$\gamma\gamma$ and γp events in PYTHIA
and
Concluding Remarks

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ABSTRACT

This talk covers two topics.
(1) A status report on a model for $\gamma\gamma$ and γp physics. This model has been implemented in the PYTHIA program, to allow the generation of complete events. A few comparisons between expected pp, γp and $\gamma\gamma$ event properties are presented.
(2) Some concluding remarks for the 'event models' session. The main observation is that the more 'physics-motivated' models as a rule contain more free parameters. There may therefore be a trade-off between sophistication and predictive power. However, a detailed physics model is required in order to understand exclusive quantities.

1. $\gamma\gamma$ and γp events in PYTHIA

The two programs PYTHIA 5.7 and JETSET 7.4 together provide a general-purpose package for the generation of multihadronic events in e^+e^-, ep, pp/p$\overline{\text{p}}$, γp and $\gamma\gamma$ collisions [1]. These initial states are given in order of increasing complexity: the e^+e^- annihilation reactions are perturbatively calculable, while a hadronic initial state implies uncertainties related to the parton distribution functions and the fate of the beam remnant. With two incoming hadrons, the possibility of multiple parton–parton interactions appears. A photon, via its VMD component, involves all the uncertainties of a hadron, but additionally other components of the photon may interact.

The model of Gerhard Schuler and myself for γp events is described in [2] and the extension to $\gamma\gamma$ in [3]. There are no major news in the programs, compared to the status in the latter report, but further theoretical studies are under way, and will eventually be reflected in an improved description of γp and $\gamma\gamma$ physics [4]. So far the studies only deal with incoming real photons; the transition from a real to a virtual photon involves additional physics aspects.

For incoming hadrons, the main building blocks of the PYTHIA/JETSET programs are the following:

- Hard process matrix elements. The lowest-order QCD processes are $\mathrm{qq}' \to \mathrm{qq}'$, $\mathrm{q\overline{q}} \to \mathrm{q'\overline{q}'}$, $\mathrm{q\overline{q}} \to \mathrm{gg}$, $\mathrm{qg} \to \mathrm{qg}$, $\mathrm{gg} \to \mathrm{q\overline{q}}$ and $\mathrm{gg} \to \mathrm{gg}$ for purely hadronic initial states, $\gamma\mathrm{q} \to \mathrm{qg}$ and $\gamma\mathrm{g} \to \mathrm{q\overline{q}}$ for one unresolved photon, and $\gamma\mathrm{g} \to \mathrm{q\overline{q}}$ for two unresolved photons. Many other hard processes are imaginable, but are unimportant for inclusive event properties.
- Parton distribution functions, which describe the Q^2-dependent composition of the incoming beam particles. An extensive compilation of existing parametrizations is available in PDFLIB [5].
- Initial- and final-state radiation, in the parton-shower approximation. This gives the QCD radiation that may occur between the hard Q^2 scale and some lower cut-off at typical hadronic scales.
- Beam remnants, which are left behind when a parton is taken out of an incoming hadron. A remnant is normally coloured, and therefore connected to the rest of the event. Additionally, the remnant contains in itself a number of partons and may therefore undergo several hard or semi-hard parton–parton interactions, so-called multiple interactions [6].
- Soft events contain no hard QCD processes, but are related to interactions in the non-perturbative sector of QCD. One expects some continuity to the hard events above, i.e. this event class should be visualizable in terms of soft gluon exchanges.
- Elastic and diffractive events, which are distinguished experimentally by the p-resence of rapidity gaps. The total, elastic and diffractive cross sections are parametrized by Regge-theory-inspired formulae [7]. The remainder, $\sigma_{\mathrm{tot}} - \sigma_{\mathrm{el}} - \sigma_{\mathrm{diff}}$, is made up of the hard and soft process classes above.
- Outgoing coloured partons fragment into colourless hadrons according to the string fragmentation description [8].
- Unstable particles subsequently decay to the stable ones.

