NNLO QCD effects in Higgs boson production through Vector Boson Fusion in NNLOJET

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arXiv:1802.02445

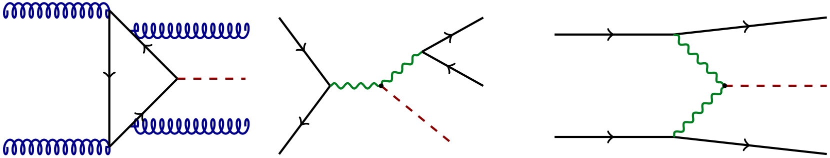
NNLOJET collaboration
IPPP (Durham University)

Outline

1. Introduction
   - State of the art
   - VBF NNLO in the DIS approach
   - IR singularities and Antenna Subtraction
2. Phenomenological Results
   - VBF vs VH vs ggF
   - Differential distributions
3. Going further
   - Higgs + 3jets at NNLO in VBF
   - Conclusions

Higgs production via Vector Boson Fusion

Several production modes contribute to Higgs production in association with 2 jets.



ggF VH (V$\to q\bar{q}$) VBF

The VBF and VH contributions are subdominant with respect to the ggF for Higgs production.

- Treat ggF and VH as background of the VBF signal.
- Exploit the VBF topology to discriminate between the different production modes.

Inclusive calculation of VBF at higher orders in QCD

The VBF inclusive cross section is currently known in the structure function approach up to N^3LO by using DIS structure function joined with a VVH matrix element.

- Inclusive NNLO corrections found to be small, at the 1% level, with a scale uncertainty of $\sim$0.5%.

  hep-ph/1003.4451, P. Bolzoni, F. Maltoni, S. Moch, M. Zaro

- Inclusive N^3LO corrections to the inclusive cross sections are at the 1-2‰ with a scale uncertainty of $\sim$0.1‰.

  hep-ph/1606.00840 F. Dreyer, A. Karlberg

Differential results of VBF at higher orders in QCD

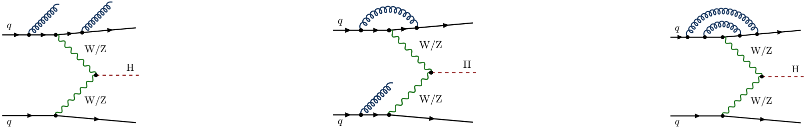
Fully differential calculations are also available:

- Implemented in NNLOJET, using antenna subtraction to control singularities.
  NNLO corrections about 3 times bigger than in the inclusive case (corrections of about ∼3% with a scale uncertainty of ∼1%).
  hep-ph/1802.02445; **J. C-M**, T. Gehrmann, N. Glover, A.Huss

- Using the Projection-to-Born method, in which the process is constructed on top of the NNLO inclusive calculation to produce differential results.
  hep-ph/1506.02660v2; M. Cacciari, F. Dreyer, A. Karlberg, G. Salam, G. Zanderighi
  Note: previous projection-to-born results suffered from a bug that propagated from VBFNLO to powheg in the Higgs +3j calculation. Revised results (v2) in agreement with NNLOJET.

Vector Boson Fusion Matrix Element

Differential results are obtained in what the DIS or "structure function" approach, which means defining Vector Boson Fusion as diagrams in which the vector boson is exchanged in the t channel and without QCD interference between the two quark currents:

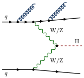


Effectively, this mean forbidding contributions which are estimated to be negligible when VBF cuts are applied:

- Gluon exchange between the upper and lower quark currents (either real or virtual).
- Interference from same flavour quarks.
- Interference between different production channels.

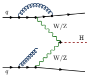
QCD NNLO Amplitudes & IR singularities

- Double Radiation matrix elements (M^0_{n+2})



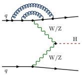
  - Implicit double unresolved singularities arise during phase space integration
  - Very computationally challenging

- Single Radiation one loop matrix elements (M^1_{n+1})



  - Explicit IR poles arising from loop integration
  - Single unresolved singularities arise during phase space integration

- Two loops matrix elements (M^2_n)



  - Only explicit IR poles arise, coming from loop integration
  - Theoretical bottleneck of most NNLO calculations

Challenges of NNLO calculations

A numerical implementation of a NNLO calculation can be very challenging even beyond the construction of Matrix Elements and Subtraction Terms

- ✗ Slow convergence of the integrand.
- ✗ Numerical stability in the singular regions.
- ✗ Bugs can go unnoticed for years until independent calculations comes along.

