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The Spin Structure of the Nucleon

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The Spin Structure of the Nucleon

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1 Introduction

For many years now, spin has played a very prominent role in QCD. The field of QCD spin physics has been carried by the hugely successful experimental program of polarized deeply-inelastic lepton-nucleon scattering (DIS), and by a simultaneous tremendous progress in theory. A new milestone has now been reached with the advent of RHIC, the world's first polarized proton-proton collider. RHIC is poised to help answer many of the important question pertaining to the spin structure of the nucleon. Recently, it has also been proposed to study spin phenomena in transversely polarized $\bar{p}p$ collisions at the planned GSI-FAIR facility. This talk describes some of the opportunities provided by RHIC and the proposed GSI experiments.

2 Nucleon helicity structure

2.1 What we have learned so far

Figure 1 shows a recent compilation [1] of the world data on the nucleon's spin structure function $g_1(x, Q^2)$. These give direct access to the helicity-dependent parton distribution functions of the nucleon,

$$\Delta f(x, Q^2) = f^+ - f^- \qquad (f = q, \bar{q}, g)\,, \tag{1}$$

which count the numbers of partons with same helicity as the nucleon, minus opposite. From $x \to 0$ extrapolation of the structure functions for proton and neutron targets it has been possible to test and confirm the Bjorken sum rule [2]. Polarized DIS data, when combined with input from hadronic β decays, have allowed to extract the – unexpectedly small – nucleon's axial charge $\sim \langle P|\bar{\psi}\,\gamma^\mu\,\gamma^5\,\psi|P\rangle$, which is identified with the quark spin contribution to the nucleon spin.

2.2 Things we would like to know

The results from polarized inclusive DIS have also led us to identify the next important goals in our quest for understanding the spin structure of the nucleon [3]. The measurement of gluon polarization $\Delta g = g^+ - g^-$ rightly is a main emphasis at several experiments in spin physics today, since the integral of Δg could be a major contributor to the nucleon spin. Also, more detailed understanding of polarized quark distributions is needed; for example, we would like to know about flavor

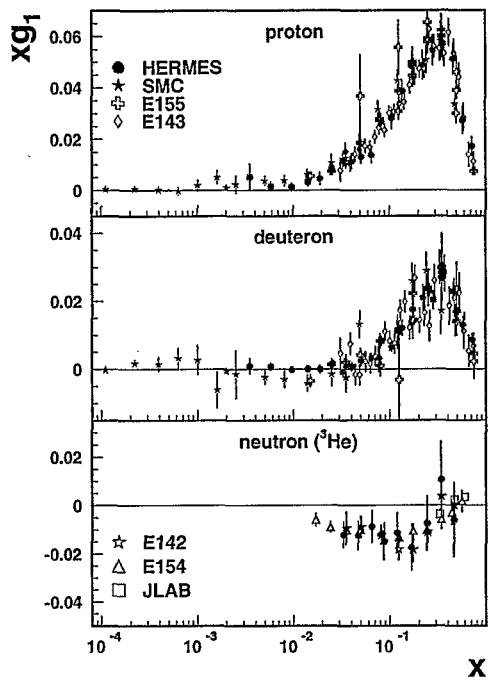

Figure 1: Data on the spin structure function g_1, as compiled and shown in [1].

symmetry breakings in the polarized nucleon sea, strange quark polarization, the relations to the F, D values extracted from baryon β decays, and about the small-x and large-x behavior of the densities. Again, these questions are being addressed by current experiments. Finally, we would like to know how much orbital angular momentum quarks and gluons contribute to the nucleon spin. Ji showed [4] that their total angular momenta may be extracted from deeply-virtual Compton scattering, which has sparked much experimental and theoretical activity also in this area [5].

A new milestone has been reached in spin physics with the advent of the first polarized proton-proton collider, RHIC at BNL. By now, several physics runs with polarized protons colliding at $\sqrt{s} = 200$ GeV have been completed, and exciting first results are emerging. In the following, we will discuss one area that is a major strength of RHIC, namely the measurement of gluon polarization in the proton. For further information on the RHIC spin physics program, see Refs. [6, 7].

2.3 Accessing gluon polarization Δg

The measurement of Δg is a main goal of several current experiments. Δg has been left virtually unconstrained [8-11] by the scaling violations observed in polarized DIS, due to the very limited lever arm in Q^2. This is demonstrated by Fig. 2. One way to access Δg in lepton-nucleon scattering more directly is to measure final states that select the photon-gluon fusion process, heavy-flavor production and $ep \to h^+h^-X$, where the two hadrons have large transverse momentum [12].

