PHYSICAL REVIEW D VOLUME 44, NUMBER 1 1 JULY 1991

Nonstandard $\gamma\gamma \to l^+l^-$ processes in relativistic heavy-ion collisions

L. D. Almeida, A. A. Natale, and S. F. Novaes
Instituto de Física Teórica Universidade Estadual Paulista, Rua Pamplona 145, CEP 01405, São Paulo, Brazil

O. J. P. Éboli
Instituto de Física – Universidade de São Paulo, Caixa Postal 20516, CEP 01498, São Paulo, Brazil
(Received 21 December 1990; revised manuscript received 11 February 1991)

We study lepton pair production in heavy-ion collisions with emphasis on nonstandard contributions to the QED subprocess $\gamma\gamma \to l^+l^-$. The existence of compositeness of fermions and/or bosons can be tested in this reaction up to the TeV mass scale. We show that for some processes the capabilities of relativistic heavy-ion colliders to disclose new physics surpass the possibilities of e^+e^- or $p\bar{p}$ machines. In particular, spin-zero composite particles which couple predominantly to two photons, predicted in composite models, can be studied in a broad range of masses.

I. INTRODUCTION

There are plans to operate the proposed CERN Large Hadron Collider (LHC) and the Superconducting Super Collider (SSC) with beams of heavy ions, with the main interest in the search of a quark-gluon plasma in central nuclear reactions. In addition to this important feature of heavy-ion colliders, peripheral collisions may give rise to a huge luminosity of photons, which opens the possibility of studying a large variety of two-photon processes which may not show up in e^+e^- or $p\bar{p}$ machines. The production of new particles in heavy-ion collisions was considered in Refs. [1] and [2], and the possibilities of studying electromagnetic physics in such collisions has been considered at length by Baur and Bertulani [3, 4]. In particular, the possibility of the search and discovery of an intermediate-mass standard Higgs boson ($M_Z < M_H < 2M_Z$) in $\gamma\gamma$ reactions induced by ion-ion collisions has been discussed by several authors [1,2,5–8].

The advantage of $\gamma\gamma$ fusion in heavy-ion collisions is that photons are emitted coherently by the nucleus of charge Ze, leading to cross sections which are enhanced by a factor Z^4. Despite this optimistic scenario there are several problems to be circumvented before saying that relativistic heavy-ion colliders are promising tools for the discovery of new particles or interactions. For instance, Cahn and Jackson [6] have shown that requiring only peripheral collisions reduces the net photon luminosity and, consequently, the chances to observe a possible intermediate-mass standard Higgs boson. Moreover, to isolate its signal from the background is also a difficult task [7]. Actually, the background problem will be solved only if there is an excellent tagging of the intact ion in the final state. Notwithstanding the problems we stated above, we cannot neglect the fact that, in peripheral ion-ion collisions, we do have a powerful photon factory, and it is important to verify what we can learn through these reactions.

One of the cleanest tests of QED is provided by the reaction $e^+e^- \to \gamma\gamma$ where the lepton is exchanged in the t and u channels. In this paper we study nonstandard contributions to the subprocess $\gamma\gamma \to l^+l^-$ ($l = e, \mu, \tau$) in heavy-ion collisions in order to explore new physics beyond the standard model, such as compositeness of fermions and/or bosons. We have chosen to study leptons in the final state in order to have the cleanest signal, since, in heavy-ion collisions, QCD processes produce an enormous background to strongly interacting final states.

The nonstandard interactions that may contribute to the electromagnetic process $\gamma\gamma \to l^+l^-$ will be introduced through effective Lagrangians involving operators of different dimensions:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{QED}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \cdots ,$$

where $\mathcal{L}_{\text{QED}}$ is the standard QED Lagrangian and $\mathcal{L}_{5,6,\ldots}$ are of dimension 5, 6, etc., and respect $\text{U}(1)_{\text{EM}}$ gauge invariance. This will give a definite idea of how worthwhile the use of $\gamma\gamma$ fusion in relativistic heavy-ion colliders is to disclose new physics beyond the standard model.

The content of our paper is distributed as follows. Section II contains a few remarks on the photon luminosity in heavy-ion collisions. In Sec. III, we exhibit the effective Lagrangians as well as their contributions to the cross section of $\gamma\gamma \to l^+l^-$. We discuss our results for $ZZ \to ZZ\gamma\gamma \to ZZl^+l^-$ in Sec. IV and, in Sec. V, we draw our conclusions.

II. REMARKS ON THE PHOTON DISTRIBUTION IN HEAVY-ION COLLISIONS

Before starting the evaluation of specific processes, it is convenient to discuss the expressions for the two-photon luminosities that can be found in the literature. As pointed out by Cahn and Jackson [6], the correct determination of the photon-photon luminosity is crucial to obtain a realistic estimate of any peripheral $\gamma\gamma$ process.

The photon distribution in the heavy-ion collision can be determined through the equivalent photon or Weizsäcker-Williams approximation [9]. Denoting by $F(x)dx$ the number of photons carrying a fraction between x and $x + dx$ of the total momentum of a nucleus of charge Ze, we can define the two-photon luminosity through

$$\frac{dL}{d\tau} = \int_\tau^1 \frac{dx}{x} F(x) F(\tau/x) \,,$$

where $\tau = \hat{s}/s$, and s ($\hat{s}$) is the square of the c.m.-system (c.m.s) energy of the ion-ion (photon-photon) system. The total cross section $ZZ \to ZZ\gamma\gamma \to ZZl^+l^-$ can be written as

$$\sigma(s) = \int_{\tau_{\min}}^1 d\tau \frac{dL}{d\tau} \hat{\sigma}(\hat{s}) \,, \tag{1}$$

where $\hat{\sigma}(\hat{s})$ is the cross section of the subprocess $\gamma\gamma \to l^+l^-$ and $\tau_{\min} = 4m^2/s$ for a produced lepton of mass m.

There remains only to determine $F(x)$. In the literature there are several approaches for doing so and we summarize the main results below. Using the equivalent-photon approximation in the classical approximation [10], the result for $F(x)$ is

$$F_{\text{clas}}(x) = \frac{2Z^2\alpha}{\pi x} \left\{ \left(\frac{x}{x_0}\right) K_0\left(\frac{x}{x_0}\right) K_1\left(\frac{x}{x_0}\right) - \frac{1}{2}\left(\frac{x}{x_0}\right)^2 \left[K_0^2\left(\frac{x}{x_0}\right) - K_1^2\left(\frac{x}{x_0}\right) \right] \right\} , \tag{2}$$

where K_0 and K_1 are the modified Bessel functions. $x_0 = (b_{\min} M)^{-1}$, with M being the nuclear mass, and $b_{\min}$ being the minimal value of the impact parameter.

