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Soft Photoproduction Physics *

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ABSTRACT
Several topics of interest in soft photoproduction physics are discussed. These include jet universality issues (particle flavour composition), the subdivision into event classes, the buildup of the total photoproduction cross section and the effects of multiple interactions.

1 Introduction

Why should we be concerned with soft photoproduction? The most obvious answer is that it is there, at an overwhelmingly large cross section, and so it is an irresistible challenge to unravel what is going on. The nature of a real photon is not well understood — its multifaceted behaviour is illustrated by the conventional but handwaving subdivision into direct and resolved components. Furthermore, the bremsstrahlung spectrum off an electron beam contains photons of varying virtuality, which prompts a study of the poorly explored transition region between a real photon and the virtual photon of DIS.

The "problems" of photoproduction should not be seen in isolation. The relation between total and diffractive cross sections in γp events is part of the same pomeron physics complex that is now under intense scrutiny in the context of rapidity gaps in DIS; the study of the transition region between real and virtual photons, in particular, may well provide further clues to the gap production mechanism. The total γp cross section is also related to the issue of multiple interactions and from there to the small-x behaviour of parton distributions and the influence of hot spots. The similarities between the photon and hadrons will allow various cross-checks between pp/p$\overline{\text{p}}$, γp and $\gamma\gamma$ physics. Jet universality issues can be explored by comparing high-$p_\perp$ (hard) with low-$p_\perp$ (soft) jets.

Finally, as a general philosophical comment, today perturbative QCD is well established. Further calculations certainly are very useful for precision physics, but

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may not bring many basic new insights. By contrast, the nonperturbative aspects still contain many challenges and opportunities.

A breakdown of the physics of photoproduction events might look something like:

- The total cross section of γp events is subdivided into a direct and a resolved component.
- The resolved class is induced by a spectrum of virtual fluctuations $\gamma \leftrightarrow q\overline{q}$, where the low-virtuality part can be associated with low-mass vector mesons such as ρ^0, ω and ϕ, and the high-virtuality "anomalous" part either with towers of excited vector mesons or with perturbative $q\overline{q}$ states.
- Each vector-meson class may in its turn have "elastic", diffractive and non-diffractive topologies.
- The jet cross section in the non-diffractive component presumably is what drives the energy dependence of the total cross section, but contributions may additionally come e.g. from soft pomeron exchange. The perturbative jet cross section is divergent in the limit $p_\perp \to 0$, so some nonperturbatively motivated cut-off procedure is required.
- When the jet cross section is large, the possibility of multiple parton–parton interactions is non-negligible, and an eikonalization approach can be invoked to address the multiplicity distribution of interactions and the mixing of event classes. The definition of the multiparton distributions of the p and γ is here far from obvious.
- Each parton–parton interaction is associated with the possibility of further radiation, to be calculated either in a matrix-elements approach or by invoking initial- and final-state parton showers. Issues include matching of hard scattering with showers, coherence effects, and cut-offs.
- The proton and a resolved photon contains a beam jet, still not well understood. The remnant takes "what is left" after the hard interaction(s) with associated radiation, including a "primordial $k_\perp$" recoil. The latter is expected to be larger for the higher-mass anomalous states than for events associated with the lowest-lying vector mesons.
- So far, only parton production has been considered. Confinement implies that these hadronize to produce a set of primany hadrons that can subsequently decay further.

The multitude and complexity of tasks reduces the scope for purely analytical studies. On the other hand, the above subdivision may be seen as a suitable starting point for the construction of event generators. Today programs such as HERWIG [1], PHOJET [2] and PYTHIA [3, 4] are used frequently to compare with data and to extract physics conclusions.

In view of the multitude of topics, only some of these will be covered in the following.

2 Hadronization

These days the issue of hadronization is considered so standard that it is not very much discussed. The recent measurements of strangeness production at HERA have brought the issue back to focus, as follows.

In our standard approach to multiparticle production, we often assume that hadronization is a universal process that can be factorized from a preceding perturbative stage. If so, the free parameters of a hadronization model can be determined once and for all, e.g. from e^+e^- data at LEP, and thereafter applied to HERA events. Such a factorization is explicit in the Lund model [5], where all hadron production is caused by the stretching and breaking of strings. Since there is only one kind of string, in principle it is only necessary to specify the parton content and string drawing topology (colour connectedness) of events to predict the structure of hadronic final states. In practice, some new aspects of nonperturbative physics do appear in $ep/\gamma p$, such as parton distributions, multiple interactions and the treatment of beam remnants. An imperfect modelling either of perturbative or of nonperturbative effects could show up in a mismatch in the total number of hadrons produced, while the relative composition of different hadron species should be rather stable.

