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Lepton-pair production and the modified Drell-Yan mechanism in high-energy unpolarized and polarized pp and $\bar{p}p$ collisions*

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A modified Drell-Yan mechanism for inclusive dilepton pair production in hadronic reactions is studied, and the significance of comparing high-energy unpolarized and polarized pp and $\bar{p}p$ collisions is discussed. The required beams are currently proposed at Fermilab and CERN.

Drell and Yan[1] have suggested the application of the parton model[2,3] to the inclusive production of lepton pairs in hadron-hadron collisions. The process is closely related to deep-inelastic lepton-hadron scattering and to electron-positron pair annihilation into hadrons. A lepton pair is assumed to originate from a virtual photon, which couples to a pair of quasifree quark and antiquark partons. They have further assumed that the effect of the hadron-hadron collision on the distributions of partons is negligible, and that the process can be computed by using the parton distributions obtained in the deep-inelastic lepton-hadron scattering. Hereafter this assumption is called the second assumption of Drell and Yan. Various calculations[4-7] based on this model, including color, agree qualitatively with the experimental data for $M(1^+1^-) > 5$ GeV at an incident hadron momentum of several hundred GeV/c,[8,9] but underestimate the yield of lepton pairs in the smaller-dilepton-mass region, roughly by a factor of ten at $M(1^+1^-) = 2$ GeV. It is pointed out[10,11] that the second assumption of Drell and Yan probably needs to be modified in order to explain this discrepancy, while the first assumption should be valid in the smaller-dilepton-mass region because of the early Bjorken scaling[3] observed in deep-inelastic lepton-nucleon scattering processes and the behavior of the ratio R of electron-positron pair annihilation into hadrons. The purpose of this note is to investigate such a modified Drell-Yan mechanism in detail, and to study its implication and the significance of comparing the high-energy unpolarized pp and $\bar{p}p$ and polarized pp and $\bar{p}p$ collisions. The construction of the high-energy polarized p and $\bar{p}$ beams required in this study are currently proposed at Fermilab and CERN.

We assume that the hadron-hadron collision will produce many slow quark- and antiquark-parton pairs which will enhance slow sea-quark distributions considerably, but will not disturb the valence-quark distributions. In this modified Drell-Yan mechanism the sea-quark distributions become unknown factors, and the model loses its predictive power for pp collisions. However, we will see that if $\bar{p}p$ and pp collisions are properly combined, this model will predict testable results, and the comparison of polarized $\bar{p}p$ and pp collisions will further strengthen the predictions.

In this modified picture the inclusive cross section of pp collision for producing a lepton pair of mass Q and longitudinal momentum P, at very high center-of-mass energy $\sqrt{s}$, is

$$\left(\frac{d\sigma}{dQ^2dP}\right)^{pp} = (\tfrac{1}{3})^a \int dx_1 dx_2 \delta(Q^2 - x_1x_2 s) \times \delta\left(P - \frac{\sqrt{s}}{2}(x_1 - x_2)\right) C_{pp}\left(\frac{d\hat{\sigma}}{dQ^2dP}\right), \quad (1)$$

with

$$C_{pp} = \sum_i e_i^2\{[f_i^V(x_1) + g_i^S(x_1,s)]\bar{g}_i^S(x_2,s) + \bar{g}_i^S(x_1,s)[f_i^V(x_2) + g_i^S(x_2,s)]\}\ .$$

Here x_1 and x_2 are fractions of the incident longitudinal momenta carried by the partons i, e_i are their charges, and $f_i^V(x)$ and $g_i^S(x,s)$ are the densities of the valence- and the sea-quark partons, respectively. The function $f_i^S(x)$ will represent the density of the sea-quark partons before they have been disturbed by the hadronic interactions. The bar over the density functions denotes the densities of antiquarks. The normalization is such that, for electroproduction,

$$\nu W_2 = x\sum_i e_i^2[f_i^V(x) + f_i^S(x) + \bar{f}_i^S(x)]\ .$$

The factor $(\frac{1}{3})^a$ accounts for the possibility of color, and is

$$a = \begin{cases} 0 & \text{no colored quarks} \\ 1 & \text{colored quarks.} \end{cases}$$

