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Calculating Higgs boson properties in the Standard Model

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Introduction

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

This implies -- for the Higgs boson physics -- that Higgs properties are completely predicted in the Standard Model once its mass is measured.

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%

Having made it to PDG, the Higgs boson is now one of well-established particles

It follows from the SM 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) its couplings to massless gauge bosons appear only at one-loop.

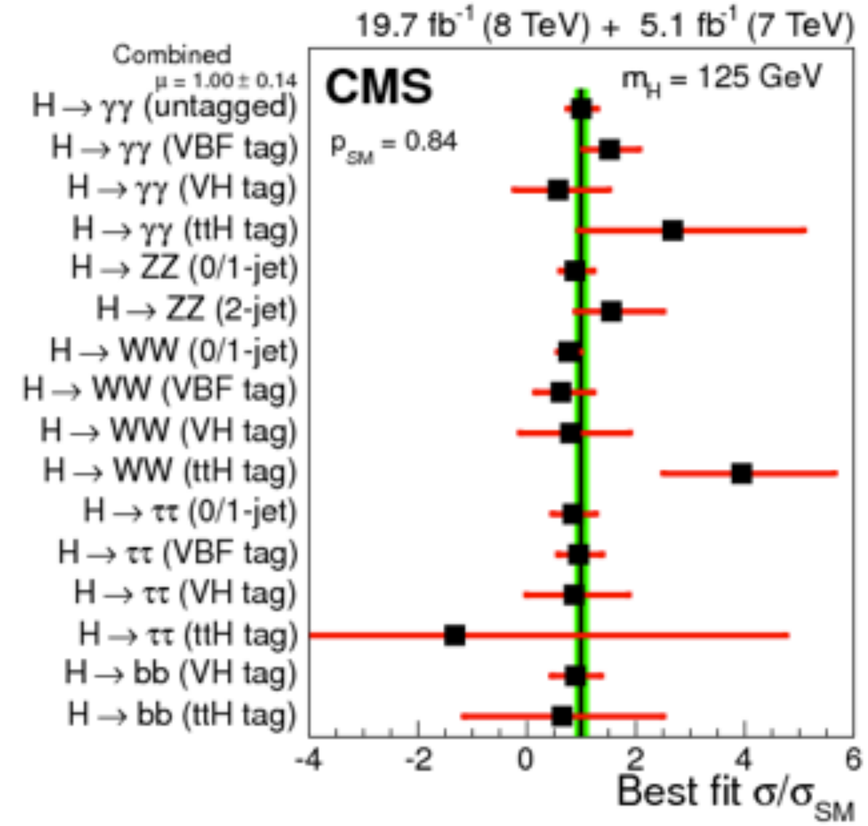
Introduction

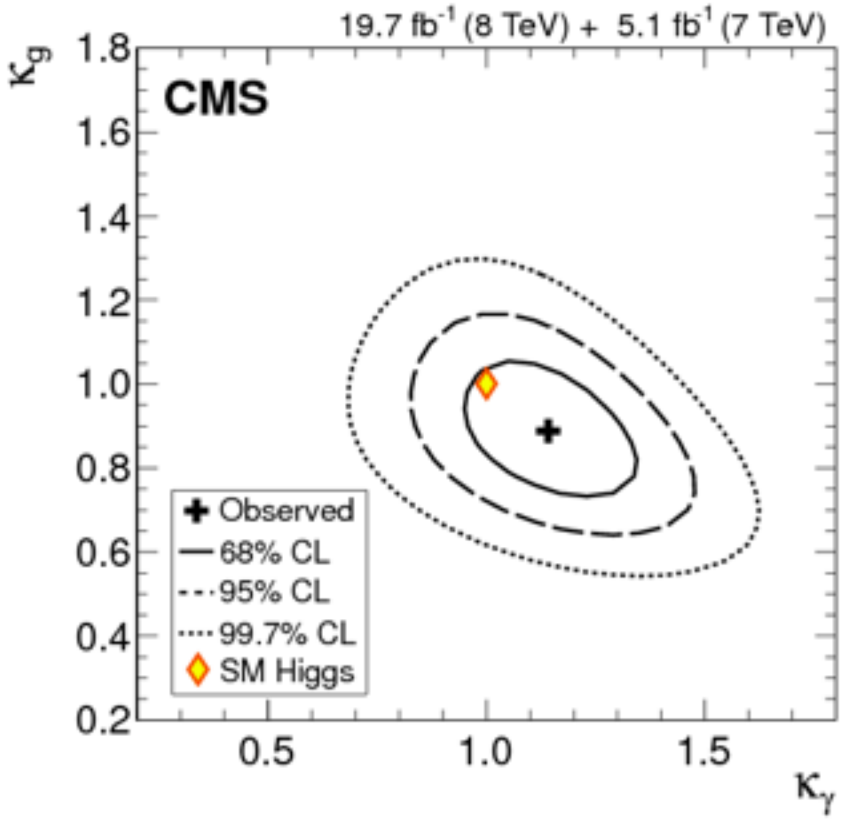
How far along are we with the verification of this picture?

1) All the indications are that the Higgs boson is indeed a spin-zero, CP-even particle. This information is obtained by analyzing shapes of certain kinematic distributions sensitive to these quantum numbers. These shapes often follow from general principles (angular momentum conservation) and are not sensitive to dynamics.

2) The Higgs couplings are more complicated a matter. Those are extracted from normalizations of cross sections that are sensitive to radiative corrections. Currently, the Higgs couplings are known experimentally with the accuracy of about 20%; recall that QCD radiative corrections increase the Higgs boson production cross section in gluon fusion by a factor of 2. Hence, already with the current data and the current level of precision, we are sensitive to radiative corrections.

Further verification of the SM Higgs mechanism will require detailed theoretical predictions for production cross sections and decay rates.





Introduction

To obtain those high-precision predictions for Higgs boson production at colliders, we use the general QCD factorization framework, studied and verified at the Tevatron and the Run I LHC.

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

The non-perturbative corrections are expected to be just a few percent for the Higgs-related observables but we do not have detailed understanding of these effects.

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

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 major Higgs production and decay channels are currently known through (at least) NLO QCD 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.)

Outline

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 three recent results that may have a potential to significantly affect the way we think about the possibility to do precision Higgs physics at hadron colliders. They include:

1) the N^3LO QCD calculation of the inclusive Higgs boson production in gluon fusion;

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

2) the NNLO QCD calculation of the fiducial cross sections for the production of a Higgs boson and a jet at the LHC;

Boughezal, Caola, K.M., Petriello, Schulze
Boughezal, Focke, Giele, Liu, Petriello
Chen, Gehrmann, Glover, Jacqueir

3) the NNLO QCD calculation of the fiducial cross section for Higgs production in weak boson fusion at the LHC.

