

Electroweak Sudakov Corrections to New Physics Searches at the LHC

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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 and Pozzorini in the event generator for multiparton processes ALPGEN. For the standard selection cuts used by the 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.

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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 (\cancel{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 \cancel{p}_T . Typically, the event selections adopted require the leading jet p_T larger than 130 GeV or the single jet p_T 's larger than 50 GeV. Moreover, the signal region is defined by $m_{\text{eff}} > 1000$ GeV, where $m_{\text{eff}} = \sum_i p_{Ti} + \cancel{E}_T$, or $H_T > 500$ GeV and $|\vec{H}_T| > 200$ GeV, where $H_T = \sum_i p_{Ti}$ and $\vec{H}_T = -\sum_i \vec{p}_{Ti}$ [1–3].

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 two and three 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 Letter 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. It is worth noting that the experimental procedure for the irreducible background determination relies on data driven methods of measuring control samples of either $\gamma +$ jets, $Z(\rightarrow l^+l^-) +$ jets, or $W(\rightarrow l\nu_l) +$ jets. Therefore, the required theoretical information is the prediction of the ratios of cross sections for the above three processes. In the ratios, the uncertainties related to QCD and parton distribution functions largely cancel, while the electroweak corrections do not [4].

Before discussing the details of the calculation, let us summarize the available QCD and EW calculations for the processes $V = W, Z +$ jets. Exact next-to-leading order (NLO) QCD corrections to $Z + 4$ jets and $W + 4$ jets, computed by means of the package BLACKHAT and interfaced to the parton shower generator SHERPA, can be found in Refs. [6–8], respectively. Fixed-order (NLO) QCD predictions for the production of a vector boson in association

with five jets at hadron colliders are presented in Ref. [9]. 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. [10–12], 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 Ref. [13]. The exact NLO EW calculation for $V = W, Z + 1$ jet, with on-shell W, Z bosons, can be found in Refs. [14–16], and the same with W, Z decays has been published in Refs. [17–19]. 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 two jets], has been completed and can be found in Ref. [20]. No EW corrections for $Z + 2$ and $Z + 3$ 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 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 boson 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 boson radiation, the physical effect of (negative) virtual corrections is singled out and can amount to tens of percent. Since these corrections originate from the infrared structure of the EW theory, they are “process independent” in the sense that they depend only on the external on-shell legs [10–12, 21–31]. As shown by Denner and Pozzorini in Refs. [26, 27], double logarithmic corrections can be accounted for by factorizing a proper correction which depends on flavor and kinematics of all possible pairs of electroweak charged external legs. Single logarithmic corrections can be accounted for by factorizing an appropriate radiator function associated with each individual external leg. Notice that our implementation includes correctly all single logarithmic terms of $O(\alpha^2\alpha_s^n)$ of both ultraviolet and infrared origin, as detailed in Ref. [32]. The above algorithm has been implemented in ALPGEN version 2.14 [33], 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. [26, 27], are calculated by means of the Goldstone boson equivalence theorem. This approximation affects part of the $O(\alpha^3)$ and $O(\alpha^3\alpha_s)$ contributions, for $Z + 2$ jets and $Z + 3$ jets, respectively, and we checked that in

view of our target precision of a few percent, it can be accepted [34].

Although in this Letter 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 and parton distribution function 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 and cuts adopted by ATLAS, namely,

$$m_{\text{eff}} > 1 \text{ TeV}, \quad \cancel{E}_T/m_{\text{eff}} > 0.3, \quad p_T^{j_1} > 130 \text{ GeV} \\ p_T^{j_2} > 40 \text{ GeV}, \quad |\eta_j| < 2.8, \quad \Delta\phi(\vec{p}_T^j, \vec{p}_T) > 0.4, \quad (1) \\ \Delta R_{(j_1, j_2)} > 0.4,$$

