STUDY OF INTERMITTENCY IN ELECTRON–POSITRON ANNIHILATION INTO HADRONS

TASSO Collaboration

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Intermittency effects have been studied directly for the first time in e^+e^- annihilation, using 37 509 hadronic events at an average CM energy of $\langle\sqrt{s}\rangle = 35$ GeV. The factorial moments F_2, F_3 and F_4 are given for the rapidity distribution and for the two-dimensional distributions in rapidity and azimuthal angle. The effects of cuts in sphericity and particle momentum are large. Comparison with several fragmentation models are made; some models like the Lund model with $O(\alpha_s^2)$ matrix element give a qualitative description of the phenomena. The importance of detector effects is demonstrated. The results are discussed in terms of various suggested interpretations of this effect.

1. Introduction

Recently Bialas and Peschanski [1–3] proposed a new method to study the statistical behaviour of distribution functions in multiparticle production in the limit of small bin sizes.

Using rapidity as an example, they consider a rapidity interval of total length Y and divide it into M equal invervals of length Y/M. Calling n_m the number of particles in the mth cell of length Y/M, with $1 \leqslant m \leqslant M$, and N the total number of particles in the rapidity interval Y, the authors of ref. [1] define the factorial moments

$$F_i = \left\langle \frac{1}{M} \sum_{m=1}^{M} \frac{n_m(n_m-1)...(n_m-i+1)}{N(N-1)...(N-i+1)} M^i \right\rangle, \qquad (1)$$

where the average is taken over all events with multiplicity N. The factorial moments have the following normalization properties:

$F_1 = 1$ for all M,

$F_i = 1$ for $M = 1$ and all i.

For slowly varying distributions, these factorial moments should be $F_i \approx 1$, if the fluctuations in the "partition number" n_m follow a Poisson distribution; if there are additional fluctuations in the underlying physical process then $F_i > 1$. In particular Bialas and Peschanski consider for large values of M a power law behaviour of these moments reminiscent of fractal effects,

$$F_i = A M^{\alpha_i}, \qquad (2)$$

i.e. fluctuations increase in size as the bin size is decreased, until the bin size gets smaller than the experimental resolution, when the factorial moments stabilize and become constant [4].

This property of fluctuations has been named in ref. [1] as intermittency, since it might have its origin in effects known e.g. from turbulence (ref. [8] in ref. [1], see also ref. [5]). It has been previously suggested that intermittent behaviour can be adapted to hadronization processes [6]. Analysing the data in terms of these fluctuations is not straightforward. A careful study of experimental effects and of hadronization models is required. In a broader context it has been pointed out [1–3,7–10] that a study of the factorial moments offers a new way to look at the properties of the hadronization process. It should also be mentioned that rapidity is not the only variable that can be studied, the only condition being that the distribution varies slowly with respect to that variable.

Indications for large fluctuations have been found experimentally in (pseudo)rapidity distributions in

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cosmic ray events [11], hadron–hadron [12–14], hadron–nucleus and nucleus–nucleus [15–17] collisions. Indirect evidence for intermittency in e^+e^- collisions has been obtained [18] by converting negative binomial distributions of the HRS Collaboration [19] into factorial moment distributions. However, no direct study with e^+e^- annihilation into hadrons has been available so far.

In this letter we present evidence for intermittency effects in e^+e^- annihilation into hadrons at $\langle\sqrt{s}\rangle = 35$ GeV using the TASSO detector at PETRA.

2. Experimental procedure and event selection

The study used the TASSO detector of which a detailed description can be found in ref. [20]. The data were collected at centre of mass energies between 30 GeV and 38 GeV, with the majority of the data at about 35 GeV. Annihilations of electrons and positrons into hadrons were selected following the procedure described in ref. [21]. In this analysis only charged particles were used. The momentum resolution was $\sigma_p = 0.017\sqrt{1+p^2}$ (with p in GeV/c) for particles perpendicular to the beam axis and the resolution in the polar angle was $\sigma_\theta = 5.2$ mrad [22]. For each event an event axis was determined using sphericity, and the rapidity of tracks was computed according to $y = \frac{1}{2}\ln[(E+p_\parallel)/(E-p_\parallel)]$, with $p_\parallel$ being the component of momentum along the sphericity axis and the energy E calculated assuming the pion mass for all particles. In order to have a reasonably uniform acceptance for the tracks considered, we required $|\cos\theta_s| < 0.7$, with θ_s being the polar angle between beam line and sphericity axis. We considered the y-interval $-2 \leqslant y \leqslant 2$, where the y distribution is roughly flat, and required a total number of charged tracks $4 \leqslant N \leqslant 20$ in that interval.

