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Spin physics in deep inelastic scattering: Summary

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Abstract. The problem of our understanding of the spin structure of the nucleon has been with us since the publication of the EMC measurements of the polarised structure function of the proton in 1987. In this talk a review of the results presented in Working Group 6 at this workshop is given.

1. Brief History

In the simple quark model the spin of the proton is carried by its three valence quarks so that $\Delta\Sigma = \Delta u + \Delta d = 1$. Here $\Delta q = \int_0^1 dx\ (q_\uparrow(x) - q_\downarrow(x))$ where $q_{\uparrow(\downarrow)}(x)$ are distributions for quarks with spin aligned (anti-aligned) to the proton spin and $q = u, d$, etc. indicates the quark flavours. The simple quark model has however proven to be inadequate long before precise measurements of the proton spin structure became available, since it predicts that the ratio of the axial vector to vector coupling constants in neutron β decay is $g_A = 5/3$ compared to the measured value of 1.26.

The parton model ascribes part of the proton spin to sea-quarks and gluons. All partons in the proton can moreover possess orbital angular momentum, which also contributes to the proton spin. Within this model, the proton spin can no longer be identified with the sum of the quark spins only, and $\Delta\Sigma$ can therefore not be predicted without making additional assumptions. The best-known theoretical prediction of $\Delta\Sigma$ is due to Ellis and Jaffe [1]. Using SU(3)-flavour symmetry with the additional assumption of vanishing of the contribution from strange quarks to the proton spin, they obtain $\Delta\Sigma \approx 0.58$.

Deep inelastic scattering (DIS) with polarised charged leptons on polarised targets allows the quark distributions $q_{\uparrow(\downarrow)}$ to be investigated. These are extracted from the structure function $g_1(x, Q^2)$ measured in polarised DIS using the parton model relation $g_1(x, Q^2) = \frac{1}{2}\sum_q e_q^2\ (q_\uparrow(x) - q_\downarrow(x))$. In the early 1980s the SLAC experiments E80 and E130 [2] reported the first measurements of polarised DIS for $x > 0.1$. In 1988, the EMC reported measurements [3] over a range down to $x = 0.015$. For $x > 0.1$ all the data (extrapolated to $x = 0$ for the determination of $\Delta\Sigma$) seemed to confirm the expectations of Ellis and Jaffe. However, as x decreased the EMC data fell progressively below the expectations of the quark parton model and yielded a very small $\Delta\Sigma$, which was even consistent with zero at that time. The value of $\Delta\Sigma$ has increased since then due to the refinement of our knowledge of F and D, the SU(3) couplings measured in hyperon beta decay (see [4] for the latest analysis). However, there is still a significant difference of the measurement from the value expected from the Ellis-Jaffe sum rule. The significance of this disagreement implies that only a small fraction of the spin of the proton is carried by quark spins.

This surprising result created great theoretical interest. Where was the spin of the nucleon ? Could it be in the gluons (Δg) as suggested in [5, 6] or could it be in orbital angular momentum (L_q, L_g) [7]. By angular momentum conservation the total spin of the nucleon of 1/2 must be equal to $1/2\ \Delta\Sigma + \Delta g + L_q + L_g$. It was also suggested that the problem did not exist and part of $\Delta\Sigma$ was missed in the unmeasured region at very small x [8]. All this interest motivated a new experimental programme to investigate the phenomenon further and this programme is now coming to fruition.

On the theoretical side, much confusion was caused by the scheme dependence of $\Delta\Sigma$ in higher orders of perturbative QCD. This problem could only be resolved three years ago with the calculation of the two-loop polarized splitting functions, [9], now allowing to define consistent transformations between different factorization schemes [10]. In the recent past, the next-to-leading order QCD corrections for the majority of the experimentally relevant polarized observables have been calculated, see for example [11] for a review.

2. Recent Experimental Results

The SMC has presented data over the widest range of x on the polarised structure functions [11, 12]. The collaboration has greatly improved the precision of the data at low x by demanding an observed hadron in each event. This rejects radiative and other events with low depolarisation factors. The remaining events are then undiluted by data of poor significance for the asymmetry determination allowing the asymmetry to be measured more precisely. Furthermore, a much lower Q^2 trigger has been implemented which allows asymmetries to be measured in the range $10^{-4} < x < 10^{-3}$. The data from this trigger serve to investigate the Regge region to search for a possible divergence at low x such as proposed in [8]. Fig. 1 shows the SMC data [13] with the behaviour of $g_1 = 0.17/x \ln^2 x$ (solid curve) proposed by [8]. Such behaviour is now excluded by the data. However, the less extreme behaviours $g_1 = -0.14 \ln x$ (dashed curve) and $g_1 = -0.085(2 + \ln x)$ (dotted curve) which were also proposed in [8] cannot be excluded. All the curves were calculated assuming a value of $R = \sigma_L/\sigma_T = 0$. Hence they represent lower limits since the curves scale as $1 + R$. The first of these behaviours would make a sizable difference to the determination of $\Delta\Sigma$ so its exclusion removes a significant uncertainty.

