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TESTING THE SPIN OF THE GLUON IN LARGE TRANSVERSE MOMENTUM LEPTON PAIR PRODUCTION

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A structure function relation sensitive to the spin of the gluon is derived for large transverse momentum lepton-pair production. A direct test of this relation is devised in terms of a specific angular correlation-asymmetry. Calculations of this correlation function and other angular coefficients are presented.

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I. INTRODUCTION: Many qualitative features of high energy hadron physics seem to be consistent with perturbative Quantum Chromodynamics (QCD). Recent observation of three-jet events in high energy e^+e^- annihilation has, in particular, given encouragement to the QCD picture of quarks and gluons as the underlying constituents of hadron physics. Whereas the spin and "flavor quantum numbers" of quarks are probed in various lepton-hadron processes through their weak-electromagnetic coupling, the properties of the gluon are much more elusive for experimental study. They do not couple directly to the lepton probes. It is the purpose of this paper to show that important information on the spin of the gluon can be extracted from the angular distribution of lepton pairs produced at large transverse momentum in hadron collisions.

Within the conventional perturbative QCD framework, the dominant mechanism for producing such lepton pairs (at least for πN and $\bar{N}N$ reactions) is quark-antiquark annihilation with the emission of a hard gluon.[1,2] This mechanism is shown in Fig. 1. As the large transverse momentum of the pair is balanced mainly by that of the recoil gluon, it is apparent that the spin of the latter should have an effect on the angular distribution of the detected leptons. It is then natural to ask whether this effect can be clearly identified and subjected to simple experimental tests. We show that the answer to both questions is yes.

II. QCD RESULTS: The angular distribution of lepton pairs produced in hadron collisions is determined by structure functions which represent independent components of the virtual photon polarization tensor (or current correlation function),

$$W_{\mu\nu} = s \int d^4z e^{iqz} \langle p_1 p_2 | J_\mu(z) J_\nu(o) | p_1 p_2 \rangle . \qquad (1)$$

The momentum labels p_1, p_2 refer to the initial state hadrons, q to the virtual photon (hence the final state lepton-pair), and s is the total center-of-mass energy squared, $s = -(p_1+p_2)^2$. The general formalism for analysing the angular distribution is developed in ref. 3, to which we refer the reader for details.

We are concerned only with <u>large transverse momentum lepton pair production in πN or $\bar{N}N$ scattering</u>. Hence we shall focus our attention on the dominant mechanism[1,2] represented by Fig. 1. The current correlation function can be written,[4]

$$W^{\mu\nu}(p_1, p_2, q) = \frac{8\pi}{9} \sum_i Q_i^2 \int \frac{d\xi_1}{\xi_1} \frac{d\xi_2}{\xi_2} \delta[(\xi_1-x_1)(\xi_2-x_2) - x_\perp^2]$$
$$\times [u_i(\xi_1)\bar{u}_i(\xi_2) + \bar{u}_i(\xi_1)u_i(\xi_2)]\omega^{\mu\nu}(\xi_1 p_1, \xi_2 p_2, q). \qquad (3)$$

Here the sum is over quark flavors. We use $x_{1,2} = (q^0 \pm q^z)/\sqrt{s}$, $x_\perp = q_\perp/\sqrt{s}$, where components of the virtual photon momentum q refer to the initial hadron CM frame. The parton (anti-parton) distribution functions $u_i(\xi_a)[\bar{u}_i(\xi_a)]$ depend on the flavor label i and the longitudinal momentum fraction ξ_a, where a=1,2 labels the incoming hadrons. The hard parton annihilation amplitude $\omega^{\mu\nu}$ is given by:

$$\omega^{\mu\nu}(\xi_1 p_1, \xi_2 p_2, q) = \omega^{\mu\nu}(\xi_2 p_2, \xi_1 p_1, q)$$
$$= 4\pi\alpha_s[\tilde{g}^{\mu\nu}(\xi_1^2 x_2^2 + \xi_2^2 x_1^2) - 4\tau(\xi_1^2 \tilde{p}_1^\mu \tilde{p}_1^\nu + \xi_2^2 \tilde{p}_2^\mu \tilde{p}_2^\nu)]/\xi_1 \xi_2 x_\perp^2 \qquad (4)$$

