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Intermittency and Bose-Einstein Correlations in e^+e^- Annihilation *

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ABSTRACT

Intermittency studies in one, two and three dimensions are presented, based on e^+e^- annihilation data taken by CELLO at the PETRA storage ring at 35 GeV centre of mass energy. The results are compared to predictions from different Monte Carlo models and are discussed in context with measurements from other experiments at PETRA and LEP. A variety of hadronization models, although based on very different approximations to QCD, all provide a consistent description of factorial moments in all dimensions. We conclude that the resolution dependence of factorial moments is due to a superposition of many effects, and that the structure of soft gluon radiation is obscured by resonance decays and therefore remains unresolved.

Bose-Einstein correlations are analyzed using two methods to obtain a reference density. The data are compared to the predictions from the approach taken in Jetset and are further used to determine the relevant Monte Carlo parameters.

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INTRODUCTION

In this talk the notion of intermittency in e^+e^- annihilation is discussed on the basis of CELLO data, with attention to results from other e^+e^- experiments. Following this, results on Bose-Einstein correlations are presented.

The basic aim of intermittency studies [1] is to analyze particle production in variable regions of phase space by means of factorial moments $\langle F_i \rangle$:

$$\langle F_i \rangle = \frac{M^i}{\langle N \rangle^i} \cdot \left\langle \frac{1}{M} \cdot \sum_{m=1}^{M} n_m(n_m - 1) \cdots (n_m - i + 1) \right\rangle \tag{1}$$

This formula defines an observable which is sensitive to density fluctuations inside *single* events and in addition is insensitive to Poissonian noise.

In e^+e^- annihilation the first direct measurement of factorial moments of rapidity (y) distributions and rapidity and azimuth (y, ϕ) correlations was performed by TASSO [2], showing qualitative agreement between data and Monte Carlo, although the quantitative description was rather poor. However, no attempt was made to tune the relevant Monte Carlo parameters. The first three-dimensional phase space analysis was done by CELLO [3], using the decomposition $dLIPS \propto dp_x/\sqrt[3]{E} \cdot dp_y/\sqrt[3]{E} \cdot dp_z/\sqrt[3]{E}$. In this analysis factorial moments were expressed in terms of fractal dimensions, making the underlying physics more transparent. Owing to the excellent Monte Carlo description, provided by Jetset 7.2 PS, the contributions to the resolution dependence of factorial moments of individual processes in the fragmentation of quarks and gluons could be isolated. At LEP, analyses in one and two dimensions are available from DELPHI [4] and OPAL [5]. Factorial moments from both experiments are well described by standard Monte Carlo programs. Here we present a comprehensive intermittency analysis in one, two and three dimensions, some aspects of which have already been presented elsewhere [6,7].

INTERMITTENCY IN ONE, TWO AND THREE DIMENSIONS

The dependence of factorial moments on the resolution scale is studied by dividing D_0-dimensional projections of phase space simultaneously in each dimension into halves. After

