IL NUOVO CIMENTO Vol. 35 C, N. 2 Marzo-Aprile 2012
DOI 10.1393/ncc/i2012-11204-y

Colloquia: Transversity 2011

Probing transverse-momentum distributions with the Drell-Yan process

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ricevuto il 20 Gennaio 2012; approvato il 30 Gennaio 2012

Summary. — The Drell-Yan process offers access, complementary to deep inelastic scattering (DIS) to the transverse-momentum distributions of the quarks within a hadron. When neither the beam nor the target are polarized, the angular distributions of Drell-Yan scattering provide access to the $h_1^\perp$, Boer-Mulders, distribution. With the addition of either a polarized beam or target, other transverse-momentum distributions (TMDs) can be accessed, in particular the Sivers' distribution, $f_1^\perp$. Existing Boer-Mulders and planned Sivers' Drell-Yan measurements of these distributions are discussed.

PACS `14.20.Dh` – Protons and neutrons.
PACS `24.85.+p` – Quarks, gluons, and QCD in nuclear reactions.
PACS `13.88.+e` – Polarization in interactions and scattering.
PACS `13.85.Qk` – Inclusive production with identified leptons, photons, or other nonhadronic particles.

The Drell-Yan process to leading order in the strong coupling constant, α_s, is the annihilation into a massive virtual photon of a quark in one hadron with an antiquark in another. The virtual photon then decays into a lepton-antilepton pair (dilepton) that is detected. This process was first observed by J. H. Christenson *et al.* [1, 2] in 1970 at the Brookhaven National Laboratory using a 29 GeV proton beam on a uranium target. The features of the observed cross-section were explained in the same year by S. D. Drell and T.-M. Yan [3, 4] in terms of the (then very new) parton model. In addition to explaining the drop in cross-section of over seven orders of magnitude as a function of the dilepton's invariant mass, the model of Drell and Yan predicted the observed angular distribution of $1 + \cos^2\theta$.

To leading order in α_s the Drell-Yan cross-section can be expressed as

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x_1\mathrm{d}x_2} = \frac{4\pi\alpha_e^2}{sx_1x_2}\sum_{q\in\{u,d,s,\dots\}} e_q^2\left[\bar{q}_1(x_1)q_2(x_2) + q_1(x_1)\bar{q}_2(x_2)\right], \tag{1}$$

where $x_{1(2)}$ represent x_{Bj}, the fractional momentum carried by the interacting beam (target) quark; $q_i(x_i)$ is the parton distribution of quark of flavor q; e_q is the charge of quark flavor q; s is the center-of-mass energy squared; $\alpha_e \approx 1/137$ is the fine structure constant; and the sum is over all quark flavors. Of course next-to-leading-order terms in α_s can contribute up to half of the observed cross-section and cannot be neglected.

One can make several interesting observations based on eq. (1). The annihilation of a u-quark with a $\bar{u}$-antiquark is enhanced by a factor of four relative to the d-$\bar{d}$ annihilation because of the charge-squared weighting. For example, with a π^- beam, containing a valence anti-up quark, on a proton target, such as at the COMPASS experiment [5] the cross-section is dominated by the annihilation of the pion's anti-up quark with the target's up quarks. Similarity, with an antiproton beam such as at GSI-FAIR [6], the cross-section is also dominated by the annihilation of a valence anti-up quark with a valence up quark. In addition, the spectrometer configuration is important. In a typical dipole-based fixed-target spectrometer such as the E-906/SeaQuest spectrometer [7], the acceptance is decidedly skewed toward large Feynman-x ($x_F = x_1 - x_2$). In a proton-proton or proton-neutron collision, this, when combined with the steeply falling sea quark distributions, produces a situation favoring the detection of events in which the quark is likely to come from the beam hadron and the antiquark from the sea of the target. When comparing current and proposed Drell-Yan experiments, it is important to remember that the different sensitivity can be very complementary.

1. – Unpolarized Drell-Yan, the Lam-Tung relation and the Boer-Mulders distribution

The Boer-Mulders distribution, denoted $h_1^\perp(x_{\mathrm{Bj}}, k_T, Q^2)$, represents the transverse polarization of quarks within an unpolarized nucleus [8]. The Boer-Mulders distribution vanishes when integrated over the transverse momentum of the interacting parton, k_T, and is naively T-odd. The existence of such a distribution that was non-zero was initially suggested to explain both single spin asymmetries in $pp^\uparrow$ scattering [9] and a large $\cos 2\phi$ dependence observed in Drell-Yan scattering [10, 11].

