Higher order QCD predictions for Higgs signals

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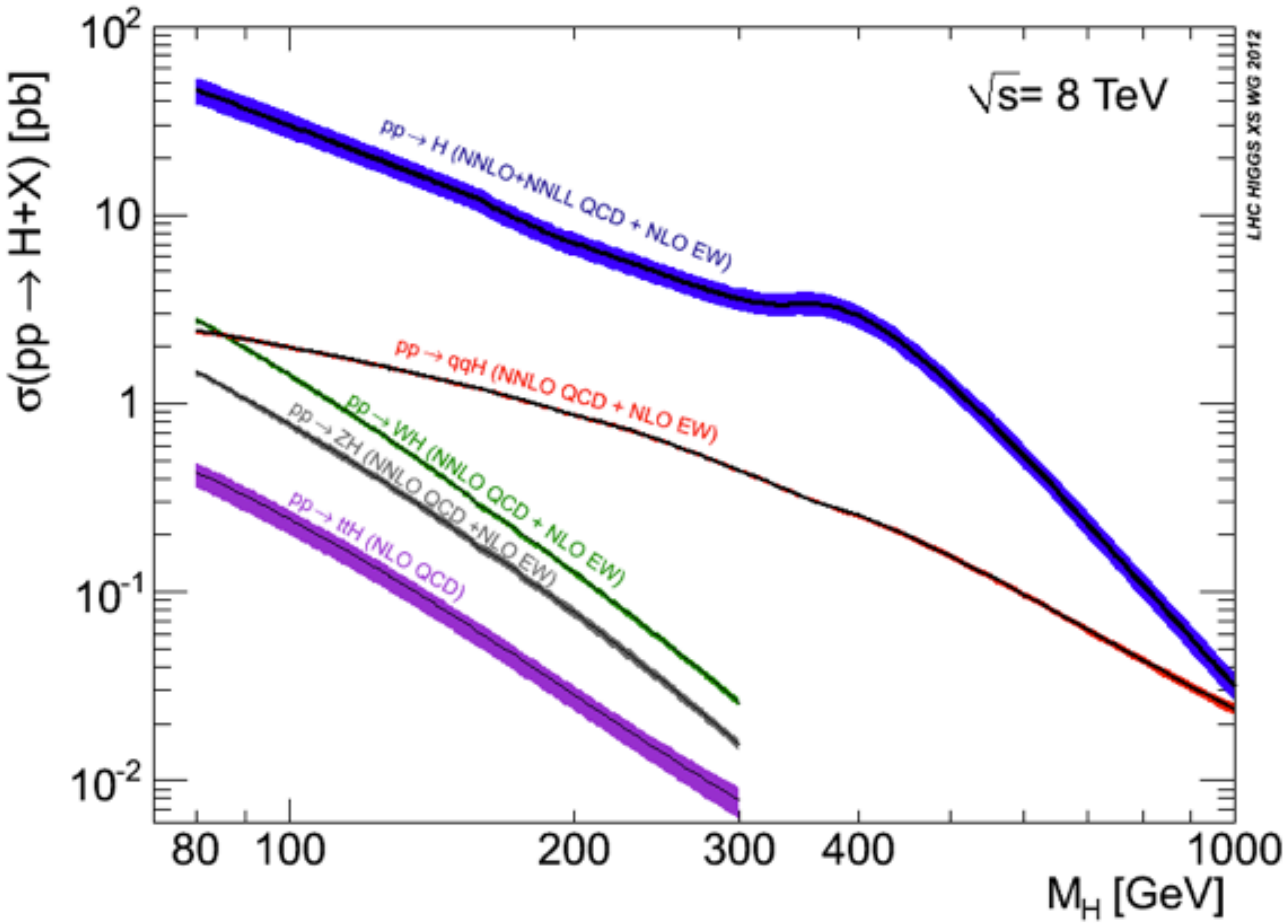
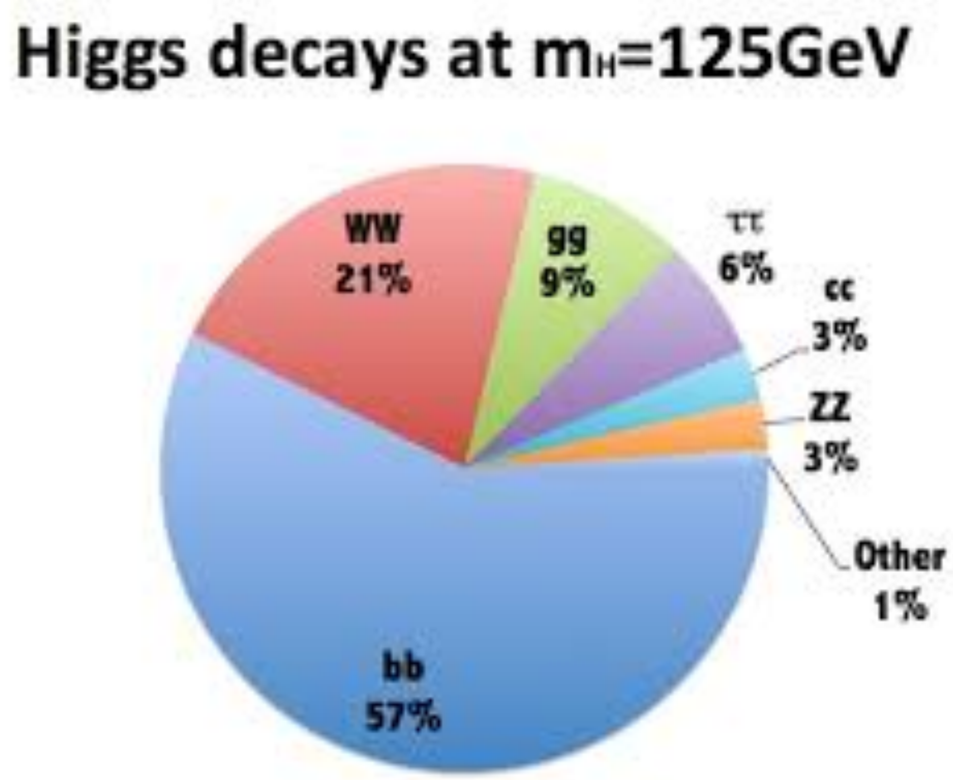
TTP KIT

Higgs couplings 2017, Heidelberg, November 6-10

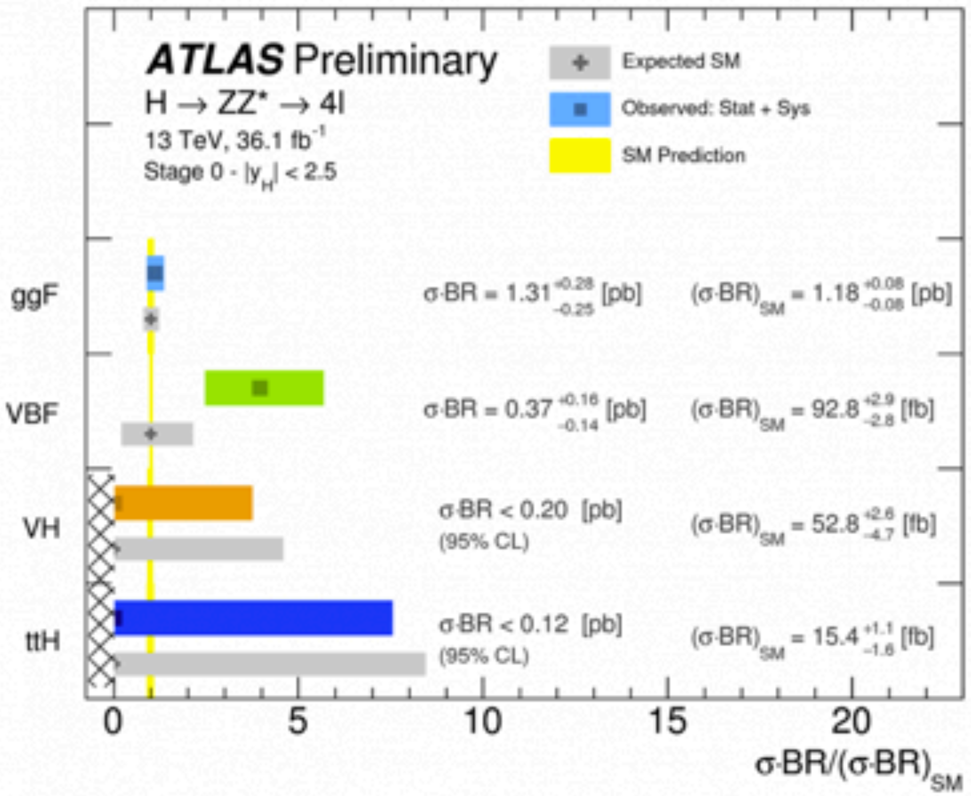
Higgs boson signals

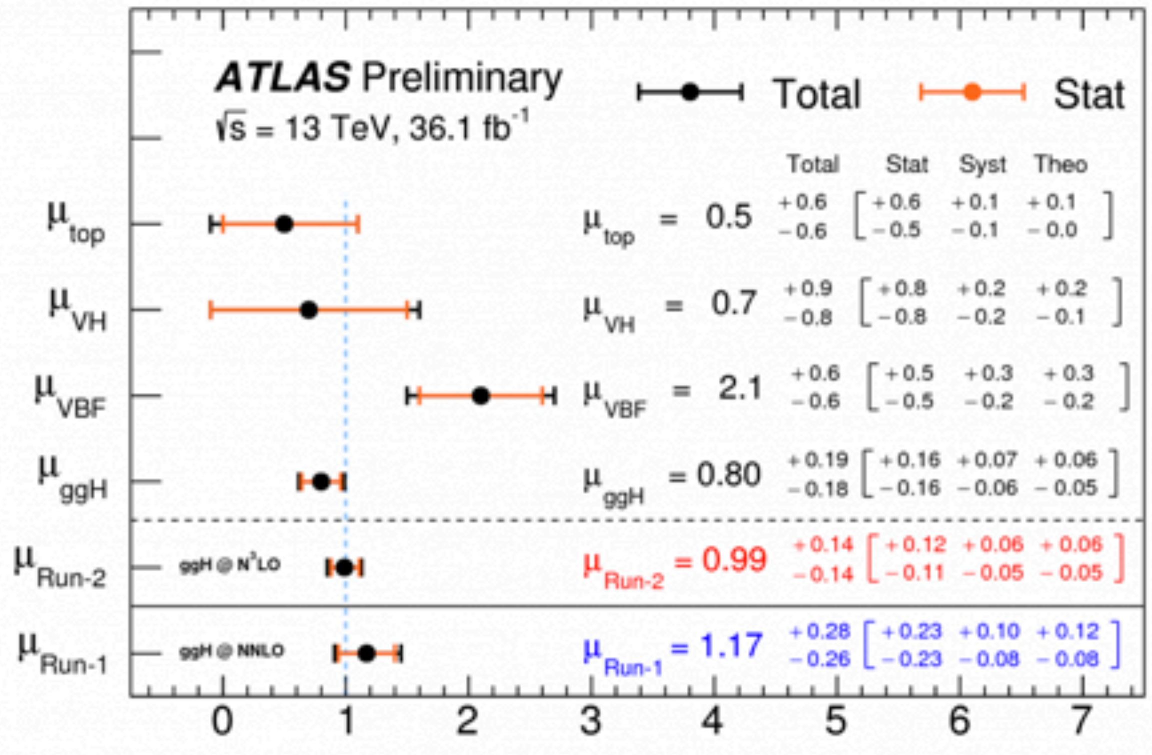
Higgs bosons at the LHC can be produced in gluon fusion, weak boson fusion and in association with vector bosons or top quarks. Higgs can decay to photons, electroweak gauge bosons, b-quarks and tau-leptons. All production and decay channels are important for elucidating Higgs properties.



