SPIN PHYSICS

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We review recent experimental and theoretical progress in spin physics, as presented in the spin parallel session of DIS2006. In particular, we discuss the status of the nucleon spin structure, transverse polarized asymmetries, and recent developments such as DVCS, polarized fragmentation and polarized resummation.

1. The polarized structure of the nucleon

Experimental and theoretical studies of spin physics in the last several years have considerably widened their scope. Inclusive polarized deep-inelastic measurements, and their interpretation in terms of polarized quark and gluon structure functions, are now supplemented by measurements of semi–inclusive processes, heavy quark production and high–P_T hadron production and deeply–virtual Compton scattering (DVCS) in lepton–nucleon scattering, by data collected in a variety of hard processes at the polarized hadron collider RHIC, and by data on polarized fragmentation from e^+e^- machines. Their interpretation requires both a deepening and a widening of available theoretical tools. The wealth of new data on the spin structure of the nucleon requires the use of the more advanced techniques that are being developed in the unpolarized case for the description of the parton structure of hadrons, specifically in view of the LHC:[1] higher order QCD computations, resummation, global parton fits with errors. Also, new quantities must be introduced, along with their theoretical interpretation within QCD: polarized fragmentation functions, transverse momentum distributions and orbital angular momentum, transverse spin distributions and their cognates.

In this brief review, based on the presentations in the spin working group at DIS06, we will first review the status of the nucleon spin problem: we will summarize new determinations of the polarized parton distributions Δq and Δg in lepton scattering at CERN and DESY and in proton–proton scattering at RHIC, and first data on DVCS from HERMES, and we will discuss their theoretical analysis and interpretation. We will then summarize recent progress on transverse spin asymmetries: we will review several recent asymmetry measurements in hadron production at CERN, DESY and RHIC, and we will review recent progress in the formulation of a unified approach to transverse single–spin asymmetries based on perturbative factorization. Finally, we will discuss several recent new developments which extend the range of experimentally accessible quantities and computational techniques to the polarized case: specifically, we will analyze measurements of polarized fragmentation (BELLE and COMPASS) and structure functions at low Q^2 (JLab experiments), and discuss the development of polarized resummation methods.

2. The nucleon spin puzzle

As well known, the nucleon spin problem[3] has to do with the fact that, loosely speaking, the measured quark spin fraction is small. One may wonder why this is a problem: given that the nucleon mass is not carried by the quark masses, and only about half of it is due to quark interactions, why should the nucleon spin be carried by the quark spin? The answer is, of course,[4] that what is surprising is the violation of the OZI rule: nucleon matrix elements of the singlet axial current are much smaller than those of the octet, i.e. $a_0 = a_u + a_d + a_s \ll a_8 = a_u + a_d - 2a_s$, where the axial charges a_i are just the forward quark current matrix elements from flavor i: $\langle N; p, s|J^{\mu}_{5,\,i}|N; p, s\rangle = a_i M_N s^{\mu}$.

Explanations of this fall in two broad classes: either the singlet is special, because it can couple to gluons, or the octet is special, because strangeness in the nucleon is much larger than one might expect. Hence, in order to understand the spin puzzle one needs precise measurements of the gluon, strange and antistrange quark distributions, specifically their first moments.

Also, a_0 and a_8 currently are not determined directly, but rather from the combination of a direct measurement and the indirect determination of an independent linear combination, obtained using SU(3) from baryon octet beta–decay rates. A direct measurement of the nucleon axial charge for each flavor would be desirable: this, in turn, entails the determination

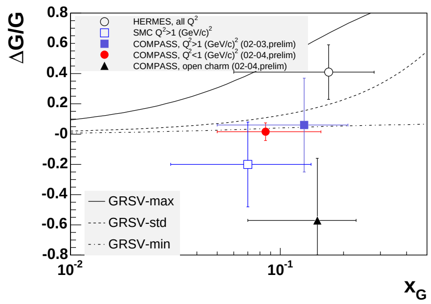

Figure 1. The gluon polarization obtained by COMPASS from high-p_T hadron pairs and open charm production, compared to SMC and HERMES determinations from high-p_T hadron pairs.

of the first moment of all polarized light quark and antiquark densities, as well as of the polarized gluon density, that mixes in the singlet.

