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POLARIZATION EFFECTS OF SUPERSYMMETRIC QCD IN LARGE-P_T DIRECT PHOTON PRODUCTION

I. ANTONIADIS

Centre de Physique Théorique de l'Ecole Polytechnique
91128 Palaiseau Cedex, France

and

A.P. CONTOGOURIS

Physique Théorique et Hautes Energies
Université Paris VII, France

ABSTRACT

The linear polarization P (∿ perpendicular minus parallel to the scattering plane) of large-p_T direct photons from unpolarized hadrons is considered. Contrary to standard QCD, where to O(1) P vanishes, and to $O(\alpha_s)$ P is very small and changes sign at angle $\theta_{cm} = 90°$, it is shown that supersymmetric theories (involving squarks and light gluinos), already to O(1), imply a substantial and positive P through a wide range of angles including $\theta_{cm} = 90°$. For $\bar{p}p \to \gamma + X$ at collider energy and $p_T \gtrsim 30$ GeV, with squark mass 20 GeV we find P ∿ 10 % -5 % decreasing with p_T. We offer a qualitative understanding and discuss the significance of our results.

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In recent years supersymmetric (SUSY) theories have attracted much attention [1,3] ; the reasons, although mainly theoretical, are quite important [4]. It is therefore of interest to study the physical implications of, at least a certain class of, SUSY theories, and to advance detailed experimental tests.

Very recently, the standard QCD predictions, up to second order, regarding the scale violations of deep inelastic structure functions have been extended in the presence of light gluinos [5] and, for large values of Q^2, of squarks as well [6]. By an extension of the Altarelli-Parisi equations the gluino and squark distributions have been determined. Thus the standard QCD approach can be extended to include subprocesses involving such SUSY partons.

Here we consider hadroproduction of large transverse momentum (p_T) direct photons ($A+B \to \gamma+X$). It is well known that in standard QCD this is well described by [7,8]

$$q + g \to \gamma + q \qquad\qquad q + \bar{q} \to \gamma + g \tag{1}$$

Now consider the linear polarization of the outgoing photon

$$P = \frac{|M_\perp|^2 - |M_\parallel|^2}{|M_\perp|^2 + |M_\parallel|^2} \tag{2}$$

where $M_\perp$ ($M_\parallel$) denotes the amplitude for γ to be polarized perpendicular (parallel) to the scattering plane. With unpolarized initial hadrons and massless quarks, $P = 0$ to $O(1)$ (leading order in α_s). To $O(\alpha_s)$, due to loop graph contributions, P is nonzero (but rather small, see below). However, even to this order, $P = 0$ at c.m. scattering angle $\theta = 90°$; in particular, P changes sign as θ varies [9].

Our purpose is to show that, *already to O(1)* (Born amplitudes), supersymmetric QCD (SQCD) implies a sizable polarization P for a wide range of angles, *including* $\theta = 90°$. In particular, $P > 0$ throughout this wide range.

We define the subprocess Mandelstam variables (Fig. 1(a)) :

$$s = (p_1 + p_2)^2 \qquad t = (q - p_1)^2 \qquad u = (q - p_2)^2 \tag{3}$$

To simplify notation we write the subprocess cross section :

$$\frac{d\sigma}{dt}(s,t) = \pi \alpha \alpha_s \sigma(s,t) \tag{4}$$

($\alpha = 1/137$), and denote by $\sigma_\Delta(s,t)$ the difference of the corresponding quantities for photons polarized perpendicular and parallel to the scattering plane

$$\sigma_\Delta(s,t) = \sigma_\perp(s,t) - \sigma_\parallel(s,t) \tag{5}$$

We use the Lagrangian [6,10]

