$W^+ W^-$ Production with Many Jets at the LHC

NLO QCD with BlackHat+Sherpa

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With Philipp Hofmann and Harald Ita [to appear]
MOTIVATION
\( t\bar{t}, \text{VBF, Gauge couplings, Experimental results, Previous calculations} \)

NLO QCD WITH BlackHat + Sherpa
\( \text{New developments, Cross checks, Pheno setup, LHC } \sqrt{s} = 7, 8, 13 \text{ TeV} \)

CORRECTIONS TO \( W^+ W^- + 3 \text{ JETS} \)
\( \text{Scale sensitivity, Jet bins, Total/diff cross sections, Radiation gap} \)
$W^+W^- + \text{Jets Signatures}$

- Measurement of **trilinear and quartic couplings**
- In $t\bar{t}$ production, as the top quarks decay $t \rightarrow W + b$
- In vector boson scattering, **vector boson fusion** (VBF)
- In Higgs phenomenology, when it decays into $W^+W^-$
- Scenarios of **BSM**, in which heavy colored particles decay in chains of leptons and jets
- In particular, $W^+W^- + 3$-Jet production is of relevance to understand **radiation gap** in and as background to VBF
$W^+ W^- + n$-Jet Measurement at CDF

CDF Run II: $L = 9.7$ fb$^{-1}$

- Measured cross section
- ALPGEN
- MC@NLO

- arXiv:1505.00801
- Full dataset analyzed
- Total and differential cross sections
- Relative good agreement between theory and data
- At the Tevatron $t\bar{t}$ background is small
SM Cross Sections at ATLAS

Standard Model Production Cross Section Measurements

- Summary plot of SM cross sections
- Impressive agreement between theory and experiment
- Di-vector boson measurements
- Jet towers to deeply test QCD
- Smallest cross section from $W^\pm W^\pm + 2$ jets
- Similar results from CMS
## Parton Level Calculations for $W^+W^- + n$ Jets

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Order</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+W^-$</td>
<td>LO (1979)</td>
<td>Brown, Mikaelian</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ohnemus; Frixione; Campbell, Ellis; Dixon, Kunszt, Signer; Campbell, Ellis, Williams</td>
</tr>
<tr>
<td></td>
<td>NLO (1991)</td>
<td>Gehrmann, Grazzini, Kallweit, Maierhfer, von Manteuffel, Pozzorini, Rathlev, Tancreedi</td>
</tr>
<tr>
<td></td>
<td>NNLO (2014)</td>
<td></td>
</tr>
<tr>
<td>$W^+W^- + 1$ Jet</td>
<td>NLO (2007)</td>
<td>Campbell, Ellis, Zanderighi; Dittmaier, Kallweit, Uwer; Campbell, Miller, Robens</td>
</tr>
<tr>
<td>$W^\pm W^\pm + 2$ Jets</td>
<td>NLO (2010)</td>
<td>Melia, Melnikov, Rontsch, Zanderighi; Campanario, Kerner, Ninh, Zeppenfeld</td>
</tr>
</tbody>
</table>
We employ the BlackHat library, based on unitarity and on-shell techniques, for the computation of the one-loop MEs.

**BlackHat:** Zvi Bern, Lance Dixon, FFC, Stefan Höche, Harald Ita, David Kosower, Adriano Lo Presti and Daniel Maitre; Berger, Diana, Forde, Gleisberg, Ozeren

We employ the Catani-Seymour Dipole subtraction implementation of Sherpa, together with their integration algorithms. We record Ntuple files for sharing and analysing results.

**SHERPA:** Höche, Krauss, Kuttimalai, Schoenherr, Schumann, Siegert, Thompson, Winter and Zapp
New Developments in BlackHat

Produced NLO QCD results for $V+3,4,5$ Jets; 4 Jets; $\gamma\gamma+2$jets; Universality in jet ratios; Ntuples for NLO QCD → (See Daniel Maître’s talk!)

