The Drell-Yan Process

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The Drell-Yan process, proposed over 45 years ago by Sid Drell and Tung-Mow Yan to describe high-mass lepton-pair production in hadron-hadron collision, has played an important role in validating QCD as the correct theory for strong interaction. This process has also become a powerful tool for probing the partonic structures of hadrons. The Drell-Yan mechanism has led to the discovery of new particles, and will continue to be an important tool to search for new physics. In this paper, we review some highlights and future prospects of the Drell-Yan process.

1 Introduction

In the late 1960s, massive lepton-pair production in hadron-hadron collision was proposed as a tool to search for intermediate vector bosons [1]. The first measurement of high-mass $\mu^+\mu^-$ pair production was reported by Christenson *et al.* in 1970, showing a rapid fall-off in cross section with increasing di-muon mass [2]. Sid Drell and Tung-Mow Yan proposed that the high-mass dileptons are produced via a process which now bears their names [3]. In this Drell-Yan process, as sketched in Fig. 1, a quark of momentum fraction x_1 from one hadron of momentum P_1 annihilates with an antiquark of momentum fraction x_2 from another hadron of momentum P_2 to form a virtual photon of momentum q with a large invariant mass, $Q = \sqrt{q^2} \gg 1/\text{fm}$, which subsequently decays into a pair of leptons (e^+e^- or $\mu^+\mu^-$). As an electromagnetic subprocess, the annihilation of quark and antiquark into the lepton-pair is exactly calculable. The hadronic cross section to produce the lepton-pair could be predicted *if* the probability distributions to find a quark or an antiquark of momentum fraction x in a colliding hadron of momentum P, often referred to as parton distribution functions (PDFs), are *known*, in the sense of being extracted or calculated independently.

Drell and Yan presented a list of predictions for the characteristics of massive dilepton production [3]. Some of these predictions, including the scaling behavior of the cross section, the angular distribution of the leptons, the linear dependence of the cross section on the mass number of the target nucleus, and the universality of the PDFs, were soon confirmed by experiments, see an early review in Ref. [4]. However, a number of significant departures from the predictions of the Drell-Yan model were also found, namely, the larger-than-expected cross sections, which were estimated by using the early naive parton model PDFs [5] extracted from the data of inclusive electron-proton and electron-neutron deep inelastic scattering (DIS) [6], by a factor of ~ 2 larger (known as the K-factor) [7]; and the larger-than-expected mean transverse momentum, which is of the order of GeV, rather than ~ 0.3 GeV [4].

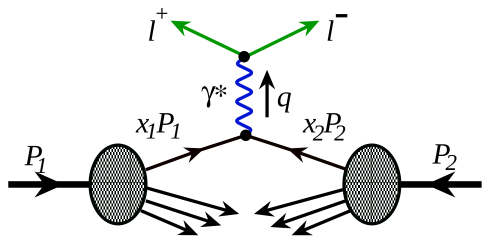

Fig. 1: Graphical sketch for the mechanism of massive lepton-pair production in hadron-hadron collisions, proposed by Drell and Yan [3].

The advent of the quantum chromodynamics (QCD) as the theory for strong interaction led to the QCD-improved Drell-Yan process, which includes quark (or antiquark)-gluon and gluon-gluon scattering subprocesses, going

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beyond the contribution from the pure electromagnetic quark-antiquark annihilation into the lepton-pair, proposed by Drell and Yan. These QCD-based corrections to the elementary subprocess readily account for the observed cross section enhancement, the K-factor, as well as providing a natural description of other observed features in hadronic dilepton production. The success of the Drell-Yan mechanism has played an important role in validating QCD as the correct theory for strong interaction.

However, the success of the Drell-Yan mechanism, and the concept to effectively factorize a hadronic cross section for producing a massive lepton-pair into a *calculable* partonic scattering subprocess convoluted with the *universal* PDFs to find the colliding quark(s) and gluon(s) inside the initial hadron(s), goes far beyond what Drell and Yan proposed over 45 years ago. This kind of factorization approach, similar to what was proposed by Drell and Yan, for hadronic cross sections with a large momentum transfer, $Q \gg 1/\text{fm}$, a characteristic hadronic scale, is now the foundation for studying high energy observables in hadronic collisions from fixed-target to collider energies, including those at the LHC.

