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PHENOMENOLOGICAL INCORPORATION OF THE EXACT QCD MATRIX ELEMENT INTO QCD PARTON CASCADE MODELS[1]

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ABSTRACT

A method for incorporating the $O(\alpha_s)$ exact matrix element into QCD parton cascade models, in a consistent way, is discussed. The improved model (based on the Webber model) is tested by comparing its predictions with data taken by JADE at PETRA. The model predictions agree reasonably well with the data for the energy-energy-correlation asymmetry and for other jet observables.

It has been shown by the JADE collaboration that the string fragmentation model of the Lund group[**1**] combined with the second order QCD matrix element describes better than independent fragmentation models the particle distribution in three jet events[**2**], the energy-energy-correlation (EEC)[**3**], the charged multiplicity distribution[**4**] and the p_t broadening of gluon jets compared with quark jets [**5**]. Although the Lund model describes the data quite well at PETRA and PEP energies, at higher energies (at SLC or at LEP) higher order QCD effects become more important, because they are more visible, since the fragmentation effects ($< p_t > \approx 0.3$ GeV) become relatively smaller. The following will be missing at higher energies in any non-cascade models based on $O(\alpha_s^2)$ perturbative QCD (like the Lund model):

(1) Events with large jet multiplicities ($N_{jet} > 4$)

(2) Continuity of distributions for $q\bar{q}$ and $q\bar{q}g$ events[3].

Recently, a QCD parton cascade model based on the leading log approximation (LLA) with soft- and collinear-gluon- interference effects approximated by an angular ordering of partons has been developed (the Webber model[**6**]). Parton cascade models are very attractive, since the above two missing physics points can be admitted simultaneously: events with

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[3] In the Lund model, $q\bar{q}$- and $q\bar{q}g$- distributions are smoothly connected by the fragmentation effects at PEP/PETRA energies, if a very small value of the infrared cut off parameter (y_{min}= 0.0125) is chosen[**3**].

more than 4 partons are naturally produced and the continuity between $q\bar{q}$ and $q\bar{q}g$ events is guaranteed by the existence of many soft gluons near the hard partons. There is, however, a serious problem in the QCD cascade models: the leading log approximation breaks down for hard processes. To solve this problem, the exact perturbative matrix elements have to be incorporated in the LLA parton cascade models.

I present here a method of achieving such an incorporation. The principle of the proposed method is that the gross structure of the event shape is described by the $O(\alpha_s)$ exact matrix element and the detailed structure (near jets) is described by the LLA parton cascade. The gross and the detailed structures are clearly defined by the invariant mass of parton combinations. Hence, the small y region ($y < y_{LIM}$) is described by the LLA parton cascade and the large y region ($y > y_{LIM}$) is described by the $O(\alpha_s)$ exact matrix element, where y is the invariant mass squared of partons normalized by E_{CM}^2. It is necessary to choose y_{LIM} sufficiently small that the LLA is good enough in the region $y < y_{LIM}$. The results should not depend too much on the matching point ($y = y_{LIM}$) if the value y_{LIM} is small enough. The following jet algorithm is used to combine the final state partons into jets in order to define the variable y.

(1) For a given event, the four-momenta of parton pairs are combined if the invariant mass is smaller than the limit ($y_{ij} < y_{LIM}$).

(2) The parton pair with the smallest invariant mass is combined first.

(3) Only the following combinations are allowed: $q + g \rightarrow q$, $\bar{q} + g \rightarrow \bar{q}$, $g + g \rightarrow g$ $q + \bar{q} \rightarrow g$. Other unphysical combinations, for example $u + u$ or $u + \bar{d}$, are not allowed.

(4) Keep at least one $q\bar{q}$ pair uncombined, because it couples with the initial virtual γ and it is necessary to avoid events with only gluons.

The jet algorithm can be used in a different way, where the combination is terminated if the number of jets is equal to some small number, say two, independent of y_{LIM}. Since the parton branching history depends on the gauge, and the interference effects must be taken into account, the history (which gluon comes from which quark in which order etc.) must not be taken seriously, since it is not physical. Therefore the jet algorithm must be independent of the history.

In the Webber model, there are two event generators: a $q\bar{q}$-generator and a $q\bar{q}g$-generator, where the LLA parton cascade is started from the $q\bar{q}$ or the $q\bar{q}g$ initial state, respectively. The initial parton distribution ($q\bar{q}$ or $q\bar{q}g$) is given by the exact QCD matrix element of $O(\alpha_s)$. In the following I will discuss how to mix the event samples from $q\bar{q}$-generator and $q\bar{q}g$-generator without double counting and with the correct ratio. In order not to have double counting for the two samples, events from the $q\bar{q}$-generator are accepted only if the jet multiplicity is exactly two, and those from the $q\bar{q}g$-generator are only accepted if it is more than two. The jet multiplicity is defined by the jet algorithm with a parameter y_{LIM} as described above. Double counting is thus avoided. In the next step, the normalizaton of the two samples has to be fixed. The two event samples should not be mixed with the ratio given by the $O(\alpha_s)$ or $O(\alpha_s^2)$ perturbative QCD calculations, since the higher order effects are effectively already taken into account by the LLA parton cascade in the Webber model. In order to obtain the normalization factor phenomenologically, partons are combined until the event has two jets and then y is defined as the larger jet invariant mass squared normalized by s of the two.

