Higgs precision calculations for the LHC

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TTP KIT

Higgs boson discovery completes the Standard Model

Discovery of the Higgs boson completed the construction of the Standard Model. For the first time in the history of physics, we have a theory that allows us to describe many (if not all) phenomena at particle colliders and elsewhere.

For the Higgs boson, this implies that Higgs properties are completely predicted in the Standard Model once its mass is measured.

The Higgs boson in the Standard Model

It follows from the Standard Model that

1) the Higgs boson is a spin-zero, neutral particle ;

2) its couplings to fermions are proportional to their masses ;

3) its couplings to massive gauge bosons are proportional to their masses squared ;

4) the Higgs boson self-coupling is proportional to the Higgs mass squared;

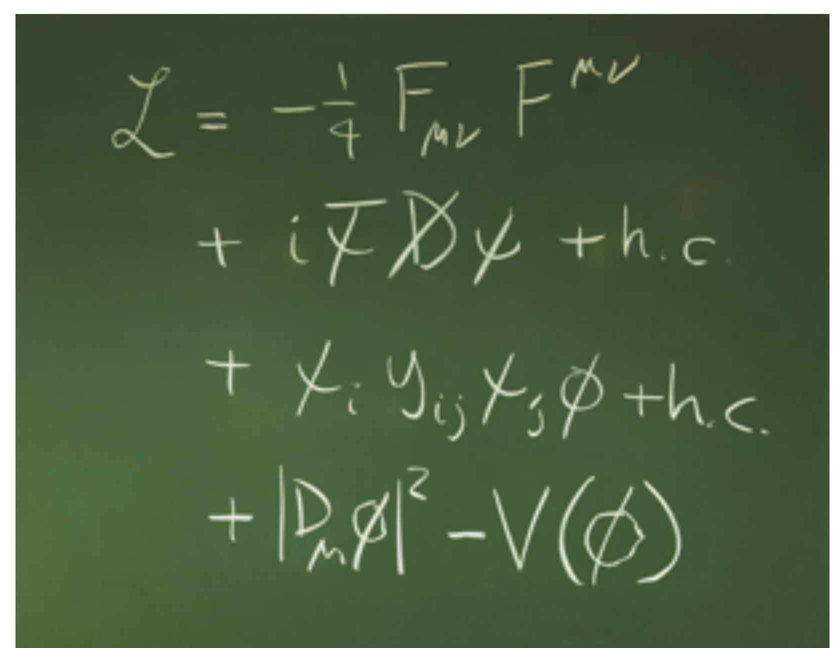
5) Higgs couplings to massless gauge bosons appear only at one-loop.

H^0 $J = 0$

Mass $m = 125.7 \pm 0.4$ GeV

H^0 Signal Strengths in Different Channels

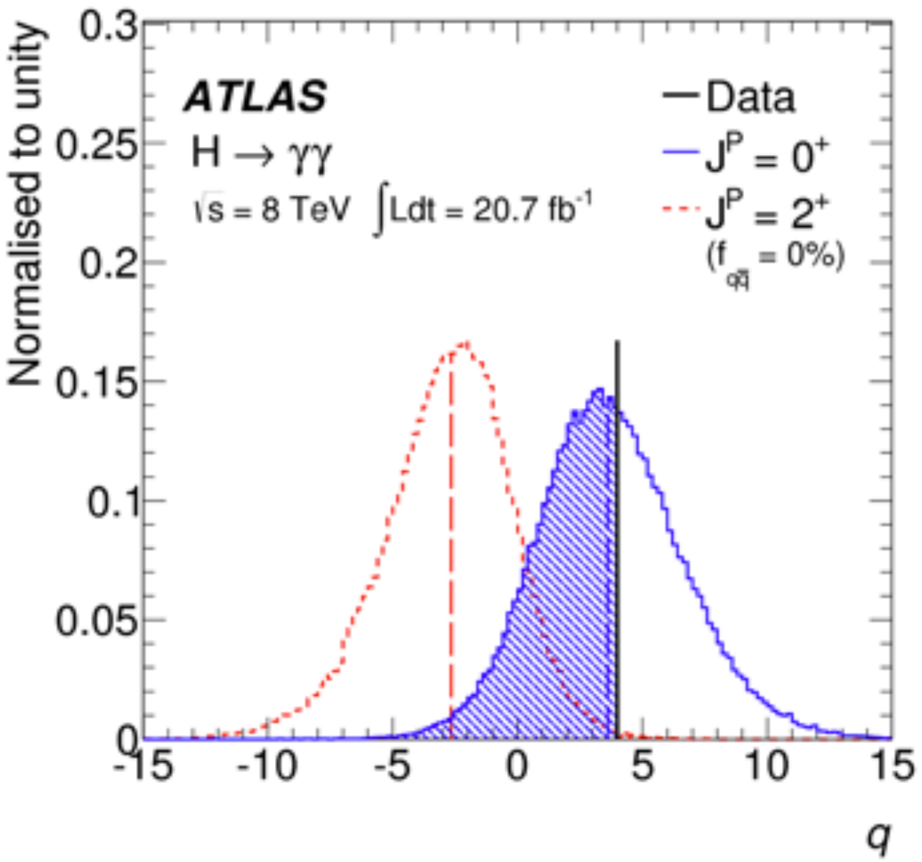
Combined Final States $= 1.17 \pm 0.17$ (S = 1.2)
$W W^* = 0.87^{+0.24}_{-0.22}$
$Z Z^* = 1.11^{+0.34}_{-0.28}$ (S = 1.3)
$\gamma\gamma = 1.58^{+0.27}_{-0.23}$
$b\bar{b} = 1.1 \pm 0.5$
$\tau^+\tau^- = 0.4 \pm 0.6$
$Z\gamma <$ 9.5, CL = 95%

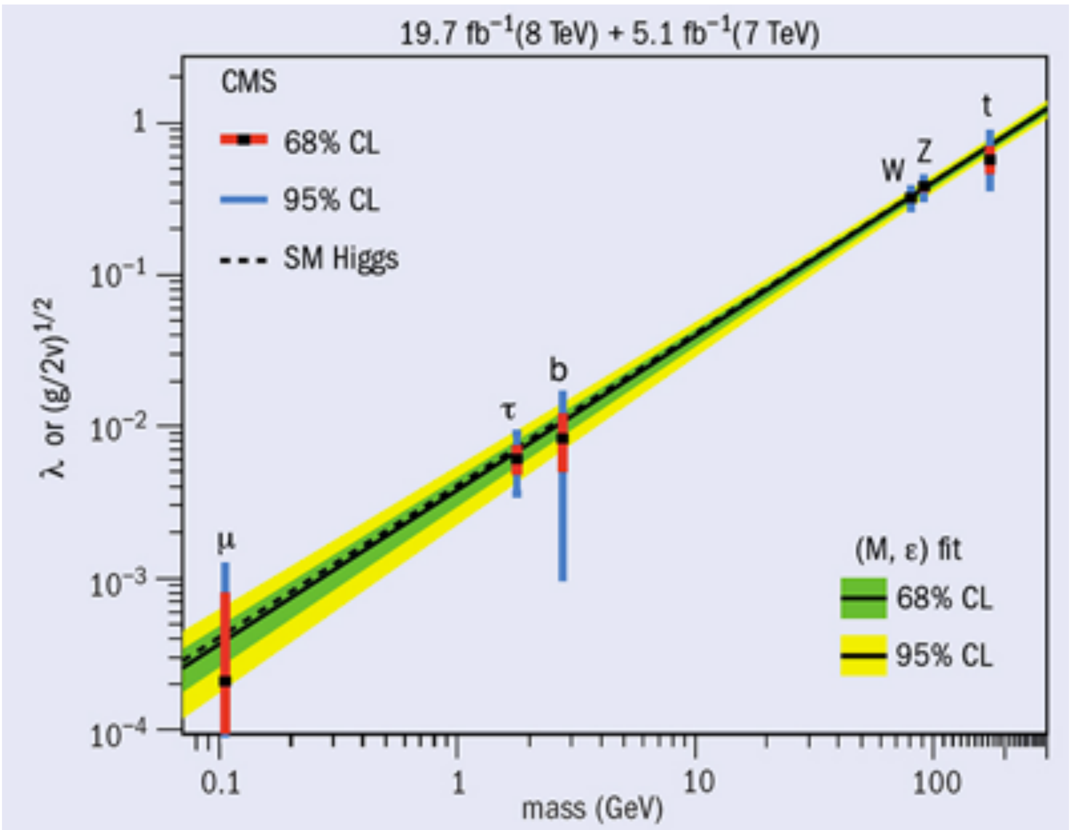


Is this a true picture ?

It is important to verify this picture. There are many reasons not to believe in it, including the fact that the Higgs sector in the Standard Model is very ad hoc. It does what it is supposed to do, but it is hard to see a reason as to why the Higgs sector should be so simplistic.

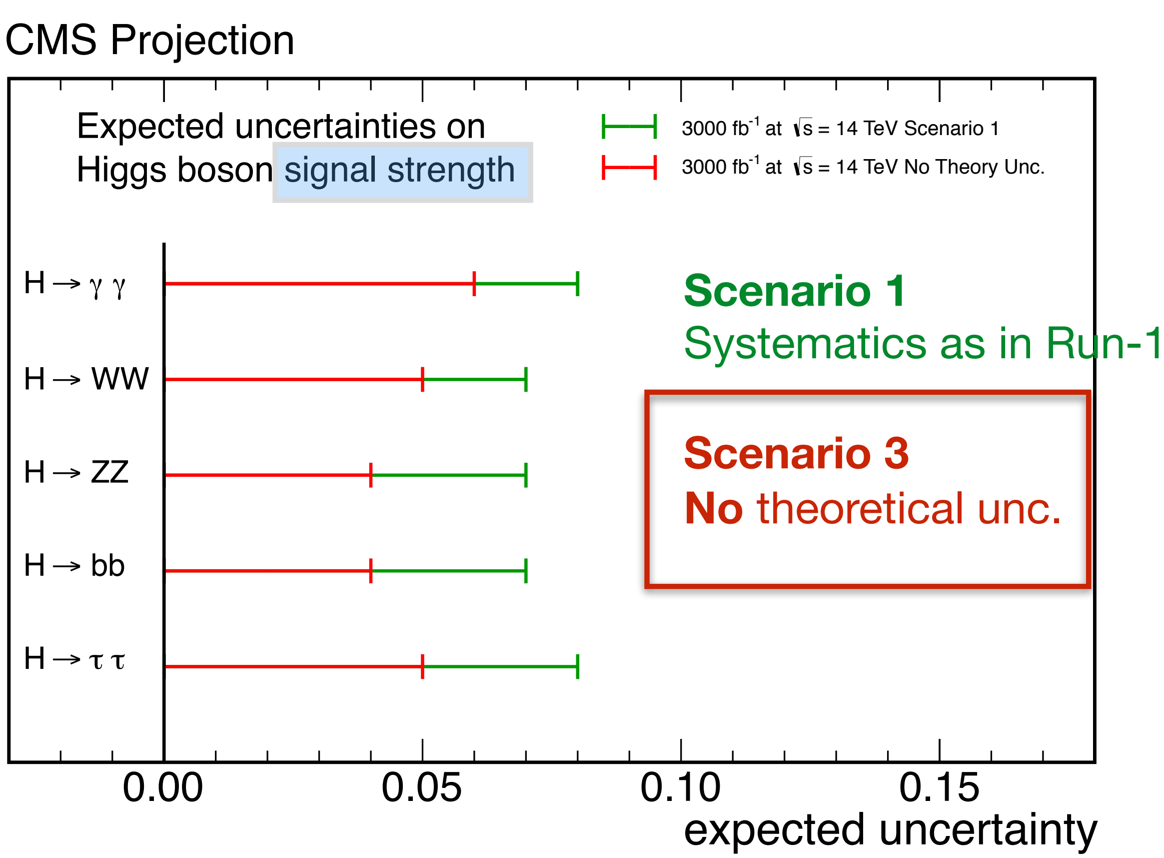
To study the Higgs sector, we explore the Higgs production and decays experimentally and theoretically, with the hope to find a feature that does not fit into the Standard Model picture. Existing experimental data constrain possible deviations in many Higgs couplings to about O(10-15) percent while others (Yukawa, 1st and 2nd generations) remain largely unconstrained.

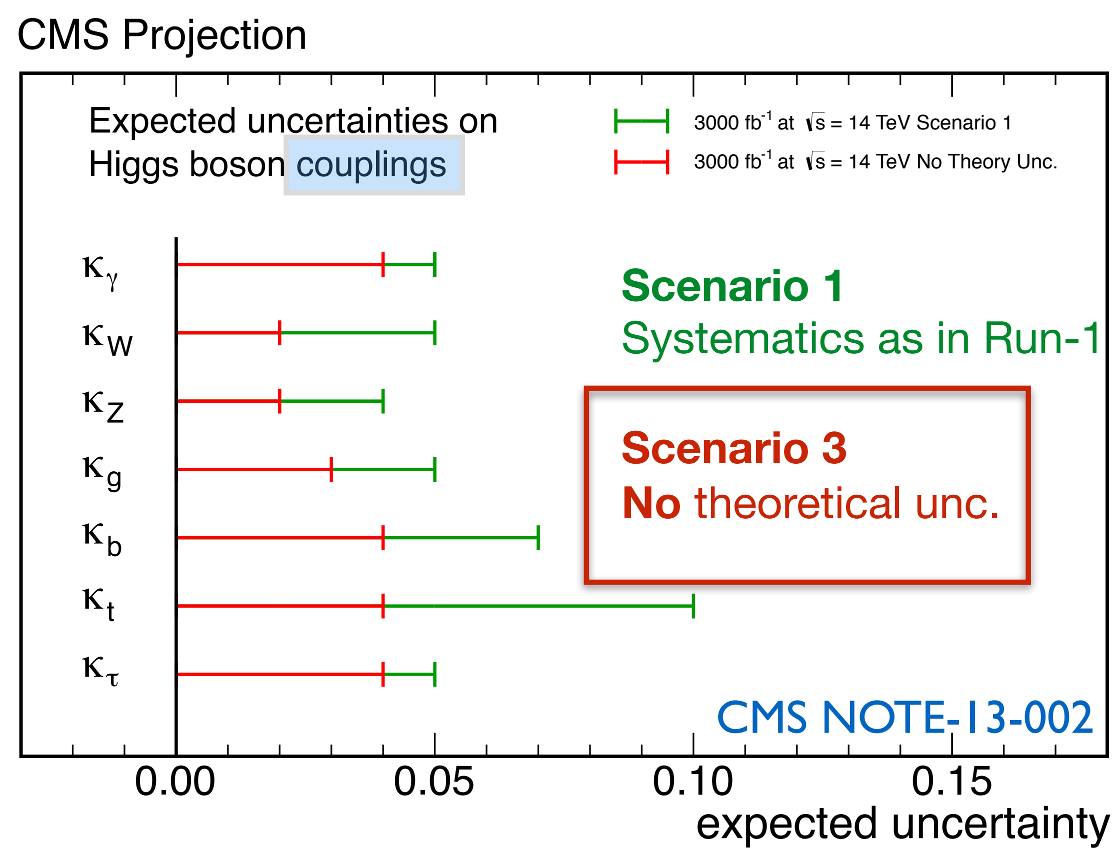




Where do we expect to get ?

Current projections (CMS/ATLAS) indicate that reaching a few percent precision for Higgs-gauge couplings and the 3rd generation Yukawa couplings is realistic with 3000 fb^{-1}. "A few percent" is an important goal to reach; it is a generic size of a deviations in Higgs couplings due to New Physics at O(1) TeV.





The Higgs boson decays

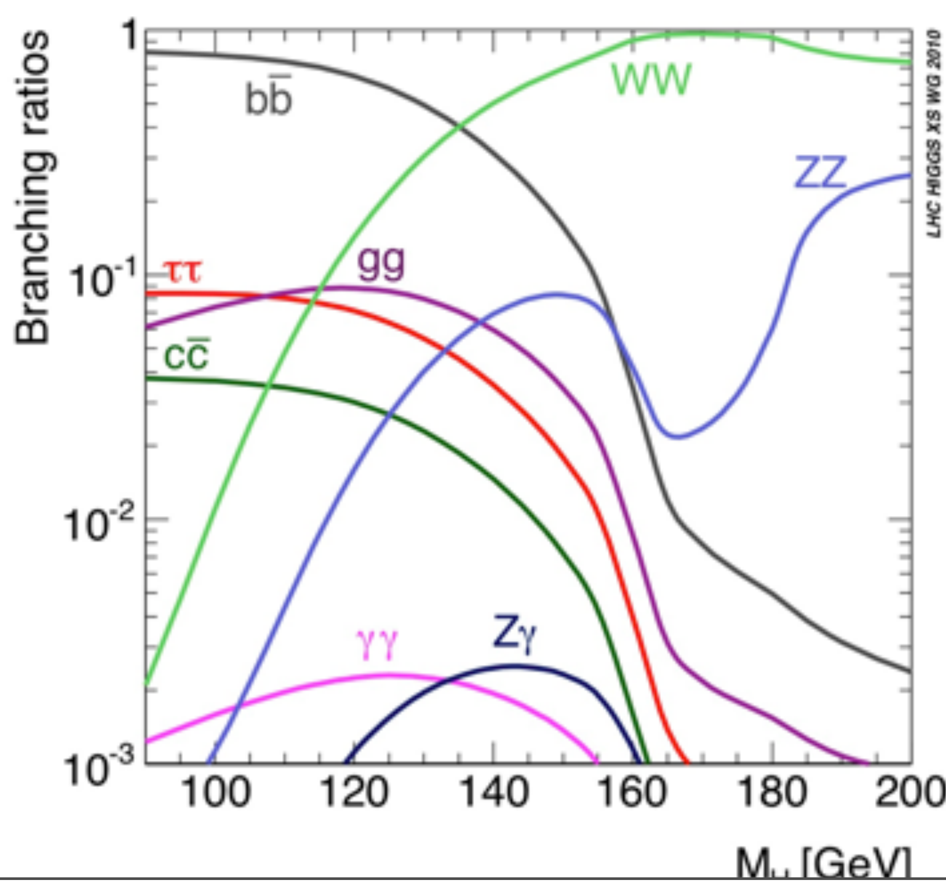
We observe the Higgs boson through its decay products. In this sense, the number of ``observed Higgses" is determined by the products of the Higgs boson production cross sections and the Higgs boson decay branching fractions.

