Higgs Production through Weak Boson Fusion

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Subjects to be discussed:

- NLO QCD corrections to VBF and VBS
- Central Jet Veto and NLO QCD corrections
- NNLO and N3LO in DIS approximation
- NNLO corrections to distributions and R dependence
- Interface to Parton Shower
Vector boson fusion \((qq\rightarrow qqH, qq\rightarrow qqV)\) and vector boson scattering \((qq\rightarrow qqVV)\) are expected to provide prime information on the dynamics of electroweak symmetry breaking at the LHC.

- We have calculated NLO QCD corrections for these and a variety of other processes with vector bosons in the final state.

Calculations are publicly available within the VBFNLO program package.

Code can be downloaded from [http://www.itp.kit.edu/~vbfnloweb/](http://www.itp.kit.edu/~vbfnloweb/)
**VBF and VBS signature**

**Characteristics:**

- energetic jets in the *forward* and *backward* directions \( (p_T > 20 \text{ GeV}) \)
- large *rapidity separation* and large *invariant mass* of the two tagging jets
  \[ m_{jj} > 600 \text{ GeV} \quad \quad \quad |y_{j_1} - y_{j_2}| > 4 \]
- Higgs/V/V/V decay products between tagging jets
Generic features of NLO QCD corrections to VBF and VBS

$t$-channel color singlet exchange $\rightarrow$ QCD corrections to different quark lines are independent

Born and vertex corrections to upper line

No $t$-channel gluon exchange at NLO

real emission contributions: upper line

Treat $s$-channel contributions (here $VH$ production with $V \rightarrow jj$ decay) and QCD processes (e.g. $VVjj$ production at order $\alpha_s^2\alpha^2$) as separate processes. Neglect interference for identical fermions: small effects in phase space where VBF/VBS is visible. Features are generic for all VBF/VBS processes.
Virtual corrections: Higgs production

Most trivial case: Higgs production
Virtual correction is vertex correction only

\[ \mathcal{M}_V = \mathcal{M}_{\text{Born}} \frac{\alpha_s(\mu_R)}{4\pi} C_F \left( \frac{4\pi \mu_R^2}{Q^2} \right)^\epsilon \Gamma(1+\epsilon) \left[ -\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + \frac{\pi^2}{3} - 7 \right] + \mathcal{O}(\epsilon) \]

- Divergent piece canceled via Catani Seymour algorithm

Remaining virtual corrections are accounted for by trivial factor multiplying Born cross section

\[ |\mathcal{M}_{\text{Born}}|^2 \left( 1 + 2\alpha_s \frac{C_F}{2\pi} c_{\text{virt}} \right) \]

- Factor 2 for corrections to upper and lower quark line
- Same factor to Born cross section absorbs most of the virtual corrections for other VBF processes
3 weak bosons on a quark line: $qq \rightarrow qqWW, qqZZ, qqWZ$ at NLO

- example: $WW$ production via VBF with leptonic decays: $pp \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu + 2j$
- Spin correlations of the final state leptons
- All resonant and non-resonant Feynman diagrams included
- NC $\rightarrow$ 181 Feynman diagrams at LO
- CC $\rightarrow$ 92 Feynman diagrams at LO

Use modular structure, e.g. leptonic tensor

Calculate once, reuse in different processes

Speedup factor $\approx 70$ compared to 2005 version of MadGraph for real emission corrections
NLO corrections to VBF Higgs Production

- Small QCD corrections of order 10%
- Tiny scale dependence of NLO result
  - ±5% for distributions
  - < 1% for \(\sigma_{\text{total}}\)
- pdf error is below 3% since pdf’s are dominated by valence quarks
- \(\approx -5\%\) EW corrections included

Ciccolini, Denner, Dittmaier, 0710.4749
Figy, Palmer, Weiglein arXiv:1012.4789

- Very small cross section error of about 3% for \(m_H = 126\text{ GeV}\)

\[ m_H = 120\text{ GeV}, \quad \text{typical VBF cuts} \]
**VBF $hjjj$ production**

- Born: 3 final state partons + Higgs via VBF

$$
\mathcal{M}_B = t_{i_1 i_a}^{a_3} \delta_{i_2 i_b} \left[ \mathcal{M}_{B,1a} : \begin{array}{c}
\text{Diagram 1a}
\end{array} \right] + \delta_{i_1 i_a} t_{i_2 i_b}^{a_3} \left[ \mathcal{M}_{B,2b} : \begin{array}{c}
\text{Diagram 2b}
\end{array} \right]
$$