Drees, Ellis, and Zeppenfeld [5] (DEZ) obtained the photon distribution by starting from the quantum amplitude for the processes and introducing the charge form factor $\mathcal{F}(Q^2)$ of the nucleus in order to get an expression for $F(x)$:

$$F_{\text{DEZ}}(x) = \frac{Z^2\alpha}{\pi x} \int_{(Mx)^2}^{\infty} \frac{dQ^2}{Q^2} |\mathcal{F}(Q^2)|^2 \left[1 - \left(\frac{Mx}{Q}\right)^2 \right] . \tag{3}$$

Assuming a Gaussian charge form factor for the nucleus

$$|\mathcal{F}(Q^2)|^2 \simeq \exp\left(\frac{-Q^2}{Q_0^2}\right) , \tag{4}$$

and a symmetric collision of ^{206}Pb nuclei at small Q^2, we have that

$$F_{\text{DEZ}}(x) = \frac{Z^2\alpha}{\pi x} \left\{ \left[1 + \left(\frac{Mx}{Q_0}\right)^2 \right] E_1\left[\left(\frac{Mx}{Q_0}\right)^2 \right] - \exp\left[-\left(\frac{Mx}{Q_0}\right)^2 \right] \right\} , \tag{5}$$

where $Q_0^2 \simeq$55–60 MeV. It is interesting to notice that for small values of x the above expressions can be approximated by [6]

$$F_{\text{app}} \simeq \frac{Z^2\alpha}{\pi x} \left[\ln\left(\frac{1}{(MRx)^2}\right) - C \right] , \tag{6}$$

where C is a constant. In order to reproduce the classical distribution Eq.(2) for small x, we should take $C = 0.768$, while $C = 0.18$ gives an approximation for the DEZ distribution Eq.(5). Setting $C = 0$ we obtain the results of Papageorgiu [1], which assumes that the two ions are nonoverlapping black disks in impact-parameter space. Using Eq.(6), it is possible to obtain an analytic expression for the luminosity [6]:

$$\frac{dL}{d\tau} = \left(\frac{Z^2\alpha}{\pi}\right)^2 \frac{2}{3\tau} \left[\ln\left(\frac{1}{M^2R^2\tau}\right) - C \right]^3 . \tag{7}$$

Cahn and Jackson [6], using a prescription proposed by Baur [11] which takes into account the requirement of peripheral collisions, obtained a photon distribution which is not factorizable. However, they were able to give a fit for the differential luminosity which is quite useful in practical calculations:

$$\frac{dL}{d\tau} = \frac{1}{\tau} L_0 \xi(2MR\sqrt{\tau}) \,, \tag{8}$$

where

$$L_0 = \frac{16Z^4\alpha^2}{3\pi^2} \,,$$

and

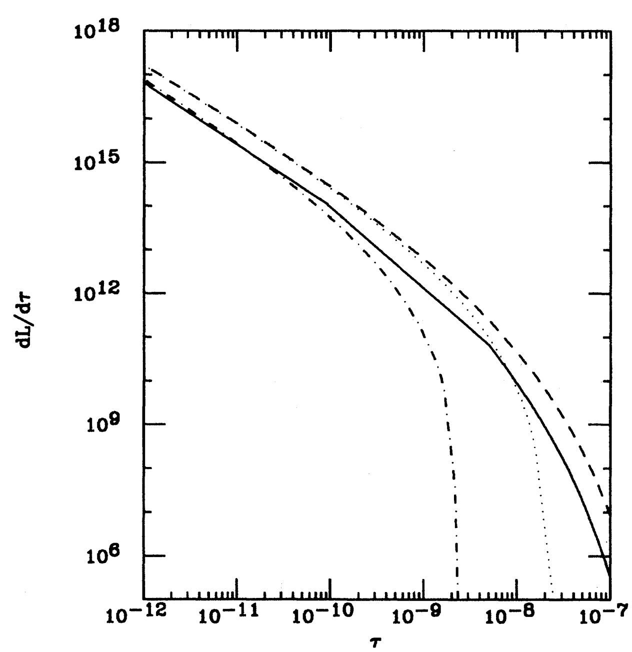

FIG. 1. Comparison of the luminosities resulting from different photon distributions. We present the results of Eq.(8) (solid line), Eq.(7) with $C = 0$ (dotted line), and $C = 0.768$ (dot-dashed line), and the luminosity associated to the distribution Eq.(3) (dashed line).

$$\xi(x) = \sum_{i=1}^{3} A_i \exp(-B_i x)$$

with $A_1 = 1.909$, $A_2 = 12.35$, $A_3 = 46.28$, $B_1 = 2.566$, $B_2 = 4.948$, and $B_3 = 15.21$.

In Fig. 1 we present the two-photon luminosities as a function of τ associated to different prescriptions of the photon distribution function [Eq.(5), Eq.(6) for $C = 0$ and $C = 0.18$, and Eq.(8)]. It is important to notice that the luminosity peaks at small τ, meaning that the major part of the photons carry only a small fraction of the ion energy. In this region all the prescriptions for the two-photon luminosity give approximately the same result.

III. ANOMALOUS CONTRIBUTIONS TO $\gamma\gamma \to L^+L^-$

Our main aim in this paper is to study possible deviations from the standard contributions of QED to the subprocess $\gamma\gamma \to l^+l^-$. There are many reasons to consider anomalous contributions to this subprocess. One of the simplest scenarios we can think of is the existence of compositeness: i.e., fermions and/or bosons may be composite and, at short distances, this would imply deviations from QED. Some other possibilities include the existence of new particles that may appear as intermediate states in the above reaction. One way to search for new physics is to work with effective Lagrangians and to study their contributions to this process. We now discuss several effective Lagrangians, and their respective contributions to the cross section of $\gamma\gamma \to l^+l^-$.

