Interplay between polarized DIS and RHIC spin physics

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Abstract

The complementarity of polarized DIS experiments and polarized Proton-Proton experiments is illustrated for two examples. It is shown how the twist-3 part of the second moment of $g_2(x, Q^2)$ and the single-spin photon asymmetry are connected and it is discussed how the polarized gluon distribution can be obtained from the measurement of direct gamma asymmetries.

Résumé

1. Introduction

In the future the information gained from polarized DIS-experiments will be supplemented by additional information from polarized proton-proton collisions planned to be investigated at RHIC starting in the year 2000 [1]. There are several very interesting experiments to be done with polarized protons [2, 3]. The most obvious ones are those allowing to determine the polarized gluon structure function $\Delta G(x)$. Several experiments along these lines have been proposed, for brevity we concentrate here only on one of these, namely the detection of spin-asymmetries in direct photon production for the collision of longitudinally polarized protons [4]. The knowledge of $\Delta G(x)$ is crucial for the interpretation of polarized DIS because the polarized structure functions measured in DIS cannot be separated from a possible anomalous gluon contribution. The form of this contribution, especially its $x$-dependence is much debated. For the perturbative contribution one can derive it from standard QCD [5].

\[ \Delta g^p_1(x) = \left( \frac{\alpha^2}{2} \right) \int_x^1 \frac{A \left( \frac{x}{z}, \frac{Q^2}{\mu^2_{\text{fac}}} \right) \Delta G(z, \mu^2_{\text{fac}})}{z} \, \frac{dz}{z} \]  

Here $\mu^2_{\text{fac}}$ is the factorization scale and $A$ is a known splitting function. However, this contribution depends strongly on the infrared regulators used, which signals that the distinction between a quark and a gluon part is ill-defined. Furthermore one would expect in addition strongly non-perturbative contributions. Although this discussion is in no way settled everybody agrees that the correction term is negligible unless $|\Delta G|$ is of order 1. To decide whether this is the case one can analyse not totally inclusive reactions in DIS like those in which a positive or negative pion is produced [6]. This will be tried by the HERMES experiment but it looks very difficult for the precision needed. The other possibility is to investigate polarized hadron-hadron collisions. We have analysed the latter possibility using a specialized Monte-Carlo programme called SPHINX [7] based on PYTHIA [8].

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2. Prompt-$\gamma$-Production

We investigated the two leading processes (i.e. first order in $\alpha_s$) for prompt-$\gamma$-production, namely the Compton process (figure 1) and the annihilation process (figure 2) and determined their contribution at RHIC energies to the cross section for different parton parametrisations. The relevant spin-difference cross-section is

$$E_\gamma \frac{d\Delta\sigma_{pp\rightarrow \gamma X}}{d^3p_\gamma}(s, x_F, p_\perp) = \sum_{ab} \int dx_a \, dx_b \, \Delta P_a(x_a, Q^2) \Delta P_b(x_b, Q^2) \ (2)$$

$$E_\gamma \frac{d\Delta\tilde{\sigma}_{ab\rightarrow \gamma X}}{d^3p_\gamma}(s, x_F, p_\perp).$$

Here the sum is over all partonic subprocesses which contributes to the reaction $pp \rightarrow \gamma X$. $\Delta P_a$ and $\Delta P_b$ denotes the polarised parton distribution functions. The latter are the difference between the probability to hit partons of the same helicity as the hadron and those of opposite helicity. For our simulation we used two parametrisations for parton densities with large gluon polarisation by Altarelli&Stirling [9] and by Ross&Roberts (set A) [10] and one parametrisation with a small gluon polarisation by Ross&Roberts (set D) [10] and one parametrisation with a large gluon polarisation by Altarelli&Stirling [9] and by Ross&Roberts (set D) [10] and one parametrisation with a small gluon polarisation by Ross&Roberts (set A).

For large gluon polarisation the Compton process is the by far dominant one and one can safely neglect the contribution of the annihilation process in (2). In this case the prompt-$\gamma$-production becomes proportional to $\Delta G$ and is thus a clean probe for the gluon polarisation. However, in a scenario with a large sea contribution to the spin of the proton and a gluon polarisation only due to Altarelli-Parisi evolution, as described by the parametrisation Ross&Roberts set A [10], the annihilation process becomes the major contribution.

For the unpolarised parton distributions we have chosen the parametrisation of Glück, Reya, and Vogt [11]. The matrix elements are implemented in leading order only. However, due to the initial and final state shower algorithm some features of higher order effects are incorporated as well [12]. Also the polarisation effects are traced in the initial state shower. For the simulations the polarised initial state shower and the final state shower were switched on. To avoid infrared divergences the hard interaction cross section must be supplemented by a lower cut off for the transverse momentum $p_\perp$. We chose $p_\perp \geq 4$ GeV.

Some results of these simulations are shown in figure 3, figure 4 and figure 5. In figure 3, the Lorentz-invariant cross section for prompt-$\gamma$-production as a function of $p_\perp$ at $x_F \approx 0$ is displayed for the Compton process (upper plot) and the annihilation process (lower plot).