A total of 37 509 events satisfied these cuts and were used in the subsequent analysis.

3. Analysis

We used all charged tracks in the above events. No correction for acceptance, losses etc. was made.

We considered two distributions, namely

(i) the y-distribution in the interval $-2 \leqslant y \leqslant 2$, and

(ii) the two-dimensional distribution in y and the azimuth angle φ around the sphericity axis in the interval $-2 \leqslant y \leqslant 2$ and $0 \leqslant \varphi \leqslant 2\pi$.

In the case (ii) (y, φ) we divided both the y- and the φ-range into roughly equal numbers $\sqrt{M}$ of intervals, leading to M rectangular domains in the y–φ plot. A study of this distribution is interesting, because bin sizes can be chosen larger than the experimental resolution even for rather large values of M. One expects [8,9] that effects of the rising factorial moments are larger in the two-dimensional (y, φ) distribution than in the simple y-distribution.

A special problem arises, because the factorial moments of eq. (1) are defined for a fixed total number of tracks N in the total rapidity interval considered. Our large statistics allowed us to compute the factorial moments for each multiplicity N of charged tracks separately. The resulting moments were then averaged over all track numbers N for the final result. We did not observe a strong dependence on N.

In order to gain further insight into the physical processes responsible for the effects seen, we also considered two special selections, viz.

(i) accepting only events with sphericity $S > 0.23$ leaving 25% of the events, thereby cutting out mostly narrow two-jet events;

(ii) accepting only tracks with a momentum $p > 0.58$ GeV/c.

Before one can draw physics conclusions from a presentation of uncorrected data, the influence of effects like particle losses in the detector, creation of e^+e^- pairs, K^0_S decays etc. must be considered. In order to estimate the possible size of these effects, we created a large number of events with Monte Carlo methods at a CM energy of 35 GeV, using the following event generators: Webber parton shower model [23], string model Lund version 6.2 $O(\alpha_s^2)$ [24], Lund parton shower model version 6.3 [25], and an $O(\alpha_s)$ independent fragmentation model [26].

We subsequently traced these events through the detector using a detailed detector simulation [27]. A comparison of the same event sample before and after detector simulation will give an indication of the importance of detector effects in this investigation. In order to allow a precise comparison with the data, all Monte Carlo events were run with a full detector simulation, using the same cuts as were applied for the data.

4. Results

Fig. 1 shows the factorial moments, F_2, F_3, F_4 for the data, computed according to eq. (1) both for the y-distribution and the (y, φ) distribution and plotted versus M, the number of divisions, leading for the y-distribution to a rapidity interval size $\delta = 4/M$. The moments are significantly bigger than one and are rising as a function of the number of divisions, with $F_4 > F_3 > F_2$, as expected from theoretical considerations [3].

The moments for the two-dimensional distribution (y, φ) show the same trends and are clearly larger than those for the y-distribution, in agreement with previous expectations [8,9]. Thus fig. 1 shows that there is clear evidence for fluctuation effects bigger than given by Poisson statistics.

In the two-dimensional plots one can achieve the same number M of two-dimensional bins by making different subdivisions along the y- and the φ-axis. We have chosen two different subdivisions for a given number M and plotted both results in fig. 1 at the same M-value. As can be seen, there is only a small difference between the two points.

In the y-distribution (fig. 1a) the moments do not show an indefinite linear rise in the $\log F$–$\log M$ plot; in particular the moment F_2 bends over and reaches a constant value. This cannot be caused by our finite experimental resolution in y: The error of y has been computed from the known momentum and angle errors of the tracks ($\sigma_\Theta = 5.2$ mrad, $\sigma_\phi = 2.1$ mrad [22]). For $|y| \leqslant 2$ the error of y is $\sigma_y \leqslant 0.04$, therefore the effects of finite experimental resolution should only be noticeable for $M > 100$. In the (y, φ) plot (fig. 1b) the moments F_3 and F_4 show a linear rise in the $\log F$–$\log M$ plot, whereas the F_2-distribution becomes constant at large M-values. The effects of experimental resolutions in y and φ are negligible in this plot.

