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 on the threshold contributions to the inclusive Drell-Yan production cross-section at third order in 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.
1 Introduction

Recently, LHC has discovered a particle with a mass at around 125 GeV \cite{1,2}, whose production cross section and decay rates are compatible with those predicted for the Higgs boson of the Standard Model (SM). However, still we have to determine its quantum numbers (spin and CP properties), mass and the strength and nature of the 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 also any hint of new physics buried within the results. Any discrepancies in its measured cross section from QCD calculations may signal deviations of the SM predictions. It is thus important to provide a precise calculation of 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 Higgs boson is produced mainly through gluon fusion, whereas the alternative channels are associated production with vector bosons namely $W/Z$ bosons, often called Higgs-Strahlung process, vector boson fusion processes, bottom quark annihilation etc. The Higgs bosons are produced primarily at the LHC via gluon gluon fusion through a top quark loop \cite{3–11}, which has been 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 \cite{12,13} and associated production with vector bosons \cite{14,15} are also known up to NNLO accuracy in QCD. The bottom-antibottom ($b\bar{b}$) annihilated inclusive production for the Higgs boson is also available at NNLO accuracy considering five active flavours i.e. including the bottom quarks in the parton density function \cite{16–21}. In the case of Higgs production, the scale dependence even at NNLO are not convincingly negligible due to potential missing higher 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 DY production beyond NNLO \cite{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 \cite{27–31}, the mass factorization kernels \cite{32}, the renormalization constant \cite{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 contributions \[34\] in \(d\) dimensions. The reported threshold corrections, which manifest them through the delta function and the plus distribution of the logarithms, was partial in the sense that the complete distribution in connection with the delta function was not available. Since then, several advances have happened \[35–38\] with the aim of obtaining the complete next-to-next-to-next-to leading order (N^3LO) result for the inclusive rate of the Higgs boson production. Recently, Anastasiou et al. \[39\] have obtained the delta function part of the threshold N^3LO contribution for the inclusive Higgs boson production through gluon fusion. This generated a plethora of results at threshold N^3LO in QCD. These include inclusive DY production \[40,62\], inclusive production of Higgs boson in bottom quark annihilation \[41\] and the general expression of the hard-virtual coefficient \[42\] combined with the threshold resummation at next-to-next-to-next-to-leading-logarithmic (N^3LL) accuracy for the production cross section of a colourless heavy particle at hadron colliders at threshold N^3LO. Apart from that, the rapidity distributions of the Higgs boson in the gluon fusion and bottom quark annihilation as well as the dileptons in DY have been reported to this accuracy in the threshold limit, see \[43, 44\]. In addition, progress in obtaining beyond the threshold corrections \[45, 46\] for the inclusive Higgs production at N^3LO is 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 \[47\].

The Higgs-Strahlung process is one of the potential channels for the Higgs boson production at the LHC. The LO amplitude 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 production of a virtual \(W\) or \(Z\) boson production (DY like) and decay rate of that virtual boson to a real vector boson and the Higgs boson, at every order in QCD. Therefore, the available higher order QCD corrections of DY like processes can be used to study the QCD effects in Higgs-Strahlung process. The QCD corrections to DY at next-to leading order (NLO) \[48\] as well as at NNLO \[9,49\] are known for long time and they have been already used in the Higgs-Strahlung process \[14,15,50–56\]. At NNLO, for the associated production of the Higgs boson with \(Z\) boson, there are additional corrections coming from the gluon fusion via a box diagram and also the quark antiquark initiated processes, where the Higgs boson is coupled to a top quark loop. These corrections have been obtained in \[15,53,54\]. The gluon induced production of the associated Higgs boson has also been reported at NLO \[57\] and the threshold resummation has been completed at NLL accuracy \[58\]. There are no such additional corrections in the case of \(W\) boson production with the Higgs boson as the final state not being a charge neutral. The vh@nnlo \[59\] program includes all these contributions separately for the \(Z\) and \(W\) boson production with the Higgs boson up to NNLO. The electroweak (EW) corrections reported in \[60,61\], have been also incorporated in this programme as a multiplicative factor based on the fact that the EW corrections for these processes do not depend on any of the QCD parameters. The NLO corrections have been found to enhance the total inclusive rate by 31% whereas the NNLO DY terms contribute towards additional 3% correction for the \(ZH\) production at LHC8. The numer-
ical values for the $WH$ production are also very similar for the DY type corrections up to NNLO. The top loop effect can be counted for 1% correction for both the processes. The additional gluon initiated box diagrams generate 5% correction in case of the $ZH$ production. These numerical values exhibit that the corrections at NNLO are small in size although it has been observed that scale dependence is reduced significantly at this level. 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 Sec. 2 we present the results contributing at N$^3$LO in threshold limit. We then discuss the numerical impacts at LHC in Sec. 3. Finally, we conclude with our findings in Sec. 4.

