Ref.TH.3744-CERN

QCD BREMSSTRAHLUNG EFFECTS IN HADRONIC PRODUCTION
OF JETS AT THE CERN $\bar{p}p$ COLLIDER

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A B S T R A C T

Effects attributable to QCD bremsstrahlung which have been recently observed in hadronic production of jets by the UA1 and UA2 collaborations are compared with theoretical expectations. The theoretical results are sensitive to the value of the QCD parameter Λ . $\Lambda \approx 0.1$ GeV gives reasonable agreement with experimentally observed effects.

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The high statistics attained in the 1982 run at the CERN $\bar{p}p$ collider have enabled the UA1¹⁾ and UA2²⁾ experiments to perform a detailed study of jet production and properties of the underlying event structure in $\bar{p}p$ collisions at $\sqrt{s} = 540$ GeV.

It is a general expectation of quantum chromodynamics (QCD) that the production of a pair of jets with large transverse energy E_T^J must be accompanied by the radiation of other partons emitted before (initial bremsstrahlung) or after (final bremsstrahlung) the occurrence of the hard parton scattering which generates the two leading jets (Fig. 1). The extra partons give rise to new distinct jets, which may be isolated experimentally if their transverse energies are large enough and if they are produced at sufficiently large angles with respect to the leading jets. Otherwise, they manifest themselves through a broadening of jet profiles and the appearance of extra excitation in transverse energy and multiplicity in the so-called underlying event, i.e., what is left in the event after the contributions of the two leading jets are taken out. In principle, the effects of initial QCD bremsstrahlung can be studied in a more clean way, and separated from those of final QCD bremsstrahlung in the production of $W^\pm$ and Z^0 , subsequently undergoing a pure leptonic decay^{3),4)}. At the moment, however, the meagre statistics available for weak boson production cannot offer the level of quantitative comparison with the theory which is possible to attain with the much richer data samples existing for hadronic jet production.

The proper theoretical framework for calculating QCD bremsstrahlung is provided by the leading pole approximation (LPA). A possible exception might be represented by very hard bremsstrahlung emission in kinematic configurations not dominated by poles. Probabilistically, however, such configurations are relatively rare and they have at most marginal relevance in the discussion of the present collider data. Within the LPA one can simultaneously calculate: i) scaling violation effects on the parton densities induced by initial bremsstrahlung; ii) the ensuing hadronic transverse energy and the transverse momentum given to the leading di-jet system; iii) the jet broadening induced by final bremsstrahlung; iv) the generation of extra jets identifiable as such experimentally. An efficient, and in practice unique, technique to implement this type of calculation is provided by the QCD Monte Carlo^{5),6)}. Some treatment along these lines of final bremsstrahlung is included in the ISAJET program⁷⁾, and it has also been the object of crude exploration elsewhere²⁾. A comprehensive treatment of initial and final bremsstrahlung in hadronic interactions can be found in Refs. 8)-11). A qualitative handling of these effects, previous imposition of arbitrary cuts to keep clear as much as possible of pole-dominated kinematic regions and neglecting soft and semi-hard emission, is also possible in the $O(\alpha_s^3)$ approximation¹²⁾.

The QCD Monte Carlo employed in the present calculations is identical to the one presented in detail in Ref. 9), where it was used for a theoretical comparison with the 1981 UA1 and UA2 data. Therefore, we omit the specifics of the calculation here. Besides the QCD calculation of the hard parton scattering and of the bremsstrahlung, the essential ingredients are the hadronization model for the partons, which are fragmented independently according to Field and Feynman cascades, and an independent emission model for the spectator jets which is tuned up to reproduce as well as possible the small p_T data of the UA1 and UA5 experiments.

To judge about the stability of the QCD Monte Carlo calculations at the parton level, it is useful to make a comparison with the results of Ref. 11) for the cross-section $d\sigma/d\hat{p}_T$, where $\hat{p}_T$ is the parton transverse momentum developed in the hard scattering proper (Fig. 2). With a transverse energy cut $10 \leq E_T \leq 11$ GeV and in absence of QCD bremsstrahlung, $d\sigma/d\hat{p}_T$ would exhibit a narrow peak contained within the $5 \leq \hat{p}_T \leq 5.5$ GeV/c interval. With QCD bremsstrahlung activated, part of the E_T is contributed by the QCD radiation and, correspondingly, $\langle \hat{p}_T \rangle$ decreases with a broadening of the $\hat{p}_T$ distribution due to event per event fluctuations in the QCD emission. As Fig. 2 shows, the two calculations are in reasonable agreement with each other, in absolute magnitude and shape. In particular, both calculations agree on the average amount of the bremsstrahlung contribution to E_T being about $\sim 20\%$ of the total parton E_T , as first pointed out in Ref. 8). The same percentual fraction is verified to be approximately maintained when moving up to collider energies (and also in $W^\pm$ and Z^0 production, making in this case reference to the "hard scale" represented by the weak boson masses)³⁾.

