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Electroweak corrections in the Sudakov limit at the LHC

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Summary. — At hadron colliders the production of a Z boson in association with jets represents an irreducible Standard Model background to direct searches for New Physics based on the signatures with several jets and missing transverse momentum. Using the algorithm developed by Denner and Pozzorini recently implemented in the ALPGEN event generator, one loop virtual weak corrections to Z+2 and Z+3 jets in the Sudakov limit have been computed. For the standard event selection considered by the ATLAS and CMS Collaborations, these corrections can grow up to −40, −45% at $\sqrt{s} = 14$ Tev and become even larger at future proton-proton colliders where the higher energies will allow to study more and more extreme kinematical regions. Finally, also the effect of real weak corrections to the processes to $Z + 2$ and $Z + 3$ jets is briefly discussed.

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At high energies and in extreme kinematical configurations electroweak (EW) corrections are enhanced by large logarithms of the kinematical invariants over the gauge boson masses known as Sudakov logs. Sudakov logs are the infrared (IR) limit of EW corrections [1-7]: these logs arise from those diagrams in which virtual and real gauge bosons are radiated by external leg particles and correspond to the soft and collinear singularities that appear in massless gauge theories such as QED or QCD. At variance with this latter case, the IR cutoffs are the weak bosons masses so that virtual and real weak corrections can be considered separately. Finally, additional gauge bosons decay and their decay products lead to final states that in principle are different from the signatures considered.

Using the universality of the IR part of virtual one loop corrections, in refs. [8, 9] a general algorithm has been developed to compute one loop EW corrections in the Sudakov limit (*i.e.* when all the kinematical invariants are of the same order and much larger than the W mass) in a process-independent way. According to this algorithm,

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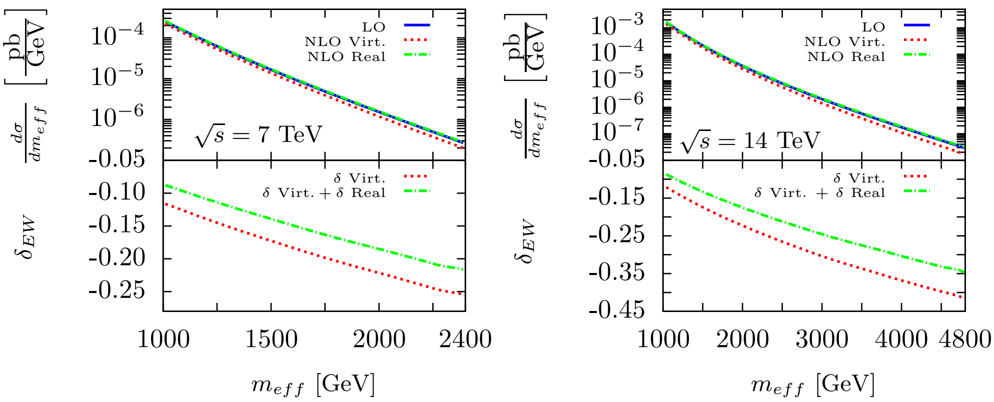

Fig. 1. – Weak corrections to $Z+2$ jets in the ATLAS setup of eqs. (1) at LHC energies of $\sqrt{s} = 7$ and 14 TeV. The upper panels show the effective mass distribution at LO (solid blue line), at NLO including only virtual one loop weak corrections (dotted red line) and at NLO including only real $\mathcal{O}(\alpha)$ corrections (dash-dotted green line). The lower panels show the relative effects ($\delta_{EW} = \frac{\mathrm{d}\sigma^{NLO} - \mathrm{d}\sigma^{LO}}{\mathrm{d}\sigma^{LO}}$) of virtual weak corrections (dotted red line) and the effect of the sum of virtual and real weak corrections (dash-dotted green line).

EW corrections in the Sudakov limit can be written as the sum of universal radiator functions which multiply tree level matrix elements: the former contain all the Sudakov logs and depend only on the flavour and the kinematics of the particles of the leading order (LO) process while the latter are the matrix elements for the LO process and their $SU(2)$ transformed ones.

The algorithm of refs. [8,9] has been implemented in the ALPGEN LO event generator [10] for the process $Z+$multi-jets [11]. The code has been checked with the results of refs. [12,13] for $Z+1$ jet and with the results of the automated package GOSAM [14] for $Z+2$ jets for the relevant subprocesses involving two fermionic currents (after subtracting the contributions coming from EW renormalization, which are not included in the present version of GOSAM). Finally we found a good agreement also with the results of ref. [15] where full one loop EW corrections to $Z+2$ gluons have been computed. Notice that our implementation includes correctly all single logarithmic terms of $\mathcal{O}(\alpha^2\alpha_s^n)$ (where n is the number of jets) of both ultraviolet and infrared origin, as detailed in ref. [16].

