TOPICAL REVIEW

Exploring the Partonic Structure of Hadrons through the Drell-Yan Process

P.E. Reimer

Physics Division, Argonne National Laboratory, Argonne, IL, 60439, USA

E-mail: `reimer@anl.gov`

Abstract. The Drell-Yan process is a standard tool for probing the partonic structure of hadrons. Since the process proceeds through a quark-antiquark annihilation, Drell-Yan scattering possesses a unique ability to selectively probe sea distributions. This review examines the application of Drell-Yan scattering to elucidating the flavor asymmetry of the nucleon's sea and nuclear modifications to the sea quark distributions in unpolarized scattering. Polarized beams and targets add an exciting new dimension to Drell-Yan scattering. In particular, the two initial-state hadrons give Drell-Yan sensitivity to chirally-odd transversity distributions.

PACS numbers: 14.20.Dh, 25.40.-h, 13.88.+e, 12.75.Cs

Submitted to: *J. Phys. G: Nucl. Phys.*

1. The Production of Massive Lepton Pairs

Sidney Drell and Tung-Mow Yan first proposed [1, 2] the process that now bears their names to explain a continuum of massive lepton-antilepton pairs (dileptons) that had been observed by Christenson *et al.* in proton-uranium collisions at the Brookhaven AGS [3, 4]. The experiment was conducted to probe the large momentum transfer region with time-like photons to complement space-like measurements from lepton-proton deep inelastic scattering (DIS) data and to search for new resonances. A distinct feature of these data was the rapid decrease in cross section as the mass of the dilepton increased, as reproduced in figure 1. While there were many plausible explanations of this spectra, it was the mechanism proposed by S. Drell and T.-M. Yan which described the spectra in terms of the (then very new) parton model of Feynman [5] that was eventually accepted. In this description, the dilepton cross section and its rapid decrease with increasing dilepton mass was explained in terms of the annihilation of a parton from one of the interacting hadrons with an anti-parton from the other hadron. The steeply falling cross section was due the paucity of large-x partons that are necessary to reach high mass.

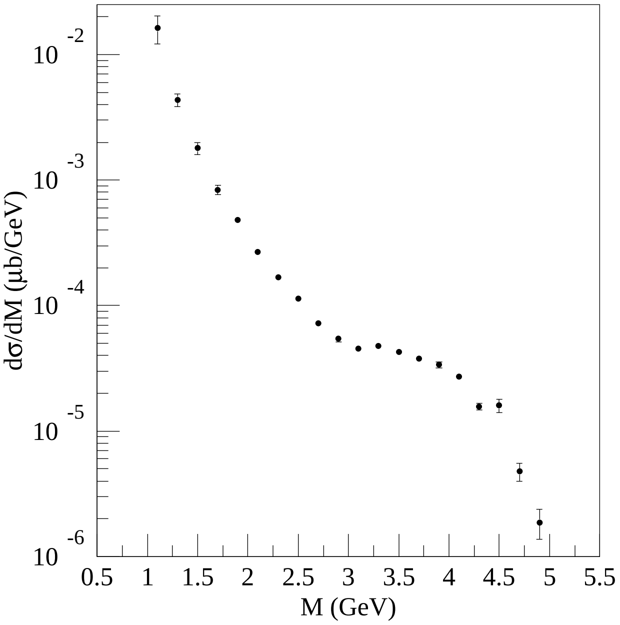

Figure 1. The dilepton cross section as measured by Christenson *et al.* [4], showing a rapid decrease as a function of dilepton mass. The excess of events in the $3 < M_{\gamma^*} < 4$ region is from the dilepton decay of the J/ψ.

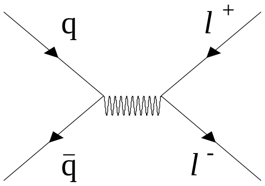

Figure 2. Feynman diagram for the leading order Drell-Yan process.

This article first reviews the basic formalism of the Drell-Yan mechanism in unpolarized scattering and its relation to parton distribution measurements. Next, angular distributions of Drell-Yan scattering and observed deviations from the expected distribution are reviewed. Finally longitudinally and transversely polarized Drell-Yan measurements are discussed. Within these discussions relevant recent and proposed Drell-Yan measurements will be presented.

2. The Drell-Yan Process

The production of massive dileptons through quark-antiquark annihilation can be expressed in terms of a hard, short-distance interaction term representing the cross section for quark-antiquark annihilation into virtual photon and subsequent decay to a dilepton pair, $\sigma_{q\bar{q}}$ (illustrated in figure 2) and the parton probability densities within

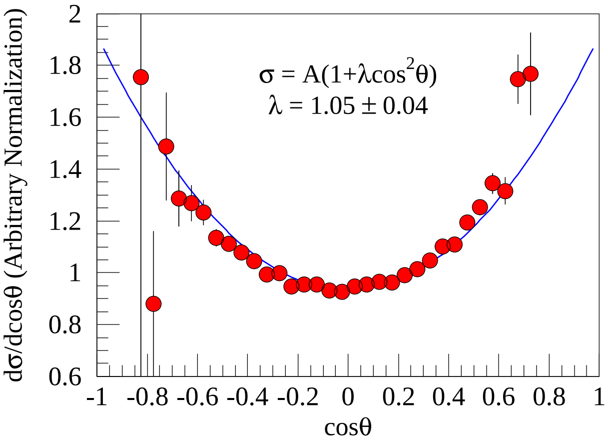

Figure 3. The $\cos\theta$ dependence of the proton-proton Drell-Yan cross section as measured by the Fermilab E866/NuSea experiment. The curve shows the result of a fit of the data to $A\left(1+\lambda\cos^2\theta\right)$ [9].

the interacting hadrons. The hard scattering cross section is given by

$$\sigma_{q\bar{q}} = \frac{4\pi\alpha^2}{3M_{\gamma^*}^2}\frac{1}{3}e_i^2, \tag{1}$$

where the cross section is reduced by the final factor of 1/3 since the color-charge of the quark and antiquark must match, e_i is the fractional charge on the quark and M_{γ^*} is the dilepton mass. To obtain the hadron-hadron cross section, it is necessary to sum over the available quark flavors and account for the parton distributions. To leading order in the strong coupling constant, α_s, the Drell-Yan cross section is then

$$\frac{d^2\sigma}{dx_1dx_2} = \frac{4\pi\alpha^2}{9M_{\gamma^*}^2}\sum_i e_i^2\left[f_i(x_1,Q^2)\bar{f}_i(x_2,Q^2)+\bar{f}_i(x_1,Q^2)f_i(x_2,Q^2)\right], \tag{2}$$

with the sum is over quark flavors, $i \in \{u, d, s, \ldots\}$. The parton distributions functions (PDFs) are given by $f_i(x, Q^2)$, where x is Bjorken-x and Q^2 is the QCD scale at which the parton distribution is probed. In the case of Drell-Yan scattering, $Q^2 = M_{\gamma^*}^2$. (In general, $M_{\gamma^*}^2$ will be used when discussing an invariant mass *measured* by an experiment and Q^2 will be used when discussing the QCD scale.) The subscripts 1 and 2 denote the interacting hadrons, which in a fixed target experiment, are conventionally take as 1 for the beam hadron and 2 for the target hadron. Detailed derivations of this cross section may be found in the literature [6, 7, 8]. The leading order Drell-Yan mechanism also predicts that the spin of the virtual photon will be aligned providing a cross section that has a $(1+\cos^2\theta)$ dependence, where θ is the polar angle of the lepton in the rest frame of the virtual photon [1], in agreement with data as shown in figure 3. Additional features of the angular distributions and their deviations from $(1+\cos^2\theta)$ are discussed in section 5.

Experimentally, one measures the momenta of the outgoing lepton and antilepton, allowing for the reconstruction of the virtual photon's mass, M_{γ^*}, longitudinal momentum, p_l and transverse momentum, p_T. It is generally more convenient to use the variables

$$\tau = M_{\gamma^*}^2/s \tag{3}$$

and

$$y = \frac{1}{2}\ln\left(\frac{E+p_l}{E-p_l}\right) \text{ (rapidity)}, \tag{4}$$

where s is the square of the center-of-mass energy of the interacting hadrons and E is the virtual photon's energy. From these, the momentum fractions x_1 and x_2 (Bjorken-x) of the interacting partons are given by

$$x_{1,2} = \left(\tau + \frac{p_T^2}{s}\right)^{1/2} e^{\pm y} \tag{5}$$

and the difference (Feynman-x)

$$x_F \equiv \frac{2p_l}{\sqrt{s}} \approx x_1 - x_2 \tag{6}$$

In the limit of $p_T \rightarrow 0$ and large $\sqrt{s}$, this is equivalent to $M_{\gamma^*}^2 = x_1 x_2 s$ and $x_F = 2p_l/\sqrt{s} = x_1 - x_2$. For a further discussion of the differences see [6].

As experiments were able to reduce the systematic uncertainty of the overall normalization of the Drell-Yan cross section, it became apparent that, while the leading order cross section (using DIS PDFs) explains many of the features of Drell-Yan scattering, it fails to predict the overall magnitude of the cross section by a factor of approximately 1.5-2. This factor, traditionally known as the "K"-factor, results from neglecting terms of higher order in α_s in the cross section formula. The next-to-leading order (NLO) in α_s terms [10, 11] of the perturbative expansion, shown schematically in figure 4 [6], appear to account for the remainder of the experimentally measured cross section, within the scale uncertainty of the measurements and systematic uncertainty of the parton distribution input to the calculations [12, 13], as shown in figure 5. (Recall, however, that while much of the global parton distribution fits is dominated by DIS scattering results, Drell-Yan measurement were also included in these fits.) Higher order QCD corrections to the cross section [19, 20], as well as electromagnetic radiative corrections to the cross section have also been calculated [21, 22].

