Charged-gluon effects in dilepton production

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(Received 15 June 1978)

The high-mass dimuon spectrum in proton-nucleus collisions and their transverse-momentum distributions are studied in the broken color gauge theory of Pati and Salam. Using the distribution function determined by Feynman and Field in deep-inelastic lepton-hadron scattering, the impulse approximation in the Drell-Yan scheme combined with the broken gauge theory of Pati and Salam fits the recent experimental data beautifully.

Recently there is considerable interest in the production of dilepton pairs with large invariant mass in proton-nucleus collisions.[1,2] A way to describe the dilepton production away from the resonance region is the Drell-Yan mechanism,[3] where two pointlike constituents annihilate to produce a virtual photon of large invariant mass which decays into the lepton pair. However, the results of calculations in the naive Drell-Yan mechanism using the distribution function[4] determined from the lepton-hadron deep-inelastic scatterings fall below the data. To explain the data, several groups have studied the dilepton production from the standpoint of quantum chromodynamics (QCD) where the color symmetry is exact.[5-9]

In this note we take the alternative unified gauge model in which the color symmetry is broken as suggested by Pati and Salam.[10] It is found that the Drell-Yan mechanism including the color effects required by the broken color theory explains the data.

In the unified color guage theory with spontaneous symmetry breaking,[10] valency and color gauge bosons mix. Diagonalization of fields generates the massless color photon A_μ and also the orthogonal color gauge partner U_μ^0 (with mass m_g), both of which contribute to the production of the dilepton pairs with large invariant mass. Four color gauge bosons among the color octets acquire charge by the above diagonalization. In addition to the quark-antiquark annihilation due to the valence part shown in Fig. 1(a) and the color part shown in Fig. 1(b), the annihilation of the charged gluons shown in Fig. 1(c) is important for the dilepton production in the impulse approximation of the Drell-Yan scheme.

The cross section for Fig. 1(a) producing a dilepton pair of invariant mass Q is well known as[3]

$$\frac{d^2\sigma}{dQdy} = \frac{8\pi\alpha^2}{3Q^3}\sum_{i,\beta} e_i^2[x_A f^A{}_{i,\beta}(x_A)x_B f^B{}_{\bar{i},\beta}(x_B) + x_A f^A{}_{\bar{i},\beta}(x_A)x_B f^B{}_{i,\beta}(x_B)]\,. \qquad (1)$$

Here $f^A{}_{i,\beta}(x)$ $[f^A{}_{\bar{i},\beta}(x)]$ is the probability of finding a quark parton [antiquark parton] of flavor type i with charge e_i and color type β, carrying a fraction x of the momentum of hadron A. The proton-nucleon center-of-mass rapidity y is related to the longitudinal momentum of the lepton pair Q_3 $(=\frac{1}{2}\xi s^{1/2})$ by $\xi = 2Q\sinh y/s^{1/2}$, where $s^{1/2}$ is the proton nucleon c.m. energy. Also, x_A and x_B are given by

$$x_A = \tfrac{1}{2}[\xi + (\xi^2 + 4Q^2/s)^{1/2}]$$

and

$$x_B = \tfrac{1}{2}[-\xi + (\xi^2 + 4Q^2/s)^{1/2}]\,. \qquad (2)$$

The cross section for Fig. 1(b) is

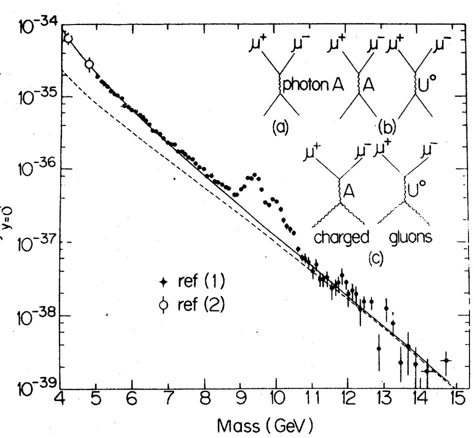

FIG. 1. High-mass dimuon spectrum per nucleon for $p+N\to\mu^+ + \mu^- + X$ by 400-GeV/c proton beams vs the effective mass of the dimuon pair. Insets show the Feynman diagrams for the production of the massive dilepton pair by the Drell-Yan process in the Pati-Salam model. (a) Quark-antiquark annihilation with the fractional charge due to the valence part, (b) quark-antiquark annihilation due to the color part, and (c) annihilation of the charged gluons. Dashed curve is the contribution by the quark-antiquark annihilation (a) using the Feynman-Field parametrization (Ref. 12). The solid line represents the calculation of the sum of (a), (b), and (c) using the Feynman-Field parametrization.

