The Physics Case for Polarized Protons at HERA

A. Deshpande$^a$

$^a$ Yale University, Physics. Dept., New Haven, CT 06520, U.S.A.

Abstract: Several important and unique measurements, within the standard model and of possible physics beyond it, could be made with polarized HERA in which both the proton and the electron beams are polarized. With a $\sim 820$ GeV proton beam and a $\sim 27.6$ GeV electron beam, the polarized HERA will enable $\bar{e} - p$ collisions with $\sqrt{s} \sim 300$ GeV and access spin variables in the kinematic range, $10^{-5} \leq x_{Bj} \leq 0.6$ and $0 \leq Q^2 \leq 10^5$, using the H1 and ZEUS detectors at DESY. This will be an increase of two orders of magnitude in both $x$ and $Q^2$ range compared to the presently explored range from fixed target experiments at CERN, SLAC and DESY. No other approved or planned spin experiment or accelerator facility will access the low $x$ and high $Q^2$ regions possible with HERA. Measurements performed with the polarized HERA collider will include the polarized structure function $g_1(x, Q^2)$ at very low $x$, the polarized gluon distribution $\Delta G(x, Q^2)$ from pQCD analysis of $g_1$, from the production of di-jet events and high-$p_T$ hadrons in photon gluon fusion process and in photoproduction, weak structure functions, valence quark distribution functions from semi-inclusive asymmetries, parton distributions inside polarized photon, and information on helicity structure of possible new physics beyond the standard model. With such a rich and broad physics program possible for HERA, not polarizing the proton beam would be a great opportunity lost.

1 Polarized DIS in a New $x - Q^2$ Region

Measurements of nucleon structure functions by lepton-nucleon deep inelastic scattering (DIS) were of fundamental importance in studying nucleon structure and have provided crucial information regarding the foundation, and later, the development of perturbative QCD (pQCD). Historically in this field important new information has been obtained when experimental measurements were extended to new kinematic regions[1]. For example, measurement of elastic scattering in the $Q^2$ range $\sim 1$ GeV$^2$ established the finite size of the proton. The extension of measurements of inelastic inclusive electron scattering to deep inelastic region $Q^2 > 1$ GeV$^2$ revealed the existence of partonic substructure of the proton, which was later studied using muon-nucleon scattering. The significant increase in the $Q^2$ accessible range, especially at low $x$, made possible by the $e - p$ collisions at HERA revealed the surprising rise in the $F_2$ at low $x$ whose measurement and analysis in the past 5 years has contributed greatly to our understanding of pQCD.

A similar historical path has been traced by events in polarized DIS[2]. First measurements of polarized DIS by the Yale-SLAC collaboration extended the $x$ range down to $x \sim 0.1$
and were consistent with the accepted quark-parton model of the proton spin at the time. Extension of the $x - Q^2$ of spin DIS measurements at CERN by the EMC collaboration (down to $x = 0.01$) revealed that the Ellis-Jaffe Sum rule was violated and the quarks contributed hardly anything towards the proton’s spin. This surprising result led to a large number of experimental measurements in the past 10 years performed by the SMC Collaboration at CERN, a series of measurements by E142, E143, E154 and E155 Collaborations at SLAC, and recently by HERMES Collaboration at DESY. These were fixed target experiments with electron beam energy between $\sim 26 - 49$ GeV at SLAC and DESY which explored the $\sqrt{s}$ range of $\sim 7 - 10$ GeV, while SMC used $\sim 200$ GeV polarized muon beam with $\sqrt{s} \sim 20$ GeV. The $x - Q^2$ range covered by these experiments together is: $0.003 \leq x \leq 0.7$ and $0.2 \leq Q^2 \leq 100$ GeV$^2$ (figure 1, Top). All experiments have confirmed the violation of the Ellis-Jaffe Sum rule, and SMC and SLAC experiments have confirmed the Björken Sum rule to about 10% accuracy[3, 4, 5]. The largest uncertainty that remains in the analyses now comes from the low $x$ unmeasured region $x < 0.003$, which none of these experiments can access. The origin of the proton spin is still an unsolved mystery. Gluons in the protons and the partonic angular moment may hold the answers. The SLAC and SMC collaborations have strongly advocated future polarized DIS measurements in the unmeasured low $x$ region[3, 5], while in near future HERMES at DESY, COMPASS at CERN, and RHICSPIN at BNL will investigate the nucleon spin differently[6].

In HERA we have a collider facility with $\sim 27.5$ GeV electron or positron beam, and a proton beam with $\sim 820$ GeV (in 1999 it has also been operated with $E_p = 925$ GeV). With such facility one can access $\sqrt{s} \sim 300$ GeV. These characteristics of the HERA accelerator together with the H1 and ZEUS detectors enable measurements of the proton structure in the $x - Q^2$ range: $5 \times 10^{-5} \leq x \leq 0.6$ and $1 \leq Q^2 \leq 5 \times 10^5$ (figure 1, Bottom). The electron beam is transversely polarized due to the Sokolov-Ternov Effect (STE)[7] during acceleration. Polarizations of $\sim 55\%$ have routinely been achieved at HERA[8] and are being used by the HERMES Collaboration[9] in their physics program. The proton beam is unpolarized. If it is polarized, measurements of spin variables could be possible in the extended kinematic range of HERA. This would be a 2 orders of magnitude increase in the $x - Q^2$ range. This is precisely the region identified by the SMC and the E154 collaborations where further measurements are needed[3, 5].