A. Excited lepton

The existence of excited states of leptons is one of the natural consequences of composite models. A spin-$\frac{1}{2}$ excited lepton gives an extra contribution to the reaction $\gamma\gamma \to l^+l^-$ through its exchange in the t and u channels. The effective Lagrangian describing the magnetic coupling of an excited lepton to a photon and a standard lepton is given by a dimension-5 operator [12]:

$$\mathcal{L}_* = \tfrac{1}{2}\bar{\psi}_*\sigma_{\mu\nu}F^{\mu\nu}(g_*^S - ig_*^P\gamma_5)\psi \; + \; \text{H.c.}\,, \qquad (9)$$

where the coupling constants $g_*^{S,P}$ are $O(1/\Lambda)$, with Λ being the scale of compositeness (mass parameter), and ψ_* is the fermionic field associated to the excited lepton.

The total cross section for the subprocess $\gamma\gamma \to l^+l^-$ is given by

$$\hat{\sigma}_*(\hat{s}) = \hat{\sigma}_{\rm QED}(\hat{s}) + \pi\alpha^2\xi_*\left\{(2-\delta) + \frac{1}{2}(1-\delta)^2\ln\left(\frac{\delta+1}{\delta-1}\right) + \left(\frac{\xi_*\hat{s}}{4}\right)\left[A_0 + A_1(\delta-1)^2\ln\left(\frac{\delta+1}{\delta-1}\right)\right]\right\}, \qquad (10)$$

where we have assumed $\sqrt{\hat{s}} \gg m$, the final state lepton mass, and we have defined

$$\xi_* = \frac{1}{e^2}[(g_*^S)^2 + (g_*^P)^2]\,, \qquad \delta = 1 + \frac{2M_*^2}{\hat{s}}\,,$$

$$A_0 = \frac{-2}{3(\delta+1)}(6\delta^3 - 12\delta^2 - \delta + 5)\,,$$

$$A_1 = \frac{1}{\delta}(2\delta^2 - 2\delta - 1)\,,$$

with M_* being the excited lepton mass and $\hat{\sigma}_{\rm QED}(\hat{s})$ being the well-known QED result

$$\hat{\sigma}_{\rm QED}(\hat{s}) = \frac{4\pi\alpha^2\beta}{\hat{s}}\left[\frac{3-\beta^4}{2\beta}\ln\left(\frac{1+\beta}{1-\beta}\right) - 2 + \beta^2\right], \qquad (11)$$

where β is the c.m.s. velocity of the final-state lepton:

$$\beta^2 = 1 - \frac{4m^2}{\hat{s}}\,.$$

As expected $\hat{\sigma}_*(\hat{s})$ has a bad high-energy behavior. Studying the unitarity bound coming from a partial-wave analysis, we learn that perturbation theory is reliable within certain range of the parameters. For instance, when $\sqrt{\hat{s}} \le 250$ GeV we must have $\xi_* \le 2\times10^{-3}$ GeV^{-2}. These conditions are met in our numerical calculations.

B. Spin-zero composite particle

It is known that in the standard model there is at least one scalar-boson remnant from the gauge symmetry breaking. The possibility of this scalar boson being composite has been considered by several authors [13]. In this case, the spin-zero boson may have anomalously large couplings to the photons, contrary to what is expected in the standard model, and generates an s-channel contribution to $\gamma\gamma \to l^+l^-$, giving rise to a peak in the invariant-mass distribution. The lowest-order effective Lagrangian describing the couplings of a scalar and pseudoscalar boson to fermions and photons can be written as

$$\mathcal{L}_\phi = \frac{m}{\Lambda_f}\bar{\psi}\psi\phi_S + \frac{1}{4}g_S F_{\mu\nu}F^{\mu\nu}\phi_S + i\frac{m}{\Lambda_f}\bar{\psi}\gamma_5\psi\phi_P + \frac{1}{4}g_P F_{\mu\nu}\tilde{F}^{\mu\nu}\phi_P\,, \qquad (12)$$

where $\phi_{S(P)}$ are the scalar (pseudoscalar) fields and $g_{S,P}$ are $O(1/\Lambda_{S,P})$.

Taking into account these new couplings, the full cross section of $\gamma\gamma \to l^+l^-$ in the limit $\hat{s} \gg m^2$ is given by

$$\hat{\sigma}_\phi(\hat{s}) = \hat{\sigma}_{\rm QED}(\hat{s}) - 4\pi\alpha^2 m^2\left[\xi_S \frac{\hat{s}-M_S^2}{(\hat{s}-M_S^2)^2+M_S^2\Gamma_S^2}\left(\ln\frac{\hat{s}}{m^2}-1\right)+\frac{1}{2}\xi_P\frac{\hat{s}-M_P^2}{(\hat{s}-M_P^2)^2+M_P^2\Gamma_P^2}\ln\frac{\hat{s}}{m^2}\right] + \frac{\pi\alpha^2 m^2}{4}\left(\xi_S^2\frac{\hat{s}^2}{(\hat{s}-M_S^2)^2+M_S^2\Gamma_S^2}+\xi_P^2\frac{\hat{s}^2}{(\hat{s}-M_P^2)^2+M_P^2\Gamma_P^2}\right), \quad (13)$$

where $M_{S(P)}$ and $\Gamma_{S(P)}$ are the mass and width of the scalar (pseudoscalar), and

$$\xi_{S(P)} = \frac{g_{S(P)}}{e^2\Lambda_f} .$$

The value of the widths $\Gamma_{S(P)}$ is a model-dependent quantity since it depends on the couplings of the composite (pseudo)scalar to all particles in the model. In our work we assumed that the main decay mode of $\phi_{S(P)}$ is into two photons, and we obtained

$$\Gamma_{\phi_{S(P)}\to\gamma\gamma} = \frac{1}{16}\frac{M_{S(P)}^3}{\Lambda_{S(P)}^2} . \quad (14)$$

We should notice that σ_ϕ is proportional to the lepton mass, and, therefore, the observation of this kind of event in $e^+e^- \to \gamma\gamma$ is unlikely to be due to the smallness of the electron mass. Furthermore, the photon luminosities in e^+e^- and $p\bar{p}$ colliders can barely be compared to the case of heavy-ion collisions. The above facts make the heavy-ion colliders the right place to look for composite scalar bosons.

