Fully differential VBF Higgs production at NNLO

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Five good reasons to study VBF Higgs production:

1. VBF is the largest cross-section that involves tree-level production, and the second of all production processes (after gluon-gluon-fusion)
VBF Higgs production

Five good reasons to study VBF Higgs production:

2. It has a **distinctive signature** that involves two forward jets (tagging jets)
VBF Higgs production

Five good reasons to study VBF Higgs production:

3. Tagging jets allow one to better tag events and identify Higgs decays that have very large backgrounds (notably $H \to \tau\tau$ and $H \to bb$)
Five good reasons to study VBF Higgs production:

4. Higgs transverse momentum is non-zero at LO. Facilitates searches of invisible decay modes

\[ p_{t,j1}, p_{t,j2}, p_{t,H} \]
VBF Higgs production

Five good reasons to study VBF Higgs production:

5. Angular correlation of forward jets brings in sensitivity to CP properties of the Higgs and to non-SM Higgs interactions (small CP odd component is still allowed)

Plehn et al ’01
VBF Higgs production

Fully inclusive VBF Higgs production was known at NNLO in the structure function approach.

The calculation suggests tiny renormalization/factorization scale uncertainties (~ 1-2%). NNLO well within the NLO band.

Bolzoni et al '10 - '11
VBF Higgs production

However, no realistic VBF cuts can be applied to it, as the calculation is totally inclusive over hadronic final states that give the same vector-boson momenta.

Differential VBF Higgs production known up to now only to NLO (+PS) and also suggests small uncertainties.

Figy, Oleari, Zeppenfeld '03
The structure function approach

Schematically, think of VBF as $\text{DIS} \times \text{DIS}$ with no cross-talk between radiation from the upper and lower sector (factorized approximation). Since the DIS coefficients used are inclusive over the hadronic final state, the calculation cannot provide differential results.
Simple kinematics

Key observation:

If the scattering is Born like, then the vector boson-momenta $q_i$, and on-shell conditions, fix the incoming and outgoing parton momenta:

$$p_{\text{in},i} = x_i P_i \quad p_{\text{out},i} = x_i P_i - q_i \quad x_i = \frac{q_i^2}{2q_i P_i}$$
Going fully differential

This work: going beyond structure function approach. Based on two ingredients

1. the inclusive contribution
   - use the SF approach and use four-vectors $q_1, q_2$ to assign Born-like (i.e. $2 \rightarrow H + 2$) kinematics using the previous eqs.
   - use the projected Born-like momenta to compute differential distributions
Going fully differential

This work: going beyond structure function approach. Based on two ingredients

2. the exclusive contribution

- use the VBF $H + 3$ jet NLO calculation in the factorized approximation

Figy et al ’07 [NLO]; Jaeger et al ’14 [NLO+PS]

- keep track, for each parton, whether it belongs to upper/lower sector; this makes it possible to deduce vector-boson momenta, $q_1, q_2$

- for each event (weight $w$), add a counter-event with projected Born kinematics (weight -$w$) deduced from $q_1, q_2$
Going fully differential

Schematically:

\[ \sigma = \int d\Phi_B (B + V) + \int d\Phi_R R \]

\[ = \int d\Phi_B (B + V) + \int d\Phi_R R_{P2B} + \int d\Phi_R R - \int d\Phi_R R_{P2B} \]

From inclusive contribution

Finite, from exclusive contribution

Combining the two pieces:

• from the exclusive contributions we get the full contributions from double-real and one-loop single-real

• after integration over phase-space, counter-events cancel projected tree-level double real and one-loop single real contributions from the inclusive

The sum gives thus the complete, fully differential NNLO result
Going fully differential

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From inclusive contribution

Finite, from exclusive contribution

The sum gives thus the complete, fully differential NNLO result.
Practicalities

For the **inclusive part** we have

- taken the phase-space from POWHEG’s VBF_H

- matrix elements coded with structure functions evaluated using parametrized versions of the DIS coefficient functions

- the structure functions evaluated with the package HOPPET
  
  https://hoppet.hepforge.org

**Checks**

- against private version of structure-function calculation *(thanks to Marco Zaro)*

- of structure functions with APFEL 2.4.1

- approx vs exact coefficient functions (negligible difference)
Practicalities

For the exclusive part we have

- taken the VBF_HJJJJ calculation in POWHEG
- extended POWHEG’s tags to uniquely associate radiation with each sector
- for each event, uniquely determined the vector-boson momenta $q_1, q_2$ and hence the counter-event (with weight -w)

