77-11-140a

71 A 10 E

Ref.TH.2400-CERN

QUARK-GLUON COLLISIONS AS THE SOURCE OF DIMUON PRODUCTION
AT LARGE TRANSVERSE MOMENTA IN PROTON-NUCLEON SCATTERING

H. Fritzsch
CERN - Geneva
and
Department of Physics
University of Wuppertal

and

P. Minkowski
Institute of Physics
University of Bern

A B S T R A C T

The hard scattering of quarks and gluons calculated within QCD produces dimuons of large mass and large transverse momenta. The latter are compensated by the emission of a "quark jet" in the opposite direction. Antiproton beams are less effective than proton beams in producing dimuons with large transverse momenta. The transverse momenta of W and Z bosons produced in proton-nucleon scattering amount to a sizeable fraction of $M_{W(Z)}$.

Ref.TH.2400-CERN

24 October 1977

1.- INTRODUCTION

A way to describe the production of dimuon pairs with large invariant mass in hadronic collisions is the Drell-Yan mechanism ¹⁾ where a quark as the constituent of one of the incoming hadrons and an antiquark as the constituent of the other hadron annihilate to produce a virtual photon of large invariant mass and limited transverse momentum. Recently several studies have been made in order to understand whether the naive Drell-Yan mechanism can be justified within QCD. Some authors reached the conclusion that the cross section for producing dimuon pairs can basically be described by the $q\bar{q}$ -annihilation diagram à la Drell-Yan, but relatively small corrections (of order κ/π , $\kappa = g_{st}^2/4\pi$, g_{st} : QCD coupling constant) have to be added ^{2,3,4)}. In this note we should like to point out that within the QCD approach there exists a process which is of order κ and yet is expected to contribute to the dimuon production cross section with about the same strength as the Drell-Yan annihilation process ^{F1)}.

Recently it has been emphasized ⁵⁾ that a QCD analog of the Compton effect is expected to exist in hadronic processes which leads to the production of direct photons carrying large transverse momenta. In this paper we show that a simple off-shell generalization of the QCD Compton process provides a mechanism for the production of dimuons with large transverse momenta; the latter grow linearly with the incoming energy. The cross section for the production of dimuons in nucleon-nucleon-scattering via the QCD Compton process is expected to be of the same order of magnitude as the cross section for dimuon production via $q\bar{q}$ -annihilation.

2.- Dimuon production via quark-gluon scattering

We base our considerations on the QCD approach for hadron physics. The interpretation of the lepton production experiments requires that a large portion of the momentum of a nucleon at high energies is carried by gluons (~50 %). We shall use for the gluon distribution function in the nucleon the following functional form:

$$G(x) = (n+1) \rho (1-x)^n / x, \quad (1)$$

where $\rho = \int G(x) x dx \approx 0.5$. Our results will turn out to be rather insensitive to the actual value of n . In various phenomenological analyses the values of n used vary between 5 and 9 (see e.g. ref. (6)).

As emphasized in ref. (5), we expect within QCD the production of direct photons with large momenta via quark-gluon scattering. The same process will also lead to the production of off-shell photons, i.e. dilepton pairs (see Fig. (1)). In Fig. (2) the diagrams for this reaction in lowest order of the QCD coupling constant g_{st} are shown.

In lowest order of κ the cross section for the process "quark + gluon $\rightarrow$ dimuon + quark" is given by

$$M^3 \frac{d\sigma}{dM} = \frac{\alpha^2 \kappa(\hat{s})}{g} \sum F(\xi, \hat{s}, m_q^2) \cdot e_q^2, \quad (2)$$

$$F(\xi, \hat{s}, m_q^2) = \left\{ (1-\xi)(1+3\xi) + 2[1-2\xi(1-\xi)] \ln \left[1 + \frac{\hat{s}(1-\xi)}{m_q^2} \right] \right\} \theta(\hat{s} - M^2)$$

$$(e_q: \text{quark charge}, \hat{s} = (\hat{k} + \hat{p})^2, \xi = \frac{M^2}{\hat{s}} \leq 1, M = \sqrt{q^2}).$$

