EW One-Loop Corrections to the Longitudinally Polarized Drell–Yan Scattering. (I) The Neutral Current Case

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Abstract—Complete one-loop electroweak corrections to neutral current Drell–Yan process $pp \rightarrow \ell^+ \ell^- X$ are presented for the case of longitudinal polarization of initial particles. The single- and double-spin asymmetries under study allow us to extract information about polarized parton distribution functions. Numerical impact of electroweak next-order corrections to asymmetries as function of the vector boson rapidity and lepton pseudorapidities in the hadron-hadron centre-of-mass frame using the MC generator ReneSANCe is thoroughly studied.

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1. INTRODUCTION

Theoretical calculations of one-loop QED and electroweak (EW) radiative corrections (RC) for Drell–Yan (DY) [1] processes at high energy hadronic colliders were performed by several groups, see [2–10] and references therein.

The measurement of the DY cross section in polarized hadron-hadron collisions would provide important information about the polarization of the quark sea in the nucleon which is currently analyzed only from the deep inelastic scattering data experiments, such as $l^-p$ scattering at HERA, SMC spin-muon collaborations at CERN and etc. Computer codes relevant for the description of polarized processes for these experiments were created in our group, namely, the Mµ code [11] for investigation of the spin dependent structure function $g_1(x)$ of the deuteron from polarized deep inelastic muon scattering [12], and the polHECTOR code [13] for deep inelastic scattering with longitudinally and transversely polarized nucleon for the HERMES experiment in HERA. The weak corrections were small and neglected.

The Relativistic Heavy-Ion Collider (RHIC) is the only high-energy spin-polarized proton facility ever built with a working longitudinally polarized mode. Currently available 93 pb$^{-1}$ of data for longitudinally polarized $p + p$ collisions at $\sqrt{s} = 200$ GeV (from 2009 and 2015 runs by PHENIX and STAR experiments at RHIC) and 569 pb$^{-1}$ at $\sqrt{s} = 510$ GeV (from 2012 and 2013 runs by PHENIX and STAR) [14, 15]. To increase the accuracy of extracting polarized parton distribution functions (PDFs), the possibility of collecting an additional 1.1 fb$^{-1}$ at an energy of 510 GeV in 2023–2025 is being considered.

xFitter [16, 17] is a well known software package for the determination of the PDFs. It incorporates experimental data from a wide range of experiments including fixed-target, Tevatron, HERA, and LHC data sets. xFitter can analyze this data using theoretical predictions. We started this work taking into account xFitter’s team interest in polarized PDFs fitting.

The research of longitudinally polarized proton-proton collisions at the QCD level has been carried out in several papers. The most important works for the longitudinally polarized DY process at QCD level are: complete analytical results for mass differential Drell–Yan type cross-sections [18, 19], investigation of the lepton helicity distributions [20, 21], complete calculations of the $O(\alpha_s)$ corrections in the MS–scheme [22], study of double and single spin asymmetries [23].

This article is the next step in the series of papers devoted to DY processes in $pp$ mode in Monte Carlo (MC) generator ReneSANCe [24] and integrator MCSANC [25–27]. In the last one, we presented description of implementation DY processes to simulate processes at hadron-hadron colliders with allowance for electroweak (EW) and QCD corrections with the next-to-leading order (NLO) accuracy and also higher-order EW corrections through $\Delta \rho$ parameter. In this paper we show results of NLO EW corrections for the neutral current (NC) massive lepton pair production in longitudinally polarized proton-proton collisions obtained by the MC event generator ReneSANCe:

$$pp \rightarrow Z/\gamma^* X \rightarrow \ell^+ \ell^- X.$$  (1)
We introduce the following combinations of fully polarized components of the hadron-hadron cross section $\sigma^{++}, \sigma^{+-}, \sigma^{-+}, \sigma^{--}$:

$$\sigma = \frac{1}{4} \left( \sigma^{++} + \sigma^{+-} + \sigma^{-+} + \sigma^{--} \right),$$  \hspace{1cm} (5)

$$\Delta\sigma_L = \frac{1}{4} \left( \sigma^{++} + \sigma^{+-} - \sigma^{-+} - \sigma^{--} \right),$$  \hspace{1cm} (6)

$$\Delta\sigma_{LL} = \frac{1}{4} \left( \sigma^{--} - \sigma^{++} - \sigma^{-+} + \sigma^{+-} \right),$$  \hspace{1cm} (7)

where $\sigma$ corresponds to unpolarized cross section.