It is here that the HERA data provide a surprise. ZEUS [6] and H1 [7] both observe a deficit of strangeness production. Interpreted in string fragmentation terms, the s/u ratio is shown to be of the order of 0.2 rather than the 0.3 normally observed in e^+e^- data (see e.g. [8] and references therein). The ZEUS study is for DIS, while the H1 one covers also photoproduction. The suppression affects both K^0_S and Λ production.

In fact, the problem is not quite new, but has been observed before at fixed-target energies, in neutrino and muon interactions [9]. However, earlier data were partly contradictory [9], and so we tended to think of it as some specific low-energy problems and not care so much. Obviously, this will not work now. Although not necessarily related, one should also keep in mind two possible anomalies in flavour production at LEP: a "strangeness deficit" in the subclass of very two-jetlike events [10] and an η production "excess" in the gluon jet in three-jet events [11].

Other existing models might solve the problem at HERA. In an approach such as PHOJET, the production of multiple small chains with a non-negligible phase-space suppression in each can make a difference. In the HERWIG approach there is no explicit jet universality: branchings $g \to q\overline{q}$ are used to split the partonic final state into clusters that then produce the hadrons according to phase space, so the cluster mass spectrum directly influences the particle composition. Based on our current understanding, the effect would go in the wrong direction: the cluster mass spectrum is universal for clusters produced by the perturbative cascades, but these cascades are suppressed close to the beam remnants, and this leads to larger remnant cluster masses with the possibility of enhanced strangeness and baryon production. Some additional source of soft-gluon emission close to the beam remnants could revert this trend, however.

Within the Lund string model, it is interesting to speculate on a true breakdown of jet universality. Here comes three examples of possible physics mechanisms:

- The "quiet string scenario". A conventional QCD cascade gives a fractal structure [12], i.e. the string is wrinked on all scales (down to some unknown infrared cut-off). The string tension $\kappa \approx 1$ GeV/fm is an effective parameter based on measurements at hadronic distance scales. The "true" string length, defined along all the wrinkes, is larger than the smoothened-out normal length, and therefore the "bare" string tension is correspondingly smaller.

If the amount of soft-gluon radiation is smaller in ep than in e^+e^-, it would lead to a less wrinkled string and therefore a smaller effective string tension. The string tension appears in the tunnelling mechanism of flavour production [5], and so a smaller κ is directly reflected in a reduced strangeness production. A prediction in such a scenario is that baryon production should be even more suppressed than strangeness is.

- Medium dependence. Unlike e^+e^-, the ep perturbative processes appear inside the "hadronic bag" of the proton, so why could not this affect particle production? The counterargument would be that hadronization is a long-distance process, that only appears once the string is stretched beyond the confines of the original proton, so somehow information would have to survive a long distance.
- A separate kind of gluon string. This is allowed within a fairly standard extension of the normal string model [13] and could be combined with a string fragmentation model giving more glueballs [14] and maybe also strangeness. So a larger amount of energetic gluons in e^+e^- than in ep could induce some of the desired difference.

To be honest, neither of the above approaches appears particularly attractive, with the first the least contrived. Further experimental input therefore is eagerly awaited. First, the observations should be verified and extended to more hadron species, especially (anti)baryons. Second, ratios such as K/all are preferrable, since then theory uncertainties in the total multiplicity divide out. Third, in DIS events a comparison of the current and target hemispheres in the Breit frame would be revealing — any difference between the current hemisphere and e^+e^- would be very difficult to explain away. Fourth, in photoproduction a corresponding subdivision would be into high-$p_\perp$ jets and beam jets, again with the former more constrained by jet universality arguments. Fifth, can the strangeness deficit be related with any other property of events, so that a pattern emerges?

3 Event Classes

The photon can fluctuate into charged fermion–antifermion pairs. Low-virtuality fluctuations may be associated with a sum over vector-meson states while high-virtuality fluctuations are better described by a continuous spectrum of states. A convenient ansatz for the photon wave function then is [4]

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

(neglecting the small contribution from Υ). 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 k_0 to separate the low- and high-virtuality parts of the $\mathrm{q\overline{q}}$ fluctuations, one similarly obtains $c_{\mathrm{q}}^2 \approx (\alpha_{\mathrm{em}}/2\pi)2e_{\mathrm{q}}^2\ln(\mu^2/k_0^2)$. The VMD part corresponds to the range of $\mathrm{q\overline{q}}$ fluctuations below k_0 and is thus μ-independent (assuming $\mu > k_0$). 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.

The leptonic component is not interesting for strong-interaction physics, but the other three can be associated with the direct, VMD and anomalous event classes.

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.