- No interference between upper and lower set of Feynman graphs due to color structure
- Two emission graphs off upper quark line interfere **destructively** for gluon emission at larger angles than scattered quark
- Analogous for gluon emission off lower quark line
- $\Rightarrow$ Little gluon radiation in rapidity region between the two quark jets
Central Jet Veto: $Hjjj$ from VBF vs. gluon fusion

[ Del Duca, Frizzo, Maltoni, JHEP 05 (2004) 064]

- Angular distribution of third (softest) jet follows classically expected radiation pattern
- QCD events have higher effective scale and thus produce harder radiation than VBF (larger three jet to two jet ratio for QCD events)
- Central jet veto can be used to distinguish Higgs production via GF from VBF
**VBF $hjjj$ production and NLO corrections**

- Born: 3 final state partons + Higgs via VBF

\[
\mathcal{M}_B = t_{i_1i_a}^{a_3} \delta_{i_2i_b} \left[ \mathcal{M}_{B,1a} : \begin{array}{c}
\text{Diagram 1a:} \\
\text{Diagram 1a:}
\end{array} \right] \\
+ \delta_{i_1i_a} t_{i_2i_b}^{a_3} \left[ \mathcal{M}_{B,2b} : \begin{array}{c}
\text{Diagram 2b:} \\
\text{Diagram 2b:}
\end{array} \right]
\]

- Catani, Seymour subtraction method

- Real: 4 final state partons + Higgs via VBF

- Virtual: Two classes of gauge invariant subsets
  - Box + Vertex + Propagator
  - Pentagon + Hexagon are small and can be neglected
    (consistent with full NLO calculation by Campanario, Figy, Plätzer, Sjodahl)
Veto Probability for the VBF Signal

\[ p_{\text{veto}} = \frac{1}{\sigma_2^{\text{NLO}}} \int_{p_{T,\text{veto}}}^{\infty} dp_{T,j}^{\text{veto}} \frac{d\sigma_3}{dp_{T,j}^{\text{veto}}} \]

Scale variations, \( p_{T,\text{veto}} = 15 \text{ GeV} \):
- LO: +33\% to −17\%
- NLO: −1.4\% to −3.4\%

Reliable prediction for perturbative part of veto probability at NLO
VBF Higgs in Structure Function Approach

QCD corrections on 2 quark lines independent, inclusive over „DIS jet hadronization“

- NLO: Han, Valencia, Willenbrock (1992)
- NNLO: Bolzoni, Maltoni, Moch, Zaro (2010)
- N3LO: Dreyer, Karlberg (2016)

- Inclusive cross section has 1-2 permille scale uncertainty pdf errors, alphas uncertainty, EW corrections dominate and are substantially larger, in percent range

- Some distributions for inclusive production
Distributions for inclusive production up to N3LO

Extreme stability of predictions at the 2 percent (NLO) to 1 permille level (N3LO)
VBF Higgs in Structure Function Approach

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- Inclusive cross section has 1-2 permille scale uncertainty; pdf errors, alphas uncertainty, EW corrections dominate
- Some distributions for inclusive production
- No VBF cuts to distinguish VBF from gluon fusion Higgs signal or from backgrounds
- Need tagging jets and their distributions
Fully differential VBF Higgs cross section and fiducial cross section at NNLO

Cacciari, Dreyer, Karlberg, Salam, Zanderighi, arXiv:1506.02660
DIS approximation: treat QCD corrections to 2 quark lines as independent
no t-channel gluon ladders

<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>$4.032 \pm 0.057$</td>
<td>$0.957 \pm 0.066$</td>
</tr>
<tr>
<td>NLO</td>
<td>$3.929 \pm 0.024$</td>
<td>$0.876 \pm 0.008$</td>
</tr>
<tr>
<td>NNLO</td>
<td>$3.888 \pm 0.016$</td>
<td>$0.826 \pm 0.013$</td>
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</tbody>
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VBF cuts:
- $m(jj) > 600$ GeV,
- $\Delta y(jj) > 4.5$,
- $pT(j) > 25$ GeV,

Opposite hemispheres for tagging jets

NNLO correction to inclusive cross section: 1%
with VBF cuts: 6%
Anti-kT jets with R=0.4: \( m(jj) > 600 \text{ GeV} \quad \Delta y(jj)> 4.5 \)

Corrections at NNLO (as compared to NLO): up to 10%

Cacciari, Dreyer, Karlberg, Salam, Zanderighi, arXiv:1506.02660
Energy flow in DIS jets: NLO correction to Jet shape

