STUDY OF HIGHER ORDER QCD EFFECTS AND BARYON CORRELATIONS WITH THE TPC AT PEP

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ABSTRACT

Higher order QCD effects have been studied in e^+e^- annihilations at 29 GeV based on the data collected by TPC/Two-Gamma collaboration at PEP. We have studied the rapidity distribution of charged hadrons in the sphericity region where two jet and three jet events merge. When compared with predictions of QCD models, we find out that the perturbative calculation based on the leading log approximation with $Q_0 \sim 1$ GeV together with the string fragmentation model for the non-perturbative part gives the best descriptions. Measurements of baryon correlations are also presented.

1 Introduction

In this talk, we present two results obtained recently by the TPC/Two Gamma detector at PEP at 29 GeV CM energy. One is a study of higher order QCD effects on the rapidity distributions of charged hadrons and the other is a study of baryon correlations. The data used in the analysis consists of two data sets. The first sample (1982-83) of 77 pb^{-1} was collected with 4 kG magnetic field and the second sample (1984-86) of 70 pb^{-1} with 13.25 kG magnetic field. Because of different detector acceptances two data sets are treated separately. Details of the detector system are described elsewhere[1)].

2 Study of Higher Order QCD Effects

In QCD, hadron production in e^+e^- annihilation is described in two steps: The first is the "hard part", where configuration of partons is given. In this part QCD can be approximated by the *perturbative* expansion. The second is the "soft part", where hadronization of partons takes place. Since we do not know the prescription to calculate this *nonperturbative* part of QCD, we rely on phenomenological models to describe it.

There exist two distinct approaches for the calculation of the perturbative part. One is the perturbative expansion in power of $\alpha_s(Q^2)$. At present the exact calculation up to the second order is available. We refer this model as the 2nd order QCD model. In this model, two partons, three partons, and four partons are produced in proportional to the corresponding matrix elements. Due to the singularities in the kinematical region where a gluon is either soft or almost collinear with a quark or an antiquark, there exists discontinuous transition between two- and three-parton events and three- and four-parton events. Also it does not account for the emission of soft or collinear gluons. The other method is to use the leading logarithmic approximation (LLA). LLA allows the stochastic calculation of the parton evolution which leads to parton cascade and thus we refer this model as parton shower model. In this approximation, the leading singularities are summed up to all orders of α_s. Although LLA applies to regions where angles or virtualities of partons are small, it contains a part of higher order terms compared with the 2nd order QCD model. Soft or collinear gluons predicted by the higher order calculation are expected to realize the smooth out transition in the parton level.

To describe the nonperturbative part of QCD, several models have been proposed. They are classified into the following three models: First is the independent fragmentation model (IF) where partons are assumed to fragment independently of each other. Second is the string fragmentation model (SF) where the linear confinement potential between partons is represented by the massless relativistic string. As partons move apart, string breaks by picking up additional $q\overline{q}$ or $(qq)(\overline{q}\overline{q})$ pairs. Each string with q,qq at one end and $\overline{q},\overline{q}\overline{q}$ at the other end hadronizes in its rest frame. The third is the cluster fragmentation model (CF) where partons form several color singlet clusters before transforming to hadrons.

In general, the non-perturbative part is satisfactorily described by the SF model[2)]. All existing measurements, however, have been based on the events with clearly separated hadronic jets. There exist a much larger number of events which do not have clear topological feature of either 3-jets or 2-jets. These events are considered to have gluons which are either soft or almost collinear with a quark or an antiquark and therefore cannot be resolved as independent jets by experiments. Events in this "jet merging" category have never been investigated.

Here we present a new analysis of these events in the jet merging region[3)]. In a hadronic event, pion tracks are selected and their rapidities y, are calculated. At the same time, the sphericity of the event is computed using charged tracks with momentum over 150 MeV. Sphericity is a measure of the shape or the jet topology of each event and closely related to the energy of emitted gluons. Events with small sphericity corresponds to two-jet like events and those with larger sphericity to more spherical events which contains more three jets. In this analysis, rapidity values is refered to the sphericity axis. In order to study the transition from two jets to three jets, we plotted the rapidity distribution as a function of a variable which characterizes the event shape. In the region where two jet and three jet merges, that is gluon energy is medium or small, the effects of soft gluons are expected to be evident.

