ZZ production at hadron colliders in NNLO QCD

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A B S T R A C T

We report on the first calculation of next-to-next-to-leading order (NNLO) QCD corrections to the inclusive production of Z-boson pairs at hadron colliders. Numerical results are presented for pp collisions with centre-of-mass energy (\(\sqrt{s}\)) ranging from 7 to 14 TeV. The NNLO corrections increase the NLO result by an amount varying from 11% to 17% as \(\sqrt{s}\) goes from 7 to 14 TeV. The loop-induced gluon fusion contribution provides about 60% of the total NNLO effect. When going from NLO to NNLO the scale uncertainties do not decrease and remain at the ±3% level.

This Letter reports on the first calculation of the inclusive production of on-shell Z-boson pairs at hadron colliders in NNLO QCD.

The NNLO computation requires the evaluation of the tree-level scattering amplitudes with two additional (unresolved) partons, of the one-loop amplitudes with one additional parton, and of the one-loop-squared and two-loop corrections to the Born subprocess \(qg \to ZZ\). All the relevant tree and one-loop matrix elements are automatically generated with OpenLoops [23], which implements a fast numerical recursion for the calculation of NLO scattering amplitudes within the SM. For the numerically stable evaluation of tensor integrals we rely on the COLLIER library [24], which is based on the Denner–Dittmaier reduction techniques [25,26] and the scalar integrals of [27]. The loop-induced gluon fusion contribution is also obtained with OpenLoops, including five light-quark flavors and massive top-quark loops.2 The SM Higgs boson contribution is also considered. Following the recent computation of the relevant two-loop master integrals [28–31] the last missing contribution, the genuine two-loop correction to the ZZ amplitude, has been computed by some of us, and will be reported elsewhere [32]. In the two-loop correction, contributions involving a top-quark loop are neglected. For the numerical evaluation of the multiple polylogarithms in the two-loop expressions we employ the implementation [33] in the GiNaC [34] library.

2 Consistently with the inclusion of five active flavors, the renormalisation of the QCD coupling \(\alpha_s\) is performed in the so-called decoupling scheme, where top-quark loops are subtracted at zero momentum transfer. In this scheme, the \(qg \to ZZg, \ qg \to ZZq\) and \(qg \to ZZq\) channels receive top-quark contributions only via ultraviolet-finite box diagrams, while the top-quark contributions to the gluon-field and \(\alpha_s\) counterterms cancel against each other.

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The production of vector-boson pairs is a crucial process for physics studies within and beyond the Standard Model (SM). In particular the production of Z-boson pairs is an irrefutable background for Higgs boson production and new-physics searches. Various measurements of ZZ hadroproduction have been carried out at the Tevatron and the LHC (for some recent results see Refs. [1–6]).

The theoretical efforts for a precise prediction of ZZ production in the Standard Model started more than 20 years ago, with the first NLO QCD calculations [7,8] with stable Z bosons. The leptonic decays of the Z bosons were then added, initially neglecting spin correlations in the virtual contributions [9]. The computation of the relevant one-loop helicity amplitudes [10] allowed complete NLO calculations [11,12] including spin correlations and off-shell effects. The loop-induced gluon fusion contribution, which is formally next-to-next-to-leading order (NNLO), has been computed in Refs. [13,14]. The corresponding leptonic decays have been included in Refs. [15–17]. Since the gluon-induced contribution is enhanced by the gluon luminosity, it is often assumed to provide the bulk of the NNLO corrections. NLO predictions for ZZ production including the gluon-induced contribution, the leptonic decay with spin correlations and off-shell effects have been presented in Ref. [18]. The NLO QCD corrections to on-shell ZZ + jet production have been discussed in Refs. [19,20], and the electroweak (EW) corrections to ZZ production have been computed in Refs. [21,22].
The implementation of the various scattering amplitudes in a complete NNLO calculation is a highly non-trivial task due to the presence of infrared (IR) singularities at intermediate stages of the calculation that prevent a straightforward application of numerical techniques. To handle and cancel these singularities at NNLO we employ the \( q_T \) subtraction method [35]. This approach applies to the production of a colourless high-mass system \( F \) in generic hadron collisions and has been used for the computation of NNLO corrections to several hadronic processes [35–39]. According to the \( q_T \) subtraction method [35], the \( pp \to F + X \) cross section at NNLO can be written as