$x_F$ is here the longitudinal momentum fraction of the photon defined by $x_F = 2p_\perp^\gamma/\sqrt{s}$. In both cases the spin averaged cross section (squares) and the cross section for the spin difference (triangles) are shown. The error bars reflect the MC error. A typical RHIC run has 320 pb$^{-1}$, such that the $10^7$ events we generated for each spin combination (with $p_\perp \geq 4$ GeV) corresponds to an integrated cross section of $3 \cdot 10^{-5}$ mb for the spin averaged case respectively to a differential cross-section of roughly $3 \cdot 10^{-5}$ mb/(4π·4 GeV) = $6 \cdot 10^{-7}$ mb/GeV in the 4 GeV bin. This implies that the MC error is roughly comparable to the expected experimental error for the prompt-$\gamma$’s and substantially larger than the anticipated experimental errors for gammas from $\pi^0$ decays.

The fact that the spin-differences are clearly non-zero shows that with this experiment one can indeed measure $\Delta G$.

2.1. Background considerations

High-$p_\perp$ $\gamma$’s are not only produced in the direct processes but at a far larger rate due to bremsstrahlung and in particular in meson decays. This background has to be separated from the direct photons very accurately in order to do not contaminate the signal substantially. This issue has many aspects we only want to illustrate them by addressing two points:

1.) The detector has to fulfill certain requirements in order to make the experiments possible, and
2.) The direct photons from a so-called background, namely $\pi^0$-decay offer a very promising signal.
An important problem is e.g. whether the detector can at all identify whether a photon comes from a $\pi^0$-decay or not. The most important issue is whether the two photon from pion decay can be distinguished, or whether they end up in the same detector. The rate of such 'fake' $\gamma$'s depends obviously on the spatial detector resolution. The minimal opening angle of a $\gamma$-pair in the rest frame of the pion is given by:

$$\chi_{\text{min}} = \frac{2m_\pi}{E_\pi},$$

and the following resolutions of the detector are considered $\chi_{\text{res}} > 0.005$ rad, 0.01 rad, or 0.02 rad. Defining the fake-\(\gamma\)-rate $R$ as the ratio between the number of unresolved pions and the total number of pions figure 4. These plots show that the planned PHENIX resolution of $\chi_{\text{res}} > 0.01$ is marginally sufficient to keep the fake-\(\gamma\)-rate down.

Figure 5 shows the yield of pions due to the QCD-Compton process in the spin averaged case (upper plot), for the spin-difference (middle) and the resulting asymmetry (lower plot) as a function of $p_T$ for parametrisations with a large gluon polarisation. The experimental statistical precision will be much better than our Monte Carlo errors. Consequently this looks like a very nice signal indeed.

### 3. $d_2$ and single-spin gamma asymmetries in $p+p(\uparrow)$

By measuring the second moments of the two spin structure functions $g_1(x)$ and $g_2(x)$ one will be able to determine the twist three contribution $d_2$ which is determined by a specific quark-gluon correlator [13].

$$\int_0^1 x^2 g_1(x,Q^2) = \frac{1}{3} a_2 + O(M^2/Q^2)$$

$$\int_0^1 x^2 g_2(x,Q^2) = -\frac{1}{3} a_2 + \frac{1}{3} d_2 + O(M^2/Q^2)$$

(4)
The spin-asymmetry in $\pi^0$-production as signal for the polarised gluon distribution

$$d_2 \sim \langle P,S \vert \left[ \gamma_\alpha g \tilde{G}_{\beta\sigma} + \gamma_\beta g \tilde{G}_{\alpha\sigma} - \text{trace} \right] \psi \vert PS \rangle$$  \hspace{1cm} (5)$$

These relations follow from operator product expansion and are thus firmly rooted in the framework of QCD. $d_2$ plays in some way the analogous role to the magnetic field in QED. In fact the situation is slightly involved, because the QED analogy can be rather misleading. In QCD the colour-magnetic field and possible correlations between transverse momenta and colour-electric fields are of equal importance. Also the fields must always be coupled to colour-singlets, e.g. by coupling them to quark and antiquark as for $d_2$. Still $d_2$ should reappear in many different places in spin physics, just as the magnetic field does for QED. One such place is the production of direct photons in the collision of a transversely polarized nucleon with an unpolarized one. One can argue for this case that the photon asymmetry $A_\gamma$ scales with $d_2$, such that

$$\frac{A_{\gamma \text{proton}}^{\text{proton}}}{A_{\gamma \text{neutron}}^{\text{neutron}}} = \frac{d_2^{\text{proton}}}{d_2^{\text{neutron}}}.$$  \hspace{1cm} (6)$$

As all four quantities will be measured (assuming that the necessary precision for the photon asymmetries can be reached experimentally, which requires a dedicated effort) it should be clear within a few years whether this prediction is fulfilled.

4. Summary

We have demonstrated for two simple examples how fruitful the interplay between polarized DIS and polarized proton-proton-collisions is. RHIC spin physics will make a major contribution to the understanding of the nucleon spin structure.

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