While the dominant term in the Drell-Yan angular distribution is $1 + \cos^2\theta$, a more general expression was derived by John Collins and Davison Soper [12]:

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

Then, in analogy to the Collin-Gross relation [13], Wu-Ki Tung and C. S. Lam derived a relation between the coefficients λ and ν [14, 15]:

$$1 - \lambda = 2\nu, \tag{3}$$

known as the Lam-Tung relation. The Lam-Tung relation has been shown to be largely unaffected by QCD corrections [15] and even resummation effects [16]. Despite its theoretical robustness, however, angular distribution measurements from π^--tungsten Drell-Yan at CERN (NA10) [11,10] and Fermilab [17] show a violation of the Lam-Tung relation at large virtual photon transverse momentum, p_T, with the size of the violation increasing as p_T increases. From examination of the data, it is clear that this violation comes almost entirely from the increase in the ν term of eq. (2), shown in fig. 1. In addition to the Boer-Mulders $h_1^\perp$ distribution mentioned earlier, several other explanations have been

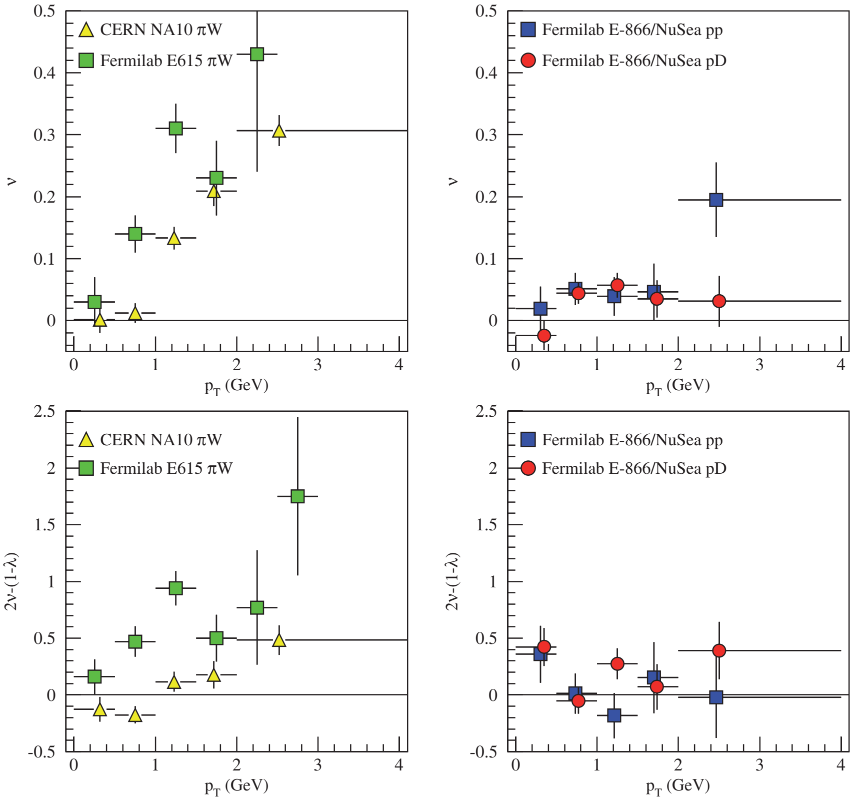

Fig. 1. – The coefficient ν for the NA10 π^-W [11, 10] (top left) and for the E-866/NuSea *pp* [23] and *pd* [24] (top right) Drell-Yan scattering. Note that in the pion case, ν grows with increasing p_T while in the proton-induced data, ν is relatively flat, with the exception of the highest p_T point for the proton-proton dataset. The corresponding violation of the Lam-Tung relation is shown for π^-W (bottom left) and *pp* and *pd* (bottom right) Drell-Yan scattering.

proposed for these observations. These include QCD factorization breaking [18, 19] and contributions from higher terms in the twist expansion [20-22]. Nuclear effects were also considered, but these were not seen in the NA10 data, although, with limited statistical precision.

More recently, the Fermilab E-866/NuSea experiment observed no such violation of the Lam-Tung relation in proton-proton [23] and proton-deuterium [24] Drell-Yan. While on the surface, these two observations seem inconsistent, there is an important difference between pion- and proton-induced Drell-Yan. In the π^- measurements there is a *valence* anti-u quark in the π^- making the dominate annihilation $\bar{u}u$, and thus probing the *valence* u-quark distributions in the target nucleon. In the proton-induced case, where the spectrometer acceptance dictates large x_F, the valence quark comes predominantly from the beam-proton and the antiquark comes from the target. This convolution could be indicating that the sea-quark $h_1^\perp(x_{\mathrm{Bj}}, k_T, Q^2)$ is small, while at the same time, the pion data indicated that the valence distribution is large. It should be noted that while the data are consistent with the Boer-Mulders description, QCD effects are not ruled out [25]. More precise data for both pion- and proton-induced Drell-Yan at larger p_T

would help to resolve these questions. The prospects of obtaining more data in both the pion- and proton-induced cases from the COMPASS [5] and SeaQuest [7] experiments are discussed in sect. **3**. Both the pion and the proton data are shown in fig. 1.

2. – Polarized Drell-Yan and the Sivers' distribution

The Sivers' distribution, $f_1^{\perp}(x_{\mathrm{Bj}}, k_T, Q^2)$, is also a naively T-odd distribution which vanishes when integrated over k_T. This distribution represents the asymmetry in the unpolarized quark distributions in transversely polarized nucleons [26, 27]. Initially, it was argued that the Sivers' distribution must be identically zero [28]. The fact that this distribution was non-zero was first proposed by D. W. Sivers [27, 26] to explain the asymmetries observed in single spin experiments [29]. One very interesting property of the Sivers' distribution is that it is non-universal. More specifically, while the magnitude is universal, the sign of the Sivers' distribution is dependent on the process being used to measure it [30]. That is

$$f_1^{\perp}\big|_{\mathrm{SIDIS}} = -\, f_1^{\perp}\big|_{\mathrm{Drell\text{-}Yan}}\,. \tag{4}$$

This sign reversal is a fundamental prediction of the gauge structure of QCD.

