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# Latest Results from HERA

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**Abstract.** Highlights are presented of the latest measurements from the H1, ZEUS and HERMES experiments at HERA.

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## 1. Introduction and Overview

Deep inelastic scattering of leptons off nucleons has played a fundamental role in the understanding of the structure of the nucleon. At the HERA electron proton collider it is possible to study the proton in new kinematic regimes, in particular at low Bjorken-$x$ and at large virtuality $Q^2$. Due to the large centre of mass energy of $\sim$ 300 GeV HERA is also an important facility to search for new phenomena. The HERMES experiment also allows the spin structure of the nucleon to be studied.

In this paper only a few of the many results from the HERA experiments are discussed. They have been chosen to give a flavour of the full scope of physics topics that are explored in high energy electron proton scattering. In the first section the measurements on the proton structure function $F_2$ are presented and interpreted in the context of perturbative QCD. Next the measurements of the DIS cross sections at high $Q^2$ in both neutral and charged current scattering are presented and the effects of the exchange of weak gauge bosons are discussed. The DIS data are then used to put constraints on extensions to the Standard Model where particles that have quantum numbers of both leptons and quarks are produced. Then a search for direct production of $W$ bosons is presented. Finally a first result on the spin of the gluon is presented.

## 2. Proton Structure

The kinematics of deep-inelastic scattering can be expressed in terms of the virtuality of the exchanged boson, $Q^2$, and Bjorken-$x$, which can be interpreted as the fraction of the proton momentum that is carried by the struck quark.

One of the most interesting results obtained at HERA is the strong rise of the proton structure function $F_2$ towards low $x$ [1]. There are now measurements with high precision confirming this observation. The measurement of the structure function $F_2$ is shown in Fig. 1 as function of $x$ at $Q^2 = 15$ GeV$^2$.

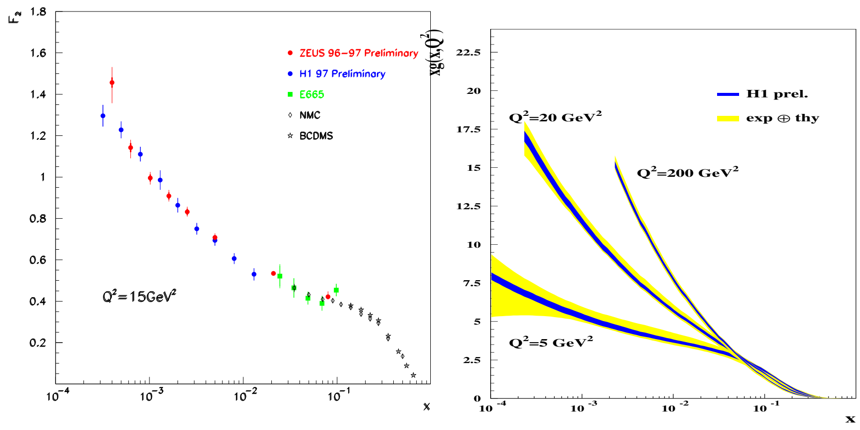


**Figure 1.** **(a)** The structure function $F_2$ at $Q^2 = 15$ GeV$^2$ as function of $x$. Shown are the H1 and Zeus data and the measurements by BCDMS, NMC and E665 . **(b)** The gluon density determined from a fit to $F_2$ data. Also shown are the experimental uncertainties and the total uncertainty which is the quadratic sum of the experimental and theoretical uncertainties.

A strong rise of the structure function towards low $x$ is observed in the HERA data. Both experiments, H1 and Zeus, give compatible results and are also consistent with the measurements from fixed-target experiments (BCDMS [2], NMC [3] and E665 [4]) at higher $x$. The precision of the HERA data is also much improved compared to previously published results [5] and is now competitive with the precision of the fixed-target experiments.

The recent results on $F_2$ are shown in Fig. 2 as function of $Q^2$ at different values of $x$. While at $x \approx 0.1$ Bjorken scaling is observed, i.e. the structure function is independent of $Q^2$, positive scaling violations are observed at lower $x$. These become stronger with decreasing $x$. At high $x > 0.1$ the scaling violations are negative.