2.1. *Experimental results on Δq and ΔG*

New experimental results relevant for the determination of polarized parton distributions have been obtained recently both in lepton DIS (COMPASS and HERMES) and in proton–proton scattering (STAR and PHENIX).

At the inclusive DIS level, the COMPASS experiment presented A_1^d and g_1^d results for $Q^2 > 1$ GeV^2.[5] This new results improves their QCD analysis, and it gives $\Delta\Sigma = 0.25 \pm 0.02$ (stat) and $\Delta G = 0.4 \pm 0.2$ (stat) at $Q^2 = 3$ GeV^2.

At the semi-inclusive level, the HERMES experiment obtained updated $\Delta s + \Delta\bar{s}$ distribution from their DIS measurement and semi-inclusive $K^+ + K^-$ measurement with the polarized-deuterium target.[6] Since the strange quarks carry no isospin and the deuteron is an isoscalar target, they obtained $\Delta s + \Delta\bar{s}$ with two assumptions, isospin symmetry between proton and neutron, and charge-conjugation invariance in fragmentation. They also obtained the fragmentation functions needed in this analysis from multiplicities directly at HERMES kinematics with the same data. The result shows that for the $K^+ + K^-$ fragmentation function from non-strange quarks the strangeness suppression factor for $s + \bar{s}$ production is important. The $\Delta s + \Delta\bar{s}$ distribution is consistent with zero with improved uncertainties.

COMPASS can access ΔG directly by three methods, high-p_T hadron-pair measurement at low Q^2 and at high $Q^2 > 1$ GeV^2, and open charm production.[7] Results are summarized in Fig.1: either ΔG is small or it has

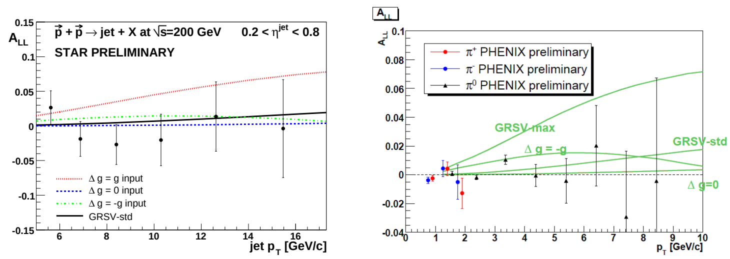

Figure 2. The double helicity asymmetry in the inclusive jet production measured by STAR (left) and that in the inclusive π^0 production measured by PHENIX (right) at midrapidity in polarized $p+p$ collisions.

a node at $x \sim 0.1$. However, a first moment of $\Delta G \sim 0.4$ at low scale is not excluded.

First results relevant for the determination of ΔG were recently obtained by RHIC experiments. The STAR experiment presented their preliminary result of the double helicity asymmetry in inclusive jet production at midrapidity in polarized $p+p$ collisions.[8] The result shown in Fig.2 is limited by statistical uncertainties and it cannot distinguish between different scenarios for the gluon polarization, though it disfavors a large value of ΔG. The PHENIX experiment presented results for the double helicity asymmetry of inclusive π^0 production at midrapidity in polarized $p+p$ collisions.[9] The result, shown in Fig.2, also disfavors large ΔG and excludes scenarios where ΔG is as large as G at low scale (GRSV-max) .

2.2. *Orbital angular momentum and DVCS*

The only known way to access experimentally the orbital angular momentum is through a measurement of generalized parton distributions (GPDs). GPDs can be determined e.g. in deeply virtual Compton scattering (DVCS). HERMES has provided a first determination of the transverse target-spin asymmetry associated with DVCS, $A_{UT}(\phi, \phi_S)$, on the proton.[10] The $\sin(\phi - \phi_S)\cos(\phi)$ term of $A_{UT}(\phi, \phi_S)$ is sensitive to J_q. A model-dependent constraint on J_u and J_d was obtained by comparing the asymmetry and the theoretical predictions based on a GPD model. Figure 3 shows the result and comparison with a quenched lattice-QCD calculation.