In order to compare with other work and to obtain slopes α_i, fits to straight lines have been performed in the $\log F$–$\log M$ plots of fig. 1. Since $\log F_i$ is approximately linear as a function of $\log M$ in the whole (y, φ) plot (fig. 1b), the slope values α_i depend only weakly on the M-interval chosen for the fit. In the y-

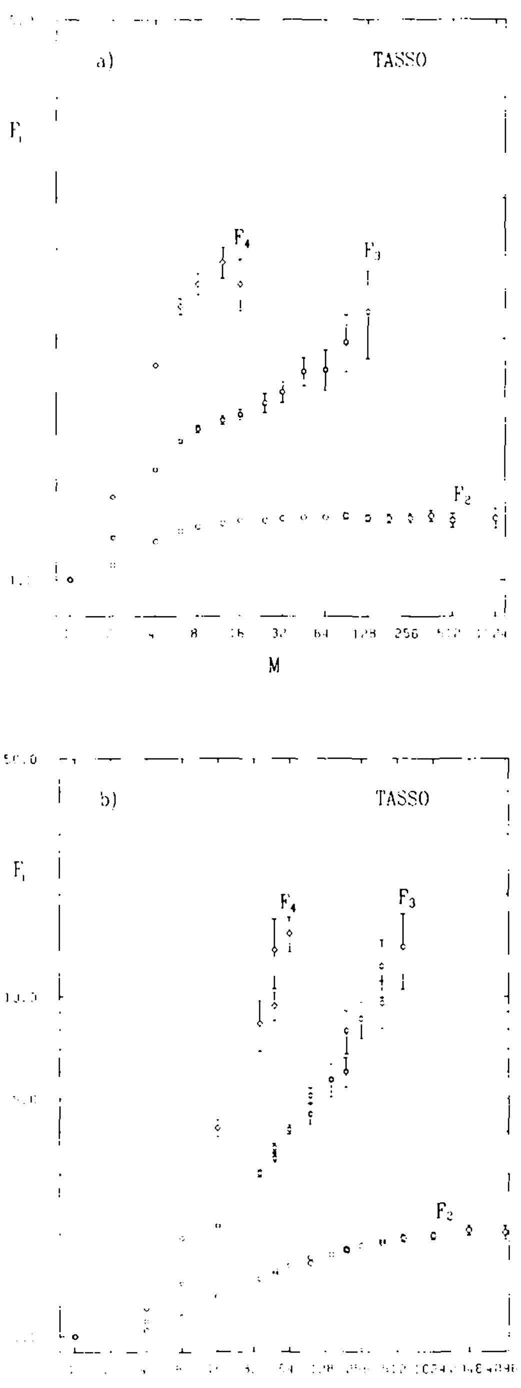

Fig. 1. Factorial moments F_2, F_3, F_4 plotted versus M = number of subdivisions (a) in the y-interval $-2 \leqslant y \leqslant 2$; (b) in the two-dimensional plot of (y, φ). The errors are statistical only.

plot (fig. 1a), the slopes depend on the M-interval chosen for the fit. The increase in F_i for $M \leq 4$, corresponding to rapidity intervals $Y/M \geq 1$, is what can be expected from conventional short range correlations.

We have thus fitted the y-plot in the interval $6 \leq M \leq 32$, corresponding to rapidity intervals between 0.7 and 0.12. Note that for F_2 the slope depends on the interval chosen. For the (y, φ) plot we typically took six points for the fit. The fitted slopes are shown in table 1. Note that they are not corrected for detector effects. There is a clear rise in the slope α_i as the rank i grows.

Within the framework of a cascade or branching model [1], which leads to intermittent behaviour, and in the limit of a large number of steps in the cascade, a simple relation between the slopes α_i of factorial moments of different rank i, has been derived [3], yielding

$$\alpha_{i+1} - \alpha_i = i\alpha_2 . \quad (3)$$

This relation was found to be approximately obeyed in nucleus–nucleus collisions [17]. Table 1 also shows the expression $2\alpha_i/[i(i-1)]$ as a function of the rank i. This expression is found to be roughly constant for all ranks, as expected if relation (3) holds. The errors in table 1 do not include the effect of correlations between the data points.

We have checked the effect of including neutral particles in the analysis with the Lund parton shower model. Similar slopes α_i have been obtained for charged particles only and for charged and neutral particles.

In order to explore the sensitivity of the results with respect to the y-range chosen, we have also computed the moments F_i for the y-range $-1<y<1$. For the y-division they are smaller than the corresponding moments in the original y-interval $(-2<y<2)$; accordingly also the slopes α_i are smaller. For the (y, φ) division there is not much difference for the different y-ranges used (see table 1).

