Towards vector boson pair production at NNLO

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*On leave of absence from INFN, Sezione di Firenze
Outline

- Introduction
- The $q_T$-subtraction method
  - $pp \rightarrow V\gamma + X$ at NNLO
    - Results for $Z\gamma$
    - Results for $W\gamma$
- Summary and Outlook
Introduction

Vector boson pair production is an important process at hadron colliders

- background to Higgs and new physics searches
- important to put limits on anomalous couplings
- new nice data available from the LHC
- accuracy of data will soon be comparable with theoretical uncertainties

Present accuracy essentially limited to NLO QCD

Extension to NNLO highly desirable
Introduction

At present, complete NNLO predictions only exist for diphoton production


This calculation allowed to resolve discrepancies in the comparison to data
Status of pp→VV’+X in QCD

$Z\gamma$, $W\gamma$, $WZ$, $WW$, $ZZ$ production known in NLO QCD since quite some time

Also including leptonic decay

The gluon fusion loop contribution (part of NNLO) to $Z\gamma$, $ZZ$ and $WW$ is also known (often assumed to provide the dominant NNLO contribution)

good this implemented in MCFM

NLO EW corrections have also been studied

Genuine $V\gamma$ two-loop amplitude computed

Planar two-loop master integrals for $WW$, $WZ$ and $ZZ$ production recently evaluated

J.Ohnemus (1993); U.Baur, T.Han, J.Ohnemus (1998)

B.Meile, P.Nason, G.Ridolfi (1991)

S.Frixione, P.Nason, G.Ridolfi (1992); S.Frixione (1993)


J.Campbell, K.Ellis (1999); D.de Florian, A.Signer (2000)

T.Binoth et al. (2005, 2008)

M.Duhrssen et al. (2005)

L.Amettler et al. (1985)

J. van der Bij, N.Glover (1988)


W.Hollik, C.Meier (2004)


A.Bierweiler, T.Kasprzik, J.Kuhn, S.Uccirati (2012)


T.Gehrmann, L.Tancredi (2012)

T.Gehrmann, L.Tancredi, E.Weihs (2014)

J.Henn, K.Melnikov, V.Smirnov (2014)
Having completed $pp\rightarrow \gamma\gamma + X$ the next logical step is $pp\rightarrow V\gamma + X$ ($V=Z,W$)

Ingredients for $pp\rightarrow V\gamma + X$ at NNLO

- One-loop squared and two-loop amplitudes for $qqbar\rightarrow V\gamma$
- One loop squared $gg\rightarrow Z\gamma$ amplitude
- One loop $V\gamma+1$ parton amplitudes
- Tree-level $V\gamma+2$ parton amplitudes

We obtain the tree-level and one-loop amplitudes with OpenLoops

The OpenLoops generator employs the Denner-Dittmaier algorithm for the numerically stable computation of tensor integrals and allows a fast evaluation of tree-level and one-loop amplitudes within the SM

The contributing amplitudes are combined with the $q_T$ subtraction method

S. Catani, MG (2007)
The \(q_T\) subtraction method

S. Catani, MG (2007)

The amplitudes contributing to the NNLO cross section are separately divergent to obtain a finite cross section out of them is still a non trivial task.

The \(q_T\) subtraction method allows us to write the cross section to produce an arbitrary system \(F\) of non colored particles in hadronic collisions as

\[
d\sigma_{(N)NLO}^{F} = \mathcal{H}_{(N)NLO}^{F} \otimes d\sigma_{LO}^{F} + \left[ d\sigma_{F+\text{jets}}^{(N)LO} - d\sigma_{CT}^{F+\text{jets}} \right]
\]

The hard-collinear function \(\mathcal{H}^{F}\) has been explicitly computed up to NNLO for vector and Higgs boson production

S. Catani, MG (2010)

Recently its general form in terms of the relevant virtual amplitudes for an arbitrary colour singlet \(F\) has been provided up to NNLO


\(\rightarrow\) the method can be applied also to vector boson pair production
Photon isolation

When dealing with photons we have to consider two production mechanisms:

- **Direct component**: photon directly produced through the hard interaction

- **Fragmentation component**: photon produced from non-perturbative fragmentation of a hard parton (like a hadron)

Experimentally photons must be isolated:

We use Frixione smooth cone isolation

\[ E_T^{had}(\delta) \leq \chi(\delta) \]

\[ \chi(\delta) = \epsilon_\gamma E_T^\gamma \left( \frac{1 - \cos(\delta)}{1 - \cos(R_0)} \right)^n \]

- \( n = 1 \)
- \( \epsilon_\gamma = 0.5 \)
- \( R_0 = 0.4 \)

Transverse hadronic energy in a cone of fixed radius \( R \) smaller than few GeV

Kills collinear emissions within the cone.
The calculation

We present results of a complete calculation of $pp \to V\gamma + X$ up to NNLO.

We compute NNLO corrections to $pp \to l^+l^-\gamma + X$ and $pp \to l\nu\gamma + X$ by consistently including the final state photon radiation from the leptons and the non-resonant diagrams.

The matrix elements are combined into a parton level generator that makes use of multichannel phase space integration and allows us to apply arbitrary kinematical cuts on the final state lepton(s), the photon and the QCD radiation.

We compute NNLO corrections to $pp \to l^+l^-\gamma + X$ and $pp \to l\nu\gamma + X$ by consistently including the final state photon radiation from the leptons and the non-resonant diagrams!

