PHYSICAL REVIEW D VOLUME 50, NUMBER 11 1 DECEMBER 1994

Consistency of data on soft photon production in hadronic interactions

Peter Lichard*
Department of Physics, State University of New York at Stony Brook, Stony Brook, New York 11794
(Received 19 August 1994)

The glob model of Lichard and Van Hove and the modified soft annihilation model (MSAM) of Lichard and Thompson are used as a phenomenological tool for relating results from various experiments on soft photon production in high energy collisions. The total phenomenological expectation is composed of contributions from classical bremsstrahlung, the soft annihilation model, and the glob model. The empirical excess above the background from hadronic decays at a very small longitudinal momenta of photons is well reproduced, as well as that for transverse momenta $p_T \gtrsim 10$ MeV/c. Some data do not require the glob model and MSAM components in the phenomenological mixture, but do not exclude them. On the basis of consistency of all data with the total theoretical expectation we argue that the results of all experiments are mutually consistent. The models are unable to describe the excess of ultrasoft photons ($p_T \lesssim 10$ MeV/c), seen by some, but not all, experiments. This may indicate an as yet unknown projectile-mass-dependent production mechanism. Possible relations of soft photon production to other phenomena are discussed. A simple-to-use, but physically equivalent version of the glob model is developed, which enables an easy check of presented results.

PACS number(s): 13.85.Qk, 12.38.Bx, 12.40.$-$y

I. INTRODUCTION

The inclusive production of soft photons in particle collisions at high energies has been studied in several experiments [1–9] using various experimental techniques.

In a pioneering bubble chamber experiment performed at the Stanford Linear Accelerator Center (SLAC), Goshaw *et al.* measured the transverse momentum distribution of photons produced in π^+p collisions at 10.5 GeV/c. Using their own data about hadronic final states they showed that the bremsstrahlung formula of classical electrodynamics [10] was able to account for all the observed photon yield.

A few years later, the experimental group led by Goldschmidt-Clermont [2] investigated the photon production in 70 GeV/c K^+p collisions using the Big European Bubble Chamber (BEBC) at the CERN Super Proton Synchrotron (SPS). In contrast with the observation of the SLAC experiment they found many more photons with very small longitudinal momentum ($2|p_L|/\sqrt{s} \lesssim 0.005$) than they expected on the basis of the classical bremsstrahlung formula and their charged hadron production data. Similarly, the unpublished [11] photon transverse momentum spectrum from the same experiment exhibited a significant excess over the bremsstrahlung estimate for $p_T \lesssim 60$ MeV/c.

The results obtained by the Axial Field Spectrometer (AFS) collaboration at the CERN Intersecting Storage Rings (ISR) [3] were in conformity with both previous experiments. They neither required an additional source to explain the observed photon signal, nor excluded an anomalous component of the size indicated by the BEBC experiment. But they did rule out a strong increase of anomalous photon production with rising collision energy (the invariant energy $\sqrt{s}$ in the AFS experiment was 63 GeV, compared to 11.5 GeV in the BEBC experiment).

In a subsequent AFS experiment [4], the direct photon production was studied in pp and $\alpha\alpha$ collisions at $\sqrt{s} = 63$ GeV. The photon momentum range explored (0.1 GeV/$c < p_T <$ 1 GeV/c) does not overlap the range in this paper ($p_T \lesssim 0.1$ GeV/c). This is the reason why we will not include these data in our comparison. Let us only note that the results of [4] did not show any excess beyond the limits dominated by systematic uncertainties.

The inclusive yield of photons from deep inelastic μp scattering at 200 GeV was measured by the European Muon Collaboration (EMC) at the CERN SPS [5]. After subtracting the contributions from hadron electromagnetic decays and Bethe-Heitler muon bremsstrahlung, residual photons were observed at a mean level of 0.15 ± 0.06 per event.

The first results of the HELIOS (NA34) experiment at the CERN SPS [6] on soft photon production in p-Be and p-Al interactions at 450 GeV/c indicated a marked excess in the region 4 MeV/$c < p_T <$ 20 MeV/c. In addition, the yield seemed to increase approximately as the square of the associated hadron multiplicity, which would have signified a collective production mechanism [12]. These findings were not confirmed by a more extensive later experiment [9] by some members of the same group.

In the experiment performed by the EHS-NA22 Collaboration [7] at the CERN SPS, the European Hybrid Spectrometer (EHS) was equipped with the Rapid Cycling Bubble Chamber (RCBC) as vertex detector. The inclusive soft photon production was studied in π^+p and K^+p collisions at 250 GeV/c. The results confirmed the

*On leave of absence from the Department of Theoretical Physics, Faculty of Mathematics and Physics, Comenius University, SK 842-15 Bratislava, Slovakia.

existence of an anomalous prompt photon signal with very similar properties as seen in the BEBC experiment [2,11].

The SOPHIE/WA83 experiment [8], which was performed at the CERN SPS, used the OMEGA spectrometer supplemented with two electromagnetic calorimeters. It differed in three important respects from the previous two hadronic collision experiments [2,7] that saw the anomalous soft photon signal. First, it used a beam of negative particles (pions with momentum of 280 GeV/c). Second, it was a purely electronic experiment without utilizing a bubble chamber. Third, it explored a kinematic region where the contribution of gammas from hadronic decays is relatively small. The fact that the results of this experiment, as concerns the existence and approximate magnitude of the anomaly, are in conformity with those of previous ones [2,7] is therefore especially valuable.

Antoš *et al.* [9] used a modified setup of the HELIOS experiment [6] and measured the inclusive p_T spectra of soft photons produced at central and slightly backward rapidities in 450 GeV/c p-Be collisions. Two independent photon measurement methods with corresponding detectors and analysis chains were used in parallel: (i) a combination of gas chambers, converter plates, and a bismuth germanium oxide (BGO) matrix for the conversion method; (ii) a BaF_2 array for the time of flight photon identification method. The authors of [9] observed a significant excess of direct photons at very low p_T (< 15 MeV/c) above the background from hadronic decays. This excess was consistent with the expected contribution from hadronic bremsstrahlung, calculated from the classical electrodynamics formula [10].

On the theoretical side, the results of the EMC photon experiment [5] were described [13] using the soft annihilation model [14,15]. Some discrepancy between experimental and theoretical spectra stimulated the creation of the modified soft annihilation model [16], which allowed, contrary to the original model, also gluons in the intermediate parton state. We will present this model in some detail in Sec. III. Every attempt to explain the photon excess seen in the BEBC experiment [2] on the same footing remained unsuccessful.

To our knowledge, the first theoretical paper that addressed the issue of very soft anomalous photons [2] was that by Van Hove [17]. He offered a common explanation of several ultrasoft phenomena observed experimentally in central rapidity regions of high energy collisions. These phenomena are characterized by very low transverse momenta (production of soft pions or photons) or very short distances in rapidity (fluctuations in rapidity distribution–"intermittency"). Van Hove argued that they could be regarded as manifestations of the occurrence, in at least some of the collisions, of an intermediate parton system with considerable lifetime and spatial extension. This system carries only a part of the collision energy and momentum and the rest of the event is "standard." The most natural framework for understanding the production mechanism and properties of such a system is provided by the QCD parton shower model [18]. It is usually assumed that the shower development stops when parton virtualities fall to $Q_0 \approx 1$ GeV. The partons with this virtuality are supposed to enter the hadronization process. Van Hove proposed that some of them may continue in showering, producing a large multiplicity ($N_p \approx 30$) system of very soft partons, a glob of cold quark-gluon plasma. The intermediate parton system consists of one or several globs with masses $M_G \approx 1$ GeV/c^2. As discussed in [17], globs need much time to hadronize, because hadronization requires a very drastic rearrangement of partonic wave functions. During their long lifetime, globs can produce photons in the subprocesses $q + \overline{q} \to \gamma + g$ and $g + q(\overline{q}) \to \gamma + q(\overline{q})$. A quantitative model for soft photon production based on the Van Hove ideas [17] was constructed and successfully compared to the BEBC data [2,11] by him and the present author in [19].

