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Study of intermittency in hadronic Z^0 decays*

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Abstract

The study of factorial moments of the rapidity distribution and of the (y, ϕ) distribution for hadrons produced in the decay of the Z^0 , by means of the DELPHI detector at LEP, has shown no deviations from the predictions of Parton Shower models. Intermittent behaviour observed in the latter case has been found to be compatible with jet cascading mechanism.

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* This article is dedicated to the memory of Professor Léon Van Hove

This article presents results of the study of fluctuations in the phase space distribution of hadrons produced in e^+e^- collisions around the Z^0 energy, by means of the DELPHI detector at LEP [1,2].

The random occurrence of peaks in the (pseudo)rapidity distribution of hadrons produced in high energy collisions was first observed in the secondary products of $p\bar{p}$ interactions [3] and in cosmic ray events [4].

In order to provide a quantitative test of such multiplicity fluctuations in variable intervals of rapidity, Bialas and Peschanski [5] proposed in 1986 to analyze the distributions of multiplicity in terms of normalized factorial moments. Given an experimental distribution of particles in the rapidity interval from $-Y/2$ to $Y/2$, the interval Y is divided into M equal subintervals, each of size $\delta y = Y/M$. By defining N to be the number of particles in the whole rapidity interval, n_m to be the number of particles in the m -th bin ($m = 1 \dots M$), the factorial moment of (integer) rank j of the distribution with respect to the partition is defined as

$$F_j(\delta y) = \frac{M^{j-1}}{\langle N \rangle^j} \langle \sum_{m=1}^M n_m(n_m - 1) \dots (n_m - j + 1) \rangle \quad (1)$$

where the average is taken over many events. The factorial moment of rank j for a rapidity interval δy acts as a filter for selecting events with j particles or more in at least one bin and is therefore highly sensitive to events with large density fluctuations.

Simple models representing the hadronization process as a random cascade with selfsimilar structure predict a powerlike increase of the factorial moments in the limit in which the bin size δy goes to zero

$$F_j \propto (1/\delta y)^{f_j} \quad (2)$$

and this behaviour was called *intermittency*, a term mutuanted from hydrodynamics, as most of the mathematical techniques used in this field [6].

Evidence for intermittent behaviour of the (pseudo)rapidity distribution has been produced in the subsequent years by accelerator experiments studying nucleus-nucleus [7] and hadron-hadron [8] collisions. The interest of these results is enhanced by the fact that the most common hadronization models fail to reproduce the effect. Intermittency in hadronic collisions has led to speculations of possible evidence for hadronic phase transitions

[9], hadronic Cherenkov radiation [10] and hadronic hydrodynamics [11]. Many authors pointed out however that self-similar cascading mechanisms [5,12,13,14] or models in which short-range correlations derived from the data are introduced *ad hoc* [15] can reproduce the effect ¹.

The situation in e^+e^- collisions is more puzzling. The first direct measurement was published by the TASSO collaboration [17], at a centre of mass energy of around 35 GeV, and claimed an intermittency effect ² that could not be explained by the JETSET Monte Carlo [19], nor by the Marchesini-Webber [20] and the Hoyer model [21]. The presence of intermittency in e^+e^- interactions would strongly favour the cascading mechanism, since hadronic reaction mechanisms, such as phase transitions, are unlikely in this case. The TASSO work was confirming the results of an indirect analysis of the HRS data [22] ($\sqrt{s} = 29$ GeV) ³. Furthermore, the predictions of various models for e^+e^- interactions differ considerably at high energies [24].

This situation motivated an investigation of possible intermittency effects in e^+e^- annihilation at the Z^0 peak. This analysis [1] was carried out by making use of data collected with the DELPHI detector [25] at the e^+e^- storage ring LEP during its first runs at the Z^0 resonance. The DELPHI detector is well suited for such a study, since it has a truly 3-dimensional detection of charged particles by a Time Projection Chamber (TPC), that guarantees a resolution in rapidity as good as $\Delta y \simeq 0.04$.