Higgs partial decay widths and branching ratios are known with a high precision -- a few percent. Further improvements may still be needed for the linear collider, but not for the LHC.

$$\sigma_X = \sigma_H \times \mathrm{Br}(H \to X)$$

$H \to b\bar{b}$	0.5%
$H \to gg$	3%
$H \to \gamma\gamma$	1%
$H \to VV$	0.5%

Uncertainties in partial widths due to uncalculated higher orders.



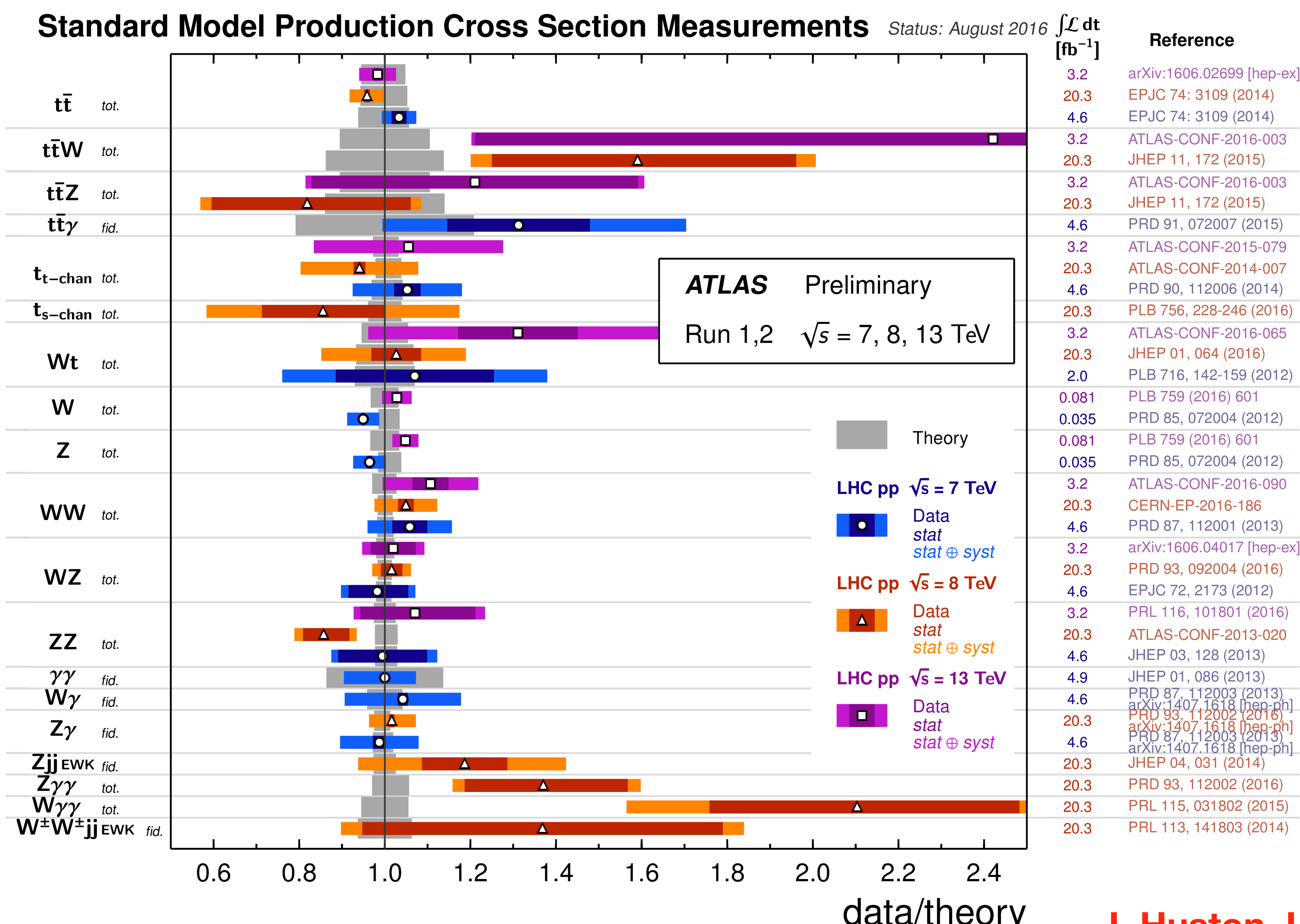
$$\alpha_s = 0.118(1.5)$$
$$\Delta m_b = \pm 0.3 \text{ GeV}$$
$$\Delta m_t = \pm 1 \text{ GeV}$$

Parametric uncertainties in branching ratios are caused by an imprecise knowledge of inputs; in many cases they are currently the largest source of uncertainties.

The pQCD framework

To obtain high-precision description of Higgs boson production at colliders, we use the QCD factorization framework, studied and verified at the Tevatron and the LHC.

$$d\sigma = \int dx_1 dx_2 f_i(x_1) f_j(x_2) d\sigma_{ij}(x_1, x_2) F_J \left(1 + \mathcal{O}(\Lambda_{QCD}/Q)\right)$$



J. Huston, Loopfest 2016

Advances in understanding the Higgs boson production

Currently, major focus in precision Higgs physics is on improving perturbative predictions for partonic cross sections and on having trustworthy parton distribution functions.

Occasionally, ideas about new ways to study Higgs properties appear; in some cases these ideas force us to focus on unconventional observables that are useful for learning about Higgs physics.

Perturbative description of partonic cross sections is an important and (very) active field of research. The level of sophistication that has been reached in connection with description of Higgs-related processes at the LHC is without a precedent. Indeed,

1) all but one major Higgs production channels are currently known through NNLO QCD (gluon fusion is known through N^3LO) and through NLO electroweak.

2) Many associated Higgs production processes with high jet multiplicity are also known at least through NLO QCD.

3) Matching and merging of NLO QCD results with parton showers is available thanks to major automated programs (MC@NLO, Powheg, Sherpa etc.)

Advances in understanding the Higgs boson properties

Although NLO QCD computations for high-multiplicity processes, as well as matching and merging are very important topics, they are also relatively well-established by now. I'll not talk about them here.

Instead, I want to spend most of my time talking about recent results that either push the precision frontier or illustrate what kind of physics needs to be understood if we try to get access to Higgs boson properties in less conventional ways.

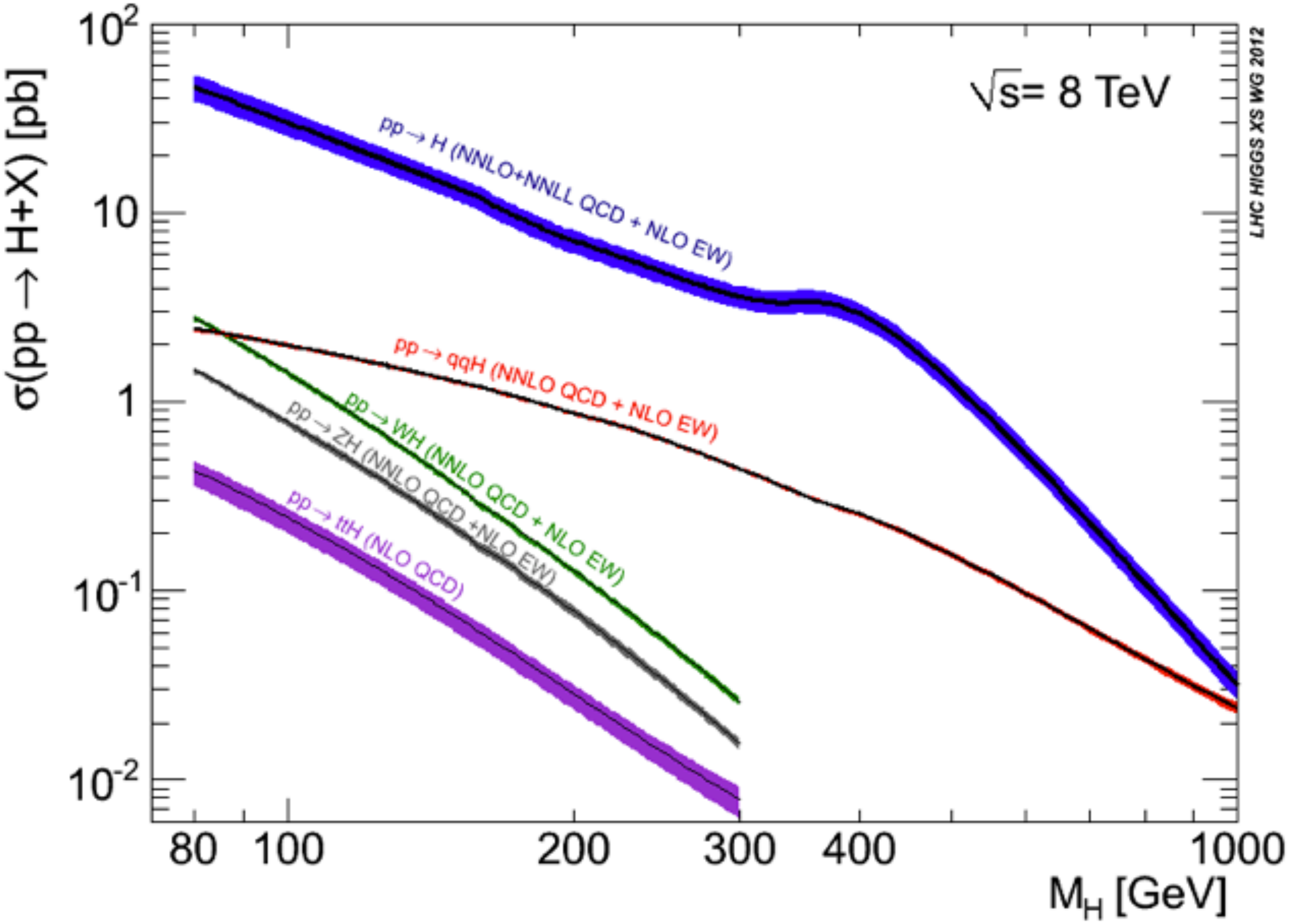
1) Higgs production in gluon fusion, including Higgs transverse momentum distribution and the double Higgs production.

2) Higgs in WBF;

3) Off-shell measurements.

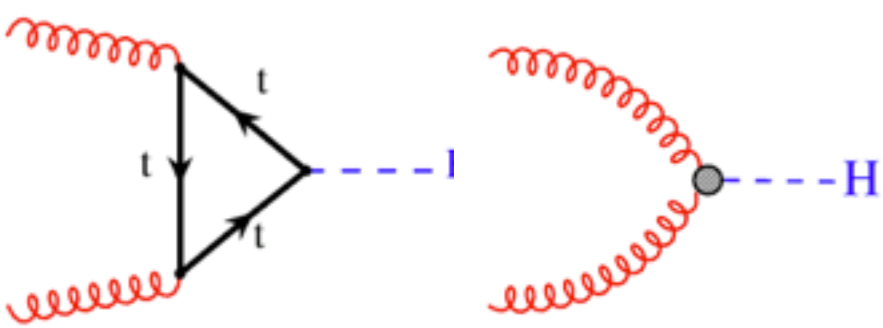
These results are important since they give us a new perspective on how well properties of the Higgs boson can be understood from the LHC data.

The largest cross section and its derivatives

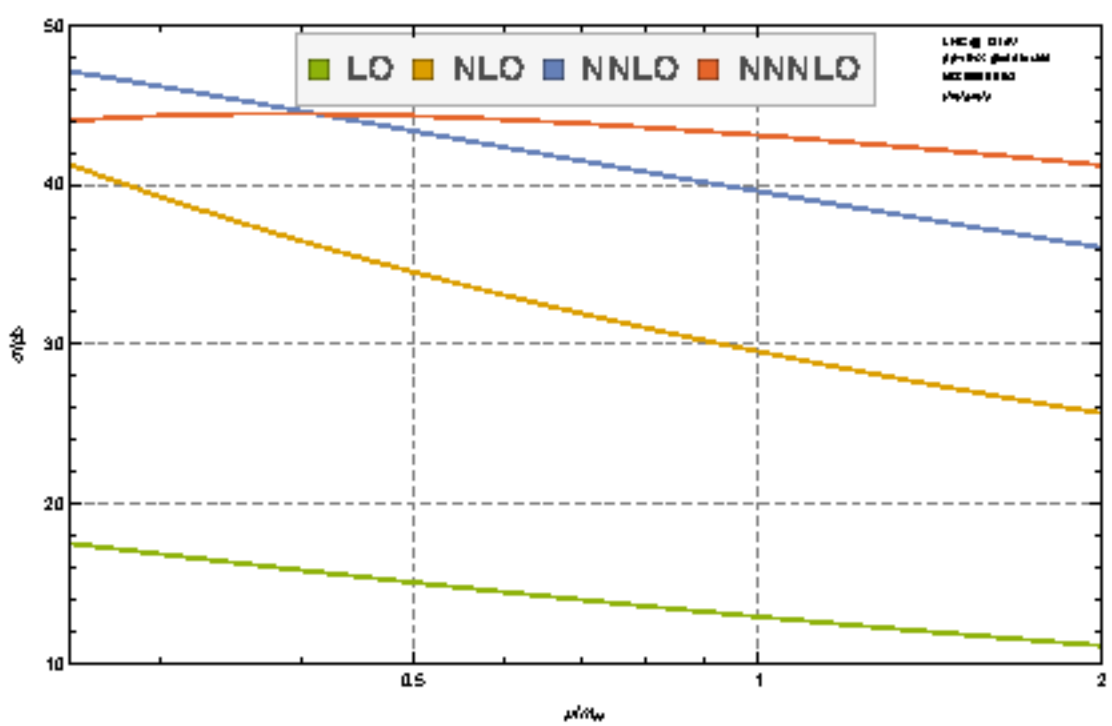


Higgs boson production in gluon fusion

Gluon fusion is the dominant production mechanism at the LHC. The production rate is known to be affected by large O(100%) QCD radiative corrections. Those corrections are currently known to three loop order (N^{3}LO) in the infinite top mass limit. This is extremely non-trivial computation whose success is the consequence of the ingenuity of its authors, powerful computational technologies developed recently and tremendous capability of modern computing facilities.



σ/pb	2 TeV	7 TeV	8 TeV	13 TeV	14 TeV
$\mu = \frac{m_H}{2}$	$0.99^{+0.43\%}_{-4.65\%}$	$15.31^{+0.31\%}_{-3.08\%}$	$19.47^{+0.32\%}_{-2.99\%}$	$44.31^{+0.31\%}_{-2.64\%}$	$49.87^{+0.32\%}_{-2.61\%}$
$\mu = m_H$	$0.94^{+4.87\%}_{-7.35\%}$	$14.84^{+3.18\%}_{-5.27\%}$	$18.90^{+3.08\%}_{-5.02\%}$	$43.14^{+2.71\%}_{-4.45\%}$	$48.57^{+2.68\%}_{-4.24\%}$



Scale uncertainty of the gluon fusion cross section

The perturbative series for gg -> H cross section appear to converge. This is no small feat as the corrections start at O(100%) at NLO, are still O(20%) at NNLO, but decrease to just O(4%) at N^{3}LO. The residual scale dependence uncertainty is just about 3%.

Anastasiou, Duhr, Dulat, Furlan, Herzog, Gehrmann, Mitzlberger etc.