The factor $(d\hat{\sigma}/dQ^2dP)$ is the cross section for a quark-antiquark pair to annihilate into a lepton pair of mass Q and longitudinal momentum P. We further assume

$$g_i^S(x,s)/f_i^S(x) \underset{x\to 1}{\longrightarrow} 1$$

to make the original Drell-Yan model consistent with the data for massive lepton pairs. In this modified mechanism the lepton pairs need to become more massive in order to agree with the original Drell-Yan mechanism as the center-of-mass energy increases.

The strong-interaction dynamics of high-energy $\bar{p}p$ collision is very similar to pp collision; for example, their total-cross-section difference vanishes as the center-of-mass energy increases. It is then natural to use the same effective sea-quark distributions in $\bar{p}p$ collisions as in pp collisions, and the factor $C_{\bar{p}p}$ becomes, with x_1 standing for $\bar{p}$ and x_2 for p,

$$C_{\bar{p}p}=\sum_i e_i{}^2\{[\bar{f}_i^V(x_1)+\bar{g}_i^S(x_1,s)][f_i^V(x_2)+g_i^S(x_2,s)] + g_i^S(x_1,s)\bar{g}_i^S(x_2,s)\} .$$

From particle-antiparticle symmetry $\bar{f}_i^V(x)=f_i^V(x)$, and $\bar{g}_i^S(x,s)=g_i^S(x,s)$ from the SU(3) properties of the sea. The subtraction of pp from $\bar{p}p$ leads to the relation

$$\left(\frac{d\sigma}{dQ^2dP}\right)^{\bar{p}p}-\left(\frac{d\sigma}{dQ^2dP}\right)^{pp} =(\tfrac{1}{3})^a\int dx_1dx_2\delta(Q^2-x_1x_2s)\delta\left(P-\frac{\sqrt{s}}{2}(x_1-x_2)\right) \times\frac{4\pi\alpha^2}{3Q^2}\sum_i e_i{}^2\bar{f}_i^V(x_1)f_i^V(x_2) , \qquad (2)$$

where $(d\hat{\sigma}/dQ^2dP)=4\pi\alpha^2/3Q^2$ is obtained by neglecting the mass squared of the leptons and the valence quarks compared to Q^2. We must note the different implications of Eq. (2) in the modified and in the original Drell-Yan mechanisms. In the original Drell-Yan mechanism the dilepton-mass region to apply Eq. (2) is the same as the region where the mechanism is applicable to pp collision itself, and we already know that the original mechanism underestimates the dilepton yield for $Q<5$ GeV. In the present modified Drell-Yan mechanism the application to pp (or $\bar{p}p$) collisions alone is not very meaningful, since the functions $g_i^S(x,s)$ are not known. However, Eq. (2) is expected to hold for $Q^2>2$ GeV^2, where the first assumption of Drell and Yan is applicable, considering the early Bjorken scaling observed in deep-inelastic lepton-nucleon scattering and the behavior of e^+e^- annihilation into hadrons. Therefore Eq. (2) in the region $Q^2>2$ GeV^2 will provide a very important test of the present modified Drell-Yan mechanism, since the density functions $f_i^V(x)$ are obtainable, in principle, from deep-inelastic lepton-nucleon scattering processes.