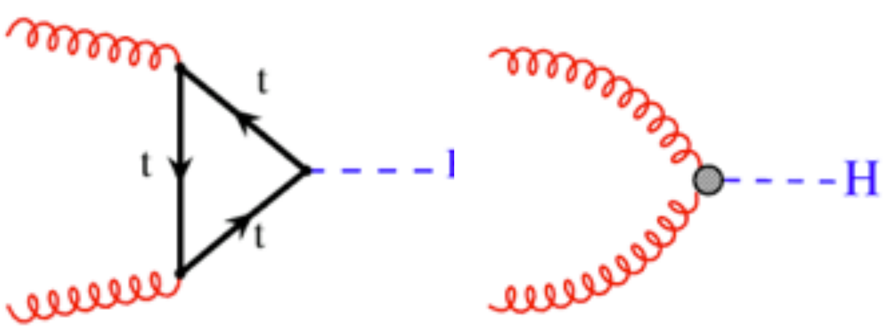
Cacciari, Dreyer, Kalberg, Salam, Zanderighi

These three results are important since they give us a new perspective on the ultimate precision achievable on the theory side in the exploration of Higgs boson physics at the LHC. Another important lesson that these results seem to teach us is that -- beyond a certain level -- fixed order results are indispensable and can not be substituted by their approximate estimates.

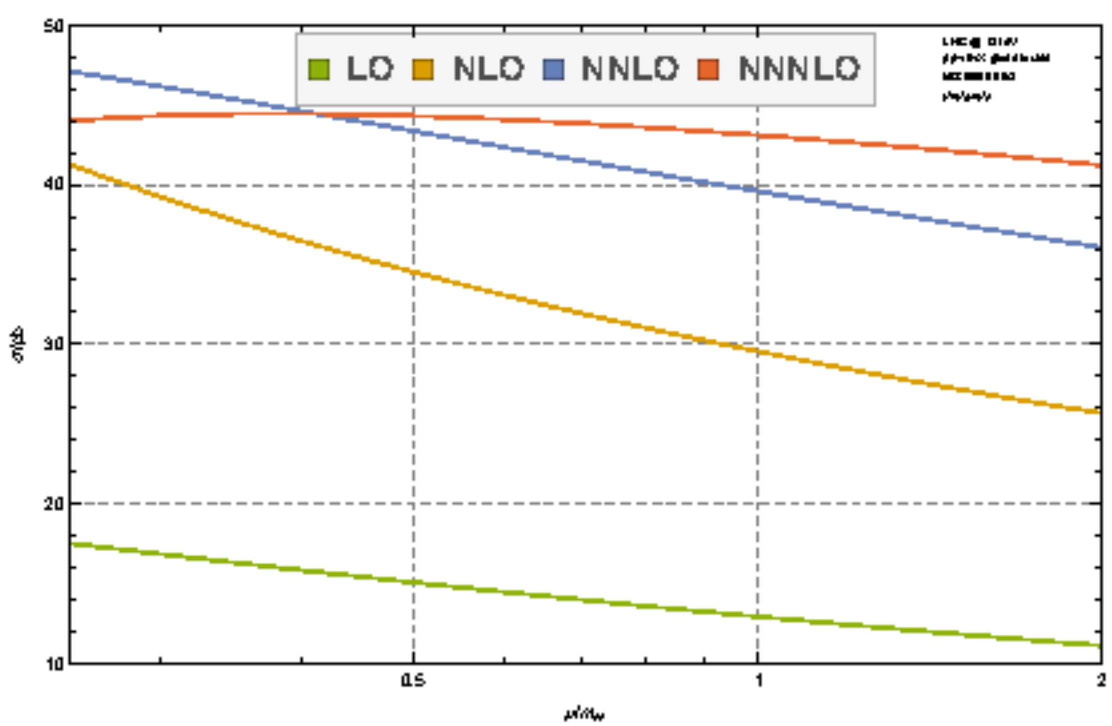
Higgs production in gluon fusion at N^{3}LO

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

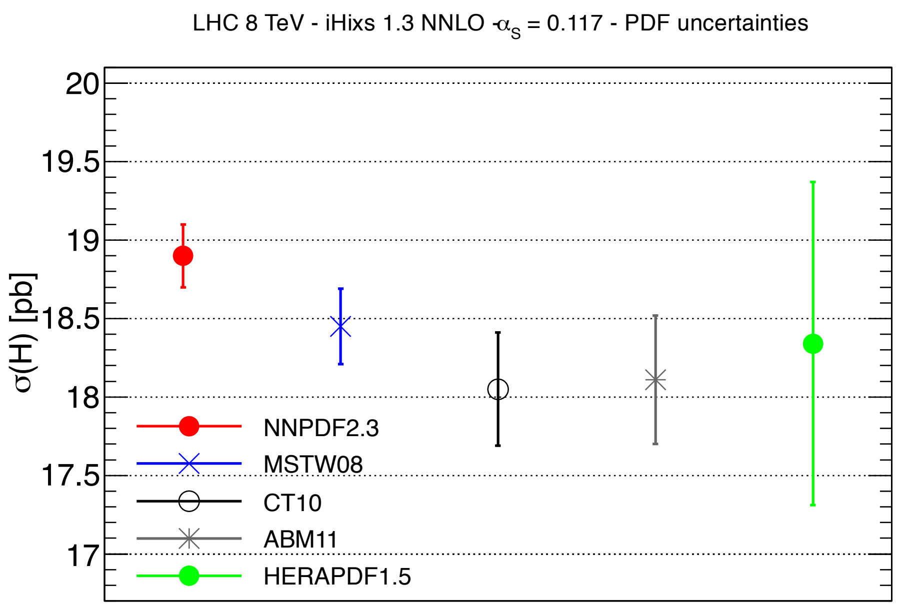
The perturbative series for gg -> H cross section appear to converge. This is no small feat as the corrections start at O(100%) at NLO, are still O(20%) at NNLO, but decrease to just O(4%) at N^{3}LO. The residual scale dependence uncertainty is just about 3%.