For extensions to γp and $\gamma\gamma$ events, the starting point is the assumed photon wave function

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

That is, in addition to its bare state, the photon may fluctuate into a fermion–antifermion pair. In general, the coefficients c_i depend on the scale μ used to probe the photon. Thus $c_\ell^2 \approx (\alpha_{\mathrm{em}}/2\pi)(2/3)\ln(\mu^2/m_\ell^2)$. Introducing a cut-off parameter p_0 to separate the low- and high-virtuality parts of the $\mathrm{q\overline{q}}$ fluctuations, one similarly obtains $c_{\mathrm{q}}^2 \approx (\alpha_{\mathrm{em}}/2\pi)2e_{\mathrm{q}}^2\ln(\mu^2/p_0^2)$. The VMD part corresponds to the range of $\mathrm{q\overline{q}}$ fluctuations below p_0 and is thus μ-independent. Finally, c_{bare} is given by unitarity: $c_{\mathrm{bare}}^2 \equiv Z_3 = 1 - \sum c_V^2 - \sum c_{\mathrm{q}}^2 - \sum c_\ell^2$. In practice, 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 $p_0 \approx 0.5$ GeV then sets the minimum transverse momentum of a perturbative branching $\gamma \to \mathrm{q\overline{q}}$.

The subdivision of the above photon wave function corresponds to the existence of three main event classes in γp events, cf. Fig. 1:

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-$p_\perp$ (soft) and high-$p_\perp$ (hard) non-diffractive events.

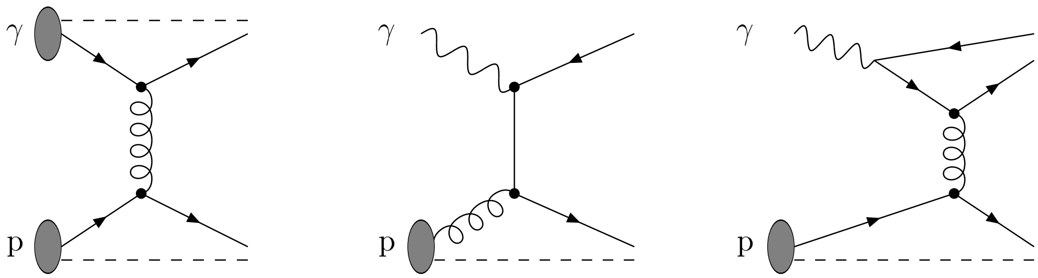

Figure 1: Contributions to hard γp interactions: a) VMD, b) direct, and c) anomalous. Only the basic graphs are illustrated; additional partonic activity is allowed in all three processes. The presence of spectator jets has been indicated by dashed lines, while full lines show partons that (may) give rise to high-$p_\perp$ jets.

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 $q\overline{q}$ 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. As we already noted, the $\ell^+\ell^-$ fluctuations are not interesting, and there is thus no class associated with them.

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. These are, cf. Fig. 2:

1. VMD×VMD: both photons turn into hadrons, and the processes are therefore the same as allowed in hadron–hadron collisions.
2. VMD×direct: a bare photon interacts with the partons of the VMD photon.
3. VMD×anomalous: the anomalous photon perturbatively branches into a $q\overline{q}$ pair, and one of these (or a daughter parton thereof) interacts with a parton from the VMD photon.
4. Direct×direct: the two photons directly give a quark pair, $\gamma\gamma \to q\overline{q}$. Also lepton pair production is allowed, $\gamma\gamma \to \ell^+\ell^-$, but will not be considered by us.
5. Direct×anomalous: the anomalous photon perturbatively branches into a $q\overline{q}$ pair, and one of these (or a daughter parton thereof) directly interacts with the other photon.
6. Anomalous×anomalous: both photons perturbatively branch into $q\overline{q}$ pairs, and subsequently one parton from each photon undergoes a hard interaction.

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.

The total cross section of γp [9] and $\gamma\gamma$ [3] events may be given in Regge-theory language as

$$\sigma_{\mathrm{tot}}^{\gamma \mathrm{p}}(s) \approx 67.7 s^{\epsilon} + 129 s^{-\eta} \quad [\mu\mathrm{b}] \;, \tag{2}$$
$$\sigma_{\mathrm{tot}}^{\gamma\gamma}(s) \approx 211 s^{\epsilon} + 297 s^{-\eta} \quad [\mathrm{nb}] \;, \tag{3}$$

