The spin structure of the nucleon as seen by HERMES

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Abstract

The status of the physics program of the HERMES experiment at DESY is presented, emphasizing results obtained on the spin structure of the nucleon and the future upgrade of the experiment with a recoil-detector to identify exclusive processes in an effort to study Generalized Parton Distributions (GPDs). In particular, we investigate inclusive and semi-inclusive lepton scattering processes from a nucleon target where both beam and target or only one of them is polarized. The target can either be Hydrogen or Deuterium with the nucleons polarized in the longitudinal or transverse direction with respect to the beam.

Introduction

In deep inelastic scattering (DIS) a lepton is scattered from a quark in a nucleon. The spin of the quark absorbing the virtual photon needs to be anti-parallel to the spin of the virtual photon due to conservation of angular momentum. This can be exploited by measuring the difference of the cross sections when the target nucleon and lepton beam are polarized either parallel or opposite to each other. In practice an asymmetry of yields is calculated, e.g. $A = \frac{N^{\uparrow\uparrow} - N^{\uparrow\downarrow}}{N^{\uparrow\uparrow} + N^{\uparrow\downarrow}}$ where $N^{\uparrow\uparrow}$ is the yield of DIS events with both beam and target spin polarized in the same direction. The normalization of the difference by its sum simplifies the large experimental effort. This asymmetry can be related to the spin structure function g_1. This function describes the distribution of longitudinally polarized quarks in a longitudinally polarized nucleon. This quantity was measured as a function of the Bjorken scaling variable x for the first time by the EMC collaboration [1]. It was found that the contribution of the quark spin to the total spin of the nucleon is surprisingly small. The inclusive DIS process, however, is only sensitive to the squared of the charge of the quark but independent from its flavor. Hence, possible contributions from the sea quarks, in particular the strange quarks, are unknown. One possible way to access the contributions of all light quarks and anti-quarks to the nucleon spin is through polarized semi-inclusive deep inelastic scattering (SIDIS) where in addition to the scattered lepton a hadron is detected and identified. This requires good particle identification (PID) as is available in the HERMES spectrometer [2][4].

The HERMES Detector

The HERMES experiment comprises a forward spectrometer with one dipole and an acceptance from 4 to 12 degrees. The lepton beams delivered by the HERA accelerator are 27.5 GeV electrons or positrons. The target is either polarized atomic Hydrogen or Deuterium gas which is injected into an open ended storage cell located in the beam line vacuum system. The beam line separates the spectrometer in an upper and lower part with independent detector systems and trigger for the top and bottom sections. For a given trigger all signals above threshold are read out by the data acquisition system of both top and bottom sections. Drift chambers before and behind the spectrometer magnet are used for track reconstruction and momentum analysis. The PID detector systems available are: a dual ring imaging cherenkov detector (RICH)[6], a transition radiation detector (TRD), a pre-shower detector and a lead glass calorimeter detector. The use of these detectors in combination allows us to identify leptons with an efficiency of 98% or better with a hadron contamination of less than 1%. The RICH plays a very important role in the system as it allows us to identify pions, kaons and protons with good efficiency in SIDIS events. This is a mandatory prerequisite in *flavor tagging*, which is the technique used to relate a struck quark of a given flavor to a produced hadron of a given type.

Flavor Tagging

For SIDIS the cross section to detect a given hadron of type h is proportional to the sum of the products of the quark distribution function and the fragmentation functions: e.g. $\sigma^h(x,z) \propto \sum_f e_f^2 q_f(x) D_q^h(z)$ (assuming factorization). Here, the fragmentation function $D_f^h(z)$ contains the probability that a struck quark of flavor f fragments into a hadron of type h. Note that it depends only on the kinematic variable $z = E_h/\nu$, the fractional energy carried by the hadron with energy E_h while ν is the energy transfer to the target as given by the difference between the initial and final lepton energy in the laboratory frame. On the other hand, the quark distribution function $q_f(x)$ depends on the Bjorken variable $x = Q^2/2M\nu$ only, with Q^2 the four momentum transfer and M the nucleon mass. Each quark flavor contributes with a weight of its charge squared. The Q^2 dependence is implicitly assumed. From these cross sections an asymmetry can be calculated for each hadron of type h

