

# Report of Spin Physics Subgroup

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## ABSTRACT

We briefly summarize spin physics options at future high energy physics machines, such as  $e^+e^-$  NLC and polarized  $ep$  DESY collider. Connection to future polarized  $pp$  programs at RHIC is also discussed.

## I. INTRODUCTION

The primary motivation for the Snowmass meeting this summer was to investigate possible future directions in high energy physics colliders and the future of the field in the United States without an SSC. One of the serious experimental efforts is the study of the possibility of a high energy  $e^+e^-$  Next Linear Collider (NLC). In the Snowmass section on QCD and Spin, a small working group was created to look at the possibility of performing a fixed target program using the high energy spent electron (or positron) beam at an NLC. The assumption was that like the NLC, the electron beam would have large polarization, an energy of 250 GeV or greater high current.

Two “spin-off” experiments in such a program were studied, one to look at a precision measurement of the Weinberg angle and the other to look at studies of the nucleon spin structure using deep inelastic scattering of polarized electrons by polarized targets. Although the first is not relevant to QCD, the study was performed partially in the QCD session, since much of the background from such an experiment would be QCD processes. The second program in deep inelastic scattering would provide one of the statistically and systematically best measurements of the proton and neutron spin structure functions over a wide range of  $Q^2$  and at low Bjorken  $x$ . The projected precision and results from such a measurement would have a significant impact on the extraction of the gluon contribution to the proton’s spin, competitive with a polarized DESY collider program and in some ways superior. The two together would map out the nucleon spin structure functions at low  $x$  with unmatched precision.

According to QCD factorization theorem, measured nucleon spin structure functions are related to polarized quark and gluon distributions,  $\Delta q(x)$  and  $\Delta G(x)$ , through some short-distance coefficient functions. Precision extraction of  $\Delta q(x)$  and  $\Delta G(x)$  from measured nucleon spin structure functions then depends

on exact values of these coefficient functions. However, expressions of these coefficient functions are not unique, and depend on the “schemes” used to calculate them, which reflect the freedom in renormalizing the polarized parton distributions. Consequently, precise results of  $\Delta q(x)$  and  $\Delta G(x)$  also depends on the “schemes”. Theoretical ambiguities and consistency in scheme choices were also studied in this working group.

A global test for spin-sector of QCD at high energies requires physical processes other than measurement of nucleon spin structure functions. Connection to spin programs at RHIC was briefly discussed.

## II. NUCLEON SPIN STRUCTURE FUNCTIONS AT AN NLC

One of the most promising attempts to extract the gluon contribution to the nucleon’s spin comes from the study of scaling violations in polarized deep inelastic scattering. Using precision data, one maps out measurements of the nucleon spin structure functions  $g_1^p$  (proton) and  $g_1^n$  (neutron) over as wide a kinematic range in  $x$  and  $Q^2$  as possible. It is especially important to study the  $Q^2$  dependence of the nucleon spin structure functions at low  $x$  where the gluon contributions are expected to be large. The last requirement to access the low  $x$  region versus  $Q^2$  necessitates the use of high energy machines.

Two accelerators that are appropriate to study very low  $x$  physics in spin dependent deep inelastic scattering are a HERA polarized electron-proton collider program at DESY and a fixed target electron scattering program at a Next Linear Collider (NLC). We compare here the  $x$  and  $Q^2$  range accessible to these two projects and also the statistical uncertainties that could be achieved.

For the HERA collider we take the conditions outlined in the Table I below. The event sample is an estimate of one year of

Table I: Assumptions for the NLC and HERA Collider Spin Physics Programs

	HERA	NLC
DIS Event Sample	15 million	100 million
Fraction of Polarized Protons	1	0.1
Electron polarization	70%	80%
Proton polarization	70%	80%
Electron Beam Energy	30 GeV	250 GeV
Proton Beam Energy	800 GeV	0

HERA data collection with the projected future high luminosity. The average  $Q^2$  of the data from the  $x$  region near  $10^{-3}$  is quite high ( $\langle Q^2 \rangle \sim 20 \text{ GeV}^2$ ). The HERA machine is assumed in this

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case to be running with 30 GeV polarized electrons colliding with 800 GeV polarized protons.