RHIC will likely dominate the measurements of Δg. Several different processes will be investigated [6, 7] that are sensitive to gluon polarization: high-p_T prompt photons $pp \to \gamma X$, jet or hadron production $pp \to \text{jet}\, X$, $pp \to hX$, and heavy-flavor production $pp \to (Q\bar{Q})X$. In addition, besides the current $\sqrt{s} = 200$ GeV,

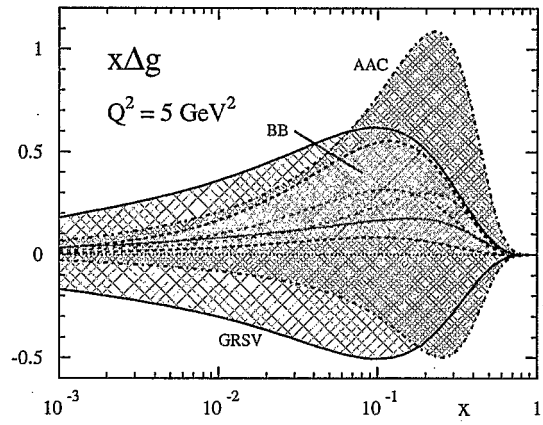

Figure 2: Results for $x\Delta g(x, Q^2 = 5\ \mathrm{GeV}^2)$ from recent NLO analyses [8-10] of polarized DIS. The various bands indicate ranges in Δg that were deemed consistent with the scaling violations in polarized DIS in these analyses. From [7].

also $\sqrt{s} = 500$ GeV will be available at a later stage. All this will allow to determine $\Delta g(x, Q^2)$ in various regions of x, and at different scales. All tools are in place now for treating the spin reactions relevant at RHIC at next-to-leading order (NLO) pQCD [13-16]. NLO corrections significantly improve the theoretical framework. We emphasize that there have already been results from RHIC that demonstrate that the NLO framework is very successful. Figure 3 shows comparisons of data from PHENIX [17] for single-inclusive pion production $pp \to \pi^0 X$ with NLO calculations based on the code of [13]. As can be seen, the agreement is excellent, even down to p_T values as low as $p_T \geq 1.5$ GeV. A similar level of agreement has been found in comparisons with STAR data [18] for $pp \to \pi^0 X$ at very forward rapidities, and with PHENIX data [19] for $pp \to \gamma X$. We note that an agreement between data and NLO calculations like the one seen in Fig. 3 is not found in the fixed-target regime (it has recently been shown that in this regime large logarithmic terms at yet higher orders are important and need to be resummed for a successful theoretical description [20]). On the right of Fig. 3 we decompose the mid-rapidity π^0 cross section into the contributions from the various two-parton initial states [21]. It is evident that processes with initial gluons dominate.

Figure 4 shows NLO predictions for the double-longitudinal spin asymmetries A_{LL} for the reactions $pp \to \mathrm{jet}\, X$ and $pp \to \gamma X$ at RHIC, based on the GRSV "theory uncertainty" band displayed in Fig. 2. One can see that the experimental uncertainties expected at RHIC are much smaller than the current uncertainty in Δg. First results for A_{LL} in $pp \to \pi X$ have now been reported by PHENIX [22].

3 Transversity

Besides the unpolarized and the helicity-dependent densities, there is a third set of leading-twist parton distributions, transversity [23]. In analogy with Eq. (1) they measure the net number (parallel minus antiparallel) of partons with transverse polarization in a transversely polarized nucleon:

$$\delta f(x, Q^2) = f^{\uparrow} - f^{\downarrow}\,. \tag{2}$$

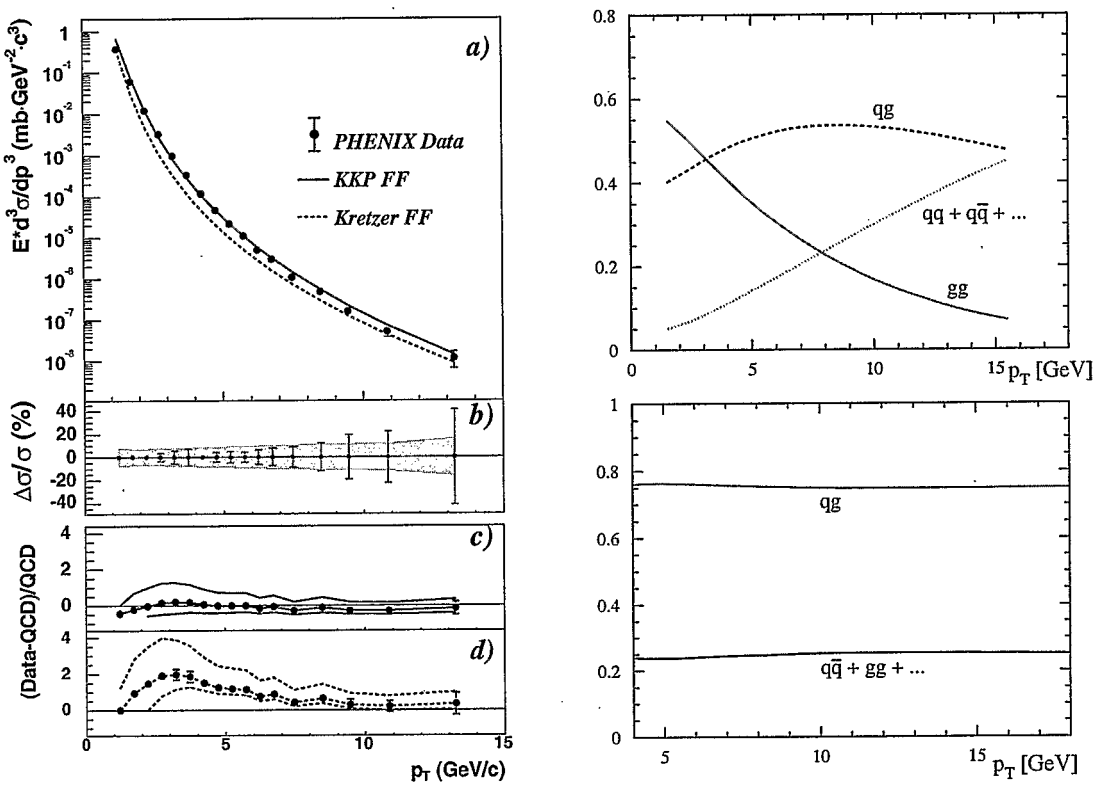

Figure 3: Left: PHENIX data [17] for the cross section for $pp \to \pi^0 X$ at $\sqrt{s} =$ 200 GeV. The lines represent the NLO calculation based on the code of [13]. Upper right: contributions to the NLO cross section for $pp \to \pi^0 X$ from gg, qg, and qq initial states [21]. Lower right: same decomposition for prompt-photon production $pp \to \gamma X$. Taken from [7], to which we refer the reader for details of the calculations.

Transversity corresponds to a helicity-flip structure, which precludes a gluon transversity distribution at leading twist. It also makes transversity a probe of chiral symmetry breaking in QCD [24]: perturbative-QCD interactions preserve chirality, and so the helicity-flip required to make transversity non-zero must primarily come from soft non-perturbative interactions for which chiral symmetry is broken.

In contrast to the distributions f and Δf, we have essentially no knowledge from experiment so far about the transversity distributions δf. Again the fact that perturbative interactions in the Standard Model do not change chirality means that inclusive DIS is not useful. Collins, however, showed [25] that properties of fragmentation might be exploited to obtain a "transversity polarimeter": a pion produced in fragmentation will have some transverse momentum $\vec{k}_T$ with respect to the momentum of the transversely polarized fragmenting parent quark. There may then be a correlation of the form $\vec{S}_T \cdot (\vec{P}_\pi \times \vec{k}_\perp)$. The fragmentation function associated with this correlation is the Collins function. It makes a leading-power [25] contribution to the single-spin asymmetry $A_\perp$ in the reaction $ep^\uparrow \to e\pi X$:

$$A_\perp \propto |\vec{S}_T| \sin(\phi + \phi_S) \sum_q e_q^2 \delta q(x) H_1^{\perp,q}(z) \ , \tag{3}$$

where ϕ (ϕ_S) is the angle between the lepton plane and the $\gamma^*\pi$-plane (and the transverse target spin). Recently factorization for semi-inclusive DIS (SIDIS) at small

