Dielectrons in $\pi^- p$ collisions via the two-photon mechanism

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Dielectron production in 16 GeV $\pi^- p$ collisions is studied using the double equivalent photon method. Equivalent photon spectra of hadrons are calculated analytically in a fully quantal and semiclassical approach. The limitation of the latter approach and the influence of the proton spin-flip terms are studied. Conclusions at variance with those of a recent letter by Bottcher *et al.* are obtained.

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I. INTRODUCTION

Dilepton production in high-energy hadron-hadron collisions is a subject of great current interest. Whereas the high-mass region is well understood in terms of the Drell-Yan mechanism, the situation is less clear in the low-mass region [1,2]. Interesting results have been obtained already [3–5]; a critical discussion is given in Ref. [2]. Without entering into these discussions, it is the purpose of the present paper to investigate dilepton production via the $\gamma\gamma$ mechanism. Whatever interesting happens, $\gamma\gamma$ dileptons will be produced and it would certainly be helpful if the contributions due to this mechanism could be assessed reliably.

The equivalent photon spectra of hadrons are well known; they can be expressed in terms of their electromagnetic form factors. In Sec. II we study the properties of the proton and the pion equivalent photon spectra, using quantal as well as semiclassical methods. It was claimed recently [6] that lepton pairs are produced to a large extent by the magnetic part of the proton current. Since we know the equivalent photon spectra in analytical form, we can study the effect of the magnetic moment of the proton in a very transparent way. Also, the influence of energy loss through γ emission can be studied by comparing the quantal and semiclassical approaches. This is done in Sec. II. With this input we study the dielectron spectra due to the $\gamma\gamma$ subprocess in Sec. III. Our conclusions are given in Sec. IV.

II. PION AND PROTON EQUIVALENT PHOTON SPECTRA

Equivalent photon spectra are derived in the literature in a quantal, plane-wave approach (for a very detailed discussion, see Ref. [7]). In this way the energy loss ω of a particle, with initial energy $E=\gamma m$, due to the emission of the virtual photon is taken into account (see Fig. 1). This is in contrast with the semiclassical method (see, e.g., Ref. [8]), where the particle is assumed to move on a straight-line path with constant velocity. For heavy ions this approach is very well justified, since the maximum fractional energy loss $x_{\max}=\omega_{\max}/E$ is given by

$$x_{\max}=\frac{\hbar c}{mR}=\frac{\lambda_{\text{Compton}}}{R}\ll 1 \ . \tag{2.1}$$

The mass of the particle is given by m, the size is characterized by R, and $\omega_{\max}=\gamma\hbar c/R$. On the other hand, $x_{\max}$ can extend up to 1 (the limit given by energy conservation) for electrons or pions. For protons, we have $x_{\max}\cong 0.9$. Thus, like an electron, a pion and a proton can emit a virtual photon and lose a substantial fraction of its energy (for heavy ions this possibility is strongly suppressed and the semiclassical approach works very well).

With a monopole form factor for the pion of

$$G_E^\pi(q^2)=\frac{\Lambda_\pi^2}{\Lambda_\pi^2+q^2} \ , \tag{2.2}$$

with $\Lambda_\pi^2=0.59$ GeV^2 (cf. with [6]), we obtain, for the equivalent photon spectrum in the quantal approach [see Eq. (D.4) of [7]],

$$N_\pi^{qu}(\omega)=\frac{\alpha}{\pi}\left[1-\frac{\omega}{E}\right]\left\{\left[1+\frac{2\omega^2}{\gamma^2\Lambda_\pi^2}\frac{1}{1-\omega/E}\right]\ln\left[1+\frac{\Lambda_\pi^2\gamma^2}{\omega^2}\left[1-\frac{\omega}{E}\right]\right]-2\right\} . \tag{2.3}$$

In the semiclassical approach, we can calculate equivalent photon spectra $N(\omega,\rho)$ of fast-moving spherical charge distributions as a function of the impact parameter [9]. The semiclassical equivalent photon spectrum $N^{sc}(\omega)$ is obtained by integrating over all impact parameters:

$$N^{sc}(\omega)=2\pi\int\rho\, d\rho\, N(\omega,\rho) \ . \tag{2.4}$$

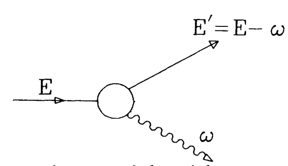

FIG. 1. Fast moving particle with mass m and energy E emits a virtual (equivalent) photon of energy ω. If this photon is energetic, the energy loss of the particle has to be taken into account.