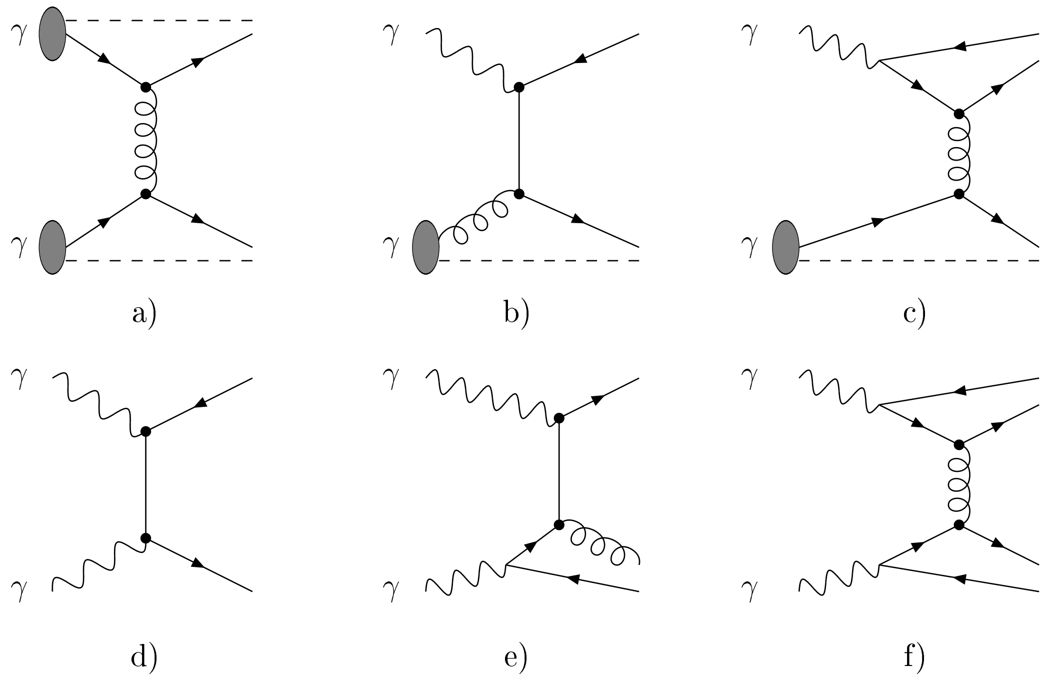

Figure 2: Contributions to hard $\gamma\gamma$ interactions: a) VMD×VMD, b) VMD×direct, c) VMD×anomalous, d) direct×direct, e) direct×anomalous, and f) anomalous× anomalous. Notation as in Fig. 1.

with $\epsilon \approx 0.0808$ and $\eta \approx 0.4525$. These cross sections are subdivided into the above components, with the VMD and VMD×VMD classes further subdivided into the various vector meson contributions and into elastic, diffractive and non-diffractive classes [2, 3, 7].

The photon wave-function ansatz also leads to an expression for the photon parton distributions:

$$f_a^{\gamma}(x,\mu^2) = f_a^{\gamma,\mathrm{dir}}(x,\mu^2) + f_a^{\gamma,\mathrm{VMD}}(x,\mu^2) + f_a^{\gamma,\mathrm{anom}}(x,\mu^2;p_0^2) = \\ = Z_3\,\delta_{a\gamma}\,\delta(1-x) + \sum_{V=\rho^0,\omega,\phi,\mathrm{J}/\psi} \frac{4\pi\alpha_{\mathrm{em}}}{f_V^2} f_a^V(x,\mu^2) + f_a^{\gamma,\mathrm{anom}}(x,\mu^2;p_0^2)\ , \qquad (4)$$

where the anomalous component is fully perturbatively calculable.

All of this involves a certain amount of arbitrariness. In particular, the transition between the different event classes is handled by sharp cut-offs, where one would rather expect a smooth joining. However, the approach outlined above does give an explicit and complete model for essentially all event properties [2, 3].

As an example, Fig. 3 shows the $\mathrm{d}E_{\perp}/\mathrm{d}y$ flow, comparing $\gamma\gamma$, γp and pp events at the same energy. The direct and anomalous event classes give more transverse activity than does the VMD one, so the $E_{\perp}$ flow is more significant in $\gamma\gamma$ than in pp (or p$\overline{\mathrm{p}}$, which is about the same as pp). The γp process interpolates between the two, closer to $\gamma\gamma$ in the photon hemisphere of the event and closer to pp in the proton hemisphere. The same pattern may be observed in other distributions, e.g. the charged-particle multiplicity and the jet rate.