In eq. (2) we have neglected terms of order $m_q^2/\hat{s}$ (m_q : effective quark mass, we shall use $m_q = 300 \text{ MeV}$) F^2 . Since large quark and gluon momenta are involved in the process, it is assumed that a perturbation expansion

in κ makes sense and that the lowest order result given by eq. (2) describes the process to a good approximation. The coupling constant κ follows the QCD renormalization group equation valid in case of three colours and four flavours:

$$\kappa(\mu^2) = \frac{\kappa(\mu_0^2)}{1 + \frac{25}{12\pi} \kappa(\mu_0^2) \ln(\frac{\mu^2}{\mu_0^2})}. \quad (3)$$

3.- Dimuons in nucleon-nucleon scattering

In case of proton-proton scattering we obtain, using eq. (2), for the dimuon production cross section due to gluon-quark scattering:

$$M^3 \frac{d\sigma^{qq}}{dM} = 2 \int_0^1 dx \frac{1}{x} F_2^{ep}(x) \int_0^1 dy G(y) \left[M^3 \frac{d\hat{\sigma}}{dM}(\hat{s}=xys) \theta_{(xys-M^2)} \right], \quad (4)$$

where $\hat{s} = xy s$ ($s = (p_1 + p_2)^2$, p_1, p_2 four-momenta of incoming protons), and $F_2^{ep}(x)$ is the electroproduction structure function of the proton: $\frac{1}{x} F_2^{ep} = \sum_{\text{quarks } q} e_q^2 (q + \bar{q})$, (q : quark distribution functions).

Most experiments are done on nucleon targets. In case of an $I = 0$ nuclear target with atomic number A the function F_2^{ep} should be replaced by $A \left(\frac{3}{2} F_2^{ep} + \frac{1}{2} F_2^{en} \right)$.

Eq. (4) can be rewritten as follows:

$$M^3 \frac{d\sigma^{qq}}{dM} = 2 \int_{\tau}^1 dy \int_{\tau}^y dz \frac{1}{z} F_2^{ep}\left(\frac{z}{y}\right) G(y) \left[M^3 \frac{d\hat{\sigma}}{dM}(\hat{s}=xys) \right], \quad (5)$$

where we have introduced the scaling variables $\tau = M^2/s$ and $z = x y$.

The recent experimental data (for a recent review see ref. (7)) show agreement with the scaling hypothesis for the dimuon production cross section:

$$M^3 \frac{d\sigma}{dM} = F(\tau). \quad (6)$$

Furthermore the observed cross section is of the order of magnitude expected within the Drell-Yan model.

Within our approach it is incorrect to describe the total cross section for dimuon production solely by the $q\bar{q}$ -annihilation mechanism à la Drell-Yan. The contributions due to the QCD Compton process, denoted here by $d\sigma^{gq}/dM$ (see eq. (5)) have to be added:

$$M^3 \frac{d\sigma}{dM} = M^3 \left(\frac{d\sigma^{q\bar{q}}}{dM} + \frac{d\sigma^{gq}}{dM} \right). \quad (7)$$

(The dimuon production cross section via $q\bar{q}$ -annihilation is denoted by $d\sigma^{q\bar{q}}$.) Furthermore there are higher order gluon corrections both to the Drell-Yan process and to the QCD Compton process, which are suppressed by powers of κ/π and are disregarded here. The quark-gluon process discussed above is the one which dominates the production of dimuons at large transverse momenta.

We have calculated the cross section for dimuon production arising by the QCD Compton process using the parametrization of $G(y)$ given in eq. (1), and $\rho=0.5$, $\kappa(2 \text{ GeV}) = 0.3$. In Fig. (3) the results of the computer calculations for $n = 5$ and $n = 7$ are shown. It is surprising to see that the calculated cross sections $d\sigma^{gq}/dM$ agree rather well (within a factor 2) with the observed cross section, which we have parametrized as given in ref. (7):

$$\left. \frac{d\sigma}{dM dy} \right|_{y=0} = 1.25 \cdot e^{-0.93M} \cdot 10^{-33} \text{ cm}^2 / \text{GeV}. \quad (8)$$

The total cross section has been calculated using eq. (8) and a dimuon x - distribution $(1-x)^4$ (x : Feynman x variable).

Since the dimuon production can also be described rather well within the Drell-Yan model (see eq. ref. (7)), we conclude that in case of nucleon-nucleon scattering the QCD Compton process and the Drell-Yan process contribute each with comparable strength to the production of very massive dimuons. We shall assume for our subsequent considerations

$$\frac{d\sigma^{q\bar{q}}}{dM} \approx \frac{d\sigma^{\bar{q}q}}{dM} \quad (9)$$

Thus the QCD Compton process, which is of order $\alpha^2 \kappa$, competes successfully with the Drell-Yan process which is of order α^2 . The reason for this surprising fact is the relatively large gluon content of the nucleon, compared to the small $\bar{q}$ content of the nucleon.