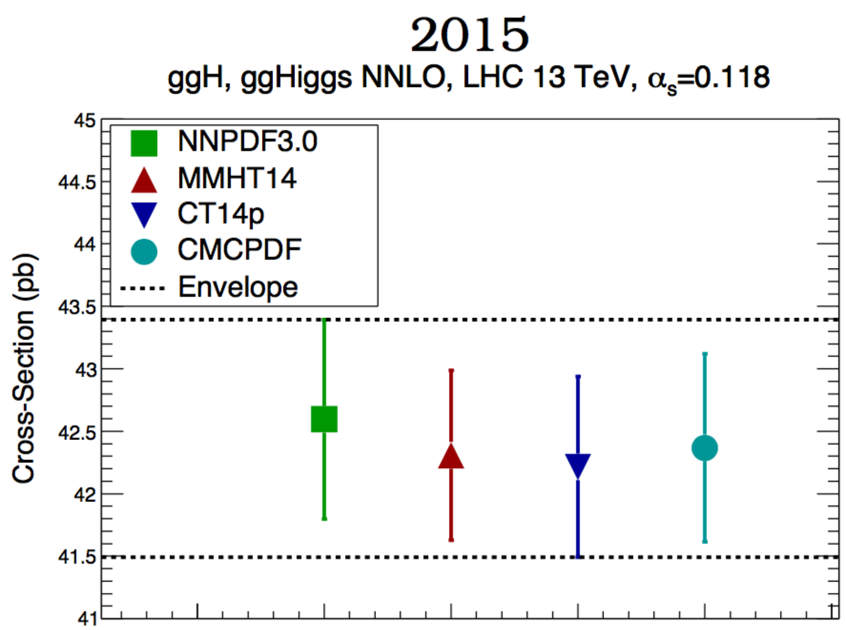
At this level of precision, many other effects (pdfs, finite top/bottom masses, electroweak corrections and even non-perturbative corrections) may become important and need to be understood and adequately controlled.

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

Parton distribution functions

As an example, let us discuss the parton distribution functions. First, different PDF-fitting groups seem to finally agree on the Higgs production cross section. Second, strictly speaking, the N^{3}LO calculation requires N^{3}LO PDFs which are not (and probably never will be) available. There is an argument (S. Forte) that for 125 GeV Higgs boson produced at 8 TeV, one does not need N^{3}LO PDFs. The argument is based on an observation that the dependence on the "order" of PDF is weak for 125 GeV/ 8 TeV combination. It is not understood why this is so; and it is not a valid feature for other energies / masses .





What is the uncertainty that we need to assign to gluon fusion cross section to account for missing N^{3}LO PDFs? This is the question that is nearly impossible to answer...

This means that -- without convincing estimate of N^{3}LO PDF effects -- it will be impossible to claim that (a would be) few percent differences seen in the measurement of the Higgs couplings relative to the SM predictions is not a consequence of higher order effects in PDFs.

Higgs boson production in gluon fusion

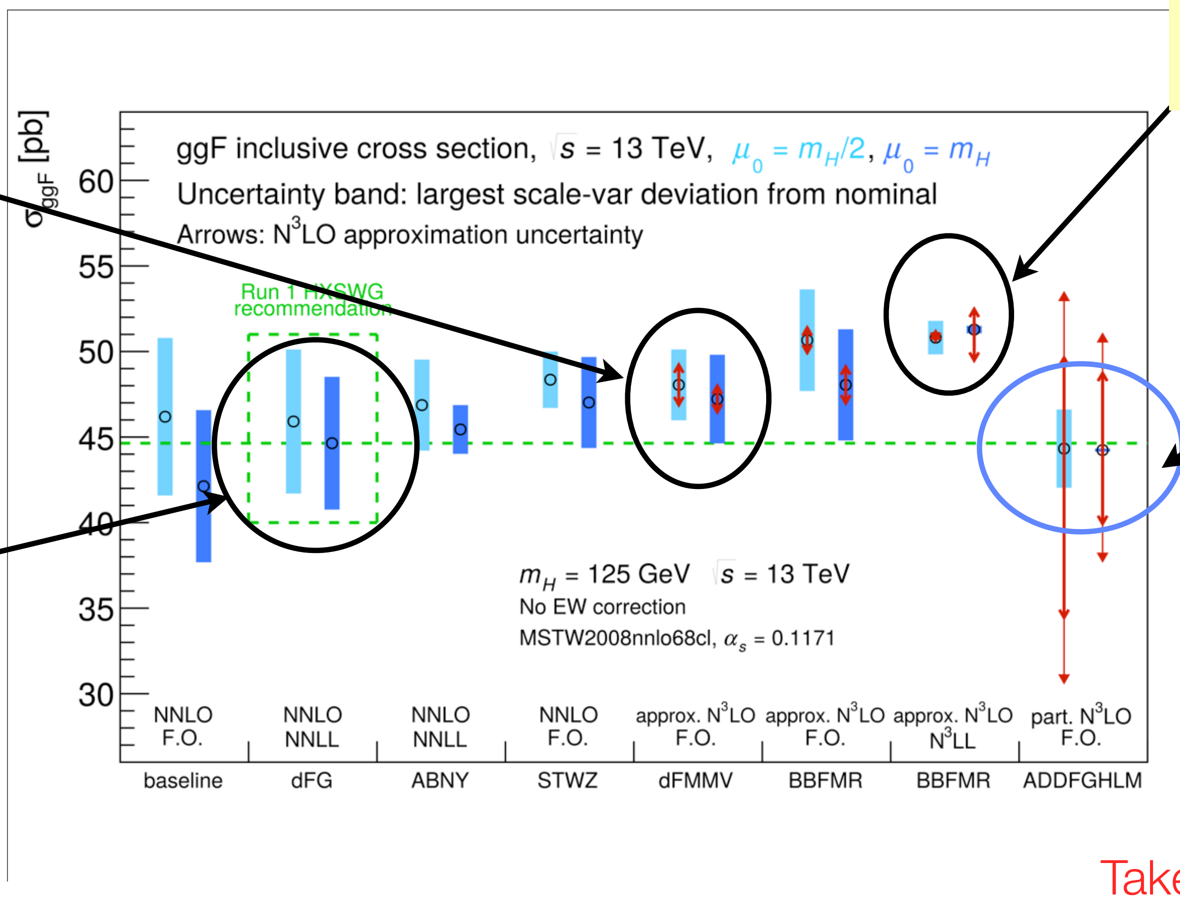
Estimates of N^{3}LO Higgs production cross sections were attempted before an exact calculation using various approximations (essentially, emission or soft gluons or powers of π are assumed to be the dominant source of QCD corrections). The HXWG has assembled various predictions for the Higgs cross section made before the N^{3}LO result became available. The picture below should tell us about the success or failure of these predictions. But it does not...; it leaves more questions than answers. However, the correct answer is important since it will teach us if approximate predictions for Higgs production cross section are reliable and to what extent.

The authors of this result claim the same increase of the cross-section relative to NNLO as the exact N3LO computation shows. Yet, the results on that plot are apparently different.

Good agreement with N3LO; obviously larger errors.

It would be important to understand why this point is so much higher than everybody else and why the claimed precision is so high.