These issues can't never be completely avoided, but we can do our best to minimise their effect.

- ✓ Grid computing and scalability of the code.
- ✓ Validation tests all our calculations need to go through.
- ✓ Daily regression test ensure bugs are not accidentally introduced.

For more information about NNLOJET see morning talk by Aude Gehrmann-De Ridder or tomorrow's talk by Duncan Walker.

NNLOJET validation suite

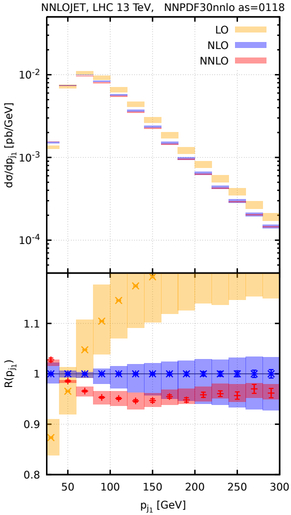
In NNLOJET validation test can be performed for different channels independently and, when possible, we also separate by color level.

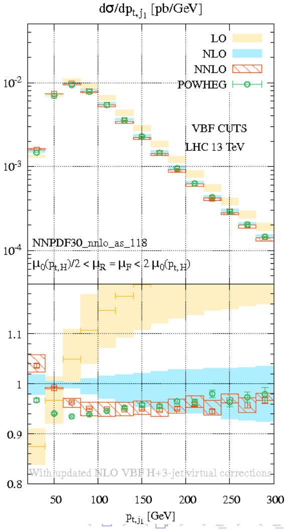
	Level	ME	Subt	Tech cut	$\frac{1}{\epsilon}$	Layer	Scale	P. Space	Incl.
LO	B	✓ (red)	-	✓ (green)	-	-	-	✓ (green)	✓ (red)
NLO	R	✓ (red)	✓ (green)	✓ (green)	-	✓ (green)	✓ (green)	✓ (green)	✓ (red)
	V	✓ (red)	-	✓ (green)	✓ (green)	✓ (green)	✓ (green)	✓ (green)	✓ (red)
NNLO	RR	✓ (red)	✓ (green)	✓ (green)	-	✓ (green)	✓ (green)	✓ (green)	✓ (red)
	RV	✓ (red)	✓ (green)	✓ (green)	✓ (green)	✓ (green)	✓ (green)	✓ (green)	✓ (red)
	VV	-	-	✓ (green)	✓ (green)	✓ (green)	✓ (green)	✓ (green)	✓ (red)

Red ticks refer to tests against external tools, green ticks are internal NNLOJET tests. Non-applicable tests are marked with an hyphen.

External comparison for NNLOJET VBF implementation

Results in agreement with updated version of 1506.02660v2





Implementation in NNLOJET

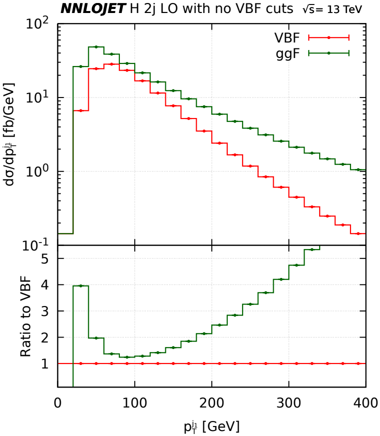
Summary so far:

- ✓ We implemented all Matrix Elements necessary for VBF in the DIS approximation, ie, forbidding colour flow between the two legs.
- ✓ We use Antenna Subtraction to control infrared divergences.
- ✓ VBF Higgs at NNLO QCD implemented in NNLOJET, which provides all analysis routines, antenna functions and integration machinery.

