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SUPERSYMMETRY IN TWO-PHOTON PROCESSES

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A B S T R A C T

The effects of supersymmetry are studied in two - photon processes in particular for the photon structure function F_2^γ. Supersymmetry not only significantly influences the x dependence of F_2^γ but the direct production of scalar quarks also has pronounced effects in $F_2^\gamma(x,Q^2)$. In the threshold region such effects should be observable at LEP provided squark masses are not larger than of order $m_{W^\pm}/2$; the absence of these effects puts lower limits on squark (slepton) masses.

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So far, supersymmetry (SUSY) is based on purely theoretical speculations [1)–3)] which, nevertheless, are very attractive and appealing because it may not only solve the "fine tuning" hierarchy problem of grand unified theories, but as a local gauge symmetry might lead also to a unification with gravity [4)]. It is clear that only detailed experiments will tell us whether there is some truth in it. Furthermore, the interest in the SUSY idea of combining fermions and bosons in common multiplets is enhanced by the belief that the supersymmetric partners (sparticles) of the standard familiar particles may be light enough to be discovered at LEP, HERA or even at the $\bar{p}p$ collider [1)–3)].

In present models of low-energy (global) SUSY these superpartners of known particles are expected to have masses typically less than a few hundred GeV although the theoretical expectations for their mass spectrum are very uncertain and depend entirely on the (arbitrarily chosen) way of how spontaneous symmetry breaking occurs [1),2),5),6)]. There are, however, two broad classes of spontaneous SUSY breaking [1)]: in the so-called 'D-type' models, where it is natural for SUSY breaking to occur at a low energy scale (TeV or less), one expects the masses of sleptons $(\tilde{\ell})$ and squarks $(\tilde{q})$, the scalar spin-0 partners of leptons and quarks, respectively, and of the fermionic gluino $(\tilde{g})$ partners of gluons to be

$$m_{\tilde{g}} < m_{\tilde{\ell},\tilde{q}} < \tfrac{1}{2} m_{W^\pm} \tag{1}$$

with $m_{\tilde{g}} = 0$ (few GeV), making squark and slepton production at LEP almost inevitable. In 'F-type' models, where masses are generated radiatively and are fed down from the SUSY breaking scale which may be larger than 10^{10} GeV, i.e., of $O(m_X)$, one expects in contrast to Eq. (1)

$$m_{\tilde{\ell}} \lesssim m_{W^\pm} < m_{\tilde{q}} < m_{\tilde{g}} = \mathcal{O}(1\ \mathrm{TeV}) \tag{2}$$

and there would be little hope of producing SUSY particles at LEP or HERA energies with a possible exception [7)] of light neutral shiggses which are mainly supersymmetric fermionic partners of Higgses. In view of these drastic ambiguities, the only reliable information so far on SUSY masses comes from PETRA experiments [8)], $m_{\tilde{\ell},\tilde{q}} \gtrsim 15$ GeV, and it is clear that, for the time being, only experiment can provide us with any further reliable information on the properties of SUSY particles.

As with almost any conceivable new object, e^+e^- machines are the best source of SUSY particles. It is well known that at LEP 2γ processes will become increasingly important [9)] because their cross-sections do not fall off with energy, as it is the case in the 1γ exchange process. The expected rates for the production of SUSY scalars at LEP are reasonable [10] provided their masses are not as large as anticipated in Eq. (2). In this letter, we concentrate on the pair production of squarks (as well as sleptons) in 2γ processes, in particular we calculate their contribution to the hadronic pointlike two-photon structure function $F_2^\gamma(x,Q^2)$ for energies in the squark threshold region, as well as for $Q^2 \gg 4m_{\tilde{q}}^2$. These effects can be dramatic, depending of course on the size of $m_{\tilde{q}}$, and should be observable at LEP. The absence of such signals, on the other hand, should provide us with stringent lower bounds on SUSY scalar masses.

