Higgs production on Vector Boson Fusion at NNLO in NNLOJET with Antenna Subtraction

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NNLOJET collaboration

IPPP Durham University

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Outline

1. Introduction
   - VBF NNLO in the DIS approach
   - IR singularities and Antenna Subtraction
2. NNLO calculation
   - Total Cross Section
   - Differential distributions
3. Conclusions

State of the art of VBF calculations

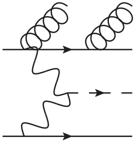
- Inclusive cross section known up to NNLO in the structure function approach. NNLO corrections found to be small.
  hep-ph/1003.4451, P. Bolzoni, F. Maltoni, S. Moch, M. Zaro, 2010
- Recent study for differential NNLO VBF Higgs production using projection to born showed relative big NNLO corrections when typical VBF cuts were applied
  hep-ph/1506.02660, M. Cacciari, F. Dreyer, A. Karlberg, G. Salam, G. Zanderighi, 2015
- Inclusive N^3LO cross section in the DIS approximation using structure functions has been recently obtained
  hep-ph/1606.00840 F. Dreyer, A. Karlberg

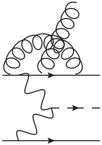
Vector Boson Fusion amplitudes

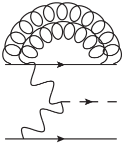
We work on what is usually known as the DIS approach, which means defining "Vector Boson Fusion" as:

- Diagrams in which the vector boson is exchanged in the t channel
- Not including exchange of gluons between upper and lower legs (either real or virtual).
- Not including same flavour quark annihilation

These contributions we ignore are estimated to be negligible when VBF cuts are applied.

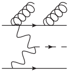






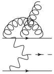
QCD NNLO Amplitudes & IR singularities

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



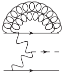
  - Implicit double unresolved singularities arise during phase space integration
  - Very computationally challenging

- 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
  - Very challenging analytically
  - Theoretical bottleneck of most NNLO calculations

Control of singularities

Different approaches can be used for NNLO calculations:

- **Projection to born**: presented in the context of VBF Higgs production at NNLO in 1506.02660[1].

- **Antenna subtraction**: implemented in NNLOJET and successfully used for many different NNLO calculations[2].

- $pp \to H, Z, W$ + 0,1 jets (1408.5325, 1507.02850, 1601.04569, 1607.08817, 1610.01843, 1712.07543)
- $pp \to$ dijets (1310.3993, 1611.01460, 1705.10271)
- $ep \to 2, 3$ jets (1606.03991, 1703.05977)
- . . .

[1] M.Cacciari, F.A.Dreyer, A.Karlberg, G.P.Salam and G.Zanderighi
[2] X.Chen, T.Gehrmann, J.C-M, J.Currie, N.Glover, T.Morgan, J.Niehues, D.Walker, R.Gauld, A.Gehrmann-De Ridder, A.Huss, J.Pires

Fully inclusive calculation

Comparison of the fully inclusive cross section computed using latest version of hoppet and proVBFH.[3]

	σ^{proVBFH} (fb)	σ^{NNLOJET} (fb)
2j LO	4007.5 $\pm$ 0.5	4007.4 $\pm$ 1.4
2j NLO	-60.04 $\pm$ 0.06	-60.2 $\pm$ 0.4
2j NNLO	-49.06 $\pm$ 0.02	-49.9 $\pm$ 0.8

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

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

Vector Boson Fusion: VBF Cuts

We use the same cuts and parameters as 1506.02660[4].

- Two tagging jets with $p_T > 25$ GeV
- Tagging jets in different hemisphere ($y_1 y_2 < 0$) where each $y_i > 4.5$ 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 corresponds to $\mu_F = \mu_R = \left\{\frac{1}{2}, 1, 2\right\}\mu_0$.

[4] M.Cacciari, F.A.Dreyer, A.Karlberg, G.P.Salam and G.Zanderighi. "Fully Differential Vector-Boson-Fusion Higgs Production at Next-to-Next-to-Leading Order" PRL 115.082002

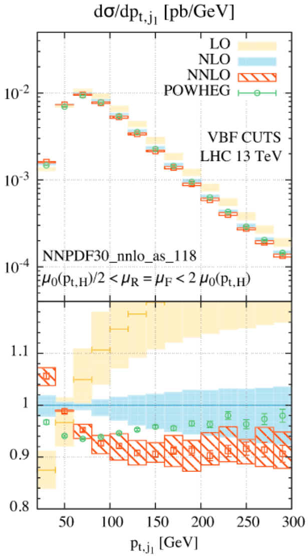
Total cross section with VBF cuts

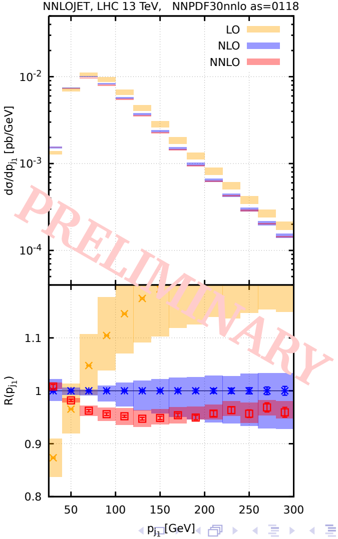
We already see some diferences at the Total Cross Section level:

	$\sigma^{hep-ph/1506.02660}$ (fb)	σ^{NNLOJET} (fb)
LO	957^{+66}_{-59}	$956.9^{+66}_{-59} \pm 0.2$
NLO	876^{+8}_{-18}	$877.0^{+7}_{-17} \pm 0.3$
NNLO	826^{+13}_{-14}	$844.1^{+9}_{-9} \pm 0.8$

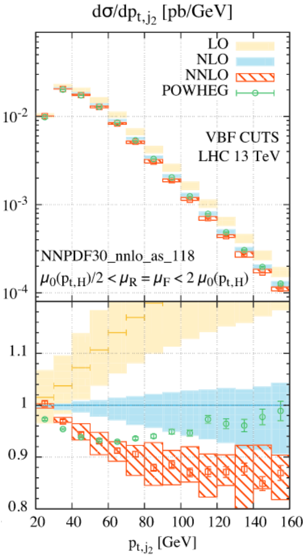
The following differential results, shown in the left hand side of this section, are taken from hep-ph/1506.02660.
Preliminary results are from NNLOJET.

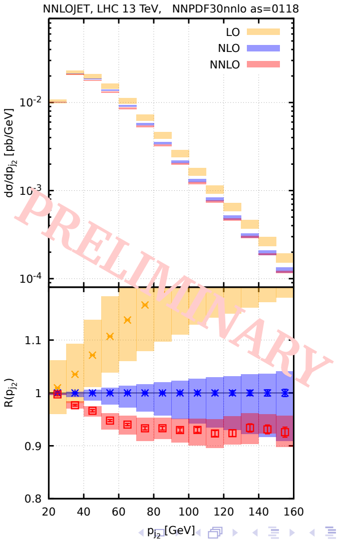
Transverse momentum of leading jet: ptj1



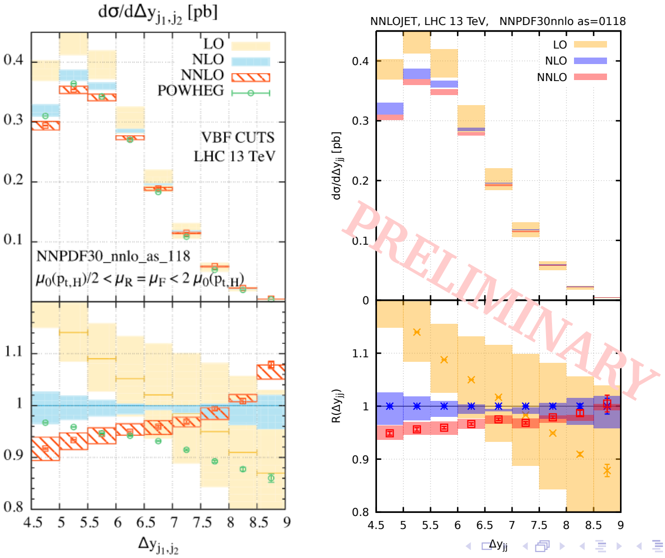


Transverse momentum of the second jet: ptj2

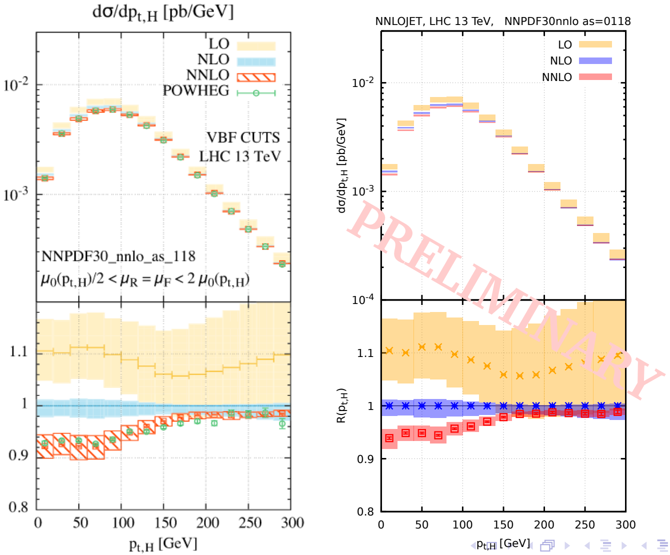




Difference of rapidity between two tagging jets: deltay_j12



Higgs transverse momentum: pth



Conclusions

Implementation in NNLOJET of NNLO corrections to VBF Higgs production in the DIS approximation is now complete and validated!