C. Spin-one composite particle

In the scenario of composite models we cannot discard the possibility of a composite gauge boson. In particular, it would be very interesting if the Z^0 turns out to be composite or if there are other neutral spin-one composite particles resembling a gauge boson. In this work, we consider a spin-one composite particle (Z^0) exhibiting an anomalous $Z^0\gamma\gamma$ coupling [14]. The effective Lagrangian describing the above coupling is assumed to be

$$\mathcal{L}_Z = \tfrac{1}{4} g_Z Z_\mu^0 (\partial^\mu \tilde{F}_{\alpha\beta}) F^{\alpha\beta} , \quad (15)$$

where g_Z is $O(1/\Lambda^2)$ and $\tilde{F}_{\mu\nu}$ is the dual of the electromagnetic tensor ($\tilde{F}^{\alpha\beta} = \epsilon^{\alpha\beta\mu\nu}F_{\mu\nu}$). This interaction generates a contribution to $\gamma\gamma \to l^+l^-$ through the exchange of a spin-one composite particle in the s channel of the reaction. The coupling of the Z^0 to the fermions is assumed to be the standard-model one. Considering this contribution, the total cross section for the subprocess $\gamma\gamma \to l^+l^-$ is

$$\hat{\sigma}_Z(\hat{s}) = \hat{\sigma}_{\rm QED}(\hat{s}) + \frac{\pi\alpha^2}{4}\frac{m^2}{M_Z^4}\xi_Z^2\hat{s}^2 , \quad (16)$$

where

$$\xi_Z = \frac{g g_Z}{4e^2\cos\theta_W} ,$$

and $\hat{\sigma}_{\rm QED}(\hat{s})$ is given by Eq.(11).

It is interesting to notice that Eq.(16) does not exhibit the Z^0 pole since it is forbidden by Yang's theorem [15]. Another interesting feature of this extra contribution is that it is proportional to m^2, the lepton mass. The search of a $Z^0\gamma\gamma$ interaction in an electron-positron collider through the reaction $e^+e^- \to \gamma\gamma$ is hopeless since it is suppressed by the same factor m^2 and the electron mass is negligible.

D. Contact interactions

It is possible to construct several effective Lagrangians containing contact terms ($\gamma\gamma l^+l^-$) which are gauge invariant and differ just in their dimension. The lowest-order effective Lagrangians, describing these contact interactions, contain operators of dimension 6, 7, and 8:

$$\mathcal{L}_6 = i\bar{\psi}\gamma_\mu(\overleftrightarrow{D}_\nu\,\psi)(g_6F^{\mu\nu}+\tilde{g}_6\tilde{F}^{\mu\nu}) , \quad (17)$$

$$\mathcal{L}_7 = \frac{1}{4}g_7^S\bar{\psi}\psi F_{\mu\nu}F^{\mu\nu} + \frac{i}{4}g_7^P\bar{\psi}\gamma_5\psi F_{\mu\nu}\tilde{F}^{\mu\nu} , \quad (18)$$

$$\mathcal{L}_8 = \frac{1}{4}\bar{\psi}\gamma^\mu(g_8^V-\gamma_5 g_8^A)\psi(\partial_\mu\tilde{F}^{\alpha\beta})F_{\alpha\beta} , \quad (19)$$

where the coupling constants g_i are $O(1/\Lambda^{(i-4)})$ and D_μ is the QED covariant derivative. These kind of interactions have been discussed by several authors in different contexts and, in particular, they were studied in the case of $e^+e^- \to \gamma\gamma$ at LEP energies [16, 17]. Some of the above Lagrangians may result in large contributions to the anomalous magnetic moment of leptons [18]. Nevertheless an appropriate choice of the coupling constants may cope with these problems and it was considered in the numerical calculations.

The total cross section for the subprocess $\gamma\gamma \to l^+l^-$ when we take into account the contribution of the operators of dimension 6, 7, and 8 are

$$\hat{\sigma}_6(\hat{s}) = \hat{\sigma}_{\rm QED}(\hat{s}) + \pi\alpha^2\xi_6\hat{s}(\tfrac{8}{3}+\tfrac{1}{5}\xi_6\hat{s}^2) , \quad (20)$$

$$\hat{\sigma}_7(\hat{s}) = \hat{\sigma}_{\rm QED}(\hat{s}) + \frac{\pi\alpha^2}{4}\xi_7\hat{s}^2 , \quad (21)$$

$$\hat{\sigma}_8(\hat{s}) = \hat{\sigma}_{\rm QED}(\hat{s}) + \frac{\pi\alpha^2}{4}\xi_8 m^2\hat{s}^2 , \quad (22)$$

where

$$\xi_6 = \frac{(g_6)^2+(\tilde{g}_6)^2}{e^2} , \qquad \xi_7 = \frac{(g_7^S)^2+(g_7^P)^2}{e^4} , \quad \xi_8 = \frac{(g_8^A)^2}{e^4} , \quad (23)$$

and $\hat{\sigma}_{\rm QED}(\hat{s})$ is given by Eq.(11). The effect of the higher-dimensional operators is softened by the presence of many powers of $1/\Lambda$ in the cross section. These cross sections, as expected, violate the unitarity bound at high energies. In the same way as before we can establish an upper limit for $\xi_{6,7,8}$, in order to preserve unitarity in the range of energy considered in this work. For example, for $\sqrt{\hat{s}} \leq 250$ GeV we must have

$$\xi_6 \leq 9 \times 10^{-8}\ \text{GeV}^{-4}, \quad \xi_7 \leq 4 \times 10^{-10}\ \text{GeV}^{-6}, \quad \xi_8 \leq (1/m)^2 4 \times 10^{-10}\ \text{GeV}^{-6}. \tag{24}$$

It is interesting to note that the helicity nature of the interaction Eq.(19) causes the appearance of the mass dependence in Eq.(22), and, once again, it is hopeless to detect such an interaction in e^+e^- annihilation into two photons [17]. Here we have another example where a relativistic heavy-ion collider may prevail over other machines, because of its higher photon luminosity and the fact that we can produce a heavy lepton in the final state enhancing the cross section.

IV. NUMERICAL RESULTS

In this section we present the results of the numerical evaluation of the cross section $ZZ \to ZZ\gamma\gamma \to ZZl^+l^-$ taking into account the contributions coming from the effective interactions discussed in Sec. III. We chose the Cahn-Jackson [6] distribution Eq.(8) in order to exhibit our numerical results. Different choices of the photon-photon luminosity (see Fig. 1) give at most a factor of ~ 2 in the final result. We consider Pb-Pb collisions at the SSC with an energy of 8 TeV per nucleon, corresponding to $\sqrt{s} = 3200$ TeV, and also discuss heavy-ion collisions at the LHC with 3.2 TeV per nucleon ($\sqrt{s} = 1400$ TeV), both operating with luminosity of 10^{28} cm^{-2} s^{-1}.