In general, the photon structure function can be written as

$$F_2^\gamma(x,Q^2) = 2x\sum^f e_q^2\,(q^\gamma + \tilde{q}^\gamma) \tag{3}$$

where q^γ denotes the well-known [11] quark distribution in the photon (antiquarks are taken care of by the factor of two), to which we will turn later, and the photonic squark distribution $\tilde{q}^\gamma = \tilde{q}^\gamma(x,Q^2)$ always refers to the <u>sum</u> of s_q and t_q squarks, $\tilde{q} = s_q + t_q$, assuming that the SUSY scalar partners s_q and t_q of the left- and right-handed quarks, respectively, are degenerate in mass. In the threshold region where $Q^2 \not\gg 4m_{\tilde{q}}^2$ (i.e., no large logs) heavy particle production is expected to be adequately described by the lowest-order process $\gamma^*\gamma \to \tilde{q}\bar{\tilde{q}}$ shown in Fig. 1a. A straightforward calculation yields *)

$$\tilde{q}^\gamma(x,Q^2) = 3e_q^2\,\frac{\alpha}{2\pi}\Big\{\big[1-8x(1-x)+\tau x(1-x)\big]v + \big[2x(1-x)+\tau x(3x-1)+\tfrac{1}{2}\tau^2x^2\big]\ln\frac{1+v}{1-v}\Big\} \tag{4}$$

where

$$v = \big[1-4m_{\tilde{q}}^2/s_{\gamma\gamma}\big]^{1/2} = \big[1-\tau x/(1-x)\big]^{1/2}$$

with $\tau = 4m_{\tilde{q}}^2/Q^2$ and the factor of three is due to colour. The threshold condition for heavy squark (or slepton) production derives from the constraint $s_{\gamma\gamma} \geq 4m_{\tilde{q}}^2$, i.e.,

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*) The F_2^γ structure function is given by

$$F_2^\gamma = \frac{12x^3}{Q^2}\,p^\mu p^\nu W_{\mu\nu} - x\,g^{\mu\nu}W_{\mu\nu}$$

with the kinematics defined in Fig. 1a and $W_{\mu\nu}$ the dimensionless photonic tensor which defines the hadronic photon structure functions [see, for example, Ref. 12), p. 275 ff.].

$$\tau \leq (1-x)/x \tag{5}$$

in order to have a finite $\tilde{q}^\gamma$. Clearly, we are mainly interested in $\tau \lesssim 1$ in order to enable a sizeable squark production in the large x region where the hadronic non-pointlike VMD contributions are small [11),13)].

The quark contribution in Eq. (3) is well known [11)] in standard QCD but in a SUSY-QCD it will get modified substantially. Since the Born-box contribution in Fig. 2a contains already a large logarithm *), $q^\gamma_{BOX} = e_q^2 h_B(x) \ln Q^2/m_q^2$ with

$$h_B(x) \equiv 3\frac{\alpha}{2\pi} P_{q\gamma} = 3\frac{\alpha}{2\pi}[x^2+(1-x)^2] \quad , \tag{6}$$

we have to add also the appropriately resummed QCD logs stemming from the gluon radiations in Fig. 2b which are obtained from

$$\frac{d q^\gamma(x,Q^2)}{d \ln Q^2} = e_q^2 h_B(x) + \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 \frac{dz}{z} P_{qq}(z)\, q^\gamma\left(\frac{x}{z},Q^2\right) . \tag{7}$$

Structly speaking, one should also add the photonic gluon, squark and gluino contributions since in a full SUSY-QCD [14)] q^γ, g^γ, $\tilde{q}^\gamma$ and $\tilde{g}^\gamma$ satisfy an inhomogeneous coupled integro-differential 4×4 matrix equation; these, however, can to a good approximation be neglected for interesting values of x ($\gtrsim 0.4$) above the non-pointlike VMD region. In a SUSY-QCD the quark splitting function in Eq. (7) is given by [14)]

$$P_{qq}(x) = \frac{4}{3}\left[\frac{1+x^2}{(1-x)_+} + \delta(1-x)\right] \tag{8}$$

where

$$\int_0^1 dx\, g(x)_+ f(x) \equiv \int_0^1 dx\, g(x)[f(x)-f(1)] \; ; \tag{9}$$

the strong coupling is given by $\alpha_s(Q^2) = 4\pi/(\beta_0 \ln Q^2/\Lambda^2)$ with

$$\beta_0 = 11 - \frac{2}{3}f - 2 - \frac{1}{3}f \tag{10}$$

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*) We always assume to be in an energy region where $Q^2 \gg m_q^2$ for all familiar quark flavours considered.