Here $\tilde{g}^{\mu\nu} = g^{\mu\nu} - q^\mu q^\nu/q^2$ is the gauge invariant projection tensor, $\tilde{p}_a^\mu = \tilde{g}^{\mu\nu} p_{a\nu}/\sqrt{s}$ (a=1,2) are the normalized gauge invariant hadron momenta, $\tau = x_1 x_2 - x_\perp^2$, and α_s is the effective strong coupling constant. Combining Eqs. (3), (4) and comparing with the definition[3] of invariant structure functions W_i, i=1,2,3,4,

$$W^{\mu\nu}(p_1, p_2, q) = \tilde{g}^{\mu\nu} W_1 + (\tilde{p}_1^\mu \tilde{p}_2^\nu + \tilde{p}_2^\mu \tilde{p}_1^\nu)(W_2 - W_4)$$
$$+ \tilde{p}_1^\mu \tilde{p}_1^\nu (W_2 - W_3 + W_4) + \tilde{p}_2^\mu \tilde{p}_2^\nu (W_2 + W_3 + W_4), \qquad (5)$$

we can summarize the results as follows,

$$W_1 = \frac{1}{2} W^{\mu}_{\mu} = x_1^2 \langle \xi_1^{-2} \rangle + x_2^2 \langle \xi_2^{-2} \rangle; \tag{6}$$

$$W_2 = W_4 = -\tau(\langle \xi_1^{-2} \rangle + \langle \xi_2^{-2} \rangle); \tag{7}$$

and $$W_3 = -2\tau(\langle \xi_1^{-2} \rangle - \langle \xi_2^{-2} \rangle). \tag{8}$$

Here

$$\langle f(\xi_1, \xi_2) \rangle = \frac{32\pi^2 \alpha_s}{9 x_\perp^2} \sum_i Q_i^2 \int_0^\infty d\zeta \, f(\xi_1, \xi_2) \left[u_i(\xi_1) \bar{u}_i(\xi_2) + \bar{u}_i(\xi_1) u_i(\xi_2) \right] \tag{9}$$

with $\xi_{1,2} = x_{1,2} + x_\perp e^{\pm\zeta}$.

<u>III. QUARK AND GLUON SPINS</u>: It has been pointed out[5] that the relation $W^{\mu}_{\mu} = 2W_1$, Eq. (6), is intimately tied to the spin $\frac{1}{2}$ nature of the quark. One can show that changing the spin of the gluon in Fig. 1 does not affect this relation. Moreover, it is valid regardless of whether the quark lines coupled to the virtual photon are on-shell and colinear with the incoming hadrons (i.e., in the Drell-Yan limit) <u>or</u> are off-shell and non-colinear (as in Fig. 1 with high $q_\perp$). Therefore, checking the <u>invariance of Eq. (6)</u> over a wide range of $q_\perp$ (in which the apparent lepton angular distribution is expected to vary substantially) should provide a critical test of the spin of the quark. (The classic Callan-Gross relation, by comparison, only holds for on-shell quark lines coupled to the virtual photon.)

