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FEATURES OF POSSIBLE POLARIZED PHOTON BEAMS AT HIGH ENERGY AND CORRESPONDING PHYSICS PROGRAMME or THE PROTON STRUCTURE FUNCTION USING REAL PHOTONS*

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ABSTRACT

In the range of electron energies available at Fermilab, 100 GeV $\leq E \leq$ 500 GeV, coherent Bremsstrahlung in crystals, particularly diamond, gives a huge enhancement to the equivalent photon spectrum at large values of x where $x = k/E$. The photons in this enhancement are polarized. Requirements on electron beam energy spread, angular divergence and spot size imposed by the use of a diamond as a radiator are discussed. The physics program emphasizes hard processes and tests of QCD using polarization.

INTRODUCTION

Consider an incident electron of energy E which radiates a photon of energy k in the field of a nucleus leaving a residual electron of energy E-k.

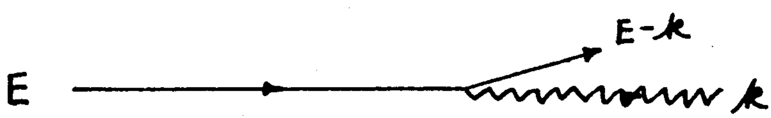

Fig. 1

For an ordinary amorphous radiator the photon yield per incident electron is

$$dN = t \times dk/k \times F(x)$$

where t is the radiator thickness in radiation lengths and $x=k/E$. For thin radiators,

$$F(x) = [1 + (1-x)^2 - 2/3\ (1-x)] \cong 1.$$

It is also a customary to write these expressions as

$$k\ dN/dk = t \times F(x)$$

The quantity $k(dN/dk)$ is called the spectrum of "equivalent photons".

The actual number of photons produced at high energies is proportional to $1/k$ and thus decreases with increasing photon energy. In order to get more photons, the radiator thickness can be increased. However, for radiator thicknesses ≥ 0.10, the high energy photon yield is decreased because the infra-red divergent low energy photon tail causes the energy of the incident electron beam to degrade as it passes through the radiator.[1] Furthermore, multi-photon emission increases; and loss of photons via conversion in the radiator becomes significant.

How can the yield of high energy photons be increased?

In the Fermilab-Tevatron energy range of $100 \leq E \leq 500$ GeV, coherent Bremsstrahlung in crystals, particularly diamond, can be used to obtain a huge enhancement of the equivalent photon spectrum at large x.

PRINCIPLES OF COHERENT BREMSSTRAHLUNG

The principles and practices of coherent Bremsstrahlung in crystals are very clearly and lucidly described in the literature.[2] They can be most simply understood in terms of the minimum momentum transfer to the nucleus. The minimum momentum transfer occurs when the outgoing electron and photon (Fig. 1) are both collinear with the incident electron:

$$q_{min} = q_L \equiv \delta = \frac{m^2}{2E} \frac{x}{1-x}$$

where m is the electron mass.

Thus the minimum momentum transfer is longitudinal, or parallel to the direction of the incident electron. If either of the outgoing particles has transverse momentum, the momentum transfer to the nucleus is increased and in general also has a transverse component. Coherent Bremsstrahlung in a crystal occurs when the total momentum transfer vector $\vec{q}$ equals a characteristic momentum of the reciprocal lattice.[3]

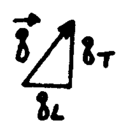

Fig. 2a

$$\vec{q} = 2\pi/a \, (H\hat{i} + K\,\hat{j} + L\,\hat{k})$$, where H, K, L are integers.