where -2 and $-\frac{1}{3}f$ are the contributions of gluinos and squarks, respectively. Whether all of these additional SUSY contributions are already fully effective in β_0 at a given value of Q^2 depends of course on the relative size of gluino and squark masses, but for definiteness we shall make the extreme assumption that β_0 is given by the full SUSY expression in Eq. (10). For comparison, we shall also use in our quantitative estimates below the β function of standard QCD where the last two terms in Eq. (10) are missing, i.e., β_0 is as large as possible. Although Eq. (7) can easily be solved numerically, we can obtain a better feeling for the origin and magnitude of the QCD corrections be retaining only the leading terms which become singular as $x \to 1$ - an approximation [13] which allows us to obtain an analytic expression for $q^\gamma(x,Q^2)$. This is easily achieved by noting that the singular term in the convolution integral in Eq. (7) can, using the definition (9), be approximated by

$$\begin{aligned}\int_x^1 dz\, g(z)_+ f\left(\frac{x}{z}\right) &= -f(x)\int_0^x dz\, g(z) + \int_x^1 dz\, g(z)\left[f\left(\frac{x}{z}\right) - f(x)\right] \\ &\simeq -f(x)\int_0^x dz\, g(z)\end{aligned} \tag{11}$$

since for $x \to 1$ the second integral in the first line of the right-hand side vanishes linearly faster than the first term. Thus Eq. (7) becomes

$$\frac{dq^\gamma(x,Q^2)}{d\ln Q^2} = e_q^2\, k_B(x) - \frac{P(x)}{\ln Q^2/\Lambda^2}\, q^\gamma(x,Q^2) \tag{12}$$

with

$$P(x) = \frac{16}{3\beta_0}\left[-\ln(1-x) - \frac{1}{2}\right] \tag{13}$$

and is expected to be adequate [13] for $x \gtrsim 0.4$. The <u>asymptotic</u> solution of (12) is straightforward and is of the well-known form

$$q^\gamma(x,Q^2) \simeq e_q^2\, \frac{k_B(x)}{1+P(x)}\, \ln\frac{Q^2}{\Lambda^2} \quad . \tag{14}$$

This shows that in SUSY-QCD the effects due to gluon radiations are larger (i.e., parton x distributions are getting softer and more depleted) than in standard QCD, not only because β_0 in Eq. (13) is smaller, but also because the constant term in square brackets in (13) is smaller than in standard QCD.

In Fig. 3, we show the quark and squark contributions to the photon structure function in Eq. (3) for energies in the squark threshold region where $Q^2 \not\gg 4m_{\tilde{q}}^2$ and choose for definiteness the number of flavours $f=6$. As we can see, the squark production rates *), according to Eq. (4), are not negligible and amount even at LEP energies [where τ is expected to be closer to 1, around 0.5 or larger [9], provided $m_{\tilde{q}}$ lies in the range of Eq. (1)] to about 10 to 20%, as compared to the dominant quark contribution. The latter one is due to Eq. (14) where we have taken $\ln Q^2/\Lambda^2 = 10$ which corresponds roughly to the required values of Q^2 for squark production with masses in the range (1), taking into account present uncertainties in the QCD scale Λ. Furthermore, we can see that the quark distribution by itself gets much flatter and softer due to gluon radiations in SUSY-QCD (dashed curve) than the one in standard QCD, where Eq. (13) is altered to $P(x) = 16[-\ln(1-x)-3/4]/3\beta_o$ with $\beta_o = 11-2f/3$. Thus if scalars indeed exist with masses not too large, one should observe photon structure functions which are <u>flatter</u> than the ones in standard QCD and strongly <u>increase</u> for decreasing values of x. On the other hand, the absence of such signals should provide us with stringent lower bounds on SUSY scalar masses.