Fig. 2 shows a comparison for the F_2 and F_3 moments between the data and the Monte Carlo generated event samples described above. The MC events were subject to a complete detector simulation, as described above, and therefore can be directly compared to the data.

It is interesting to see that also the Monte Carlo curves show a rise of the factorial moments with M, in qualitative agreement with the data. The independent jet fragmentation model of Hoyer et al. seems to give the largest effects. Lund $O(\alpha_s^2)$ does somewhat better than Lund parton shower. However, it should be noted that we used Monte Carlo models with parameters adjusted to a previous analysis [28]. It cannot be excluded that some models could be better tuned to the data in fig. 2 without destroying the agreement with the other distributions.

Fig. 2 also shows the influence of detector effects. Events were generated with the Lund (parton shower) program. The factorial moments computed from these generator data, free of any detector effects, are shown in fig. 2. The same events were then subjected to a full detector simulation and they are also plotted in fig. 2 for comparison. It is evident that part of the effect observed in the data is of an instrumental nature; the size of these detector effects may be estimated from the difference of the two lowest F_2 and F_3 curves in fig. 2. The effect is not large enough to invalidate qualitative conclusions; however, for

Table 1
Slopes α_i and the expression $2\alpha_i/[i(i-1)]$ for the various moments F.

Rank i	Distribution	$-2<y<2$		$-1<y<1$	α_i for
		α_i	$2\alpha_i/(i(i-1)$	α_i	same sign charge
2	y	0.023 ± 0.003	0.023 ± 0.003		
3	y	0.080 ± 0.014	0.027 ± 0.005		
4	y	0.134 ± 0.052	0.022 ± 0.008		
2	(y, φ)	0.153 ± 0.004	0.153 ± 0.004	0.180 ± 0.004	0.117 ± 0.006
3	(y, φ)	0.475 ± 0.017	0.158 ± 0.006	0.492 ± 0.011	0.371 ± 0.025
4	(y, φ)	0.957 ± 0.086	0.159 ± 0.014	0.883 ± 0.027	0.645 ± 0.178