We plot a few reciprocal lattice points in momentum space, and consider an electron incident in the 100 direction ($\hat{i}$ axis):

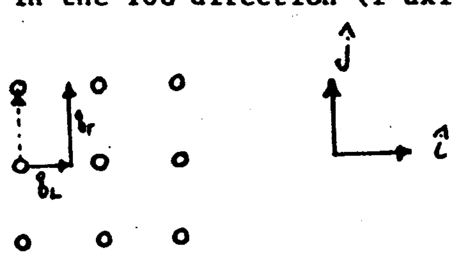

Fig. 2b

For a q_T corresponding to the 010 reciprocal lattice point, coherence can occur at $q_L = 0$ (dashed arrow). This will cause the beam to blow up into an infinity of zero energy photons. Thus the crystal must be tilted so that q can equal a lattice momentum for $q_L \neq 0$.

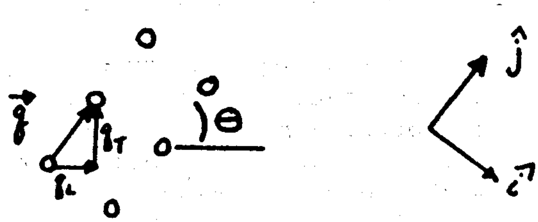

Fig. 3

Obviously, the crystal must be tilted in two directions to avoid the same effect in the other plane (i,k). In terms of the polar and azimuthal angles (θ,ψ) of the rotated crystal i axis about its original direction:

$$q_L = \sin\theta\ (K\cos\psi + L\sin\psi).$$

Typically, the rotation of the crystal is obtained by first aligning the crystal axis with respect to the beam and then tilting the crystal about the horizontal axis by a small angle θ_H and turning it about the vertical axis by a small angle θ_V. In order to prevent ψ from swinging wildly due to small changes in these angles, one of these small angles must be made much larger than the other one.

TYPICAL BEAMS POSSIBLE AT FERMILAB

The equivalent photon spectra from electrons of 150 GeV or 450 GeV incident on a diamond or silicon crystal radiator are shown in Figures 4, 5 & 6. The beam is incident along the 100 axis of the crystals, with the 010 axis at an azimuthal angle of 44.75˚. The crystal mount is turned by 200 mrad about the vertical axis and tilted 1.25 mrad about the horizontal axis. For 150 GeV incident a huge coherent peak at x = 0.80 is observed which is about 3.5 times better for diamond than for silicon.

