The polarized Drell–Yan process
at $\mathcal{O}(\alpha_s)$

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Abstract

The results of a recent calculation of the QCD corrections to the polarized Drell–Yan process are summarized. Some implications for the production of vector bosons at RHIC are discussed.

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The production of lepton pairs in hadron collisions, the Drell–Yan process [1], is one of the most powerful tools to probe the structure of hadrons. Its parton model interpretation is straightforward – the process is induced by the annihilation of a quark–antiquark pair into a virtual photon which subsequently decays into a lepton pair. The Drell–Yan process in proton–proton or proton–nucleus collisions therefore provides a direct probe of the antiquark densities in protons and nuclei. Experimental data on the Drell–Yan process in unpolarized collisions are crucial to constrain the behaviour of the sea quark distributions at large $x$ and to determine the flavour structure of the light quark sea. It is therefore natural to expect that a measurement of the Drell–Yan cross section in polarized hadron–hadron collisions will yield vital information on the polarization of the quark sea in the nucleon, which is presently only poorly constrained [2] from deep inelastic scattering data.

Apart from the invariant mass distribution, one usually studies the distribution of the lepton pairs as function of the Feynman parameter $x_F$ or of the hadron–hadron centre-of-mass rapidity $y$. The resulting distributions at fixed invariant mass can be directly related to the $x$-dependence of the parton distributions in beam and target. Moreover, most fixed target experiments have only a limited kinematic coverage in $x_F$ or $y$, such that only these distributions can be measured without extrapolation into experimentally inaccessible regions.

The rather large QCD corrections to the unpolarized Drell–Yan cross section [3] suggest that a reliable interpretation of the Drell–Yan process in terms of partonic distribution function is only possible if higher order corrections are taken into account. Following closely the method of the unpolarized calculation [3], we have recently calculated [4] the next-to-leading order corrections.
to the $x_F$- and $y$-distributions of lepton pairs produced in collisions of longitudinally polarized hadrons.

Truncated up to $\mathcal{O}(\alpha_s)$, the cross section for the polarized Drell–Yan process receives contributions from the $q\bar{q}$–annihilation process at leading and next-to-leading order and the quark-gluon Compton scattering process. It can be expressed as:

$$
\frac{d\Delta\sigma}{dM^2dx_F} = \frac{4\pi\alpha^2}{9M^2S} \sum_i e_i^2 \int_{x_1}^{1} dx_1 \int_{x_2}^{1} dx_2 \times \left\{ \left[ \frac{d\Delta\hat{\sigma}_{q\bar{q}}^{(0)}}{dM^2dx_F}(x_1, x_2) + \frac{\alpha_s}{2\pi} \frac{d\Delta\hat{\sigma}_{q\bar{q}}^{(1)}}{dM^2dx_F}(x_1, x_2, \frac{M^2}{\mu_F^2}) \right] \Delta q_i(x_1, \mu_F^2) \Delta\bar{q}_i(x_2, \mu_F^2) + \Delta\bar{q}_i(x_1, \mu_F^2) \Delta q_i(x_2, \mu_F^2) \right\} \\
+ \left[ \frac{\alpha_s}{2\pi} \frac{d\Delta\hat{\sigma}_{qg}^{(1)}}{dM^2dx_F}(x_1, x_2, \frac{M^2}{\mu_F^2}) \Delta G(x_1, \mu_F^2) \{ \Delta q_i(x_2, \mu_F^2) + \Delta\bar{q}_i(x_2, \mu_F^2) \} + (1 \leftrightarrow 2) \right],
$$

where analytic expressions for the parton level cross sections in the $\overline{\text{MS}}$–scheme are listed in [4]. The expression for the $y$-distribution of the Drell–Yan pairs takes a similar form. Integration over $x_F$ yields the Drell–Yan mass distribution which agrees with earlier results [5].

The numerical importance of these different contributions is illustrated in Figure 1, which shows the ratio between polarized and unpolarized Drell–Yan cross sections for the collision of a proton beam ($E_p = 820$ GeV) on a fixed proton target [6]. All curves are obtained with the polarized GS(A) parton densities [7] and are shown for $M = 8$ GeV. The polarized subprocess

![FIGURE 1. Contributions of the individual parton level subprocesses to the polarized Drell–Yan cross section (see text).]}
contributions are normalized to the full unpolarized cross section at next-to-leading order. The relative magnitude of the individual contributions is similar to the unpolarized Drell–Yan process [3]. The \( \mathcal{O}(\alpha_s) \) correction to the \( q\bar{q} \)–annihilation process enhances significantly the lowest order prediction while the quark–gluon Compton process contributes with a sign opposite to the annihilation process. However, the relative magnitude of annihilation and Compton process depends on the magnitude of the gluon distribution at large \( x \), which is completely undetermined at present [7,8]. This uncertainty prevents the sensible prediction of a \( K \)–factor between the cross sections at leading and next-to-leading order.

All above results on the Drell–Yan process can immediately be applied to the production of massive vector bosons at the polarized proton–proton collider RHIC [9], which has so far only been studied at leading order [10]. Measuring the production asymmetries for \( W^\pm \) and \( Z^0 \) bosons at RHIC will in principle allow to determine the sea quark polarization at large \( x \), a discrimination between \( W^+ \) and \( W^- \) will moreover allow for a flavour decomposition of the

**FIGURE 2.** Expected asymmetries in the production of vector bosons at RHIC \((\sqrt{s}=200 \text{ GeV})\).

**FIGURE 3.** Expected asymmetries in the production of vector bosons at RHIC \((\sqrt{s}=500 \text{ GeV})\).
polarized quark sea, as $W^+$ mainly originate from $u\bar{d}$–annihilation, whereas $W^-$ are produced via $d\bar{u}$–annihilation.

Using different up-to-date parametrizations [7,8] of polarized parton distributions, it is possible to estimate the size of the asymmetry which should be expected in the production of vector bosons at RHIC. Figures 2 and 3 show these asymmetries (obtained in the small width approximation, e.g. [11]) for the different centre-of-mass energies ($\sqrt{s} = 200$ GeV and $\sqrt{s} = 500$ GeV) planned for RHIC. It can be seen in these figures that the production asymmetries for vector bosons at RHIC are sizable (around 10% at 200 GeV and around 5% at 500 GeV) and that the different parametrizations yield significantly different predictions – reflecting the present lack of knowledge on the polarized sea quark distributions at large $x$. The larger asymmetry at 200 GeV may suggest a measurement at this energy to be favourable; it should however be kept in mind that the vector boson production cross sections at this energy are several hundred times smaller than at 500 GeV.

In summary, the complete $O(\alpha_s)$ corrections to the $x_F$- and $y$-dependence of the longitudinally polarized Drell–Yan cross section have been derived recently [4]. These corrections are quantitatively similar to the corrections in the unpolarized case and hence sizable even at collider energies. They enable a consistent next-to-leading order determination of the polarization of sea quarks in the nucleon from future measurements of lepton pair production at fixed target energies or from massive vector boson production at RHIC.

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