✓✓ The results are fully validated using our very intensive suite of checks and against external tools.

Gluon fusion Vs Vector Boson Fusion

For a detailed study of Higgs electroweak production via VBF it becomes crucial to discriminate against the gluon fusion background.

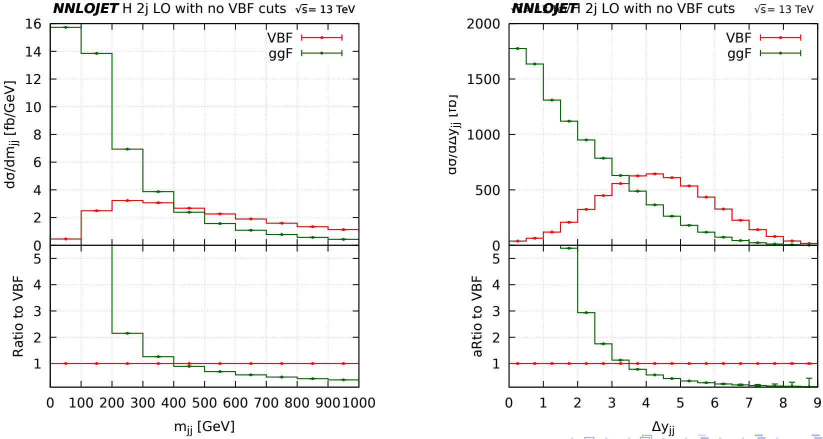


The ggF process heavily dominates most distributions.
Its total production rate is several times that of the VBF mode.

We can exploit the VBF topology in order to discriminate between different processes.

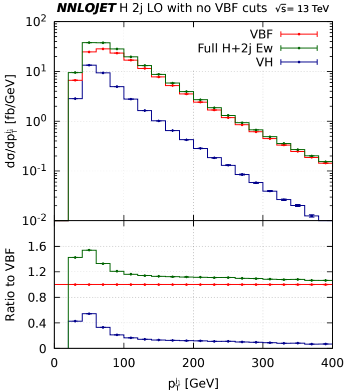
Gluon fusion Vs Vector Boson Fusion

Two tagging jets define the process at the Born level. Their invariant mass and spacial distribution can be used to discriminate between different production modes.



Associated VH (V$\to q\bar{q}$) production Vs Vector Boson Fusion

A complete study of electroweak Higgs production in association with two jets must include Vector Boson plus Higgs associated production with the Vector Boson decaying into two jets.

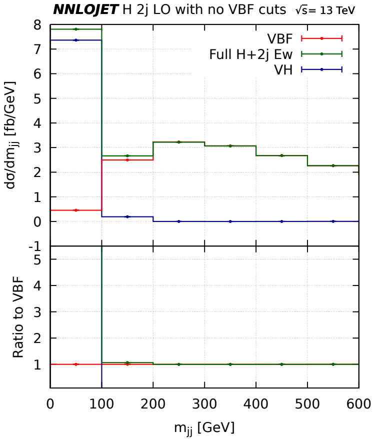


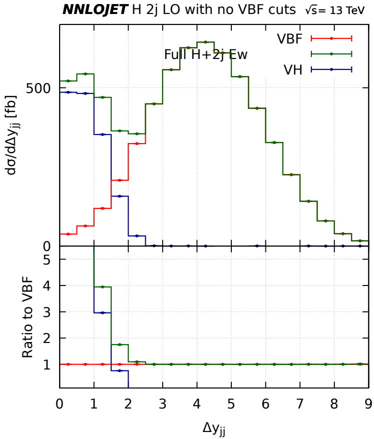
In the DIS approximation we neglect the VH contribution. This approximation is perfectly valid once VBF cuts are applied.

The same observables used to discriminate between ggF and VBF can be used to suppress the VH (V$\to q\bar{q}$) mode.