With the validity of factorization for the hadronic cross sections, the precisely calculable partonic scattering subprocesses could play the role of the perturbatively controllable probes for exploring the internal structure as well as the dynamics inside the colliding hadrons. With the color confinement of strong force, the defining property of QCD, no modern detector could see quarks and gluons in isolation. Such controllable probes, able to access the QCD color interaction, is critically important for studying the confined motion, as well as spatial distributions, of quarks and gluons inside a color neutral hadron, to get necessary information for us to understand better the still "unsolved" mystery of the color confinement.

In addition, with different partonic scattering subprocesses, the Drell-Yan mechanism could be applied to the production of massive lepton pairs via various color neutral intermediate boson states, such as heavy quarkonia, $W^{\pm}$ and Z^0 gauge bosons, as well as Higgs boson H^0. The same factorized production mechanism, here, we refer it as the Drell-Yan process, could be a well-defined and controllable discovery channel for new, heavy, and unknown (beyond the Standard Model) color neutral particles.

In the rest of this article, we will briefly review the success of the Drell-Yan mechanism, and the physics reasoning for the validity of this mechanism beyond the dilepton production via a virtual photon. In the next section, we discuss the intuitive reasons in QCD why the Drell-Yan mechanism works, and so successfully. In Sec. 3, we review the success of the Drell-Yan process going beyond the original process proposed by Drell and Yan over 45 years ago. We also explore Drell-Yan process as a unique and controllable tool to probe the internal structure of hadrons in Sec. 4. Finally, we present our brief summary and outlook in Sec. 5. For reference, we list here several earlier review articles on the Drell-Yan process focussing on various topics [4, 8, 9, 10, 11, 12].

2 Drell-Yan Process and QCD

Hadrons (proton, neutron, pion, ...) are strongly interacting, relativistic bound states of quarks and gluons (in general, referred to as partons) in QCD. In hadronic collisions, even with a large momentum transfer, $Q \gg 1/\text{fm}$, every quarks and gluons of colliding hadrons could participate in the interactions, and the hadronic cross sections are in general non-perturbative, and not calculable in QCD perturbation theory. The original Drell-Yan mechanism, as sketched in Fig. 1, seems missing a lot of contributions to the cross sections from the multiple quark and gluon radiations and interactions from QCD dynamics. However, the success of the Drell-Yan mechanism, involving only the single quark-antiquark annihilation to a lepton pair, the lowest order partonic process in QCD, clearly indicates that it captures the very important contribution to the cross sections when the mass of the dilepton Q is much greater than the characteristic hadronic scale, $1/\text{fm} \sim \Lambda_{\text{QCD}}$.

The Drell-Yan mechanism effectively factorizes a physical hadronic cross section for the massive dilepton production in hadronic collisions, which is measurable and a classical probabilistic quantity, into a product (or more precisely, a convolution) of three "probabilities": a partonic hard part evaluated at the hard scale, Q, and two universal PDFs, which depend on the properties

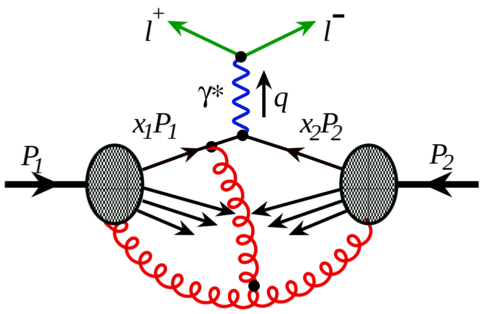

Fig. 2: Graphical sketch for the additional QCD contribution to the Drell-Yan mechanism involving soft gluon interactions between the colliding hadrons, as well as the active partons.

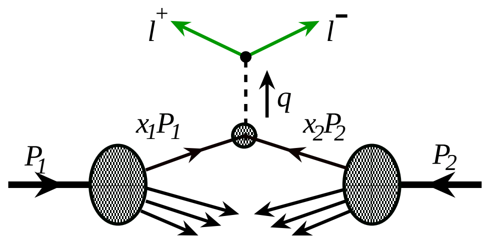

Fig. 3: Graphical sketch for the factorizable Drell-Yan process, where the active colliding parton could be a quark, an antiquark, or a gluon, and the produced color neutral intermediate boson could be a $W^\pm$ or Z^0 gauge boson, as well as a Higgs boson.

of the colliding hadrons, but, independent of the details of the local partonic hard part. The predictive power of this approach for the hadronic cross section relies on the validity of the factorization and the universality of the PDFs, which are non-trivial, especially, in hadronic collisions. As sketched in Fig. 2, any soft gluon interactions between colliding hadrons have the potential to alter the probability to find the colliding quarks and gluons, resulting in the breaking of the universality and the loss of the capability to make predictions.