$$A_1^{\mathrm{h}}(x) = \frac{\sigma_{1/2}^h - \sigma_{3/2}^h}{\sigma_{1/2}^h + \sigma_{3/2}^h} = \frac{\sum_f e_f^2 \Delta q_f(x) \int dz D_f^{\mathrm{h}}(z)}{\sum_f e_f^2 q_f(x) \int dz D_f^{\mathrm{h}}(z)} \frac{(1+R(x))}{(1+\gamma^2)}$$

with $\gamma^2 = Q^2/\nu$ and R the ratio of longitudinal to transverse photon absorption cross sections. The factor $\frac{1+R}{1+\gamma^2}$ accounts for the contribution of longitudinal photons as is done in most parameterizations of parton distribution functions (PDF) $q(x,Q^2)$. The data sets measured in HERMES contains DIS asymmetries on Hydrogen and Deuterium as well as SIDIS asymmetries for pions and kaons giving in total eight different asymmetries. In order to obtain the desired information on the quark helicity distribution the equation to solve is $\vec{A} = P\vec{Q}$, where the vector $\vec{A} = (A_{1,p}(x), A_{1,d}(x), A_{1,p}^{\pi^\pm}(x), A_{1,d}^{\pi^\pm}(x), A_{1,d}^{K^\pm}(x))$ represents the measured asymmetries and the matrix P contains the *purities*

$$P_f^h = \frac{e_f^2 q_f(x) \int D_f^{\mathrm{h}}(z) dz}{\sum_{f\prime} e_{f\prime}^2 q\prime(x) \int D_{f\prime}^{\mathrm{h}}(z) dz}$$

The purities depend solely on unpolarized quantities and represent the probability of detecting a hadron of type h after a quark of flavor f has been struck. The vector $\vec{Q} = (\frac{\Delta u}{u}, \frac{\Delta d}{d}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta \bar{d}}{\bar{d}}, \frac{\Delta s}{s})$ contains the sought after polarized helicity distributions of the different quark flavors. The purities have to be calculated from Monte Carlo simulation to take into account the acceptance of the HERMES detector. The leading order parameterization for the unpolarized PDFs are taken from CTEQL5 [5], while the the fragmentation parameters of JETSET are tuned to match the multiplicity distributions measured in HERMES. Nuclear effects due to the D-state probability of the Deuteron are taken into account. As can be seen from figure 1 the dominant contribution for all particle types comes from the u quark. However, the contributions from kaons will dominate the final result on strangeness; in particular those for the $K^- = \bar{u}s$ as an all sea object. The result of the fits is a set of polarized quark density functions, which are shown in figure 2 together with leading order (LO) QCD fits to the inclusive world data set. As already expected from inclusive results the u quarks are polarized preferably parallel to the nucleon whereas the d quarks are polarized anti-parallel to the nucleon. The sea quark polarization is compatible with zero.More in particular a negative strange sea quark polarization is not observed within the given uncertainties of the experimental results of HERMES [3]. Going one step further the quantity $\Delta\bar{u} - \Delta\bar{d}$ is compared with theoretical calculations [7] in figure 3. The data are seen to be consistent with zero while the theoretical prediction yield a large and positive asymmetry. However, the statistical precision of the data is such that the calculation can not be discarded.

