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What can more Drell-Yan data tell us about QCD?

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Summary. — The Drell-Yan process may be used as a unique probe of the partonic structure of hadrons and of fundamental QCD interactions, providing complementary information to deep inelastic scattering (DIS) measurements. Drell-Yan provides the ability to distinguish between the quarks and antiquarks based on kinematics. Unpolarized Drell-Yan provides access to the longitudinal distributions *anti*-quarks in the proton. Angular distributions are sensitive to the $h_1^\perp$, Boer-Mulders, distribution. With the addition of polarization, other transverse momentum distributions (TMDs) can be accessed, including the Sivers' distribution, $f_{1T}^\perp$.

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.

1. – Introduction

To leading order in the strong coupling constant, α_s, the Drell-Yan process is the annihilation of a quark from one hadron with an antiquark from another hadron into a massive virtual photon. The virtual photon then decays into a lepton-antilepton pair (dilepton). This process was first observed by J.H. Christenson *et al.* [1,2] at Brookhaven National Laboratory using a proton beam on a uranium target. The features of the cross section were explained by S.D. Drell and T.-M. Yan [3,4] in terms of the (then very new) parton model as a hard scattering of point-like particles multiplied by a convolution of the parton distributions of the interacting hadrons:

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x_1\,\mathrm{d}x_2} = \frac{4\pi\alpha_e^2}{qsx_1x_2} \sum_{q\in\{u,d,s,\dots\}} e_q^2 \left[\bar{q}_1(x_1)q_2(x_2) + q_1(x_1)\bar{q}_2(x_2)\right], \tag{1}$$

where $x_{1(2)}$ represent Bjorken-x, x_{Bj}, the fractional momentum carried by the interacting beam (target) quark; $q_i(x_i)$ is the parton probability 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. The e_q^2 weighting of the parton distributions implies that the cross section is primarily sensitive to the u- and $\bar{u}$-quark distributions. In fixed target experiments, the subscript 1(2) refers to the beam (target) hadron. This expression is only leading order, and next-to-leading order (NLO) terms in α_s contribute up to half of the cross section.

In a typical fixed-target experiment, the acceptance is biased toward large Feynman-x, $x_\mathrm{F} = x_1 - x_2$, and thus the beam parton is generally a large x_Bj valence parton. For a proton beam this implies that the interaction is between a valence beam quark and a lower-x_Bj target *anti*-quark. For a π^- beam, the predominant annihilation is a $\bar{u}$-quark from the pion with a u-quark from the target. With these and other differences, the sensitivity from different beam and target combinations is very complementary.

2. – Unpolarized Drell-Yan and longitudinal parton distributions

Initially, it was believed that, at some very low energy scale, the proton could be described by empirically derived distributions of three valence quarks [5]; however, it soon became apparent that this approach disagreed with existing data [6]. Nevertheless, the assumption that the sea was flavor symmetric was maintained until measurements by NMC [7] of the Gottfried sum rule [8] showed otherwise. Because of its sensitivity to the anti-quarks, Martin suggested that a comparison of proton-proton to proton-deuterium Drell-Yan would be an excellent method to study this difference [9]. Using the approximations that the Drell-Yan cross section is dominated by u_beam and $\bar{u}_\mathrm{target}$ annihilations and that the proton and neutron are charge symmetric, the approximate sensitivity is:

$$\frac{\sigma^\mathrm{pd}}{2\sigma^\mathrm{pp}} \approx \frac{1}{2}\left(1 + \frac{\bar{d}}{\bar{u}}\right), \tag{2}$$

where $\sigma^{\mathrm{pp}(d)}$ is the proton (deuterium) cross section and $\bar{d}$ ($\bar{u}$) is the anitdown (antiup) quark distribution. This was seized upon by the CERN NA51 [10] and the Fermilab E-866/NuSea [11, 12] experiments, whose results are shown in fig. 1. The Fermilab NuSea data revealed a surprising trend in the flavor asymmetry—returning to unity as x_Bj increases—but with decreasing statistical precision at larger x_Bj. The Fermilab E-906/SeaQuest experiment will measure this ratio up to $x_\mathrm{target} \approx 0.45$. SeaQuest had an engineering run in spring 2012 and will start recording production data in 2013.

SeaQuest will also provide better data on the nuclear dependence of the sea quarks. The European Muon Collaboration (EMC) [17] discovered that parton distributions in free and bound nucleons are different. Almost all data on this effect is from DIS measurements. Sea quark nuclear effects may be entirely different, but a DIS experiment would less be sensitive to this. With Drell-Yan, no modifications to sea quark distributions were observed by Fermilab E-772 [14]. (See fig. 1.) Models of nuclear binding that explain the EMC effect rely on the exchange of virtual mesons [18]. Based on these models, significant enhancements of the antiquark distributions in nuclei were expected [15]. The lack of sea-quark nuclear effects prompted a number of new models [16]. For $x > 0.2$, the E-772 statistical uncertainties allow significant freedom for these models.

