MULTIPLICITY AND RAPIDITY STRUCTURES IN THE QCD PARTON SHOWER MODEL

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ABSTRACT
Continuing our previous work on the QCD Parton Shower Model for electron positron annihilation we have investigated the rapidity and multiplicity structures of the $q\bar{q}$ and gg systems at c.m. energies $\sqrt{s}$ = 200 GeV and $\sqrt{s}$ = 2000 GeV in terms of the jets produced by the two initially created partons. The corresponding distributions of final partons are found to be remarkably simple and control the observed distribution by Local Parton Hadron Duality (LPHD). In this paper we discuss the single g-jet structure resulting by separating the gg system.

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1. Introduction

This paper is continuing a research program on the QCD Parton Shower Model for electron positron annihilation, which started few years ago [1],[2].

In Ref. [1] the model has been applied to the study of charged hadrons and partons multiplicity distributions (MD's) for symmetric c.m. rapidity windows produced in $q\bar{q}$ and gg systems at various energies ($\sqrt{s}$ = 29, 200 and 2000 GeV). It was found that MD's are described well at partonic and hadronic level by the Negative Binomial (NB) distribution. Moreover it was discovered that Local Parton Hadron Duality (LPHD) is contained in the model.

In Ref. [2] we investigated the dependence of the above regularities on parton virtuality cut-off Q_0 ($Q_0 = 1 \div 2$ GeV) and we discussed the relevance for our findings on MD's of the angular ordering option incorporated in the model. It has been shown that Lund hadronization prescription led to infrared stable results and that the dependence on angular ordering affected mean multiplicities only, leaving substancially unchanged the other parameters of the distributions.

The motivation of the present work is based on the following considerations. Most successful parton shower models [3],[4] have one important feature in common, i.e., the evolution of the shower at perturbative level is described in terms of the Altarelli-Parisi (AP) equations; models differ however in the hadronization prescription (string fragmentation in Ref. [3] and independent cluster fragmentation in Ref. [4]). Our point of view is that the perturbative level is indeed controlled by AP equations, whereas the hadronization of the parton shower follows approximate LPHD.
The latter is in fact a very essential part of our approach to multiparticle dynamics. LPHD was formulated in Ref. [1] in terms of n-partons (p) and n-hadrons (h) inclusive rapidity distributions $Q_n^{(p,h)}(y_1, \ldots, y_n)$. It says that

$$Q_n^{(h)}(y_1, \ldots, y_n) = \rho^n Q_n^{(p)}(y_1, \ldots, y_n)$$

with ρ constant.
The fact that LPHD is contained in the QCD Parton Shower Model with string fragmentation, when applied to quark-antiquark ($q\bar{q}$) and gluon-gluon (gg) systems, allows to limit our study to rapidity and multiplicity structures at partonic level only. Since both $q\bar{q}$ and gg systems have two jets generated by two ancestor partons, we decided in our search for simplicity to study them separately.
No major difference was discovered in the partonic properties of the two systems when separated in their single-ancestor jet components. Accordingly, we concentrate our attention in this paper on the study of single-ancestor g-jet resulting in the gg system from a sample of 2000 events generated using the QCD Parton Shower Model as imple-

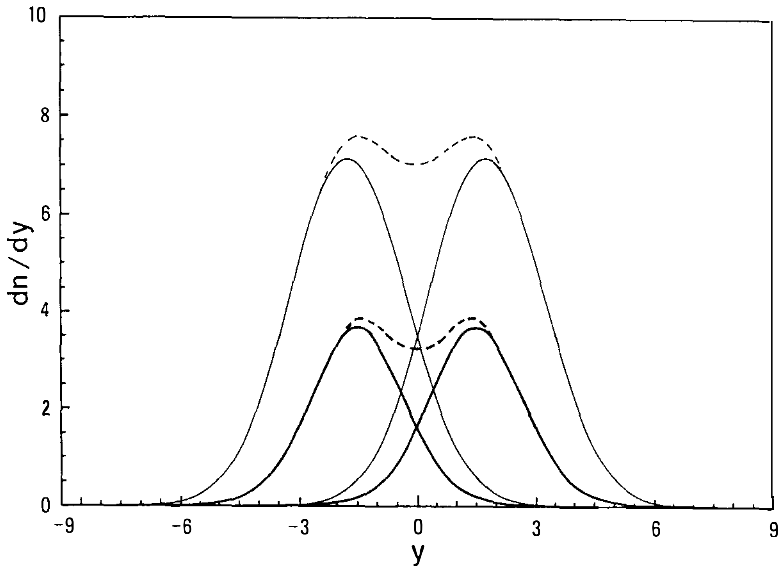

Figure 1. Final partons rapidity distribution of forward and backward g-shower with respect to the gg c.m. system at $\sqrt{s} = 200$ GeV (heavy continuous lines) and at $\sqrt{s} = 2000$ GeV (thin continuous lines) vs rapidity y; gg final partons rapidity distributions at $\sqrt{s} = 200$ GeV (heavy dashed line) and at $\sqrt{s} = 2000$ GeV (thin dashed line) vs rapidity y. The distributions here and in the following figures are normalized to the mean number of partons $\langle n \rangle$ and drawn in a symmetrized form.