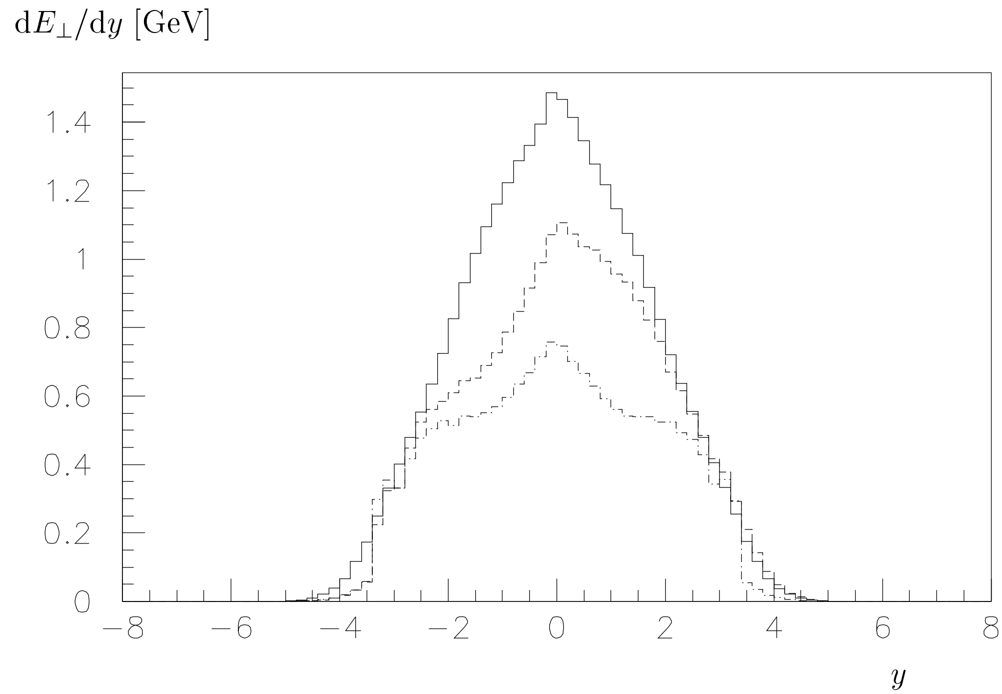

Figure 3: Transverse energy flow for $E_{\mathrm{cm}} = 25$ GeV as a function of rapidity for different beams: $\gamma\gamma$: full histogram; γp: dashed one; and pp: dash-dotted one.

2. Concluding Remarks

In this section I will make a few comments on the status of our modelling of $\gamma\gamma$ and γp physics. This is to be seen as a complement to the information given in the other talks of this session (by Kessler, Drees, Schuler, Seymour and Butterworth), and of the workshop in general. There is no attempt at completeness, neither in the text nor in the references.

The ultimate goal is to understand *everything* about γp and $\gamma\gamma$ interactions:

1. (Semi)inclusive quantities such as
   - $\sigma_{\mathrm{tot}}^{\gamma\mathrm{p}}(s)$, $\sigma_{\mathrm{tot}}^{\gamma\gamma}(s)$,
   - $F_2^\gamma(x, Q^2)$.
2. (Semi)exclusive quantities such as
   - subdivision of σ_{tot} into σ_{VMD}, σ_{direct}, $\sigma_{\mathrm{anomalous}}$, and maybe more,
   - subdivision of the VMD cross section by vector meson species and by elastic, diffractive and non-diffractive components,
   - differential distributions $\mathrm{d}\sigma_{\mathrm{elastic}}/\mathrm{d}t$, $\mathrm{d}\sigma_{\mathrm{diffractive}}/\mathrm{d}t\,\mathrm{d}M^2$,
   - charged multiplicity distribution, $E_\perp$ flow and other simple event properties,
   - jet rates and jet–jet correlations,
   - underlying event activity, signatures for multiple interactions and pedestal effects,
   - the character of the beam jets and its relation to the process type,
   - rapidity gaps and other irregularities,
   - the change in event properties when moving continuously from real to virtual photons,
   - heavy-flavour production rates,
   - and so on.

