Electroweak Sudakov Corrections to New Physics Searches at the CERN LHC

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(Dated: May 30, 2013)

We compute the one-loop electroweak Sudakov corrections to the production process $Z(\nu\bar{\nu}) + n$ jets, with $n = 1,2,3$, in $pp$ collisions at the LHC. It represents the main irreducible background to new physics searches at the energy frontier. The results are obtained at the leading and next-to-leading logarithmic accuracy by implementing the general algorithm of Denner-Pozzorini in the event generator for multiparton processes ALPGEN. For the standard selection cuts used by ATLAS and CMS collaborations, we show that the Sudakov corrections to the relevant observables can grow up to $-40\%$ at $\sqrt{s} = 14$ TeV. We also include the contribution due to undetected real radiation of massive gauge bosons, to show to what extent the partial cancellation with the large negative virtual corrections takes place in realistic event selections.

PACS numbers: 12.15.Lk, 12.60.-i, 13.85.-t

Important searches for new phenomena beyond the Standard Model (SM) of particle physics at the proton-proton ($pp$) collider LHC at the CERN laboratory are based on the analysis of events with jets and missing transverse momentum ($p_T$). Typical examples of such studies are searches for squarks and gluinos in all-hadronic reactions containing high-$p_T$ jets, missing transverse momentum and no electrons or muons, as predicted in many supersymmetric extensions of the SM. These final states can appear in a number of R-parity conserving models where squarks and gluinos can be produced in pairs and subsequently decay to standard strongly interacting particles plus neutralinos that escape detection, thus giving rise to a large amount of $E_T$. Typically the event selections adopted require the leading jet $p_T$ larger than 130 GeV or the single jets $p_T$’s larger than 50 GeV. Moreover, the signal region is defined by $m_{\text{eff}} > 1000$ GeV, where $m_{\text{eff}} = \sum_i p_{iT_i} + E_T$, or $H_T > 500$ GeV and $|\vec{H}_T| > 200$ GeV, where $H_T = \sum_i p_{iT_i}$ and $\vec{H}_T = -\sum_i \vec{p}_i$.

The main SM backgrounds to the above mentioned signal(s) are given by the production of weak bosons accompanied by jets ($W/Z + n$ jets), pure QCD multiple jet events and $t\bar{t}$ production. Among these processes only $Z+n$ jets (in particular with $Z \rightarrow \nu\bar{\nu}$) constitutes an irreducible background, particularly relevant for final states with 2 and 3 jets.

Because new physics signals could manifest themselves as a mild deviation with respect to the large SM background, precise theoretical predictions for the processes under consideration are needed. Moreover, for these extreme regions, it is known that the observables are affected by large electroweak (EW) Sudakov corrections. The aim of the present paper is to compute the one-loop EW Sudakov corrections to the production process $Z(\nu\bar{\nu}) + n$ jets, with $n = 1,2,3$, in $pp$ collisions at the LHC.

Before discussing the details of the calculation, let us summarize the available QCD/EW calculations for the processes $V = W,Z +$ jets. Exact NLO QCD corrections to $Z +$ jets and $W +$ jets, computed by means of the package BlackHat and interfaced to the parton shower generator SHERPA can be found in Refs. [1] and [5], respectively. Fixed-order (NLO) QCD predictions for the production of a vector boson in association with 5 jets at hadron colliders are presented in Ref. [2]. Leading and next-to-leading EW corrections to the processes $V = \gamma,Z,W + 1$ jet, with on-shell $W,Z$ bosons, can be found in Refs. [8][10], where two-loop Sudakov corrections are also investigated. Very recently EW and
QCD corrections to the same processes have been computed using the soft and collinear effective theory in [11]. The exact NLO EW calculation for $V = W, Z + 1$ jet, with on-shell $W, Z$ bosons can be found in Refs. [12] [13], and the same with $W/Z$ decays has been published in Refs. [14] [15]. Recently the exact NLO EW calculation for $Z(\nu\bar{\nu}) + 2$ jets, for the partonic subprocesses with one fermion current only (i.e. including only gluon-gluon (gg) contributions to 2 jets), has been completed and can be found in Ref. [16]. No EW corrections for $Z + 2/3$ jets production including all partonic subprocesses are available at the moment.

For energy scales well above the EW scale, EW radiative corrections are dominated by double and single logarithmic contributions (DL and SL, respectively) whose argument involves the ratio of the energy scale to the mass of the weak bosons. These logs are generated by diagrams in which virtual and real gauge bosons are radiated by external leg particles, and correspond to the soft and collinear singularities appearing in QED and QCD, i.e. when massless gauge bosons are involved. At variance with this latter case, the weak bosons masses put a physical cutoff on these “singularities”, so that virtual and real weak bosons corrections can be considered separately. Moreover, as the radiation of real weak bosons is in principle detectable, for those event selections where one does not include real weak bosons radiation the physical effect of (negative) virtual corrections is singled out, and can amount to tens of per cent. Since these corrections originate from the infra-red structure of the EW theory, they are “process independent” in the sense that they depend only on the external on-shell legs.

