Soft Particle Emission Accompanying Dijet Photoproduction

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Abstract. The intensity of the soft bremsstrahlung depends on the colour charges of the hard-scattered partons. This intensity is larger in dijet production with resolved photons by the factor $C_A/C_F = 9/4$ in comparison with direct photoproduction for particular configurations. It is investigated how these effects are reflected in Monte Carlo models.

The idea that the shape of inclusive hadron spectra can be derived from the perturbatively calculated parton distributions (Local Parton Hadron Duality \cite{1}) has been quite successful in general. There are some specific predictions for the very soft particles. Because of their long wavelength the soft gluons “probe” only the colour factors of the primary hard partons (the “colour antennae patterns” \cite{1}) and then their production properties can be derived directly from the lowest order perturbative diagrams. Recently the case of soft particles has been investigated in more detail \cite{2}. In the simplest case of $e^+e^- \rightarrow q\bar{q}$ the density of the soft gluons is predicted to be practically energy independent. Remarkably, it was found that the soft hadrons indeed follow this expectation suggesting the relevance of the duality picture even for low momentum particles ($p < \sim 300$ MeV).

This success could be accidental and may reflect purely hadronic properties. It is therefore important to test more specifically the perturbative origin of the soft phenomena. A direct consequence of the dominance of the lowest order diagrams is the proportionality of the soft particle density to the primary parton colour factor which is $C_F = \frac{4}{3}$ and $C_A = 3$ for a $q\bar{q}$ and $gg$ antenna respectively. Then low momentum particles are produced with the relative intensity $\frac{9}{4}$. It is important to recall that the total event multiplicities approach this ratio rather slowly with energy. As a $gg$ system is difficult to prepare one has to find an equivalent parton antenna with the appropriate effective colour factors. Such a realization is provided by, for example, dijet photoproduction.

1. Tests with Photoproduction of Dijets

One can distinguish in the leading order QCD approach the direct and the resolved processes. In the first case the photon participates directly in the hard scattering subprocess by photon-gluon-fusion or QCD-Compton scattering and transfers a large fraction ($x_{\gamma} \sim 1$) of its primary energy to the secondary jets. In the second case, the hard scattering subprocess involves the partons ($q, \bar{q}$ and $g$) in the photon and in the
proton and the energy fraction $x_\gamma < 1$. At HERA the dominant direct and resolved processes correspond to quark and gluon exchange respectively and the expected distributions in the dijet cms scattering angle $\Theta_s$ have been clearly observed at HERA [3].

Particularly simple results arise for the soft radiation perpendicular to the scattering plane [2]. In this case complications with the cut-off in the transverse momentum $k_\perp \geq Q_0$ disappear and all formulae depend only on the angles between the hard partons. In the simplest case of a $q\bar{q}$ dipole the density of gluons with momentum $p_\perp$ perpendicular to $q\bar{q}$ is

$$\frac{dN_{q\bar{q}}}{d\Omega dp} = \frac{\alpha_s}{(2\pi)^2} 2C_F(1 - \cos \Theta_{q\bar{q}}).$$

The soft radiation in more complicated hard processes involving gluons, relevant in the present discussion, can be obtained from appropriate superpositions of elementary dipoles.

We consider the ratio $R^i_\perp$ of the perpendicular radiation in the process $i$ and in a standard $q\bar{q}$ process with $\Theta_{q\bar{q}} = \pi$. With this normalization one finds for the direct processes a) $\gamma g \rightarrow q\bar{q}$ and b) $\gamma q \rightarrow qg$

$$R^a_\perp = 1, \quad R^b_\perp = \frac{N_C}{4C_F} \left[ 3 - \cos \Theta_s - \frac{1}{N_C}(1 + \cos \Theta_s) \right].$$

In both cases $R^i_\perp \rightarrow 1$ for scattering angle $\Theta_s \rightarrow 0$, i.e. in this limit both processes behave like $q\bar{q}$ antennae. In the QCD-Compton process b) the $q\bar{q}$ antenna changes into a $gg$ type antenna for $\Theta_s \rightarrow \pi$.