In this paper I will argue, based on the possible physics program with polarized $e - p$ collisions at HERA and the profound impact it may have on our understanding of pQCD, that it would be unfortunate not to polarize the proton beam in HERA. The measurements at HERA will include spin structure function $g_1$ at low $x$, the measurement of polarized gluon distribution using three or four independent methods, each with different sources of experimental systematic uncertainties giving ample opportunity to check the results against each other, measurement of parton distributions inside the polarized photon, semi-inclusive measurements to give us access to the valence quark distributions, measurement of the weak structure functions $g_5$, weak interaction physics at high $Q^2$, and possible physics beyond the Standard Model (SM) including lepto-quarks, contact interactions, and SUSY searches. I will make the case that, with the diverse physics measurements possible with the accelerator and the two collider detectors that already exist and operational, it would be unfortunate not to pursue the physics program with polarized protons at DESY.

Dedicated studies on the physics topics presented in this paper started in a working group of the 1995/96 DESY workshop on Future Physics at HERA[10] and were carried through in detail mainly in the 1997 DESY workshop on Physics with Polarized Protons at HERA (hence
Figure 1: Top: The $x - Q^2$ range explored by the CERN, SLAC and DESY fixed target experiments today. Bottom: the $x - Q^2$ range accessible by polarized HERA with H1 or ZEUS collider detectors compared with the fixed target experiments.

2 Physics with Polarized Protons at HERA

Although the extension of $x - Q^2$ range of the unpolarized structure function measurements has been the principal motivation for building the HERA accelerator and the two collider detectors,
exciting new and unexpected physics has resulted from the unpolarized DIS measurements[13, 14]. Guided by this hindsight, while the major motivation for the measurement of spin variables at HERA is the measurement of spin structure function $g_1$ at low $x$ and the measurement of polarized gluon distribution, in order to explore the full potential of the polarized HERA Collider other topics were also pursued in the Workshop[11]. In this section only the most important topics out of a long list are reviewed. The following set of machine parameters and running conditions were assumed in most of the studies:

1. **Integrated luminosity** over three to four years: $L = 200 − 500 \text{ pb}^{-1}$
   $\Rightarrow$ Consistent with the $\sim 170 \text{ pb}^{-1}/\text{year}$ expected after the HERA luminosity upgrade in 2001.

2. **Proton and electron/positron beam polarizations**: $P_{p/e} = 70%$
   $\Rightarrow$ For electrons this is the design goal of HERA. While 55% has been achieved routinely, up to 65% has been achieved for short periods. For protons it is the goal with which the machine physics effort is being made[15].

3. **Beam polarimetry**: relative uncertainty $\left[\delta(P_{p/e})/P_{p/e}\right] \leq 5%$
   $\Rightarrow$ For electrons this has already been achieved, while for protons this remains a goal.

4. A **fast detector simulation** of a HERA Collider detector[16] was made available which could be used for measurability studies of different physical processes.

### 2.1 Polarized Structure Functions of the Nucleons

The measurement method for the spin structure function $g_1$ is well defined. The ratio of the difference between the event rate of $\vec{e} − \vec{p}$ scattering when the longitudinal spin vectors of the $\vec{e}$ and $\vec{p}$ are parallel and when they are anti-parallel to the sum of the event rates is the measured asymmetry $A_m$. $A_m$ is used to evaluate the spin structure function $g_1[3]$ using the knowledge of kinematic factors such as the depolarization factor $D(y)$, the proton and electron polarizations $P_{p/e}$, the unpolarized structure function ratio $R = \sigma_T/\sigma_L$, and the unpolarized proton structure function $F_2$.

#### 2.1.1 Spin Structure of the Proton

The possibility of $g_1^p$ measurement with the polarized HERA collider was studied in detail[17, 18]. It was found to be one of the most important and unique measurement that could be performed with the existing collider detectors at DESY. Figure 2(a) shows the statistical uncertainties in the measurement of $g_1^p$ possible with polarized HERA with $L = 500 \text{ pb}^{-1}$, both beam polarizations 70%, and using any one of the collider detectors at HERA. Also shown in the figure are three different low-$x$ extrapolations, based on the available data from the fixed target experiments. The HERA (pseudo)data are superimposed on the extrapolation of pQCD calculation based on a fit to fixed target data in the region $x > 0.003$ and $Q^2 > 1 \text{ GeV}^2$. The Regge inspired extrapolation $g_1(x \rightarrow 0) \sim x^\alpha; 0 \leq \alpha \leq 0.5$ is shown for the value of $\alpha = 0[3, 4]$. A more exotic behavior with a functional form $1/\left[x(\ln^2(x))\right]$ proposed in [19] is also shown. Not shown in this figure are low $x$ QCD predictions dominated by double logarithmic resum-mations as suggested in [20], which are similar to the pQCD curve, but even more divergent. It is obvious from this figure that measurements with polarized HERA would easily resolve between these different theoretical scenarios. Since the underlying physics that drives these three behaviors is different, experimental confirmation of any of them would significantly enhance our understanding of the low $x$ region.
Figure 2: Top: The statistical uncertainty in the measurement of $g_1^p$ possible at HERA shown with $\mathcal{L} = 500\text{pb}^{-1}$, 70% polarization of beams and using H1/ZEUS detectors. Bottom: The statistical accuracy of $g_1^n$ measurement with $^3\text{He}^{+2}$ accelerated and stored in the proton ring of HERA. In both cases SMC and SLAC measurements are shown for comparison. All theoretical curves are drawn at $Q^2 = 10 \text{ GeV}$. 

$P_{\text{He}} = 546 \text{ GeV/c}, P_e = 27.5 \text{ GeV/c}$
A subtle difficulty in this measurement is that the measured asymmetries predicted at low \(x\) are very small \(\sim 10^{-4} - 10^{-3}\)\cite{17, 18}. To explore the low \(x\) region, one must keep the systematic uncertainties smaller than the statistical errors. Two important sources have been looked into. First, the systematic uncertainties due to uncertainties in radiative corrections have been studied and were found to be small for the kinematic regions of our interest\cite{21}. Second, the effect of event migration due to the material present in the detectors and event reconstruction could be potentially disastrous if a large number of events migrate and dilute or enhance the physics asymmetries. Using a fast detector simulation\cite{16} this was studied recently\cite{22}. It was found that changes in the measured values of \(g_1^p\) were less than the 1\(\sigma\) statistical uncertainties indicated in Figure 2(a). Spin structure function \(g_1^p\) could be reliably measured with polarized HERA.