The process $Z+$multi-jets (with the Z decaying into $\nu\overline{\nu}$) is an irreducible Standard Model background to the direct searches for New Physics based on the analysis of events with multi-jets and missing transverse momentum $\vec{\not{p}}_T$ (in the following $\not{E}_T = |\vec{\not{p}}_T|$). Since these analysis look at extreme kinematical regions, it is possible to use the algorithm of refs. [8,9] to compute the one loop virtual weak corrections to the background process $Z+$multi-jets in the Sudakov limit.

Figures 1–3 show the results of refs. [11] and [17,18] where weak Sudakov corrections to $Z+2$ and $Z+3$ jets have been computed (the logarithms of photonic origin are a gauge invariant subset for the leading subprocesses of $\mathcal{O}(\alpha^2\alpha_s^{njets})$ and for inclusive observables give rise to moderate contributions). The plots in figs. 1–3 have been obtained using the default ALPGEN parameters and pdf sets and applying two sets of cuts which mimic the event selection used by the LHC Collaborations ATLAS [19] and CMS [20,21], respectively.

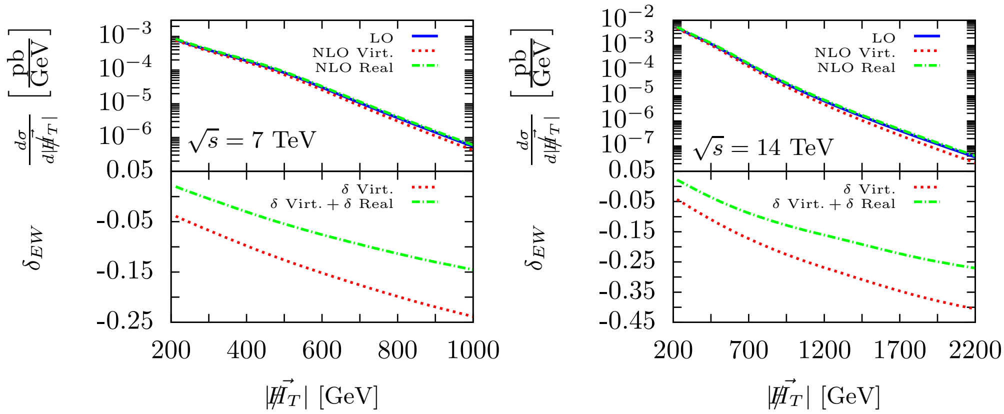

Fig. 2. – Weak corrections to $Z + 3$ jets in the CMS setup of eqs. (2) at $\sqrt{s} = 7$ and 14 TeV, with the same notations and conventions of fig. 1.

Figure 1 shows the effect of weak Sudakov corrections on the effective mass distribution ($m_{\text{eff}} = \sum_{j=1}^{njets} p_{Tj} + \not{E}_T$) for $Z + 2$ jets under the ATLAS cuts:

$$\begin{array}{lll} m_{\text{eff}} > 1\,\text{TeV}, & \not{E}_T/m_{\text{eff}} > 0.3, & \\ p_T^{j_1} > 130\,\text{GeV}, & p_T^{j_2} > 40\,\text{GeV}, & |\eta_j| < 2.8, \\ \Delta\phi(\vec{p}_T^{\,j}, \vec{\not{p}}_T) > 0.4, & \Delta R_{(j_1,j_2)} > 0.4, & \end{array} \tag{1}$$

(where j_1 and j_2 are the hardest and next to hardest jets, respectively). As can be seen, at $\sqrt{s} = 7$ TeV the size of virtual weak corrections in the m_{eff} region considered in ref. [19] is of order -20, -25% while at 14 TeV it grows up to -40, -45%.