Large QCD effects and many small corrections

Current ``best” estimate of the gluon fusion cross section includes large number of subtle effects and requires careful evaluation of the residual uncertainty.

$$\sigma = 48.58\ \mathrm{pb}^{+2.22\ \mathrm{pb}(+4.56\%)}_{-3.27\ \mathrm{pb}(-6.72\%)}(\mathrm{theory}) \pm 1.56\ \mathrm{pb}\ (3.20\%)(\mathrm{PDF}+\alpha_s)$$

$$\begin{aligned}
48.58\,\mathrm{pb} = \quad & 16.00\,\mathrm{pb} && (+32.9\%) && (\mathrm{LO,\ rEFT}) \\
& +20.84\,\mathrm{pb} && (+42.9\%) && (\mathrm{NLO,\ rEFT}) \\
& -\ \ 2.05\,\mathrm{pb} && (-4.2\%) && ((t,b,c),\ \mathrm{exact\ NLO}) \\
& +\ \ 9.56\,\mathrm{pb} && (+19.7\%) && (\mathrm{NNLO,\ rEFT}) \\
& +\ \ 0.34\,\mathrm{pb} && (+0.7\%) && (\mathrm{NNLO},\ 1/m_t) \\
& +\ \ 2.40\,\mathrm{pb} && (+4.9\%) && (\mathrm{EW,\ QCD\text{-}EW}) \\
& +\ \ 1.49\,\mathrm{pb} && (+3.1\%) && (\mathrm{N^3LO,\ rEFT})
\end{aligned}$$

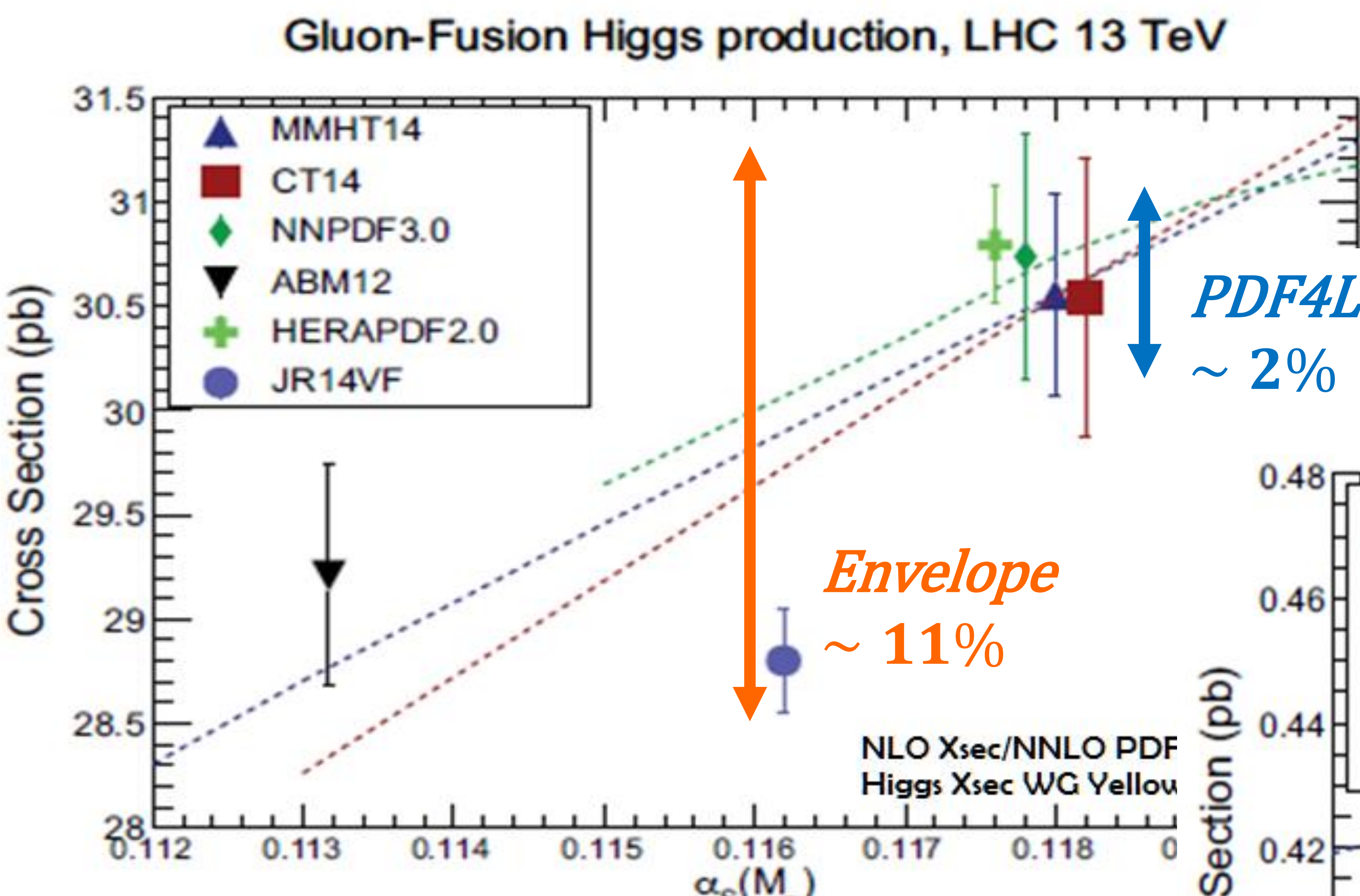
....

δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
$^{+0.10\ \mathrm{pb}}_{-1.15\ \mathrm{pb}}$	± 0.18 pb	± 0.56 pb	± 0.49 pb	± 0.40 pb	± 0.49 pb
$^{+0.21\%}_{-2.37\%}$	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger

Inputs for the Higgs production

Parton distribution functions, obtained by different fitting groups, give very different results for the gluon fusion Higgs production cross sections! The differences between predictions obtained with different PDF sets may disagree by as much as O(10%).



Recall that the uncertainty of the theory prediction on ggH without PDFs is O(5%); uncertainty on ttH is similar.

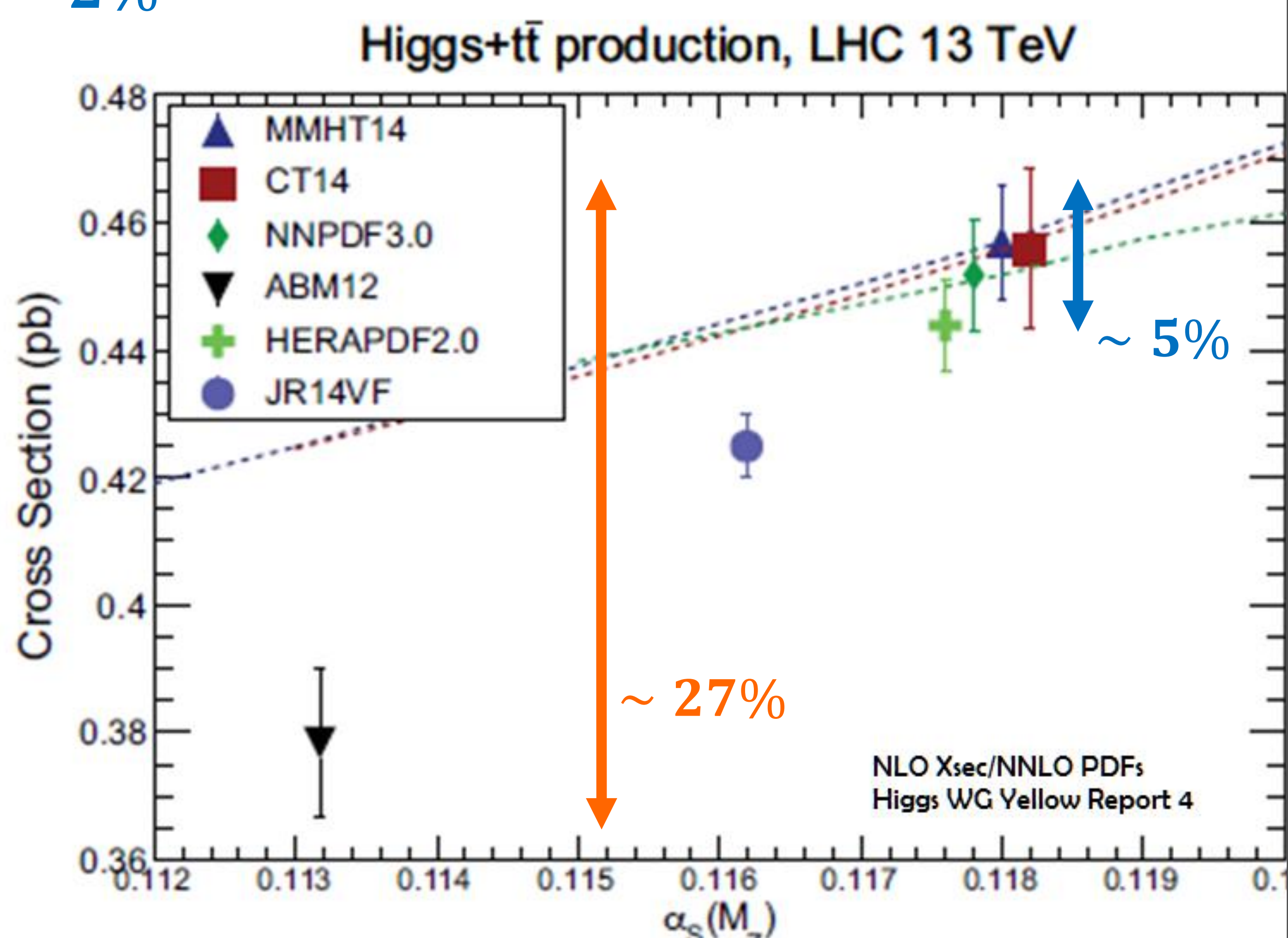


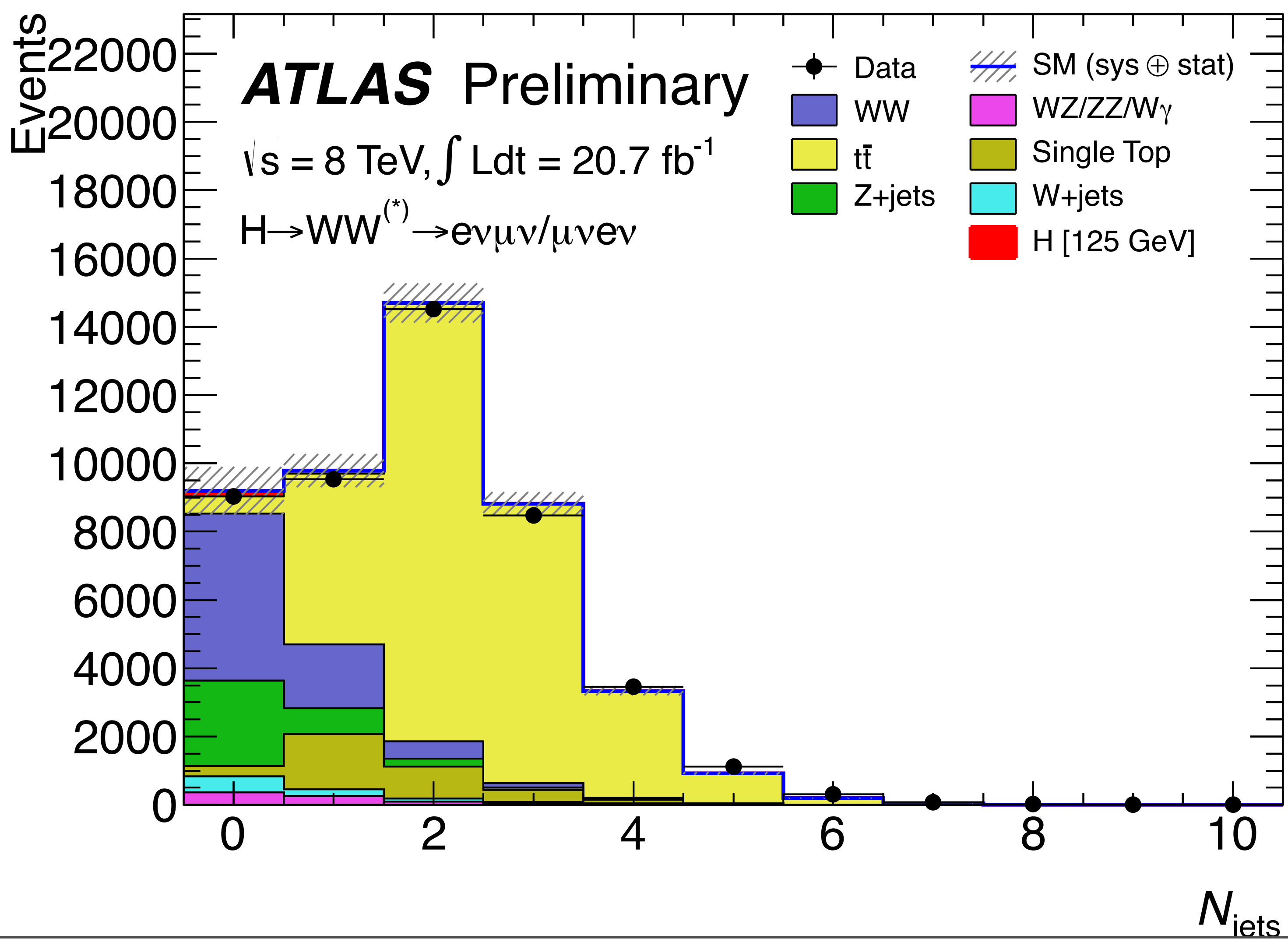
Figure by J. Rojo

Differences in predictions are real; they are related to the use of different flavor schemes that are used by ABM and the rest; a combination of different values of the strong coupling constants and PDFs leads to rather different predictions for the Higgs cross sections.

Realistic cross sections

The Higgs boson couplings are extracted from cross sections that are subject to kinematic constraints on the final states. This happens because detectors have restricted angular coverage and because by selecting final states with particular kinematic properties, certain backgrounds can be significantly reduced.

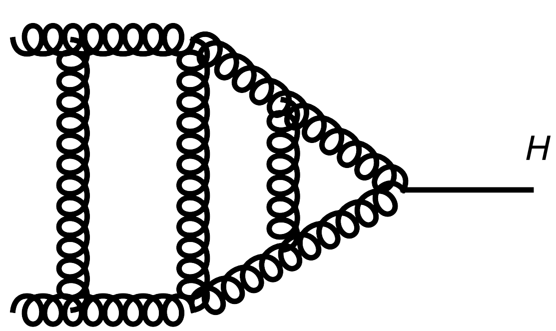
This requires precision predictions for exclusive/fiducial cross sections, including jet-binning, Higgs boson decays etc, making them highly non-trivial. However, without such predictions, the Higgs couplings can not be extracted from the LHC data with the ultimate precision.

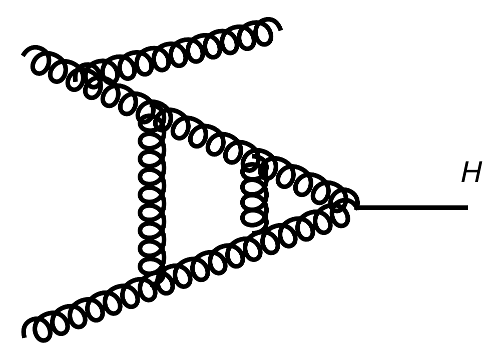


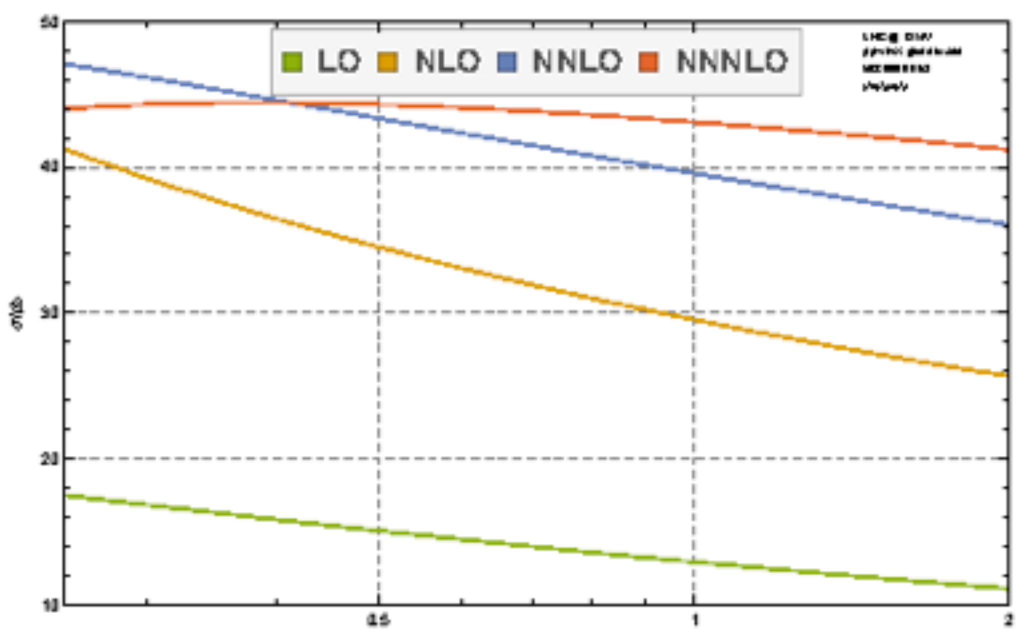
Jet-binned cross sections

Suppose that we are interested to know the cross section for Higgs production without detectable QCD radiation. To obtain this (zero-jet bin) cross section, we subtract the one-jet inclusive cross section from the total inclusive cross section, at matching orders in pQCD.

