Radiative corrections to $W^{\pm}$ hadroproduction with longitudinal polarization of initial states

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MMCP-2024, Yerevan, Armenia
21-25 Oct, 2024

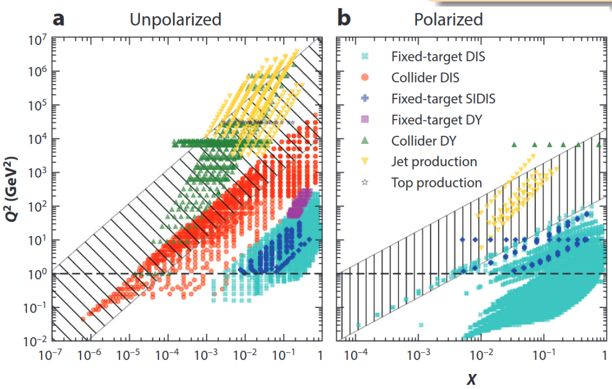
Motivation: global analysis of polarized parton distribution functions

This research **contributes to a global next-to-leading order (NLO) analysis of polarized parton distributions**.

Analysis of all the accumulated data will help us better understand how nucleons are structured.

Upcoming projects

LHeC [arXiv:2007.14491] in CERN, eRHIC [arXiv:1409.1633] is "successor"of RHIC, EIC [website] ...



[arXiv:2001.07722]

$Q^2 = 2xM\nu$,

$\nu = \dfrac{q \cdot P}{M}$.

x – Bjorken variable,
q – transferred momentum,
P – nucleon momentum,
M – nucleon mass.

Motivation: the problem we solved

The problem we solved

We estimated the contribution of one-loop electroweak (EW) radiative corrections to the charged-current Drell-Yan processes $pp \to \ell^+\nu_\ell(+X)$ and $pp \to \ell^-\bar{\nu}_\ell(+X)$ for the case of longitudinal polarization of initial states [arXiv:2405.12692] using `SANC` [arXiv:0812.4207] and `ReneSANCe` [10.1016/j.cpc.2022.108646]. We also have the opportunity to provide QCD radiative corrections at the one-loop level using `MCSANC` [10.1016/j.cpc.2013.05.010] and `ReneSANCe`.
We wanted to test how significant EW contribution is at the RHIC energy of $\sim$ 500 GeV.

Features of charge current Drell-Yan:

- Large scattering cross section;
- Clear experimental signal;
- Absence of hadronic fragmentation;
- $W^\pm$ bosons naturally choose left-quark and right-antiquark orientations $\to$ are good probes of the proton's helicity structure;

RHIC – relativistic heavy ion collider.

- **Location:** Brookhaven National Laboratory, New York;
- **Bunches:** heavy ions, longitudinally polarized protons;
- **Max. energy:** 255 GeV per proton beam, 100 GeV/nucleon in Au ion beam.
- **Luminosity:** $2.45 \times 10^{32}/(\text{cm}^2 \times \text{sec})(pp)$, $1.55 \times 10^{28}/(\text{cm}^2 \times \text{sec})(AuAu)$
- **Collaborations:** STAR and PHENIX.

Hadronic and partonic levels of DY process

Hadronic level

$$d\sigma(\Lambda_1,\Lambda_2,s) = \sum_{q_1 q_2} \sum_{\lambda_1 \lambda_2} \int_0^1 \int_0^1 dx_1 dx_2 f_{q_1}^{\Lambda_1 \lambda_1}(x_1) \times f_{q_2}^{\Lambda_2 \lambda_2}(x_2)\, d\hat{\sigma}_{q_1 q_2}(\lambda_1,\lambda_2,\hat{s})$$

where $\Lambda_i = \pm 1$ and $\lambda_i = \pm 1$ are the helicities of each proton and quark (q_1, q_2), respectively, with $\hat{s} = x_1 x_2 s$.

Parton distribution functions

Parton distributions $f_{q_i}^{\Lambda_i \lambda_i}$ can be obtained from unpolarized f_{q_i} and longitudinally polarized Δf_{q_i} PDFs: $f_{q_i}^{\Lambda_i \lambda_i} = \frac{1}{2}(f_{q_i} + \Lambda_i \lambda_i \Delta f_{q_i})$.

