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γp and $\gamma\gamma$ QCD Physics at High Energies*

Torbjörn Sjöstrand

Department of Theoretical Physics,
University of Lund, Sölvegatan 14A,
S-223 62 LUND, Sweden

ABSTRACT

The challenge of γp and $\gamma\gamma$ studies is a complexity in excess of that encountered elsewhere in particle physics. In order to construct a complete and consistent model of all main phenomena, several aspects have to be mastered. Here is presented a status report on progress towards such a model. Topics covered include the nature of the photon, total and partial cross sections, parton distributions and event shapes (comparing pp, γp and $\gamma\gamma$). Remaining problems are enumerated, with emphasis on eikonalization aspects of the anomalous part of the cross section.

1. Introduction

In this talk I review a model for γp and $\gamma\gamma$ events being developed in collaboration with Gerhard Schuler. By necessity, most topics will be covered very briefly. It is therefore important to note that several papers have already appeared on various aspects [1, 2, 3, 4]. The emphasis is on QCD physics in collisions between (almost) real photons, while aspects such as photon flux factors or experimental acceptances are left aside.

The study of γp and $\gamma\gamma$ physics has a long history, and so it would not be possible to give a complete survey of related previous studies. Further references may be found in other presentations at this meeting and at other recent workshops [5].

2. The model

To first approximation, the photon is a point-like particle. However, quantum mechanically, it may fluctuate into a (charged) fermion–antifermion pair. The fluctuations $\gamma \leftrightarrow \mathrm{q}\overline{\mathrm{q}}$ can interact strongly and therefore turn out to be responsible for the major part of the γp and $\gamma\gamma$ total cross section. The spectrum of fluctuations may be split into a low-virtuality and a high-virtuality part. The former part can be approximated by a sum over low-mass vector-meson states, customarily restricted

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to the lowest-lying vector multiplet. Phenomenologically, this Vector Meson Dominance (VMD) ansatz turns out to be very successful in describing a host of data. The high-virtuality part, on the other hand, should be in a perturbatively calculable domain.

In total, the photon wave function can then be written as

$$|\gamma\rangle = c_{\mathrm{bare}}|\gamma_{\mathrm{bare}}\rangle + \sum_{V=\rho^0,\omega,\phi,\mathrm{J}/\psi} c_V|V\rangle + \sum_{\mathrm{q=u,d,s,c,b}} c_{\mathrm{q}}|\mathrm{q}\overline{\mathrm{q}}\rangle + \sum_{\ell=\mathrm{e},\mu,\tau} c_\ell|\ell^+\ell^-\rangle \; . \tag{1}$$

In general, the coefficients c_i depend on the scale μ used to probe the photon. Introducing a cut-off parameter k_0 to separate the low- and high-virtuality parts of the $\mathrm{q}\overline{\mathrm{q}}$ fluctuations, one obtains $c_{\mathrm{q}}^2 \approx (\alpha_{\mathrm{em}}/2\pi)2e_{\mathrm{q}}^2\ln(\mu^2/k_0^2)$. The c_V coefficients are μ-independent and phenomenologically determined. The c_{bare} is always close to unity. Usually the probing scale μ is taken to be the transverse momentum of a $2 \to 2$ parton-level process. Our fitted value $k_0 \approx 0.6$ GeV (see below) then sets the minimum transverse momentum of a perturbative branching $\gamma \to \mathrm{q}\overline{\mathrm{q}}$.

The subdivision of the above photon wave function corresponds to the existence of three main event classes in γp events:

1. The VMD processes, where the photon turns into a vector meson before the interaction, and therefore all processes allowed in hadronic physics may occur. This includes elastic and diffractive scattering as well as low-$p_\perp$ and high-$p_\perp$ non-diffractive events.
2. The direct processes, where a bare photon interacts with a parton from the proton.
3. The anomalous processes, where the photon perturbatively branches into a $\mathrm{q}\overline{\mathrm{q}}$ pair, and one of these (or a daughter parton thereof) interacts with a parton from the proton.

All three processes are of $O(\alpha_{\mathrm{em}})$. However, in the direct contribution the photon structure function is of $O(1)$ and the hard scattering matrix elements of $O(\alpha_{\mathrm{em}})$, while the opposite holds for the VMD and the anomalous processes.