In case of the dominant resolved processes the results in Eqs. (58-61) were derived [2] for small scattering angles. There is only a weak dependence on this angle and for $\Theta_s \rightarrow 0$, where the gluon exchange dominates, they approach

$$R^i_\perp = C_A/C_F = 2.25.$$  \hspace{1cm} (3)

Using the known full expressions for the soft gluon radiation patterns [3] we found the approximate results for the leading processes $gg \rightarrow gg$ and $qg \rightarrow qg$ to be correct within $\sim 10\%$ for $\Theta_s < \pi/2$; within this accuracy one can safely neglect the contribution from the process $gg \rightarrow q\bar{q}$ (see Eqs. (A7-A9) in [4c]). In the table we show the results for the ratios $R^i_\perp$ in the case when the final partons are not identified, i.e. after symmetrization as in Eq. (53) of [2]. One can see that the result [2] remains approximately valid at arbitrary scattering angles within $\sim 20\%$.

| $\cos \Theta_s$ | 1.0 | 0.9 | 0.8 | 0.7 | 0.6 | 0.5 | 0.4 | 0.3 | 0.2 | 0.1 | 0.0 |
|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $\gamma g \rightarrow q\bar{q}$ | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| $\gamma q \rightarrow qg$ | 1.0 | 1.16 | 1.29 | 1.39 | 1.46 | 1.52 | 1.56 | 1.59 | 1.61 | 1.62 | 1.62 |
| $gg \rightarrow gg$ | 2.25 | 2.31 | 2.36 | 2.41 | 2.46 | 2.51 | 2.55 | 2.58 | 2.61 | 2.62 | 2.62 |
| $qg \rightarrow qg$ | 2.25 | 2.23 | 2.19 | 2.15 | 2.10 | 2.04 | 1.98 | 1.92 | 1.87 | 1.84 | 1.83 |

Table 1. Angular dependence of symmetrized cross section ratios $R_\perp$ for quark and leading gluon exchange processes.
2. Monte Carlo Studies

We have made a ‘Monte Carlo measurement’ of this ratio using the HERWIG program. HERWIG contains coherent QCD radiation effects and a cluster hadronization model. However, since HERWIG produces a complete simulation of events, realistic jet algorithms and detector acceptance cuts can be applied. Thus, if HERWIG is consistent with the analytical results, this is an indication that the perturbative calculations are relevant for soft particles as well, that the results are insensitive to detector acceptance effects, and that the measurement is likely to be feasible.

HERWIG events with a hard scatter of \( p_T > 6 \text{ GeV} \) were generated for HERA beam conditions in the region \( 0.2 < y < 0.85, Q^2 < 1 \text{ GeV}^2 \), where \( y \) is the usual inelasticity variable and \( Q^2 \) is the virtuality of the photon exchanged between the proton and the positron. The \( k_T \) jet finder was run in inclusive mode on the hadronic final state, and two jets with \( E_{\text{jet}}^T \geq 6 \), at least one of which must have \( E_{\text{jet}}^T > 7 \text{ GeV} \), were demanded, in the pseudorapidity region \( |\eta| < 2 \). We have also imposed the cut \( |\eta_1 + \eta_2|/2 < 1 \), constraining the boost of the dijet system so to achieve a more uniform acceptance in jet scattering angle, as described in [3]. Together, these cuts correspond to a region in which measurements have previously be made at HERA. Only 4.5 \( \text{pb}^{-1} \) of simulated data was used.

The particle \( p_T \) spectrum down to 50 MeV for particles within a cone of one unit in \( \eta - \phi \) from the vector perpendicular to the dijet system in the dijet centre of mass system is then obtained.

