LEPTON CHARGE ASYMMETRY FROM W DECAYS AT HADRON COLLIDERS IN NNLO QCD

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We present the next-to-next-to-leading order (NNLO) QCD computation of the charged leptons asymmetry from $W^{\pm}$ boson decays in hadron collisions. Our calculation includes the dependence on the lepton kinematical cuts applied in actual experimental analyses. We compare numerical results on the charge asymmetry in $p\bar{p}$ collisions with some of the available Tevatron data. We show illustrative results for the asymmetry in pp collisions at LHC energy.

1 Introduction

The asymmetry in the rapidity distribution of charged leptons from $W^{\pm}$ decay is an important observable at hadron colliders [a]. In $p\bar{p}$ collisions, the W^+ and W^- bosons are produced with equal rates; however, the W^+ tends to be produced along the proton beam direction (i.e. at positive rapidity) and the W^- along the antiproton direction (i.e. at negative rapidity). In pp collisions, W production is forward–backward symmetric; however, the W^- production rate is smaller than the W^+ production rate and, moreover, the W^- is mostly produced at central rapidities, while the W^+ is mostly produced at larger rapidities.

These W^+/W^- asymmetries are related to the proton content of u and d quarks and, in particular, to the fact that u quarks carry, on average, a larger fraction of the proton's momentum than d quarks. Therefore the W boson charge asymmetries provide important quantitative information on the u and d quark momentum distribution in the proton [1].

At hadron colliders, the produced W bosons are identified by their leptonic decay $W \to l\nu_l$. Since the longitudinal component of the neutrino momentum is unmeasured, what is actually measured is the rapidity of the charged lepton and the corresponding lepton charge asymmetry [b], which is defined as

$$A_{h_1h_2}(y_l) = \frac{d\sigma_{h_1h_2}(l^+)/dy_l \ - \ d\sigma_{h_1h_2}(l^-)/dy_l}{d\sigma_{h_1h_2}(l^+)/dy_l \ + \ d\sigma_{h_1h_2}(l^-)/dy_l} \ , \tag{1}$$

where h_1 and h_2 label the two incoming hadrons and $d\sigma_{h_1h_2}(l^{\pm})/dy_l$ is the charged lepton ($l^{\pm}$) rapidity (y_l) distribution.

In actual experimental determinations, the measured rapidity cross sections and charge asymmetries depend on the kinematical cuts and variables that are used to identify and select the observed $W \to l\nu_l$ events. Our computation of the lepton charge asymmetry is carried

[a] We consider the charged leptons in the massless approximation, thus the lepton rapidity y_l coincides with the pseudorapidity η_l.

[b] A direct determination of the W charge asymmetry has recently been presented by the CDF collaboration [2].

out by using the partonic Monte Carlo program `DYNNLO` [3], which encodes the NNLO radiative corrections to the Drell-Yan process at the fully-differential level[c]. This allows us to compute the lepton charge asymmetry by including the kinematical cuts applied in experimental analyses [5].

Our N^{n}LO (with $n = 0, 1, 2$) computation uses the expression of $\alpha_S(\mu_R^2)$ at the n-th order (i.e., we use the μ_R dependence at the level of $(n + 1)$ loops), and it is consistently convoluted with parton densities at each corresponding order. The reference value of $\alpha_S(M_Z)$ is fixed at the actual value used in the corresponding set of parton densities. We consider finite-width effects, treating the W boson off shell, and we include the spin correlations of the W leptonic decay. The values of the electroweak parameters used in our computation can be found in Ref. [5].

Since our main purpose is the study of asymmetries up to NNLO QCD, we consider only the parton distribution function (PDF) sets of Refs. [6], [7] and [8] which include NNLO parton densities with $N_f = 5$ (effectively) massless quarks. Among these PDFs sets only the global fit of Ref. [6] includes some data on the lepton charge asymmetry at the Tevatron: the ensuing parton densities are thus expected to produce better agreement with available measurements of charge asymmetries.

2 Charged lepton asymmetry at the Tevatron

In the following we present our perturbative QCD calculations up to NNLO, and their comparison with some of the published Tevatron data. We note that our calculation is invariant under CP transformations. Therefore, in $p\bar{p}$ collisions, the charge asymmetry fulfils $A_{p\bar{p}}(-y) = -A_{p\bar{p}}(y)$.