The interpretation of the observed dilepton spectra in terms of parton distributions relies on the factorization of the Drell-Yan cross section into an infrared safe, short range hard scattering and the parton distributions. It further requires that these parton distributions have the same meaning as DIS parton distributions. In a twist expansion, the cross section can be expressed in terms of powers of $1/(QR)$ where Q^2 is the hard scale and $R \approx \mathcal{O}(1/\Lambda_{\rm QCD})$ represents a non-perturbative scale [23, 24].

$$\sigma_{\rm DY} = \sigma_{\rm Hard} + \sum_n \mathcal{F}_{n=1}\left[1/(QR)^n\right], \tag{7}$$

where $\sigma_{\rm Hard}$ represents the convolution of the hard scattering quark-antiquark cross section with the PDFs. In leading order in α_s, $\sigma_{\rm Hard}$ is given by (2) but more generally

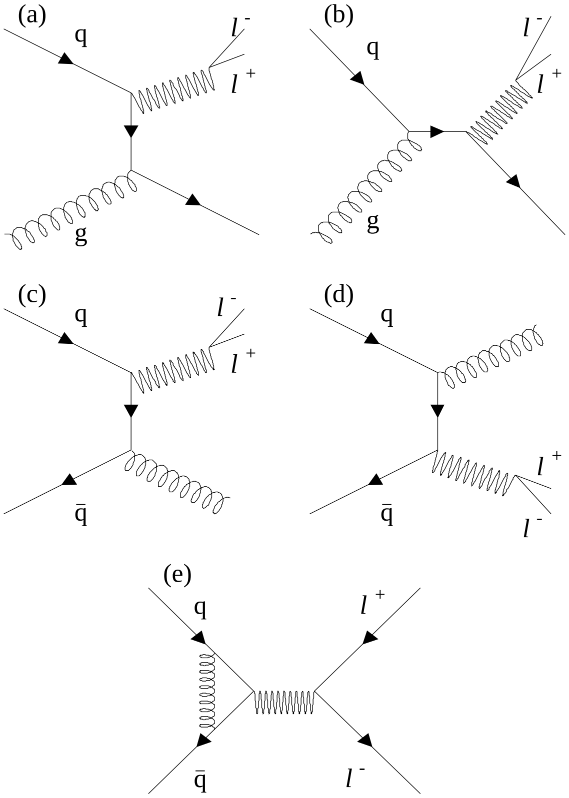

Figure 4. Feynman diagram for the terms of next-to-leading order in α_s for the Drell-Yan process: (a) and (b) QCD Compton; (d) and (e) gluon production and (f) vertex correction [6].

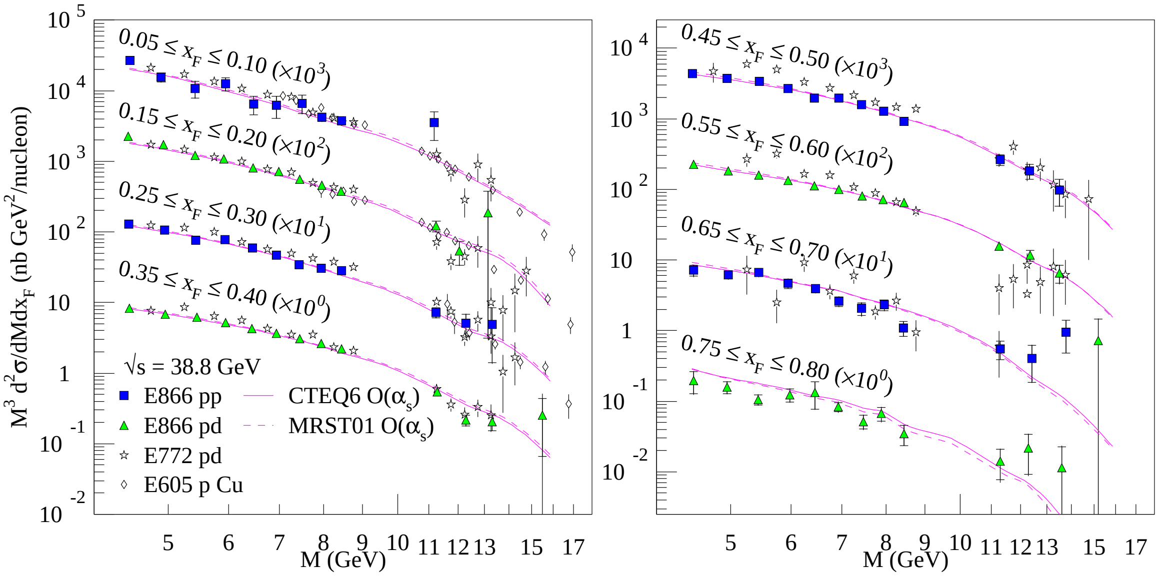

Figure 5. Drell-Yan absolute cross sections measured by Fermilab E866/NuSea (proton-proton and proton deuterium) [12, 13], E772 (proton-deuterium) [14, 15] and E605 (proton-copper) [16] compared with NLO cross section calculations based on the CTEQ6 [17] and MRST [18] parton distributions. There is an overall 6.5% normalization uncertainty on the E866/NuSea data.

includes higher powers of α_s. The sum over $\mathcal{F}_n$ represent terms of higher twist. Collins, Soper and Sterman [25, 26] and Bodwin [27] have shown that for the leading twist term, $1/(QR)^0$, in this expansion the contributions of non-factorisable soft gluons cancel and so the leading twist term is factorisable. Qiu and Sterman showed that factorization can be extended to the $1/(QR)^2$ term for unpolarized scattering and to $1/(QR)$ in a polarized asymmetry [23, 24]. Factorization breaks down for terms in the expansion beyond this, but is not generally a problem since the Q^2 of the typical Drell-Yan experiment is greater than the J/ψ mass squared, suppressing higher powers of $1/(QR)$. It may be possible, however, to observe the effects of power corrections by investigating regions in which the leading twist terms are suppressed such as high-x. Indeed, one possible explanation of an observed departure at large-x in pion-induced Drell-Yan from the $(1 + \cos^2\theta)$ dependence [28, 29, 30, 31, 32] is the presence of higher twist terms as suggested by Berger and Brodsky [33, 34]. Drell-Yan angular distributions are discussed in greater detail in section 5. This explanation is consistent with the work of Qiu and Sterman [24].

In the $\tau \equiv M^2_{\gamma^*}/s \to 1$ limit, the cross section is no longer adequately described by an expansion in α_s to any fixed order. In this regime, the energies of soft and of collinear gluons are no longer negligible when compared with the available energy in the system. In the cross section, the leading-logarithmic terms of the form

$$\alpha_s^k \frac{\ln^{m-1}(1-z)}{1-z} \text{ with } (m \le 2k) \tag{8}$$

are responsible for large corrections, where $z = \tau/(x_1 x_2)$ represents a partonic level version of τ. These terms must be "resummed" to all orders in α_s to adequately describe the process. Resummation was pioneered for the Drell-Yan process by G. Sterman [35] and S. Gatani and L. Trentadue [36, 37], where the resummation is described in terms of a Mellin transformation. A more recent alternative approach by A. Idilbi and X. Ji for Drell-Yan [38, 39] uses soft-collinear effective field theory, based on a similar description by A. Manohar [40] for DIS, and arrives at the same result.

The vast majority of Drell-Yan data is not near $\tau \to 1$ limit, which would require the interaction of very large-x parton from each hadron–a limit very difficult to reach when one of the partons is a sea antiquark. (Although, arguments have been made that resummation should be considered in any case [41], and the effects of neglecting resummation have been included estimates of the uncertainties in parton distributions [42].) Recently, the PAX collaboration [43] has proposed Drell-Yan measurements using an antiproton-proton collisions, thus making available valence antiquarks at large-x. In addition, the center of mass energy range is relatively small, with $30 \lesssim s \lesssim 200$ GeV^2. In these kinematics, the effects described by resummation will contribute substantially to the cross section [44], but are well understood.

3. Sea Quark Distributions from Unpolarized Drell-Yan Measurements

In a fixed target environment, where the decay leptons are boosted far forward, Drell-Yan scattering has a unique sensitivity to the antiquark distribution of the target hadron.

Combining this boost with the acceptance of the typical dipole-based spectrometer restricts the kinematic acceptance of the detector to $x_F \gtrsim 0$ and consequently to very high values of x_1, where the sea quarks are suppressed by several orders of magnitude compared with the valence distributions. These beam valence quarks must then annihilate with an antiquark in the target, thus preferentially selecting the first term in (2). This feature has been used by several recent experiments to study the sea quark distributions in the nucleon and in nuclei. Two new experiments have been proposed to extend these measurements to larger values of x_2.

Both experiments are conceptually similar to earlier fixed target Drell-Yan experiments. The Fermilab E906 experiment [45] will use a 120 GeV proton beam extracted from the Fermilab Main Injector. The experiment is already approved and expects to begin data collection in 2009. It will have a kinematic coverage of $0.08 \lesssim x_2 \lesssim 0.45$. At the JPARC facility, a similar experiment using a 50 GeV proton beam has been proposed with kinematic coverage of $0.2 \lesssim x_2 \lesssim 0.6$. An initial program (JPARC Phase I) using a 30 GeV beam to study J/ψ physics was also proposed [46].

3.1. Isospin Symmetry of the Light Quark Sea

For many years, it was believed that the proton's sea quark distributions were $\bar{d}$-$\bar{u}$ symmetric, arising from approximately equal splitting of gluons into $d\bar{d}$ and $u\bar{u}$ pairs. While there were indications of $\bar{d} \neq \bar{u}$ from Drell-Yan data in the early 1980's [47] it was observation of a violation of the Gottfried Sum Rule [48] in muon DIS by the New Muon Collaborations [49, 50] that forced this belief to be reconsidered. Because of its sensitivity to the antiquark distributions Ellis and Stirling suggested [51] using Drell-Yan as a probe of the light quark flavor asymmetry with hydrogen and deuterium targets. To illustrate this sensitivity, in leading order with the $x_1 \gg x_2$, assuming charge symmetry and the dominance of the $u\bar{u}$ annihilation term, the ratio of the per nucleon proton-proton to proton-deuterium Drell-Yan yields can be expressed as

$$\left.\frac{\sigma_{pd}}{2\sigma_{pp}}\right|_{x_1 \gg x_2} = \frac{1}{2}\left[1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right]. \tag{9}$$

The NLO terms in the cross section provide a small correction to this *ratio* and are considered in the analysis of the data, along with the deviation from the $x_1 \gg x_2$ limit. Fermilab E772 used their existing proton induced Drell-Yan data to compare the W/C and $W/{}^2H$ yields to extract upper limits on the isospin asymmetry for $0.04 \leq x \leq 0.27$ [52]. The first dedicated measurement of the $\bar{d}/\bar{u}$ asymmetry using Drell-Yan scattering was made by the CERN NA51 experiment [53]. The acceptance of the NA51 toroid-based detector was such that the average rapidity $\langle y \rangle = 0$ and $x_1 = x_2 = 0.18$. The asymmetry measured by NA51 was

$$A_{\mathrm{DY}} = 2\frac{\sigma^{pp}}{\sigma^{pd}} - 1 = \frac{\sigma^{pp} - \sigma^{pn}}{\sigma^{pp} + \sigma^{pn}} = -0.09 \pm 0.02 \text{ (stat.)} \pm 0.025 \text{ (syst.)}, \tag{10}$$

with the second equality only valid if nuclear effects are ignored. From this NA51 extracted

$$\left.\frac{\bar{u}}{\bar{d}}\right|_{x=0.18} = 0.51 \pm 0.04\ (\mathrm{stat.}) \pm 0.05\ (\mathrm{syst.}), \qquad (11)$$

a clear signal for isospin symmetry violation in the sea antiquark distributions.