Associated VH (V$\rightarrow q\bar{q}$) production Vs Vector Boson Fusion

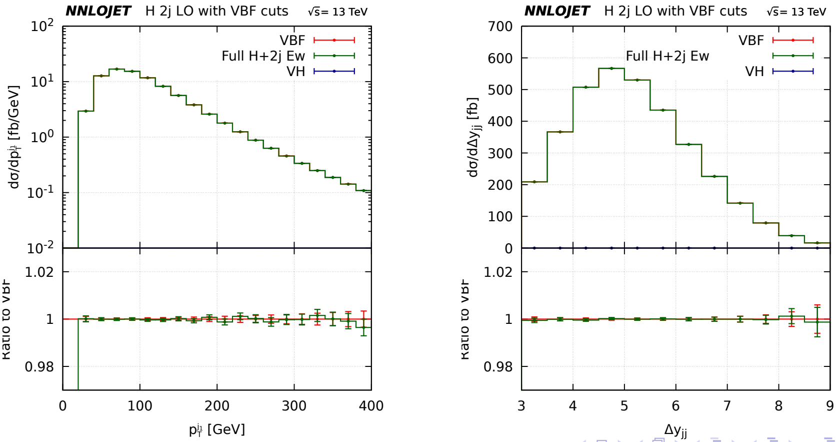
The VH (V$\rightarrow q\bar{q}$) production is concentrated in the low m_{jj} and low Δy_{jj} regions.





Associated VH (V$\rightarrow q\bar{q}$) production Vs Vector Boson Fusion

Imposing relatively loose cuts of $m_{jj} > 400$ GeV and $\Delta y_{jj} > 3$ we **completely** suppress contributions due to color flow between the incoming quarks.



Vector Boson Fusion: VBF Cuts

For a phenomenological description of the effect of the NNLO QCD corrections we impose tight VBF cuts, as used in hep-ph/1802.02445:

- Two tagging jets with $p_T > 25$ GeV
- Tagging jets in different hemisphere ($y_1 y_2 < 0$) where each have $y_i < 4.5$ and $\Delta y_{12} > 4.5$

$$\mu_0^2(p_{T,H}) = \frac{M_H}{2}\sqrt{\left(\frac{M_H}{2}\right)^2 + p_{t,H}^2} \qquad m_{jj} > 600 \text{ GeV}$$

$$\sqrt{s} = 13 \quad \text{TeV} \qquad M_H = 125 \text{ GeV}$$

Scale variations corresponding to $\mu_F = \mu_R = \left\{\frac{1}{2}, 1, 2\right\}\mu_0$.

Total cross section with VBF cuts

Once we impose VBF cuts, the relative size of the NLO and NNLO coefficients increments.

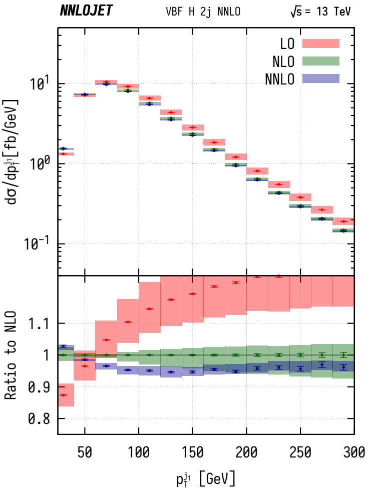
	$\sigma^{\text{Inclusive}}$ (fb)	$\sigma^{\text{VBF cuts}}$ (fb)
LO	4032^{+57}_{-69}	957^{+66}_{-59}
NLO	3927^{+25}_{-24}	876^{+8}_{-18}
NNLO	3884^{+16}_{-12}	844^{+8}_{-8}

Higher order corrections are negative, ranging from 1% at NNLO in the fully inclusive case to a 3% using tight VBF cuts.