Finally, let us comment on the predictions for the energy region where $Q^2 \gg 4m_{\tilde{q}}^2$, i.e., far above threshold which, for presently expected scalar masses, appears to be rather academic since such energies are unlikely to be reached by presently foreseeable e^+e^- machines. In this limit the logarithmic term in Eq. (4) dominates, and which reduces to $\tilde{q}^\gamma = e_q^2 \tilde{h}_B(x) \ln Q^2/m_{\tilde{q}}^2$ with

$$\tilde{h}_B(x) \equiv 3\frac{\alpha}{2\pi} P_{\tilde{q}\gamma}(x) = 3\frac{\alpha}{2\pi}\, 2x(1-x) \tag{15}$$

which is just the scalar counterpart of the fermionic leading-log box contribution in Eq. (6). The occurrence of a large leading-log term requires again the inclusion of QCD corrections, due to the gluon radiations in Fig. 1b, which are of comparable size and very large in the large x region and are, in analogy with Eq. (7), obtained from

$$\frac{d\tilde{q}^\gamma(x,Q^2)}{d\ln Q^2} = e_q^2\tilde{h}_B(x) + \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 \frac{dz}{z} P_{\tilde{q}\tilde{q}}(z)\,\tilde{q}^\gamma\left(\frac{x}{z},Q^2\right) \tag{16}$$

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*) Needless to say that these rates, as well as Eq. (4), apply also to heavy slepton production where $\tilde{\ell} = s_\ell + t_\ell$.

where [14)]

$$\mathcal{P}_{\tilde{q}\tilde{q}}(x) = P_{qq}(x) - \frac{4}{3}(1-x) \tag{17}$$

with P_{qq} given by Eq. (8). Again, this (decoupled) evolution equation is strictly valid only in the interesting large x region [where the hadronic non-pointlike VMD contributions are negligibly small [11),13)]] since the remaining off-diagonal splitting functions [14)] are not singular as $x \to 1$. Since according to Eq. (17) $P_{\tilde{q}\tilde{q}} \simeq P_{qq}$ for $x \to 1$, the QCD corrections to the photonic squark distribution are the same as those for quarks in Eq. (7), and we can use the same approximation for solving Eq. (16) as for the quark contribution in (14) with the result

$$\tilde{q}^{\gamma}(x,Q^2) \simeq e_q^2 \, \frac{\tilde{h}_B(x)}{1+P(x)} \ln \frac{Q^2}{\Lambda^2} \tag{18}$$

where $P(x)$ is given by Eq. (13). Thus, far above threshold of all SUSY scalars and for large values of x ($\gtrsim 0.4$), the QCD corrections to the scalar contributions to the photon structure function are the <u>same</u> as those for quarks

$$F_2^{\gamma}(x,Q^2) = 2x \sum^{f} e_q^4 \, \frac{h_B(x) + \tilde{h}_B(x)}{1+P(x)} \ln \frac{Q^2}{\Lambda^2} \tag{19}$$

and the drastically different x dependence $2x(1-x)$ of squarks as compared to $x^2+(1-x)^2$ of quarks becomes fully effective. This is demonstrated in Fig. 4 where the total photon structure function is expected to <u>increase</u> strongly for decreasing x in contrast to the flat quark contribution and even more to the standard QCD expectations, where no supersymmetry is employed and which are expected to fall with decreasing x.

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FIGURE CAPTIONS

Figure 1 : (a) Diagrams for heavy scalar particle production in the threshold region, and

(b) Additional gluon radiations giving the dominant QCD contributions for $Q^2 \gg 4m_{\tilde{q}}^2$.

Figure 2 : (a) Quark box diagrams, together with

(b) Gluon radiations giving the dominant QCD contribution to the photon structure function.

Figure 3 : Squark $(\tilde{q})$ and quark (q) contributions to the photon structure function due to Eqs. (4) and (14), respectively, for various fixed values of $\tau = 4m_{\tilde{q}}^2/Q^2$ in the squark threshold region $(Q^2 \not\gg 4m_{\tilde{q}}^2)$. The total contribution to F_2^γ is denoted by $q+\tilde{q}$. The dotted curve refers to the quark distribution in photons as predicted by standard (non-SUSY) QCD as explained in the text. The quark contributions are plotted for $f = 6$ in β_0 and $\ell n Q^2/\Lambda^2 = 10$.

Figure 4 : Predicted x dependence of squarks $(\tilde{q})$ and quark (q) contributions to F_2^γ according to Eqs. (18) and (14), respectively, for energies far above scalar thresholds where $Q^2 \gg 4m_{\tilde{q}}^2$ using $f = 6$. Apart from the $\ell n Q^2/\Lambda^2$ factor, the quark contributions are the same as in Fig. 3.