The Fermilab E866/NuSea experiment used Drell-Yan to measure x-dependence of the $\bar{d}/\bar{u}$ ratio. Fermilab E866/NuSea used a spectrometer composed of three dipole magnets. The first two magnets served to focus large transverse momentum, p_T, dimuons into the spectrometer while tracking surrounding the third magnet provided a momentum measurement of the individual muons. The experiment used 800 GeV protons extracted from the Fermilab Tevatron incident on hydrogen and deuterium targets. The remainder of the beam which did not interact in the targets was intercepted by a copper beam dump contained within the first magnet. Additionally, the entire aperture of the first dipole was filled with copper, carbon and borated polyethylene, absorbing essentially all particles other than muons produced in the interaction of the beam with the targets or beam dump. (Fermilab E772 [54] used essentially the same apparatus.) E866/NuSea recorded 360,000 Drell-Yan events, approximately two thirds from a deuterium target and the remainder from a hydrogen target. The ratio of Drell-Yan cross sections, $\sigma^{pd}/\left(2\sigma^{pp}\right)$, measured by E866/NuSea as well as the extracted ratio $\bar{d}(x)/\bar{u}(x)$ is shown in figure 6. When these cross section ratios were included in global parton distribution fits [17, 55, 56], they completely changed the perception of the sea quark distributions in the nucleon.

The E866/NuSea data present an interesting picture of the sea quark distributions of the nucleon that may shed some light on the origins of the sea quarks. At moderate values of x the data show greater than 60% excess of $\bar{d}$ over $\bar{u}$, but as x grows larger, this excess disappears and the sea appears to be symmetric again. If the sea's origins are purely perturbative, then it is expected to have only a *very* small asymmetry between $\bar{d}$ and $\bar{u}$ [60, 61]. Many non-perturbative explanations for the origin of the sea including meson cloud models [62, 63], chiral perturbation theory [64, 65] or instantons [66, 67] have been suggested which can explain a large asymmetry, but not the return to a symmetric sea which is seen as $x \rightarrow 0.3$. These models are reviewed elsewhere [68]. It is interesting to note the importance of dynamical chiral symmetry breaking that Thomas *et al.* have related to the $\bar{d} - \bar{u}$ difference through the presence of Goldstone bosons which form a pion cloud around the nucleon [69]. Henley *et al.* have calculated the coordinate-space distribution of the $\bar{d} - \bar{u}$ asymmetry and observe that this distribution agrees with what is expected if $\bar{d} - \bar{u}$ originates from a pion cloud surrounding the nucleon [70]. Plotted in terms of $\bar{d}(x) - \bar{u}(x)$, the observed E866/NuSea asymmetry, as shown in figure 7 [57], can be compared directly to non-perturbative models since the (flavor symmetric) perturbative component of the sea is removed.

The E866/NuSea data become less precise as x increases beyond 0.25 and the exact trend of $\bar{d}/\bar{u}$ is not clear. To help understand this region better, Fermilab E906 experiment has been approved to collect Drell-Yan data in this region. The Fermilab

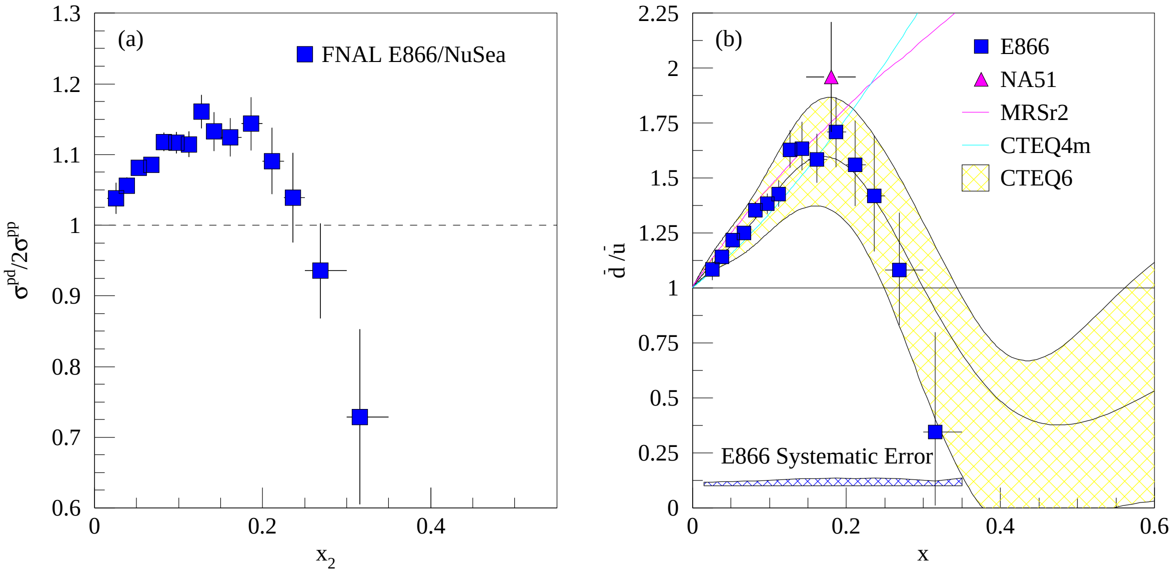

Figure 6. (a) The blue squares show the ratio the proton-deuterium to twice the proton-proton Drell-Yan cross sections versus x_2 as measured by Fermilab E866/NuSea [57]. (b) The blue squares show $\bar{d}(x)/\bar{u}(x)$ ratio extracted by E866/NuSea [57] The magenta triangle is the NA51 [53] measurement of $\bar{d}/\bar{u}$. The central curve in the cross filled band shows the $\bar{d}/\bar{u}$ ratio from the CTEQ6m fit [17], which included the E866/NuSea data, and the band represents the uncertainty from the fit. The curves labeled CTEQ4M [58] and MRS(r2) [59] show the parameterizations of $\bar{d}(x)/\bar{u}(x)$ which included the NA51 point and the EMC integral but not the E866/NuSea data.

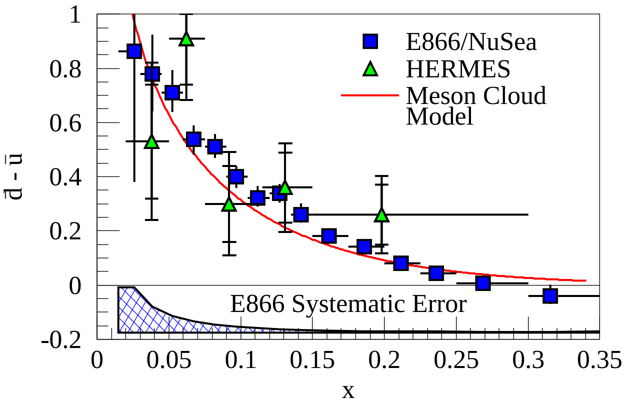

Figure 7. The $\bar{d}(x) - \bar{u}(x)$ distribution as extracted by E866/NuSea (blue squares) using Drell-Yan [57] and by HERMES (green triangles) using semi-inclusive DIS [71]. Also shown are a pion model calculation of Peng *et al.* [62] based on the procedure of Kumano [63].

E906/Drell-Yan experiment [45] is modeled after its predecessors, Fermilab E772 and E866/NuSea. The E906 experiment will use a 120 GeV proton beam rather than the 800 GeV beam used by E866 and E772. Experimentally, the lower beam energy has two significant advantages. First, the primary background in the experiment comes from J/ψ decays, the cross section of which scales roughly with s. The lower beam energy implies less background rate in the spectrometer and allows for a correspondingly higher instantaneous luminosity. Second, the Drell-Yan cross section at fixed x_1 and x_2 is inversely proportional to s (recall $M^2_{\gamma^*} \approx x_1 x_2 s$) and thus the lower beam energy provides a larger cross section. The muons produced in a 120 GeV collision have a significantly smaller boost, which forces the apparatus to be shortened considerably in order to maintain the same p_T acceptance. The smaller boost will also create a larger background from pion decay. Fermilab E906 expects to have statistical precision better than 1% for $x < 0.35$ and 10% for $0.35 < x < 0.45$, a clear improvement over the E866/NuSea data.

A similar experiment [46] has also been proposed for the JPARC facility. This experiment would employ a 50 GeV proton beam with an apparatus similar in design to the E906/Drell-Yan apparatus. The initial phase of the JPARC facility is for a 30 GeV synchrotron, which kinematicly has insufficient phase space above the J/ψ in mass for a Drell-Yan experiment; although, once the entire facility is completed, including capabilities for 50 GeV beam, a significant Drell-Yan program could be mounted.

3.2. Antiquark Distributions of Nuclei

The distributions of partons within a free nucleon differ from those of a nucleon bound within a heavy nucleus, an effect first discovered by the European Muon Collaboration (EMC) in 1983 [72]. These nuclear effects are now generally divided into four regions in x-space: the shadowing region with $x \lesssim 0.1$, the anti-shadowing region covering $0.1 \lesssim x \lesssim 0.3$, the EMC effect region for $0.3 \lesssim x \lesssim 0.6$ and finally a region dominated by Fermi motion of the nucleons with $0.6 \lesssim x$. (For a review of the nuclear EMC effect, see [73].) Almost all of the data on nuclear dependencies is from charged lepton DIS experiments, that are sensitive only to the charge-weighted sum of all quark and antiquark distributions. Nuclear effects in the sea quark distributions may be entirely different from those in the valence sector [74], but an electron or muon DIS experiment would not be sensitive to this. With the ability to probe the antiquark distributions of the target, Drell-Yan presents an ideal tool with which to distinguish between sea and valence effects.