The strong rise at low $x$ is interpreted in perturbative QCD as a strong rise of the gluon density with decreasing $x$. Using those preliminary data together with the data at higher $Q^2$ and the NMC data a QCD analysis was performed in Next-To-Leading order. This NLO QCD fit describes the data well in the entire kinematic range, i.e. $4 < Q^2 < 30000$ GeV$^2$ and $10^{-4} < x < 0.65$ as can also be seen from Fig. 2.

The gluon density as determined by the NLO QCD fit is shown in Fig. 1 as function of $x$ for different values of $Q^2$. The experimental precision on the gluon density is about $5\%$. When considering also uncertainties on the theoretical input (as e.g. the value of the charm mass or the value of $\alpha_s$) an additional error arises, so that the total uncertainty on the gluon density is about $10\%$ at $Q^2 = 25$ GeV$^2$ for $x < 0.1$.

The validity of the gluon extracted from the QCD analysis of the $F_2$ data may be tested directly by analysing the charm production in DIS. In the QCD fit it is assumed that charm

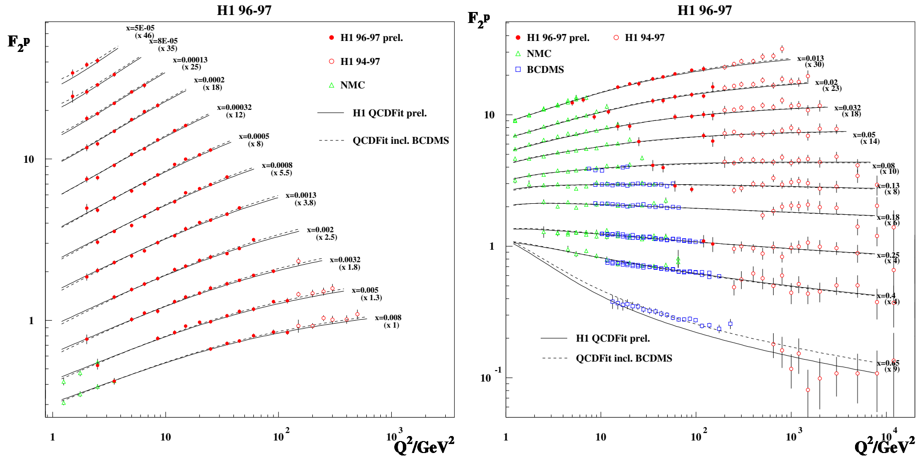


**Figure 2.** $F_2$ as function of $Q^2$ for fixed values of $x$. Shown are the H1, BCDMS and NMC measurements and a NLO QCD Fit (full line) to those data.

is produced only by gluons splitting into a $c\bar{c}$ pair, i.e. by the process shown in Fig. 3.

The cross section for this process can be measured directly by tagging the charm meson in the final state. A recent measurement of the DIS cross section for $D^*$ production allowed the charm induced structure function $F_2^{c\bar{c}}$ to be measured. The fraction of $F_2^{c\bar{c}}$ to the inclusive $F_2$, $F_2^{c\bar{c}}/F_2$, is shown in Fig. 3. At low $Q^2$ this fraction is only about $5\%$ but it increases to values of about $30\%$ at $Q^2 = 100$ GeV$^2$. The data are well described in the entire range by the QCD fit showing that indeed charm is produced via the process indicated in Fig. 3 as assumed in the QCD prediction.

## 3. Deep–inelastic Scattering at Very High $Q^2$

The large integrated luminosity collected in both lepton charges in the colliding $ep$ beams of the HERA accelerator have allowed the phase space of inclusive DIS cross section measurements to be extended into new kinematic regions of very high $Q^2$ up to $50\,000$ GeV$^2$. In this region where $Q^2 \simeq M_Z^2$ or $M_W^2$, the $Z^0$ and $W^\pm$ boson masses squared, the effects of the electroweak sector of the Standard Model (SM) can be tested in DIS. In addition signals of new physics beyond the Standard Model may be expected to arise at the highest $Q^2$ where the smallest distance scales of proton structure are probed.