For the collision between two polarized protons, one with the spin $S_1=S$ and the other $S_2=\pm S$, Eq. (1) is replaced by

$$\left(\frac{d\sigma}{dQ^2dP\,d\phi}\right)^{pp}_{S_1S_2}=(\tfrac{1}{3})^a\int dx_1dx_2\delta(Q^2-x_1x_2s)\delta\left(P-\frac{\sqrt{s}}{2}(x_1-x_2)\right)\sum_{\lambda_1=\pm S_1}\sum_{\lambda_2=\pm S_2}C_{pp}(\lambda_1,\lambda_2;S_1,S_2)\left(\frac{d\hat{\sigma}}{dQ^2dP\,d\phi}\right)_{\lambda_1\lambda_2} \qquad (3)$$

Here ϕ is the angle between the spin-three vector $\vec{S}$ and the production plane of the dilepton pair, and it becomes redundant if $\vec{S}$ is along the longitudinal direction. The function $C_{pp}(\lambda_1\lambda_2;S_1S_2)$ is

$$C_{pp}(\lambda_1,\lambda_2;S_1,S_2)=\sum_i e_i{}^2\{[f_i^V(x_1,\lambda_1;S_1)+g_i^S(x_1,s,\lambda_1;S_1)]\bar{g}_i^S(x_2,s,\lambda_2;S_2) +\bar{g}_i^S(x_1,s,\lambda_1;S_1)[f_i^V(x_2,\lambda_2;S_2)+g_i^S(x_2,s,\lambda_2;S_2)]\} ,$$

where $f_i(x,\lambda;S)$ is the density of the ith quark parton with spin λ inside a proton of spin S, and so on. For the collision between a polarized $\bar{p}$ and a polarized p, $C_{\bar{p}p}(\lambda_1\lambda_2;S_1S_2)$ is

$$C_{\bar{p}p}(\lambda_1,\lambda_2;S_1,S_2)=\sum_i e_i{}^2\{[\bar{f}_i^V(x_1,\lambda_1;S_1)+\bar{g}_i^S(x_1,s,\lambda_1;s_1)][f_i^V(x_2,\lambda_2;S_2)+g_i^S(x_2,s,\lambda_2;S_2)] +g_i^S(x_1,s,\lambda_1;S_1)\bar{g}_i^S(x_2,s,\lambda_2;S_2)\} .$$

The subtraction of pp from $\bar{p}p$ leads to the relation

$$\left(\frac{d\sigma}{dQ^2dP\,d\phi}\right)^{\bar{p}p}_{S_1S_2}-\left(\frac{d\sigma}{dQ^2dP\,d\phi}\right)^{pp}_{S_1S_2}=(\tfrac{1}{3})^a\int dx_1dx_2\delta(Q^2-x_1x_2s)\delta\left(P-\frac{\sqrt{s}}{2}(x_1-x_2)\right) \times\sum_{\lambda_1=\pm S_1}\sum_{\lambda_2=\pm S_2}\left(\frac{d\hat{\sigma}}{dQ^2dP\,d\phi}\right)_{\lambda_1\lambda_2}\sum_i e_i{}^2\bar{f}_i^V(x_1,\lambda_1;S_1)f_i^V(x_2,\lambda_2;S_2) . \qquad (4)$$

The cross sections for a polarized quark-antiquark pair to annihilate into two leptons are

$$\left(\frac{d\hat{\sigma}}{dQ^2dP\,d\phi}\right)_{S_1S_2}=\frac{\alpha^2}{3Q^2}\begin{cases}(1+2\cos^2\phi), & S_1=S_2\\ (3-2\cos^2\phi), & S_1=-S_2\end{cases}$$

for transversely polarized quarks, and

$$\left(\frac{d\hat{\sigma}}{dQ^2dP\,d\phi}\right)_{S_1S_2}=\begin{cases}4\alpha^2/3Q^2, & S_1=S_2\\ 0, & S_1=-S_2\end{cases}$$

for longitudinally polarized quarks. The density functions $f_i^V(x,\lambda;S)$ are again obtainable, in principle, from the deep-inelastic polarized lepton-nucleon scattering processes, and Eq. (4) provides a further test of this modified Drell-Yan mechanism. Equation (4) is expected to be valid in the region $Q^2>2\ \mathrm{GeV}^2$ as discussed following Eq. (3).

