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Associated production of Higgs boson with vector boson at threshold N^{3}LO in QCD

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Abstract: We present the results for the associated production of Higgs boson with vector boson computed at threshold N^{3}LO in QCD. We use the recently available result of the threshold contributions to the inclusive Drell-Yan production cross-section at third order in the strong coupling constant. We have implemented it in the publicly available computer package `vh@nnlo`, thereby obtaining the numerical impact of threshold N^{3}LO contributions for the first time. We find that the inclusion of such corrections do reduce theoretical uncertainties resulting from the renormalization scale.

Keywords: Higgs Physics, Resummation, QCD, Standard Model

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Contents

1 Introduction

Recently, LHC has discovered a particle with a mass of about 125 GeV [1, 2], whose production cross sections and decay rates are compatible with those predicted for the Standard Model (SM) Higgs boson (H). However, we still have to determine its quantum numbers (spin and CP properties), mass, and the strength and the nature of its couplings to other standard model particles accurately. The close inspection of the accumulating luminosity over a longer period will not only reveal the complete picture of the electroweak symmetry breaking sector but may also hint any hidden new Physics. Any discrepancy between its measured cross sections and the theory results may signal deviations from the SM predictions. It is thus important to provide precise theory predictions for the production of the Higgs boson with a reliable estimate of the theoretical error due to the missing higher order terms. In the SM, the production of Higgs boson is mainly through gluon fusion channel whereas the alternative channels include vector boson fusion process, Higgs-strahlung process wherein the Higgs is produced in association with vector bosons (W/Z), bottom quark annihilation process etc. In the gluon fusion channel via a top quark loop [3–11], the Higgs production cross sections are known up to next-to-next-to leading order (NNLO) in the literature for a long time. The sub-dominant channels for the production comprising of the vector boson fusion [12, 13] and associated production with vector bosons [14, 15] are also known up to NNLO accuracy in QCD. The bottom-antibottom ($b\bar{b}$) annihilation process for inclusive Higgs production is also available at NNLO accuracy considering five active flavours i.e. including the bottom quarks in the parton distribution functions [16–21].

In the case of Higgs production, the scale dependence even at NNLO is not convincingly negligible due to potential missing higher order terms. Hence there is a constant pursuit of increasing the accuracy of the results with the systematic inclusion of higher order terms in QCD and there are on going efforts to go beyond the existing NNLO level. The partial results on inclusive Higgs boson production and also on Drell-Yan production beyond NNLO [22–26] have been reported after taking into account the dominant effects of the soft gluon radiations from higher orders, using the available results of the quark and gluon form factors [27–31], the mass factorization kernels [32], the renormalization constant [33] for the effective operator describing the coupling between the Higgs boson and the SM fields in the infinite top quark mass limit and the NNLO soft gluon radiations [34]

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in d dimensions. The reported threshold corrections, which manifest themselves through the delta function and the plus distributions, were partial results as the contribution from the delta function was not available. Since then, there have been several advancements [35–38] with the aim of obtaining the complete next-to-next-to-next-to leading order (N^{3}LO) results for the inclusive rate of the Higgs boson production. Recently, Anastasiou et al. [39] have obtained the delta function part of the threshold N^{3}LO contribution for the inclusive Higgs boson production through gluon fusion. This generated a plethora of results at threshold N^{3}LO in QCD. These include inclusive DY production [40, 41], inclusive production of Higgs boson in bottom quark annihilation [42] and the general expression of the hard-virtual coefficient [43] combined with the threshold resummation at next-to-next-to-next-to-leading-logarithmic (N^{3}LL) accuracy for the production cross section of a colourless heavy particle at threshold N^{3}LO. Apart from that, the rapidity distributions of the Higgs boson in the gluon fusion channel and in the bottom quark annihilation channel as well as of the dileptons in DY have been reported to this accuracy in the threshold limit, see [44, 45]. In addition, the efforts for obtaining the beyond threshold corrections [46, 47] for the inclusive Higgs production at N^{3}LO are already underway. Recently, the full next to soft as well as the exact results for the coefficients of the first three leading logarithms at this order have been obtained for the first time in [48].

