THE QCD SPIN STRUCTURE OF NUCLEONS (SUMMARY OF PARALLEL SESSION 2)

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This paper attempts to summarise the highlights of the talks presented in Parallel Session II of the SPIN 2004 Symposium dedicated to the QCD spin structure of nucleons. Emphasis is put on new data and theoretical developments.

1. Introduction

The enormous interest in the spin structure of nucleons is reflected in the 55 accepted parallel talks in this session, comprising about an even number of theoretical and experimental presentations. About two-thirds of the experimental results came from lepton–nucleon scattering, while the rest were from pp interactions. A focus of the theory contributions was on transversity and single-spin asymmetries. This paper will not attempt to cover the excellent plenary talks on spin structure nor can it do justice to all the excellent talks in the parallel session.

2. Quark Helicity Distributions

The spin-dependent structure functions $g_1(x, Q^2)$ of the proton, the deuteron and the neutron are well known by now. However, the lack of data from colliders at small x and large Q^2, limit the information obtainable from an analysis of the Q^2 evolution. HERMES at DESY completed its programme with longitudinal polarisation and presented their quasi-final results[1] for g_1 of the proton, the deuteron and the neutron. COMPASS showed its first A_1 deuteron data[2] from the 2002 and 2003 runs. For $x < 0.03$ these are the most precise data yet (Fig. 1). The somewhat negative tendency of the SMC data in this region is not reproduced. During 2004 about the same amount of data was recorded and the larger-x region will additionally profit from an improved trigger set up.

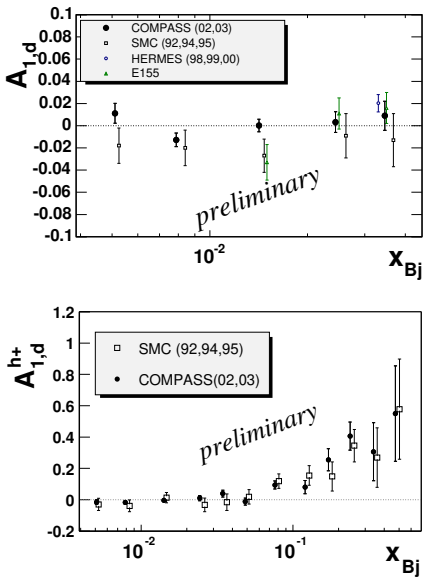

Figure 1. Virtual photon asymmetry $A_1^{\rm d}$ for the deuteron from COMPASS 2002 and 2003 data:[2] inclusive asymmetry for $x < 0.04$ (top), asymmetry for positive hadrons (full x-range, bottom).

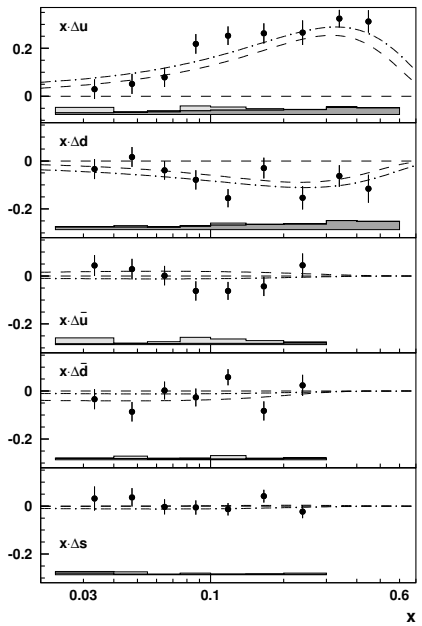

Figure 2. The quark helicity distributions $x\Delta q(x)$ at fixed $Q^2 = 2.5$ GeV^2 from HERMES.[4] The strange quark distribution $x\Delta s$ was determined assuming $x\Delta\overline{s} \equiv 0$.

