Single–spin Asymmetries in Semi–inclusive Pion Production

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Abstract. For the first time single–spin asymmetries in semi–inclusive pion production are measured by the HERMES experiment with a transversely polarised hydrogen target. Two different sine–modulations are extracted which can be related to the transversity $\delta q(x)$ and Sivers $f_{1T}^{q\perp}(x)$ quark distribution functions. The extracted sine–moments still contain small sub–leading twist contributions which can be extracted from HERMES data combining the results from the transversely polarised hydrogen target with previously measured results from a longitudinally polarised hydrogen target.

Keywords: Photon and charged-lepton interactions with hadrons, Polarization in interactions and scattering, Protons, Quarks

PACS: 13.60.-r, 13.88.+e, 14.20.Dh, 14.65.-q

1. Introduction

For the last decades deep inelastic scattering (DIS) was and still is a very successful tool to investigate the structure of the nucleon. In this process a lepton scatters off a nucleon via the exchange of a single virtual photon. A measure of the spatial resolution in the scattering process is the four–momentum transfer to the target nucleon. In DIS processes this momentum transfer is large enough to resolve the constituents of the nucleon.

In the quark parton model in which the virtual photon is assumed to scatter incoherently off the quarks in the nucleon, the DIS cross section can be expanded in terms of quark distribution functions. The leading–twist distribution functions (DF) can be interpreted as probability densities dependent on the longitudinal quark momentum in a frame in which the nucleon is moving towards the photon with “infinite” momentum. When integrating the leading–twist DFs over the intrinsic transverse quark momentum $p_T$, only three of them remain. Two of these DF have already been explored for different quark flavours $q$ by several experiments \cite{1, 2}.
Fig. 1. Schematic illustration of the deep inelastic scattering process off a transversely (left) and longitudinally (right) polarised target.

These are the unpolarised DF \( q(x) \) and the helicity DF \( \Delta q(x) \), which gives the probability to find a quark with its helicity parallel to the nucleon helicity. Here \( x \) is the dimensionless Bjorken scaling variable. It can be identified with the fractional momentum of the nucleon carried by the struck quark. The last of the three DFs is the chiral–odd transversity \([3, 4, 5]\) function \( \delta q(x) \). In the basis of transverse spin eigenstates it has the simple interpretation of the degree to which the quarks are polarised along the proton’s spin direction when the proton is polarised transversely to the virtual photon.

Since DIS is a hard scattering process in which chirality is conserved, transversity can only be measured combined with another chiral–odd object. This can be a fragmentation function (FF) which appears in addition to the DFs in the cross section of semi–inclusive DIS when produced hadrons are detected in addition to the scattered lepton. In unpolarised semi–inclusive DIS for instance the cross section is proportional to the product of the unpolarised DF \( q(x) \) and the unpolarised FF \( D_f^q(z) \) which gives the probability density that a struck quark of flavour \( q \) produces a certain final state hadron with the fractional energy \( z \). In case of a transversely polarised nucleon target, the transversity distribution enters the cross section combined with the chiral–odd FF \( H_{1q}^{±}(z) \) known as Collins function \([6]\). In addition a second DF \( f_{1T}^{±q} \) appears in the cross section together with the unpolarised FF. This DF – which is called Sivers function \([7]\) – relates the quark transverse momentum with the transverse polarisation of the nucleon. The property of the Sivers function to be odd under time reversal (T–odd) was believed to forbid its existence. But recently it was realised that final–state interactions via a soft gluon offer a mechanism to create the necessary interference of amplitudes \([8]\) for the existence of the so–called “naïve T–odd” nature of the Sivers function. For DFs in DIS “naïve T–odd” means time–reversal odd neglecting final-state interaction. An interesting consequence of a non–zero Sivers function is the existence of orbital angular momentum of the quarks \([8, 9]\).
2. Azimuthal Asymmetries

Since Sivers and Collins functions do not survive integration over the intrinsic transverse momentum \( p_T \) and the transverse momentum \( k_T \) acquired in the fragmentation process, respectively, the tools to measure the objects of interest are azimuthal asymmetries. These asymmetries depend on two azimuthal angles \( \phi \) and \( \phi_S \) drawn in Fig. 1. The angle \( \phi_S \) is the angle between the lepton scattering plane containing the incoming and outgoing lepton and the transverse spin component of the target nucleon. The hadron angle \( \phi \) is defined between the lepton scattering plane and the hadron production plane spanned by the produced hadron and the virtual photon.