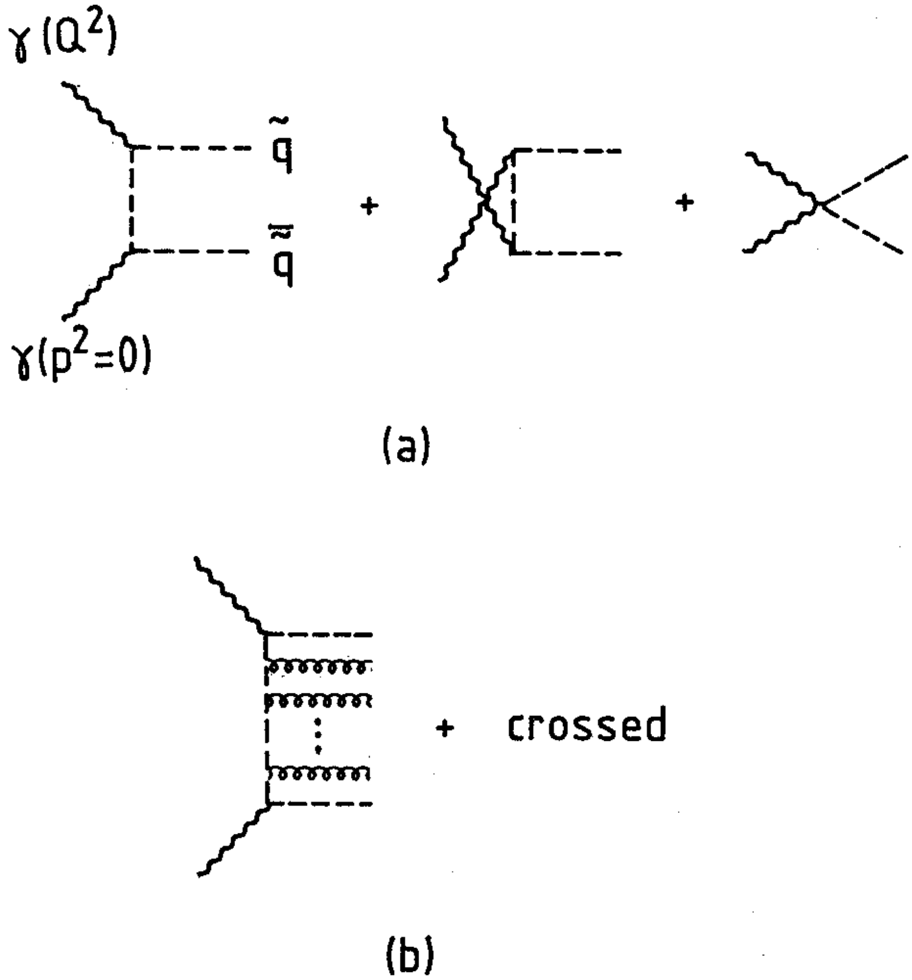


Fig. 1

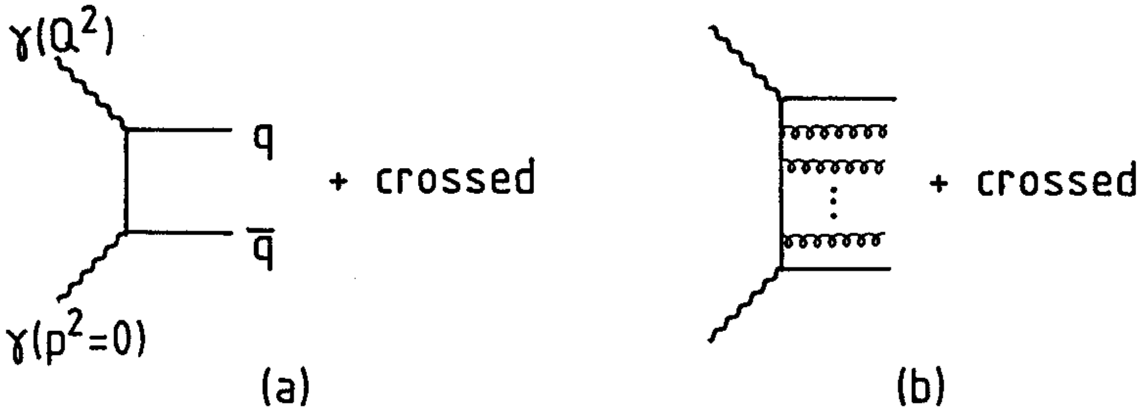
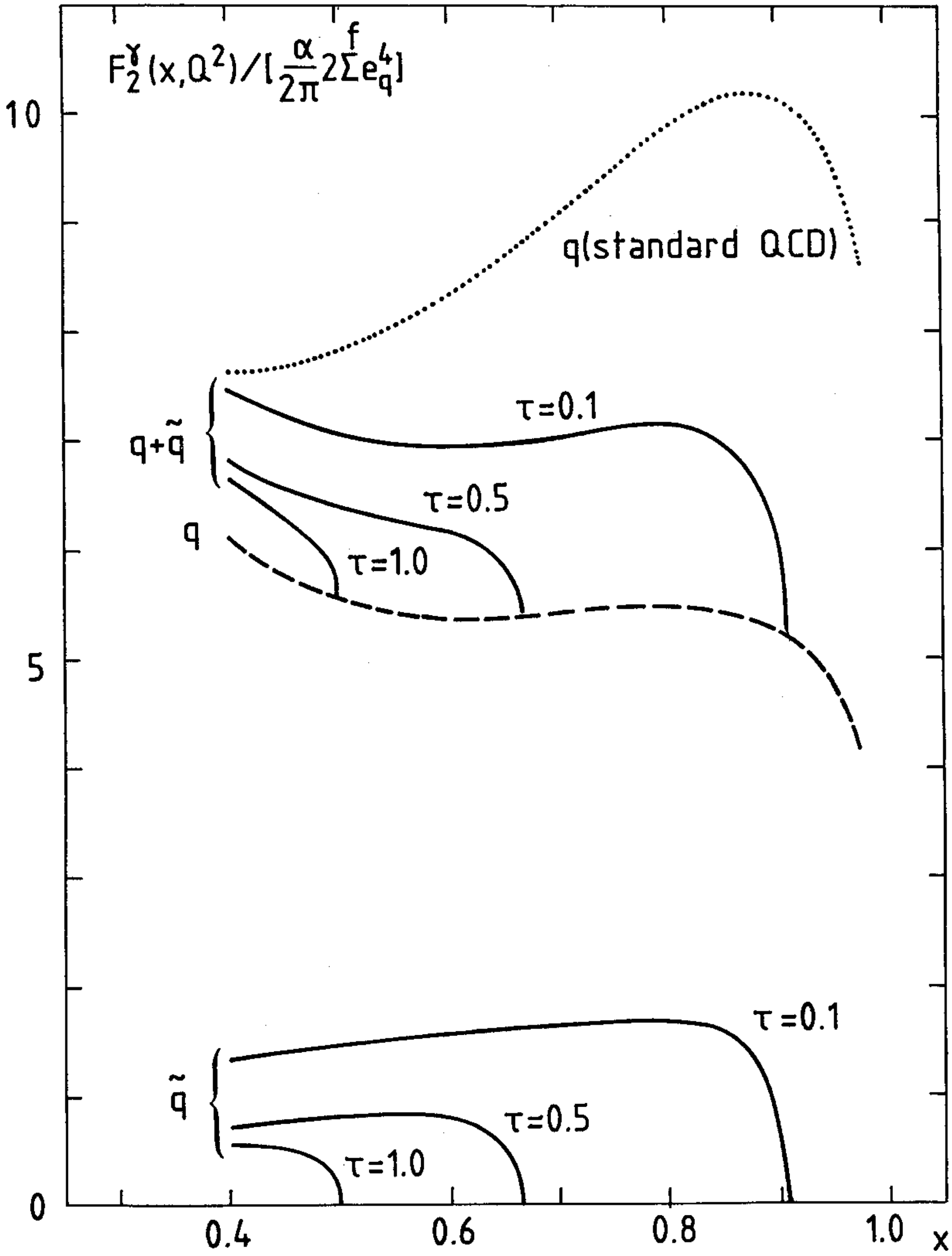


Fig. 2



$F_2^\gamma(x,Q^2)/[\frac{\alpha}{2\pi}2\sum^f e_q^4]$
10
5
0
q(standard QCD)
$q+\tilde{q}$
q
$\tilde{q}$
τ=0.1
τ=0.5
τ=1.0
τ=0.1
τ=0.5
τ=1.0
0.4
0.6
0.8
1.0
x