We use following definitions for the single-spin asymmetry

$$A_L(I) = \frac{\Delta d\sigma_L(I)/dI}{d\sigma/I},$$  \hspace{1cm} (8)

and for the double-spin asymmetry

$$A_{LL}(I) = \frac{\Delta d\sigma_{LL}(I)/dI}{d\sigma/I}.$$  \hspace{1cm} (9)

Variable $I$ is the $Z$ boson rapidity

$$y_z = \frac{1}{2} \ln \left( \frac{E_{\ell^+} + p_{\ell^+}^z}{E_{\ell^-} - p_{\ell^-}^z} \right).$$  \hspace{1cm} (10)

($E_{\ell^\pm}$ and $p_{\ell^\pm}^z$ are the energy and $z$-component of a momentum of the $\ell^+\ell^-$ pair in the laboratory frame) or the lepton pseudorapidity

$$\eta_{\ell^\pm} = -\ln \tan \frac{\vartheta_{\ell^\pm}}{2}.$$  \hspace{1cm} (11)

Here $\vartheta_{\ell^\pm}$ is the angle of the $\ell^\pm$ in the laboratory frame. The $z$ axis is directed along the momentum of the first proton.

3. NUMERICAL RESULTS

3.1. Input Parameters

Numerical calculations were performed in the $\alpha(0)$ scheme at $\sqrt{s} = 500$ GeV and the following set of input parameters was used:

$$\alpha_s^{-1}(0) = 137.035999084,$$

$$G_F = 1.1663787 \times 10^{-5} \text{ GeV}^{-2},$$

$$M_W = 80.379 \text{ GeV, } M_Z = 91.1876 \text{ GeV},$$

$$M_H = 125.25 \text{ GeV, }$$

$$\Gamma_W = 2.085 \text{ GeV, } \Gamma_Z = 2.4952 \text{ GeV, }$$

$$|V_{ud}| = 0.9737, \quad |V_{us}| = 0.2252,$$

$$|V_{cb}| = 0.221, \quad |V_{cs}| = 0.987, \quad |V_{ub}| = 0, \quad |V_{ub}| = 0,$$

$$m_c = 0.51099895 \text{ MeV, }$$

$$m_t = 1.17686 \text{ GeV, }$$

$$m_d = 0.066 \text{ GeV, } m_u = 0.066 \text{ GeV, }$$

$$m_s = 0.15 \text{ GeV, } m_c = 1.67 \text{ GeV, }$$

$$m_b = 4.78 \text{ GeV, } m_t = 172.76 \text{ GeV.}$$
The values of the parameters were taken from PDG-2020 [31], except for the masses of light quarks ($u$, $d$ and $s$) which were chosen as in [32]. We used the NNPDF23_nlo_as_0119 [33] PDF set for unpolarized parton distributions, and the NNPDFpol11_100 [34] PDF set for longitudinally polarized parton distributions via LHAPDF6 [35] library with factorization scale $\mu_F = M_{\ell\ell}$.

Following cuts were also applied:

\[
p_L(\mu^\pm) > 25 \text{ GeV}, \quad |\eta(\mu^\pm)| < 2.5,
\]
\[
M(\mu^+\mu^-) > 50 \text{ GeV}.
\]

3.2. Differential Distributions

We demonstrate numerical calculations for the $Z$ boson rapidity $y_z$ and lepton pseudorapidities $\eta_{\ell^\pm}$ distributions at the Born (LO) and NLO EW level and corresponding difference $\Delta A = A^{\text{NLO EW}} - A^{\text{LO}}$ for the single-spin asymmetry in Figs. 1–3, for the double-spin asymmetry in Figs. 4–6. The same distributions for cross sections in pb and corresponding relative corrections $\delta$ in % are shown in Figs. 7–9.

A significant contribution of the NLO EW corrections to several distributions is observed. Polarization asymmetries themselves do not change their signs—$A_L$ is always positive while $A_L^{LL}$ is negative in whole kinematic region.

EW radiative corrections strongly depend on kinematic variables and change the sign.

Corrections to $A_L^{LL}$ for rapidity $y_z$ distribution are compatible with zero while for distributions of pseudorapidities $\eta_{\mu^+}$ and $\eta_{\mu^-}$ the corrections are mostly positive and oscillating near mean value of about 1%.

The partial differential cross-sections as a function of rapidity $y_Z$, pseudorapidities $\eta_{\mu^+}$ and $\eta_{\mu^-}$ are sensitive to the polarization of incoming particles. The line 00 shows unpolarized case while other lines are for the 100% polarized beams. One sees that relative corrections $\delta$ are negative and strongly depend on beam polarization, and vary from $-3$ to $-5\%$ in the central region of variable $y_Z$ and from $-12$ to $-20\%$ in the for-
Fig. 3. The same as in Fig. 1 but for the muon $\eta_\mu$ pseudorapidity.