2.3. *The state of the art: partial results and global fits*

Inclusive deep-inelastic experiments can only lead to the determination of one linear combination of quark plus antiquark polarized densities,

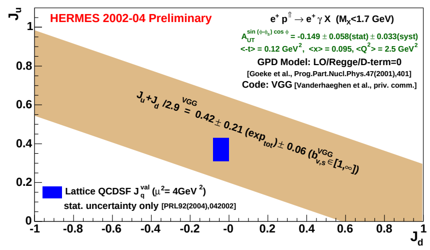

Figure 3. A model-dependent constraint on J_u and J_d obtained by HERMES and comparison with a quenched lattice-QCD calculation.

$g_1 \sim \sum_i e_i^2 (q_i + \bar{q}_i)$ — two, if proton and deuteron targets are available. Also, they only provide a weak handle on the gluon through scaling violations, due to the smallness of the relevant first moments of polarized anomalous dimension (see Fig 4). Hence, they only determine accurately the isotriplet (Bjorken sum rule), while the singlet quark and gluon first moments are affected by large uncertainties, and there is essentially no information on total strangeness.[3] Recent more precise inclusive data[5] further improve the Bjorken sum rule and provide some more information on the small x behavior of the g_1 structure function, but cannot change this situation.

This is why recent effort has concentrated on less inclusive observables. Semi–inclusive deep–inelastic scattering (SIDIS) seems especially useful for the determination of individual polarized flavors and antiflavors. At leading perturbative order, one can form combinations of measurable asymmetries which are independent of fragmentation and thus measure polarized flavors and antiflavors directly: specifically, the strange polarized distribution.[6]

However, such a leading–order analysis is only accurate if the dominant contribution to fragmentation into a given hadron comes from the quark carrying the corresponding flavor quantum number: i.e., it assumes the validity of the very OZI rule whose violation we are trying to understand. Indeed, a full NLO fit including all available DIS and SIDIS data[13] (see Fig 5) shows that e.g. the first moment of the anti-up distributions changes by a factor two from LO to NLO, and can even change sign according to

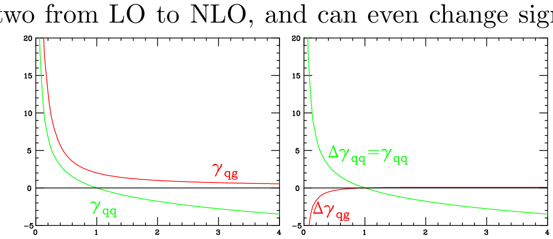

Figure 4. Unpolarized (left) and polarized (right) anomalous dimensions.

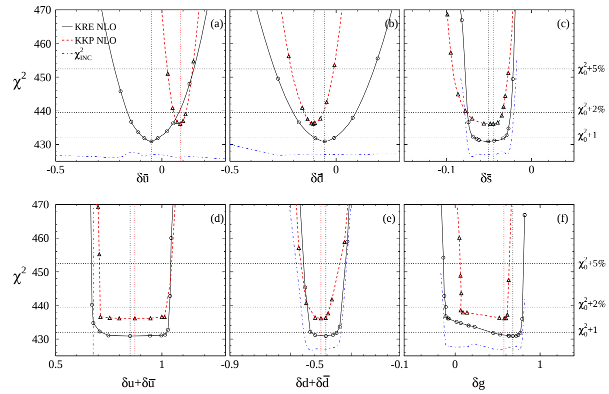

Figure 5. Global fit to inclusive and semi–inclusive deep–inelastic scattering data . (From Ref. [13])

the choice of fragmentation functions.

Analogously, there are intriguing suggestions that available information may provide a handle on Δg: for example, a shortfall of a leading–order determination of inclusive DIS polarized asymmetries at medium–small $x \sim 0.05$ may be related[11] to the presence of a sizable positive $\Delta g(x)$ at large $x \sim 0.3$ (see Fig. 6). However, the same effect can also be explained by higher twist contributions[12] (see Fig. 8).