Some early models of the EMC effect were based on the convolution of a virtual pion cloud with the nucleon. In these models, virtual pion contributions to nuclear structure functions were expected to lead to sizable increases in sea distributions of the nuclei compared with deuterium [75, 76, 77]. Early Drell-Yan studies at both CERN [78, 79] and Fermilab [47] lacked the statistical sensitivity to observe the expected effects. In 1990, measurements by Fermilab E772 [54] found that the expected enhancement was

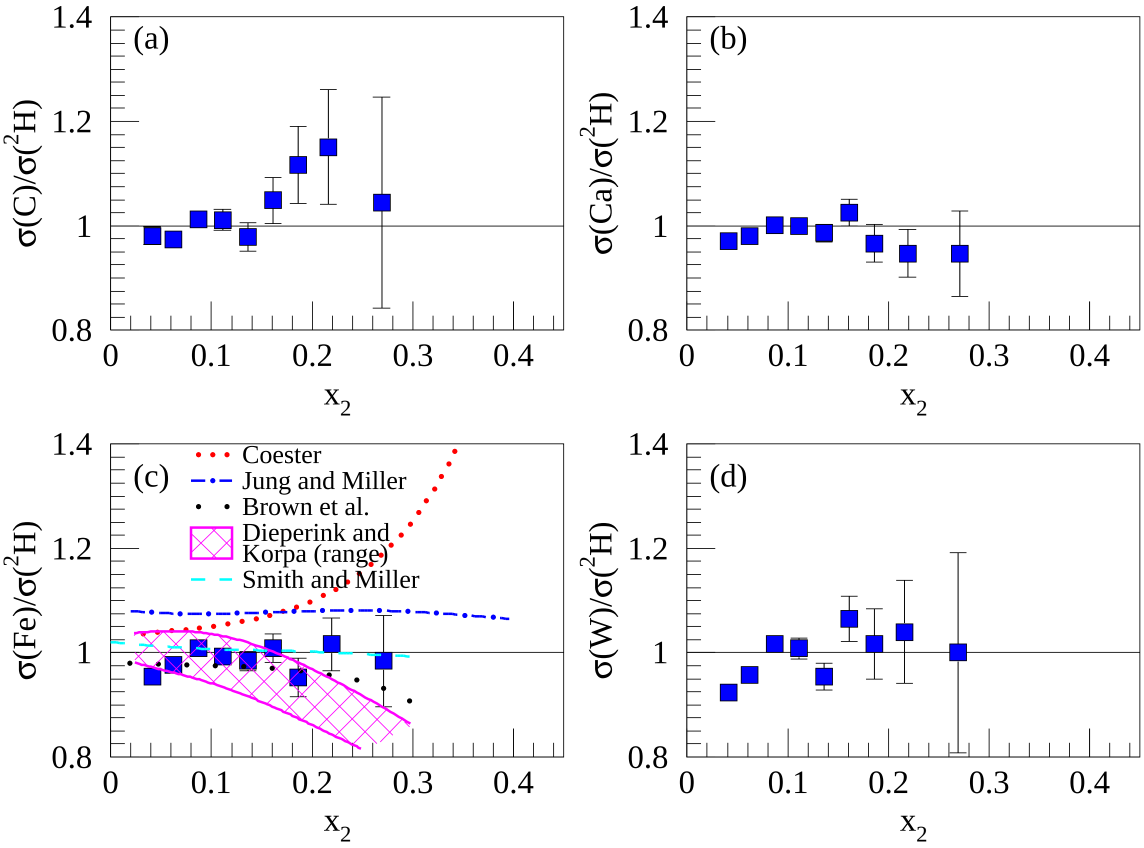

Figure 8. E772 measurements of the ratio of Drell-Yan cross sections on (a) carbon, (b) calcium, (c) iron and (d) tungsten to deuterium [54]. Aside from shadowing in the $x_2 < 0.2$ region, no nuclear effects are observed. In (c), to illustrate the level of effects expected, curves based on several different representative models are also plotted [75, 76, 77, 81, 82, 83, 84]. The differences between these curves is discussed briefly in the text.

clearly *absent*, as shown in figure 8. The non-observation of evidence of a pion excess calls into question the most widely believed traditional meson-exchange model [80] of the nucleus. The expected enhancement to the sea is illustrated in Fig. 8c, which shows the expected Drell-Yan ratio in iron to deuterium, based on nuclear convolution model calculations by Coester [75, 76, 77] meant to explain the originally observed EMC effect.

More recent calculations [81, 82, 83, 84], made in light of the E772 data, predict a smaller nuclear dependence, consistent with the statistical uncertainties of E772. Jung and Miller [81] revisited the calculations of Berger and Coester and examined the effect of the quantization of the pions on the light cone versus at “equal time”. With “equal time” quantization, they calculate a roughly flat 8% increase in the Drell-Yan iron cross section over the deuterium cross section. Brown *et al.* [82] argue that with the partial restoration of chiral symmetry, the masses of hadrons made up of light quarks decrease with density. This rescaling leads to altered couplings, which lead to an overall x-dependent *decrease* in the Drell-Yan cross section in nuclei. Dieperink and Korpa [83] also argue that the Drell-Yan cross section ratio should decrease in a nucleus. Their arguments are based on particle- and delta-hole model, which results in a strong distortion of the free pion structure function. Based on the chiral quark soliton model, Smith and Miller predict essentially no nuclear dependence for Drell-Yan, while at the same time qualitatively explaining the observed EMC effect [84]. For $x > 0.2$, the E772 statistical uncertainties allow some freedom for these models. At $x \approx 0.3$ these newer models have nuclear effects of the order 5 to 15% in the Drell-Yan ratio and tend to diverge from each other. Fermilab E906 will provide the sensitivity needed to see these differences with an expected statistical precision of 1% at $x = 0.3$ and data out to $x = 0.45$ [45].

4. Unpolarized Parton Distributions at Large-x of the Beam Hadron

In addition to probing the sea quark distribution of the target nuclei, Drell-Yan scattering can be used to probe the structure of the beam hadron. As shown in (2), the cross section is a convolution of the beam and target parton distributions. The same feature of the acceptance which allows fixed target experiments to probe the target's sea quark distributions gives experimental access to the high-x, valence parton distributions of the incoming hadron. Absolute cross section measurements have been used to explore both pionic and protonic parton distributions; although, some authors suggest that there may be breakdown in factorization at large-x [33, 34]. Such effects could cloud the partonic interpretation of these data.

The large-x parton distributions of the proton are relatively unknown, both in absolute magnitude and in the ratio of d/u. Experimentally, these have been accessed through DIS. Unfortunately, much of the high-x data used in DIS measurements involve nuclear targets with relatively unknown and possibly large nuclear corrections (even to deuterium) [85]. Proton induced Drell-Yan, which is sensitive to the $4u + d$ distribution of the beam proton, is an alternative way to reach high-x with no nuclear corrections. The proton-proton and proton-deuterium cross section measurements of Fermilab E866/NuSea when compared with NLO calculations based on both the CTEQ6m [17] and MRST [55] parton distributions show a small but systematic trend suggesting an overestimation of the strength of this parton distribution at large-x ($x < 0.8$ however) [12]. Future Drell-Yan experiments such as Fermilab E906 [45] or a JPARC-based experiment [46] will be able to improve dramatically on these measurements in both statistical precision and reach in x.

The pion's parton distributions are of considerable interest because of the pion's many unique roles in nuclear physics. The pion's valence antiquarks have been used to explain partially the observed $\bar{d}/\bar{u}$ ratio in the proton through a pionic cloud around the bare nucleon. (See Sec. 3.1.) Models of nuclear binding depend on pion exchange, and so the pionic quark distributions should modify the parton distributions in nuclei. (See Sec. 3.2.) While the pion is a $q\bar{q}$ system, its extremely low mass arises from its role as the Goldstone boson of dynamical chiral symmetry breaking and this role must be considered in any descriptions of the pion's partonic nature.

There are a variety of theoretical and model-based descriptions of the pion's valence parton structure. At large-x valence structure of the pion can be parameterized as $(1-x)^{\beta}$, where QCD evolution of the parton distributions makes β a function of Q^2. At low Q^2, arguments based on the parton model [86], pQCD [87, 88] and Dyson-Schwinger equations [89] require that $\beta \approx 2$. At the same time the Drell-Yan-West relation [90, 91], duality arguments [92] and Nambu-Jona-Lasinio models [93, 94, 95, 96] favor a linear dependence of $\beta \approx 1$. An early leading order analysis of pion induced Drell-Yan data found $\beta = 1.26 \pm 0.04$ [32] with $\langle M_{\gamma^*} \rangle = 5.2$ GeV. Noting that the strength of higher order diagrams could have a kinematic dependence, a fit to the same data, this time in NLO found $\beta = 1.54 \pm 0.08$ [97], still somewhat in between a linear and quadratic $1-x$ behavior. Some future pionic Drell-Yan experiment with improved kinematic resolution in the high-x_1 region could help to resolve this question.

5. Unpolarized Angular Distributions

In leading order, ignoring transverse momenta (k_T) of the interacting partons, the Drell-Yan angular distribution is naively expected to have the form $(1 + \cos^2\theta)$. More generally, Collins and Soper [98] have shown that the expression for the angular distribution is

$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi, \tag{12}$$

where θ is the polar angle of the positive lepton in the rest frame of the virtual photon and ϕ is the azimuthal angle. The additional terms arise from the k_T of the interacting partons and higher order graphs in α_s. After consideration of the intrinsic k_T of the partons, care must be taken in precisely defining the the z-axis of rest frame of the virtual photon. The most common choices for this definition are the u-channel frame where the the z-axis points anti-parallel to the target nucleon direction; the Gottfried-Jackson frame (t-channel) [99] has the z-axis pointing parallel to the beam nucleon and the Collins-Soper [98] frame where the z-axis bisects the angle between the u-channel and Gottfried-Jackson z-axes, in an attempt to minimize the effects of k_T on the observed angular distributions. The transformation between λ, μ and ν in the three frames is straight-forward [31].

In NLO, a relationship between λ and ν of the general angular distribution formula in (12) was derived by C.S. Lam and W.-K. Tung [100]. In analogy to the Callan-Gross relationship of DIS [101], the Lam-Tung relation states that

$$1 - \lambda = 2\nu. \tag{13}$$

Unlike the Callan-Gross relation, the Lam-Tung relation is expected to be largely unaffected by QCD [100], including resummation effects [102].