Transversity

In HERMES Run II a transversely polarized Hydrogen target is used with the objective to measure transversity[8], the distribution of transversely polarized quarks in a transversely polarized nucleon. Due to relativistic effects this is not just a mere transformation of the longitudinal distribution. Contrary to the longitudinal case this distribution can only be accessed in SIDIS processes as both the quark and the nucleon need to flip their spin. Hence, additional angular momentum needs to be absorbed by a hadron produced in the reaction. The transverse polarization of the struck quark can influence the transverse

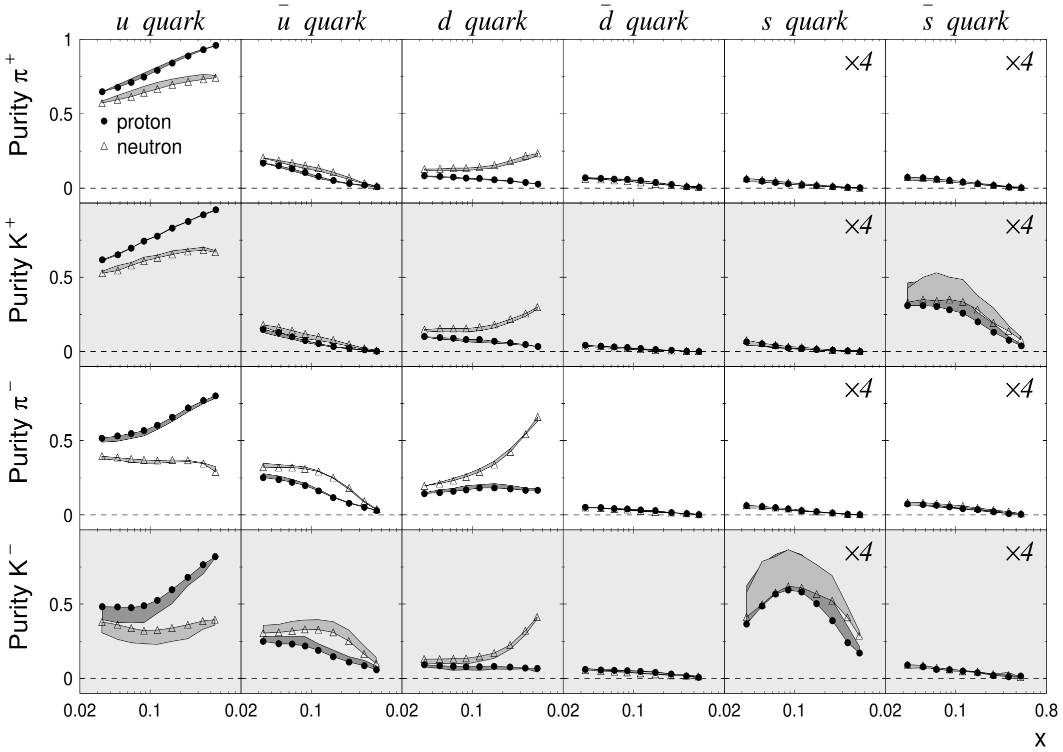

Figure 1: Purities as extracted from the HERMES Monte Carlo for pions and kaons on a proton and free neutron target.

momentum component $P_{h\perp}$ of the produced hadron orthogonal to the virtual photon, thereby leading to an azimuthal angle ϕ dependence of the cross section about the virtual photon direction in the lepton scattering plane. A fragmentation function describing this spin-momentum correlation indeed exists and is known as the Collins fragmentation function $H_1^\perp$. It represents the interference of two scattering amplitudes with different imaginary parts giving rise to single-spin asymmetries. In contrast to the example above this asymmetry is not a feature of the integrated cross section but depends on the azimuthal angle ϕ. In the following we look at single-spin azimuthal asymmetries from semi-inclusive scattering processes with a transverse target polarization.