In order to extend the library to handle Di-vector boson processes, we have made the following extensions:

- Tree on-shell recursion relations with quarks, gluons and several vector bosons (with leptonic decay products)
- To cross check, tree level off-shell recursions (Berends-Giele) have been implemented
- Added infrastructure to compute loop amplitudes based on new tree amplitudes
- Automated assembly of tree- and loop-level MEs
Our Setup

- We employ a leading-color approximation (only) for the virtual correction of $W^+W^- + 3\text{ Jet}$. We have checked that this approximation works well, at the level of 1%, in the lower point cases.
- We consider double resonant contributions and include Breit-Wigner propagator for intermediate $W$ and $Z$ bosons.
- Top quark contributions are excluded. We drop also finite bottom quark contributions.
- We work with a diagonal CKM matrix.
- We decay the $W$ bosons into different lepton flavors ($e$ & $\mu$).
Cross Checks of Results

- We have checked IR/UV poles of (full-color) virtual matrix elements
- We have checked collinear limits
- We have cross checked lower point \((n = 0, 1, 2)\) one-loop matrix elements with GOSAM
- We have cross checked our results with independent implementations within BlackHat
- We have checked \(\alpha_{\text{dipole}}\) independence of the real corrections
We employ a dynamical scale \( \mu = \mu_r = \mu_f = \hat{H}_T \) and the MSTW2008 set of PDFs. We take the \( \alpha_s \) provided by the PDF sets and employ \( M_W = 80.399 \ \text{GeV}, \ M_Z = 91.188 \ \text{GeV}, \ \Gamma_W = 2.085 \ \text{GeV} \) and \( \Gamma_Z = 2.4952 \ \text{GeV} \). For the results we present we employ the following kinematical cuts:

- \( p_T^{e,\mu} > 20 \ \text{GeV} \)
- \( |\eta^{e,\mu}| < 2.4 \)
- \( \not{E}_T > 30 \ \text{GeV} \)
- \( p_T^{e\mu} > 30 \ \text{GeV} \)
- \( m_{e\mu} > 10 \ \text{GeV} \)
- Jets defined with anti-\( k_T \) algorithm
- \( R = 0.4 \)
- \( p_T^{jet} > 30 \ \text{GeV} \)
- \( |\eta^{jet}| < 4.5 \)

We have collected results for the LHC with \( \sqrt{s} = 7, 8 \) and 13 TeV.
Scale Sensitivity for $W^+ W^- + n$-Jet Production

- Total cross sections as function of unphysical scales
- $W^+ W^- + 0$ jet not shown (corrections very large, NNLO needed $\rightarrow$ (See D. Rathlev’s talk!)
- Small scale sensitivity at NLO
- Large multiplicity needs NLO

PRELIMINARY
Total Cross Section and Jet Ratios at $\sqrt{s} = 8$ TeV

(in fb)

<table>
<thead>
<tr>
<th>$n$</th>
<th>$W^+ W^- + n$ jet</th>
<th>$(W^+ W^- + n$ jet) / $(W^+ W^- + (n-1)$ jet)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LO</td>
<td>NLO</td>
</tr>
<tr>
<td>0</td>
<td>141.7(4)$^{+3.7}_{-5.3}$</td>
<td>207.9(7)$^{+5.4}_{-3.5}$</td>
</tr>
<tr>
<td>1</td>
<td>61.1(2)$^{+9.8}_{-8.0}$</td>
<td>76.4(4)$^{+3.6}_{-4.0}$</td>
</tr>
<tr>
<td>2</td>
<td>29.44(7)$^{+9.99}_{-6.92}$</td>
<td>28.8(2)$^{+0.3}_{-1.9}$</td>
</tr>
<tr>
<td>3</td>
<td>11.12(2)$^{+5.74}_{-3.51}$</td>
<td>9.22(16)$^{+0.17}_{-1.05}$</td>
</tr>
<tr>
<td>4</td>
<td>3.59(2)$^{+2.50}_{-1.37}$</td>
<td>—</td>
</tr>
</tbody>
</table>