mented in the program JETSET version 6.3 [3], at c.m. energies of 200 and 2000 GeV. The optimal values of the shower evolution parameters are $\Lambda = 0.4$ GeV (QCD scale in LLA) and $Q_0 = 1$ GeV (cut-off for parton evolution).

2. Final partons rapidity distributions in single-ancestor g-jet

After defining as usual parton rapidity y with respect to the linear sphericity axis of the total gg system, we separate the two g-jets (showers) according to the sign of their ancestor rapidities. We call forward (backward) ancestor g-jet or forward (backward) g-shower the set of partons stemming from the ancestor with positive (negative) rapidity.

Final partons rapidity distributions, dn/dy, of forward (backward) g-shower with respect to the gg c.m. system at $\sqrt{s} = 200$ GeV (heavy continuous line) and at $\sqrt{s} = 2000$ GeV (thin continuous line) are shown in Figure 1. Final partons rapidity distributions of the forward and backward g-shower are symmetric and can be fitted

Table I. Final parton mean rapidity $\langle y\rangle$ in the gg c.m. frame and dispersion $D_y = \sqrt{\langle(y-\langle y\rangle)^2\rangle}$, ancestor mean rapidity $\langle y_{anc}\rangle$ in the same frame and dispersion $D_{y_{anc}} = \sqrt{\langle(y_{anc}-\langle y_{anc}\rangle)^2\rangle}$ are compared at c.m. energies $\sqrt{s}$ = 200 and 2000 GeV. The rapidity distributions are normalized to the mean number of partons $\langle n\rangle$ (last column). Numerical values in the table are averages over corresponding values for the forward and backward g-shower.

$\sqrt{s}$	$\langle y\rangle$	D_y	$\langle y_{anc}\rangle$	$D_{y_{anc}}$	$\langle n\rangle$
200 GeV	1.42	1.28	1.52	0.64	11.4
2000 GeV	1.69	1.41	1.84	0.80	25.3

by gaussian distributions at both energies. Their superposition explains gg final partons rapidity distributions (dashed lines in Fig. 1) and the occurrence of the dip in the central rapidity region. The increase with energy of the shape of the final partons rapidity distribution is reflected in the fact that the mean parton rapidity $\langle y\rangle$ and the dispersion D_y are growing slowly (10 and 20 percent respectively) from 200 GeV to 2000 GeV, whereas the mean number of partons $\langle n\rangle$ obtained by integrating dn/dy over all phase space is more than two times larger (see Table I).

Figure 2 shows the forward single-jet final partons rapidity distributions dn/dY, ($Y = y - y_{anc}$), with respect to the rapidity of the forward ancestor. A totally symmetric situation occurs for the backward ancestor g-jet. It is to be pointed out that dispersions do not vary very much with energy; this result can be compared with the strong increase in the peak height of the distribution at 2000 GeV with respect to 200 GeV. Partons at the two energies are produced within the same spread in rapidity and their number is determined by the virtualities of the ancestors. In addition, mean rapidity of the ancestor in the two gluon c.m. system, $\langle y_{anc}\rangle$, is a little more forward (backward) than final partons mean rapidity, $\langle y\rangle$, and ancestor rapidity dispersion, $D_{y_{anc}}$, is narrower than the corresponding dispersion for final partons, D_y. The two mentioned features show why peaks are higher and narrower for ancestor than for final partons distributions.

3. Final partons multiplicity distributions in single-ancestor g-jet

MD's in the forward and backward ancestor jet system have been studied in symmetric rapidity windows, $|Y| < Y_0$, and in full phase space. Results are given in Table II. They are limited to forward ancestor jet system. For MD's in full phase space we consider the distribution of newly created partons, i.e., of final partons after subtracting the ancestor(s) parton(s).

We find that MD's in the g ancestor frame are well described by NBMD's. The general trend in rapidity and energy is similar to that already found for the gg system [1].