The single differential cross-sections $\mathrm{d}\sigma/\mathrm{dQ}^2$ for NC and CC are shown in Fig.4 for $y \leq 0.9$. The measurements show the published $e^+p$ data [6,7], and new preliminary measurements of the $e^-p$ data [8,9]. The positron data were taken at $\sqrt{s} \approx 300$ GeV, whilst the electron data were taken at $\sqrt{s} \approx 320$ GeV. The data are compared to the CTEQ4 [10] prediction which is obtained from a NLO QCD analysis of global hard scattering data. The new NC and CC measurements presented here were not included in the QCD fit.

The data are found to be in good agreement with the expectation. For $Q^2 > 3\,000$ GeV$^2$ the NC $e^-p$ cross-section is observed to be systematically larger than the $e^+p$ cross-

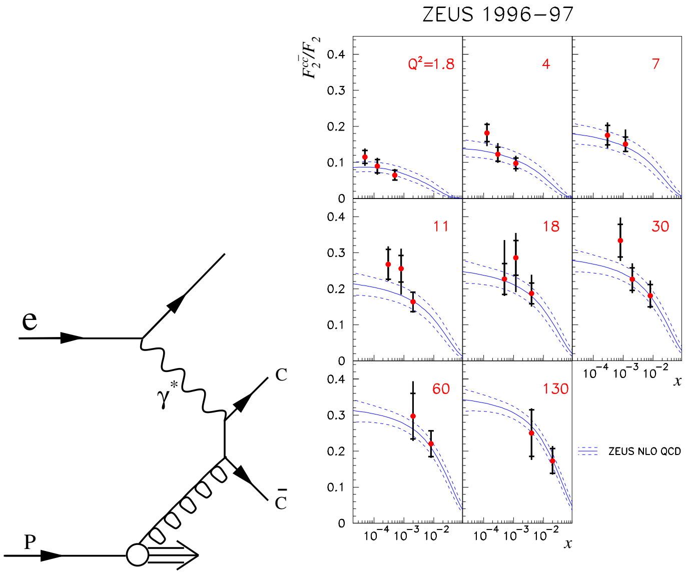


**Figure 3.** **(a)** Diagram for charm production via the boson-gluon fusion process. **(b)** Fraction $F_2^{c\bar{c}}/F_2$ as function of $x$ for different values of $Q^2$.

section. The influence of the increased centre-of-mass energy is indicated by the dashed line and predicts an increased cross-section of $\approx 7\%$ for $Q^2 < 1\,000$ GeV$^2$ rising to 50% at $Q^2 = 30\,000$ GeV$^2$. However, at high $Q^2$ this is approximately an order of magnitude smaller than the increase expected from the different lepton charge. The cross-sections are consistent with the SM expectation of the contribution of $Z^0$ exchange.

The $Q^2$ dependence of the CC cross-section for $e^+p$ and $e^-p$ scattering is shown in Fig.4b. The electron data are found to have a larger cross section everywhere, by up to a factor of ten at $Q^2 = 15\,000$GeV$^2$. The effect of the increased centre-of-mass energy is expected to be relatively small, and is shown as the dashed curve in Fig.4b. The CC cross-sections are in good agreement with the SM expectation based on the H1 $e^+p$ QCD fit. The $Q^2$ dependence of the cross-section at high $Q^2$ is largely due to the effect of the electroweak propagator and therefore $M_W$. Therefore the CC data are consistent with the expectation for $t$-channel $W$ exchange.

## 4. Search for Leptoquarks

In the Standard Model leptons and quarks interact only through the electroweak gauge bosons. Many extensions of the Standard Model discuss possible other interactions between these particles. One scenario is a coupling of quarks and leptons to so-called leptoquarks (LQ). Examples of such theories have been discussed in the context of Grand Unification and Superstring E(6) models [11].