2.1.2 Spin Structure of the Neutron

If \(^3\text{He}^+\) can be accelerated in the HERA ring with sufficient polarization and intensity, measurement of \(g_1^n\) is possible\cite{17}. The measurement is further improved if the hadronic (proton) remanent the in the \(e^-\text{He}^-\) collision is tagged and thus the dilution factor in the collision is improved. Figure 2(b) shows results of such measurement using 500 and 200 \(\text{pb}^{-1}\) luminosity plotted on the extrapolation based on the pQCD prediction in the region \(x \leq 0.003\) where no direct or indirect measurements exist for \(g_1^n\). Also shown is the Regge inspired extrapolations of the neutron structure function in this region. This measurement would be especially important in view of the observations by the E154 collaboration of a possible divergent trend in \(g_1^n\) at low \(x\)\cite{5}. Clearly, polarized HERA with helium ions in the proton ring would be of great experimental value. Further, in combination with the \(g_1^n\) measurements at HERA, it would then be possible to improve upon the accuracy of experimental verification of Björken which presently is limited by the lack of measurements in the \(x < 0.003\) region\cite{3}.

2.2 Polarized Gluon Distribution Function

In the framework pQCD the first moment of the polarized gluon distribution, \(\Delta G\), contributes to the proton spin. Presently all published results on polarized gluon distribution, \(\Delta G(x, Q^2)\), come from pQCD analyses of the \(g_1^{p,d,n}\) data\cite{3, 4, 5}. In this section I present the impact of polarized HERA on this method and also present other ways to determine \(\Delta G(x, Q^2)\) with polarized HERA.

2.2.1 \(\Delta G(x, Q^2)\) from Perturbative QCD Analysis of \(g_1\) and HERA

Since gluon appears in the DGLAP equations at the Next-to-Leading-Order (NLO), this method of determination of \(\Delta G(x, Q^2)\) is somewhat weak. However, it is the only method successfully employed to access the gluon distribution in the polarized DIS until now. The value of \(\Delta G\) using the world set of data at the time of the study was \(\Delta G \sim 1.0 \pm 0.3\text{(stat)} \pm 1.0\text{(theo)}\)\cite{17, 18}. The large theoretical uncertainty results from the fact that very little is known about the \(g_1\) and its evolution in the low \(x\) region, precisely where polarized HERA will make a difference. To study the impact of polarized HERA on this measurement the available data from fixed target and the possible future HERA data were analyzed together\cite{17, 18}. It was estimated that the statistical accuracy in the \(\Delta G\) would be reduced by a factor \(\sim 2\) and the theoretical...
uncertainty by a factor $\sim 3$. This is a significant improvement in the determination of $\Delta G$ from pQCD analysis in NLO of the spin structure function data.

### 2.2.2 Photon Gluon Fusion: Di-Jet and High-$p_T$ Hadron Production

The NLO analysis mentioned in the previous subsection allows the determination of the first moment of the polarized gluon distribution, while the functional form of the polarized gluon distribution remains only loosely determined. Further, it is biased by the functional form of the initial parton distribution input into the analysis. The most promising way to get around this problem and to determine $\Delta G(x, Q^2)$ is to make measurements of physical processes in which the polarized gluon enters into the interaction at Leading-Order (LO). One such process is the photon gluon fusion process which gives rise to a $q\bar{q}$ pair in the interaction. Depending on the energy of these quark pairs, either jets are seen in the detector or the two jets hadronize and two oppositely charged hadrons with high transverse momenta ($p_T$) are detected. The rate asymmetry in the production of two jets (di-jet) or the two hadrons is related to the the polarized gluon distribution.

![Figure 3: Statistical accuracy with polarized HERA in measurement of a) $\Delta G/G$ and b) $x \Delta G$ vs. $x$ using the asymmetry in di-jet production shown superposed on three different polarized gluon fit results.](image)

The study of what polarized HERA can contribute in this measurement was undertaken in the 1997 workshop\[23, 24\]. Using LO theoretical calculations, realistic detector acceptances and simulations it was shown that polarized gluon distribution could be determined very accurately with this method. Three different but equally likely polarized gluon distributions, based on fits to the available data at the time, are shown in Fig. 3 for di-jets and Fig. 4 for di-hadrons. The possible statistical(error bars) are shown as well in the two figures. The systematic(shaded horizontal bands) uncertainties are shown for the di-jet (the band for di-hadron analysis is expected to be of the same order). Clearly, the polarized HERA will easily be able to distinguish between different scenarios.

From the experimental point of view, an important advantage is that the two methods rely on different components of the the detector: di-jet on jet-detection and hadronic calorimeter, and charged hadron detection on tracking subdetectors. As such the systematic uncertainties are different. This would then be independent methods to arrive at the polarized gluon distribution.
2.2.3 Combined pQCD Analysis of $g_1$ and Di-Jet Events

Perturbative QCD analysis of $g_1$ data results in the first moment of the gluon distribution. It also gives the shape of the distribution $\Delta G(x)$ at a fixed initial $Q_0^2$, but that functional form is input to the analysis and is only loosely determined. On the other hand the polarized gluon distribution determination via photon-gluon fusion process can constrain the shape of the distribution better. The limitation in this case is whether complete range of $x_g$ is being explored by the accelerator/detector. HERA, with its large beam energies and two large acceptance collider detectors, provides the best opportunity to explore the largest possible $x_g$ range compared to any other experimental facility. The two methods combined (pQCD of $g_1$ and di-jet) clearly should complement each other and thus improve upon the resulting uncertainty in the determination $\Delta G(x, Q^2)$ and its first moment. It was shown in that the power of such combined analysis is significant and a further reduction of factor of 2 in the uncertainty of $\Delta G(x, Q^2)$ and its first moment is possible by combining the two analyses.