where j_1 and j_2 are the leading and next-to-leading p_T jets. We also considered radiative processes: vector boson pairs plus jets, as enumerated in Table I, in order to give an estimate of the (partial) cancellation between virtual NLO and real radiation in the presence of a realistic event selection [35]. We consider as real electroweak radiation any contribution to the experimental event selection of $O(\alpha^2\alpha_s^n)$, with $n \leq 2$. In a purely perturbative language, only $n = 2$ should be considered as $O(\alpha)$ electroweak corrections (final states in the upper panel of Table I). On the other hand, the included additional processes contribute to the same experimental signature and moreover are the most relevant ones among the real EW radiation contributions (final states in the lower panel of Table I). For the CMS event selection, $n = 3$ has to be taken instead of $n = 2$, as detailed below. In the case of W bosons decaying to $l\nu$, these contributions are included in the real correction only if the charged lepton is lost according to the adopted selection criteria. It is worth noting that in our calculation, weak bosons are produced on shell and decay afterwards. We shall refer to the colored partons present in the matrix element (ME) computation as ME jets and to those arising from V decay as V jets. In principle, if the ME jets are

TABLE I. Vector boson radiation processes contributing to the considered signatures. In parentheses, we specify vector boson decay channels, while outside the parentheses, j stands for a matrix element QCD parton. The above processes are for the $Z + 2$ jet final state, whereas for three jet final state the processes are the same ones plus an additional QCD parton.

$ZW(\rightarrow \nu_l\bar{\nu}_l jj) + jj$	$ZZ(\rightarrow \nu_l\bar{\nu}_l jj) + jj$	$WW(\rightarrow \nu_l l jj) + jj$
$ZW(\rightarrow \nu_l \nu_l \nu_l) + jj$	$ZW(\rightarrow \nu_l ll) + jj$	$ZZ(\rightarrow \nu_l \nu_l ll) + jj$
$ZZ(\rightarrow \nu_l \nu_l \nu_l \nu_l) + jj$	$WW(\rightarrow \nu_l \nu_l ll) + jj$	$ZW(\rightarrow \nu_l l jj) + jj$
$ZW(\rightarrow \nu_l \bar{\nu}_l jj)$	$ZW(\rightarrow \nu_l l jj)$	$ZZ(\rightarrow \nu_l \bar{\nu}_l jj)$
$WW(\rightarrow \nu_l l jj)$	$ZW(\rightarrow \nu_l l jj) + j$	$ZW(\rightarrow \nu_l \bar{\nu}_l jj) + j$
$ZZ(\rightarrow \nu_l \bar{\nu}_l jj) + j$	$WW(\rightarrow \nu_l l jj) + j$	

allowed to become unresolved, a QCD infrared problem arises. However, in the calculation, the ME jets are always required within the acceptance cuts, and hence no infrared problem is present. This corresponds to a leading order (LO) prediction of the real contribution that can be considered as a first estimate of the effect. The treatment of real QCD radiation with partons below threshold would require the inclusion of (not yet available) next-to-next-to-leading order QCD corrections to ZV , for the $Z + 2$ jets signature, and to ZVj for the $Z + 3$ jets signature, which could in principle be sizeable but is beyond the approximation adopted here. Moreover, in the presence of the adopted event selections, the numerical sizes of $ZVjj(j)$ and $ZV(j)$ (the additional jet in parentheses refers to the CMS event selection) are much smaller than the dominant ZVj , and hence any inaccuracy in the estimate of the former contributions should be less important at the level of the total real radiation effect [39]. In order to give an idea of the hierarchy of the various contributions, we report the cross sections, with the event selection of Eq. (1), for the three final states $ZW(\rightarrow \nu\bar{\nu}jj)$, $ZW(\rightarrow \nu\bar{\nu}jj) + j$, and $ZW(\rightarrow \nu\bar{\nu}jj) + jj$ [40] at $\sqrt{s} = 14$ TeV (the same hierarchy applies to all other processes of Table D):

$$\begin{aligned}\sigma[ZW(\rightarrow \nu\bar{\nu}jj)] &= 0.1911(1) \text{ fb}, \\ \sigma[ZW(\rightarrow \nu\bar{\nu}jj) + j] &= 6.834(1) \text{ fb}, \\ \sigma[ZW(\rightarrow \nu\bar{\nu}jj) + jj] &= 1.213(3) \text{ fb}.\end{aligned}$$