Fig. 3

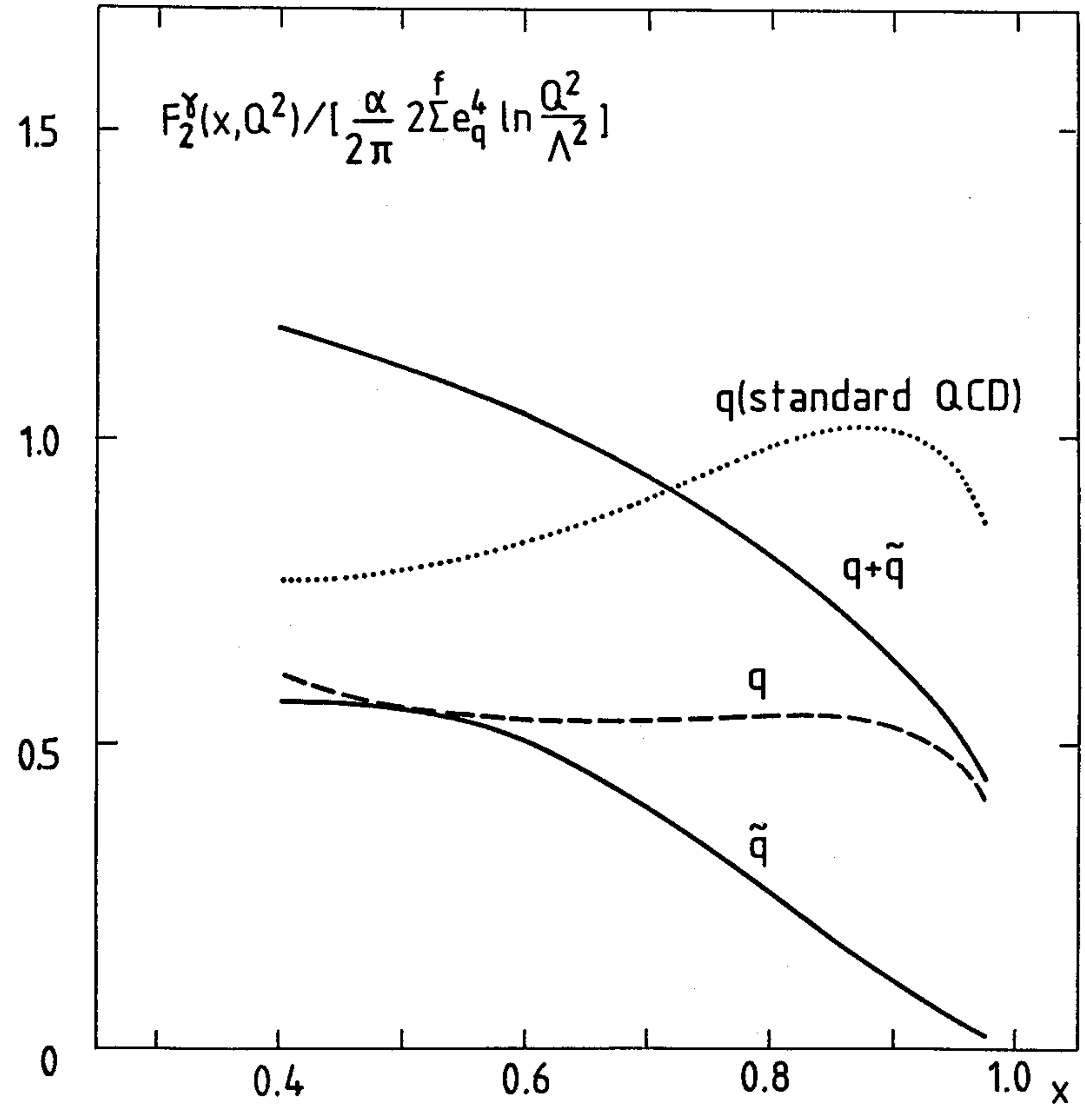

$F_2^\gamma(x,Q^2)/[\frac{\alpha}{2\pi}\,2\sum^f e_q^4 \ln\frac{Q^2}{\Lambda^2}]$
1.5
1.0
0.5
0
0.4
0.6
0.8
1.0
x
q(standard QCD)
q+q̃
q
q̃

Fig. 4