The main point of the present paper is to generalize the above idea to get a handle on the spin of the much more elusive gluon. (This is one of the few places where effects due to a single gluon can be subjected to detailed study.) For this purpose, we take the quark to be a conventional spin $\frac{1}{2}$ particle. To see the effect of the gluon spin, we contrast the QCD predictions of the last section with corresponding formulas resulting from emission of a hard <u>scalar</u> gluon. A straightforward calculation yields, for the latter case,

$$W_1 = \frac{1}{2} W^{\mu}_{\mu} = \frac{1}{2} <(1 - \frac{\tau}{\xi_1 \xi_2})^2> \tag{10}$$

$$W_2 = - \tau(<\xi_1^{-2}> + <\xi_1^{-1} \xi_2^{-1}> + <\xi_2^{-2}>) \tag{11}$$

$$W_3 = - 2\tau(<\xi_1^{-2}> - <\xi_2^{-2}>) \tag{12}$$

$$W_4 = - \tau(<\xi_1^{-2}> - <\xi_1^{-1} \xi_2^{-1}> + <\xi_2^{-2}>) \tag{13}$$

where $< >$ has the same meaning as in Eq. (9).

As mentioned before, the relation $W^{\mu}_{\mu} = 2W_1$, Eqs. (7), (10), is valid irrespective of the nature of the gluon. On the other hand, the second parton model-QCD relation $W_2 = W_4$ is sensitive to the spin of the gluon. Thus, from Eqs. (7), (11) and (13):

$$W_2 - W_4 = \begin{cases} 0 \\ -2\tau<\xi_1^{-1} \xi_2^{-1}> \end{cases} \text{for} \begin{Bmatrix} \text{vector} \\ \text{scalar} \end{Bmatrix} \text{gluon} . \tag{14}$$

This statement holds true for any parton distributions ($u_i(\xi)$ and $\bar{u}_i(\xi)$), hence, is independent of any uncertainties associated with these functions. There are other differences in detail between Eqs. (6)-(8) and Eqs. (10)-(13). They will influence the numerical calculations of section V. But, for the moment, we would like to focus on Eq. (14). Question: is it possible to translate this simple theoretical result into an equally clear-cut experimental test?

IV. ANGULAR CORRELATION AND ASYMMETRY TESTS: The angular distribution of the leptons are normally studied in the lepton-pair CM frame. It has the general form:[3]

$$\frac{1}{\sigma} \frac{d\sigma}{d\Omega} = \frac{3}{8\pi} [\hat{W}_T(1+\cos^2\theta) + \hat{W}_\Delta \sin 2\theta \cos\phi + (\hat{W}_L + \hat{W}_{\Delta\Delta}\cos 2\phi)\sin^2\theta] \tag{15}$$

where σ refers to the cross-section integrated over the lepton angles (but may be differential in the hadron variables which we suppress). The lepton angles (θ,ϕ) and the associated coefficients[6] $\hat{W}_i$ in Eq. (15) obviously depend on the choice of coordinate axes in this frame. In order to translate Eq. (14) into a statement on the lepton angular distribution, one needs the relations between $\hat{W}_i$, $i=T,L,\Delta,\Delta\Delta$, and the invariant structure functions of the previous sections. These are given in ref. 3. It turns out that, when expressed in terms of $\hat{W}_i$, the form of Eq. (14) is frame-dependent and quite complicated for all conventional choices of axes. It seemed, therefore, that in spite of its theoretical simplicity, Eq. (14) could not be directly tested. But, it is not so!

Let us forget about the frame-dependent Eq. (15), and go back to the basic formula $d\sigma \propto L^{\mu\nu} W_{\mu\nu}$ where $W_{\mu\nu}$ is defined by Eq. (1) and $L_{\mu\nu}$ is the familiar lepton tensor (square of the lepton-virtual-photon vertex) $L^{\mu\nu} = g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2} - \frac{k^\mu k^\nu}{k^2}$, ($k$ is the relative momentum of the two leptons). Observe that <u>$L^{\mu\nu}$ is the projection operator which, when contracted with any 4-vector, projects the latter onto the plane perpendicular to both q^μ and k^μ</u>. In the lepton CM frame, this plane is the 2-plane perpendicular to the lepton momenta, (see Fig. 2). Contracting $L^{\mu\nu}$ with the general form of $W_{\mu\nu}$ given by Eq. (5), we obtain

$$d\sigma \propto 2W_1 + \hat{p}_1^2(W_2 - W_3 + W_4) + \hat{p}_2^2(W_2 + W_3 + W_4) + 2\hat{p}_1 \cdot \hat{p}_2(W_2 - W_4) \qquad (16)$$

where $\hat{p}_1$ and $\hat{p}_2$ are the projections of the initial hadron momenta onto the 2-plane just described (cf. Fig. 2).

