Drell-Yan Mechanism and Its Implications

Tung-Mow Yan*

Laboratory of Elementary Particle Physics, Cornell University, Ithaca, NY 14853, USA

The Drell-Yan mechanism is an important tool for discovering new fundamental constituents of nature. Thus, we begin this paper with a brief history of the search for discrete fundamental constituents of matter. It is followed by a quick summary of the quark model, deep inelastic electron scatterings and the parton model. The search for other processes to apply the parton model led to the investigation of lepton pair productions. Drell and I showed that the parton model is applicable to this process provided the pair production is through the annihilation of a parton from one hadron and an anti-parton from another hadron, and both the pair mass and the center of mass energy of the colliding hadrons are high. This is now known as Drell-Yan mechanism. We then give a general review of the developments of the Drell-Yan mechanism for the last forty years. Our presentation avoids too much details in formulations and focus on general picture. We conclude that this mechanism is an important tool for discovery of new physics.

1 Introduction

The Drell-Yan mechanism was proposed 46 years ago in 1970 [1]. This topic is still a very active area of research both theoretically and experimentally. The generalized Drell-Yan mechanism involves two colliding high energy hadrons with one constituent from one projectile and another one from the other projectile in a hard process. As we will show later, this mechanism has become an important tool for discovery of new quantum numbers or new particles. Thus, it is natural to trace the history of human endeavor of searching for the most fundamental constituents of matter. Since ancient times, the concepts of discrete building blocks for matter were suggested by philosophers first and pursued later by scientists. The word “atom” derives from a Greek word meaning indivisible. Our current understanding of the fundamental constituents of matter has been developed over several hundred years. Here we mention some of the major milestones:

(1) **The Periodic Table.** Dmitri Mendeleev [2] published in 1869 the first widely recognized periodic table. It showed that all the material we know are made of a finite number of elements. This number is about 100. All elements from atomic number 1 (hydrogen) to 118 (ununoctium) have been discovered or synthesized. The first 94 elements exist naturally.

(2) **The Electron.** J. J. Thomson discovered the electron in 1897 [3].

(3) **The Nucleus.** In 1909, Hans Geiger and Ernest Marsden [4] who were colleagues of Ernest Rutherford shot alpha particles at thin sheets of metal and measured their deflections. A small fraction of the alpha particles experienced heavy deflections. Rutherford concluded that the positive charge of the atom must be concentrated in a very tiny volume to produce an electric field intense enough to deflect the alpha particles so strongly. This led Rutherford [5] to propose a planetary model of an atom in which electrons orbit around a nucleus of positive charge. These positive charge particles are the protons.

(4) **The Neutron.** James Chadwick discovered the neutron in 1932 [6].

(5) **The Atom.** The three particles: the electron, the proton and the neutron, can account for all the known atoms in nature. A nucleus is composed of protons and neutrons, and electrons orbit the nucleus.

---

[*] Email: ty18@cornell.edu; this is a popular-science article.

(6) **The Quark Model.** Many new strongly interacting particles (hadrons) were discovered in the 1950s and 1960s. In an attempt to sort out the particle's spectrum, M. Gell-Mann [7] and Y. Ne'eman [8] showed that these particles can be fit into an octet (mesons and baryons) or a decuplet (hyperons) representation of a symmetry group called SU(3). A peculiar feature is that the simplest representation of the group, a triplet, was not realized in Nature. Later, Gell-Mann [9] and Zweig [10] independently discovered that if one proposes the existence of three spin $\frac{1}{2}$ fundamental particles, which Gell-Mann called quarks, then a meson can be treated as a bound state of a quark and an antiquark, and a baryon can be treated as a bound state of three quarks. To accomplish this feat, however, the fundamental constituents quarks must possess very strange properties: their electric charge must be fractional (1/3 or 2/3 of an electronic charge), and they must violate spin-statistics connection. Later, a new quantum number color [11] was proposed to resolve these difficulties. This was the birth of the quark model in 1964. However, it was not clear at the time of proposal whether these quarks were real and existed in Nature or just a mathematical construct for classification of hadrons.