Figure 2 shows the results for $Z + 3$ jets under the CMS cuts:

$$\begin{array}{lll} H_T > 500\,\text{GeV}, & |\vec{\not{H}}_T| > 200\,\text{GeV}, & \\ p_T^j > 50\,\text{GeV}, & |\eta_j| < 2.5, & \Delta R_{(j_i,j_k)} > 0.5, \\ \Delta\phi(\vec{p}_T^{\,j_1,j_2}, \vec{\not{H}}_T) > 0.5, & \Delta\phi(\vec{p}_T^{\,j_3}, \vec{\not{H}}_T) > 0.3, & \end{array} \tag{2}$$

(where $H_T = \sum_{j=1}^{njets} p_{Tj}$, $\vec{\not{H}}_T = -\sum_{j=1}^{njets} \vec{p}_{tj}$, j_1 and j_2 are the hardest and next-to-hardest jets while j_3 is the remaining jet). As in the case of $Z + 2$ jets, the size of virtual weak corrections in the tails of the $|\vec{\not{H}}_T|$ distribution at $\sqrt{s} = 7$ and 14 TeV is of order -25% and -45%, respectively.

Figure 3 shows the scaling of one loop virtual weak corrections to $Z + 2$ and $Z + 3$ jets with the center-of-mass energy of the collisions going from 14 to 33 and 100 TeV (*i.e.* to the energies of future proton-proton colliders such as HE-LHC and TLEP [22]). As can be seen, the negative corrections due to Sudakov logs for both processes are of the order of some tens of per cent, raising to about 40% (60%, 70–80%) in the extreme regions at $\sqrt{s} = 14$, (33, 100) TeV, respectively. Both for the m_{eff} and for the $|\vec{\not{H}}_T|$ distributions, for a given bin the relative EW corrections are practically the same, regardless of the collider center of mass energy.

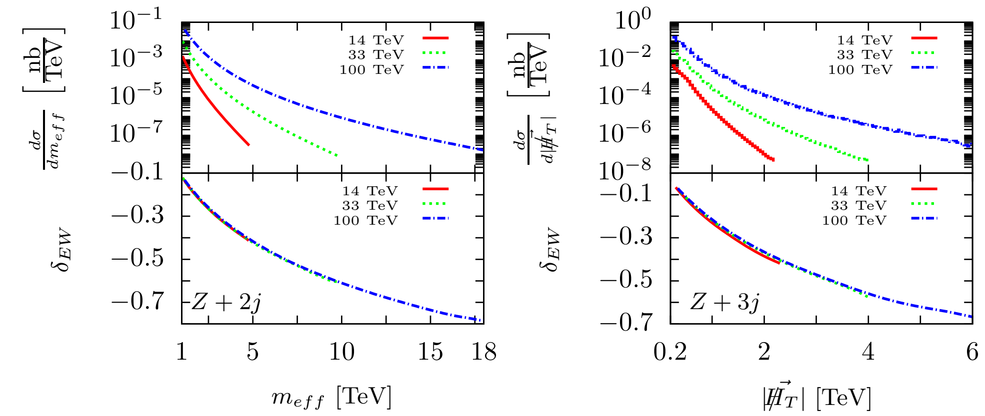

Fig. 3. – Virtual one loop weak corrections to $Z+2$ jets in the ATLAS setup and to $Z+3$ jets in the CMS setup at $\sqrt{s}=14$, 33 and 100 TeV. The upper panels show the LO $m_{\rm eff}$ distributions for $Z+2$ jets (left plot) and the $|\vec{\not{H}}_T|$ distributions for $Z+3$ jets (right plot) at 14, 33 and 100 TeV (solid red lines, dotted green lines and dash-dotted blue lines, respectively). The lower panels show the relative effects of virtual $\mathcal{O}(\alpha)$ corrections for the three different values of $\sqrt{s}$: in the region where all the curves are defined they almost overlap.

Even if in refs. [7, 23, 24] has been pointed out that also for inclusive observables the cancellation of the Sudakov logarithms in the sum of real and virtual weak corrections may be only partial (Bloch-Nordsieck violations), real weak corrections in the Sudakov limit can lead to sizeable positive contributions which can partially compensate the large negative virtual corrections. Following the approach of ref. [25], in ref. [11] any contribution to the experimental event selection of $\mathcal{O}(\alpha^2\alpha_S^n)$ with $n \leq 2$ for $Z+2$ jets ($n \leq 3$ for $Z+3$ jets) has been considered as real weak radiation. From a purely perturbative point of view, only the processes with $n=2$ (for $Z+2$ jets, $n=3$ for $Z+3$ jets) should be considered as real $\mathcal{O}(\alpha)$ corrections (upper panel of table I), however also the processes in the lower panel of table I contribute to the same experimental signature and moreover are the most relevant ones among the real EW radiation contributions. Finally, in ref. [11] jets coming from vector bosons decay are distinguished from the other jets

Table I. – *Vector boson radiation processes contributing to the considered signatures. In parenthesis vector boson decay channels are specified, 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.*

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

(called matrix element jets) and the latter are always required within the acceptance cuts in order to avoid infrared QCD singularities: this can be considered as a LO prediction of the real contributions which provides at least a first estimate of the effect of real weak corrections to the processes considered. A more detailed description of the calculation of the real contributions can be found in ref. [11]. The numerical results for the real weak corrections to $Z+2$ and $Z+3$ jets are shown in the lower panels of figs. 1 and 2 respectively: as can be seen, the size of these contributions in the tails of the distributions at $\sqrt{s} = 14$ TeV is of order 10–15%.