The separation is very convenient in a leading-order description, but in higher-order contributions the various components appear mixed. This certainly is a complication, but it should not be over-stressed. We expect that the (numerically) dominant contributions will come from event topologies that can still be classified as above. For instance, in lowest order the direct process is characterized by the complete absence of a beam remnant in the photon direction, while some energy flow can always be expected in higher orders. Such a smearing is already included in generators by the addition of standard (coherent) parton-shower activity. To leading-log accuracy, the direct process then is characterized by a ladder diagram where the largest virtuality is found in the ladder adjacent to the photon, while resolved processes have the largest virtuality somewhere in between the photon and the proton, with decreasing virtualities on either side. Alternatively, it is possible to imagine functional separations, with some fraction ϵ of energy allowed within a cone δ around the beam direction for direct processes, along what is done experimentally.

Whichever approach is adopted, it is important that physics should impose a smooth joining between the event classes. Any classification is a matter of convenience. However, at our current level of understanding, phenomenological studies can be made more realistic if they are based on a pragmatic division of γp (and $\gamma\gamma$ [15]) events into separate subclasses.

4 The Total Cross Section

There are two common approaches to the issue of the total cross section in γp (as well as pp and $\gamma\gamma$) collisions. One is the Regge-theory ansatz, where σ_{tot} is given as the sum of two terms, the pomeron one ($\propto s^{\epsilon}$, $\epsilon \approx 0.08$) and the reggeon one ($\propto s^{-\eta}$, $\eta \approx 0.45$) [16]. 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 $\sigma_{\mathrm{tot}}(s) = \sigma_{\mathrm{soft}}(s) + \sigma_{\mathrm{jet}}(s, p_{\perp\mathrm{min}})$ [17]. 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 [18], 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 [19].

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 $\mathrm{q\overline{q}}$ states (the anomalous component) [20]. 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.

Unless the energy-dependence of σ_{soft} is fine-tuned, it is difficult to obtain a turnover from a falling to an increasing $\sigma_{\mathrm{tot}}(s)$ at as low energies ($\sqrt{s} \simeq 10$ GeV) as observed experimentally, simply because the jet rate above some reasonable $p_{\perp\mathrm{min}} \gtrsim 1$ GeV only picks up at larger energies. It appears plausible that soft, non-perturbative multiple interactions in fact drive the change of σ_{tot} at low energies. One attractive framework for putting it all together is DTU (dual topological unitarization), where both the soft and hard interactions, the triple- and loop-pomeron graphs responsible for diffractive topologies, and higher-order pomeron graphs are all put together [21]. New parameters include several pomeron and reggeon couplings.

In the end, even this complex machinery is hardly more successful than the simple Regge-theory-based one we started out with. In fact, if the only criterion is predictive power for the total cross section at higher energies, it could be argued that the simple 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.

One test is provided by partial cross sections to “elastic” and diffractive topologies. The elastic process $\gamma\mathrm{p} \to \rho^0\mathrm{p}$ turns out to be very well predicted, both the cross section and the t slope. This certainly is a major success for the VMD approach: the picture with $\gamma \leftrightarrow V$ fluctuations is now shown to hold independently of energy. Discrimination between models is obtained by the H1 study of diffractive cross sections [22]. Here the DTU approach [21] does best among the ones studied; specifically, it correctly predicts that the “photon-diffractive” process $\gamma\mathrm{p} \to X\mathrm{p}$ has a much larger cross section than the “proton-diffractive” one $\gamma\mathrm{p} \to VX$. Many further tests can be expected in the years to come.

5 Multiple Interactions

The importance of multiple parton–parton interactions is more discussed and established among HERA physicists than it is among $\mathrm{p\overline{p}}$ collider people, in spite of the larger energies available to the latter. This is an interesting paradox, which can only be understood if one considers the "historical prejudices" of the two communities. DESY has a background in $\mathrm{e^+e^-}$ physics, where the combination of a perturbative (shower) picture and a universal hadronization stage is firmly established. When such a picture applied to photoproduction events gives too little activity at small transverse momenta, both in "minimum-bias" events and in the "underlying event" of jets, it is therefore interpreted as a sign of additional (semi)perturbative activity with its associated universal hadronization, in line with predictions [4].

Experiments at hadron colliders, on the other hand, have a tradition stretching back to before the days of QCD-based models for multihadron production. Therefore another philosophy has developed in that field: high-$p_\perp$ jets are considered as standard QCD objects but the low-$p_\perp$ activity is described in terms detached from any jet universality constraints. A common attitude is that "soft hadronic physics is so dirty that you cannot predict anything; let us therefore simply parametrize whatever we observe". The litmus test of multiple interactions, namely the observation of an excess of two jet pairs in the same event, with the pairs identified e.g. by each having vanishing net transverse momentum, is very difficult experimentally. Therefore studies have not been conclusive, though the picture with multiple interactions is favoured [23]. And, strictly speaking, the observation of multiple interactions at moderately large $p_\perp$ does not tell anything about their possible rôle in the soft region.