Since we want to observe effects of new physics beyond the standard model, characterized by a large mass scale (Λ), we should look at processes with large $\hat{s}$. Furthermore, the QED background (coming from the usual $\gamma\gamma \to l^+l^-$ contributions) falls very fast with the increase of the center-of-mass energy. In order to reduce the background, we introduce a cut in $\hat{s}$ (or, equivalently, a minimum value of τ) when computing the total cross section [Eq.(1)]. The higher is τ_{min}, the larger is the difference between the cross section of QED and the ones containing anomalous contributions. After introducing this cut we should still have a reasonable number of events. We found out that $\hat{s}_{\text{min}} = 100$ (200) GeV are good choices for the LHC (SSC) using the luminosity of 10^{28} cm^{-2} s^{-1}. If the luminosity is decreased (increased) we should decrease (increase) the value of the cut.

In order to estimate the excess of anomalous events over the QED background, we consider the quantity

$$\Delta = \frac{\sigma_{\text{tot}} - \sigma_{\text{QED}}}{\sigma_{\text{QED}}} \times 100\%, \tag{25}$$

where the total cross section (σ_{tot}) is obtained, for each anomalous contribution of Sec. III, introducing the subprocess cross section ($\hat{\sigma}$) into Eq.(1) and taking into account the appropriated cuts, whereas σ_{QED} stands for the total cross section due to QED. We demand, as a criterion to identify nonstandard contributions to lepton pair production, a value of Δ larger than 10% with at least 100 events/year above the QED background.

Let us start by analyzing the effect of excited leptons in the $\mu^+\mu^-$ production. In order to overcome the bounds on compositeness, coming from the experimental limit of the anomalous magnetic moment of the electron [18], one must have $|g_*^S| = |g_*^P|$. Nevertheless, we should consider that the couplings of excited leptons may not be equal for different flavors and, in this case, the constraints from $g-2$ are lessened for μ's and τ's. In particular, we assumed that $g_*^S = g_*^P = \sqrt{4\pi}/\Lambda$ in Eq.(10), where the factor $\sqrt{4\pi}$ is the *ad hoc* normalization condition used in experimental bounds for Λ.

Figure 2 contains the numerical results for Δ [Eq.(25)] as a function of the excited lepton mass (M_*) for $\Lambda = M_*$ and 0.5, 1, and 2 TeV. Figures 2(a) and 2(b) were obtained for the LHC energy with $\hat{s}_{\text{min}} = 50$ and 100 GeV, respectively. Figures 2(c) and 2(d) are for the SSC energy with the cuts $\hat{s}_{\text{min}} = 100$ and 200 GeV. We verify that if we double $\hat{s}_{\text{min}}$, Δ increases at least one order of magnitude. The values $\hat{s}_{\text{min}} = 100$ and 200 GeV are reasonable cuts for the LHC and SSC since we improve the signal-to-background ratio for the anomalous events and we still obtain a large number of events. For instance, requiring at least 100 anomalous events/year at the SSC, with the cut of 200 GeV and the excited-lepton mass $M_* = 200$ GeV, we may test a compositeness mass scale Λ up to 3 TeV.

For the excited-lepton contribution, there is no significant differences between e, μ or τ-lepton production for the chosen values of the cut (s_{min}). Taking into account that, for $\hat{s}_{\text{min}} = 100$ (200) GeV for LHC (SSC), we have $\sigma_{\text{QED}} = 37.4$ (16.9) nb, we can get the number of events of excited leptons with a given mass M_* for $\Lambda = 1$ TeV. These results are presented in Table I.

The existence of a spin-zero composite scalar may be one of the most suitable processes to be investigated through $\gamma\gamma$ fusion in heavy-ion collisions. Since the width of the spin-zero composite is expected to be small, the best way to unravel its existence is through the search of a narrow peak in the quantity

$$(d\sigma/dm^2)_{\text{tot}}/(d\sigma/dm^2)_{\text{QED}}\ .$$

In order to estimate the signal-to-background ratio for the composite scalar (pseudoscalar), we computed Δ integrating over a bin of 2 GeV around the scalar peak. Δ can be evaluated using the narrow resonance approximation to integrate over the bin around the Breit-Wigner peak, resulting in

$$\Delta = \frac{1}{s}\frac{m^2}{\Lambda_f^2}\frac{1}{\int d\tau (dL/d\tau)\sigma_{\text{QED}}}\frac{dL}{d\tau}(M_S^2/s)\ ,$$

where $dL/d\tau$ is the photon-photon luminosity. Since σ_{QED} and $dL/d\tau$ are slowly varying functions of τ in the range of integration, we can take them as a constant to write