The Higgs-Strahlung process is one of the potential channels for the Higgs boson production at the LHC. Precise theory predictions for this process are useful in measuring the Higgs-gauge boson couplings accurately. At LO, it is an electroweak process and hence the higher order QCD corrections enter only in the initial state comprising of a quark and an antiquark. This fact prompted this process to be represented in terms of the convolution of the production of a virtual vector boson (W/Z) (DY like) with its decay to a real vector boson and the Higgs boson, at every order in QCD. Therefore, the available higher order QCD corrections to DY process can be used to study the QCD effects in Higgs-Strahlung process. The QCD corrections to DY at next-to leading order (NLO) [49] as well as at NNLO [9, 50] are known for a long time and they have already been used for the Higgs-Strahlung process [14, 15, 51–57]. At NNLO, for the associated production of the Higgs boson with Z boson, there are additional corrections coming from the gluon fusion subprocess via box diagrams and also from the quark antiquark initiated subprocesses where the Higgs boson is coupled to top quark loops. These corrections have been obtained in [15, 54, 55]. In [58], the threshold logarithms have been resummed to NNNLL accuracy matched to NNLO fixed order results, while the transverse momentum logarithms are resummed to NLL accuracy matched to NLO results. In the gluon fusion channel, the associated Higgs boson production cross sections have also been reported at NLO [59] and the threshold resummation has been achieved at NLL accuracy [60]. However, the final state not being charge neutral, there are no such additional corrections for the associated production of the Higgs with the W-boson.

The `vh@nnlo` [61] program includes all these contributions for the associated productions of ZH and WH separately up to NNLO. The electroweak (EW) corrections reported in [62, 63] have also been incorporated in this program as a multiplicative factor based on the fact that the EW corrections for these processes do not depend on any of the QCD parameters. For LHC8, the NLO corrections have been found to enhance the total inclusive rate by 31% whereas the NNLO DY like corrections contribute towards an additional 3% correction for the ZH production. The numerical values for the WH production are also very similar to the DY like corrections up to NNLO. The top loop effects can be counted for about 1% correction for both the processes. The additional gluon fusion subprocesses generate 5% correction in the case of ZH associated production. These numerical values show that the corrections at NNLO are small in size. Besides, these NNLO corrections are found to reduce the scale dependence significantly. However, the inclusion of higher order terms is important to assess the reliability of the perturbative calculations as well as to have a better understanding of the pattern of these corrections at higher orders.

The paper is organized as follows. In the section 2.8 we present the results contributing at N^{3}LO in the threshold limit. We then discuss the numerical impact of these corrections at the LHC in section 3. Finally, we conclude with our findings in section 4.

2 Threshold corrections beyond NNLO

The inclusive production of Higgs boson in association with vector boson comes from factorizable and non factorizable partonic subprocesses. The factorizable ones can be written as convolution of the production of virtual vector boson with its decay to Higgs and a real vector boson. They are often called DY like. The hadronic cross section for this DY like process $P(p_1) + P(p_2) \rightarrow V(p_V) + H(p_H)$ can be expressed as

$$\sigma\left(S, M_V^2, M_H^2\right) = \int_{(M_H+M_V)^2}^{S} \mathrm{d}q^2 \sigma^{V^*}\left(q^2, S\right) \frac{\mathrm{d}\Gamma\left(M_V^2, M_H^2, q^2\right)}{\mathrm{d}q^2} \tag{2.1}$$

where p_1 and p_2 are the incoming hadronic momenta and $S = (p_1 + p_2)^2$ is the hadronic center of mass energy squared. The corresponding one for the incoming partons is given as $\hat{s} = (k_1 + k_2)^2$ and the momentum of the virtual gauge boson V^* is $q = (p_V + p_H)$. The parton level cross section for the production of virtual vector boson V^* is denoted by σ^{V^*} and $\frac{d\Gamma}{dq^2}$ represents its decay rate to a real vector boson and the Higgs boson as given by:

$$\frac{\mathrm{d}\Gamma\left(M_V^2, M_H^2, q^2\right)}{\mathrm{d}q^2} = \frac{G_F M_V^4}{2\sqrt{2}\pi^2} \frac{\lambda^{1/2}\left(M_V^2, M_H^2; q^2\right)}{\left(q^2 - M_V^2\right)^2} \left(1 + \frac{\lambda\left(M_V^2, M_H^2; q^2\right)}{12 M_V^2/q^2}\right) \tag{2.2}$$

where $\lambda(x, y; z) = \left(1 - \frac{x}{z} - \frac{y}{z}\right)^2 - 4\frac{xy}{z^2}$ is the usual phase-space function for the two body final state. Now the DY like production cross-section can further be written as:

$$\sigma^{V^*}(q^2, S) = \frac{1}{S} \sum_{a,b} \int_0^1 dx_1 \int_0^1 dx_2 \int_0^1 dz f_a(x_1, \mu_F^2)\, f_b(x_2, \mu_F^2)\, \Delta_{ab}^{V^*}\left(z, q^2, \mu_F^2\right) \delta(\tau - x_1 x_2 z)\,. \tag{2.3}$$

Here f_a and f_b are the parton distribution functions renormalized at the scale μ_F. We have defined $\Delta_{ab} \equiv \hat{s}\hat{\sigma}$ with $\tau = q^2/S$ and $z = q^2/\hat{s}$. This finite Δ_{ab} can be expanded in terms of the strong coupling constant as follows:

$$\Delta_{ab}\left(z, q^2, \mu_F^2\right) = \sum_{i=0}^{\infty} \left(a_s\left(\mu_R^2\right)\right)^i \Delta_{ab}^{(i)}\left(z, q^2, \mu_F^2, \mu_R^2\right), \tag{2.4}$$

where $a_s\left(\mu_R^2\right) = \frac{g_s\left(\mu_R^2\right)^2}{16\pi^2}$.

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Beyond LO (i.e. $i=0$) the perturbative coefficients $\Delta_{ab}^{(i)}$ can be split into two parts.

$$\Delta_{ab}^{(i)}\left(z,q^2,\mu_F^2,\mu_R^2\right) = \Delta_{ab}^{\text{hard},(i)}\left(z,q^2,\mu_F^2,\mu_R^2\right) + \delta_{aq}\delta_{b\bar{q}}\Delta_{q\bar{q}}^{\text{SV},(\text{i})}\left(z,q^2,\mu_F^2,\mu_R^2\right). \tag{2.5}$$

The hard part $\Delta_{ab}^{\text{hard},(i)}$ contains the regular terms in the variable z and the part $\Delta^{\text{SV},(i)}$ is simply proportional to $\delta(1-z)$ and $\mathcal{D}_k$ terms resulting from the soft plus virtual (SV) corrections i.e.

$$\Delta_{ab}^{\text{SV},(\text{i})}(z) = \Delta_{ab}^{\text{SV},(\text{i}),\delta}\delta(1-z) + \sum_{k=0}^{(2i-1)}\Delta_{ab}^{\text{SV},(\text{i}),(\text{k})}\mathcal{D}_k \tag{2.6}$$

with

$$\mathcal{D}_k = \left(\frac{ln^k(1-z)}{(1-z)}\right)_+. \tag{2.7}$$

As we have already discussed, the hard and soft parts of $\Delta_{ab}^{(i)}$ are known up to NNLO level in QCD. At N^{3}LO level, only $\Delta_{q\bar{q}}^{\text{SV},(3)}$ is known, see [40, 41, 43]. The computation of SV part of $\Delta_{q\bar{q}}^{(3)}$ in [40] uses the factorization property of the QCD amplitudes and the Sudakov resummation of soft gluons. At N^{3}LO level in QCD, SV part requires quark form factor as well as the diagonal terms of the mass factorization kernels up to three loop level and the contributions of soft gluon radiations in the single, double and triple gluon emission subprocesses to third order in the strong coupling constant. While the form factor and the kernels are available to desired accuracy for quite some time, the third order soft gluon effects from real emission subprocesses have been missing to get N^{3}LO results till recently. A spectacular achievement by Anastasiou et al. [39] in obtaining the contributions of the third order soft gluon radiations for the inclusive Higgs production process and for the better understanding of the soft gluon resummation paved the way to obtain several third order results as has been discussed earlier in the section 1. Along this direction, the results of [40, 41, 43] can be used for the Higgs-Strahlung processes to get an estimate of the threshold N^{3}LO corrections as is the case for the pure DY process where these corrections are found to be significant. Up to NNLO, DY like corrections can be found in [9, 50]. At N^{3}LO, the analytic result for the threshold corrections is identical to that of DY process. At this order, the threshold contributions from plus distributions $\mathcal{D}_i$ can be found in [22–26] while for $\delta(1-z)$ term, see [40, 41, 43]. For completeness, we give the full result for the scale choice of $\mu_R=\mu_F=Q$ as follows:

$$\begin{aligned}\Delta_{q\bar{q}}^{\text{SV},(3)} = \delta(1-z)\Bigg(&C_A^2C_F\left(\frac{13264}{315}\,\zeta_2{}^3+\frac{14611}{135}\,\zeta_2{}^2-\frac{884}{3}\,\zeta_2\zeta_3+843\zeta_2-\frac{400}{3}\,\zeta_3{}^2\right.\\&\left.+\frac{82385}{81}\,\zeta_3-204\,\zeta_5-\frac{1505881}{972}\right)+C_AC_F^2\left(-\frac{20816}{315}\,\zeta_2{}^3-\frac{1664}{135}\,\zeta_2{}^2+\frac{28736}{9}\,\zeta_2\zeta_3\right.\\&\left.-\frac{13186}{27}\,\zeta_2+\frac{3280}{3}\,\zeta_3{}^2-\frac{20156}{9}\,\zeta_3-\frac{39304}{9}\,\zeta_5+\frac{74321}{36}\right)+C_AC_Fn_f\left(-\frac{5756}{135}\,\zeta_2{}^2\right.\\&\left.+\frac{208}{3}\,\zeta_2\zeta_3-\frac{28132}{81}\,\zeta_2-\frac{6016}{81}\,\zeta_3-8\,\zeta_5+\frac{110651}{243}\right)+C_F^3\left(-\frac{184736}{315}\,\zeta_2{}^3+\frac{412}{5}\,\zeta_2{}^2\right.\end{aligned}$$

$$+\,80\,\zeta_2\zeta_3-\frac{130}{3}\,\zeta_2+\frac{10336}{3}\,\zeta_3{}^2-460\,\zeta_3+1328\,\zeta_5-\frac{5599}{6}\Bigg)+C_F^2n_f\left(\frac{272}{135}\,\zeta_2{}^2\right.$$

$$-\,\frac{5504}{9}\,\zeta_2\zeta_3+\frac{2632}{27}\,\zeta_2+\frac{3512}{9}\,\zeta_3+\frac{5536}{9}\,\zeta_5-\frac{421}{3}\Bigg)+C_Fn_{f,v}\left(\frac{N^2-4}{N}\right)\left(-\frac{4}{5}\,\zeta_2{}^2\right.$$

$$\left.+\,20\,\zeta_2+\frac{28}{3}\,\zeta_3-\frac{160}{3}\,\zeta_5+8\right)+C_Fn_f^2\left(\frac{128}{27}\,\zeta_2{}^2+\frac{2416}{81}\,\zeta_2-\frac{1264}{81}\,\zeta_3-\frac{7081}{243}\right)\Bigg)$$

$$+C_A^2C_F\mathcal{D}_0\left(-\frac{2992}{15}\,\zeta_2{}^2-\frac{352}{3}\,\zeta_2\zeta_3+\frac{98224}{81}\,\zeta_2+\frac{40144}{27}\,\zeta_3-384\,\zeta_5-\frac{594058}{729}\right)$$

$$+\,C_A^2C_F\mathcal{D}_1\left(\frac{704}{5}\,\zeta_2{}^2-\frac{12032}{9}\,\zeta_2-704\,\zeta_3+\frac{124024}{81}\right)+C_A^2C_F\mathcal{D}_2\left(\frac{704}{3}\,\zeta_2-\frac{28480}{27}\right)$$