The analysis was based on a sample of $\approx 8,000$ hadronic Z^0 decays selected by means of "hard" cuts that reduce to a negligible level ($< 0.3\%$) the possible contamination from events due to beam-gas scattering, $\gamma\gamma$ interactions $\tau^+\tau^-$ decays. At present, the same analysis has been extended to a sample of $\approx 36,000$ events after the cuts [2], leading to the same conclusions.

In Ref. [1], factorial moments of ranks 2-5 for the rapidity ⁴ distribution

¹A more complete review of the theoretical understanding of the phenomenon can be found in Ref. [16]

²Very recently, CELLO reported on contrasting result at the same energy as TASSO [18]

³More recently, the HRS collaboration has provided a direct analysis [23], whose conclusions are in agreement with the previous one, although no explicit comparison with Monte Carlos is done in the article.

⁴defined with respect to the sphericity axis

in the interval between -2 and +2 are compared with the predictions of QCD Monte Carlo models, both the ones based on parton cascades and the ones based on the exact second order QCD matrix element followed by string fragmentation. In particular:

1. the JETSET 6.3 [19] Parton Shower model (referred to as JETSET PS in the following), with default parameters;
2. the JETSET 7.2 Monte Carlo with a matrix element calculation up to $O(\alpha_s^2)$ with default parameters (JETSET ME);
3. the JETSET 7.2 Monte Carlo with a matrix element calculation up to $O(\alpha_s^2)$ with an "optimized" scale in the definition of the coupling constant and a further tuning of the string fragmentation parameters [26,27] to describe correctly the rapidity distribution (JETSET ME retuned).

The essential features of these hadronization Monte Carlos are summarized in Ref.[24]. Models 1. and 3. (this last by construction) reproduce correctly the overall rapidity distribution as observed in the LEP experiment, but a disagreement is observed with model 2 [27,28], which predicts a significantly lower number of particles in the central rapidity region.

Fig. 1 compares the uncorrected factorial moments for the DELPHI data sample with those calculated from the accepted events from JETSET PS, after detector simulation. Data are in good agreement with the Monte Carlo. A somehow less good, but still satisfactory, agreement, was found with the Marchesini-Webber Monte Carlo [20], that also reproduces the single-particle inclusive distributions [27].

Expression (1) is in principle a biased estimator of the "true" value of the factorial moments. For this reason, the amount of simulated data in Fig. 1 was chosen to be of approximately the same size as the amount of real data. However, the effect of bias has been checked by comparing the factorial moments of a Monte Carlo sample (JETSET PS at generator level) of the size of $\simeq 10,000$ events with a ten times larger sample, and a sample of real data from 10,000 events with a three times larger sample. Results are in good agreement, making us confident that at the Z^0 energy a statistics of $\simeq 10,000$ events is adequate to make the bias negligible up to the factorial moment of rank 5.

Fig. 2 compares the factorial moments with the predictions at generator level of JETSET PS, JETSET ME and JETSET ME retuned. (data are here corrected via Monte Carlo for the resolution of the detector; the correction factors differ from 1.0 by less than 5% on average). The non-tuned ME model (using the default parameters in the JETSET Monte Carlo program, obtained from data around $\sqrt{s}=30$ GeV) displays a striking disagreement, as predicted in Ref. [29]. The retuning of the fragmentation parameters for the longitudinal and transverse momenta, such that the multiplicity and rapidity distributions in the ME model agree with the same distributions in the PS model [26,27], causes a drastic change both in the magnitude of the factorial moments and in the slope of their distribution for small values of δy . However, even after retuning, the ME model fails to reproduce quantitatively the data.

For all ranks, the growth of the logarithms of the factorial moments as function of the logarithm of the number M of subdivisions appears to flatten off for $\delta y < 0.4$, and it is questionable if a positive slope f_j exists for very small δy .