Partonic level

$$\bar{d}(p_1,\lambda_1) + u(p_2,\lambda_2) \to l^+(p_3,\lambda_3) + \nu_l(p_4,\lambda_4)\ (+\gamma(p_5,\lambda_5)),$$
$$\bar{u}(p_1,\lambda_1) + d(p_2,\lambda_2) \to l^-(p_3,\lambda_3) + \bar{\nu}_l(p_4,\lambda_4)\ (+\gamma(p_5,\lambda_5)).$$
$$\hat{\sigma}^{\text{1-loop}} = \hat{\sigma}^{\text{Born}} + \hat{\sigma}^{\text{virt}}(\lambda) + \hat{\sigma}^{\text{soft}}(\lambda,\omega) + \hat{\sigma}^{\text{hard}}(\omega) + \hat{\sigma}^{\text{Subt}}.$$

Helicity amplitudes of virtual contribution

The cross-section is proportional to the square of the helicity amplitudes $\sigma \sim |\mathcal{H}|^2$. For both channels two non-zero HAs survive in the limit with of lepton mass $m_l^2 = 0$.

Virtual contribution $\hat{\sigma}^{\text{virt}}(\lambda)$ in case of W^+-channel:

$$\begin{aligned} \mathcal{H}^{W^+}_{+--+} &= -e^2(1+\cos\vartheta_{23})\chi_W(\hat{s})\frac{1}{\sqrt{\hat{s}}}\mathcal{F}_{LL}, \\ \mathcal{H}^{W^+}_{+---} &= -e^2\sin\vartheta_{23}\chi_W(\hat{s})\left(\frac{m_l}{\hat{s}}\mathcal{F}_{LL}+\mathcal{F}_{LRD}\right); \end{aligned}$$

and for W^--channel:

$$\mathcal{H}^{W^-}_{+--+} = \mathcal{H}^{W^+}_{+--+}, \quad \mathcal{H}^{W^-}_{+-++} = \mathcal{H}^{W^+}_{+---}\left(\mathcal{F}_{LRD}\to\mathcal{F}_{LLD}\right),$$

Helicity amplitudes of hard contribution

Helicity amplitudes of hard contribution $\hat{\sigma}^{\text{hard}}(\omega)$ were calculated using the spinor formalism. They split into the sum of two gauge independent contributions from initial (ISR) and final states radiation (FSR):

$$\mathcal{H}^{\text{hard}} = ie^2 \Big[\frac{\chi_W(\hat{s}_{34})}{\hat{s}_{34}} A^{\text{ISR}} + \frac{\chi_W(\hat{s}_{12})}{\hat{s}_{12}} A^{\text{FSR}} \Big]$$

Contributions from ISR and FSR in massless limit:

$$A^{\text{ISR}}_{+,+-+-} = 2\Big(\frac{Q_1}{z_{15}} - \frac{Q_2}{z_{25}}\Big) \frac{\langle 5|2\rangle \langle 5|1\rangle \langle 3|4\rangle [2|3]^2}{z_{15}+z_{25}},$$

$$A^{\text{FSR}}_{+,+-+-} = 2\Big(\frac{Q_3}{z_{35}} - \frac{Q_4}{z_{45}}\Big) \frac{\langle 5|4\rangle \langle 5|3\rangle \langle 1|2\rangle [2|3]^2}{z_{35}+z_{45}},$$

$$A^{\text{ISR}}_{-,+-+-} = 2\Big(\frac{Q_1}{z_{15}} - \frac{Q_2}{z_{25}}\Big) \frac{[1|5]\,[2|5]\,[3|4] \langle 4|1\rangle^2}{z_{15}+z_{25}},$$

$$A^{\text{FSR}}_{-,+-+-} = 2\Big(\frac{Q_3}{z_{35}} - \frac{Q_4}{z_{45}}\Big) \frac{[3|5]\,[4|5]\,[1|2] \langle 4|1\rangle^2}{z_{35}+z_{45}}.$$

Q_i is the charge of a particle with momentum p_i. $z_{i\dots j} = p^2_{i\dots j} - (m_i + \dots + m_j)^2$, where $p_{i\dots j} = p_i + \dots + p_j$ and $Q_{1234} = 0$. More details about the spinor formalism [arXiv:2211.11467, arXiv:2005.04748].