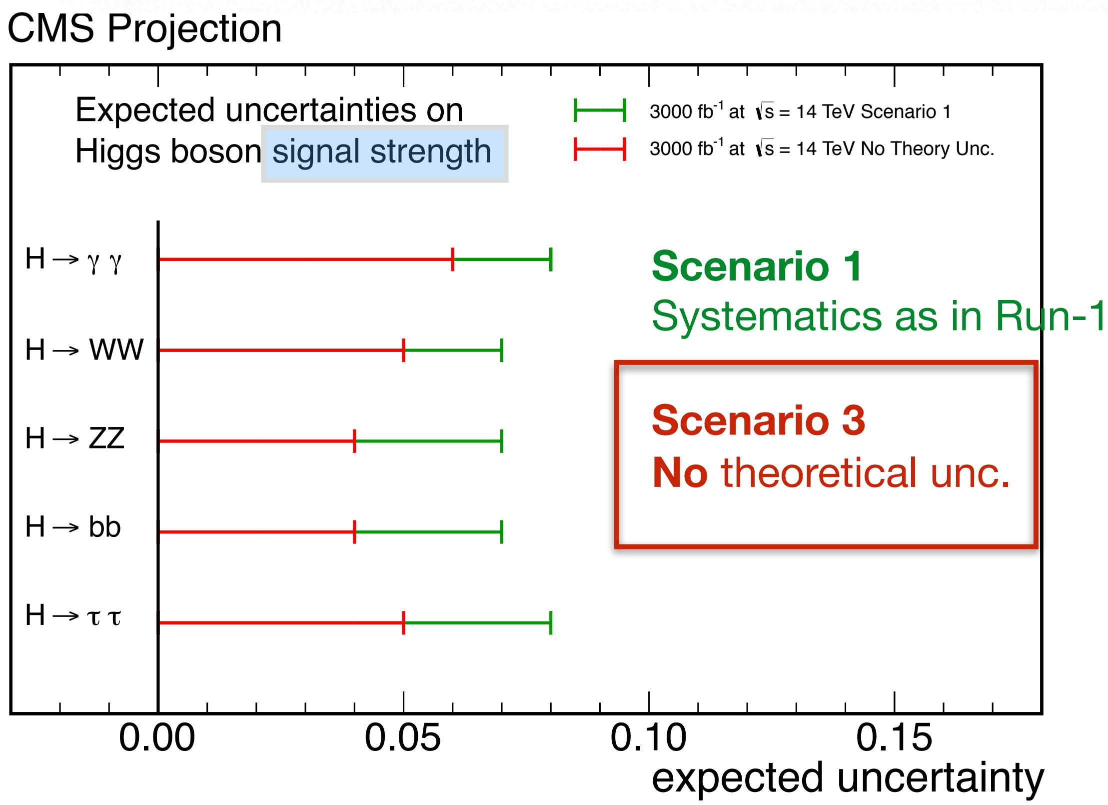


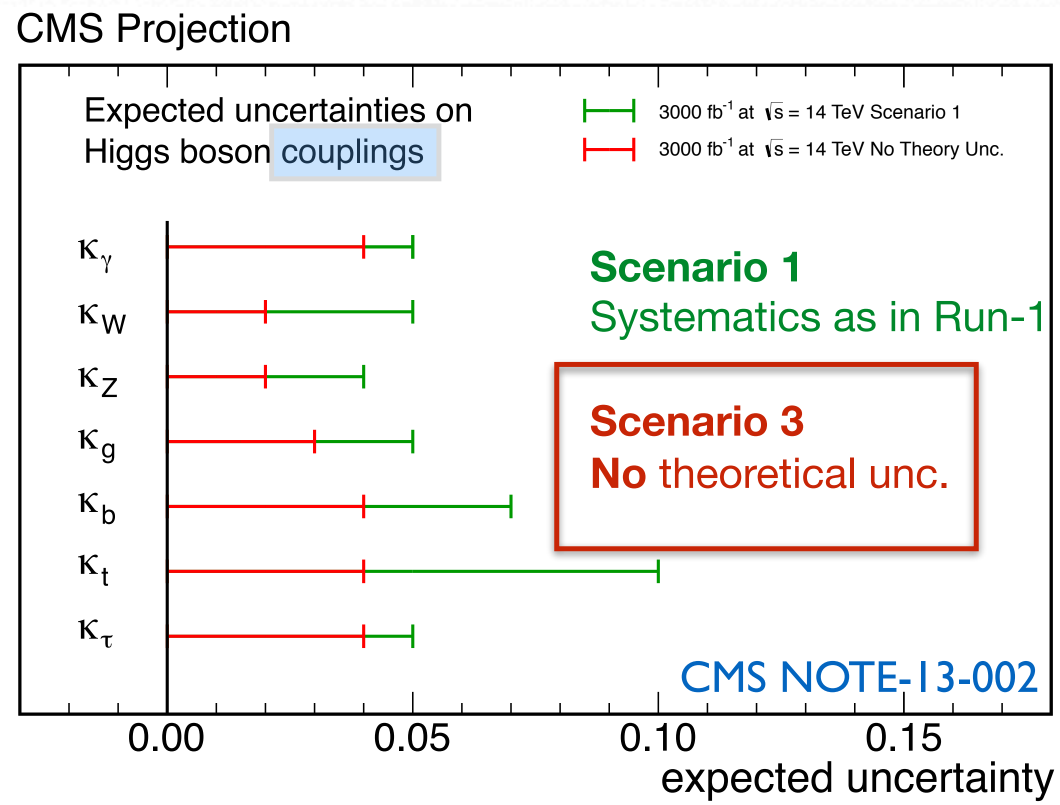
Higgs boson signals: current and future





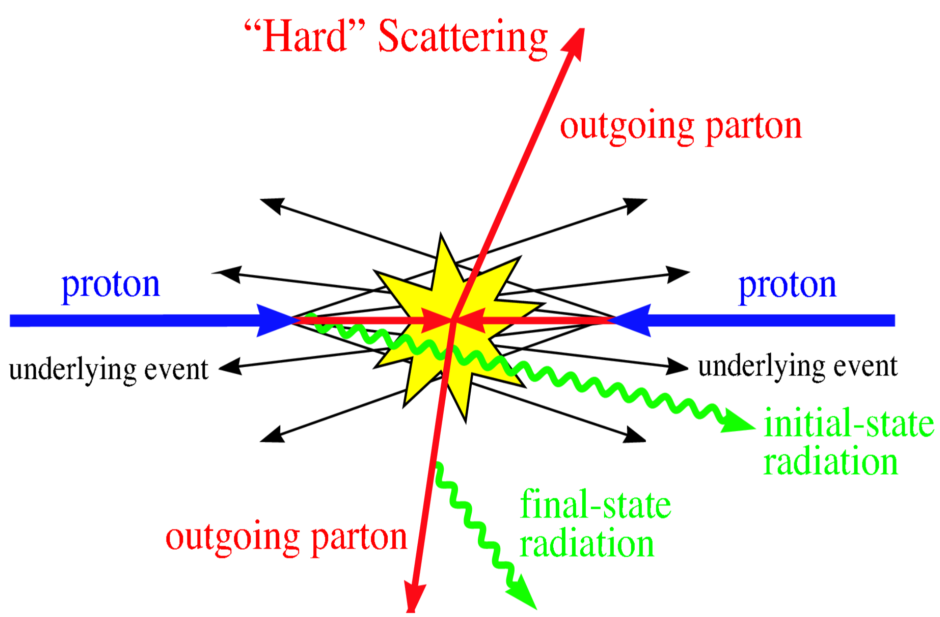
ATLAS-CONF-2017-047

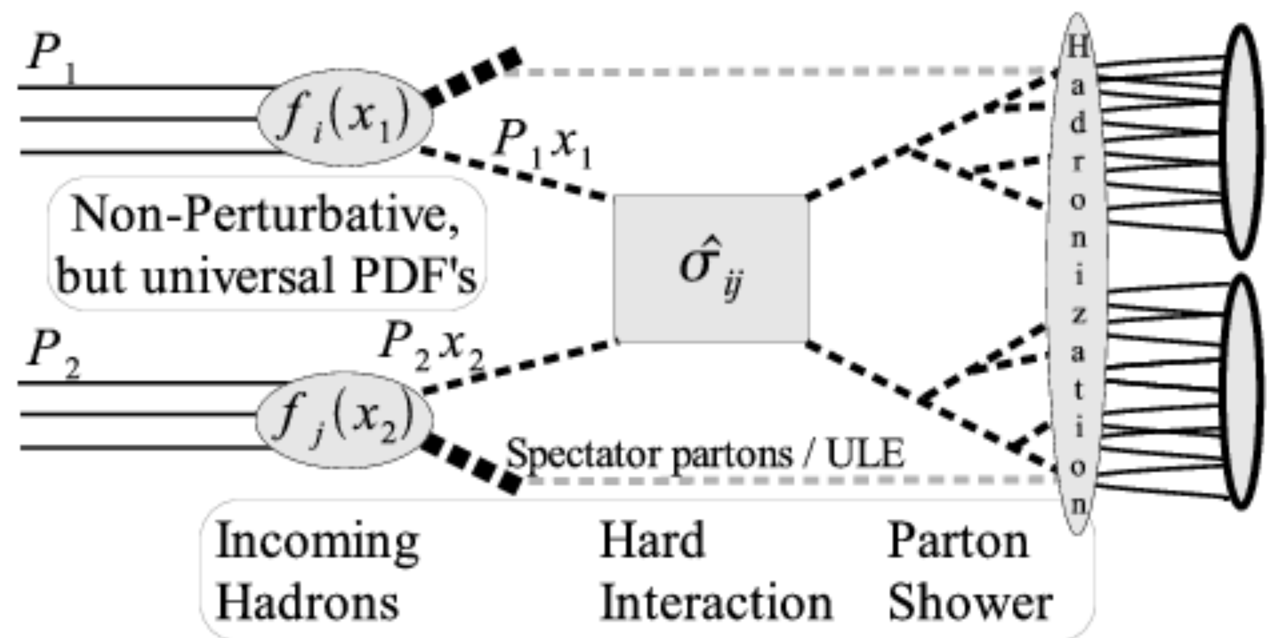




The framework

To describe Higgs production at the LHC, we employ the standard framework of perturbative QCD where production cross sections are computed by convoluting parton distribution functions and partonic cross sections.

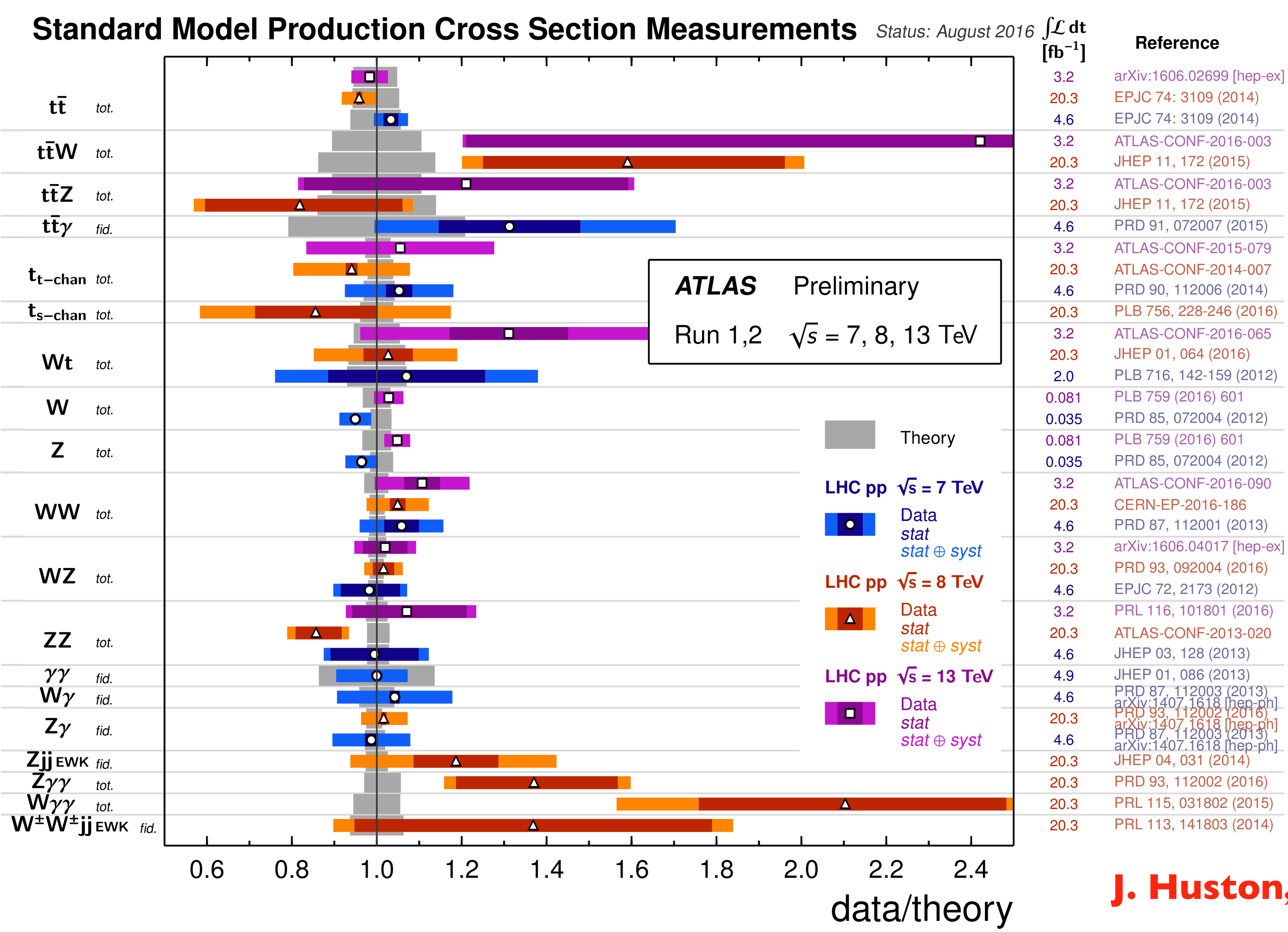




$$\mathrm{d}\sigma = \int \mathrm{d}x_1 \mathrm{d}x_2 f_i(x_1) f_j(x_2) \mathrm{d}\sigma_{ij}(x_1, x_2) F_J \left(1 + \mathcal{O}(\Lambda_{\mathrm{QCD}}/Q)\right)$$

Not just the Higgs production

This pQCD framework is standard; it was used at the LHC and the Tevatron to successfully describe large number of hard scattering processes in the SM.



J. Huston, Loopfest 2016

Advances in understanding the Higgs boson production

The level of sophistication that has been reached in describing Higgs signals at the LHC is without a precedent in particle physics.

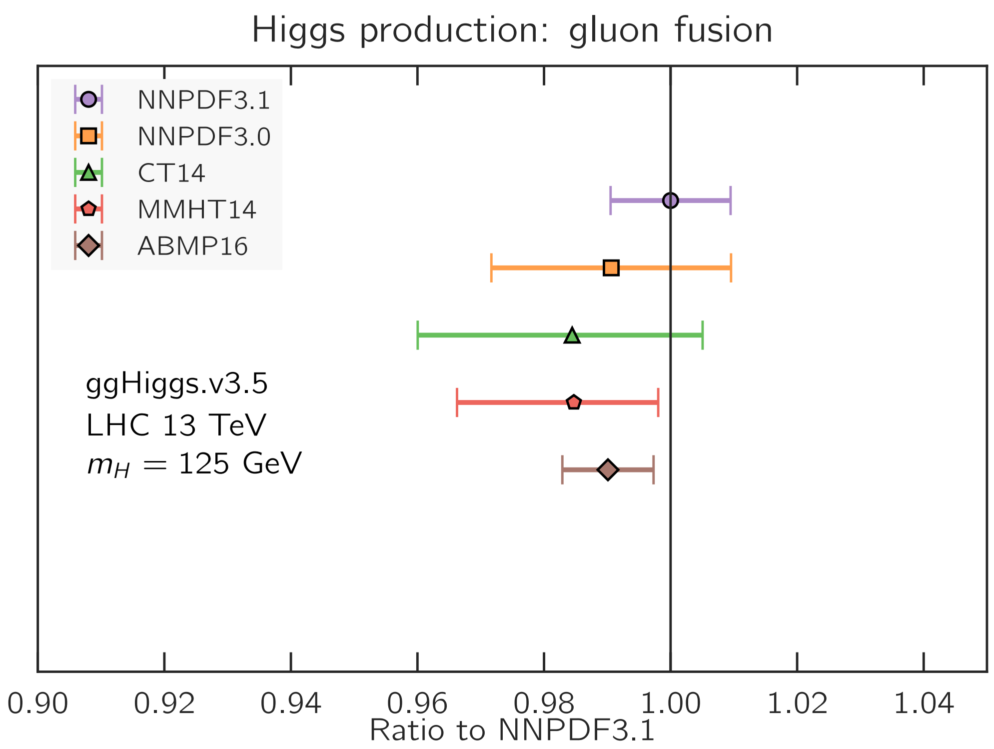
1) all but one major Higgs production channels are currently known through NNLO QCD (gluon fusion and inclusive WBF are known through N^3LO) and through NLO electroweak.

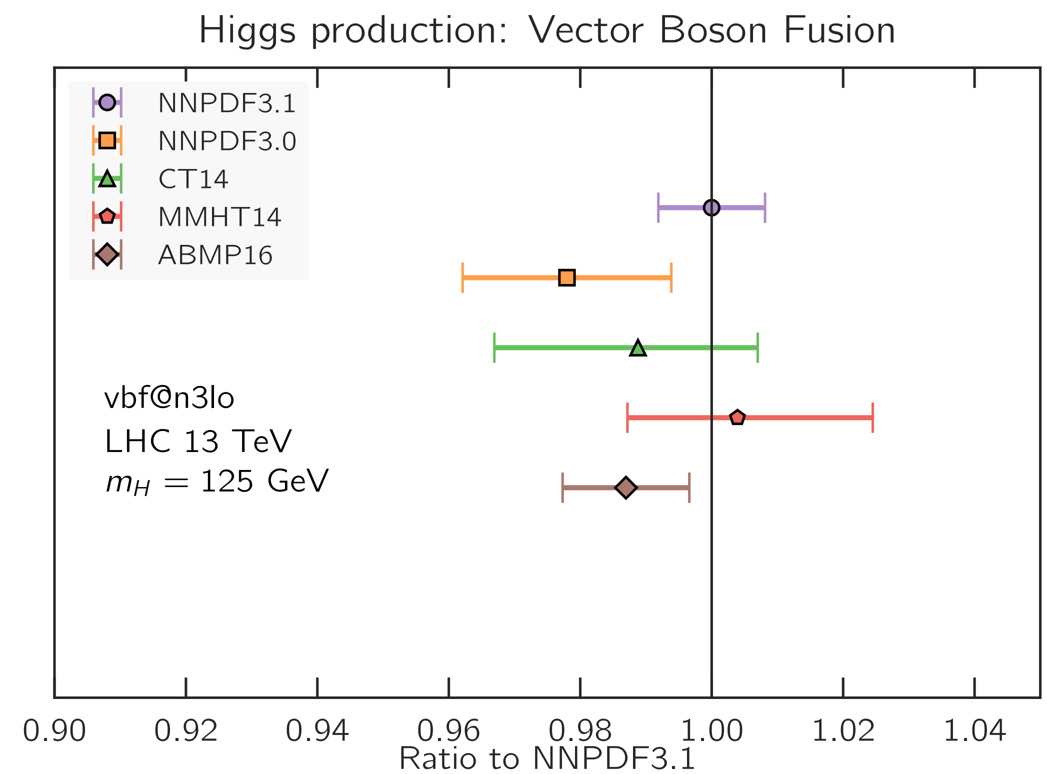
2) processes where Higgs boson is produced in association with several jets are known through NLO QCD.