With the large momentum transfer, Q, we could expand the differential Drell-Yan cross section, $d\sigma/dQ^2$, as $d\sigma^{(\mathrm{LP})}/dQ^2[1+\mathcal{O}(1/Q)^n]$ with the leading power (LP) contribution plus a power series of corrections. In general, every term of this expansion could depend on the physics and interaction at the hadronic scales, in addition to those taking place at the hard scale, as well as the quantum interference between these two scales. That is, like the total contribution to the measured cross section, every term of this expansion could be complicated and not calculable in QCD perturbation theory. However, when $Q \gg 1/\mathrm{fm}$, as an approximation, it has been proven [13] that the first term of this power expansion in $1/Q$ can be factorized into a product (or more precisely, a convolution) of a perturbatively calculable partonic scattering hard part, evaluated at the hard scale Q, and two non-perturbative and universal PDFs, as sketched in Fig. 3. The quantum interference between the dynamics taking place at the hard scale Q and those taking place at the hadronic scale $1/\mathrm{fm} \sim \Lambda_{\mathrm{QCD}}$ is power suppressed in terms of the ratio of these two scales, $(\Lambda_{\mathrm{QCD}}/Q)^n$. The proof of the factorization is valid beyond the production with an exchange of a virtual photon in Fig. 1, and actually, is valid for the production with the exchange of any color neutral massive boson, such as $W^\pm$ and Z^0 gauge boson. Therefore, in Fig. 3, the dashed line was used in the place of the virtual photon in Fig. 1. The sketch in Fig. 3 is a clear extension of the Drell-Yan mechanism shown in Fig. 1. More precisely, the Drell-Yan mechanism is equal to the leading order term in perturbative calculation of this QCD improved factorization picture in Fig. 3.

It was also demonstrated [14] that the first subleading term in this $(1/Q)^n$ power expansion of the contributions to the massive dilepton production in hadronic collisions could also be factorized into a product (or a convolution) of three factors: similar to the leading power case, a perturbatively calculable partonic hard part for the physics and dynamics taking place at the hard scale Q, and one nonperturbative but universal PDF, plus a nonperturbative and universal multiparton correlation functions (three-parton correlation functions for scattering involving a transversely polarized colliding hadron, and four-parton correlation functions for the collision of unpolarized or two longitudinally polarized colliding hadrons). These two situations correspond to the $n = 1, 2$ terms of the power expansion of Drell-Yan cross section, respectively. Actually, the factorization of the first subleading terms in this power expansion is also valid for a number of hard scattering processes, beyond the Drell-Yan process, such as the hadronic heavy quarkonium production at high transverse momentum p_T [15].

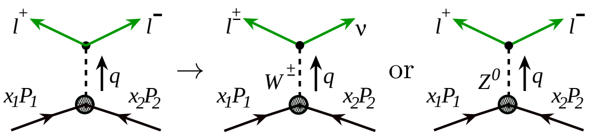

Fig. 4: Graphical sketch for the generalized partonic hard part of the Drell-Yan process, when the produced intermediate gauge boson is a $W^\pm$ or Z^0 gauge boson.

Through explicit calculations, it was shown [16] that the term beyond this first subleading term in the power expansion of Drell-Yan cross section was not factorizable. That is, it is very important to make sure that the power corrections are sufficiently small when we compare the data of Drell-Yan process with theoretical predictions based on the factorized formalism.

3 New Particles Produced by the Drell-Yan-like Process

As pointed out by Yan [17], one could generalize the definition of the Drell-Yan process to include the exchange of bosons other than the virtual photon, by replacing the hard partonic subprocess in Fig. 1 (or in Fig. 3) by those with an exchange of other virtual or heavy particles, such as $W^\pm$, Z^0, and Higgs H^0 boson, as well as any color neutral heavy particles beyond those in the Standard Model.