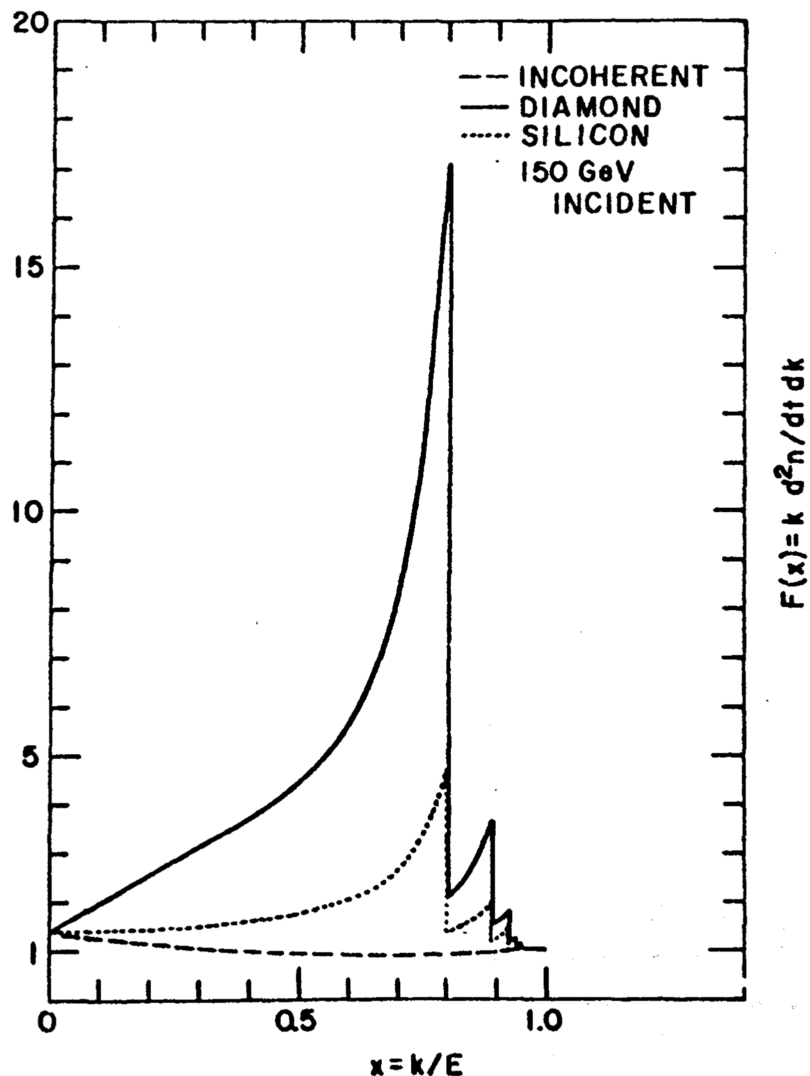

Fig. 4

For 450 GeV electrons the coherent peak remains the same height and moves out to x = 0.92. Neither the angular divergence of the beam nor the mosacity of the crystals has been included in these figures. However, Figure 6 shows the effect of variations of θ_V and θ_H typical of the Fermilab beam divergence.[4] (Table I). The polarization of the beam is given on this figure.

The following conclusions can be drawn:

i) The effect is not sensitive to incident energy and has the nice feature that the x of the coherent peak increases with increasing electron energy so that you win twice. The energy of the coherent photons increases faster than the incident energy.

ii) The effect is very sensitive to the beam angular divergence but is ok at Fermilab if the beam has no tails. Only one angular divergence of the beam is required to be small.

iii) Diamond is 3 times better than silicon. However, the use if a diamond implies that the beam spot size at the radiator must be very small.