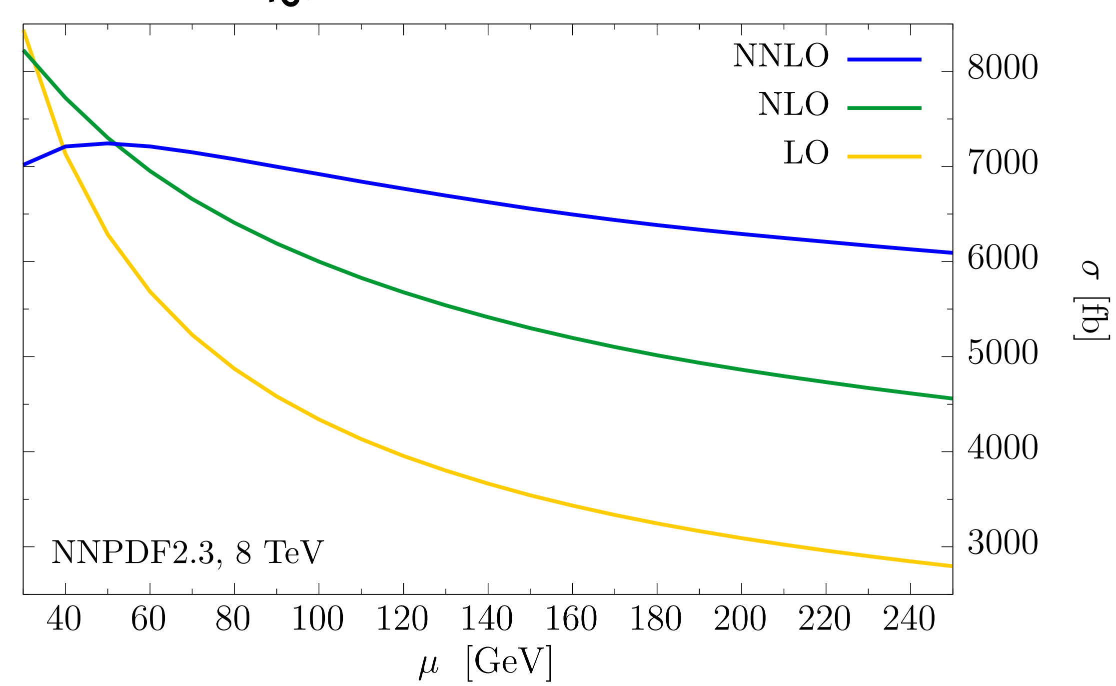
The inclusive Higgs production is available through N^3LO and the H+jet production is computed through NNLO QCD; these are matching orders in perturbation theory.   Using these results, one can improve on predictions for jet-binned cross sections.







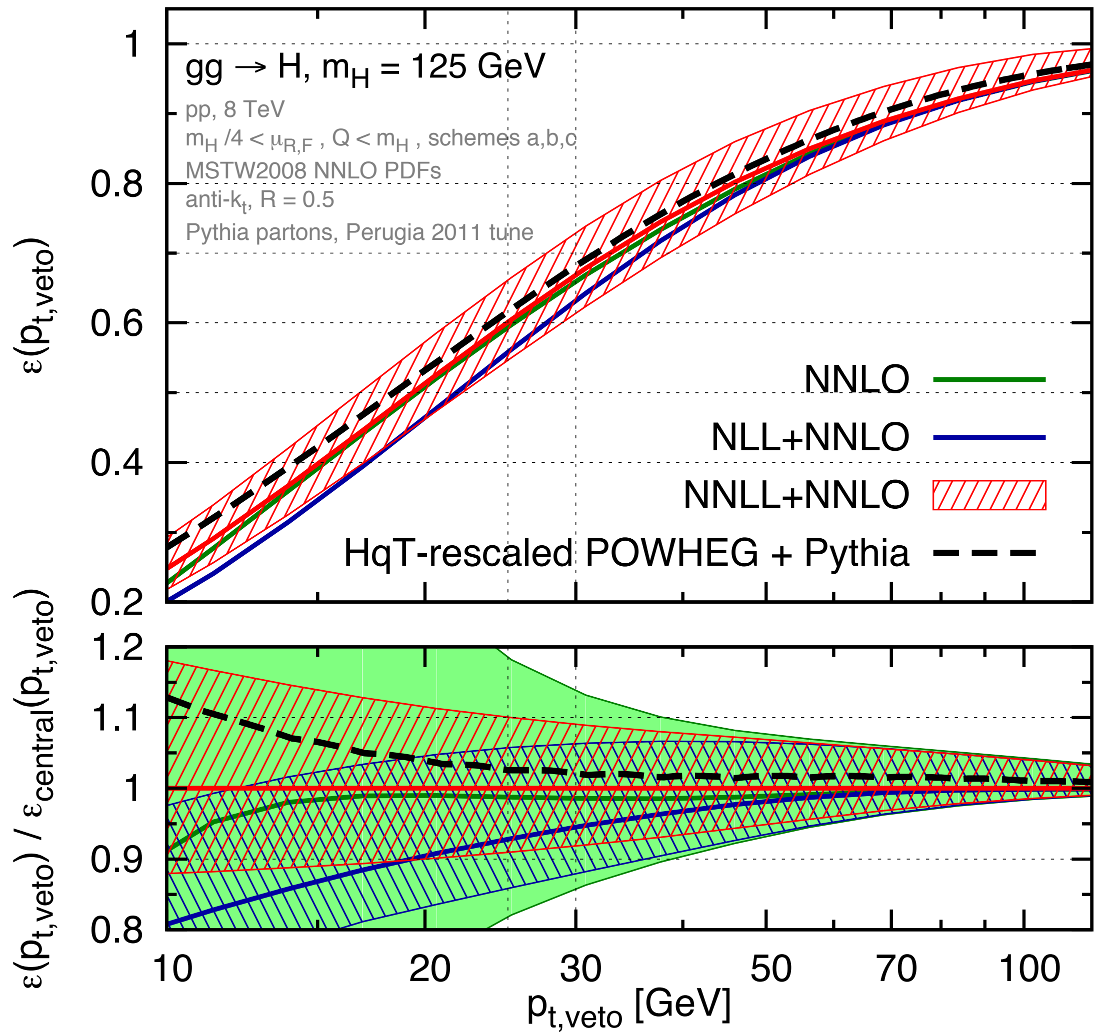
Anastasiou, Duhr, Dulat, Furlan, Herzog, Gehrmann, Mistlberger etc.

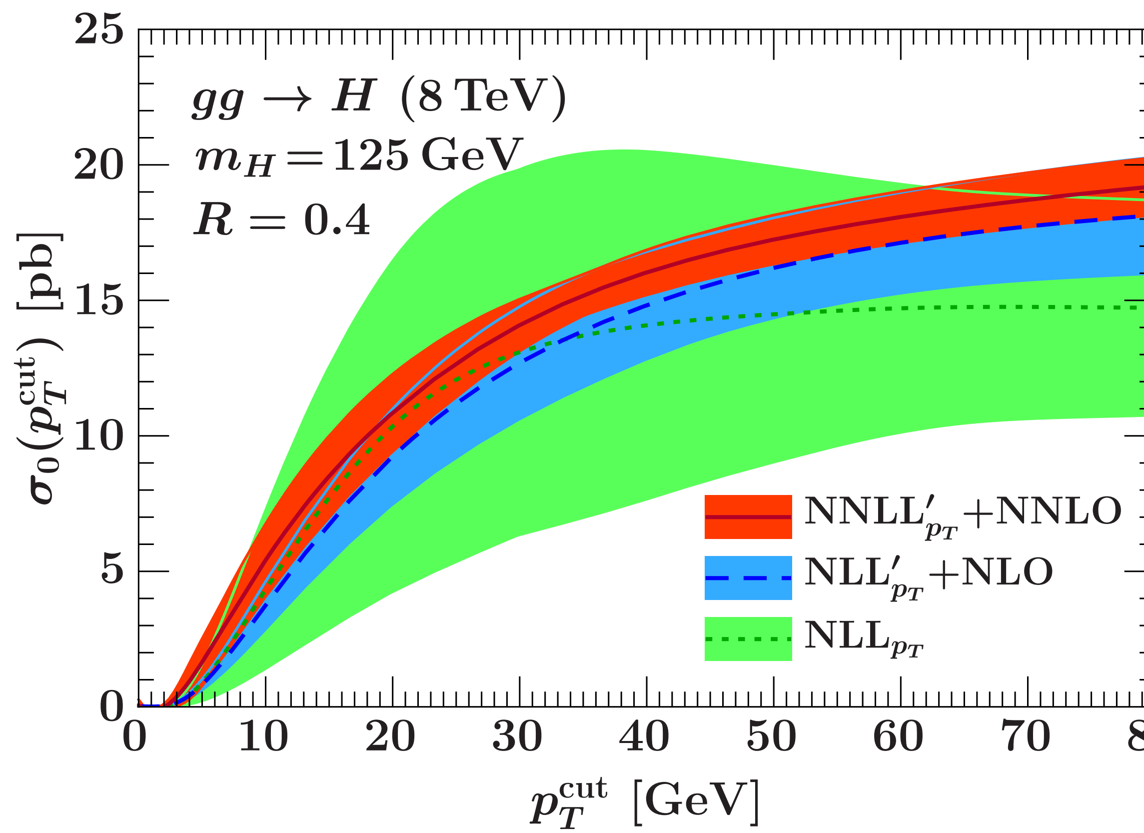


R. Boughezal, F. Caola, K.M., F. Petriello, M. Schulze; Chen, Cruz-Martinez, Gehrmann, Glover, Jacquer

Jet veto acceptances

Jet binning requires jet identification and selection; this may make perturbative computations unstable. To see if this happens, we consider low p_t cuts and narrow jets. Then, resummations of the logarithmically enhanced terms (logarithms of the transverse momentum cut and the jet radius) can be performed. An alternative way to get the quasi-realistic answer.





Are the logarithms large? Does the resummation really help?

$$\epsilon_{p_{t,\mathrm{veto}}} = \frac{[\Sigma_0 + \Sigma_1 + \Sigma_2 + \Sigma_3](p_{t,\mathrm{veto}})}{\sigma_0 + \sigma_1 + \sigma_2 + \sigma_3}$$

$$\alpha_s \ln^2 p_{\perp j}/m_H \gg 1 \qquad \ln R \gg 1$$

Banfi, Zanderighi, Salam; Tackmann, Zuberi, Walsh; Becher, Neubert

Jet-binned cross sections

The results of N^{3}LO computation for inclusive Higgs production, NNLO for the H+j production as well as advances with re-summations of jet-radius logarithms allow one to improve on existing predictions for 0-jet and 1-jet cross sections.

For the 13 TeV LHC, using NNPDF2.3, anti-k$_T$, R=0.5, μ_0=m$_H$/2, Q$_{res}$ = m$_H$/2 and accounting for top and bottom mass effects, one finds the following results:

0-jet bin

LHC 13 TeV	$\epsilon^{\mathrm{N^3LO+NNLL+LL_R}}$	$\Sigma_{\text{0-jet}}^{\mathrm{N^3LO+NNLL+LL_R}}$ [pb]	$\Sigma_{\text{0-jet}}^{\mathrm{N^3LO}}$	$\Sigma_{\text{0-jet}}^{\mathrm{NNLO+NNLL}}$
$p_{\mathrm{t,veto}} = 25\,\mathrm{GeV}$	$0.539^{+0.017}_{-0.008}$	$24.7^{+0.8}_{-1.0}$	$24.3^{+0.5}_{-1.0}$	$24.6^{+2.6}_{-3.8}$
$p_{\mathrm{t,veto}} = 30\,\mathrm{GeV}$	$0.608^{+0.016}_{-0.007}$	$27.9^{+0.7}_{-1.1}$	$27.5^{+0.5}_{-1.1}$	$27.7^{+2.9}_{-4.0}$

≥1-jet bin

LHC 13 TeV	$\Sigma_{\geq\text{1-jet}}^{\mathrm{NNLO+NNLL+LL_R}}$ [pb]	$\Sigma_{\geq\text{ 1-jet}}^{\mathrm{NNLO}}$ [pb]
$p_{\mathrm{t,min}} = 25\,\mathrm{GeV}$	$21.2^{+0.4}_{-1.1}$	$21.6^{+0.5}_{-1.0}$
$p_{\mathrm{t,min}} = 30\,\mathrm{GeV}$	$18.0^{+0.3}_{-1.0}$	$18.4^{+0.4}_{-0.8}$

- No breakdown of fixed order perturbation theory for p$_T$ ~ 25- 30 GeV ;
- Reliable error estimate from lower orders ; residual errors O(3-5) percent for the two jet bins; proper correlation of errors.
- Re-summed results change fixed-order results within the error bars of the former/ latter. There seems to be little difference between re-summed and fixed order results.

A. Banfi, F. Caola, F. Dreyer, P. Monni, G.Salam, G. Zanderighi, F. Dulat

H+jet @ NNLO : fiducial results

Since pQCD perfectly describes jet-vetoed cross sections, one can use it to predict fiducial volume cross sections including Higgs boson decays to photons or leptons. What makes these calculation even more interesting is that there are measurements of the ATLAS and CMS collaborations at the 8 TeV LHC that can be directly compared to the results of the fiducial volume calculation (results are shown for infinitely heavy top quark).

Atlas cuts on photons and jets

$$\mathrm{anti}-\mathrm{k}_t, \quad \Delta R = 0.4, \quad p_{j\perp} = 30\ \mathrm{GeV}, \mathrm{abs}(y_j) < 4.4$$
$$p_{\perp,\gamma_1} > 43.75\ \mathrm{GeV}, \quad p_{\perp,\gamma_2} = 31.25\ \mathrm{GeV}, \quad \Delta R_{\gamma j} > 0.4$$

$$\sigma^{\mathrm{fid}}_{1j,\mathrm{ATLAS}} = 21.5 \pm 5.3(\mathrm{stat}) \pm 2.3(\mathrm{syst}) \pm 0.6\ \mathrm{lum\ fb}$$

$$\sigma^{\mathrm{fid}}_{\mathrm{LO}} = 5.43^{+2.32}_{-1.5}\ \mathrm{fb} \qquad \sigma^{\mathrm{fid}}_{\mathrm{NLO}} = 7.98^{+1.76}_{-1.46}\ \mathrm{fb} \qquad \sigma^{\mathrm{fid}}_{\mathrm{NNLO}} = 9.46^{+0.56}_{-0.84}\ \mathrm{fb}$$

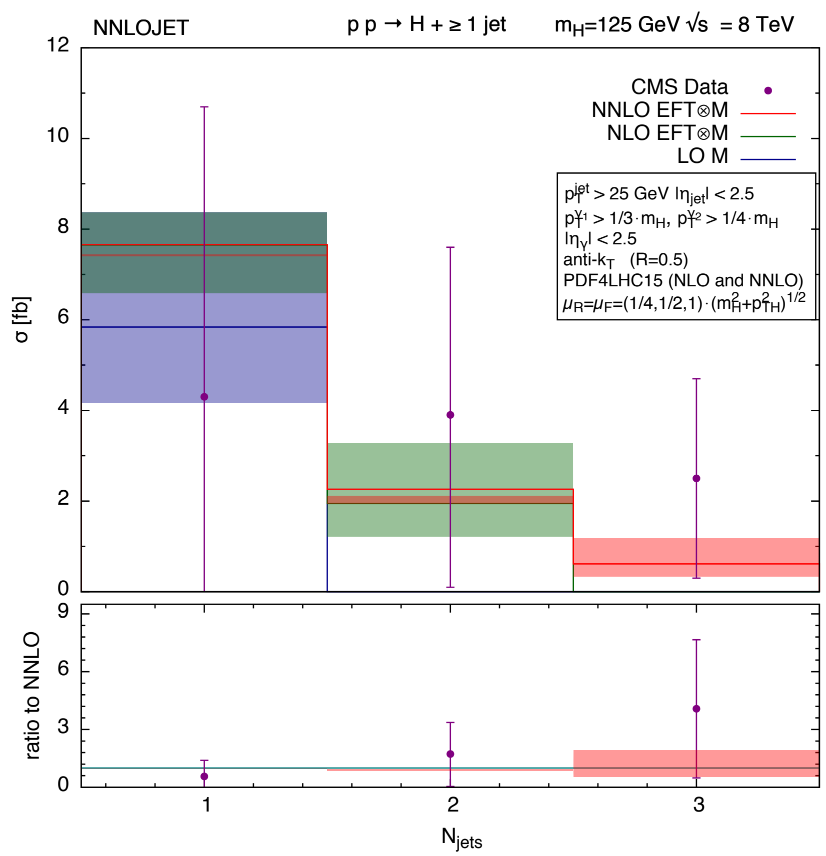
The difference between the ATLAS H+j measurements and the SM prediction is close to two standard deviations; the ratio of central values is larger than in the inclusive case.