We have calculated the cross section eq. (5) for various values of s ; it turns out that the logarithmic factors play a very little rôle, and scaling (eq. (6)) is a very good approximation for $\sqrt{s} < 10^5$ GeV. However, we have not taken into account scale breaking effects in the quark and gluon distribution functions (For an attempt to include scale breaking effects see ref. (8)).

Furthermore we have calculated the average transverse momentum $\langle q_{\perp} \rangle$ of the dimuon pairs. For the subprocess "gluon + quark $\rightarrow$ dimuon + quark" $\langle \hat{q}_{\perp} \rangle$ is given by:

$$\begin{aligned} \langle \hat{q}_{\perp} \rangle &= \frac{\int \frac{d\sigma}{dM d\Omega} q_{\perp} d\Omega}{\frac{d\sigma}{dM}} \\ &= M \frac{\pi \alpha^2 \kappa}{72} \cdot \frac{7\bar{s}(1-\bar{s})(\bar{s}-14\bar{s}+13\bar{s}^2)}{M^3 \frac{d\sigma}{dM}} \end{aligned} \quad (10)$$

(Ω is the solid angle in the quark-gluon c.m.s.). In case of proton-proton scattering we find for the average transverse momentum, neglecting the transverse momenta of the initial quarks and gluons:

$$\langle \tilde{q}_\perp \rangle = \left(M^3 \frac{d\sigma}{dM} \right)^{-1} \frac{\pi \alpha^2}{36} M \sqrt{s} \int_0^1 dy \int_0^y dz \, \kappa(xys) \frac{F_2^{ep}(\frac{z}{y}) G(\gamma)}{2 \sqrt{s}} \left(1 - \frac{\gamma}{2} \right) \left[9 - 14 \left(\frac{\gamma}{2} \right) + 13 \left(\frac{\gamma}{2} \right)^2 \right]. \quad (11)$$

Note that $\langle \tilde{q}_\perp \rangle$ increases like $\sqrt{s}$ for a fixed value of τ . In order to compare this result with experiment, we use eq. (9) and take into account the "primordial" transverse momenta $p_\perp$ of the initial quarks and gluons both for the QCD Compton process and the Drell-Yan process. The transverse momenta of the initial quarks and gluons are parametrized by a Gaussian. For very high transverse momenta of the dimuon the initial transverse momenta can be neglected, and one has $\langle q_\perp \rangle \approx \langle \tilde{q}_\perp \rangle$. In case of $\sqrt{s} = 27.4 \text{ GeV}$ the result is displayed in Fig. (4). For $\sqrt{\langle p_\perp^2 \rangle} \sim 0.3 - 0.5 \text{ GeV}$ the experimental data ⁷⁾ are well reproduced. We interpret the occurrence of relatively large transverse momenta in dimuon production as due to the QCD Compton process.

In Fig. (5) we display $\langle q_\perp \rangle$ for $\sqrt{s} = 58 \text{ GeV}$ (ISR) and $\sqrt{s} = 400 \text{ GeV}$. In the latter case transverse momenta up to $\sim 8.3 \text{ GeV}$ are obtained. The shape of $\langle q_\perp \rangle$ as a function of τ is universal; the maximum of $\langle q_\perp \rangle$ is reached for $\tau = 0.14$. In Fig. (6) we show $\langle q_\perp \rangle_{\text{max}} = \langle q_\perp \rangle (\tau \approx 0.14)$ as a function of $\sqrt{s}$. Above $\sqrt{s} = 100 \text{ GeV}$ $\langle q_\perp \rangle_{\text{max}}$ is essentially a straight line, described rather well by

$$\langle q_\perp \rangle_{\text{max}} \approx 1.1 + 0.0175 \sqrt{s} [\text{GeV}], \quad (\sqrt{s} > 100 \text{ GeV}). \quad (12)$$

In the region $\sqrt{s} > 100$ GeV the initial transverse momenta of the quarks and gluons are negligible, and $\langle q_{\perp} \rangle$ is approximately scale invariant (see eq. 11).