Finally we discuss the collision of a polarized proton with an unpolarized proton, and the spin of one of the outgoing leptons is measured to produce observable effects. Only the longitudinally polarized case is considered here, and the spin of the outgoing lepton is denoted as $\pm\lambda$. The cross section is

$$\left(\frac{d\sigma}{dQ^2dP\,d\cos\theta}\right)^{pp}_{S;\pm\lambda}=(\tfrac{1}{3})^a\int dx_1dx_2\delta(Q^2-x_1x_2s)\delta\left(P-\frac{\sqrt{s}}{2}(x_1-x_2)\right)\sum_{\lambda_1=\pm S}C_{pp}(\lambda_1;S)\left(\frac{d\hat{\sigma}}{dQ^2dP\,d\cos\theta}\right)_{\lambda_1;\pm\lambda} \tag{5}$$

and

$$C_{pp}(\lambda_1;S)=\sum_i e_i{}^2\{[f_i^V(x_1,\lambda_1;S)+g_i^S(x_1,s,\lambda_1;S)]\bar{g}_i^S(x_2,s)+\bar{g}_i^S(x_1,\lambda_1;S)[f_i^V(x_2)+g_i^S(x_2,s)]\}\ .$$

The quark-antiquark annihilation cross section $(d\hat{\sigma}/dQ^2dP\,d\cos\theta)_{\lambda_1;\pm\lambda}$ at $P=0$ is $\pi\alpha^2(1\pm\cos\theta)^2/8Q^2$. Here θ is the scattering angle of the outgoing lepton whose spin is measured. The cross section for $\bar{p}p$ collision can be written similarly, and the subtraction leads to

$$\left(\frac{d\sigma}{dQ^2dP\,d\cos\theta}\right)^{\bar{p}p}_{S;\pm\lambda}-\left(\frac{d\sigma}{dQ^2dP\,d\cos\theta}\right)^{pp}_{S;\pm\lambda}$$
$$=(\tfrac{1}{3})^a\int dx_1dx_2\delta(Q^2-x_1x_2s)\delta\left(P-\frac{\sqrt{s}}{2}(x_1-x_2)\right)\sum_{\lambda_1=\pm S}\left(\frac{d\hat{\sigma}}{dQ^2dPd\cos\theta}\right)_{\lambda_1;\pm\lambda}\sum_i e_i{}^2\bar{f}_i^V(x_1,\lambda_1;S)f_i^V(x_2)\ . \tag{6}$$

Equations (2), (4), and (6) are three relations from subtractions which can be tested if the valence-quark distributions are known, or they may be used to extract the valence-quark distributions if the modified Drell-Yan mechanism is assumed to be valid. Substituting these valence-quark distributions into Eqs. (1), (3), and (5), the effective sea-quark distributions can be determined, and the strong-interaction dynamics studied from the knowledge of how the sea quarks are produced during hadronic interactions. In particular, the sea-quark distributions obtained from Eqs. (1) and (5) should be the same, and this will serve as a consistency check of the approach.

So far we have not discussed detailed quark-parton models[12–15] which predict distributions of the valence quarks. We will only consider a very simple model here as an illustration. There exist the constraints $f_i^V(x,S;S)+f_i^V(x,-S;S)=f_i^V(x)$, where i stands for u or d quarks, and from SU(3) symmetry $\int dx f_u^V(x)=2\int dx f_d^V(x)=2$. We assume that the spin of the proton is simply the sum of the spin of the valence quarks.[16] This leads to the constraint

$$\int dx[f_u^V(x,S;S)-f_u^V(x,-S;S)]+\int dx[f_d^V(x,S;S)-f_d^V(x,-S;S)]=1\ . \tag{7}$$

The relation $f_i^V(x,S;S)=a_if_i^V(x)$ is further introduced to complete this simple quark model. Substituting these relations into Eq. (7), and with the help of the constraints, we obtain the relation $a_d=2(1-a_u)$.