$$\begin{aligned} \mathcal{L} = & -\frac{1}{4} G^a_{\mu\nu} G^a_{\mu\nu} + i\bar{q}_i \not{D} q_i + \frac{i}{2} \bar{\lambda}^a \not{D} \lambda^a + (D_\mu s_i)^+ (D_\mu s_i) \\ & + (D_\mu t_i)^+ (D_\mu t_i) + ig\sqrt{2} \, (\bar{\lambda}_a \frac{1+\gamma_5}{2} s_i^+ T_a q_i + \bar{\lambda}_a \frac{1-\gamma_5}{2} t_i^+ T^a q_i - \text{h.c.}) \\ & - \frac{1}{2} g^2 (s_i^+ T^a s_i - t_i^+ T^a t_i)^2 + \text{mass terms} \end{aligned} \tag{6}$$

where $G^a_{\mu\nu}$ is the gluon field strength, q_i and λ^a stand for quark and gluino fields, s_i and t_i for s- and t-squark fields, D_μ is the covariant derivative, i runs over flavors, a the color index and T_a the SU (3) generators in the fundamental representation. We assume that the s- and t-squarks are degenerate with mass M, and subsequently we denote by s both types of them. We also take the gluinos as Majorana fermions.

For the subprocess $g+s \to \gamma+s$ (Fig. 1(a)) we find, including group factors :

$$\sigma_\Delta = \frac{10}{3}\,\frac{t(us-M^4)M^2}{(s-M^2)^4\,(u-M^2)^2} \qquad \sigma = \frac{5}{3}\,\frac{1}{(s-M^2)^2} - \sigma_\Delta \tag{7}$$

and for $q+\bar{s} \to \gamma+\lambda$

$$\sigma_\Delta = \frac{16}{9}\,\frac{(us-M^2m^2)(M^2-m^2)}{t(s-M^2)^2\,(u-M^2)^2} \qquad \sigma = \frac{8}{9}\,\frac{m^2-s}{t(s-M^2)^2} - \sigma_\Delta \tag{8}$$

where m is the gluino mass. We are subsequently restricted to $m \lesssim 4$ GeV. For $q+\lambda \to \gamma+s$ the contribution is obtained from (8) by $u \leftrightarrow s$ crossing the amplitudes (Fig. 1(a)) and replacing the factor 16/9 (8/9) by 2/3 (1/3).

Some care is needed in the running coupling constant $\alpha_s(Q^2)$ entering the contributions (4) - (8) [5]. We use

$$\alpha_s(Q^2) = \frac{4\pi}{\beta\,\log(Q^2/\tilde{\Lambda}^2)} \tag{9}$$

Above the squark (and gluino) threshold the β-function :

$$\beta = 11 - \frac{2}{3}N_f - 2 - \frac{1}{3}N_f \tag{10}$$

where N_f is the number of flavors, and -2 and $-\frac{1}{3} N_f$ are the contributions of gluinos and squarks. $\tilde{\Lambda}$ is obtained from the standard QCD scale Λ by matching $\alpha_s(Q^2)$ at each threshold [5]. We use $\Lambda = 0.4$ GeV, and above the squark threshold $N_f = 6$.

For the contribution $Ed\sigma_\Delta/d^3p$ to the physical process $A+B \to \gamma+X$ from σ_Δ of the subprocess $ab \to cd$, we first replace s, t, u by the usual $\hat{s}$, $\hat{t}$, $\hat{u}$; e.g. for (7), (8) :

$$\hat{s} = x_a x_b \frac{s}{2} + x_a \left(x_b^2 + \frac{4M^2}{s}\right)^{1/2} \frac{s}{2} + M^2$$
$$\hat{t} = -x_a x_T \frac{s}{2} \tan\frac{\theta}{2} \qquad (11)$$

where now $s = (p_A + p_B)^2$, $x_T = 2p_T/\sqrt{s}$ and x_a, x_b are momentum fractions ; then σ_Δ is multiplied by the parton distributions $F_{a/A}(x_a, Q^2)$, $F_{b/B}(x_b, Q^2)$ and integrated. For squarks and gluinos these are given in Refs[5, 6]. The polarization P is obtained by dividing $Ed\sigma_\Delta/d^3p$ by $Ed\sigma/d^3p$ of $A+B \to \gamma+X$.

