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Electroweak corrections to large transverse momentum production of W bosons at the LHC

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Abstract

To match the precision of present and future measurements of W-boson production at hadron colliders, electroweak radiative corrections must be included in the theory predictions. In this Letter we consider their effect on the transverse momentum (p_{T}) distribution of W bosons, with emphasis on large p_{T}. We evaluate the full electroweak $\mathcal{O}(\alpha)$ corrections to the process $pp \to Wj$ including virtual and real photonic contributions. We also provide compact approximate expressions which are valid in the high-energy region, where the electroweak corrections are strongly enhanced by logarithms of $\hat{s}/M_W^2$. These expressions include quadratic and single logarithms at one loop as well as quartic and triple logarithms at two loops. Numerical results are presented for proton-proton collisions at 14 TeV. The corrections are negative and their size increases with p_{T}. At the LHC, where transverse momenta of 2 TeV or more can be reached, the one- and two-loop corrections amount up to -40% and $+10\%$, respectively.

1. Introduction

The study of gauge–boson production has been among the primary goals of hadron colliders, starting with the discovery of the W and Z bosons more than two decades ago [1]. The investigation of the production dynamics, strictly predicted by the electroweak theory, constitutes one of the important tests of the Standard Model. Differential distributions of gauge bosons, in rapidity as well as in transverse momentum (p_{T}), have always been the subject of theoretical and experimental studies.

At large p_{T} the final state of the leading-order (LO) process consists of an electroweak gauge boson plus one recoiling jet. The high center-of-mass energy at the Large Hadron Collider (LHC) in combination with the enormous luminosity will allow to explore parton–parton scattering up to energies of several TeV and correspondingly production of gauge bosons with transverse momenta up to 2 TeV or even beyond. In this energy range the electroweak corrections from virtual weak-boson exchange are strongly enhanced, with the dominant terms in L-loop approximation being leading logarithms (LL) of the form $\alpha^L \log^{2L}(\hat{s}/M_W^2)$, next-to-leading logarithms (NLL) of the form $\alpha^L \log^{2L-1}(\hat{s}/M_W^2)$, and so on. These corrections, also known as electroweak Sudakov logarithms, may well amount to several tens of percent [2–7]. A recent survey of the literature on electroweak Sudakov logarithms can be found in Ref. [8]. Specifically, the electroweak corrections to the p_{T} distribution of photons and Z bosons at hadron colliders were studied in Refs. [5,6]. In Ref. [6], it was found that at transverse momenta of $\mathcal{O}(1\ \mathrm{TeV})$ the dominant two-loop contributions to these reactions amount to several percent and must be included to match the precision of the LHC experiments.

In this Letter we study the electroweak corrections to the hadronic production of W bosons at large p_{T}. In contrast to the case of Z and γ production, the contributions from virtual and real photons cannot be separated from the purely weak corrections and will thus be included in our analysis.

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The partonic reactions $\bar{q}q' \to W^\pm g(\gamma)$, $q'g \to W^\pm q(\gamma)$ and $\bar{q}g \to W^\pm \bar{q}'(\gamma)$ with $q = u, d, s, c, b$ are considered. All of them are, however, trivially related by CP- and crossing-symmetry relations. Quark-mass effects are neglected throughout, which allows to incorporate the effect of quark mixing through a simple redefinition of parton distribution functions (see Section 2). The calculation of the virtual corrections is described in Section 3. In this section we also present compact analytic expressions for the high-energy behaviour of the corrections which include quadratic and linear logarithms at one loop as well as quartic and triple logarithms at two loops. The calculation of the real corrections is performed using the dipole subtraction formalism [9–11], as described in Section 4. After convolution with parton distribution functions, we obtain radiatively corrected predictions for p_T distributions of W bosons at the LHC, presented in Section 5. Concerning perturbative QCD, our predictions are based on the lowest order. To obtain realistic absolute cross sections, higher-order QCD corrections [12] must be included. However, the relative rates for W^+, W^- and Z production are expected to be more stable against QCD effects. Therefore, in Section 5 we also study the impact of the electroweak corrections on these ratios.

2. Lowest order and kinematics

The p_T distribution of W bosons in the reactions $h_1h_2 \to W^\pm j$ is given by

$$\frac{d\sigma^{h_1h_2}}{dp_T} = \sum_{i,j,k} \int_0^1 dx_1 \int_0^1 dx_2\, \theta(x_1x_2 - \hat{\tau}_{min}) \times f_{h_1,i}(x_1,\mu^2) f_{h_2,j}(x_2,\mu^2) \frac{d\hat{\sigma}^{ij\to W^\pm k}}{dp_T}, \quad (1)$$

