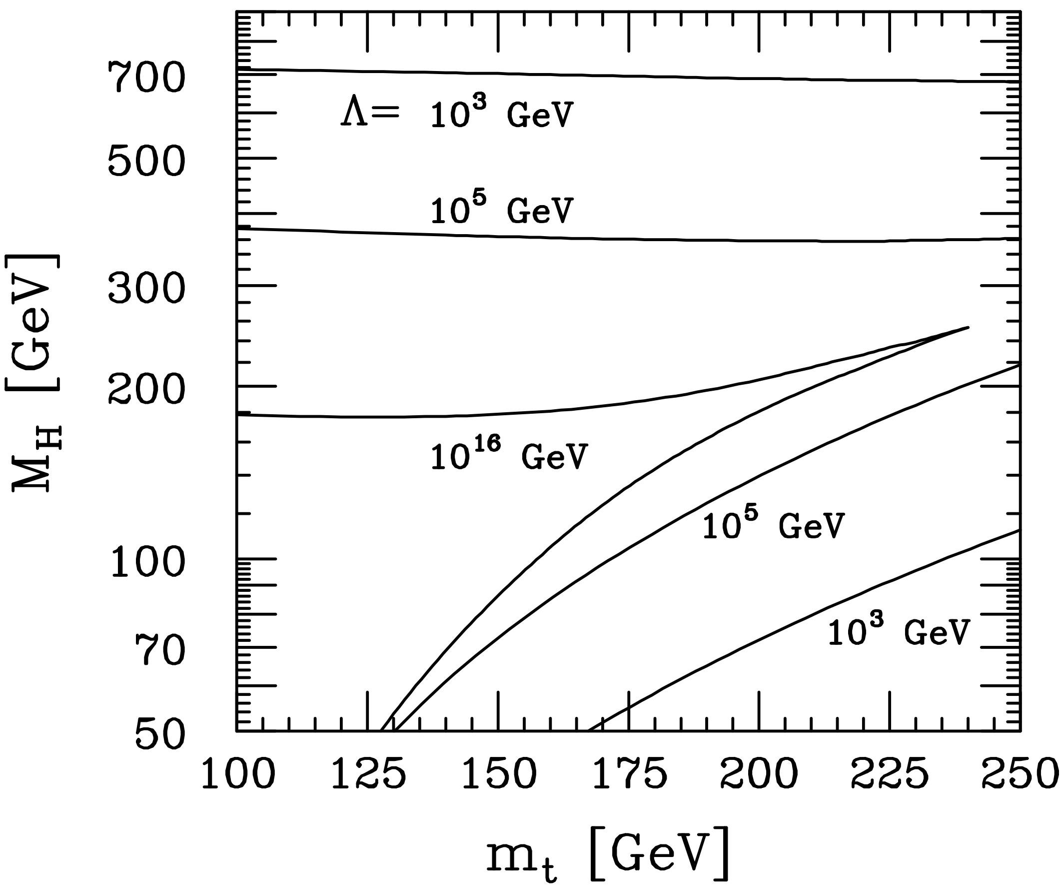
2.) avoid vacuum instability (for small/negative λ): $V(v) < V(0) \Rightarrow \lambda(\Lambda) > 0$

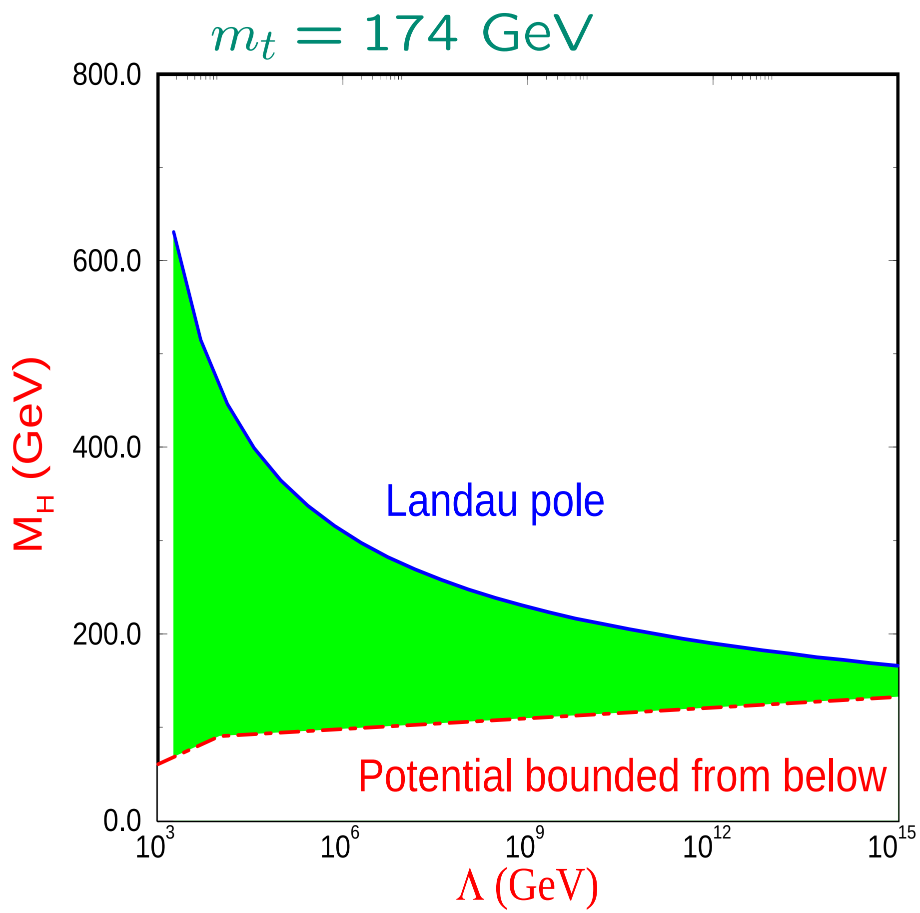
$$\frac{d\,\lambda}{d\,t} = \frac{3}{8\,\pi^2}\left[-g_t^4 + \frac{1}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]$$

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

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

Both limits combined:



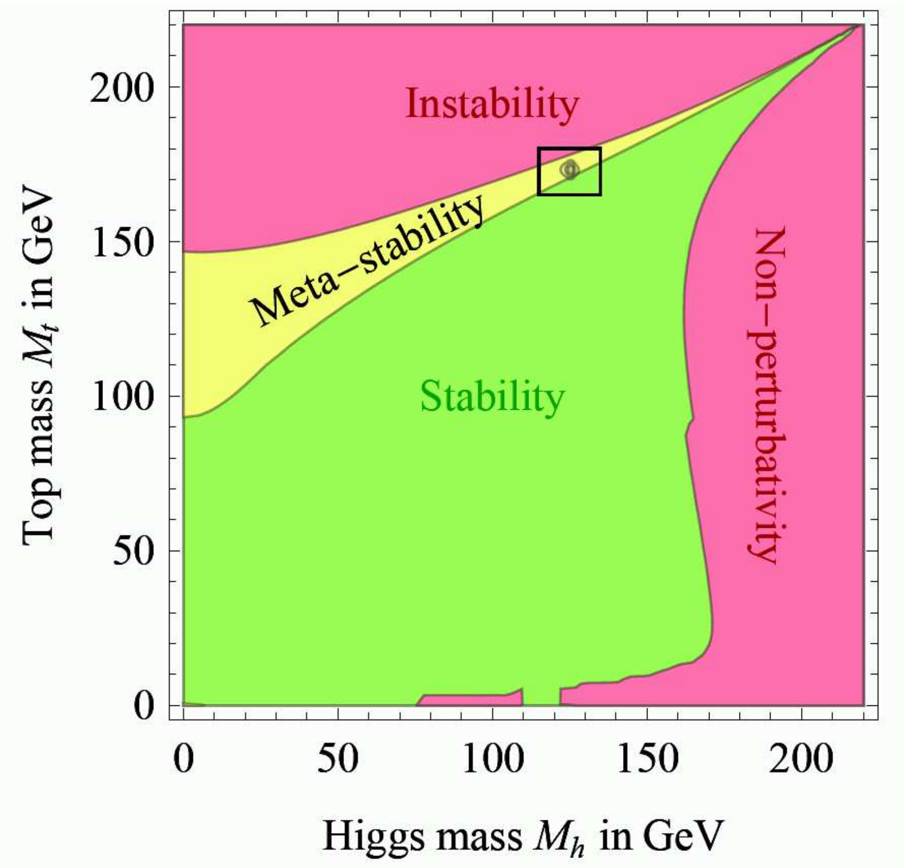


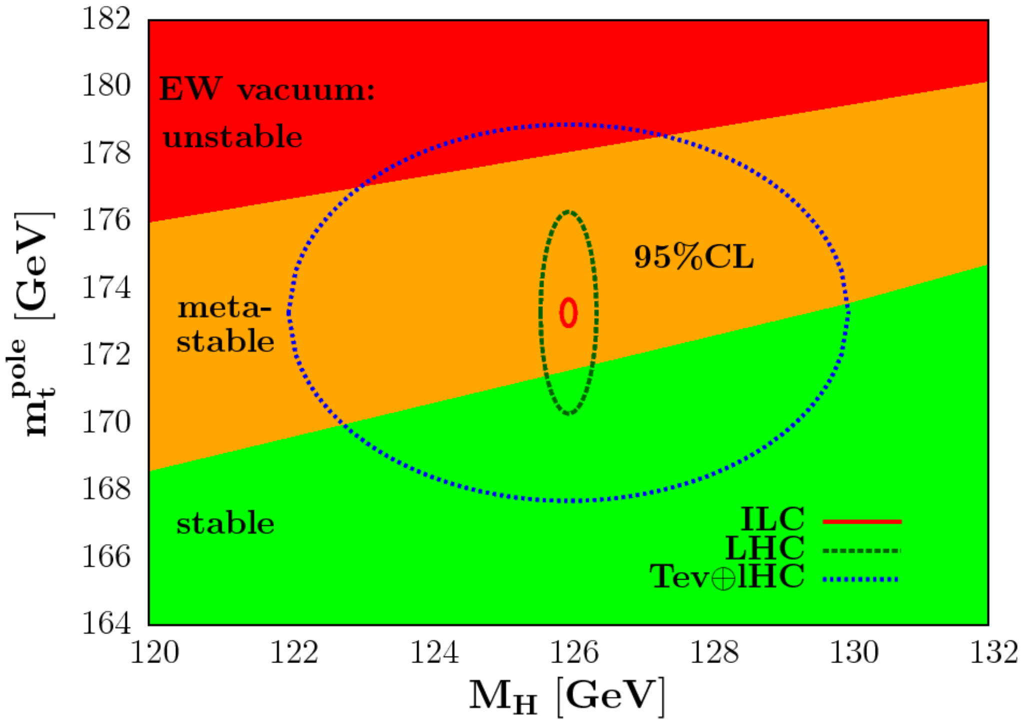
Λ: scale up to which the SM is valid

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

$M_H = 125$ 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!

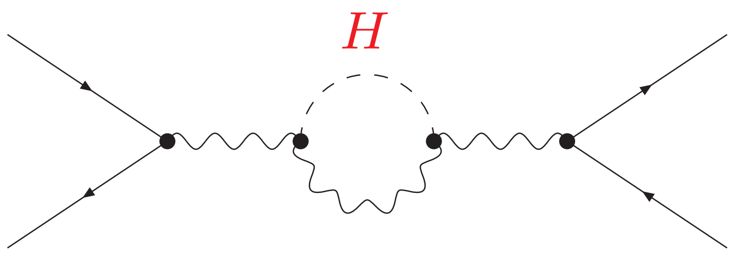
Electroweak Precision Observables (EWPO) and the Higgs mass:

Comparison of electro-weak precision observables with theory:

EW Precision data:		Theory:
$M_W, \sin^2\theta_{\rm eff}, a_\mu$	$\leftrightarrow$	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

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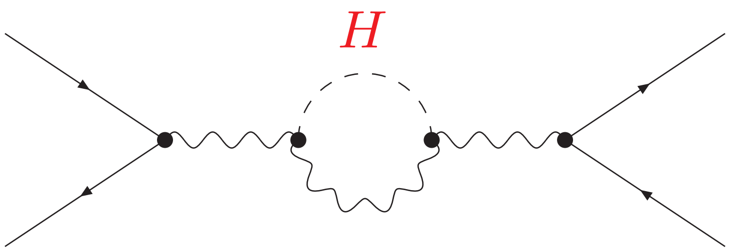


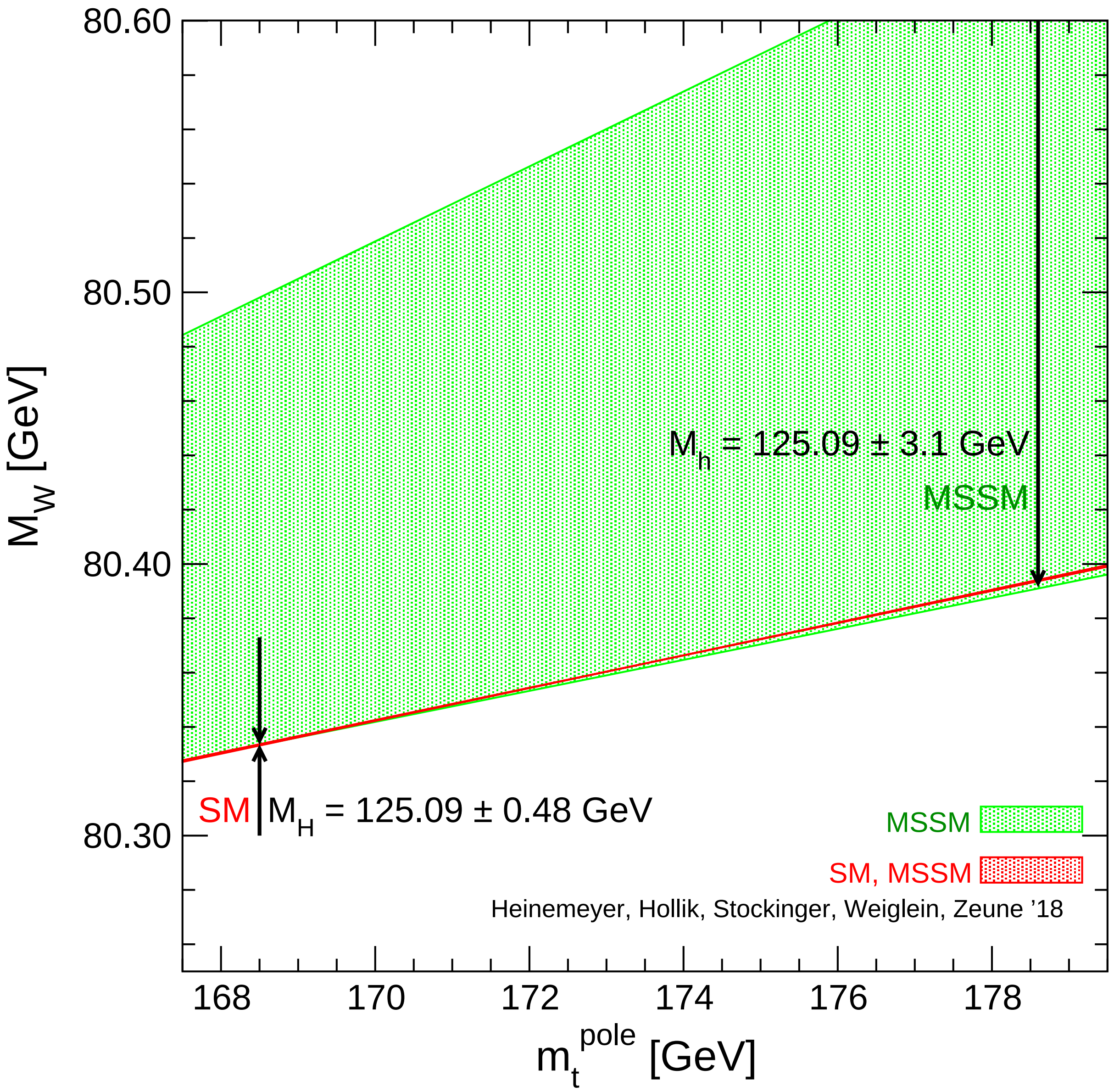
$\Downarrow$

SM: limits on M_H

Q: What are important diagrams? In the SM? In the MSSM?