As shown by Denner and Pozzorini in Refs. [17] [18], DL corrections can be accounted for by factorizing a proper correction which depends on flavour and kinematics of all possible pairs of electroweak charged external legs. SL corrections can be accounted for by factorizing an appropriate radiator function associated with each individual external leg. The above algorithm has been implemented in ALPGEN v2.1.4 [19], where all the contributing tree-level amplitudes are automatically provided. Since the matrix elements in ALPGEN are calculated within the unitary gauge, for the time being we do not implement the corrections for the amplitudes involving longitudinal $Z$, which, according to Refs. [17] [18], are calculated by means of the Goldstone Boson Equivalence Theorem. This approximation affects part of the $O(\alpha^2)$ and $O(\alpha^2\alpha_s)$, for $Z + 2$ jets and $Z + 3$ jets, respectively, and we checked that in view of our target precision of few percent it can be accepted [20].

Despite in this paper we limit ourselves to a purely parton-level analysis and a specific signature, the implementation is completely general. As such it can be generalized to other processes and fully matched and showered events can be provided.

Our numerical results have been obtained by using the code ALPGEN with default input parameters/PDF set and applying two sets of cuts that mimic the real experimental event selections of ATLAS and CMS, respectively. For $Z + 2$ jets we consider the observable/cuts adopted by ATLAS, namely

\begin{align*}
    m_{\text{eff}} &> 1 \text{ TeV} & E_T/m_{\text{eff}} &> 0.3 \\
    p_T^l &> 130 \text{ GeV} & p_T^{\bar{l}} &> 40 \text{ GeV} & |\eta_l| &< 2.8 \\
    \Delta\phi(p_T^l, p_T^{\bar{l}}) &> 0.4 & \Delta R_{(j_1,j_2)} &> 0.4
\end{align*}

(1)

where $j_1$ and $j_2$ are the leading and next-to-leading $p_T$ jets. We considered also radiative processes: vector boson pairs plus jets, as enumerated in Tab. [1] In this respect further details about the adopted event selection are necessary. They mimic in a simplified way the ATLAS procedure. Missing transverse energy is defined as $H_T = -\sum_i \vec{p}_T^i$, where $i$ is either a tagged jet or a jet with $p_T > 40 \text{ GeV}$ or $2.8 < |\eta_j| < 4.5$ (in our simulation this is necessarily a jet coming from vector boson decay), or an untagged charged lepton. By tagged jet we mean a jet with $|\eta_j| < 2.8$ and $p_T > 40 \text{ GeV}$. Jets from vector boson decays are recombined with other jets if they fall within a separation cone with radius $R = 0.4$. The event is discarded if it contains a tagged charged lepton, i.e. a lepton ($e$, $\mu$ or $\tau$) with $p_T > 20 \text{ GeV}$ and $|\eta_l| < 2.4$. For the tagged jets, an additional requirement is imposed: if $\Delta R_{jl} < 0.2$, the jet is considered untagged. After this step, the leptons with a separation from any tagged jet $\Delta R_{jl} < 0.4$ are considered untagged. Finally the event is accepted if it contains exactly two tagged jets and no surviving tagged lepton and it satisfies the cuts of Eq. (1).

For the $Z + 3$ jets final state we consider the observables/cuts used by CMS [21], namely

\begin{align*}
    H_T &> 500 \text{ GeV} & |\vec{H}_T| &> 200 \text{ GeV} \\
    p_T^l &> 50 \text{ GeV} & |\eta_l| &< 2.5 & \Delta R_{(j_1,j_2)} &> 0.5 \\
    \Delta\phi(p_T^{l_{1-2}}, \vec{H}_T) &> 0.5 & \Delta\phi(p_T^{l_3}, \vec{H}_T) &> 0.3
\end{align*}

Concerning additional real vector boson radiation, in this case the missing transverse energy receives contribution from tagged jets only, namely jets with $p_T^l > 50 \text{ GeV}$ and $|\eta_l| < 2.5$. Jets from vector boson decays are recombined with other jets if they fall within a separation cone with