Whereas RHIC provides us with many processes which are sensitive to Δg, and for which higher twist corrections are small and no further non–perturbative input (such as from fragmentation functions) is required, it remains true that NLO corrections are generally quite large. In particular, polarized K–factors are neither small nor constant (see Fig. 7), and therefore the full available NLO information must be used.[14]

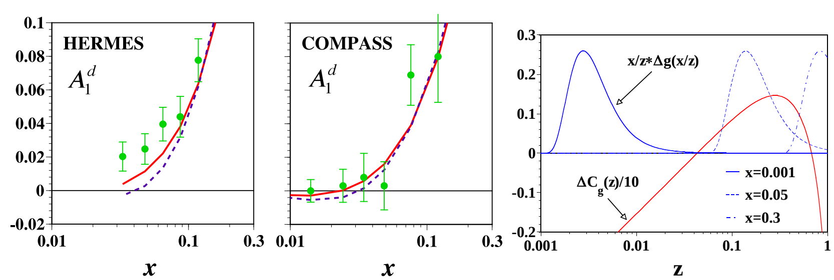

Figure 6. Possible evidence for large $\Delta g(x)/g(x$ at large x from HERMES and COMPASS data. (From Ref. [11])

Furthermore, it is important to remember that the scale dependence of the first moment of ΔG is quite strong: at leading order, it evolves as $\frac{1}{\alpha_s(Q^2)}$, so that e.g. it varies by a factor two when the scale is increased from, say 1 to 15 GeV^2 (see Fig. 9). This, together with the potentially large K–factors, should be kept in mind when comparing different determinations of ΔG, such as in fig. 1 Therefore, the interesting COMPASS charm production data are likely to play a significant role in the determination of ΔG only if the corresponding NLO corrections (presently available for polarized charm photoproduction and hadroproduction, but not electroproduction) will become available, while double–inclusive large p_T hadrons are unlikely to play an important role in the near future.

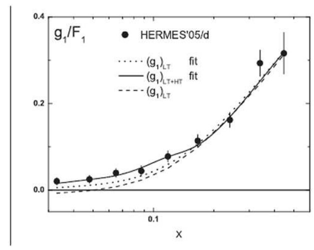

Figure 8. Possible evidence for higher twist contributions from HERMES data. (From Ref. [12])

Because the very many independent processes which will soon be measured at RHIC are sensitive to both the gluon and individual light flavors and antiflavors, it is likely that both a direct determination of a_0, a_8 and a handle on the first moment of Δg will soon be possible. Yet, the separation of polarized strangeness and antistrangeness will probably only be possible at a neutrino factory. and a precise determination of ΔG including the

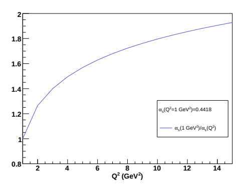

Figure 9. Leading–order scale dependence of the first moment of ΔG.

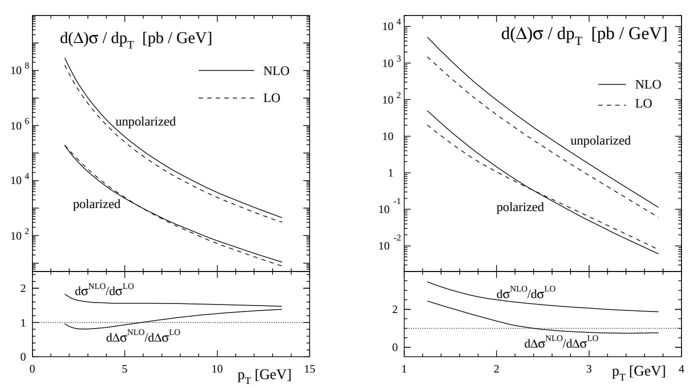

Figure 7. Cross–sections and K–factors for single–inclusive pion production at RHIC (left) at COMPASS (right). (From Ref. [14])

small x region will have to wait for eRHIC. However, it will only be possible to extract this information from the data through a global fit, and no single experiment is likely to be sufficient.