F. Caola, K.M., M. Schulze

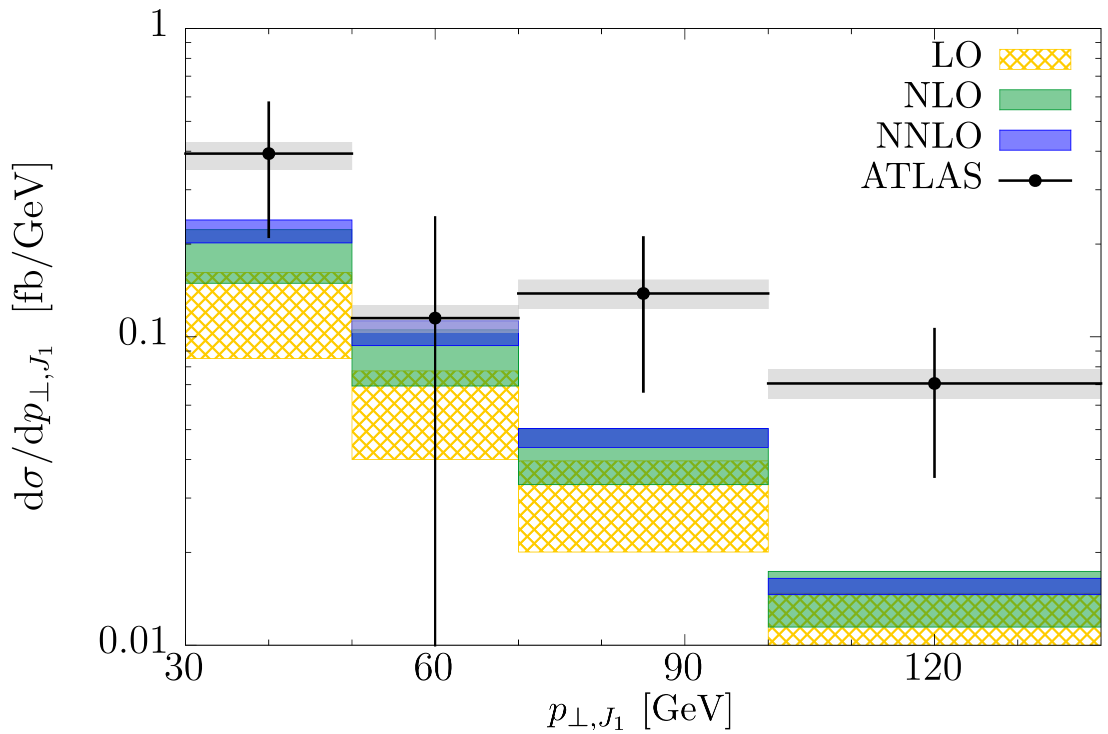
H+jet @ NNLO : fiducial results

Once Higgs boson decays are included on the theory side, any fiducial cross section or distribution can be obtained. To make the long story short, I only show a few plots where comparison with the results of CMS and ATLAS is performed.

The comparison is not very impressive; at the moment, the luminosity/energy is simply too low to make meaningful comparison possible. The good news is that we have everything to make theory/data comparison. The existence of precise theory predictions should serve as a motivation for refined experimental analyses, this time at 13 TeV



Exclusive jet cross sections



Transverse momentum distribution of a leading jet

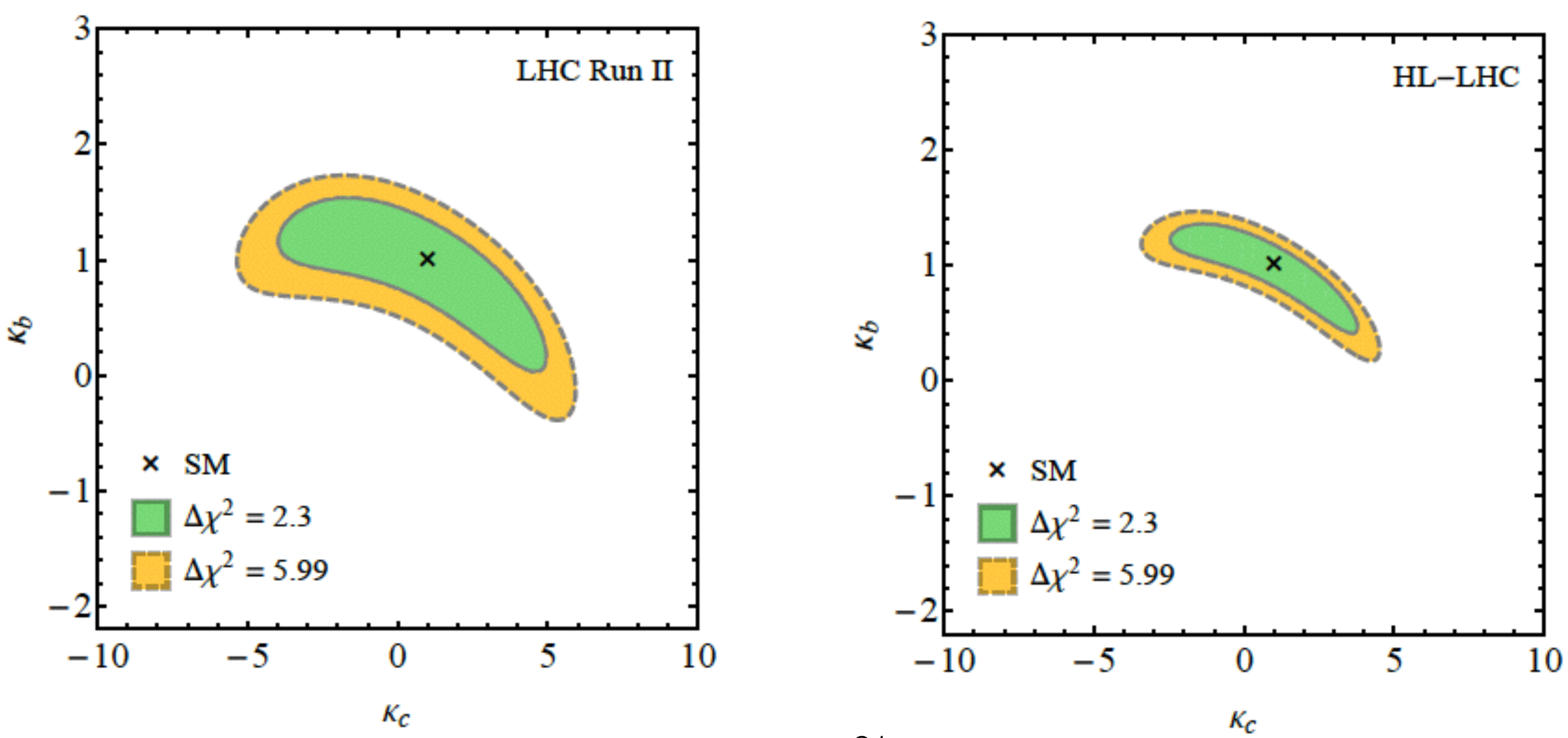
Chen, Cruz-Martinez, Gehrmann, Glover, Jacquer

F. Caola, K.M., M. Schulze

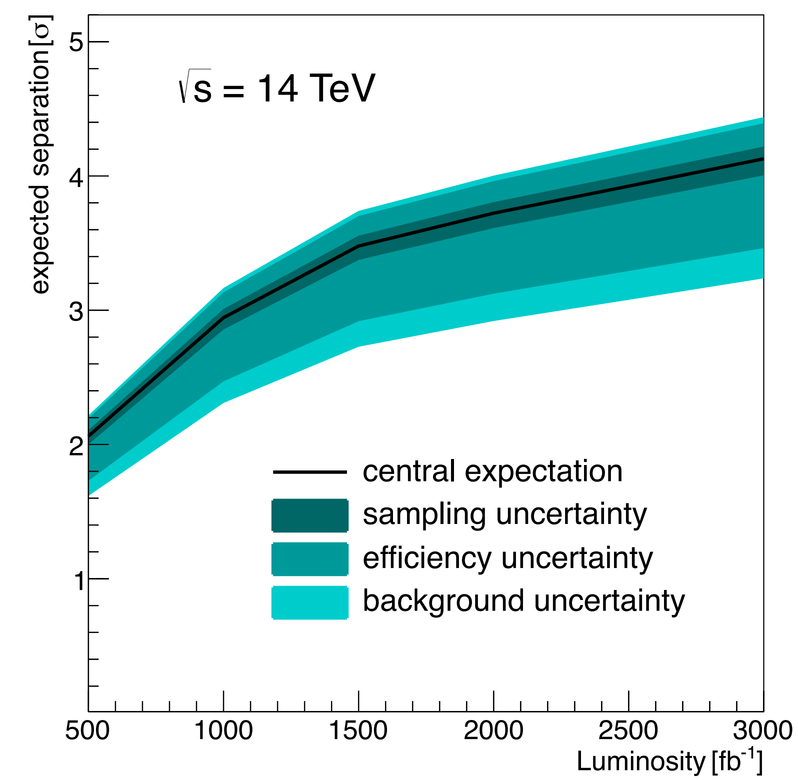
The Higgs boson transverse momentum distribution

Knowledge of the Higgs boson transverse momentum distribution is important for signal modeling, but it can also provide unique information about Higgs properties.

For example, it can be used to constrain Yukawa couplings of light quarks, or to probe for contributions of additional ultra-heavy particles to Higgs coupling to gluons. The problem is to get the SM theory right in both cases.



Sensitivity to bottom and charm Yukawa couplings from kinematic distributions in Higgs production.



Expected separation of point-like Hgg coupling from the realistic one, as a function of the LHC luminosity.

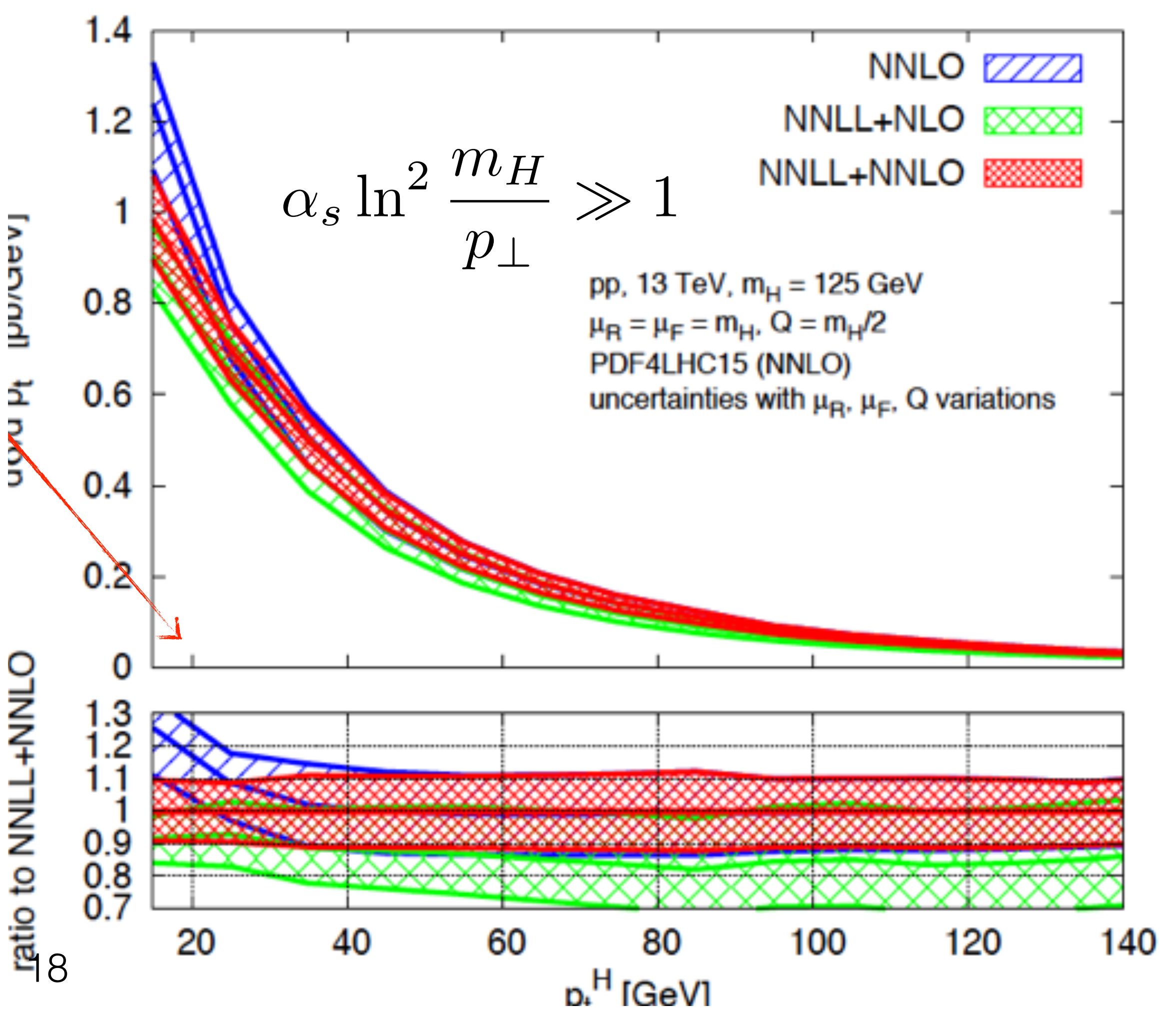
Bishara, Haisch, Monni; Soreq, Zhu, Zupan; Bonner, Logan

Langenegger, Spira, Strebel

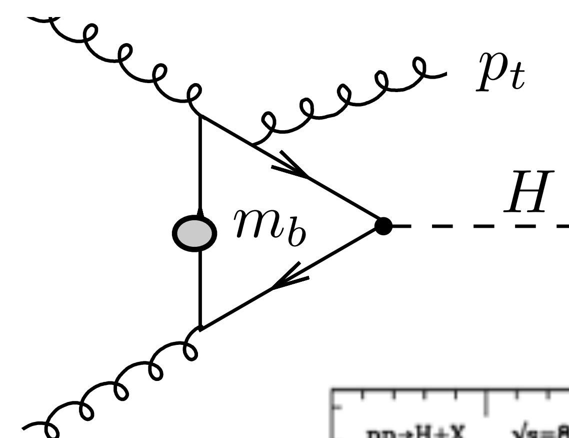
The Higgs boson transverse momentum distribution

In principle, transverse momentum distribution of a color-neutral particle can be computed following well-established procedures at low (resummation) and high (perturbation theory) transverse momentum.

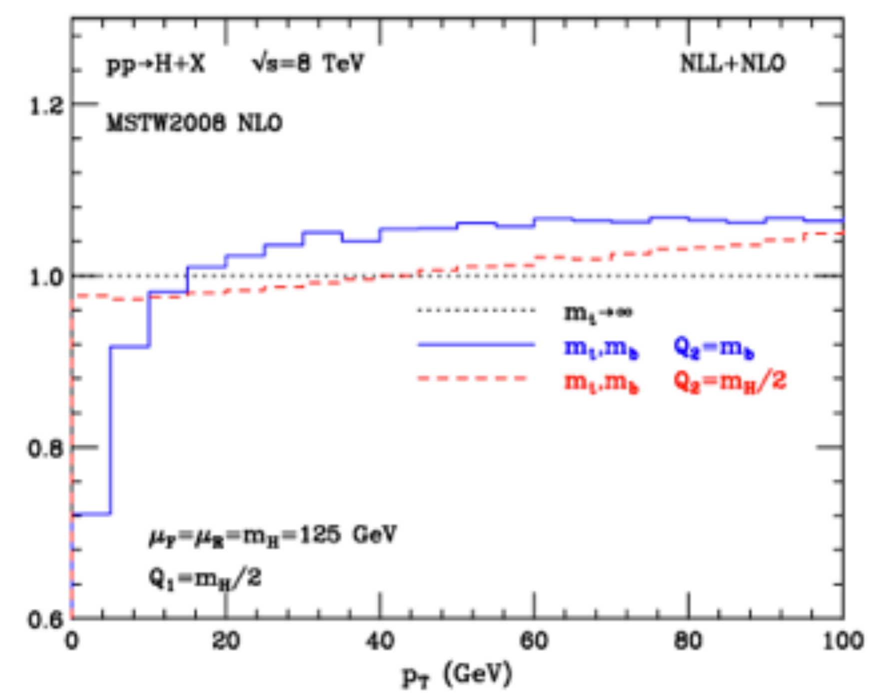
However, the Higgs boson is a special case since the Hgg vertex is not point-like. At small p_t , b-loops leads to the appearance of Sudakov-like double logarithmic corrections, related to the helicity flip on the `soft" fermion line; origin of these logarithms, let alone their resummation, is not understood.