| Process | $ZW(\to \nu\bar{\nu}jj)$ | $ZW(\to \nu\bar{\nu}jj) + j$ | $ZW(\to \nu\bar{\nu}jj) + jj$ |
|---------|-----------------|-----------------|-----------------|
| Process | $ZW(\to \nu\bar{\nu}jj)$ | $ZW(\to \nu\bar{\nu}lj) + j$ | $ZW(\to \nu\bar{\nu}lj) + jj$ |
| Process | $ZZ(\to \nu\bar{\nu}jj)$ | $ZZ(\to \nu\bar{\nu}lj) + j$ | $ZZ(\to \nu\bar{\nu}lj) + jj$ |
| Process | $WW(\to \nu\bar{\nu}lj)$ | $WW(\to \nu\bar{\nu}lj) + j$ | $WW(\to \nu\bar{\nu}lj) + jj$ |
| Process | $ZW(\to \nu\bar{\nu}l\mu l\mu)$ | $ZW(\to \nu\bar{\nu}l\mu l\mu) + j$ | $ZW(\to \nu\bar{\nu}l\mu l\mu) + jj$ |
| Process | $ZZ(\to \nu\bar{\nu}l\mu l\mu)$ | $ZZ(\to \nu\bar{\nu}l\mu l\mu) + j$ | $ZZ(\to \nu\bar{\nu}l\mu l\mu) + jj$ |

TABLE I. Vector boson radiation processes contributing to the considered signatures. In parenthesis we specify vector boson decay channels, while outside the parenthesis $j$ stands for a matrix element QCD parton. The above processes are for the $Z+2$ jet final state, whereas for three jet final states the processes are the same ones plus an additional QCD parton.
$R = 0.5$ and charged leptons with $\Delta R_{jl} < 0.2$ are recombined as well. Events with tagged surviving (not recombined with jets) charged leptons are discarded. Leptons are tagged if $p_T > 10$ GeV and $|\eta| < 2.5$.

As a first test, it is worth assessing the applicability of the theoretical approach just described. In Refs. [17, 18] the underlying hypothesis is that all kinematical invariants are much larger than $M_W$. Fig. 1 shows the maximum invariant mass distributions for the processes $Z + 2, 3$ jets at $\sqrt{s} = 7, 14$ TeV, obtained by considering, on an event by event basis, all possible combinations of invariant masses between electroweak charged particles at the parton level. One can notice that most of the events are characterized by at least one invariant mass above, say, 500 GeV. We expect that the approximation of Refs. [17, 18] still holds since radiator contributions depending on large kinematical invariants are reliable, whereas those depending on small kinematical invariants (at any rate of the order of $M_W$), as ensured by the applied cuts, lead to unreliable contributions, which, however, are numerically below the stated accuracy, since the involved logs are of order one or below. The above argument has been validated with results available in the literature as follows: first, we compared the predictions for $Z + 1$ jet and $W + 1$ jet with Refs. [9, 10], finding a level of agreement better than 1%; second, we estimated the corrections to $p_T^Z$ and to the leading jet $p_T$ distributions in the large tails for the process $Z + 2$ jets with only one fermionic current, as discussed in Ref. [16], finding good agreement. For the same kind of process we cross-checked our results with the automatic package GOSAM v1.0 [22], with the event selection adopted in the present study. Since the electroweak renormalization is not yet available in the present version of GOSAM, we subtracted the logarithmic terms due to the renormalization counterterms from the formulae of Refs. [17, 18] and tested the asymptotic behaviour of all relevant distributions. In particular we performed this analysis for different subprocesses: $qq \to Z qg$, $gq \to Z q''q''$, $qq \to Z qq$ and $qq' \to Z qq'$ (with $q$ and $q'$ belonging to the same isodoubler). For all the above cases we found that the shape of the distributions predicted by the two calculations is in good agreement. In particular, the relative weight of two-quark and four-quark subprocesses is about 75% and 25% for total cross sections, while for the observables under consideration and in the high tails is about 50% each at the LO, respectively.

![FIG. 1. $Z+2,3$ jets: distributions of the maximum invariant mass at $\sqrt{s} = 7, 14$ TeV](image1)

![FIG. 2. $Z+2$ jets: ATLAS $m_{\text{eff}}$ and EW correction at $\sqrt{s} = 7, 14$ TeV](image2)
be as large as +20%.

To summarize, we computed the NLO Sudakov EW corrections to $Z + n$ jets, $n = 1, 2, 3$, as the main background to NP searches at the LHC. We found that such corrections represent a sizable effect, of the order of tens of per cents, that has to be taken into account, together with the partially compensating contribution of weak bosons real radiation. The calculation described represents the first implementation of the Denner-Pozzorini algorithm in a multiparton LO generator, and paves the way to future applications to other multiple particle production processes at the energy frontier.

This work was supported in part by the Research Executive Agency (REA) of the European Union under the Grant Agreement number PITN-GA-2010-264564 (LHCPhenoNet), and by the Italian Ministry of University and Research under the PRIN program 2010-2011. The work of L.B. is supported by the ERC grant 291377, “LHCtheory - Theoretical predictions and analyses of LHC physics: advancing the precision frontier”. F.P. would like to thank the CERN PH-TH Department for partial support and hospitality during several stages of the work.

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