The conclusion on Δs and ΔG from present–day data is therefore not very different from what it was after the latest and most precise inclusive DIS data:[3] the first moment of the polarized gluon is likely to be positive, though there are some indications that it might be smallish (i.e. $\left(\frac{n_f}{2\pi}\right)\alpha_s(Q^2)\Delta G \lesssim \frac{1}{2}a_0$), and the first moment of the total strangeness is likely to be negative.

3. Transverse spin asymmetries

Many new determinations of transverse spin asymmetries have been performed recently, both in lepton proton and proton–proton scattering. Correspondingly, significant progress has been made in the interpretation of these measurements.

3.1. *Experimental results*

Collins moments and Sivers moments of the transverse single-spin asymmetry (SSA) with a polarized-proton target for semi-inclusive charged pions and kaons have been determined by HERMES.[15] The Collins moments of π^+ and π^- have positive and negative asymmetries respectively, that of K^+ has a small or zero asymmetry, and that of K^- has a positive asymmetry. The Sivers moments of π^+ and K^+ have positive asymmetries, and those of π^- and K^- show small or zero asymmetries. These results support the existence of non-zero chiral-odd and T-odd structures that describe the transverse structures of the nucleon. First measurement for kaons suggest that sea quarks may provide an important contribution to the Sivers function.

COMPASS presented their SSA results with a polarized deuterium target for Collins and Sivers moments.[16] Both are consistent with zero. The difference in comparison to HERMES may be explained by a cancellation between proton and neutron.

From RHIC, new SSA results, shown in Fig.10, were presented by the BRAHMS experiment.[17] The SSA of π^+ (π^-) displays positive (negative) asymmetries, of order 5-10% for $0.1 < x_F < 0.3$. The SSA of π^+ for $0.2 < x$ is in agreement with twist-3 calculations. The SSAs of K^+ and K^- are positive and similar to each other, in disagreement with naive expectation from valence quark fragmentation. The SSA for the proton is consistent

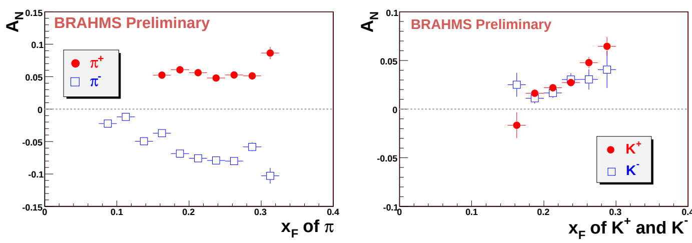

Figure 10. Single spin asymmetries of pions and kaons at BRAHMS.

with zero, while that for the antiproton is positive. The cross sections for $\pi^{\pm}$, $K^{\pm}$, proton and antiproton measured in the same kinematic ranges are in agreement with NLO QCD calculations.

STAR presented π^0 asymmetries obtained with their forward and backward detectors.[18] The asymmetries are positive in the forward region, and consistent with zero in the backward region. The forward asymmetries bhave as $1/p_T$, as expected from perturbative QCD.

PHENIX presented updated asymmetries of charged hadrons at midrapidity, which are consistent with zero.[19] They also presented neutron asymmetries in the most forward region. The asymmetry is higher when there is a charged particle activity in the beam-beam counters. The SSA is produced via interference of spin flip and spin non-flip amplitudes. The one pion exchange model may explain the result, as it aslo explains the neutron cross sections at ISR.[20]

Table 1. Summary of single spin asymmetry measurements.

HERMES			COMPASS		
proton	Collins	Sivers	deuteron	Collins	Sivers
π^+	+	+	h^+	0	0
π^-	−	0	h^-	0	0
K^+	0	+			
K^-	+	0			

PHENIX			STAR			BRAHMS		
h^+	midrapidity	0				π^+	forward	+
h^-	midrapidity	0				π^-	forward	−
π^0	midrapidity	0	π^0	forward	+	K^+	forward	+
n	zero-degree	−	π^0	backward	0	K^-	forward	+
						p	forward	0
						$\bar{p}$	forward	+

The measured SSAs are summarized in Table 1. A full theoretical understanding of these results is still missing.

