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Intermittency in Hadronic Decays of the Z^0

The OPAL Collaboration

Abstract

A factorial moment analysis has been performed on the differential multiplicity distributions of hadronic final states of the Z^0 recorded with the OPAL detector at LEP. The moments of the one dimensional rapidity and the two dimensional rapidity versus azimuthal angle distributions are found to exhibit "intermittent" behaviour attributable to the jet structure of the events. The moments are reproduced by both parton shower and matrix element QCD based hadronisation models. No evidence for fluctuations beyond those attributable to jet structure is observed.

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1 Introduction

Over recent years there has been much interest in the possible existence of non statistical density fluctuations in (pseudo)rapidity distributions of particles produced in high energy hadronic interactions [1]. These fluctuations would result in localised spikes in the particle rapidity distributions of individual events. This phenomenon has been generally termed "intermittency" by analogy with similar properties in turbulent flow fluid dynamics, although the term intermittency actually implies a particular property for the fluctuations (see below). The main source of interest has centred around the apparent inability of current models of hadron production to predict correctly the observed rates and strengths of fluctuations, with implications for the possible existence of new phenomena. In particular the models have failed to predict the small scale (rapidity intervals smaller than one unit) behaviour of various multiplicity moments in nucleon-nucleon [2], proton-antiproton [3] and electron-positron [4] [5] collisions. There has been much speculation [6] [7] [8] upon the possible sources of the observed fluctuations, particularly in nucleon-nucleon and proton-antiproton collisions. However, most of the proposed mechanisms involve interaction with a nuclear medium and are not expected to be relevant for electron-positron collisions. One class of model which could produce intermittent behaviour in both hadronic and electron–positron collisions is that involving the self-similar cascade mechanism [7] [8]. In these models, hadron production is realised via repeated application of a stochastic branching process which appears the same at all resolution scales. It is tempting to identify this branching with the parton shower of perturbative QCD. Recent experimental studies in electron-positron annihilation at the Z^0 energy [9] have found good agreement between measured multiplicity moments for small rapidty intervals and the JETSET parton shower model in contrast to the previous results at lower energies.

To determine the statistical significance of fluctuations is often a difficult problem. Bialas and Peschanski have proposed [7] that a suitable method for such an analysis is to study the factorial moments of kinematic distributions as a function of phase space resolution. In particular they suggest studying the development of these moments as a function of the size of the phase space bins.

To illustrate this method we take particle rapidity as an example. The rapidity, y, is given by

$$y = \frac{1}{2}\ln(\frac{E+P_l}{E-P_l}) \tag{1}$$

where E is the particle energy and P_l is the momentum component along a chosen event axis. The width of the rapidity region of interest, Y, is divided into M bins of width $\delta y = Y/M$. The normalised factorial moment of order j is then defined as

$$F_j(M) = \frac{1}{\langle \bar{n}_m \rangle^j} \langle \frac{1}{M} \sum_{m=1}^{M} n_m(n_m-1)...(n_m-j+1) \rangle \tag{2}$$

with:

$$\bar{n}_m = \frac{1}{M} \sum_{m=1}^{M} n_m$$

where the sum is over all bins, n_m is the number of particles in bin m and the angle brackets imply an average over all events. These moments, valid for all event multiplicities [7], have the following properties:

1. Contributions to the numerator for moments of order j come only from bins containing j or more particles, hence, the moments act as a filter for highly populated bins.

2. The moments $F_j(M)$ are independent of the number of bins, M, into which the rapidity interval is divided if the number of particles in any bin is governed simply by the mean bin population and random (Poisson) fluctuations.

3. Non statistical fluctuations or correlations in the distribution of particles will produce moments which increase with increasing number of bins while the bin size δy is larger than the characteristic correlation length. Beyond this the moments will saturate and remain constant with increasing M. Non statistical fluctuations on many different scales will lead to a continued increase of the moments with M. Of particular interest is the case where the fluctuations are self-similar in nature (appear the same at all resolution scales). In this case, in the limit of small bin size, a power law dependence is expected:

$$F_j \propto M^{f_j} \qquad \text{with } f_j > 0 \tag{3}$$

This property is called "intermittency". In practice this behaviour will be smeared out when the bin size becomes comparable with the detector resolution, at which point the moments will saturate.