2 Deep Inelastic Electron Scattering and the Parton Model

In 1968 SLAC [12] published results of the scattering process

$$e^- + N \to e^- + anything \qquad (1)$$

which is depicted in the Fig. 1.

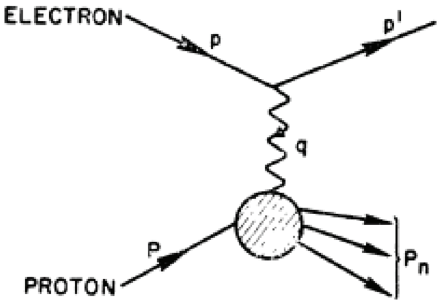

Fig. 1:

This is very similar to the Rutherford scattering discussed earlier. The key difference is that the target, a proton or neutron, is allowed to become any final state consistent with conservation laws. The results have two important features. The size of the cross sections is comparable with that for a point-like target; and the cross sections exhibit a scaling property known as Bjorken scaling (There are two structure functions for the e-N scattering and they depend on two Lorentz invariant kinematic variables . Bjorken scaling means that in large momentum transfers, these structure functions become a function of the ratio of the two variables). Both features were predicted before the experiments were carried out [13-14].

Feynman [15] and Bjorken [16] interpreted the Bjorken scaling as the point-like nature of the nucleon's constituents. In procees (1), they were incoherently scattered by the incident electron. Feynman named the point-like constituents partons. This is the parton model. Feyman left open the possibility that the partons need not be the quarks. However, theorists quickly identify the partons with quarks (in the late 1960s and early 1970s QCD did not exist, and so gluons did not enter the picture). A nucleon consists of three "valence" quarks which carry the nucleon's quantum numbers and a "sea" of quark-antiquark pairs. This identification led to many predictions for electron and neutrino (and antineutrino) scatterings from a nucleon [17]. The parton model accomplishes two things: First, Bjorken scaling follows naturally from the point-like constituents of the nucleon and the incoherent scattering from the incident electron; second, parton model identifies the structure functions as the fractional longitudinal momentum distribution functions of the nucleon, this interpretation gives a very physical meaning to otherwise mathematical objects.

3 Lepton Pair Production

In late 1960s Christenson et. al. [18] studied the reaction

$$p + U \to \mu^+\mu^- + X \qquad (2)$$

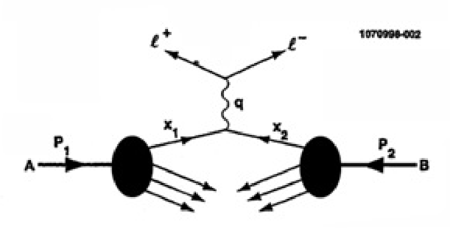

Fig. 2:

at BNL for proton energies 22-29 GeV, and the muon pair mass 1-6.7 GeV.

Drell and I got interested in this process in part because we would like to know if the parton model idea can be applied here. The key idea in our approach was the impulse approximation. First, we picked an appropriate infinite momentum frame to exploit the time dilation. In this frame, if we were able to establish that the time duration of the external probe τ_{probe} is much shorter than the lifetimes of the relevant intermediate states $\tau_{\text{int}.states}$, i.e.

$$\tau_{probe} \ll \tau_{\text{int}.states}, \tag{3}$$

Then the constituents could be treated as free during the interaction. Thus, the cross section in the impulse approximation is a product of the probability to find the particular parton configuration and the cross section for the free partons. Consider the lepton pair production from two initial hadrons

$$P_1 + P_2 \to \ell^+\ell^- + X \tag{4}$$

We recall that in the parton model for deep inelastic electron scattering, the point-like constituents of the proton are scattered incoherently by the incident electron. It is then reasonable to assume that the lepton pair in the above process is produced by the annihilation of one parton from one of the incident hadron and an antiparton from the second incident hadron.

The pair production by the parton-antiparton annihilation satisfies the criteria of impulse approximation [1] (see Fig. 2).