The validity of the Lam-Tung relation has been studied with both pion-induced Drell-Yan by CERN NA10 [30, 29] and Fermilab E615 [31, 32] and proton induced Drell-Yan by Fermilab E866/NuSea [103]. Pionic Drell-Yan experiments have observed a violation of the Lam-Tung relation. This violation is most prominent at high transverse momentum of the dilepton, p_T, where ν rises without a corresponding decrease in λ, as

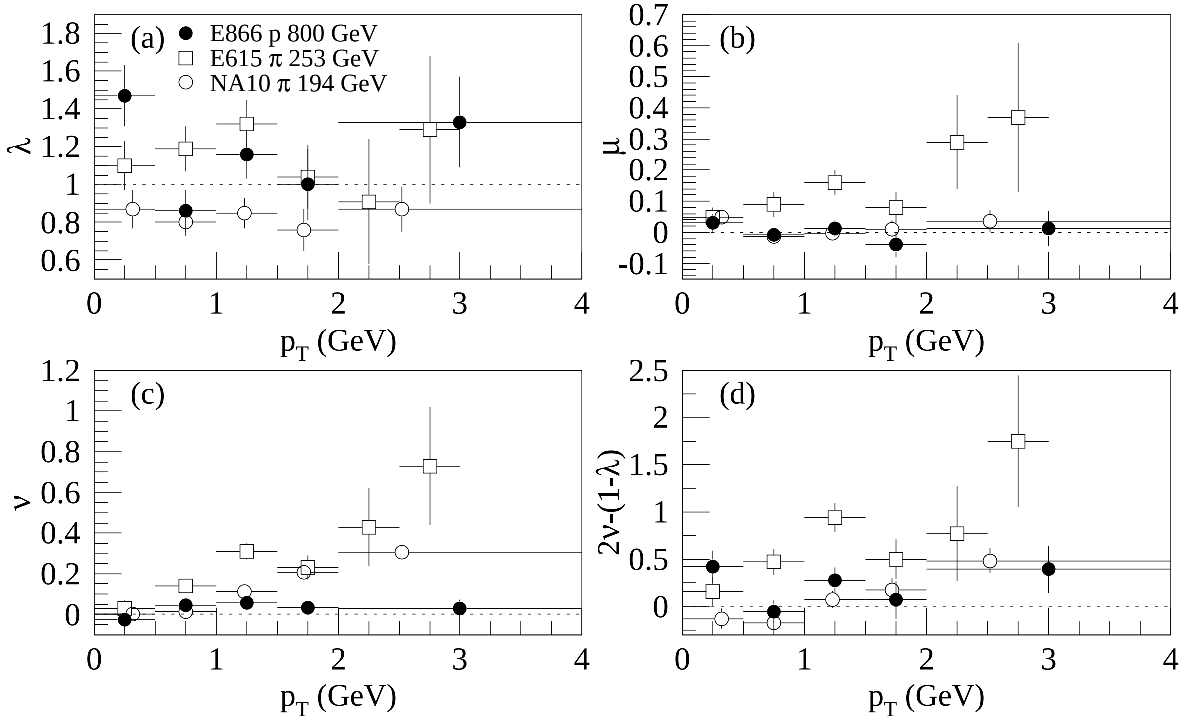

Figure 9. The parameters (a) λ, (b) μ and (c) ν [see (13)] of fits to the angular distributions as a function of p_T from pion (CERN NA10 [30, 29] and Fermilab E615 [31, 32]) and proton (Fermilab E866 [103]) induced Drell-Yan scattering. For the NA10 experiment, the data set with the best statistical precision, 194 GeV, is shown. Plotted in (d) is $2\nu - (1 - \lambda)$ which is predicted to be zero by the Lam-Tung relation. For the pionic Drell-Yan data there is evidence for a violation of the Lam-Tung sum rule, especially at large-p_T. The uncertainties are statistical only and in (d) do not include possible correlations between λ and ν.

shown in figure 9. The violation appears to be independent of the target nucleus [29]. In contrast, the recently released Fermilab E866 proton induced Drell-Yan data are consistent with the Lam-Tung relation, even at high-p_T [103].

Berger and Brodsky have suggested that as $x \rightarrow 1$, higher-twist effects cause the polarization of the virtual photon to change from $(1 + \cos^2\theta)$ to a k_T-dependent $\sin^2\theta$ [33]. While effects consistent with this have been observed in pionic Drell-Yan data [32] at high-x, the violation of the Lam-Tung relation is seen over a much broader range in x than would be expected by this explanation. Brandenburg, Nachtmann and Mirke hypothesized a spin correlation in the violation of factorization that would give rise to a nonzero $\cos 2\phi$ distribution [104], which could explain the pionic Drell-Yan data.

An alternative explanation proposed by Boer [105] based on the existence of a chiral-odd, T-odd distribution function, $h_1^{\perp}(x, k_T)$, with an intrinsic transverse momentum dependence, k_T, of Boer and Mulders [106]. This *distribution* function is an analog of the Collins *fragmentation* function [107]. It represents the correlation of the parton's transverse spin and k_T in an unpolarized nucelon. Boer argues that the presence of the $h_1^\perp(x, k_T)$ distribution function will induce a $\cos 2\phi$ dependence to the Drell-Yan cross section and fits the observed NA10 [30] data to a crude model of this distribution function. Within a quark spectator-antiquark model, Lu and Ma have shown that the observed $\cos 2\phi$ distribution can be reproduced with nonzero $h_1^\perp(x, k_T)$ in both the pion and target nucleon [108]. Other transversity distributions are discussed again in section 6.

When considering any of these explanations for the violation of the Lam-Tung relation in pion-induced Drell-Yan, it is important to remember that these results must be reconciled with the apparent absence of a violation in proton-induced Drell-Yan. One significant difference is that the valence antiquark in the pion-induced case allows the experiment to probe the quark distributions of the target, while in the proton induced case, only the target antiquark distributions are probed. Alternatively, the possible interpretation as a higher-twist effect might have a kinematic dependence on $\sqrt{s}$ [104]. Recall that the pionic data had $\sqrt{s} = 11$ and 16 GeV while the protonic data had $\sqrt{s} = 39$ GeV. Such an effect should clearly be seen then in the upcoming Fermilab E906 experiment with proton-induced Drell-Yan at $\sqrt{s} = 15$ GeV.

6. Transversity Measurements with Drell-Yan Scattering

Polarized beams and targets add an extra dimension to Drell-Yan scattering, enabling it to be used to study both quark helicity (longitudinal) and transversity distributions. Close and Sivers suggested that the sea quarks produced through gluon splitting would be polarized and that this effect could be observed with longitudinally polarized Drell-Yan scattering [109]. Ralston and Soper considered the possibility not only of longitudinally polarized but also of transversely polarized scattering, proposing the measurement of certain asymmetries as a test of the Drell-Yan Model [110].

In the near future, there are several proposed experiments at polarized beam facilities. One of the options that may be available in Phase II of the JPARC program would include a polarized proton beam. The FAIR program [111] at GSI includes plans for a polarized antiproton ring. The PAX collaboration has proposed [43] a series of Drell-Yan and charm measurements using this beam. The first phase of the experiment would involve polarized (or unpolarized) antiproton beams of up to 3.5 GeV colliding with an internal polarized hydrogen target. In the second phase, the PAX experiment will be run as a collider experiment with up to 15 GeV polarized antiprotons colliding with a beam of 3.5 GeV polarized protons. The RHIC-spin program also offers opportunities for measuring polarized Drell-Yan scattering either with the existing detectors or a new detector dedicated to polarized Drell-Yan physics [112, 113].

In leading twist, in addition to the unpolarized parton distributions, f, and the helicity distributions, Δf, a complete description of the proton requires knowledge of the transversely polarized parton distributions, denoted h_1. (Various notations for transversity distributions are used in the literature. This notation corresponds to that of Jaffe, Ji and Mulders [114, 115]. Alternatively, $\Delta_T f$ in the notation of Barone and Ratcliffe [116, 117] or δq have been used.) The quantity h_1 represents the net transverse helicity of the quarks in a transversely polarized hadron. This distribution is just as fundamental as the unpolarized and helicity distributions; although, much less studied. While the existence of the transverse parton distributions was recognized in the late 1970's [110], they received little consideration in discussions of proton structure until recently. This is, perhaps, largely because of the difficulty in measuring these distributions. Because transversity is a chirally odd quantity, it cannot be probed in inclusive DIS, the traditional tool for deducing parton distributions. In order to observe h_1 chirality must be flipped twice [118]. This requires two hadrons in the interaction, for example, one each in the initial and final state or two in the initial state. Thus, both semi-inclusive DIS and Drell-Yan scattering offer excellent opportunities to study transversity distributions. In the spin-$\frac{1}{2}$ nucleon, there is no gluon transversity distribution and so the QCD evolution of h_1 is quite different from the QCD evolution of Δf. The distribution h_1 evolves as a flavor non-singlet quantity [117].

With the additional consideration of intrinsic transverse momentum, k_T, in the proton, two other distributions emerge. The Boer-Mulders function, $h_1^\perp(x, k_T)$ [106], was introduced in section 5 to explain the observed $\cos 2\phi$ distributions in Drell-Yan scattering. The Sivers distributions function, $f_{1T}^\perp(x, k_T)$, characterized a correlation in a polarized nucleon of the unpolarized parton density with k_T [119, 120], and can be observed in single spin asymmetries as discussed in section 6.1. While these distributions functions vanish when integrated over k_T, their possible existence and k_T-dependence offers a window into spin-orbit correlations in the nucleon. Recent measurements of semi-inclusive DIS have provided an initial insight into both transversity distributions and fragmentation functions; although disentangling the effects of fragmentation from the distribution functions can be difficult. With Drell-Yan scattering, the fragmentation functions are not relevant and one has a clean probe of only the distribution functions. For excellent reviews of the physics of transversity, see [116, 117].