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

[S.H., W. Hollik, D. Stockinger, G. Weiglein, L. Zeune '18]



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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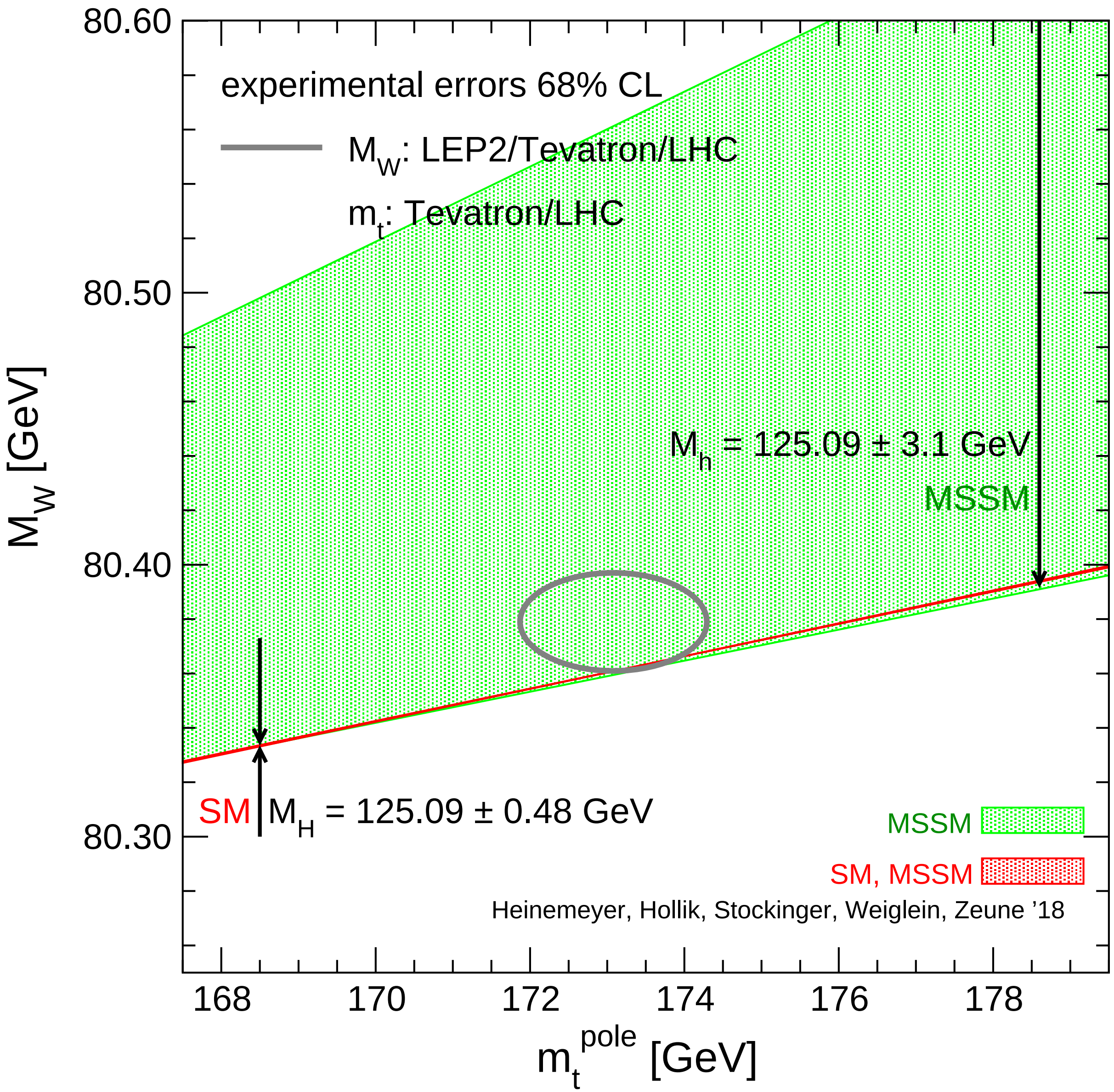

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Examples for precision observables

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]

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

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

Examples for precision observables

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

A) Theoretical prediction for M_W in terms

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

$\Updownarrow$

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:

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

Results for M_H from other EWPO:

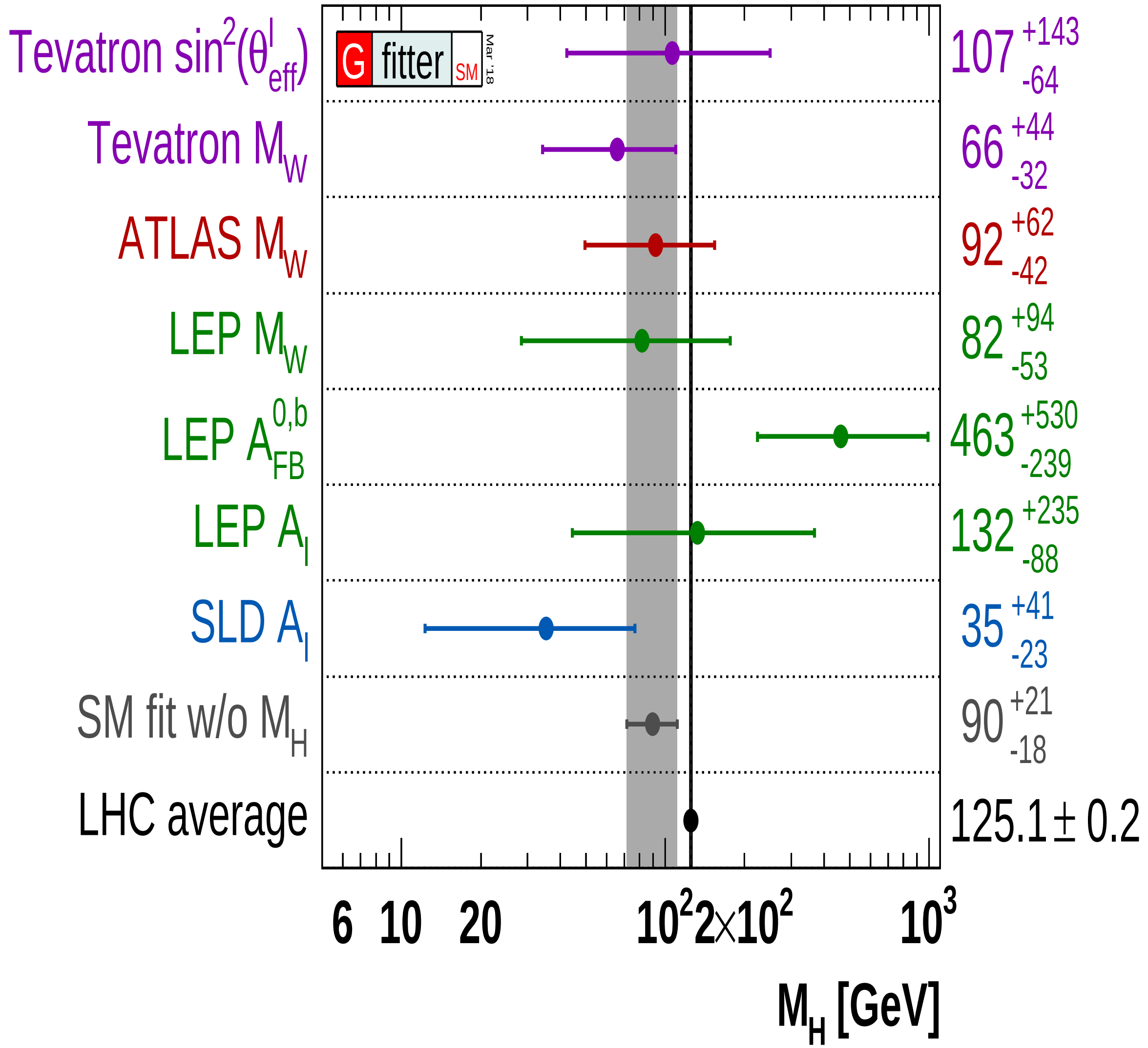
light Higgs preferred by:

M_W, $A^l_{\rm LR}$ (SLD)

heavier Higgs preferred by:

$A^b_{\rm FB}$ (LEP)

⇒ keeps SM alive



⇒ light Higgs boson preferred

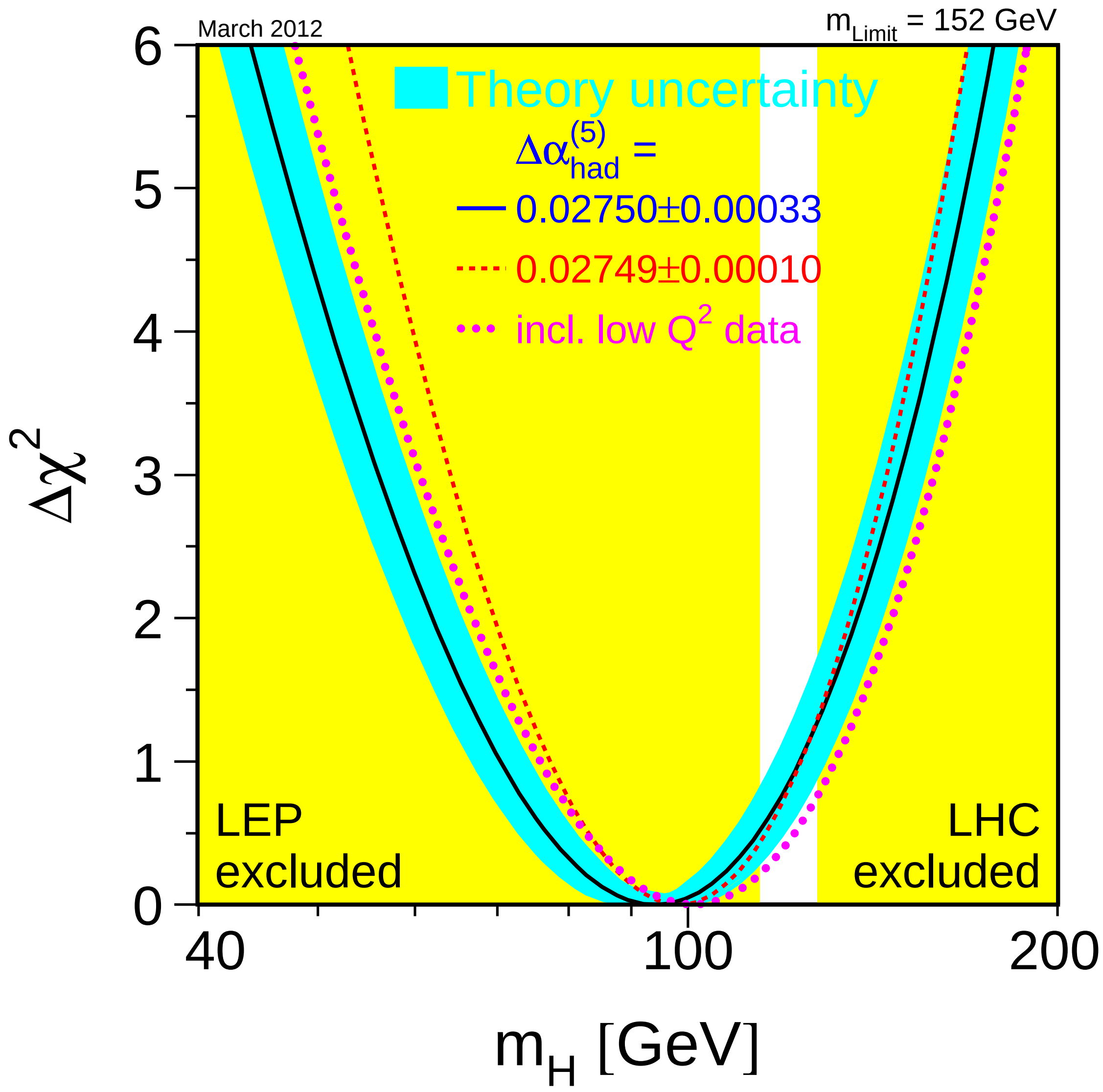
[GFitter '18]