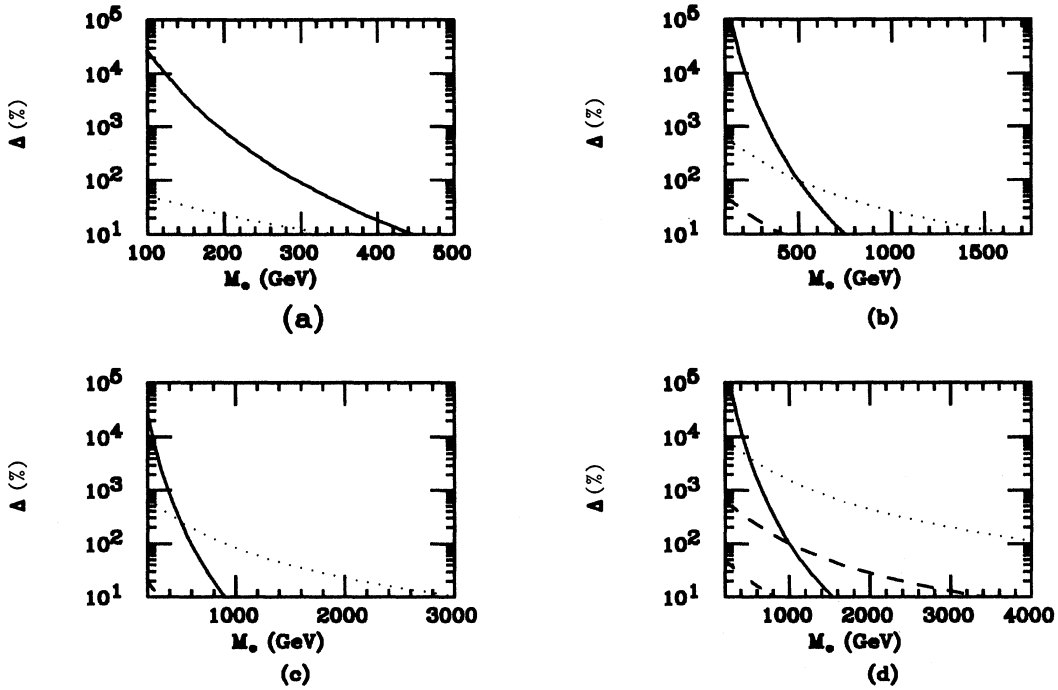

FIG. 2. Δ for the production of $\mu^+\mu^-$ as a function of the excited lepton mass for different values of Λ, i.e., $\Lambda = M_*$ (solid line), $\Lambda = 0.5$ TeV (dotted line), $\Lambda = 1$ TeV (dashed line), and $\Lambda = 2$ TeV (dot-dashed line): (a) LHC with a cut in $\sqrt{\hat{s}}$ of 50 GeV, (b) LHC with a cut of 100 GeV, (c) SSC with a cut of 100 GeV, and (d) SSC with a cut of 200 GeV

$$\Delta = \frac{1}{8\alpha^2}\left(\frac{m}{\Lambda_f}\right)^2 \frac{M_S}{2\text{ GeV}} \frac{1}{\ln(M_S^2/m^2) - 1} \ . \qquad (26)$$

An interesting feature of the last expression is that Δ does not depend either on the considered machine (LHC or SSC), or on the scale characterizing the (pseudo)scalar photon coupling ($\Lambda_{S(P)}$).

In order to exhibit our results we must make a choice for Λ_f. Initially, let us assume that the coupling of the spin-zero boson to the fermions is proportional to their masses and inversely proportional to the scale of compositeness, i.e., $\Lambda_f = \Lambda_S(P) = \Lambda$. Apparently, if $\Lambda \geq v$, the Weinberg-Salam symmetry-breaking scale, we have a suppression of the process $\gamma\gamma \to \phi_{S(P)} \to l^+l^-$ when compared to the standard-model Higgs-boson production [1–8]. Nevertheless, this suppression is counterbalanced by the coupling of the scalar (or pseudoscalar) to the photons, which is strongly suppressed in the standard model.

In Fig. 3 we show Δ for τ-pair production, obtained without the narrow resonance approximation, as a function of Λ for scalar masses $M_S = 75$ and 100 GeV. We assumed Γ_S given by Eq.(14). The contribution of the pseudoscalar is similar to the scalar one. For a scalar boson of mass $M_S = 100$ GeV at the LHC or SSC we can reach a Λ scale of 750 GeV when we require at least 100 anomalous events per year above the QED background and $\Delta \geq 10\%$.

We can also think of a scenario in which the coupling of scalar fermions is given by the standard model one (i.e., $\Lambda_f = v = 246$ GeV). In this case, we obtain $\Delta \sim 100\%$ for $M_S \simeq 100$ GeV and $\tau^+\tau^-$ production. It is interesting to notice that, in this scenario, the ranges in M_S of the heavy-ion colliders LHC and SSC are limited only by statistics, i.e., by the total number of events expected for QED.

The $\tau^+\tau^-$ pair can be easily identified either in leptonic or hadronic decay modes [19]. Nevertheless, in this case we must also measure the invariant mass of the pair in order to unravel the resonance peak of the (pseudo)scalar boson. This can be performed looking for high-multiplicity decays of the τ leptons [20]. However, the inevitable presence of neutrinos introduces an uncertainty in the invariant-mass measurement, which is minimum for multiprong decays. In any case, the excess of τ pairs, above the QED prediction, can just be an indication of the presence of the (pseudo)scalar in the reaction. In order to measure the invariant-mass distribution with higher precision, we can rely on other decay channels such as $\bar{b}b$, as suggested in Refs. [1, 5–7]. In

TABLE I. Number of anomalous events per year above the QED background due to excited leptons, for $\Lambda = 1$ TeV and different values of its mass.

M_* (GeV)	200	500	1000
LHC	1040	260	70
SSC	9900	4800	1700

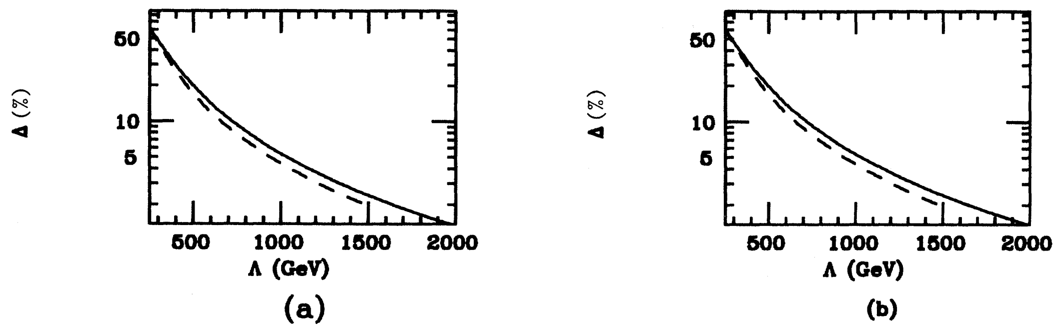

FIG. 3. Δ for the production of $\tau^+\tau^-$ with $M_S - 1$ GeV $\leq \sqrt{\hat{s}} \leq M_S + 1$ GeV as a function of Λ for $M_S = 75$ GeV (dashed line) and $M_S = 100$ GeV (solid line), assuming that $\Lambda_f = \Lambda$: (a) LHC and (b) SSC.

this case, the signal-to-background ratio is larger than in the $\tau^+\tau^-$:

$$\Delta_{\bar{b}b} = 9 \left(\frac{m_b}{m_\tau}\right)^2 \frac{\ln(M_S^2/m_\tau^2) - 1}{\ln(M_S^2/m_b^2) - 1}\, \Delta_{\tau^+\tau^-} . \quad (27)$$

For $M_S = 100$ GeV we have that $\Delta_{\bar{b}b} \simeq 100 \times \Delta_{\tau^+\tau^-}$. Certainly, this composite particle yields more $\bar{b}b$ pairs than the standard-model Higgs boson. This large sample of events enable us to make a good measurement of the boson mass.