Table II. Standard NB parameters $(\bar{n}, k)$, corresponding average number of partonic clans, $\bar{N}$, and average number of partons per clan, $\bar{n}_c$, of multiplicity distributions in symmetric windows of $Y = y - y_{anc}$ and in full phase space (PS) for forward ancestor g-jet, and in full phase space only for gg system are compared at c.m. energies $\sqrt{s}$ = 200 and 2000 GeV. χ^2/number of degrees of freedom (NDF) for NB fits are given in the last column.

g-jet	$\bar{n}$	k	$\bar{N}$	$\bar{n}_c$	χ^2/NDF
$\|Y\| < 0.5$					
200 GeV	4.05 ± 0.06	4.03 ± 0.27	2.80 ± 0.06	1.44 ± 0.04	12.74/17
2000 GeV	8.26 ± 0.16	1.61 ± 0.06	2.92 ± 0.07	2.83 ± 0.09	55.35/38
$\|Y\| < 1.0$					
200 GeV	7.28 ± 0.08	8.52 ± 0.60	5.26 ± 0.10	1.38 ± 0.03	26.46/21
2000 GeV	15.17 ± 0.22	2.94 ± 0.12	5.34 ± 0.12	2.84 ± 0.08	58.35/52
$\|Y\| < 2.0$					
200 GeV	10.34 ± 0.08	27.83 ± 3.44	8.79 ± 0.17	1.18 ± 0.02	29.17/24
2000 GeV	22.61 ± 0.22	7.59 ± 0.33	10.48 ± 0.22	2.16 ± 0.05	58.27/54
...	...	...	...	...	...
Full PS					
200 GeV	10.23 ± 0.09	23.91 ± 2.53	8.52 ± 0.16	1.20 ± 0.02	48.05/25
2000 GeV	23.98 ± 0.24	9.00 ± 0.42	11.69 ± 0.25	2.05 ± 0.05	86.76/58
gg system	$\bar{n}$	k	$\bar{N}$	$\bar{n}_c$	χ^2/NDF
Full PS					
200 GeV	20.79 ± 0.08	57.89 ± 5.01	17.76 ± 0.22	1.17 ± 0.02	35.36/37
2000 GeV	48.38 ± 0.21	19.56 ± 0.62	24.35 ± 0.34	1.99 ± 0.03	109.3/77

We conclude that NB universality extends to the single g ancestor system. In particular it is to be mentioned that the average number of clans $\bar{N}$ in fixed rapidity windows up to $Y_0 = 1.0$ is energy independent within errors; for $Y_0 \geq 2.0$ a characteristic bending effect shows up [1]. In Table II are also shown NBMD's fits in full phase space for the forward ancestor g-jet and for the total gg system. They are related by the following simple relations

$$2\bar{n}_g \simeq \bar{n}_{gg} \quad , \quad 2k_g \simeq k_{gg}$$

Corresponding clan structure analysis gives

$$2\bar{N}_g \simeq \bar{N}_{gg} \quad , \quad (\bar{n}_c)_g \simeq (\bar{n}_c)_{gg}$$

A careful comparison of the two cases shows that NB properties in the single g ancestor system –although still quite good– are a little worse than in the gg system. This fact

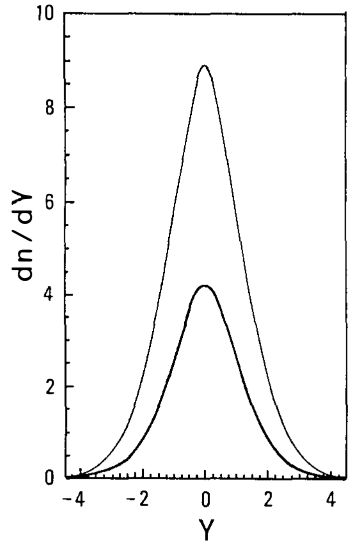

Figure 2. Single shower final partons rapidity distribution at $\sqrt{s} = 200$ GeV (heavy line) and at $\sqrt{s} = 2000$ GeV (thin line) vs rapidity $Y = y - y_{anc}$ with respect to the ancestor.

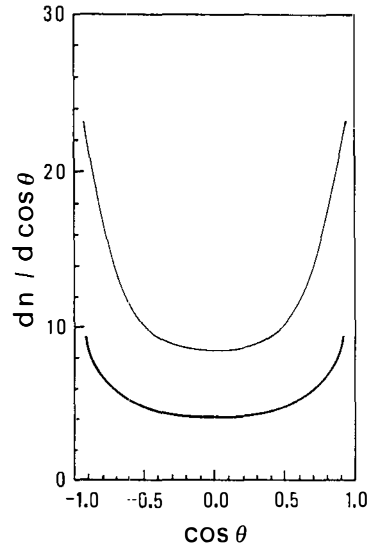

Figure 3. Final partons distribution in polar angle θ at $\sqrt{s} = 200$ GeV (heavy line) and at $\sqrt{s} = 2000$ GeV (thin line) with respect to the ancestor frame vs $\cos\theta$. The z-axis coincides with the rapidity axis, $\cos\theta = p_z/p$.

could be regarded as an indication of the existence of correlations between forward and backward g-shower. We found indeed that at c.m. energy $\sqrt{s} = 200$ GeV there is a weak correlation in the virtuality distributions of the ancestors. The effect shows up when examining the forward ancestor's virtuality distribution after making a cut in the backward ancestor's virtuality Q_B. When the latter has small virtuality ($Q_B < 13$ GeV at c.m. energy $\sqrt{s} = 200$ GeV) the forward distribution has a longer tail; when it has large virtuality ($Q_B > 35$ GeV), the distribution has a higher peak. On the other hand no correlation is visible in the multiplicities confirming the fact that their convolution explains MD's for the total gg system.