Checks

- results for VBF_HJJJJ unchanged
- sum of inclusive + exclusive at NLO, agrees with VBF_H (NLO)
- once the rapidity between the two jets increases, there is a decreasing rate of partons assigned to the “wrong” sector
Check of tagging

- partons are tagged as up or down (U/D)
- classify events into 3- or 4- jet events
- check if the U/D assignment of the partons in a given jet corresponds to the jet rapidity (positive or negative)
- the rate for “non-correspondence” must decrease when the rapidity separation between the leading jets increases

similar plots available for gluons in opposite side (UD,DU)
Check of tagging

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Phenomenology

Take 13 TeV LHC collisions. Jets: anti-\( k_t \) with \( R=0.4 \). \( M_H = 125 \) GeV, NNPDF3.0_{nnlo_as0118} (\textit{also at LO, NLO}), standard EW parameters.

Choose as central scale (which approximates well \( \sqrt{Q_1 Q_2} \))

\[
\mu_0^2(p_{t,H}) = \frac{M_H}{2} \sqrt{\left(\frac{M_H}{2}\right)^2 + p_{t,H}^2}
\]

Take VBF cuts

- at least two jets with \( p_{t,j} > 25 \text{GeV} \)
- the two hardest (tagging jets) should have
  \[
  \Delta y_{j1j2} > 4.5 \quad m_{j1j2} > 600 \text{ GeV} \quad |y_j| < 4.5 \quad y_{j1} y_{j2} < 0
  \]
Phenomenology

Cross-sections: inclusive and with VBF cuts

<table>
<thead>
<tr>
<th></th>
<th>$\sigma^{(\text{no cuts})}$ [pb]</th>
<th>$\sigma^{(\text{VBF cuts})}$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LO</td>
<td>$4.032^{+0.057}_{-0.069}$</td>
<td>$0.957^{+0.066}_{-0.059}$</td>
</tr>
<tr>
<td>NLO</td>
<td>$3.929^{+0.024}_{-0.023}$</td>
<td>$0.876^{+0.008}_{-0.018}$</td>
</tr>
<tr>
<td>NNLO</td>
<td>$3.888^{+0.016}_{-0.012}$</td>
<td>$0.826^{+0.013}_{-0.014}$</td>
</tr>
</tbody>
</table>

- NNLO outside the NLO band
- NNLO about 5% (1%) with (without) VBF cuts
- NNLO corrections appear to make jets softer, hence fewer events pass the VBF cuts (see next plots)
Distributions: $p_{t,j1}$ and $p_{t,j2}$

- NNLO corrections appear to make jets softer
- NNLO corrections up to $\sim 10\%-12\%$, typically outside the NLO band
Distributions: $p_{t,H}$ and $\Delta y_{j1,j2}$

- Sometimes parton-shower (NLOPS) agrees well with NNLO ($p_{t,H}$), sometimes it does not ($\Delta y_{j1,j2}$)
- Non-trivial kinematic dependence of K-factors (NLO/LO and NNLO/NLO)

![Graph showing distributions of $p_{t,H}$ and $\Delta y_{j1,j2}$](image)
3 versus 7 scale bands for \( p_{t,H} \)

3 scales: black lines; 7 scales: all lines

3 scales: \( \mu_R = \mu_F = \mu_0 \{1/2, 1, 2\} \)

7 scales: \( (\mu_R, \mu_F) = \mu_0 \{(1/2, 1/2), (1/2, 1), (1, 1/2), (1, 1), (1, 2), (2, 1), (2, 2)\} \)
3 versus 7 scale bands for $p_{t,H}$

3 scales: black lines; 7 scales: all lines

Conclusion: 3 and 7 scale bands very similar
Conclusions

• shown first **fully differential NNLO results for VBF Higgs production using a new “projection to Born” method**

• **NNLO reveals that practical VBF (i.e. with cuts) has non-trivial effects beyond NLO, hence differential NNLO is necessary for precision phenomenology** (corrections up to 10-12%)  

• power of the method highlighted by the fact that **NNLO has been achieved for the first time for a 2 → 3 LHC process** (thanks also to the fact. approx)  

• **this method opens up the prospect for the only N^3LO hadron-collider calculation in the foreseeable future beyond 2 → 1**
Extra slides
Different NLOPS with POWHEG

Comparison between different showers with and without hadronization within NLOPS-POWHEG. Similar effects for other observables.
Different PDFs at various orders

- LO with LO PDFs
- NLO with NLO PDFs
- NNLO with NNLO PDFs
Different PDFs at various orders

- LO with LO PDFs
- NLO with NLO PDFs
- NNLO with NNLO PDFs