$$\frac{d^2\sigma}{dQdy} = \frac{8\pi\alpha^2}{3} Q \left(\frac{1}{Q^2} - \frac{1}{Q^2 - m_g^2}\right)^2 \sum_{i,\beta} e_\beta^2 \left[x_A f^A{}_{i,\beta}(x_A) x_B f^B{}_{\bar{i},\beta}(x_B) + x_A f^A{}_{\bar{i},\beta}(x_A) x_B f^B{}_{i,\beta}(x_B)\right], \qquad (3)$$

where m_g is the mass of the U_μ^0 gauge boson and e_β is the quark charge of the color part.

The cross section for Fig. 1(c) is calculated[11] as

$$\frac{d^2\sigma}{dQdy} = \frac{4\pi\alpha^2}{9} Q \left(\frac{1}{Q^2} - \frac{1}{Q^2 - m_g^2}\right)^2$$
$$\times \frac{(x_A^2 + 4m_g^2/s)^{1/2} + (x_B^2 + 4m_g^2/s)^{1/2}}{(\frac{1}{4} x_A^2 s + m_g^2)^{1/2} (\frac{1}{4} x_B^2 s + m_g^2)^{1/2}} \frac{1}{s} \left(\frac{1}{12}\frac{Q^8}{m_g^4} + \frac{4}{3}\frac{Q^6}{m_g^2} - \frac{17}{3} Q^4 - 4mg^2 Q^2\right) \frac{1}{x_A + x_B}$$
$$\times \sum_j \left[g_j^{+A}(x_A) g_j^{-B}(x_B) + g_j^{-A}(x_A) g_j^{+B}(x_B)\right], \qquad (4)$$

where $g_j(x)$ is the distribution function of the jth charged color gluon in the color gluon octets.

To compare with the experimental data,[1,2] Feynman-Field parametrization[12] is used for the valence and the sea distribution functions. The color gluon distribution is assumed as $g_j(x) = (\frac{1}{8})(\frac{1}{2})(n+1)(1-x)^n/x$ to carry 50% of the nucleon momentum. The dilepton production data fit best with $n = 7$ and $m_g = 1.3$ GeV. These values are consistent with our previous analysis on deep-inelastic Compton scattering.[13]

The recent experimental data[1,2] are compared in Fig. 1 with the results of the calculations of the cross section for the muon pairs produced in the proton-nucleus collision as a function of the effective mass of the muon pair. The predictions of the Drell-Yan model without the color parts [Fig. 1(a) only] fall below the data. Including the color effects [sum of Figs. 1(a), 1(b), and 1(c)], the results of the calculations agree very well with the data.

Since the dilepton pairs are produced by the annihilations of the quark-antiquark and charged gluons in our scheme, the transverse-momentum distribution of the dilepton pair directly reveals the transverse-momentum distribution of the annihilating quark and gluon partons inside the hadron. The transverse-momentum distribution $f(\vec{k}_\perp)$ of the quark and gluon partons inside the hadron are parametrized by a Gaussian, independent of Q^2 and x:

$$f(\vec{k}_\perp) = \exp(-k_\perp^2/b)/(b\pi), \qquad (5)$$

where a typical choice for b is 0.9156 GeV^2 to give average transverse momentum $\langle k_\perp \rangle = 0.848$ GeV.[14] The transverse-momentum dependence of the invariant cross section ($E\, d^3\sigma/dp^3$) of the dimuon is calculated using the above initial transverse-momentum distribution and is compared in Fig. 2 with the experimental data.[1] The agreement between the calculated values and the data is excellent for all the invariant-mass region except the Υ(9.4) resonance region. Furthermore, the calculated mean and the mean square transverse momenta are 1.2 and 1.86 GeV, respectively, while the experimental values are 1.2 and 1.9 GeV.