- Noticeable reduction of scale sensitivity
- For $W^+ W^- + 3$ Jets goes from 45% to 15%
- Jet ratios seem to decrease for larger multiplicities
Total Cross Section and Jet Ratios at $\sqrt{s} = 13$ TeV

(in fb)

<table>
<thead>
<tr>
<th>$n$</th>
<th>$W^+W^- + n\ jet$</th>
<th>$(W^+W^- + n\ jet) \div (W^+W^- + (n-1)\ jet)$</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>LO</td>
<td>NLO</td>
</tr>
<tr>
<td>0</td>
<td>231.7(6)$^{+13.7}_{-16.8}$</td>
<td>363(2)$^{+7.7}_{-4.8}$</td>
</tr>
<tr>
<td>1</td>
<td>132.0(3)$^{+16.4}_{-14.0}$</td>
<td>166(1)$^{+7.4}_{-7.4}$</td>
</tr>
<tr>
<td>2</td>
<td>77.2(2)$^{+23.0}_{-16.5}$</td>
<td>72.6(4)$^{+0.1}_{-2.8}$</td>
</tr>
<tr>
<td>3</td>
<td>35.62(7)$^{+16.68}_{-10.56}$</td>
<td>26.7(4)$^{+0.0}_{-2.5}$</td>
</tr>
<tr>
<td>4</td>
<td>14.15(9)$^{+9.08}_{-5.15}$</td>
<td>—</td>
</tr>
</tbody>
</table>

- With more jets, cross sections increase more with energy
- Jet ratios increase, as more energy available for radiation
- Need to explore jet ratios behavior more detailed
Jet $p_T$ Spectra

$\sqrt{s} = 8$ TeV

$\mu_R = \mu_F = \hat{H}_T / 2$

$\mu_R = \mu_F = \hat{H}_T / 2$

$p_T$ distributions for softer jets fall more steeply

Quantum corrections only shift softest jet $p_T$ distribution

More structure for harder jet emissions

Similar trends to what is observed in NLO QCD corrections to $V+Jets$

PRELIMINARY
Hadronic Transverse Energy

- Sum of transverse energy of jets
- Important for BSM searches
- The dynamical scale chosen appears as natural
- Considerable reduction of scale sensitivity

\[ \sqrt{s} = 13 \text{ TeV} \]
\[ \mu_R = \mu_F = \frac{H_T}{2} \]

BlackHat+Sherpa

PRELIMINARY
Lepton Rapidities

- Lepton $\eta$ distributions shapes not affected by corrections
- Very similar distributions (both leptons are treated massless)
- Considerable reduction of scale sensitivity

PRELIMINARY
Missing Transverse Energy

- Neutrinos escape detector, and produce $\not{E}_T$
- Important observable for BSM searches
- Experimental analyses favor $\not{E}_T^{\text{rel}}$, to avoid instrumental backgrounds

PRELIMINARY
A clear signature of VBF processes is a low rate of radiation in the gap between tagging forward and backward jets.

Background processes can have very different features.

A way to study this: look at ratios of $W^+W^- + 3$ Jets to $W^+W^- + 2$ Jets.

Left plot jets $p_T$ ordered and right are $\eta$ ordered.

Noticeable reduction for large $\Delta \eta$ when $\eta$ ordered.
We presented first NLO QCD correction to $W^+ W^- + 3$-Jet production. This results joins the few NLO QCD results for processes with more than 5 objects in the final state ($V + 4, 5$ Jets from BlackHat+Sherpa and 5-Jet Production from NJet).

We are ready to explore in general NLO QCD production of Di-vector bosons with jets.

Ntuple sets are ready for phenomenological studies.

NLO QCD corrections provide reliable predictions for large multiplicity predictions.

More dedicated results will follow, including jet ratio observables.
Outlook

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- We are ready to explore in general NLO QCD production of Di-vector bosons with jets
- Ntuple sets are ready for phenomenological studies
- NLO QCD corrections provide reliable predictions for large multiplicity predictions
- More dedicated results will follow, including jet ratio observables

Thanks!