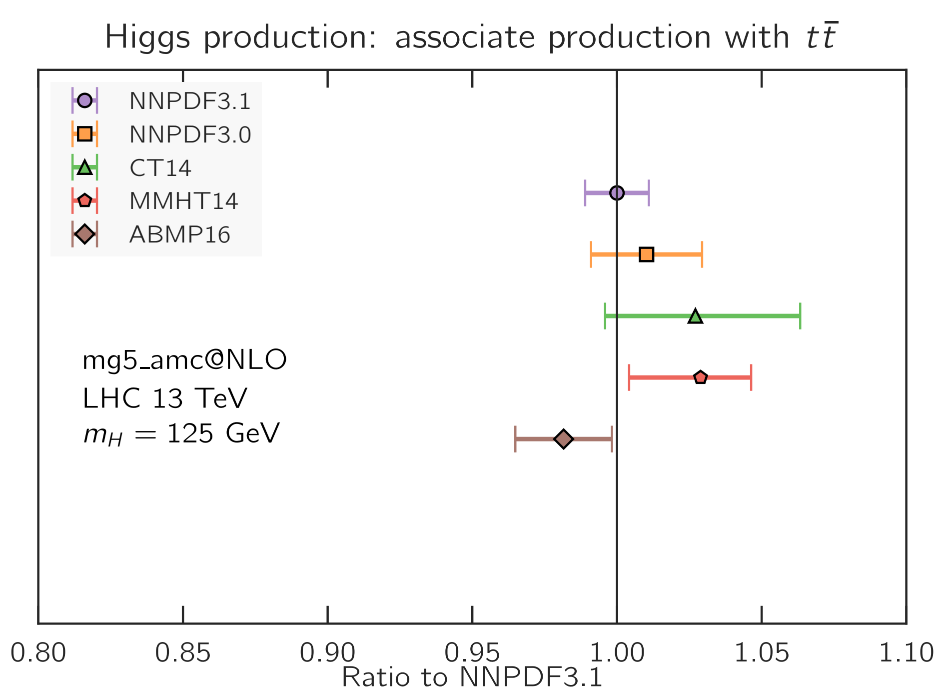
3) Matching and merging of NLO and NNLO QCD results with parton showers is available thanks to major automated programs (MC@NLO, Powheg, Sherpa etc.)

4) All important Higgs decay channels are known through (at least) NNLO QCD and NLO electroweak.

Parton distribution functions





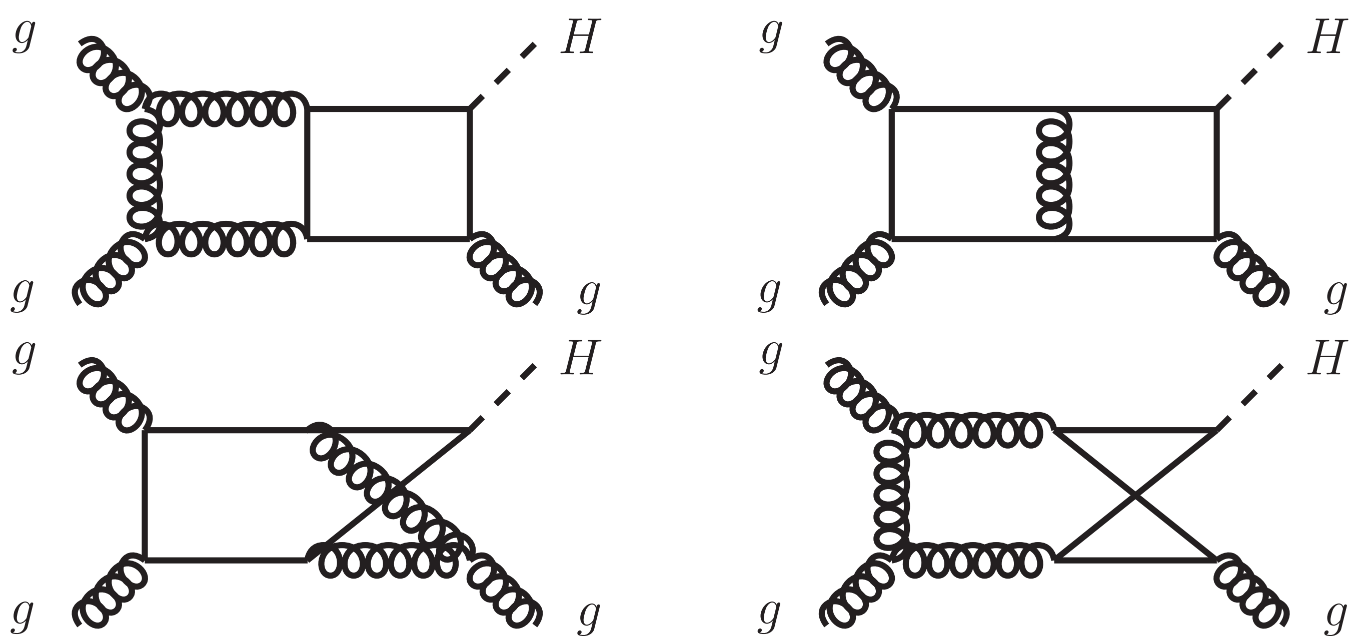


Knowledge of parton distribution functions affects all production channels. The current situation appears to be quite satisfactory; convergence of different PDF sets -- compared to what we have seen in the previous years -- is reassuring.

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

Theory behind the NNLO computations

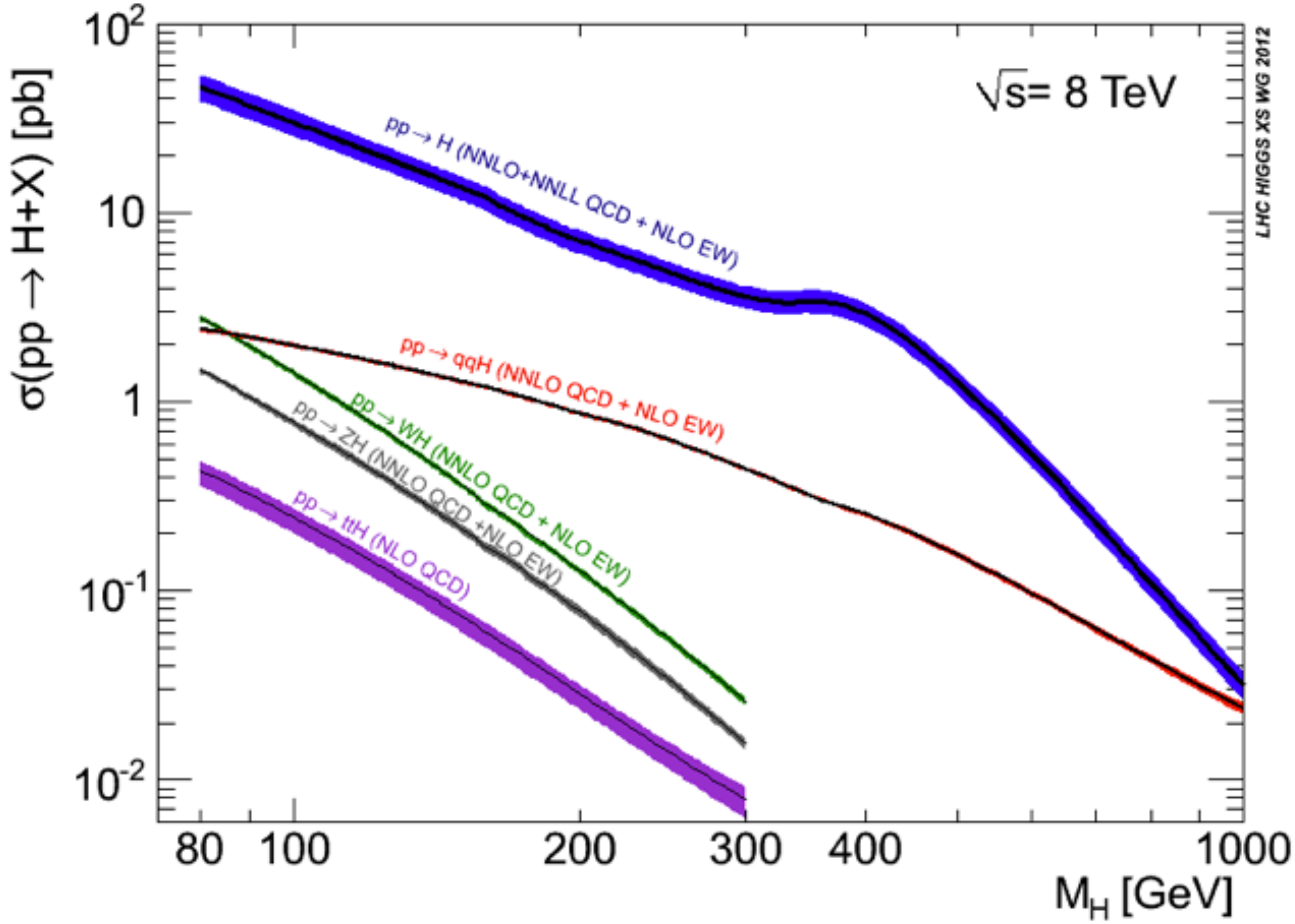
1) We require computation of complicated two (and higher) loop diagrams / amplitudes.



2) We need to understand how to combine processes with different parton multiplicities to enable theoretical predictions for infra-red safe observables.

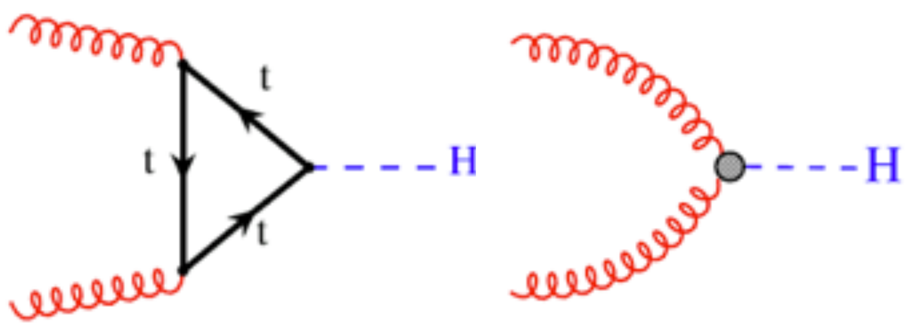
For example, an IR/collinear finite result for H+j @ NNLO arises if e.g. gg -> H+g (2-loops) , gg -> H+gg (1-loop), gg -> H+ggg (0-loops) are combined (and additional collinear subtractions / pdf renormalizations are undertaken).

Gluon fusion

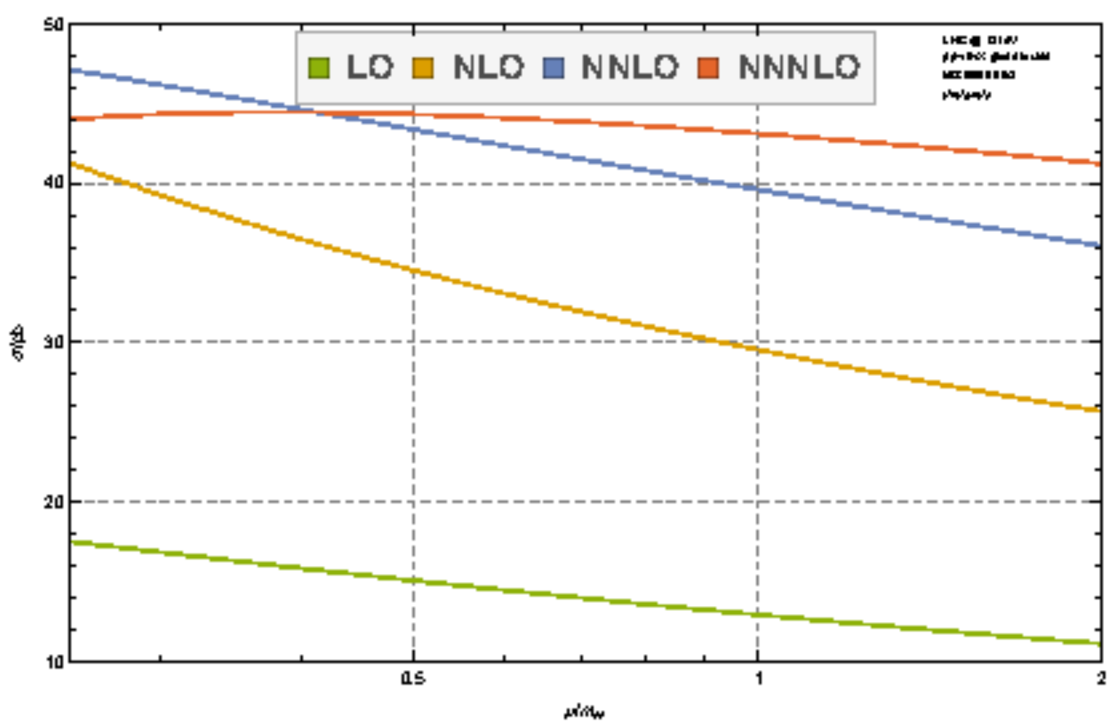


Higgs boson production in gluon fusion

Higgs production in gluon fusion is affected by large O(100%) QCD corrections. These corrections are currently known to three loop order (N^3LO) in the infinite top mass limit.



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^3LO. 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 estimates of the gluon fusion cross section include large number of subtle effects and require careful evaluation of the residual uncertainty.

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

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

....

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

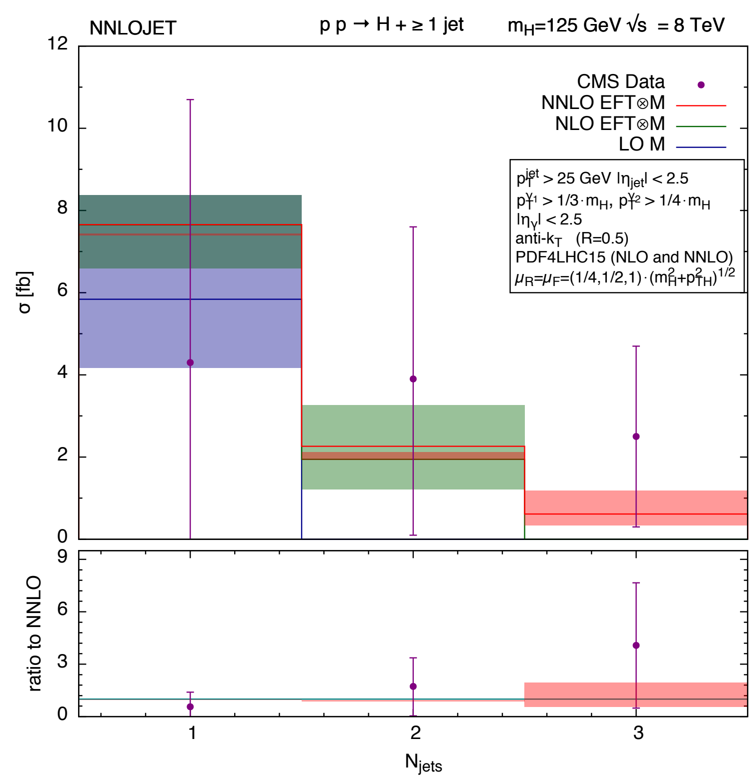
Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger

H+jet @ NNLO : fiducial results

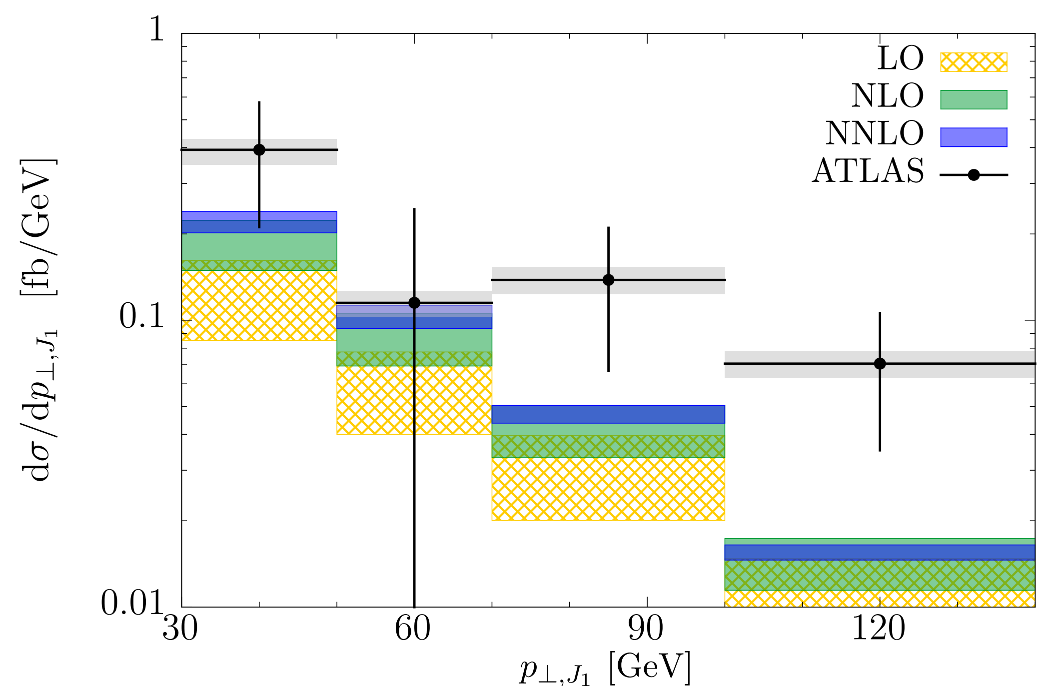
H+jet production is known through NNLO in pQCD, including decays of the Higgs boson into electroweak final states. The current comparison of theory predictions with ATLAS and CMS data is not very impressive but it provides a good starting point for refined studies at 13 TeV.