- ✓ Inclusive VBF H at NNLO compared against proVBFH.
- ✗ Differential VBF H at NNLO:
  differences found with 1506.02660 traced back to a bug in VBFNLO

  - Effects of NNLO corrections in distributions smaller than 1506.02660.
  - Scale uncertainty in ratio plots reduced (from $\sim \pm 5 - 10\%$ to $\sim \pm 2 - 3\%$).

Backup slides

Total cross section at NLO

Comparison results at NLO obtained with MCFM.

	σ^{MCFM} (fb)	σ^{NNLOJET} (fb)
2j LO	3449.2 $\pm$ 0.8	3448.3 $\pm$ 1.3
3j LO	1144.6 $\pm$ 0.5	1143.5 $\pm$ 0.7
2j NLO coef	-44.7 $\pm$ 0.9	-45.3 $\pm$ 0.5

Results obtained with a single cut of $p_{t,j} > 15$ GeV ,
$\sqrt{s} = 13000$ GeV and $\mu_F = \mu_R = m_H$.
Pdfset: NNPDF30_nnlo_as_0118.

VBF Results at NLO

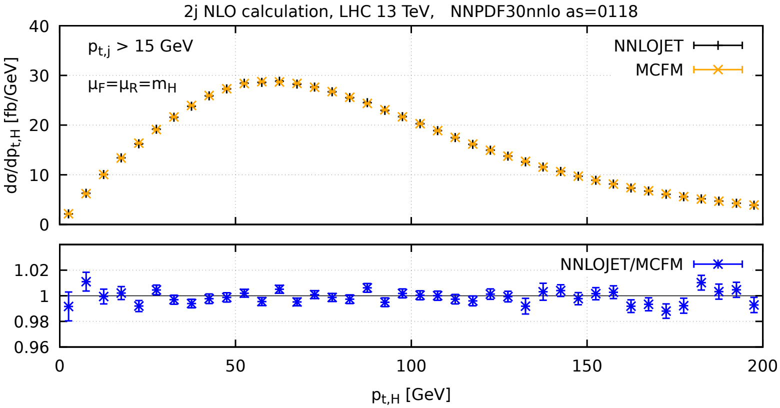


Figure: Comparison between our code and MCFM at NLO. Transverse momentum of the Higgs.

VBF Results at NLO

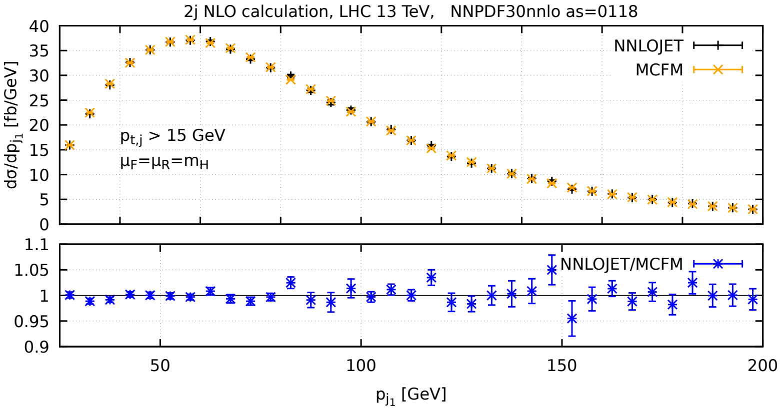
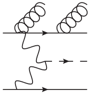
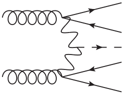
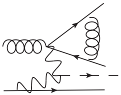


Figure: Comparison between our code and MCFM and NLO. Transverse momentum of the hardest jet.

Pointwise comparison of the ME

Process	NNLOJET	Madgraph	Ratio
	5.1406085025982153E-014	5.1406085025982185E-014	1.0000000000000007
	4.0982703031871614E-017	4.0982703031871552E-017	1.00000000000000163
	-5.9293779081794126E-011	-5.9293779081799606E-011	0.99999999999990763

Similar checks were made against OpenLoops[5]

[5] Thanks to J. Lindert for providing the relevant MEs

VBF+J at NLO

We compare the inclusive cross section with VBFNLO[6].

$$\sigma^{VBFNLO} = 457 \pm 2\ fb$$
$$\sigma^{NNLOJET} = 423 \pm 2\ fb$$

This difference traced back to a bug in VBFNLO.

[6] Published version, 2.7