2 Threshold Corrections Beyond NNLO

The inclusive production of Higgs boson in association with vector boson come from factorizable and non factorizable partonic subprocess. The factorizable ones can be written as convolution of the production of virtual vector boson and its decay to Higgs boson. They are often called DY type. The DY type contribution to the hadronic cross-section $P (p_1) + P (p_2) \rightarrow V (p_V) + H (p_H)$ can be expressed as:

$$\sigma (S, M_V^2, M_H^2) = \int_{(M_H+M_V)^2}^{S} dq^2 \sigma^{V^*} (q^2, S) \frac{d\Gamma (M_V^2, M_H^2, q^2)}{dq^2}$$

(2.1)

where, $p_1$ and $p_2$ are the incoming hadronic momenta and $S$ is the hadronic center of mass energy squared ($S \equiv (p_1 + p_2)^2$). The corresponding one for the incoming partons at the partonic level is given as $\hat{s} = (k_1 + k_2)^2$. 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 $V^*$ which is of DY type is denoted by $\sigma^{V^*}$ and $\frac{d\Gamma}{dq^2}$ is the decay rate of that virtual boson to a real vector boson and the Higgs boson and is given by:

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

(2.2)

with, $\lambda(x, y, z) = (1 - \frac{x}{2} - \frac{y}{2})^2 - 4\frac{x y}{z}$, being the usual phase-space function for the two body final state. Now, the DY type production cross-section can be expressed as:

$$\sigma^{V^*}(q^2, S) = \frac{1}{S} \sum_{a,b} \int_{0}^{1} dx_1 \int_{0}^{1} dx_2 \int_{0}^{1} dz f_a (x_1, \mu_F^2) f_b (x_2, \mu_F^2) \Delta_{ab} \left( z, q^2, \mu_F^2 \right) \delta (\tau - x_1 x_2 z)$$

(2.3)

The $f_a$ and $f_b$ are the parton density function renormalized at $\mu_F$. We have defined $\Delta_{ab} \equiv \hat{s}\delta$ with $\tau = q^2/S$ and $z = q^2/\hat{s}$. This finite $\Delta_{ab}$ can be expanded in terms of the strong coupling constant as follows:

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

(2.4)
where, \( a_s(\mu_R^2) = \frac{g_s(\mu_R^2)^2}{4\pi^2} \).

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

\[
\Delta_{ab}^{(i)}(z, q^2, \mu_F^2, \mu_R^2) = \Delta_{ab}^{\text{hard},(i)}(z, q^2, \mu_F^2, \mu_R^2) + \delta_{aq}\delta_{bq}\Delta_{ab}^{\text{SV},(i)}(z, q^2, \mu_F^2, \mu_R^2)
\]

The hard part \( \Delta_{ab}^{\text{hard},(i)} \) contains the regular terms in the variable \( z \) and the SV part \( \Delta_{ab}^{\text{SV},(i)} \) is simply proportional to \( \delta(1 - z) \) and \( D_k \) resulting from virtual and soft gluon radiations, that is

\[
\Delta_{ab}^{\text{SV},(i)}(z) = \Delta_{ab}^{\text{SV},(i)}(1 - z) + \sum_{k=0}^{\infty} \Delta_{ab}^{\text{SV},(i),(k)} D_k
\]

with

\[
D_k = \left( \frac{\ln^k(1 - z)}{(1 - z)} \right)
\]

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 \( \Delta_{ab}^{\text{SV},(3)} \) is known, see [40, 42, 62]. The computation of SV part of \( \Delta_{ab}^{(3)} \) 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 strong coupling constant. While 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 third order soft gluon radiations in the inclusive Higgs production and better understanding of the soft gluon resummation paved the way to obtain several third order results as has been discussed earlier in the Sec. 1. Along this direction, the results of [40, 42, 62] can be used in Higgs-Strahlung processes to get an estimate of the effects from threshold N\(^3\)LO DY type of corrections as the threshold effects in DY production are found to be significant. Up to NNLO, DY type of corrections can be found in [9, 49] and the threshold N\(^3\)LO DY correction with \( \mu_R = \mu_F = Q \) is given here for completeness:

\[
\Delta_{SV}^{(3)} = \delta(1 - z) \left( C_A^2 C_F \left( \frac{13264}{315} \zeta_3^3 + \frac{14611}{135} \zeta_2^2 - \frac{884}{3} \zeta_2 \zeta_3 + 843 \zeta_2 - \frac{400}{3} \zeta_3^2 \right) + \frac{82385}{81} \zeta_3 - 204 \zeta_5 - \frac{1505881}{972} \right) + C_A C_F^2 \left( - \frac{20816}{315} \zeta_2^3 - \frac{1664}{135} \zeta_2^2 + \frac{28736}{9} \zeta_2 \zeta_3 - \frac{13186}{27} \zeta_2 + \frac{3280}{3} \zeta_3^2 - \frac{20156}{9} \zeta_3 - \frac{39304}{9} \zeta_5 + \frac{74321}{36} \right) + C_A C_F n_f \left( - \frac{5756}{135} \zeta_2^2 + \frac{208}{3} \zeta_2 \zeta_3 - \frac{28132}{81} \zeta_2 - \frac{6016}{81} \zeta_3 - 8 \zeta_5 + \frac{110651}{243} \right) + C_F^3 \left( - \frac{184736}{315} \zeta_2^3 + \frac{412}{5} \zeta_2^2 + 80 \zeta_2 \zeta_3 - \frac{130}{3} \zeta_2 + \frac{10336}{3} \zeta_3^2 - 460 \zeta_3 + 1328 \zeta_5 - \frac{5599}{6} \right) + C_F^2 n_f \left( \frac{272}{135} \zeta_2^2 \right)
\]
where, $\zeta_i$ are the Riemann zeta functions, $C_F = (N^2 - 1)/2N$, $C_A = N$ are the casimirs for $SU(N)$ gauge theory, $n_f$ is the number of active quark flavours and $n_{f,e}$ is the effective number of flavours resiling from some special class of diagrams at three loop [31].
3 Numerical Results

| $E_{\text{CM}}$ | LO    | NLO$_{SV}$ | NLO  | NNLO$_{SV}$ | NNLO | N$^3$LO$_{SV}$ |
|----------------|-------|------------|------|-------------|------|--------------|
| 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) for different center of mass energies (TeV) at LHC with MSTW2008 PDFs. The factorization and renormalization scales are set to $\mu_F = \mu_R = Q$.

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 $\beta$ 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 gauge 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 $D_k$, 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 type contributions to the $ZH$ associated production up to N$^3$LO in QCD for different LHC energies in table 1. Here NLO$_{SV} = \text{LO} + a_\gamma \Delta_{\gamma\gamma}^{SV,(1)}$, NNLO$_{SV} = \text{NLO} + a_\gamma^2 \Delta_{\gamma\gamma}^{SV,(2)}$ and N$^3$LO$_{SV} = \text{NNLO} + a_\gamma^3 \Delta_{\gamma\gamma}^{SV,(3)}$. We observe that the soft plus virtual 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. The first and second order SV corrections are found to be positive and enhance the cross sections while the third order one is 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 $D_k$ terms in magnitude. It can be noted that the impact of the QCD corrections increases with the decrease in the proton-proton collision energy.

Next, we study the scale uncertainties by varying the arbitrary factorization and renormalization scales. In fig.1, we show the scale dependence of the DY like cross sections up to N$^3$LO$_{SV}$ 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$^3$LO only the soft plus virtual corrections are available. However, with the availability
Figure 1. Scale uncertainties of DY type cross sections for LHC13 by varying the factorization and renormalization scales in the range $0.1 < \mu/Q < 10.0$, where $\mu = \mu_F = \mu_R$.

Figure 2. Scale uncertainties of DY type 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 $\mu_R$.

of the respective hard functions and the PDFs, the scale uncertainty is expected to improve further.

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

Apart from the DY like contributions, there will also be other subprocess contributions such as $gg \to ZH$ via quark loops, $q\bar{q} \to ZH$ via top-loops at NNLO level. Moreover, electroweak corrections for this process are already available and they do not depend on the QCD parameters. For consistency, we include in our analysis all these contributions as in [15,53,61] and the corresponding third order result is given by

$$\sigma_{N^3LO}^{tot} = \sigma_{N^3LO}^{DY}(1 + \delta_{EW}) + \sigma_{gg}^{NNLO} + \sigma_{top}^{NNLO}$$ (3.1)

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 type 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 initiates subprocess contributions rises to about 9% making the total cross sections larger than those of DY type. In all these cases, the third order QCD corrections are about 0.1% but negative. Finally 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.

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

| $E_{CM}$ (TeV) | LO | NLO | NNLO | N$^3$LO$_{SV}$ |
|---------------|----|-----|------|---------------|
| 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 3. Total cross sections (in pb) for different PDFs at 13 TeV LHC.

| PDFs          | LO  | NLO | NNLO | N$^3$LO$_{SV}$ |
|---------------|-----|-----|------|---------------|
| 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 |

4 Conclusion

In this work we have computed the N$^3$LO QCD threshold corrections to the associated production of the Higgs with vector boson using the inclusive third order DY corrections, which became available very recently. With both the threshold logarithms $D_k$ 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 \texttt{vh@nnlo} to obtain the state of the art results. For our predictions, we have restricted ourselves only to the $ZH$ associated production and similar predictions can be made for $WH$ as well. We have also estimated the theory uncertainties from the factorization and renormalization scales and from the choice of the parton distribution functions. While the hard part at the $N^3$LO 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 LHC.

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