$$\sigma^{\rm fid}_{1j,{\rm ATLAS}} = 21.5 \pm 5.3({\rm stat}) \pm 2.3({\rm syst}) \pm 0.6 \ {\rm lum\ fb} \qquad H \to \gamma\gamma, \quad 8 \ {\rm TeV}$$

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



Exclusive jet cross sections



Transverse momentum distribution of a leading jet

Chen, Cruz-Martinez, Gehrmann, Glover, Jacquer

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

Jet-binned cross sections

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

For the 13 TeV LHC, using NNPDF2.3, anti-k_T, R=0.5, $\mu_0=m_H/2$, $Q_{res} = m_H/2$ and accounting for top and bottom mass effects, one finds the following results:

0-jet bin

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

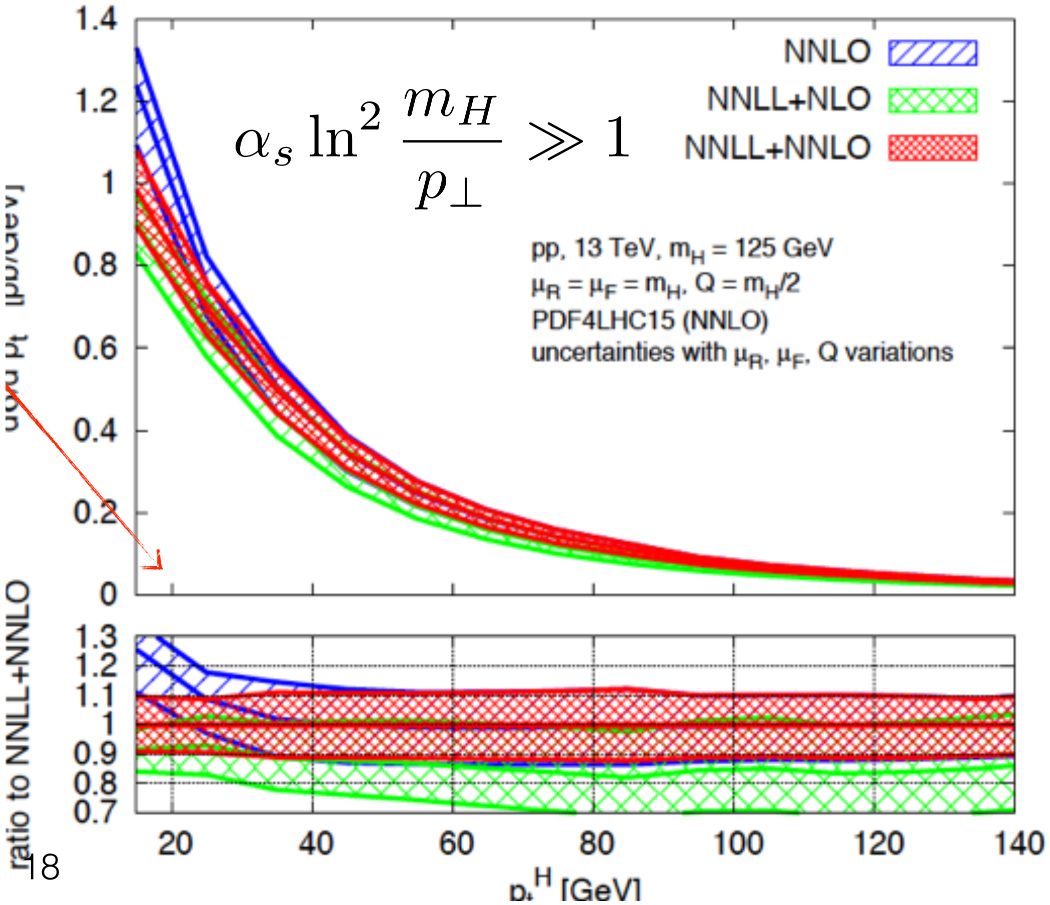
LHC 13 TeV	$\Sigma_{\geq 1\text{-jet}}^{NNLO+NNLL+LL_R}$ [pb]	$\Sigma_{\geq 1\text{-jet}}^{NNLO}$ [pb]
$p_{t,min} = 25$ GeV	$21.2^{+0.4}_{-1.1}$	$21.6^{+0.5}_{-1.0}$
$p_{t,min} = 30$ GeV	$18.0^{+0.3}_{-1.0}$	$18.4^{+0.4}_{-0.8}$

- No breakdown of fixed order perturbation theory for $p_T \sim 25$- 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 cross sections once we arrive at sufficiently high orders in both cases.

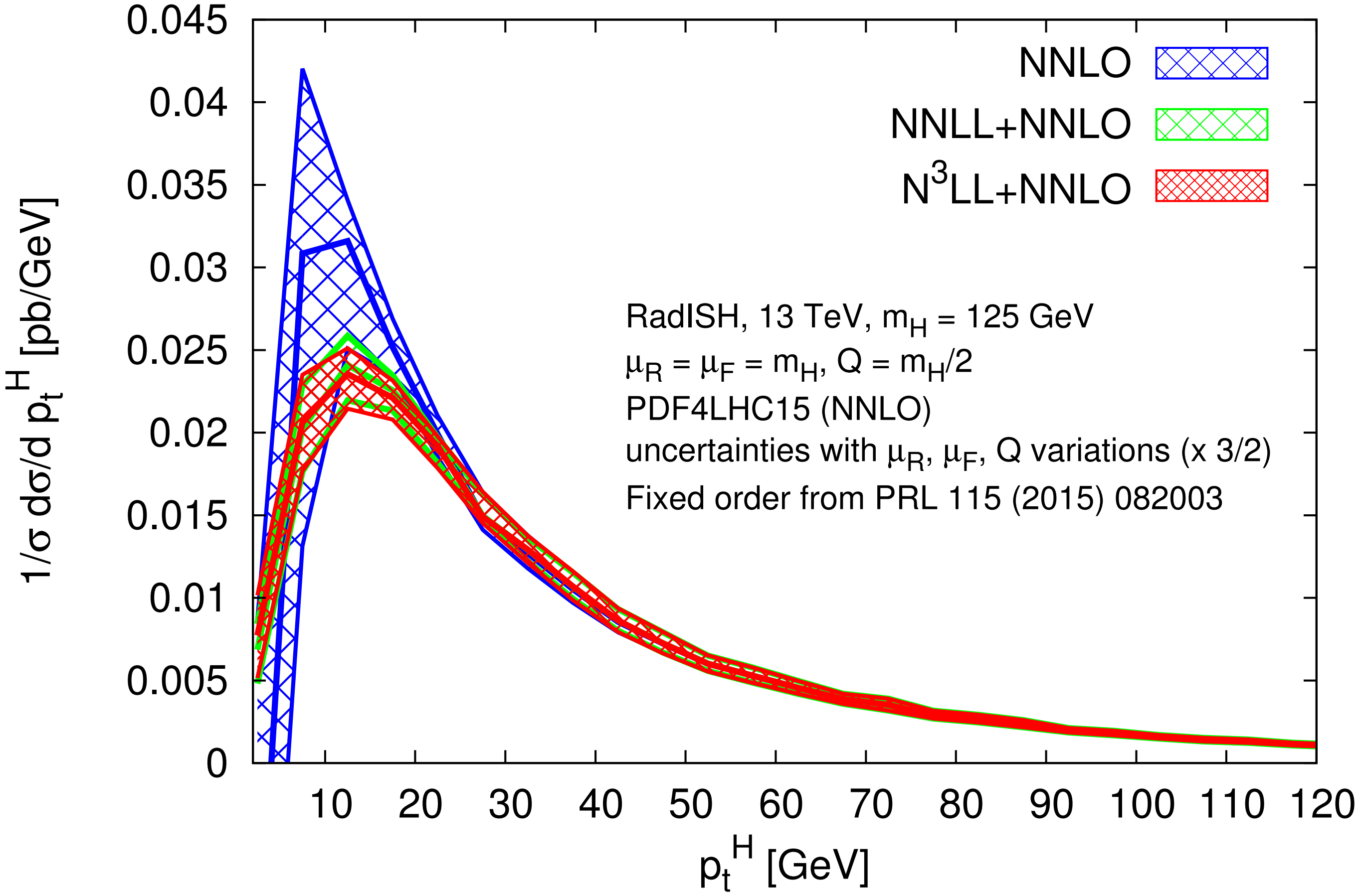
A. Banfi, F. Caola, F. Dreyer, P. Monni, G.Salam, G. Zanderighi, F. Dulat

The Higgs boson transverse momentum distribution

A transverse momentum distribution of a color-neutral particle can be computed following well-established procedures at low (resummation) and high (perturbation theory) transverse momentum. There was an important progress on that recently (N^3LL re-summation matched to NNLO fixed order).



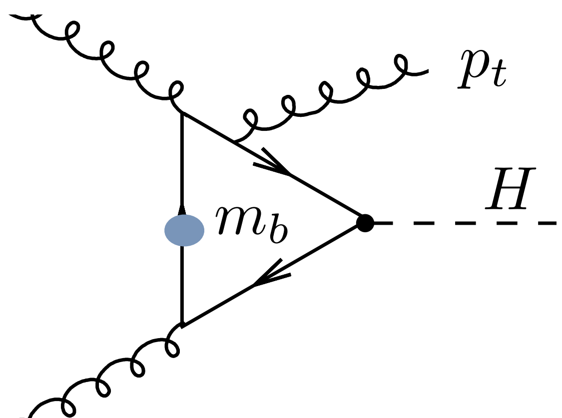
Monni, Re, Torrielli



Bizon, Monni, Re, Rottoli, Torrielli

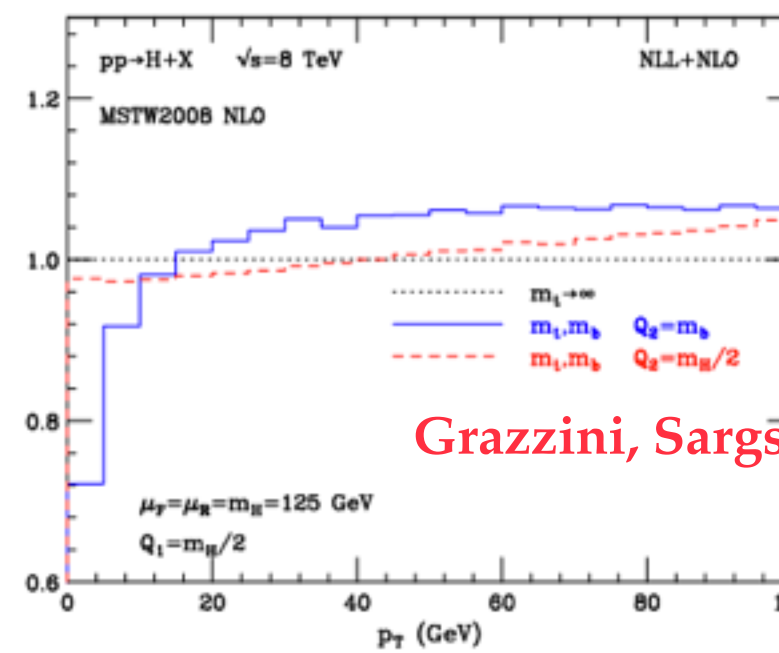
Quark masses and Higgs p_t distribution

The Higgs boson is a special case since the Hgg vertex is not point-like. At small p_t , b-quark loops lead to Sudakov-like double logarithmic corrections, related to the helicity flip on the ``soft'' fermion line; resummation of these logarithms is not well-understood.

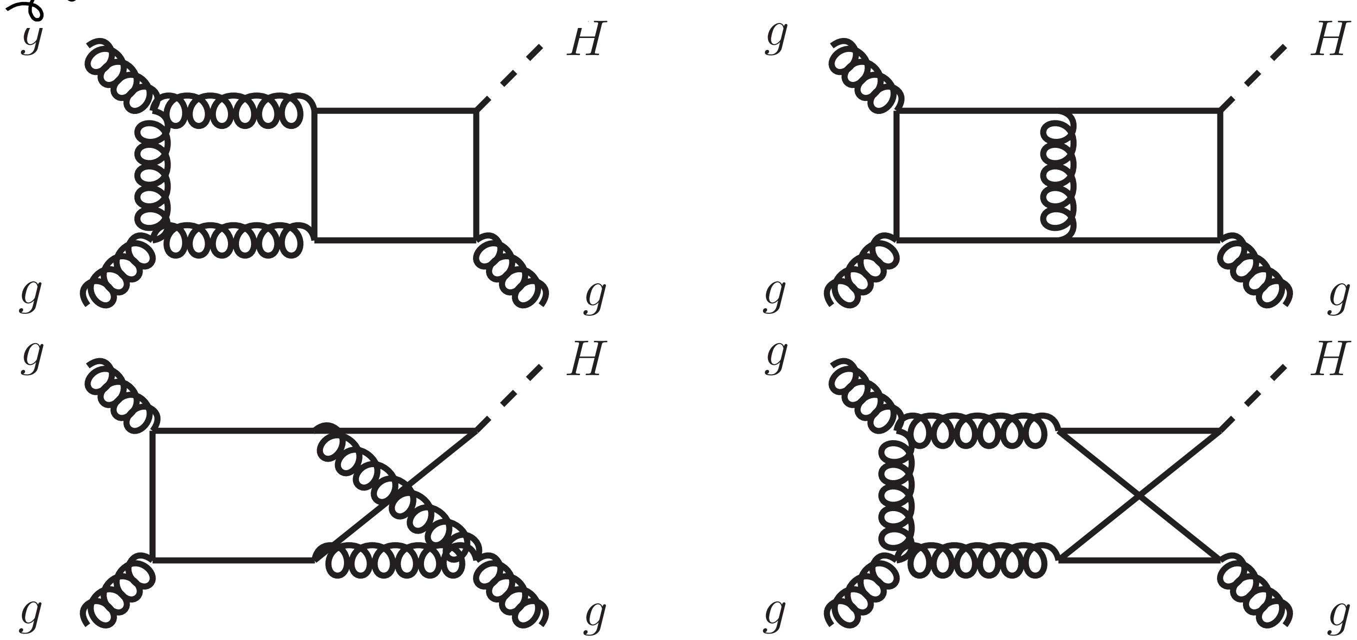


$$m_b/p_\perp \ll 1$$

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



Grazzini, Sargsyan



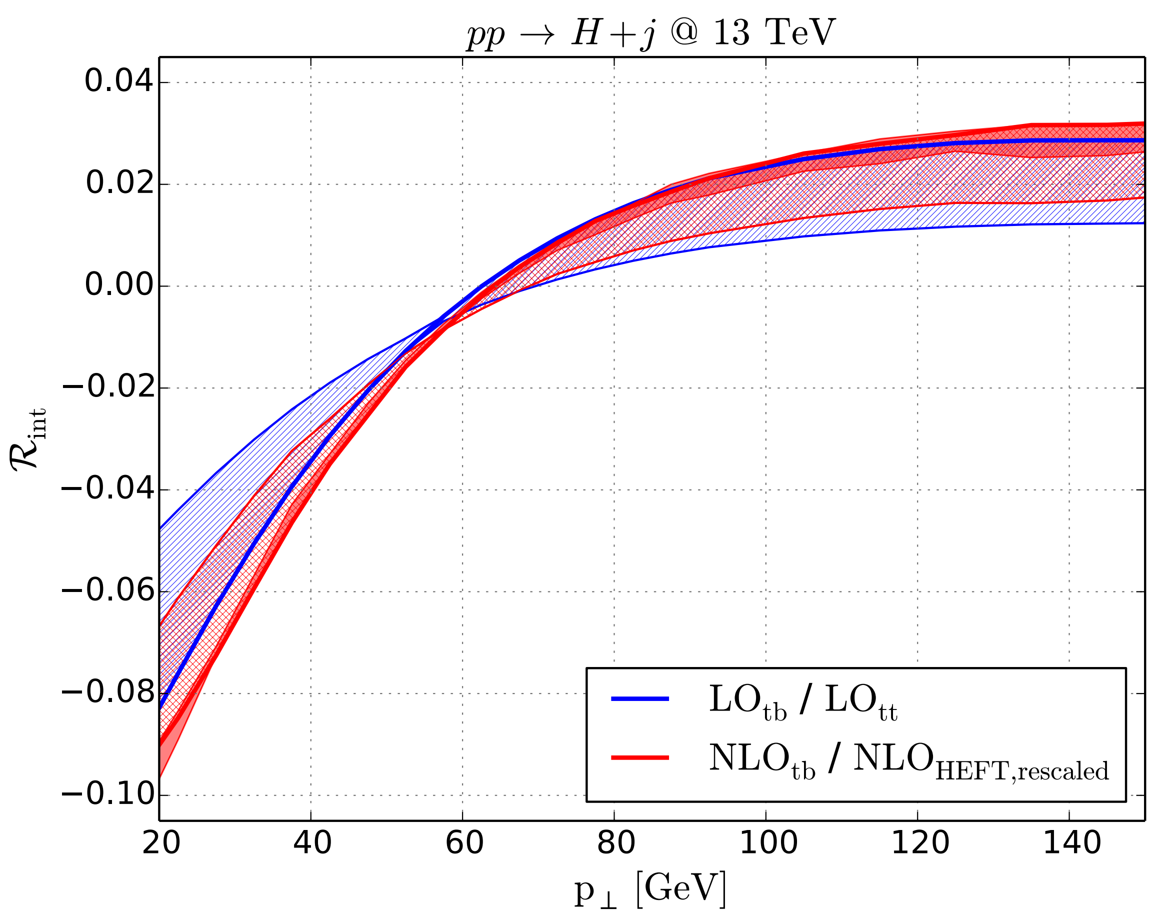
Planar master-integrals with full mass dependence were recently computed by R. Bonciani et al.