It is important to notice that: (i) only physical variables appear in Eq. (16) (i.e., it is independent of the choice of coordinate axes); and (ii) <u>the last term involving correlation between $\hat{p}_1$ and $\hat{p}_2$ measures exactly the combination of structure functions</u> $(W_2 - W_4)$ <u>that we are interested in</u>. Hence, Eq. (14) can be translated into the simple statement: <u>if QCD is correct, there should be no correlation between $\hat{p}_1$ and $\hat{p}_2$</u>; on the other hand, <u>if the gluon is not a vector</u>

particle (as exemplified by the scalar case) there should be a nonvanishing correlation.

To go into a little detail, we note $\hat{p}_1^2 = x_2^2 \sin^2\theta_1/4\tau$, $\hat{p}_2^2 = x_1^2 \sin^2\theta_2/4\tau$, and $\hat{p}_1 \cdot \hat{p}_2 = x_1 x_2 \sin\theta_1 \sin\theta_2 \cos\phi_{12}/4\tau$ where the angles θ_1, θ_2, ϕ_{12} are defined in Fig. 2. For a fixed set of hadron variables (say, s, M, x_F, $q_\perp$), the three angles are constrained by one kinematic relation. However, if we integrate over one or more hadron variables, these angles become independent (except at kinematic boundaries). The term of interest to us in Eq. (16) is then the only one which depends on $\cos\phi_{12}$. It can be singled out by an asymmetry, measuring the difference in the fractional number of events with ($\hat{p}_1$, $\hat{p}_2$) on the same side ($\cos\phi_{12}>0$) and that on opposite sides ($\cos\phi_{12}<0$). With a possible proportionality constant of order 1 which depends on the details of the integration over hadron variables, this asymmetry measures directly the breaking of the QCD relation $W_2 = W_4$ represented by the parameter,

$$\kappa = x_1 x_2 (W_2 - W_4)/8\tau W^\mu_\mu. \tag{17}$$

V. NUMERICAL RESULTS: To gain some feeling on the practicality of the proposed tests, we calculated the structure functions and the angular coefficients for the case of πN scattering at 225 GeV/c. The parton distribution functions needed in these calculations are already determined by existing experiments at the same energy[7] (using data dominated by low $q_\perp$ events). We present in Fig. 3 typical results obtained for the QCD violating asymmetry parameter κ. Dependences of this parameter on the variables M, x_F, and $q_\perp$ can be readily read off. κ vanishes identically in (lowest order) QCD, it is of the order 0.1 - 0.4 if the gluon has spin zero. For this test case, κ is larger for higher values of M, and lower values of $|x_F|$ and $q_\perp$.

In addition to the clear cut κ=0 test, other aspects of the lepton angular distribution can also reflect the influence of the spin of the recoil gluon.

As an example, we calculate the angular coefficient α in the traditional $(1+\alpha\cos^2\theta)$ distribution[7] $[\alpha = (\hat{W}_T - \hat{W}_L)/(\hat{W}_T + \hat{W}_L)]$. For definiteness, we pick the Collins-Soper frame.[3] Representative results are presented in Fig. 4. We see that the ranges of α characterizing the vector and scalar cases are essentially non-overlapping for large values of M and $q_\perp$. (For low $q_\perp$, kinematics plus the general relation $W^\mu_\mu = 2W_1$ forces $\alpha \to 1$ in both cases.)

