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# Parton-shower matching for electroweak corrections

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**Abstract**

The matching of next-to-leading order (NLO) QCD calculations to parton showers is the state of the art for precision predictions in LHC phenomenology. Following the POWHEG method, we extend this matching procedure to include NLO electroweak (EW) corrections within the Standard Model. The matching also implies a consistent treatment of photons, which can be emitted either as real radiation in the NLO calculation or as part of the parton-shower simulation which includes multiple photon emissions. Presenting the parton-level results in terms of events, the EW corrections can be employed in LHC analyses in a standard way by feeding them to a parton shower. The method has been applied to the Drell-Yan process, a standard candle at the LHC.

*Keywords:* LHC phenomenology, electroweak corrections, parton-shower matching

## 1. Introduction

Predictions for LHC phenomenology are constantly improved. During recent years, next-to-leading order (NLO) QCD corrections have become available even for multi-leg final states. As a further improvement, the available NLO precision for inclusive observables can be combined with the leading-log resummation of parton showers. Since radiation can be generated by the real-emission contribution within the NLO calculation as well as by parton splittings within the parton-shower simulation, double counting has to be avoided. A consistent combination is known as parton-shower matching [1, 2]. In the following, we consider the POWHEG method [1].

Besides the dominant QCD effects, electroweak (EW) corrections can also play an important role for LHC phenomenology. For precision measurements, even the generically expected percent-level corrections due to EW corrections have to be taken into account. Moreover, EW corrections can be logarithmically enhanced. In particular, the LHC probes the so-called Sudakov regime where EW corrections for high-energy reactions with large Mandelstam $s$ include Sudakov-double logarithms $\log^2(M_V^2/s)$ due to loop-diagrams with weak bosons of mass $M_V$. At TeV energies, which are made available by the LHC for the first time, these corrections can amount up to several tens of percent, depending on the process under consideration. The other source of large EW logarithms is due to final-state radiation of photons. In particular, if leptons are defined as bare objects without any jet-like lepton–photon recombination, the small lepton mass can appear as the argument of logarithms. While the weak Sudakov logarithms are due to virtual corrections, the photonic corrections are approximated by a parton shower which includes photon radiation. Here, we aim at generalizing the POWHEG method to include EW corrections. By properly extending the matching procedure, one can include all virtual corrections in the Standard Model as well as all photonic effects in a consistent way. As an additional benefit, the POWHEG method allows to present the results in terms of events. Hence, the calculated EW corrections are made available in a form which can be easily used for experimental analyses.

For the Drell-Yan process, POWHEG matching including EW corrections has already been investigated by other groups [3, 4]. For the matching, an NLO calculation for the physical final state is needed. In recent years, quite a few of these calculations have become available [5–11] for final states including the leptons from weak boson decays. Hence, applications beyond the Drell-Yan process are within reach.

In the following section, we report on work in progress [12–14] for parton-shower matching including EW corrections using the POWHEG method.

## 2. Using the POWHEG method for EW corrections

The POWHEG method is discussed in great detail in Ref. [1], where the POWHEG formula

$$\mathrm{d}\sigma = \mathrm{d}\sigma_{\mathrm{NLO}} \left[ \Delta(p_T^{\min}) + \Delta(p_T) \frac{R(\Phi_{n+1})}{B(\Phi_n)} \mathrm{d}\Phi_{\mathrm{rad}} \right] \quad (1)$$

is introduced. To achieve NLO accuracy, the differential NLO cross section $\mathrm{d}\sigma_{\mathrm{NLO}}$ replaces the Born cross section in a standard parton shower. Moreover, the ratio of the full real-emission matrix element $R$ and the Born matrix element $B$ replaces the splitting function to describe the hardest emission with respect to transverse momentum $p_T$. Also the Sudakov form factor $\Delta(p_T)$, i.e. the probability to have no emission down to a given $p_T$, has to be based on the same ratio of matrix elements. It is well-known how to generate events based on Eq. (1) and how to shower these events consistently [1].

The NLO cross section

$$\mathrm{d}\sigma_{\mathrm{NLO}} = \bar{B}(\Phi_n)\,\mathrm{d}\Phi_n = \left( B + V + \int \mathrm{d}\Phi_{\mathrm{rad}}\,\mathrm{R} \right) \mathrm{d}\Phi_n$$

is differential with respect to the complete Born phase space $\Phi_n$ of the $n$-particle final state and includes the Born contribution $B$, the virtual corrections $V$ and the real-emission matrix elements $R$ integrated over the radiation phase space $\Phi_{\mathrm{rad}}$.