2.3 Study of Photoproduction with Polarized HERA

In the photoproduction limit, i.e. region where the intermediate photon virtuality is small, the $e - p$ cross section can be approximated as a product of photon flux factor and an interaction cross section of the real photon with the proton. Measurements in this photoproduction limit in the unpolarized physics program at HERA have not only led to significant improvement in our knowledge of the structure of the proton and the photon, but also in the transition from virtual to real photon. In the Workshop most of these physics topics were explored assuming polarized proton and electron beams at HERA. The two most attractive results are discussed in sections 2.3.1 and 2.4.

Other topics such as open charm production, Drell-Yan processes, large $p_T$ photon and inelastic $J/\Psi$ production were also studied. It was however concluded that some of them
would need either higher luminosities than conservatively assumed in the Workshop or would need upgrades in the present detectors to achieve the required efficiently for event tagging or detection. These upgrades although not ruled out, would need further considerations in terms of detector upgrade. As such, they are not included in this paper, but the reader is referred to the proceedings [11].

2.3.1 Jets and High-\(p_T\) Tracks in Photoproduction

A detailed study[26] of physics with single jets and high-\(p_T\) tracks in polarized photoproduction including detector acceptance and standard analysis cuts was performed. It showed that the study of photoproduction of single inclusive jets as well as hadrons with polarized HERA would be an extremely significant probe in investigating not only \(\Delta G(x, Q^2)\) but also the parton distribution inside the polarized photon, \(\Delta q^\gamma\). (See figures 5(a),(b)). With a modest luminosity of 100 pb\(^{-1}\), different theoretical scenarios for the \(\Delta G(x, Q^2)\) as well as the \(\Delta q^\gamma(x, Q^2)\) could be resolved using the asymmetry in the jet and hadron production. The single hadron production rate is somewhat lower than the jet production rate, but it still could result in comparable measurements of \(\Delta G\) and \(\Delta q^\gamma\) to those from jet production since less stringent constraints on the hadron track selections are warranted compared to the jet selection cuts. Although no quantitative estimates of the improvement of uncertainty on \(\Delta G(x, Q^2)\) and \(\Delta q^\gamma(x, Q^2)\) were made, the figures clearly indicate that the statistical uncertainty being so small compared to the spread in different possible theoretical scenarios, the improvement in knowledge of polarized gluon and photon structure would indeed be significant.

A similar study for di-jet photoproduction was also taken up and resulted in equally positive prospect of measurement of \(\Delta G\) and \(\Delta q^\gamma\). Figure 5 (c) and (d) show the statistical accuracy for di-jet photoproduction with 50 pb\(^{-1}\) HERA luminosity, standard analysis cuts, and after a fast detector simulation, compared with different scenarios for the polarized gluon and photon distribution. Clearly the different possible scenarios are distinguishable from each other using the polarized HERA data in this case as well. It also indicates that the detector affects the measurement of the process minimally, as such, the measurement withstands the process of detection. Certainly these measurements performed with more luminosity will give significant information on the structure of the photon as well as the polarized gluon distribution.

While the measurement of structure of the polarized photon is possible at other accelerator/detector facilities (LEP for example) these measurements are not planned by the experimental collaborations. The collisions in fixed target experiments are not energetic enough to access the photon structure. Measurements of the photon structure with polarized HERA will be unique and will provide valuable information.

2.4 Inclusive Photoproduction Measurements

In section 2.3.1 we discussed the physics based on photoproduction using only the detection of jets or high-\(p_T\) hadrons. Other topic which could be studied using photoproduction and can be characterized as “inclusive measurements” is discussed below.

The H1 and ZEUS detectors routinely take data using the “electron taggers” situated in the beam pipe 6 to 45 meters downstream from the detectors. They are used to measure the scattered electrons from events which have \(Q^2\) in the range of \(10^{-8} \rightarrow 10^{-2} \text{ GeV}^2\) and \(\sqrt{s}\) in
Figure 5: Statistical uncertainty in the measurement of asymmetry with 100 pb$^{-1}$ HERA luminosity for (a) single jet and (b) single hadron photoproduction while with 50 pb$^{-1}$ luminosity (c) differential cross section for dijet photoproduction and (d) asymmetry in di-jet photoproduction. Different scenarios of polarized gluon distributions (indicated by the legends) and possible scenarios regarding polarized photon distribution (top and bottom in (a) and (b) and middle and bottom in (c) and (d)) are shown. Max. Sat. $\gamma \rightarrow \Delta \gamma = \gamma$ and Min. Sat. $\gamma \rightarrow \Delta \gamma = 0$. 
the range $60 \to 250$ GeV. The total cross section in this region is $\sigma \sim 150 \mu b$. With these event characteristics the Drell-Hearn-Gerasimov (DHG) sum rule, which relates the $\sigma_{\gamma p}^\uparrow\downarrow$ and $\sigma_{\gamma p}^{\uparrow\uparrow}$, to the anomalous magnetic moment $\kappa$ of the nucleon (proton in this case)

$$\int_{\nu_{th}}^{\nu_{h}} \frac{d\nu}{\nu} (\sigma_{\gamma p}^\uparrow\downarrow - \sigma_{\gamma p}^{\uparrow\uparrow})(\nu) = -\frac{4\pi^2 \alpha \kappa^2}{2m_p^2},$$

(1)
can be measured in the $\nu$ range of $10 \to 40$ TeV[27]. Although the contribution to the DHG integral from this region is small, a measurement at HERA would be unique, because all other tests to check the sum rule have been made using Regge inspired extrapolations of data from low energy fixed target experiments which explore $\nu$ values in the 10s of GeV range. Measurements at HERA will explore the energy dependence of the cross section in this yet unexplored region directly, and check the validity of the different Regge behaviors presently assumed.