VI. CONCLUSION: If perturbative QCD is relevant for large transverse momentum lepton-pair production, the angular distribution of the leptons can provide valuable information on the spin of the gluon. This information is not easily obtained elsewhere. The structure function combination $W_2 - W_4$ provides the most clear cut test for vector gluons in QCD, cf. Eq. (14). It can be directly measured by an experimental asymmetry, cf. Eq. (16). 'Background effects' due to higher order diagrams should be small if perturbative QCD makes sense but clearly needs to be calculated. Ad hoc 'intrinsic transverse momentum' of the partons might also introduce breaking of the relation $W_2 = W_4$, but current thinking is that this is part of the higher order effect, and it is inconsistent to put such terms in by hand.[8]

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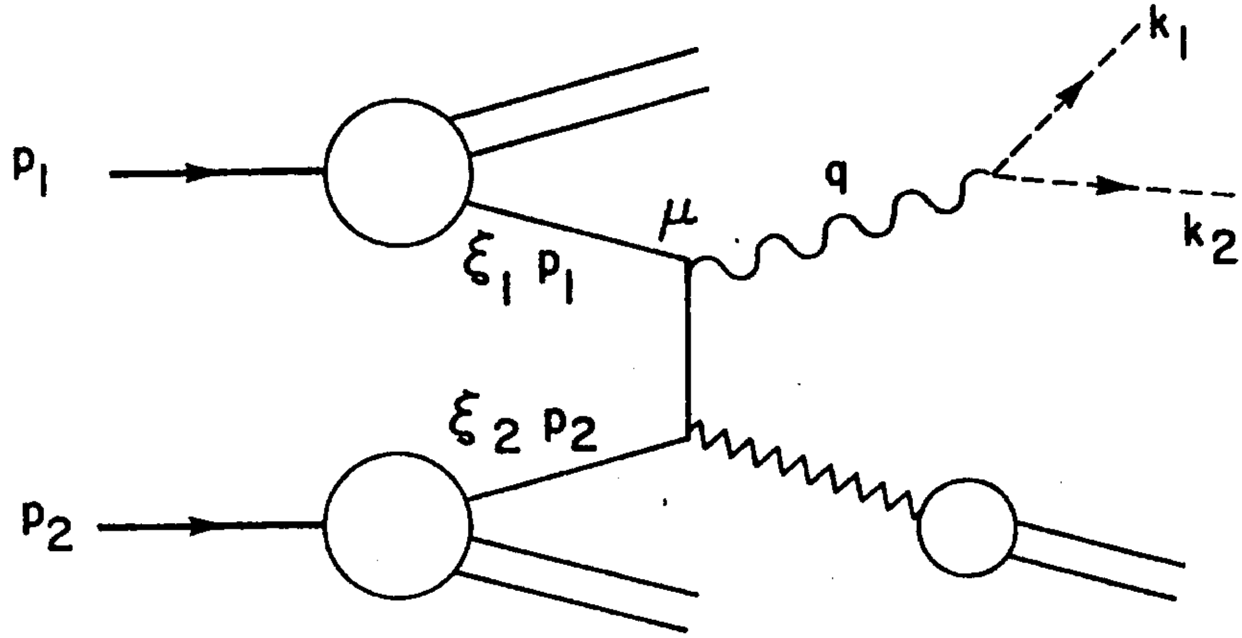
FIGURE CAPTIONS

1. Dominant mechanism for producing large transverse momentum lepton-pairs in πN and $\bar{N}$N scattering: hard gluon emission.