To include EW corrections, the corresponding virtual corrections and the contributions due to real photon emission have to be included in the $\bar{B}$-function in addition to the QCD contributions. For the neutral-current Drell-Yan process, $pp \to l^+l^-$, we have used virtual and real matrix elements which have been extensively tested against the calculation of Ref. [15]. To consistently describe the Z-boson resonance at NLO with respect to the EW corrections, we have employed the complex-mass scheme [16]. Concerning QCD, there is only initial-state radiation in the Drell-Yan process. Including EW corrections, also final-state radiation due to photon emission from the charged leptons has to be considered.

A general framework for QCD applications using the POWHEG method has been made available as the POWHEG BOX [17]. The POWHEG BOX is a Fortran code which only needs the matrix elements and the flavor structures, i.e. information on the external particles, of the considered process as input. Given this input, the generation of events according to Eq. (1) is performed automatically.

We have chosen different approaches to obtain a parton-shower matched calculation including EW corrections for the neutral-current Drell-Yan process. One approach is based on modifying the POWHEG BOX.

The virtual EW corrections can be easily added. For real emissions, the POWHEG BOX uses the FKS method [18] due to Frixione, Kunszt, and Signer to define the radiation phase space and to associate each emission consistently to one emitting particle. In addition to colored particles as the standard source of (QCD) radiation, also charged leptons have to be considered as possible sources of (photon) radiation. Of course, color has to be replaced by charge in all relevant formulae inside the POWHEG BOX for the generation of photon radiation and the fine-structure constant $\alpha$ replaces the strong coupling constant $\alpha_s$. Since the running of $\alpha$ can be neglected as a good approximation, the evaluation of the Sudakov form factors is adapted accordingly. Using a modified POWHEG BOX, we have successfully generated events including photon emission which can be compared before parton showering to our fixed-order results at NLO. In Fig. 1 [14], we show the EW corrections to the invariant-mass distribution of the two final-state leptons at the LHC. Here, no QCD effects are considered. We use the $G_\mu$ scheme to define $\alpha$ and recombine leptons and photons within a small cone of size $\Delta R = 0.1$. The EW corrections hardly depend on the LHC energy, the PDF or scale choices. The lower tail of this invariant-mass distribution is enhanced by hard final-state radiation from events at the Z-boson peak. Since hard multi-photon radiation is a small effect, the difference between the POWHEG and the fixed-order result is minor.

A second approach is based on the Catani-Seymour (CS) dipole subtraction formalism [19] which has also been introduced in the context of the POWHEG method [1]. Our NLO calculation of the EW corrections has been performed using CS. Employing this calculation, we have created an independent implementation of the POWHEG method.

Starting from a Born phase-space point, we use an inverse dipole mapping of CS to define the radiation phase space for a given particle emitting a photon. To calculate the subtracted real-emission matrix element in CS, all dipoles are needed for each phase-space point. However, the dipoles are associated to different Born phase-space points via the dipole mappings. Only the dipole whose inverse mapping is used to define the radiation phase space is mapped back to the original Born phase-space point. Hence, the calculation of a local K-factor for a given Born phase-space point in our CS approach needs additional considerations.

In contrast to FKS, CS is designed to work independently of the method to generate the real-emission phase space. Hence, it necessarily has to associate different Born configurations to a given real-emission phase-space point, which can have different singular limits. FKS, in contrast, is based on particular phase-space parameterizations of the singular limits. Each parameterization covers one singular limit using plus-distributions to isolate the singularities. The necessary partitioning of the phase space into singular regions is rather arbitrary (as long as there is only one singular limit per region).

To recover the local K-factor within CS, we have to use an analog of the phase-space partitioning in FKS. Therefore, we generate a phase space for each inverse dipole mapping. To avoid double counting we use a projection of the real-emission matrix element, which is based on the dipoles themselves. It is designed so that, in singular regions, the matrix element is projected onto the dipole which is used for generating the given radiation phase-space. Hence, only this dipole is needed for subtraction and the local K-factor can be established. However, in our approach, the computational effort is rather large. For each dipole, one has to generate a radiation phase-space point. In turn at each of those points, all the dipoles are needed to calculate the projected matrix element. For Drell-Yan, the computational cost is, of course, manageable and we have been able to reproduce the results obtained within the POWHEG BOX. However, for more complicated processes, the prospects of our CS-based approach are questionable. For independent cross-checks of our POWHEG BOX implementation, it is indeed more promising to set up the NLO calculation using the FKS method and to use the POWHEG method based on this FKS calculation.