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 $1.8\,\sigma$

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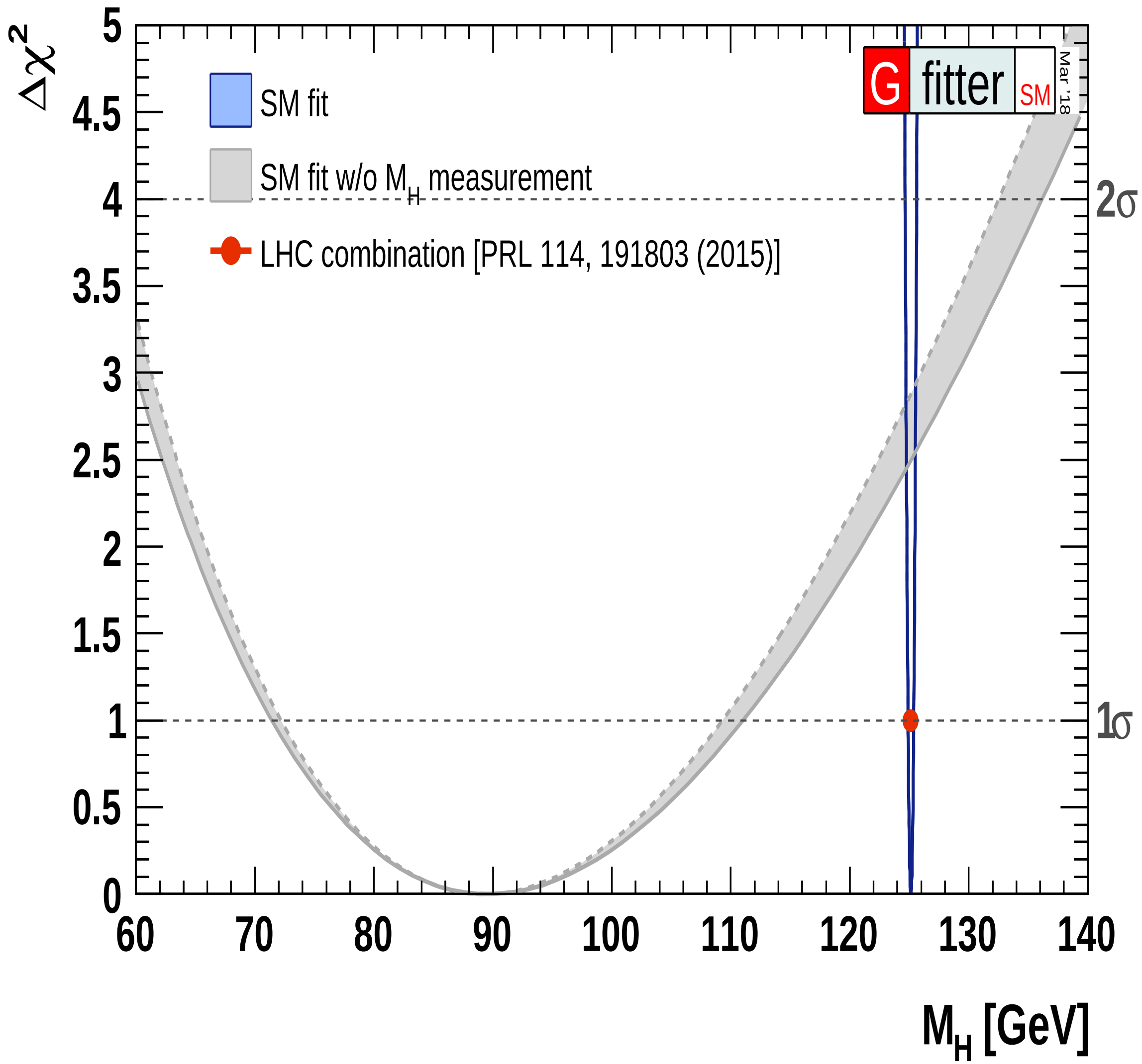
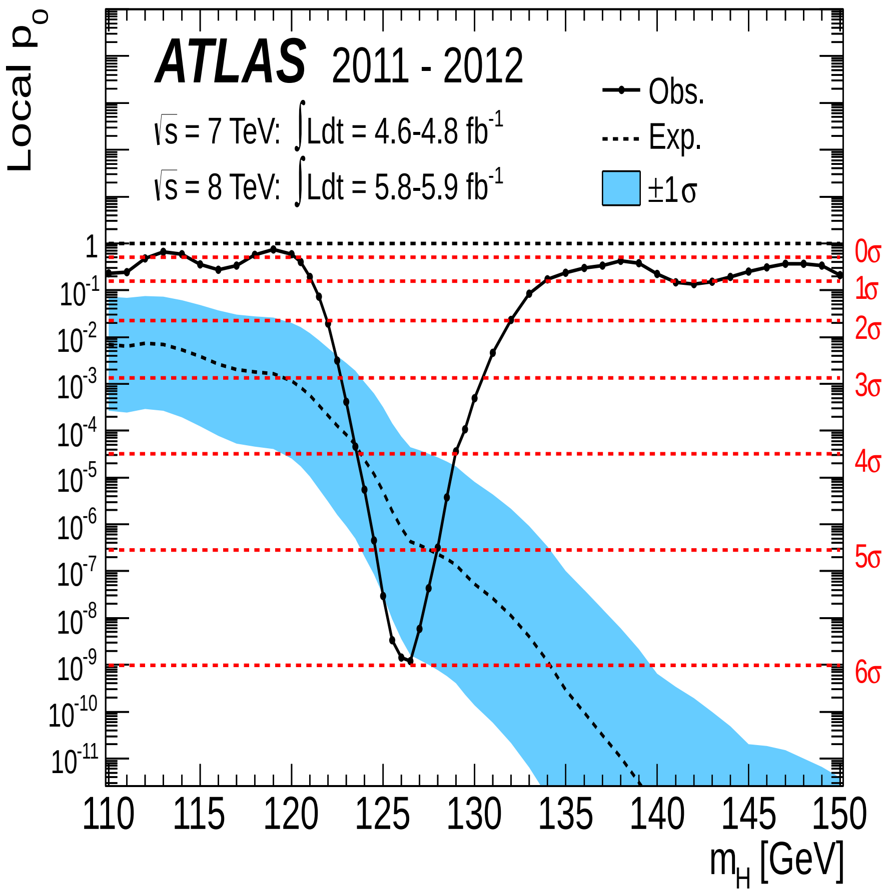


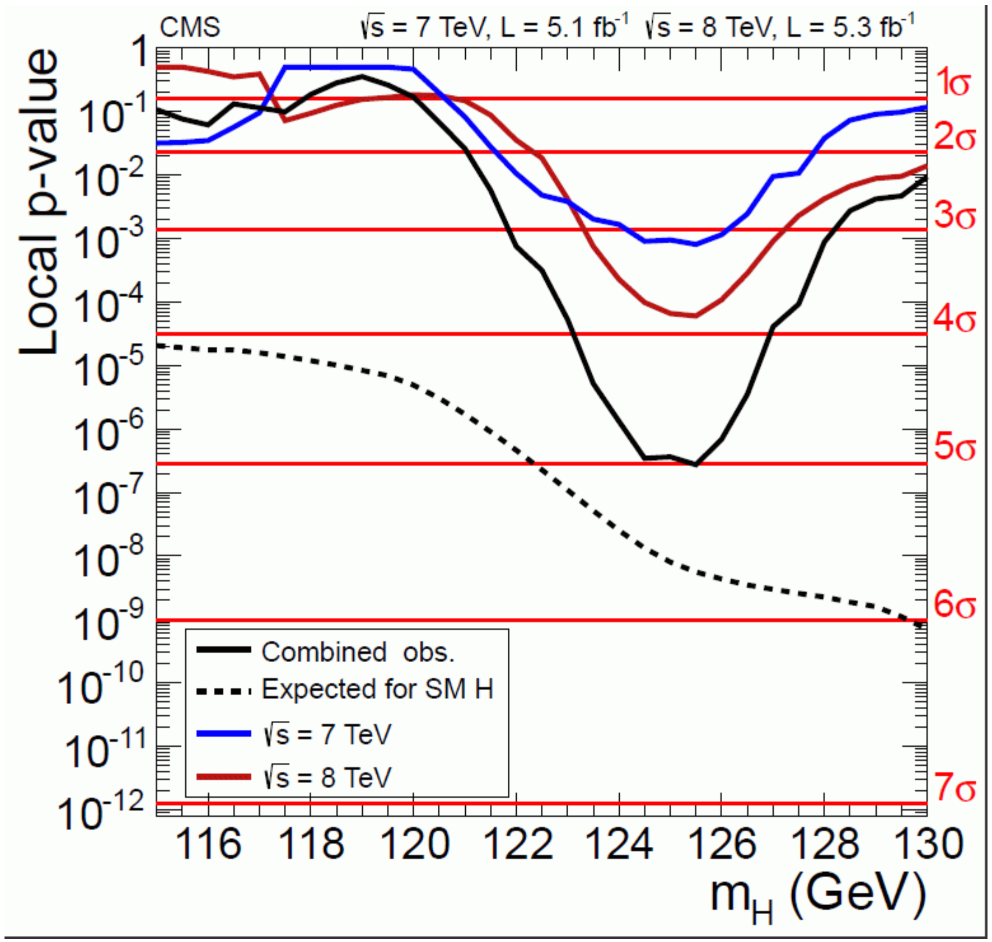
$\Rightarrow$ slightly rising "tension" over the last years . . .

Why July 4th is celebrated (not only in the US):

The physics world changed on 04.07.2012:

We have a discovery!





Let's vote!

1) The discovered particle is the Higgs boson?
   The discovered particle is not the Higgs boson?

2) The SM is now complete.
   The SM is not complete.

$\Rightarrow$ we will discuss the answers later!

We have a discovery!

But what is it?

Q: Is it a Higgs boson?

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?

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How can we decide?

A: Measure all its characteristics

A: Compare to the predictions of the various models

A: search for additional Higgs bosons above and below 125 GeV

We have a discovery!

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⇒ Overview about Higgs phenomenology in the SM and BSM!

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

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

Q: What is the most important (fermionic) decay channel?

3. Properties of the SM Higgs boson

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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, $\gamma\gamma$):

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Q: How is this possible?
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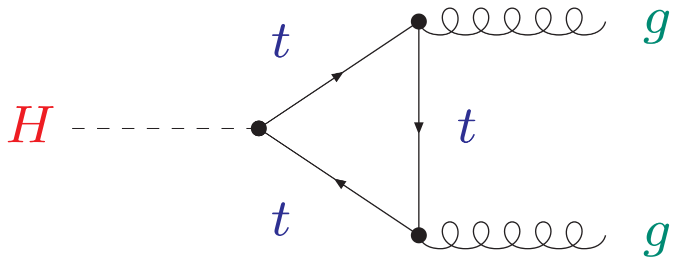
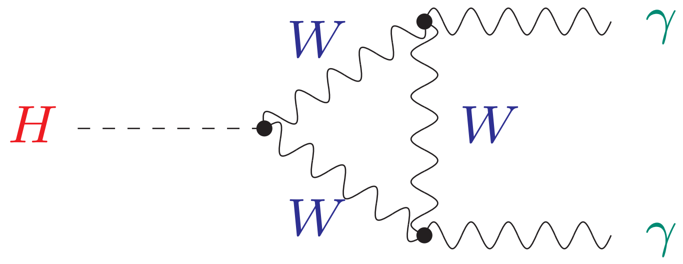
Q: What are the most important loops?