Fig. 4. The $Z$ boson rapidity $y_z$ distribution for the single-spin asymmetry $A_{LL}(y_z)$ at the Born and NLO EW level (left panel) and corresponding difference $\Delta A_{LL}(y_z)$ (right panel).

Fig. 5. The same as in Fig. 4 but for the anti-muon $\eta_{\mu^*}$ pseudorapidity.

Fig. 6. The same as in Fig. 4 but for the muon $\eta_\mu$ pseudorapidity.
4. CONCLUSIONS

In the paper for the first time the study of spin effects at NLO EW level in neutral current Drell–Yan processes in collisions of longitudinally polarized hadrons is presented. We have shown numerical results for observables obtained by MC event generator ReneSANCe. The effects of complete one-loop electroweak radiative corrections to NC DY processes are significant.

Obtained NLO EW corrections can be used for reduction of the systematic uncertainty in measurement of polarized parton distributions.

We also expect a valuable effect of EW radiative corrections in polarized production of charged vector...
boson and plan to study it. Another direction of our investigation is to include effects from transverse momentum-dependent distribution of partons.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

1. S. D. Drell and T. M. Yan, “Massive lepton pair production in hadron–hadron collisions at high-energies,” Phys. Rev. Lett. 25, 316–320 (1970); Erratum: Phys. Rev. Lett. 25, 902 (1970).
2. V. A. Mosolov and N. M. Shumeiko, “Electromagnetic effects in Drell–Yan processes,” Nucl. Phys. B 186, 397–411 (1981).
3. A. V. Soroko and N. M. Shumeiko, “Electromagnetic corrections to Drell–Yan processes in quark parton model,” Yad. Fiz. 52, 329–334 (1990).
4. D. Wackeroth and W. Hollik, “Electroweak radiative corrections to resonant charged gauge boson production,” Phys. Rev. D 55, 6788–6818 (1997). arXiv:hep-ph/9606398.
5. U. Baur, S. Keller, and D. Wackeroth, “Electroweak radiative corrections to W boson production in hadronic collisions,” Phys. Rev. D 59, 013002 (1999). arXiv:hep-ph/9807417.
6. S. Dittmaier and M. Krämer, “Electroweak radiative corrections to W boson production at hadron colliders,” Phys. Rev. D 65, 073007 (2002). arXiv:hep-ph/0109062.
7. U. Baur, O. Brein, W. Hollik, C. Schappacher, and D. Wackeroth, “Electroweak radiative corrections to neutral current Drell–Yan processes at hadron colliders,” Phys. Rev. D 65, 033007 (2002). arXiv:hep-ph/0108274.
8. U. Baur and D. Wackeroth, “Electroweak radiative corrections to weak boson production at hadron colliders,” Nucl. Phys. B Proc. Suppl. 116, 159–163 (2003). arXiv:hep-ph/0211089.
9. U. Baur and D. Wackeroth, “Electroweak radiative corrections to \( p\bar{p} \to W^\pm \to e^\pm\nu \) beyond the pole approximation,” Phys. Rev. D 70, 073015 (2004). arXiv:hep-ph/0405191.
10. C. M. Carloni Calame, G. Montagna, O. Nicrosini, and A. Vicini, “Precision electroweak calculation of the charged current Drell–Yan process,” J. High Energy Phys. 12, 016 (2006). arXiv:hep-ph/0609170.
11. D. Bardin and L. Kalinovskaya, “QED corrections for polarized elastic MU-E scattering,” (1997). arXiv:hep-ph/9712310.
12. D. Adams et al. (Spin Muon (SMC) Collab.), “The spin dependent structure function g_1(x) of the deuteron from polarized deep inelastic muon scattering,” Phys. Lett. B 396, 338–348 (1997).
13. D. Bardin, J. Blumlein, P. Christova, and L. Kalinovskaya, “\( O_\alpha \) QED corrections to neutral current polarized deep inelastic lepton–nucleon scattering,” Nucl. Phys. B 506, 295–328 (1997). arXiv:hep-ph/9612435.
14. E. C. Aschenauer et al., “The RHIC cold QCD plan for 2017 to 2023: A portal to the EIC,” (2016). arXiv:1602.03922.
15. M. Tokarev, “Recent STAR spin results and spin measurements at RHIC,” Phys. Part. Nucl. Lett. 15, 478–491 (2018).
16. S. Alekhin et al., “HERA Fitter,” Eur. Phys. J. C 75, 304 (2015). arXiv:1410.4412 [hep-ph].
17. H. Abdolmaleki et al. [xFitter Collab.], “xFitter: An open source QCD analysis framework. A resource and reference document for the Snowmass study,” (2022). arXiv:2206.12465.
18. B. Kamal, “QCD corrections to spin dependent Drell–Yan and a global subtraction scheme,” Phys. Rev. D 53, 1142–1152 (1996). arXiv:hep-ph/9511217.
19. B. Kamal, “Drell–Yan forward-backward and spin asymmetries for arbitrary vector boson production at next-to-leading order,” Phys. Rev. D 57, 6663–6691 (1998). arXiv:hep-ph/9710374.
20. J. Kodaira and H. Y. okoya, “Lepton helicity distributions in polarized Drell-Yan process,” Phys. Rev. D 67, 074008 (2003). arXiv:hep-ph/0301228.
21. C. Bourrely and J. Soffer, “Parton distributions from W^+ and Z production in polarized p p and p n collisions at RHIC,” Nucl. Phys. B 423, 329–348 (1994). arXiv:hep-ph/9405250.
22. T. Gehrmann, “QCD corrections to the longitudinally polarized Drell-Yan process,” Nucl. Phys. B 498, 245–266 (1997). arXiv:hep-ph/9702263.
23. T. Gehrmann, “QCD corrections to double and single spin asymmetries in vector boson production at polarized hadron colliders,” Nucl. Phys. B 534, 21–39 (1998). arXiv:hep-ph/9710508.
24. S. Bondarenko, Ye. Dydyshka, L. Kalinovskaya, R. Sadikov, and V. Yermolchyk, “Hadron–hadron collision mode in ReneSANCe-v1.3.0,” (2022). arXiv:2207.04332.
25. D. Bardin, S. Bondarenko, P. Christova, L. Kalinovskaya, L. Rumiantssev, A. Saponov, and W. von Schlippe, “SANC integrator in the progress: QCD and EW contributions,” JETP Lett. 96, 285–289 (2012). arXiv:1207.4400 [hep-ph].
26. S. G. Bondarenko and A. A. Saponov, “NLO EW and QCD proton-proton cross section calculations with mcsanc-v1.01,” Comput. Phys. Commun. 184, 2343–2350 (2013). arXiv:1301.3687 [hep-ph].
27. A. Arbuzov, D. Bardin, S. Bondarenko, P. Christova, L. Kalinovskaya, U. Klein, V. Kolesnikov, L. Rumiantssev, R. Sadikov, and A. Saponov, “Update of the MC-
SANC Monte Carlo integrator, v. 1.2.0,” JETP Lett. 103, 131–136 (2016). arXiv:1509.03052.