The simplest choice of a_u is $a_u=a_d=\frac{2}{3}$, obtained from the scheme that a u quark and a d quark are equally probable to be polarized to any direction. The asymmetry from the processes related to Eq. (4), defined as $\mathcal{A}\equiv[(\Delta\sigma)_{S,S}-(\Delta\sigma)_{S,-S}]/[(\Delta\sigma)_{S,S}+(\Delta\sigma)_{S,-S}]$, is $(-1+2\cos^2\phi)/18$ for transversely polarized p and $\bar{p}$, and $\frac{1}{9}$ for longitudinally polarized incident particles, where $(\Delta\sigma)_{S_1S_2}$ stands for the left-hand side of Eq. (4). Similarly the polarization of the outgoing lepton from the processes related to Eq. (6), defined as $\mathcal{P}\equiv[(\Delta\tilde{\sigma})_{S,\lambda}-(\Delta\tilde{\sigma})_{S,-\lambda}]/[(\Delta\tilde{\sigma})_{S,\lambda}+(\Delta\tilde{\sigma})_{S,-\lambda}]$, is $2\cos\theta/3(1+\cos^2\theta)$ at $P=0$, where $(\Delta\tilde{\sigma})_{S,\pm\lambda}$ represents the left-hand side of Eq. (6). The left-hand side of Eq. (2) will be denoted as $\Delta\sigma$ for later use.

If $a_u\neq\frac{2}{3}$, we obtain from Eqs. (3) and (5) the relations

$$2(a_u-a_d)(a_u+a_d-1)e_u{}^2\bar{f}_u^V(x_1)f_u^V(x_2)=3^a[(\Delta\tilde{\sigma})_{S,S}-(\Delta\hat{\sigma})_{S,-S}]^{-1}(\Delta\hat{\sigma})^{-1}\times\tfrac{1}{2}s\sqrt{s}(x_1+x_2)[(\Delta\hat{\sigma})(\Delta\sigma)_{S,S}-A_d]\ ,$$

and

$$2(a_u - a_d)(a_u + a_d - 1)e_d{}^2 \bar{f}_d^V(x_1) f_d^V(x_2) = 3^a[(\Delta\hat{\sigma})_{S,S} - (\Delta\hat{\sigma})_{S,-S}]^{-1}(\Delta\hat{\sigma})^{-1} \times \tfrac{1}{2} s\sqrt{s}(x_1 + x_2)[A_u \Delta\sigma - (\Delta\hat{\sigma})(\Delta\sigma)_{S,S}] \;.$$

Here $\Delta\hat{\sigma} = 4\alpha^2/3Q^2$, and $(\Delta\bar{\sigma})_{S_1 S_2} = (d\hat{\sigma}/dQ^2 dP\, d\phi)_{S_1 S_2}$, which are listed following Eq. (4). The factors A_u and A_d are defined as

$$A_i \equiv [a_i{}^2 + (1 - a_i)^2](\Delta\hat{\sigma})_{S,S} + 2a_i(1 - a_i)(\Delta\hat{\sigma})_{S,-S},$$

for $i = u$ or d. Therefore in the case $a_u \neq \frac{2}{3}$ the valence-quark distribution functions $f_i^V(x)$ are expressed in terms of two measurable quantities, $\Delta\sigma$ and $(\Delta\sigma)_{S,S}$, and a constant a_u which can be fixed by comparing with the deep-inelastic lepton-nucleon scattering processes.

In summary a modified Drell-Yan mechanism was studied, and its implications for three cases were discussed:

(1) unpolarized pp and $\bar{p}p$ collisions,
(2) polarized pp and $\bar{p}p$ collisions,
(3) polarized $p(\bar{p})$ and unpolarized p collisions with the spin of one of the outgoing leptons measured.

A simple quark-parton model was given to illustrate how the measurable quantities are used to extract the valence-quark distributions.

We finally note that some models[17] based on the bremsstrahlung or production of photons are recently proposed to explain the production of copious low-mass, high-p_T pairs in pp collision. When these models are applied to $\bar{p}p$ collision, a term of $q_V \bar{q}_V$ annihilation can be added and the results of Eqs. (2), (4), and (6) reproduced. Instead by the processes discussed in this note, these models can be tested by observing the yield of real photons in hadron-hadron collisions.[11]

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