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

The Higgs Sector of the SM

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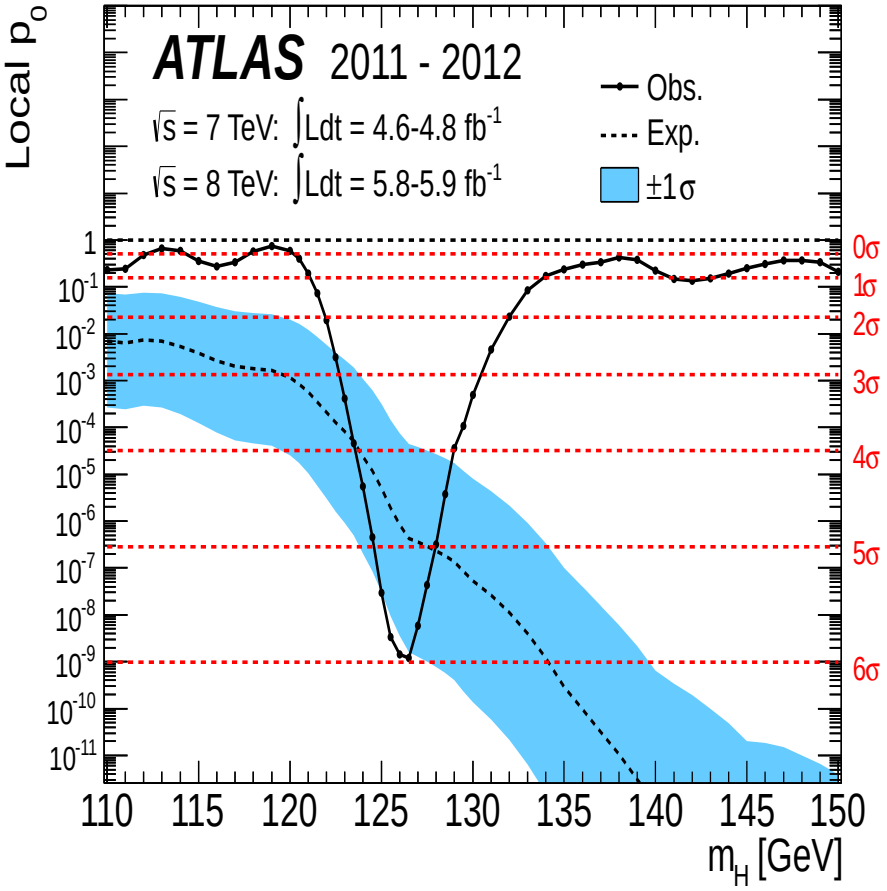
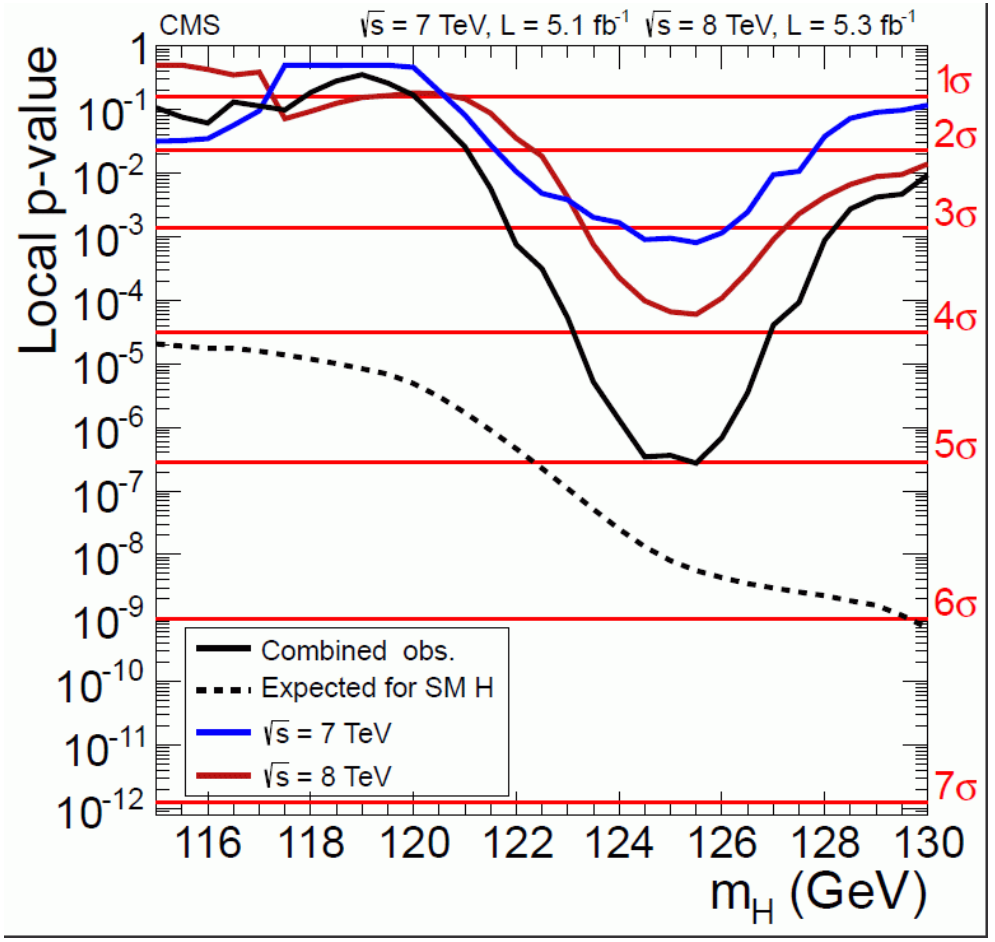
Dubna, 07/2018

1. Properties of the SM Higgs boson
2. Higgs Production and Decay at the LHC
3. Higgs BRs with uncertainties

The physics world changed on 04.07.2012:

We have a discovery!