28. A. Andonov, A. Arbuzov, D. Bardin, S. Bondarenko, P. Christova, L. Kalinovskaya, G. Nanava, and W. von Schlippe, “SANCscope—v.1.00,” Comput. Phys. Commun. 174, 481–517 (2006), Erratum: Comput. Phys. Commun. 177, 623–624 (2007). arXiv:hep-ph/0411186.

29. A. Arbuzov, D. Bardin, S. Bondarenko, P. Christova, L. Kalinovskaya, G. Nanava, and R. Sadykov, “One-loop corrections to the Drell–Yan process in SANC. (II). The neutral current case,” Eur. Phys. J. C 54, 451–460 (2008). arXiv:0711.0625 [hep-ph].

30. A. Arbuzov, D. Bardin, S. Bondarenko, P. Christova, L. Kalinovskaya, G. Nanava, and R. Sadykov, “One-loop corrections to the Drell–Yan process in SANC. (I). The charged current case” Eur. Phys. J. C 46, 407–412 (2006), Erratum: Eur. Phys. J. C 50, 505 (2007). arXiv:hep-ph/0506110.

31. P. A. Zyla et al. (Particle Data Group Collab.), “Review of particle physics.” Prog. Theor. Exp. Phys. 2020, 083C01PTEP (2020).

32. S. Dittmaier and M. Huber, “Radiative corrections to the neutral-current Drell–Yan process in the Standard Model and its minimal supersymmetric extension,” J. High Energy Phys. 01, 060 (2010). arXiv:0911.2329 [hep-ph].

33. R. D. Ball et al., “Parton distributions with LHC data,” Nucl. Phys. B 867, 244–289 (2013). arXiv:1207.1303 [hep-ph].

34. E. R. Nocera et al. (NNPDF Collab.), “A first unbiased global determination of polarized PDFs and their uncertainties,” Nucl. Phys. B 887, 276–308 (2014). arXiv:1406.5539 [hep-ph].

35. A. Buckley, J. Ferrando, S. Lloyd, K. Nordström, B. Page, M. Rüfenacht, M. Schönherr, and G. Watt, “LHAPDF6: parton density access in the LHC precision era,” Eur. Phys. J. C 75, 132 (2015). arXiv:1412.7420 [hep-ph].