The uncertainties concerning the fragmentation scheme have been discussed in Ref. 9). It is our view that the modeling of the fragmentation process should be fixed by a quantitative comparison with the relevant data, maintaining as basic theoretical criterion that alterations of the perturbative QCD energy flow should be minimal. Otherwise, the very idea of having an almost direct test of perturbative QCD by exploiting calorimetric data would become untenable. It is not yet possible to make a comparative assessment of the Field-Feynman fragmentation scheme used here [and also in ISAJET⁷⁾] with the colour-singlet fragmentation scheme used in Ref. 11) with regard to $\bar{p}p$ collider data, since no results from the latter scheme have been worked out so far at collider energies.

QCD bremsstrahlung effects, apart from scaling violations of the parton densities, are hardly evident in quantities like the jet cross-section $d\sigma/E_T^j$ (Fig. 3). Due account of the transverse momenta given to the two colliding partons by the initial radiation should increase $d\sigma/dE_T^j$ at large E_T^j . But that is

compensated by the degradation of the final partons due to final bremsstrahlung. As a result, the outcome is practically indistinguishable from that of a simple minded parton scattering calculation including only the effects of longitudinal scaling violations in the parton densities [see, e.g., Ref. 13]. Similar compensating mechanisms apply when varying the value of Λ . A higher Λ increases the α_s^2 in front of the QCD matrix element for hard scattering, but at the same time increases the degradation of the initial partons before scattering (Fig. 3).

The most dramatic effect of initial bremsstrahlung is in providing an extra source of excitation in the event structure underlying the leading jets. The experimental presence of such an extra excitation is clearly put in evidence by the UA2 data²⁾ shown in Fig. 4, where the distribution $\Sigma \tilde{E}_T$, the residual transverse energy after the leading jet contributions have been taken out, is plotted. The residual transverse $\Sigma \tilde{E}_T$ within the angular domain $|\eta| < 1$, $30^\circ < \phi < 330^\circ$ is determined for a sample of events having at least two jets with transverse energies $E_T^1, E_T^2 > 15$ GeV, $E_T^1 + E_T^2 > 60$ GeV, and pseudorapidities $|\eta_{1,2}| < 0.85$. The data in Fig. 4a are obtained neglecting the possible presence of a third jet, whereas in Fig. 4b the contribution of a third jet with $E_T > 5$ GeV, if present, is also subtracted. The theoretical curves have been obtained by identifying jet transverse energies and directions with those of the originating partons and imposing the above cuts. The residual $\Sigma \tilde{E}_T$ has been computed by taking out of the total E_T within $|\eta| < 1$ the contributions of calorimetric cells $\Delta\theta \times \Delta\phi = 10^\circ \times 15^\circ$ whose geometrical centres are distant less than 30° from one of the leading jets, and multiplying the residual transverse energy so obtained by 5/6 to correct for the limited azimuthal acceptance. The normalization has been set equal to that of the data. Also shown is the corresponding transverse energy distribution for minimum bias events as given by the Monte Carlo.

UA2²⁾ also estimates the mean value $\langle P_T^{ij} \rangle$ of the transverse momentum of the leading di-jet system. For that, it uses a sample of two-jet events, with both jets well contained within the calorimetric acceptance and having $E_T^1, E_T^2 > 20$ GeV, $E_T^1 + E_T^2 > 50$ GeV. $\langle P_T^{jj} \rangle = 5 \pm 2$ GeV/c is thus found experimentally. Under the same conditions (we require $|\eta_j| < 0.85$) we calculate $\langle P_T^{jj} \rangle = 6.6$ GeV/c for $\Lambda = 0.1$ GeV and $\langle P_T^{jj} \rangle = 7.7$ GeV/c for $\Lambda = 0.5$ GeV. With a cut in the di-jet mass at 70 GeV, we find $\langle P_T^{jj} \rangle = 6.5$ and 7.6 GeV/c for $\Lambda = 0.1$ and 0.5 GeV, respectively, below the cut, $\langle P_T^{jj} \rangle = 6.9$ and 8.4 GeV/c, for $\Lambda = 0.1$ and 0.5 GeV, respectively, above the cut. This, in agreement with the negligible variation observed experimentally.

Evidence for extra excitation in the underlying event is also found by UA1¹⁾. The way the data are presented (jet profiles) is not suitable, however, for a direct comparison with theory, since the granularity of the apparatus and other experimental uncertainties give smearing effects which cannot be neglected in discussing the sharp shape of the jet. In the plateau regions well away from the jet centres, these experimental effects become less important, though. In these regions we find an approximate doubling of $\langle E_T \rangle$ and $\langle N_{ch} \rangle$ with respect to the minimum bias level (essentially given by initial gluon bremsstrahlung), which is in qualitative agreement with what is found experimentally.