Direct comparison of these data with the double logarithmic small-x resummations of [14] is difficult due to the low Q^2 values involved. A model for extending these resummations into the low Q^2 region is discussed in detail in these proceedings [15], it is in good agreement with the data.

The SMC group have made NLO QCD fits to the world data in an attempt to determine Δg, [11, 12, 16]. The theoretical error on this quantity can be estimated by varying renormalization and factorization scales in the fits [10]. These variations generate terms which are compensated only in the NNLO order expressions, such that the resulting error can be taken as a measure of the importance of higher orders in the perturbative series. In [12] this error is assessed by varying the scales between the limits of $Q^2/2$ and $2Q^2$, resulting in a rather large variation of Δg. Given that most of the data included in the fit are at moderate $Q^2 \sim 1 \ldots 10$ GeV^2, one would

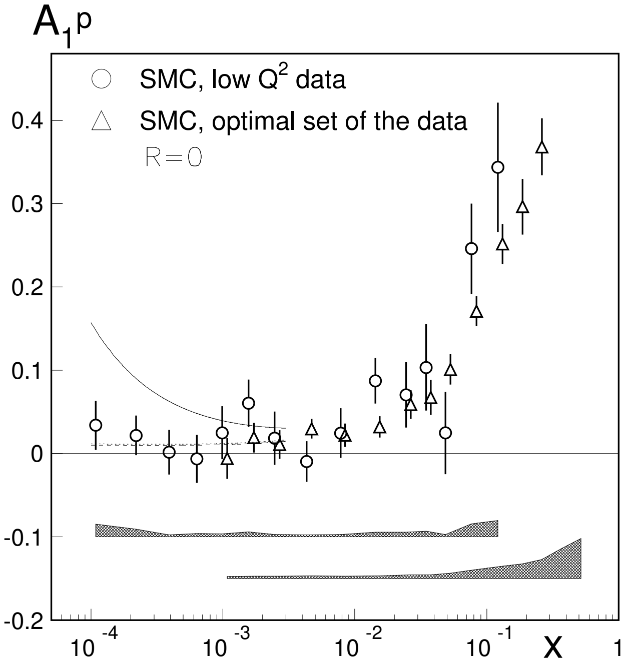

Figure 1. The values of A_1^p as a function of x measured by SMC [13] (preliminary). The smooth curves show the expected behaviour of A_1^p as $x \to 0$ proposed in [8]. The solid curve shows the behaviour for $g_1^p \sim 1/x \ln^2 x$, the dashed curve for $g_1 \sim \ln x$ and the dotted curve $g_1 \sim (2 + \ln x)$.

indeed assume that perturbative corrections beyond NLO (as well as target mass corrections [17]) could be sizable. It should however be pointed out that theoretical error and statistical error on Δg are of a similar magnitude, such that improvement on the theoretical side only would not be sufficient for a better determination of Δg. This clearly illustrates the necessity for a direct measurement of this quantity.

Interesting recent results have also been reported to this workshop from HERMES [11] in which the semi-inclusive distributions of charged hadrons have been used to deduce the parton distributions for individual quark flavours to the spin of the proton. These data add to earlier SMC measurements [18]. Upgrades to the HERMES detector will soon allow separation of different hadron species, which might yield the first flavour decomposition of the light quark sea [11].

3. Theoretical Progress

A consistent extraction of parton distributions at next-to-leading order requires knowledge of both NLO splitting functions and subprocess cross sections for all experimental observables included in a global fit. Up to now, these fits were restricted to structure function measurements only. However, the range of polarized observables will soon be extended with a variety of new reactions to be measured at COMPASS and RHIC [19]. For many of these, subprocess cross sections are now available at NLO.

Most recently, NLO corrections to the photoproduction of heavy quarks have been calculated [20]. An important outcome of this calculation is the relative smallness of light quark induced contributions in photoproduction of charm. The considerably improved dependence on factorization and renormalization scale at next-to-leading order indicates moreover the perturbative stability of this observable, which can therefore be used for a reliable determination of Δg once data become available.