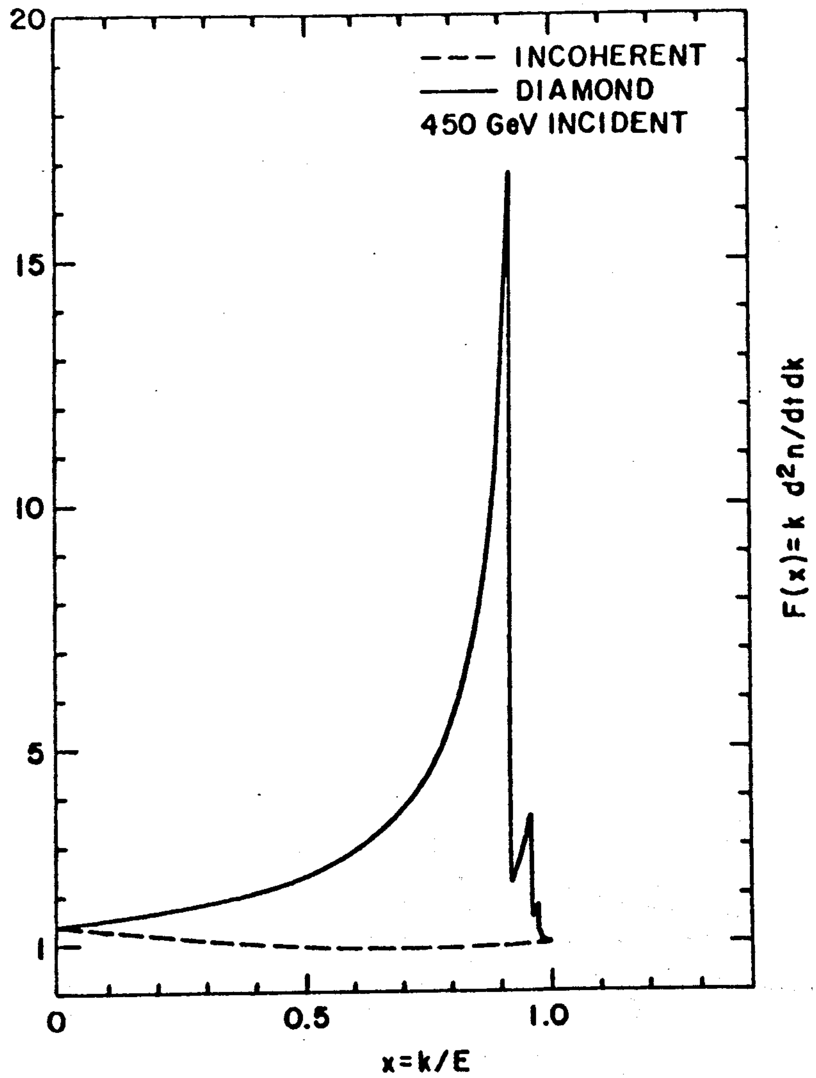

Fig. 5

Table I
Size of Fermilab Electron Beam

	$\Delta\theta$ mrad	Full Size Dimension At Target mm	90' Downstream Equivalent to Full Size At Radiator 90' Upstream mm
DOUBLET			
HORIZ	± 0.44	4.6	25.4
VERT	± 0.14	6.9	6.1
TRIPLET			
HORIZ	± 0.61	8.4	33.9
VERT	± 0.17	8.3	9.0