Attempts to produce support for multiple interactions based on jet universality arguments [24] have not caught on in the $\mathrm{p\overline{p}}$ community, though the "evidence" is reasonably compelling (in the eyes of the believers). To give a few examples:

- The charged multiplicity and the transverse energy is increasing with energy much faster than the $\ln s$ that could be expected from the increasing rapidity range.
- The multiplicity distribution is much broader than the roughly Poissonian shape that is predicted from a single (or double) string. A reasonable account of the experimental "negative Binomial" distribution, with a relative width $\sigma(n_{\mathrm{ch}})/\langle n_{\mathrm{ch}}\rangle$ that increases with energy, can be obtained by adding the further element of randomness caused by a variable number of semihard interactions in events.
- The data also contains strong forward–backward multiplicity correlations: if one hemisphere of an event has a large multiplicity then, normally, so does the other. A varying number of strings, frequently stretched over both hemispheres, easily explains this phenomenon.

In spite of the lower energy, HERA has a chance to provide many further interesting tests of multiple interactions, and put the whole game on much firmer footing. The main reason is the variability offered by the photon probe:

1. Multiple interactions are expected to vanish gradually as the photon virtuality Q^2 is increased. This may be seen as a consequence of the reduced number of (resolved) partons in a higher-virtuality photon.

2. The direct events are not expected to contain multiple interactions. This can be observed as a decrease of multiplicity and $E_{\perp}$ for events with larger x_{γ}.
3. Within the resolved class, the anomalous events are expected to have less multiple interactions than the VMD ones. This may be understood by considering a $\gamma \to \mathrm{q}\overline{\mathrm{q}}$ branching at a transverse momentum $k_{\perp}$, where the latter quantity in principle is measurable from the $p_{\perp}$ of the remnant jet. The $k_{\perp}$ sets a virtuality scale, like Q in the first point above, with reduced evolution range and therefore fewer partons in a photon branching at a larger $k_{\perp}$. Additionally, the $p_{\perp\mathrm{min}}$ cut-off of (semi)hard interactions can be expected to increase with $k_{\perp}$, thus further reducing multiple interactions.
4. Points 2 and 3 above come together in the variation of the multiple-interaction rate as a function of the $p_{\perp}$ of an observed jet. It is here well-known that a larger $p_{\perp\mathrm{jet}}$ biases the event sample towards direct and anomalous events, and hence should give fewer multiple interactions. This "anti-pedestal" effect should take over at larger $p_{\perp\mathrm{jet}}$, whereas the smaller $p_{\perp\mathrm{jet}}$ events should show the conventional pedestal effect [25] presumably caused by an impact-parameter variation [24].
5. Multiple interactions could offer a chance to probe "hot spots" in the proton. A virtual photon with virtuality $Q \gtrsim m_{\rho}$ probes a region of size $\sim 1/Q$, and a (real) anomalous photon with a branching $k_{\perp} \gtrsim m_{\rho}$ probes a region of size $\sim 1/k_{\perp}$, so by increasing Q or $k_{\perp}$ a smaller region of the proton is probed. As discussed above, the multiple interaction rate should go down in either case, but the question is whether it does so uniformly. If the proton contains hot spots, with several nearby partons, a photon probe hitting such a spot will still have a non-negligible chance of multiple interactions. In terms of an inclusive distribution of the charged multiplicity or summed $E_{\perp}$, the average value should be independent of the existence of hot spots, but the event-by-event fluctuations around this average would go up with hot spots present. Results on this topic would tie in with the small-x behaviour of parton distributions and saturation effects.

6 Summary

After a few years of exciting HERA results, it is clear that existing models do a reasonable job of explaining the data. In this sense, we do have a zeroth approximation to work with. This is always useful as a guide to help us classify and understand phenomena, but it should not straight-jacket our thinking. Moreover, agreement between data and models is far from perfect, so there is no reason for complacency. There are several areas where more work is needed to see whether we actually have all the necessary ingredients at hand. It is in no sense excluded that we need to develop new ways of thinking. Among the many issues one may mention:

- jet universality and systematic comparisons with $\mathrm{e}^{+}\mathrm{e}^{-}$, $\mathrm{p}\overline{\mathrm{p}}$, DIS $\gamma\mathrm{p}$ and $\gamma\gamma$ events;
- the change in event properties (such as rapidity gaps) when moving from a real to a virtual photon;
- multiple interactions and hot spots;

- the smooth joining of event classes;
- the character of beam jets; and
- the mass spectrum of diffractive states.

In view of this, it is important to remember that we are only at the beginning of the story.

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