N3LO result



Taken from the HXWG summary

H + jet at NNLO

H+jet @ NNLO

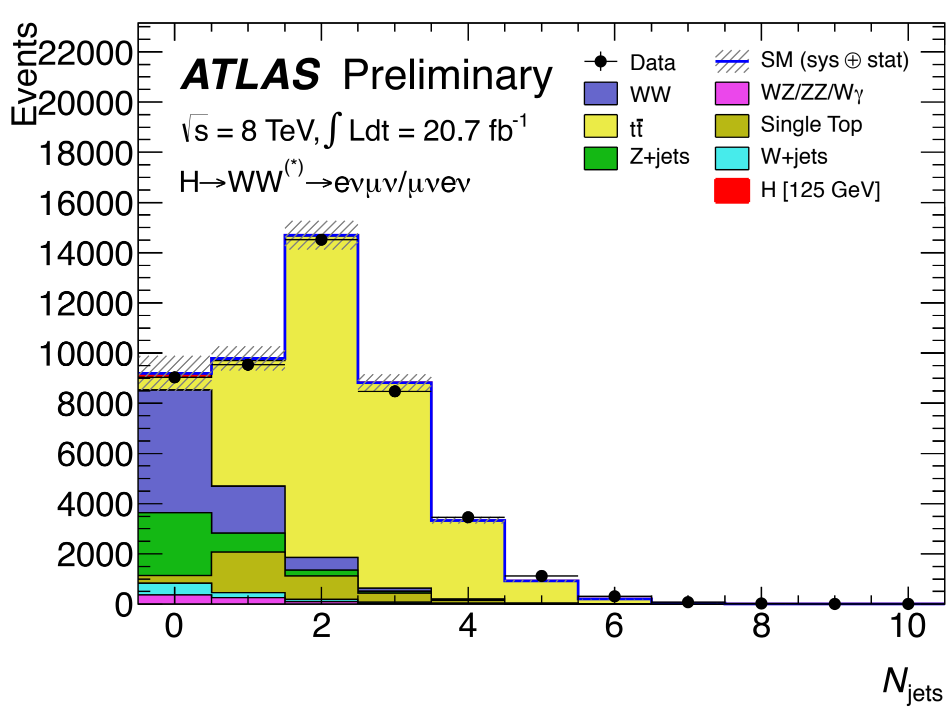
Fiducial cross sections are measured in experiment; theory predictions for measurable quantities are very important.   A ``fiducial partner" of the total Higgs production cross section at N^3LO, is the H+j cross section at NNLO QCD.

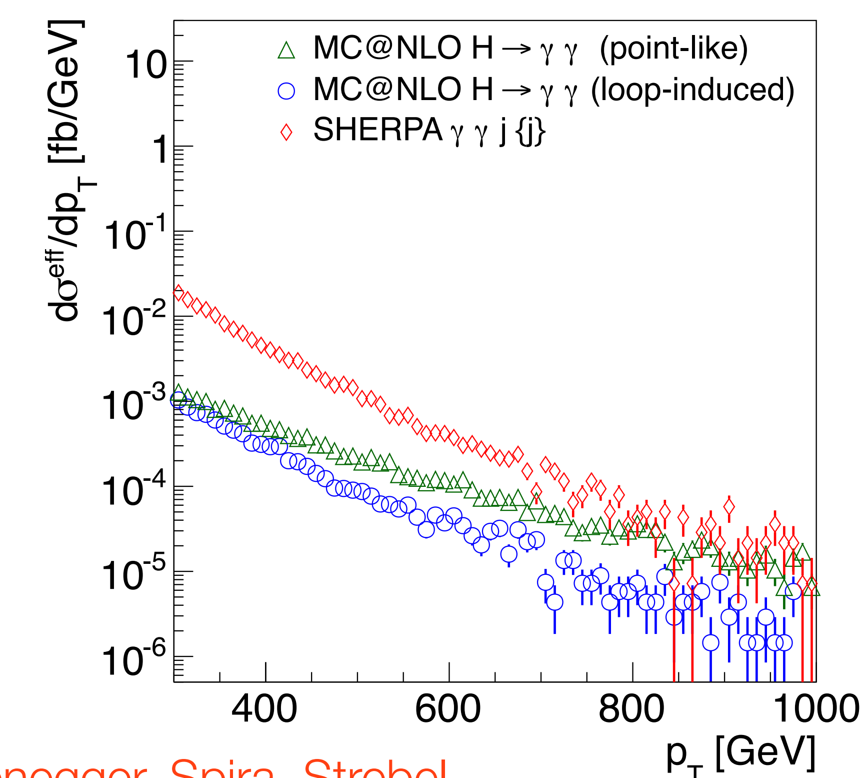
H+jet production is important since

1) it has relatively large cross section;

2) jet-binning is essential for proper background rejection;

3) gluon radiation generates the transverse momentum of the Higgs boson; testing Higgs transverse momentum distribution offers a way to probe a ``point-like" component of the HGG vertex.