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

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$\Rightarrow$ Overview about Higgs predictions in the SM, (N)MSSM, . . . !

1. 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 ($M_H > 2M_V$):

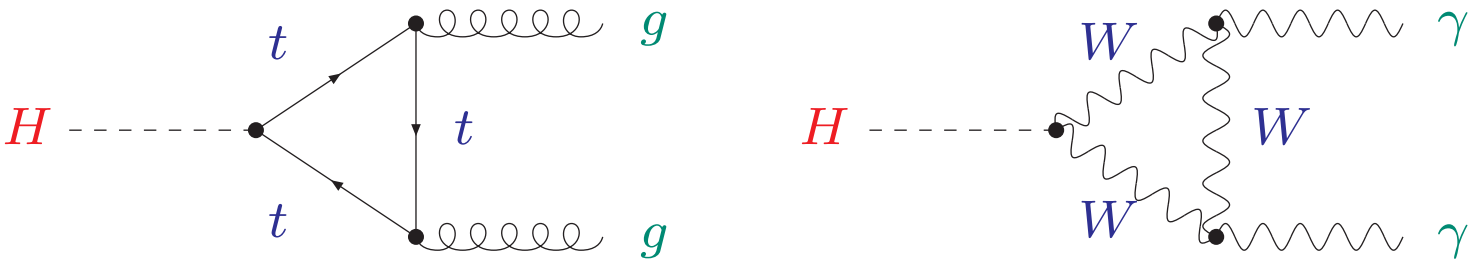
$$\Gamma(H \to VV) = \delta_V \frac{G_\mu M_H^3}{16\sqrt{2}\,\pi} \left(1 - 4\frac{M_V^2}{M_H^2} + 12\frac{M_V^4}{M_H^4}\right) \left(1 - 4\frac{M_V^2}{M_H^2}\right)^{1/2}$$

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

Total width:

sum over all decay widths

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

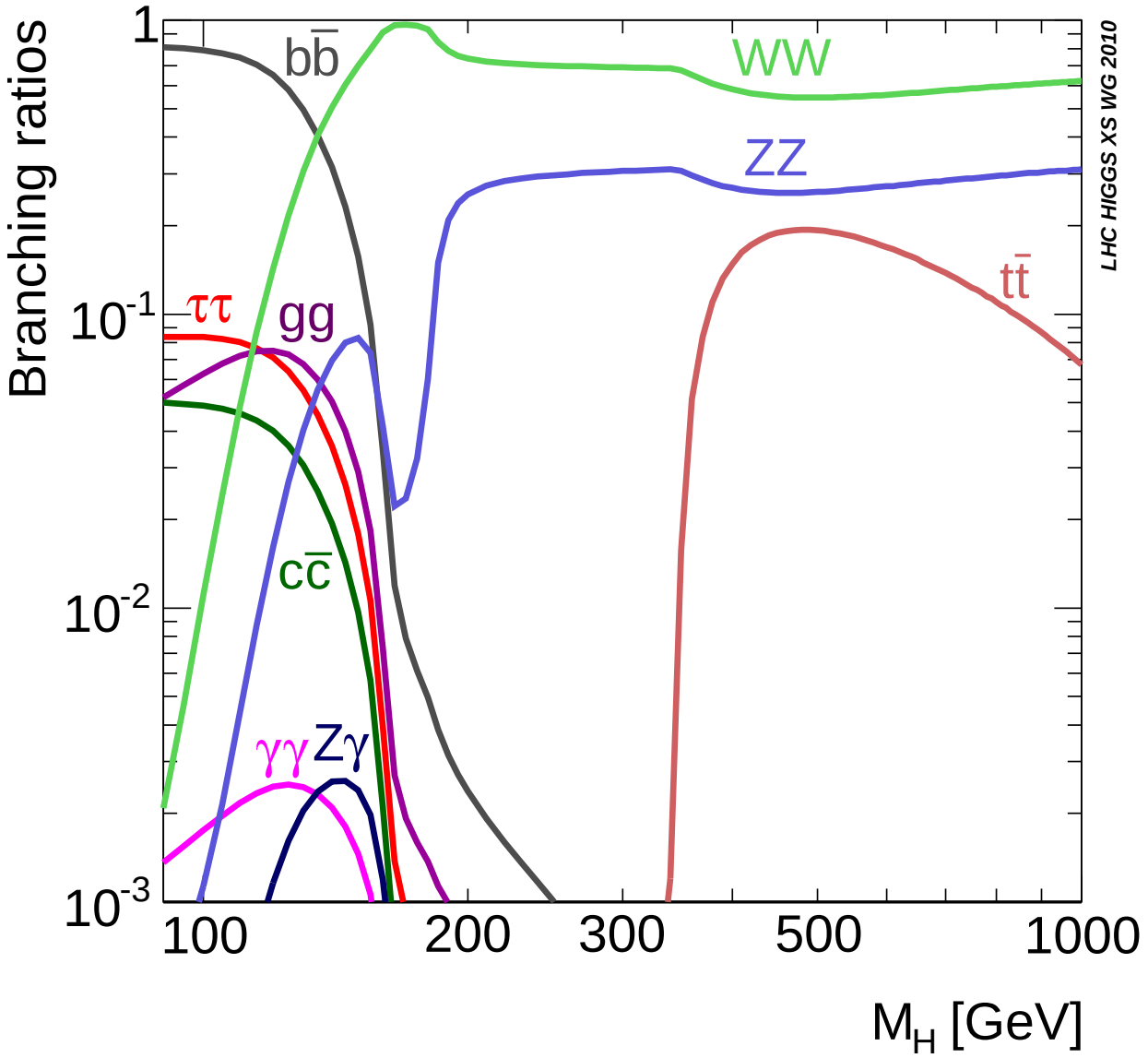
Branching ratio:

probability that a particle decays to a certain final state

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

"First" theory predictions for the SM Higgs: branching ratios

[*LHC Higgs XS WG '10*]



"First" theory predictions for the SM Higgs: total width

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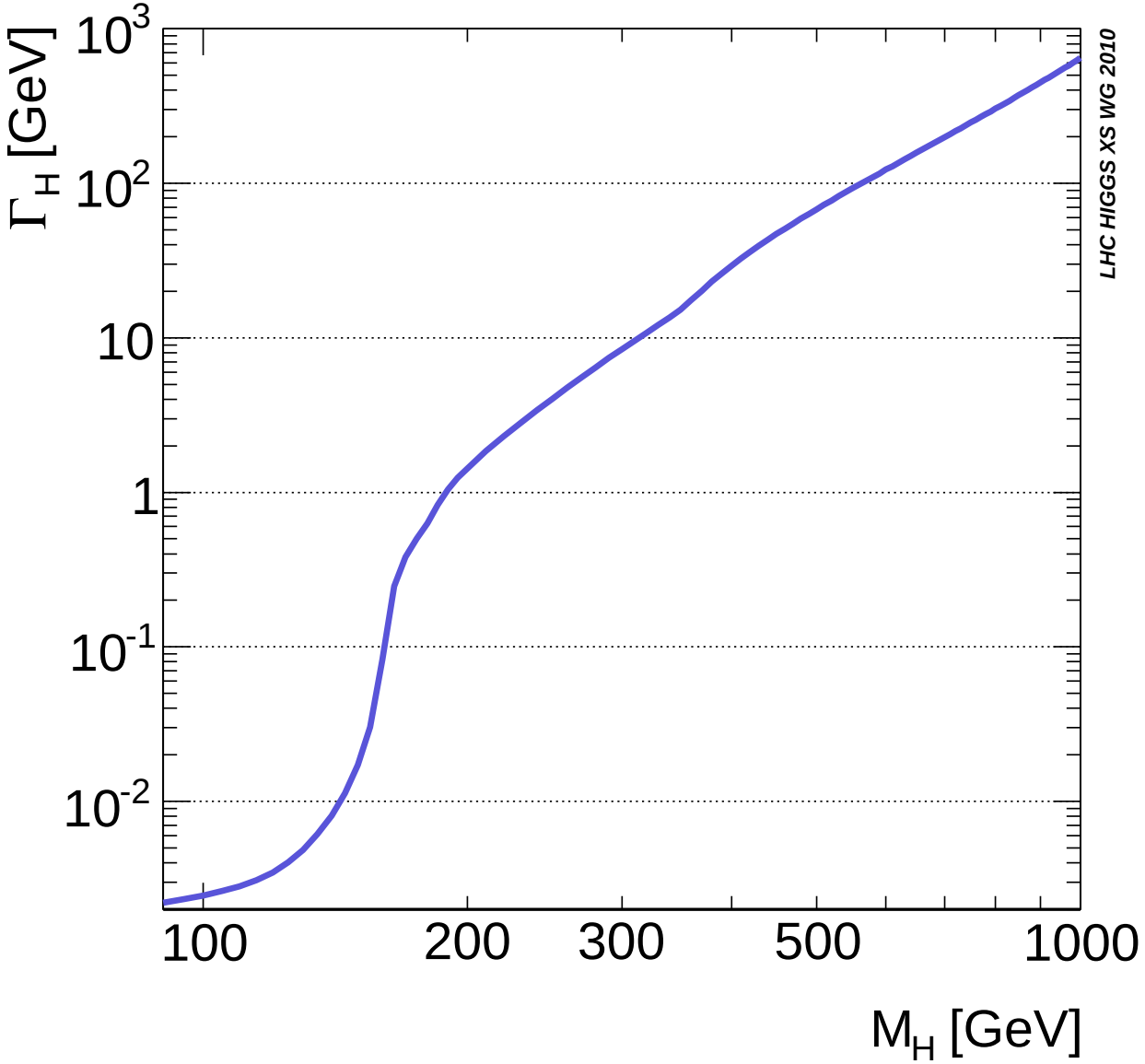
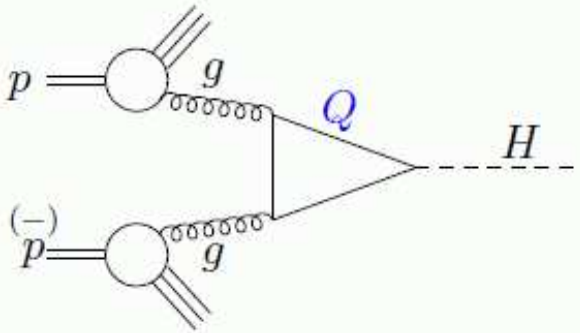