\[
\sigma_{\text{NNLO}}^F = \sigma_{\text{NNLO}} + \sigma_{\text{CT}} \overset{\text{CT}}{\sigma}_{\text{NNLO}} \overset{\text{NNLO}}{\sigma} \left[ \sigma_{\text{NLO}}^{\text{F+jet}} - \sigma_{\text{NLO}}^{\text{T}} \right],
\]

where \( \sigma_{\text{NLO}}^{\text{F+jet}} \) is the cross section for the inclusive production of the system \( F \) plus one jet at NLO accuracy, and can be evaluated with any available version of the NLO subtraction formalism. When the transverse momentum \( q_T \) of the colourless system \( F \) is non-vanishing, \( \sigma_{\text{NLO}}^{\text{F+jet}} \) is the sole contribution to the NNLO cross section. The IR subtraction counterterm \( \sigma_{\text{CT}} \) in Eq. (1) has the purpose of cancelling the singularity developed by \( \sigma_{\text{NLO}}^{\text{F+jet}} \) as \( q_T \to 0 \) and is obtained from the resummation of the logarithmically-enhanced contributions to \( q_T \) distributions [40]. The function \( \overset{\text{CT}}{\sigma}_{\text{NNLO}} \), which also compensates for the subtraction of \( \sigma_{\text{NLO}}^{\text{T}} \), corresponds to the NNLO truncation of the process-dependent perturbative function

\[
\sigma_{\text{NNLO}}^{\text{F}} = 1 + \frac{\alpha_s}{\pi} \sigma_{\text{F}}^{(1)} + \left( \frac{\alpha_s}{\pi} \right)^2 \sigma_{\text{F}}^{(2)} + \ldots
\]

The NLO calculation of \( \sigma_{\text{F}}^{\text{NLO}} \) requires the knowledge of \( \sigma_{\text{F}}^{(1)} \), and the NNLO calculation also requires \( \sigma_{\text{F}}^{(2)} \).

The general structure of \( \sigma_{\text{F}}^{(1)} \) is known [41]; \( \sigma_{\text{F}}^{(1)} \) is obtained from the process-dependent scattering amplitudes by using a process-independent relation. Exploiting the explicit results of \( \sigma_{\text{F}}^{(2)} \) for Higgs [42] and vector-boson [43] production, the process-independent relation of Ref. [41] has been extended to the calculation of the NNLO coefficient \( \sigma_{\text{F}}^{(2)} \) [44]. Such results have been confirmed with a fully independent calculation of the relevant coefficients in the framework of Soft-Collinear Effective Theory (SCET) [45,46]. We have performed our NNLO calculation for ZZ production according to Eq. (1), starting from a computation of the \( \sigma_{\text{NNLO}}^{\text{F+jet}} \) cross section with the dipole-subtraction method [47,48]. The numerical calculation employs the generic Monte Carlo program that was developed for Ref. [39]. Although the \( q_T \) subtraction method and our implementation are suitable to perform a fully exclusive computation of ZZ production including the leptonic decays and the corresponding spin correlations, in this Letter we restrict ourselves to the inclusive production of on-shell Z bosons.