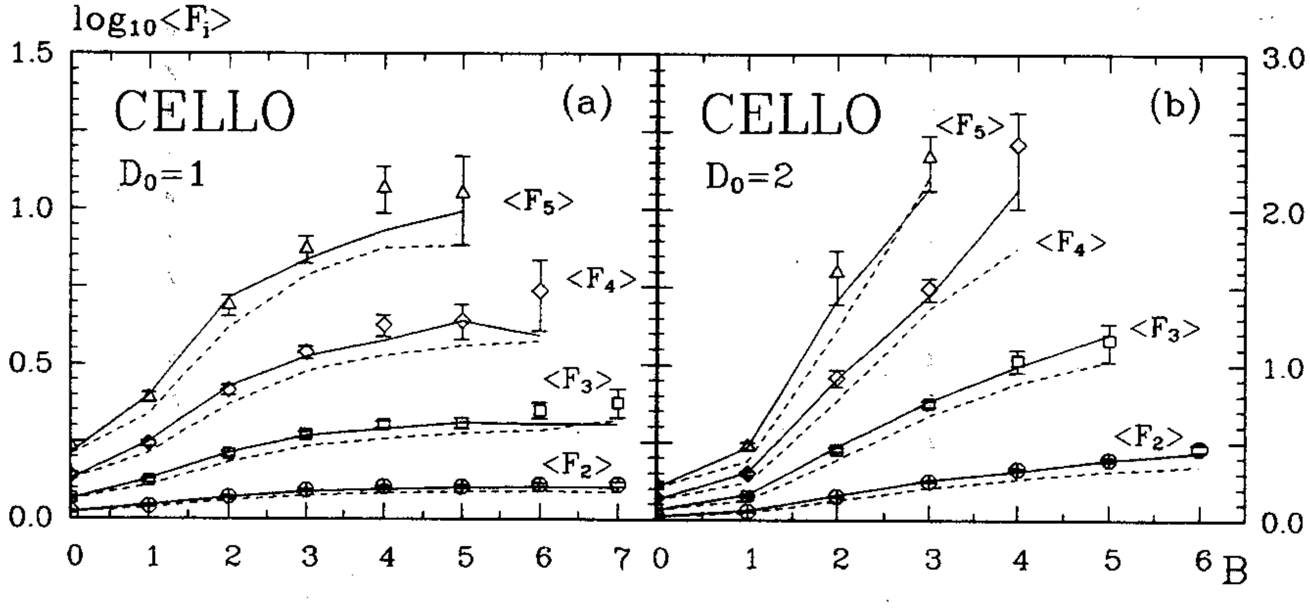

Figure 1: $F_2 - F_5$ from analyses in y (a) and y, ϕ (b) projections. The rapidity has been restricted to the interval $-2 \leq y \leq +2$. The data are shown with statistical errors, the dashed lines correspond to results from Jetset 7.2 PS after detector simulation, the solid lines include Bose-Einstein correlations. The detector resolution limit is between $B = 5 - 6$.

B bisections a total of $M = 2^{D_0 \cdot B}$ symmetric bins is obtained. In Fig. 1a the results from a one-dimensional y analysis are seen to be in perfect agreement with the Jetset 7.2 PS Monte Carlo [9]. It is also evident that the inclusion of Bose-Einstein correlations, as treated in Jetset, results in larger moments, consistent with the data. This increase reflects the effective reduction of phase space for identical pions. Apparently the moments in the one-dimensional analysis saturate after a strong initial rise.

Such an effect is expected for a multi-dimensional system being projected on to a one-dimensional axis [10]. In the two-dimensional y, ϕ analysis (Fig. 1b), the bending effect, although still visible, is much less severe, indicating that the underlying process is probably three-dimensional. This is as expected, of course. As before, excellent agreement between data and Monte Carlo is observed, with the Bose-Einstein effect accounting partly for the observed effect. In Fig. 2 a comparison between predictions from Jetset 7.2 [9], Ariadne 3.1 [11] and Herwig 5.0[1] [12] is presented. Striking agreement is observed amongst the different approaches. This is in fact astounding since these models differ in the treatment of the perturbative QCD phase (parton shower, dipole radiation or matrix element) and moreover use different hadronization schemes (cluster or strings).