### 2.5 Polarized Quark Distribution Functions

Inclusive DIS measurements from $\gamma^*$ exchange are sensitive to the sum of all quark flavors weighted by their charge squared. Using data from $e^- p$ and $e^- n$ scattering it is possible to extract singlet and non-singlet quark distributions, however, to extract separate quark flavors additional information from semi-inclusive DIS measurements is necessary. Ideally the measurement should be of the scattered hadron that carries the struck quark, but in practice the situation is complicated because one can not avoid the effect of fragmentation function and its convolution with various parton distributions.

A detailed study of various issues relevant to semi-inclusive DIS measurements at HERA was performed[28]. Using the PEPSI Monte Carlo to study the purity of flavored fragmentation functions for different values of $z = P \cdot P_h / P \cdot q$ revealed that at HERA purities $\sim 90\%$ are possible at high values of $z$. As such, HERA is a good facility to study the semi-inclusive scattering. Study of $\pi^\pm$ production in low $x$ region showed that polarized valence and sea quark distributions could be measured with HERA luminosity $\geq 500 \text{ pb}^{-1}$, but another factor of 2 increase in the luminosity would be desirable.

One can distinguish between the positively and negatively charged flavors via $W^\pm$ exchange, i.e. via charged current (cc) interactions. It was also shown in [28] that with a modest luminosity of $\sim 200 \text{ pb}^{-1}$, asymmetries are measurable for $W^\pm$ and using the pion and kaon identification it would be possible to measure the relative contribution to the spin from $\pi$ and $\bar{d}$ quarks compared to the $u$ quarks.

Using the data from charged current, one can also explore the parity violating structure function $g_5^{W\pm}$. The asymmetry defined by

$$A^{W\pm} = \frac{d\sigma_{\gamma p}^{W\pm} - d\sigma_{\gamma p}^{\uparrow\uparrow}}{d\sigma_{\gamma p}^{\uparrow\downarrow} + d\sigma_{\gamma p}^{\uparrow\uparrow}} = \frac{\pm 2bg_1^{W\pm} + ag_5^{W\pm}}{aF_1^{W\pm} + bF_3^{W\pm}} \approx \frac{g_5^{W\pm}}{F_1^{W\pm}},$$

(2)

where $a = 2(y^2 - 2y + 2)$ and $b = y(y - 2)$ and $g_5^{W-} = \Delta u + \Delta c - \Delta \bar{d} - \Delta \bar{s}$ and $g_5^{W+} = \Delta d + \Delta s - \Delta \bar{u} - \Delta \bar{c}$. A Monte Carlo study including detector effects showed[29] that the measurement of the above asymmetry and hence the weak structure function $g_5$ was easily possible with the present detectors. The study concentrated on $Q^2 \geq 225 \text{ GeV}^2$. Figure 6 shows the result of the study. The statistical errors are clearly small enough to make very
good measurement of $A^{W\pm}$ and $g_5$. The assumption made of course was that before the HERA is polarized a good measurement of the unpolarized structure function $F_1^{W\pm}$ will exist. From these measurements assuming that the contribution from $\Delta c$ is negligible, the distributions $\Delta u$ and $\Delta d$ could be extracted.

### 2.6 High $Q^2$ Physics Outside The Standard Model

Detection of neutral current events by the H1 and ZEUS collaborations at high $Q^2$ and high $x$ in excess compared to the Standard Model prediction resulted in a great excitement two years ago[30]. These observations prompted considerable discussion in the particle physics community as possible evidence for anomalies in the parton distributions of the proton or of physics beyond the Standard Model. Since then both collaborations have doubled their data sets but no new events have been found[31]. As such, the statistical significance of the excess events originally observed is now reduced. Although this is the case, there are other features that have been observed in the data which, if confirmed with more statistical significance, may shed light on physics within or outside of Standard Model. Most such effects are expected to have helicity specific properties. What makes the investigations at HERA even most interesting is the fact that some of these scenarios would result in situations in which neither Tevatron nor LEP2 data could resolve between different hypotheses, where as investigations with $e^\pm - p$ scattering could. Polarization of protons could add further information[32] towards our understanding of these outside-the-Standard Model scenarios. Investigation of physics at high $Q^2$ with the
polarized \( e - p \) scattering will hence be important to understand the chiral structure of these interactions. Some specific cases investigated in the Workshop are discussed below.

Investigations of physics at high \( Q^2 \) with polarized protons and electrons included the search for the evidence of R-Parity violating SUSY[32], Contact Interactions (CI)[33], and also search for the Instanton in protons[34]. In a specific scenario: (leptoquarks) in R-parity violating SUSY it was predicted[32] that the \( \tilde{t} \) production cross section off of \( d \) quark: 

\[
\sigma(e_R^+ p_R) \ll \sigma(e_R^- p_L), \quad \text{where } L, R \text{ indicate the left and right handedness of the beams.}
\]

Measurement of these cross sections would be crucial to confirm these predictions and their underlying mechanism. If the \( \tilde{t} \) production happens through an \( e \cdot s \) process, the cross sections were predicted to have the following relations:

\[
\sigma(e_R^+ p_R) < \sigma(e_R^- p_L) \quad \text{and} \quad \sigma(e_R^- p_L) < \sigma(e_L^+ p_R).
\]

Again, polarized proton beams in HERA would be essential to measure these cross sections.