When the virtual photon in Fig. 1 is replaced by the weak interaction heavy gauge boson, like $W^\pm$ or Z, as sketched in the Fig. 4, Drell-Yan process was indeed the leading production mechanism for the discovery of $W^\pm$ and Z bosons by the UA1 [18] and UA2 [19] experiments. Because of the charge current nature of the $W^\pm$ production, the generalized Drell-Yan process for $W^\pm$ production provides the excellent source of information on the quark flavor separation, since the QCD subprocess in proton-proton and proton-antiproton collisions are flavor sensitive: $u\bar{d} \to W^+$, $d\bar{u} \to W^-$, and $q\bar{q} \to Z$ at the leading order. With the polarized proton beam, the spin asymmetries of $W^\pm$ production at RHIC provides the much needed information on the asymmetries of the polarized sea quarks in a polarized proton.

When the intermediate spin-1 gauge boson in Fig. 4 is replaced by the scalar Higgs boson, the generalized Drell-Yan process with the gluon-gluon fusion subprocess, $gg \to H$, as sketched in Fig. 5, was actually the leading discovery channel of the Higgs boson at the LHC [20, 21].

The detection of resonance structures in the dilepton mass spectra in proton-nucleus collisions led to the discovery of charm and beauty quarks [22, 23]. The leading order underlying production mechanism involves the annihilation of a light quark-antiquark pair or a pair of gluons into a $c\bar{c}$ or $b\bar{b}$ quark pairs, respectively. The heavy quark pairs then transmute into the heavy quarkonium bound states of corresponding flavors, which subsequently decay into a pair of charged leptons. The top quark was discovered in proton-antiproton collision [24, 25] where a light quark annihilates with a light antiquark into a pair of top and anti-top quarks. That is, the three heavy quarks, c, b, t, were all discovered in the Drell-Yan-like processes.

In addition to the Standard Model particles, the Drell-Yan process could also be an ideal channel for discovering color neutral, heavy new particles beyond the Standard Model. In particular, the dilepton final states are very sensitive to a wide variety of new phenomena predicted by some new models with the physics beyond the Standard Model. For instance, models with extended gauge particles would often allow additional $U(1)$ symmetries with new spin-1 Z' bosons. Sensitive searches for Z' produced in the Drell-Yan-like process are being carried out at LHC [26]. In the search for supersymmetric particles, events of opposite-sign dileptons resulting from the decays of neutralinos (e.g. $\tilde{\chi}_2^0 \to l^- l^+ \tilde{\chi}_1^0$) have been studied at the LHC [27].

While the Z boson could be regarded as a "heavy photon", there has been intense interest to search for the "dark photon", which is posited as a gauge boson in the dark matter sector. Through the mechanism of "kinetic mixing", the dark photon could couple to the Standard Model particles. In particular, in a Drell-Yan-like process, a dark photon instead of the ordinary virtual photon could be produced, resulting in a resonance peak in the detected dilepton mass spectrum [28]. Experiments to search for dark photon by using such a Drell-Yan-like process at a proton beam dump has been proposed [29].

The Drell-Yan process with its capability of

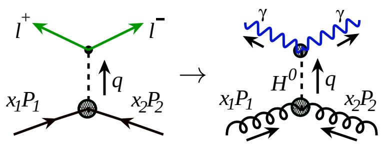

Fig. 5: Graphical sketch for the generalized partonic hard part of the Drell-Yan process, when the produced intermediate gauge boson is a Higgs boson.

applying it to the production of any color neutral states with a large invariant mass $Q \gg 1/\text{fm}$ provides a tremendous potential for the Drell-Yan process to be a well-controlled and precise discovery channel for new physics.

4 Hadron Structure Probed by the Drell-Yan Process

The proton and neutron, known as nucleons, are the fundamental building blocks of all atomic nuclei and make up essentially all the visible matter in the universe, including the stars, the planets, and us. The nucleons are not static but have a very complex internal structure, the dynamics of which are only beginning to be revealed in modern experiments. With the factorization, and our capability to control and improve the precision of the short-distance partonic hard part, the Drell-Yan process could be an excellent probe for exploring the internal structure of hadrons, complementary to the well-studied lepton-hadron deep inelastic scattering.

