Polarized Hadroproduction of Open Heavy Quarks in NLO QCD at JHF and RHIC

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Abstract. We present the complete next-to-leading order QCD corrections to the polarized hadroproduction of heavy flavors. This reaction can be studied experimentally in polarized pp collisions at the JHF and at the BNL RHIC in order to constrain the polarized gluon density. It is demonstrated that the dependence on the unphysical renormalization and factorization scales is strongly reduced beyond the leading order. We also discuss how the high luminosity at the JHF can be used to control remaining theoretical uncertainties. An effective method for bridging the gap between theoretical predictions for heavy quarks and experimental measurements of heavy meson decay products is introduced briefly.

INTRODUCTION

The gluon helicity density $\Delta g$ remains weakly constrained [1, 2]. Current data are compatible with $\Delta g = 0$ at a low input scale $\mu_r^2 = 0.4 \text{ GeV}^2$, but even full saturation cannot be excluded [1]. Hence the gluonic contribution to the nucleon spin is unknown: $-0.8 \lesssim \Delta g_p \lesssim 1.7$. Polarized DIS data has been the only source of information so far. But the severely restricted kinematical range, in which approximate “scaling” holds, thwarts attempts to pin down the gluon. Furthermore, the helicity sum rule is useless for constraining $\Delta g$ without independent angular momentum measurements. Data from exclusive processes may ameliorate the polarized parton fits.

Two experiments will be or are collecting data for the hadroproduction of open heavy quarks: the JHF and the BNL RHIC [3]. We provide here the first corresponding complete calculation in NLO QCD. Note that our calculation is also necessary for obtaining the resolved photon contributions in NLO QCD for our older NLO photoproduction analysis [4, 5].

RESULTS FOR THE JHF

In Fig. 1 left we show the ratio of $\Delta \sigma_{ij}/\Delta \sigma_{tot}$ at JHF energies of $\sqrt{S} = 10$ GeV, with the subprocesses $ij = gg, q\bar{q}, gq + g\bar{q}$ and $\Delta \sigma_{tot} = \sum \Delta \sigma_{ij}$. The ratio for the gluon-gluon fusion is shown in thick lines and the ratio for the quark-antiquark annihilation is shown by thin lines. The gluon-(anti)quark subprocess contributes little and is omitted. Note that given the total asymmetry $A \equiv \Delta \sigma_{tot}/\sigma_{tot}$, if we require $A \equiv \sum A_{ij}$ of the sub-processes, then the shown ratio corresponds to the subprocess asymmetry contribution $A_{ij} = \Delta \sigma_{ij}/\Delta \sigma_{tot}$. 
FIGURE 1. Left: Subprocess importance depending on $p_T \geq p_T^{\text{min}}$ for different helicity densities at the JHF. Right: Gluon-gluon contribution to $\Delta\sigma$ depending on the $x_1$ and $x_2$ of the gluons. See text for details.

$A^c_{pp}(f,c)/A^c_{pp}(2.5,1.4) - 1$

Several helicity density sets have been used [1, 2], and $\sigma_{ij}/\sigma_{\text{tot}}$ with the unpolarized GRV’98 distributions [6] is shown for comparison. The curves depend on a cut in transverse momentum $p_T \geq p_T^{\text{min}}$. The polarized GRSV’00 std. and the unpolarized GRV’98 curves show optimal behavior: the gluon-gluon subprocess dominates and there is almost no dependence on the $p_T$-cut. For the smaller GRSV’00 val. set $\Delta g$ the quark-
antiquark subprocess contributes significantly. Also there is now a strong dependence on the cut (although the “pole” is due to \( \Delta \sigma_{\text{tot}} = 0 \)). For the very small DS i- \( \Delta g \), quark-antiquark annihilation dominates. Hence at the small JHF energy, one cannot simply assume gluon-gluon fusion dominance.

![Figure 3](image)

**FIGURE 3.** The NLO cross section at JHF depending on a cut \( p_T \geq p_T^{\min} \) as \( \mu_f^2 \), \( \mu_r^2 \) and \( m_c \) are varied. The GRV’98 distributions [6] are used. The statistical error after one day using \( \mathcal{L} = 64 \text{ pb}^{-1} \) is shown.