6.1. Single Transverse Spin Asymmetries and the Sivers Function

In hadron-hadron interactions with one of the two hadrons is transversely polarized and the other is unpolarized, surprisingly large asymmetries of the form

$$A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}, \tag{14}$$

have been observed (*e.g* the Fermilab E704 experiment [121] which measured $p^\uparrow p \to \pi X$). D. Sivers suggested (prior to the publications of the E704 results) that these single transverse-spin asymmetries (SSA) could be used to provide information on the k_T-dependence of unpolarized partons in a transversely polarized nucleon and that these SSA were non-vanishing when the transverse motion of the individual partons is considered [119, 120]. He applied these argument to the reaction $hp^\uparrow \to \pi X$, where h represents any unpolarized hadron, $p^\uparrow$ is a transversely polarized target and π represents any detected spinless final state meson. The asymmetry arising from unpolarized quarks in a transversely polarized hadron is known as the "Sivers asymmetry" with the associated "naively" T-odd $f_{1T}^{\perp}(x, k_T)$ parton distribution. Initially, it was *incorrectly* believed that A_N would vanish because of time-reversal invariance [107]. In QCD at leading twist it is also expected to be zero [122]. It was later shown that with correct consideration of Wilson lines that the "Sivers asymmetry" can be non-vanishing at *leading twist*. The Wilson lines provide for the gauge invariance in the parton number densities and appear as soft initial-state interactions in Drell-Yan [123, 124]. Alternatively, with collinear QCD factorization at twist-three, it was recognized that there could be a non-zero SSA [125, 126]. Both mechanisms, the k_T-dependent parton distribution approach and twist-three QCD approach, provide mechanisms to explain the same physical observable–a large SSA. Within the context of Drell-Yan scattering, the k_T-dependent parton distributions are best applied to the domain in which $p_T \ll M_{\gamma^*}$ while the twist-three QCD approach is more applicable for $\Lambda_{\text{QCD}} \ll p_T$. Recent work by Ji *et al.* has shown that these two approaches are in fact related, and that they give the same result in the overlap region, $\Lambda_{\text{QCD}} \ll p_T \ll M_{\gamma^*}$ [127, 128].

The single spin asymmetries observed in the Fermilab E704 experiment [121] could either be attributed to the $f_{1T}^{\perp}(x, k_T)$ distribution in the proton or to a transversity dependent "Collins" fragmentation function [107]. While these two mechanism have similar signatures in the E704 experiment, they produce different angular distributions in semi-inclusive DIS. Recently, the first experimental evidence for both the Sivers $f_{1T}^{\perp}(x, k_T)$ distribution function and the Collins $H_1^{\perp}$ fragmentation function has been observed by the HERMES experiment [129]. Both the Sivers distribution and Collins fragmentation functions have been extracted with global analyses [130, 131] based on observations from HERMES [129] and COMPASS [132]. These analyses and model calculations [133] predict asymmetries of approximately 8% in $p^{\uparrow}\bar{p}$ Drell-Yan in the kinematics of the proposed PAX experiment [43], well within their statistical precision. For $p^{\uparrow}p$ Drell-Yan at RHIC, these analyses predict a 1–10% asymmetry on the kinematics accepted. One very interesting consequence is that the Sivers asymmetry should have the opposite sign when measured in Drell-Yan scattering [123], *i.e.*

$$f_{1T}^{\perp}(x, k_T)\big|_{\text{DIS}} = - \, f_{1T}^{\perp}(x, k_T)\big|_{\text{DY}} \, . \tag{15}$$

The experimental verification of (15) is a key to validating the current understanding of k_T effects in transversity distributions and is one of the goals of the next generation of transversely polarized Drell-Yan experiments.

6.2. Double Spin Asymmetries

Doubly, transversely polarized Drell-Yan scattering offers the possibility of measuring $h_1(x)$ without any complications from fragmentation. The asymmetry is given by [110, 117, 116]

$$A_{TT}^{\text{DY}} = \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}}$$

$$= \alpha_{TT} \frac{\sum_i e_i^2 \left[h_{1i}(x_1)\bar{h}_{1i}(x_2) + \bar{h}_{1i}(x_1)h_{1i}(x_2)\right]}{\sum_i e_i^2 \left[f_i(x_1)\bar{f}_i(x_2) + \bar{f}_i(x_1)f_i(x_2)\right]}, \tag{16}$$

where

$$\alpha_{TT} = \frac{\sin^2\theta \cos(2\phi)}{1+\cos^2\theta}. \tag{17}$$

Note that this represents a convolution of the *quark* $h_1(x_1)$ and *antiquark* $\bar{h}_1(x_2)$ transversity distributions. Unlike unpolarized Drell-Yan scattering, which also measured a quark-antiquark convolution, the assumption that the quark distributions are known from previous data (primarily DIS) is no longer valid and so a significant amount of data is required to untangle this convolution. Furthermore, because the gluons do not directly couple to h_1, it is expected that the sea contributions to the asymmetry may be small.

As an alternative to this, the PAX collaboration [43] has proposed the measurement of antiproton-proton Drell-Yan scattering in a collider mode. In this case the cross section is dominated by valence antiquarks annihilating with valence quarks. Assuming the dominance of the u-quark terms, the asymmetry in (16) reduces to [43]

$$A_{TT}^{\mathrm{DY}} = \alpha_{TT} \frac{h_{1u}(x_1)h_{1u}(x_2)}{u(x_1)u(x_2)}, \tag{18}$$

thus giving a direct experimental access to $|h_{1u}|$. Statistically, this is a challenging measurement, as polarized antiprotons are difficult to create. By relaxing the usual mass requirement for Drell-Yan to include events both above and below the J/ψ, PAX hopes to be able to obtain statistical precision of 10%. The relatively low energy of PAX places some data in a region in which resummation may be important in interpreting the overall cross sections. Fortunately, it appears that the asymmetry A_{TT}^{DY} is largely unaffected by resummation [44].

7. Measurement of Quark Helicity with Longitudinally Polarized Drell-Yan

The total spin of the proton can be decomposed into the spin and orbital contributions from the quarks and gluons:

$$\langle s_z^N \rangle = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g, \tag{19}$$

where $\Delta\Sigma$ and ΔG represent the contributions of the quark and gluon helicity respectively and L_q and L_g are the orbital angular momentum of the quarks and gluons. Motivated by the observation of the European Muon Collaboration (EMC) that only a very small fraction of the total spin of the proton is carried by the quarks [134, 135], an analysis of the world's data by the SMC group finds the fraction of the proton's spin carried by quarks at $\Delta\Sigma = 0.38 \pm 0.06$ [136]. The quark spin, $\Delta\Sigma$, can further be decomposed into contributions of the individual flavors of quarks and antiquarks.

The HERMES experiment at DESY has been extremely successful at studying the flavor decomposition of $\Delta\Sigma$ using semi-inclusive DIS [137]. The results of this type of experiment depend on precise knowledge of both the polarized and unpolarized fragmentation functions. Some authors have argued that the contributions of the sea quarks to the polarized asymmetries are small, reducing the sensitivity of this type of experiment [138, 139]. In Drell-Yan scattering, however, this is not the case [138, 140], and knowledge of the fragmentation functions is not necessary.

As with unpolarized Drell-Yan, polarized Drell-Yan scattering offers a window into the sea quark distributions. The asymmetry for longitudinally polarized Drell-Yan, A_{LL}^{DY} is given by [109]

$$\begin{aligned} A_{LL}^{\mathrm{DY}} &= \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} - d\sigma^{+-}} \\ &= \frac{\sum_i e_i^2 \left[\Delta f_i(x_1)\Delta \bar{f}_i(x_2) + \Delta \bar{f}_i(x_1)\Delta f_i(x_2)\right]}{\sum_i e_i^2 \left[f_i(x_1)\bar{f}_i(x_2) + \bar{f}_i(x_1) f_i(x_2)\right]}. \end{aligned} \tag{20}$$

Here, $d\sigma^{++}$ ($d\sigma^{+-}$) denotes the spin parallel (anti-parallel) Drell-Yan cross sections. Making the same "fixed target" assumptions as in the unpolarized case, (20) shows that A_{LL}^{DY} measures $\Delta\bar{u}$ in the target proton, convoluted with the large-x Δu distribution in the proton. In the limit of exact SU(6), Close and Sivers [109] have shown that

$$A_{LL}^{\mathrm{DY}}(x_1, x_2) = \frac{1}{3}\frac{g_A}{g_V}\frac{\Delta \bar{f}(x_2)}{\bar{f}(x_2)}. \tag{21}$$

With the addition of a polarized deuterium target, it would be possible to extract $\Delta\bar{d}$ as well, providing that the valence spin distributions are known. Such a measurement has already been proposed for the J-PARC Phase II facility with a 50 GeV polarized proton beam. The proposed experiment expects to be able to achieve 10% statistical precision for $0.3 \leq x \leq 0.5$ [46].

8. Conclusions

Over the last 35 years, Drell-Yan scattering has played an important role in elucidating the hadronic structure and will continue to do so with the arrival of several new polarized and unpolarized experiments. Unpolarized Drell-Yan scattering has been critical in measuring the sea quark structure of the nucleon and the nucleus. Fermilab E866/NuSea has probed the flavor asymmetry of the antiquark sea, showing conclusively that non-perturbative processes contribute to the sea. Fermilab E772 measured the nuclear effects on the sea quark distributions, finding that widely accepted models of nuclear binding to be lacking. With transversely polarized beams, these experiments will enable the extraction of the $h_1(x)$ transversity structure function. In combination with DIS scattering, transverse single spin asymmetries will test the understanding of the k_T dependent Sivers function, $f_{1T}^{\perp}(x, k_T)$.

Acknowledgments

This review has benefited greatly from suggestions and careful review by J.-C. Peng and J. Qiu. This work was supported the U.S. Department of Energy, Office of Nuclear

Physics, under Contract No. DE-AC-02-06CH11357.