Barshay [20] investigated the role of pion condensation [21,22] in soft photon production. He showed that this collective coherent mechanism implied that the photon emission was proportional to the square of the associated pion multiplicity. At that time, this feature seemed to be indicated by the preliminary HELIOS data [6].

Shuryak [23] showed that the backward reflection of pions at the boundary of a hadronic system, induced by the modification of the pion dispersion curve by many-particle interactions, strongly increases soft photon emission. A complex view of the dense interacting pion matter was presented in the subsequent work [24] together with the implications for experimentally observed phenomena. The photon yield was calculated by applying the classical bremsstrahlung formula along the paths of many times rescattered pions. As stated in the original paper [24], this approach could not describe the observed excess of real photons at low transverse momenta.

Balek, Pišútová, and Pišút [25] (a more detailed discussion of some issues can be found in their later papers: [26] in collaboration with Zinovjev, and [27]), first briefly reviewed experimental information on, and theoretical understanding of the production of very soft photons. Then they studied some effects which were not considered in the bremsstrahlung calculation of the HELIOS Collaboration [6] and found them very small. They also suggested two photon production mechanisms: (1) shock waves in the system of final state hadrons and (2) bremsstrahlung emitted by a quark that tries to escape from the intermediate parton system. They concluded that none of them could explain the soft photon anomaly observed in experiments [2,6].

Czyż and Florkowski [28] used the classical bremsstrahlung formula to calculate soft photon emission within the framework of the boost-invariant color-flux tube model [29]. The ratio of their photon production rate to the classical one depends strongly on the direction of the photon and is very sensitive to the assumed mass of quarks. For photons emitted perpendicular to the collision axis and $m_q \approx 10$ MeV/c^2 it can reach 10. The strong angular dependence is a feature that saliently distinguishes this model from the essentially isotropic glob model [19].

Only a few of the theoretical approaches mentioned above have attempted to make a detailed comparison with actual experimental data, including the very important and delicate matter of experimental acceptance and cuts.

While technical and experimental problems are substantial, an important problem in assessing the reality of the anomalous photon production is that the experiments have been performed under very different conditions. The varied experimental conditions have included different projectiles and targets, different collision energies, different instrumental setups with different photon momentum coverage and acceptances. So it is very difficult to say whether they are consistent among themselves or not, whether they witness about the same phenomenon, whether their contradictory claims are really significantly inconsistent. In this complicated situation we see only one way of pursuing the matter: to use some theoretical model as a tool for connecting various experiments. The guiding idea is that if a model is able, after modulated by the experimental acceptances, to describe several pieces of data without tuning its parameters for each particular case, then the data are mutually consistent. It may also indicate that the model is physically sound, but this need not always be the case. The model may simply simulate an important conventional contribution which was not properly taken into account in every experimental analysis considered.

The purpose of this paper is to assess the consistency of various data on soft photon production in hadronic interactions by using the glob model [19] and the modified soft annihilation model [16] as interpolation tools.

In the next section we deal with the glob model of Van Hove and the present author. We first recapitulate its assumptions and equations, as well as the way its parameters were chosen. Then we develop a simpler, but physically equivalent mutation of the glob model, which will be used throughout this paper. It can easily be implemented by anyone wishing to perform her or his own calculations. Section III deals similarly with the modified soft annihilation model of Thompson and the present author. Unfortunately, here we are unable to offer a user-friendly version. The central part of the paper is Sec. IV, where we show the results of model calculations and their comparison with experimental data. Conclusions are summarized and commented upon in Sec. V, where we also discuss the possible relation of anomalous soft photon production to other phenomena.

II. GLOB MODEL

A. The original version

As mentioned in Sec. I we assume that in some percentage of high-energy inelastic collisions, a long-living, large, and dense system consisting of light quarks, antiquarks, and gluons is formed. For the physical parameters of such a system, called glob, we will use the original estimates [17,19]: the glob mass $M_G = 1$ GeV$/c^2$; the number of partons within a glob $N_p = 40$; the gluon/parton number ratio = 0.5; and the light quark number ratio $u/d = 1$.

Because of the fixed invariant energy, the momentum distribution of partons is governed by the microcanonical distribution. The mean number n_γ^G of photons emitted by a glob is therefore given by the expression

$$n_\gamma^G = k(M_G^2)\frac{t_0}{V_0}\sum_{i=2}^{N_p}\sum_{j<i}\int\left[(p_i\cdot p_j)^2 - m_i^2 m_j^2\right]^{1/2} \times\frac{\sigma_{ij}(s_{ij})}{E_iE_j}\delta\left(\sum_{k=1}^{N_p}E_k - M\right)\delta\left(\sum_{k=1}^{N_p}\mathbf{p}_k\right)\prod_{k=1}^{N_p}\frac{d^3p_k}{E_k}, \tag{2.1}$$

where $\mathbf{p}_k$ is the momentum of the kth parton in the glob rest frame and $\sigma_{ij}(s_{ij})$ is the cross section for photon production in head-on collisions of the ith and jth partons. The processes $q+\overline{q}\rightarrow\gamma+g$ and $g+q(\overline{q})\rightarrow\gamma+q(\overline{q})$ are considered in the lowest order of QED and QCD. The phase-space normalization constant is

$$\left[k(M_G^2)\right]^{-1} = \int\delta\left(\sum_{k=1}^{N_p}E_k - M\right)\delta\left(\sum_{k=1}^{N_p}\mathbf{p}_k\right)\prod_{k=1}^{N_p}\frac{d^3p_k}{E_k}. \tag{2.2}$$

The total cross section σ_{ij} in Eq. (2.1) can be written as

$$\sigma_{ij}(s_{ij}) = \int dt_{ij}\frac{d\varphi_{ij}}{2\pi}\frac{d\sigma_{ij}}{dt_{ij}}, \tag{2.3}$$

where t_{ij} is the four-momentum transfer squared from one parton to the photon in the collision of the ith and jth partons and φ_{ij} is the azimuthal angle of the photon in their rest frame. After inserting (2.3) into (2.1) and mapping the independent variables onto a $(3N_p-2)$-dimensional unit cube [30], we arrive at the equation that served in [19] as the master equation for a Monte Carlo generator of the photon momenta in the glob rest frame.

To transform the photon momentum from the glob rest frame to the collision center-of-mass frame we need to know the glob momentum distribution in the latter. In [19] it was assumed that the distribution in the glob rapidity and transverse momentum squared

$$\frac{d^2N_G}{dy_G dp_{T,G}^2} = N_G F_G\left(y_G, p_{T,G}^2\right), \tag{2.4}$$

with the function F_G normalized to unity, factorizes. To proceed further, a Gaussian glob rapidity distribution with the width proportional to the maximum c.m.s. rapidity (i.e., $\log s$) was chosen, with $\langle y_G^2\rangle^{1/2} = 0.6$ for $\sqrt{s} = 11.51$ GeV (the BEBC experiment [2]). The exponential $p_{T,G}^2$ distribution was assumed to be collision energy independent with $\langle p_{T,G}\rangle = 0.3$ GeV$/c$. In each Monte Carlo "event," the rapidity and transverse momenta were generated, increasing the number of independent variables to $3N_p$. Then the photon momentum was transformed into the collision center-of-mass frame.

To complete the model, the mean number of globs per event N_G is multiplied by the mean number of photons per glob n_γ^G to give the mean number of photons per event n_γ. Keeping in mind that the cross sections of photon production subprocesses are proportional to the strong coupling constant α_s, the overall multiplication constant that fixes the absolute normalization of photon yield is

$$B = \alpha_s N_G \frac{t_0}{V_0} \, . \tag{2.5}$$

In order to fit the BEBC data [2], its value was fixed in [19] at $B = 5 \times 10^{-3}\ c^{-1}\ \mathrm{fm}^{-2}$. To get the predictions for photon spectra at different collision energies or with different incident particles it was suggested in [19] to scale the mean number of globs N_G according to empirically known hadron multiplicity.