2. Higgs production modes at the LHC:

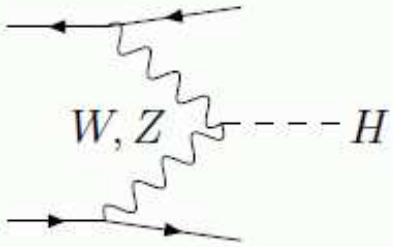
- **Gluon Gluon Fusion**

$pp \to gg \to H$



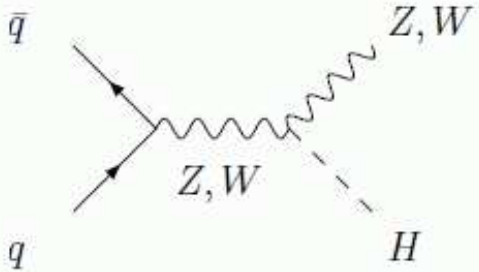
- **W/Z Fusion**

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



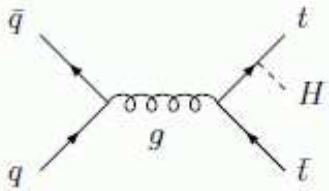
- **Higgs-strahlung**

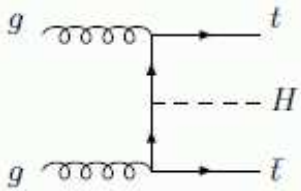
$pp \to W^*/Z^* \to W/Z + H$



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