$$\alpha_s \ln^2 \frac{m_H}{p_\perp} \gg 1$$



$$\alpha_s \ln^2 \frac{p_\perp}{m_b} \gg 1$$



Monni, Re, Torrielli

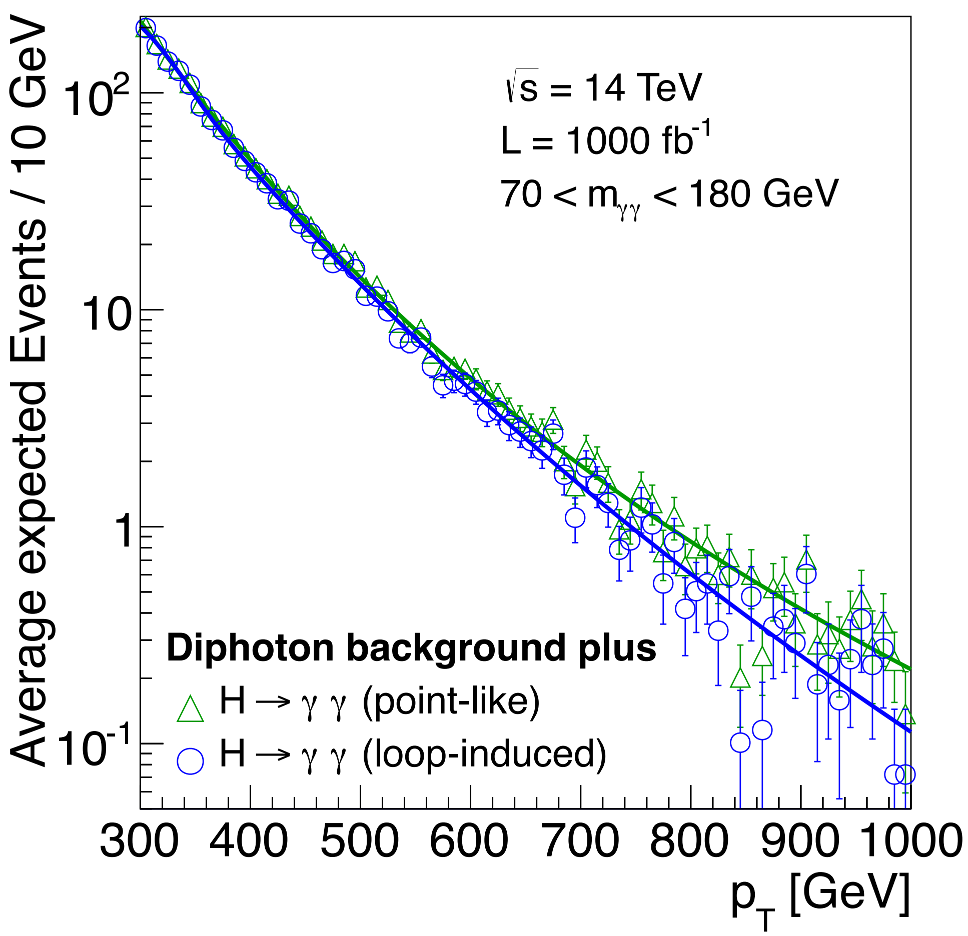
Grazzini, Sargsyan

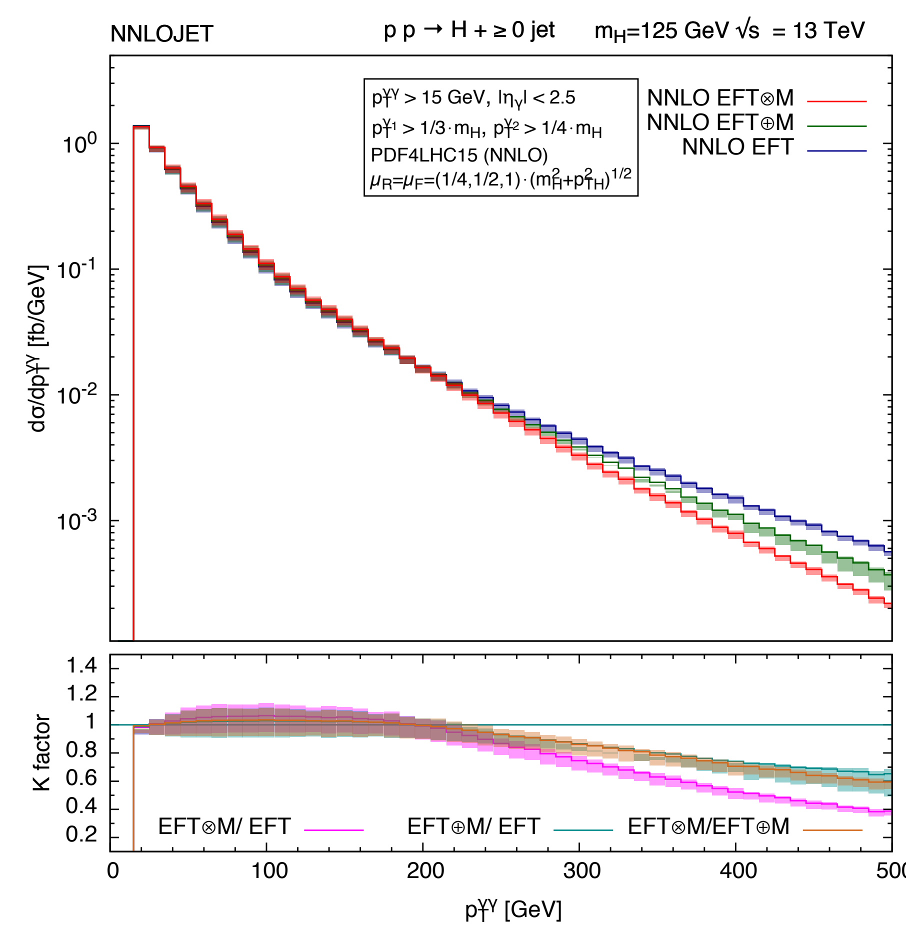
Higgs transverse momentum distribution

At large transverse momentum the situation is also interesting since the top quark loop gets resolved and an additional point-like component of the ggH vertex can be detected -- if present (the point-like coupling leads to harder spectrum).

If boosted techniques can be used to identify the Higgs boson at high transverse momentum through its decays to b-quarks, very reasonable number of events can be expected. However, even the di-photon final state does not look hopeless.

$$\mathcal{L}_6 \in a_t |H|^2 \bar{Q}_L \tilde{H} t_R + a_g |H|^2 G_{\mu\nu} G^{\mu\nu}$$





Langenegger, Spira, Strebel

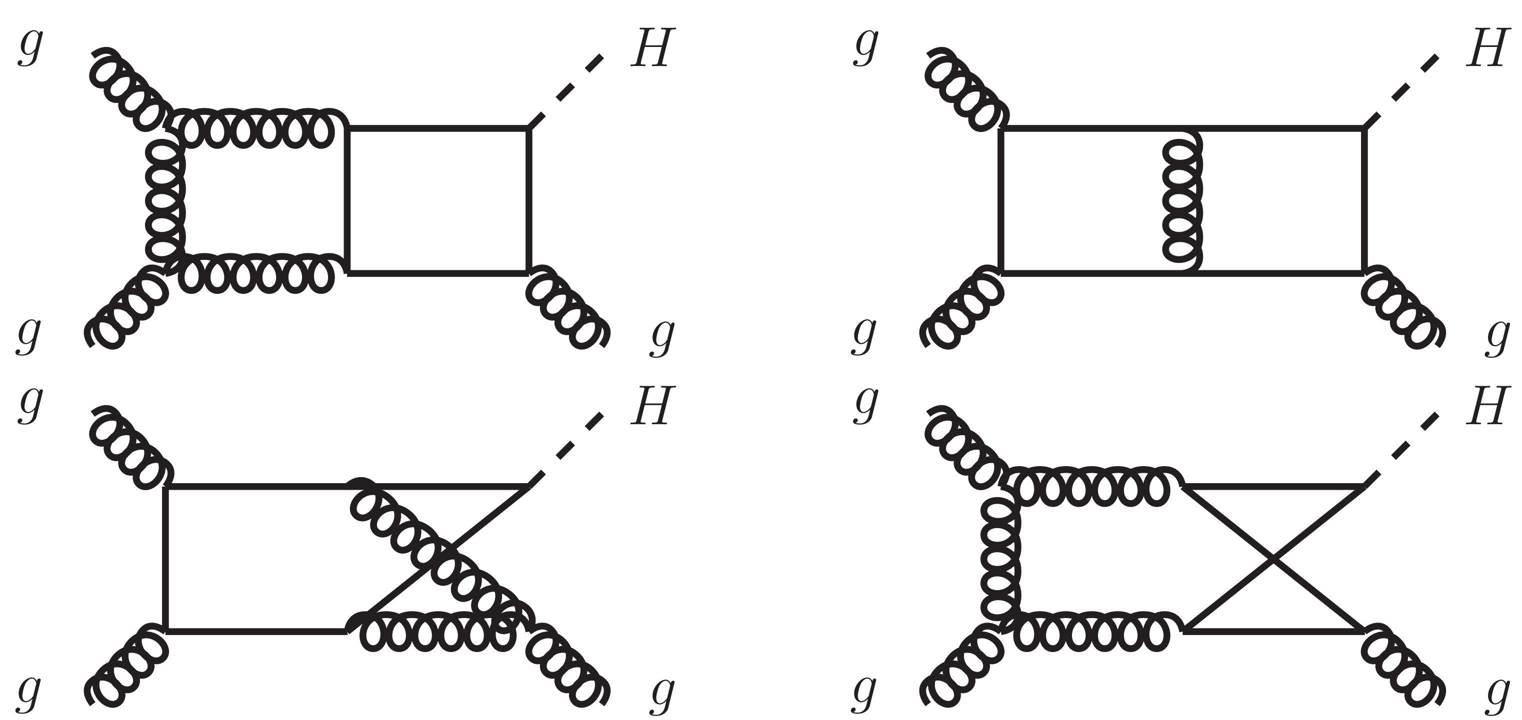
Chen, Cruz-Martinez, Gehrmann, Glover, Jacquer

Mass effects in the Higgs boson transverse momentum distribution

For both, high- and low- Higgs boson transverse-momentum region, one has to compute complicated Feynman integrals with internal masses. This is a general problem that goes beyond the H+j production.

The recent progress is encouraging and suggests that we will have good understanding of these effects by the time 500 fb^{-1} are collected at the LHC. Planar master-integrals were recently computed by R. Bonciani, V. Del Duca, H. Frellesvig, J. Henn, F. Moriello and V. Smirnov.

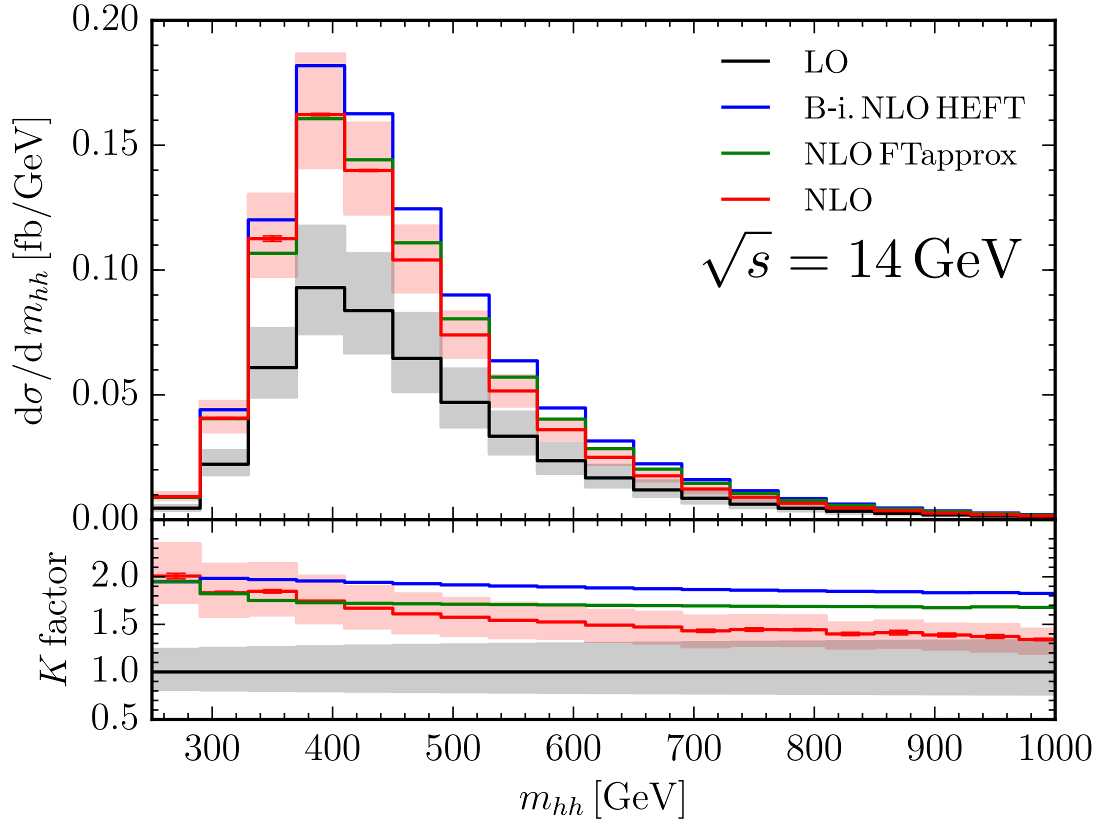
Complete gg -> Hg amplitude in the limit of a small mass of the quark that facilitates the gg->Hg transition was also obtained recently (L. Tancredi, C. Wever, K.M.). First phenomenological results are coming.

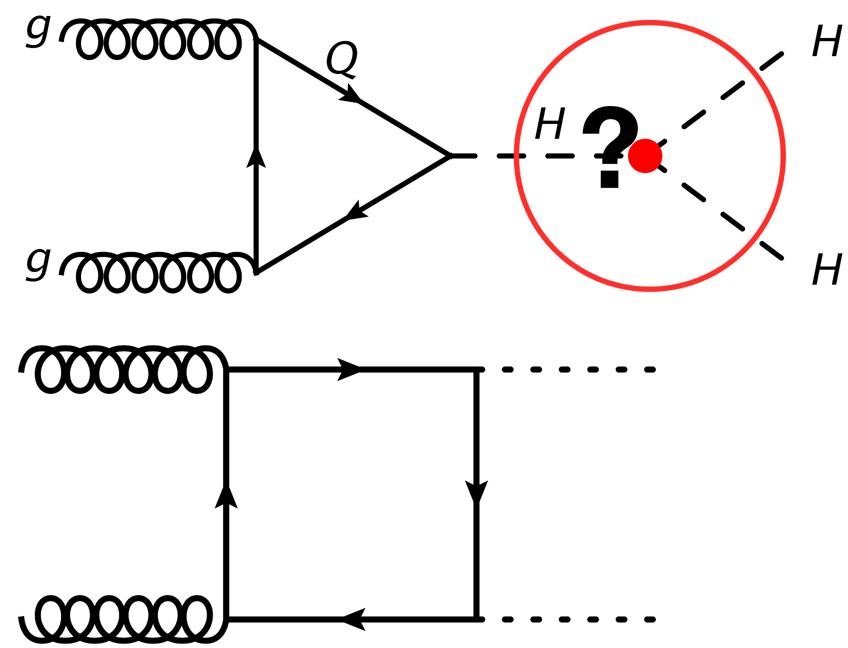


How large is the triple Higgs coupling ?

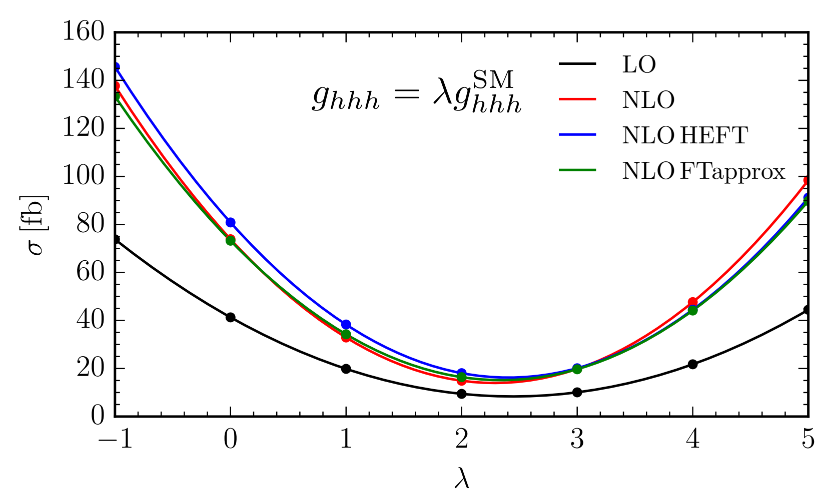
Learning about triple Higgs coupling is the first step towards profiling the EW-symmetry breaking potential.   Extracting it from the LHC data with decent precision is a non-trivial problem for both experimenters (low rates) and theorists (best observables, modeling the signal, expectations in the SM).

``Masses in loops" issue was numerically overcome is the double Higs production; the computational technology used there is generalizable.