where $\hat{\tau}_{min} = (p_T + m_T)^2/s$, $m_T = \sqrt{p_T^2 + M_W^2}$ and $\sqrt{s}$ is the collider energy. The indices i, j denote initial-state partons and $f_{h_1,i}(x,\mu^2)$, $f_{h_2,j}(x,\mu^2)$ are the corresponding parton distribution functions. $\hat{\sigma}^{ij\to W^\pm k}$ is the partonic cross section for the subprocess $ij \to W^\pm k$ and the sum runs over all i, j, k combinations corresponding to the subprocesses

$$\begin{aligned} &\bar{u}_m d_n \to W^- g, && d_n \bar{u}_m \to W^- g, \\ &g d_n \to W^- u_m, && d_n g \to W^- u_m, \\ &\bar{u}_m g \to W^- \bar{d}_n, && g\bar{u}_m \to W^- \bar{d}_n, \end{aligned} \quad (2)$$

for W^- production, and similarly for W^+ production. The dependence of the partonic cross sections on the flavour indices m, n amounts to an overall factor $|V_{u_m d_n}|^2$. This factor can be easily absorbed in the parton distribution functions of down-type quarks by redefining

$$f_{h,d_m} \to \sum_{n=1}^3 |V_{u_m d_n}|^2 f_{h,d_n}, \qquad f_{h,\bar{d}_m} \to \sum_{n=1}^3 |V_{u_m d_n}|^2 f_{h,\bar{d}_n}. \quad (3)$$

The partonic cross sections can then be computed using a trivial CKM matrix δ_{mn}. The Mandelstam variables for the subprocess $ij \to W^\pm k$ are defined in the standard way

$$\hat{s} = (p_i + p_j)^2, \qquad \hat{t} = (p_i - p_W)^2, \qquad \hat{u} = (p_j - p_W)^2. \quad (4)$$

Momentum conservation implies $\hat{s} + \hat{t} + \hat{u} = M_W^2$, and the invariants are related to the collider energy s and the transverse momentum p_T by $p_T^2 = \hat{t}\hat{u}/\hat{s}$ with $\hat{s} = x_1x_2s$.

The p_T distribution for the unpolarized partonic subprocess $ij \to W^\pm k$ reads

$$\frac{d\hat{\sigma}^{ij\to W^\pm k}}{dp_T} = \frac{p_T}{8\pi N_{ij}\hat{s}|\hat{t} - \hat{u}|}\left[\overline{\sum}|\mathcal{M}^{ij\to W^\pm k}|^2 + (\hat{t} \leftrightarrow \hat{u})\right], \quad (5)$$

where $\overline{\sum} = \frac{1}{4}\sum_{pol}\sum_{col}$ involves the sum over polarization and color as well as the factor 1/4 for averaging over initial-state polarization. The factor $1/N_{ij}$ accounts for the initial-state color average.

The unpolarized squared matrix elements for all partonic processes relevant for W^+ and W^- production are related by crossing- and CP-symmetry relations. Thus the explicit computation of the unpolarized squared matrix element needs to be performed only once, e.g. for $\bar{u}d \to W^- g$. For this reaction, to lowest order in α and α_S, we have

$$\overline{\sum}|\mathcal{M}_{Born}^{\bar{u}d\to W^- g}|^2 = 32\pi^2 \frac{\alpha}{s_w^2}\alpha_S \frac{\hat{t}^2 + \hat{u}^2 + 2M_W^2\hat{s}}{\hat{t}\hat{u}}, \quad (6)$$

where $s_w = \sqrt{1 - c_{w^2}}$ denotes the sine of the weak mixing angle.

3. Virtual corrections

The one-loop diagrams were reduced to a minimal set of coupling structures, standard matrix elements and scalar integrals as in Ref. [6]. The electroweak coupling constants were renormalized in the G_μ-scheme, where $\alpha = \sqrt{2}G_\mu M_W^2 s_w^2/\pi$ is expressed in terms of the Fermi constant G_μ and $s_w^2 = 1 - M_W^2/M_Z^2$. Soft and collinear singularities resulting from virtual photons were regularized and combined with corresponding singularities from real photons as described in Section 4. Complete analytic results for the one-loop corrections and their asymptotic behaviour will be provided in Ref. [13]. The numerical evaluation and detailed cross checks were performed with two independent programs. For the scalar loop integrals we used the Fortran library [14] and the FF library [15].

In the following, we present compact analytic expressions for the one- and two-loop NLL contributions at high energy. As in the case of Z and γ production [6], the NLL terms are obtained from the Born result by multiplication with a global factor. For the process $\bar{u}d \to W^- g$ we have

$$\overline{\sum}|\mathcal{M}^{\bar{u}d\to W^- g}|^2 = \overline{\sum}|\mathcal{M}_{Born}^{\bar{u}d\to W^- g}|^2\left[1 + \left(\frac{\alpha}{2\pi}\right)A^{(1)} + \left(\frac{\alpha}{2\pi}\right)^2 A^{(2)}\right]. \quad (7)$$