When including azimuthal dependencies the cross section can be expanded in terms of different sine and cosine modulations of \( \phi \) and \( \phi_S \). It contains among others:

\[
\sigma(x, y, z, \phi, \phi_S) \sim \ldots S_\perp \sin(\phi + \phi_S) + \ldots S_\perp \sin(\phi - \phi_S),
\]

where \( S_\perp \) is the transverse target polarisation with respect to the virtual photon and \( e_q \) is the charge of the different quark flavours \( q \). The superscript \( (1/2) \) denotes the \( |p_T| \)– or \( |k_T| \)–moment of the DF or FF, respectively. Gaussian distributions are assumed for \( p_T \) and \( k_T \) in order to solve the convolution integrals in which the products of DF and FF appear \[10\].

Experimentally the various terms in the cross section can be extracted by measuring azimuthal single–spin asymmetries and picking up the interesting sine modulations. For the two terms in Eq. (1) one needs a polarised target. The luminosity normalised count rate asymmetry between opposite target spin states \((\uparrow, \downarrow)\) reads:

\[
A_{UT}(\phi, \phi_S) = \frac{N^\uparrow(\phi, \phi_S) - N^\downarrow(\phi, \phi_S)}{S_\perp N^\uparrow(\phi, \phi_S) + N^\downarrow(\phi, \phi_S)} = 2\langle \sin(\phi + \phi_S) \rangle_{UT} \sin(\phi + \phi_S) + 2\langle \sin(\phi - \phi_S) \rangle_{UT} \sin(\phi - \phi_S),
\]

where the subscript UT indicates an unpolarised lepton beam and a transversely polarised target. The asymmetry moments \( \langle \sin(\phi \pm \phi_S) \rangle_{UT} \) are extracted using a two–dimensional fit.

3. The HERMES Experiment

The HERMES experiment at DESY uses the 27.5 GeV positron beam provided by the HERA storage ring. The beam interacts with an internal hydrogen gas target \[11\] which was longitudinally polarised with an average polarisation of \( 0.83 \pm 0.04 \) (systematic) in the years 1996 and 1997. In the year 2002 the polarisation was rotated to achieve a transversely polarised target with an average polarisation of
0.78 ± 0.04 (systematic). The scattered positrons and the produced hadrons are detected with the HERMES spectrometer [12]. This spectrometer provides lepton identification with an average efficiency of 98% at a hadron contamination of less than 1%. The gas threshold Čerenkov detector which was used for pion identification was replaced by a Ring-Imaging Čerenkov detector (RICH) in 1998 which allows the efficient identification of charged pions, kaons, and protons over almost the complete momentum range and hence leads to a very clean pion sample.

4. Transverse Target Results

In Fig. 2 the measured asymmetry moments \(2\langle \sin(\phi \pm \phi_S) \rangle_{UT}\) for charged pions are plotted [13], where in the left (right) column the dependency on the kinematic variable \(x\) \((z)\) is shown. In addition to the plotted statistical uncertainties there is an overall 8% scale uncertainty in the moments dominated by the uncertainty of the target polarisation. The asymmetry moments \(\langle \sin(\phi + \phi_S) \rangle_{UT}\) containing transversity and the Collins FF include an additional kinematic factor (for details see [13]). These moments are positive for positive pions and negative for negative pions, consistent with the expectation of a positive transversity \(\delta u\) for \(u\)–quarks and a negative \(\delta d\). Astonishing is the larger absolute value of the moments for \(\pi^-\) compared to the moments for \(\pi^+\). This could be explained by a disfavoured Collins function with the opposite sign and the same magnitude as the favoured Collins function. The asymmetry moments \(\langle \sin(\phi - \phi_S) \rangle_{UT}\) are compatible with zero for negative pions but significantly positive for \(\pi^+\). This is the first hint of a “naïve T-odd” DF from DIS. The data samples include pions coming from decays of diffractively produced vector mesons. The contribution estimated with the PYTHIA6 event generator [14] is shown in the lowest panel.
5. Longitudinal Single–Spin Asymmetries Revisited