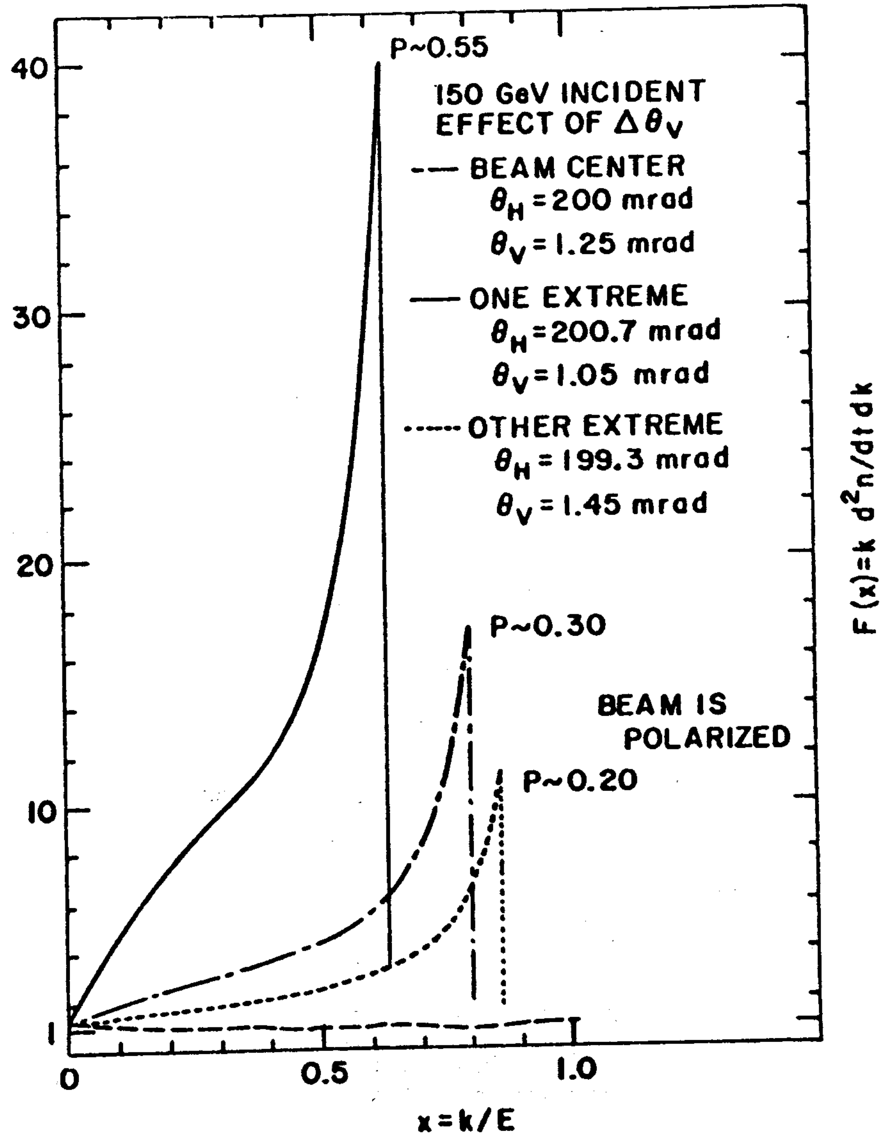

Fig. 6

PRACTICAL CONSIDERATIONS

In order to see what this means in practical terms, an exploded view of a diamond octohedron showing the crystal axes is given in Figure 7. (This fixture comes from Roy Schwitters' thesis.) The sizes of the diamond octahedra as a function of the dimension of an edge are given below.

TABLE II

Sizes of Diamond Octahedra ρ = 3.53 1gm = 5 carats

Edge Dimension mm	Point-to-Point Distance mm	Weight Carats
7.0	9.9	2.85
8.0	11.3	4.26
8.5	12.0	5.11
10.0	14.4	8.32

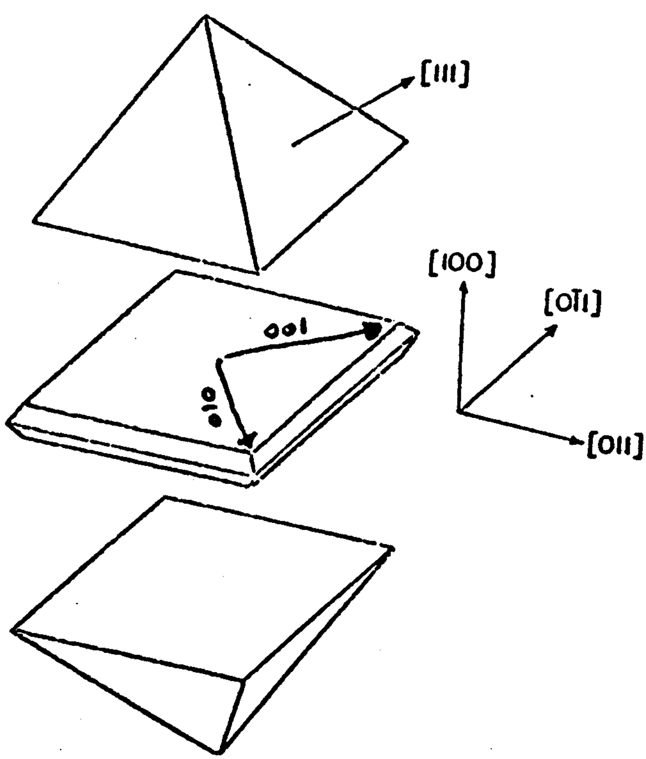

Fig. 7

The most reasonable size is 8.5 mm on an edge or 5.1 carats. Miraculously with the orientation specifed above for Figs. 4, 5, & 6, two such diamonds would be decently matched to the Fermilab beam spot size. A beam eye view of the radiator is:

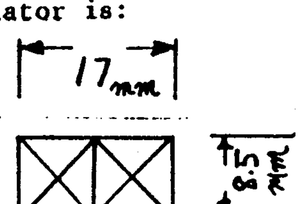

Fig. 8

Note that if the beam could be focused on the radiator instead of on the target (90' further down stream) then only one diamond would be required.