In the valence-quark region $x > 0.2$ new highly precise data became available from Jefferson Lab. The ^{3}He neutron data[3] from E99-117 show for the first time a clearly positive asymmetry $A_1^{\rm n}$ for $x \simeq 0.6$. The deviation from pQCD predictions may hint to a possible effect due to quark orbital angular-momentum.[3]

To disentangle the contributions of the various quark flavours to g_1 requires semi-inclusive deep inelastic scattering, where the detected final-state hadron 'remembers' the flavour of the originally hit quark. In particular the interesting polarisation of the strange quarks cannot be determined by inclusive DIS off proton and neutron (deuteron) targets. New semi-inclusive asymmetries were presented by COMPASS.[2] In Figure 1 (bottom) the asymmetries for positive hadrons are shown reaching down to $x \simeq 5 \cdot 10^{-3}$ for $Q^2 > 1$ GeV^2. Similar results exist for negative hadrons, while the kaon asymmetries are still being analysed. HERMES analysed its data, including the asymmetries from identified kaons, in terms of the

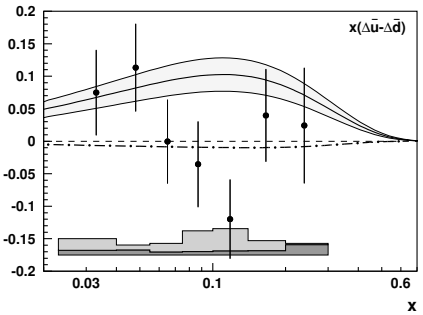

Figure 3. The difference $x(\Delta\overline{u} - \Delta\overline{d})$ as function of x from HERMES[4] at $Q^2 = 2.5$ GeV^2.

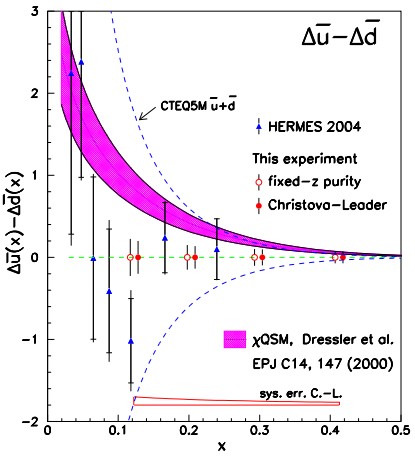

Figure 4. Results for $\Delta\overline{u}(x) - \Delta\overline{d}(x)$ expected from Semi-SANE.[7]

five quark distributions:[4] Δu, Δd, $\Delta\overline{u}$, $\Delta\overline{d}$ and Δs at fixed $Q^2 = 2.5$ GeV^2 and assuming $\Delta\overline{s} \equiv 0$. The up and down quark data confirm, with higher precision, earlier results. The up and down antiquark distributions as well as that of the strange quarks are compatible with zero (Fig. 2).

It is well known that there is a strong isospin asymmetry[5] in the unpolarised quark distributions $\overline{u}(x) - \overline{d}(x) \neq 0$, first observed as a violation of the Gottfried sum rule. The models describing this asymmetry predict also an isospin asymmetry for $\Delta\overline{u}(x) - \Delta\overline{d}(x)$. The HERMES data[4] are shown in Fig. 3 with two model predictions.[6] The data rather favour a symmetric sea. High precision data for $\Delta\overline{u}(x) - \Delta\overline{d}(x)$ with $x > 0.1$ are expected from a new JLAB experiment, semi-SANE (E04-113).[7] In Figure 4 the projected results are shown. The scattered electron is detected in a calorimeter, while the final-state hadron is detected in a magnetic spectrometer. The inversion of the magnetic field yields the same acceptance for oppositely charged hadrons while leaving the scattered-electron acceptance untouched. This opens the way to using a model-independent NLO method[8] involving positive and negative hadron data, in which the fragmentation functions cancel. A method using the first moments of the quark helicity distributions to determine $\Delta\overline{u}(x) - \Delta\overline{d}$ was also discussed.[9]

Higher-twist effects, double logarithm resummation, and matrix solutions for PDFs were presented in separate contributions.[10]

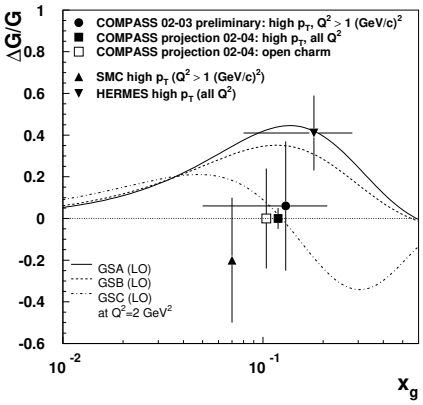

Figure 5. Gluon polarisation $\Delta G/G$ as function of x-gluon. The triangles and the circle correspond to data[11,12,13] while the squares indicate COMPASS projections.[12]