Other contributions

Two remaining contributions are subtraction of the quark mass singularities and the soft photon Bremsstrahlung $\hat{\sigma}^{\rm soft}(\lambda, \omega)$.

The subtraction procedure at the parton level is implemented in the same way as in [arXiv:0506110].

$$\hat{\sigma}^{\rm Subt} \sim \ln(\hat{s}/m_{u,d}^2).$$

In the case of hadronic collisions they are already effectively accounted in the PDF functions.

$\hat{\sigma}^{\rm soft}(\lambda, \omega)$ is factorized in front of the Born level cross section:

$$\mathrm{d}\hat{\sigma}^{\rm soft}_{\lambda_1\lambda_2}(\lambda,\omega) = \frac{\alpha}{2\pi} K^{\rm soft}(\lambda,\omega) \mathrm{d}\hat{\sigma}^{\rm Born}_{\lambda_1\lambda_2}.$$

The infrared divergences of the soft photon contribution compensates the corresponding divergences of the one-loop virtual QED radiative corrections.

Observables

Single- and double-spin combinations of polarized components (σ^{++}, σ^{+-}, σ^{-+}, σ^{--}) of the hadron-hadron cross section:

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

Definitions of single-spin ($\mathrm{A_L}$) and double-spin ($\mathrm{A_{LL}}$) asymmetries:

$$\mathrm{A_{L(LL)}}(Y) = \frac{\Delta d\sigma_{\mathrm{L(LL)}}/d\eta_\ell}{d\sigma/d\eta_\ell}, \quad \Delta\mathrm{A_L} = \mathrm{A_L^{NLO}} - \mathrm{A_L^{LO}},$$

η_ℓ – pseudo-rapidity of lepton in the final state:

$$\eta_\ell = -\ln\left(\tan\frac{\vartheta_\ell}{2}\right).$$

Here ϑ_ℓ is the angle of the ℓ in the laboratory frame. The z-axis is directed along the momentum of the first proton.

These asymmetries are crucial because they provide insights into the spin structure of nucleons.

Kinematic cuts, input parameters and conditions

Numerical results were obtained using the Monte Carlo generator `ReneSANCe` [arXiv:2207.04332].

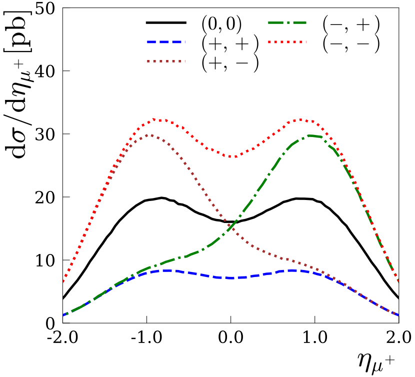
Input parameters and conditions:

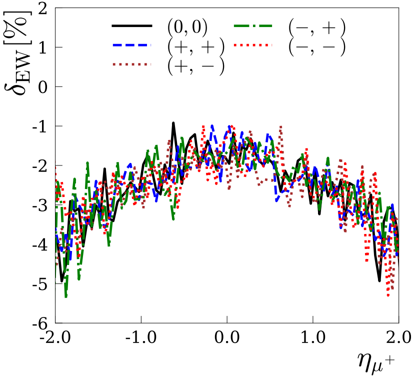
1. G_{F} scheme; energy of c.m.s. is $\sqrt{s} = 500\mathrm{GeV}$;
2. Set of input parameters [arXiv:2211.03561];
3. PDF: `NNPDF23_nlo_as_0119` for unpolarized parton distributions f_{q_i} и `NNPDFpol11_100` for longitudinally polarized parton distributions Δf_{q_i} from `LHAPDF6` library with factorization scale $\mu_F = M_{\ell\ell}$ [arXiv:1406.5539].
4. One-loop EW radiative correction is represented as $\delta = \sigma^{\mathrm{NLO,EW}}/\sigma^{\mathrm{LO}} - 1, \%$.