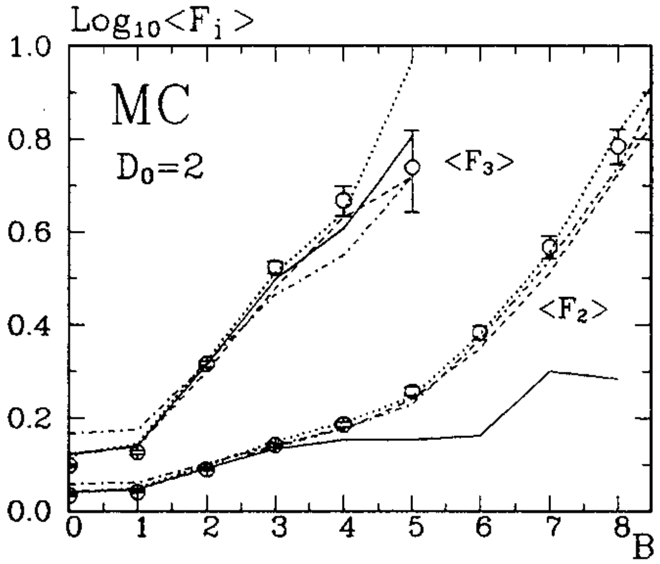

Figure 2: Monte Carlo studies of F_2 and F_3 in y, ϕ. The points with error bars correspond to Jetset 7.2 PS (parton shower+string), the dotted curve is Jetset 7.2 ME (Matrix element+string). The results from Ariadne 3.1 (dipole radiation+string) are shown as the dashed curve and the Herwig 5.0 model (parton shower+cluster) gives the dash-dotted curves. The solid line is Jetset 7.2 PS without π^0 Dalitz decays.

From this we conclude that the sensitivity of factorial moments to details of the soft hadronization process is rather poor. In particular resonance decays obscure the fine structure of F_2, explicitly shown in Fig. 2 for the π^0 Dalitz decay. It is to note that besides the common interpretation of intermittent behaviour as a consequence of random cascading, an equally good explanation is provided by the matrix element approach.

It has been argued that there is a discrepancy between TASSO and CELLO data, the former being only qualitatively reproduced by the Monte Carlo, whilst the latter is perfectly described. However, this effect is to a large extend due to the different Monte Carlo programs and parameters used. This is apparent in Fig. 3, where factorial moments obtained

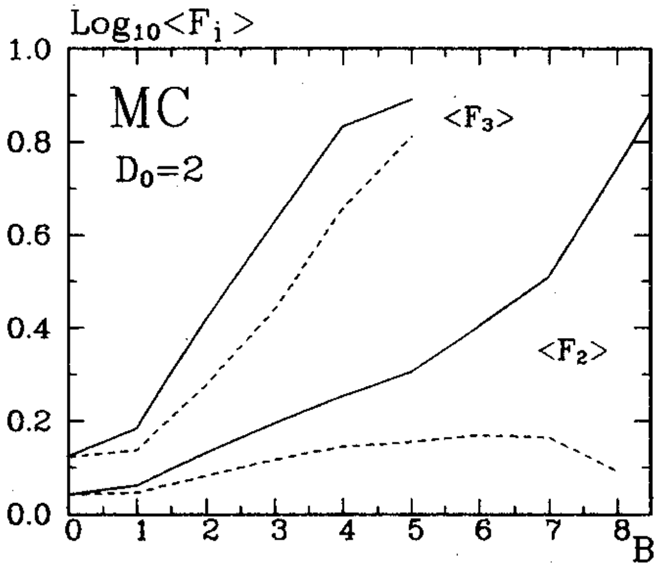

Figure 3: Comparison of F_2 and F_3 in y, ϕ from Jetset 6.3 PS as used by TASSO [15] (dashed curves) and Jetset 7.2 PS, including Bose-Einstein correlations, as used by CELLO (solid lines).

[1]Herwig has been modified to invoke Jetset for particle decays.

from the TASSO version of Jetset 6.3 PS [15] are compared to the corresponding results from the default Jetset 7.2 PS, as used in our studies.