A plateau is expected in the rapidity distribution, if particles are created with limited transverse momenta and proportionally to the longitudinal phase space available. A dip has been observed, however, in e^+e^- annihilation at PEP and PETRA. No explanation has been made for its origin. By plotting distributions as a function of sphericity we try to explain it in terms of the QCD model. The rapidity distributions are plotted at various sphericity region in fig 1(a). Each distribution is normalized by the number of events observed in the specified sphericity region. At small sphericity regions, experimental data show rather flat distributions as expected. At higher sphericity regions particles are populated at the central rapidity region, since emission of hard gluon produces particles with high $p_\perp$ with respect to the sphericity axis. Clear dip structure is observed at regions between two jet and three jet. For comparison with the 2nd order QCD model, we use the LUND Monte Carlo version 5.3[4], together with IF and SF for the nonperturbative part. As shown in fig.1 (b) and (c), IF and SF show the same structure at two jet regions and three jet regions. However neither of them produce the dip seen in the data. In SF, a small dip appears which may be related to emission of gluons relative to the quark/antiquark[3], but it is much smaller than what is observed in the experiment.

In order to quantify the structure in the central region, the ratio of the rapidity yield at $0.0 \leq |y| < 1.0$ to the yield at $1.5 \leq |y| < 2.5$ is calculated as:

$$R(S) = \frac{dN/dy(0.0 \leq |y| < 1.0, S)}{dN/dy(1.5 \leq |y| < 2.5, S)}. \tag{1}$$

One merit of using this ratio is that possible systematic errors in normalization cancel out. The ratio for pions are compared with prediction of the 2nd order QCD model in fig.2. The prediction agrees with the data in regions with large sphericity where clear three jet events are populated. Disagreement is pronounced around $S \sim 0.07$, where the gluon energy becomes small or medium and the gluon jet is irresolvable from the quark jet by the experiment. In IF, hadrons obtain energy only from its parent parton. A gluon has to fragment even if energy is small. Addition of soft gluons to the $\overline{q}q$ configuration, leads to excess of soft particles at the central rapidity region. In other words, IF can not smooth out discontinuity at the parton level. On the other hand, SF has a built-in mechanism for smooth jet merging[5]. In the SF model, gluons are modeled as a kink in the string. Therefore, as the gluon energy decreases three jet events continuously transform back to two jet events. The reason for the failure of the 2nd order QCD model with SF is less obvious at this level.

For the next step, we tried to make a comparison with the parton cascade model. In this model, partons radiate more gluons if the virtuality of parent parton is greater than the cut off value Q_0. The importance of the LLA method is that it is applicable to much lower cutoff energies than is possible with 2nd order QCD model. Smaller Q_0 means that partons radiate more soft gluons. We use the most recent LUND Monte Carlo program (version 6.3)[6] as an implementation of LLA. In this program, the hard three jet fraction is obtained by first order QCD and all partons are connected by strings that follows the color flow as determined by the time development in the perturbative part. This scheme reproduces observed global jet distributions and inclusive particle production well and enables us to make a direct comparison with data. As shown in fig. 3, the parton cascade model exhibits similar structure as seen by the experiment. The point is that the dip appears only if one uses a low cutoff value. By lowering the value of cutoff, the size of the dip increases. The ratio R and predictions of the parton cascade model with cutoff values 1 GeV, 2 GeV and 4 GeV are presented in fig. 4. One can see that the parton cascade model with Q_0=1 GeV or 2 GeV reproduces the data in the entire sphericity region.

We have investigated other possibilities which may produce the observed dip. For example, misidentification of heavy particles as pions, or kinematics of heavy quark. In the latter case, the fragmentation function for charm quarks were changed such that the average $< z_{D*} >$ is over 3σ away from experimental data. The multi-parameter fit was performed to obtain optimum parameters in the QCD jet models. Fig. 4 shows the distributions of x_p, $< p_{\perp in} >$ and $< p_{\perp out} >$ with predictions of the models. Systematic errors in the model predictions are estimated by changing the parameters in the models that differ from the value obtained by the best fits by one standard deviation. The ratio R, changes 1.5% typically. We found out that the structure in the rapidity distribution is stable against change in the parameters of the fragmentation models. None of these possibilities explains the observed dip.

Through the comparison of the measured ratio R with the predictions of the QCD models, we found out that the emission of soft collinear gluons to be essential to explain the rapidity distribution. A dip is interpreted due to the followings: If each parton evolves to a sufficiently low mass scale, Q_0, more soft or collinear gluons emerge. The gluon multiplicity reaches about 6.6 for the parton cascade model with Q_0=1 GeV, whereas it is only 2.8 for the 2nd order QCD model. Such gluons produces asymmetry in the parton rapidity spectrum with respect to the origin ($y = 0$). The resultant particle rapidity spectrum will be asymmetric. When many such asymmetrical distributions are added statistically, a dip appears in the center. In the 2nd order QCD model or parton cascade model with Q_0=4 GeV, gluons are not emitted abundantly to reproduce the dip in the rapidity distributions.