Kinematic cuts ($\ell = e,\ \mu$):

$W^+ : p_\perp(\ell^+) > 25\ \mathrm{GeV},\ p_\perp(\nu_\ell) > 25\ \mathrm{GeV},\ M(\ell^+\nu_\ell) > 1\ \mathrm{GeV}$
$W^- : p_\perp(\ell^-) > 25\ \mathrm{GeV},\ p_\perp(\bar{\nu}_\ell) > 25\ \mathrm{GeV},\ M(\ell^-\bar{\nu}_\ell) > 1\ \mathrm{GeV}.$

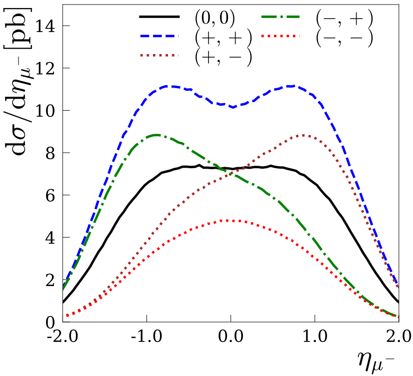
W^+: differential cross section and corresponding $\delta_{\mathbf{EW}}$

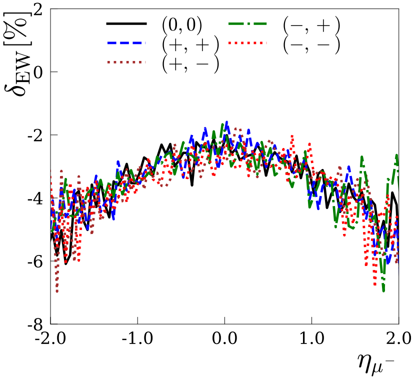




Differential cross section over lepton pseudo-rapidity in the LO for different values of polarization of the initial states (left). δ_{EW} of electroweak correction in percent (right).

W^-: differential cross section and corresponding $\delta_{\mathbf{EW}}$

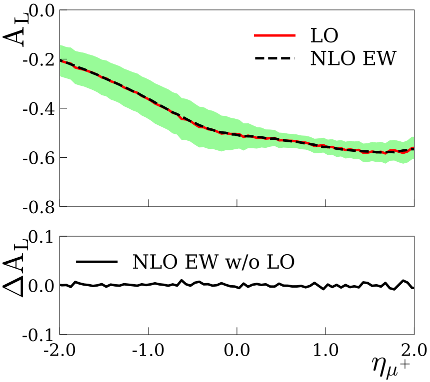




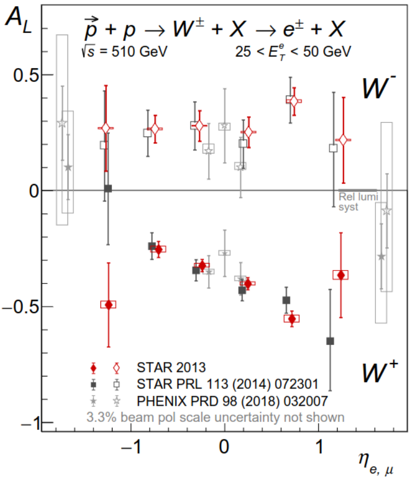
Differential cross section over lepton pseudo-rapidity in the LO for different values of polarization of the initial states (left). δ_{EW} of electroweak correction in percent (right).

W^+: single-spin asymmetry

$$\Delta A_L = A_L^{NLO} - A_L^{LO}$$



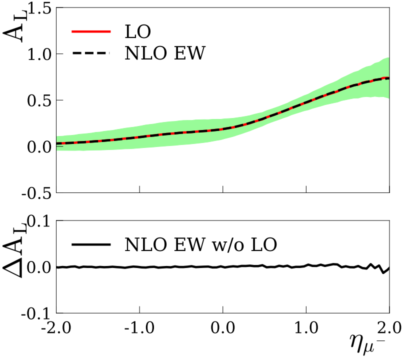
Single-spin asymmetry in the LO and in the NLO.