The calculation is carried for $\bar{p}+p \to \gamma+X$ at $\sqrt{s} = 540$ and $M = 20$ GeV. To estimate the magnitude of P we determine $Ed\sigma/d^3p$ in terms of the standard subprocesses (1). For gluons and quarks we use the complete set of CDHS distributions including their scale violations [11]. We mention that the resulting $Ed\sigma/d^3p$ for $\bar{p}p \to \gamma+X$ is in agreement with preliminary data of the UA2 Collaboration in the range $15 \lesssim p_T \lesssim 30$ GeV (γ/jet $\sim 10^{-3}$) [12]. For $Ed\sigma_\Delta/d^3p$ we use the same gluon and quark distributions.

To lowest order in α_s there is a well-known ambiguity in the choice of the large variable Q^2. In Figs 1(b) and 2 we present results with $Q^2 = \hat{s}$ and comment below on other choices.

Fig. 1(b) shows the contributions $Ed\sigma_\Lambda/d^3p$ of the SQCD subprocesses involved. It is remarkable that the contribution of $q\lambda \rightarrow \gamma s$ is way below the other two, and decreases very fast with p_T compared to $q\bar{s} \rightarrow \gamma\lambda$. The reason is that the gluino distribution decreases very fast with X [5,6]. This is in contrast with the squark distribution, which contains a valence part that decreases much slower [6] ; we discuss below the significance of this point. The contribution of $gs \rightarrow \gamma s$ decreases faster than of $q\bar{s}\rightarrow\gamma\lambda$; this is due to the steepness of the gluon distribution as compared to the quark valence [13].

Fig. 2 shows our results on the polarization P. Clearly SQCD implies a sizable P even at p_T as large as 80 GeV. In the same figure we plot the QCD prediction of Ref.[9](their Eq. (4) and Fig. 2) calculated at p_T = 45 GeV with $Q^2 = 2p_T^2$ and Λ = 0.4 GeV ; it is well below the corresponding SQCD. More important, consider the average polarization <P> in the range $60° \lesssim \theta \lesssim 120°$; QCD predicts <P> $\sim$ 0 almost independently of p_T ; SQCD predicts <P> $\sim$ 10 – 3 %, depending on p_T.

The order of magnitude and the dependence on p_T of P are understandable : First, our SQCD polarization is a mass effect, due to the (large) squark mass M (see Eqs. (7), (8)) ; this allows some helicity flip even to the lowest order in α_s. Thus, roughly, at the subprocess level, $\hat{P} \sim M^2/\hat{s}$ or $\hat{P} \sim M^2/(-\hat{t})$. With $X_a \sim X_b \sim X_T$ [14], this becomes $\hat{P} \sim M^2/p_T^2$. Now in the range of X of interest, the squark distribution (with which Eqs (7) and (8) are convoluted to obtain $Ed\sigma_\Lambda/d^3p$) is, roughly, 10 –15 % of the quark and gluon distribution [6]. When p_T is not much larger than M, this finally implies P $\sim$ 10 %. As p_T increases, P decreases.

Regarding the choice of the large variable Q^2, for $p_T \lesssim 30$ GeV (not far from M), the results are quite sensitive ; however, for $p_T \gtrsim 40$ GeV they are fairly stable [15].

One may ask whether other sources, hitherto neglected, may produce polarizations comparable to those of Fig. 2. First, higher twist effects [16] should be reasonably discarded at such high energies and p_T. A top quark (t), if it exists, should generally produce $P \neq 0$. Unfortunately, t-distributions are not available, so a detailed calculation cannot be carried out. However, we may speculate that the t-distribution in the nucleon would fastly decrease with X, since the t's may exist only in the sea ; this is in contrast to the total squark distribution. In addition, the t represents only one flavor, whereas the squark appears in several [5,6,10]. Thus we may anticipate that t polarizations will be significantly lower.