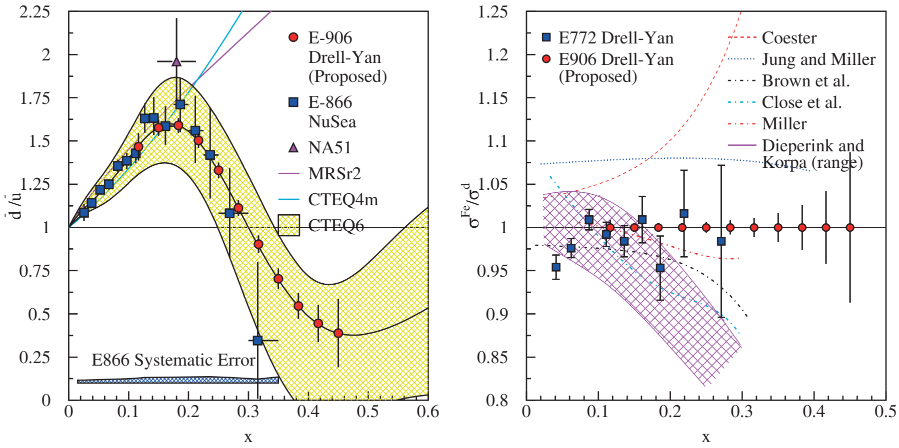

Fig. 1. – (Left) Measurements of $\bar{d}(x)/\bar{u}(x)$ by NuSea [11, 12] (blue squares) and NA51 [10] (green triangles) are shown. The curve shows $\bar{d}/\bar{u}$ from the CTEQ5M fit, which included the E-866/NuSea and NA10 data. The red circles represent the expected statistical precision of E-906/SeaQuest [13]. (Right) Ratio of iron to deuterium Drell-Yan cross sections (blue squares) [14] and the expected precision of SeaQuest (red circles). Curves based on several models are also plotted [15, 16].

3. – The Lam-Tung relation and Boer-Mulders distribution

The dominant term in the unpolarized Drell-Yan angular distribution is $1 + \cos^2\theta$, but a more general expression derived by John Collins and Davison Soper [19] is

$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi. \tag{3}$$

Wu-Ki Tung and C. S. Lam derived a relation between the coefficients λ and ν [20, 21]:

$$1 - \lambda = 2\nu. \tag{4}$$

The Lam-Tung relation is largely unaffected by QCD corrections [21] and resummation effects [22]. Despite its theoretical robustness, angular distribution measurements from π^--tungsten Drell-Yan at CERN (NA10) [23,24] and Fermilab E615 [25] show a violation of the Lam-Tung relation at large virtual photon transverse momentum, p_T. From the data, shown in fig. 2, it is clear that this violation comes from the ν term of eq. (3).

A non-zero Boer-Mulders distribution could explain these observations. The Boer-Mulders distribution, denoted $h_1^\perp(x_{\rm Bj}, k_T, Q^2)$, represents the transverse polarization of quarks within an unpolarized nucleus [26]. Both the Boer-Mulders and Sivers' (discussed in sect. **4**) distributions vanish when integrated over the transverse momentum of the interacting parton, k_T and are naively T-odd. The existence of such a distribution was initially suggested to explain both single spin asymmetries in $pp^\uparrow$ scattering [27] and a large $\cos 2\phi$ dependence observed in Drell-Yan scattering [24, 23]. In addition to the Boer-Mulders distribution, other explanations have been proposed, including QCD factorization breaking [28, 29] and contributions from higher terms in the twist expansion [30-32]. Nuclear effects were also considered, but were not seen in the NA10 data with limited statistical precision.