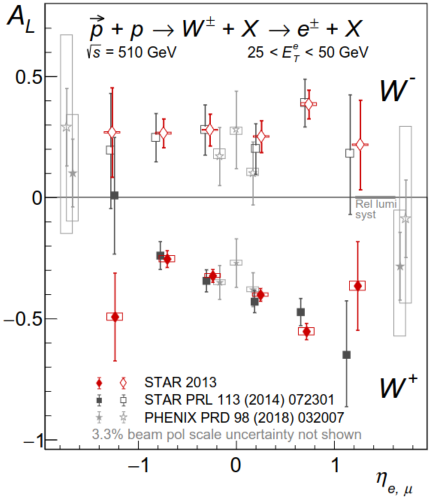


Recent data from the RHIC have been obtained by the PHENIX and STAR. [arXiv:2302.00605].

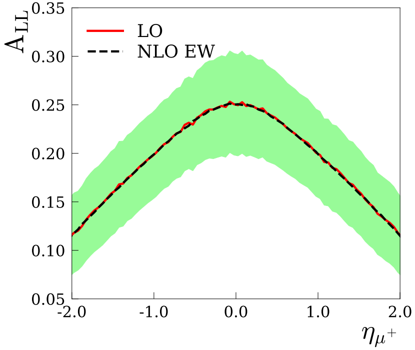
W^-: single-spin asymmetry

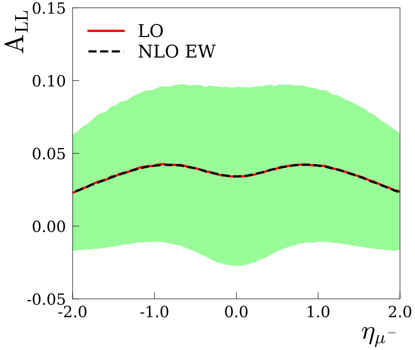
$$\Delta A_L = A_L^{NLO} - A_L^{LO}$$





$W^{\pm}$: double-spin asymmetry





Double-spin asymmetry in the LO and in the NLO.

Comparison in the unpolarized case

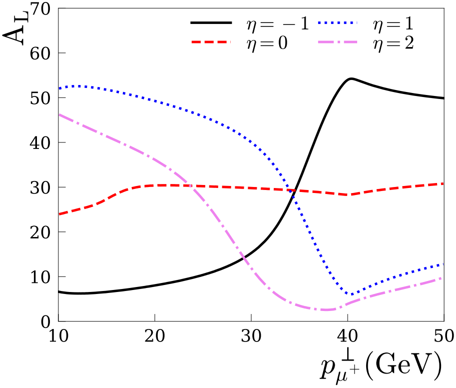
To test the validity of our calculation, we compared our results for the unpolarized case with independent NLO calculations performed using the programs `HORACE` [arXiv:hep-ph/0303102, arXiv:hep-ph/0609170], `WGRAD2` [arXiv:hep-ph/9807417] and `SANC` [arXiv:hep-ph/0506110].
The results of the tuned comparison of kinematic distributions at the NLO are shown in section 4.4 of [arXiv:0705.3251]. The results are in good agreement.
Results of computational module for σ^{hard} are in agreement with [arXiv:1207.4400 , arXiv:1301.3687, arXiv:0705.3251].

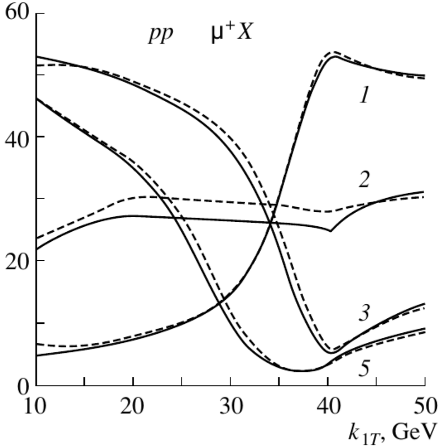
Comparison in the polarized case: ReneSANCe vs V.A. Zykunov

The one-loop electroweak radiative corrections for the polarized case were first presented in: [10.1007/s1010501c0009, 10.1134/1.1577911]. Agreement was obtained for differential cross sections, single-spin and double-spin asymmetries. (We used the set of input parameters and definitions of asymmetries from these papers).