The particle helicities and charges could play a most crucial role in the investigation of possible Contact Interactions[33] as well. Motivated by the present results on the high \( Q^2 \) anomaly being related to possible Contact Interactions (CI), predictions were made for specific asymmetries, some of them parity violating, some parity conserving, while some of them mixed[33]. It was shown that if the CI effects should be visible with the HERA’s kinematic reach at high \( Q^2 \), various types of CIs should manifest themselves in form of asymmetries different from those predicted by the Standard Model. The CI lagrangian is given by

\[
\mathcal{L}_{CI} = \sum_{q=u,d} \eta_{i,j}(\bar{e}_i \gamma^\mu e_i)(\bar{e}_j \gamma_\mu e_j)
\]

where \( \eta_{i,j} = (4\pi \epsilon) / \Lambda_{i,j} \), \( \epsilon = \pm 1 \) and \( i, j \) stand for \( L, R \), for left and right handedness. Including the freedom to construct the asymmetries using these eight different types of interactions and the differently charged \( e \) beams and their helicities along with the proton beam helicities, one can construct numerous asymmetries. The most sensitive of these helicities were parity violating (PV) and mixed, are given by,

\[
A_{LL}^{PV} = \frac{\sigma_{--} - \sigma_{++}}{\sigma_{--} + \sigma_{++}}, \quad B_2^2(\text{mixed}) = \frac{\sigma_{--} - \sigma_{++}}{\sigma_{++} + \sigma_{++}}
\]

where the subscript indicates the charge of the electron beam, while the superscript stands for the positive and negative helicities of colliding beams. It was estimated that with the kinematics of the HERA accelerator and the presently running detector acceptances and capabilities, the helicity structure sensitivity up to \( 3 - 7 \) TeV could be reached. The asymmetries \( A_{LL}^{PV} \) and \( B_2^2 \) estimated for different kinds of contact interactions, as a function of \( Q^2 \) are shown in Figures 7(a) and (b) respectively, and are compared with the Standard Model predictions along with the statistical accuracy that can be achieved with polarized HERA. The luminosity assumed in this study was 250 \( \text{pb}^{-1} \) for each of the \( e^\pm \) beam run with either helicity. Detector acceptances were included in this study. Apparently with polarized HERA the potential to indicate unambiguously if any deviation from the Standard Model occurs and to resolve some of its helicity structure is good.

It was pointed out[34] that in the Instanton Liquid Model a large effects from the instantons comes from high \( Q^2 \) and at high \( x \). In stark contrast with pQCD which predicts that the virtual photon-proton asymmetry \( A_1^{\text{pQCD}} \sim +1 \) at high \( x \), if instantons play a significant role in protons, the same asymmetry \( A_1^{\text{inst}} \rightarrow -1 \) as \( x \rightarrow 1 \) and at high \( Q^2 \). Measurements of \( A_1 \) at HERA should easily be able to resolve this.
Figure 7: $A_{LL}^{PV}$ and $B_2^2$ vs. $Q^2$. Different theoretical scenarios shown with the possible statistical uncertainty with 250 pb$^{-1}$ luminosity for each of the $e^\pm$ and $\bar{e}-\bar{p}$ helicity combination. Standard Model prediction is shown for comparison.
2.7 Spin and Fragmentation

The probability distribution of the proton fragmenting into a particular parton in the polarized $e - p$ collisions is the polarized fragmentation function of the proton. The measurement of polarized fragmentation functions is difficult because this involves the measurement of the spin of the final state particles, in fact, it is only possible in cases like $\Lambda$ baryon for which the dominant decay mode is parity violating. Such studies, it should be noted, do not need polarized protons beam. Only polarized electron beam can suffice. As such these could start immediately after the electron spin rotators are installed in the HERA ring during the luminosity upgrade. Different scenarios for the spin transfer mechanism to $\Lambda$ baryon have been studied[35, 36, 37]. It was demonstrated in [35] that the LEP data alone was not able to differentiate between the different scenarios for the spin transfer assumed. However, with a moderate luminosities of $100 \text{ pb}^{-1}$ $e - p$ scattering data at HERA, it would be easy to disentangle these scenarios.

Introducing polarized protons in the above scheme enables possibilities of new measurements. Fixed target polarized DIS experiments normally can access only the current fragmentation region. At HERA however one can easily study the current and the target fragmentation regions unambiguously within the collider detectors. Polarized DIS at HERA will hence allow for the first time measurements of polarized target fragmentation. Of particular interest is the scenario in which all the proton momentum would be detected in the target fragmentation region of the polarized DIS. In such an eventuality the fracture function is expected to factorize into a transition probability of proton into a meson and another baryon, and the structure function of the baryon. The experimental signature of this scenario would be a highly energetic meson. Such measurements would lead us to the structure functions of unstable baryonic excitations. If they are made on different targets, i.e. with different hadron beams in the HERA ring, one could measure the Ellis-Jaffe sum rule for different targets, and check if the sum rule violation is target independent and indeed related to a fundamental property of the QCD vacuum[38].

3 Technical Challenges To Achieve Polarized HERA

So far I have reviewed a few important topics out of the possible physics program that could be pursued with a polarized HERA collider. The breadth of the program and the fundamental nature of the problems it will address already make a compelling argument to do what it takes to achieve that goal. However, the argument in favor of polarized HERA, would not be complete without some comments the technical challenges facing the project, the details of these which are discussed elsewhere in these proceedings. In this section I argue that although the goals from the technical side seem daunting, the pace of advances in the recent past has been impressive. The final goal of a polarized HERA collider could be realized, after all, if enough effort is made now.

High Luminosity: Presently, $\sim 35-40 \text{ pb}^{-1}$ luminosity is delivered by HERA to the two collider detectors per year, and their efficiency to convert that into useful data is of the order of $\sim 70-80\%$. Most of the measurements discussed in section 2 assumed typically 4 times higher luminosities than these. A major effort is underway at DESY to increase the HERA luminosity by a factor of 4-5 to $\sim 170-200 \text{ pb}^{-1}$/year. This luminosity increase is essential for the electroweak and the high $Q^2$ physics program planned from 2001-2005 at HERA[39]. A
polarized HERA program with such luminosity for ~3-4 years would be sufficient for most of the physics topics in section 2.