Let us now analyze the results for the contribution of a composite Z^0 boson. As can be seen from Eq.(16), there is no interference between the QED and composite vector-boson contribution, as well as the resonance peak is absent due to the suppression of the process for the Z^0 on mass shell [15]. Since the cross section is proportional to the square of the lepton mass, this process will have a considerable signal over the QED background only for τ-lepton production as shown in Fig. 4. In this case the signal consists only of an excess of τ pairs and there is no need for a precise measurement of the pair invariant mass. However, even for τ pairs, we may test values of Λ not larger than $\sim 10^2$ GeV. Despite the gloomy result we believe that any other experiment to discover this kind of interaction ($Z^0\gamma\gamma$) at larger mass scales will be quite difficult to perform.

We now discuss processes generated by contact terms which are suppressed by large powers of $(1/\Lambda)$. The results for the dimension-6, -7, and -8 interactions are shown, respectively, in Figs. 5, 6, and 7. Notice that the results of Fig. 7 were obtained only for τ-lepton production, since for lighter leptons this cross section is unobservable. Requiring the detection of 100 events/year above the QED background (with $\Delta = 10\%$), the maximum values of Λ that can be probed for each interaction are given in Table II for $\tau^+\tau^-$ final states. The results for muons are quite similar for dimension-6 and -7 operators and negligible for dimension 8. Our results indicate that these interactions can be tested only at very small mass scales, hardly larger than 1 TeV. However, in any other kind of collisions, we would not be able to extract any information about these interactions.

V. CONCLUSIONS

Our main aim in this work was to show that the photon-photon process in relativistic heavy-ion collision may open a window for investigating new physics beyond the standard model. We discussed the effects of the possible existence of excited leptons, spin-zero and -one composite bosons, as well as effective contact interactions. We found out that nonstandard contributions to the QED process $\gamma\gamma$ into l^+l^- can be studied up to TeV scale.

At this point it is interesting to comment on the capability of the different kinds of machines (pp, e^+e^-, and

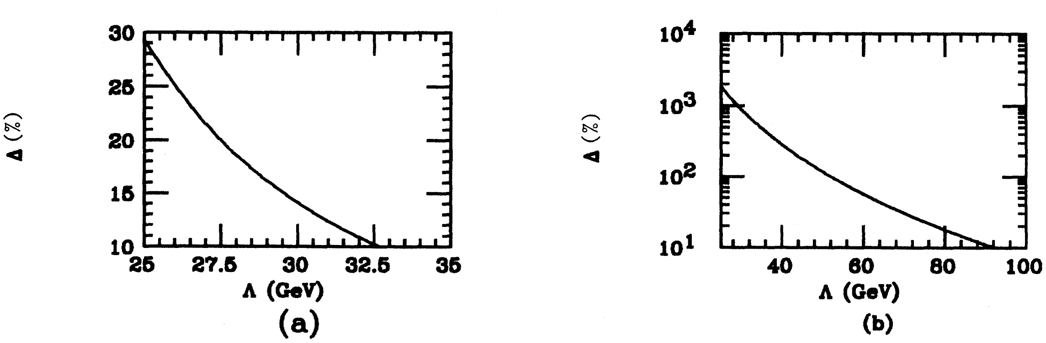

FIG. 4. Δ for the production of $\tau^+\tau^-$ as a function of Λ for the contribution of the composite Z^0: (a) LHC with $\sqrt{\hat{s}} \geq 100$ GeV and (b) SSC with $\sqrt{\hat{s}} \geq 200$ GeV.

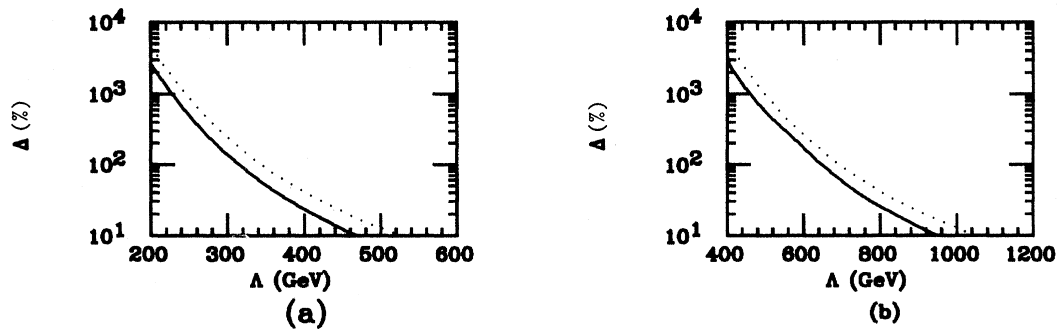

FIG. 5. Δ as a function of Λ taking into account the contribution of the dimension-6 operator Eq.(17) for the production of $\mu^+\mu^-$ (solid line) and $\tau^+\tau^-$ (dotted line): (a) LHC with $\sqrt{\hat{s}} \geq 100$ GeV, (b) SSC with $\sqrt{\hat{s}} \geq 200$ GeV.

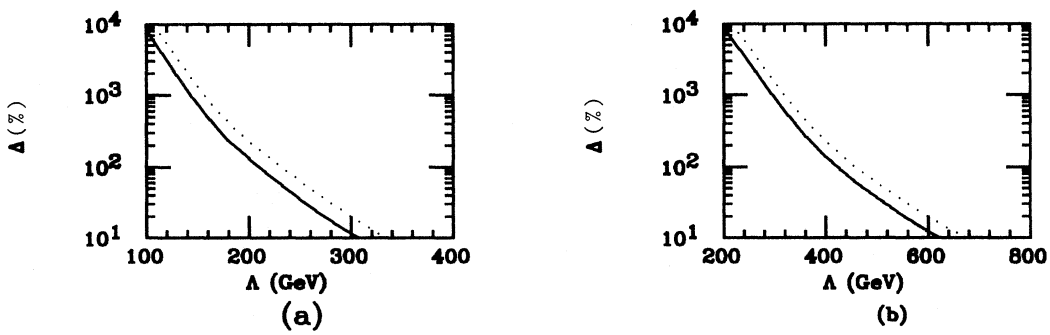

FIG. 6. The same as Fig. 5 for the dimension-7 operator Eq.(18) .

