Evidence for Longitudinal Photon Polarization in Muon-Pair Production by Pions

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Data on μ-pair production by pions are examined as a function of x and P_T for longitudinal photon polarization. Evidence in the form of a $\sin^2\theta^*$ term in the helicity angular distribution is observed for x near 1. This is conclusive evidence that production in this region is not predominantly through on-shell quark annihilation. The result is consistent with a calculation based on quantum chromodynamics.

We have recently reported results from an experiment studying μ-pair production in hadron-hadron interactions.[1-3] Such data reflect the coupling of timelike virtual photons to hadrons in the same way that deep-inelastic lepton-nucleon scattering reflects the coupling of spacelike photons. In terms of structure functions which characterize the photon-hadron coupling, the cross section is[4]

$$E\frac{d\sigma}{dx_F\,dP_T{}^2\,dM\,d\Omega^*} = \frac{1}{8}\frac{1}{(2\pi)^3}\frac{e^4}{Ms^{3/2}}\left[W_T(1+\cos^2\theta^*)+W_L\sin^2\theta^*+W_\Delta\sin2\theta^*\cos\varphi^*+W_{\Delta\Delta}\sin^2\theta^*\cos2\varphi^*\right], \quad (1)$$

where the structure functions W can depend on pair mass (M), Feynman x (x_F), transverse momentum of the pair (P_T), and center-of-mass energy ($\sqrt{s}$). The angles θ^* and φ^* specify the μ^- direction in the pair rest frame. In the following analysis the reference direction for θ^* is taken as the beam direction (t-channel frame) unless otherwise noted.

In this expression, W_T and W_L are the structure functions for transverse and longitudinally polarized virtual photons, while W_Δ and $W_{\Delta\Delta}$ are the single-spin-flip and double-spin-flip structure functions which involve the off-diagonal density-matrix elements for the pair. The contribution of the last two terms is zero after integration over φ^* and, in this case, the angular distribution is $d\sigma/d\cos\theta^*\propto 1+\alpha\cos^2\theta^*$, where $\alpha=(W_T-W_L)/(W_T+W_L)$. Our published measurements[2] show that for πN interactions with M above the J/ψ the bulk of the production cross section is characterized by $\alpha\approx 1$, corresponding to transverse virtual photons. This Letter reports a detailed study of α in a variety of kinematic regions.

In the Drell-Yan process the longitudinal variables x_1 and x_2 specify the fractional momentum of the annihilating quarks from the beam and target hadrons, respectively. In terms of the μ-pair variables, we have $x_1-x_2=x_F$ and $x_1x_2=M^2/s$, neglecting quark masses and transverse momenta. We use x_1 below to facilitate model comparisons.

Figures 1(a)–1(d) show the measured angular distribution in four intervals of x_1 for all events with $M\geqslant 4$ GeV. After acceptance correction the mean mass of these data is 5 GeV and the mean transverse momentum is 1.2 GeV/c. In each x_1 interval the form $1+\alpha\cos^2\theta^*$ is a good representation of the data. The α coefficients and χ^2 values for the fits are given in Table I. The data have been corrected for the variation of efficiency with $\cos\theta^*$ which is shown as a dashed curve in Fig. 1.

The structure functions W and hence α depend on the reference frame for θ^*. To gauge the sensitivity of the result to the choice of reference direction, the analysis was repeated with use of the Collins-Soper frame[5] which, in the context of the quark-parton model, minimizes effects of