The definition of the event selection for real radiation processes requires further details on the adopted event selection with respect to Eq. (1), in order to mimic, in a simplified way, the ATLAS procedure. Missing transverse energy is defined as $\vec{H}_T = -\sum_i \vec{p}_{Ti}$, where i is either a tagged jet or a jet with $p_{Tj} < 40$ 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 $p_{Tj} > 40$ 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 , μ , or τ) with $p_T > 20$ GeV and $|\eta| < 2.4$. 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 observable and cuts used by CMS [41], namely,

$$\begin{aligned}H_T &> 500 \text{ GeV}, & |\vec{H}_T| &> 200 \text{ GeV}, \\ p_T^j &> 50 \text{ GeV}, & |\eta_j| &< 2.5, & \Delta R_{(j_i, j_k)} &> 0.5, \\ \Delta\phi(\vec{p}_T^{j_1, j_2}, \vec{H}_T) &> 0.5, & \Delta\phi(\vec{p}_T^{j_3}, \vec{H}_T) &> 0.3.\end{aligned}$$

Concerning additional real vector boson radiation, in this case, the missing transverse energy receives contribution from tagged jets only, namely, jets with $p_T^j > 50$ GeV and $|\eta_j| < 2.5$. Jets from vector boson decays are recombined with other jets if they fall within a separation cone with $R = 0.5$, 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 $p_T^l > 10$ GeV and $|\eta_l| < 2.5$.

As a first test, it is worth assessing the applicability of the theoretical approach described above for the virtual EW Sudakov corrections. In Refs. [26,27], the underlying hypothesis is that all kinematical invariants are much larger than M_W . Figure 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. [26,27] 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. [11,12], 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. [20], finding good agreement. For the same kind of process, we cross-checked our results with the automatic package GOSAM version 1.0 [42], with the event selection adopted in the present study. Since the electroweak renormalization

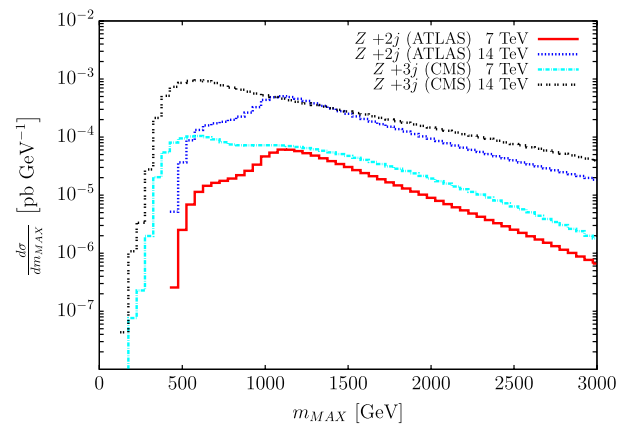


FIG. 1 (color online). $Z + 2, 3$ jets: distributions of the maximum invariant mass at $\sqrt{s} = 7, 14$ TeV.