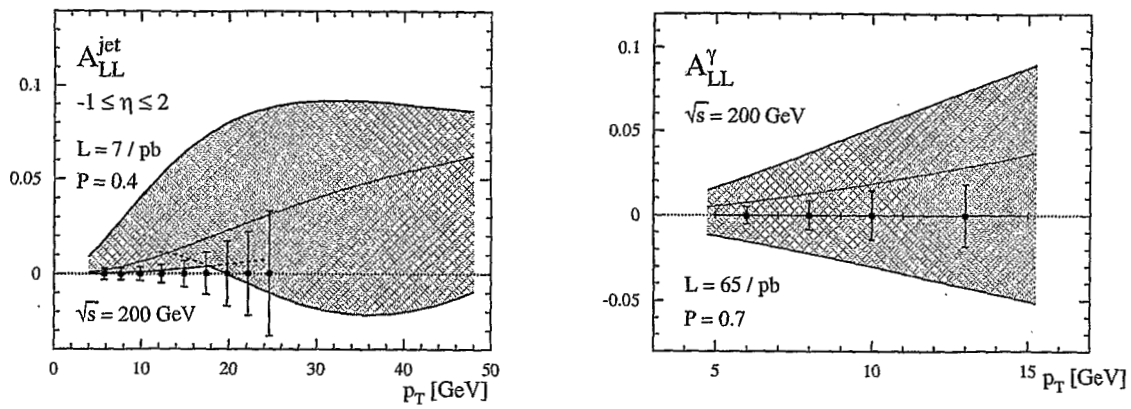

Figure 4: "NLO theory bands" for $pp \to$ jet X at $\sqrt{s} = 200$ for rapidities $-1 \le \eta \le 2$ at STAR (left), and for mid-rapidity prompt-photon production at PHENIX (right). The bands illustrate the current "uncertainty" due to Δg, using the GRSV Δg band shown in Fig. 2. The "errors" are projections. Taken from [7].

transverse momentum has been proven [26]. HERMES has reported [27] clear signs of a nonvanishing Collins asymmetry in $ep^{\uparrow}$ scattering. Measurements by COMPASS using a deuteron target have been presented as well [28]. Very recently, first independent information on the Collins functions has come from BELLE measurements in e^+e^- annihilation [29]. It is hoped that combination of these results with those from lepton scattering would eventually give some information on transversity.

Clean and direct information on transversity might be gathered from polarized proton-proton collisions at RHIC, using the Drell-Yan process [6, 7]. In pp collisions, however, the Drell-Yan process probes products of valence quark and sea antiquark distributions. It is possible that antiquarks in the nucleon carry only little transverse polarization since the perturbative generation of transversity sea quarks from $g \to q\bar{q}$ splitting is missing. Also, at RHIC the partonic momentum fractions are fairly small, so that the denominator of $A_{\rm TT}$ is large. NLO studies [30] estimate the size of $A_{\rm TT}$ at RHIC to be at most a few per cent.

It has recently been proposed to add polarization to planned $\bar{p}p$ experiments at the GSI-FAIR facility, and to extract transversity from measurements of $A_{\rm TT}$ for the Drell-Yan process [31-33]. This clearly is a very exciting idea. Initially, experiments could be performed in a fixed-target mode, using the 15 GeV antiproton beam. At later stages of operations, there are plans for an asymmetric $\bar{p}p$ collider, with an additional proton beam of energy 3.5 GeV. The results from such measurements would be complementary to what can be obtained from RHIC or SIDIS. In $\bar{p}p$ collisions the Drell-Yan process mainly probes products of two *quark* densities, $\delta q \times \delta q$, since the distribution of antiquarks in antiprotons equals that of quarks in the proton. In addition, kinematics in the proposed experiments are such that rather large partonic momentum fractions, $x \sim 0.5$, are probed. One therefore accesses the valence region of the nucleon, where the polarization of partons is expected to be large. Estimates [33] for the GSI PAX and ASSIA experiments show that the expected spin asymmetry $A_{\rm TT}$ should indeed be very large, of order 30% or more.