An important feature of the Drell-Yan process is that it is ideal for probing the antiquark contents in hadrons, since the Drell-Yan cross section is dominantly a convolution of the quark and antiquark density distributions of the two colliding hadrons. This is in striking contrast to the DIS, where the contributions from antiquarks are often overshadowed by those of the much more abundant quarks.

Another unique feature of the Drell-Yan process is that it can probe the partonic structures of pion, kaon, antiproton, and hyperons, which are not available as targets for performing the DIS experiments, but are available as hadron beams. Indeed, practically all information on the parton structures of pion, kaon, and antiproton has been obtained from the Drell-Yan process.

4.1 Sea-Quark Distributions in Nucleons and Nuclei

One of the predictions put forward by Drell and Yan in their paper [3] is that the high-mass dilepton cross section depends linearly on the mass number (A) of the target nucleus. This prediction was soon confirmed by the early experiments [4], albeit with limited statistics. The linear A dependence of the Drell-Yan cross section lends support to the idea that the partonic structure in nuclei is an incoherent sum of that in the nucleon, and that the produced dileptons traverse the nucleus with negligible final-state interactions. In 1983, the EMC Collaboration found that the DIS cross sections on iron target deviate significantly from the expectation of linear A dependence. This surprising finding, called "EMC effect", inspired much theoretical work [30]. A Drell-Yan experiment [10] with 800 GeV proton beam on nuclear targets, which is sensitive to the antiquark contents in the nuclei, was carried out to test the various models. Contrary to the prediction of the "pion-excess" model, where the mesons responsible for the nuclear binding can enhance the antiquark distributions in nuclei, no enhancement of antiquark content in nuclei was found [31]. A follow-up Drell-Yan measurement showed evidence of suppression of antiquark content at the small x region [32], suggesting the presence of nuclear shadowing effect. An on-going experiment at Fermilab will extend the measurement to larger values of x [33]. The partonic content of heavy nuclei is an important input for understanding relativistic nucleus-nucleus collsion at the RHIC and the LHC colliders. The latest parametrizations of the nuclear parton distribution functions [34, 35, 36, 37] all utilize the Drell-Yan data as a sensitive constraint for the antiquark distributions in heavy nuclei.

The sea quarks in the proton, dubbed wee-partons by Feynman [38], were assumed to be up-down flavor symmetric due to the nearly equal probability for gluon to split into a $u\bar{u}$ or a $d\bar{d}$ pair. This assumption was not based on any fundamental physics principles and required experimental verification. Indeed, early DIS data from SLAC indicated that this symmetry does not hold, prompting Field and Feynman [39] to suggest that the flavor-asymmetric valence quark

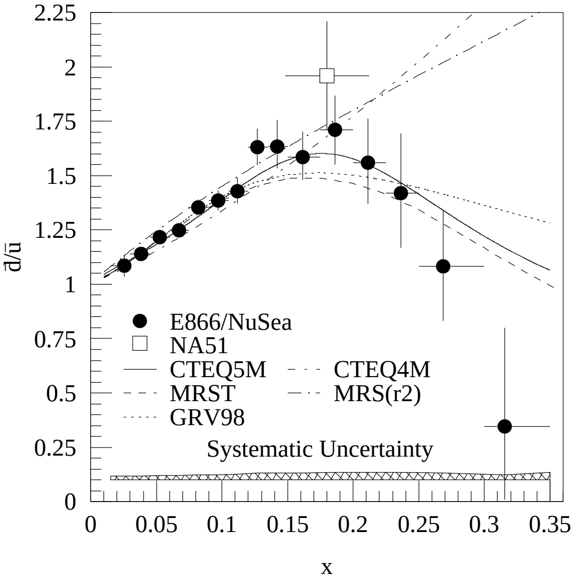

Fig. 6: $\bar{d}(x)/\bar{u}(x)$ versus x extracted from FNAL E866. Parametrizations from various PDFs and the data point from NA51 are also shown. From [42].

structure in the proton would inhibit the $g \to u\bar{u}$ process, leading to a $\bar{d} > \bar{u}$ asymmetry in the proton. The early SLAC data was later confirmed by a more precise DIS measurement at CERN [40].