3 Baryon Baryon Correlation

Baryon is a good probe of the hadronization process, because it is less affected by resonance decays. We have measured two-particle correlations in the rapidity space. As a measure for the correlation between two baryons a and b, the correlation function C_{ab} is defined to be:

$$C_{ab}(y_a, y_b) = \rho_{ab}(y_a, y_b)/\rho_a(y_a)\rho_b(y_b) - 1 \tag{2}$$

Here, $\rho(y) = (1/\sigma_{tot})d\sigma/dy$ denotes the single-particle density as a function of rapidity y, and $\rho_{ab}(y_a, y_b) = (1/\sigma_{tot})d^2\sigma/dy_a dy_b$ is the two particle density. The annihilation cross section into hadrons is denoted by σ_{tot}. If baryon number is conserved locally, i.e., baryon and antibaryon are produced close in rapidity space, C_{ab} becomes positive. If there is no correlation between baryons produced in a jet, C_{ab} becomes 0.

The correlation functions between $\overline{p}$ or $\overline{\Lambda}$ and an additional $p, \overline{p}, \Lambda$, or $\overline{\Lambda}$ are presented in fig.6. In these figures, C_{ab} is presented for a given combination of particle types a and b as a function of y_b, keeping y_a fixed within a certain interval. The rapidity interval of particle a extends from 0 to 1.25 for $\overline{p}$ and $y_a > 0$ for $\overline{\Lambda}$. A strong positive correlation between baryons and antibaryons with evidence for local compensation of baryon number is observed in fig 6 (a)-(d). This indicates that a baryon and an antibaryon are produced in association with each other. Furthermore, the first observation of anticorrelation between baryons with the same baryon number are demonstrated in Fig.6 (e)-(h) for $C_{\overline{p}\overline{p}}$, $C_{\overline{p}\overline{\Lambda}}$ $C_{\overline{\Lambda}\overline{p}}$ and $C_{\overline{\Lambda}\overline{\Lambda}}$. The suppression of production rate for another heavy object with the same charge was estimated by measuring the correlation between $\overline{p}$ and three π system with about the same invariant mass and the same charge. We could not, however, observe anticorrelation comparable in strength to that seen for the baryon case. The observed anticorrelation among baryons is interpreted as follows: In fragmentation process, two primary hadrons with the same baryon number are separated by at least two steps in their "color order" which decreases along the "color flow" from the initial quark to the antiquark. If their order in the rapidity order closely reflects their color order, we are not likely to find two baryons or two antibaryons close in the rapidity coordinate. In fragmentation models where color flow is taken into account such as SF, this condition is fulfilled for any reasonable choice of the momentum-sharing function $f(x)$ where x is the fraction of parton momentum taken by the hadron. Indeed, the SF model with the symmetric Lund function reproduces the anticorrelation effect, whereas models using the standard Lund or the Feynman-Field fragmentation function do not. These studies show that particles are produced through the basic picture represented in the recent SF model and give an evidence for a close correspondence between the color order and their rapidity order.

4 Summary

We have observed a clear dip in the rapidity distribution in the sphericity region where two jet and three jet events merge. Through comparison with QCD models, our analysis have shown that the dip is reproduced only by the parton cascade model with cutoff $Q_0 \sim 1$ GeV. Thus we conclude that emission of soft or collinear gluons plays an important role in producing the dip, because the paton cascade model with cutoff $Q_0 \sim 1$ GeV is the unique for its large gluon multiplicity.

Through measurements of two particle correlation between baryons, we have found an evidence for local conservation of baryon number, and we have observed a pronounced anticorrelation between baryons with the same value of the baryon number.

References

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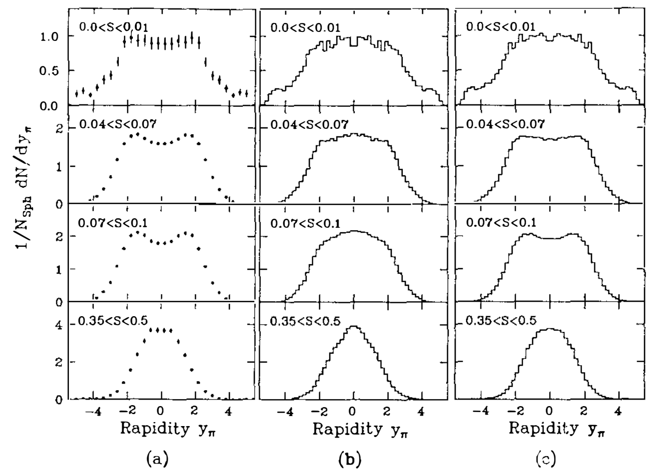

Figure 1: The rapidity distributions for pions at various sphericity. (a) Experimental data. (b),(c) Predictions of the 2nd order QCD model with IF and SF.