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



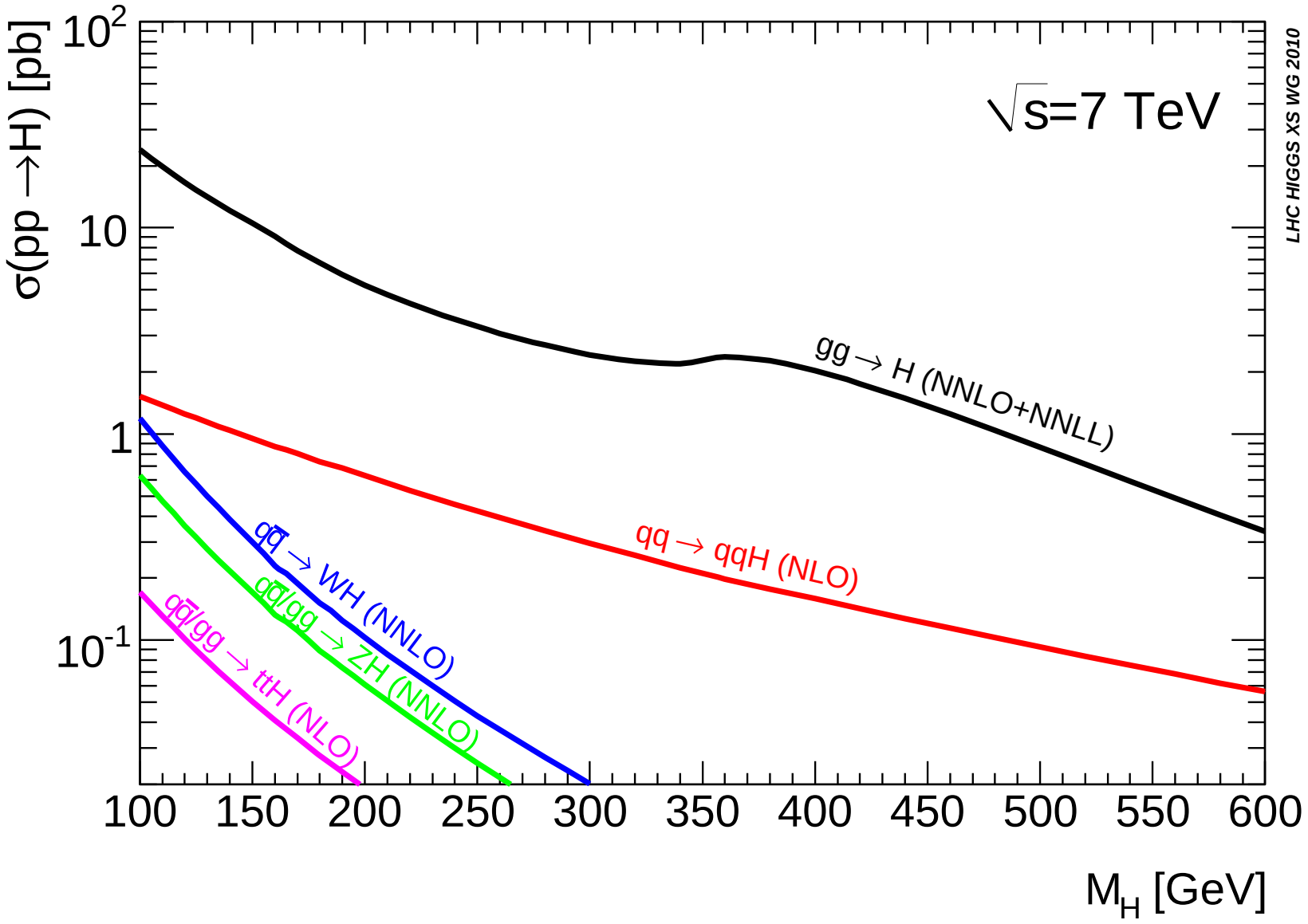


dominant

[taken from M. Mühlleitner]

Latest theory predictions for the SM Higgs: LHC production XS

[*LHC Higgs XS WG '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:

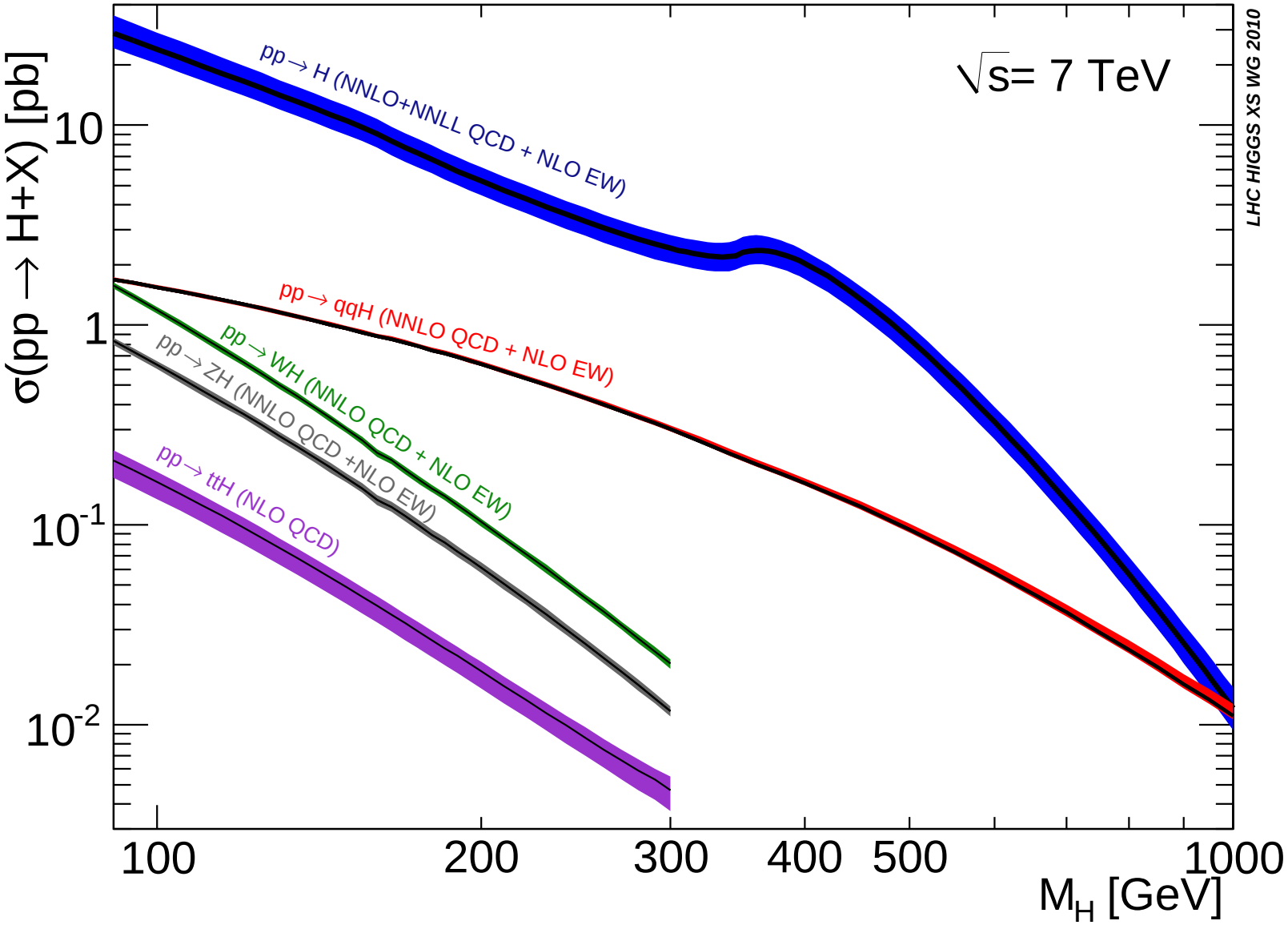
uncertainty in the prediction due to error in the input parameters

– m_t, α_s, PDFs, ...