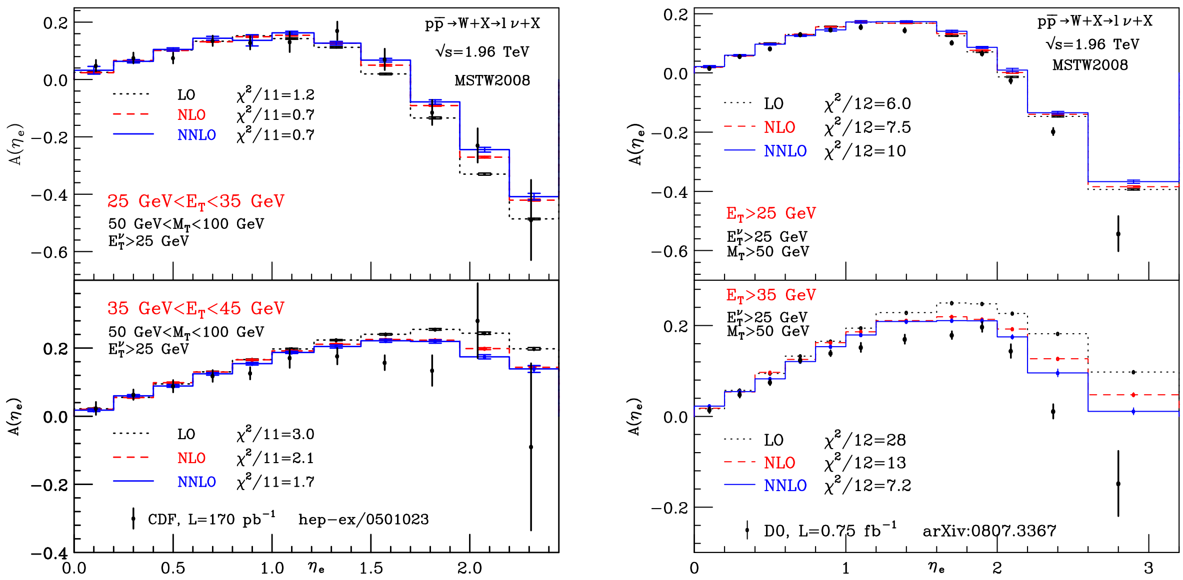
We first consider the electron charge asymmetry in the experimental configuration of the CDF data at the Tevatron Run II [9]. The events are required to have a missing transverse energy $E_T^\nu > 25$ GeV and a transverse mass 50 GeV $< M_T <$ 100 GeV. The charged lepton must be in the central rapidity region ($|y_l| \leq 2.45$) and must be isolated[d] i.e. $E_T^{\rm iso}/E_T < 0.1$, where $E_T^{\rm iso}$ is the hadronic (partonic) transverse energy in a cone of radius $R = 0.4$ (in pseudorapidity–azimuth space) along the lepton momentum and E_T is the electron transverse energy. Following the experimental analysis we consider two kinematical region of the electron transverse energy: 25 GeV $< E_T <$ 35 GeV (low-E_T) and 35 GeV $< E_T <$ 45 GeV (high-E_T).

In Fig. 1(a) we report the CDF data and present the results of our LO, NLO and NNLO results using the corresponding parton densities from the MSTW2008 Collaboration [6], which include the CDF data [9] in their fit. At small values of η_e, the radiative corrections lead to little effects. In the low-E_T bin, as η_e increases, both the NLO and NNLO effects slightly increase the value of the asymmetry. In the high-E_T bin, as η_e increases, the NLO and NNLO effects are negative and the asymmetry slightly decreases. The NNLO effects are not yet quantitatively relevant in comparison with the size of the experimental uncertainties. The data are well fitted by the MSTW2008 NNLO partons, especially in the low-E_T region, this is confirmed by the values of χ^2 from the comparison of the data with the QCD calculations reported in Fig. 1(a).

We then consider the D0 data for the electron charge asymmetry [10] at the Tevatron Run II. The D0 measurement extends to high rapidities, $|\eta_e| \leq 3.2$, the missing transverse energy is required to be $E_T^\nu > 25$ GeV and the transverse mass to be $M_T > 50$ GeV. As for lepton isolation the D0 procedure is similar to the CDF one, with the requirement $E_T^{\rm iso}/E_T < 0.15$. We examine two regions of electron transverse energy: $E_T > 25$ GeV (wide E_T region) and $E_T > 35$ GeV (high-E_T region). Let us note that the D0 electron asymmetry data [10] are not included in the MSTW PDF fit [6]: their inclusion in the global analysis does not permit to obtain a good quality fit, with significant tension between the D0 electron asymmetry data and other data.

[c] This Monte Carlo program is based on the NNLO subtraction method introduced in Ref. [4].

[d] The charged lepton isolation has a small impact on our results, since it is not effective at the leading order and the radiative corrections are not large.



(a) (b)