Recently, the Sivers' distribution has been measured using semi-inclusive deep inelastic scattering (SIDIS) by both the HERMES [31] and by the COMPASS [32] collaborations. In the future, there are several planned SIDIS measurements which will take place at Thomas Jefferson National Accelerator Facility (JLab) [33-35]. It is important to note that the measurement of individual kinematic points with either SIDIS or Drell-Yan is not sufficient to make this comparison if the points are not at exactly the same kinematics because of QCD evolution. Rather, as much of the function as possible must be measured in both SIDIS and Drell-Yan to allow for evolution to common kinematics for the comparison [36].

3. – Anticipated Drell-Yan measurements

There are several measurements at various stages of planning, construction and data collection that will use the Drell-Yan process to explore the transverse structure of the proton. These include both polarized and unpolarized experiments. The Fermilab E-906/SeaQuest experiment expects to collect data in 2012-14 using a 120 GeV unpolarized proton beam on proton, deuterium and nuclear targets [7, 37]. The primary goals of this experiment are measurement of the longitudinal sea quarks distributions in the proton and their modification in a nuclear environment. In addition, the angular distributions measured in this experiment will also provide information on the Boer-Mulders distribution as mentioned in sect. **1**.

At Brookhaven National Laboratory, the $\mathrm{A_N}$DY experiment [38] has completed the first stage of a three-stage program, completing in 2013 the Drell-Yan program using polarized protons in RHIC. The experimental goal is to measure the sign of $f_1^{\perp}$ at one kinematic point, $\langle x_{\mathrm{F}}\rangle = 0.2$, $M > 4\,\mathrm{GeV}$ and $p_T < 2\,\mathrm{GeV}$. In addition, $\mathrm{A_N}$DY will be a demonstration of feasibility for the forward upgrades of STAR and PHENIX.

The COMPASS experiment will measure Drell-Yan scattering with a π^- beam on a polarized proton or deuterium targets to study the transversity distributions of the valence distributions in the target nucleon [5]. For the proton target, this will result in a measurement of the Boer-Mulders' distribution of the u-quarks. The initial phase of this program will be completed in 2014 and will measure several points covering roughly the same kinematics at their previous Sivers DIS measurements [39], providing a basis for comparison with these measurements. In addition, the angular distributions, averaged of target polarization, should provide better measurements of the Boer-Mulders' distribution and its behavior as a function of p_T.

There are two possible upgrades to the Fermilab E-906/SeaQuest experiment which would allow for singly or, when combined, even doubly polarized Drell-Yan measurements. A study has just been completed on the technical feasibility and cost of polarizing the Fermilab Main Injector [40]. The estimated cost is *very roughly* US$4M. The polarized beam could then be extracted to the existing E-906/SeaQuest apparatus [37], giving access to the valence quarks in a polarized proton. This plan would allow for a relatively complete measurement over a broad range in $x_{\rm Bj}$. As noted in the talk by Werner Vogelsang [36], to make a valid comparison of the relation of the Sivers' DIS and Drell-Yan distributions, it is necessary to know the distributions, rather than only a few, kinematically isolated points, especially if there is a node in the distribution or if there are substantial differences between the Drell-Yan and DIS kinematics. At the same time, it is possible to measure the Sivers' function for the sea quarks by using a polarized target with the existing E-906/SeaQuest apparatus [41].

4. – Conclusions

The Drell-Yan process offers access, complementary to deep inelastic scattering (DIS) to the transverse-momentum distributions of the quarks within a hadron. When *neither* the beam nor the target are polarized, the angular distributions of Drell-Yan Scattering provide access to the $h_1^{\perp}$, Boer-Mulders, distribution. The available data from pion- and proton-induced Drell-Yan scattering can be interpreted to say that the Boer-Mulders distribution for sea quarks is small, while for the valence distributions it is somewhat larger. This interpretation is clouded by the poor statistical precision of the data at large-x, but fortunately soon there should be more data available from COMPASS for pion-induced Drell-Yan and SeaQuest for proton-induced Drell-Yan. With the addition of either a polarized beam or target, other transverse-momentum distributions (TMDs) can be accessed, in particular the Sivers' distribution, $f_1^{\perp}$. While the Sivers' distribution has been measured in SIDIS, it has yet to be measured with Drell-Yan scattering. A fundamental prediction of the gauge nature of QCD is that this distribution will have opposite sign when measured with Drell-Yan scattering: $f_1^{\perp}|_{\rm SIDIS} = -f_1^{\perp}|_{\rm Drell\text{-}Yan}$. Several experiments will soon be collecting Drell-Yan data to test this prediction.

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This work is supported in part by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357.

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