It is the development of the moments with the phase space scale (or, equivalently, the number of bins) which provides the information about the sources of any correlations. The properties listed above are strictly true only for moments of quantities for which the mean distribution, averaged over many events, is flat or slowly varying. The rapidity distribution, when restricted to the central plateau region, is a good example. For this reason an analysis of the moments of the rapidity distribution is usually restricted to the central rapidity region, typically $-2 < y < 2$.

In the following sections the factorial moments are analysed for the rapidity and the rapidity versus ϕ distributions, where ϕ is the azimuthal angle around the event axis. For the two dimensional case (y vs ϕ) events are divided into equal numbers of ϕ ($0° < \phi < 360°$) and rapidity ($-2 < y < 2$) bins. The moments are then calculated according to equation 2, with M the total number of y versus ϕ bins. The two dimensional distribution has the advantage that the event phase space may be subdivided into many more bins before the limits of detector resolution are reached than is possible with one dimension. It has been pointed out by Ochs [10] that an intermittency signal present in two dimensions may be invisible or smeared out when projected onto one dimension. In the projection the factorial moments will tend towards a finite value as M increases.

2 Data Selection and Analysis

The data used in this analysis were recorded with the OPAL detector at the CERN e^+e^- collider, LEP. The OPAL detector is described in detail in reference [11]. The analysis is based on approximately 140000 multihadronic events recorded during 1990 at centre of mass energies between 88.3 and 95.0 GeV. The mean energy for the events is 91.3 GeV. The analysis is restricted to charged particles for which the most relevant components of the detector are the central tracking chambers. These consists of a central high precision drift chamber for vertex reconstruction, a large diameter jet chamber for high precision measurements in the plane perpendicular to the colliding beam axis and an outer layer of longitudinal drift chambers for accurate position measurements in the direction parallel to the beam. The complete system allows detection of charged particles over 98% of the full solid angle. The momentum resolution which is presently achieved for charged particles is $\sigma(p)/p = \sqrt{(0.0023p)^2 + (0.018)^2}$ for particles perpendicular to the beam axis, with a resolution in polar angle of $\sigma(\theta) = 5$ mrad.

A sample of well contained multihadron events was selected as follows. For each event well measured charged tracks were defined as those with:

- At least 20 measured points (out of a possible maximum of 159) recorded in the Jet chamber
- A measured closest distance of approach to the electron positron collision point less than 5cm perpendicular to and less than 40cm along the beam direction.
- A measured momentum of greater than 0.15 GeV/c perpendicular to the beam direction.
- A measured polar angle, θ, of the track with respect to the beam direction which satisfied $|\cos(\theta)| < 0.93$.

The multihadron event sample was then selected by requiring events to have

- At least 5 good charged tracks as defined above.
- A momentum imbalance, defined as the magnitude of the vector sum of momenta of all charged particles, of less than $0.4 \times E_{cm}$, with E_{cm} the centre of mass energy.
- A total energy of charged tracks (assumed to be pions) greater than $0.2 \times E_{cm}$.
- $|\cos(\theta_s)| < 0.7$, where θ_s is the polar angle between the beam axis and the sphericity axis [12] of the event, calculated using all accepted tracks.

The first three of the event selection criteria remove background from non hadronic Z^0 decays, two photon interactions and beam-gas and beam-wall interactions. The last cut ensures that the events are well contained in the detector. A total of 89236 events remain after these cuts.

Except where explicitly stated otherwise the sphericity axis of the events is used as the event axis for the calculation of rapidity and azimuthal angle. The analysis is restricted to particles in the central rapidity interval $-2 < y < 2$.

