# Gluon-induced QCD Corrections to $pp \to ZZ \to \ell\bar{\ell}\ell'\bar{\ell}'$

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A calculation of the loop-induced gluon-fusion process $gg \to Z^*(\gamma^*)Z^*(\gamma^*) \to \ell\bar{\ell}\ell'\bar{\ell}'$ is presented, which provides an important background for Higgs boson searches in the $H \to ZZ$ channel at the LHC. We find that the photon contribution is important for Higgs masses below the $Z$-pair threshold and that the $gg$-induced process yields a correction of about 15% relative to the NLO QCD prediction for the $q\bar{q}$-induced process when only a $M_{\ell\bar{\ell}}, M_{\ell'\bar{\ell}'} > 5$ GeV cut is applied.

## 1 Introduction

Accurate theoretical predictions for the hadronic production of vector boson pairs are needed not only for tests of the non-Abelian gauge structure of the Standard Model, but also to determine an important background to Higgs boson searches at the LHC [1, 2, 3]. Due to the large gluon flux at the LHC the contribution from gluon-gluon and gluon-quark scattering is enhanced. In vector boson pair production such subprocesses do not contribute at leading order (LO). In LHC Higgs searches higher order corrections to background predictions can be further enhanced by experimental selection cuts. For example, the $gg$-induced subprocess to $pp \to WW \to \ell\bar{\nu}\bar{\ell}'\nu'$, which contributes formally at next-to-next-to-leading order QCD, gives a 30% correction to the next-to-leading order (NLO) QCD prediction when realistic Higgs search selection cuts are applied [4, 5].

In this article we consider the hadronic production of $Z$-boson pairs. It has been studied extensively in the literature including higher order corrections [6, 7]. Production of $Z$ boson pairs through gluon fusion contributes at $\mathcal{O}(\alpha_s^2)$ relative to $q\bar{q}$ annihilation, but its importance is likewise enhanced by the large gluon flux at the LHC. It was analyzed in Refs. [8, 9]. Leptonic $Z$ decays were subsequently studied for on-shell [10] and off-shell [11] vector bosons.

Here, we present the first complete calculation of the gluon-induced loop process $gg \to Z^*(\gamma^*)Z^*(\gamma^*) \to \ell\bar{\ell}\ell'\bar{\ell}'$, allowing for arbitrary invariant masses of the $Z$ bosons and including the $\gamma$ contributions. Our calculation employs the same methods as Refs. [4, 5]. The tensor reduction scheme of Refs. [12, 13] has been applied to obtain one amplitude representation implemented in our program. We compared it numerically with an amplitude representation based on FeynArts/FormCalc [14, 15] and found agreement. Note that single resonant diagrams (in the case of massless leptons) and the corresponding photon exchange diagrams give a vanishing contribution. A combination of the multi-channel [16] and phase-space-decomposition [17] Monte Carlo integration techniques was used with appropriate mappings to compensate peaks in the amplitude.

## 2 Parton-level results

In Ref. [2] we presented numerical results for the process $pp \to Z^*(\gamma^*)Z^*(\gamma^*) \to \ell\bar{\ell}\ell'\bar{\ell}'$ at the LHC, i.e. for the production of two charged lepton pairs with different flavor[a] focusing on resonant $Z$-pair production and decay by applying the window cut 75 GeV $< M_{\ell\ell} <$ 105 GeV to the invariant masses of $\ell\bar{\ell}$ and $\ell'\bar{\ell}'$, which suppresses the photon contribution to less than 1%. One finds that enhanced by the large gluon flux at the LHC the $gg$ process yields a 14% correction to the total $ZZ$ cross section calculated from quark scattering at NLO QCD. Relative to the LO $q\bar{q} \to ZZ$ prediction the $gg$ contribution is about 20% (in agreement with Ref. [11]). The remaining theoretical uncertainty introduced by the QCD scale was estimated by varying the renormalization and factorization scales independently between $M_Z/2$ and $2M_Z$. For the gluon fusion process we found a renormalization and factorization scale uncertainty of approximately 20%. The scale uncertainty of the $q\bar{q} \to ZZ$ process at NLO is approximately 4%. In addition to cross sections for the LO, NLO QCD and $gg$ processes, the distributions in the invariant mass $M_{4l}$ of the four produced leptons and the pseudorapidity of the negatively charged lepton are also shown in Ref. [2].

For Higgs masses below the $Z$-pair threshold, the virtual photon contribution to the $Z^*(\gamma^*)Z^*(\gamma^*)$ background cannot be neglected, since almost always one of the produced $Z$ bosons will be off resonance. We thus present numerical results calculated with a minimal set of cuts, i.e. only $M_{\ell\bar{\ell}}, M_{\ell'\bar{\ell}'} > 5$ GeV in order to exclude the photon singularity, and using the following set of input parameters: $M_W = 80.419$ GeV, $M_Z = 91.188$ GeV, $G_\mu = 1.16639 \times 10^{-5}$ GeV$^{-2}$, $\Gamma_Z = 2.446$ GeV. The weak mixing angle is given by $c_\mathrm{w} = M_W/M_Z$, $s_\mathrm{w}^2 = 1 - c_\mathrm{w}^2$. The electromagnetic coupling is defined in the $G_\mu$ scheme as $\alpha_{G_\mu} = \sqrt{2}G_\mu M_W^2 s_\mathrm{w}^2/\pi$. The masses of external fermions are neglected. The values of the heavy quark masses in the intermediate loop are set to $M_t = 170.9$ GeV and $M_b = 4.7$ GeV. The $pp$ cross sections are calculated at $\sqrt{s} = 14$ TeV employing the CTEQ6L1 and CTEQ6M [18] parton distribution functions at tree- and loop-level, corresponding to $\Lambda_5^{\mathrm{LO}} = 165$ MeV and $\Lambda_5^{\overline{\mathrm{MS}}} = 226$ MeV with one- and two-loop running for $\alpha_s(\mu)$, respectively. The renormalization and factorization scales are set to $M_Z$.