To summarize, using the POWHEG method, we have included EW corrections into an NLO calculation which is matched to a parton shower including photon radiation for the Drell-Yan process. In the future, the method can also be applied to other processes where the NLO EW corrections are available.

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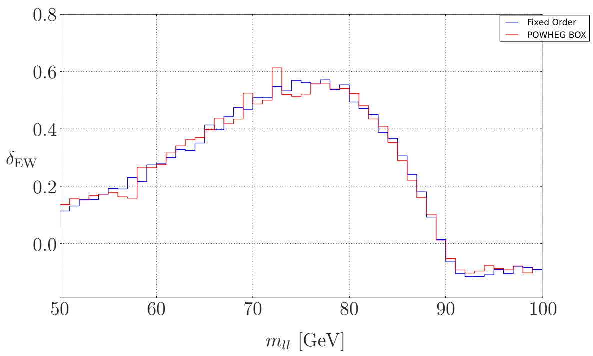


Figure 1: Relative EW corrections $\delta_{\rm EW}$ to the invariant-mass distribution of the lepton pair in the neutral-current Drell-Yan process [14] at NLO and using a modified POWHEG BOX. Photons and leptons with $\Delta R < 0.1$ are recombined.

## References


[1] S. Frixione, P. Nason and C. Oleari, JHEP **0711** (2007) 070 [arXiv:0709.2092 [hep-ph]].

[2] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.-S. Shao and T. Stelzer *et al.*, JHEP **1407** (2014) 079 [arXiv:1405.0301 [hep-ph]] and references therein.

[3] C. Bernaciak and D. Wackeroth, Phys. Rev. D **85** (2012) 093003 [arXiv:1201.4804 [hep-ph]].

[4] L. Barze, G. Montagna, P. Nason, O. Nicrosini and F. Piccinini, JHEP **1204** (2012) 037 [arXiv:1202.0465 [hep-ph]].

[5] M. Ciccolini, A. Denner and S. Dittmaier, Phys. Rev. Lett. **99** (2007) 161803 [arXiv:0707.0381 [hep-ph]].

[6] A. Bredenstein, A. Denner, S. Dittmaier and M. M. Weber, JHEP **0702** (2007) 080 [hep-ph/0611234].

[7] S. Brensing, S. Dittmaier, M. Krämer and A. Mück, Phys. Rev. D **77** (2008) 073006 [arXiv:0710.3309 [hep-ph]].

[8] A. Denner, S. Dittmaier, T. Kasprzik and A. Mück, JHEP **0908** (2009) 075 [arXiv:0906.1656 [hep-ph]].

[9] A. Denner, S. Dittmaier, T. Kasprzik and A. Mück, JHEP **1106** (2011) 069 [arXiv:1103.0914 [hep-ph]].

[10] A. Denner, S. Dittmaier, S. Kallweit and A. Mück, JHEP **1203** (2012) 075 [arXiv:1112.5142 [hep-ph]].

[11] S. Kallweit, J. M. Lindert, P. Maierhöfer, S. Pozzorini and M. Schönherr, arXiv:1412.5157 [hep-ph].

[12] M. Kraus, A. Mück, L. Oymanns and C. Weiss, work in progress.

[13] M. Kraus, Master Thesis RWTH Aachen University, "The POWHEG method using Catani-Seymour subtraction for electroweak corrections".

[14] C. Weiss, Master Thesis RWTH Aachen University, "Electroweak Corrections in the POWHEG BOX".

[15] S. Dittmaier and M. Huber, JHEP **1001** (2010) 060 [arXiv:0911.2329 [hep-ph]].

[16] A. Denner, S. Dittmaier, M. Roth, L. H. Wieders, Nucl. Phys. B **724** (2005) 247 [hep-ph/0505042].

[17] S. Alioli, P. Nason, C. Oleari and E. Re, JHEP **1006** (2010) 043 [arXiv:1002.2581 [hep-ph]].

[18] S. Frixione, Z. Kunszt and A. Signer, Nucl. Phys. B **467** (1996) 399 [hep-ph/9512328].

[19] S. Catani and M. H. Seymour, Nucl. Phys. B **485** (1997) 291 [Erratum-ibid. B **510** (1998) 503] [hep-ph/9605323].