Finally, one may wonder why in SQCD polarizations are sizable (a few percent) even at p_T as large as 80 GeV (in fact, at such p_T our results are quite stable against various choices of Q^2). The reason, already stated, is that the squark distribution contains a valence part, which, although small, does not steeply fall with X [6]. But then, observation of the polarization effects of Fig. 2 will be an important verification of the short distance structure of SQCD. Of course, we are well aware of the practical difficulties of such an experiment.

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[13] The CDHS gluon distribution [11] is $\sim (1+3.5\,X)(1-X)^{5.9}$ at $Q_o^2 = 5\ \mathrm{GeV}^2$.

[14] This region is known to give a dominant part in the integral expressing $E d\sigma/d^3p$ in terms of $d\sigma/d\hat{t}$ [8].

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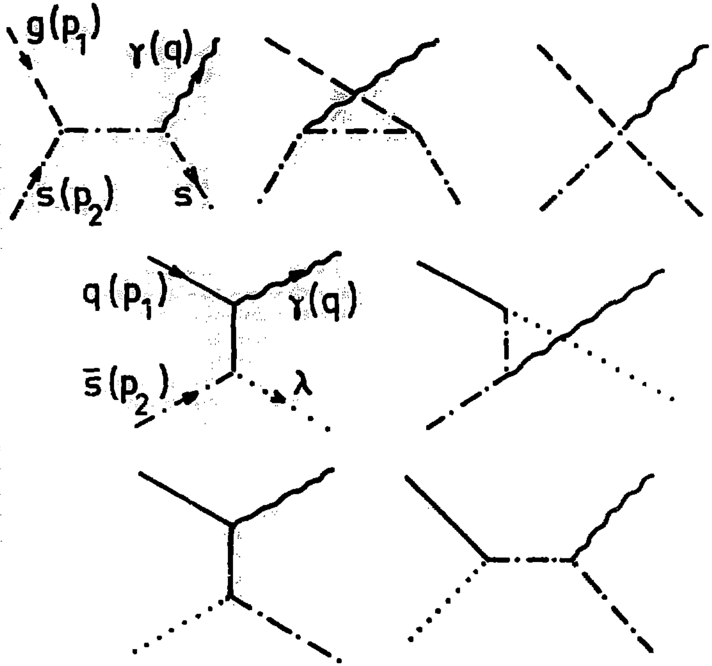
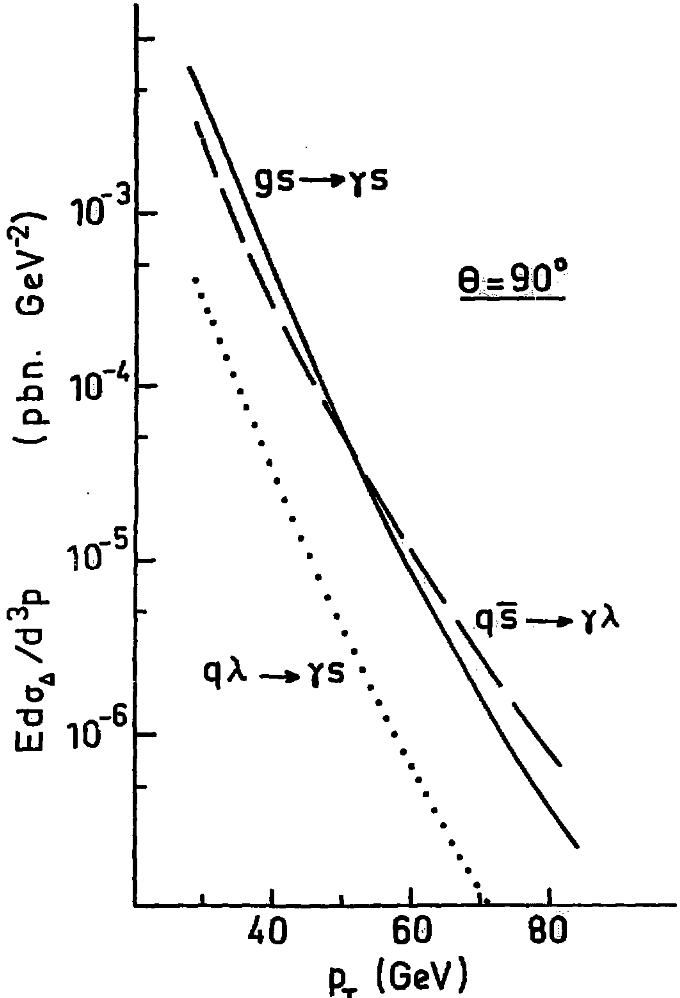