2. Kinematics in the Center-of-Mass frame of the lepton pair.

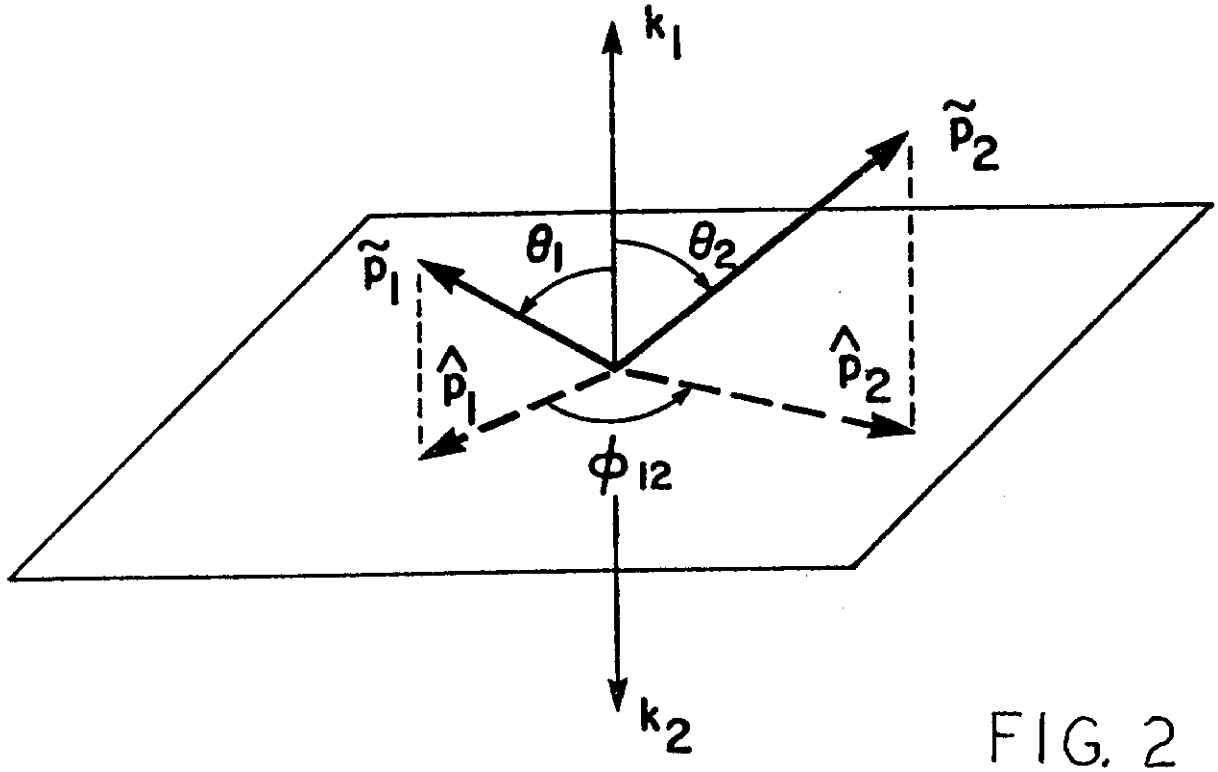
3. The asymmetry parameter κ as a function of $q_\perp$ for various values of M and x_F if the gluon has spin 0. (QCD predicts, κ=0)

4. The angular coefficient $\alpha = (W_T-W_L)/W_T+W_L)$ as a function of $q_\perp$ for various values of M, x_F in the two cases of vector- and scalar-gluon.