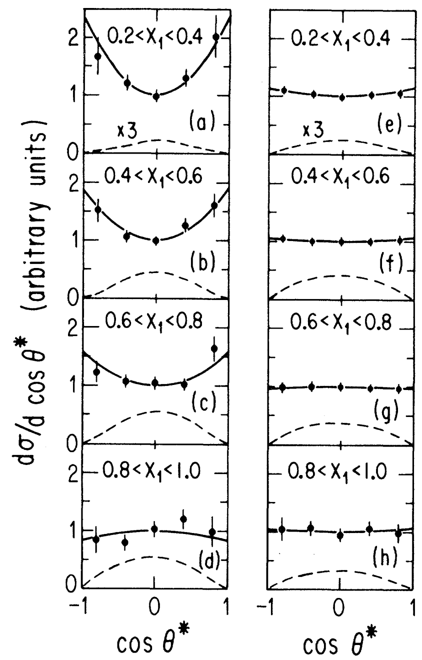

FIG. 1. $d\sigma/d\cos\theta^*$ in the t-channel helicity frame for various x_1 intervals. (a)–(d) Results for the mass continuum with $M>4$ GeV; (e)–(h) results for the J/ψ resonance in the same x_1 intervals. Data are integrated over P_T. The dashed curve shows the variation of detection efficiency with $\cos\theta^*$. The same arbitrary efficiency scale applies in each section of the figure except where noted.

the quark transverse momenta. The average angle between the t channel and Collins-Soper directions is 14° for $M>4$ GeV. The results of this analysis are also given in Table I.

The α coefficients are plotted versus x_1 in Fig. 2 and a clear departure of α from +1 is seen at high x_1. This indicates that W_L is comparable to W_T in this region. The conclusion is independent of the choice of reference frame. The model prediction shown in Fig. 2 is discussed below.

For comparison, Figs. 1(e)–1(h) give the angular distributions for the J/ψ resonance. They are strikingly different from the continuum. No evidence for spin alignment of the resonance is seen in any x_1 interval. Since the variation of detection efficiency with $\cos\theta^*$ is comparable in the two mass regions, this is strong evidence that the resonance and continuum production mechanisms differ and that we are sensitive to the differences.

The stability of α-vs-x_1 dependence of the J/ψ data demonstrates that systematic effects are not leading to the change in α at large x_1 in the continuum data. We have examined the acceptance in φ^* vs x_1 of the experiment and conclude that the observed effect cannot be accounted for by the W_Δ or $W_{\Delta\Delta}$ terms. No correlation is seen in $\langle p_T\rangle$ and x_F in the data.[1] If we divide the data into two p_T intervals, no large correlation with p_T is observed in α vs x_1.

To understand the significance of these results we note that the annihilation of two on-shell, massless, spin-$\frac{1}{2}$ fermions (quarks) traveling along the polar axis of the coordinate system leads to $W_L=W_\Delta=W_{\Delta\Delta}=0$ in Eq. (1) and hence $d\sigma/d\cos\theta^*\propto 1+\cos^2\theta^*$. A deviation from this distribution indicates either a different production mechanism or an effect due to the choice of coordinate systems.

The exact quark directions are unknown since only the sum of their transverse momenta is measurable. This leads to a slight modification of the angular distribution. For distributions integrated over P_T, the magnitude of the effect can be expressed[5] in terms of the measured quantities $\langle P_T{}^2\rangle$ and M. For the data reported here one expects $\alpha\sim 0.85$ in the Collins-Soper system independent of x_1 if the data arise from the annihilation of massless, on-shell quarks. We conclude that at high x_1 this is not the dominant production mechanism.

We have also looked for a variation of α with transverse momentum, integrating over x_1. Results are given in Table I. The value of α is plotted versus P_T in Fig. 3 for the continuum data. Evidence for longitudinal polarization is seen in the t-channel frame although the magnitude of the effect is reduced in the Collins-Soper system.

The source of μ pairs at high P_T has been suggested to be quantum chromodynamic (QCD) diagrams involving the annihilation of off-shell quarks and Compton-like processes.[6] The original motivation was to explain the unexpectedly large value of $\langle P_T\rangle$. There have been a number of calculations of the dependence of α on P_T. All predict that α should fall as P_T increases. The calculation from Kajantie *et al.*[7] is shown in Fig. 3 and is consistent with the data.