In addition to the Collins mechanism a complete different source of single-spin azimuthal asymmetries was identified over a decade ago that stems from correlations between the transverse polarization of the target nucleon and the intrinsic transverse momentum p_T of the quarks. Part of this intrinsic p_T can survive the photo-absorption and hadronization process, thereby influencing the transverse momentum component $P_{h\perp}$ of the produced hadron which in turn can influence its azimuthal distribution relative to the target spin axis. This correlation between p_T and the target polarization is described by $f_{1T}^\perp$, the Sivers distribution function which involves a helicity-flip of the target nucleon only in the forward scattering amplitude. As a consequence this must involve orbital angular momentum of the unpolarized quark. With the help of a transversely polarized target the Collins and Sivers mechanisms can be separated since they have different azimuthal dependences with respect to the axis of transverse polarization. While the Sivers mechanism gives rise to a $\sin(\phi - \phi_S)$ behavior the Collins mechanism exhibits a $\sin(\phi + \phi_S)$ behavior in the azimuthal asymmetry with ϕ being the azimuthal angle between the hadron production plane and the lepton scattering plane and ϕ_S the angle between the lepton scattering plane and the transverse target polarization vector as indicated in figure 4. There is a correlation between the transverse momentum component P_T of the detected hadron and the intrinsic transverse momentum p_T of the quark in case of the Sivers effect or, in case of the Collins effect, with the acquired transverse momentum k_T of the struck quark in the fragmentation process which in its turn depends on the transverse polarization of the initial quark.

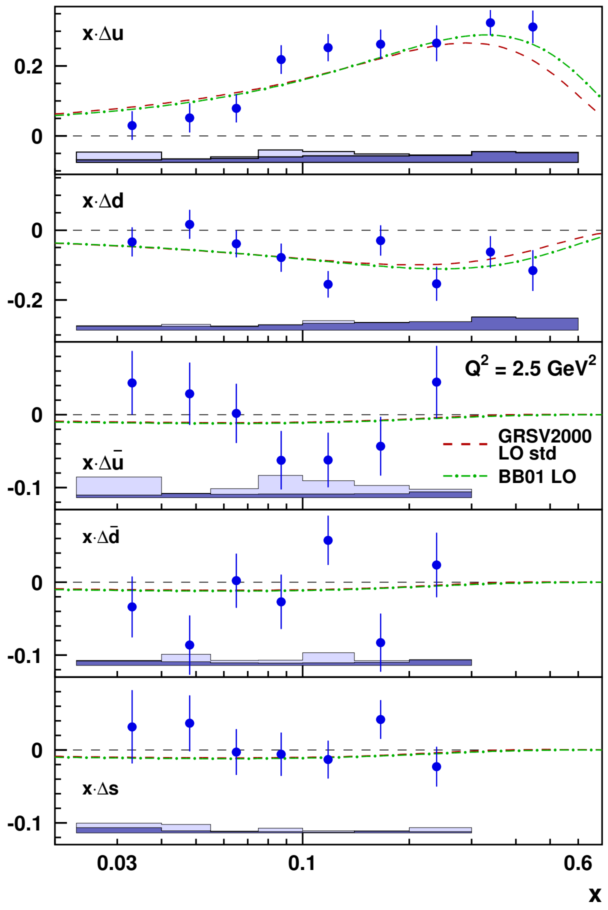

Figure 2: Quark helicity distribution at average $Q^2 = 2.5$ GeV^2 as a function of Bjorken x with two leading order QCD fits to the inclusive world data set.

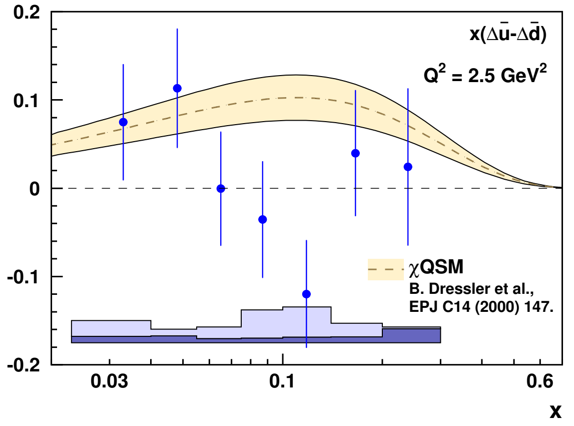

Figure 3: The light sea quark flavor asymmetry of the helicity distribution, as a function x.