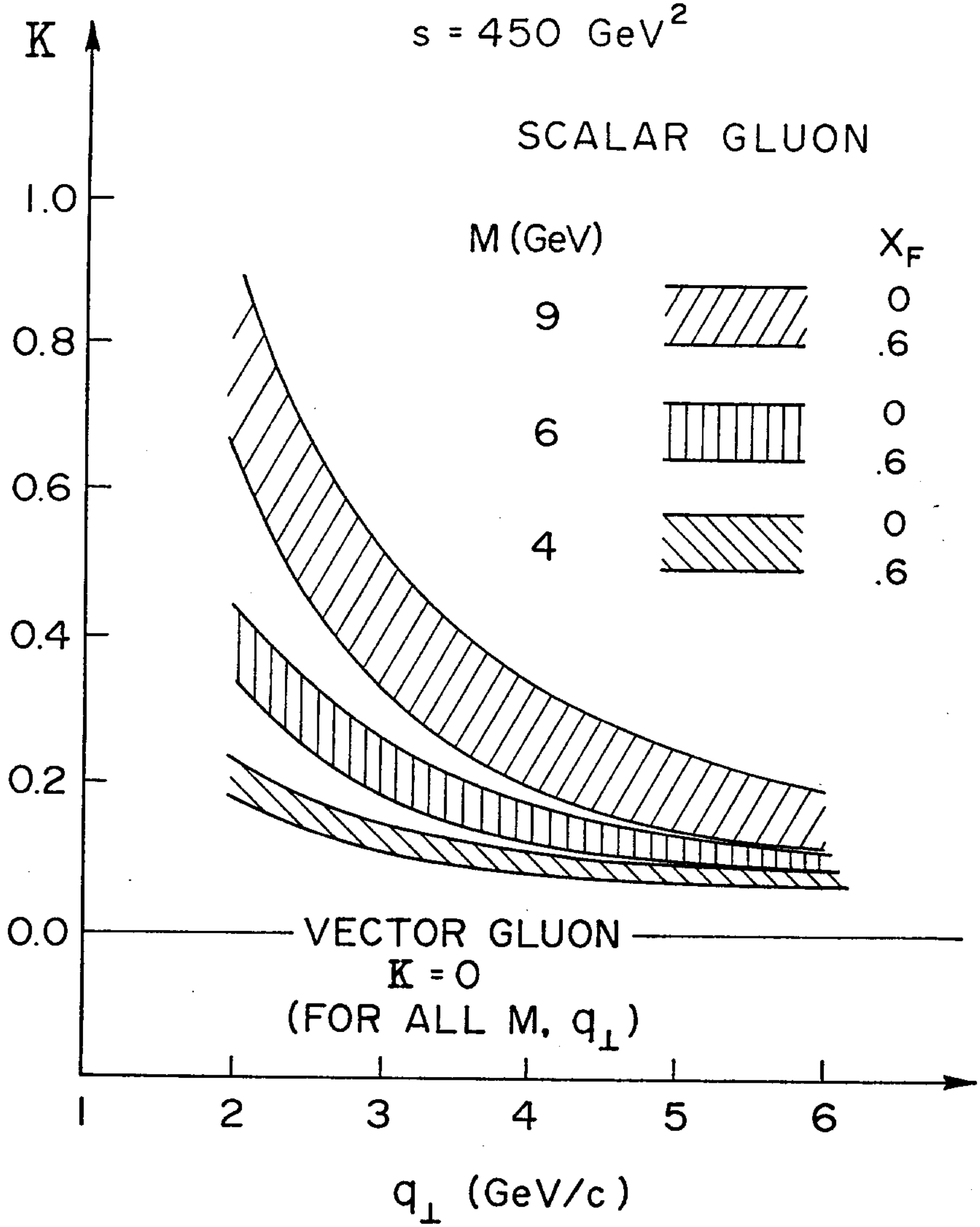
p_1
p_2
$\xi_1\ p_1$
$\xi_2\ p_2$
μ
q
k_1
k_2

FIG. 1



k_1
k_2
$\tilde{p}_1$
$\tilde{p}_2$
$\hat{p}_1$
$\hat{p}_2$
θ_1
θ_2
ϕ_{12}

FIG. 2



K
s = 450 GeV^2
SCALAR GLUON
M (GeV)
X_F
9
0
.6
6
0
.6
4
0
.6
1.0
0.8
0.6
0.4
0.2
0.0
VECTOR GLUON
K = 0
(FOR ALL M, $q_\perp$)
1
2
3
4
5
6
$q_\perp$ (GeV/c)