The first numerical realization of the glob model [19], which we have just briefly sketched, had serious disadvantages. With N_p fixed at 40, the dimension of the integral which was to be evaluated by the Monte Carlo method was 120. Determination of a detailed distribution in photon momentum with low statistical errors thus became a computer-time-consuming task. Also the computer code was complicated and difficult to use. It was practically impossible to use the glob model as an event generator for Monte Carlo studies of experimental setups. In the next subsection we remove these drawbacks of the original glob model [19] and suggest a computing scheme which is easy to reproduce.

B. A simplified version of the glob model

In the glob model it is assumed that the internal properties of the glob (total invariant energy of partons $M_G c^2$, their number N_p, as well as their momentum and flavor distributions) depend neither on the type of process under study nor on the incident energy. This allows us to construct a new version of the glob model, which is physically equivalent to the original one, but much easier to use.

The invariant photon distribution in a general reference frame can be written as a convolution of the photon distribution in the glob rest frame with the momentum distribution of globs in the general frame

$$E_\gamma \frac{d^3 n_\gamma}{d^3 p_\gamma} = \int d^3 p_G \frac{d^3 N_G}{d^3 p_G} \; E_\gamma^* \frac{d^3 n_\gamma^G}{d^3 p_\gamma^*} \, . \tag{2.6}$$

The asterisk refers to quantities in the glob rest frame and

$$\mathbf{p}_\gamma^* = \mathbf{p}_\gamma + \frac{\mathbf{p}_G}{M_G} \left(\frac{1}{E_G + M_G} \mathbf{p}_G \cdot \mathbf{p}_\gamma - E_\gamma \right) \, . \tag{2.7}$$

According to the basic assumptions of the glob model, the photon momenta are distributed isotropically in the glob rest frame. It is thus sufficient to consider only the energy spectrum in the latter frame. We can write

$$\frac{1}{E_\gamma^*} \frac{dn_\gamma^G}{dE_\gamma^*} = \alpha_s \frac{t_0}{V_0} f(E_\gamma^*) \, . \tag{2.8}$$

A study of this quantity in the framework of the original Monte Carlo version of the glob model has showed that

TABLE I. Parameters of the photon energy distribution in the glob rest frame.

E_γ^G (GeV)	a ($\mathrm{fm}^{-2}\mathrm{GeV}^{-2}$)	b (GeV^{-1})	c (GeV^{-2})
< 0.02	6.60×10^5	3.39×10^1	1.61×10^3
(0.02, 0.04)	1.05×10^6	8.15×10^1	4.04×10^2
> 0.04	1.63×10^6	1.02×10^2	1.82×10^2

the function $f(E_\gamma^*)$ can be parametrized as

$$f(E_\gamma^*) = a \exp\left\{ -bE_\gamma^* - c(E_\gamma^*)^2 \right\} \, , \tag{2.9}$$

with parameters a, b, and c given in Table I. Comparison of the photon energy distribution in the glob rest frame based on the parametrization (2.9) with the original Monte Carlo calculation in Fig. 1 shows that they are identical.

Introducing the distribution in the glob rapidity and transverse momentum squared (2.4) and using Eq. (2.8), we can cast Eq. (2.6) in the form

$$\frac{d^2 n_\gamma}{dp_{L,\gamma} dp_{T,\gamma}} = \frac{B}{4\pi} \frac{p_{T,\gamma}}{E_\gamma} \int F_G \left(y_G, p_{T,G}^2 \right) f\left(E_\gamma^* \right) dy_G \, dp_{T,G}^2 d\phi \, , \tag{2.10}$$

where B is again given by Eq. (2.5) and

$$E_\gamma^* = \frac{1}{M_G} \left(E_G E_\gamma - p_{L,G} p_{L,\gamma} - p_{T,G} p_{T,\gamma} \cos\phi \right) \, . \tag{2.11}$$

Even if the integrals in Eq. (2.10) can be evaluated by more conventional numerical methods, a Monte Carlo approach is convenient to utilize, especially if the experimental acceptance has to be taken into account.

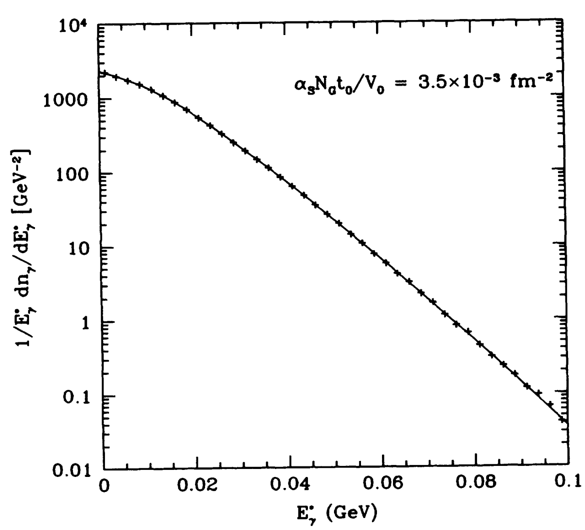

FIG. 1. Parametrization of the photon energy spectrum in the glob rest frame (curve) and its comparison to the results of original Monte Carlo calculation (crosses).

III. MODIFIED SOFT ANNIHILATION MODEL

The original soft annihilation model (SAM) [14] was inspired by Bjorken and Weisberg [31] who suggested an explanation of an unexpectedly large production of low-mass lepton pairs discovered in many experiments [32]. In the SAM, dileptons arise from an intermediate parton system (IPS) by annihilation of quarks and antiquarks ($q\bar{q} \to l^+l^-$ and $q\bar{q} \to l^+l^- gluon$) produced in the initial stages of the reaction. Unlike the IPS system of Van Hove [17], the IPS of the SAM carries all the collision energy and is the only source of final-state hadrons. Its parameters are therefore fixed by data on the production of hadrons [33]. In 1981, the SAM was compared [15] to all the dilepton data available at that time and appeared to be in satisfactory agreement with them.

Later on, the data on electron production at the CERN Intersecting Storage Rings (ISR) were extended to lower values of the transverse momentum [34]. The SAM was not able to follow a steep rise of the e^+/π ratio with decreasing transverse momentum. The comparison of the SAM (with the subprocess $q\bar{q} \to \gamma + g$) to the EMC photon data was not without flaws either. Both longitudinal and transverse spectra (in the hadronic system rest frame) were flatter than the experimental one [13]. To bring the calculations closer to reality, a gluon component was introduced into the IPS in the modified soft annihilation model [16] together with corresponding subprocesses $g + q(\bar{q}) \to \gamma + q(\bar{q})$ and $g + q(\bar{q}) \to l^+l^- + q(\bar{q})$. With the quark and antiquark multiplicities fixed at the same values as in the SAM (in order not to change outgoing hadron multiplicities), the mean energies of partons became smaller, which also made the spectra of dileptons and photons softer. This improved the agreement not only with the results of [5,34], but also with some older dilepton data (see [16]). We refer the reader to [16] for technical details of the model, which we will use also in this work. Let us only note that the model, when applied to soft photon production, does not contain any free parameters. For each projectile, target, and incident energy combination, the mean number of partons in IPS was fixed by the mean hadron multiplicity.

IV. COMPARISON OF MODELS TO DATA

In this section we compare the outcomes of the glob model [19] and the modified soft annihilation model (MSAM) [16] with existing data. For data which provide absolute normalization, the procedure is straightforward. They are those listed in the Introduction except for the AFS [3] and Antoš *et al.* [9] experiments.