Results and plots shown in this section are from: arXiv:1802.02445[1]

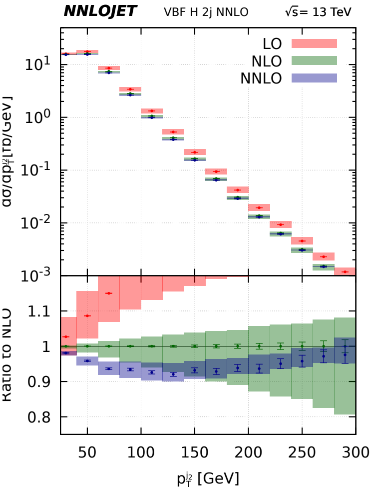
[1] **J.C-M**, T. Gehrmann, N. Glover, A. Huss

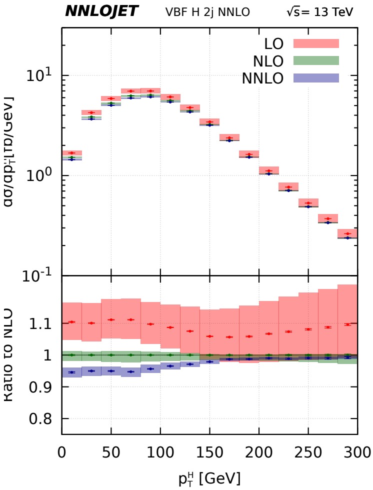
Transverse momentum of leading jet



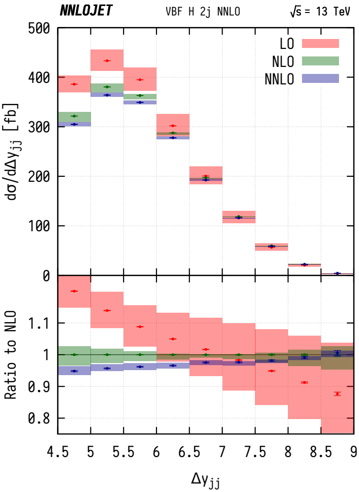
- We find the NNLO corrections to notably reduce the scale uncertainty of the prediction.
- For low values of the transverse momentum the NNLO correction falls outside the NLO bands, whereas for moderate to high values of $p_T^{j_1}$ the correction falls exactly within the NLO bands.
- Similar features are found in other differential distributions:

Transverse momentum of the second jet and Higgs p_T





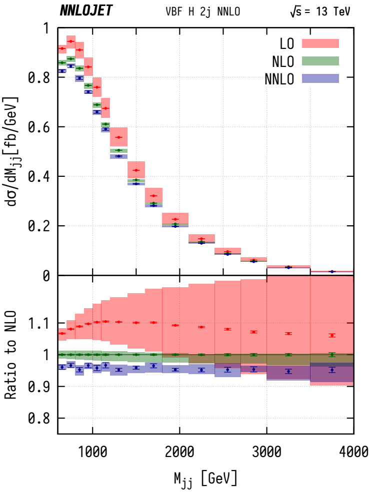
Difference of rapidity between the two tagging jets



The rapidity gap between the two tagging jets (Δy_{jj}) directly affects the VBF cuts.

- NNLO corrections fall outside the NLO scale bands for most of the considered range
- Corrections of about 3-5% in the most important regions of the distribution.
- A reduction of the scale uncertainty indicates a good convergence of the perturbative series.

Invariant mass of the dijet system



NNLO corrections to the invariant mass of the dijet system formed by the two tagging jets systematically fall outside the NLO scale bands.

Both NLO and NNLO corrections preserve the shape of the observable, finding about a $\sim 10\%$ correction at NLO and $\sim 5\%$ at NNLO.

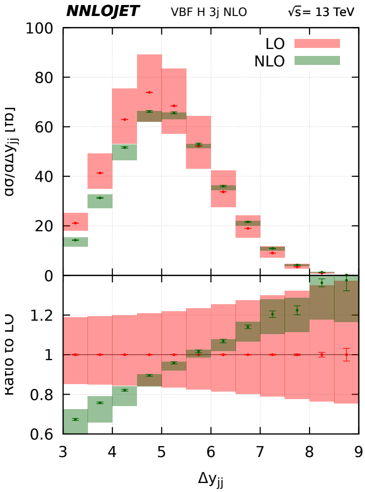
Further development.