Also the parton distributions of the photon can be split according to the pattern of eq. (1). Four different parametrizations along these lines are presented in ref. [4].

A generalization of the above picture to $\gamma\gamma$ events is obtained by noting that each of the two incoming photons is described by a wave function of the type given in eq. (1). In total, there are therefore three times three event classes. By symmetry, the 'off-diagonal' combinations appear pairwise, so the number of distinct classes is only six: VMD$\times$VMD, VMD$\times$direct, VMD$\times$anomalous, direct$\times$direct, direct$\times$anomalous and anomalous$\times$anomalous. The first three classes above are pretty much the same as the three classes allowed in γp events, since the interactions of a VMD photon and those of a proton are about the same.

Empirically, both the pp and γp total cross sections are well described by a pomeron plus reggeon ansatz. If the same approach is extended to $\gamma\gamma$, one obtains a prediction

$$\sigma_{\mathrm{tot}}^{\gamma\gamma}(s) \approx 211\, s^{0.0808} + 215\, s^{-0.4525} \quad [\mathrm{nb}] \; . \tag{2}$$

The VMD component of the γp cross section, about 80% of the total, is also given by a pomeron plus reggeon parametrization. The remaining part can be fitted to a sum of direct and anomalous cross sections, by picking a lower cut-off $k_0 \approx 0.6$ GeV for

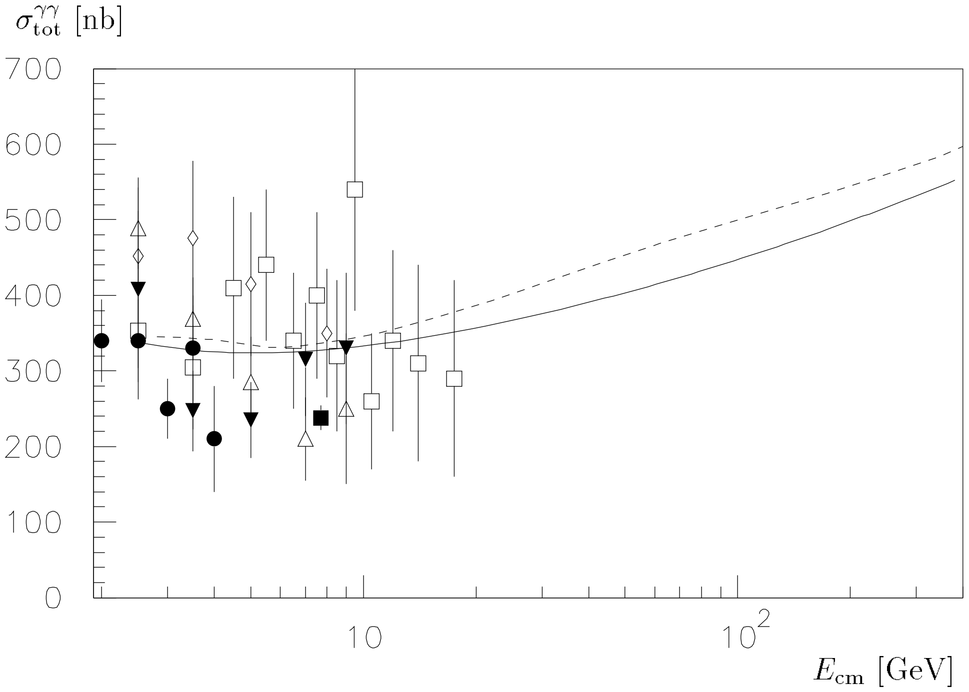

Figure 1: The total $\gamma\gamma$ cross section. Full curve: the parametrization of eq. (2). Dashed curve: result from sum of integrations of the six components. Data points: open triangles PLUTO 1984, filled triangles PLUTO 1986, open squares TPC/2γ 1985, spades TPC/2γ 1991, circles MD-1 1991, filled square CELLO 1991.

$\gamma \leftrightarrow q\overline{q}$ fluctuations plus a cut-off $p_{\perp\rm min}^{\rm anom} = 0.7 + 0.17\log^2(1 + E_{\rm cm}/20)$ [GeV] for QCD processes in the anomalous sector. Here SaS set 1D is used for the parton distributions of the photon, and CTEQ set 2L for those of the proton. With parameters determined in γp physics, the cross section for each of the six $\gamma\gamma$ components can be obtained. In Fig. 1 the sum is compared with the parametrization (2). The good agreement, also with the data, indicates that the model with six components is internally consistent.