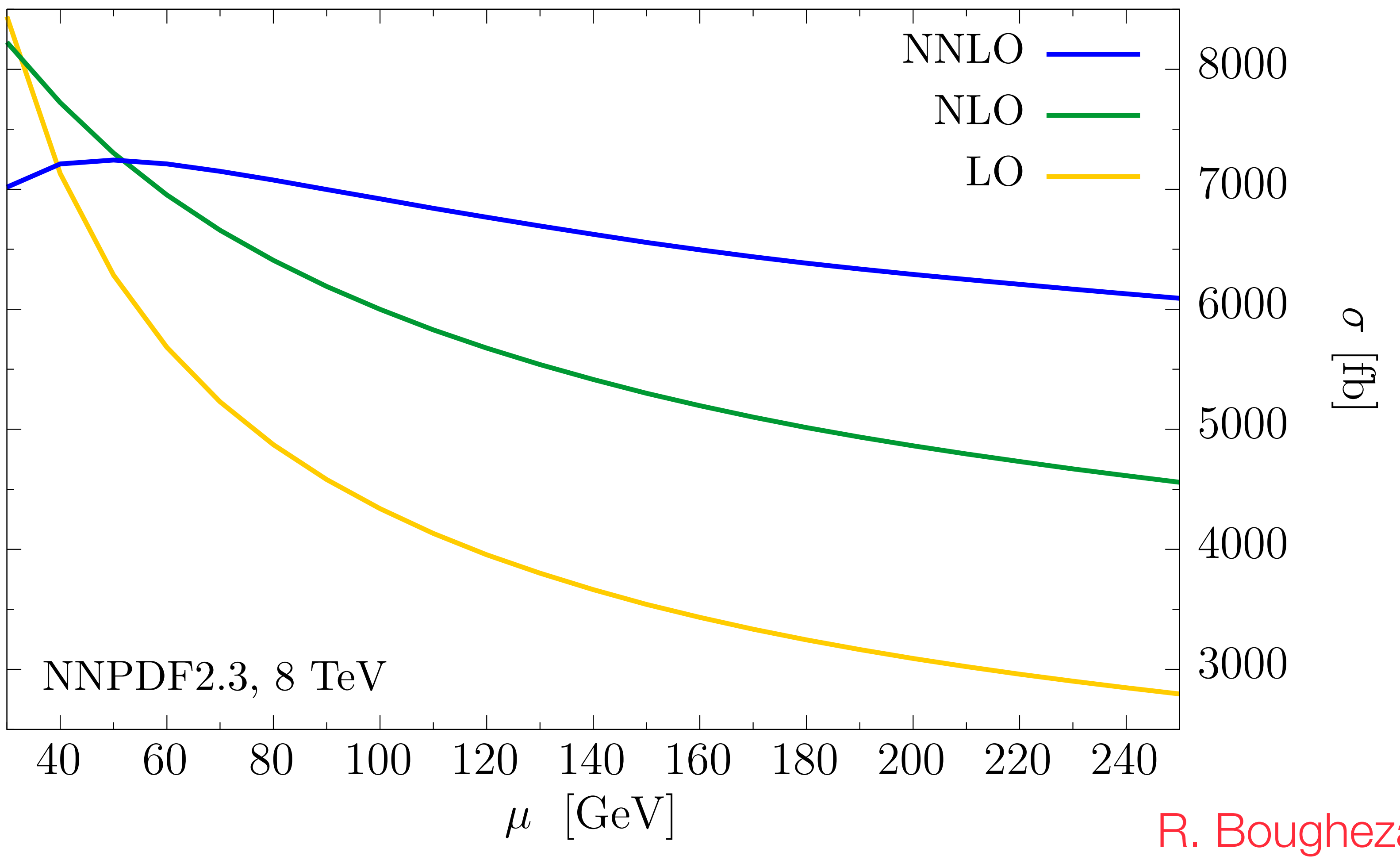




Langenegger, Spira, Strebel

H+jet @ NNLO

The NNLO QCD corrections to H+jet production at the LHC were computed recently. They increase the H+jet production cross section by O(20%) and significantly reduce the scale dependence uncertainty . This is similar to corrections to the inclusive Higgs production cross section although corrections to H+j are slightly smaller.



$$\sigma_{\rm LO} = 3.9^{+1.7}_{-1.1}\ {\rm pb}$$

$$\sigma_{\rm NLO} = 5.6^{+1.3}_{-1.1}\ {\rm pb}$$

$$\sigma_{\rm NNLO} = 6.7^{+0.5}_{-0.6}\ {\rm pb}$$

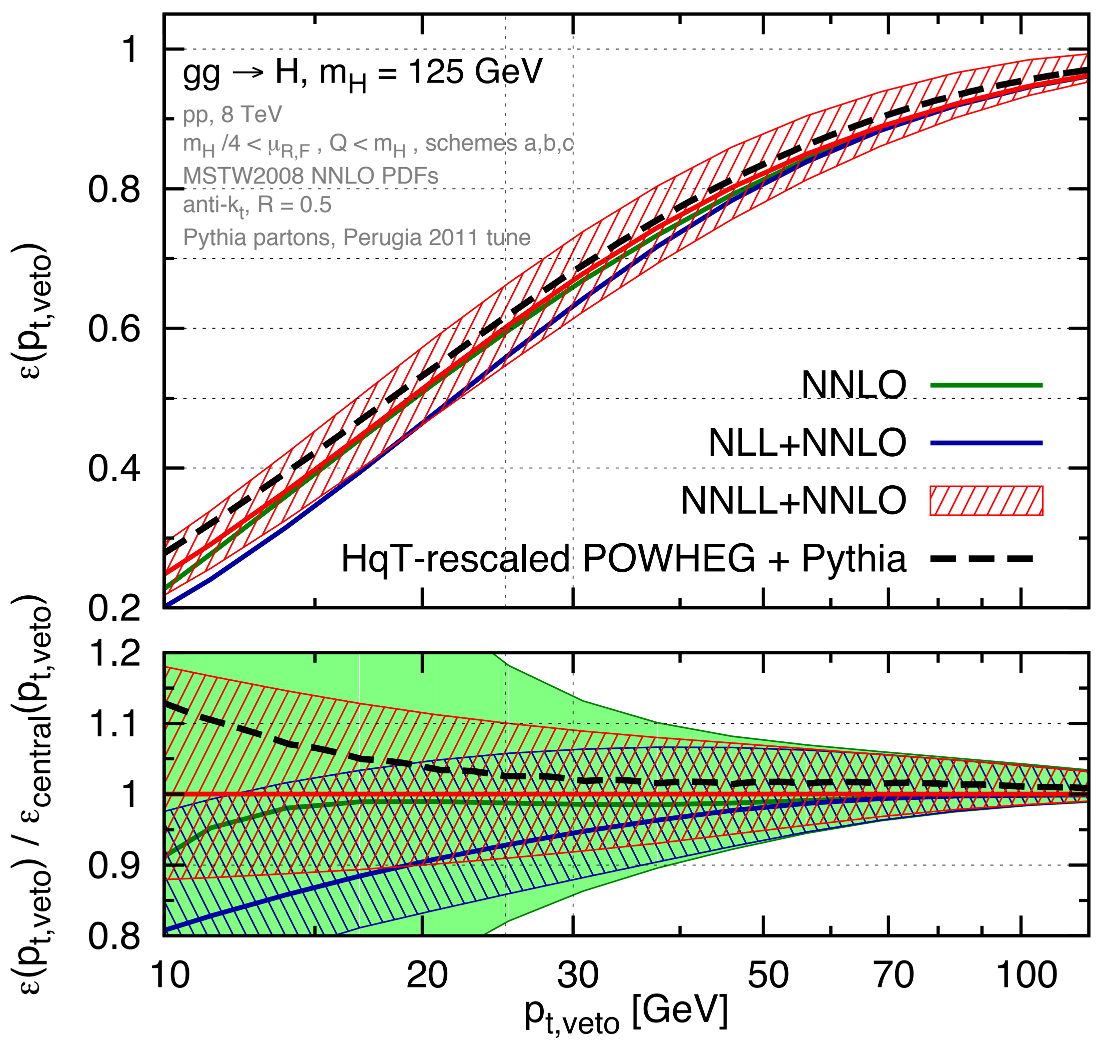
The cross sections for the anti-k_t algorithm with the jet transverse momentum cut of 30 GeV at the 8 TeV LHC.