In paper [3] the AFS Collaboration presented the p_T spectrum of photons observed in pp collisions at $\sqrt{s} =$ 63 GeV (their Fig. 13) normalized to expectations. The latter were, in turn, given in terms of ratios to the $(\pi^+ + \pi^-)/2$ yields (AFS Fig. 12). The comparison of models to their results would be possible, but would require the recall of information from other experiments and the inclusion of the AFS efficiences and acceptance. As we have already mentioned, the AFS Collaboration found their data compatible with the other data known at the time [1,2], which will be explored here in detail. We would be unlikely to add much to their statement even if we compared [3] with our models.

With the data of Antoš *et al.*, the situation is different. At first glance they seem to be incompatible with all the experiments that have reported the existence of the soft photon anomaly. It is therefore very important to include results by Antoš *et al.* in our study. But in the paper [9] they presented the results only in "arbitrary units." A plausible way of comparing models to data [9] was suggested to us by Schukraft. It is described in the relevant subsection below.

Unlike in the original paper on the glob model [19], more detailed and statistically more precise results of the simplified version of the glob model can now be combined with the other independent sources of photons (MSAM, bremsstrahlung calculated by experimentalists on the basis of empirical charged hadron distributions or hadron production models) producing a total theoretical expectation. The latter is then compared to the experimental data. We can thus also determine the basic parameter of the glob model $B = \alpha_S N_G t_0 / V_0$ more reliably.

A. BEBC experiment by Chliapnikov *et al.* [2]

We start with the BEBC data [2] because they were used in [19] to fix the absolute normalization of the glob model. The experimental cut $E_\gamma^{\rm lab} > m_\pi c^2/2$ was enforced in computations within both models, as in bremsstrahlung calculations [2]. In Fig. 2 we show the data on the distribution of photons in $x = 2p_{L,\gamma}/\sqrt{s}$ together with the leading term bremsstrahlung calculation from [2] and with the outcome of the glob model. The total theoretical expectation, which should be compared to data, is the sum of the glob and bremsstrahlung curves. In the glob model calculation we used the value $B = 3.5 \times 10^{-3}\, c^{-1}\, \text{fm}^{-2}$ of the overall multiplication constant (2.5). The present value of B, which is 0.7 times the value used in [19], was chosen to give good agreement of the theoretical x spectra not only with the BEBC results, but also with the data [7] on prompt photon production in K^+p and π^+p interactions at 250 GeV/c (see below).

The reader has certainly noticed that the MSAM curve is not shown in Fig. 2. Neither are the MSAM photons included into the total theoretical expectation, which should be compared with data. The reason is that their x distribution is almost flat on the scale of Fig. 2 and over a wider range it resembles the spectrum of photons from π^0 decays (not shown). It was the virtue of the experimental procedure used in [2] for isolating the anomalous component in the x spectrum that the photons with a spectrum similar to that from the π^0 decays were subtracted from the total yield. In this way, the MSAM photons were also subtracted and are not present in the data points shown in Fig. 2.

The transverse momentum spectra of photons produced in 70 GeV/c K^+p collisions are depicted in Fig. 3. We can see that the data above $p_T \approx 15$ MeV/c are

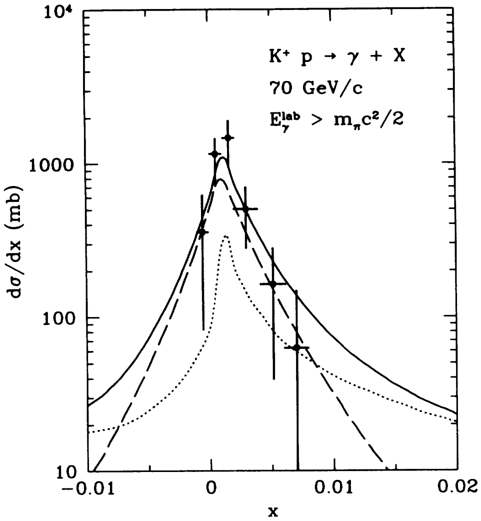

FIG. 2. BEBC data [2] compared to the classical bremsstrahlung formula (dotted), the glob model (dashed), and their sum (solid).

well described by the superposition of both models and bremsstrahlung. The glob model provides the most important contribution up to $p_T \approx 45$ MeV/c, where the MSAM takes over. The classical bremsstrahlung formula is dominant below $p_T \approx 5$ MeV/c (as expected from the Low formula), but even it is unable to account for all the experimentally observed yield. For $p_T < 10$ MeV/c, the mean excess of data above the total expectation (solid curve) is roughly equal to the total expectation itself.

B. SLAC experiment by Goshaw *et al.* [1]

The inclusive p_T^2 distribution of photons from π^+p interactions at 10.5 GeV/c is shown in Fig. 4. The central

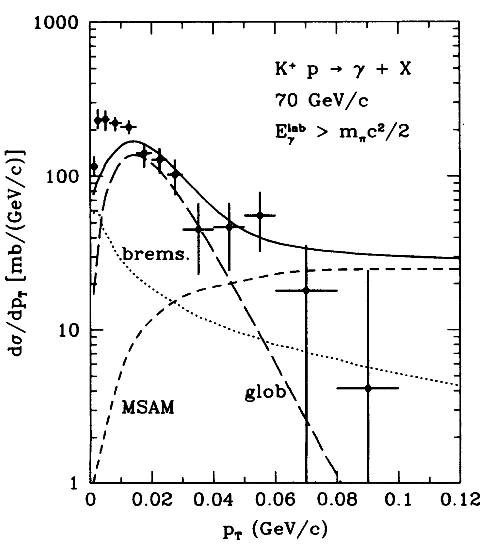

FIG. 3. BEBC data [11] and their comparison with the sum (solid) of the classical bremsstrahlung formula, the glob model, and the modified soft annihilation model (MSAM).

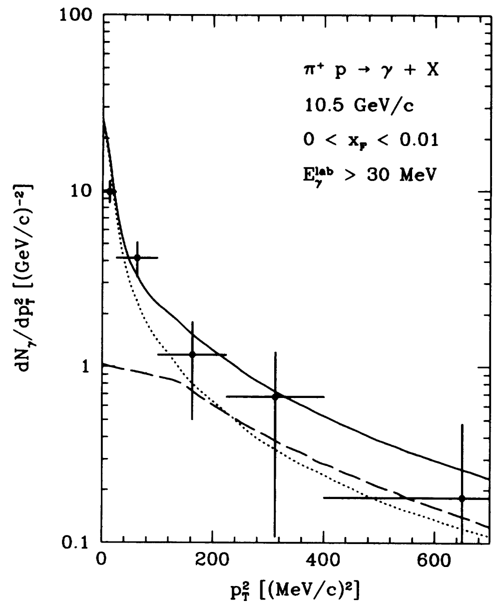

FIG. 4. Goshaw *et al.* data [1] compared to the classical bremsstrahlung calculation (dotted), the glob model (dashed), and their sum (solid).

values of all but one data point lie above the dotted curve, which represents a classical bremsstrahlung calculation. But, accounting for experimental errors, this does not represent a statistically significant discrepancy.

To perform a glob model calculation, we have to rescale the multiplicative constant B to the new energy. In [19] it was suggested that it should be done according to the mean hadron multiplicity. But we feel that at this very low energy ($\sqrt{s} = 4.54$ GeV) this is inadequate. Because of the energy-momentum constraints it is much more difficult to produce a glob with mass 1 GeV in addition to a baryon in the final state than a pion (pions account for most of the produced multiplicity) with a mass roughly seven times smaller. The dependence of N_G on the collision energy should be, at small energies, much steeper than that of overall hadron multiplicity and should behave more like, let us say, the mean multiplicity of centrally produced $\phi(1020)$'s. Guided by the experimental results on the production of the latter in pp collisions (see, e.g., Fig. 3 in [35]), we assume that the glob multiplicity at 10.5 GeV/c is three times smaller than that at 70 GeV/c. In this way we mimic the threshold effect which must exist in the production of globs in low-energy collisions. Scaling according to the ratio of produced charged hadron multiplicities in 70 GeV/c K^+p and 10.5 GeV/c π^+p collisions would lead to a decrease by a little smaller factor of 2.1. The ratio of charged multiplicities is 1.6.