We compare the projections to what could be achieved in a fixed target experiment at the NLC. As shown in Fig. 1, one sees that the NLC probes the range of  $x \sim 10^{-3}$  at lower average  $Q^2$  around  $2 \text{ GeV}^2$ . The NLC is assumed to have in the first stage a 250 GeV polarized electron beam, and for this comparison we assume that the experiment scatters off a polarized ammonia ( $\text{NH}_3$ ) target. The  $x$  and  $Q^2$  range is essentially the same as that obtained by the SMC experiment [1]; however, the statistical precision of the NLC experiments represent a substantial improvement. Systematic uncertainties from an NLC experiment should be manageable, since both the beam and target spins can be reversed rapidly. They should be similar to the present day SLAC fixed target program [2]. The new facets of an NLC experiment will be building a large acceptance spectrometer to ensure high enough statistics at the higher beam energy. The NLC scenario outlined assumes a pessimistic present-day target technology for the polarized targets. Improvements in polarized proton and neutron targets could easily represent improvements compared to the projections, possibly up to an order of magnitude by gaining in the fraction of polarized protons in the target. New LiD targets are already planned to improve the neutron measurements in the upcoming SLAC E155 experiment [3]. Improvements in target technology could also be used to reduce the event rate and build more conservative spectrometers.

The comparison of the NLC fixed target data with the DESY collider data would provide a strong test of the  $Q^2$  dependence of  $g_1^p$  at low  $x$  and be valuable for extracting  $\Delta G(x)/G(x)$ . Naively, the extraction of  $\Delta G$  from present day experiments provides an uncertainty of typically  $\pm 1$ . With the NLC results, it is possible that this could be improved by an order of magnitude, moving into the regime in which the theoretical errors will

be dominant.

### III. AMBIGUITIES IN DEFINING POLARIZED PARTON DISTRIBUTIONS

Like cross sections, nucleon spin structure functions (e.g.,  $g_1(x)$ ) are physical observables directly measured in experiments. Extraction of these spin structure functions from polarized deep inelastic scattering experiments has very little to do with QCD, the underline theory for strong interactions.

In contrast, polarized parton distributions,  $\Delta q(x)$  and  $\Delta G(x)$ , are introduced by theorists as matrix elements of parton field operators in QCD. In principle, they are not directly measurable quantities like cross sections.

According to QCD factorization theorem, the measured spin structure functions can be expressed in terms of polarized parton distributions with calculable coefficients,  $C(x)$ , plus power suppressed contributions from many unknown high twist matrix elements. For example, proton spin structure function

$$g_1^p(x, Q^2) = \sum_q \Delta C_q(x, \alpha_s(Q^2)) \otimes \Delta q(x, Q^2) + \Delta C_g(x, \alpha_s(Q^2)) \otimes \Delta G(x, Q^2) + \mathcal{O}\left(\frac{1}{Q}\right). \quad (1)$$

In Eq. (1), factorization and renormalization scales are set to be  $Q^2$ ; and “ $\otimes$ ” is a convolution over parton momentum fraction linking polarized parton distributions and the coefficients. It is clear that these polarized parton distributions become physically measurable quantities only after we truncate the perturbation series, and specify coefficients,  $\Delta C_q$  and  $\Delta C_g$ .

Coefficients,  $\Delta C_q$  and  $\Delta C_g$ , are calculable within QCD perturbation theory. But, absolute values of these coefficients are not uniquely fixed due to ambiguities to renormalize the matrix elements for polarized parton distributions. Such ambiguities exist in spin averaged processes as well, and are known as the choice of “schemes”. Since coefficients,  $\Delta C_q$  and  $\Delta C_g$ , are scheme dependent, while nucleon spin structure functions are directly measured from data and scheme independent, polarized parton distributions,  $\Delta q(x)$  and  $\Delta G(x)$ , extracted from nucleon spin structure functions are scheme dependent. Consequently, in most case, amount of quark or gluon contribution is a scheme dependent statement.