At HERA leptoquarks could be produced as an $s$-channel resonance from the interaction

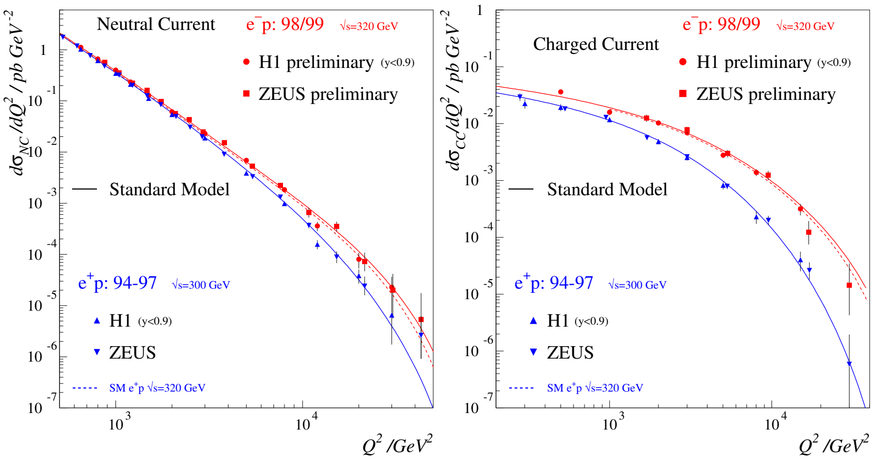


**Figure 4.** The $Q^2$ dependence of the NC (a) and CC (b) cross-sections $d\sigma/dQ^2$ are shown for the preliminary $e^-p$ (solid points) and published $e^+p$ (open points) measurements. The data are compared to the SM expectation. The influence of the increased centre-of-mass energy is shown as the dashed curve.

of the beam electron and one quark in the proton if the mass is lower than the centre-of-mass energy. The production cross section and the width of the leptoquark depend on the unknown Yukawa coupling $\lambda$. The leptoquarks can decay in $eq$ or $\nu_e q$ (first generation LQ) but may also violate lepton number conservation and decay into $\mu$ or $\tau$ leptons. I will here concentrate on the search for first generation leptoquarks.

The topology of the final state is in this case identical to those of the Standard Model DIS processes. Since such particles would be produced in the $s$-channel they would cluster at the value of the invariant mass $M_{LQ}$. They may be distinguished from the DIS While the dependance of the DIS cross section on $y$ is $1/y^2$ scalar leptoquarks decay isotropically in the centre-of-mass system resulting in a flat $y$-distribution.

After optimising the $y$-cut for the search for leptoquarks there is a slight deviation at a mass of $\approx 200$ GeV in the H1 data which was already observed in the 1994-96 data [12]. Assuming that this deviation is only a statistical fluctuation limits can be placed on the leptoquark as function of its mass and Yukawa coupling $\lambda$. These are shown in Fig. 5. The limits from HERA can be seen to be very competitive with limits from other colliders especially for low values of the branching fraction $\beta(LQ \to eq)$. For a branching ratio of 100% scalar leptoquarks are excluded for masses up to 275 GeV for a coupling equal to the electromagnetic strength ($\lambda = 0.3$).

## 5. $W$ Production

In the Standard Model $W$ bosons are produced predominantly in photoproduction ($ep \to eWX$) via Bremsstrahlung off a quark. In certain scenarios beyond the Standard Model $W$s may be produced via decays of heavier particles. For instance if single top quarks