Finally, a high-statistics measurement of the single-spin asymmetry of the proton–proton elastic scattering in the Coulomb Nuclear Interference (CNI) region has been presented by the RHIC polarimeter group.[21] The measured real and imaginary parts of the hadronic spin-flip amplitude, as well as the transverse double-spin asymmetries are consistent with zero, suggesting that double spin-flip amplitudes are very small. New beam-energy dependence results have been presented for the proton–Carbon elastic scattering in the CNI region.

3.2. *Theoretical progress*

The measurement of large transverse spin asymmetries is theoretically challenging, because these asymmetries are negligible in the parton model: a transverse single spin asymmetry requires a helicity flip, and it is thus $O\left(\alpha_s \frac{m_q}{\sqrt{Q^2}}\right)$. In perturbative QCD, transverse asymmetries in the Collins and Sivers processes can be viewed in two distinct ways: from a parton point of view, as a manifestation of the presence of an intrinsic dependence of parton distributions on transverse momentum, or from an operator point of view as the effect of contributions from twist three quark–gluon correlation.

Recent theoretical progress[22,23] has led to a common picture, where these two point of views can be unified, analogously to what happens for the standard leading–twist collinear factorization. The basis of the unification is a relation between the transverse–momentum dependent quark distribution, and the relevant twist three operator. Specifically a transverse cross section difference (e.g. in SIDIS or Drell-Yan) can be schematically factorized as

$$\Delta d\sigma \sim \epsilon_{\alpha\beta} s_\perp^\alpha p_\perp^\beta \int \frac{dx}{x} \int \frac{dz}{z} q(z) T_F(x, x - xg), \qquad (1)$$

where $q(z)$ is a conventional (collinear) quark distribution and $T_F(x_1, x_2)$ is a twist–three quark-gluon correlation. It can then be shown[22] that the quark–gluon correlation is related by $T_F(x,x) = \int d^2k_\perp |\vec{k}_\perp|^2 q_T(\vec{k}_\perp, x)$ to the transverse–momentum dependent quark distribution $q_T(\vec{k}_\perp, x)$, defined in terms of a suitable nucleon matrix element of a quark-quark bilinear connected by a gauge link.

One can show[23] that when $k_\perp \ll Q$ the single–spin asymmetries can be factorized in terms of $q_T(\vec{k}_\perp, x)$, convoluted with a transverse fragmentation function (Sivers function), and a perturbatively computable factor related to soft gluon radiation. The $k_\perp$ dependence of $q_T(\vec{k}_\perp, x)$ can then be computed perturbatively. Substituting the result of the latter computation in the former factorized expression, the expression eq. (1) for the cross section is reobtained, thus showing the equivalence of the two approaches. Furthermore, it can be shown that the transversity structure is universal:[22] for instance, the Sivers functions for Drell-Yan and SIDIS are both given in terms of a single process-independent function, determined by partonic matrix elements. In fact, the Boer–Mulders $h_1^\perp$ and Sivers $f_{1T}^\perp$ functions can all be expressed in terms of $2n_f + 1$ universal quark and gluon matrix elements. These results impose powerful constraints on phenomenological studies of single spin asymmetries, and they can guide the construction of phenomenological models[24] for the Sivers function.

4. Stretching the boundaries

The widening of the scope of spin physics has led to an extension to the polarized case of lines of experimentation and theoretical analysis which hitherto had been explored only at the unpolarized level.

4.1. *Fragmentation*

The BELLE experiment has measured a significant non-zero asymmetry in the double ratio of unlike-sign pion pairs to like-sign pion pairs (UL/L) produced from $e^+e^- \rightarrow q\bar{q}$ reactions in the off-resonance region.[25] The asymmetry is sensitive to the Collins fragmentation function, but it is not very sensitive to the favored to disfavored Collins function ratio. A new double ratio of unlike-sign pion pairs to charged pion pairs (UL/C), which is sensitive to the favored + unfavored Collins function, has been measured to be about half of the UL/L asymmetry.