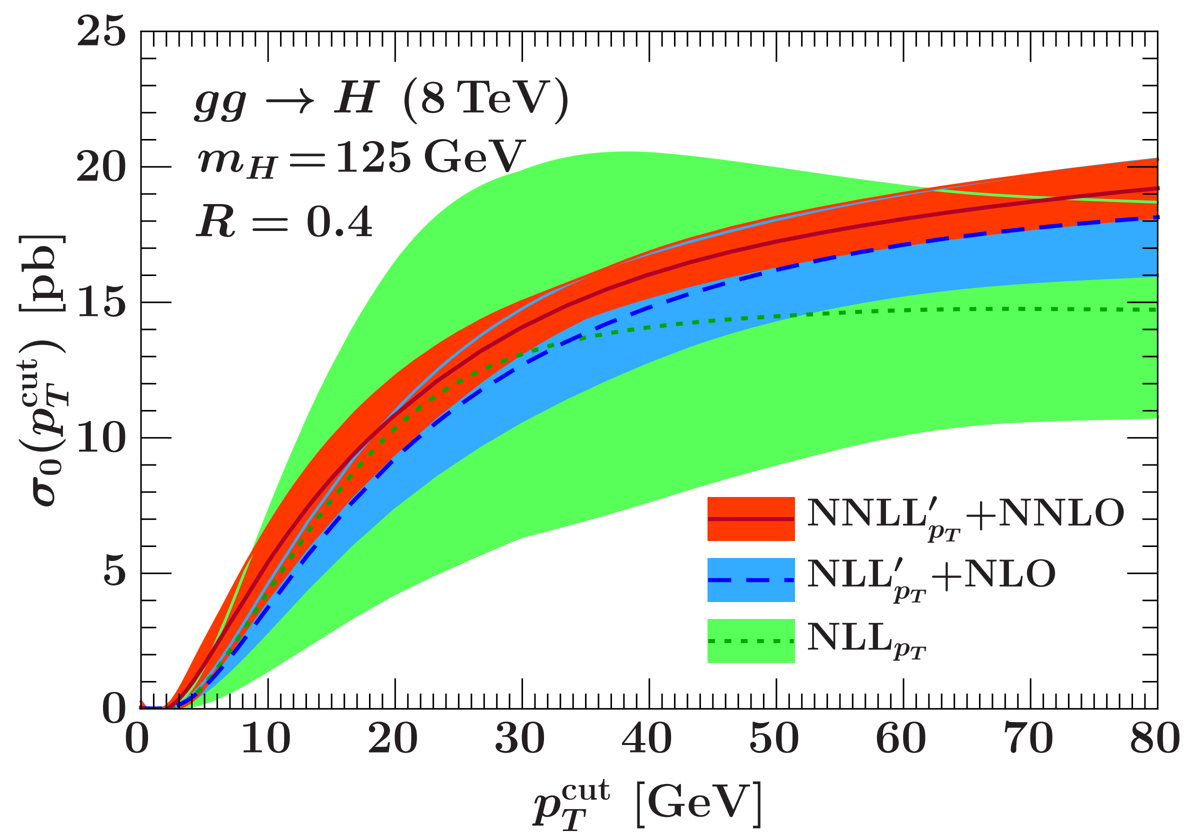
R. Boughezal, F. Caola, K.M., F. Petriello, M. Schulze

Using these results and the N^{3}LO computation of the Higgs total cross section, one can find the fraction of Higgs boson events without detectable jet radiation.

Jet veto acceptances

To this end, one has to subtract the inclusive H+j production cross section from the inclusive Higgs production cross section in matching orders of pQCD; the result will be the Higgs production cross section with zero jets. Until very recently -- such analysis was restricted to NNLO, this year -- an opportunity to extend it to N^3LO.





Re-summation of many different potentially enhanced terms (logarithms of the transverse momentum cut and the jet radius) were performed by many groups. Matching to fixed order results is supposed to have a major impact.

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

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

Jet veto acceptances

Consider the following scenario

- LHC13, NNPDF2.3
- anti-k_T, R=0.5, $\mu_0=m_H$, $Q_{res} = m_H/2$, $p_{T,veto}$ = 30 GeV
- any other setup can be obtained [as well as $\varepsilon(p_{T,veto})$]

0-jet bin

ord	$\sigma^{\text{f.o.}}_{0-\text{jet}}$ (JVE)	$\sigma^{\text{f.o.+NNLL}}_{0-\text{jet}}$ (JVE)	$\sigma^{\text{f.o.+NNLL}}_{0-\text{jet}}$ (scales)
NNLO	$26.2^{+4.0}_{-4.0}$ pb	$25.8^{+3.8}_{-3.8}$	$25.8^{+1.6}_{-1.6}$
N^3LO	$27.2^{+2.7}_{-2.7}$ pb	$27.2^{+1.4}_{-1.4}$	$27.2^{+0.9}_{-0.9}$

≥1-jet bin

ord	$\sigma^{\text{f.o.}}_{\geq 1-\text{jet}}$ (scales)	$\sigma^{\text{f.o.}}_{\geq 1-\text{jet}}$ (JVE)	$\sigma^{\text{f.o.+NNLL}}_{\geq 1-\text{jet}}$ (JVE)
NLO	$14.7^{+2.8}_{-2.8}$ pb	$14.7^{+3.4}_{-3.4}$	$15.1^{+2.7}_{-2.7}$
NNLO	$17.5^{+1.3}_{-1.3}$ pb	$17.5^{+2.6}_{-2.6}$	$17.5^{+1.1}_{-1.1}$

- No breakdown of fixed order perturbation theory for $p_T \sim 30$ GeV ;
- Reliable error estimate from lower orders ;
- Re-summed results do not improve fixed order results. Access to higher order predictions is crucial !