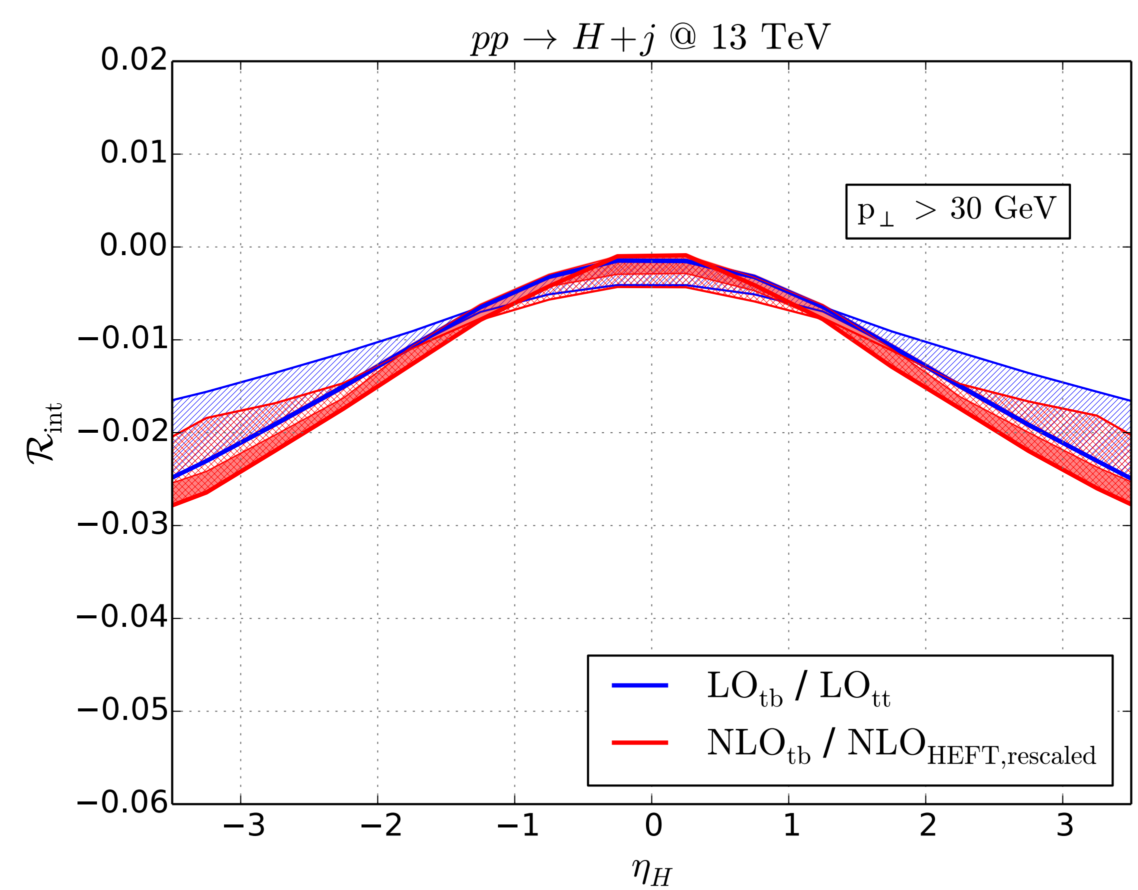
Using the smallness of the mass to transverse momentum ratio, all the relevant two-loop scattering amplitudes can be computed (L. Tancredi, C. Wever, K.M).

Quark masses and Higgs p_t distribution

The two-loop amplitudes were combined with the OpenLoops (Pozzorini et al.) to calculate mass-suppressed contributions to Higgs + jet production at NLO QCD. The corrections to the mass-suppressed interference terms are large but they appear similar to large corrections to a point-like top-loop contribution.

$$\mathcal{R}_{int}(\mathcal{O}) = \frac{\int d\sigma_{tb}\, \delta(\mathcal{O} - \mathcal{O}(\vec{x}))}{\int d\sigma_{tt}\, \delta(\mathcal{O} - \mathcal{O}(\vec{x}))}$$





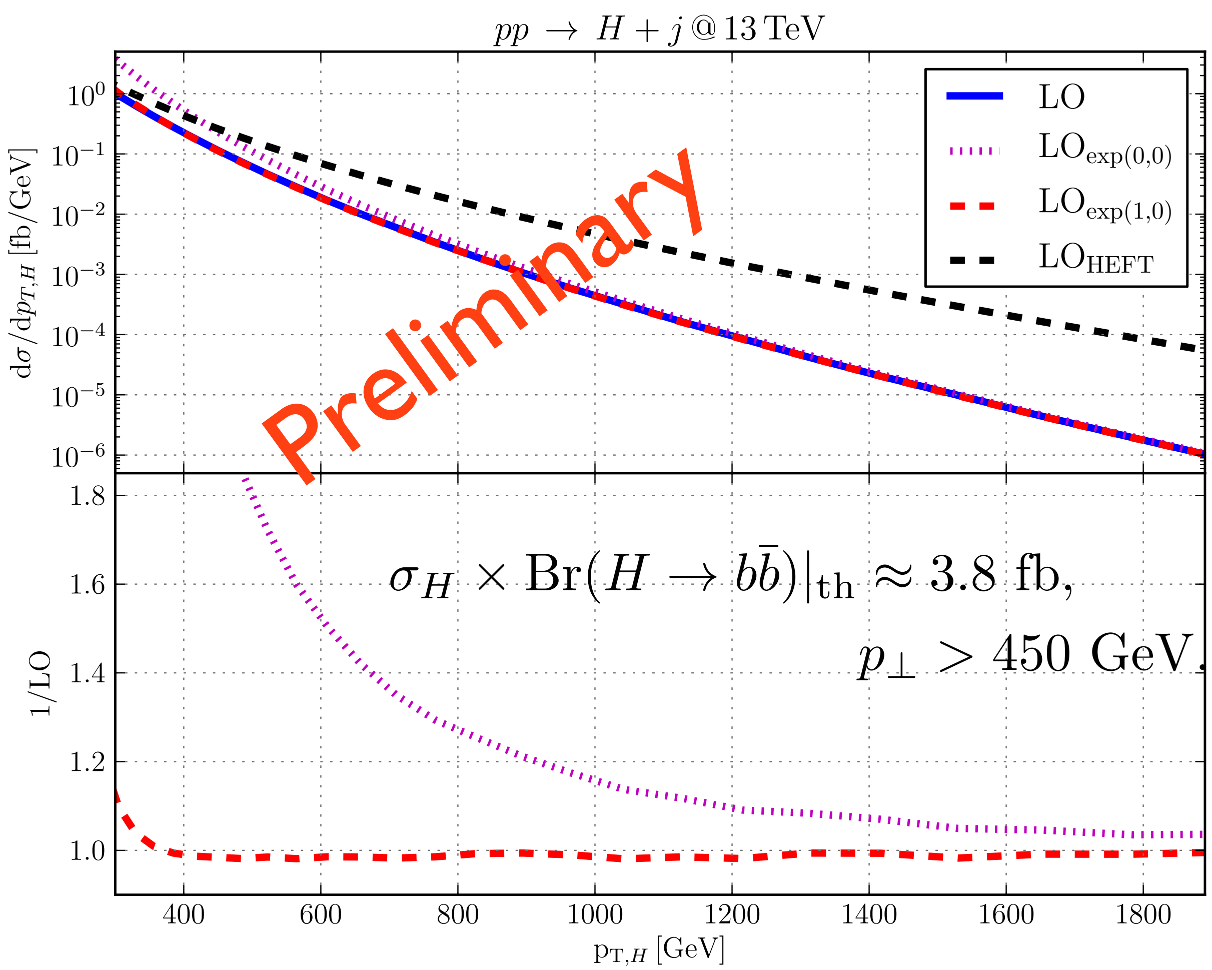
J. Lindert, K.M., L. Tancredi, C. Wever

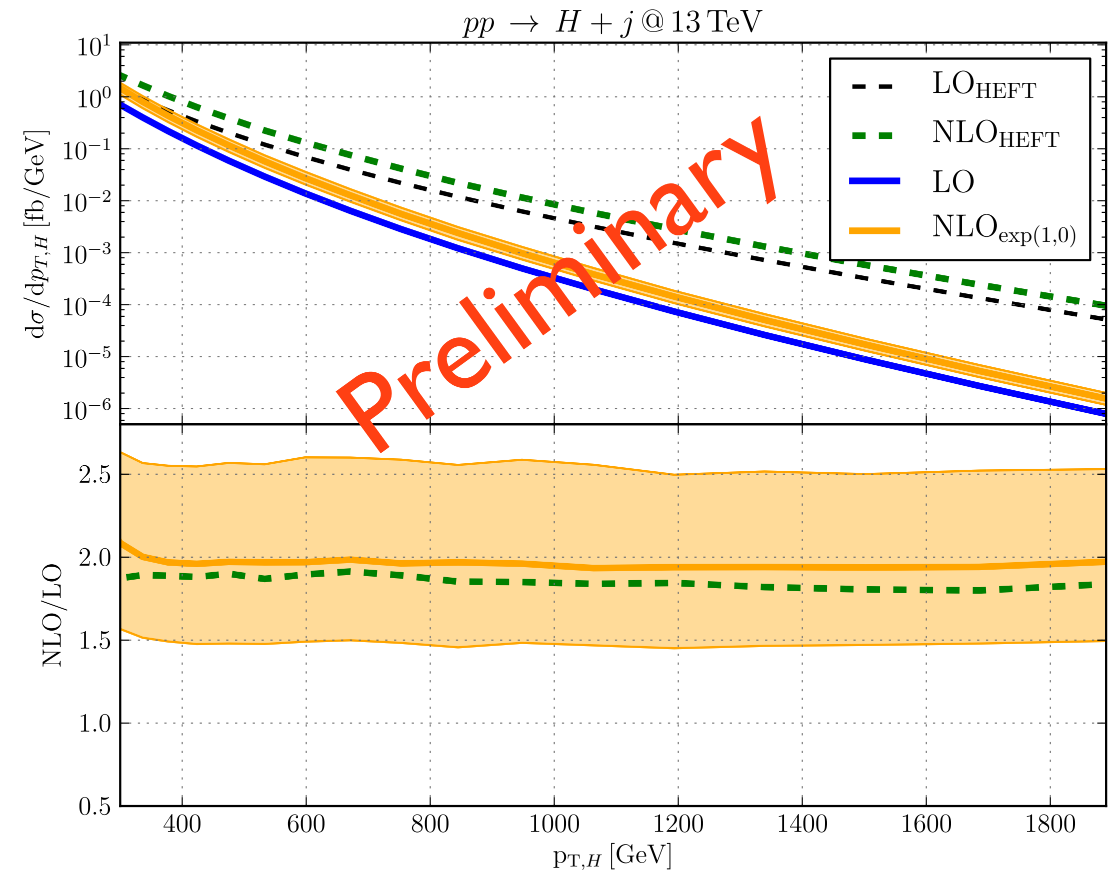
Quark masses and Higgs p_t distribution

Another interesting region is that of the high ($>$ 400 GeV) p_t of the Higgs boson. Higher-order QCD corrections can be computed expanding in the mass of the top quark relative to all kinematic variables. Wonderful convergence. Exact K-factor is O(10) percent larger than the K-factor computed in $m_t \to \infty$ approximation.

$$\mathcal{L} \sim C_1\; H G^a_{\mu\nu} G^{a,\mu\nu} + C_2\; H \bar{t} t$$

$$\sigma_H \times \mathrm{Br}(H \to b\bar{b})|_{\rm CMS} = 74 \pm 50 \text{ fb}, \quad p_\perp > 450 \text{ GeV}.$$

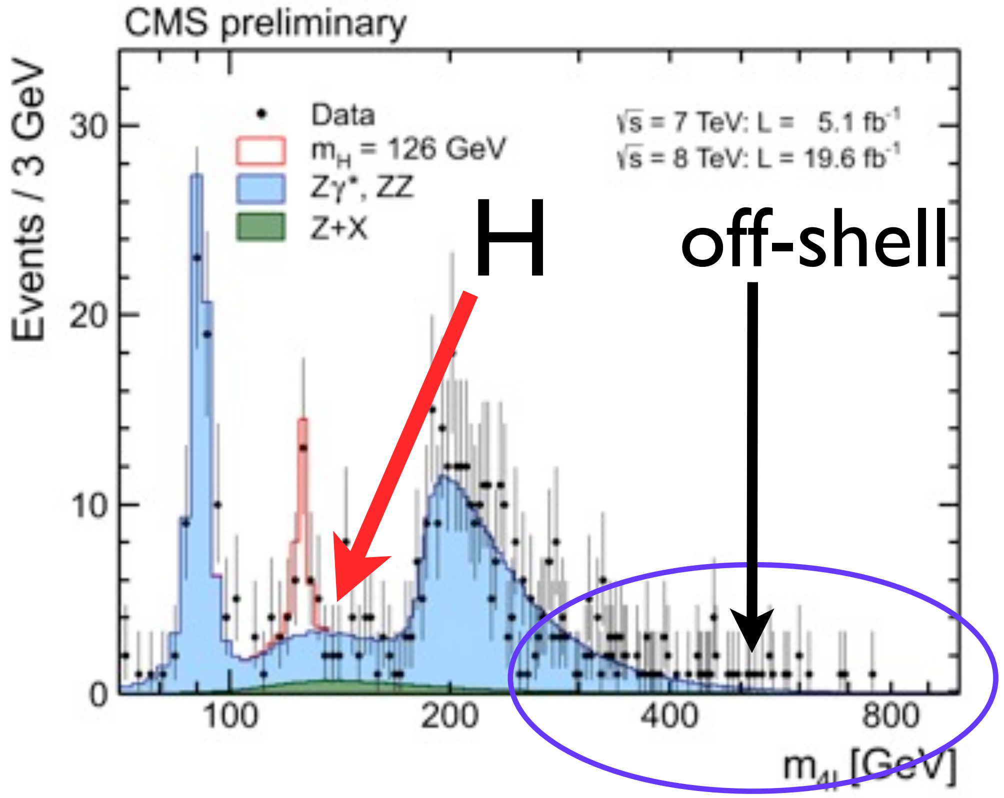




$$\sigma_H \times Br(H \to b\bar{b})|_{\rm th,NLO} = 6.5 \text{ fb}, \quad p_\perp > 450 \text{ GeV}$$