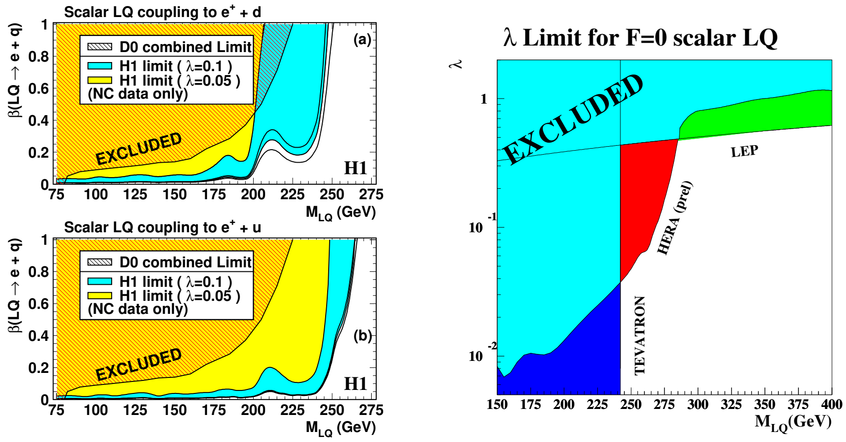


**Figure 5.** **(a)** Mass dependent exclusion limits at $95\ \%$ CL on the branching ratio $\beta(LQ \to eq)$ for scalar leptoquarks produced by $e^+d$ and $e^+u$ fusion. Two exclusion regions corresponding to $\lambda = 0.1$ and $\lambda = 0.05$ are shown. **(b)** Comparison of coupling limits as function of the LQ mass a specific F=0 scalar leptoquark with a branching ratio of $100\%$. The LEP result is from Opal, and the HERA result is from Zeus for $M_{LQ} < 290$ GeV and from H1 for larger masses. The Tevatron result is the combined CDF and D0 analysis.

were produced (via the reaction $\gamma c \to t$, as proposed in [13]) $W$s would be observed in the decay $t \to bW$. A similar decay chain is possible for the production of a single stop in super symmetry models where the stop decays to $W$ sbottom [14]. In such models the $W$ would be produced along side a hadronic jet with high transverse momentum.

$W$ events are searched for in the $W \to e\nu$ and $W \to \mu\nu$ decay channels, by selecting events with large missing transverse energy, signifying a neutrino, and an isolated electron or muon [15,16]. The events may contain in addition a hadronic jet and/or the scattered electron. Further cuts [16] are introduced to suppress backgrounds that arise mainly from: NC events, where the scattered electron is misidentified as the decay lepton and particles losses in the beam pipe give rise to an apparent missing transverse momentum; CC events where a final state particle is misidentified as the decay lepton; and events containing a muon pair $ep \to eX\mu^+\mu^-$, where one of the muons is not identified.

At H1 a total of eight $W$ candidate events are found, all of which appeared in the $e^+p$ data sample. Three of these events are observed in the $W \to e\nu$ channel compared to $2.24 \pm 0.67$ expected from $W$ production and $0.88 \pm 0.19$ from background sources. The other five candidate events are observed in the $W \to \mu\nu$ channel compared to $0.87 \pm 0.26$ expected from $W$ production and $0.14 \pm 0.09$ from other Standard Model sources. In the $e^-p$ data sample the zero events observed should be compared with 2.0 events expected from Standard Model processes.

The Zeus collaboration observes 5 $W$ candidate events in good agreement with the standard model expectation. All the events were observed in the electron decay channel. 3 are observed in $e^+p$ data compared with and expectation of 3.5 $\pm$ 0.7. 2 are seen in the $e^-p$

data compared with $0.8 \pm 0.4$ expected. The zero events in the muon decay channel should be compared with $2.8 \pm 0.5$ expected.

The excess of H1 events in the muon channel is even more striking when the events are looked at differentially as a function of $P_T^X$. At low $P_T^X$ there is no significant deviation from the Standard Model. At $P_T^X > 40$ GeV 3 muon events are observed compared to a Standard Model expectation of 0.60 ($e^+$ and $e^-$, $e$ and $\mu$ decay channels combined).

Although the present number of candidate $W$ events is very small, the event yield after the HERA luminosity upgrade will be at least a factor of 20. Thus if the observed excess really is a signal of new physics such a discovery would certainly be made at HERA in the following years.

## 6. Extraction of the Gluon Spin

It is still unclear how the proton spin is made of the individual constituents of the proton. In the most general case the total spin of the proton is the sum of four components:

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

where $\Delta\Sigma$ is the sum of the spins of the light quarks. which is determined experimentally to be between 0.2 and 0.4. $\Delta G$ is the spin of the gluon and $L_q$ and $L_g$ are the orbital angular momenta of the quarks and the gluons. Neither the orbital momenta nor the gluon spin has ever been measured directly. How the individual quark flavours contribute to $\Delta\Sigma$ is also not yet well known.