**Electron Beam Polarization and Polarimetry:** The electron beam at HERA is naturally polarized. Though not at its maximum achievable value ~70% yet, ~55% has been routinely achieved and occasional short periods with 65% polarizations have been reported during dedicated accelerator tuning studies. Effort towards achieving the maximum possible electron polarization are expected to continue through the luminosity upgrade program. Polarization measurement has also improved gradually. Starting from \( \delta P_e/P_e \sim 5.5\% \) in 1995 the best published value today is \( \delta P_e/P_e \sim 3.4\% \) from 1997. This is already at the level that is sufficient for the polarized HERA physics program in section 2. In addition, there is a dedicated effort to reduce the uncertainty further to \( \leq 2\% \) by year 2000.

It is expected that the luminosity upgrade program at HERA will have some effect on the electron beam polarization due to beam-beam interactions in the interaction region. However, there is nothing to indicate that the electron beam polarization would be completely lost. It will have to be studied as the luminosity upgrade program proceeds.

**Proton Beam Polarization and Polarimetry:** Polarization of the proton beam is a challenging problem. The protons being much heavier than electron, the synchrotron radiation and hence, the natural polarization due to STE is almost negligible. Realising a high energy polarized proton beam in a storage ring will require first, the development of a strong enough polarized \( \text{H}^- \) source, followed by acceleration to high energy without destroying the beam polarization, and finally, storage of the high energy polarized beam in the storage ring.

The Relativistic Heavy Ion Collider (RHIC) at BNL plans to circulate polarized proton beams in the energy range 50-100 GeV by mid 2000 (eventually 250 GeV). They will be utilized for the RHIC-SPIN program. Although not quite at the very high energy of HERA, knowledge and experience gained in every aspect of the polarized proton beams at RHIC would be invaluable towards achieving the polarized proton beam at HERA.

A detailed study dedicated to polarized protons at HERA identified two major problems: a) adequately intense and highly polarized \( \text{H}^- \) source and b) acceleration and retention of polarization in HERA.

HERA will need a polarized \( \text{H}^- \) source of with the following specifications: I=20 mA in 100 \( \mu \)s pulses at 0.25 Hz with emittance \( 2\pi \text{ mm-mr} \) and polarization \( P \sim 80\% \). The most promising approach at the moment seems to be the Optically Pumped Polarized Ion Source (OPPIS) development at TRIUMF. Much progress has been made in the last one year towards improving the source properties using this approach. The polarized \( \text{H}^- \) source which will be used in the polarized proton beam at RHIC is in its final stage of development at TRIUMF and is being brought at BNL as this article goes to print. Studies towards achieving the HERA source specifications are under way.

Acceleration and storage of high energy polarized protons is difficult mainly because of the depolarizing resonances. The large anomalous magnetic moment of the proton \( (\mu_p/\mu_N = 2.79) \) results in high number of spin precision per orbit (spin tune) equal to \( G\gamma \sim 1530 \) for HERA at 800 GeV. The spin motion is thus very sensitive to the magnetic field, and in particular to the imperfection and intrinsic resonances which can lead to depolarization of the beam. Use of Siberian Snake Magnets (SSM) can avoid this depolarization. SSMs have been tested.
successfully recently at BNL for the RHIC. Dedicated design study for HERA continues at DESY[44].

Proton beam polarimetry at high energy is being actively pursued at BNL. Until recently no definite answers existed as to what could be used for the RHIC SPIN program. Developments in the last one year however has changed this situation. Polarimeters based on three different reactions are being considered[46, 47]: 1) $\vec{p} \cdot C$ elastic scattering in the Coulomb Nuclear Interference (CNI) region, 2) Inclusive pion production $\vec{p}C \rightarrow \pi^+ X$, and 3) $\vec{p}p$ elastic scattering using a polarizable jet target. The $\vec{p} \cdot C$ CNI and inclusive pion production polarimeters were recently tested successfully at the AGS[46]. Because of its low cost and possible high statistical precision in a short time, the CNI polarimeter became a natural choice for RHIC in its first year. It is being built now and expected to be ready by the end of 1999.

4 A Case for Polarized HERA

A future physics program at HERA with polarized proton and polarized $e^\pm$ beams would push study of the nucleon structure into an entirely new regime using the spin as a tool, in addition to the high energy. Not only are there clearly defined outstanding problems in the field which might be addressed by future data with polarized HERA, but it will also access possible new physics beyond the reach of any other accelerator facility, namely, the study of spin variables the low $x$ physics within the Standard Model, and the chiral structure of possible high $Q^2$ physics outside of it. History of this field has shown that exciting new results were obtained both in the unpolarized and the polarized DIS, every time a new $Q^2$ barrier was crossed. Polarized HERA will be just such a step in polarized DIS.

Most of the components needed to pursue such a program already exist at DESY: $\bar{e} - p$ collider with sufficiently high energy, polarized $e^\pm$ beam and a reliable measurement of the polarization, two working collider detectors H1 and ZEUS, and the people who have experience with both the machine and the detectors. The only missing component is the polarized proton beam.

With so much already at hand it would be unfortunate not to make a determined pursuit of this goal with all the resources and efforts possible.

Acknowledgement: It was a privilege to present this case on behalf of all the participants of the 1997 Workshop on Polarized Protons at HERA. Special thanks are due to A. De Roeck and G. Rädel for their help in collecting all the material for the presentation. This work was supported by a grant from U.S. Department of Energy.