We distinguish "raw" moments and "corrected" moments. The raw moments are calculated directly from the data without correction for acceptance effects. The "corrected" moments are corrected to take account of the detector acceptance, kinematic cuts, initial state radiation and particle decays. The correction procedure adopted is essentially the same as that described in [13]. Two samples of multihadron events are generated using the JETSET Monte Carlo program (version 7.2) [14] The first sample is generated without initial state radiation and all particles with lifetimes greater than 3×10^{-10} seconds are considered stable; the factorial moments, $F_j(M)_{gen}$, are then calculated directly from the generated stable charged particles, applying no further selection criteria to events or tracks. In the second sample, which includes the effects of finite lifetimes, initial state radiation and a simulation of the OPAL detector, the moments, $F_j(M)_{det}$ are calculated after the events have been subjected to the same reconstruction algorithms and selection criteria as the data. The corrected moments $F_j(M)_{corrected}$ are then given by

$$F_j(M)_{corrected} = F_j(M)_{raw} \times \frac{F_j(M)_{gen}}{F_j(M)_{det}}$$

The limitations of detector resolution are important when studying the development of the factorial moments as the moments will saturate when the resolution limit is reached. If the measured momentum

resolution of the OPAL central detector is applied as a simple Gaussian smearing of track parameters to tracks generated using the JETSET Monte Carlo, the corresponding RMS resolution on the measured particle rapidities is 0.02 units for particles in the central rapidity region ($|y| < 2$). The measured values of the moments are distorted before this limit is reached due to non Gaussian tails in the resolution. To determine the sensitivity of the current measurement several Monte Carlo samples were generated including well defined intermittency "signals" according to the models of [7] and [10]. A wide range of signal "strengths" were studied including one consistent with the published TASSO data [5] as determined in [10]. The events were constrained to describe the measured mean charged multiplicity and inclusive charged particle momentum distribution but were generated according to a rapidity probability density determined (event by event) as in [7] and [10]. The rapidity distribution averaged over all events is flat in these models, however, the rapidity distributions for individual events may contain self similar fluctuations manifested as localised spikes. These events were then passed through a simulation of the OPAL detector and the factorial moments were calculated and compared with those calculated from the generated tracks. The factorial moments for the generated events show a linear increase of $\ln(F_j)$ with $\ln(M)$, as expected. In all cases the moments after detector simulation also show a continued rise with M up to $M = 400$ ($\delta y = 0.01$), the largest value of M used. However, these moments start to deviate from the simple linear dependence of $\ln(F_j)$ on $\ln(M)$ for $M > 10$ to 20 ($\delta y < 0.4$ to 0.2). Beyond this the moments fall gradually further and further below those obtained at the generator level. A rise of the moments with increasing M was not observed when events were generated with rapidity distributions flat event by event or determined by the measured rapity distribution. Thus, this analysis is sensitive to a possible signal up to $M = 400$ ($\delta y = 0.01$). Detector resolution effects become important for $M > 20$ ($\delta y = 0.2$) and, consequently, a quantitative measurement for smaller bin sizes requires use of a detailed modelling of the detector.

In the following sections the data are compared with the predictions of the following Monte Carlo programs:

- JETSET version 7.2 [14], using the parton shower (PS) followed by string formation and fragmentation. The parameters of the program have been tuned to provide a good description of many global event shape distributions [13].
- HERWIG version 4.3 [15], using a parton shower followed by cluster fragmentation, again tuned to reproduce the global event properties [13].
- JETSET version 7.2 [14], using the second order matrix element formalism of Ellis, Ross and Terrano (ERT) [16] followed by string formation and fragmentation. This model has also been tuned to reproduce the global event shape distributions in the same way as described in [13].

3 Results

The raw 2^{nd} to 5^{th} factorial moments as a function of number of bins, M, are shown in figure 1. The moments are observed initially to rise with increasing number of bins and then to flatten. Also shown in figure 1 are the moments calculated for a sample of 100000 JETSET Monte Carlo events which have been passed through a detailed detector simulation. In both cases the errors shown are statistical only and are dominated by the error on the numerator in equation 2. The points in figure 1 are not independent as the same events may contribute to each data point. The Monte Carlo reproduces the data well although some small systematic differences are apparent. These differences are discussed further below.

The good agreement between data and simulation in figure 1 suggests that the acceptance correction procedure described in the previous section is valid. The correction factors, shown in figure 2, tend to reduce the measured moments. The corrections become larger for higher order moments and with increasing M. The corrections for all distributions presented here amount to 10% on average and are always less than 50%. To avoid introducing the statistical fluctuations in the correction factors for $F4$ and $F5$ into the data the correction factors for the last 5 bins for $F4$ and $F5$ have been smoothed (the errors shown in figure 2 are retained). The correction factors were calculated using the JETSET Monte Carlo; similar results are obtained if a sample of events generated with the HERWIG Monte Carlo program is used instead.