ADVANTAGES OF A COHERENT BEAM

Depending on the exact details of the mosaicity and dimensions of available diamonds, and the spot size of the beam at the radiator, the coherent Bremsstrahlung beam using a diamond radiator might actually produce more high energy photons than obtainable with a conventional thick radiator. For instance the beam shown in Figure 4, with a diamond radiator 6 mm thick, will produce the number of equivalent photons corresponding to an amorphous radiator 0.22 radiation lengths thick, averaged over the whole spectrum. However, the number of high energy equivalent photons, $x > 0.5$, produced corresponds to a 0.30 thick radiator, while the low energy photons $x < 0.5$, corresponds to a 0.12 thick radiator. Note that these values are averaged over the respective x intervals. At the discontinuity point, $x=0$, there is no coherent enhancement so the radiator appears to have its incoherent thickness of 0.05 radiation lengths. If the degrading[1] of the beam is governed only by the apparent radiation length at $x = 0$, then the thick target Bremsstrahlung corrections for the coherent beam will be much less than the thick target corrections for amorphous radiators. This point remains to be checked quantitatively.

In summary, the coherent photon beam at Fermilab energies has three nice features when compared to conventional beams:

i) The photon spectrum is strongly peaked at high energy.
ii) There are fewer low energy photons per high energy photon by a large factor.
iii) The photons in the coherent peak are linearly polarized.

PHYSICS PROGRAMME

My original motivation for trying to obtain increased yields of high energy photons, was to study "hard" or large transverse momentum processes induced by photons. In proton-proton collisions, particle production at large transverse momentum (P_T) has a very strong center-of- mass energy ($\sqrt{s}$) dependence.[5] The invariant cross section for inclusive π° production near 90° in the c-m system follows the form

$$E\, d^3\sigma/dP^3 \sim P_T^{-8.6}\,(1-x_T)^{10.6} \quad \text{For} \quad 3 \le P_T \le 7 \text{ GeV/c}$$

and

$$\sim P_T^{-5.1}\,(1-x_T)^{12.1} \quad \text{For } 7.5 \le P_T \le 14 \text{ GeV/c}$$

where $x_T = 2P_T/\sqrt{s}$. The x_T dependence is characteristic of the structure functions of the constituents in both protons while the P_T dependence is characteristic of the force law governing the constituent scattering.

A very important issue in hadron initiated large P_T reactions is whether and how often direct single γ rays are produced. The experiments[5] are very difficult because of the fierce background of photons from the decays of the more dominantly produced hadrons. The theoretical interest arises from the prediction[6] of the constituent reaction:

Quark + Gluon ------→ Quark + Photon
Also known as the "QCD Compton Effect"

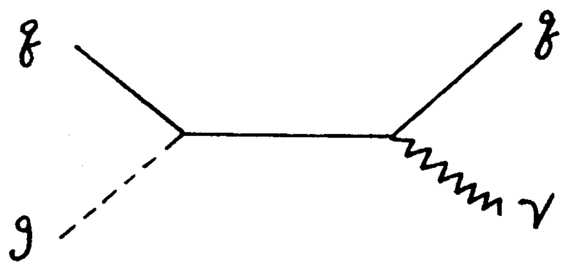

Fig. 9

The exact same reaction can be studied using incident photons. The principal advantage is that you are certain of the identity of the incident photon. Parenthetically, the field of large P_T reactions initiated by photons has hardly, if at all, been studied.

In the jargon of the field[7], there are two classes of photon initiated large P_T events: three jet events and four jet events. The three jet events represent the QCD Compton effect:

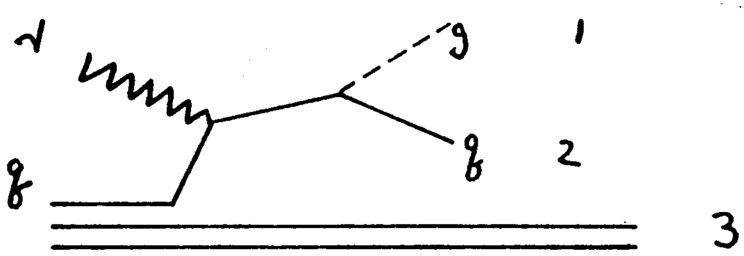

Fig. 10

The four jet events come from the "photon structure function", i.e., the photon acts like a source of q $\bar{q}$ pairs:

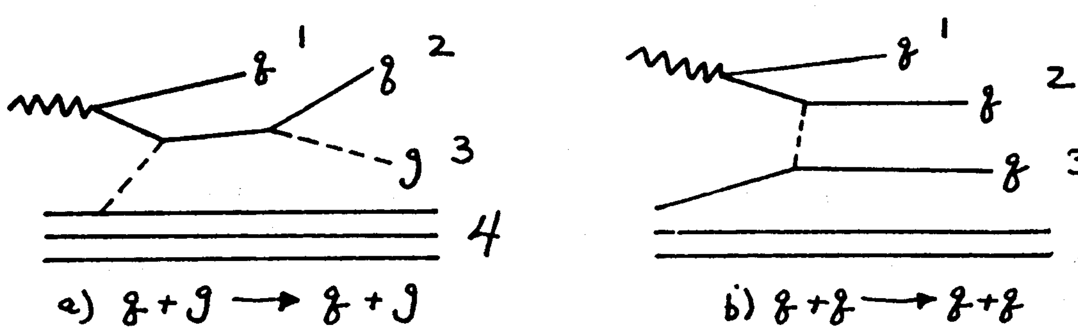

Fig. 11

In Fig. 11a) a quark from the photon structure function scatters from a gluon inside the nucleon; in Fig. 11b a quark from the photon scatters from a quark in the nucleon. Obviously there are even more complicated topologies to consider. Note that in Figures 11a and b the lines labelled 2 and 3 represent high P_T jets while lines 1 and 4 represent low P_T beam and target jets. In the three jet events of Figure 10, the beam jet is absent.

Owens[7] has calculated the cross sections for these reactions in great detail. I have taken the liberty of parameterizing his calculations for jet production by photons near 90° c-m by the simple form:

$$E \frac{d^3\sigma}{dp_3} \cong 1.8 \times 10^{-29} \text{ cm}^2/\text{GeV}^2 \; P_T^{-5.1} \; (1-x_T)^{2.5}$$

The predicted $\sqrt{s}$ dependence is much less than that observed in proton-proton collisions and is a consequence of the pointlike nature of the photon. If this slow $\sqrt{s}$ dependence were indeed observed, it would be a marvelous confirmation of the theory but would also have the practical consequence of lessening the need for the highest energy photons and thus allowing higher rates and higher polarizations to be achieved.

The three-jet events test QCD in a very fundamental way and have several very important properties. If the incident photon energy is known, then the kinematics of the two high P_T jets is constrained so that the 3-jet events can be uniquely separated from the 4-jet events. If the QCD constituent Compton cross section is considered as "known", then the proton structure function can be determined from the observed rate of 3-jet events. (Or vice vèrsa.) Finally, and most relevant to this conference, there are polarization effects which are said to provide "A rigorous test of perturbative QCD as well as an important check on the color hypotheses".[8]

In QED, the well known effect in pair production by polarized photons is that the plane of the produced e^+e^- pair tends to lie parallel to the plane of the incident photon polarization. In QCD, all the polarization effects are said[8] to vanish in lowest order to the extent that the quark mass is zero. Thus, QCD polarization effects are sensitive to higher order processes, in particular the three-gluon coupling, and are predicted[8] to be opposite in sign to the QED correlation.

For reactions like charmed particle pair photoproduction which involve heavy quarks[9], lowest order polarization effects are large and provide different QCD tests. For vector gluons, the asymmetry correlation is like QED, for scalar gluons it has the opposite sign, and for pseudoscalar gluons it is zero.[9] Regardless of the theoretical details[10] the observation of a correlation between the electric field direction of an incident photon and the plane of outgoing hadron states from a "hard" collision would be striking confirmation of the constituent composition of protons and the intimate connection between electromagnetism and strong interactions.

ACKNOWLEDGMENTS

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