Drell-Yan Mechanism

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In this paper we present a brief history 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

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 [1] and Y. Ne'eman [2] 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 [3] and Zweig [4] 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 ($\frac{1}{3}$ or $\frac{2}{3}$ of an electronic charge), and they must violate spin-statistics connection. Later, a new quantum number color [5] was proposed to resolve these difficulties. This was the birth of the quark model in 1964.

In the mean time, after the success of QED in the late 1940s and 1950s, popularity of canonical quantum field theories was in decline due to the absence of a viable field theory for strong interactions. Instead, Gell-Mann [6] postulated that the equal time commutation relations derived from the spin $\frac{1}{2}$ quark fields for the vector and axial vector currents be exact whether the quarks exist or not and the underlying symmetry $SU(3) \times SU(3)$ is exact or not. These current algebras and in combination with PCAC (partially conserved axial current) [7] and soft pion theorems provide a framework for extracting dynamical information on strong and weak interactions. Initial applications focused on low energy phenomena. The first application of current algebra to high energy processes was made by S. Adler [8] who derived sum rules for high energy neutrino and anti-neutrino scatterings. At the time the prospect for neutrino scatterings was quite remote. J. Bjorken [9] obtained from these sum rules an inequality for high energy electron nucleon scatterings by an isospin rotation. The inequality showed that the cross sections for electron nucleon scatterings is of comparable size with that for a point-like target, and this could be tested by the ongoing SLAC-MIT experiment at SLAC.

In an attempt to understand the Adler's sum rules and Bjorken's inequality, Bjorken proposed that the structure functions that describe the cross-sections for the inelastic electron scatterings satisfy a scaling property known as Bjorken scaling [10]. There are two Lorentz invariant kinematic variables for the inelastic electron scatterings. The structure functions depend on these two variables. Bjorken scaling means that in the large momentum transfers, these structure

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functions become a function of the ratio of the two variables. Bjorken scaling was quickly confirmed by the experiments at SLAC [11]. Feynman [12] interpreted the Bjorken scaling as the point-like nature of the nucleon's constituents when 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 [13]. 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 partons inside the nucleon, this interpretation gives a very physical meaning to otherwise mathematical objects.

In the fall of 1968 soon after Feynman's parton model was proposed, Sidney Drell, Don Levy and I embarked on a comprehensive program [14, 15, 16, 17, 18] to understand and apply the parton model in a quantum field theory framework. This program has been recently reviewed by two of us [19]. We were also interested in the possibility of applying the parton model to other processes. At the time, a process came to our attention. Namely, the lepton pair production by proton-proton collision which was under study by Christenson, et al. [20] at BNL. Our investigation showed that the parton model is applicable if the lepton pair is produced by the annihilation of a parton from one proton and an anti-parton from another proton and both the center of mass energy of the two colliding protons and the lepton pair mass are sufficiently high. This is now known as Drell-Yan mechanism [21].

2 Lepton Pair Production

In late 1960s Christenson et al. [20] studied the reaction

$$p + U \to \mu^+\mu^- + X \tag{1}$$

at BNL for proton energies 22-29 GeV, and the muon pair mass 1-6.7 GeV. Two features of the data stand out: (1) the shoulder-like structure near the muon pair mass of 3GeV, and (2) the rapid fall-off of the cross section with the muon pair mass. We know now that the shoulder-like structure is due to the J/ψ resonance which was discovered in 1974 by a muon pair production experiment at BNL [22] and an e^+e^- colliding beam experiment at SLAC [23].

We got interested in the process (1) for two reasons: (1) we were looking for applications of the parrton model outside deep inelastic lepton scatterings, and (2) we wanted to understand if the rapid decrease of the cross section with the muon pair mass could be reconciled with the point-like cross sections observed in the deep inelastic electron scatterings.