References

[1] Drell S D and Yan T M 1970 *Phys. Rev. Lett.* **25**(5) 316–320

[2] Drell S D and Yan T M 1970 *Phys. Rev. Lett.* **25**(13) 902

[3] Christenson J H, Hicks G S, Lederman L M, Limon P J, Pope B G and Zavattini E 1970 *Phys. Rev. Lett.* **25**(21) 1523–1526

[4] Christenson J H, Hicks G S, Lederman L M, Limon P J, Pope B G and Zavattini E 1973 *Phys. Rev. D* **8**(7) 2016–2034

[5] Feynman R P 1969 *Phys. Rev. Lett.* **23**(24) 1415–1417

[6] Kubar J, Le Bellac M, Meunier J L and Plaut G 1980 *Nucl. Phys.* **B175** 251

[7] Kenyon I R 1982 *Rept. Prog. Phys.* **45** 1261

[8] Stirling W J and Whalley M R 1993 *J. Phys.* **G19** D1–D102

[9] Reimer P (Fermilab E866/NuSea) 2007 Unpublished

[10] Altarelli G, Ellis R K and Martinelli G 1979 *Nucl. Phys.* **B157** 461

[11] Harada K, Kaneko T and Sakai N 1979 *Nucl. Phys.* **B155** 169

[12] Webb J C 2003 *Measurement of continuum dimuon production in 800-GeV/c proton nucleon collisions* Ph.D. thesis New Mexico State University (*Preprint* `hep-ex/0301031`)

[13] Webb J C *et al.* (E866/NuSea) 2003 (*Preprint* `hep-ex/0302019`)

[14] McGaughey P L, Moss J M, Alde D M, Baer H W, Carey T A, Garvey G T, Klein A, Lee C, Leitch M J, Lillberg J, Mishra C S, Peng J C, Brown C N, Cooper W E, Hsiung Y B, Adams M R, Guo R, Kaplan D M, McCarthy R L, Danner G, Wang M, Barlett M and Hoffmann G 1994 *Phys. Rev. D* **50**(5) 3038–3045

[15] McGaughey P L, Moss J M, Alde D M, Baer H W, Carey T A, Garvey G T, Klein A, Lee C, Leitch M J, Lillberg J, Mishra C S, Brown C N, Cooper W E, Hsiung Y B, Adams M R, Guo R, Kaplan D M, McCarthy R L, Danner G, Wang M, Barlett M and Hoffmann G 1999 *Phys. Rev. D* **60**(11) 119903

[16] Moreno G, Brown C N, Cooper W E, Finley D, Hsiung Y B, Jonckheere A M, Jostlein H, Kaplan D M, Lederman L M, Hemmi Y, Imai K, Miyake K, Nakamura T, Sasao N, Tamura N, Yoshida T, Maki A, Sakai Y, Gray R, Luk K B, Rutherfoord J P, Straub P B, Williams R W, Young K K, Adams M R, Glass H and Jaffe D 1991 *Phys. Rev. D* **43**(9) 2815–2835

[17] Pumplin J *et al.* 2002 *JHEP* **07** 012 (*Preprint* `hep-ph/0201195`)

[18] Martin A D, Stirling W J and Thorne R S 2006 *Phys. Lett.* **B636** 259–264 (*Preprint* `hep-ph/0603143`)

[19] Rijken P J and van Neerven W L 1995 *Phys. Rev. D* **51**(1) 44–63

[20] Hamberg R, van Neerven W L and Matsuura T 1991 *Nucl. Phys.* **B359** 343–405

[21] Baur U, Keller S and Sakumoto W K 1998 *Phys. Rev. D* **57**(1) 199–215

[22] Baur U, Brein O, Hollik W, Schappacher C and Wackeroth D 2002 *Phys. Rev. D* **65**(3) 033007

[23] Qiu J w and Sterman G 1991 *Nucl. Phys.* **B353** 105–136

[24] Qiu J w and Sterman G 1991 *Nucl. Phys.* **B353** 137–164

[25] Collins J C, Soper D E and Sterman G 1985 *Nucl. Phys.* **B261** 104

[26] Collins J C, Soper D E and Sterman G 1988 *Nucl. Phys.* **B308** 833

[27] Bodwin G T 1985 *Phys. Rev. D* **31**(10) 2616–2642

[28] Anderson K J, Coleman R N, Karhi K P, Newman C B, Pilcher J E, Rosenberg E I, Thaler J J, Hogan G E, McDonald K T, Sanders G H and Smith A J S 1979 *Phys. Rev. Lett.* **43**(17) 1219–1222

[29] Guanziroli M *et al.* (NA10) 1988 *Z. Phys.* **C37** 545

[30] Falciano S *et al.* (NA10) 1986 *Z. Phys.* **C31** 513

[31] Conway J S, Adolphsen C E, Alexander J P, Anderson K J, Heinrich J G, Pilcher J E, Possoz A,

Rosenberg E I, Biino C, Greenhalgh J F, Louis W C, McDonald K T, Palestini S, Shoemaker F C and Smith A J S (Fermilab E615) 1989 *Phys. Rev. D* **39**(1) 92

[32] Heinrich J G, Biino C, Greenhalgh J F, Louis W C, McDonald K T, Palestini S, Russell D P, Shoemaker F C, Smith A J S, Adolphsen C E, Alexander J P, Anderson K J, Conway J S, Pilcher J E, Possoz A and Rosenberg E I (Fermilab E615) 1991 *Phys. Rev. D* **44**(7) 1909–1932

[33] Berger E L and Brodsky S J 1979 *Phys. Rev. Lett.* **42**(15) 940–944

[34] Berger E L 1980 *Z. Phys.* **C4** 289

[35] Sterman G 1987 *Nucl. Phys.* **B281** 310

[36] Catani S and Trentadue L 1989 *Nucl. Phys.* **B327** 323

[37] Catani S and Trentadue L 1991 *Nucl. Phys.* **B353** 183–186

[38] Idilbi A and Ji X d 2005 *Phys. Rev.* **D72** 054016 (*Preprint* `hep-ph/0501006`)

[39] Idilbi A, Ji X d and Yuan F 2006 *Nucl. Phys.* **B753** 42–68 (*Preprint* `hep-ph/0605068`)

[40] Manohar A V 2003 *Phys. Rev.* **D68** 114019 (*Preprint* `hep-ph/0309176`)

[41] Bolzoni P 2006 *Phys. Lett.* **B643** 325–330 (*Preprint* `hep-ph/0609073`)

[42] Martin A D, Roberts R G, Stirling W J and Thorne R S 2004 *Eur. Phys. J.* **C35** 325–348 (*Preprint* `hep-ph/0308087`)

[43] Barone V *et al.* (PAX) 2005 (*Preprint* `hep-ex/0505054`)

[44] Shimizu H, Sterman G, Vogelsang W and Yokoya H 2005 *Phys. Rev.* **D71** 114007 (*Preprint* `hep-ph/0503270`)

[45] Reimer P, Geesaman D *et al.* (Fermilab E906/Drell-Yan) 2001 Fermilab Proposal 906, Unpublished

[46] Peng J C, Sawada S *et al.* 2006 JPARC Proposal, Unpublished

[47] Ito A S, Fisk R J, Jöstlein H, Kaplan D M, Herb S W, Hom D C, Lederman L M, Snyder H D, Yoh J K, Brown B C, Brown C N, Innes W R, Kephart R D, Ueno K and Yamanouchi T 1981 *Phys. Rev. D* **23**(3) 604–633

[48] Gottfried K 1967 *Phys. Rev. Lett.* **18**(25) 1174–1177

[49] Amaudruz P, Arneodo M, Arvidson A, Badelek B, Baum G, Beaufays J, Bird I G, Botje M, Broggini C, Brückner W, Brüll A, Burger W J, Ciborowski J, Crittenden R, van Dantzig R, Döbbeling H, Domingo J, Drinkard J, Dzierba A, Engelien H, Ferrero M I, Fluri M L, Grafstrom P, von Harrach D, van der Heijden M, Heusch C and Ingram Q 1991 *Phys. Rev. Lett.* **66**(21) 2712–2715

[50] Arneodo M, Arvidson A, Badelek B, Ballintijn M, Baum G, Beaufays J, Bird I G, Björkholm P, Botje M, Broggini C, Brückner W, Brüll A, Burger W J, Ciborowski J, van Dantzig R, Dyring A, Engelien H, Ferrero M I, Fluri L, Gaul U, Granier T, von Harrach D, van der Heijden M, Heusch C, Ingram Q, Janson-Prytz K and de Jong M 1994 *Phys. Rev. D* **50**(1) R1–R3

[51] Ellis S D and Stirling W J 1991 *Phys. Lett.* **B256** 258–264

[52] McGaughey P L, Moss J M, Alde D M, Baer H W, Carey T A, Garvey G T, Klein A, Lee C, Leitch M J, Lillberg J W, Mishra C S, Peng J C, Brown C N, Cooper W E, Hsiung Y B, Adams M R, Guo R, Kaplan D M, McCarthy R L, Danner G, Wang M J, Barlett M L and Hoffmann G W 1992 *Phys. Rev. Lett.* **69**(12) 1726–1728

[53] Baldit A *et al.* (NA51) 1994 *Phys. Lett.* **B332** 244–250

[54] Alde D M, Baer H W, Carey T A, Garvey G T, Klein A, Lee C, Leitch M J, Lillberg J W, McGaughey P L, Mishra C S, Moss J M, Peng J C, Brown C N, Cooper W E, Hsiung Y B, Adams M R, Guo R, Kaplan D M, McCarthy R L, Danner G, Wang M J, Barlett M L and Hoffmann G W 1990 *Phys. Rev. Lett.* **64**(21) 2479–2482

[55] Martin A D, Roberts R G, Stirling W J and Thorne R S 2005 *Eur. Phys. J.* **C39** 155–161 (*Preprint* `hep-ph/0411040`)

[56] Gluck M, Reya E and Vogt A 1998 *Eur. Phys. J.* **C5** 461–470 (*Preprint* `hep-ph/9806404`)

[57] Towell R S *et al.* (FNAL E866/NuSea) 2001 *Phys. Rev.* **D64** 052002 (*Preprint* `hep-ex/0103030`)

[58] Lai H L *et al.* 1997 *Phys. Rev.* **D55** 1280–1296 (*Preprint* `hep-ph/9606399`)

[59] Martin A D, Roberts R G and Stirling W J 1996 *Phys. Lett.* **B387** 419–426 (*Preprint*

`hep-ph/9606345`)

[60] Ross D A and Sachrajda C T 1979 *Nucl. Phys.* **B149** 497

[61] Steffens F M and Thomas A W 1997 *Phys. Rev. C* **55**(2) 900–908

[62] Peng J C *et al.* (E866/NuSea) 1998 *Phys. Rev.* **D58** 092004 (*Preprint* `hep-ph/9804288`)

[63] Kumano S 1991 *Phys. Rev. D* **43**(9) 3067–3070

[64] Eichten E J, Hinchliffe I and Quigg C 1992 *Phys. Rev. D* **45**(7) 2269–2275

[65] Szczurek A, Speth J and Garvey G T 1994 *Nucl. Phys.* **A570** 765–781

[66] Dorokhov A E and Kochelev N I 1991 *Phys. Lett.* **B259** 335–339

[67] Dorokhov A E and Kochelev N I 1993 *Phys. Lett.* **B304** 167–175

[68] Garvey G T and Peng J C 2001 *Prog. Part. Nucl. Phys.* **47** 203–243 (*Preprint* `nucl-ex/0109010`)