Comparison in the polarized case: ReneSANCe vs V.A. Zykunov

$\eta = -1$, curve 1; $\eta = 0$, curve 2; $\eta = 1$, curve 3; $\eta = 2$, curve 5;





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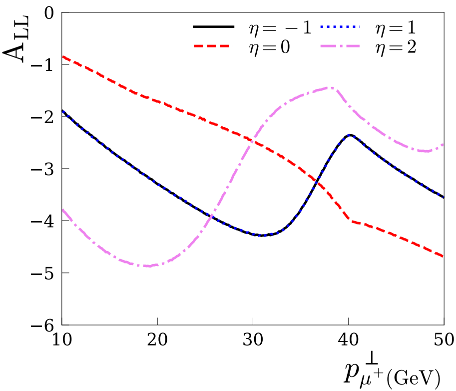
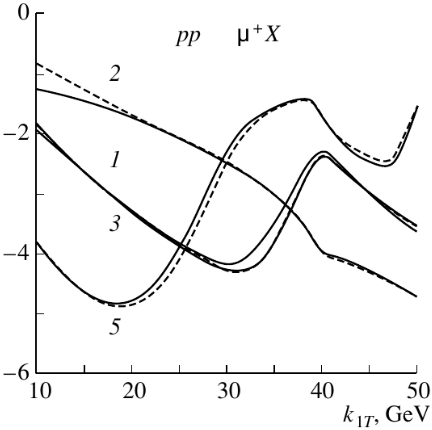
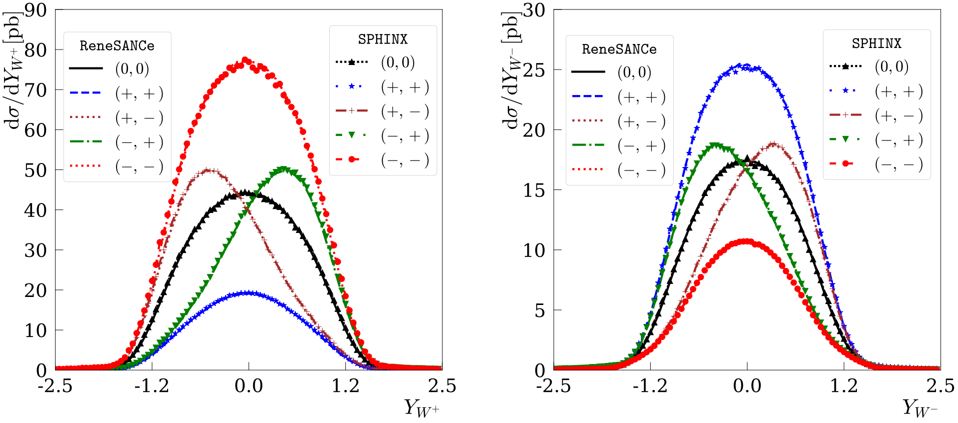




Comparison in the polarized case: ReneSANCe vs SPHINX

We also performed comparison with the SPHINX program [arXiv:hep-ph/9612278] at the Born level. The asymmetries also coincide, as they are combinations of the polarized components of the total cross section.



Conclusions

1. The calculation of one-loop electroweak radiative corrections for the charged current Drell-Yan processes was performed.
2. The influence of radiative corrections on cross sections, single-spin and double-spin asymmetries was investigated.
3. It is shown that the influence of one-loop electroweak radiative corrections on single- and double-spin asymmetries is negligible under RHIC conditions.
4. Agreement with the SPHINX program and works [10.1007/s1010501c0009, 10.1134/1.1577911] was obtained at the Born level for both polarized and unpolarized cases.

Funding

This work was supported by the Russian Science Foundation, project No. 22-12-00021.

Thank you for paying attention!