Definitive observation of this surprisingly large flavor asymmetry was later reported by two Drell-Yan experiments at CERN [41] and Fermilab [42]. From a comparison of the Drell-Yan cross sections in proton-deuteron and proton-proton collision, the $\bar{d}/\bar{u}$ ratios can be extracted as a function of x, as shown in Fig. 6. The complementarity between the DIS and the Drell-Yan in probing the partonic structures in hadron is nicely illustrated here. While the DIS experiments first suggested the possible asymmetry between $\bar{u}$ and $\bar{d}$, the Drell-Yan experiments provide a precise determination of the momentum dependence of this flavor asymmetry.

Many theoretical models have been proposed to explain this striking flavor asymmetry, reviewed in [43, 44, 45, 46]. Most of these models considered the important role of meson cloud for nucleon's sea, first pointed out by Sullivan [47] and later applied to the $\bar{d}/\bar{u}$ asymmetry by Thomas [48]. This asymmetry was also utilized recently to extract the "intrinsic" light-quark sea content in the nucleons, and the result [49, 50] is in qualitative agreement with the model first suggested by Brodsky and collaborators [51].

An on-going Drell-Yan experiment at Fermilab, E906, aims at extending the measurement of $\bar{d}(x)/\bar{u}(x)$ over the region $0.25 < x < 0.5$ [33] to shed further light on the origin of this asymmetry. Using polarized proton beams at the RHIC collider, the STAR Collaboration succeeded to measure the polarization of the $\bar{u}$ and $\bar{d}$ quarks via the $W^{\pm}$ boson production [52]. As a generalized Drell-Yan process, the W^+ (W^-) production in polarized p−p collision is sensitive to $\bar{d}$ ($\bar{u}$) polarization. The first result from STAR shows $\Delta\bar{u}(x) > \Delta\bar{d}(x)$, showing that the flavor asymmetry extends to the sea-quark polarization as well. Finally, Drell-Yan experiments with kaon beams could explore the possible asymmetry between the $s(x)$ and $\bar{s}(x)$ distributions, predicted by kaon-cloud models. An RF-separated high-intensity kaon beam at CERN, required for carrying out such a measurement, is currently being considered.

4.2 Drell-Yan Process with Meson Beams

Although the Drell-Yan process was first discovered in dilepton production with proton beam, this process could also be explored utilizing other types of hadron beams. In particular, Drell-Yan experiments with meson beams have been studied at CERN and Fermilab since the late 1970s. Highlights of the results from these measurements can be found in Refs. [4, 8, 11]. As pions and kaons are spin-0 particles containing valence anti-quarks, they could provide information complementary to that obtained with the proton beam which only contains valence quarks. Moreover, the well known structure of the nucleons can be used to probe the poorly known meson structure, since the Drell-Yan cross section is a convolution of the parton distributions of the two interaction hadrons. As the mesons are not available as targets for the DIS experiments, the Drell-Yan process is a unique experimental tool to study the partonic structures of mesons.

The pion has played a central role in particle and nuclear physics. It is well known that pion is responsible for the long-range nuclear force. As discussed above, pion can even account for the flavor asymmetry of the nucleon sea observed in

DIS and Drell-Yan experiments. While pion is described as a quark-antiquark bound state in the constituent quark model, its small mass is attributed to dynamical chiral-symmetry breaking. Studying the internal structure of the pion is of great interest to undertand the dual roles of pion as the lightest meson and the Goldstone boson [53].

The Fermilab E615 Collaboration extracted the valence quark distribution of pion from the pion-induced Drell-Yan experiment [54]. The distribution was found to fall off linearly, $\sim (1-x)$, as x approaches 1. Although this is consistent with the expectations from constituent quark model and Nambu-Jona-Lasinio model, it is at variance with predictions based on perturbative QCD and Dyson-Schwinger equation. A subsequent analysis [55] taking into account the soft-gluon resummation, necessary at the large x region, found a $\sim (1-x)^2$ dependence, in good agreement with predictions of perturbative QCD and Dyson-Schwinger equation approach [56]. Kaon-induced Drell-Yan data with marginal statistics have also been collected by the NA3 Collaboration [57]. These data indicated that the valence strange quarks carry larger momentum than the lighter valence up quarks, in good agreement with calculation [58] based on Dyson-Schwinger equation. The proposal for an RF-separated high-intensity meson beam at CERN would significantly improve our knowledge on the internal structure of the two lightest mesons, pions and kaons, in the future.