For the inclusive quantities, approaches entirely based on analytical formulae are meaningful. However, the more exclusive the quantity studied, the larger the need for a Monte Carlo implementation. The event generator approach is useful for its modular and flexible book-keeping capabilities: in terms of possible subprocesses, or partons emitted in parton showers, or hadrons produced in the fragmentation stage, etc.

Although the above list gives the impression of covering a host of separate topics, it all hangs together. The total cross section is here an interesting case study. Currently there are two main approaches to a description. The one is the Regge-theory ansatz, where σ_{tot} is given as the sum of two terms, the pomeron one (s^{ϵ}) and the reggeon one ($s^{-\eta}$), cf. eqs. (2) and (3). This ansatz gives a very handy parametrization of cross sections, that seems to be in good agreement with data. However, it does not necessarily lead to any understanding of the underlying physics.

More appealing is the second main approach, where the rise of the total cross section at large energies is related to the increase of the jet cross section. In its simplest variant one would write $\sigma_{\mathrm{tot}}(s) = \sigma_{\mathrm{soft}}(s) + \sigma_{\mathrm{jet}}(s, p_{\perp\mathrm{min}})$ [10]. The σ_{jet} term is obtained by integrating the perturbative $2 \to 2$ hard-scattering cross section in the region $p_\perp > p_{\perp\mathrm{min}}$. Uncertainties come from the choice of $p_{\perp\mathrm{min}}$ scale, from parton distributions, from higher-order corrections to the lowest-order matrix elements, from the choice of a $\sigma_{\mathrm{soft}}(s)$, and so on. Furthermore, if one attempts to limit the arbitrariness by keeping $p_{\perp\mathrm{min}}$ independent of s, the approach breaks down at large energies, where the jet cross section is known to increase faster than the total one.

We understand that this is linked to the emergence of events with several parton–parton interactions above the $p_{\perp\mathrm{min}}$ scale. For instance, an event with two interactions should count twice against the hard-scattering cross section, but only once against the total one. The eikonalization approach is a convenient way of accounting for an arbitrary number of interactions. Normally the direct processes are assumed unaffected, i.e. only the ones with a resolved photon are eikonalized. In addition to the input already mentioned, one here needs to specify the probability for a photon to turn into a hadron [11], the impact parameter dependence of the eikonal (obtained as a convolution of the matter densities of the two incoming particles), the rôle of elastic and diffractive topologies, and so on. Sub-variants are possible, such as leaving σ_{soft} out of the eikonalization machinery [12].

In a further level of sophistication, the probability for a photon to interact like a hadron can be replaced by a sum over discrete vector-meson states plus an integral over a continuum of perturbative $\mathrm{q}\overline{\mathrm{q}}$ states (the anomalous component) [13]. Each state is now to be eikonalized separately, and each with its own set of free parameters: soft cross sections, matter densities, and so on. The only area where the freedom is reduced by this choice is for parton distributions, where the VMD ones in principle are measurable (though in practice not, so one uses e.g. the π ones) and the anomalous ones are calculable.

In the end, even this complex machinery is hardly more successful than the simple Regge-theory-based one. In fact, if the only criterion is predictive power for the total cross section at higher energies, it could be argued that the pomeron-type ansatz is the best bet. Somewhat surprisingly, the experience outlined above teaches us that there is a tradeoff between sophistication and predictive power: the more advanced we try to be, the more free parameters we have to play with, and the less constrained we are about what will happen at energies not yet explored.

So when we still persevere to build ever more detailed models for the total cross section, it is because the ultimate goal is to reach an understanding of the nature of the photon and its interactions. If we have reasons to believe that the photon has a complex nature, then we should not expect to get away with simple recipes for everything. A sophisticated approach also provides a blueprint for how to model or predict a number of exclusive event properties. Testability therefore comes not only from the total cross section. Let us illustrate this point with a few examples.