The HERMES experiment has also published single–spin asymmetries on longitudinally polarised hydrogen \[15\]. For this measurement the nucleons were polarised longitudinally with respect to the incoming lepton beam under an angle \(\theta_{\gamma^*}\) to the direction of the virtual photon \(q\) (see Fig. 1). Therefore both polarisation components \(S_{\parallel}\) and \(S_{\perp}\) exist where the transverse component is suppressed by the factor \(\sin \theta_{\gamma^*}\). In the following, the measured asymmetry moments with respect to the lepton beam get a primed subscript \(UL'\) or \(UT'\), respectively. Asymmetry moments with unprimed subscripts are defined with respect to the virtual photon. Since the angle \(\phi_S\) has the constant value \(\pi\), the moments \(\langle \sin(\phi \pm \phi_S) \rangle_{UT}\) reveal themselves as a \(\sin \phi\) modulation of the cross section, proportional to the small polarisation component \(S_{\perp}\). Also in the cross section for scattering off longitudinally polarised nucleons with respect to the virtual photon \((S_{\parallel})\) a \(\sin \phi\) modulation exists. The corresponding moment \(\langle \sin \phi \rangle_{UL}\) is a subleading–twist contribution in contrast to \(\langle \sin(\phi \pm \phi_S) \rangle_{UT}\) which involves only leading–twist DFs and FFs \[16\]. Due to the suppression of subleading–twist contributions the HERMES results have been interpreted in terms of the Collins or Sivers functions neglecting some or all the contributions from the longitudinal polarisation component.

With measurements on longitudinal and transverse targets it is now possible to extract the subleading–twist contribution to the cross section:

\[
\langle \sin \phi \rangle_{UL} = \langle \sin \phi \rangle_{UL'} + \sin \theta_{\gamma^*} \left[ \langle \sin(\phi + \phi_S) \rangle_{UT'} + \langle \sin(\phi - \phi_S) \rangle_{UT'} \right],
\]

which is valid up to corrections of order \(\sin^2 \theta_{\gamma^*}\). \[17\]. \(\sin \theta_{\gamma^*}\) can be calculated from the lepton kinematics. In Fig. 3 the extracted subleading–twist components are shown for different kinematic bins together with the longitudinal asymmetry moments of reference \[15\], which were reanalysed to have the same binning in \(x\) and \(z\). In addition, the sum of the measured transverse asymmetry moments multiplied by the suppression factor \(\sin \theta_{\gamma^*}\) (see Eq. 3) is plotted. The overall systematic uncertainty of the subleading–twist component \(2\langle \sin \phi \rangle_{UL}\) is less than 0.003. For negative pions \(2\langle \sin \phi \rangle_{UL}\) is compatible with zero, for positive pions the subleading–twist component is positive and of the order of 2–5%. This is a strong indication for large subleading–twist DFs and FFs. In case of \(\pi^+\) they clearly dominate the results of the measurement with a longitudinally polarised hydrogen target. For both pion types the contribution from the transverse polarisation component is small.

One should note that also the measured transverse asymmetry moments have a small contribution of the longitudinal polarisation component \(S_{\parallel} = \sin \theta_{\gamma^*} \cos \phi_S\) which couples to the \(\sin \phi\) modulation of the longitudinal cross section. In order to estimate the subleading–twist contribution to the measured transverse asymmetry moments \(2\langle \sin(\phi \pm \phi_S) \rangle_{UT'}\), the extracted subleading–twist component has to be multiplied by \(\frac{1}{2} \sin \theta_{\gamma^*}\). \[17\]. The resulting maximum contribution to the measured moments in reference \[13\] amounts to an absolute value of 0.004. For the measured transverse asymmetry moments in Fig. 2 that corresponds to a correction which is negligible compared to the statistical uncertainty.
Fig. 3. The extracted subleading-twist component $2\langle \sin \phi \rangle_{UL}$ (●) and the measured moments $2\langle \sin \phi \rangle_{UL}$ and $-2\sin \theta_{p} \cdot \left[ \langle \sin(\phi + \phi_{S}) \rangle_{UT} + \langle \sin(\phi - \phi_{S}) \rangle_{UT} \right]$ for longitudinally (▲) and transversely (■) polarised targets, respectively.

Notes

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