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

Total width:

sum over all decay widths

$$\begin{aligned}\Gamma_{H,\text{tot}} &:= \sum_{\text{dd}'} \Gamma(H \to \text{dd}') \\ &= \quad \Gamma(H \to t\bar{t}) + \Gamma(H \to b\bar{b}) + \Gamma(H \to c\bar{c}) + \ldots \\ &\quad + \Gamma(H \to \tau^+\tau^-) + \Gamma(H \to \mu^+\mu^-) + \ldots \\ &\quad + \Gamma(H \to WW^{(*)}) + \Gamma(H \to ZZ^{(*)}) + \Gamma(H \to \gamma\gamma) + \ldots \\ &\quad + \ldots\end{aligned}$$

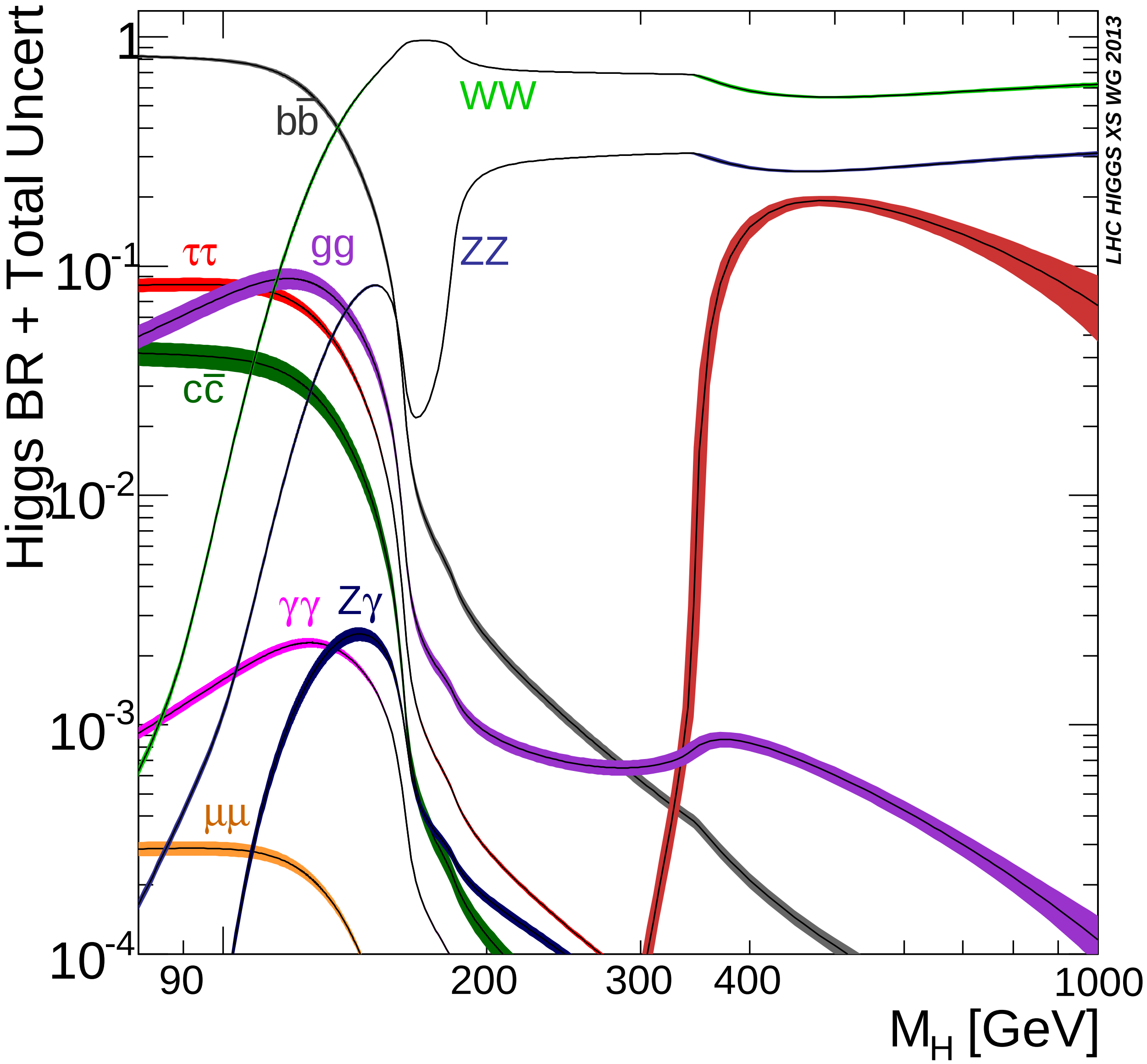
Branching ratio:

probability that a particle decays to a certain final state

$$\text{BR}(H \to \text{dd}') := \frac{\Gamma(H \to \text{dd}')}{\Gamma_{H,\text{tot}}}$$

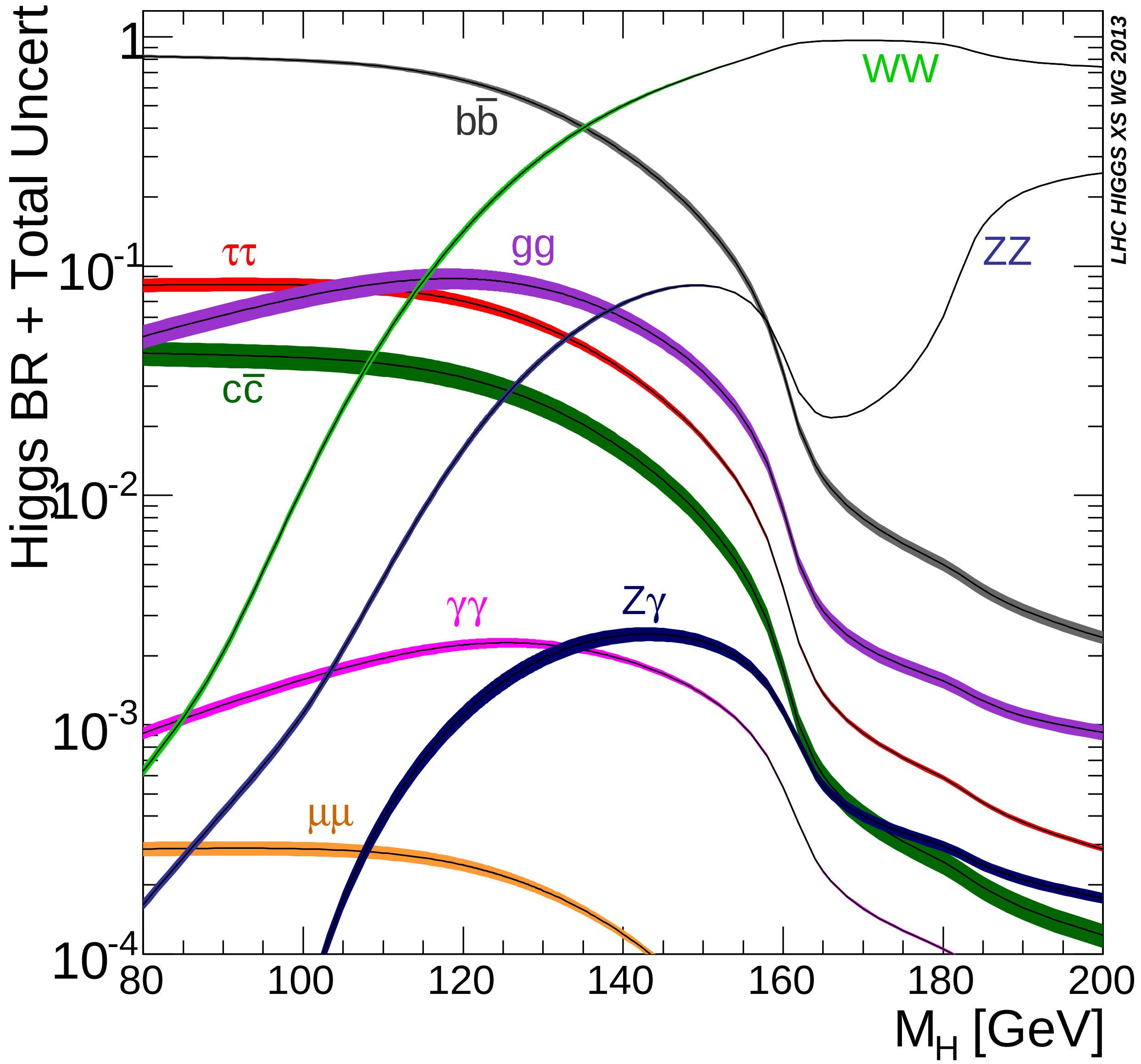
Latest theory predictions for the SM Higgs: branching ratios