K. Kudashkin, J. Lindert, K.M., C. Wever

Off-shell measurements

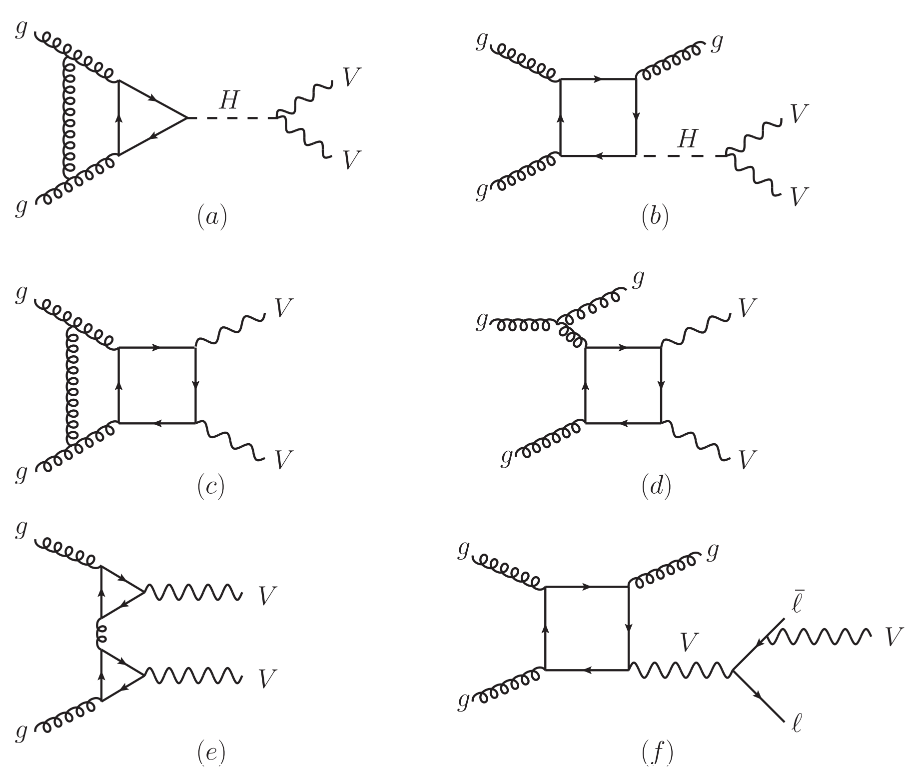


$$\sigma_{\rm on} \propto g_i^2 g_f^2/\Gamma_H \qquad \sigma_{\rm off} \propto g_i^2 g_f^2$$

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

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

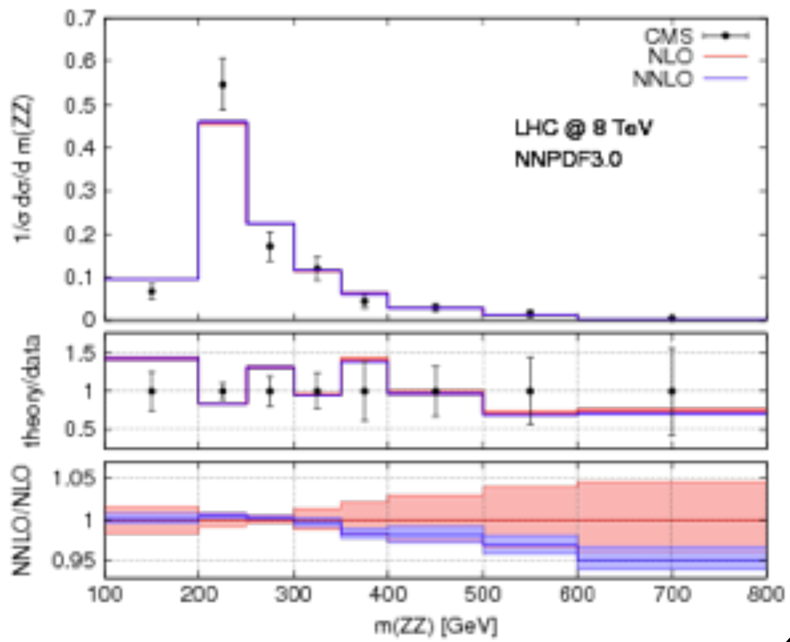
Need precise prediction for ZZ production both in quark-antiquark and gluon fusion, including the interference with the off-shell Higgs in the gg channel.



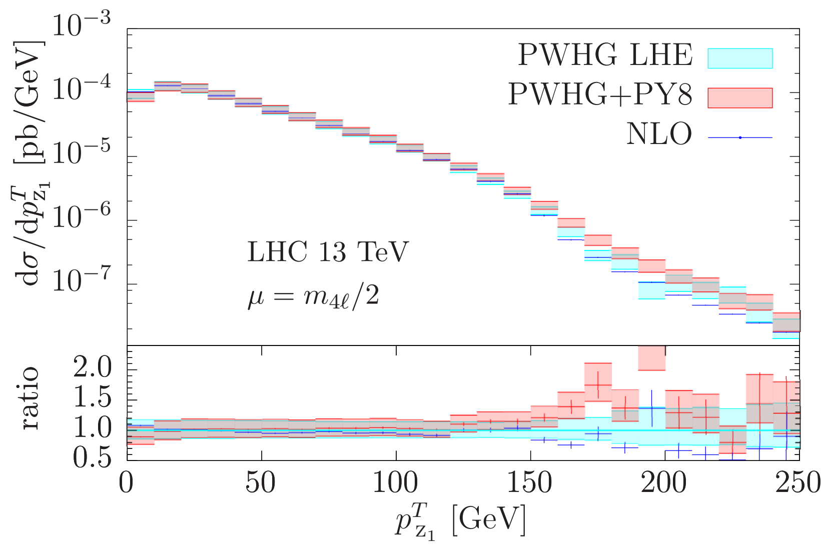
		4ℓ	$2\ell 2\nu$
(a)	total gg ($\Gamma_H = \Gamma_H^{SM}$)	1.8 ±0.3	9.6 ±1.5
	gg signal component ($\Gamma_H = \Gamma_H^{SM}$)	1.3 ±0.2	4.7 ±0.6
	gg background component	2.3 ±0.4	10.8 ±1.7
(b)	total gg ($\Gamma_H = 10 \times \Gamma_H^{SM}$)	9.9 ±1.2	39.8 ±5.2
(c)	total VBF ($\Gamma_H = \Gamma_H^{SM}$)	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

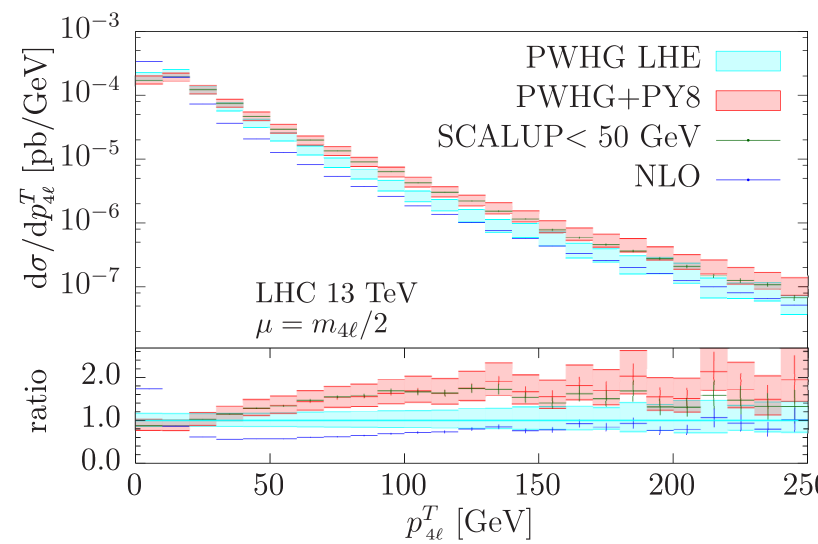
Off-shell measurements

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



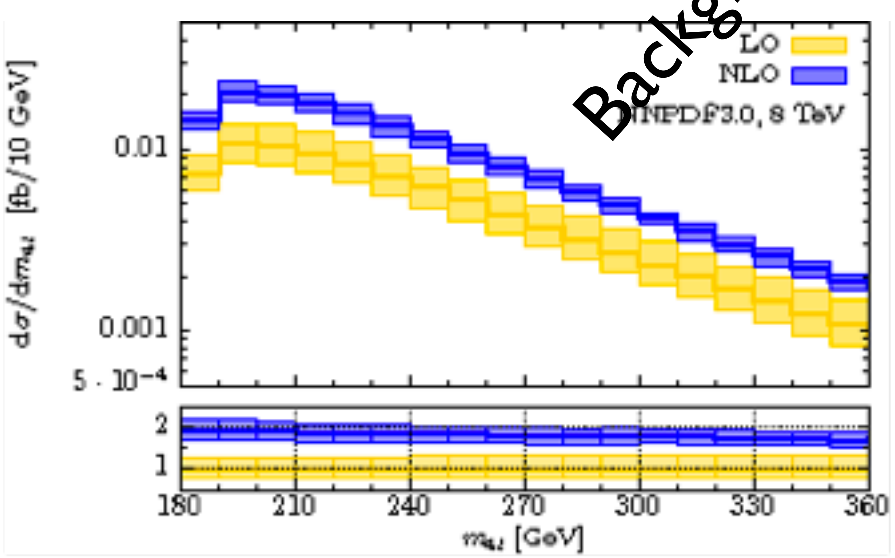
M. Grazzini, S. Kallweit, P. Maierhoefer, D. Rathlev



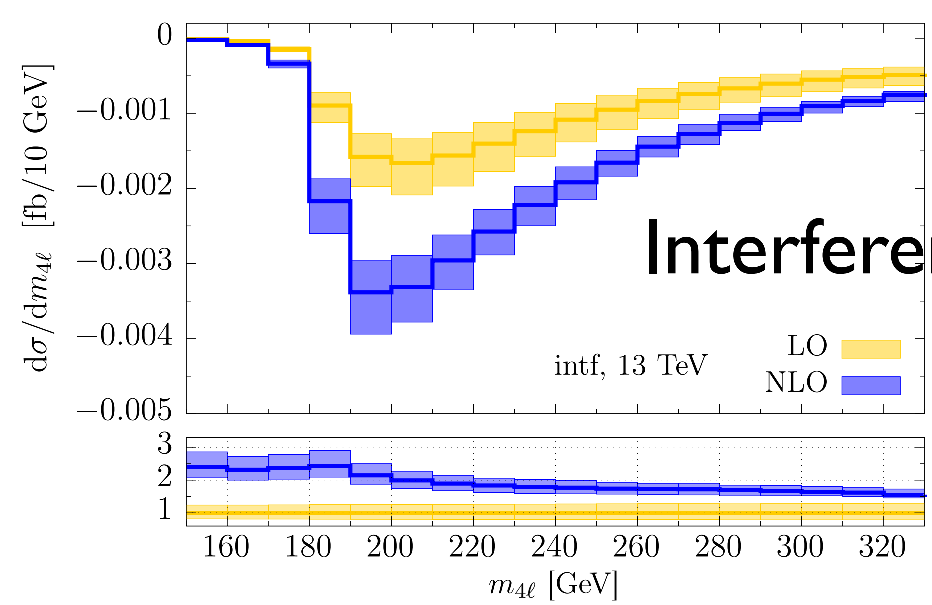


S. Alioloi, F. Caola, J. Luisoni, R. Rontsch.

Backgrounds

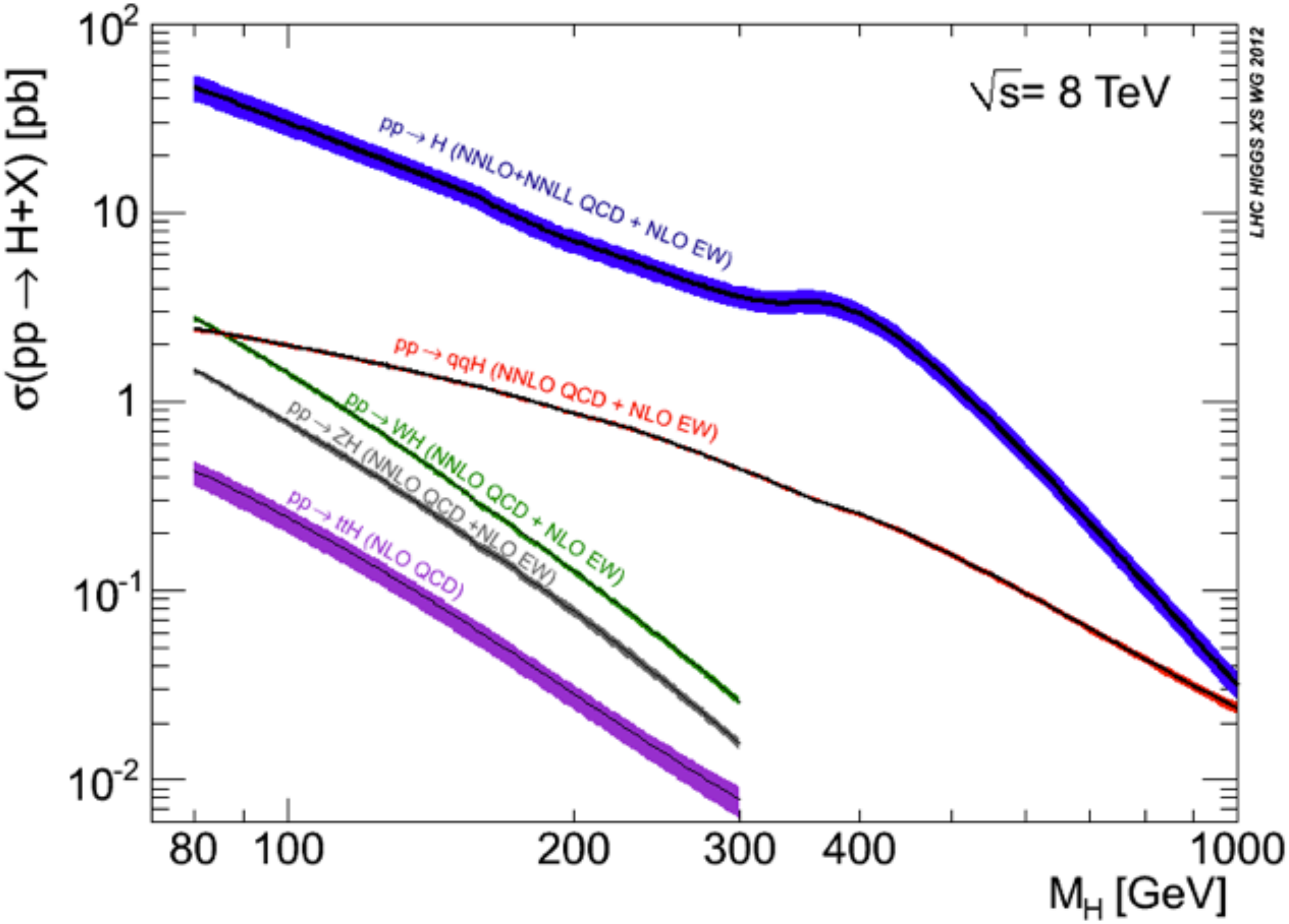


Interference



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

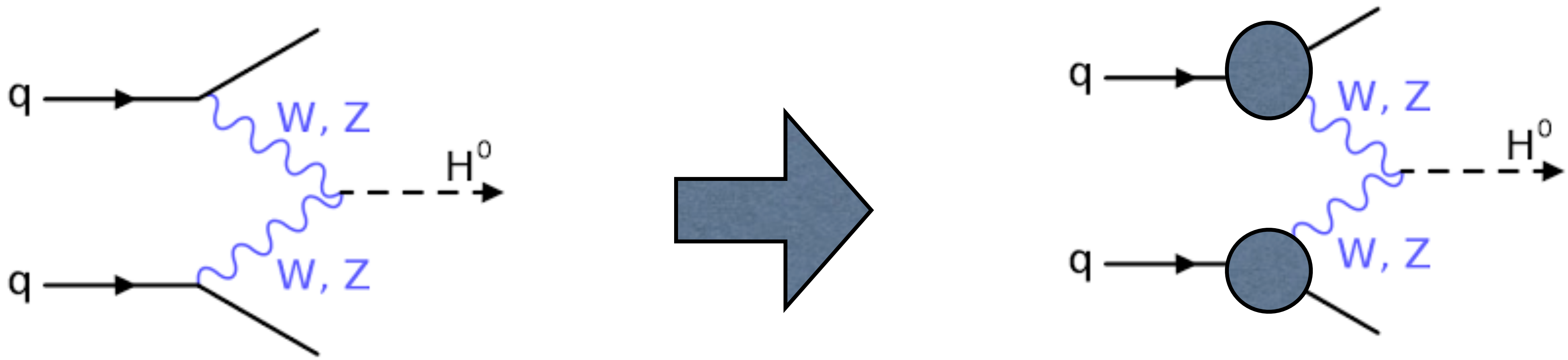
Weak boson fusion



Higgs boson production in weak boson fusion

In the large - N_c approximation, upper and lower quark lines do not talk to each other and QCD corrections to weak boson fusion can be read off from the QCD corrections in deep inelastic scattering. Especially simple are corrections to inclusive cross section since they are given by QCD corrected DIS structure functions.