Given a large enough \( \Delta g \), which regions of \( x \) does gluon-gluon fusion probe? From kinematics we have \( x_1 x_2 \geq 4 m_c^2 / S \) for the momentum fractions of the gluons. In Fig. 1 right we show

\[
\frac{x_1 x_2}{\alpha_s^2 / m^2} \Delta g(x_1, \mu_f^2) \Delta g(x_2, \mu_f^2) \Delta \hat{\sigma}_{gg}(x_1 x_2),
\]

with \( \mu_f^2 = 2.5 \cdot (1.4 \text{ GeV})^2 \), \( \Delta g \) of the GRSV’00 std. set, and the partonic cross section \( \Delta \hat{\sigma}_{gg} \). The \( x_1 x_2 \) is multiplied to give the appropriate volume impression with logarithmic axes and a general \( \alpha_s^2 / m^2 \) dependence has been divided out. Apart from that the integrals over \( x_1 \) and \( x_2 \) of (1) gives the hadronic \( \Delta \sigma_{gg} \). The main contribution comes from the kinematic edge \( x_1 x_2 \simeq 4 m_c^2 / S \). Furthermore it is peaked at \( x_1 \simeq x_2 \). Hence \( \hat{x} \simeq \sqrt{4 m_c^2 / S} \) is mainly probed. At the JHF for charm \( \hat{x}_c \simeq 0.3 \) and at the BNL RHIC \( \hat{x}_c \simeq 0.01, 0.006 \) for \( \sqrt{S} = 200, 500 \text{ GeV} \). For photoproduction with \( x_2 \equiv 1 \) one can similarly show \( \hat{x} \simeq 4 m_c^2 / S \). Hence the COMPASS experiment [7], at the same center-of-mass energy \( \sqrt{S} = 10 \text{ GeV} \) as the JHF, further complements the probed range with \( \hat{x}_c \simeq 0.08 \).

In Fig. 2 we show the deviation in % from a central prediction of the asymmetry \((\mu_r^2 = \mu_f^2 = 2.5 m_c^2 \text{ and } m_c = 1.4 \text{ GeV})\) as renormalization and factorization scales, which are set equal, and the charm mass are varied. We see a massive reduction in the the theoretical uncertainty in NLO as compared to LO, basically only the dependence on \( m_c \) of \( \pm 30\% \) is left. However, Fig. 3 shows that this amazing improvement is partly due to strong cancellations in \( \Delta \sigma / \sigma \). The underlying uncertainty of \( \sigma \) is massive. However,
FIGURE 4. The NLO charm asymmetry $A$ at $\sqrt{s} = 10$ GeV for JHF depending on a cut $p_T \geq p_T^{\text{min}}$. An estimate for the statistical error after 120 days using $\mathcal{L} = 7.66$ fb$^{-1}$ is shown.

the error bars of the shown statistical accuracy of one day of measurements at the JHF are too small to be seen. Hence there is hope that the scales can be pinned down first in precise unpolarized measurements.

Finally, we present in Fig. 4 predictions for the JHF with a range of older and newer helicity distributions [1, 2]. When compared to the expected statistical uncertainty at the JHF with a detection efficiency $\varepsilon_c = 0.001$, we see that one will be able to see any but the smallest gluons and that one can even clearly distinguish between several groups of sets. The situation is similar at the BNL RHIC, as we will see below.

RESULTS FOR THE BNL RHIC

Obtaining similar predictions for the PHENIX experiment at the BNL RHIC is more involved, because its detector cannot reasonably be approximated by an uniform detection efficiency $\varepsilon_c$. We use the software employed by PHENIX to generate a $\varepsilon_{\text{eff}}$ depending on $p_T$ and the pseudo-rapidity $\eta$, which takes into account hadronization, decay product cuts, and the detector acceptance. For Fig. 5, see [8] for more details, $\varepsilon_{\text{eff}}$ is then convoluted with our double differential partonic results

$$\tilde{\sigma}_{\text{eff}}(p_T^c > 1 \text{GeV}) = \int_0^{p_T^{\text{max}}} dp_T \int_{\eta_{\text{max}}}^\eta d\eta \ v_{\text{eff}}(p_T, \eta; p_T^c > 1 \text{GeV}) \frac{d^2 \tilde{\sigma}}{dp_T d\eta}. \quad (2)$$
FIGURE 5. The NLO charm asymmetry $A$ at $\sqrt{s} = 200$ GeV for PHENIX depending on $x_T^{\text{min}} = p_T^{\text{min}} / p_T^{\text{max}}$. $A$ is rescaled by $1/x_T^{\text{min}}$. An estimate for the statistical error using $\mathcal{L} = 320$ pb$^{-1}$ is shown.

CONCLUSIONS

We have shown that the NLO predictions for the JHF and the BNL RHIC show great promise for pinning down $\Delta g$ at $x$ values of about 0.3 and 0.01 (200 GeV), 0.006 (500 GeV), respectively. The theoretical uncertainties for the asymmetry are much improved in NLO, but the large uncertainty of the unpolarized cross section should be reduced first by employing the fantastic luminosity of the JHF. We have also shown a method of taking into account the complicated experimental setup of PHENIX at the BNL RHIC.

REFERENCES

7. COMPASS Collaboration, G. Baum et al., reports CERN/SPSLC 96-14, -30.