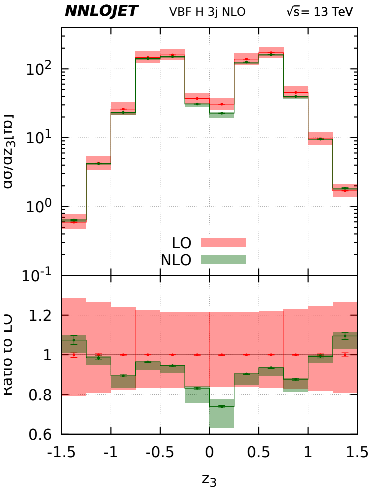
✓ Previous result include the decay of the Higgs to two photons, although no cuts are imposed on these decay products. Working on including the full decay library of the Higgs.

✗ The NLO corrections to Higgs production in association with three jets via VBF are quite sizeable and the scale uncertainties are still quite relevant.

✓ NNLO QCD corrections for the VBF Higgs plus three jet process will likely solve these issues.

Difference of rapidity between the two tagging jets, Higgs + 3jets

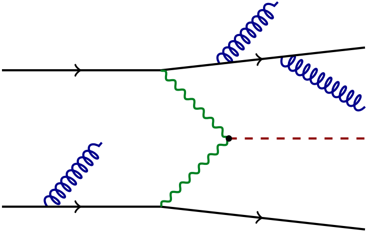




Higgs + 3jets at NNLO

The size of the NLO corrections and the scale uncertainty bands motivates going an order higher in order to take these under control.

Most ingredients for this calculation in the DIS approximation are already in the NNLOJET codebase.



Double real corrections to the Higgs plus three jets process via VBF

✓ Pushes the limits of the resources available to us as for computing NNLO corrections to a three jets final state.

Conclusions

We have presented our implementation in NNLOJET of the Higgs production process in the DIS approximation.

- ✓ Fully validated against internal and external tools.
- ✓ DIS approximation for VBF-H is well justified when VBF cuts are applied.
- ✓ NNLO QCD corrections put the scale uncertainties completely under control.

Further development:

- ✓ Implementation of new Higgs decays to our current code.
- ✓ New NNLO QCD calculations for Higgs physics.

Thanks!

Check: fully inclusive calculation at NNLO QCD

Results for NLO and NNLO correspond to only the N(N)LO correction. Using a fixed scale $\mu_F = \mu_R = m_H$.

	σ^{proVBFH}[1] (fb)	σ^{NNLOJET} (fb)
LO	4007.5 $\pm$ 0.5	4007.4 $\pm$ 1.4
NLO correction	-60.04 $\pm$ 0.06	-60.2 $\pm$ 0.4
NNLO correction	-49.06 $\pm$ 0.02	-49.9 $\pm$ 0.8

This comparison is a very powerful check of the validity of our implementation. Also very challenging as we dwell in the most unstable pieces of the calculation.
QCD corrections (NLO and NNLO) to the inclusive cross section are found to be negative and very small compared to the LO cross section.

[1] M.Cacciari, F.A.Dreyer, A.Karlberg, G.P.Salam and G.Zanderighi.

Comparison with Projection To Born results

Imposing VBF cuts, we also find agreement with the revised results of hep-ph/1506.02660v2.
Imposing VBF cuts to our calculation increments the relative size of the NLO and NNLO coefficients.

	$\sigma^{\text{projection to born}}$ (fb)	σ^{NNLOJET} (fb)
LO	957^{+66}_{-59}	957^{+66}_{-59}
NLO	876^{+8}_{-18}	877^{+7}_{-17}
NNLO	844^{+8}_{-8}	844^{+9}_{-9}

Logistics of the calculation at NNLO QCD

The double radiation for this process corresponds to a $2 \to 5$ (or 6/8, if we take into account possible Higgs decays), making it computationally very intensive.

Part	Warmup (cpu h)	Production (cpu h)	% error in $\sigma^{\$part}$
RV	200	18,000	0.1
RR	5000	100,000	5

Note: LO and NLO computational times are negligible compared to the most expensive parts of the NNLO calculation.