The QCD corrections to inclusive WBF cross section 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 is indicative for fiducial cross sections.



Bolzoni, Maltoni, Moch, Zaro;Dreyer, Kalberg

Higgs boson production in weak boson fusion

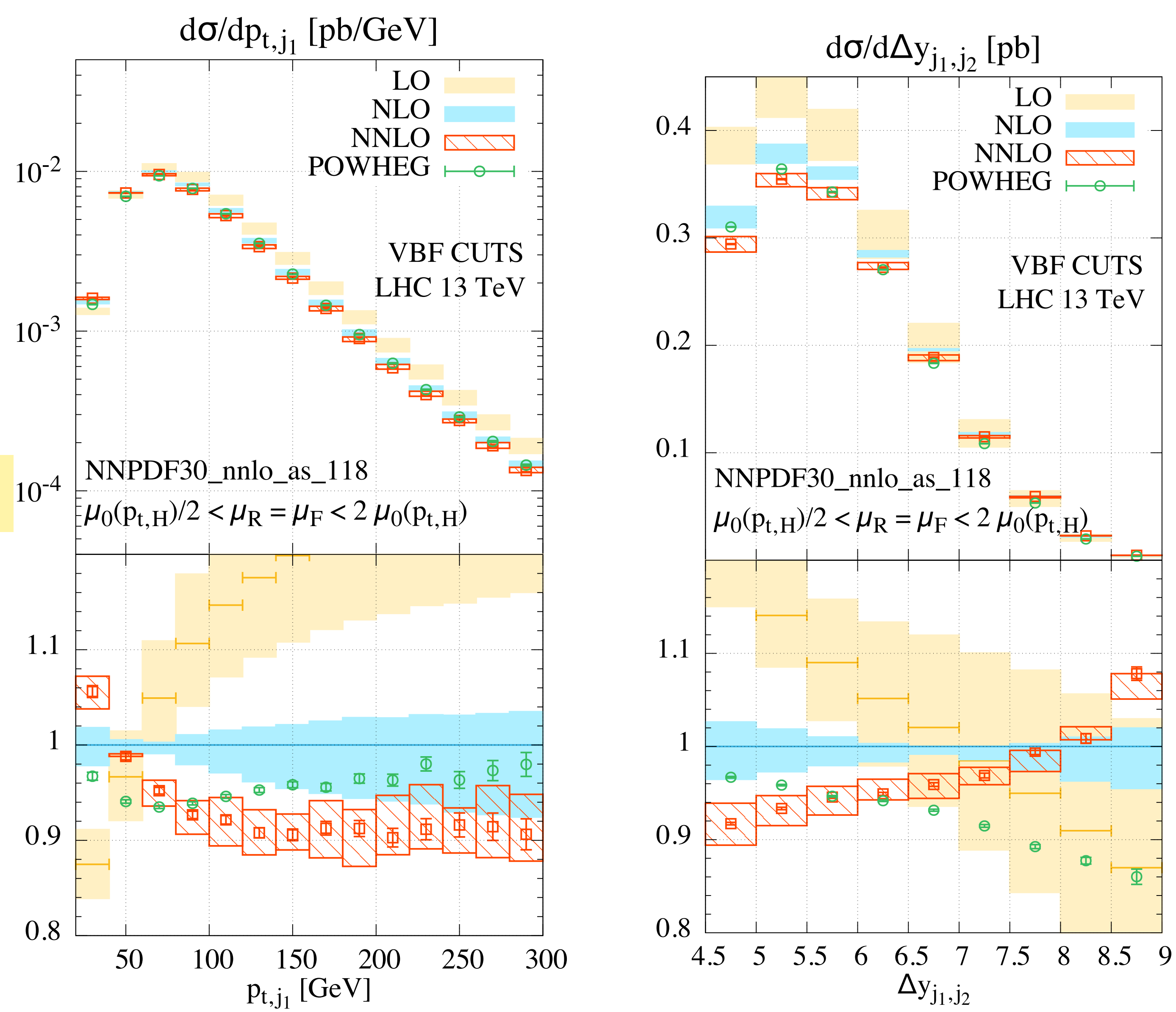
However, this assumption turns out to be incorrect and, in fact, one can get larger O(6-10%) corrections for fiducial (WBF cuts) cross sections and kinematic distributions. Often, the shape of those corrections seems rather different from both the NLO and/or parton shower predictions.

WBF cuts

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

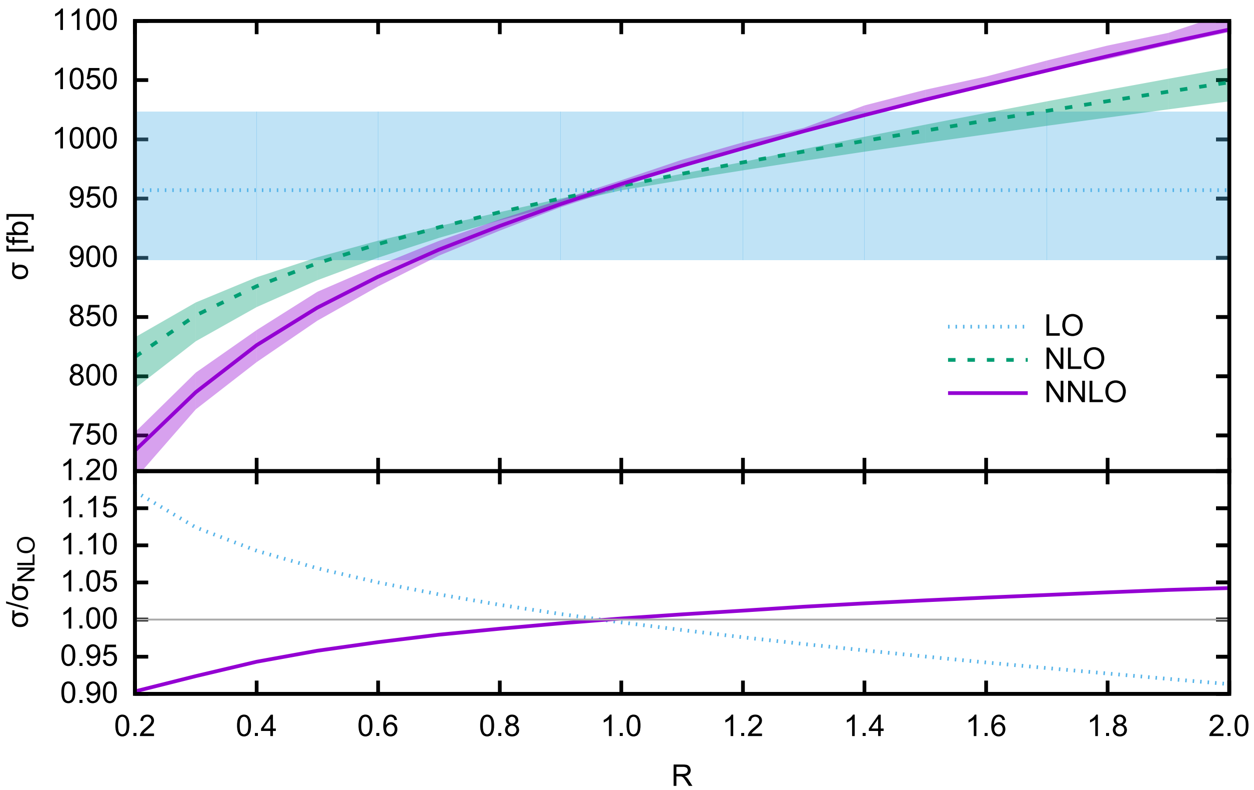
Cross sections with and without WBF cuts

	σ^{nocuts}[pb]	$\sigma^{\text{VBF cuts}}$[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	$3.888^{+0.016}_{-0.012}$	$0.826^{+0.013}_{-0.014}$

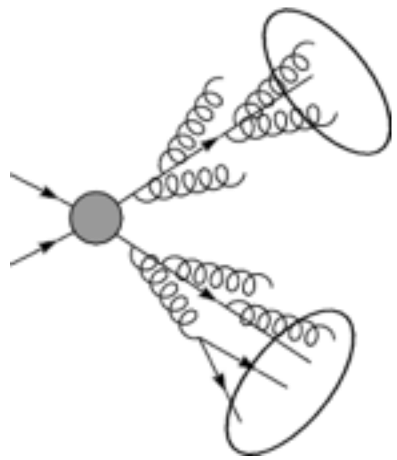


Cacciari, Dreyer, Kalberg, Salam, Zanderighi

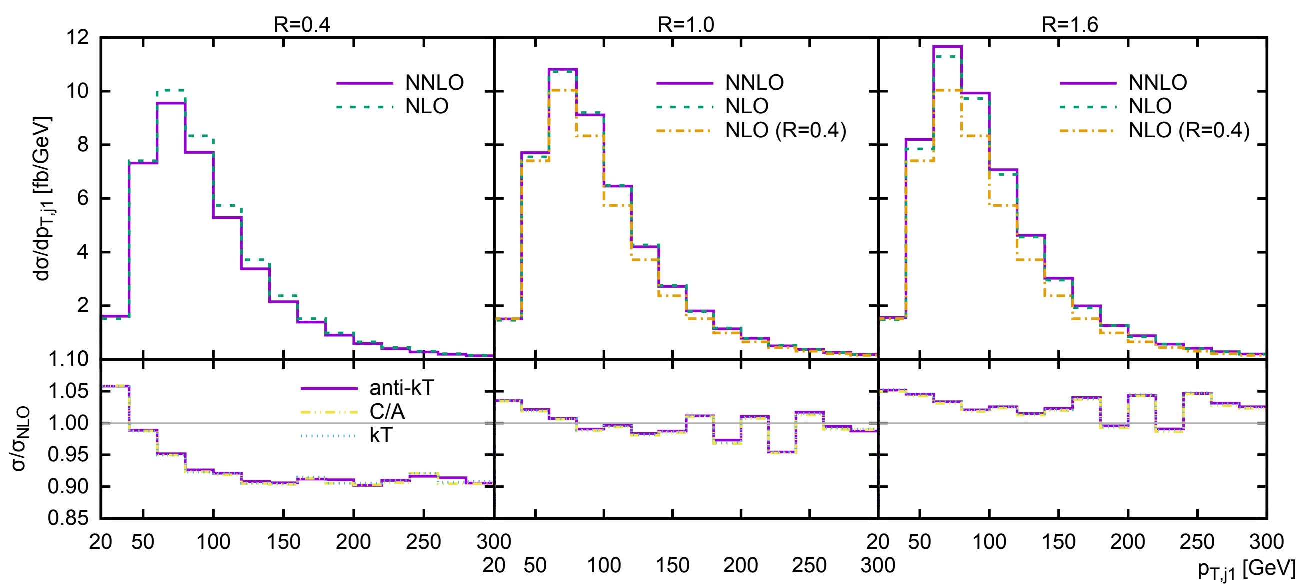
Higgs boson production in weak boson fusion

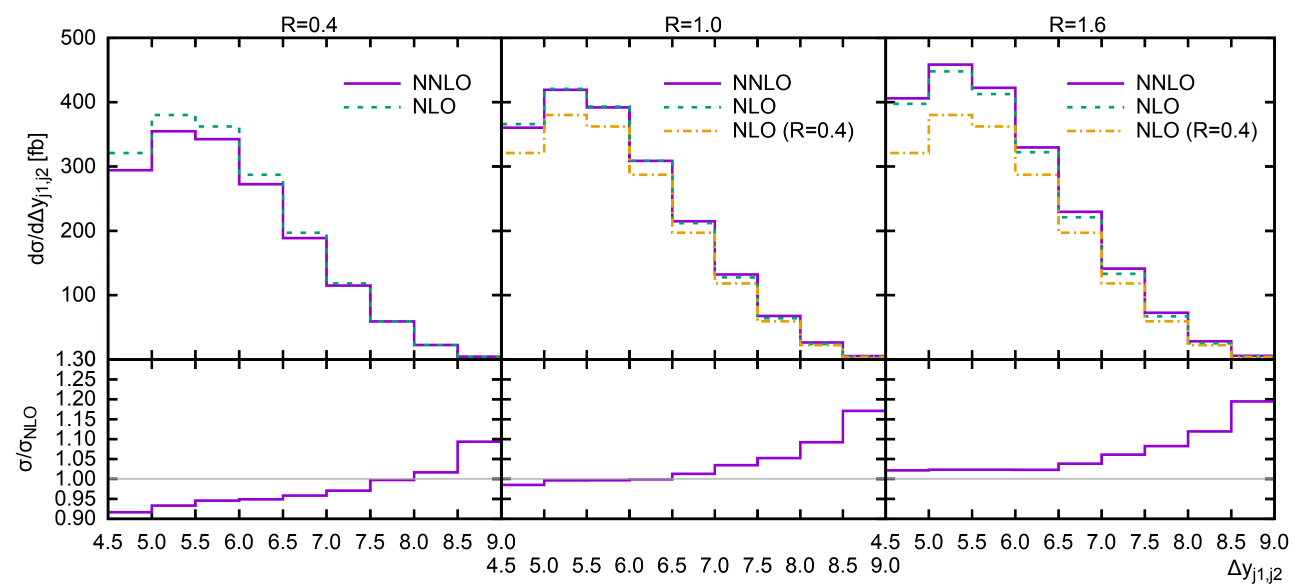


Fiducial WBF cross section at NLO and at NNLO show strong dependence on the jet clustering radius. Broader jets at NNLO relative to NLO.