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Using again the monopole form factor Eq. (2.2), we finally get the result

$$N_{\pi}^{\rm sc}(\omega)=\frac{\alpha}{\pi}\left\{\left[1+\frac{2\omega^2}{\gamma^2\Lambda_\pi^2}\right]\ln\left[1+\frac{\Lambda_\pi^2\gamma^2}{\omega^2}\right]-2\right\} . \qquad (2.5)$$

From Eqs. (2.3) and (2.5), it is straightforward to show that in the limit of negligible fractional energy loss the quantal approach reduces to the semiclassical one. This is a general result for spin-zero particles. The integration over the impact parameter ρ in Eq. (2.4) can be done analytically, and the result for $n(\omega)$ of Refs. [10] and [11] is obtained.

For a pion with $E_\pi^{\rm c.m.}=2.7$ GeV (this corresponds to the case which we will study in Sec. III), the equivalent photon spectrum is plotted as a function of the photon energy ω in Fig. 2. The solid line corresponds to the spectrum calculated in the quantal approach (i.e., which takes energy loss into account [Eq. (2.3)]), while the dashed line corresponds to the semiclassical calculation [Eq. (2.5)]. The influence of the energy loss is clearly seen at the high-energy end. As is expected, the semiclassical calculation overestimates the spectrum; for photon energies above 1.5 GeV, the difference is of nearly one order of magnitude.

A closed-form expression for the proton equivalent photon spectrum was obtained recently in Ref. [12] [see his Eq. (3.13)], where standard dipole form factors were used:

$$G_E^p(q^2)=\left[\frac{\Lambda_p^2}{\Lambda_p^2+q^2}\right]^2 ,$$
$$G_M^p(q^2)=bG_E^p(q^2) . \qquad (2.6)$$

For Λ_p, we take $\Lambda_p=0.71$ GeV. The physical value of b is given by $b=2.79$; however, we can vary this parameter in order to investigate the influence of the magnetic moment on the proton equivalent photon spectrum. To switch off the spin-flip contributions, we put $b=0$ in Eq.

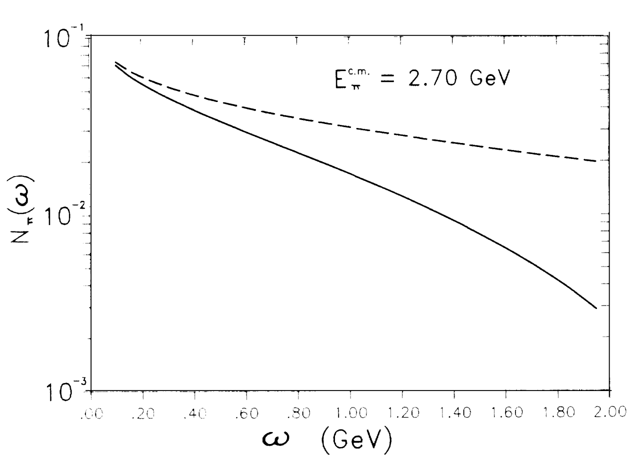

FIG. 2. Equivalent photon spectrum of a pion of c.m. energy $E_\pi^{\rm c.m.}=2.7$ GeV as a function of the photon energy ω. The solid line corresponds to the calculation in the quantal approach, while the dashed line shows the semiclassical approach.