We emphasize that the increase of $\langle q_{\perp} \rangle$ due to the QCD Compton process is balanced by the emission of a quark in the opposite direction (see Fig. (1)). Thus those dimuon events which occur at high $q_{\perp}$ should be accompanied by a jet of particles ("quark jet") emitted in the opposite direction in the $p_{\perp}$ -space. It is important to check this by experiment.

4.- Dimuons in nucleon-antinucleon scattering

In antiproton-nucleon scattering we expect $d\sigma_{\bar{q}q}/dM(\bar{p}N) \gg d\sigma_{\bar{q}q}/dM(pN)$ for relatively large values of τ .

On the other hand we have

$$\frac{d\sigma_{gg}}{dM}(\bar{p}N) = \frac{d\sigma_{gg}}{dM}(pN), \quad (13)$$

thus at relatively large values of τ ($\tau > 0.05$) the QCD Compton process plays only a minor rôle for $\bar{p}N$ scattering; the dimuon production is dominated by the annihilation of valence quarks and antiquarks.

For large $\langle q_{\perp} \rangle$, where eq. (11) applies, we find

$$\frac{\langle q_{\perp} \rangle(\bar{p}N)}{\langle q_{\perp} \rangle(pN)} = \frac{\frac{d\sigma}{dM}(pN)}{\frac{d\sigma}{dM}(\bar{p}N)}. \quad (14)$$

In case $\tau \gtrsim 0.05$ this ratio is expected to be very small ($\lesssim 0.1$), i.e. at a fixed value of $\tau \gtrsim 0.05$ the average transverse momentum of the muon pairs produced in $\bar{p}$ -N collisions is much less than in p-N collisions; it is essentially given by the "primordial" transverse momenta of the incoming quarks and antiquarks. Especially for energies of the order of $\sqrt{s} \approx 20 - 30$ GeV we expect

$$\langle q_{\perp} \rangle (\bar{p} N, M > 2 \text{ GeV}) < 0.8 \text{ GeV}.$$

It would be very interesting to carry out experiments with high energy antiproton beams and to see if $\langle q_{\perp} \rangle$ is indeed significantly less than in case of proton beams. This would be a crucial test of the mechanism described in this paper.

Dimuons produced in pion-nucleon reactions at relatively large values of τ are expected to be produced mainly by the annihilation of valence quarks and antiquarks. In this case the QCD Compton process will contribute only relatively little to the total cross section, and we expect the average transverse momenta of the dimuons to be significantly smaller than the ones observed in proton-nucleon collisions.

5.- Consequences for W and Z production

We should like to add a short remark about W and Z production in high energy hadron collisions. The mechanism discussed here contributes, of course, also to W and Z production; in Fig. (2) the photon has to be replaced by a W or Z boson. The various production cross sections can be estimated easily, e.g. using the CVC arguments of ref. (9).

We expect the average transverse momentum of W or Z bosons produced in hadronic collisions to increase, if $\sqrt{s}$ increases. For $M_{\text{Boson}} = 80$ GeV and $n = 5$ the result is shown

in Fig. (7). Note the relatively strong increase of $\langle q_{\perp} \rangle$ if $\sqrt{s}$ increases from 100 GeV to 500 GeV.

In case of a colliding beam facility with $\sqrt{s} = 800$ GeV (e.g. ISABELLE project) we expect $\langle q_{\perp} \rangle \approx 10$ GeV. These transverse momenta are fairly large, compared to M_{Boson} ; it will be impossible to determine accurately the mass of W-bosons produced eventually in hadronic collisions.

In $\bar{p}p$ -collisions the transverse momenta are expected to be much less (of the order of 1 GeV in case of $\sqrt{s} = 400$, $M_{\text{Boson}} = 80$ GeV). Therefore the W-boson signal will be much clearer in $\bar{p}p$ collisions than in pp -collisions. This may serve as an argument in favor of $\bar{p} - p$ colliders for the study of W production.

6.- Concluding remarks

In this paper we have shown that in proton-nucleon collisions the production of dimuons with large invariant mass and large transverse momenta proceeds via the off-shell analog of the QCD Compton process. The transverse momenta of the muon pairs are balanced by the emission of a jet ("quark jet") in the opposite direction. The transverse momenta of dimuons produced in $\bar{p}$ -nucleon scattering are significantly smaller than the transverse momenta of dimuons produced in p -nucleon scattering. The transverse momenta of W and Z bosons produced in p -nucleon scattering are estimated to be sizable compared to $M_{W(Z)}$.

