Higher order QCD effects in $WW$ production with jets

Raoul Röntsch

Fermilab
with Tom Melia, Kirill Melnikov, Markus Schulze, Giulia Zanderighi

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Outline

- Motivation
- Brief outline of generalized unitarity
- $WWjj$ to NLO in QCD
- Gluon fusion effects in $WW$, $WWj$
- Conclusion
$H \rightarrow WW$ decay mode

**Evidence of Higgs in this channel (4.0 $\sigma$)**

CMS-PAS-HIG-13-003

Higgs searches:
- $H \rightarrow WW$ subdominant mode
- Leptonic decay $\rightarrow$ mass reconstruction not possible

CMS Preliminary
$\sqrt{s}=7$ TeV, $L = 4.9$ fb$^{-1}$
$\sqrt{s}=8$ TeV, $L = 19.5$ fb$^{-1}$
$H \rightarrow WW \rightarrow 2l2\nu\ 0/1$-jet

95% C.L. Limit on $\sigma/\sigma_{SM}$

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Electroweak-Higgs coupling

- $H \rightarrow WW$ probes coupling of Higgs to EW sector
- Tree-level relation between $W, Z$ mass and coupling to Higgs protected by custodial symmetry
- Rescaling of $W$- and $Z$-coupling to Higgs parametrized by $\kappa_W, \kappa_Z$.
- $\lambda_{W,Z} = \kappa_W / \kappa_Z = 1$ in SM
- Current CMS value: $\lambda_{W,Z} = [0.60, 1.40]$ at 95% CL using $H \rightarrow WW, ZZ$ ratios (CMS PAS-HIG-13-005)
- Consistent with SM, but tighter bounds desirable
**WW** as background to GF and VBF Higgs

- Higgs signals sorted into 0,1,2+ jet bins
  → allows identification of backgrounds in each bin
- Around 30% of Higgs created with one jet, around 15% with two (or more) jets
- $H(\rightarrow WW)jj$ created through weak boson fusion (WBF) as well as gluon fusion (GF)
- WBF has characteristic **forward jets** with little hadronic activity between them
- $WW(+\text{jets})$ is irreducible background to all processes
$W W$ production as signal

$W W$ production also interesting in its own right, or as place where New Physics may be found (e.g. in trilinear vector boson couplings)

- Recent CMS result for $W W$ production finds
  $\sigma = 69.9 \pm 2.8 \pm 5.6 \pm 3.1$ pb (CMS PAS SMP-12-013)

- Prediction: $\sigma = 57.3^{+2.4}_{-1.6}$ pb

- $2\sigma$ effect ...
Comparisons with Tevatron data show LO is insufficient - NLO needed
NLO corrections can be large (\(\sim 60\%\) enhancement for \(WW\) production)
No guarantee that this enhancement (or suppression) will be consistent over phase space or distribution
Factorization/renormalization scale uncertainty significantly reduced at NLO
Three ingredients needed for NLO calculations:

- Real emission correction
- Virtual (one-loop) amplitudes → generalized unitarity/OPP procedure
- Matching of IR divergences in real emission corrections to those in virtual amplitudes → Catani-Seymour dipoles
Generalized Unitarity method

Bern, Dixon, Kosower; Ossola, Papadopoulos, Pittau; Ellis, Giele, Kunszt, Melnikov, ...

Review: Ellis, Kunszt, Melnikov, Zanderighi, hep-ph:1105.4319

- Virtual amplitudes stripped of color factors to give **partial amplitudes** → **primitive amplitudes**
- OPP subtraction: tensor integrals in primitive amplitudes written in terms of **scalar integrals** (known) and **coefficients** $c(l)$
- Analytic form of coefficients known - polynomial in $(l.n_i)$
- By choosing (complex) momenta such that **propagators vanish**, can solve for coefficients
Generalized Unitarity method

- Equivalent to performing a **unitarity cut** on the primitive amplitudes, resulting in tree-level helicity amplitudes
  
  \[ \rightarrow \] computed with **Berends-Giele currents** (also used to calculate Born amplitudes and real emission corrections)
**WWjj** production

Two distinct **strong** production processes:

**Two quark, two gluon processes:**

All permutations of $W$-bosons with gluons

**Four quark processes:**

Also $t$-channel contributions $\rightarrow$ Complicated flavor structure
Virtual corrections

Four primitive amplitudes for $2q,2g$ process:

\[ A_1^1(\bar{q}_1, q_2, q_3, q_4) \]

\[ A_1^2(\bar{q}_1, q_2, g_3, q_4) \]

\[ A_1^3(q_1, q_2, g_3, g_4) \]

Five primitive amplitudes $4q$ process:

\[ A_1^{1'}(\bar{q}_1, q_2, q_3, q_4) \]

\[ A_1^{2'}(\bar{q}_1, q_2, q_3, q_4) \]
Parameters for Tevatron

**Signature:** two opposite-sign leptons, missing energy, two or more jets

Cuts used similar to CDF in Higgs searches:

- Jets defined using $k_T$-algorithm with $\Delta R_{j1j2} > 0.4$
- Jet cuts: $p_{T,j} > 15$ GeV and $|\eta_j| < 2.5$
- Lepton cuts: $p_{T,l1} > 20$ GeV, $|\eta_{l1}| < 0.8$; $p_{T,l2} > 10$ GeV, $|\eta_{l2}| < 1.1$
- Lepton isolation: jets within $\Delta R = 0.4$ of a lepton must have $p_{T,j} < 0.1p_{T,l}$.
- Lepton cuts: $m_{ll} > 16$ GeV and $p_{T,\text{miss}}^{\text{spec}} \equiv p_{T,\text{miss}} \sin\left[\min(\Delta \phi, \pi/2)\right] > 25$ GeV
Tevatron Results

\[ \sigma_{\text{LO}} = 2.5 \pm 0.9 \text{ fb}, \quad \sigma_{\text{NLO}} = 2.0 \pm 0.1 \text{ fb} \]

- At LO, **uncertainty** in background four times larger than **signal**!
- Uncertainty reduced at NLO by order of magnitude, but still **comparable** to signal.
Parameters for LHC

Look at $WWjj$ as **signal**:

- Center-of-mass energy $\sqrt{s} = 7$ TeV
- Jets defined with anti-$k_t$ algorithm with $\Delta R_{jj} = 0.4$
- Jets cuts: $p_{T,j} > 30$ GeV and $|\eta_j| < 3.2$
- Lepton cuts: $p_{T,l} > 20$ GeV, $|\eta_l| < 2.4$, $p_{T,\text{miss}} > 30$ GeV
LHC cross-sections

- \(\sigma_{LO} = 46 \pm 13 \text{ fb}, \sigma_{NLO} = 42 \pm 1 \text{ fb}\)
- At NLO, approximately linear increase in cross-section as \(\sqrt{s}\) increased
- “Optimal” factorization/renormalization scale: \(2m_W\) at \(\sqrt{s} = 7\) TeV, \(4m_W\) at \(\sqrt{s} = 14\) TeV
LHC angular distribution

To discriminate between signal and background: distributions

Useful distribution: opening angles between leptons $\phi_{e^-\mu^+}$.

Higgs: small angle; background: back-to-back

[Graph showing the distribution of $\phi_{e^-\mu^+}$ for LO and NLO calculations.]
LHC mass distribution

Linked to $\phi_{e^-\mu^+}$ is mass of lepton system $m_{ll}$

From Klämke and Zeppenfeld, hep-ph:0703202
Today’s signal is tomorrow’s background

Higgs created through GF has central jets; through VBF has forward jets

From Campbell, Ellis, Williams, hep-ph:1001.4495

Background jets central

Cut on central jets removes both \(WWjj\) and GF background

NLO results greatly reduce scale uncertainty → improved reliability
Mild softening at high scales - indication that fixed scale is too small, and dynamic scale would be better

Reduced scale uncertainty again apparent
Gluon fusion in $WW$ production

$WW + n$ jets with no external quarks - only gluons - through a fermion loop

No corresponding tree-level amplitude:
- One-loop amplitude is finite
- Enters as a NNLO correction to $pp \rightarrow WW + n$ jets

Finite, gauge invariant, self-contained contribution to NNLO correction.

Additional factors of $\alpha_s \leftrightarrow$ Large gluon flux at LHC
Gluon-induced $WW$ production

$gg \rightarrow WW$ studied by Binoth, Ciccolini, Kauer, Krämer


Find highly cut-dependent contribution to overall cross-section:

- For generic cuts*, $\sigma_{gg+NLO}/\sigma_{NLO} = 1.06$
- For Higgs search cuts**, $\sigma_{gg+NLO}/\sigma_{NLO} = 1.30$

* $p_T,l > 20$ GeV, $|\eta| < 2.5$, $p_T,\text{miss} > 25$ GeV

** $35 \text{GeV} < p_T,\text{lmax} < 50$ GeV, $p_T,\text{lmin} > 25$ GeV, $\Delta \phi_{ll} < 0.78$, $m_{ll} < 35$ GeV, $p_T,j > 20$ GeV, $|\eta| < 3$

BUT these cuts are not what LHC uses:

- Initially proposed: $\Delta \phi_{ll} < 1.8$, $m_{ll} < 50$ GeV

Standard cuts

Looked at $gg \to WW$ and $gg \to WWg$:

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_{\text{LO}}$ (fb)</th>
<th>$\sigma_{\text{incl}}$ (fb)</th>
<th>$\delta\sigma_{\text{NNLO}}$ (fb)</th>
<th>$\delta\sigma_{\text{NNLO}}/\sigma_{\text{incl}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 TeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$WW$</td>
<td>141.0(1)$^{+2.8}_{-4.0}$</td>
<td>232.0(4)$^{-5.8}_{+7.5}$</td>
<td>8.1(1)$^{+1.7}_{-2.2}$</td>
<td>3.5%</td>
</tr>
<tr>
<td>$WWj$</td>
<td>87.8(1)$^{+10.9}_{-13.5}$</td>
<td>111.3(2)$^{-5.5}_{+4.9}$</td>
<td>3.4(1)$^{+1.0}_{-1.6}$</td>
<td>3.1%</td>
</tr>
<tr>
<td>14 TeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$WW$</td>
<td>259.6(2)$^{+14.2}_{-17.2}$</td>
<td>448.3(5)$^{-7.4}_{+11.6}$</td>
<td>23.6(1)$^{+4.1}_{-3.2}$</td>
<td>5.3%</td>
</tr>
<tr>
<td>$WWj$</td>
<td>203.4(1)$^{+19.9}_{+22.9}$</td>
<td>254.5(4)$^{-10.2}_{+9.0}$</td>
<td>11.8(4)$^{+5.2}_{+4.7}$</td>
<td>4.6%</td>
</tr>
</tbody>
</table>

- For $WW$ production, results similar to Binoth et al.
- Gluon-induced production more important at $\sqrt{s} = 14$ TeV
- Gluon-induced production less important for $WWj$ production
### Higgs cuts

#### Higgs search cuts

<table>
<thead>
<tr>
<th>8 TeV</th>
<th>( \sigma_{\text{LO}} ) (fb)</th>
<th>( \sigma_{\text{excl}}^{\text{NLO}} ) (fb)</th>
<th>( \delta \sigma_{\text{NNLO}} ) (fb)</th>
<th>( \delta \sigma_{\text{NNLO}} / \sigma_{\text{excl}}^{\text{NLO}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( WW )</td>
<td>35.6(1)(+0.9)(-1.3)(+1.8)</td>
<td>38.8(1)(+1.0)(-0.8)</td>
<td>2.7(1)(+0.7)(-0.2)</td>
<td>7.0%</td>
</tr>
<tr>
<td>( \gamma W )</td>
<td>12.6(1)(+1.5)(+1.8)</td>
<td>10.6(1)(+0.3)(-0.9)</td>
<td>0.6(1)(+0.2)(+0.2)</td>
<td>5.7%</td>
</tr>
<tr>
<td>14 TeV</td>
<td>( \sigma_{\text{LO}} ) (fb)</td>
<td>( \sigma_{\text{excl}}^{\text{NLO}} ) (fb)</td>
<td>( \delta \sigma_{\text{NNLO}} ) (fb)</td>
<td>( \delta \sigma_{\text{NNLO}} / \sigma_{\text{excl}}^{\text{NLO}} )</td>
</tr>
<tr>
<td>( WW )</td>
<td>63.4(1)(+3.9)(-4.7)</td>
<td>63.4(2)(+2.1)(-2.0)</td>
<td>7.5(1)(+1.5)(-0.5)</td>
<td>11.8%</td>
</tr>
<tr>
<td>( \gamma W )</td>
<td>28.7(1)(+2.6)(+2.9)</td>
<td>20.5(1)(+1.7)(-2.2)</td>
<td>1.8(2)(+0.7)(+0.7)</td>
<td>8.8%</td>
</tr>
</tbody>
</table>

- **Important contribution to overall cross-section** (comparable to NLO scale uncertainty)
- **BUT** not as large as 30% contribution
- \( Hj \) production: \( \sigma \approx 2 \text{ fb at } \sqrt{s} = 8 \text{ TeV}, \ 5 \text{ fb at } \sqrt{s} = 14 \text{ TeV} \)
  - gluon-induced **NNLO contribution** to background **third** of signal cross-section
NNLO $K$-factor

Define

$$K_{\text{NNLO}} = \frac{d\sigma_{\text{NLO}+\delta\text{NNLO}}}{d\sigma_{\text{NLO}}}$$

$K$-factor is not uniform over phase space and its distribution can be cut-dependent.
Conclusions

- NLO QCD corrections to strong production of $WWjj$ computed.
- **Moderate** (10-20%) change in cross-section compared to LO, but scale uncertainty reduced by up to order of magnitude.
- Improves reliability of distributions aiding discrimination between Higgs signal and $WW$ background: $\phi_{ll}$, $m_{ll}$, $\Delta \eta_{jj}$
  → allow discovery in this channel; study Higgs-EW couplings
- NNLO gluon-induced corrections to $WW$ and $WWj$ production computed
- These are **cut-dependent**, more important as cuts become more aggressive
- May be as large as NLO scale uncertainty, and factor 2-3 smaller than signal