The single spin azimuthal asymmetry A^h_{UT} for a given hadron h with an unpolarized beam and a transversely polarized target thus depends on the two azimuthal angles ϕ and ϕ_S. It was shown with Monte Carlo studies that it is mandatory to extract the Collins and Sivers moments simultaneously from the data set in order to avoid correlations in the result. Hence, the Collins azimuthal moment $< sin(\phi + \phi_S) >^h_{UT}$ and the Sivers azimuthal moment $< sin(\phi - \phi_S) >^h_{UT}$ are extracted by a fit to the data given by $A^h_{UT}(\phi, \phi_S) = \frac{1}{S_T} \frac{N^\uparrow_h(\phi,\phi_S) - N^\downarrow_h(\phi,\phi_S)}{N^\uparrow_h(\phi,\phi_S) + N^\downarrow_h(\phi,\phi_S)}$ where $N^{\uparrow(\downarrow)}_h$ is the normalized yield of a given hadron type h with the transverse target polarization up $\uparrow$ (or down $\downarrow$). These asymmetries are evaluated as functions of the Bjorken variable x and the momentum fraction of the detected hadron z. As shown in the figures 5 and 6 the moments for $< sin(\phi + \phi_S) >^h_{UT}$ and $< sin(\phi - \phi_S) >^h_{UT}$ are extracted from the asymmetries at different mean values of x-Bjorken and fractional hadron momentum z for the charged and neutral pions. The gray shaded band indicates an upper limit for possible contributions from pions coming from unidentified ρ decay due to the limited acceptance of the detector. The data have not been corrected for acceptance effects and smearing. Note that in the fit of the asymmetries different weights are applied to the Collins and Sivers moments to take kinematical factors into account. This first result is based on a data sample of about 1 million DIS events.

The Collins asymmetries for positive pions are positive but small while the results on negative pions are negative and somewhat larger in absolute value. The asymmetries for the neutral pion are consistent with zero. Having the helicity densities (Δq) in mind one would naively expect opposite signs for the

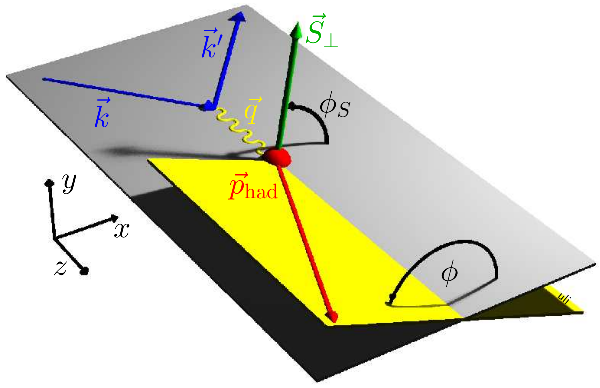

Figure 4: Definition of the azimuthal angles ϕ and ϕ_S. The lepton scattering plane is defined by the vectors k and k', the incoming and outgoing lepton. The hadron production plane is defined by the virtual photon $\vec{q}$ and the detected hadron $\vec{p}_{had}$. The transverse polarization of the target is represented by the vector $\vec{S}_\perp$.

transversity densities of the u and d quark respectively (positive and negative pion) and $|\delta d| < |\delta u|$. While the opposite sign is apparent, the magnitude of the moments for the negative pion are at least as large as the ones for positive pions. As a function of x this feature becomes even more pronounced at large x where the contribution from valence quarks tends to be dominant. This might tell us that one has to take into account the contributions from sea quarks or the disfavored Collins fragmentation function. The Sivers moments tend to be very small but positive in case of the positive pions and compatible with zero in case of the negative pions. Assuming u-quark dominance this positive asymmetry in combination the with the use of the azimuthal angle as defined in figure 4 one would expect a negative value for the Sivers function of this flavor. The results from neutral pions are also close to zero with limited statistics however.

By the end of the transversity program in HERMES the total amount of statistics is expected to be six times larger than what is used in this analysis. This will allow us to study these asymmetries in much more detail as functions of x, z and also other kinematic variables.