By examining the ratio $R\equiv\sigma(\pi^+C\to\mu^+\mu^-X)/\sigma(\pi^-C\to\mu^+\mu^-X)$ as a function of x_1 and P_T we can distinguish between quark-antiquark processes ($R<1$) and Compton-like terms ($R=1$). In our data this ratio reveals no strong dependencies on either x_1 or P_T and is 2 standard deviations below $R=1$.

Berger and Brodsky have considered the varia-

TABLE I. The results of fitting the data in different kinematic regions by the form $d\sigma/d\cos\theta^* \sim 1+\alpha\cos^2\theta^*$.

Mass interval (GeV)	P_T interval (GeV/c)	x_1 interval	t-channel axis α	χ^2/D [a]	Collins-Soper axis α	χ^2/D [a]
$M>4$	All	0.2–0.4	1.40 ± 0.50	1.1/3	2.09 ± 0.70	3.4/3
		0.4–0.6	0.88 ± 0.28	2.1/3	1.14 ± 0.35	3.8/3
		0.6–0.8	0.57 ± 0.28	2.9/3	0.85 ± 0.33	4.3/3
		0.8–1.0	−0.16 ± 0.32	4.0/3	−0.32 ± 0.32	6.2/3
J/ψ, $2.7<M<3.5$	All	0.2–0.4	0.13 ± 0.10	0.3/3	−0.21 ± 0.09	2.1/3
		0.4–0.6	0.06 ± 0.10	0.2/3	−0.05 ± 0.10	1.1/3
		0.6–0.8	−0.03 ± 0.11	0.2/3	0.04 ± 0.13	1.3/3
		0.8–1.0	0.06 ± 0.25	0.8/3	0.71 ± 0.46	0.9/3
$M>4$	0–0.5	All	1.55 ± 0.54	2.5/3	1.56 ± 0.52	3.1/3
	0.5–1.0		0.86 ± 0.31	4.9/3	1.18 ± 0.36	10.9/3
	1.0–1.5		0.93 ± 0.34	2.9/3	0.82 ± 0.37	1.8/3
	>1.5		0.07 ± 0.23	2.5/3	0.75 ± 0.40	1.4/3
J/ψ, $2.7<M<3.5$	0–0.5	All	0.03 ± 0.11	2.6/3	−0.01 ± 0.12	0.9/3
	0.5–1.0		0.08 ± 0.11	2.9/3	−0.09 ± 0.10	4.2/3
	1.0–1.5		0.00 ± 0.10	0.7/3	−0.30 ± 0.10	0.5/3
	>1.5		0.16 ± 0.11	2.3/3	−0.24 ± 0.14	2.4/3

[a] D is the number of degrees of freedom.

tion of α with x_1.[8] They point out that if the annihilation involves a quark from the pion with transverse momentum k_T and longitudinal momentum fraction x, then the quark is in general off shell with a squared four-momentum of[9] $-[k_T^2+xm_R^2-x(1-x)m_\pi^2]/(1-x)$, where m_R is the effective mass of the pion fragments other than the quark. Thus from kinematics alone, as $x\to 1$, a quark from the pion must be far off shell. This results in longitudinal photon polarization. The magnitude of the effect for their explicit model is shown as the smooth curve in Fig. 2.

This same model leads to a pion structure function of the form $x\bar{u}(x)\sim x[(1-x)^2+(2/9)\langle k_T^2\rangle/M^2]$. The first term is associated with a $1+\cos^2\theta^*$

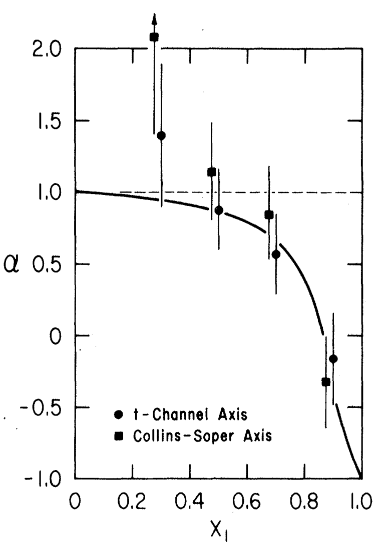

FIG. 2. The dependence of α on x_1 for data with $M>4$ GeV. The dashed line is the expected result for the naive Drell-Yan model. The solid curve is the QCD prediction of Berger and Brodsky (Ref. 8).