[*LHC Higgs XS WG '13*]



Latest theory predictions for the SM Higgs: branching ratios

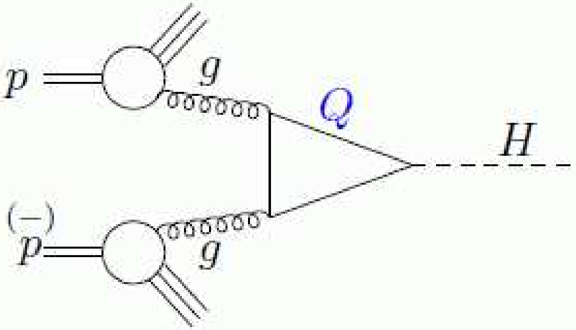
[*LHC Higgs XS WG '13*]



4. Higgs production modes at the LHC:

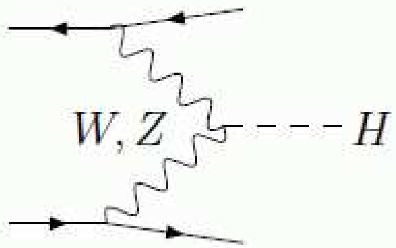
- **Gluon Gluon Fusion**

  $pp \to gg \to H$



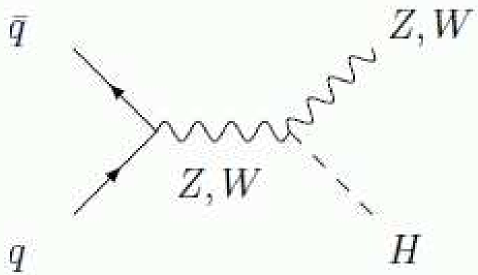
- **W/Z Fusion**

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



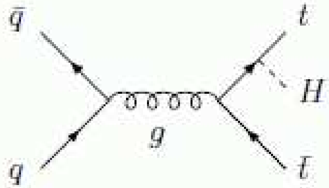
- **Higgs-strahlung**

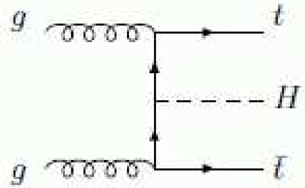
  $pp \to W^*/Z^* \to W/Z + H$



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

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



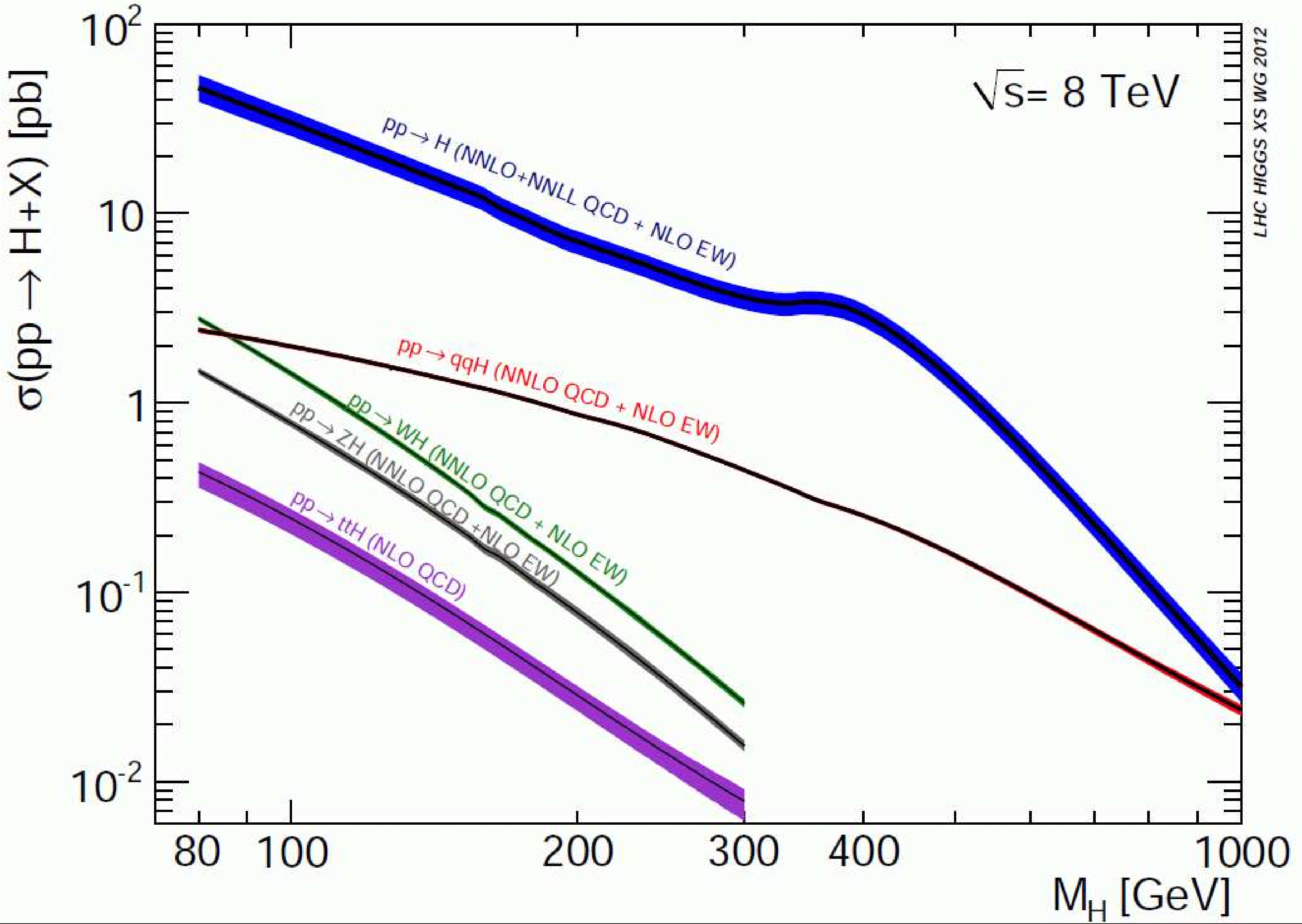


dominant

[taken from M. Mühlleitner]

Latest theory predictions for the SM Higgs: LHC production XS

[*LHC Higgs XS WG '12*]



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?