In order to be able to compare the model predictions with the data we have taken into account the experimental cuts $0 < x < 0.01$ and $E_\gamma^{\rm lab} > 30$ MeV, number of events (33 676), and detection efficiency (0.25) given in [1]. The results of the glob model are depicted by a dashed curve in Fig. 4, the results of the MSAM lie below the lower edge of the diagram. The sum of all three theoretical components (solid curve) is now higher than the central values of most of the data points, but is as compatible with them as was the pure bremsstrahlung component. We can thus conclude that even if the results of the SLAC experiment [1] do not require any additional mechanism rather than classical bremsstrahlung, they do not exclude an additional contribution of the size given by the glob model. The glob mechanism dominates over bremsstrahlung for $p_T \gtrsim 15$ MeV/c.

C. EMC experiment by Aubert *et al.* [5]

This experiment, which measured the inclusive photon production in deep inelastic scattering of 200 GeV/c muons in hydrogen, is usually included into a common list with experiments on anomalous soft photon production in hadronic collisions. We will show here that the kinematic range and probably also the production mechanism of the anomaly observed in [5] are different from those reported by hadronic experiments [2,7,8].

The inclusive photon distributions in [5] are normalized to all deep inelastic events. We will deal with two of them that are presented in transverse momentum p_T to the virtual photon current and fractional energy z, defined as $E_\gamma^{\rm lab}/\nu$, where ν is the energy lost by the scattered muon. Because we did not have access to empirical distributions in ν and in the invariant energy of hadronic system W, we fixed them at their mean values $\langle\nu\rangle = 113$ GeV, $\langle W^2\rangle = 195$ GeV^2, quoted in [5]. When calculating the transverse momentum distribution, we applied the cut $z > 0.05$. In virtue of both models we are using here, we assume that the intermediate parton systems they are dealing with are bound to the rest frame of the hadronic system produced in deep inelastic scattering.

The z distribution of photons from the glob model and the MSAM (taken from [16]) is compared with the data in Fig. 5. We can see that the photons from the glob

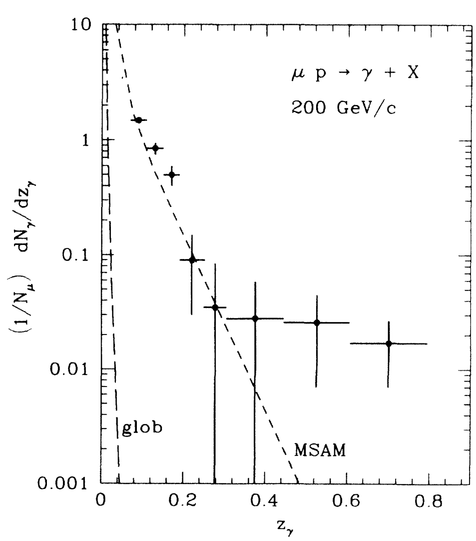

FIG. 5. EMC data [5] compared to the modified soft annihilation model (MSAM) and the glob model. The rightmost data points can be explained as a bremsstrahlung from the scattered muon [5].

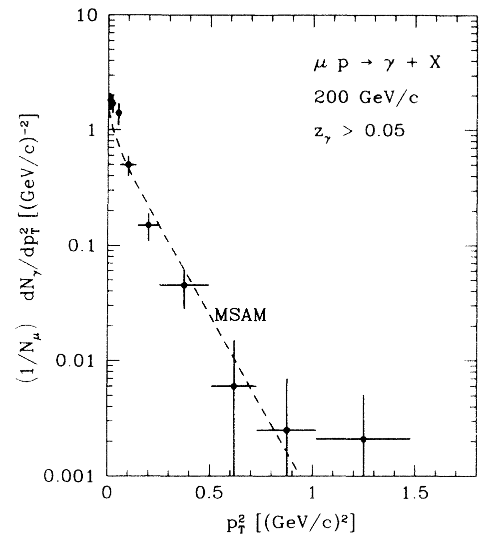

FIG. 6. EMC data [5] compared to the modified soft annihilation model (MSAM). Because of the z cut, the radiation from globs does not contribute at all (compare Fig. 5).

model are completely irrelevant here, because their energies are much smaller than those of the prompt anomalous photons observed in [5]. Having so little energy, the glob photons are below the z cut and do not appear at all in Fig. 6, which shows the p_T^2 distribution of anomalous prompt photons. The glob model alone provides a successful description of data in both cases.

This points out to a completely different production mechanism of the EMC anomalous photons. Rather than being generically related to the anomalous soft photons in hadronic collisions, they have more in common with the trimuons discovered a long time ago [36]. It is indicated by the fact that also the trimuon production was satisfactorily described by the soft annihilation model [37].

D. EHS-NA22 experiment by Botterweck *et al.* [7]

The EHS-NA22 Collaboration studied inclusive cross sections of prompt soft photon production in K^+p and π^+p interactions at 250 GeV/c. In our calculations within the glob model and the MSAM we applied the cut $E_\gamma^{\rm lab} > m_\pi c^2/2$, as introduced in the experiment.

The models are compared with the experimental inclusive photon production cross section in $x = 2p_L/\sqrt{s}$ in Figs. 7 (K^+p collisions) and 8 (π^+p collisions). The contribution from the MSAM is not included for the same reasons as in Sec. IV A. The agreement between data and the combined theoretical expectation is very good. Of course, keeping in mind the inevitably large experimental errors (each data point was obtained as a difference of two big numbers—the total yield minus the calculated yield from the radiative decays of hadrons), theoretical curves scaled down by a factor of, say, ≈ 1.5 would be also acceptable.

In Figs. 9 and 10, the measured inclusive differential cross sections in transverse momentum are presented to-

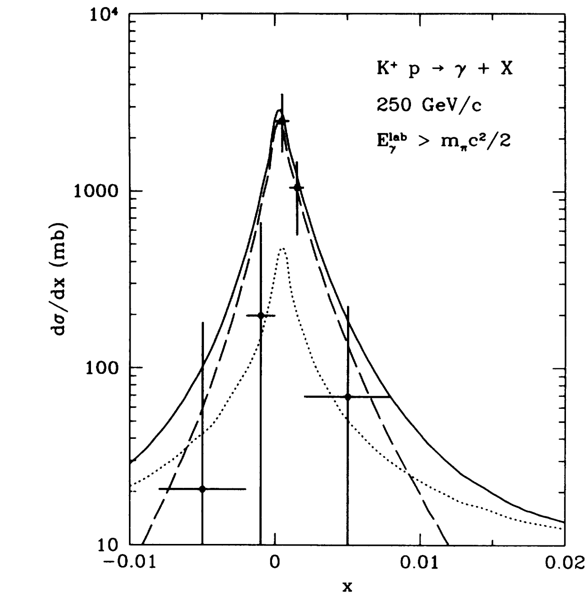

FIG. 7. NA22 K^+p data [7] compared to the sum (solid) of the classical bremsstrahlung calculation (dotted) and the glob model (dashed).