The COMPASS experiment has measured both longitudinal and transverse polarization transfers of Λ and $\bar{\Lambda}$ production.[26] By averaging over the target polarization, they determine the polarized fragmentation functions, $\Delta D_{\Lambda/q}(z_h)$. The longitudinal polarization transfer provides a test of $q\bar{q}$ symmetry of the polarized strange sea in the nucleon. Results shows similar longitudinal polarization for Λ and $\bar{\Lambda}$ in spite of different production mechanism. The transverse polarization transfer gives information on initial transverse quark polarization $\Delta q_T(x)$ in the nucleon. The result shows a slight tendency towards negative polarization transfer, and a small positive spontaneous transverse polarization of Λ and unpolarized $\bar{\Lambda}$.

4.2. *Structure functions at low Q^2*

Structure function measurements have been recently extended to the low-Q^2 region. At low Q^2 and low x, g_1 can be compared to predictions from Regge theory, VMD and low–energy models. The COMPASS experiment presented a high precision A_1^d measurement at $Q^2 < 1$ GeV^2 $0.00005 < x < 0.02$.[16] The measured A_1^d and g_1^d are compatible with zero.

The JLab experiments are measuring g_1 in the nucleon resonance region, thereby investigating parton-hadron duality, both global (integrated in x) and local in x. The CLAS experiment in Hall B has investigated the duality property of g_1^p and g_1^d at low Q^2.[27] Quark-hadron duality seems to be supported at the global level, and and also locally in some of the resonance regions. The E01-012 experiment at Hall A is measuring g_1 and g_2 on the ^{3}He target,[28] and the RSS experiment at Hall C is measuring them on proton and deuteron targets.[29]

4.3. *Resummation*

Current and future polarized experiments will involve processes and kinematical regions where fixed order computations are not sufficient, and this has stimulated the extension to the polarized case of resummation techniques: specifically, resummation of an inclusive process close to its kinematic threshold, such as Drell-Yan when $Q^2 \to s$, and resummation of the p_T distribution at small p_T.

Threshold resummation for the polarized Drell-Yan process is important for future experiments at J-PARC and GSI. Threshold resummation up to the next-to-leading logarithmic (NLL) level for the transverse Drell-Yan spin asymmetries have been performed in Ref.[30], both inclusive and differential in rapidity; and up to NNLL in the unpolarized case. The resummed K-factors are large, leading to an increase of the cross section by a large factor for invariant masses above ~ 4 GeV^2, but essentially spin independent, so that the asymmetry is only moderately affected.

The resummation of the q_T distribution for the transversely polarized Drell-Yan process is necessary even at RHIC energies, because the unresummed cross section diverges as $q_T \to 0$. A determination of the resummed cross section up to the NLL level [31] shows that unresummed result are in fact unreliable even for intermediate values of $q_T \sim Q/4$, where the cross–section difference is peaked: the resummation gives the dominant contribution, and unresummed results are reproduced only for large $q_T \sim Q$, where the cross section is very small.

The resummation of the q_T distribution has also been performed [32] for the q_T spectrum of single–inclusive hadron production in DIS, in the unpolarized case, for longitudinally polarized electron and proton, for longitudinally polarized incoming electron and outgoing hadron, and both for longitudinally and transversely polarized incoming proton and outgoing hadron. The case of longitudinal *ep* polarization is relevant for the COMPASS and HERMES experiments discussed in Sect. 2. In this case, one finds that, for the kinematics of these experiments, the impact of resummation effects is again rather large, but it largely cancels in the asymmetry.

A difficulty in the determination of resummed results is due to ambiguities caused by the fact that at the resummed level the strong coupling hits the Landau pole. These ambiguities are moderate in threshold resummation, but become more important in q_T resummation. For the case of SIDIS, the ambiguity can be as large as the whole resummation, which suggests that a purely perturbative treatment of the process is not really possible, and further undermines its usefulness for determinations of the polarized hadron structure.

5. Outlook

Considerable progress is expected in the near future thanks to the completion of the COMPASS and especially RHIC experimental programs. On top of the forthcoming determinations of ΔG discussed in Sect. 2, RHIC experiments will determine the flavor decomposition of quark and antiquark polarization through W production at $\sqrt{s} = 500$ GeV.[33,34] Future experiments at J-PARC and GSI will further explore longitudinal and transverse polarized distributions of quarks and antiquarks through the Drell-Yan process.[35]

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