One of the successes of the naive Drell-Yan model is the experimental confirmation of the prediction that the vitual photon is transversely polarized leading to a $1 + \cos^2\theta$ lepton angular distribution [17]. It was soon realized that a more general expression for the Drell-Yan angular distribution, taking into consideration the intrinsic transverse momentum of the interacting partons and the QCD processes, is given as

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

where θ and ϕ are the polar and azimuthal angles of the l^- in the dilepton rest frame. While $\lambda = 1, \mu = \nu = 0$ in the naive Drell-Yan model, the inclusion of QCD processes would introduce azimuthal asymmetry causing $\mu, \nu \neq 0$ and $\lambda \neq 1$. Howevere, it was pointed out by Lam and Tung that the deviation of λ from 1 will be compensated by the deviation of ν from zero, namely, $1 - \lambda = 2\nu$ [59]. This so-called "Lam-Tung" relation was tested in pion-induced Drell-Yan experiments at CERN [60] and Fermilab [54]. A surprisingly large violation of the Lam-Tung relation was observed, prompting many novel interpretations. In particular, Boer showed that the presence of a novel transverse-momentum dependent (TMD) structure function, called the Boer-Mulders function, can explain the violation of the Lam-Tung relation [61]. An interesting recent development is the measurements of the lepton angular distribution of Z-boson production in $p-p$ collision at the Large Hadron Collider [62]. The high-statistics LHC measurements clearly showed that the Lam-Tung relation is violated even at the large transverse momentum region (p_T up to $\sim$ 300 GeV) where the TMD effect is negligible. This violation of Lam-Tung relation was interpreted as evidence for high-order perturbative QCD effects [63]. It also suggests that perturbative QCD effect must be accounted for before reliable extraction of the Boer-Mulders function could be obtained [64].

4.3 The Drell-Yan Process with Longitudinally Polarized Beams

As the spin of the proton is 1/2, it has been a subject of great interest to understand how proton's spin is shared among its constituents, namely, quarks, antiquarks, and gluons, as well as their motion. The surprising finding from the polarized DIS experiment [65], showing that only a small fraction of proton's spin is carried by the spin of quarks and antiquarks, has led to global efforts to find the whereabout of the missing spin. The Drell-Yan process utilizing longitudinally polarized protons is ideal for determining the spin carried by antiquarks, as discussed in this section.

The surprisingly large $\bar{d}(x)/\bar{u}(x)$ asymmetry observed in the Drell-Yan experiments suggests that large flavor asymmetry could also exist for the polarized light-quark sea, namely, $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$. A powerful experimental tool to measure the sea-quark polarization is the hadronic W-boson production with only one colliding proton beam longitudinally polarized, taking advantage of the parity-violating weak interaction. At the negative rapidity region (opposite to the direction of the polarized proton beam), The parity-violating single-spin asymmetry, A_L, in proton-proton collision, with one longitudinally polarized proton beam, for W^+ and W^- production is directly sensitive to $\Delta\bar{d}(x)$ and $\Delta\bar{u}(x)$, respectively [66]. First measurement of A_L was reported by the STAR Collaboration [52], showing evidence for an asymmetric polarized $\bar{u}$ and $\bar{d}$ sea. It is interesting that the data suggested $\Delta\bar{u}(x) > \Delta\bar{d}(x)$, which is opposite to the asymmetry of the unpolarized sea, $\bar{d}(x) > \bar{u}(x)$. This result, if confirmed by further high-statistics data, can put stringent constraints on models describing the sea-quark polarization.

While the W boson production only requires one of the colliding protons to be polarized in order to access the sea-quark polarization, because of the parity violation of the weak interaction, a parity-conserving Drell-Yan process requires both colliding protons to be longitudinally polarized, and its leading contribution comes from the collision of a polarized quark from one proton colliding with a polarized antiquark from the other proton. A measurement of the Drell-Yan double-spin asymmetry, A_{LL}, could provide very valuable and complementary information on the quark and antiquark helicity distributions inside a polarized proton, but, has not yet been reported, although it is within the capability of the RHIC facility to pursue it in the future.