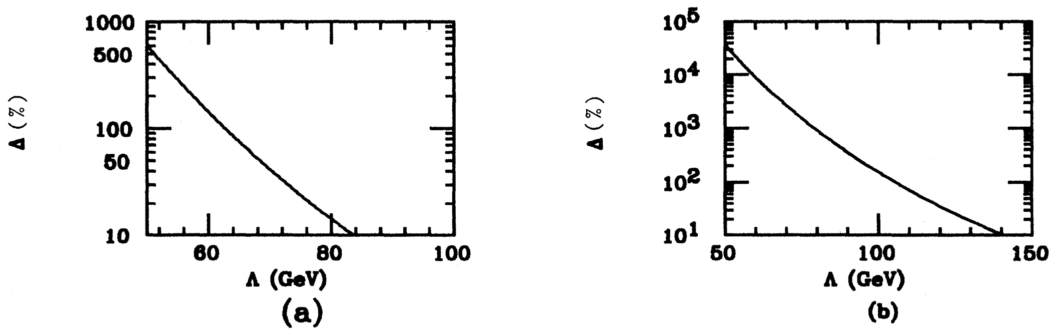

FIG. 7. Δ for the production of $\tau^+\tau^-$ as a function of Λ taking into account the contribution of the dimension-8 operator Eq.(19): (a) LHC with $\sqrt{\hat{s}} \geq 100$ GeV, (b) SSC with $\sqrt{\hat{s}} \geq 200$ GeV.

TABLE II. Maximum value of Λ in GeV accessible for LHC (SSC) with a cut in $\sqrt{\hat{s}}$ of 100 (200) GeV with $\tau^+\tau^-$ as the final state.

Dimension	6	7	8
LHC	520	330	85
SSC	1050	680	140

ZZ) in exploring the existence of the new interactions discussed in this paper. The ion-ion machines are more suitable to explore the reaction $\gamma\gamma \rightarrow l^+l^-$ than the pp one since the coherent nuclei interaction yields an enhancement of the photon-photon luminosity by a factor of Z^4.

On the other hand, in e^+e^- machines, the natural process to be studied is $e^+e^- \rightarrow \gamma\gamma$, which possesses the same matrix element as the reverse reaction $\gamma\gamma \rightarrow l^+l^-$. It is obvious that the ion-ion machines will be more suitable than the e^+e^- for searching for interactions whose cross sections are proportional to the lepton mass since, in the latter one, we are constrained to use electron as the initial state, whereas in the ion-ion machines these cross sections can be enhanced by studying the production of heavy-lepton pairs. For instance, the right place to observe (pseudo)scalar particles that interact strongly with two-photons is in the relativistic heavy ion colliders.

Another way to look for the existence of these new interactions is through the study of spin effects on the angular distribution of the events [21]. Although this procedure is more sensitive to the existence of a new physics, it is very hard to implement experimentally since it requires the measurement of the polarization of the produced leptons.

ACKNOWLEDGMENTS

One of us (A.A.N.) would like to thank C. A. Bertulani for discussions. This work was partially supported by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and Coordenadoria de Aperfeiçoamento de Pessoal de Nível Superior (CAPES).

[1] E. Papageorgiu, Phys. Rev. D **40**, 92 (1989); Phys. Lett. B **250**, 155 (1990)

[2] M. Grabiak *et al.*, J. Phys. G **15**, 25 (1989).

[3] G. Baur and C. A. Bertulani, Nucl. Phys. **A505**, 835 (1989).

[4] G. Baur and C. A. Bertulani, Phys. Rep. **163**, 299 (1988).

[5] M. Drees, J. Ellis, and D. Zeppenfeld, Phys. Lett. B **223**, 454 (1989).

[6] R. N. Cahn and J. D. Jackson, Phys. Rev. D **42**, 3690 (1990).

[7] G. Altarelli and M. Traseira, Phys. Lett. B **245**, 658 (1990).

[8] C. Bottcher, A. K. Kerman, M. R. Strayer, and J. S. Wu, Particle World **1**, 174 (1990).

[9] C. F. von Weizsäcker, Z. Phys. **88**, 612 (1934); E. J. Williams, Phys. Rev. **45**, 729 (1934).

[10] J. D. Jackson, *Classical Electrodynamics*, 1st ed. (Wiley, New York, 1962), p.523.

[11] G. Baur, in *Relativistic Aspects of Nuclear Physics*, proceedings of the Workshop, Rio de Janeiro, Brazil, 1989, edited by T. Kodama *et al.* (World Scientific, Singapore, 1990).

[12] F. E. Low, Phys. Rev Lett. **14**, 238 (1965).

[13] F. M. Renard, Phys. Lett. **126B**, 59 (1983); W. Hollik, F. Schrempp, and B. Schrempp, *ibid.* **140B**, 424 (1984); F. W. Boop *et al.*, Z. Phys. C **24**, 367 (1984); K. Hikasa, Phys. Rev D **33**, 3203 (1986).

[14] F. M. Renard, Nucl. Phys. **B196**, 93 (1982); Y. Tomozawa, Phys. Lett. **139B**, 455 (1984); Z. Ryzak, Nucl. Phys. **B289**, 301 (1989).

[15] C. N. Yang, Phys. Rev. **77**, 242 (1950).

[16] P. Mery, M. Perrottet, and F. M. Renard, Z. Phys. C **38**, 579 (1988).

[17] D. A. Dicus and X. Tata, Phys. Lett **155B**, 103 (1985); D. A. Dicus, Phys. Rev. D **31**, 2999 (1985).

[18] F. M. Renard, Phys. Lett. **116B**, 264 (1982); F. del Águila, A. Méndez, and R. Pascual, *ibid.* **140B**, 431 (1984); J. Grifols and S. Peris, *ibid.* **168B**, 264 (1986).

[19] See, for instance, UA1 Collaboration, Phys. Lett. B **185**, 233 (1987), or R. K. Ellis, I. Hinchliffe, M. Soldate, and J. J. van der Bij, Nucl. Phys. **B297**, 221 (1988).

[20] J. F. Gunion, G. L. Kane, and J. Wudka, Nucl. Phys. **B299**, 231 (1988).

[21] C. Bourrely, J. Soffer, F. M. Renard, and P. Taxil, Phys. Rep. **177**, 319 (1989).