Generalized Parton Distribution

In recent years theorists realized that the concept of generalized parton distributions (GPDs) has the potential to link lepton scattering experiments directly to the total angular momentum of the quarks in the nucleon [9]. While inclusive and semi-inclusive processes in DIS are described using PDFs, hard exclusive reactions can be described by GPDs. The simplest of these exclusive reactions, theoretically, is deeply virtual compton scattering or DVCS. Here a hard virtual photon is absorbed by a quark and re-emitted as a hard real photon while the target nucleon stays intact as a whole, see fig.7.

The cross section can be written as $\sigma \sim |\tau^{DVCS} + \tau^{BH}|^2 = (\tau^{DVCS})^2 + (\tau^{BH})^2 + I$. The Bethe-Heitler (BH) process where the initial or final lepton radiates a photon will lead to the same final state as the DVCS process. This will introduce an interference term I in the cross section. At second glance this is important since in the kinematic regions accessible at relatively low incident energy the cross section for DVCS is very small and BH dominates. Due to this interference the small effect of DVCS can be observable. In particular calculating asymmetries with respect to either the spin of the lepton beam or the charge of the lepton beam as a function of the azimuthal angle ϕ of the outgoing real photon projects out the parts of the interference term which are related to the imaginary and real part of the generalized parton distribution $H(x, \xi, t)$. In more detail the beam spin asymmetry A_{LU} [10] at leading twist will exhibit a $\sin(\phi)$ behavior which is proportional to the imaginary part of the amplitude $M^{1,1}$. Similarly a beam charge asymmetry A_C will exhibit a $\cos(\phi)$ behavior which is proportional to the real part of the amplitude:

$$A_{LU} \sim s_1^I \sin(\phi) \sim Im(M^{1,1}) \sin(\phi)$$

$$A_C \sim c_1^I \cos(\phi) \sim Re(M^{1,1}) \cos(\phi)$$

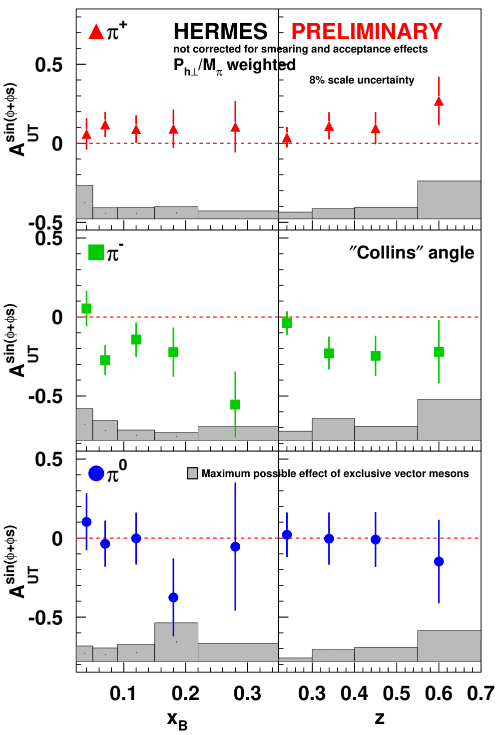

Figure 5: Moments for the Collins fragmentation function and transverse helicity distribution function for charged and neutral pions as function of x and z.