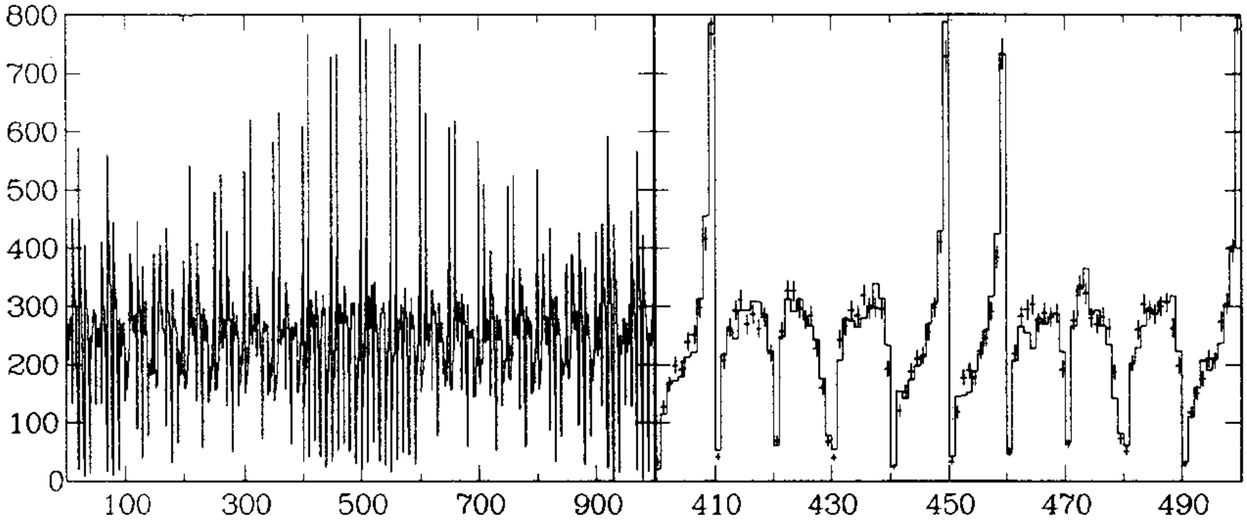

Figure 4: Particle density after the transformation [16], for ten bins in each dimension. The resulting 1000 boxes are labeled $100 * I(\tilde{y}) + 10 * I(\tilde{\phi}) + I(\tilde{p}_\perp^2) : I = 0, ..., 9$. The right plot shows a detail, where the data (crosses) are compared to the Jetset 7.2 PS simulation (histogram).

Besides the three-dimensional analysis presented in [3] we have applied the procedures advocated by Ochs [16] and Bialas and Gazdzicki [17]; for details the reader is referred to a forthcoming publication [8]. The basic aim of both procedures is to unfold fluctuations induced by non constant inclusive distributions. This is of special importance in a three-dimensional analysis, involving strongly varying distributions such as $p_\perp^2$. In [17] this is achieved by dividing the phase space in a way that on average every phase space box contains the same number of particles. The method proposed by Ochs treats the three variables (e.g. $y, \phi, p_\perp^2$) independently. In the ideal case of uncorrelated variables the particle distribution in the transformed space would be flat, i.e. every box would contain the same number of particles. This condition is apparently not fulfilled (Fig. 4), since a clearly non constant