Polarized parton distributions certainly have the same ambiguities as those associated with the well-studied spin-averaged parton distributions. In addition, polarized parton distributions have extra potential ambiguities. One example, which has attracted a lot of attention in recent years, is how to handle the anomaly contribution associated to the first moment of polarized quark distributions [4, 5]. Another less noticeable example is how to handle the ambiguities associated with the definition of  $\gamma_5$  in  $n$ -dimension [6, 7]. Both ambiguities can result into different expressions for coefficients,  $\Delta C_q$  and  $\Delta C_g$  for nucleon spin structure functions, as well as different expressions for the partonic hard parts of Drell-Yan, direct photon, and other processes in polarized hadronic collisions.

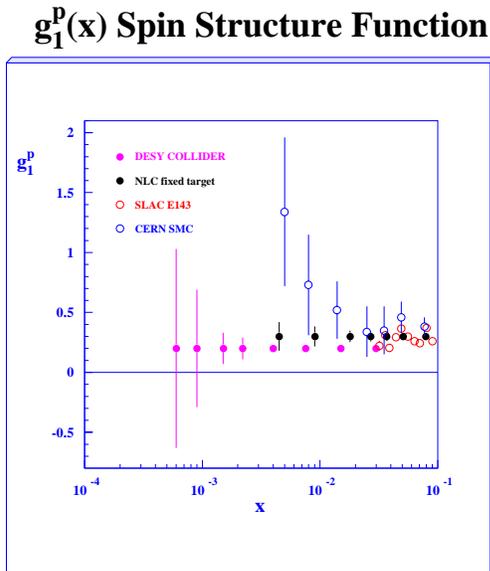


Figure 1: Comparison of statistical uncertainties on  $g_1^p(x)$  measurements at current and future machines.

Calculation of  $\Delta C_q$  and  $\Delta C_g$  in perturbation theory relies on the fact that  $\Delta C_q$  and  $\Delta C_g$  are infrared-safe short-distance quantities. For example, in Eq. (1), they are not sensitive to details of the proton, on which the structure function,  $g_1^p$ , is defined. Therefore, we can apply Eq. (1) onto a parton state (quark or gluon), and extract  $\Delta C_q$  and  $\Delta C_g$  by calculating  $g_1$ ,  $\Delta q$  and  $\Delta G$  on the parton state, perturbatively. The scheme dependence in  $\Delta C_q$  and  $\Delta C_g$  are the consequence of ambiguities in renormalizing and/or defining  $g_1$ ,  $\Delta q$  and  $\Delta G$  on partonic states.

The debate on handling axial anomaly is clearly a reflection of these ambiguities. Applying Eq. (1) onto a gluon state,  $\Delta C_g$  at order of  $\alpha_s$  can be obtained

$$\Delta C_g^{(1)}(x) = g_1^{g(1)}(x) - \sum_q \Delta C_q^{(0)}(x) \otimes \Delta q^{g(1)}(x), \quad (2)$$

where superscript ‘‘g’’ means that  $g_1$  and  $\Delta q$  here are evaluated on a gluon state. From Eq. (2), clearly,  $\Delta C_g$  depends on how  $\Delta q$  is renormalized, and what is the finite part after the renormalization. At the first moment,  $\Delta q$  corresponds to a matrix element of a local operator, which is proportional to the axial vector current. Because of local nature of the axial anomaly, where we should include the anomaly contribution becomes an issue of debate when we renormalize the  $\Delta q^{g(1)}$  in Eq. (2). One can either include the anomaly contribution as an explicit gluonic contribution, which leads to a non-vanish  $\Delta C_g(x)$  at the first moment, or leave it as a part of polarized quark distribution,  $\Delta q$  [8]. However, no matter what choice is made for the first moment, one has to make a consistent choice of  $x$ -dependent distribution  $\Delta q^{g(1)}(x)$  for calculations done for DIS as well as for hadron-hadron collisions [7].