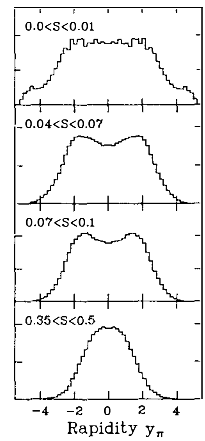

Figure 3: The predictions by the parton cascade model with the SF model.

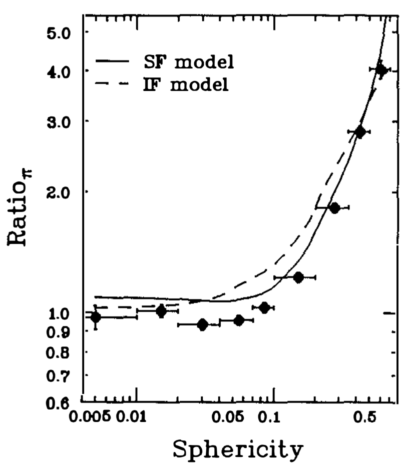

Figure 2: The ratio R of the particle yield in the central rapidity $(0.0 < |y| < 1.0)$ and the high rapidity region $(1.5 < |y| < 2.5)$ for pions with the prediction of the 2nd order QCD model (SF: solid line and IF: broken line.).

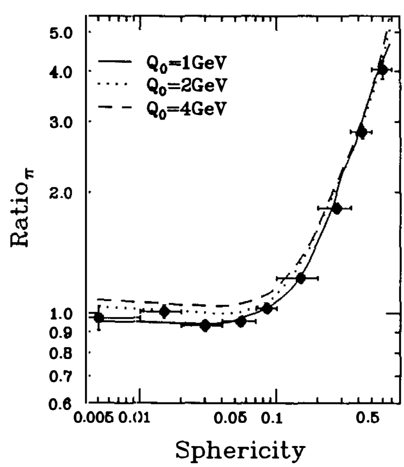

Figure 4: The ratio R and predictions of the parton cascade model with changing a cutoff Q_0; (Q_0=1 GeV: solid line, 2 GeV: dotted line, and 4 GeV: broken line).

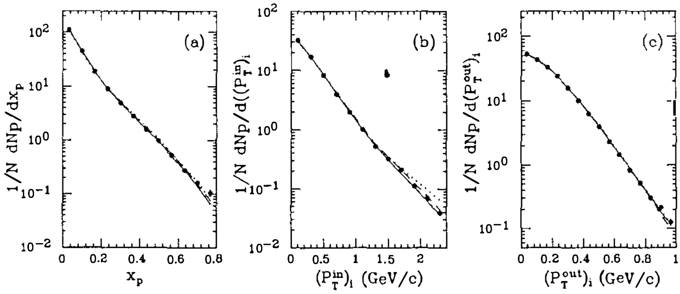

Figure 5: Distributions of jet properties with predictions of the QCD models. (a) The scaled momentum distribution $x_p = 2p/E_{cm}$. (b),(c) The single particle inclusive P_T^{in} and P_T^{out} distributions (the 2nd order QCD model with SF (dashed line) and IF (dotted line) and the parton cascade model with SF (solid line).).

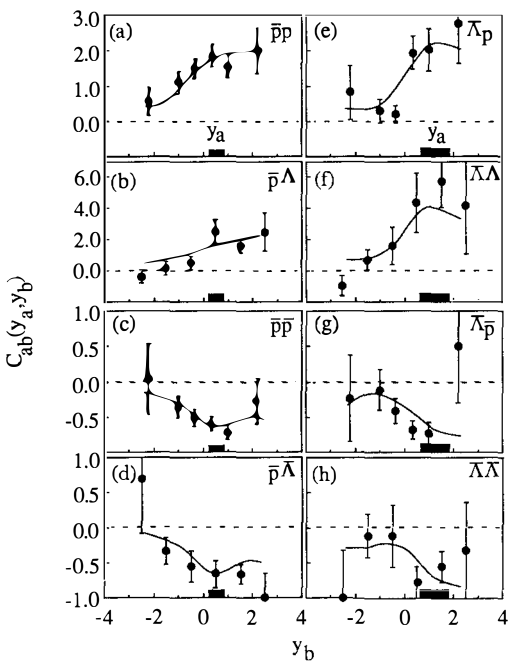

Figure 6: (a)-(d) Correlation function $C_{ab}(y_a, y_b)$ for a $\bar{p}$ in the rapidity interval $0 < y_a < 1.25$ and an additional baryon b at rapidity y_b, for (a) p, (b) Λ, (c) $\bar{p}$, (d) $\bar{\Lambda}$. The rms width of the rapidity distribution of the $\bar{p}$ a is indicated by the black bar. (e)-(h) The corresponding correlation functions for a $\bar{\Lambda}$ in the rapidity range $y_a > 0$ as particle a. Curves indicate predictions by the 2nd order QCD model with SF.