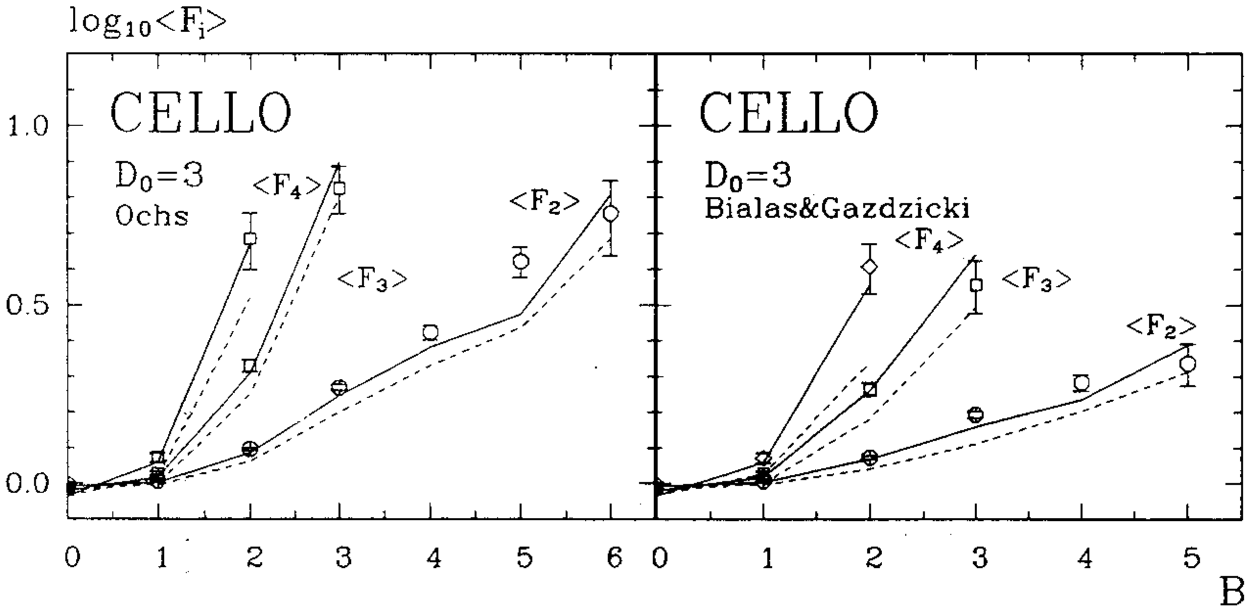

Figure 5: $F_2 - F_4$ from three-dimensional analyses according to the procedures proposed in [16] and [17]. The Jetset 7.2 PS simulations are superimposed as the solid (including Bose-Einstein correlations) and dashed lines.

particle density is observed after the transformation. The high quality of the Monte Carlo simulation is demonstrated in Fig. 4, where it is seen to reproduce the phase space population extremely well. In Fig. 5 the results from both procedures are displayed together with the corresponding Monte Carlo curves. As for the one- and two-dimensional analyses, good agreement is observed between data and Monte Carlo. It is also seen that the method [16] results in larger moments compared to the method [17]. This is due to the fact that in the former procedure the inclusive distribution is not constant (Fig. 4).

It should be noted that even after the transformation [17], fluctuations remain due to the mixture of different event topologies; e.g. 2-jet and 3-jet events, or light and heavy quark events. Since the correction procedure is based on the average of all events, fluctuations are eventually induced in the subgroups, complicating the interpretation of the data. This is clearly a disadvantage compared to the method used in [3].

To illustrate the influence of different physical processes on the factorial moments we have performed some studies with Jetset. In addition, the analysis of 2-jet events gives information about the contribution from hard gluon radiation. In Fig. 6 the resulting moments are presented; compared to the total event sample in Fig. 5, a much slower rise is observed.

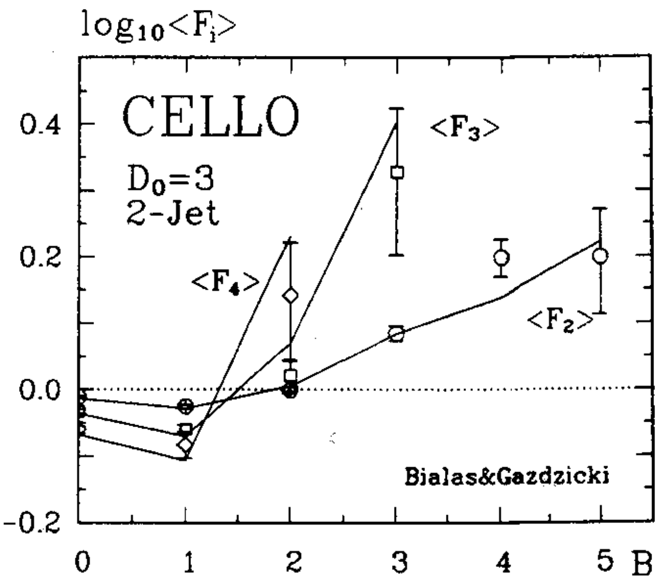

Figure 6: $F_2 - F_4$ from a three-dimensional analysis of 2-jet events according to [17]. The Jetset 7.2 PS simulation including Bose-Einstein correlations is represented by the solid lines.