$$+\,C_A^2C_F\mathcal{D}_3\left(\frac{7744}{27}\right)+C_AC_F^2\mathcal{D}_0\left(\frac{1408}{3}\,\zeta_2{}^2-1472\,\zeta_2\,\zeta_3-\frac{12416}{27}\,\zeta_2+\frac{26240}{9}\,\zeta_3\right.$$

$$\left.+\,\frac{25856}{27}\right)+C_AC_F^2\mathcal{D}_1\left(\frac{3648}{5}\,\zeta_2{}^2-\frac{11648}{9}\,\zeta_2-5184\,\zeta_3-\frac{35572}{9}\right)$$

$$+\,C_AC_F^2\mathcal{D}_2\left(\frac{11264}{3}\,\zeta_2+1344\,\zeta_3-\frac{4480}{9}\right)+C_AC_F^2\mathcal{D}_3\left(\frac{17152}{9}-512\,\zeta_2\right)$$

$$+\,C_AC_F^2\mathcal{D}_4\left(-\frac{7040}{9}\right)+C_AC_Fn_f\mathcal{D}_0\left(\frac{736}{15}\,\zeta_2{}^2-\frac{29392}{81}\,\zeta_2-\frac{2480}{9}\,\zeta_3+\frac{125252}{729}\right)$$

$$+\,C_AC_Fn_f\mathcal{D}_1\left(384\,\zeta_2-\frac{32816}{81}\right)+C_AC_Fn_f\mathcal{D}_2\left(\frac{9248}{27}-\frac{128}{3}\,\zeta_2\right)$$

$$+\,C_AC_Fn_f\mathcal{D}_3\left(-\frac{2816}{27}\right)+C_F^3\mathcal{D}_0\Big(-6144\,\zeta_2\,\zeta_3-4096\,\zeta_3+12288\,\zeta_5\Big)$$

$$+\,C_F^3\mathcal{D}_1\left(-\frac{14208}{5}\,\zeta_2{}^2+2976\,\zeta_2-960\,\zeta_3+2044\right)+C_F^3\mathcal{D}_2\Big(10240\,\zeta_3\Big)$$

$$+\,C_F^3\mathcal{D}_3\Big(-3072\,\zeta_2-2048\Big)+C_F^3\mathcal{D}_5\Big(512\Big)+C_F^2n_f\mathcal{D}_0\left(-\frac{1472}{15}\,\zeta_2{}^2+\frac{1952}{27}\,\zeta_2\right.$$

$$\left.-\,\frac{5728}{9}\,\zeta_3-6\right)+C_F^2n_f\mathcal{D}_1\left(\frac{2048}{9}\,\zeta_2+1280\,\zeta_3+\frac{4288}{9}\right)+C_F^2n_f\mathcal{D}_2\left(\frac{544}{9}\right.$$

$$\left.-\,\frac{2048}{3}\,\zeta_2\right)+C_F^2n_f\mathcal{D}_3\left(-\frac{2560}{9}\right)+C_F^2n_f\mathcal{D}_4\left(\frac{1280}{9}\right)+C_Fn_f^2\mathcal{D}_0\left(\frac{640}{27}\,\zeta_2\right.$$

$$\left.+\,\frac{320}{27}\,\zeta_3-\frac{3712}{729}\right)+C_Fn_f^2\mathcal{D}_1\left(\frac{1600}{81}-\frac{256}{9}\,\zeta_2\right)-C_Fn_f^2\mathcal{D}_2\frac{640}{27}$$

$$+\,C_Fn_f^2\mathcal{D}_3\left(\frac{256}{27}\right), \tag{2.8}$$

where ζ_i are the Riemann zeta functions, $C_F = \big(N^2-1\big)/2N$ and $C_A = N$ are the casimirs

E_{CM}	LO	NLO_{SV}	NLO	$NNLO_{SV}$	NNLO	N^3LO_{SV}
7	0.2415	0.2987	0.3183	0.3203	0.3257	0.3254
8	0.2977	0.3667	0.3901	0.3932	0.3993	0.3991
13	0.6120	0.7363	0.7788	0.7900	0.7975	0.7970
14	0.6801	0.8150	0.8604	0.8730	0.8808	0.8807

Table 1. DY like contributions (in pb) to ZH production cross sections at the LHC for different center of mass energies (TeV) with MSTW2008 PDFs. The factorization and renormalization scales are set to $\mu_F = \mu_R = Q$.

for SU(N) gauge theory, n_f is the number of active quark flavours and $n_{f,v}$ is the effective number of flavours resulting from some special class of diagrams at three loop level [31].