– future expectations?

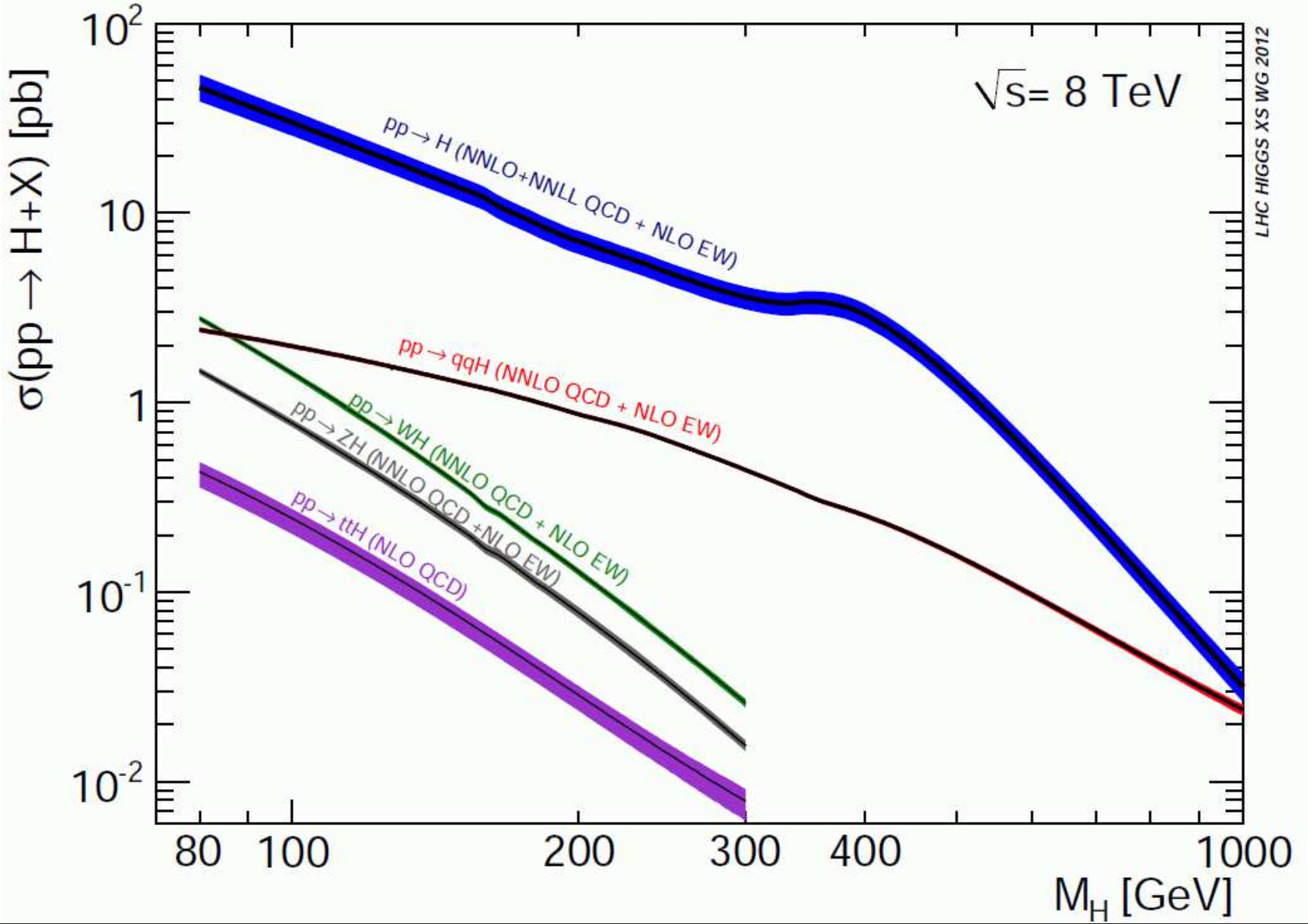
Latest theory predictions for the SM Higgs: LHC production XS

[*LHC Higgs XS WG '10*]