The theoretical framework for GSI kinematics is somewhat more involved than for RHIC, since in the region to be accessed higher-order corrections to the partonic cross sections are particularly important. The NLO corrections for the transversely

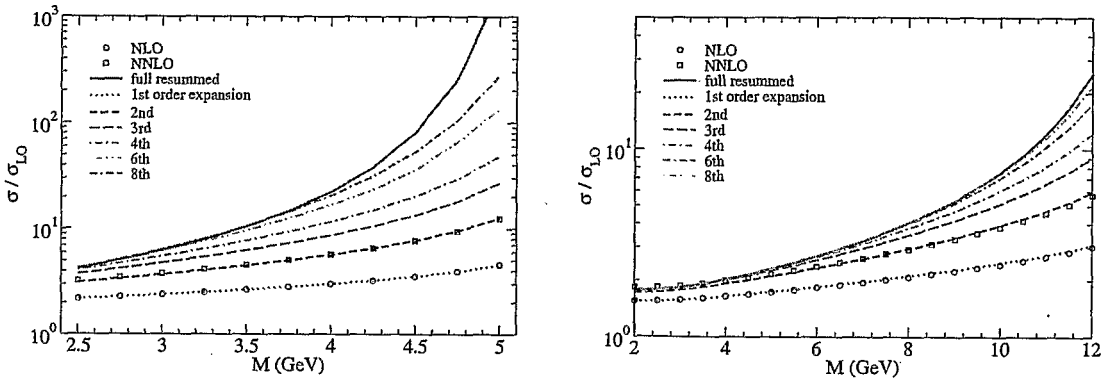

Figure 5: "K-factors" for the Drell-Yan cross section in fixed-target $\bar{p}p$ collisions at $s = 30$ GeV^2 (left) and for an asymmetric collider mode with $s = 210$ GeV^2 (right), as functions of lepton pair invariant mass M. For details, see [36].

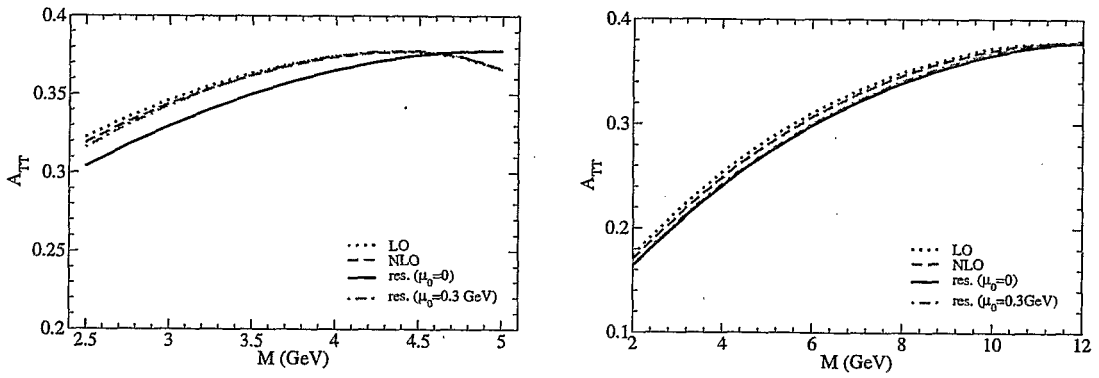

Figure 6: Corresponding spin asymmetries $A_{\rm TT}(\phi = 0)$ at LO, NLO and for the NLL resummed case.

polarized Drell-Yan cross section have been calculated in [34]. In the region of interest here, however, certain logarithmic terms in the partonic cross section become important to *all* orders in perturbation theory and need to be resummed. Such a "threshold resummation" is a well established technique in QCD [35]. For $A_{\rm TT}$ for the Drell-Yan process it has been addressed in detail recently in [36].

Figure 5 shows results of [36] for the K factors for the unpolarized Drell-Yan cross section at $s = 30$ GeV^2 (left) and $s = 210$ GeV^2 (right), at NLO, NNLO, and for the next-to-leading logarithmic (NLL) resummed case, along with various higher-order expansions of the resummed result. As can be seen, the corrections are very large, in particular in the lower-energy case. Figure 6 shows the corresponding spin asymmetries $A_{\rm TT}$. $A_{\rm TT}$ turns out to be extremely robust and remarkably insensitive to higher-order corrections. Perturbative corrections thus make the cross sections larger independently of spin. They would therefore make easier the study of spin asymmetries, and ultimately transversity distributions. For further details, including a discussion on the role of nonperturbative effects, see [36]. We finally note that it has recently also been proposed [37] to study the spin asymmetry $A_{\rm TT}$ for the reaction $\bar{p}p \to \pi^0 X$, which would give additional information on transversity.

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