A physical observable, such as a nucleon structure function or a cross section, should not depend on the choice of  $\gamma_5$  in  $n$ -dimension. But, coefficients,  $\Delta C_q$  and  $\Delta C_g$ , for nucleon structure functions in DIS, and/or partonic hard parts for other physical processes, can depend on the choice of  $\gamma_5$  in  $n$ -dimension [6, 7]. Define dimension  $n = 4 - 2\epsilon$ . For any Feynman diagrams *without* divergence, different choice of  $\gamma_5$  in  $n$ -dimension results into an extra term proportional to  $\epsilon$ , which vanishes as  $n \rightarrow 4$ . However, diagrams with divergence (e.g., those contribute to  $\Delta q$  and  $\Delta G$  on partonic states) will have following structure

$$\left(\frac{1}{\epsilon}\right) [A(x) + \epsilon B(x)] + \text{finite as } \epsilon \rightarrow 0, \quad (3)$$

where functions  $A(x)$  and  $B(x)$  are finite as  $\epsilon \rightarrow 0$ , and  $B(x)$  depends on the choice of  $\gamma_5$  in  $n$ -dimension. If  $\overline{\text{MS}}$  scheme is chosen to remove the pole term,  $A(x)/\epsilon$  in Eq. (3), a finite function  $B(x)$ , which depends on the choice of  $\gamma_5$  in  $n$ -dimension, will be left to the perturbatively calculated partonic contributions. For example, the calculated coefficients, such as  $\Delta C_q$  for nucleon structure functions, can depend on the choice of  $\gamma_5$  in  $n$ -dimension [7]. Consequently, polarized parton distributions extracted with measured nucleon structure functions will depend on the choice of  $\gamma_5$  in  $n$ -dimension as well, if one uses coefficients calculated with different  $\gamma_5$  definitions.

All these ambiguities in defining polarized parton distributions are the results of freedom to renormalize and/or define the

polarized parton distributions on partonic states. Precise definition of polarized parton distributions on partonic states are necessary for calculating short-distance hard parts in QCD perturbation theory. Therefore, such ambiguities cannot be avoid in most perturbative calculations. Difference between these ambiguities is in principle calculable within QCD perturbation theory. Therefore, it is a matter of introducing a consistent and well-accepted convention [6, 7]. No apple would be compared with an orange.

## IV. RHIC SPIN PROGRAMS

With future NLC and a polarized DESY collider program, polarized lepton-hadron deep inelastic scattering will provide precision information on polarized parton distributions. However, a global test of spin-sector of QCD at high energies requires physical processes other than measurement of nucleon spin structure functions in DIS. RHIC spin program [9] will provide a complimentary tests of spin physics in a hadronic environment.

RHIC, a relativistic heavy ion collider, is now under construction at Brookhaven National Laboratory. The construction is expected to be completed by 1999. In addition to its heavy ion program, around 10% of machine time will be contributed to spin physics with polarized proton beams of energy around 200 GeV. With an ability to polarize the beam in both longitudinal and transverse direction, many interested physical processes can be explored, and many issues of physics can be tested, including some which are very difficult to test in spin-averaged processes.

From spin-averaged experiments, it is clear that the leading power perturbative QCD modified parton model works for interpreting data from high energy collisions. Going beyond the leading power QCD has been a very difficult task for both theorists and experimentalists, because signals beyond the leading power QCD are very weak in existing spin-averaged processes. With polarization, we can eliminate many leading power contribution, and directly test the theory beyond the leading power. One example is the single transverse-spin asymmetries. It is known [10] that leading power QCD predicts a vanishing single transverse-spin asymmetry. Any measured non-vanish asymmetries signal physics beyond leading power QCD. Current data [11] has indeed provided a strong evidence that such single transverse-spin asymmetries exist and large. Future experimental tests at RHIC can open a new window to study QCD dynamics beyond the parton model.

Many valuable and interesting physical processes have been proposed to study spin physics at RHIC. Details can be found in Ref. [9].

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