In conclusion, in refs. [11, 17, 18] the one loop weak Sudakov corrections have been computed to the process $Z + n$ jets (with $n \leq 3$), which is an irreducible Standard Model background to the direct search for New Physics at the LHC in the signatures with multi-jets and missing transverse momentum. At the LHC the effect of virtual weak corrections in the event selections considered is large and it becomes even larger at future proton-proton colliders (where the higher energy allows to look at more and more extreme kinematical regions). Therefore these corrections should be included in theoretical predictions together with the partially compensating contribution of weak boson real radiation that may not be negligible at high energies.

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REFERENCES

[1] Beccaria M., Montagna G., Piccinini F., Renard F. M. and Verzegnassi C., *Phys. Rev. D*, **58** (1998) 093014.
[2] Ciafaloni P. and Comelli D., *Phys. Lett. B*, **446** (1999) 278.
[3] Beccaria M., Ciafaloni P., Comelli D., Renard F. M. and Verzegnassi C., *Phys. Rev. D*, **61** (2000) 073005.
[4] Fadin V. S., Lipatov L. N., Martin A. D. and Melles M., *Phys. Rev. D*, **61** (2000) 094002.
[5] Ciafaloni M., Ciafaloni P. and Comelli D., *Phys. Rev. Lett.*, **84** (2000) 4810.
[6] Ciafaloni M., Ciafaloni P. and Comelli D., *Nucl. Phys. B*, **589** (2000) 359.
[7] Ciafaloni M., Ciafaloni P. and Comelli D., *Phys. Rev. Lett.*, **87** (2001) 211802.
[8] Denner A. and Pozzorini S., *Eur. Phys. J. C*, **18** (2001) 461.
[9] Denner A. and Pozzorini S., *Eur. Phys. J. C*, **21** (2001) 63.
[10] Mangano M. L., Moretti M., Piccinini F., Pittau R. and Polosa A. D., *JHEP*, **07** (2003) 001.
[11] Chiesa M., Montagna G., Barzè L., Moretti M., Nicrosini O., Piccinini F. and Tramontano F., *Phys. Rev. Lett.*, **111** (2013) 121801.
[12] Kuhn J. H., Kulesza A., Pozzorini S. and Schulze M., *Nucl. Phys. B*, **727** (2005) 368.
[13] Kuhn J. H., Kulesza A., Pozzorini S. and Schulze M., *JHEP*, **03** (2006) 059.
[14] Cullen G., Greiner N., Heinrich G., Luisoni G., Mastrolia P., Ossola G., Reiter T. and Tramontano F., *Eur. Phys. J. C*, **72** (2012) 1889.

[15] Actis S., Denner A., Hofer L., Scharf A. and Uccirati S., *JHEP*, **04** (2013) 037.
[16] Pozzorini S., hep-ph/0201077.
[17] Mishra K., Becher T., Barzè L., Chiesa M., Dittmaier S., Garcia i Tormo X., Huss A., Kasprzik T. *et al.*, arXiv:1308.1430 [hep-ph].
[18] Campbell J. M., Hatakeyama K., Huston J., Petriello F., Andersen J., Barzè L., Beauchemin H., Becher T. *et al.*, arXiv:1310.5189 [hep-ph].
[19] Aad G. *et al.* (ATLAS Collaboration), *Phys. Lett. B*, **710** (2012) 67.
[20] Chatrchyan S. *et al.* (CMS Collaboration), *JHEP*, **08** (2011) 155.
[21] Chatrchyan S. *et al.* (CMS Collaboration), *Phys. Rev. Lett.*, **109** (2012) 171803.
[22] Bicer M.*et al.* (TLEP Design Study Working Group Collaboration), *JHEP*, **01** (2014) 164.
[23] Bell G., Kuhn J. H. and Rittinger J., *Eur. Phys. J. C*, **70** (2010) 659.
[24] Stirling W. J. and Vryonidou E., *JHEP*, **04** (2013) 155.
[25] Baur U., *Phys. Rev. D*, **75** (2007) 013005.