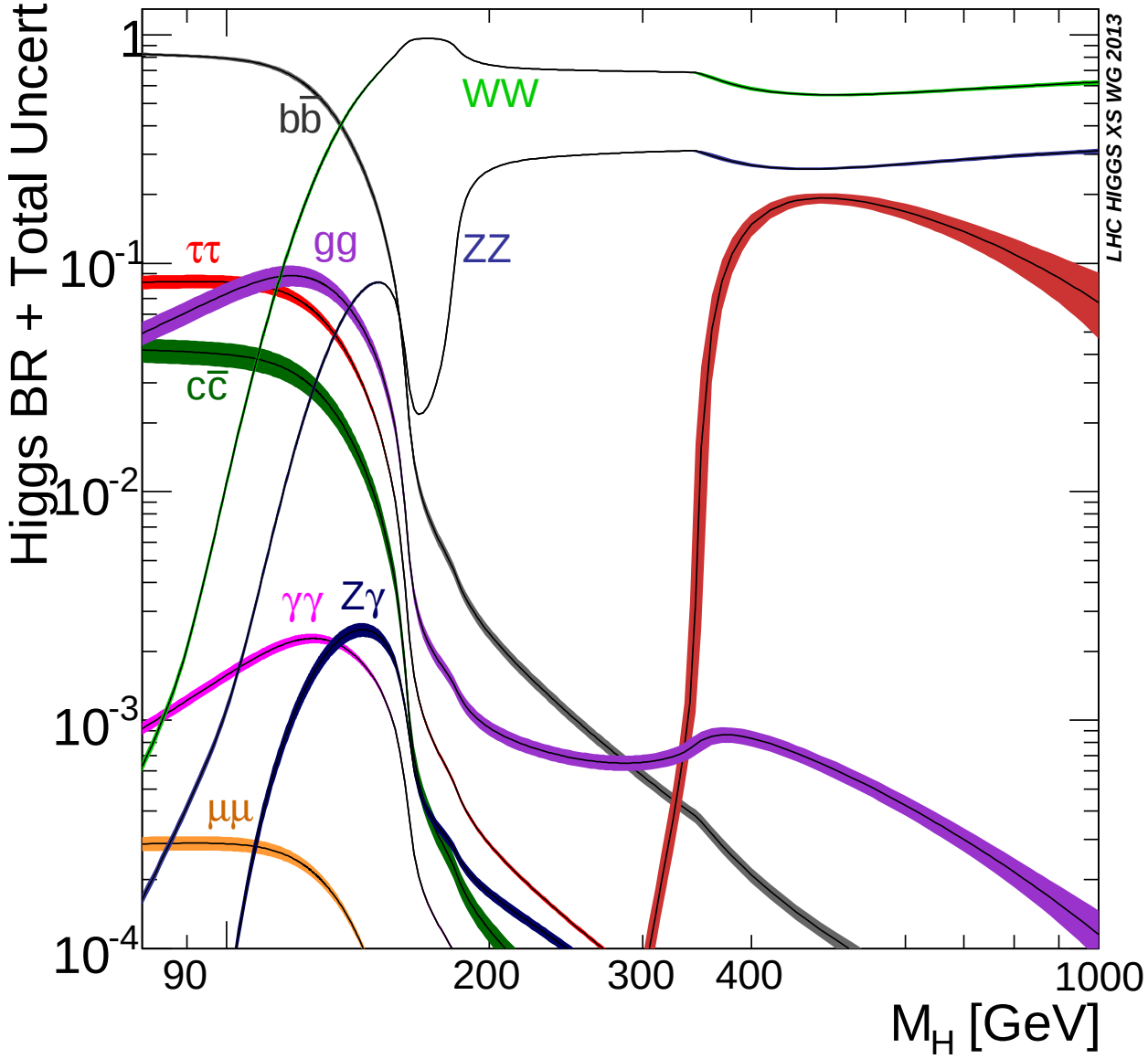
Latest theory predictions for the SM Higgs: LHC production XS

[*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

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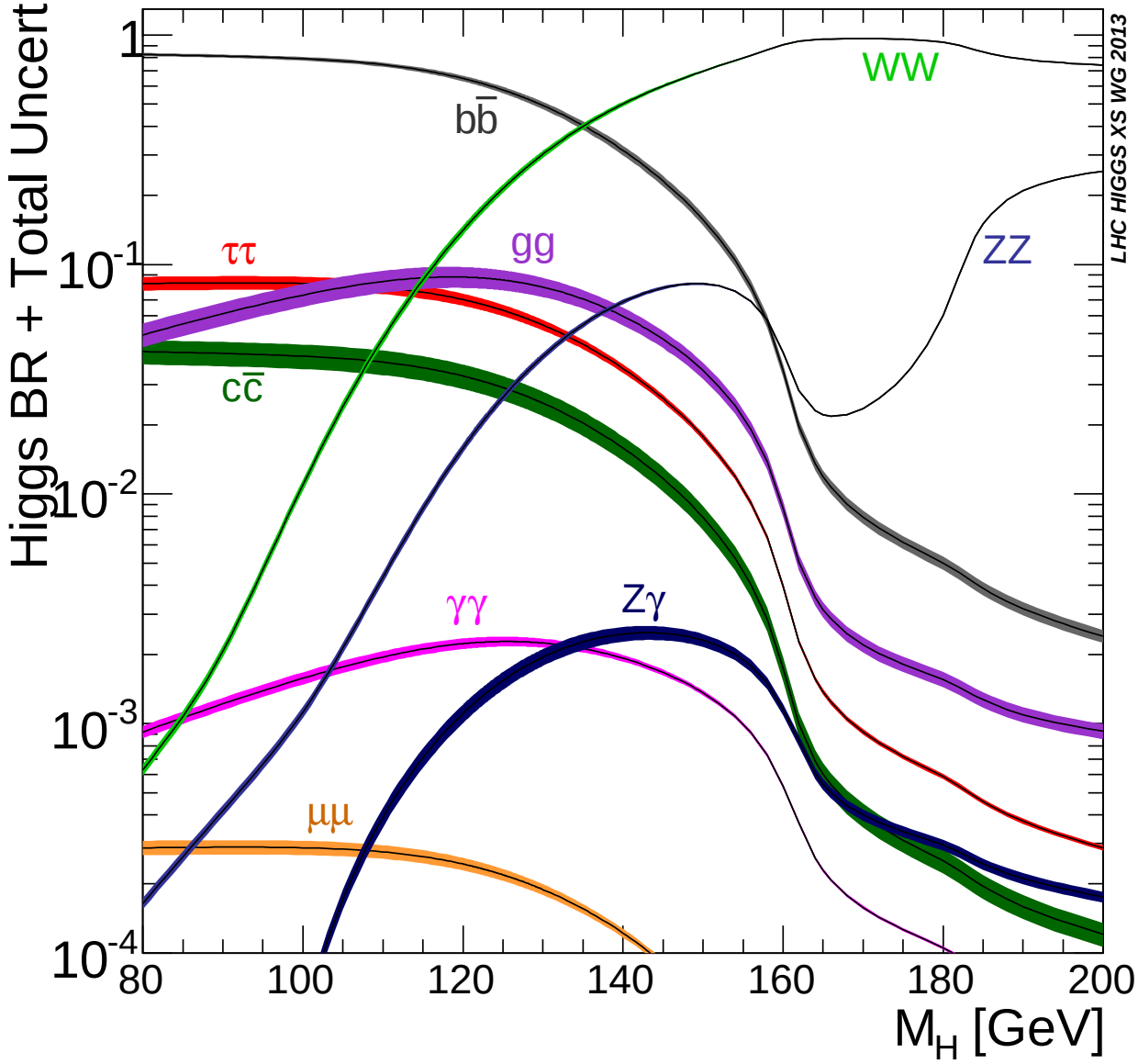