In Table 1 we compare cross sections for $\ell\bar{\ell}\ell'\bar{\ell}'$ production in gluon scattering with LO and NLO results for the quark scattering processes at the LHC.[b] The LO and NLO quark scattering processes are computed with MCFM [7], which implements helicity amplitudes with full spin correlations [19] and includes finite-width effects and single-resonant corrections. The gluon fusion process is calculated with our program `GG2ZZ` [2, 20]. For $pp \to Z^*(\gamma^*)Z^*(\gamma^*) \to \ell\bar{\ell}\ell'\bar{\ell}'$ we find a NLO $K$-factor of 1.13 when only a $M_{\ell\bar{\ell}}, M_{\ell'\bar{\ell}'} > 5$ GeV cut is applied. The $gg$ process yields an additional correction of 14% relative to the NLO prediction for the $q\bar{q}$ process. In Fig. 1, invariant mass $M_{4l}$ distributions for the $gg$ subprocess are compared by taking into account only the $Z^*Z^*$ contribution as well as all contributions. We observe that for Higgs masses below the $Z$-pair threshold, where one $Z$ boson is produced off-shell, the photon contribution to the background is important.

[a] Note that no flavor summation is applied.

[b] Since we are interested in $Z^*(\gamma^*)Z^*(\gamma^*)$ production as a background, the $gg \to H \to ZZ$ signal amplitude is not included.

| $\sigma(pp \to Z^*(\gamma^*)Z^*(\gamma^*) \to \ell\bar{\ell}\ell'\bar{\ell}')$ [fb] | | | | |
|---|---|---|---|---|
| $gg$ | $q\bar{q}$ | | $\frac{\sigma_{\rm NLO}}{\sigma_{\rm LO}}$ | $\frac{\sigma_{\rm NLO+gg}}{\sigma_{\rm NLO}}$ |
| | LO | NLO | | |
| 16.3(1) | 105.2(1) | 118.9(2) | 1.13 | 1.14 |

Table 1: Cross sections for the gluon and quark scattering contributions to $pp \to Z^*(\gamma^*)Z^*(\gamma^*) \to \ell\bar{\ell}\ell'\bar{\ell}'$ at the LHC ($\sqrt{s} = 14$ TeV), where a minimal cut $M_{\ell\bar{\ell}}, M_{\ell'\bar{\ell}'} > 5$ GeV is applied. The integration error is given in brackets. We also show the ratio of the NLO to LO cross sections and the ratio of the combined NLO+$gg$ contribution to the NLO cross section. Input parameters are defined in the main text.

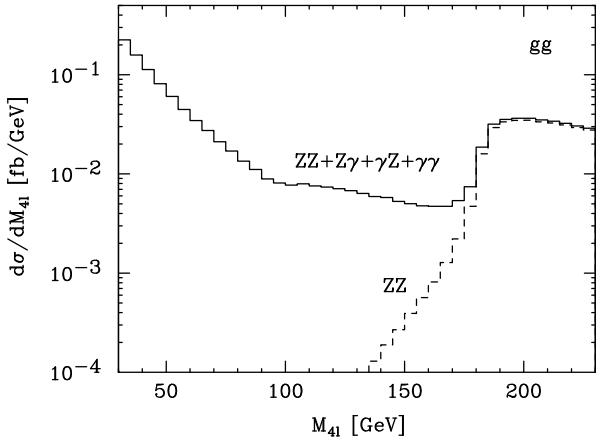


Figure 1: Distribution in the $\ell\bar{\ell}\ell'\bar{\ell}'$ invariant mass $M_{4l}$ for the gluon scattering process $gg \to Z^*(\gamma^*)Z^*(\gamma^*) \to \ell\bar{\ell}\ell'\bar{\ell}'$ at the LHC with $Z^*Z^*$ contribution only (dashed) and all contributions (solid). Other details as in Table 1.

## 3 Conclusions

We have calculated the loop-induced gluon-fusion process $gg \to Z^*(\gamma^*)Z^*(\gamma^*) \to \ell\bar{\ell}\ell'\bar{\ell}'$, which provides an important background for Higgs boson searches in the $H \to ZZ$ channel at the LHC. Our calculation demonstrates that the photon contribution is important for Higgs masses below the $Z$-pair threshold. The $gg$-induced process yields a correction of about 15% relative to the NLO QCD prediction for the $q\bar{q}$-induced process when only a $M_{\ell\bar{\ell}}, M_{\ell'\bar{\ell}'} > 5$ GeV cut is applied. We conclude that the complete gluon-gluon induced background process should be taken into account for an accurate determination of the discovery potential of Higgs boson searches in the $pp \to H \to ZZ \to$ leptons channel if $M_H < 2M_Z$.

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[20] `GG2ZZ` program: `http://hepsource.sf.net/programs/GG2ZZ/`

[21] Slides:
`http://indico.cern.ch/contributionDisplay.py?contribId=55&sessionId=27&confId=24657`