This indicates that hard gluon radiation is an important source of fluctuations at PETRA energies and probably the dominant source at LEP energies [4,5]. The dominant contribution of hard gluon radiation, in contrast to the *noise* from soft gluons, to the fluctuations observed in hadronization processes is also discussed in [13]. At coarse resolution the 2-jet data show negative slopes, which can be interpreted as anti-correlations [14]. Such an effect is expected as a consequence of local $p_\perp$ conservation, which reduces the probability to find particles with the same y and ϕ coordinates. This is made clearer in Fig. 7, where strong anti-correlations are observed for primary particles produced in $q\bar{q}$ events without gluon radiation. The decay products of these primary particles show only a residual effect, since the momentum transfer involved in the decays (cf. Fig. 9) is of the same order

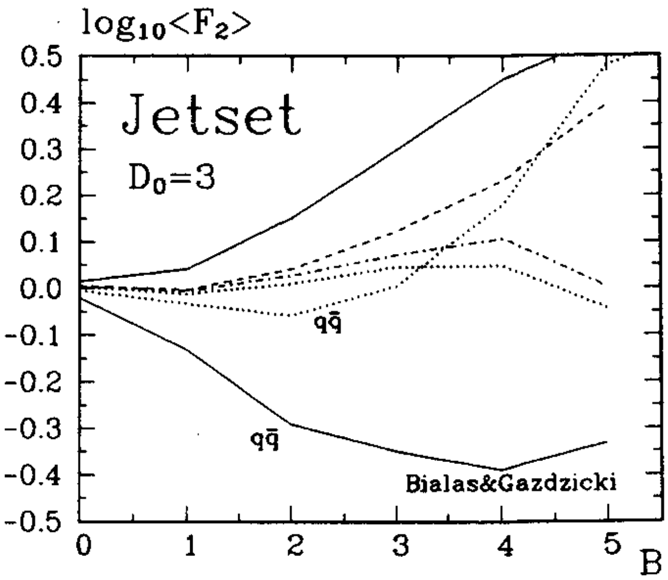

Figure 7: F_2 from various Jetset 7.2 scenarios: **Curves labeled $q\bar{q}$:** Solid line: primary particles from $q\bar{q}$ events: Dotted line: ditto, after decays. **Unlabeled curves:** Dashed line: default PS simulation: Solid line: ditto, including initial state radiation: Dash-dotted line: default PS, neglecting e^+e^- pairs from π^0 Dalitz decays: Dotted line: ditto, in addition $\pi^+\pi^-$ pairs from $\eta \to \pi^+\pi^-\pi^0$ and $\eta' \to \pi^+\pi^-\eta$ decays are neglected.

of magnitude as the $p_\perp$ in the fragmentation process. The factorial moments are strongly influenced by both hard photon and hard gluon radiation. This becomes very clear in Fig. 7 where a simple $q\bar{q}$ model is compared to the standard Jetset 7.2 parton shower with and without initial state photon radiation. This situation is different on the Z^0 resonance, where initial state radiation is suppressed. Particle decays are of prime importance for understanding the intermittency behaviour in e^+e^- interactions, as is demonstrated by the π^0 Dalitz decay and the decays $\eta \to \pi^+\pi^-\pi^0$ and $\eta' \to \pi^+\pi^-\eta$, which are responsible for the main part of the effect observed at intermediate and high resolution.

BOSE-EINSTEIN CORRELATIONS

In the previous discussion of intermittency, the relevance of particle correlations has been pointed out. In this context the analysis of Bose-Einstein correlations can provide further information on the underlying physics. Bose-Einstein correlations appear as an enhancement