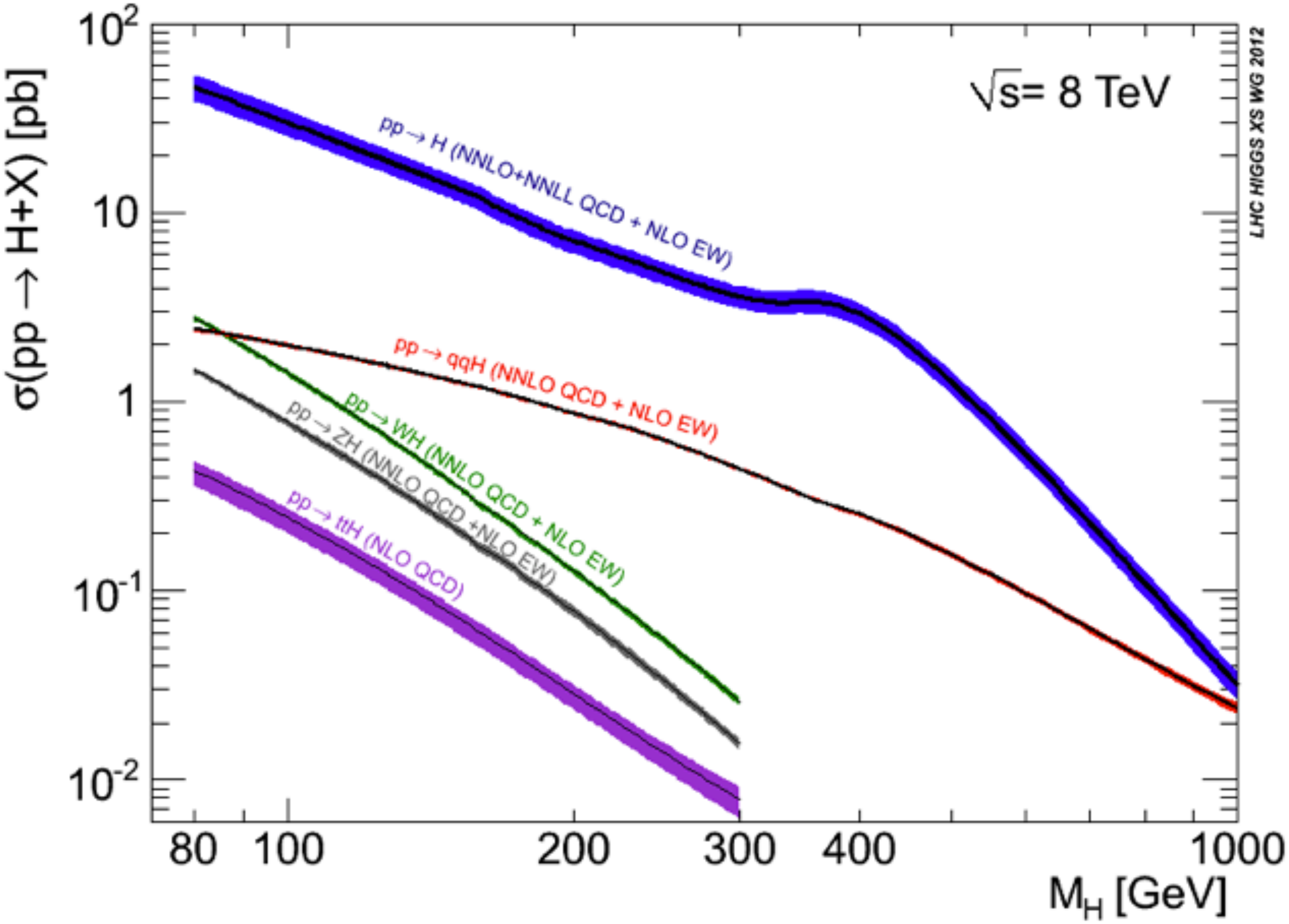


	$\sigma_{\rm LO}$ (fb)	$\sigma_{\rm NLO}$ (fb)
B.I. HEFT	$19.85^{+27.6\%}_{-20.5\%}$	$38.32^{+18.1\%}_{-14.9\%}$
FTapprox	$19.85^{+27.6\%}_{-20.5\%}$	$34.26^{+14.7\%}_{-13.2\%}$
Full Theory	$19.85^{+27.6\%}_{-20.5\%}$	$\mathbf{32.91^{+13.6\%}_{-12.6\%}}$



Borowka, Greiner, Heinrich, Kerner, Schenk, Schubert, Zirke

Higgs production in vector boson fusion

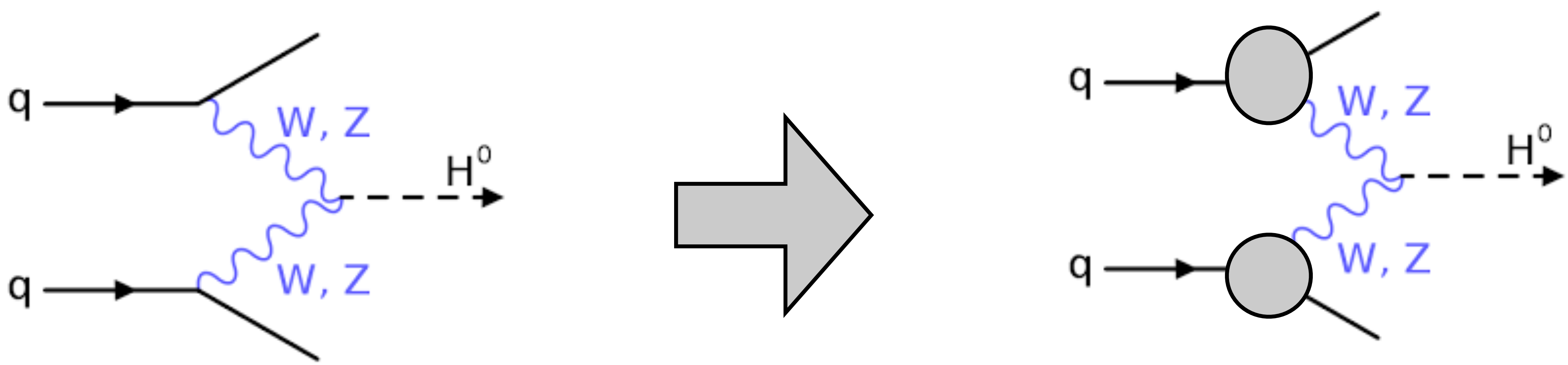


Higgs boson production in weak boson fusion

The Higgs boson production in weak boson fusion is an interesting process for a variety of reasons, including the direct access to HVV (V = Z,W) coupling etc.

Due to color conservation, computations of NLO QCD corrections are simple -- the upper and lower qqV vertices receive QCD corrections but the two blocks do not talk to each other. As the consequence, one can view the structure of QCD corrections -- to the total inclusive cross section --- as the `` Deep Inelastic Scattering squared" and use the DIS building blocks - the structure functions - to calculate the corrections. For NLO QCD, this observation is not essential but it is useful for NNLO since those results for the coefficients functions are available.

The QCD corrections obtained in this approach are small (O(5%) NLO, O(3%) NNLO, O(0.1%) at N^3LO) ; it then seemed natural to assume that this size of QCD corrections will be indicative for the fiducial cross sections.



Bolzoni, Maltoni, Moch, Zaro, Dreyer, Kalberg

Higgs boson production in weak boson fusion

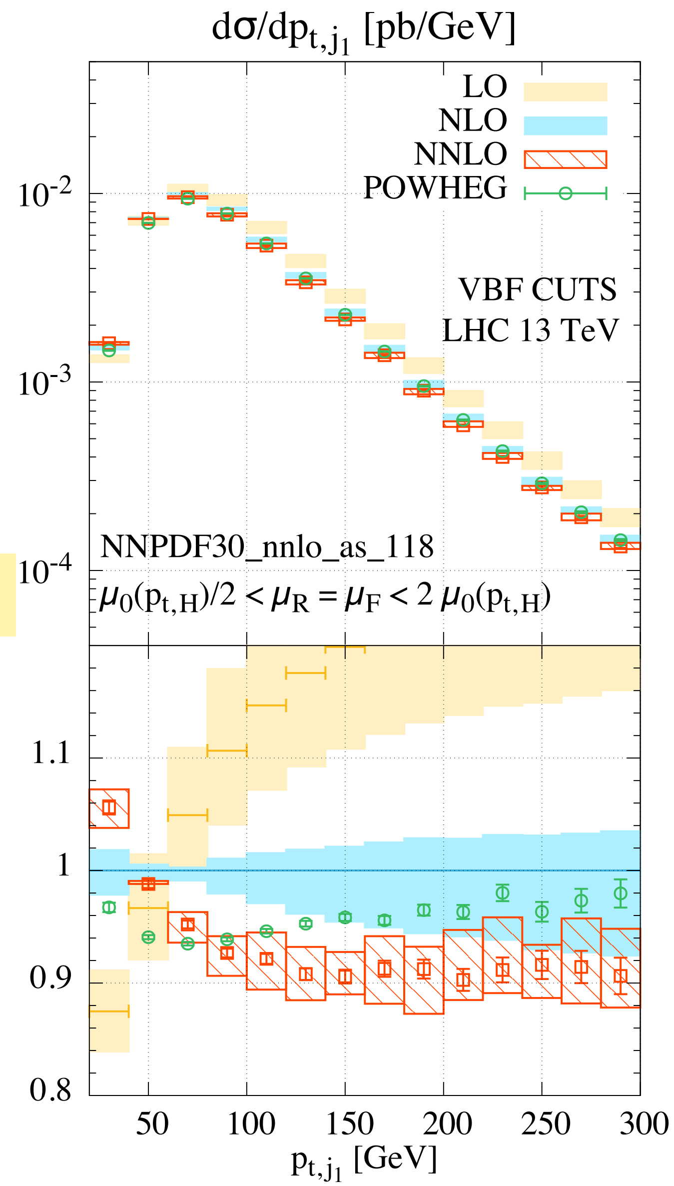
However, this assumption turns out to be incorrect and, in fact, one can get larger O(6-10%) corrections for fiducial (WBF cuts) cross sections and kinematic distributions. Often, the shape of those corrections seems rather different from both the NLO and/or parton shower predictions.

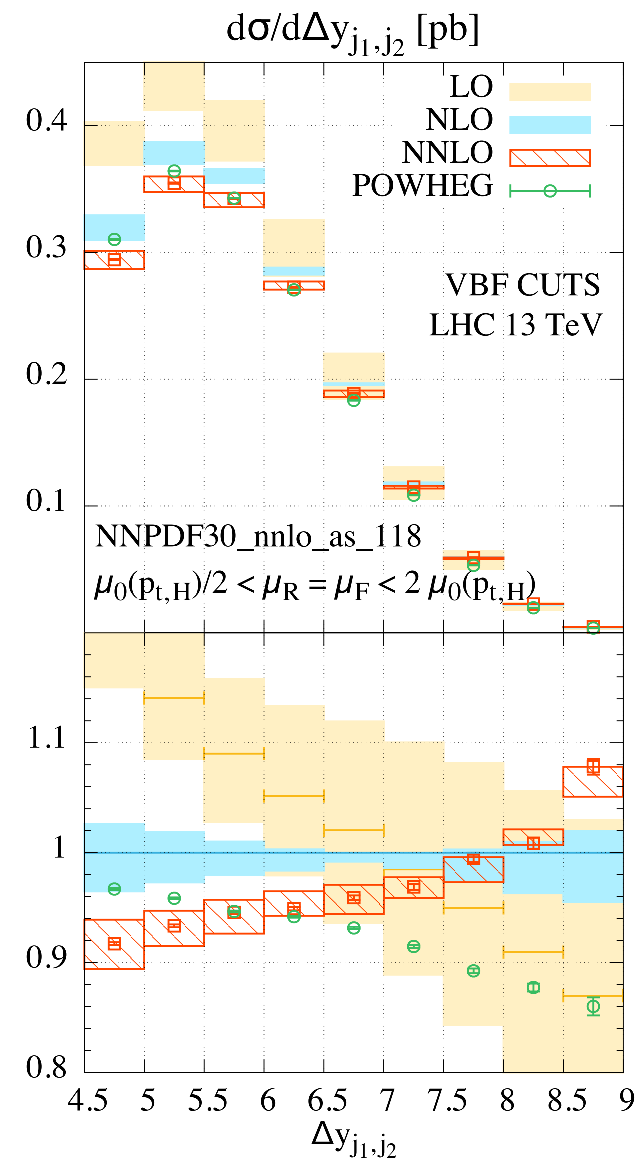
WBF cuts

$$p_\perp^{j_{1,2}} > 25~\text{GeV}, \quad |y_{j_{1,2}}| < 4.5,$$
$$\Delta y_{j_1,j_2} = 4.5, \quad m_{j_1,j_2} > 600~\text{GeV},$$
$$y_{j_1} y_{j_2} < 0, \quad \Delta R > 0.4$$

Cross sections with and without WBF cuts

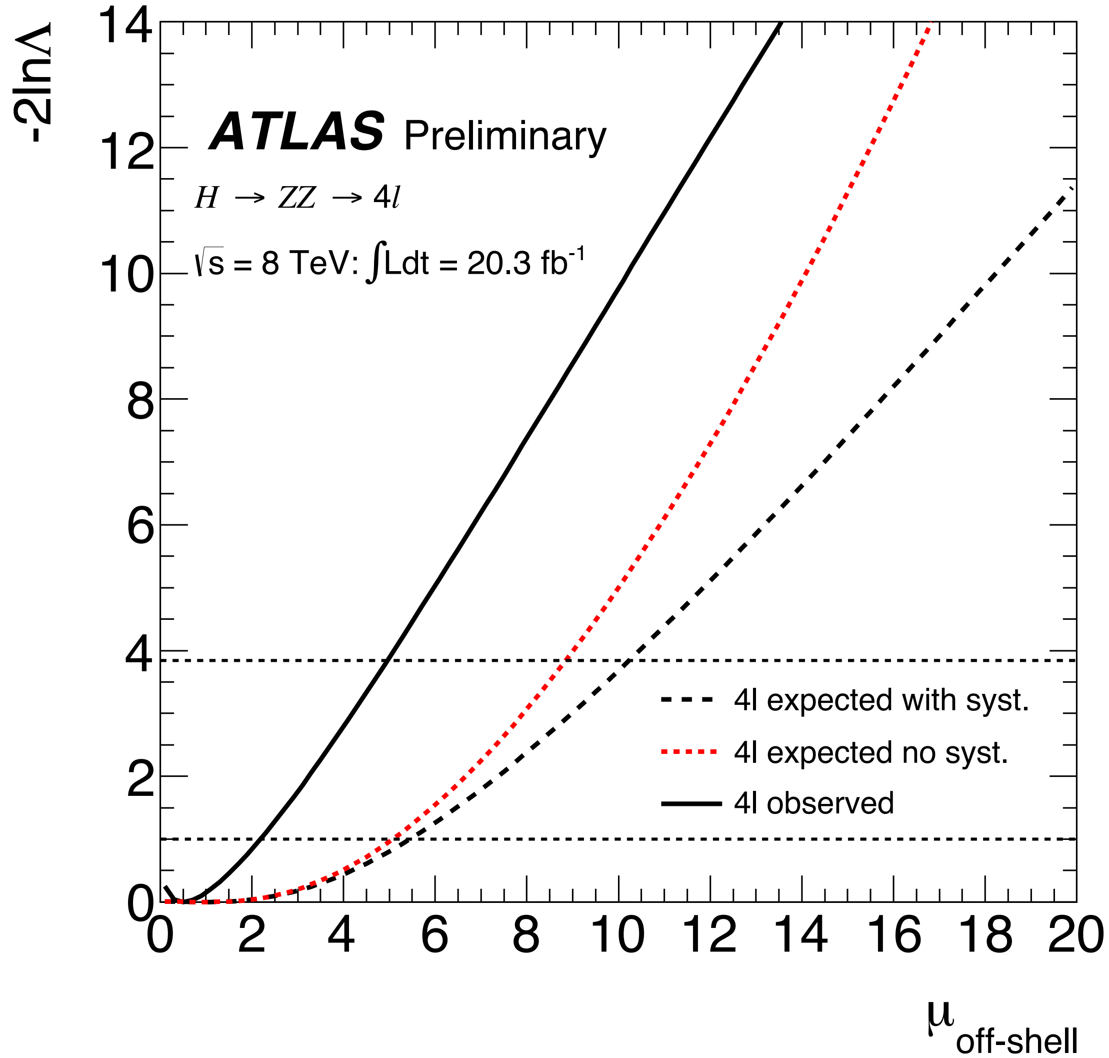
	$\sigma^{\text{nocuts}}[\text{pb}]$	$\sigma^{\text{VBF cuts}}[\text{pb}]$
LO	$4.032^{+0.057}_{-0.069}$	$0.957^{+0.066}_{-0.059}$
NLO	$3.929^{+0.024}_{-0.023}$	$0.876^{+0.008}_{-0.018}$
NNLO	$3.888^{+0.016}_{-0.012}$	$0.826^{+0.013}_{-0.014}$