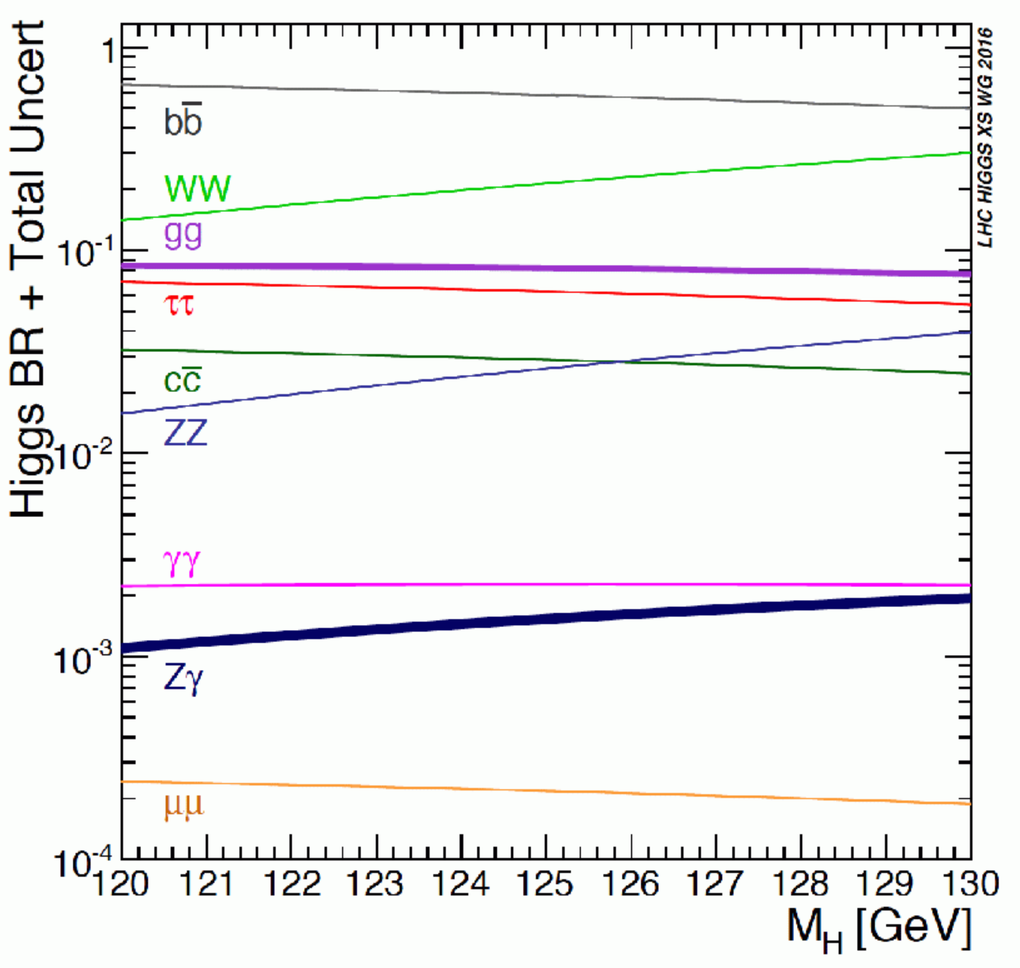
LHC Higgs Cross Section Working Group

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
  - ...
- ⇒ more workforce always appreciated!

5. Higgs BRs with uncertainties

[LHCHXSWG '16]



Based on HDECAY and Prophecy4f:

$$\Gamma_H = \Gamma^{\text{HD}} - \Gamma^{\text{HD}}_{ZZ} - \Gamma^{\text{HD}}_{WW} + \Gamma^{\text{P4f}}_{4f}$$

Theoretical uncertainties: General recipe: [LHCHXSWG BR group '15]

1. Parametric Uncertainties: $p \pm \Delta p$
   - Evaluate partial widths and BRs with p, $p + \Delta p$, $p - \Delta p$ and take the differences w.r.t. central values
   - Upper ($p + \Delta p$) and lower ($p - \Delta p$) uncertainties summed in quadrature to obtain the Combined Parametric Uncertainty

2. Theoretical Uncertainties:
   - Calculate uncertainty for partial widths and corresponding BRs for each theoretical uncertainty
   - Combine the individual theoretical uncertainties linearly to obtain the Total Theoretical Uncertainty

   $\Rightarrow$ estimate based on "what is included in the codes"!

3. Total Uncertainty:

   Linear sum of the Combined Parametric Uncertainty and the Total Theoretical Uncertainties

Current/future parametric uncertainties:

"future" = expected precision on g^2_{Hxx} in $\mathcal{O}(20)$ years

Partial width	QCD	electroweak	total	future	future
$H \to b\bar{b}$	$\sim 0.2\%$	$< 0.3\%$	$< 0.4\%$	$\sim 0.2\%$	$\sim 1.0\%$
$H \to c\bar{c}$	$\sim 0.2\%$	$< 0.3\%$	$< 0.4\%$	$\sim 0.2\%$	$\sim 1.7\%$
$H \to \tau^+\tau^-$	–	$< 0.3\%$	$< 0.3\%$	$< 0.1\%$	$\sim 1.3\%$
$H \to \mu^+\mu^-$	–	$< 0.3\%$	$< 0.3\%$	$< 0.1\%$	$\sim 15\%$
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3.2\%$	$\sim 1\%$	$\sim 2\%$
$H \to \gamma\gamma$	$< 0.1\%$	$< 1\%$	$<1\%$	$< 1\%$	$\sim 3.6\%$
$H \to Z\gamma$	$\lesssim 0.1\%$	$\sim 5\%$	$\sim 5\%$	$\sim 1\%$	
$H \to WW \to$ 4f	$< 0.5\%$	$< 0.3\%$	$\sim 0.5\%$	$\lesssim 0.4\%$	$\sim 0.5\%$
$H \to ZZ \to$ 4f	$< 0.5\%$	$< 0.3\%$	$\sim 0.5\%$	$\lesssim 0.3\%$	$\sim 0.4\%$
Γ_{tot}				$\sim 0.3\%$	$\sim 1\%$

$\Rightarrow$ non-negligible for $H \to WW/ZZ \to$ 4f

Future parametric uncertainties for decay widths:

decay	fut. intr.	fut. para. m_q	para. α_s	para. M_H	fut. exp.
$H \to b\bar{b}$	$\sim 0.2\%$	0.6%	$< 0.1\%$	–	$\sim 1.0\%$
$H \to c\bar{c}$	$\sim 0.2\%$	$\sim 1\%$	$< 0.1\%$	–	$\sim 1.7\%$
$H \to \tau^+\tau^-$	$< 0.1\%$	–	–	–	$\sim 1.3\%$
$H \to \mu^+\mu^-$	$< 0.1\%$	–	–	–	$\sim 15\%$
$H \to gg$	$\sim 1\%$		0.5%	–	$\sim 2\%$
$H \to \gamma\gamma$	$< 1\%$	–	–	–	$\sim 3.6\%$
$H \to Z\gamma$	$\sim 1\%$	–	–	$\sim 0.1\%$	
$H \to WW$	$\lesssim 0.4\%$	–	–	$\sim 0.1\%$	$\sim 0.5\%$
$H \to ZZ$	$\lesssim 0.3\%$	–	–	$\sim 0.1\%$	$\sim 0.4\%$
Γ_{tot}	$\sim 0.3\%$	$\sim 0.4\%$	$< 0.1\%$	$< 0.1\%$	$\sim 1\%$

Γ_{tot} applies "to all" (partial cancelations . . .)
$\Rightarrow$ non-negligible in particular for $H \to WW/ZZ \to$ 4f (δm_b optimistic?)

Future theory uncertainties?

Parametric uncertainties:

– largely driven by δm_b $\Rightarrow$ improvement unclear (to me)
  lattice community does not seem to agree

– some improvement in α_s possible

Intrinsic uncertainties:

$H \to b\bar{b}, H \to c\bar{c}$: higher-order EW corrections ??

$H \to \tau^+\tau^-, H \to \mu^+\mu^-$: higher-order EW corrections ?

$H \to gg$: improvement difficult

$H \to \gamma\gamma$: already very precise . . .

$H \to Z\gamma$: EW corrections could help . . .

$H \to WW^*, H \to ZZ^*$: already very precise, two-loop corrections unclear

$\Rightarrow$ PhD/Postdoc work on intrinsic uncertainties needed! :-)