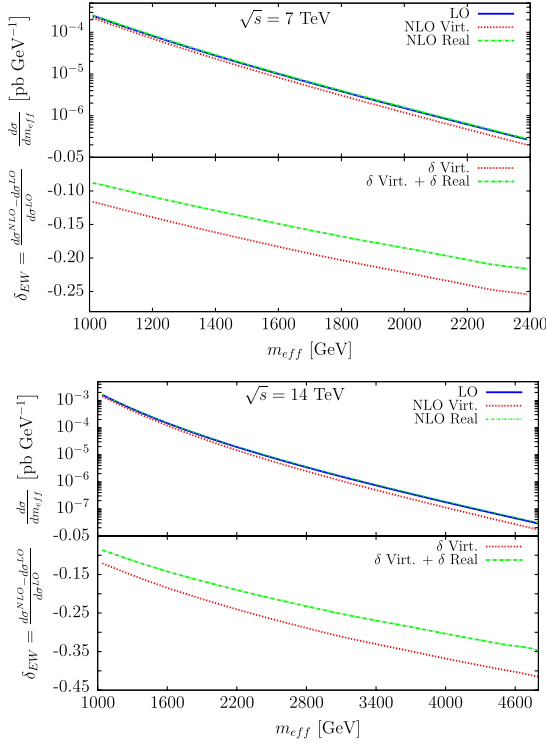


FIG. 2 (color online). $Z + 2$ jets: ATLAS m_{eff} and EW correction at $\sqrt{s} = 7, 14$ TeV.

is not yet available in the present version of GOSAM, we subtracted the logarithmic terms due to the renormalization counterterms from the formulas of Refs. [26,27] and tested the asymptotic behavior of all relevant distributions. In particular, we performed this analysis for different subprocesses: $q\bar{q} \rightarrow Zgg$, $q\bar{q} \rightarrow Zq''\bar{q}''$, $qq \rightarrow Zqq$, and $qq' \rightarrow Zqq'$ (with q and q' belonging to the same isodoublet). 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 it is about 50% each at the LO, respectively.

Figure 2 shows the effect of the Sudakov logs on the effective mass distribution in the process $Z + 2$ jets under ATLAS conditions. In both windows, the upper panel displays the effective mass distribution at LO (solid blue line) and including the approximate NLO virtual corrections (dotted red line) due to weak bosons in the Sudakov limit as given by Denner and Pozzorini, respectively. The effect of the inclusion of real radiation of electroweak bosons is also shown (dash-dotted green line). The lower panel represents the relative correction due to virtual contributions only (dotted red line) and the sum of virtual and real radiation (dash-dotted green line). The two windows correspond to $\sqrt{s} = 7, 14$ TeV, respectively. As can be seen, the negative correction due to Sudakov logs is of the order

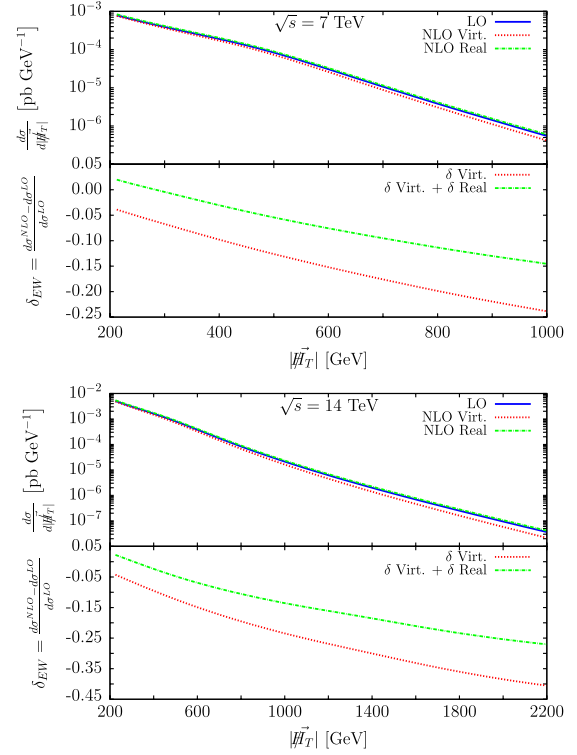


FIG. 3 (color online). $Z + 3$ jets: CMS $|\vec{H}_T|$ and EW correction at $\sqrt{s} = 7, 14$ TeV.

of some tens of percent, raising to about 40% in the extreme region at $\sqrt{s} = 14$ TeV. Real radiation partially cancels the effect, introducing a positive contribution of about some percent. Figure 3 is analogous to Fig. 2 for the observable $|\vec{H}_T|$ under CMS conditions. Also in this case, the virtual correction is large and negative, reaching the value of -25% at $\sqrt{s} = 7$ TeV and -45% at $\sqrt{s} = 14$ TeV. In these experimental conditions, real radiation gives a positive correction slightly larger than before, that can be as large as about $+15\%$.

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

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