F. Caola, shown at the HCWG meeting, June 2015

H+jet @ NNLO : fiducial results

The drawback of these results is that they still can not be used to describe fiducial volume cross sections since decays of the Higgs boson are not included. This is, however, easy to do since the Higgs boson is a scalar particle and no spin correlations are involved. What makes this 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

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

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

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

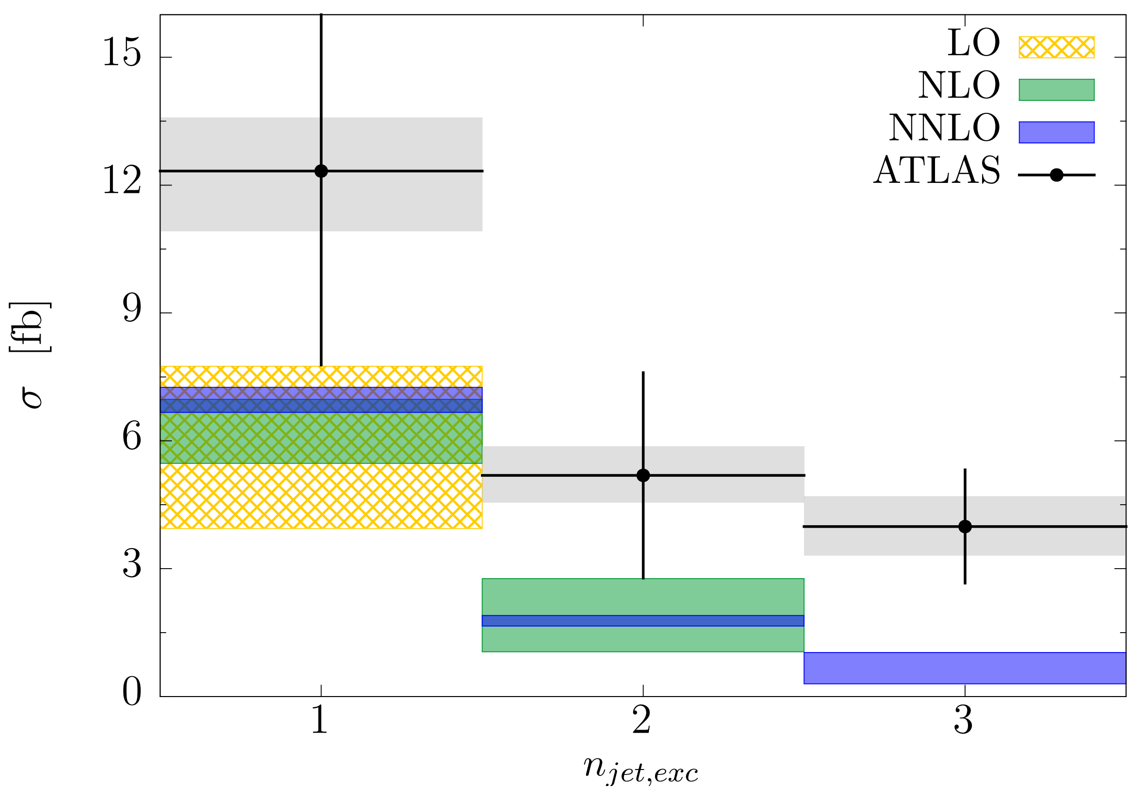
The difference between the ATLAS H+j measurements and the SM prediction is close to two standard deviations; the ratio of central values is larger than in the inclusive case.

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

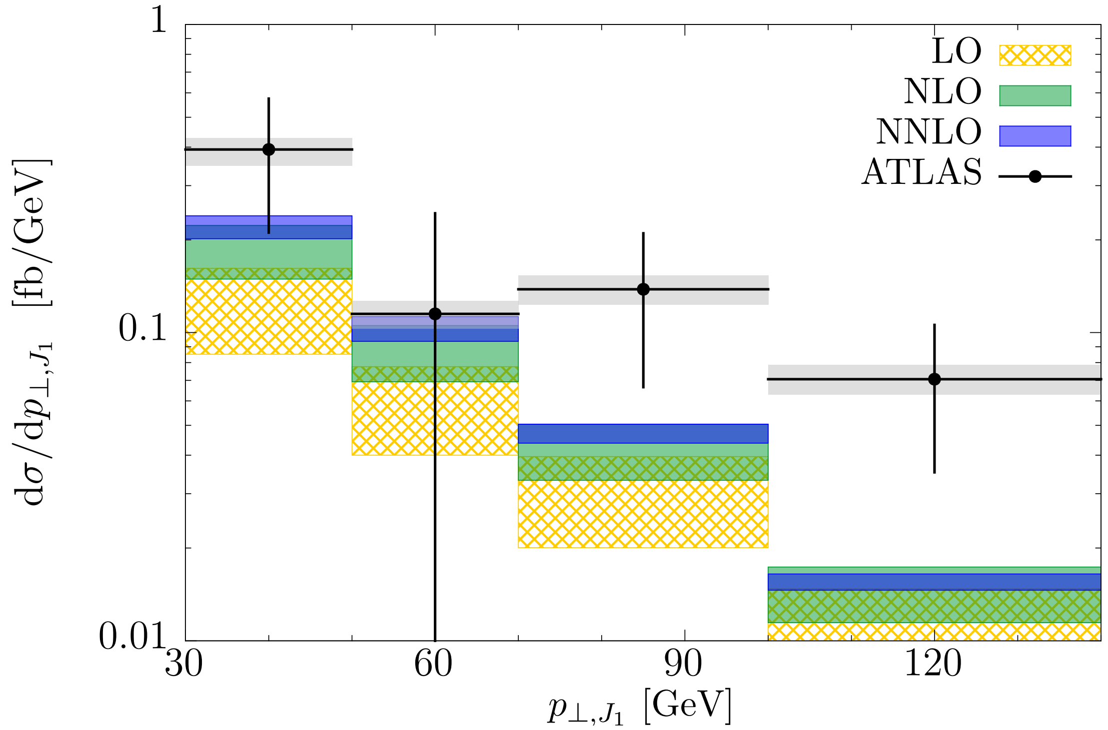
H+jet @ NNLO : fiducial results

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 the ATLAS data is performed.

Data is always higher than the theory prediction; shapes of jet transverse momentum distribution are also different. Although these discrepancies are not statistically significant, they are peculiar. 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

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

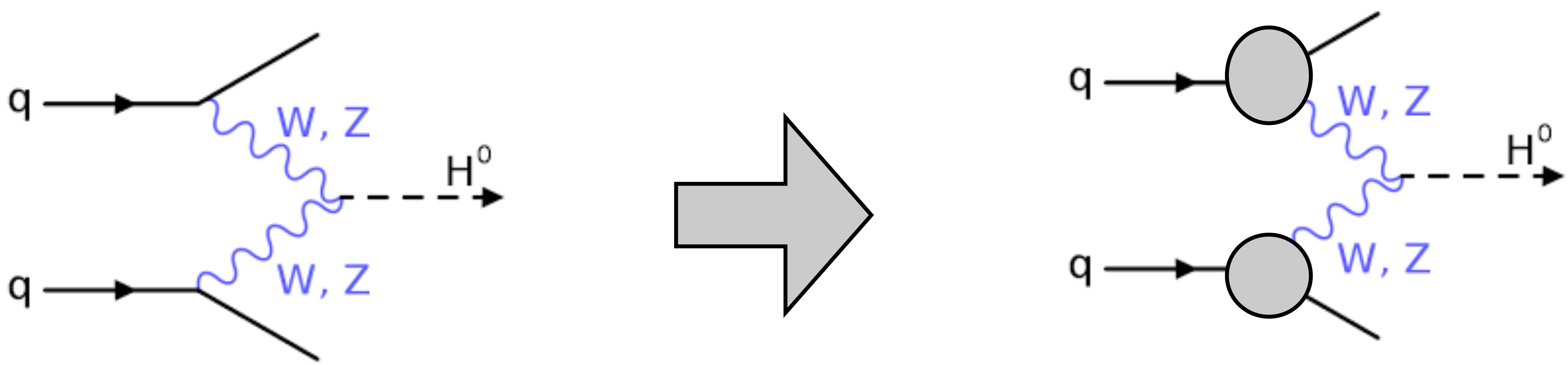
Higgs in WBF at NNLO

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) ; it then seemed natural to assume that this size of QCD corrections will be indicative for the fiducial cross sections.