ACKNOWLEDGEMENT :

We are indebted to F. Halzen and M. Jacob for instructive discussions. One of us (P.M.) would like to thank the Theory Division at CERN for the hospitality during his stay at CERN in August 1977, where this work was completed.

FOOTNOTES

F 1) We shall base ourselves on lowest order calculations in α and κ . Thus we do not address the question whether a suitably modified Drell-Yan formula, taking into account consistently scale breaking effects in the quark and gluon distribution functions, is still valid within QCD. Such a claim was recently made in ref. (4); our results are not in disagreement with such a claim.

F 2) The presence of the logarithmic term in eq. (2) (logarithmic dependence on m_q) is caused by our use of lowest order perturbation theory. In a consistent treatment taking into account all orders the logarithmic dependence on m_q may be absorbed in the initial quark wave function, such as indicated in ref. (4).

REFERENCES :

- 1) S. D. Drell and T. M. Yan, Phys. Rev. Lett. 25 (1970) 316.
- 2) J. B. Kogut, Phys. Lett. 65B (1976) 377.
- 3) D. E. Soper, Princeton University preprint (1977),
"Large Transverse Momentum Partons and Massive μ -Pair
Production".
- 4) H. D. Politzer, Harvard University preprint HUTP-77/A029
(May 1977), "Gluon Corrections to Drell-Yan Processes".
- 5) H. Fritzsch and P. Minkowski, Phys. Lett. 69B (1977) 316.
- 6) A. Buras and K. J. F. Gaemers, CERN preprint TH 2368
(August 1977), "Energy Dependence of Neutral and Charged
Current Cross Sections from Asymptotic Freedom",
M. Glück and E. Reya, University of Mainz report MZ-TH 77/3
(1977), to be published in Nucl. Phys. B.
- 7) L. Lederman, to be published in the Proceedings of the
1977 Int. Symposium on Lepton and Photon Interactions at
High Energies, Hamburg (1977).
- 8) I. Hinchliffe and C.H. Llewellyn Smith, Phys. Lett. 66B
(1977) 281.
- 9) Y. Yamaguchi, Nuovo Cimento 43, (1966) 193,
L. Okun, Yad. Fiz. 3 (1966) 590.

Figure captions

Fig.(1): The production of a dimuon pair in nucleon-nucleon scattering via gluon-quark scattering. The incoming nucleons dissociate into quarks (—) and gluons (---), two of which scatter to produce an off-shell photon (muon pair) and a quark. Only the relevant quark- and gluon lines are shown. The quark and gluon momenta are denoted by $\hat{p}$, $\hat{k}$. The outgoing hadrons in the forward and backward direction are not shown.

Fig.(2): The two diagrams for describing the production of an off-shell photon in gluon-quark scattering. Note that in diagram Fig. (2a) a virtual quark of large mass is produced which disintegrates into an off-shell photon and a quark.

Fig.(3): The cross section $M^3 d\sigma^{gq}/dM$ as a function of τ . The solid line displays the case $n = 5$, the dashed line $n = 7$. The dotted line shows the parametrization of the experimental data (see eq. (8)).

Fig.(4): $\langle q_{\perp} \rangle$ as a function of M for $\sqrt{s} = 27.4$ GeV. The initial transverse momenta p of the quarks and gluons are parametrized by a Gaussian. The solid line shows the case $\sqrt{\langle p_{\perp}^2 \rangle} = 0.5$ GeV, the dashed line the case $\sqrt{\langle p_{\perp}^2 \rangle} = 0.3$ GeV.

Fig.(5): $\langle q_{\perp} \rangle$ is given for $\sqrt{s} = 58$ GeV (a) and $\sqrt{s} = 400$ GeV(b) (solid lines: $\sqrt{\langle p_{\perp}^2 \rangle} = 0.5$ GeV, dashed lines: $\sqrt{\langle p_{\perp}^2 \rangle} = 0.3$ GeV).

Fig.(6): The maximal transverse momenta $\langle q_{\perp} \rangle_{\text{Max}}$ as a function of $\sqrt{s}$ (solid line: $\sqrt{\langle p_{\perp}^2 \rangle} = 0.5$ GeV, dashed line: $\sqrt{\langle p_{\perp}^2 \rangle} = 0.3$ GeV).

Fig.(7): The average transverse momentum $\langle q_{\perp} \rangle$ of W- and Z bosons with a mass of 80 GeV produced in hadronic collisions.

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5a

FIG. 5b

FIG. 6

FIG. 7