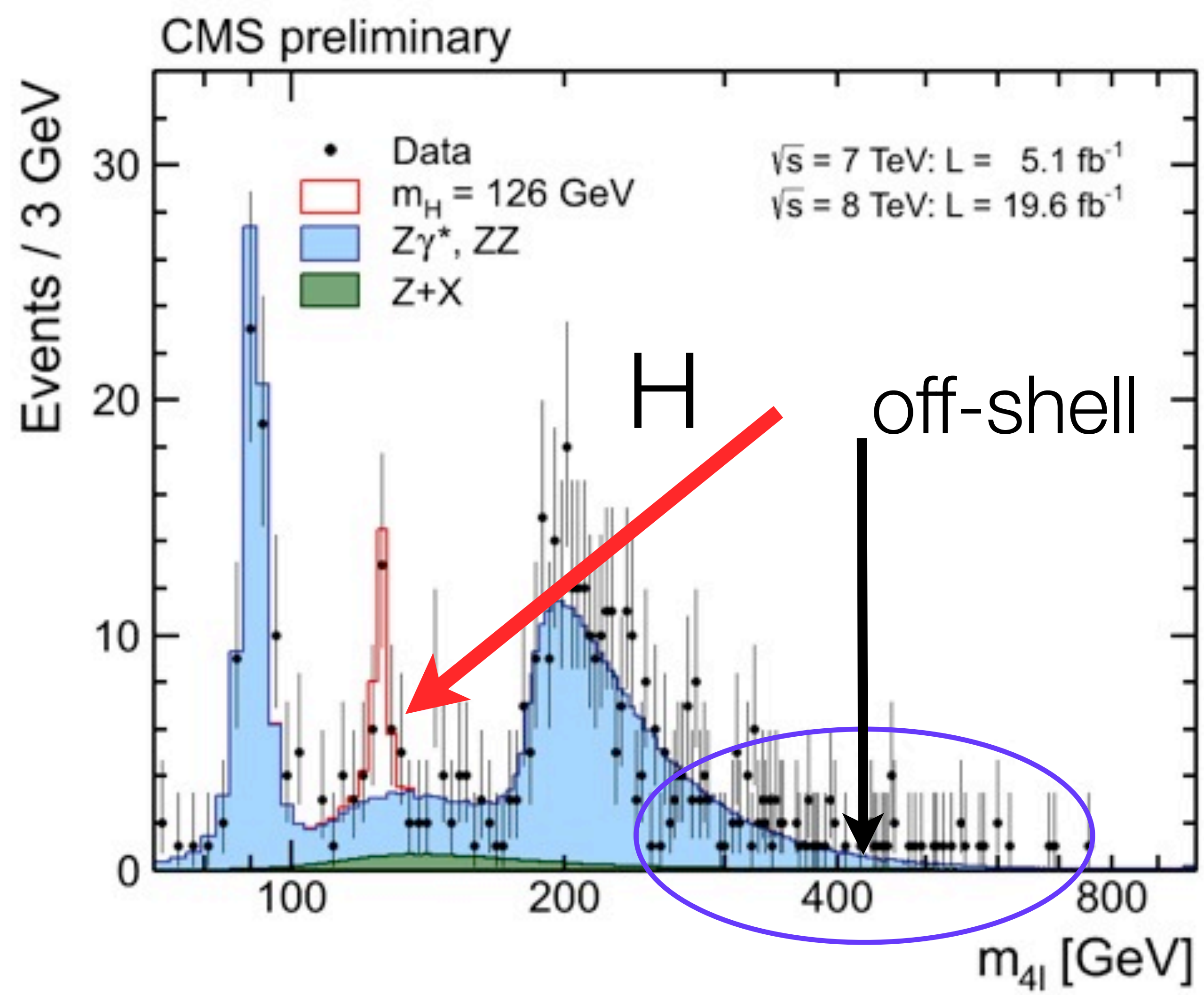




Cacciari, Dreyer, Kalberg, Salam, Zanderighi

Off-shell measurements





$\Gamma_H < 4.8\text{-}7.7\ \Gamma_{H,SM} = 20\text{-}32$ MeV @ 95CL

The Higgs width

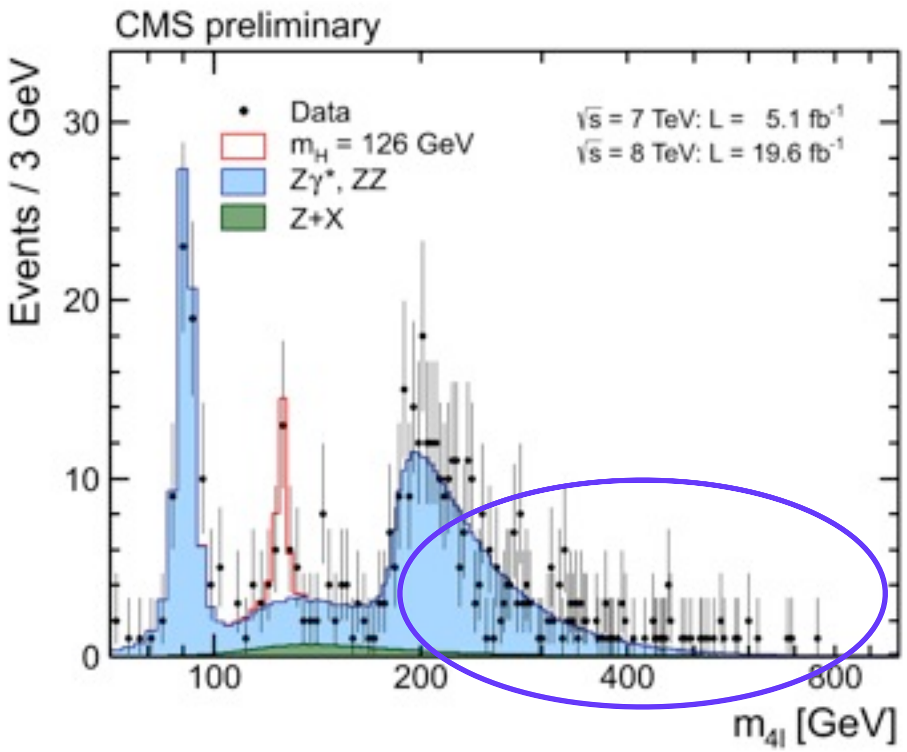
Direct measurement of the Higgs width is very imprecise; hardly improvable. The off-shell measurement bounds couplings far off the pole and uses them back on the pole -- potential contamination from "anomalous couplings" but can be dealt with through a combination of alternative measurements.

Need precise prediction for ZZ production both in quark-antiquark and gluon fusion.

$$\sigma_{\rm on} \propto g_i^2 g_f^2/\Gamma_H \qquad \sigma_{\rm off} \propto g_i^2 g_f^2$$

$$\Rightarrow \Gamma_H \propto \frac{\sigma_{\rm off}}{\sigma_{\rm on}}$$ **indirect constraint on width**

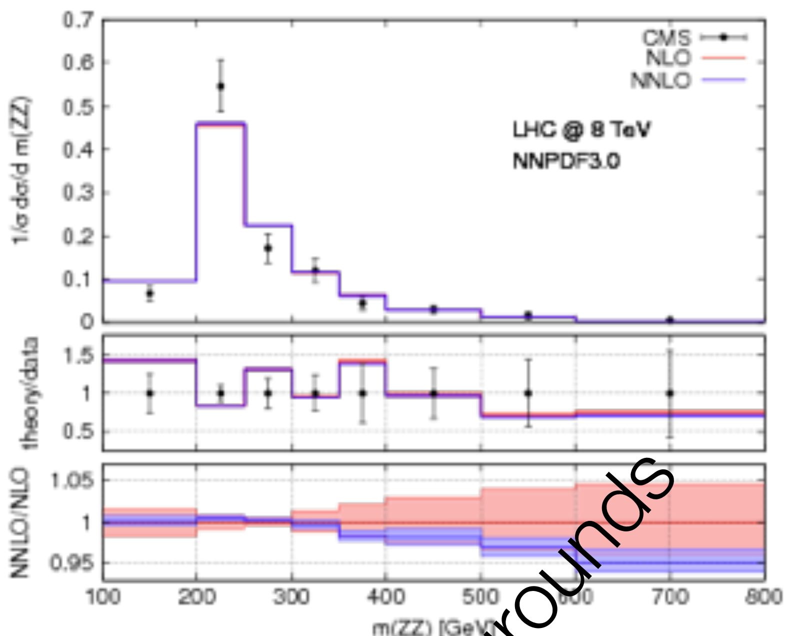
CMS: $\Gamma_H < 13\ \mathrm{MeV}$ **ATLAS:** $\Gamma_H < 23\ \mathrm{MeV}$

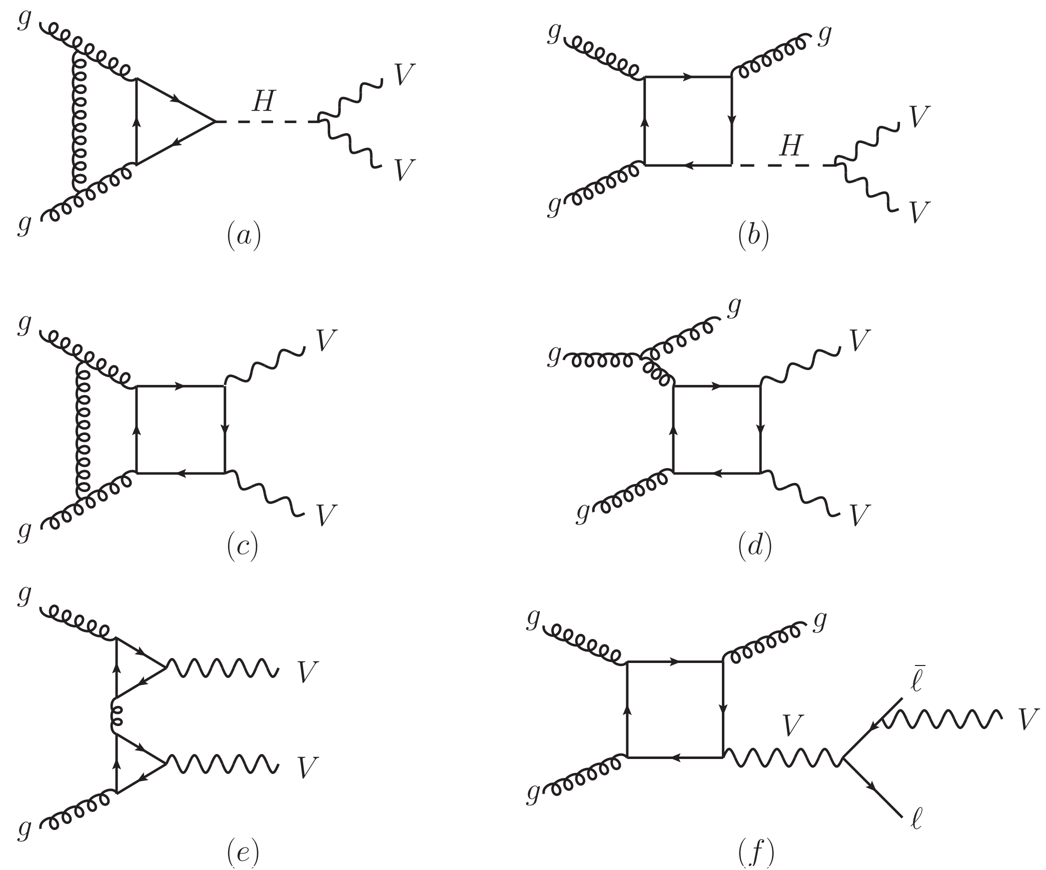


		4ℓ	$2\ell 2\nu$
(a)	total gg ($\Gamma_H = \Gamma_H^{SM}$)	1.8 ±0.3	9.6 ±1.5
	gg signal component ($\Gamma_H = \Gamma_H^{SM}$)	1.3 ±0.2	4.7 ±0.6
	gg background component	2.3 ±0.4	10.8 ±1.7
(b)	total gg ($\Gamma_H = 10 \times \Gamma_H^{SM}$)	9.9 ±1.2	39.8 ±5.2
(c)	total VBF ($\Gamma_H = \Gamma_H^{SM}$)	0.23 ±0.01	0.90 ±0.05
	VBF signal component ($\Gamma_H = \Gamma_H^{SM}$)	0.11 ±0.01	0.32 ±0.02
	VBF background component	0.35±0.02	1.22 ±0.07
(d)	total VBF ($\Gamma_H = 10 \times \Gamma_H^{SM}$)	0.77 ±0.04	2.40 ±0.14
(e)	$q\bar{q}$ background	9.3 ±0.7	47.6 ±4.0
(f)	other backgrounds	0.05 ±0.02	35.1 ±4.2
(a+c+e+f)	total expected ($\Gamma_H = \Gamma_H^{SM}$)	11.4 ±0.8	93.2 ±6.0
(b+d+e+f)	total expected ($\Gamma_H = 10 \times \Gamma_H^{SM}$)	20.1 ±1.4	124.9 ±7.8
	observed	11	91

The Higgs width

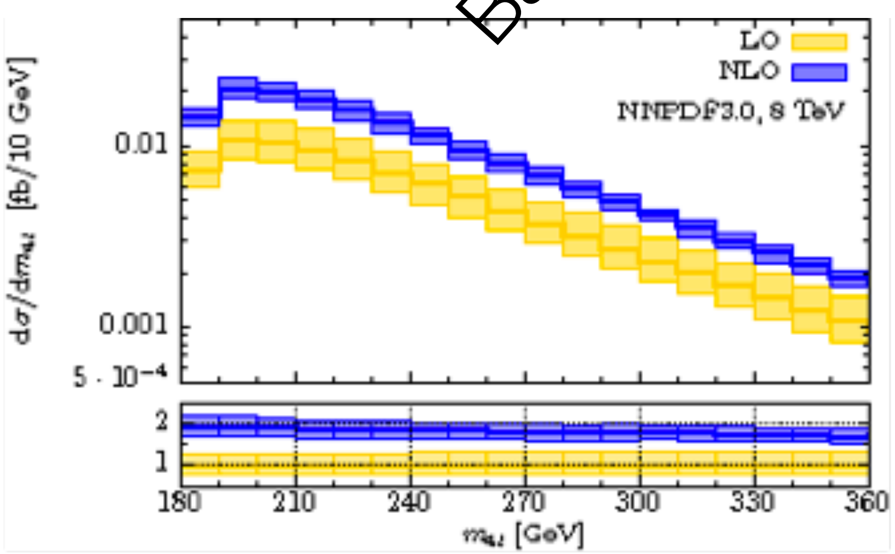
Quark-antiquark annihilation to ZZ is known through NNLO QCD and the gluon fusion -- to NLO, including interference with the signal. Integrals with top quark loops are known approximately. Close proximity of K-factors for the signal and the background.

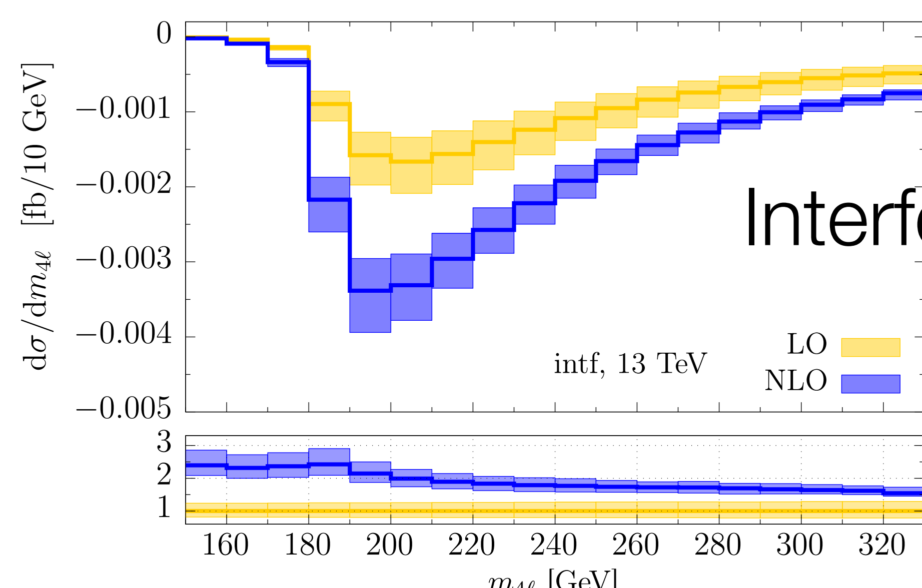




Backgrounds

M. Grazzini, S. Kallweit, P. Maierhoefer, D. Rathlev





Interference

F. Caola, K. Melnikov, R. Rontsch, L. Tancredi; interference also: J. Campbell, M. Czakon, K. Ellis, S. Kirchner

Conclusion

Availability of precise predictions for Higgs boson production and decay processes in the Standard Model is a crucial element of the research program aimed at detailed studies of Higgs boson properties at the LHC.

We have seen an impressive progress in this field in the past year (inclusive Higgs through N^3LO, H+jet at NNLO, Higgs in WBF at NNLO). In addition, there are significant improvements with the general understanding of strong dynamics in hadron collisions (NLO QCD computations for complex processes, improved parton showers, matching and merging).

This progress gets translated into an overall confidence that reliable and (sometimes) precise exploration of Higgs boson properties is possible at the LHC.

$\boxed{H^0}$ $J = 0$

Mass $m = 125.7 \pm 0.4$ GeV

H^0 Signal Strengths in Different Channels

Combined Final States $= 1.17 \pm 0.17$ (S = 1.2)

$W W^* = 0.87^{+0.24}_{-0.22}$

$Z Z^* = 1.11^{+0.34}_{-0.28}$ (S = 1.3)

$\gamma\gamma = 1.58^{+0.27}_{-0.23}$

$b\overline{b} = 1.1 \pm 0.5$

$\tau^+\tau^- = 0.4 \pm 0.6$

$Z\gamma <$ 9.5, CL = 95%

The status of the Higgs physics

Now this is not the end. It is not even the beginning of the end.
But it is, perhaps, the end of the beginning.