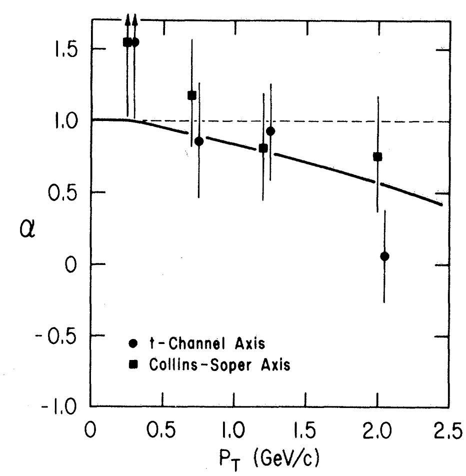

FIG. 3. The dependence of α on P_T for data with $M>4$ GeV. The smooth curve is the QCD prediction from Kajantie *et al.* (Ref. 7). These authors consider only $x_F=0$ while the data are integrated over x_F.

angular distribution while the second corresponds to a $\sin^2\theta^*$ component and is explicitly scale breaking. Our published data[3] are well represented by $x\bar{u}(x) \sim 1-x$. Fitting with the proposed form, we find satisfactory agreement (χ^2 probability 13%) and a value $\langle k_T^2 \rangle = 1.1 \pm 0.2$ $(\text{GeV}/c)^2$. However, replacing M^2 by a constant gives an equally good fit, indicating weak sensitivity of our data to the existence of a scale-breaking term. Better data are needed at high x to critically test this prediction.

In conclusion, we have observed direct evidence for longitudinal photon polarization in μ-pair production at large x. The magnitude of the effect is consistent with predictions based on QCD. Analysis of the φ^* distribution is continuing in an attempt to understand this effect in more detail.

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[9]The analysis of Berger and Brodsky actually uses the light-cone variable $x_a = (E_a + P_{az})/(E_\pi + P_{\pi z})$. Since x_a involves the quark mass m_q and transverse momentum k_T it is not directly measurable. We use the longitudinal variable x_1 instead of x_a in the present analysis.

New Approach to Transitions from Bound to Continuum Three-Nucleon States: The Case of Muon Capture by a Triton

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A new approach to the problem of the transition of an $A=3$ ground state to scattering states via a weakly acting Hamiltonian is presented; calculations are made feasible with realistic nucleon-nucleon potentials. Muon capture by ^{3}H leading to three neutrons is taken as a test case and is carried through till numerical results are obtained.

The action of electromagnetic and weak fields upon ^{3}He and ^{3}H in their ground states has been the subject of many investigations.[1] While these processes may leave the target ^{3}He-^{3}H in its ground state (e.g., $\mu^- + {}^3\text{He} \to {}^3\text{H} + \nu_\mu$, $e^- + {}^3\text{H} \to e^- + {}^3\text{H}, \ldots$) they also may give rise to unbound final nuclear states (e.g., $\mu^- + {}^3\text{He} \to n + n + p + \nu_\mu$, $\gamma + {}^3\text{He} \to d + p, \ldots$). In these latter cases, complexity due to the dynamics of the three-body continuum has prevented investigators so far from taking full advantage of available data. This Letter presents an approach to this question from a new point of view.

These problems, e.g., transitions of an $A=3$ ground (bound) state $|\varphi_{\text{bd}}\rangle$ to a final scattering state of nucleons $|\psi_{\text{sc}}\rangle$ via a weak perturbation H_w, had been initiated by Aaron, Amado, and Yam[2]; several authors applied it to photodisin-