g(p1)
γ(q)
s(p2)
s
q(p1)
γ(q)
s̄(p2)
λ

Fig. 1(a)



gs → γs
θ = 90°
q s̄ → γλ
qλ → γs
10-3
10-4
10-5
10-6
Edσ/d3p (pbn. GeV-2)
40
60
80
pT (GeV)

Fig. 1 (b)

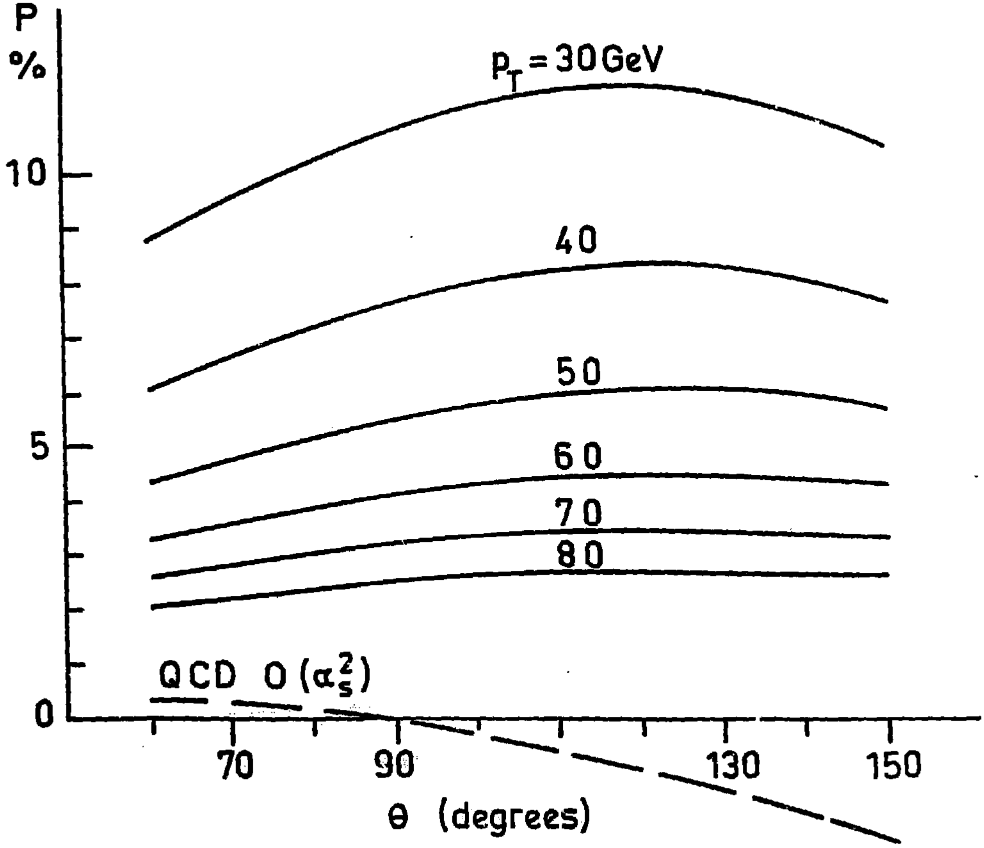

P
%
$p_T = 30\,GeV$
40
50
60
70
80
10
5
0
QCD $O(\alpha_s^2)$
70
90
130
150
θ (degrees)

Fig. 2