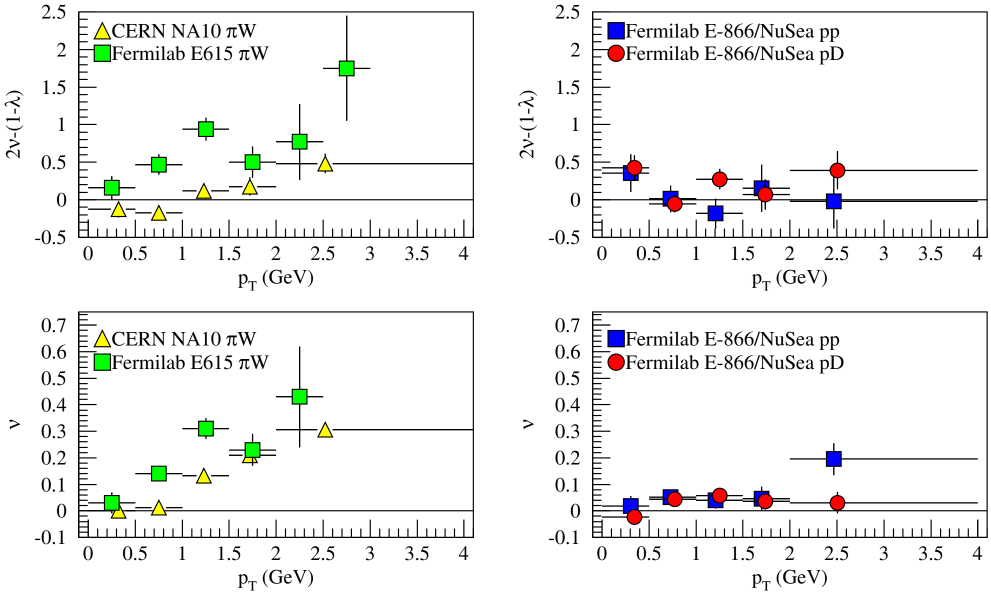

Fig. 2. – The violation of the Lam-Tung relation is shown for π^-W NA10 [23,24] and E-615 [25] (top left) and NuSea *pp* and *pd* (top right) [33, 34]. The corresponding coefficient ν for π^-W (bottom left) and *pp* and *pd* (bottom right) Drell-Yan scattering. In the pion case, ν grows with increasing p_T while in the proton-induced data, ν is relatively flat.

More recently, the Fermilab E-866/NuSea experiment observed no violation of the Lam-Tung relation in proton-proton [33] and proton-deuterium [34] Drell-Yan. This inconsistency may be explained by observing that in π^- measurements there is a *valence* anti-u quark in the π^- making the dominant annihilation $\bar{u}_\pi u_{\text{proton}}$, thus probing the *valence* u_{proton} 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 while the antiquark is from target. This convolution could be indicating that the sea-quark $h_1^\perp(x_{\text{Bj}}, k_T, Q^2)$ is small, while at the same time, the pion data indicated that the valence distribution is large. More precise data for both pion- and proton-induced Drell-Yan at larger p_T would help resolved these questions and may be available from the COMPASS [35] and SeaQuest [13] experiments in the near future. Both the pion and the proton data are shown in fig. 2.

4. – Polarized Drell-Yan and Sivers' Distribution

Sivers' distribution, $f_1^\perp(x_{\text{Bj}}, k_T, Q^2)$ represents the asymmetry of unpolarized quarks in transversely polarized nucleons [36,37]. D.W. Sivers [37,36] noted that if this distribution were non-zero, it could explain asymmetries observed in single spin experiments [38]. A fundamental prediction of the gauge structure of QCD and factorization is that the sign of Sivers' distribution is process dependent [39]:

$$f_1^\perp|_{\text{SIDIS}} = -\, f_1^\perp|_{\text{Drell-Yan}}\,. \tag{5}$$

Recently, Sivers' distribution has been measured using semi-inclusive deep inelastic scattering (SIDIS) by both HERMES [40] and COMPASS [41], and there are several planned SIDIS measurements that will take place at Thomas Jefferson National Accelerator Facility (JLab) [42]. The measurement of individual kinematic points with either SIDIS or Drell-Yan, however, 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 [43].

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 [35]. For the proton target, this will result in a measurement of Boer-Mulders' distribution of the u-quarks. The initial phase of this program will be completed in 2014 [44].

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 [45]. The estimated cost is *very roughly* US$10M. The polarized beam could then be extracted to the existing E-906/SeaQuest apparatus [46], giving access to the valence quarks over a broad range in x_{Bj}. In addition, it is possible to measure Sivers' function for the sea quarks by using a polarized target with the existing E-906/SeaQuest apparatus [47].

5. – Conclusions

The Drell-Yan process offers access, complementary to deep inelastic scattering (DIS) to the longitudinal and transverse momentum distributions of the quarks within a hadron. When *neither* the beam or target are polarized, the angular distributions of Drell-Yan Scattering provide access to the $h_1^\perp$, Boer-Mulders, distribution. Available data from pion- and proton-induced Drell-Yan may be interpreted to give a small Boer-Mulders distribution for sea quarks and a somewhat larger valence distributions, but more precise data are needed. With the addition of either a polarized beam or target, the Sivers' distribution, $f_1^\perp$ distribution can be accessed. While Sivers' distribution has been measured in SIDIS, it has yet to be measured with Drell-Yan as a test of the fundamental prediction of the gauge nature of QCD that $f_1^\perp|_{\mathrm{SIDIS}} = -f_1^\perp|_{\mathrm{Drell\text{-}Yan}}$. Several experiments will soon be collecting Drell-Yan data to test this prediction.

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