The key idea in our approach was once again 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.

$$\tau_{probe} \ll \tau_{\text{int}.states}, \tag{2}$$

Then the constituents could be treated as free. 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. In the case of lepton pair production from two initial hadrons

$$P_1 + P_2 \to \ell^+\ell^- + X \tag{3}$$

The pair production by the parton-antiparton annihilation satisfies the criteria of impulse approximation [21] (see Fig. 1).

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

$$\tau = x_1 x_2 = \frac{Q^2}{s} \tag{4}$$

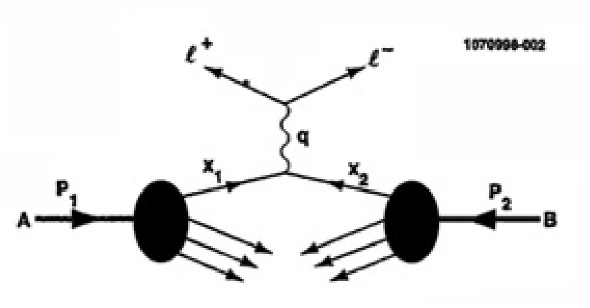

Fig. 1:

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

$$y = \frac{1}{2} \ln \frac{x_1}{x_2} \tag{5}$$

The predictions stated in our original paper [21] are

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

$$\frac{d\sigma}{dQ^2 dy} = \frac{4\pi\alpha^2}{3Q^4} (\frac{1}{N_c}) \sum_p x_1 fp(x_1) x_2 f\bar{p}(x_2) \tag{6}$$

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 [24]. 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.

In this model, the rapid decrease of the cross section with Q^2 as seen in (1) is related to the rapid fall-off of structure functions as $x \to 1$ in deep inelastic electron scatterings.

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 [25] applied similar ideas to large transverse momentum processes:

$$h_1 + h_2 \to h(large P_T) + X \tag{7}$$

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 [26], the basic picture of lepton pair production has been confirmed theoretically and the details have been greatly improved [27]. 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

$$\text{QCD} = \text{parton model} + \text{small corrections}. \tag{8}$$

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 (2) now becomes

$$Q^2 \gg \Lambda^2_{QCD}, \tag{9}$$

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

$$f_i \Rightarrow f_i(x, \ln Q^2). \tag{10}$$

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 [28, 29]. The main complication arises from the new feature of initial and final state interactions between the hadrons [30]. The result is fairly simple to state

$$\frac{d\sigma^{AB}}{dQ^2dy} = \sum_{a,b}\int_{X_A}^{1} d\xi_A \int_{X_B}^{1} d\xi_B f_{a/A}(\xi_A, Q^2) f_{b/B}(\xi_B, Q^2) H_{ab} \quad (11)$$

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

$$H_{ab} = \frac{d\hat{\sigma}}{dQ^2dy}. \quad (12)$$

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

$$< k_T^2 >= a + \alpha_s(Q^2)\alpha_s f(\tau, \alpha_s) \quad (13)$$

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 [31]. For small k_T the θ dependence is close to $1 + \cos^2\theta$. Recent data from the CMS Collaboration [32] has studied the angular distributions for k_T up to 300 GeV. Pronounced dependence on k_T of the angular distributions was found. The situation has been analyzed theoretically by Peng et al. [33].

Many of the predictions have been tested and confirmed by many experiments at Fermilab and CERN and elsewhere [34]. 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.

3 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 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 pat which had employed this process to help:

(1) It was used to design the experiments at CERN that discovered the W and Z bosons [35].

(2) The process was also crucial in the discovery of the top quark at Fermilab [36].

(3) The discovery of the Higgs Boson at CERN in 2012 [37] 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.

Recently, there have been reports from LHC [38] that there are tantalizing hints of a resonance at about 750 GeV. If future investigations confirm the existence of the new resonance, it may lead us to new physics. Theorists have proposed [39] that this possible resonance is produced by either gluon fusion or photon fusion, if true, this is again a Drell-Yan mechanism.

4 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 [21] 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 naive model, the QCD improved version, has been confirmed by the experiments carried out in the last forty years. 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 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.

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