3 Numerical results

In what follows we present the numerical results for associated production of the Higgs boson with vector boson at the LHC for the proton-proton center of mass energies of $7, 8, 13$ and 14 TeV. The hadronic cross sections are obtained by folding the respective LO, NLO and NNLO partonic cross sections with the parton distribution functions (PDFs) measured at the same order in the perturbation theory and by using the corresponding strong coupling constant $\alpha_s(\mu_R)$. For N^{3}LO threshold corrections, however, we use NNLO PDFs and the $\alpha_s(\mu_R)$ obtained from the 4-*loop* β function. Unless mentioned otherwise, we use MSTW2008 PDFs for our results. Except for the scale uncertainties, both the renormalization and the factorization scales are set to $\mu_R = \mu_F = Q$, where $Q^2 = (p_V + p_H)^2$ is the invariant mass of the vector boson and the Higgs boson.

For the numerical implementation of the N^{3}LO threshold corrections, we have included the additional subroutines for the contributions coming from the $\delta(1-z)$ term and the logarithmic contributions $\mathcal{D}_k$, in the code `vh@nnlo` in a similar fashion as at the 2-loop level. This easily enables one to compute the N^{3}LO threshold corrections using the PDFs supplied by `LHAPDF` and the strong coupling constant as in the code `vh@nnlo`.

First, we present the DY like contributions to the ZH associated production up to N^{3}LO in QCD for different LHC energies in table 1. Here $\text{NLO}_{\text{SV}} = \text{LO} + a_s \Delta_{q\bar{q}}^{\text{SV},(1)}$, $\text{NNLO}_{\text{SV}} = \text{NLO} + a_s^2 \Delta_{q\bar{q}}^{\text{SV},(2)}$ and $\text{N}^3\text{LO}_{\text{SV}} = \text{NNLO} + a_s^3 \Delta_{q\bar{q}}^{\text{SV},(3)}$. The first and second order SV corrections are found to be positive and enhance the cross sections while the third order ones are found to be negative for all different energies. We also observe here that at 3-loop level the $\delta(1-z)$ term can contribute as much as the $\mathcal{D}_k$ terms in magnitude.

For LHC14 we observe that the SV contributions make up to 75% of the exact QCD correction at NLO level while they are about 60% at NNLO level, showing the significant contribution of the large logarithms that arise in the threshold limit. At NNLO, for DY type processes, there will be many more subprocesses exhausting almost all possible combinations of the initial state partons, that will contribute to the beyond threshold corrections. Such is not the case at NLO. Hence, naively one would expect that the contributions of the

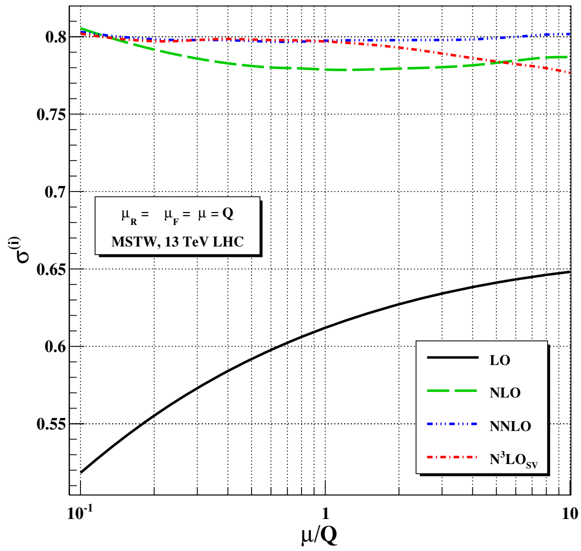

Figure 1. Scale uncertainties of DY like contributions to ZH production cross sections for LHC13 by varying the factorization and renormalization scales in the range $0.1 < \mu/Q < 10.0$, where $\mu = \mu_F = \mu_R$.

beyond threshold corrections to the total cross section will increase from NLO to NNLO. At N^3LO level, as the full result including the beyond threshold corrections is yet to be available, it is not possible to make such a quantitative estimation of the SV contributions and also it is not clear if a similar behavior will continue. However, they constitute an important component of the full N^3LO result and hence we investigate their numerical impact. In addition, the trend of their contributions at previous orders indicates that they can be numerically non-negligible and can compete with the beyond threshold effects. We also notice, from the results in table 1, that the QCD corrections in general increase with the decrease in the proton-proton collision energy.