We consider \( pp \) collisions with \( \sqrt{s} \) ranging from 7 to 14 TeV. As for the EW couplings, we use the so-called \( G_{\mu} \) scheme, where the input parameters are \( G_F, m_W, m_Z \). In particular we use the values \( G_F = 1.16639 \times 10^{-5} \text{ GeV}^2 \), \( m_W = 80.399 \text{ GeV} \), \( m_Z = 91.1876 \text{ GeV} \). The top mass \( m_t = 173.2 \text{ GeV} \) and the Higgs mass \( m_H = 125 \text{ GeV} \) only enter through the loop-induced gluon fusion contribution.\(^3\) We use the MSTW 2008 [49] sets of parton distributions, with densities \( \alpha_s \) evaluated at each corresponding order (i.e., we use \( (n + 1) \)-loop \( \alpha_s \) at NLO, with \( n = 0, 1, 2 \)), and we consider \( N_f = 5 \) massless quark flavors. The default renormalization \( (\mu_R) \) and factorization \( (\mu_F) \) scales are set to \( \mu_R = \mu_F = m_Z \).

\(^3\) Since we consider the production of on-shell Z bosons, the Higgs contribution is strongly suppressed, and provides only about 1% to the loop-induced \( gg \to ZZ \) cross section.

![Fig. 1. ZZ cross section at LO (dots), NLO (dashes), NLO + gg (dot dashes) and NNLO (solid) as a function of \( \sqrt{s} \). The ATLAS and CMS experimental results at \( \sqrt{s} = 7 \text{ TeV} \) and \( \sqrt{s} = 8 \text{ TeV} \) are also shown for comparison [3–6]. The lower panel shows the NNLO and NLO + gg results normalized to the NLO prediction.](image-url)
Table 1
Inclusive cross section for ZZ production at the LHC at LO, NLO and NNLO with $\mu_F = \mu_R = \mu_Z$. The uncertainties are obtained by varying the renormalization and factorization scales in the range 0.5$\mu_Z$ < $\mu_F$, $\mu_R$ < 2$\mu_Z$ with the constraint 0.5 < $\mu_F$/$\mu_R$ < 2.

<table>
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<th>$\sqrt{s}$ (TeV)</th>
<th>$\sigma_{LO}$ (pb)</th>
<th>$\sigma_{NLO}$ (pb)</th>
<th>$\sigma_{NNLO}$ (pb)</th>
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</thead>
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<tr>
<td>7</td>
<td>4.167±0.7%</td>
<td>6.044±2.9%</td>
<td>6.735±2.9%</td>
</tr>
<tr>
<td>8</td>
<td>5.060±1.6%</td>
<td>7.369±3.9%</td>
<td>8.284±3.9%</td>
</tr>
<tr>
<td>9</td>
<td>5.981±2.4%</td>
<td>8.735±3.9%</td>
<td>9.931±3.9%</td>
</tr>
<tr>
<td>10</td>
<td>6.927±3.1%</td>
<td>10.14±3.9%</td>
<td>11.60±3.9%</td>
</tr>
<tr>
<td>11</td>
<td>7.895±3.8%</td>
<td>11.57±3.9%</td>
<td>13.34±3.9%</td>
</tr>
<tr>
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<td>13.03±3.9%</td>
<td>15.10±3.9%</td>
</tr>
<tr>
<td>13</td>
<td>9.887±5.4%</td>
<td>14.51±3.9%</td>
<td>16.91±3.9%</td>
</tr>
<tr>
<td>14</td>
<td>10.91±6.4%</td>
<td>16.01±3.9%</td>
<td>18.77±3.9%</td>
</tr>
</tbody>
</table>

We have reported the first calculation of the inclusive cross section for the production of on-shell Z-boson pairs at the LHC up to NNLO in QCD perturbation theory. The NNLO corrections increase the NLO result by an amount varying from 11% to 17% as $\sqrt{s}$ ranges from 7 to 14 TeV. The loop-induced gluon fusion contribution provides more than half of the complete NNLO effect. Our calculation of the total cross section is based on the two-loop matrix element for $q\bar{q} \rightarrow ZZ$ for on-shell Z bosons. A computation of the two-loop helicity amplitudes will open up a spectrum of more detailed phenomenological studies at NNLO, including off-shell effects, differential distributions of the Z boson decay products and direct comparison with the experimentally measured fiducial cross sections.

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