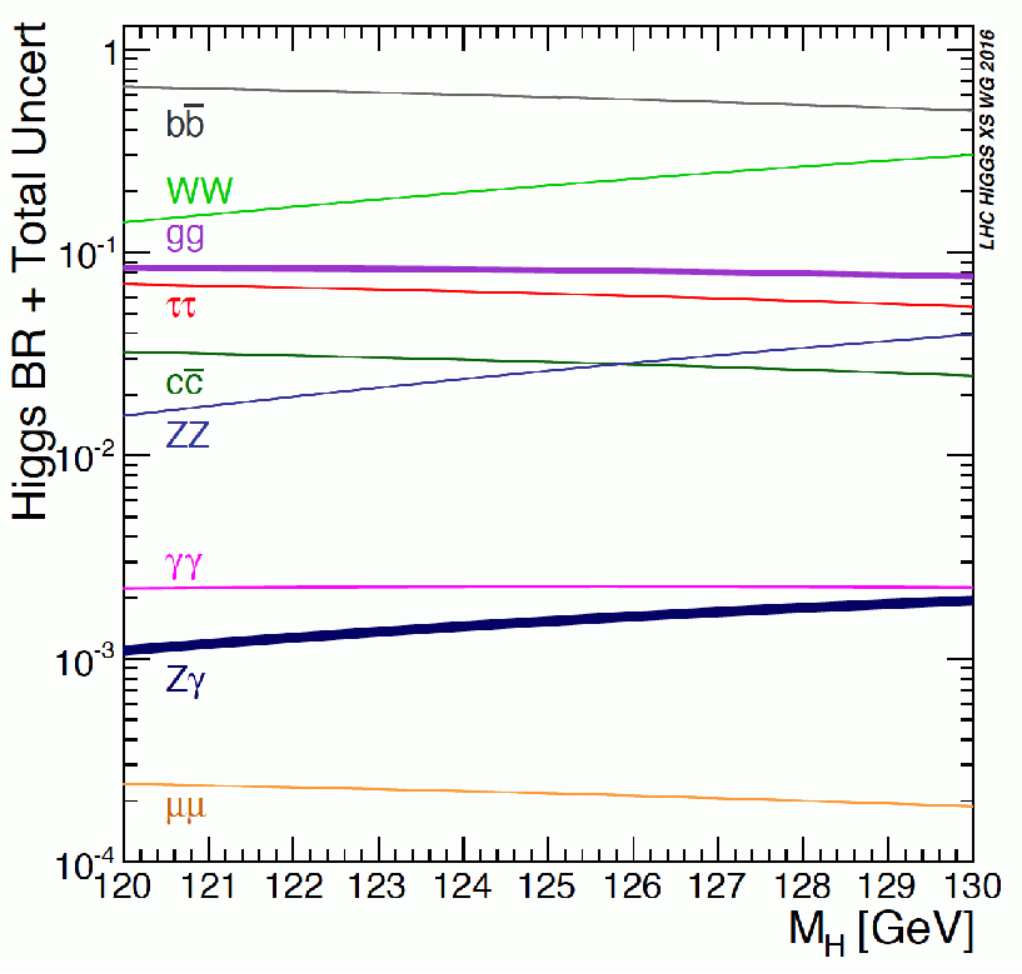
LHC Higgs Cross Section Working Group

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!

3. Higgs BRs with uncertainties

[*LHCHXSWG '16*]



Based on HDECAY and Prophecy4f:

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

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

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

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 $\delta m_b \Rightarrow$ 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! :-)