Next, we study the scale uncertainties by varying the arbitrary factorization and renormalization scales. In figure 1, we show the scale dependence of the DY like cross sections up to N^3LO_{SV} by varying the scales in the range $0.1 < \mu/Q < 10.0$, where $\mu = \mu_R = \mu_F$. The scale uncertainties are found to decrease with the order in the perturbation theory. Here, at N^3LO only the soft plus virtual corrections are available. However, with the availability of the respective hard functions and the PDFs, the scale uncertainty is expected to improve further.

In the right panel of figure 2, we show only the factorization scale dependence of the DY like cross sections by varying μ_F in the range $0.1 < \mu_F/Q < 10.0$ and keeping $\mu_R = Q$ fixed. The observations are similar to those found in figure 1. In the left panel of figure 2, we show the renormalization scale dependence by varying it in the range $0.1 < \mu_R/Q < 10.0$ and keeping $\mu_F = Q$ fixed. Here the N^3LO threshold results are found to be more stable than the lower order ones as expected.

Apart from the DY like contributions, there will also be other subprocess contributions such as $gg \to ZH$ via quark loops ($\sigma^{\rm gg}$), $q\bar{q} \to ZH$ via *top*-loops ($\sigma^{\rm top}$) at NNLO

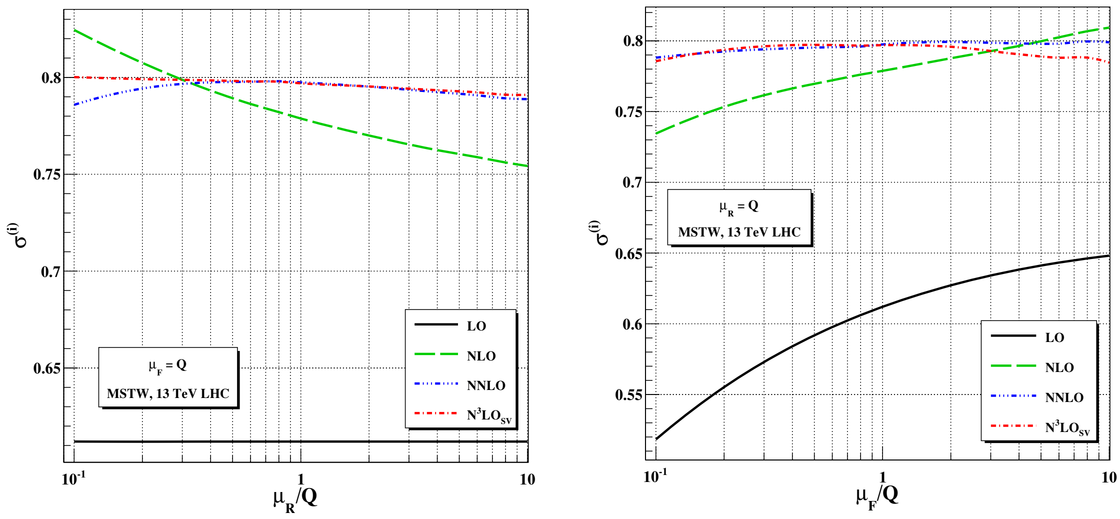

Figure 2. Scale uncertainties of DY like contributions to ZH production cross sections for LHC13. In the left panel, we show the renormalization scale uncertainty for $0.1 < \mu_R/Q < 10.0$ keeping $\mu_F = Q$ fixed. In the right panel, we show the factorization scale uncertainty for the similar range variation as μ_R.