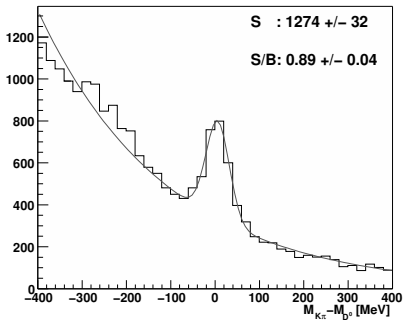

Figure 6. COMPASS invariant mass peak $M_{\mathrm{K}\pi} - m_{\mathrm{D}^0}$ from the $\mathrm{D}^0 \to \pi\mathrm{K}$ decay.[12]

3. Gluon Polarisation

Still little is known about the gluon helicity distribution, ΔG, which can in DIS either be determined from the Q^2 evolution of the quark helicity distributions or from processes involving photon–gluon fusion (PGF). The longitudinal double-spin asymmetry

$$A^{\ell N \to \ell' h h X} = \frac{\Delta G}{G} \langle \hat{a}_{LL} \rangle^{PGF} R^{PGF} + \frac{\Delta q}{q} \left\{ \langle \hat{a}_{LL} \rangle^{LP} R^{LP} + \langle \hat{a}_{LL} \rangle^{QCDC} R^{QCDC} \right\}$$

contains terms involving $\Delta G/G$ and those involving $\Delta q/q$. The latter is rather well known experimentally and the size of the relative contributions R must be estimated by Monte Carlo simulations. The partonic asymmetries $\langle \hat{a}_{LL} \rangle$ are known from theory. Determinations of $\Delta G/G$ from PGF using unidentified high-p_T hadron pairs and $Q^2 > 1$ GeV^2 were reported by SMC[11] and by COMPASS[12] (2002–2003 data). The results are shown in Fig. 5 together with a previous result from HERMES[13] (all Q^2). Both new results are compatible with zero and smaller than the HERMES value. Hadron pairs at $Q^2 < 1$ GeV are 10 times more abundant at COMPASS but their analysis is more model dependent and must take into account contributions from resolved photon processes. The cleanest signature for a PGF process is open-charm in the final state. COMPASS showed the first

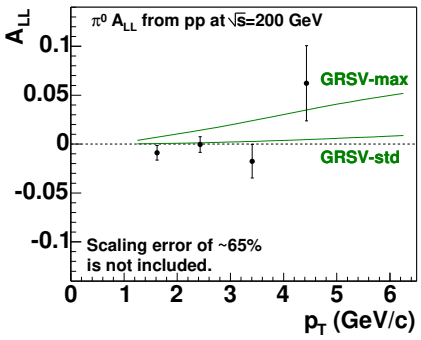

Figure 7. Double-spin asymmetry A_{LL} for π^0 production as a function of p_T from PHENIX.[14] The curves correspond to the respective GRSV[18] input gluon-distributions.

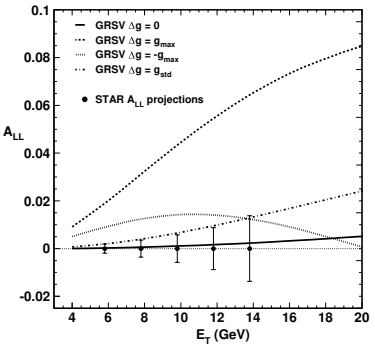

Figure 8. Projected data for A_{LL} from $\mathrm{pp} \to \mathrm{jet} + X$ at STAR. The curves correspond to GRSV:[18] g_{max}, g_{std}, $g = 0$, $-g_{max}$ (top to bottom on right side).

mass peak for D mesons (Fig. 6). The projected precision for $\Delta G/G$ from D^0 asymmetries and from all-Q^2 hadron pairs for their 2002–2004 data are also shown in Fig. 5.

The polarised proton–proton collisions at RHIC offer many channels to study the gluon polarisation. Given the limited beam polarisation (2003) and beam time (2004) the most promising channel is the double spin asymmetry in π^0 production, $\mathrm{pp} \to \pi^0 X$. The results[14] from PHENIX are shown in Fig. 7. The statistical significance is still very limited, but the big potential of this measurement becomes apparent taking into account the improvement in 2004 with respect to the 2003 data,[15] which is largely due to the improved beam polarisation. Also the STAR experiment expects significant data[16] for the gluon polarisation from the process $\mathrm{pp} \to \mathrm{jet} + X$ from the 2005 run (Fig. 8). In pp collisions gluon–gluon, gluon–quark and quark–quark partonic processes contribute yielding terms proportional to $(\Delta G/G)^2$, $(\Delta G/G)(\Delta q/q)$ and $(\Delta q/q)^2$. As a consequence an ambiguity concerning the sign of ΔG arises. Because of the quadratic term in ΔG there is almost no possibility to generate a negative asymmetry[17] as illustrated in Figs. 7 and 8.