Bolzoni, Maltoni, Moch, Zaro

Higgs boson production in weak boson fusion

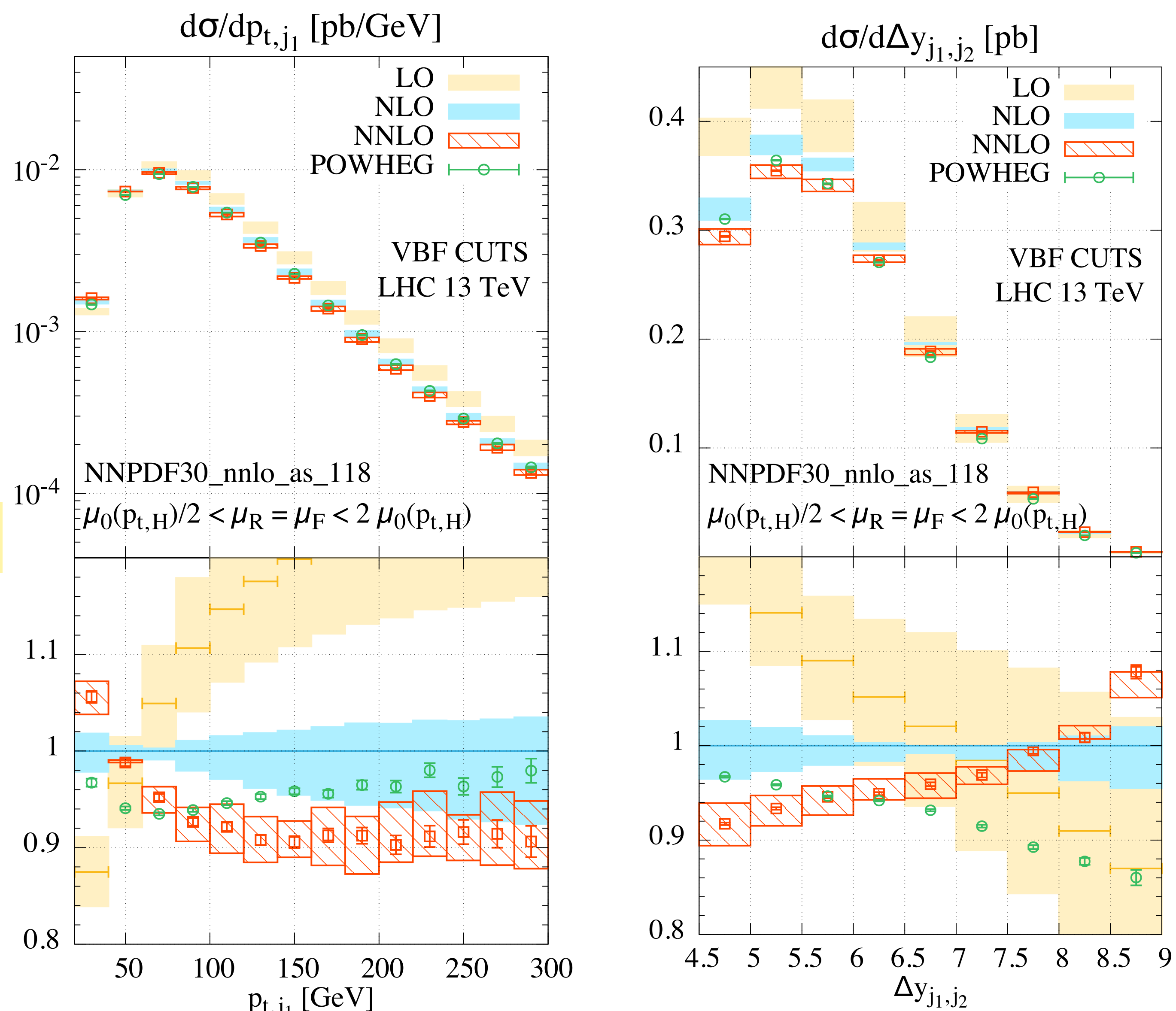
However, this assumption turns out to be incorrect and, in fact, one can get larger O(6-10%) corrections for fiducial (WBF cuts) cross sections and kinematic distributions. Often, the shape of those corrections seems rather different from both the NLO and/or parton shower predictions. The message -- again -- seems to be that fixed order computations are required beyond certain level of precision; approximate results may indicate their magnitude but not much beyond that.

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

	$\sigma^{\rm nocuts}$[pb]	$\sigma^{\rm VBF~cuts}$[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

Conclusion

Availability of precise predictions for Higgs 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 N^{3}LO, H+jet at NNLO, Higgs in WBF at NNLO). NNLO predictions for fiducial cross sections and kinematic distributions are becoming available; this will make extraction of the Higgs coupling constants much more accurate than previously anticipated.

These fixed order predictions can be compared to various approximations invented to estimate expected magnitude of radiative corrections. It appears (c.f. N^{3}LO, H+j and H@WBF) that approximate methods do not provide satisfactory estimates although more studies are needed for definite conclusions.

The impressive progress with fixed order computations as well as with merging and matching should enable us to verify -- or disprove -- the Standard Model nature of the Higgs boson at the LHC in a convincing and reliable way.

Luminosity	300 fb^{-1}	3000 fb^{-1}
Coupling parameter	7-parameter fit	
κ_γ	$5-7\%$	$2-5\%$
κ_g	$6-8\%$	$3-5\%$
κ_W	$4-6\%$	$2-5\%$
κ_Z	$4-6\%$	$2-4\%$
κ_u	$14-15\%$	$7-10\%$
κ_d	$10-13\%$	$4-7\%$
κ_ℓ	$6-8\%$	$2-5\%$
Γ_H	$12-15\%$	$5-8\%$