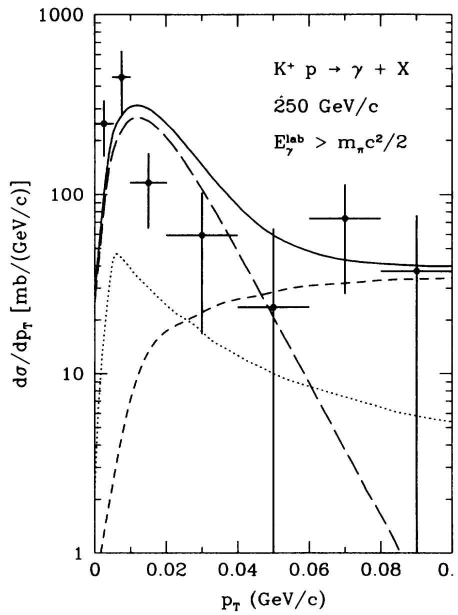

FIG. 9. NA22 K^+p data [7] and their comparison with the sum (solid) of the classical bremsstrahlung formula (dotted), the glob model (long dash), and the modified soft annihilation model (short dash).

gether with the classical bremsstrahlung estimate made by experimenters, two model curves, and a sum of these three components. For both K^+p and π^+p initial states, the theoretical expectation does not match the data very well. It is below the data for ultrasoft photons ($p_T \lesssim 10$ MeV/c) and overshoots the data in the medium region (10 MeV/$c \lesssim p_T \lesssim 50$ MeV/c). The former feature is common with other hadronic experiments and will be discussed later. The latter may have several origins. First of all, the procedure of extrapolations to different collision energies suggested in [19] may be unreliable. This interpretation is somewhat called into question by the good agreement with the results of the WA83/SOPHIE experiment [8] (see below), which was done at even a slightly higher collision energy ($p_{\rm lab} = 280$ GeV/c). Another reason may lie in our inadequate simulation of experimental conditions. Besides the energy cut mentioned above, the experimenters introduced several others in an effort to minimize systematic errors. The latter would be very difficult to implement in our model calculations, because

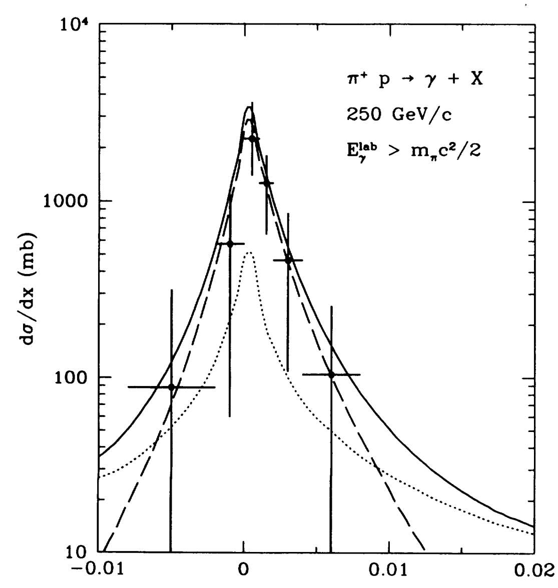

FIG. 8. Same as Fig. 7, but with a π^+ projectile.

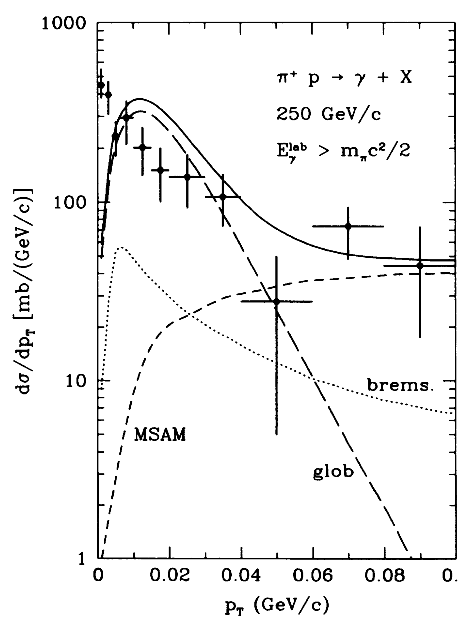

FIG. 10. Same as Fig. 9, but with a π^+ projectile.

such a task would require a detailed knowledge about the experimental setup and a model for the conversion of photons to electrons in the metal foils placed inside the Rapid Cycling Bubble Chamber. We are not, of course, able to assess here how reliably it was possible to correct for all those cuts, and to what extent they persist in the final experimental distributions.

There is another important issue to be discussed in connection with the paper [7]. In their Figs. 7(a) and 7(b) and 8(a) and 8(b), the authors of [7] show the predictions of the glob model, which differ a little from what we presented here. In fact, their model histograms are lower than our curves and provide a better description of differential cross sections in p_T. Unfortunately, the model predictions in [7] were obtained under oversimplified assumptions. The model histograms [19] for K^+p collisions at 70 GeV/c were only multiplied by the ratios of total inelastic cross sections at 250 and 70 GeV/c. The authors of [7] thus neglected the change of mean glob multiplicity with the collision energy and assumed that the form of distributions is collision-energy independent, x and p_T were treated as "scaling variables."

E. SOPHIE/WA83 experiment by Banerjee *et al.* [8]

The high statistics study [8] of direct soft photon production in $\pi^- p$ collisions at 280 GeV/c was based on a sample of 310 390 events observed in the apparatus consisting of the OMEGA spectrometer and two electromagnetic calorimeters. The results are given in the numbers of photons per bin in the variable under consideration (p_T or $E_\gamma^{\rm lab}$). The numbers have been corrected for the γ detection efficiency, but no attempt has been made to correct for the geometrical acceptance and extract the differential cross sections. Generally speaking, for experiments with a nontrivial geometrical acceptance that covers only a part of the phase space, such a way of presenting results is least biased and therefore most valuable [38]. Any attempt to go beyond it would require some assumptions about either the production mechanism or the photon distribution in inaccessible phase-space regions. In order to compare a model with data, one has to modulate theoretical distributions with experimental acceptance.

We took full advantage of the possibilities provided by the simplified version of the glob model and merged it with a program that described the geometrical acceptance of the WA83 experiment[1] in order to calculate the same sort of distributions as shown in [8]. Such a project would be very difficult to accomplish with a very inefficient photon generator based on the original version. For the MSAM, the acceptance modulated calculations do not represent a novelty [15,16].

The photon transverse momentum spectra from models are compared to the experimental one in Fig. 11. Again, a reasonable agreement has been achieved for $p_T \gtrsim 10$ MeV/c. The transition from the glob model to the MSAM is now located at $p_T \approx 30$ MeV/c. It is interesting that the size of the classical bremsstrahlung is roughly equal to that of the model which just dominates. The excess of data over the total theoretical expectation in the ultrasoft region ($p_T \lesssim 10$ MeV/c) is huge, about sevenfold for the lowest data point.

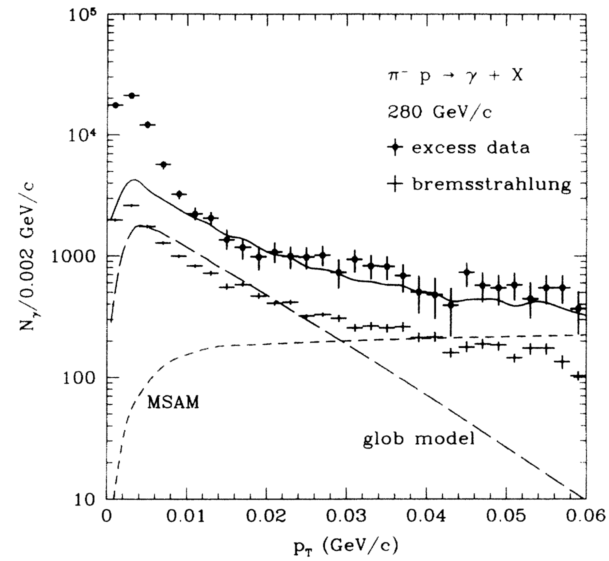

FIG. 11. Comparison of the excess in WA83 data [8] over known sources with the sum (solid curve) of the photon yields from classical bremsstrahlung, glob model, and modified soft annihilation model (MSAM).