Of central importance for the determination of $\Delta G/G$ from π^0 or prompt-photon production at RHIC is that the cross-section is well understood and reproduced by theory. Figures 9 and 10 demonstrate the good level of agreement for collider c.m.s. energies. Next-to-leading logarithm resummation and power corrections are an important element in the

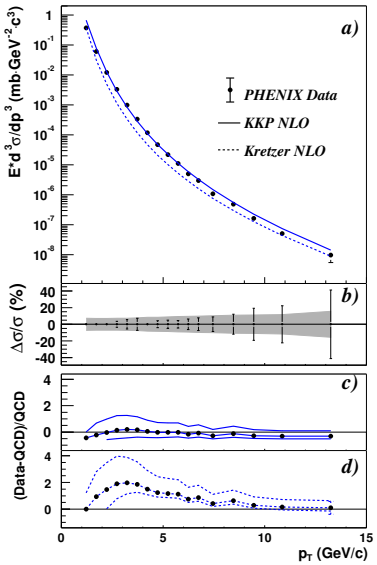

Figure 9. The invariant differential cross-section for inclusive π^0 production from PHENIX as function of p_T.[19,20] For details see Ref. 20.

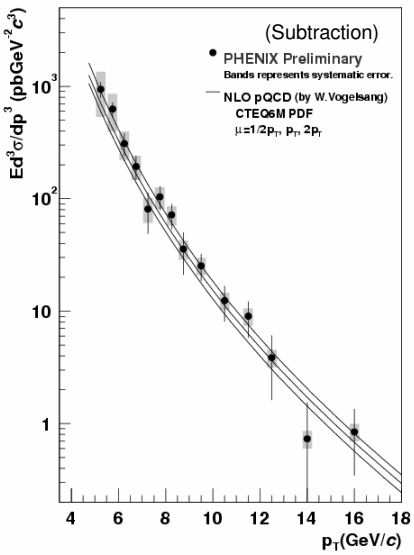

Figure 10. The invariant differential cross-section for photon production from PHENIX as function of p_T.[21]

calculation.[19,22]

The determination of the first moment of ΔG requires an extension of the limited kinematic range in which the gluon momentum fraction x_g is accessible with the present RHIC detectors. A considerable upgrade programme[23] is proposed for PHENIX, which will extent the limits down to $x_g \simeq 0.001$ at $\sqrt{s} = 200$ GeV. Hyperon polarisation and new observables in pp collisions were also discussed.[24]

4. Transverse Spin

New measurements of the single-spin transverse asymmetry A_N for neutral pion production were reported by PHENIX[25] for $x_F = 0$ and by STAR[26] for $0.2 < |x_F| < 0.6$. The asymmetry is consistent with zero for $x_F < 0.4$ and positive for larger x_F. This behaviour is reproduced[27] by the Sivers effect in a generalised leading-order pQCD model[28] using k_T-dependent PDFs and fragmentation functions. The model also describes the FNAL-E704 pion data[29] by the Sivers effect (Fig. 11). On the other hand even a fully saturated Collins mechanism[30] cannot reproduce these data (Fig. 12).

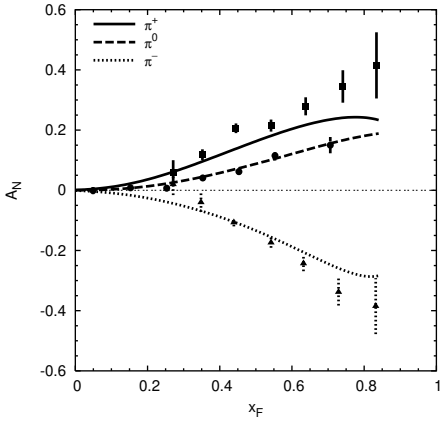

Figure 11. E704 data[29] described by the Sivers effect in the k_T model.[27,28]