- If the photon is assumed to have a VMD component, with an energy-independent probability for a photon to turn into a given vector meson, then the rate for various VMD elastic processes $\gamma \mathrm{p} \to V\mathrm{p}$ can be predicted by analogy with $\pi\mathrm{p} \to \pi\mathrm{p}$ Regge-theory parametrizations. HERA data nicely agree with this expectation of a production rate increasing with energy above about 10 GeV [14]. Had the low-energy elastic ρ^0 production been just an effect of finite energies, the cross section could rather have gone to zero. So the VMD concept is useful and predictive.
- The beam remnant structure is different for direct and VMD photons, Figs. 1 and 2: a direct photon leaves behind no remnant jet, while a VMD one does. (The assumed third process class, the anomalous one, gives intermediate properties. For simplicity we leave it out of the following discussion; it does not change anything qualitatively.) A separation into (at least) two event classes is clearly visible in the HERA plots on the energy flow in the photon direction [15]. However, on ideological grounds, we may expect a smooth transition between the two, as follows. The primordial $k_\perp$ distribution of a VMD beam remnant is expected to fall off for values larger than about 0.5 GeV. Here the direct processes should take over, i.e. the jets of the 'hard' interactions should stretch down to make contact with the 'soft' region. If this is not the case, e.g. if the $p_{\perp\mathrm{min}}$ cut-off of direct processes is at around 2 GeV, a hole in the primordial $k_\perp$ distribution should one day be visible.
- For the calculation of an inclusive jet rate, it is enough to define one set of parton distributions inside a photon. However, if one wants to take one step further and simulate the initial (and final) state parton showers that come with the hard interactions, it is important to recognize that the parton distributions obey inhomogeneous evolution equations. Then a branching $\gamma \to \mathrm{q}\overline{\mathrm{q}}$ may initiate the shower at a scale $k_\perp$ larger than the normal lower cut-off Q_0. This case can be handled in standard shower algorithms, but it is not transparent. An alternative representation is given if the (resolved) photon is split into a set of discrete VMD states plus a continuum of perturbative $\mathrm{q}\overline{\mathrm{q}}$ states. Then each state obeys standard homogeneous evolution equations. The shower cut-off is Q_0 for the VMD states and $\max(Q_0, k_\perp)$ for the anomalous states. Also the parton distributions are (in principle, at least) predicted by this approach.
- The eikonalization phenomenon is closely associated with the emergence of multi-jet events, where several parton–parton interactions occur. Backgrounds, such as perturbative four-jet production ($2 \to 4$) may make experimental detection difficult, but not impossible. If the resolved photon is considered as a single homogeneous event class, a simple trigger bias leads to an enhanced multiple-interaction rate in high-$p_\perp$ events — possibly the origin of the pedestal effect observed in hadron colliders [16, 6]. However, if each VMD and anomalous photon state is to be eikonalized separately instead, there will be a class of large-$k_\perp$ anomalous events for which eikonalization should be negligible, and the underlying event activity therefore reduced. This class could be tagged by the beam jet structure.

In summary, we need models for total $\gamma\mathrm{p}$ and $\gamma\gamma$ cross sections, both what they are (for which the pomeron+reggeon ansatz seems to work well) and why they are whatever they are (for which more sophisticated approaches may be needed). Also exclusive quantities need to be understood, in their own right and because 'ordinary' photon events may constitute the major background to a number of more 'interesting' processes. We should also not exclude the possibility of stumbling across some new and unexpected piece of QCD physics.

While many studies can be performed analytically, the event generator approach is the one that offers most flexibility for the future. Today the $\gamma\gamma$ studies are largely dominated by various packages developed inside experimental collaborations. These packages often lead a life of their own. Presumably we will see the major packages such as HERWIG [17] and PYTHIA play a more dominant rôle in the future, as is already the case in γp. This has the advantage of emphasizing the common physics aspects, e.g. between $\gamma\gamma$, γp and pp.

The work that has been done so far, both by theory and by experiment (today largely dominated by HERA, of course), has gone a long way towards improving our understanding of the photon. However, there are many areas that still are in need of further study. Two well-defined questions are whether and how a smooth joining is obtained between the different event classes, and how the transition between a real and a virtual photon looks in detail.

If we keep on working in this field, it is not because we should expect easy answers. On the contrary, as I have tried to make clear, a full understanding of $\gamma\gamma$ physics may well be the ultimate challenge of minimum-bias physics (leaving heavy-ion physics aside). So even if we should never quite reach this goal, we should remember that it is more honourable to not quite have made it to the top of Mt. Everest than to not quite have scaled the Jura mountains.

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