In Fig.1a and 1b, the y distributions are plotted for the $q\bar{q}$- and for the $q\bar{q}g$-sample, separately, with the parameter y_{LIM} = 0.1. The infrared cut off parameter y_{min} for cal-

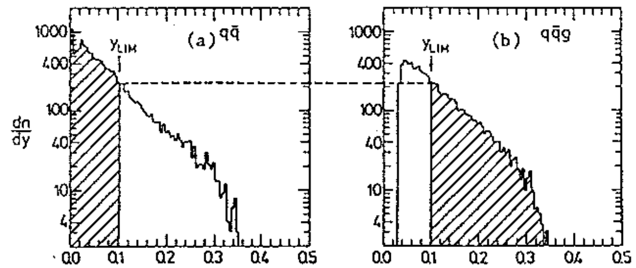

Fig. 1

culating the $q\bar{q}g$ matrix element is set to 0.03 (this is technically the smallest value) as shown in Fig.1b. Since the LLA is a good approximation at small y, the height of the distributions for the two samples has to match in the small y. The normalization is thus obtained by requiring the two distributions to match at $y = y_{LIM}$, as indicated in Fig.1: $\frac{dn}{dy}(y = y_{LIM}; q\bar{q}) = \frac{dn}{dy}(y = y_{LIM}; q\bar{q}g)$. The matching point y_{LIM} must be far from y_{min}, and at the same time, it must be small enough so that the LLA is a good approximation. In summary, the complete set of the events are taken from the $q\bar{q}$-sample with $y \leq y_{LIM}$ and from the $q\bar{q}g$-sample with $y > y_{LIM}$ and the normalization of the samples has to be fixed at $y = y_{LIM}$.

The model is experimentally tested by comparing the predicted distributions of jet observables with data. The first observable tested is the asymmetry in the energy- energy correlation (EEC). Since the EEC asymmetry is an additive observable, in the mixing of the $q\bar{q}$- and the $q\bar{q}g$- event samples, the total asymmetry $A(\theta) \cdot \sin\theta$ is a weighted sum of $A_{q\bar{q}}(\theta) \cdot \sin\theta$ and $A_{q\bar{q}g}(\theta) \cdot \sin\theta$:

$$A(\theta) \cdot \sin\theta = f_{q\bar{q}} \cdot A_{q\bar{q}}(y \leq y_{LIM}; \theta) \cdot \sin\theta + (1 - f_{q\bar{q}}) \cdot A_{q\bar{q}g}(y > y_{LIM}; \theta) \cdot \sin\theta,$$

where $f_{q\bar{q}}$ is the fraction of events from the $q\bar{q}$-generator obtained by the matching. As shown in Fig.2a, the prediction of the original Webber model in the large θ region, does not agree with the data (dots), since the LLA is poor in that region. The EEC asymmetry $A(\theta) \cdot \sin\theta$ after the incorporation of the exact matrix element is shown by the full curve, compared with the data (dots) in Fig.2b. The model prediction agrees reasonably well with the data, exept for the small angle region[1].

The QCD scale parameter Λ_{QCD} in the model was optimized to get a good agreement of the EEC asymmetry distribution with the data after incorporating the exact matrix element. The small value of Λ_{QCD} (0.15 GeV) may partially be due to using p_t^2 as an argument of α_s in the model[2]. As a test of the matching point invariance of the method, y_{LIM} was

[1] The discrepancy between the prediction and the data at small θ is essentially due to the overconstraint of the kinematics in the model: all the final state partons are on mass shell.

[2] In the Webber model, the argument Q^2 of α_s is defined at each branching and is approximately p_t^2 of the branching. Therefore the α_s is a running coupling constant even within one event. In order to be consistent with this feature of the running coupling constant in the Webber model, the $O(\alpha_s)$ exact $q\bar{q}g$ cross section was modified as follows:

$$\alpha_s(Q^2) \cdot \frac{x_q^2 + x_{\bar{q}}^2}{(1 - x_q)(1 - x_{\bar{q}})},$$

where Q^2 is not a constant value of E_{CM}^2 but the same argument which is used in the Webber model. However, the difference in the EEC asymmetry distribution for the two cases, using the correct Q^2 or using E_{CM}^2, is small.