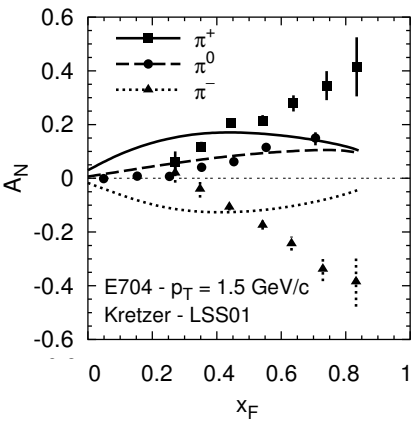

Figure 12. Attempt to describe the E704 data[29] purely by the Collins effect.[28,30]

In the same model it was shown that D-meson production at RHIC in $\mathrm{p}\uparrow \mathrm{p} \to \mathrm{D}X$ is an ideal place to study the gluon Sivers-distribution.[31] Also the Sivers asymmetries from HERMES[32] can be described in this model.[33]

A full next-to-leading order calculation[34] is now available for prompt-photon production and other cross-sections in $\mathrm{p}\uparrow \mathrm{p}\uparrow$ collisions. The scale dependence is strongly reduced as compared with LO calculations.

Both, COMPASS[35] and HERMES,[32] presented first results on Collins and Sivers asymmetries (Figs. 13 and 14). For the deuteron, both the Collins and Sivers asymmetries, are compatible with zero while for the proton there is a hint of positive values for favoured and of negative values for unfavoured fragmentation. For both experiments more data are available and being analysed. New quark polarimeters may help to get a better handle on the transversity distributions. The experiments had already a first look[36] at the proposed di-hadron fragmentation,[37] which avoids a k_T convolution. Drell–Yan processes in polarised pp collisions and even $\mathrm{p}\bar{\mathrm{p}}$ collisions at the future PAX experiment are other channels to look for transversity.[38]

New precise COMPASS data[39] on the spin transfer to lambdas and antilambdas and the spin density matrix in exclusive ρ production are in good agreement with previous data. New data also were presented on transverse lambda polarisation.[40]

In the context of Generalised Parton Distributions HERMES presented new results for the beam-charge asymmetry in deeply-virtual Compton-scattering off a deuteron target and for vector meson production.[41]

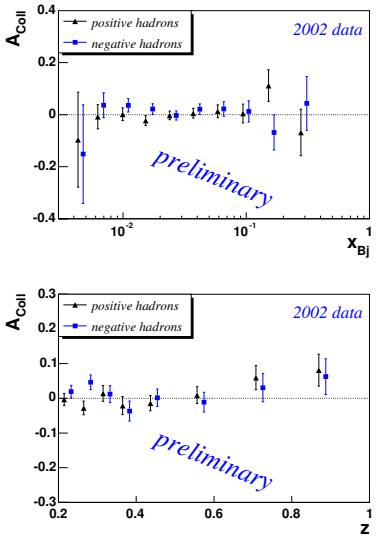

Figure 13. COMPASS 2002 deuteron data:[35] Collins asymmetries as function of x_{Bj} (top) and of z_h (bottom) for positive and negative hadrons.

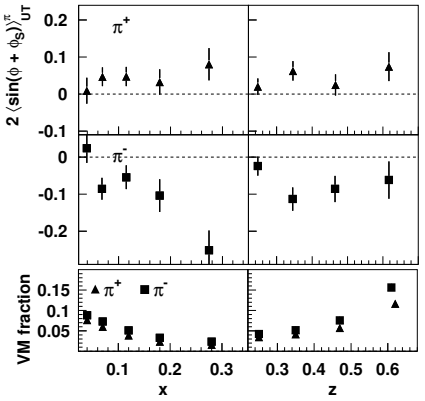

Figure 14. HERMES 2002/3 proton data:[32] Collins asymmetries as function of x_{Bj} (left) and of z_h (right) for positive (top) and negative (bottom) pions. The bottom panel shows the indicated the contribution from exclusively produced vector mesons from PHYTHIA Monte Carlo.

5. Outlook

A wealth of new experimental results was presented at the Spin Symposium including first data from COMPASS and RHIC. A precise measurement of the gluon polarisation in lepton–nucleon and in pp interactions is around the corner and first results were already presented. The second missing piece in our understanding of the nucleon's spin structure is transversity and also here we saw first data from COMPASS and HERMES. The progress of the phenomenological models as well as that in NLO QCD theory will allow us to take full advantage of the wealth of experimental results.

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