It is easily shown that the fractional longitudinal momenta of the annihilating partons satisfy

$$\tau = x_1 x_2 = \frac{Q^2}{s} \tag{5}$$

where Q^2 and s are, respectively, the pair mass squared and the square of the C.M. energy of the initial hadrons. The rapidity of the pair is given by

$$y = \frac{1}{2} \ln \frac{x_1}{x_2} \tag{6}$$

The predictions stated in our original paper [1] are

(1) The magnitude and shape of the cross section are determined by the parton and antiparton distributions measured in deep inelastic lepton scatterings;

$$\frac{d\sigma}{dQ^2 dy} = \frac{4\pi\alpha^2}{3Q^4}(\frac{1}{N_c})\Sigma_p x_1 fp(x_1) x_2 f\bar{p}(x_2) \tag{7}$$

where a color factor N_c is included in anticipating QCD;

(2) The cross section $Q^4 \frac{d\sigma}{dQ^2}$ depends only on the scaling variable $\tau = \frac{Q^2}{s}$;

(3) If a photon, pion, kaon, or antiproton is used as the projectile, its structure functions can be measured by lepton pair production [19]. This is the only way we know of to study the parton structure of a particle unavailable as a target for lepton scatterings;

(4) The transverse momentum of the pair should be small ($\sim$ 300-500 MeV);

(5) In the rest frame of the lepton pair, the angular distribution is $1 + \cos^2\theta$ with respect to the hadron collision axis, typical of the spin $\frac{1}{2}$ pair production from a transversely polarized virtual photon;

(6) The same model can be easily modified to account for W boson productions.

The lepton pair production considered here is the first example of a class of hard processes involving two initial hadrons. These processes are not dominated by short distances or light cone. So the standard analysis using operator product expansion is not applicable. But the parton model works. Soon after our work, Berman, Bjorken, and Kogut [20] applied similar ideas to large transverse momentum processes:

$$h_1 + h_2 \to h(largeP_T) + X \tag{8}$$

induced by deep inelastic electromagnetic interactions. At that time, it was believed that strong interactions severely suppressed large transverse momenta, therefore, electromagnetic interactions would quickly dominate the large transverse momentum processes. This was the precursor of the point-like gluon exchanges in QCD.

After the advent of QCD [21], the basic picture of lepton pair production has been confirmed theoretically and the details have been greatly improved [22]. It is no longer a model. That lepton pairs are produced by parton-antiparton annihilation is a consequence of QCD. In QCD, the partons are quarks, antiquarks, and gluons, and the number of color $N_c = 3$. The unique property of QCD being an asymptotically free gauge theory makes the parton model almost correct, namely for deep inelastic processes we have

$$\text{QCD=parton model + small corrections.} \tag{9}$$

In the modern language, the impulse approximation is replaced by the more precise concept of factorization which separate the long distance and short distance physics and the condition (3) now becomes

$$Q^2 \gg \Lambda_{QCD}^2 \tag{10}$$

where Λ_{QCD} is a typical momentum scale in QCD. The constituents are almost free leading to logarithmic corrections to the structure functions

$$f_i \Rightarrow f_i\left(x, \ln Q^2\right). \tag{11}$$

Factorization for the lepton pair production works in QCD, but in a more complicated manner and it has taken the hard work of many people and many years to establish [23,24]. The main complication arises from the new feature of initial and final state interactions between the hadrons [25]. The result is fairly simple to state

$$\begin{aligned} & \frac{d\sigma^{AB}}{dQ^2dy} \\ = & \sum_{a,b}\int_{X_A}^1 d\xi_A \int_{X_B}^1 d\xi_B \\ & f_{\frac{a}{A}}(\xi_A, Q^2) f_{\frac{b}{B}}(\xi_B, Q^2) H_{ab} \end{aligned} \tag{12}$$

where the sum over a and b are over parton species. The parton distribution functions are the same as those in deep inelastic lepton scatterings with the understanding that Q^2 is its absolute value. The function H_{ab} is the parton level hard scattering cross section computable in perturbative QCD and is often written as

$$H_{ab} = \frac{d\hat{\sigma}}{dQ^2dy} \tag{13}$$

Beside the logarithmic scaling violation, a large transverse momentum of the lepton pair can be produced by recoil of quarks or gluons. A simple dimensional analysis gives

$$< k_T^2 >= a + \alpha_s(Q^2)\alpha_s f(\tau, \alpha_s) \tag{14}$$

The constant a is related to the primordial or intrinsic transverse momentum of the partons.