4.4 The Drell-Yan Process with Transversely Polarized Beams

In the last decades there have also been intense efforts to explore the various transverse spin and momentum dependent PDFs. Among them, much attention has been centered on the transversity and the Sivers function, both of which can be measured with the Drell-Yan process using transversely polarized protons. The correlation between the transverse spins of the colliding quark and its parent proton defines the "transversity" distribution, while the correlation between quark's transverse motion and the direction of the colliding proton's transverse spin leads to the Sivers function.

The chiral-odd transversity distribution cannot be measured in observables involving only one identified hadron, like DIS, but can be accessed in polarized Drell-Yan via the double-spin asymmetry, A_{TT} [67]. Of particular interest is the zeroth moment of the transversity distribution, known as the "tensor charge", which can be calculated in various theoretical models and in lattice QCD. A proposal to produce polarized antiproton beam at the FAIR facility [68] would allow the measurement of valence-quark transversity distribution via A_{TT} in $\bar{p}+p$ collision. Measurements of A_{TT} in polarized $p+p$ at RHIC can further pin down sea-quark transversity distributions.

The quantum correlation between the direction of hadron spin and the confined motion of quarks and gluons inside the polarized colliding proton is a fundamental property of QCD dynamics, and is encoded in the transverse momentum dependent PDFs of the polarized proton (or simply, TMDs). However, the typical transverse momentum of quarks and gluons inside a colliding proton is of the characteristic hadronic scale, much less than the momentum transfer of the hard collision. In order to access the information on the confined transverse motion of quarks and gluons, it is necessary to have physical observables sensitive to two very different momentum scales. The large scale is necessary for probing the particle nature of quarks and gluons, while the small scale provides the sensitivity needed to "see" the partons' transverse motion. With the large invariant mass of the produced lepton pair, and the naturally small net transverse momentum of the pair with respect to the direction of the two colliding hadrons, the Drell-Yan process in the collisions of transversely polarized proton(s) is an ideal observable to explore the TMDs and the correlation between the hadron property, such as the spin, and the confined partonic dynamics.

Unlike the collinear PDFs, the TMDs are not necessarily universal and could depend on the process they are extracted from. Fortunately, the process-dependence of TMDs is limited to a possible sign-change, due to the parity and time-reversal invariance of the strong interaction [69], preserving the predictive power of the QCD calculations. For example, the Sivers function extracted from the measurement of transverse single-spin asymmetry of semi-inclusive (SIDIS), A_N, is predicted to have the opposite sign from the Sivers function extracted from the A_N measurement of Drell-Yan type hard process, while keeping the same magnitude as well as functional dependence. This remarkable prediction remains to be tested by experiment. Since the sign and functional form of the valence-quark Sivers functions have recently been extracted from the SIDIS data, the test hinges on the measurements of valence-quark Sivers functions in the Drell-Yan process.

Recently, the STAR Collaboration at RHIC reported the first measurement of A_N of $W^{\pm}$ production in proton-proton collisions with one proton beam transversely polarized [70]. Although the RHIC result has large uncertainties, it is consistent with predictions incorporating the sign-change of Sivers function [71].. RHIC spin program has the plan to perform the additional measurements of A_N of the $W^{\pm}$ production in the coming RHIC runs, and new and more precise data should be extremely important for testing this sign change of the Sivers function.

A dedicated Drell-Yan experiment at COMPASS using 190 GeV pion beam and transversely polarized hydrogen target has taken first data in 2015 [72], and should be able to test this predicted sign change of the Sivers function at a momentum scale similar to what are measured in SIDIS. Since the scale of the momentum transfer involved in $W^{\pm}$ production is much larger than that in SIDIS, the nature of QCD evolution of the Sivers function becomes an important issue [73], which is under intensive theoretical investigation. The new data from RHIC, together with the COMPASS Drell-Yan data currently being analyzed, could provide very definite and important tests on the predicted sign-change of the Sivers function, as well as its QCD-evolution.

5 Conclusions

When the Drell-Yan process was first proposed in 1970, before QCD was even invented, it had the main goal of describing the mechanism of high-mass dilepton production in hadron-hadron collision. However, this seemingly simple factorization approach to describing the hard scattering processes in hadronic collisions has evolved over the years as a major arena for testing and understanding QCD, as a unique tool to reveal the internal structures of hadrons, and as a powerful method to find new particles and new physics. The "naive" Drell-Yan mechanism has indeed come a long way, and it will continue to lead to many important new findings in the future.

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