Definition: Jet shape = 
\[ \psi(r) = \text{fraction of jet ET in cone of radius } r \]

Differential jet shape: \[ \rho(r) = d\psi/dr \]

Observation for DIS at HERA (1999)

Energy flow is considerably narrower in NLO quarks jets (=LO jet shape) than in NNLO jets (with up to 3 partons)

Small cone \((R=0.4)\) misses some fraction of jet energy \(\rightarrow\) reduced \(m(jj)\) \(\rightarrow\) fewer events survive \(m(jj)> 600 \text{ GeV cut}\)
VBFNLO study using NLO hjjj code (with Michael Rauch)

- hjjj (NLO) code has virtual corrections to h+3partons and real emission of 4 partons.
- h+2parton 2-loop corrections are missing. They only contribute to jet shape at r=0
- Change (in cross sections or distributions) between R=0.4 and other values does not require 2-loop contributions
- Start from Cacciari et al. results and study dependence on jet radius R in anti-kT algorithm at full NNLO
  - Cuts and parameters identical to arXiv:1506.02660

- We find dependence on jet algorithm (kT vs anti-kT vs Durham/Aachen) to be small at NNLO
R-dependence of hjj cross section with VBF cuts

Anti-kT jets \[ m(jj) > 600 \text{ GeV} \] \[ \Delta y(jj) > 4.5 \]

(M. Rauch)
pT of hardest tagging jet: anti-kT, R=0.4, 1.0, 1.6

At R=1 also most distributions show best agreement between NLO and NNLO
pT(j2) and Higgs pT at R=1

(M. Rauch)
Rapidity separation of tagging jet pair

Change in shape of the $\Delta y(jj) = |y(j1) – y(j2)|$ distribution is not simply a result of the change in jet-shape. Possible explanations:

- Suppressed radiation between tagging jets
- Effect of 2-loop contribution

(M. Rauch)
Beware of jet observables

- For any process with jets at LO, an NLO cross section calculation simulates only LO jet shapes (and LO dependence on jet algorithms).
- This results in sizable QCD corrections at higher order since jet shapes change substantially from LO to NLO (i.e. when going to an NNLO calculation). NLO and NNLO results cannot agree at all jet radii R.
- Jet shape variation, R-dependence and jet algorithm dependence is not captured by scale variation of NLO cross sections. From VBF Higgs example, assign an additional (order 10%) uncertainty to NLO cross sections with jets in the final state, especially when scale variation is exceptionally small, like in VBF.
- Uncertainty will depend on number of jets in LO process, quark vs gluon jet, steepness of jet pT distributions etc.
- Disclaimer: There is nothing special or good about a fat jet choice with R=1 in the case of VBF Higgs production. It would induce large corrections due to underlying event or pile-up…
Parton Shower approximation for VBF Higgs

NNLO effects in jet distributions are partially modeled already by parton shower on top of NLO approximation.

Cacciari, Dreyer, Karlberg, Salam, Zanderighi, arXiv:1506.02660
Veto Jets beyond fixed order: Parton Shower interface

Interface of NLO calculations with Herwig and PYTHIA via Powheg Box has been implemented by Franziska Schissler

- How well can “veto jets” be modeled directly by parton shower approach?
- Differences between basic shower models (PYTHIA vs. default Herwig shower vs. dipole shower)
- Improvements when adding true NLO corrections
Veto jet distribution: LO $qq \rightarrow qqh$ matrix elements

Schissler thesis, 2014

Pure parton-shower generation of central jets does not produce reliable results

Collinear approximation inherent in PS approach is not valid in veto region for VBF events

Extra parton must be included in hard matrix element
Veto jet distribution: VBF $Wjjj$ production at LO

Inclusion of third parton at ME level produces reasonable agreement between NLO $Vjj$ calculations and parton shower programs
Veto jet distribution: VBF $hjjj$ production at NLO

Further improvement with NLO $hjjj$ calculation matched to PS programs

Reliable simulation of veto jet candidates is possible but requires matrix elements with sufficiently high parton multiplicity
Conclusions

- Excellent understanding of VBF Higgs production:
  - EW corrections known at NLO
  - NNLO corrections known for distributions in the factorization approximation
  - N3LO QCD corrections available in the structure function approach for inclusive VBF production

- Resulting percent level accuracy of simulations is sufficient for LHC analyses

- Surprisingly large NNLO corrections to distributions are related to energy flow inside jets, which is modeled at LO only in NLO cross section calculations

- Dependence on jet-shape and hence on jet radius R should be considered as an additional uncertainty for (N)NLO cross sections of processes with jets at LO