F. Soft photon experiment by Antoš *et al.* [9]

As we have already mentioned, the experiment measured the photon production in pBe interactions at 450 GeV/c. For those who want to compare its results with theoretical estimates, the missing absolute normalization is an obstacle. Schukraft, member of both the HELIOS Collaboration [6] and the experimental group [9], suggested to us to fix the model normalization by comparing the bremsstrahlung estimates in [6] to those in [9]. Because of similarities between the two apparatus, they should be identical. But the former is given in terms of the double differential cross section, the latter in "arbitrary units." This allowed us to recalculate the cross sections provided by models to the "arbitrary units" of the experiment [9]. For this purpose we used the Be results of Fig. 13 from the Schukraft presentation in Ref. [6].

Figure 12 shows the p_T distribution of photons produced with zero rapidity in the proton-nucleon center-of-mass system after subtraction of the decay background. The data taken by both detection methods are shown. The systematic errors of the data, the decay background, and the bremsstrahlung calculation are not reproduced from the original Fig. 5(a) to keep our figure uncluttered. The total theoretical expectation agrees nicely with the

[1] I am indebted to M. Spyropoulou-Stassinaki for providing me with the necessary information and to A. Belogianni for checking the relevant part of my computer code.

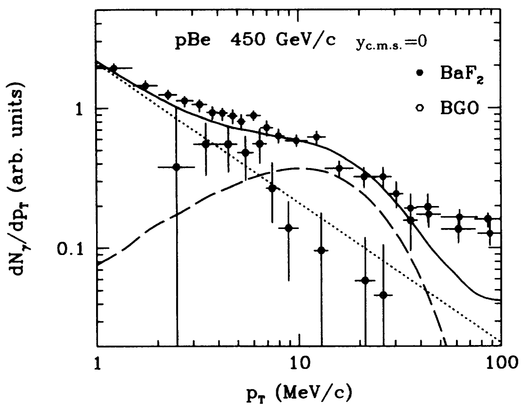

FIG. 12. 450 GeV/c p-Be direct photon data [9] compared to the sum (solid curve) of the classical bremsstrahlung calculation (straight line), the glob model (long dash), and MSAM (under the scale).

results from the BaF_2 detector and is compatible, taking into account the large systematic errors, with the BGO array results. In the kinematic region of the experiment [9], the MSAM contributes very little. The glob model provides the most important contribution in the medium region 8 MeV/$c \lesssim p_T \lesssim$ 40 MeV/c. There is practically no excess in data over the theoretical expectation in the ultrasoft region.

V. CONCLUSIONS AND COMMENTS

We have seen in the previous section that in the prompt photon production it is useful to distinguish among three different kinematical regions: (1) ultrasoft, with photon transverse momenta less than, say, 10 MeV/c; (2) very soft, 10 MeV/$c \lesssim p_T \lesssim$ 50 MeV/c; and (3) soft, characterized by $p_T \gtrsim$ 50 MeV/c.

Of the various components that we included in our phenomenological approach, the classical bremsstrahlung formula is invincible in the ultrasoft region. In the very soft region, the main contribution to the total theoretical expectation comes from the glob model [19]. The yield from the modified soft annihilation model [16] peaks somewhere beyond the range explored by the hadronic experiments considered here and is therefore the only theoretical component which rises with p_T. Whether and where it will be above the remaining two components (classical bremsstrahlung and glob model) depends on the incident energy and the setup of the experiment. But it usually dominates in the soft region.

The experimental data are mixed, with some experiments showing a much larger excess over the hadronic decay background than expected from their classical bremsstrahlung calculation, and other experiments claiming agreement between the excess and bremsstrahlung. The main result of this work is that, for all the experiments the observed x and p_T distributions of direct photons are reasonably well described above $\approx$ 10 MeV/c (that is except for the ultrasoft transverse momentum region), by a mixture consisting of the classical bremsstrahlung calculation (taken from original experimental papers) and two theoretical models. The latter are detailed enough to include experimental cuts and acceptances. The rules for extrapolating them to different energies have clearly been stated beforehand. On the basis of agreement of all data with the theoretical expectation, we conclude that all the experimental data (except for the p_T distributions in the ultrasoft region) on anomalous soft photon production are mutually consistent.

It should be stressed that the magnitudes of different components in the phenomenological mixture did not come out as a result of fitting the experimental data, but are given as an interplay between their physics properties and experimental conditions (incident energy, instrumental cuts, and acceptances). The actual numbers may be very different in different cases. For example, in the p_T distribution from the BEBC experiment [11], the maximum glob/bremsstrahlung ratio is almost seven (see Fig. 3), whereas in the pBe collisions at 450 GeV/c [9], it does not exceed four (Fig. 12), and is able to squeeze into the empirical upper limits of direct photons provided by the BaF_2 method in [9] (their Fig. 6). In the former experiment, the MSAM gives the dominant contribution for $p_T \gtrsim$ 50 MeV/c, but is below the bremsstrahlung up to the highest p_T's in Fig. 12. In the WA83/SOPHIE experiment [8], the size of bremsstrahlung in the very soft and soft regions is roughly equal to that of the dominating model (glob or MSAM, see Fig. 11).

Let us turn now to the ultrasoft region, where some experiments agree with the theoretical expectation (completely dominated and therefore represented here exclusively by the classical bremsstrahlung formula), whereas others see a significant excess. While the delicacy of the experiments is underlined by the juxtaposition of the early HELIOS [6] results and those of [9], and the differing results could lie in differing experimental techniques, the apparent contradiction between the experiments might also be due to different underlying physics conditions. Without any theory or model able to describe the anomalous excess, the field is open to speculations. Here is one possibility:

The data seem to suggest (compare Figs. 3, 9, 10, 11, and 12) that the ultrasoft excess decreases with increasing mass of the projectile. There is one experiment that seems to contradict this suggestion: the historically first photon experiment [1], which did not see anything anomalous with pions. But let us recall that this is the only experiment which used, besides the laboratory energy cut $E_\gamma^{\rm lab} > 30$ GeV, also the cut on the longitudinal photon momentum in the c.m. system (c.m.s.) $0 < 2p_{L,\gamma}/\sqrt{s} < 0.01$. The combination of those two cuts suppresses the yield of low-p_T photons, especially if they are produced in a narrow cone around the projectile momentum. So the absence of the excess in this case need not mean its true nonexistence.

The regularity above may imply that the excess is caused by bremsstrahlung from the projectile experiencing a (multiple) small-angle scattering. If we ignore instrumental effects (residual gas, thick target, stray photons from background interactions), we can think, e.g., about (multiple) soft gluon exchange between projectile and target before the hard, multiparticle production interaction takes place.

Of course, there is still a possibility that the experimenters who saw the excess significantly greater than the classical bremsstrahlung in the ultrasoft region neglected some important conventional contribution.

In the context of the ultrasoft region, it must be also noted that the classical bremsstrahlung formula [10], which was used by all experimenters to assess the expected level of photon production, is a big unknown. It has been shown a long time ago that it should be valid also in the quantum world in the limit of negligibly small photon momenta. It enables one to estimate the photon yield if the cross section of the corresponding nonradiative reaction is known. For higher photon energies, the nonleading terms in the Low expansion [39] become important. But they cannot be evaluated without a more detailed knowledge of the underlying strong dynamics of the collisions. It is not clear what is the region of validity of the classical approximation. In some examples, see, e.g., [40], it is very narrow.

As already stated in Sec. I, the agreement of the models with experimental data need not imply that the mechanisms of photon productions they are based on are real. But let us assume for a moment that the models we used in this work[2] are more than a clever parametrization of all existing data, that they explain the very origin of additional photons. We can then go beyond mere phenomenology and address, at least qualitatively, two important issues, which may have experimental implications.