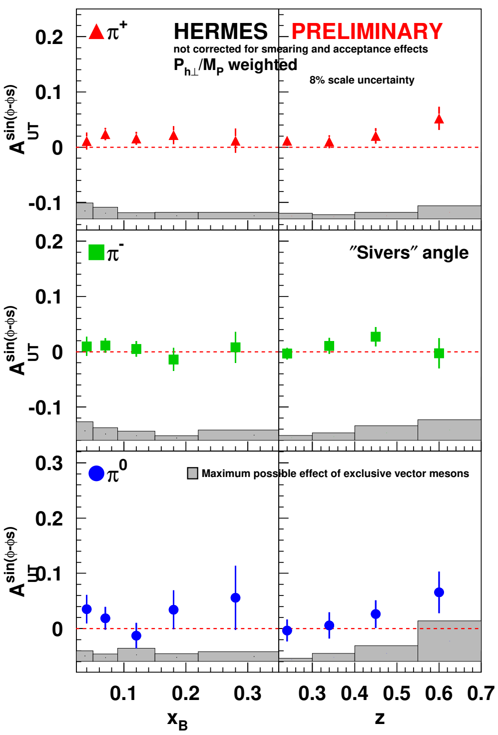

Figure 6: Moments for the Sivers distribution function and unpolarized fragmentation function for charged and neutral pions as function of x and z.

with

$$M^{1,1} = F_1(t)H_1(\xi,t) + \frac{x_B}{2-x_B}(F_1(t)+F_2(t))\tilde{H}_1(\xi,t) - \frac{t}{4M^2}F_2(t)E_1(\xi,t)$$

The amplitude $M^{1,1}$ is seen to depend on the Dirac and Pauli form factors F_1 and F_2 as well as on the so-called Compton form factors (CFFs) $H_1, \tilde{H}_1$ and E_1. Here is where the GPDs are coming in. These CFFs are convolutions of the hard scattering amplitude and the GPDs $H, \tilde{H}$ and E. At small values of x-Bjorken x_B and momentum transfer t the main contribution to the amplitude originates from the CFF H_1 and therefore only on the GPD H. For each quark flavor there exists such a GPD that depends on the three kinematic variables x, ξ and t (see fig. 7) where x runs from -1 to +1 and negative x refers to the anti-quark of a particular flavor. The range in ξ is always smaller than the range in x.

Measurements of the DVCS process with a polarized lepton beam or different lepton beam charges both available from the HERA storage ring at DESY can give insights to the GPD H. The HERMES spectrometer has a momentum resolution of about 1% - 2%. This is not sufficient to ensure that the process is exclusive and the proton remained in the ground state. The missing mass technique still leaves some background from DIS processes and nucleon resonances in the data sample. In order to improve on this issue a Recoil-Detector is under construction that is designed to measure the recoiling nucleon in coincidence with the scattered lepton and the hard photon. Around the target cell in the HERA machine vacuum a silicon strip detector is mounted. It has two layers of silicon wavers each with double sided readout to have spatial positioning as well as particle identification by energy loss measurements. The momentum range covered by proton identification goes from 130 MeV/c to about 400 MeV/c. The lower limit is given by the wall thickness of the storage cell. Outside the beam vacuum system two cylindrical scintillation fiber detector barrels are installed. Each consists of two planes of two rows of scintillation fibers. The two planes have an angle of 10 degree with respect to each other in order to extract position information. The fiber thickness is 1 mm. The momentum range covered goes from about 300 MeV/c

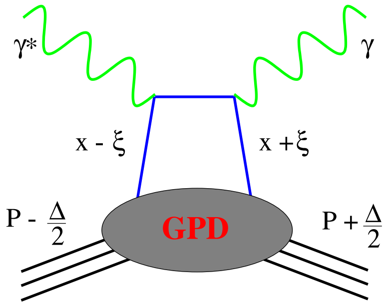

Figure 7: The DVCS process has a virtual photon and a nucleon in the initial state and a real photon and a nucleon in the final state. The variable x is the longitudinal momentum fraction of the nucleon carried by the quark and ξ is half the longitudinal momentum transfer in the scattering process.

to 1400 MeV/c where the lower limit is given by the energy loss in the material between the target gas and the first barrel. Again particle identification can be achieved by using the energy loss information measured by the fibers. The outer most part of the recoil detector is a photon detector consisting of 3 layers of tungsten and slabs of plastic scintillators. It will be used to detect neutral particles like photons from π^o decay to identify resonance production. The whole detector system will be mounted within the warm bore of a super-conducting solenoid with a central field of 1 Tesla. This is necessary to keep the enormous numbers of Moller and Bhabha scattered leptons confined within the beam pipe in order to protect the detectors from too high rates.

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