References

[1] The structure of the proton, R. G. Roberts, Cambridge Monographs on Mathematical Physics, 1990

[2] E. Gabathuler in the proceedings of The workshop on Polarized Protons at High Energies: Accelerator Challenges and Physics Opportunities, DESY May 17-20, 1999
[3] SMC Collaboration, B. Adeva et al., *Phys. Rev.* D58, 112001 (1998); SMC Collaboration, B. Adeva et al., *Phys. Rev.* D58, 112002 (1998)

[4] E143 Collaboration, K. Abe et al., *Phys. Rev.* D58, 112003 (1998)

[5] E154 Collaboration, K. Abe et al., *Phys. Rev. Lett.* 79, 26-30 (1997); E154 Collaboration, K. Abe et al., *Phys. Lett.* B405, 180-190 (1997)

[6] R. L. Jaffe in the proceedings of *The workshop on Polarized Protons at High Energies: Accelerator Challenges and Physics Opportunities*, DESY May 17-20, 1999

[7] A. A. Sokolov & I. M. Ternov, Sov. Phys. Doklady 8, 1203 (1964)

[8] D. Barbar et al., *Phys. Lett.* B343 436, (1995) and the references therein

[9] Hermes Collaboration, A. Airapetian et al., *Phys. Lett.* B442, 484 (1998); Hermes Collaboration, K. Ackerstaff et al., *Phys. Lett.* B404, 383 (1997)

[10] Proceedings of *Future Physics at HERA*, Eds. G. Ingelman, A. De Roeck, R. Klanner, DESY 96-235, http://www.desy.de/~heraws96

[11] Proceedings of DESY workshop on *Physics with Polarized Protons at HERA*, Eds. A. De Roeck & T. Gehrmann, DESY-Proceedings-1998-01, February 1998

[12] W. D. Nowak, in the proceedings of *The workshop on Polarized Protons at High Energies: Accelerator Challenges and Physics Opportunities*, DESY May 17-20, 1999

[13] A. M. Cooper-Sarkar et al., *Int. J. Mod. Phys.* A13 3385 (1998)

[14] H. Abramowicz and A. Caldwell, *HERA Collider Physics*, hep-ex/9903037

[15] D. Barber et al., DESY-Proceedings-1998-01, pp 241 (1998)

[16] J. Contreras, DESY-Proceedings-1998-01, pp 232 (1998)

[17] A. Deshpande et al., DESY-Proceedings-1998-01, pp 26 (1998)

[18] A. De Roeck et al., *Eur. Phys. J.* C6, 121-131 (1999)

[19] F. E. Close & R. G. Roberts, *Phys. Lett.* B336 257 (1994)

[20] J. Kwiecinski & B. Ziaja, DESY-Proceedings-1998-01, pp 90 (1998)

[21] J. Bartels et al., DESY-Proceedings-1998-01, pp 44 (1998); *hep-ph/9711228*

[22] C. Aidala et al., in the proceedings of *The workshop on Polarized Protons at High Energies: Accelerator Challenges and Physics Opportunities*, DESY May 17-20, 1999

[23] G. Rädel et al., DESY-Proceedings-1998-01, pp 54 (1998)

[24] G. Rädel & A. De Roeck, DESY-Proceedings-1998-01, pp 77 (1998)

[25] G. Altarelli et al., *Nucl. Phys.* B496 (1997) 337

[26] J. M. Butterworth et al., DESY-Proceedings-1998-01, pp 120 (1998)
[27] S. D. Bass et al., DESY-Proceedings-1998-01, pp 183 (1998)
[28] M. Maul et al., DESY-Proceedings-1998-01, pp 112 (1998)
[29] J. Contreras et al., DESY-Proceedings-1998-01, pp 103 (1998)
[30] H1 Collaboration, C Adloff et al., Z. Phys. C74, 191 (1997); ZEUS Collaboration, J. Breitweg et al., Z. Phys. 74, 207 (1997)
[31] ZEUS Collaboration, J. Breitweg et al., DESY-99-56, Submitted to the Euro. Phys. J. C, May 1999
[32] J. Ellis et al., Phys. Lett. B408 252-260 (1997)
[33] J.-M. Virey, DESY-Proceedings-1998-01, pp 152 (1998)
[34] N. Kochelev, DESY-Proceedings-1998-01, pp 225 (1998)
[35] D. de Florian, et al., DESY-Proceedings-1998-01, pp 140; hep-ph/9710410
[36] A. Kotzinian et al., Eur. Phys. J. C2 329-337 (1998)
[37] M. Burkardt & R. L. Jaffe, Phys. Rev. Lett. 70 2537 (1993)
[38] S. Narison et al., Nucl. Phys. B433 209 (1995)
[39] R. Cashmore et al., Proc. of Future Physics at HERA Workshop 1995/96, Vol.2, pp-129
[40] D. Barber et al., Nucl. Inst. & Meth. Phys. Res. A338 166-184 (1994)
[41] Proposal Polarization 2000, V. Andreev et al., DESY-PRC-98-07
[42] Polarized Proton Collider at RHIC, Design Manual, July 1999
[43] A. Krisch et al., SPIN Collaboration & DESY Polarization Team, UM-HE 96-30; C.D.P. Levy & A. N. Zelenski in UM-HE 99-05, June 1999
[44] G. Hoffstadter, in proceedings of The Workshop on Polarized Protons at High Energies - Accelerator Challenges and Physics Opportunities, May 17-20, 1999.
[45] A. Zelenski & L. Anderson, Comments At. Mol. Phys. 32, No.5 (1996) 281
[46] G. Bunce & K. Kurita, in the proceedings of The Workshop on Polarized Protons at High Energies - Accelerator Challenges and Physics Opportunities, May 17-20, 1999.
[47] V. W. Hughes & A. Deshpande, To be published in the proceedings of DIS99, ‘A Polarized HERA Collider’, Eds. J. Blümlein et al.; hep-ex/9906006