4. Event structure in the single ancestor rest frame

In the ancestor rest frame with the z axis made to coincide with the rapidity axis we studied the final partons distribution in polar angle θ ($\cos\theta = p_z/p$), $dn/d\cos\theta$ (see

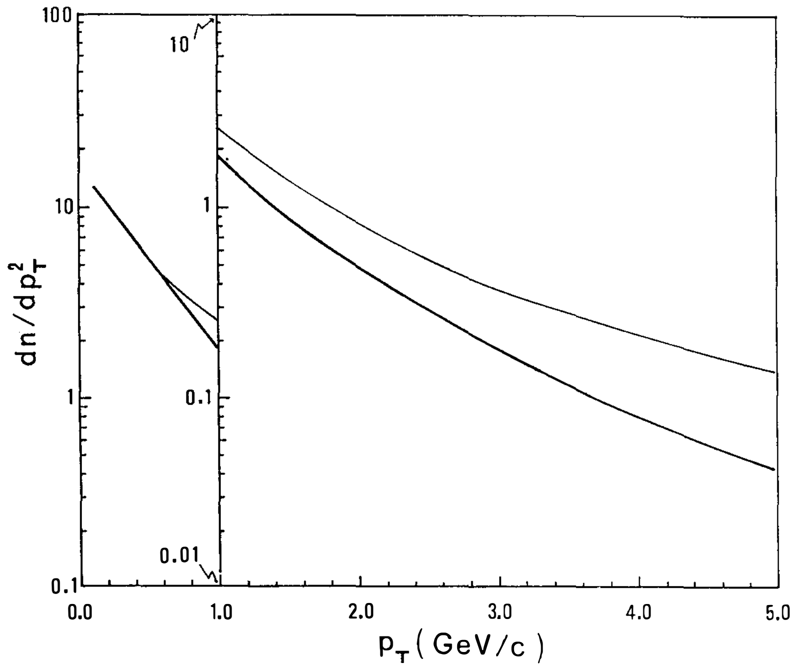

Figure 4. Final partons distribution in transverse momentum squared vs p_T at $\sqrt{s} = 200$ GeV (heavy lines) and at $\sqrt{s} = 2000$ GeV (thin lines); on the left in the figure the peak zone is given with the ordinate rescaled by a factor 10.

Fig. 3). Bins corresponding to $\theta \sim \pi$ and $\theta \sim 0$ are much more populated than those with $\theta \sim \pi/2$ indicating the presence of an elongated structure along the rapidity axis which becomes more pronounced as the c.m. energy increases.

Within the above conditions we looked also at final partons distribution in transverse momentum p_T ($p_T = \sqrt{p_x^2 + p_y^2}$), dn/dp_T^2. Results are plotted in Fig. 4. They confirm the trend seen in Fig. 3. Moreover it is shown that final partons distribution in transverse momenta is energy independent for $p_T \leq 0.6$ GeV (Fig. 4 on the left).

5. Conclusions

We have studied single-ancestor g-jet properties. They are remarkably simple. Final partons rapidity distributions in the two gluons c.m. system are explained in terms of the superposition of forward and backward g-shower. Ancestors' virtuality controls the spread in multiplicity in the single ancestor frame. Final partons multiplicity distributions in symmetric rapidity windows and in full phase space are well fitted by NB MD's and are simply related to partons MD's of the total gg system. No correlation was found in the number of partons produced by the forward and backward ancestor g-jet; a weak correlation is visible in the virtuality distribution of the ancestors of the two showers. We consider this correlation as responsible for the fact that NB fits get somewhat worse when disentangling the two jets. Event shape has also been explored and found to be elongated along the rapidity axis. We discovered that the distribution in transverse momentum is energy independent for $p_T \leq 0.6$ GeV.

Similar results are obtained by separating the $q\bar{q}$ system in its single-ancestor components. In addition for the $q\bar{q}$ system there is the possibility to study the evolution of heavy flavors from initial $b\bar{b}$ down to beauty hadrons [5].

This work confirms our main idea that *complex* structures which we observe might very well be, at the origin of their evolution, *elementary*, and have *simple* properties.

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