We present a preliminary comparison with ATLAS data based on 4.9 fb$^{-1}$.
Results: $Z\gamma$

- **ATLAS setup (arXiv:1302.1283)**
  
  \[
  p_T^{\gamma} > 15 \text{ GeV} \quad p_T^l > 25 \text{ GeV} \quad \Delta R(l/\gamma,\text{jet}) > 0.3
  \]
  \[
  |\eta^l| < 2.37 \quad |\eta^\gamma| < 2.47 \quad \Delta R(l,\gamma) > 0.7
  \]
  
  \[
  m_\ll > 40 \text{ GeV}
  \]

- **CMS setup (arXiv:1308.6832)**
  
  photon isolation:
  \[
  \varepsilon = 0.5 \quad R = 0.4
  \]
  
  jets: anti-kt with $D=0.4$
  
  \[
  p_T^{\text{jet}} > 15 \text{ GeV} \quad |\eta^{\text{jet}}| < 2.47
  \]

  \[
  p_T^{\gamma} > 15 \text{ GeV} \quad p_T^l > 20 \text{ GeV} \quad \Delta R(l,\gamma) > 0.7
  \]
  \[
  |\eta^\gamma| < 2.5 \quad |\eta^l| < 2.5 \quad m_\ll > 50 \text{ GeV}
  \]

<table>
<thead>
<tr>
<th>$\sigma$ (fb)</th>
<th>LO</th>
<th>NLO</th>
<th>NNLO</th>
<th>data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T^{\gamma} &gt; 15$ GeV</td>
<td>850.7±0.2</td>
<td>1226.2±0.4</td>
<td>44%</td>
<td>1305±3 6%</td>
</tr>
<tr>
<td>$p_T^{\gamma} &gt; 40$ GeV</td>
<td>77.48 ± 0.06</td>
<td>132.89±0.07</td>
<td>71%</td>
<td>152.5 ±0.5 15%</td>
</tr>
<tr>
<td>CMS setup</td>
<td>1333.6 ± 0.2</td>
<td>1843.8 ± 0.7</td>
<td>38%</td>
<td>1917± 8 4%</td>
</tr>
</tbody>
</table>
gg fusion contribution provides only 8% of the NNLO correction

NNLO effect not uniform in $m_{ll\gamma}$: the effect is larger where the cross section is smaller (constant K factor does not work here!)

Results: $Z\gamma$
Results: $W\gamma$

S.Kallweit, D.Rathlev, A.Torre, MG (to appear)

- ATLAS setup (arXiv:1302.1283)

  $p_T^{\gamma} > 15$ GeV
  $p_T^l > 25$ GeV
  $\Delta R(l,\gamma) > 0.7$
  $\Delta R(l/\gamma,\text{jet}) > 0.3$
  $|\eta^\gamma| < 2.37$
  $|\eta^l| < 2.47$
  $p_T^{\text{miss}} > 35$ GeV
  $p_T^{\text{jet}} > 15$ GeV
  $|\eta^{\text{jet}}| < 2.47$

  photon isolation:
  $\epsilon = 0.5$
  $R = 0.4$
  $\text{jets: anti-kt with } D=0.4$

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<tr>
<td>$W^+\gamma$</td>
<td>511.0±0.2</td>
<td>1155.3±0.8</td>
<td>126%</td>
<td>1371±5</td>
</tr>
<tr>
<td>$W^-\gamma$</td>
<td>395.3±0.2</td>
<td>909.9±0.4</td>
<td>130%</td>
<td>1085±4</td>
</tr>
<tr>
<td>total</td>
<td>906.3±0.3</td>
<td>2065.2±0.9</td>
<td>128%</td>
<td>2456±6</td>
</tr>
</tbody>
</table>

Some tension between data and NLO result

QCD corrections are much larger than for $Z\gamma$

$\Rightarrow$ NNLO significantly improves Data/Theory agreement
Results: $W\gamma$

NNLO effect ranges from 15 to 25% as a function of $p_{T}^{\gamma}$
Scale Uncertainties

When studying scale variations around \( \mu_0 = \sqrt{m_V^2 + (p_T^\gamma)^2} \)

we find that symmetric scale variations \( \mu_F = \mu_R = a \mu_0 \) with \( 0.5 < a < 2 \)
give tiny effects, especially for \( Z\gamma \)

we follow the suggestion of MCFM authors and use asymmetric scale variations \( \mu_F = a \mu_0, \mu_R = \mu_0/a \) with \( 0.5 < a < 2 \)

<table>
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<th>( \sigma (\text{fb}) )</th>
<th>NLO</th>
<th>NNLO</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Z\gamma )</td>
<td>1226.2 (-5%+4%)</td>
<td>1305 (\pm 2%)</td>
</tr>
<tr>
<td>( W^+\gamma )</td>
<td>1155.3 (+7%)</td>
<td>1371 (+5-4%)</td>
</tr>
<tr>
<td>( W^-\gamma )</td>
<td>909.9 (+7%)</td>
<td>1085 (+4%)</td>
</tr>
</tbody>
</table>

In the case of \( W\gamma \) the NLO uncertainty does not cover the large NNLO effect which is due to the qg channel breaking of the radiation zero \( (\cos \theta^* = \pm 1/3) \) present at LO

K.Mikaelian et al. (1979); J.Ohnemus (1993)
Summary

- Vector boson pair production is an essential process at hadron colliders: it is a background for Higgs and new physics searches and it allows studies of anomalous couplings

- I have presented an NNLO QCD calculation of $Z\gamma$ and $W\gamma$ production at the LHC and a preliminary comparison to experimental data

- In the case of $Z\gamma$ production the impact of NNLO corrections is moderate, with a slight improvement of the agreement with ATLAS data

- In the case of $W\gamma$ production the impact of NNLO corrections is sizable, and the agreement with ATLAS data significantly improves

- With the recent progress in the computation of the two-loop master integrals relevant for $WW$, $ZZ$, and $WZ$ production, the corresponding NNLO calculation could be close to be completed

Stay tuned!