3. Event properties

The subdivision of the total γp and $\gamma\gamma$ cross sections above, with the related choices of cut-off parameters and so on, specifies the event composition at the hard-scattering level. For studies of the complete event structure, it is necessary to add models for initial- and final-state QCD radiation (parton showers), for beam remnants, and for fragmentation and secondary decays. A Monte Carlo generation of complete hadronic final states is obtained with PYTHIA/JETSET [6]. Thus any experimental quantity can be studied. In particular, we can compare the properties of pp (which is similar to $\overline{\rm p}$p for the quantities studied here), γp and $\gamma\gamma$ events.

In general, event properties show an hierarchy, with $\gamma\gamma$ events having the most activity and pp ones the least. It is mainly related with the large activity expected for interactions involving the anomalous photon component, because of the larger $p_{\perp\rm min}^{\rm anom}$. The transverse energy flow distribution in Fig. 2 also illustrates how γp interpolates between pp and $\gamma\gamma$: the γp events look like the $\gamma\gamma$ ones around the photon direction,

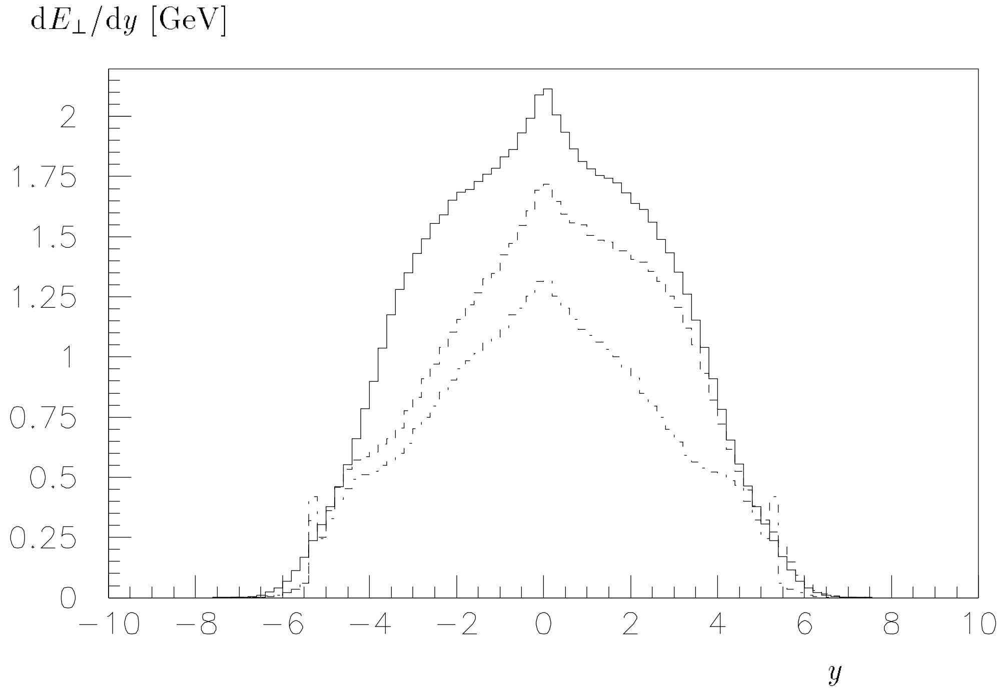

Figure 2: Transverse energy flow as a function of rapidity, d$E_\perp$/dy, at 200 GeV c.m. energy. Dashed-dotted histogram is pp, dashed one γp (with the original photon moving in the $+z$ direction) and full one $\gamma\gamma$.

while they look more like pp ones in the opposite direction, with an intermediate behaviour in the central region.

The spectacular differences in the jet rate at large $p_\perp$ are highlighted in Fig. 3. They mainly come about because the direct component involves the full energy of the incoming photon. Differences are not as visible in minimum-bias events, but the inclusive $p_\perp$ spectrum of charged particles shows the same hierarchy.

Distributions show the same pattern at all energies, with most activity for the $\gamma\gamma$ events. Therefore differences can be detected at any convenient energy.