There are many studies concerning the production of massive muon pairs in the proton-nucleus collision from the standpoint of QCD, where the color symmetry is exact. Kogut and Shigemitsu[5] incorporate the Q^2-dependent distribution function in the quark-antiquark annihilation (asymptotic free parton model). Fritzsch and Minkowski[6] calculated the higher-order gluon-quark scattering in addition to the annihilation diagram. Politzer[7] and Altarelli, Parisi, and Petronzio[8] combined the gluon-quark scattering with Q^2-dependent parton distribution functions.

In QCD, the higher-order diagrams and the modified sea distribution seem to be required to fit the experimental data. But Sachrajda[9] argues that the independent inclusion of the higher-order processes involves double-counting. In our analysis, the impulse approximation using the lowest order in the Drell-Yan scheme without modifying

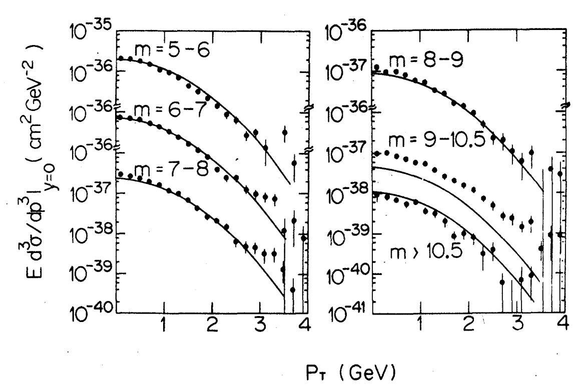

FIG. 2. Dependence of invariant cross section ($E\, d^3\sigma/dp^3$) evaluated at $y = 0$ on the transverse momentum. The lines are the predictions with the initial transverse-momentum distributions as Gaussian (Ref. 14).

the sea distribution fits the data nicely. Furthermore, the fractional momentum region of the incoming partons ($0.15 < x < 0.4$) in this analysis is where the scale violation in the lepton-hadron deep-inelastic scattering is mild.[15] For the fractional momentum region ($0.4 < x < 0.55$), Q^2-dependent correction might be appreciable, but the experimental data in the dilepton production have relatively large errors in this region. So Q^2-dependent corrections for the distribution function in the dilepton production are not included for the mass region discussed here.

At this point, it is appropriate to point out that the charged gluon effects give small contributions to the R ratio in e^+e^- annihilation in which the similar Feynman diagrams as in our analysis appear. Because of the opposite sign in amplitudes between A_μ and U_μ^0 exchanges, the color effects are suppressed by a factor $\Delta^2 = Q^4[1/Q^2 - 1/(Q^2 - m_g{}^2)]^2$. This factor suppresses the color effects in e^+e^- annihilation for the same range of Q^2 as in our analysis. But in the dilepton production by the proton-nucleus collision, the large ratio of the probability (weighted by the color charge) to find the annihilating gluons over the probability (weighted by the flavor charge) to find annihilating quark and antiquark makes the gluon effects significant despite the above suppression. Thus the charged gluon effects are enhanced in the dilepton production without significant contribution to the e^+e^- annihilation.

Next it is necessary to comment on the experimental status of the U^0 gauge boson. The mass of 1.3 GeV is consistent with the constraint on m_g (1.1–1.8 GeV) given by Pati, Sucher, and Woo.[16] An existing experiment by K. J. Anderson *et al.*[17] does not appear to exclude production cross section of (1–2) μb of neutral color gluons in this mass region. New experimental results on e^+e^- by the Frascati group[18] are not inconsistent with the existence of some narrow resonances in this mass region, but more experimental data are necessary to make definite conclusions.

In summary, the distribution function determined by Feynman and Field in lepton-hadron deep-inelastic scattering is used. Explicitly the sea distributions are $x\bar{u}(x) = 0.17(1-x)$,[10] $x\bar{d}(x) = 0.17(1-x)$,[7] and $x\bar{s}(x) = 0.1(1-x)$.[8] With these Feynman-Field parametrizations, the color effects required by the broken color symmetry by Pati and Salam beautifully fit the dimuon spectrum and the transverse-momentum distribution in the impulse approximation of the Drell-Yan scheme.

We express our gratitude to H. J. Shin and C. R. Ji for checking the calculations. This research was supported in part by Euisuk Research Foundation and by KOSEF-NSF cooperative research program.

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