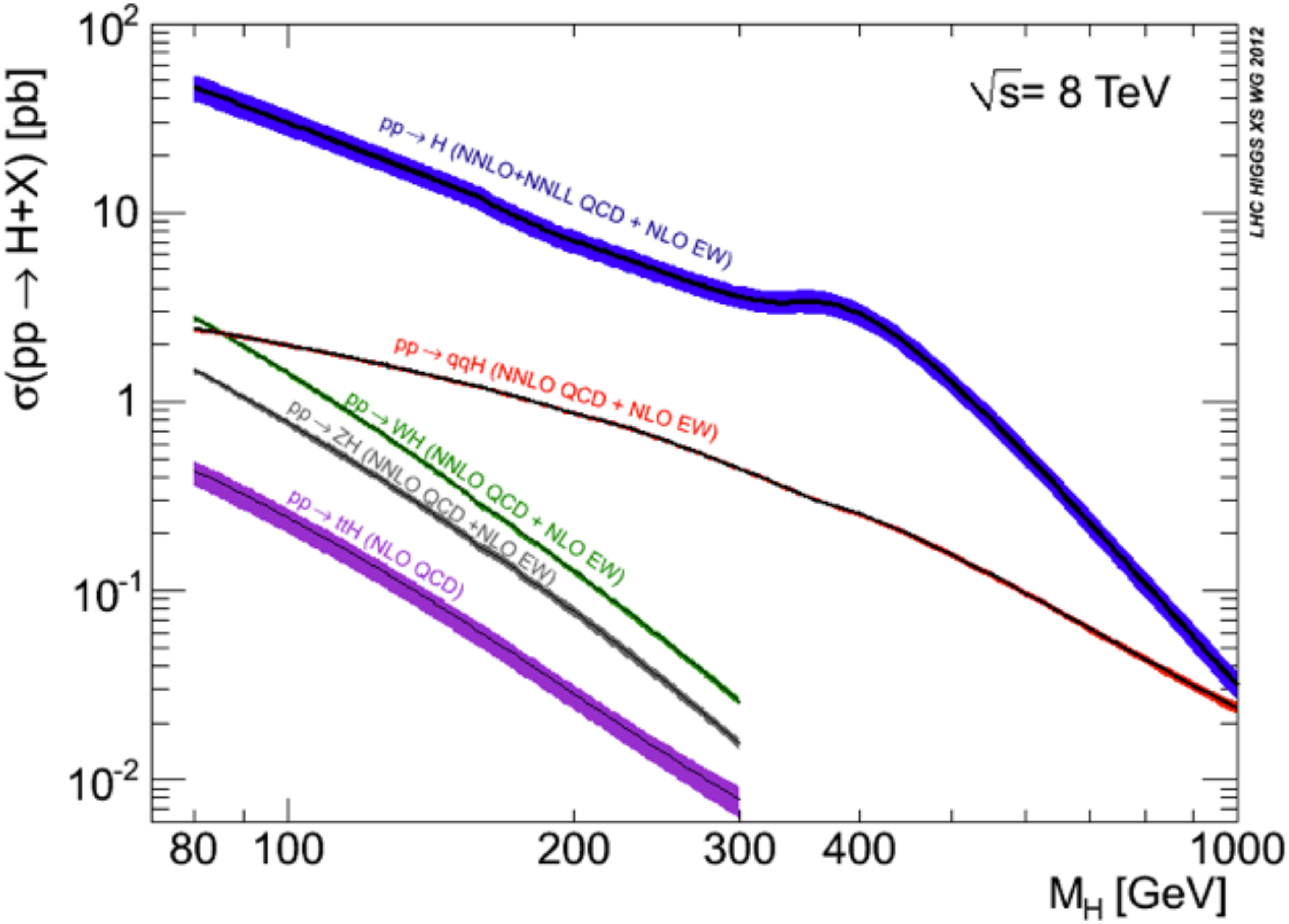
M. Rauch and D. Zeppenfeld





Leading jet pt and rapidity distributions in dependence on the jet clustering radius

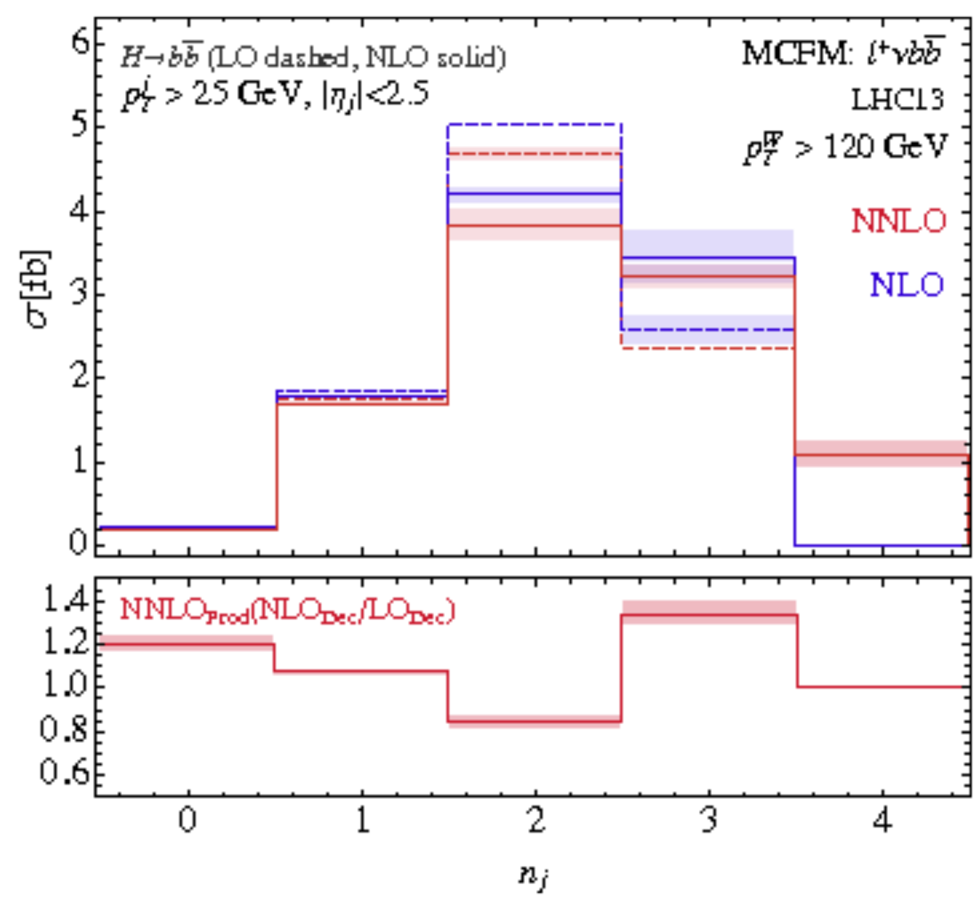
VH associated production

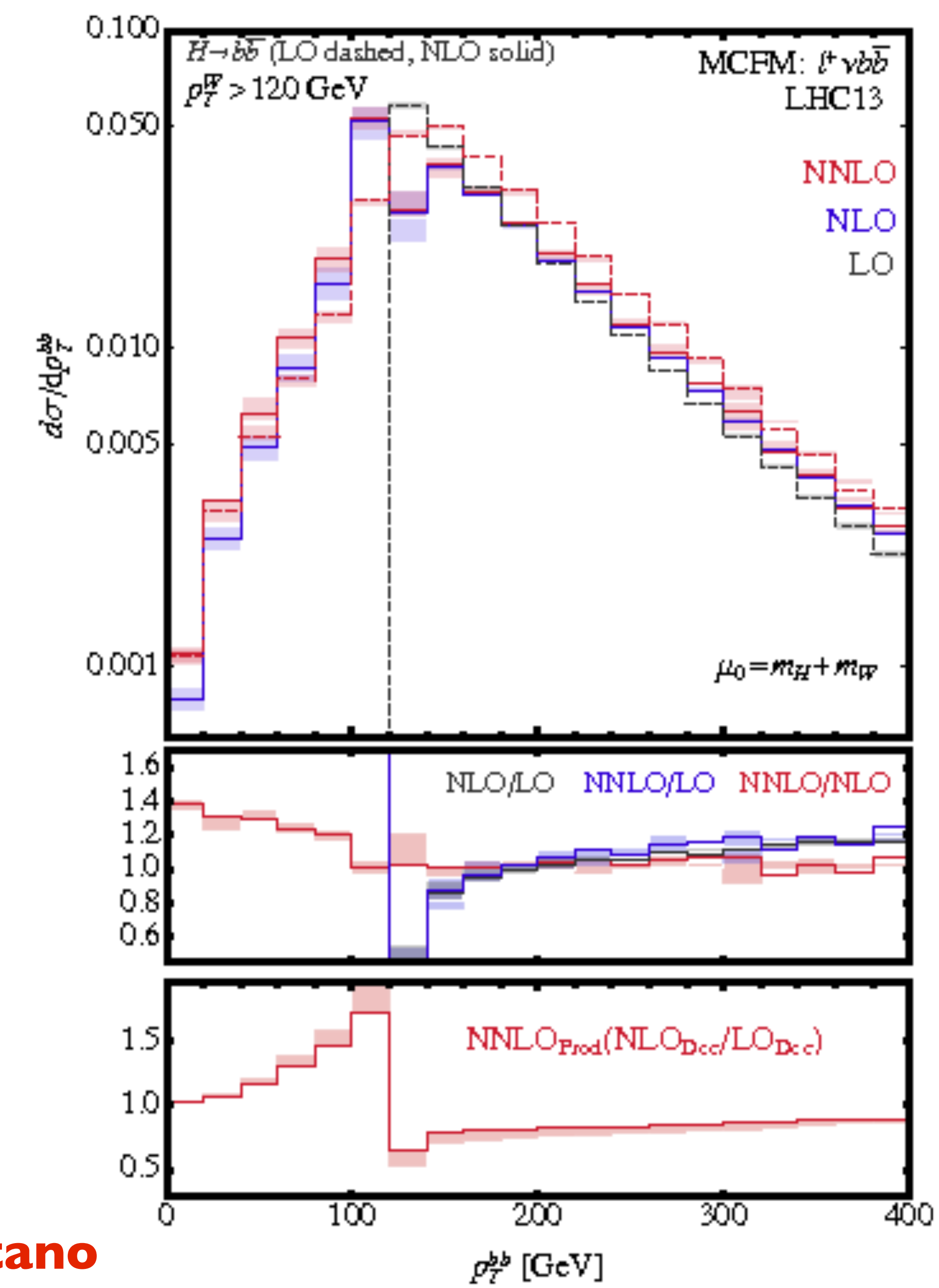


Associated production: VH(bb)

The associated production was studied extensively using NNLO approximation for the production and NLO approximation for decay. Some observables exhibit relatively large corrections due to radiation in decays due to fiducial volume cuts.

$$d\sigma^{\rm NNLO} \sim d\sigma^{(0)} \times \frac{d\Gamma^{(0)} + d\Gamma^{(1)}}{\Gamma^{(0)} + \Gamma^{(1)}} + \left(d\sigma^{(1)} + d\sigma^{(2)}\right) \times \frac{d\Gamma^{(0)}}{\Gamma^{(0)}}$$

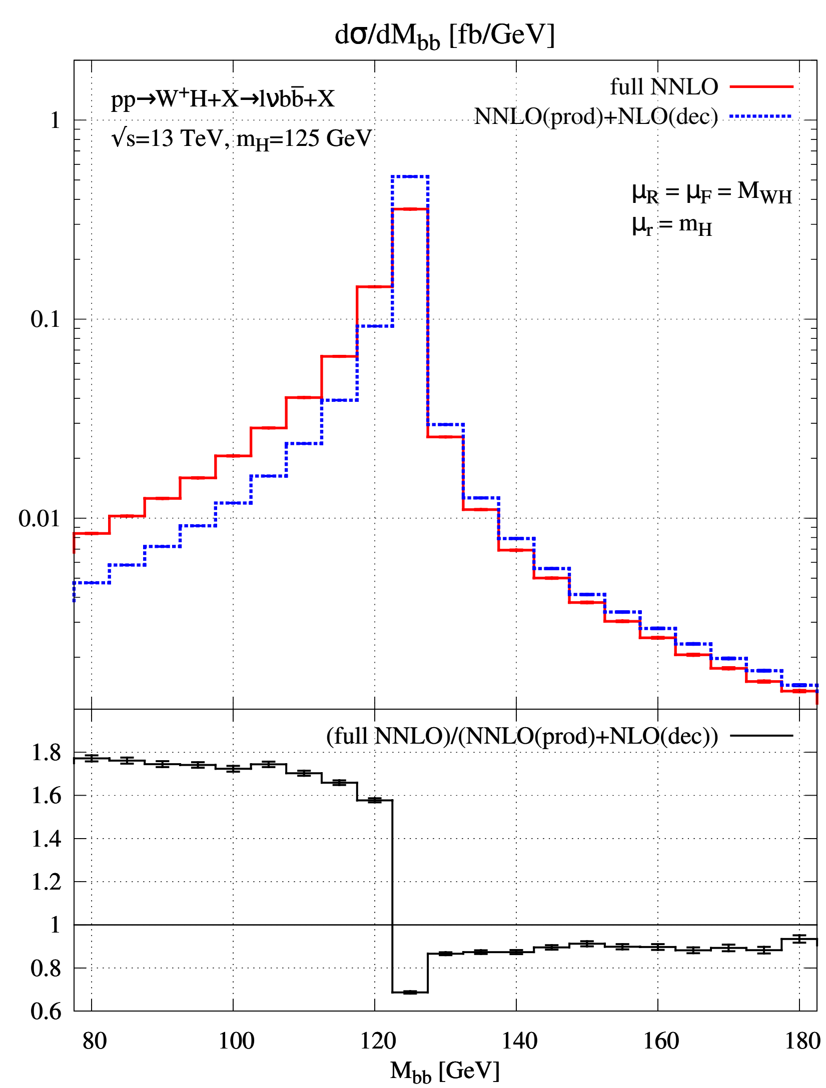


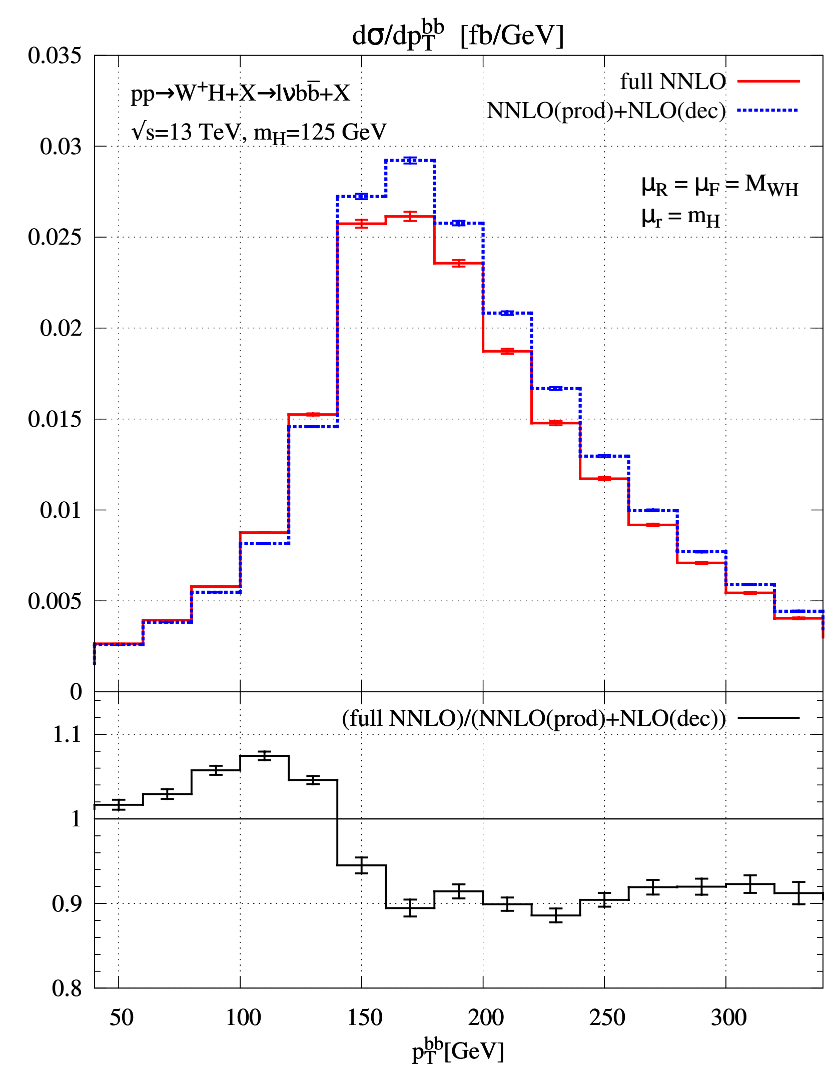


Campbell, Ellis, Williams; Ferrera, Grazzini, Tramontano

Associated production: VH(bb)

Extension of these results to include NNLO QCD corrections in the decay, for massless b-quarks. Relatively large effects on kinematic distributions (some are explained by being NLO corrections to ``radiative'' Higgs decay). NNLO effects in the decay cause additional O(-5%) corrections to the fiducial cross section.





Ferrera, Somogyi, Tramontano

Conclusion

Precision predictions for Higgs boson production 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 years (inclusive Higgs through N^3LO, H+jet at NNLO, Higgs in WBF at NNLO, mass effects and the resummation in Higgs pt spectrum, NLO for off-shell and HH). 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 precise exploration of Higgs boson properties will be possible at the LHC.