Based upon the variable \( x_\gamma^{\text{OBS}} \), the fraction of the photon’s momentum which enters into the dijet system, we then divide the events into two samples - \( x_\gamma^{\text{OBS}} > 0.75 \) (‘resolved’) and \( x_\gamma^{\text{OBS}} < 0.75 \) (‘direct’). The ratio of the \( p_T \) spectra for resolved/direct events is calculated, and is shown in the upper two figures for two regions of scattering angle, large (left) and small (right) - solid points. The small scattering angle region is defined by \( |\Delta \eta| > 2 \) and the large by \( |\Delta \eta| < 2 \). In terms of \( \cos \Theta_s \), these ranges correspond approximately to \( 0 < \cos \Theta_s < 0.76 \) and \( 0.76 < \cos \Theta_s < 0.96 \). The plots also show the predictions above for these kinematic ranges. The line shows the prediction taking the subprocess mixture as given by HERWIG. The band shows the uncertainty in the prediction if absolutely no knowledge of the partonic subprocess type, but a perfect separation of resolved and direct type diagrams is assumed. In all cases, processes not included in the table are neglected.

The HERWIG results approach the analytic predictions at low \( p_T \). Also shown (clear circles) is the result from HERWIG when multiparton interactions are allowed with a \( p_T^{\text{min}} \) for the hard scatter of 2.5 GeV. Multiparton interactions are often appealed to as a means of improving agreement between data and MC in the HERA region. They raise the ratio slightly, moving it closer to the prediction for high angle scattering, and further away for small angle scattering.

Because the resolved cross section peaks strongly at low scattering angles while the direct matrix element does not, the high \( x_\gamma^{\text{OBS}} \) sample for small scattering angles in fact consists of 30% resolved-type diagrams. This is why the ‘prediction’ lies outside the band, since in constructing the band it was assumed that the separation between resolved and direct LO diagrams was perfect. The extra contamination from resolved acts against the enhancement in the ratio coming from the angular dependence of the radiation. Clearly a better way of distinguishing resolved and direct type diagrams is required - either a new variable, or a harder cut on \( x_\gamma^{\text{OBS}} \). We have tried cutting at
Figure 1. Ratio of the average track transverse momentum in high $x_{\gamma}^{\text{OBS}}$ to low $x_{\gamma}^{\text{OBS}}$ events (i.e. ‘Resolved/Direct’) for large jet scattering angles (left) and for small jet scattering angles (right).

$x_{\gamma}^{\text{OBS}} = 0.9$, at the same moving the separation between low and high angular regions to $|\Delta \eta| = 1.5(\cos \Theta_s = 0.64)$. The results are shown in the lower plots. The prediction for low angle scattering is raised slightly and the agreement with HERWIG is rather good. So it looks like for these distributions the HERWIG results reproduce duality picture quite closely. Further improvements in these tests are undoubtedly possible.

The results presented reiterate that it is of great interest to measure these distributions in HERA data. The direct comparison of the low momentum particle production in direct and resolved processes should yield the ratio of colour factors $C_A/C_F$. Its observation is a crucial test of the significance (or otherwise) of multiparton interaction models and, more fundamentally, of the perturbative picture for soft particle production.

[1] Ya. I. Azimov, Yu. L. Dokshitzer, V. A. Khoze and S. I. Troyan, Z. Phys. C27 (1985) 65; C31 (1986) 213; Phys. Lett. B165 (1985) 147.
[2] V. A. Khoze, S. Lupia and W. Ochs, Phys. Lett. B394 (1997) 179; Eur. Phys. J. C5 (1998) 77.
[3] ZEUS Coll., M. Derrick et al., Phys. Lett. B348 (1995) 665; B384 (1996) 401.
[4] Yu. L. Dokshitzer, V. A. Khoze and S. I. Troyan, Sov. J. Nucl. Phys. 46 (1987) 712 and 50 (1989) 505; R. K. Ellis, G. Marchesini and B. Webber, Nucl. Phys. B286 (1987) 643; Erratum: Nucl. Phys. B294 (1987) 1180; J. Ellis, V. A. Khoze and W. J. Stirling, Z. Phys. C75 (1997) 287.
[5] G. Marchesini et al., Comp. Phys. Comm. 67 (1992) 465.
[6] S.Catani et al., Nucl. Phys. B 406 (1993) 187.
S.D.Ellis and D.E.Soper, Phys. Rev. D 48 (1993) 3160.
[7] J. M. Butterworth, J. R. Forshaw and M. H. Seymour, Zeit. f. Phys. C72 (1996) 637.