The first remark concerns the dependence of the prompt photon yield on the associated hadron multiplicity. The prediction [12] of faster than linear dependence in dilepton production, and the experiment that seemed to observe it [41] evoked a false impression that this effect must take place wherever an anomalous electromagnetic signal is encountered. As discussed in more detail in [42] (and, to some extent, already in [12]), the actual behavior depends on the production mechanism. We expect a roughly linear dependence if the dominant mechanism is bremsstrahlung and faster than linear dependence for the (modified) soft annihilation model [12]. In the case of photon production from the glob model, the intermediate parton system represents only a part of the event and most of the final state hadrons do not originate from it. We therefore expect no correlation between the very soft photon production rate and the associated hadron multiplicity.

Let us also note that a simultaneous observation of two (or more) ultrasoft effects would be a nice confirmation of Van Hove's glob mechanism [17]. It may manifest itself, for example, by stronger short-range correlations among pions in events with very soft photons.

The photon production in high energy collisions remains intriguing and lacking complete explanation and therefore deserves continuing experimental and theoretical attention.

[2]In fact, we do not know about any other model which would have been compared in detail with a broad set of data.

ACKNOWLEDGMENTS

I am indebted to P. Braun-Munziger, C. Fabjan, U. Goerlach, J. Kapusta, O. Nachtmann, J. Pišút, M. Prakash, J. Schukraft, E. Shuryak, P. Sonderegger, M. Spyropoulou-Stassinaki, J. Stachel, J. Thompson, X.-N. Wang, and C. Woody for stimulating discussions. It must be noted, however, that not all of them share the views expressed in this work. Special thanks are due to J. Thompson, who helped me to clarify my understanding of the experimental situation, read the manuscript very carefully, and suggested many improvements of the text. My interest in soft photon production, like that of many others, was stimulated by the late Yves Goldschmidt-Clermont. The collaboration with the late Léon Van Hove was very pleasant and profitable for me. The stay at the State University of New York at Stony Brook was supported by the U.S. Department of Energy under Grant No. DE-FG02-88ER-40388. This work was initiated when I participated in the program Strong Interactions at Finite Temperatures at the Institute of Theoretical Physics, University of California at Santa Barbara. My stay there was made possible by the National Science Foundation under the Grant No. PHY89-04035. A part of the work was done during a visit to the CERN Theory Division, the hospitality of which is gratefully acknowledged.

[1] A. T. Goshaw *et al.*, Phys. Rev. Lett. **43**, 1065 (1979).
[2] P. V. Chliapnikov *et al.*, Phys. Lett. **141B**, 276 (1984).
[3] T. Åkesson *et al.*, Phys. Rev. D **36**, 2615 (1987).
[4] T. Åkesson *et al.*, Phys. Rev. D **38**, 2687 (1988).
[5] J. J. Aubert *et al.*, Phys. Lett. B **218**, 248 (1989).
[6] HELIOS Collaboration, U. Goerlach, in *Proceedings of the 24th International Conference on High Energy Physics*, Munich, 1988, edited by R. Kotthaus and J. Kuhn (Springer, Berlin, 1988), p. 1412; J. Schukraft (HELIOS Collaboration), in *Quark Matter '88*, Proceedings of the Seventh International Conference on Ultrarelativistic Nucleus-Nucleus Collisions, Lenox, Massachusetts, 1988, edited by G. Baym, P. Braun-Munziger, and S. Nagamiya [Nucl. Phys. A **498**, 79c (1989)].
[7] F. Botterweck *et al.*, Z. Phys. C **51**, 541 (1991).
[8] S. Banerjee *et al.*, Phys. Lett. B **305**, 182 (1993).
[9] J. Antoš *et al.*, Z. Phys. C **59**, 547 (1993).
[10] J. D. Jackson, *Classical Electrodynamics* (Wiley, New York, 1975).
[11] W. Beusch *et al.*, CERN Report No. SPSC 85-22, 1985 (unpublished).
[12] V. Černý, P. Lichard, and J. Pišút, Z. Phys. C **31**, 163

(1986).
[13] P. Lichard, N. Pišútová, and J. Pišút, Z. Phys. C **42**, 641 (1989).
[14] V. Černý, P. Lichard, and J. Pišút, Phys. Lett. **70B**, 61 (1977).
[15] V. Černý, P. Lichard, and J. Pišút, Phys. Rev. D **24**, 652 (1981), and references therein.
[16] P. Lichard and J. A. Thompson, Phys. Rev. D **44**, 668 (1991).
[17] L. Van Hove, Ann. Phys. (N.Y.) **192**, 66 (1989).
[18] A. Petersen *et al.*., Phys. Rev. D **37**, 1 (1988); L. Van Hove and A. Giovannini, Acta Phys. Pol. B **19**, 917 (1988); **19**, 931 (1988).
[19] P. Lichard and L. Van Hove, Phys. Lett. **245B**, 605 (1990).
[20] S. Barshay, Phys. Lett. B **227**, 279 (1989).
[21] A. B. Migdal, Zh. Eksp. Teor. Fiz. **61**, 2209 (1972) [Sov. Phys. JETP **34**, 1184 (1972)]; **63**, 1993 (1972) [**36**, 1052 (1973)].
[22] S. Barshay, G. E. Brown, and G. Vagradov, Phys. Lett. **43B**, 359 (1973); S. Barshay and G. E. Brown, *ibid.* **47B**, 103 (1973).
[23] E. V. Shuryak, Phys. Lett. B **231**, 175 (1989).
[24] E. V. Shuryak, Phys. Rev. D **42**, 1764 (1990).
[25] V. Balek, N. Pišútová, and J. Pišút, Acta Phys. Pol. B **21**, 149 (1990).
[26] V. Balek *et al.*, Acta Phys. Slovaca **41**, 86 (1991).
[27] V. Balek, N. Pišútová, and J. Pišút, Acta Phys. Slovaca **41**, 158 (1991).
[28] W. Czyż and W. Florkowski, Z. Phys. C **61**, 171 (1994).
[29] A. Bialas *et al.*, Phys. Lett. B **229**, 398 (1989); Z. Phys. C **46**, 439 (1990); A. Dyrek and W. Florkowski, Acta Phys. Pol. B **22**, 325 (1991).
[30] For mapping the energy-momentum conservation constrained parton momentum space onto the $(3N_p - 4)$-dimensional unit cube we used the procedure by S. Jadach, Comput. Phys. Commun. **9**, 297 (1975).
[31] J. D. Bjorken and H. Weisberg, Phys. Rev. D **13**, 1405 (1976).
[32] References can be found, e.g., in [15,16].
[33] V. Černý, P. Lichard, and J. Pišút, Phys. Rev. D **16**, 2822 (1977); **18**, 2409 (1978).
[34] T. Åkesson *et al.*, Phys. Lett. **152B**, 411 (1985).
[35] P. Sixel *et al.*, Nucl. Phys. **B199**, 381 (1982).
[36] B. C. Barish *et al.*, Phys. Rev. Lett. **38**, 577 (1977); T. Hansl *et al.*, Nucl. Phys. **B142**, 381 (1978).
[37] V. Černý, P. Lichard, and J. Pišút, Acta Phys. Pol. B **9**, 269 (1978); Czech. J. Phys. B **29**, 1394 (1979).
[38] An alternative way is to present cross sections within the acceptance region of the apparatus. This approach was chosen in an unlike electron pair experiment by the Dilepton Spectrometer (DLS) Collaboration at the Lawrence Berkeley Laboratory (LBL). See H. Z. Huang *et al.*, Phys. Lett. B **297**, 233 (1992), and references therein.
[39] F. E. Low, Phys. Rev. **110**, 974 (1958).
[40] P. Lichard, Report No. SUNY-NTG-94-16 (unpublished).
[41] T. Åkesson *et al.*, Phys. Lett. B **192**, 463 (1987).
[42] P. Lichard, in *Soft Lepton Pair and Photon Production*, Proceedings of the Pittsburgh Workshop, edited by J. A. Thompson (Nova Scientific, Commack, NY, 1992).