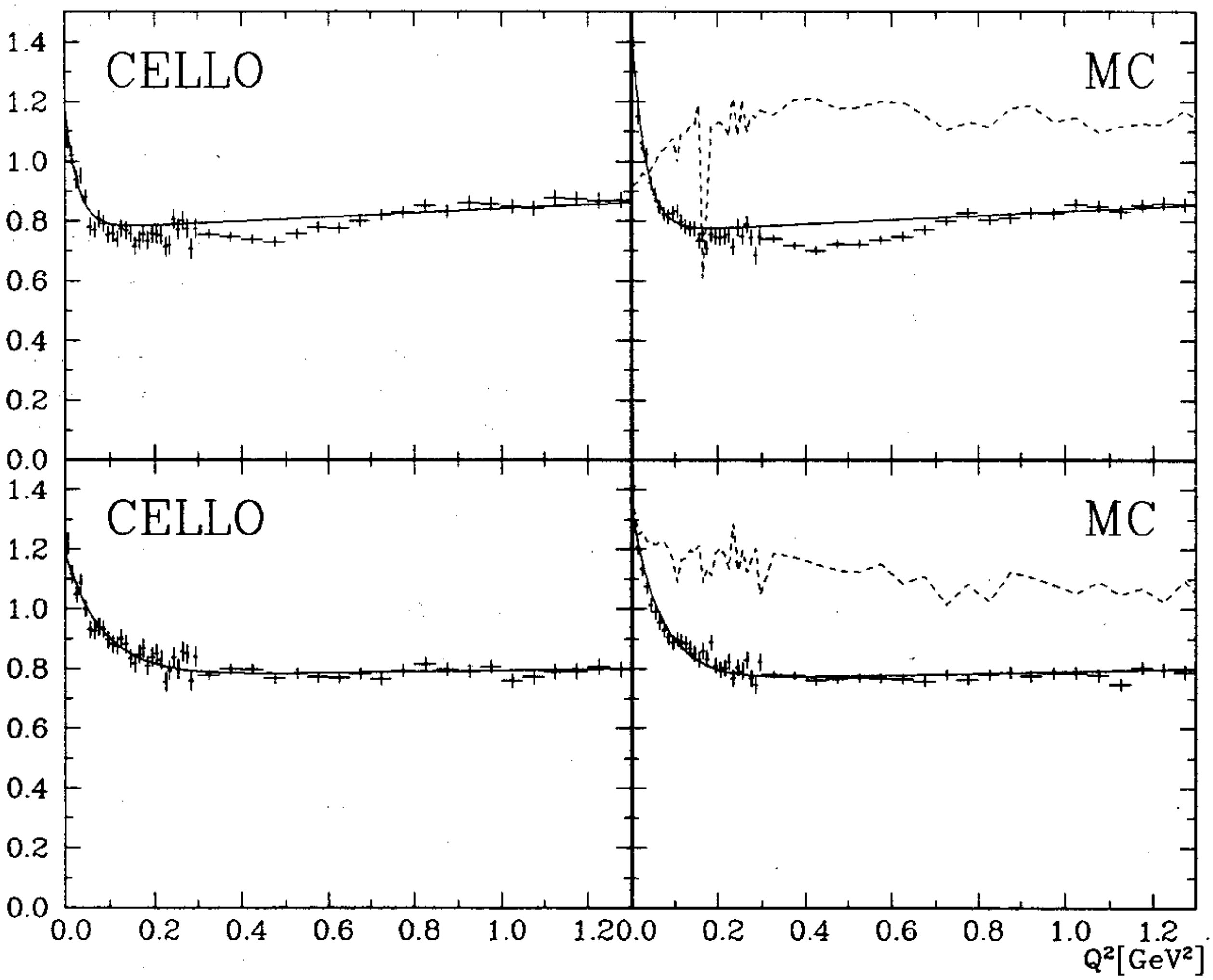

Figure 8: Ratio of Q^2 distributions, the solid line shows the fit result and the dashed curve shows the Monte Carlo correction function. Upper plots: reference density from $\pi^+\pi^-$ pairs. Lower plots: reference density from $\pi^+\pi^-$ pairs after *jet mixing*.

in the Q^2 distribution of like sign pion pairs over a suitably chosen reference density. Here we have applied two procedures to obtain the reference density: The conventional way is to take $\pi^+\pi^-$ combinations from the same event. This method is fairly simple, but suffers from strong contributions of resonance decays and kinematical reflections in the interesting Q^2 range (Fig. 9). The corresponding ratios of Q^2 distributions are displayed in Fig. 8. Correlations due to resonance decays and kinematical reflections can be circumvented by reflecting all positive particles at a plane perpendicular to the sphericity axis *(jet mixing)* [7]. By means of this procedure, correlations due to unlike sign pion pairs are destroyed, whilst Bose-Einstein correlations are retained and moreover the event topology is preserved.