The main aim of the HERMES experiment is the measurement of the contribution to the proton spin from the individual quark flavours. The most recent result on this topic can be found in [18]. However, the collaboration has also made a first attempt of extracting the spin of the gluon which is presented here.

In order to access the spin of the individual components of the proton the lepton beam is polarised longitudinally and collided with a polarised target. The HERMES spectrometer records the particles produced in that interaction. The data that are presented here are obtained when Hydrogen and $He^3$ was used as targets.

There are in principle several methods of measuring $\Delta G/G$. It can be obtained from scaling violations of the polarised structure function $g_1$ as it is done in the unpolarised case (see section 2.) from the scaling violations of $F_2$. With the presently available data sets this is, however, not possible due to the small range in $Q^2$. Another possibility is the tagging of charm events as also already discussed for the unpolarised case (see section 2.). This is also not possible yet at HERMES since the statistics is too small. Therefore HERMES has adapted a different method which, however, relies on a number of assumptions so that it can not be viewed as a direct measurement.

The idea is to tag events with two hadrons with high momentum which are back to back in the detector and have opposite charge. This topology is mainly expected from events produced in boson-gluon-fusion (BGF) (see fig. 3). This can be seen in fig. 6 where the Monte Carlo expectation is shown for the BGF, the QCD-Compton and QPM-process. The latter two have no sensitivity to the gluon. It is seen that the BGF process is expected to give the largest contribution in particular at high values of $P_t^h$. The details of the selection criteria and the analysis can be found in [19].

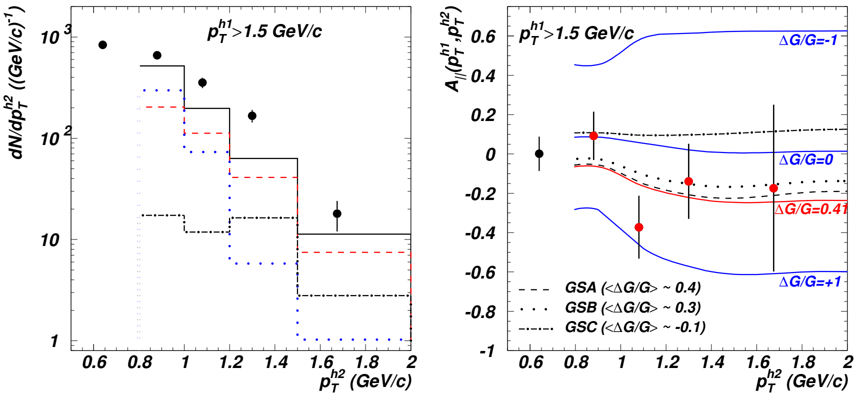


**Figure 6.** **(a)** Comparison of Data (circles) and Monte Carlo simulation (full line) for $dN/dP_T^{h2}$ for $P_T^{h1} > 1.5$ GeV. The dashed, dashed-dotted and dotted lines represent the contributions from BGF, Vector-Meson-Production (VMD) and QCD-Compton processes respectively. The full line is their sum. **(b)** $A_{||}$ for high-$P_T$ hadron production measured at HERMES compared with Monte Carlo predictions for $\Delta G/G = \pm 1$ (lower/upper solid curves), $\Delta G/G = 0$ (middle solid curve) and for the phenomenological LO QCD fits for three values of $\Delta G/G$ (dashed,dashed-dotted and dotted curves)

The data are analysed in terms of the asymmetry

$$A_{||} = \frac{N^{\uparrow\downarrow}\mathcal{L}^{\uparrow\uparrow} - N^{\uparrow\uparrow}\mathcal{L}^{\uparrow\downarrow}}{N^{\uparrow\downarrow}\mathcal{L}_P^{\uparrow\uparrow} - N^{\uparrow\uparrow}\mathcal{L}_P^{\uparrow\downarrow}}$$

where $N^{\uparrow\uparrow}$ ($N^{\uparrow\downarrow}$) is the number of oppositely charged pairs for target spin parallel (anti-parallel) to the lepton beam spin orientation. The luminosities for each target spin state are $\mathcal{L}^{\uparrow\uparrow}$ ($\mathcal{L}^{\uparrow\downarrow}$) and $\mathcal{L}_P^{\uparrow\uparrow}$ ($\mathcal{L}_P^{\uparrow\downarrow}$), the latter being weighted by the product of the beam and target polarisations for each spin state.