The full angular distributions in both θ and ϕ depend on input quark and gluon densities and are rather complicated [26]. For small k_T the θ dependence is close to $1 + \cos^2\theta$. Recent data from the CMS Collaboration [27] has studied the angular distributions for k_T up to 300 GeV. Pronounced dependence on k_T of the angular distributions were found. The situation has been analyzed theoretically by Peng et al. [28].

Many of the predictions have been tested and confirmed by many experiments at Fermilab and CERN and elsewhere [29]. We will not go into the details. We will only point out that the model is so successful that its data have become an integral component of the global fit together with the deep inelastic lepton scatterings in determining the parton distributions inside a nucleon.

4 The Process as a Tool for New Discoveries

It seems natural to broaden the definition of Drell-Yan process to mean a class of high energy hadron-hadron collisions in which there is a subhard process involving one constituent from each of the two incident hadrons. New physics always manifests itself in production of new quantum numbers or new particle(s), and the ordinary particles do not carry the new quantum number of the new physics. To discover new physics in a hadron-hadron collider therefore requires annihilation of the ordinary particles to create these new particles. Thus, the Drell-Yan mechanism is an ideal tool for the new discoveries. Let us mention three important discoveries in the recent past which had employed this process to help:

(1) It was used to design the experiments at CERN that discovered the W and Z bosons [30].

(2) The process was also crucial in the discovery of the top quark at Fermilab [31].

(3) The discovery of the Higgs Boson at CERN in 2012 [32] was perhaps the most dramatic example of the utility of the process. The Higgs Boson is the last particle that appears in the Standard model to have been found.

5 Conclusions

Since the first experiment at BNL and the naïve model proposed to understand it, both experiments and theory have come a long way. It is interesting to note that our original crude fit [1] did not remotely resemble the data. We went ahead to publish our paper because of the model's simplicity and our belief that future experiments would be able to definitely confirm or demolish the model. It is gratifying to see that the successor of the naïve model , the QCD improved version, has been confirmed by the experiments carried out in the last forty years and more. Lepton pair production process has been an important and active theoretical arena to understand various theoretical issues such as infrared divergences, collinear divergences leading to the factorization theorem in QCD for hard processes involving two initial hadrons. The generalized Drell-Yan process has been so well understood theoretically that it has become a powerful tool for discovering new physics. We can expect to find new applications of this process in the future.

Acknowledgement

We thank Professor Jen-Chieh Peng and Professor Matthias Neubert for useful communications.

References

[1] S. D. Drell and Tung-Mow Yan, Phys. Rev. Lett. **25**, 316 (1970), and Ann. Phys. (N. Y.) **66**, 578 (1971).

[2] Dmitri Mendeleev, “Ueber die Beziehungen der Eigenschaften zu den Atomgewichten der Elemente”, Zeitschrift für Chemie. **12**, 405-406 (1869).

[3] J.J. Thomson, Philosophical Magazine **44** (269), 293 (1897).

[4] H. Geiger, Proceedings of the Royal Society **A83**, 492-504 (1910).

[5] Ernest Rutherford, Philosophical Magazine **21**(4), 669 (1911).

[6] James Chadwick, Nature **129** (3252), 312 (1932).

[7] M. Gell-Mann, California Institute of Technology Synchrotron Laboratory Report No. CTSL-20, (1961), unpublished.

[8] Y. Ne'eman, Nucl. Phys. **26**, 222 (1961).

[9] M. Gell-Mann, Phys. Lett. **8**, 214 (1964).

[10] G. Zweig, CERN preprints 401, 412 (1964), unpublished.

[11] O. W. Greenberg, Phys. Rev. Lett. **13**, 598 (1964), M. Y. Han and Y. Nambu, Phys. Rev. **139B**, 1006 (1965).