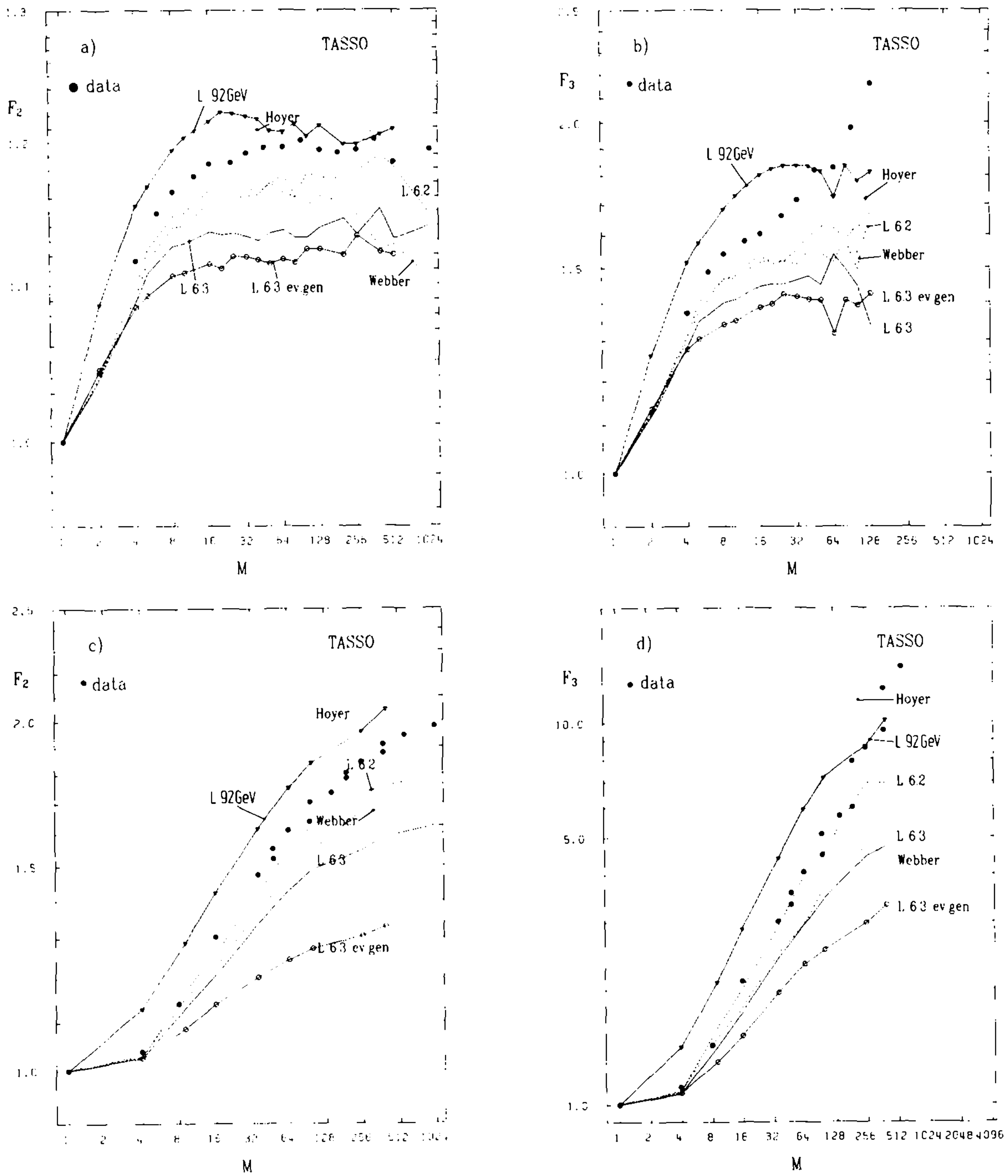

Fig. 2. (a) Factorial moments F_2 in the y-distribution plotted versus M = number of subdivisions. (b) Factorial moments F_3 in the y-distribution. (c) Factorial moments F_2 in the two-dimensional (y, φ) distribution plotted versus M. (d) Factorial moments F_3 in the two-dimensional (y, φ) distribution plotted versus M. Solid dots: data, error not shown for clarity; open circles: Lund version 6.3 (parton shower) event generator, no detector effects; triangles: the same, but at 92 GeV CM energy; solid line: Lund version 6.3 after full detector simulation; dotted line: Hoyer model with full detector simulation; dashed line: Lund model, version 6.2 $O(\alpha_s^2)$ matrix element, full detector simulation; dot-dashed line: Webber model, full detector simulation. All Monte Carlo results are for 35 GeV CM energy, unless stated otherwise.

quantitative comparison these effects should be taken into account.

The Lund parton shower event generator was also applied to study the dependence of the intermittency effects on CM energy. In fig. 2, a comparison is shown between the factorial moments computed for 35 GeV CM energy and at 92 GeV CM energy. There is a sizeable energy dependence, such that the factorial moments are growing with energy. The same effect is also seen with the Lund second order matrix element model. Therefore, care must be taken when comparing data at different CM energies.

Fig. 3 shows for the experimental data the influence of selecting events with sphericity $S>0.23$ and selecting tracks with momentum $p>0.58$ GeV/c.

For both cuts the factorial moments get larger. It has been shown with a Lund model simulation [9] that the factorial moments get larger if one selects events with a broad angular distribution. Our data are in qualitative agreement with this finding.

The Lund model version 6.2, also shown in fig. 3, gives a qualitative description of the data except for the highest M values.

We have also calculated the factorial moments separately for each jet in two- and three-jet event samples, as defined in ref. [28]. For this study, the rapidity and azimuth angle were calculated with respect to the individual jet axis rather than the event sphericity axis. Using the (y, φ) slicing, similar intermittency effects are obtained for jets from both two-jet and three-jet events, which seems to indicate that intermittency studies can be done separately on single jets.

Finally we made some checks. We can exclude that the effects are a result of Bose–Einstein correlations from studies where we use particles of one sign of charge only. In this case the factorial moments become smaller (see table 1). Omitting at random half the tracks in each event leaves the factorial moments equal or slightly bigger than in the like sign case. This is consistent with the conclusion of a Monte Carlo study [9] that Bose–Einstein effects are of minor importance to the intermittency phenomenon in e^+e^- collisions.