The result is shown in figure 6. There is a clear asymmetry observed at large values of $P_T^{h2}$ of the second hadron. Such an asymmetry could be caused by a non-zero spin of the gluons as can be seen from the curves in the figure which are based on a LO QCD fit [20]. Assuming the PYTHIA Monte Carlo model the gluon spin is determined to be

$$\Delta G/G = 0.41 \pm 0.18(\mathrm{stat.}) \pm 0.03(\mathrm{exp.syst.})$$

at $\langle x_G \rangle = 0.17$ and $\langle \hat{P}_T^2 = 2.1$ GeV$^2$. The systematic error does not include the dependence on the model assumption.

Although the result is not a direct measurement and it is consistent with a $\Delta G/G = 0$ it is an encouraging result which will hopefully be confirmed in future when the HERMES collaboration has taken more data so that it can be measured from charm tagging and when first results are available from the RHIC [**?**] experiment.

## 7. Acknowledgements

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## References

[1] H1 Collab., I. Abt et al., Nucl. Phys. **B407** (1993) 515.
ZEUS Collab., M. Derrick et al., Phys. Lett. **B316** (1993) 412.
[2] BCDMS Collab., A. Benvenuti et al., Phys. Lett. **B223** (1989) 485.
[3] NMC Collab., M. Arneodo et al., Phys. Lett. **B364** (1995) 107.
[4] E665 Collab. M.R. Adams et al., Nucl. Instr, Meth. **A291** (1990) 179.
[5] H1 Collab., T. Ahmed et al., Nucl. Phys. **B439** (1995) 471.
ZEUS Collab., M. Derrick et al., Z. Phys. **C65** (1995), 379.
[6] ZEUS Collab., J.Breitweg et al., C 11 (1999) 3, 427-445
ZEUS Collab., J.Breitweg et al., Eur.Phys.J. C 12 (2000) 3, 411-428.
[7] H1 Collab., DESY 99-107, hep-ex/9908059, accepted by Eur.Phys.J.
[8] ZEUS Collab., paper 549 and 558 contributed to International Europhysics Conference on High Energy Physics, 15-21 July 1999, Tampere, Finland HEP99
[9] H1 Collab., paper 157b contributed to International Europhysics Conference on High Energy Physics, 15-21 July 1999, Tampere, Finland HEP99
[10] H. Lai et. al., Phys.Rev.**D55**, 1280, (1997)
[11] J.-A. Hewett and T.G. Rizzo, Phys. Reports 183 (1989) 193.
[12] H1 Collab., A Search for Leptoquark Bosons in DIS at High $Q^2$ at HERA, ICHEP 98-Vancouver, 98-580 (1998).
[13] H. Fritzsch and D. Holtmannspötter, Phys.Lett. B457 (1999) 186.
[14] T. Kon, T. Matsushita, T. Kobayashi, Mod.Phys.Lett. A12 (1997) 3143.
[15] H1 Collab., C. Adloff et al., Eur. Phys. J. C 5 (1998) 575.
[16] H1 Collab., "$W$ production in $e^{\pm}p$ collisions at HERA", Prepared for the 9th International Symposium on Lepton and Photon Interactions at High-Energies, Stanford, USA, August 1999.
[17] T. Sjöstrand, Comp. Phys. Comm. **82** (1994) 74.
[18] K. Ackerstaff et al, Phys. Lett. B464 (1999) 123-134.
[19] HERMES Collab., A. Airapetian et al, Phys. Rev. Lett. 84 (2000) 2584-2588.
[20] T. Gehrmann, W. J. Stirling, Phys. Rev. **D53** (1996) 6100.
[21] RHIC Spin Collab., D. Hill et al., RHIC-SPIN-LOI-1991, May 1991. 7pp.