The corrected moments, listed in table 1, are shown in figure 3, compared with the predictions of the Monte Carlo programs. The errors shown are statistical only but include the statistical error on the correction factor, added in quadrature. The general features of the data are well reproduced by all 3 models. The divergence of the model predictions for small M is a reflection of their slightly different predictions for the shape of the total charged multiplicity distribution. Although the mean multiplicities for all three models agree well with the data, the distributions for the HERWIG (JETSET/ERT) program have a slight excess (deficiency) of high multiplicity events, relative to JETSET/PS, producing significantly larger (smaller) factorial moments for small M or large rapidity bin size. The observed differences between the model predictions are of the same order as their sensitivity to changes in the individual fragmentation parameters, as defined by the error values given in [13] for JETSET/PS and HERWIG, and as such are not significant.

The absolute values of the moments are sensitive to the choice of the event axis. Obviously, in the present analysis the exact details of the determination of the sphericity axis may affect the final results. One way to eliminate this sensitivity is to choose the beam axis as the reference axis. The factorial moments calculated with respect to the beam axis are given in table 2 and plotted in figure 4. The moments in figure 4 are larger than those calculated with respect to the sphericity axis although the qualitative behaviour is the same. Again the Monte Carlo predictions agree well with the data.

The moments of the two dimensional y versus ϕ distribution (again using the sphericity axis as the event axis) are listed in table 3 and are shown in figure 5. The two dimensional moments exhibit a much stronger rise than those for the one dimensional distributions and do not saturate over the range studied, which is limited by the available statistics. The three hadronisation models again reproduce the data well.

A possible source of particle correlations which could contribute to the observed behaviour of the factorial moments and which is not generally included in models of hadronisation is the Bose Einstein effect [17]. The possible contribution from this source has been investigated by restricting the analysis to like sign charged particles. If the Bose-Einstein effect were the major source of the observed signal then this restriction should result in a stronger increase of the moments with increasing M. This is not observed, indicating that Bose-Einstein correlations are not important in this context.

4 Discussion and Conclusions

Since the QCD models used for our study reproduce the measured factorial moments well, we observe no evidence for anomalous statistical behaviour, in agreement with the results of [9]. To probe the source of the observed increase in the factorial moments with decreasing phase space scale, the predictions of each of the three QCD models have been examined in detail. None of the models has been specifically tuned to reproduce the measured factorial moment distributions. The observed

signal (increase of the factorial moments with decreasing bin size) in all cases arises during the perturbative and fragmentation stages. The subsequent decay of produced hadrons does not contribute significantly to the signal [1]. The relative contributions from the perturbative and non-perturbative stages in the hadronisation differ in the models as outlined below. The choice of reference axis also affects the relative importance of each contribution for the three models. Choosing the sphericity axis emphasizes the sensitivity to multi-jet events which populate the central rapidity region; in this case the perturbative stage (parton shower or matrix element) is the major source of the observed signal. Using the electron beam axis as the reference axis, however, enhances the contribution from two jet events, for which the jets may now fall in the central rapidity region. In this case the relative contribution of the non-perturbative stage to the observed signal is increased.

For HERWIG, which contains a coherent parton shower including the effects of soft gluon interference (coherence) and cluster fragmentation, the major source of the signal is the parton shower. With the sphericity axis as the reference axis the moments are larger at the parton level than at the hadron level; they appear to be smeared out somewhat during the subsequent cluster formation and decay. With the electron beam axis as reference axis the parton shower remains the major source of signal. In this case, however, the moments are smaller at the parton level than at the hadron level, the subsequent cluster fragmentation tending to enhance the observed signal.

For JETSET, with a coherent parton shower and string fragmentation, both the perturbative and fragmentation stages contribute to the increase of the factorial moments with increasing M. The relative importance of each contribution depends upon the choice of reference axis as described above. This is also true if the matrix element approach is adopted. However, in this case, due to the limited number of partons produced in the perturbative stage, the non-perturbative stage is always required to produce significant signals.