[12] W. Panofsky, in Proc. 14th Int. Conf. on High Energy Physics (Vienna) (ed. J. Prentki and J. Steinberger) CERN, Geneva, 1968.

[13] S. Adler, Phys. Rev. **143**, 1144 (1966), J. D. Bjorken, Phys. Rev. Lett. **16**, 408 (1966).

[14] J. D. Bjorken, Phys. Rev. **179**, 1547 (1969).

[15] R.P. Feynman, Phys. Rev. Lett. **23**, 1415 (1969).

[16] J. D. Bjorken and E. A. Paschos, Phys. Rev. **185**, 1975 (1969); these authors had worked on similar ideas independently of Feynman.

[17] see F. Close, An Introduction to Quarks and Partons, Academic Press (1979).

[18] J. H. Christenson, G. H. Hicks, L. Lederman, P. J. Limon, B. G. Pope, and Zavatini, Phys. Rev. Lett. **25**, 1523(1970), and Phys. Rev. **D8**, 2016 (1973).

[19] For a review of the status of pion structure functions measured by pion induced lepton pair production, see W. C. Chang and D. Dutta, Int. J. Mod. Phys. **E22**, 1330020 (2013), arXiv:1306.3971.

[20] S. Berman, J. Bjorken, and J. Kogut, Phys. Rev. **D4**, 3388 (1971).

[21] D. Gross and F. Wilczek, Phys. Rev. Lett. **30**, 1343 (1973); H. D. Politzer, Phys. Rev. Lett. **30**, 1346 (1973).

[22] There has been a vast amount of literature on QCD improved lepton pair production and related processes. Here we list two comprehensive reviews on theoretical and experimental status up to the mid 1990s , the reader can also consult the references cited therein: G.F. Sterman, *et al.*, Rev. Mod. Phys. **67**, 157 (1995); R. K. Ellis, W. J. Stirling and B. R. Weber, QCD and Collider Physics, Cambridge press (1996).

[23] J. C. Collins, D. E. Soper, and G. F. Sterman, Adv. Ser. Direct. High Energy Phys. **5**, 1 (1988), arXiv: hep-ph/0409313.

[24] J. C. Collins, Foundations of Perturbative QCD, Cambridge press (2011).

[25] For a most recent review on the subject of factorization and related topics see the rapporteur's talk by M. Neubert at LHCP 2014, Columbia University, New York, 2-7 June 2014: https://indico.cern.ch/event/279518/other-view?view=standard. Many references are cited therein.

[26] J. C. Collins and d. E. Soper, Phys. Rev. **D16**, 2219 (1977); C. S. Lam and W. K. Tung, Phys. Rev. **D18**, 2447 (1978 ibid. **D21**, 2712 (1980); E. L. Berger and S. J. Brodsky, Phys. Rev. Lett. **42**, 940 (1979).

[27] CMS Collaboration, V. Khachatryan, *et al.*, Phys. Lett. **B750**, 154 (2015).

[28] Jen-Chieh Peng, Wen-Chen Chang, Randall Evan McClellan, and Olg Teryaev, arXiv:1511.08932.

[29] For a review and analysis of the situation, see J. C. Peng and J. W. Qiu, Prog.Part. Nucl. Phys. **76**, 43 (2014), arXiv:1401.0934. See also Jen-Chieh Peng, The Universe **4**, no.1, 12 (2016) for more on probing hadron structure with Drell-Yan process.

[30] UA1 collaboration, G. Arnison, *et al.*, Phys. Lett. **B122**, 103 (1983); UA2 collaboration, G. Banner, *et al.*, Phys. Lett. **B122**, 476 (1983).

[31] CDF Collaboration, F. Abe, *et al.*, Phys. Rev. Lett. **74**, 2626 (1995); D0 Collaboration, S. Abachi, *et al.*, Phys. Rev. Lett. **74**, 2632 (1995).

[32] CMS Collaboration, Phys. Lett. **B716**,30 (2012); ATLAS Collaboration, Phys. Lett. **B716**, 1 (2012).