4. Problems and Outlook

The perturbatively calculated jet cross-section above some fixed $p_{\perp\mathrm{min}}$ scale is steeply increasing with the c.m. energy, and ultimately exceeds the total cross section. In pp physics the most likely solution to this problem is to allow multiple parton-parton interactions in an event [7]. Since hadrons consist of many partons, such an approach is fairly natural, although there are several elements of arbitrariness involved in constructing explicit models. If the photon is considered as a hadron, the same "eikonalization" approach can also be applied for γp and $\gamma\gamma$ events.

We argue, however, that only the VMD part of the photon can be treated in straight analogy with hadrons, and that the anomalous and direct parts have to be considered separately. In fact, each fixed-$k_\perp$ component of $\gamma \leftrightarrow \mathrm{q}\overline{\mathrm{q}}$ fluctuations can be considered as a separate "hadron species", with a density of states $\mathrm{d}k_\perp^2/k_\perp^2$. The parton distribution inside such a state is perturbatively calculable, and leads to a decreasing jet rate with increasing $k_\perp$. The fall-off is rather slow, however, and

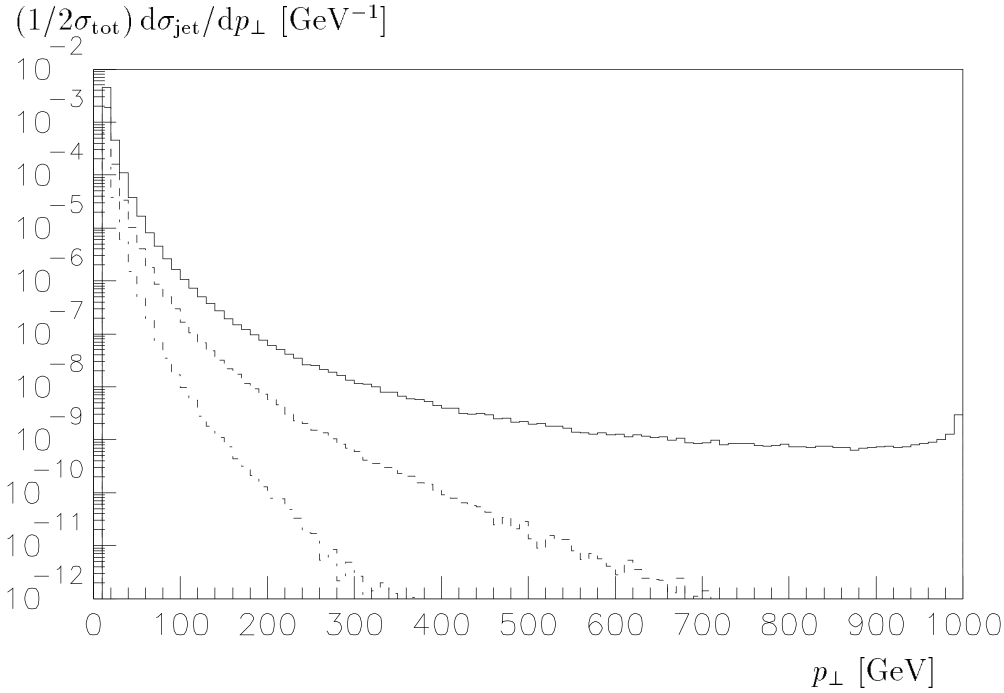

Figure 3: Parton-level jet $p_\perp$ distribution at 2 TeV c.m. energy. Dashed-dotted histogram is pp, dashed one γp and full one $\gamma\gamma$. The factor 1/2 compensates for there being 2 jets per event.

becomes gradually slower as the c.m. energy is increased. The total γp cross section therefore comes out as increasing faster than data. Standard eikonalization (with smaller photon size for increasing $k_\perp$, according to the uncertainty relation) dampens the growth, but not enough. It therefore seems clear that further aspects have to be taken into account, such as momentum conservation, coherence effects or stricter geometrical cut-offs. This is thus one area where further studies are necessary.

Also many other aspects need to be studied. The transition between the VMD, anomalous and direct classes should obey certain consistency criteria. The transition from a real γ to a virtual γ^* is still not well understood. The profile of beam jets and the structure of uderlying events is not well described at HERA. Jet production in diffractive systems currently attract much attention. Further issues could be mentioned, but the conclusion must be that much work remains before we can claim to have a complete overview of the physics involved in γp and $\gamma\gamma$ events, let alone understand all the details.

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