[69] Thomas A W, Melnitchouk W and Steffens F M 2000 *Phys. Rev. Lett.* **85**(14) 2892–2894

[70] Henley E M, Renk T and Weise W 2001 *Phys. Lett.* **B502** 99–103 (*Preprint* `hep-ph/0012045`)

[71] Ackerstaff K, Airapetian A, Akopov N, Akushevich I, Amarian M, Ashenauer E C, Avakian H, Avakian R, Avetissian A, Bains B, Baumgarten C, Beckmann M, Belostotski S, Belz J E, Benisch T, Bernreuther S, Bianchi N, Blouw J, Böttcher H, Borissov A, Brack J, Brauksiepe S, Braun B, Bray B, Brons S, Brückner W and Brüll A 1998 *Phys. Rev. Lett.* **81**(25) 5519–5523

[72] Aubert J J *et al.* (European Muon) 1983 *Phys. Lett.* **B123** 275

[73] Geesaman D F, Saito K and Thomas A W 1995 *Ann. Rev. Nucl. Part. Sci.* **45** 337–390

[74] Kulagin S A and Petti R 2006 *Nucl. Phys.* **A765** 126–187 (*Preprint* `hep-ph/0412425`)

[75] Berger E L, Coester F and Wiringa R B 1984 *Phys. Rev.* **D29** 398

[76] Berger E L, Coester F and Wiringa R B 1984 *Phys. Rev. D* **29**(3) 398–411

[77] Coester F 2001 private communication

[78] Bordalo P *et al.* (NA10) 1987 *Phys. Lett.* **B193** 368

[79] Bordalo P *et al.* (NA10) 1987 *Phys. Lett.* **B193** 373

[80] Carlson J and Schiavilla R 1998 *Rev. Mod. Phys.* **70** 743–842

[81] Jung H and Miller G A 1990 *Phys. Rev.* **C41** 659–664

[82] Brown G E and Rho M 1995 *Nucl. Phys.* **A590** 527c–530c

[83] Dieperink A E L and Korpa C L 1997 *Phys. Rev.* **C55** 2665–2674 (*Preprint* `nucl-th/9703025`)

[84] Smith J R and Miller G A 2003 *Phys. Rev. Lett.* **91** 212301 (*Preprint* `nucl-th/0308048`)

[85] Kuhlmann S *et al.* 2000 *Phys. Lett.* **B476** 291–296 (*Preprint* `hep-ph/9912283`)

[86] Farrar G R and Jackson D R 1975 *Phys. Rev. Lett.* **35**(21) 1416–1419

[87] Ji X d, Ma J P and Yuan F 2005 *Phys. Lett.* **B610** 247–252 (*Preprint* `hep-ph/0411382`)

[88] Brodsky S J, Burkardt M and Schmidt I 1995 *Nucl. Phys.* **B441** 197–214 (*Preprint* `hep-ph/9401328`)

[89] Hecht M B, Roberts C D and Schmidt S M 2001 *Phys. Rev. C* **63**(2) 025213

[90] Drell S D and Yan T M 1970 *Phys. Rev. Lett.* **24**(4) 181–186

[91] West G B 1970 *Phys. Rev. Lett.* **24**(21) 1206–1209

[92] Melnitchouk W 2003 *Eur. Phys. J.* **A17** 223–234 (*Preprint* `hep-ph/0208258`)

[93] Shigetani T, Suzuki K and Toki H 1993 *Phys. Lett.* **B308** 383–388 (*Preprint* `hep-ph/9402286`)

[94] Davidson R M and Ruiz Arriola E 1995 *Phys. Lett.* **B348** 163–169

[95] Weigel H, Ruiz Arriola E and Gamberg L P 1999 *Nucl. Phys.* **B560** 383–427 (*Preprint* `hep-ph/9905329`)

[96] Bentz W, Hama T, Matsuki T and Yazaki K 1999 *Nucl. Phys.* **A651** 143–173 (*Preprint* `hep-ph/9901377`)

[97] Wijesooriya K, Reimer P E and Holt R J 2005 *Phys. Rev.* **C72** 065203 (*Preprint* `nucl-ex/0509012`)

[98] Collins J C and Soper D E 1977 *Phys. Rev. D* **16**(7) 2219–2225

[99] Gottfried K and Jackson J D 1964 *Nuovo Cim.* **33** 309–330

[100] Lam C S and Tung W K 1980 *Phys. Rev. D* **21**(9) 2712–2715

[101] Callan C G and Gross D J 1969 *Phys. Rev. Lett.* **22**(4) 156–159

[102] Boer D and Vogelsang W 2006 *Phys. Rev.* **D74** 014004 (*Preprint* `hep-ph/0604177`)

[103] Zhu L Y *et al.* (FNAL-E866/NuSea) 2006 (*Preprint* `hep-ex/0609005`)

[104] Brandenburg A, Nachtmann O and Mirkes E 1993 *Z. Phys.* **C60** 697–710

[105] Boer D 1999 *Phys. Rev. D* **60**(1) 014012

[106] Boer D and Mulders P J 1998 *Phys. Rev. D* **57**(9) 5780–5786

[107] Collins J C 1993 *Nucl. Phys.* **B396** 161–182 (*Preprint* `hep-ph/9208213`)

[108] Lu Z and Ma B Q 2005 *Phys. Lett.* **B615** 200–206 (*Preprint* `hep-ph/0504184`)

[109] Close F E and Sivers D 1977 *Phys. Rev. Lett.* **39**(18) 1116–1120

[110] Ralston J P and Soper D E 1979 *Nucl. Phys.* **B152** 109

[111] Gutbrod H H, Augustin I, Eickhoff H, Gross K D, Henning W F, Krmer D and Walter G, eds 2006 *FAIR Baseline Technical Report*

[112] 2006 Future science at the relativistic heavy ion collider Tech. Rep. BNL-77334-2006-IR Brookhaven National Laboratory http://www.bnl.gov/physics/rhicIIscience

[113] Perdekamp M G 2006 in *2nd Workshop on the QCD Structure of the Nucleon (QCDN06)* http://www.lnf.infn.it/conference/qcdn06

[114] Mulders P J and Tangerman R D 1996 *Nucl. Phys.* **B461** 197–237 (*Preprint* `hep-ph/9510301`)

[115] Jaffe R L and Ji X 1991 *Phys. Rev. Lett.* **67**(5) 552–555

[116] Barone V and Ratcliffe P G 2003 *Transverse spin physics* (World Scientific)

[117] Barone V, Drago A and Ratcliffe P G 2002 *Phys. Rept.* **359** 1–168 (*Preprint* `hep-ph/0104283`)

[118] Jaffe R L and Ji X D 1992 *Nucl. Phys.* **B375** 527–560

[119] Sivers D 1990 *Phys. Rev. D* **41**(1) 83–90

[120] Sivers D 1991 *Phys. Rev. D* **43**(1) 261–263

[121] Bravar A, Adams D L, Akchurin N, Belikov N I, Bonner B E, Bystricky J, Corcoran M D, Cossairt J D, Cranshaw J, Derevschikov A A, En'yo H, Funahashi H, Goto Y, Grachov O A, Grosnick D P, Hill D A, Iijima T, Imai K, Itow Y, Iwatani K, Kharlov Y V, Kuroda K, Laghai M, Lehar F, de Lesquen A, Lopiano D and Luehring F C 1996 *Phys. Rev. Lett.* **77**(13) 2626–2629

[122] Kane G L, Pumplin J and Repko W 1978 *Phys. Rev. Lett.* **41**(25) 1689–1692

[123] Collins J C 2002 *Phys. Lett.* **B536** 43–48 (*Preprint* `hep-ph/0204004`)

[124] Brodsky S J, Hwang D S and Schmidt I 2002 *Phys. Lett.* **B530** 99–107 (*Preprint* `hep-ph/0201296`)

[125] Efremov A V and Teryaev O V 1985 *Phys. Lett.* **B150** 383

[126] Qiu J and Sterman G 1991 *Phys. Rev. Lett.* **67**(17) 2264–2267

[127] Ji X, Qiu J W, Vogelsang W and Yuan F 2006 *Phys. Lett.* **B638** 178–186 (*Preprint* `hep-ph/0604128`)

[128] Ji X, Qiu J W, Vogelsang W and Yuan F 2006 *Phys. Rev.* **D73** 094017 (*Preprint* `hep-ph/0604023`)

[129] Airapetian A *et al.* (HERMES) 2005 *Phys. Rev. Lett.* **94** 012002 (*Preprint* `hep-ex/0408013`)

[130] Anselmino M *et al.* 2005 *Phys. Rev.* **D72** 094007 (*Preprint* `hep-ph/0507181`)

[131] Vogelsang W and Yuan F 2005 *Phys. Rev.* **D72** 054028 (*Preprint* `hep-ph/0507266`)

[132] Alexakhin V Y *et al.* (COMPASS) 2005 *Phys. Rev. Lett.* **94** 202002 (*Preprint* `hep-ex/0503002`)

[133] Collins J C *et al.* 2006 *Phys. Rev.* **D73** 094023 (*Preprint* `hep-ph/0511272`)

[134] Ashman J *et al.* (European Muon) 1988 *Phys. Lett.* **B206** 364

[135] Ashman J *et al.* (European Muon) 1989 *Nucl. Phys.* **B328** 1

[136] Adeva B, Akdogan T, Arik E, Badelek B, Bardin G, Baum G, Berglund P, Betev L, Birsa R, de Botton N, Bradamante F, Bravar A, Bressan A, Bültmann S, Burtin E, Cavata C, Crabb D, Cranshaw J, Çuhadai T, Dalla Torre S, van Dantzig R, Derro B, Deshpande A, Dhawan S, Dulya C, Eichblatt S and Fasching D 1998 *Phys. Rev. D* **58**(11) 112002

[137] Airapetian A *et al.* (HERMES) 2005 *Phys. Rev.* **D71** 032004 (*Preprint* `hep-ex/0412027`)

[138] Dressler B, Goeke K, Schweitzer P, Weiss C and Polyakov M V 2000 *Prog. Part. Nucl. Phys.* **44** 293–303

[139] Dressler B, Goeke K, Polyakov M V and Weiss C 2000 *Eur. Phys. J.* **C14** 147–157 (*Preprint* `hep-ph/9909541`)

[140] Dressler B *et al.* 2001 *Eur. Phys. J.* **C18** 719–722 (*Preprint* `hep-ph/9910464`)