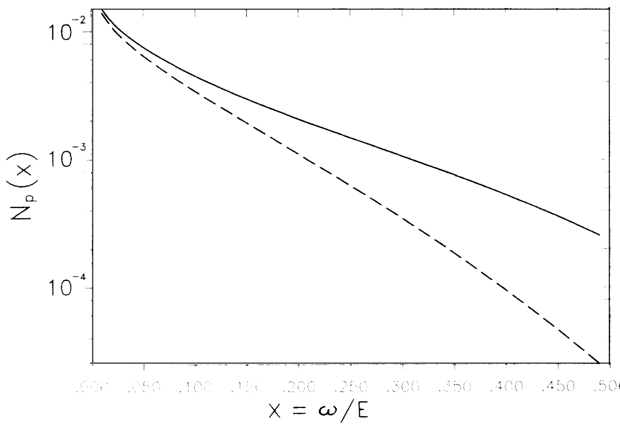

FIG. 3. Equivalent photon spectrum of a proton as a function of the scaling variable $x=\omega/E$ (fractional energy loss). The solid line corresponds to a calculation using the full result of Ref. [12]. In the calculation for the dashed line, the spin-flip contributions have been eliminated (i.e., $b=0$).

(3.13) of Ref. [12]. In Fig. 3 we plot the proton equivalent photon spectrum as a function of the fractional energy loss $x=\omega/E$. The solid line shows the calculation including spin-flip terms (i.e., $b=2.79$), while the dashed line corresponds to the non–spin-flip case (i.e., $b=0$). For small fractional energy loss, the difference is small; above $x\cong 0.3$, the non–spin-flip calculation starts to decrease more rapidly, leading to a one order of magnitude difference to the full calculation already at fractional energy losses of $x\cong 0.5$. A semiclassical treatment of the proton equivalent spectrum is in preparation [13].

III. DIELECTRON PRODUCTION IN THE DOUBLE EQUIVALENT PHOTON METHOD

With the pion and proton equivalent photon spectra, on the one hand, and the on-shell $\gamma\gamma\to e^+e^-$ cross section, on the other hand, we can now study dielectron production in the double equivalent photon approximation. For the on-shell dielectron production cross section, we use the lowest-order QED result [see, e.g., Eq. (E.4) of Ref. [7]]. In Ref. [7], $\gamma\gamma$ cross sections are given for finite q^2 of the photon momenta [see also the approximation Eq. (6.25) in Ref. [7]]. In the limit of invariant mass $W \gg m$, which we are dealing with, this correction is very small; it would only further slightly decrease the dielectron production cross section.

The dielectron production cross section in the double equivalent photon approximation for pion-proton collisions is given by

$$d\sigma_{\rm EPA}(\omega_1,\omega_2)=\sigma_{\gamma\gamma}(\omega_1\omega_2)N_\pi(\omega_1)N_p(\omega_2)\frac{d\omega_1}{\omega_1}\frac{d\omega_2}{\omega_2} . \qquad (3.1)$$

In Eq. (3.1) we neglected the strong interaction between π^- and p (this is also done in [6]). It is not quite clear how good this approximation is, since the strong interaction certainly modifies the particle currents. Probably the unmodified currents give an upper limit. In an analogous context, a 20–30 % reduction of dilepton production due to strong interactions is estimated for p-p collisions [14]. To evaluate Eq. (3.1), we use the c.m. system of the colliding particles. We assume that the equivalent photons move in the beam direction; in order to obtain the equivalent photon spectra, integration over transverse momenta was carried out (see, e.g., Ref. [7]). To compare our results with published ones, we choose the kinematical variables $W^2=4\omega_1\omega_2$ and $x_F=2p_L/\sqrt{s}$, where $p_L=\omega_2-\omega_1$ is the longitudinal momentum of the e^+e^- pair in the c.m. system.

In Fig. 4 we plot the double-differential cross section $d^2\sigma/dW\,dx_F$ at $x_F=0$ as a function of the invariant mass W of the system for a c.m. energy of $s=30.92$ GeV^2, which corresponds to the 16-GeV/c experiments. The solid line is due to the calculation via the quantal approach for both the pion and proton equivalent photon spectra. The dashed line corresponds to a straight-line approximation for the pion equivalent photon spectrum, while the proton equivalent photon spectrum is still calculated in the quantal approach. This approximation is very good for small invariant masses (i.e., below 1.5 GeV); a significant overestimate is present at the high-energy end above 3 GeV.