While the above effects are almost exclusively due to initial bremsstrahlung, there are other effects detected experimentally which should be attributed to an intermixing of initial and final QCD radiation. Among these are the appearance of a third hard jet and the broadening of the p^{out} distribution, as measured by UA1.

p^{out} , as defined by UA1¹⁾, is given by the sum of the absolute values of the E_T vector components perpendicular to the plane defined by the energy axis of the trigger jet and the beam direction, divided by two. The p^{out} distribution measured by UA1, Fig. 5a, refers to a sample of events having at least one jet with $E_T > 30$ GeV and $|\eta| < 1.2$, playing the role of the trigger jet. There is also an azimuthal restriction on the trigger jet direction, ϕ contained within $\phi = \pm 60^\circ$ with respect to the horizontal plane of the apparatus, which, however, is not relevant for a comparison with theory except for the sake of normalization (we multiply the theoretical result by 2/3 to account for it). p^{out} receives contributions from all E_T vectors having $|\eta| < 2.5$, except for those belonging to the trigger jet. In the theoretical calculation, transverse energy and angle of the trigger jet are identified with those of the parton originating it, the E_T vector contributions are given by the individual hadrons, and the hadrons of the trigger jet are counted out using Monte Carlo information. In Fig. 5a, besides the theoretical results for $\Lambda = 0.1$ and 0.5 GeV, the outcome of a two-jet Monte Carlo calculation in which QCD bremsstrahlung is deactivated, is also shown. UA1 also gives $d\sigma/dp^{out}$ including only the E_T contributions from cells belonging to jets (Fig. 5b). Of course, this result is more dependent on the jet cluster algorithm used. The theoretical curves plotted in Fig. 5b for comparison correspond to the result at the purely parton level.

UA1¹⁾ determines the fraction of three-jet events, where besides the trigger jet, defined as above, there are other two jets with $E_T^j > 15$ GeV and $|\eta_j| < 2.5$. In Fig. 6 this quantity is plotted vs. the E_T of the trigger jet. The theoretical curve has been calculated at the purely parton level. The dependence on Λ is rather modest in this case, and negligible with respect to the experimental uncertainties.

UA2²⁾ also presents evidence for jet broadening and angular correlations of the third jet with the two leading jet. But these results are too much dependent on the details of the cluster algorithm to allow for a direct comparison with a theoretical calculation. In studying angular correlations of the third jet, one should not forget that the latter may be due both to initial or final bremsstrahlung.

In conclusion, QCD bremsstrahlung effects observable in the UA1 and UA2 data for hadronic jet production have a magnitude well consistent with theoretical expectations. For some of these effects the result of the theoretical calculations is sensitive to the value of Λ . A value as large as $\Lambda = 0.5 \text{ GeV}$ appears to be unfavoured by the data, which instead are reasonably well reproduced by $\Lambda \approx 0.1 \text{ GeV}$. In comparison, the calculation of the jet cross-section turns out to be largely independent of the value of Λ , and therefore much less suitable for its determination.

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FIGURE CAPTIONS

- Fig. 1 : Scheme of the QCD Monte Carlo calculation.
- Fig. 2 : Comparison of the results for $d\sigma/d\hat{p}_T$, where $\hat{p}_T$ is the parton transverse momentum generated in the hard scattering, obtained in the QCD Monte Carlo calculations of the present article and of Ref. 11) for proton-proton collisions at $\sqrt{s} = 24$ GeV. A cut $10 \leq E_T \leq 11$ GeV on the total parton transverse energy is imposed.
- Fig. 3 : Jet cross-section. The calculations are done at the parton level, with no fragmentation. Results are reported for $\Lambda = 0.1$ and 0.5 GeV. Also shown is the result one obtains when considering only longitudinal scaling violation effects on parton densities. Data from Refs. 1) and 2).
- Fig. 4 : Distribution in the residual transverse energy of the underlying event in two-jet and three-jet events. Data from UA2²⁾. a) Contribution of a possible third jet not subtracted. b) Contribution of a third jet taken out. Also shown are the experimental distributions in transverse energy for minimum bias events²⁾, and the corresponding theoretical result from the Monte Carlo.
- Fig. 5 : Differential cross-section $d\sigma/dp^{\text{out}}$, as defined by UAL¹⁾. a) Including all hadron contributions, except those belonging to the trigger jet. b) Considering only hadron contributions belonging to jets - theoretical results in this case are computed at the parton level only. Also shown are the results of a two-jet Monte Carlo, neglecting QCD bremsstrahlung.
- Fig. 6 : Fraction of three-jet events vs. transverse energy of the trigger jet. $\Lambda = 0.1$ GeV. Data from UAL¹⁾.

SPECTATOR JETS

Fig. 1

Fig. 2

Fig. 3

Fig. 4b

Fig. 4a

Fig. 5

Fig. 6