The observed signal thus appears to be a consequence of the multi-jet nature of the events. The initial (hard) parton branching combined with a limited p_t development of the jets (whether realised primarily through further parton branching, fragmentation, or a combination of both) is the dominant effect. This has been checked further by comparison of the measured moments both with the ERT matrix element option of JETSET followed by independent parton fragmentation and with the COJETS Monte Carlo program (version 6.12) [19], which contains an incoherent parton shower followed by independent parton fragmentation. Both of these programs (not shown) are also able to reproduce the measured moments [2].

Thus it has been found that current models of hadron production reproduce well the observed behaviour of the factorial moments of the rapidity and the rapidity versus azimuth distributions. For the parton shower models the apparent saturation of the moments of the one dimensional rapidity distributions is also observed at the parton level indicating that the observed saturation is indeed an intrinsic property of the models rather than a limitation of detector resolution. The major factor determining the development of the moments with decreasing phase space scale appears to be the jet structure of the events and no evidence for unexplained fluctuations is observed.

[1] Decays do contribute to the second order moments for small phase space bins where narrow resonances may be a significant source of correlated two particle production, as noted in [18]

[2] For the independent parton fragmentation models we use a slightly softer fragmentation function for gluons than for quarks.

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M	F2	F3	F4	F5
1	1.21 ± 0.01	1.71 ± 0.02	2.75 ± 0.05	4.9 ± 0.1
2	1.33 ± 0.01	2.24 ± 0.03	4.48 ± 0.09	10.0 ± 0.3
4	1.44 ± 0.01	2.85 ± 0.04	7.29 ± 0.20	22.6 ± 1.1
6	1.49 ± 0.01	3.14 ± 0.05	8.74 ± 0.24	29.6 ± 1.5
8	1.51 ± 0.01	3.33 ± 0.05	9.77 ± 0.30	35.5 ± 2.1
10	1.53 ± 0.01	3.42 ± 0.05	10.30 ± 0.34	38.5 ± 2.6
12	1.53 ± 0.01	3.49 ± 0.05	10.83 ± 0.36	42.5 ± 2.7
16	1.55 ± 0.01	3.56 ± 0.06	11.07 ± 0.41	41.4 ± 3.2
20	1.54 ± 0.01	3.58 ± 0.06	11.26 ± 0.45	43.3 ± 4.0
24	1.54 ± 0.01	3.62 ± 0.07	11.76 ± 0.51	48.9 ± 4.6
28	1.55 ± 0.01	3.65 ± 0.07	11.82 ± 0.55	46.9 ± 5.2
32	1.55 ± 0.01	3.63 ± 0.07	11.80 ± 0.60	47.5 ± 6.3
36	1.55 ± 0.01	3.61 ± 0.07	11.81 ± 0.62	50.7 ± 6.4
40	1.55 ± 0.01	3.62 ± 0.07	11.59 ± 0.63	45.6 ± 6.0
44	1.54 ± 0.01	3.64 ± 0.08	11.81 ± 0.69	46.9 ± 6.7
48	1.56 ± 0.01	3.68 ± 0.08	12.03 ± 0.76	49.2 ± 8.0
56	1.54 ± 0.01	3.56 ± 0.09	11.71 ± 0.88	46.3 ± 7.4
64	1.55 ± 0.01	3.56 ± 0.09	11.43 ± 0.98	46.9 ± 14.8
72	1.54 ± 0.01	3.50 ± 0.09	11.11 ± 0.94	40.0 ± 8.1
80	1.55 ± 0.01	3.60 ± 0.10	11.56 ± 1.14	51.3 ± 18.5
120	1.56 ± 0.02	3.48 ± 0.13	9.40 ± 1.40	
160	1.55 ± 0.02	3.36 ± 0.15		
240	1.57 ± 0.02	3.55 ± 0.22		
320	1.55 ± 0.02	3.57 ± 0.27		
400	1.57 ± 0.02	3.31 ± 0.31		

Table 1: Corrected factorial moments of the rapidity distribution with respect to the sphericity axis.