In Fig. 8 the resulting Q^2 distributions are shown. Compared to the previous case, a much smoother behaviour is observed. Also the correction function, i.e. passing from Monte Carlo generator to the detector level, is well behaved. To determine the correlation strength and the associated radius of the pion source, the following function has been fitted to the Q^2 distributions: $F(Q^2) = a\cdot(1+b\cdot Q^2)\cdot(1+c\cdot\exp[-d\cdot Q^2])$, where a is the correlation strength and d is related to the radius by $r = 0.193/\sqrt{d}$. The resulting values are listed in Table 1. It is worthwhile noting that the radius generated by Jetset is recovered when using *jet mixing* to compute the reference density, while the simple method results in an approximately 50% larger radius.

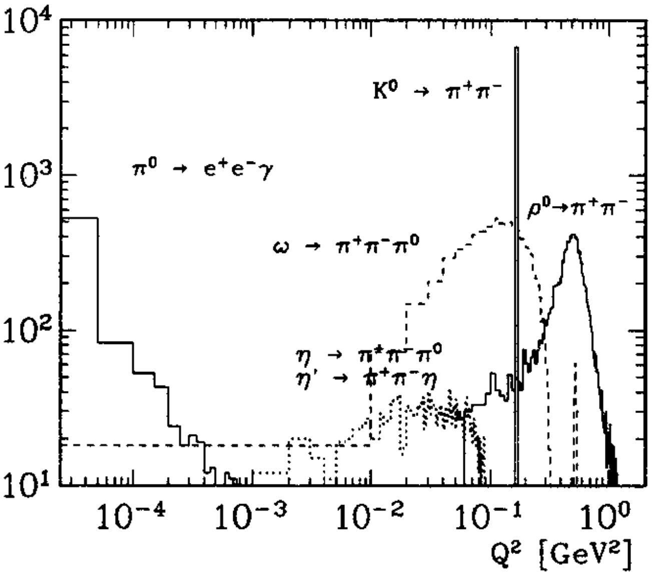

Figure 9: Q^2 distribution from resonance decays and kinematical reflections.

Reference density	Strength	Radius[fm]
$\pi^+\pi^-$	0.52 ± 0.06	1.2 ± 0.1
$\pi^+\pi^-$ from mixed jets	0.53 ± 0.04	0.69 ± 0.06
Jetset 7.2	$PARJ(92)$	$PARJ(93)$
	$2.6 \pm 0.2 \pm 0.2$	$0.25 \pm 0.02 \pm 0.02$

Table 1: Bose-Einstein results and parameters for Jetset 7.2.

CONCLUSIONS

In summary we have presented intermittency analyses in one, two and three dimensions. In general the data appear to be consistently described by conventional Monte Carlo models. This holds for the PETRA data (TASSO, CELLO) as well as for the LEP data (DELPHI, OPAL) and can be regarded as a great success for these models, since they have never been tuned with respect to factorial moments. The equally good description of factorial moments provided by various QCD inspired Monte Carlo models indicates a lack of sensitivity for details of the soft gluon phase. In particular, hard gluon and hard photon radiation appear to be the dominant source of fluctuations observed in e^+e^- annihilation. Besides this, strong effects due to resonance decays are found, making it impossible to resolve the fine correlation structure.

Bose-Einstein correlations are found to give a contribution to the observed resolution dependence of factorial moments. Their parameters have been measured using the conventional method and a new method, avoiding contributions from resonance decays, has been proposed.

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