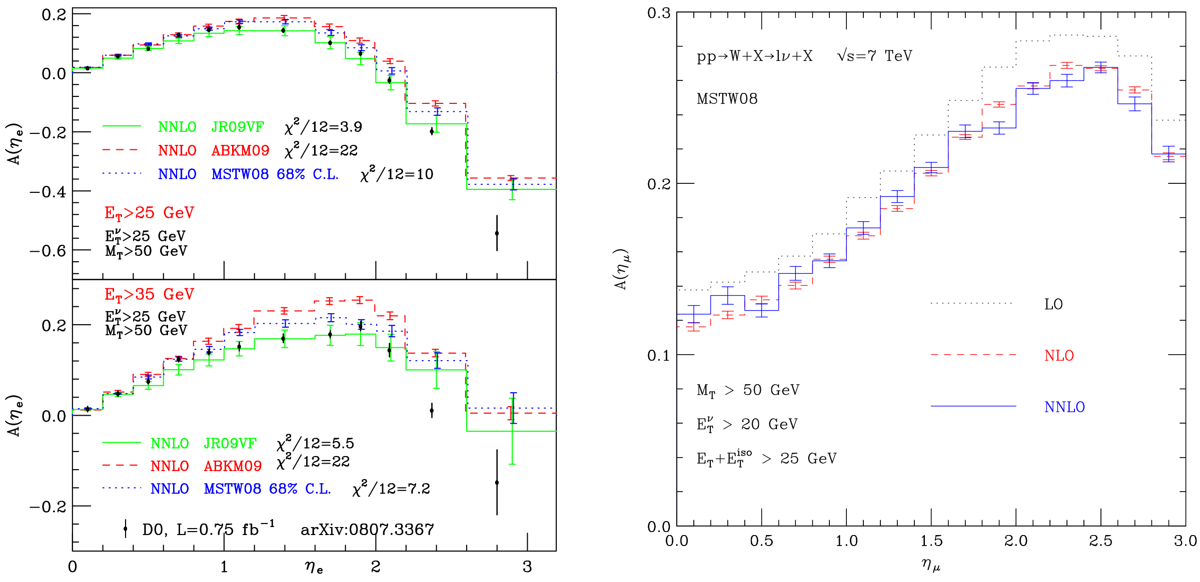
Figure 1: Electron charge asymmetry up to NNLO compared to a) CDF data in the lower E_T region (upper panel) and higher E_T region (lower panel); b) D0 data in the wide E_T region (upper panel) and (high-E_T) region.

In Fig. 1(b) we display the D0 electron data and present the corresponding QCD results at LO, NLO and NNLO using the corresponding MSTW2008 PDFs. In the wide E_T region at high values of the electron rapidity, the effect of the NLO and NNLO corrections is positive and increases the deviation of the QCD results from the D0 data. We see that the agreement between the QCD calculations and the data is poor. This is quantitatively confirmed by the values of χ^2 reported in Fig. 1(b). We note that the value of χ^2 increases in going from LO to NLO and to NNLO. In the high-E_T region (as in the case of the high-E_T bin in Fig. 1(a)) the effect of the NLO and NNLO corrections is negative as the lepton rapidity increases toward high values. This effect reduces the difference between the QCD calculations and the D0 data, although a substantial disagreement between them still persists at the NNLO. The value of χ^2 decreases in going from LO to NLO and to NNLO.

The NNLO results of Fig. 1(b) are reported in Fig. 2(a) by including the PDF errors (68% C.L.) from the MSTW2008 [6], ABKM09 [7] and JR09VF [8] set of PDFs. The ABKM09 PDF errors are slightly smaller than the errors of the MSTW2008 set and the ABKM09 result tends to overshoot the MSTW2008 result. The JR09VF PDF errors are larger than the PDF errors of the MSTW2008 set and the JR09VF result tends to undershoot the MSTW2008 result in most of the rapidity bins. The PDF errors are comparable to (or, larger than) the D0 experimental errors; the inclusion of the PDF errors thus reduces the differences between the NNLO results and the D0 electron data, although a substantial disagreement can be noticed from the value of χ^2 for different sets of PDFs reported in Fig. 2(a).

3 Charged lepton asymmetry at the LHC

We now consider pp collisions and we present results of our QCD calculations at the centre–of–mass energy $\sqrt{s} = 7$ TeV. The lepton charge asymmetry at the LHC is sensitive to parton densities with momentum fractions that are smaller than those probed at the Tevatron. To the purpose of presenting some quantitative, though illustrative, results on the lepton asymmetry at the LHC, we refer to the framework considered in a recent 'Physics Analysis' [11] of the CMS Collaboration. The study of Ref. [11], based on data sets from Monte Carlo simulations, regards



(a) (b)

Figure 2: a) Electron charge asymmetry at NNLO with PDF uncertainties compared to D0 data in the lower E_T region (upper panel) and higher E_T region (lower panel); b) Muon charge asymmetry up to NNLO at the LHC.

the muon rapidity cross sections and charge asymmetry that can be measured with the CMS detector at the LHC. The lepton selection cuts applied in Ref.[11] require the transverse mass and the missing transverse energy to be $M_T > 50$ GeV and $E_T^\nu > 20$ GeV, respectively. The muons are isolated: the hadronic (partonic) transverse energy $E_T^{\rm iso}$ in a cone of radius $R = 0.3$ is required to fulfil the constraints $E_T^{\rm iso}/E_T < z/(1-z)$ with $z = 0.05$, and $E_T + E_T^{\rm iso} > E_T^{\rm max} = 25$ GeV.

The results for the lepton charge asymmetry at $\sqrt{s} = 7$ TeV are presented in Fig. 2(b). The three histograms show the LO, NLO and NNLO results of our calculation with the MSTW2008 parton densities. Considering the effect of the QCD radiative corrections, we see that, the NLO corrections tend to decrease the asymmetry, and the NNLO corrections do not significantly change the NLO result thus indicating a very good quantitative convergence of the truncated perturbative expansion.

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