level. Moreover, the $\mathcal{O}(\alpha)$ electroweak corrections to the DY like processes are already available. These electroweak corrections are assumed to be factorizable from the QCD corrections and hence they are included as a multiplicative factor at each order in the QCD perturbation theory. For consistency, we include in our analysis all these contributions as in [15, 54, 61, 63] and the corresponding third order result is given by

$$\sigma^{\text{tot}}_{\text{N}^3\text{LO}} = \sigma^{\text{DY}}_{\text{N}^3\text{LO}} \left(1 + \delta_{\text{EW}}\right) + \sigma^{\text{gg}} + \sigma^{\text{top}} \,. \tag{3.1}$$

Here, the δ_{EW} is given at percent level and is the same as defined in the `vh@nnlo` package. In table 2, we present the total cross sections up to N^{3}LO in QCD for different center of mass energies. For LHC7 and LHC8, the gluon initiated subprocess contributions are about 5% of DY like at NNLO while the EW corrections are of the same size but with opposite sign. Consequently, the total NNLO cross sections here are almost the same as those of pure DY contributions. However, for LHC13 and LHC14, the gluon initiated subprocess contributions rise to about 9% making the total cross sections larger than those of the DY like processes. In all these cases, the third order QCD corrections are about 0.1% but negative. In table 3, we present the total cross sections up to N^{3}LO for LHC13 for different parton distribution functions, namely, ABM11, CT10, NNPDFs and MSTW2008 PDFs.

Finally, we give the total cross sections as defined above for the associated production of W-boson and Higgs in table 4. The WH production cross sections are found to be higher than those of ZH process. As mentioned previously, there will be no gluon fusion contribution for this process at NNLO owing to the electric charge conservation. However, there will be top-loop contributions at NNLO from quark initiated subprocesses. The threshold N^{3}LO corrections are found to be negative similar to the case of ZH production. For both ZH and WH productions, however, the impact of QCD corrections are found to

E_{CM}	LO	NLO	NNLO	N^3LO_{SV}
7	0.2292	0.3021	0.3230	0.3227
8	0.2826	0.3702	0.3984	0.3982
13	0.5797	0.7377	0.8146	0.8141
14	0.6440	0.8148	0.9037	0.9035

Table 2. Total cross sections (in pb) for ZH production at the LHC for different center of mass energies (in TeV).

PDFs	LO	NLO	NNLO	N^3LO_{SV}
MSTW2008	0.5797	0.7377	0.8146	0.8141
ABM11	–	0.7716	0.8308	0.8305
NNPDF	0.6199	0.7234	0.7997	0.7994
CT10	0.6307	0.7312	0.8132	0.8128

Table 3. Total cross sections (in pb) for ZH production at LHC13 for different PDFs.

E_{CM}	LO	NLO	NNLO	N^3LO_{SV}
7	0.4254	0.5590	0.5785	0.5779
8	0.5208	0.6809	0.7043	0.7038
13	1.0474	1.3306	1.3803	1.3800
14	1.1607	1.4671	1.5220	1.5218

Table 4. Total cross sections (in pb) for WH production at the LHC for different center of mass energies (in TeV).

be similar at each order in the perturbation theory. Moreover, the electroweak corrections here are found to decrease the cross sections by about 6.7% in contrast to the ZH case where they decrease the cross sections by about 5%.

4 Conclusion

In this work we have computed the N^3LO QCD threshold corrections to the associated production of the Higgs with vector boson using the third order threshold corrections for inclusive DY process, which became available very recently. With both the threshold logarithms $\mathcal{D}_k$ and the $\delta(1-z)$ term, these results are expected to augment the previously available exact NNLO results for this process. For the numerical computation, we have incorporated these corrections in the code `vh@nnlo` to obtain the state of the art results. We gave predictions for ZH as well as WH processes and found that the effects of higher order QCD corrections are similar in both the cases. We have also estimated the theory uncertainties from the factorization and renormalization scales and also from the choice of the parton distribution functions. While the hard part at the N^3LO level is yet to be computed, we believe that these results, providing the first predictions in this direction towards the computation of the full N^{3}LO for Higgs-Strahlung processes, will be useful for the phenomenological studies related to Higgs Physics at the LHC.

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