Again, the double-differential cross section $d^2\sigma/dW\,dx_F$ at $x_F=0$ is plotted in Fig. 5 as a function of the invariant mass W of the system. The solid line is the same calculation as in Fig. 4, where both spectra are calculated in the quantal approach. The dashed line now corresponds to a calculation where the spin-flip terms in the proton equivalent photon spectrum are eliminated by setting $b=0$. This elimination leads to a reduction of the cross section, which is very small below 1.5 GeV. For high invariant masses, the non-spin-flip calculation decreases much faster than the full one, leading to deviations bigger than one order of magnitude.

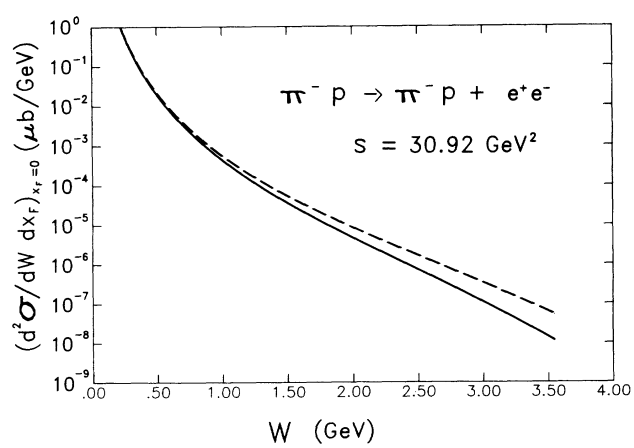

FIG. 4. Double-differential cross section $d^2\sigma/dW\,dx_F$ for e^+e^- production at $x_F=0$ as a function of the invariant mass W of the $\pi^- p$ system for a c.m. energy of $s=30.92$ GeV^2. The solid line corresponds to a fully quantal calculation, while the dashed line shows a calculation where the semiclassical pion equivalent photon spectrum was used.

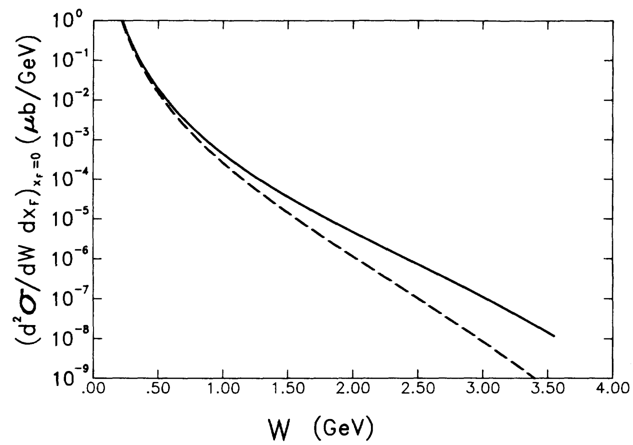

FIG. 5. Same as in Fig. 4 except the dashed line now shows the effect of omitting the spin-flip terms in the proton equivalent photon spectrum (i.e., $b=0$).

To compare our results with the measurements of Refs. [3–5], an integration over the invariant mass W has to be carried out. For experimental reasons [3,4] this integration is extended over the finite interval 0.2 GeV $\le W \le$ 1.2 GeV. In this region the effect of the spin-flip terms of the proton equivalent photon spectrum is very small. Figure 6 shows the differential cross section $d\sigma/dx_F$ as a function of x_F in comparison with data from Refs. [3–5]. The data labeled (a) are from Ref. [5], those labeled (b) are set "pair A" from Refs. [3,4], and those labeled (c) are set "pair B" from Refs. [3,4]. The solid line again is the calculation of Fig. 4 using the quantal approach for both spectra. The dashed line is a calculation where the spin-flip terms in the proton equivalent photon spectrum have been omitted. There is no