First progress towards the calculation of the polarized splitting functions at NNLO has been reported by Gracey [21]. Using the $1/N_f$ expansion, several terms of the polarized splitting functions could be determined to all orders. These results could serve as a consistency check once full results for the splitting functions become available. Another important test of higher order corrections are the relations between polarized and unpolarized results: these are discussed in [22].

Presently, the contribution of partonic angular momentum to the proton spin is not at all determined. Using the recently derived renormalization group equations for the angular momentum distributions [23], it is now feasible to model these distributions.

The behaviour of the polarized proton structure at small x is expected to be governed by leading double logarithmic terms of the form $\alpha_s^n \ln^{2n} x$, which are absent in the unpolarized singlet structure functions. A resummation of these terms has been performed in [14], and their impact has been the topic of extensive discussions during the workshop. It is commonly agreed that the effect of the small-x resummation can not be tested on the current small-x data from SMC [13], which correspond to only very low photon virtualities. A model for g_1 at low Q^2 and small x incorporating resummation was proposed by Badelek and Kwieciński and yields a decent description of the experimental data [15]. Further observables studied in the same double logarithmic framework are g_2 at small x [24] and the diffractive content of g_1 [25], which are however inaccessible at present experiments. Like in the unpolarized case, decent probes of phenomena at small x would only be possible with a polarized electron-proton collider, such as the currently discussed polarized HERA option.

In inclusive DIS, the measurement of the polarized gluon distribution is indirect. Various more direct measurements of Δg have proposed such as the observation of charm production at COMPASS and in HERMES as well as di-jet production using polarised protons in RHIC and in HERA [26]. A problem which was discussed extensively at the workshop was the associated production of charmed baryons and mesons. First Monte Carlo studies based on the LUND string model [27] indicate that such backgrounds may not be serious at COMPASS energies but could become substantial at HERMES energies. As a result of the workshop, more involved theoretical studies have been carried out. Modeling associated production as interchange of constituent quarks, Ryskin and Leader confirm [28] that an open charm production measurement at HERMES will suffer from a large contamination due to associated production, such that it will not yield conclusive information on Δg.

Another potential probe of the polarized gluon distribution is the photoproduction of J/ψ mesons. The inelastic production is induced by boson-gluon fusion, and thus directly proportional to the gluon distribution. Under realistic experimental conditions, it is however very hard to separate inelastic from elastic production. A decent theoretical description of unpolarized inelastic J/ψ production is given in the perturbative two gluon exchange model of [29]. This model has now been applied by Mankiewicz and Vänttinen [30] to compute production asymmetries in elastic J/ψ production. Contrary to earlier claims in the literature, it could be proven that the elastic J/ψ production cross section is insensitive to the spin states of probe and target, a small spin dependence is induced only from relativistic corrections. As a consequence, elastic J/ψ production can not be used to probe the polarized gluon distribution, as initially hoped.

4. Conclusions

Ten years after the release of the EMC measurement of the small contribution of quark spins to the proton spin, an extensive amount of spin structure function measurements is available. Confirming the initial EMC observation, these measurements have contributed much information on the polarized quark distributions in the proton. Our picture of the proton spin structure is however far form being complete: current data yield only loose constraints on the polarized gluon distribution, and no information is available yet on angular momentum contributions to the proton spin.

The theoretical understanding of the spin structure of the nucleon has vastly improved, with the large majority of accessible observables now being calculated to NLO. Theoretical efforts are now extending in various directions: understanding of spin effects at small x, computation of NNLO corrections and investigation of angular momentum distributions are examples of currently ongoing research work.

Making further experimental progress towards a determination of Δg seems to be harder than originally anticipated. Concerning the prospects of extracting Δg from charm production at HERMES energies, the working group has concluded that neither elastic J/ψ production (vanishing asymmetry at partonic level) nor open charm production (large background from associated production) are reliable channels. A measurement from open charm production at COMPASS energies looks far more promising due to the much reduced background. With the recently calculated NLO corrections, the theoretical uncertainties of this observable appear also to be under control.

In addition to COMPASS, other future experiments promise to yield new valuable information on the nucleon's spin structure. A whole range of new observables will become accessible at the RHIC polarized proton-proton collider, which is currently constructed at BNL. The option of polarizing the HERA proton beam, which is under extensive study for the moment, would largely extend the kinematical region covered by present fixed target experiments and allow to study a variety of new channels probing the spin structure of both photon and proton.

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