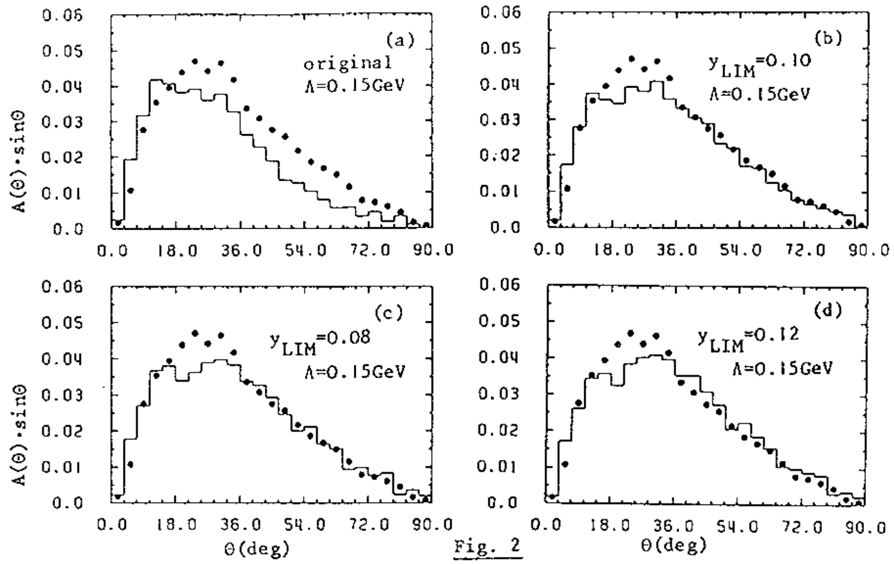

Fig. 2

varied from 0.10 to 0.08 and to 0.12, and the total EEC asymmetry was plotted using the same procedure. The EEC asymmetriy distribution is almost invariant under the change of y_{LIM} as shown in the Fig.2c and 2d. Other jet variables are also tested. For example, the sphericity distribution is significantly lower than the data for the original Webber model in the large sphericity region, as shown in Fig.3a. This can be improved by incorporating the exact matrix element (Fig.3b).

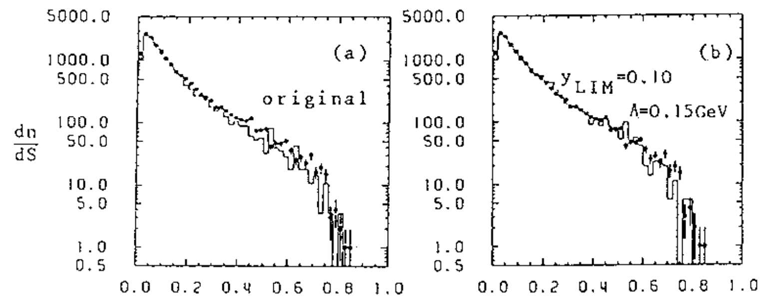

Fig. 3

The method for incorporating the $O(\alpha_s^2)$ exact QCD matrix element into the LLA parton cascade model would be an extension of the method just described. The LLA parton cascade is started from $q\bar{q}$ or $q\bar{q}g$ states, as well as from $q\bar{q}gg$ or $q\bar{q}q'\bar{q}'$ states. The parton distributions for the above initial states are based on the $O(\alpha_s^2)$ exact QCD matrix element. After the LLA parton cascade, the three event samples cannot be simply added because there are overlaps. To avoid double counting, 2-jet events are selected only from the $q\bar{q}$ event sample, 3-jet events are chosen only from the $q\bar{q}g$ event sample, and $\geq$4-jet events from $q\bar{q}gg + q\bar{q}q'\bar{q}'$ sample. The jet multiplicities for the three event samples are defined by the same jet algorithm with the same y_{LIM} for the three samples. The normalization of the sizes of the three event samples is determined by the matching condition at $y = y_{LIM}$. The normalization of the size of the sample from the $q\bar{q}g$- event generator to that from the $q\bar{q}$ generator is obtained in the same way as discussed for $O(\alpha_s)$: the matching condition is $\frac{dn}{dy}(y = y_{LIM}; q\bar{q}) = \frac{dn}{dy}(y = y_{LIM}; q\bar{q}g)$, where y is the larger jet invariant mass squared (normalized by s) of the two jets, when the final state partons are combined until the events have two jets. The normalization of the $q\bar{q}g$- event sample to the $q\bar{q}gg + q\bar{q}q'\bar{q}'$- event sample is obtained by the following formula: $\frac{dn}{dy}(y = y_{LIM}; q\bar{q}g) = \frac{dn}{dy}(y = y_{LIM}; q\bar{q}gg + q\bar{q}q'\bar{q}')$, where y is the largest jet invariant mass squared (normalized by s) of the three jets, when the partons are combined until the events have three jets.

Since it is not at present possible to calculate the exact $O(\alpha_s^3)$ QCD matrix elements, the incorporation of the $O(\alpha_s^2)$ QCD matrix element into LLA parton cascade model is the practical solution to handle the higher order QCD at higher energies. The method which I have discussed here can be used rather generally also for other dressing schemes, e.g. a la Sterman-Weinberg. The improved model can be a powerful tool not only for studying higher order QCD effects but also for controlling the background from ordinary multihadron events to look for new phenomena. For example, to extract heavy quark (top or 4-th generation) signal at SLC/LEP, the control of the spherical event background from higher order QCD is essential.

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