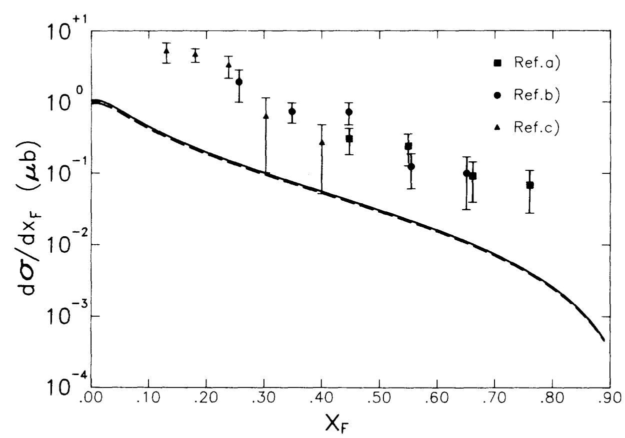

FIG. 6. Differential cross section $d\sigma/dx_F$ for e^+e^- production in $\pi^- p$ collisions as a function of x_F in comparison with data from Refs. [3–5]. The data labeled (a) are from Ref. [5], those labeled (b) are set "pair A" from Refs. [3,4], and those labeled (c) are set "pair B" from Refs. [3,4]. The solid line is again the calculation where both the proton and pion equivalent photon spectra are calculated in the quantal approach, while in the dashed line the spin-flip terms of the proton equivalent photon spectrum are omitted. Integration over the invariant mass W was carried out over the interval 0.2 GeV < W < 1.2 GeV.

significant difference between these two calculations. The calculations underestimate the measurements by a factor of 10 over the whole range of x_F values. This indicates that the $\gamma\gamma$ mechanism is not sufficient to explain the anomalous pair production.

In Fig. 7 we compare the full calculation of Fig. 6 with a calculation neglecting the energy loss of the pion (dashed line) and the data from Refs. [3–5]. The data are labeled as in Fig. 6. The semiclassical treatment of the pion photon spectrum leads to larger cross sections for higher x_F in comparison with the full calculation. This results in a better agreement of this calculation with the data, which was stated by Bottcher *et al.* [6]. We want to point out that this agreement is purely due to the semiclassical treatment of the photon spectrum, which is not justified in the kinematical region of high x_F because energy conservation is badly violated.

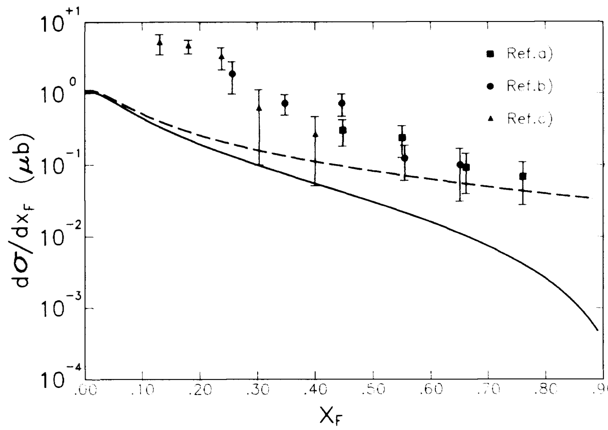

FIG. 7. Same plot as in Fig. 6. The data and full calculation are compared with a calculation (dashed line) where the pion equivalent photon spectrum is calculated semiclassically.

IV. CONCLUSIONS

Despite much effort, dilepton continuum spectra in the low-mass region have not been unraveled. It was the aim of this paper to calculate the $\gamma\gamma$ contribution to these spectra. We made essentially two assumptions: q^2(photon)$\cong 0$ and the neglection of strong interactions between π^- and p to calculate the currents. Both assumptions tend to overestimate the effect. Comparison with published x_F spectra shows that the $\gamma\gamma$ contribution is a small effect. This is in contrast with a recent result [6] where essential agreement with experiment and large contributions due to spin-flip terms were found. We find practically no influence due to spin-flip contributions and can show that the agreement of the $\gamma\gamma$-induced cross sections with the data stated in [6] is mainly due to the unjustified semiclassical treatment of the spectra in this work. Inclusion of energy loss results in a clear reduction of the cross sections. We conclude that other effects have to be investigated (see, e.g., Refs. [1,2]).

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