We also generated completely random events with a random number generator programmed to reproduce the measured y-distribution. For this case all

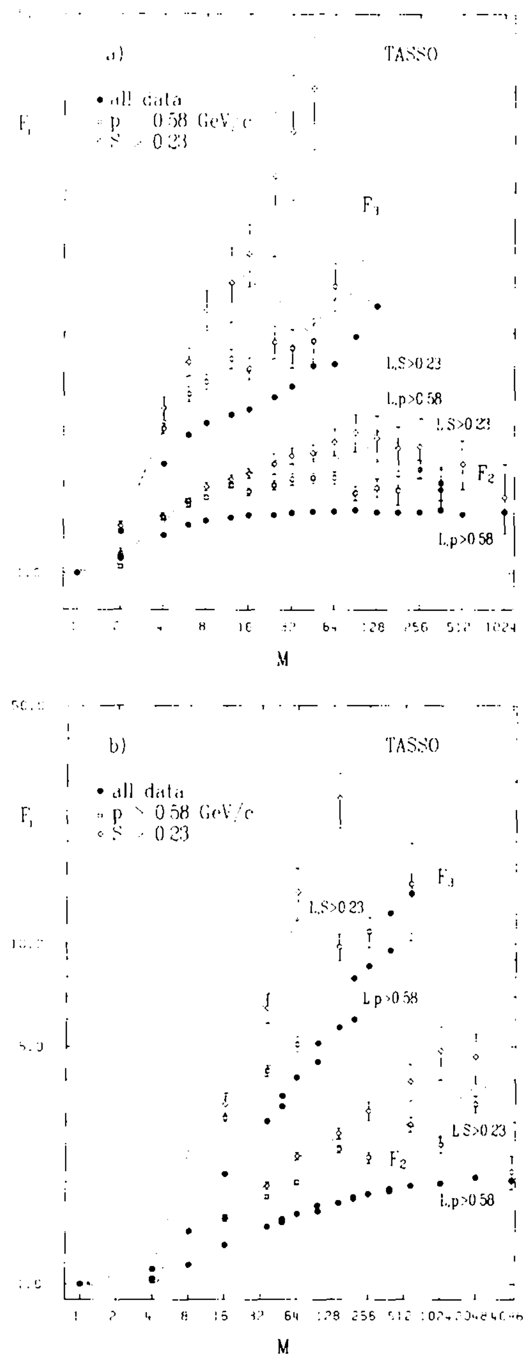

Fig. 3. Factorial moments F_2 and F_3 (a) in the y-distribution, (b) in the two-dimensional (y, φ) distribution. Solid dots: data, error not shown for clarity; open squares: data, particle momenta $p>0.58$ GeV/c; diamonds: data, sphericity $S>0.23$; dotted line: Lund model 6.2, $p>0.58$ GeV/c; dot-dashed line: Lund model 6.2, $S>0.23$.

factorial moments were equal to one within statistics.

5. Conclusions

The first direct measurement of intermittency in e^+e^- annihilation into hadrons is reported. The effects is qualitatively similar to intermittency phenomena found in hadron–hadron (hh) and nucleus–nucleus (AA) collisions. Quantitatively, we observe higher slopes α_i compared to the hadronic reactions, thus confirming the suggested hierarchy of slopes [8]: $\alpha_i(e^+e^-) > \alpha_i(hh) > \alpha_i(AA)$. Note, however, that the linear behaviour of $\log F$ versus $\log M$ does not consistently hold for large values of M (small values of the y-bin). These results are consistent with the interpretation of the particle density fluctuation effects as a jet cascading mechanism in multiparticle production as predicted in refs. [1–7,8]. It has been argued [14] that, seeing the effect in the e^+e^- channel is probably not consistent with other interpretations of the intermittency effect as originating from hadron reaction mechanisms, such as quark–gluon plasma phase transition or hadronic Čerenkov radiation. The intermittency effect is more pronounced with a simultaneous (y, φ) slicing than with a y-slicing only. This is consistent with the interpretation that the increase in the factorial moments is due to clusters of particles, yielding a correlation between local y-fluctuations and local φ ones. The effect is weaker in two-jet events, indicating the importance of gluon emission in the creation of the random jet cascading effect.

All available hadronization models yield a similar behaviour of the factorial moments, but none of them reproduces the data well with the presently used set of adjustable parameters. The intermittency effect is probably quite sensitive to the details of the hadron formation process, and will therefore provide a good test of fragmentation models. We can exclude that the effects are a result of Bose–Einstein correlations. Comparison of Monte Carlo events before and after detector simulation shows that part of the fluctuations are due to instrumental effects. Another comparison shows that the effect increases with the available energy and is predicted to be much stronger at SLC–LEP energies, probably due to the dominance of multi-jet events and to narrower jet profiles.

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