Two critical points for the experimental determination of the slopes (f_j) in Eq. 2 are:

- a. fitting the factorial moments which are highly correlated [30];
- b. choosing the interval for the fit, since definition (2), although theoretically unambiguous, can give subjective answers when one has to face with problems of finite detector resolution.

By keeping into account the full covariance matrix of the data points in the fit, DELPHI observed a slope compatible with 0 within two standard deviations when the leftmost point was corresponding to a bin size smaller than $\delta y = 0.4$. By using the same interval as TASSO, however, positive slopes compatible with the TASSO results were found.

A check of the influence of Bose-Einstein correlations is important, since in current hadronic Monte Carlos this effect is neglected, or simply kept into account through parametrizations. This was done according to the following procedure. Factorial moments F_{q+} ($q = 2...4$) were calculated by considering for each event i only the N_{i+} secondary products with positive

charge assignment. Secondly, a number N_{i+} of charged particles was extracted at random from the event, thus obtaining a value F_{qr} . Factorial moments from the distribution of like sign particles appear to be equal or smaller than those from the distribution of randomly chosen particles. This is consistent with the expectation that Bose-Einstein effects do not play an important role in intermittency in e^+e^- collisions [29].

Recent theoretical works [31] suggest that saturation of factorial moments at $\delta y \simeq 0.1$ is an effect of smearing of fluctuations due to the projection of phase space into a one-dimensional subspace. Stronger intermittency effects should then appear in two-dimensional and three-dimensional spectra. When intermittency is investigated with respect to the 2-dimensional (y, ϕ) distribution ⁵, the existence of a positive slope according to Eq. 2 becomes in fact no more questionable. Also in this case, however, the predictions of JETSET PS are in good agreement with the data.

To summarize, what has been learned from the study of intermittency at the Z^0 peak allows to update substantially the conclusions drawn one year ago in Ref. [24].

No hints of new physics on top of Parton Shower models come from the study of the factorial moments of the y and of the (y, ϕ) distributions. These models predict factorial moments rising as δy decreases. Due to not exact scale invariance, the growth does not display exact power behaviour, and the slopes are energy dependent.

The presence of intermittency in the y distribution is questionable. A strong intermittency signal is observed in the (y, ϕ) distribution, as predicted by JETSET PS. This signal is thus consistent with the jet cascading + hadron fragmentation in the Lund Monte Carlo.

We finally learned that, whenever "conventional" QCD branching does not fit the data on factorial moments, the sensitivity to the fragmentation parameters has to be studied, since it is likely [32] that small variations on the hypotheses on fragmentation, causing a minor effect on single-particle inclusive distributions and event shape variables, change drastically the values of factorial moments and their rate of growth as $\delta y \rightarrow 0$.

⁵ ϕ is the azimuth with respect to the sphericity axis.

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Figure captions

1. (a) Dependence of the factorial moments of rank 2, 3, 4 and 5 on the number M of subdivisions of the rapidity interval. DELPHI uncorrected data (white circles) compared with JETSET 6.3 PS after detector simulation (asterisks).
(b) Detail of (1a) for factorial moments of ranks 2 and 3.
2. Dependence of the factorial moments of rank 2 (a), 3 (b), 4 (c) and 5 (d) on the number M of subdivisions of the rapidity interval. DELPHI corrected data (white circles), compared with the predictions at generator level of JETSET 6.3 PS (solid line), JETSET 7.2 ME (dotted line) and JETSET 7.2 ME retuned (dashed line).
3. Logs of the factorial moments of rank 2, 3, 4 and 5 versus $\log_2 M$, where M is the number of subdivisions of the (y, ϕ) interval. For each even point in the abscissa, the y and ϕ intervals have the same number of subdivisions. DELPHI uncorrected data (white circles) compared with JETSET 6.3 PS after detector simulation (asterisks).

Fig. 1

Fig. 2

Fig. 3