FIG. 3

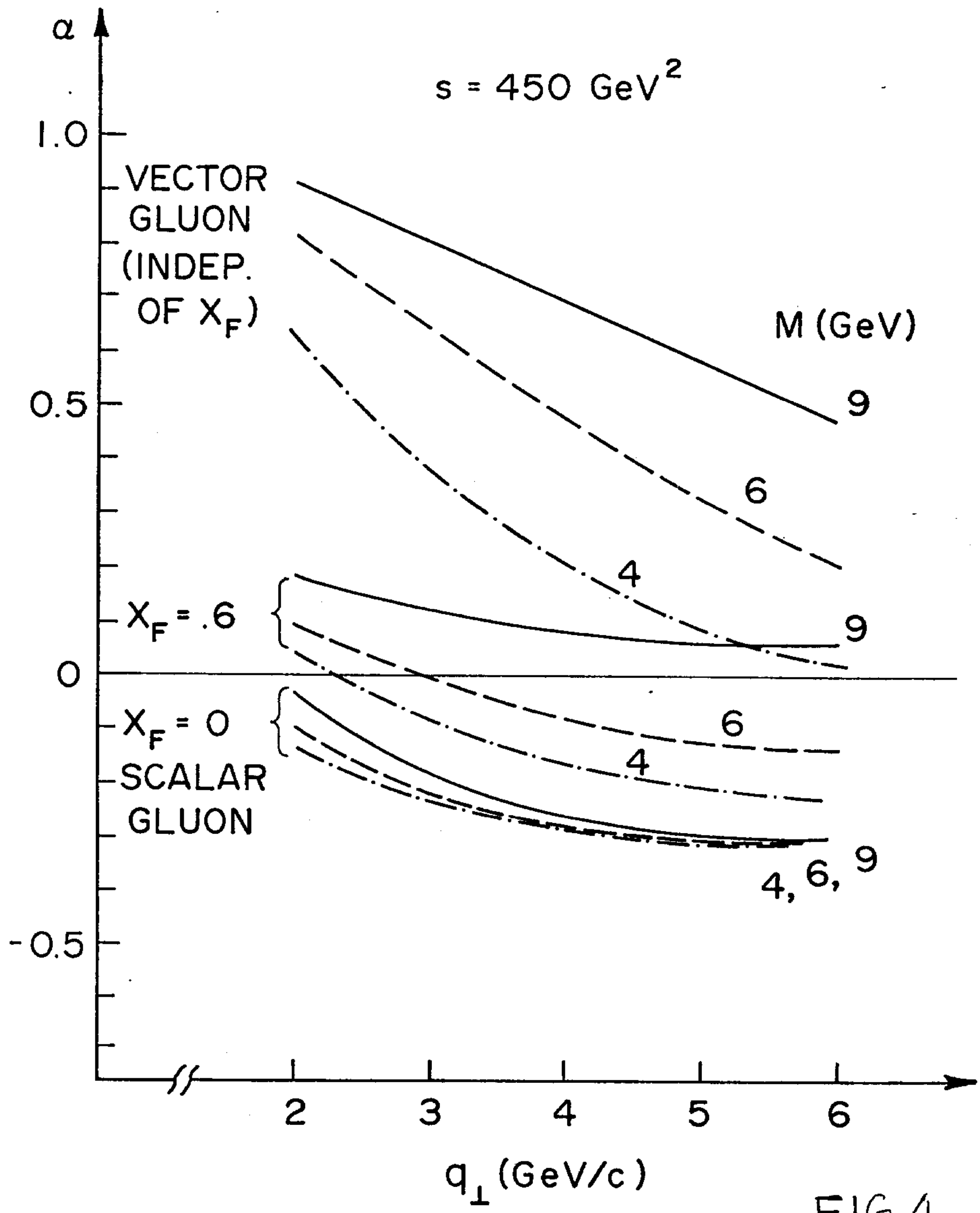

α
s = 450 GeV²
1.0
0.5
0
-0.5
VECTOR GLUON (INDEP. OF X_F)
M (GeV)
9
6
4
X_F = .6
9
6
4
X_F = 0 SCALAR GLUON
4, 6, 9
2
3
4
5
6
q⊥ (GeV/c)

FIG. 4