M	F2	F3	F4	F5
1	1.05 ± 0.01	1.15 ± 0.01	1.34 ± 0.02	1.62 ± 0.02
2	1.07 ± 0.01	1.23 ± 0.01	1.53 ± 0.02	2.02 ± 0.03
4	1.60 ± 0.01	3.06 ± 0.02	6.49 ± 0.08	15.0 ± 0.3
6	1.87 ± 0.01	4.42 ± 0.04	11.90 ± 0.16	35.6 ± 0.7
8	2.02 ± 0.01	5.32 ± 0.05	16.37 ± 0.23	56.5 ± 1.3
10	2.12 ± 0.01	6.04 ± 0.05	20.33 ± 0.31	77.3 ± 1.9
12	2.19 ± 0.01	6.57 ± 0.06	23.58 ± 0.37	96.0 ± 2.5
16	2.29 ± 0.01	7.30 ± 0.07	28.35 ± 0.48	126.1 ± 3.7
20	2.35 ± 0.01	7.82 ± 0.07	31.95 ± 0.57	150.8 ± 5.1
24	2.37 ± 0.01	8.09 ± 0.08	33.89 ± 0.63	165.2 ± 5.7
28	2.39 ± 0.01	8.32 ± 0.09	35.76 ± 0.70	179.4 ± 6.7
32	2.42 ± 0.01	8.54 ± 0.09	37.48 ± 0.78	194.0 ± 7.8
36	2.44 ± 0.01	8.67 ± 0.09	38.89 ± 0.85	208.1 ± 9.0
40	2.44 ± 0.01	8.73 ± 0.09	39.39 ± 0.89	214.6 ± 10.2
44	2.45 ± 0.01	8.79 ± 0.09	39.92 ± 0.94	218.7 ± 10.8
48	2.44 ± 0.01	8.77 ± 0.10	39.93 ± 0.99	223.5± 12.4
56	2.45 ± 0.01	8.85 ± 0.10	40.80 ± 1.09	232.2 ± 14.2
64	2.45 ± 0.01	8.90 ± 0.11	40.79 ± 1.16	228.6 ± 15.6
72	2.46 ± 0.01	8.97 ± 0.11	41.99 ± 1.27	246.7 ± 18.4
80	2.45 ± 0.01	8.83 ± 0.11	40.21 ± 1.30	227.2 ± 19.4

Table 2: Corrected factorial moments of the rapidity distribution with respect to the electron beam axis.

M	F2	F3	F4	F5
1	1.21 ± 0.01	1.73 ± 0.03	2.81 ± 0.07	5.2 ± 0.2
4	1.42 ± 0.01	2.64 ± 0.04	5.9 ± 0.2	15.2 ± 0.6
16	1.69 ± 0.01	4.31 ± 0.07	14.6 ± 0.6	62.7 ± 5.9
64	2.32 ± 0.03	11.09 ± 0.31	80.1 ± 6.0	776. ± 132.
256	2.78 ± 0.04	21.0 ± 1.1	270. ± 47.	4920. ± 2188.
1024	2.97 ± 0.06	30.9 ± 3.3	723. ± 327.	
4096	2.96 ± 0.10	41.5 ± 10.7		

Table 3: Corrected factorial moments of the rapidity (with respect to the sphericity axis) versus ϕ distribution. For each point the M bins are constructed from equal numbers of y and ϕ bins.

Figure Captions

Figure 1 The measured raw 2^{nd} to 5^{th} factorial moments of the rapidity distribution (solid circles), calculated with respect to the sphericity axis, compared with the predictions of the JETSET Monte Carlo (version 7.2, open circles) prediction calculated after detailed detector simulation. The moments are shown as a function of the number of bins, M, into which the rapidity interval $| y | < 2$ is divided. The upper axis gives the individual rapidity bin size.

Figure 2 The correction factors applied to the 2^{nd} to 5^{th} factorial moments.

Figure 3 The corrected 2^{nd} to 5^{th} factorial moments (solid circles) of the rapidity distribution (with respect to the sphericity axis) compared with the predictions of the JETSET v7.2 parton shower (solid line), HERWIG v4.3, (dashed line) and JETSET/ERT matrix element (dotted line) Monte Carlo programs.

Figure 4 The corrected 2^{nd} to 5^{th} factorial moments with respect to the electron beam axis.

Figure 5 The 2^{nd} to 5^{th} factorial moments of the 2-d y versus ϕ distribution.

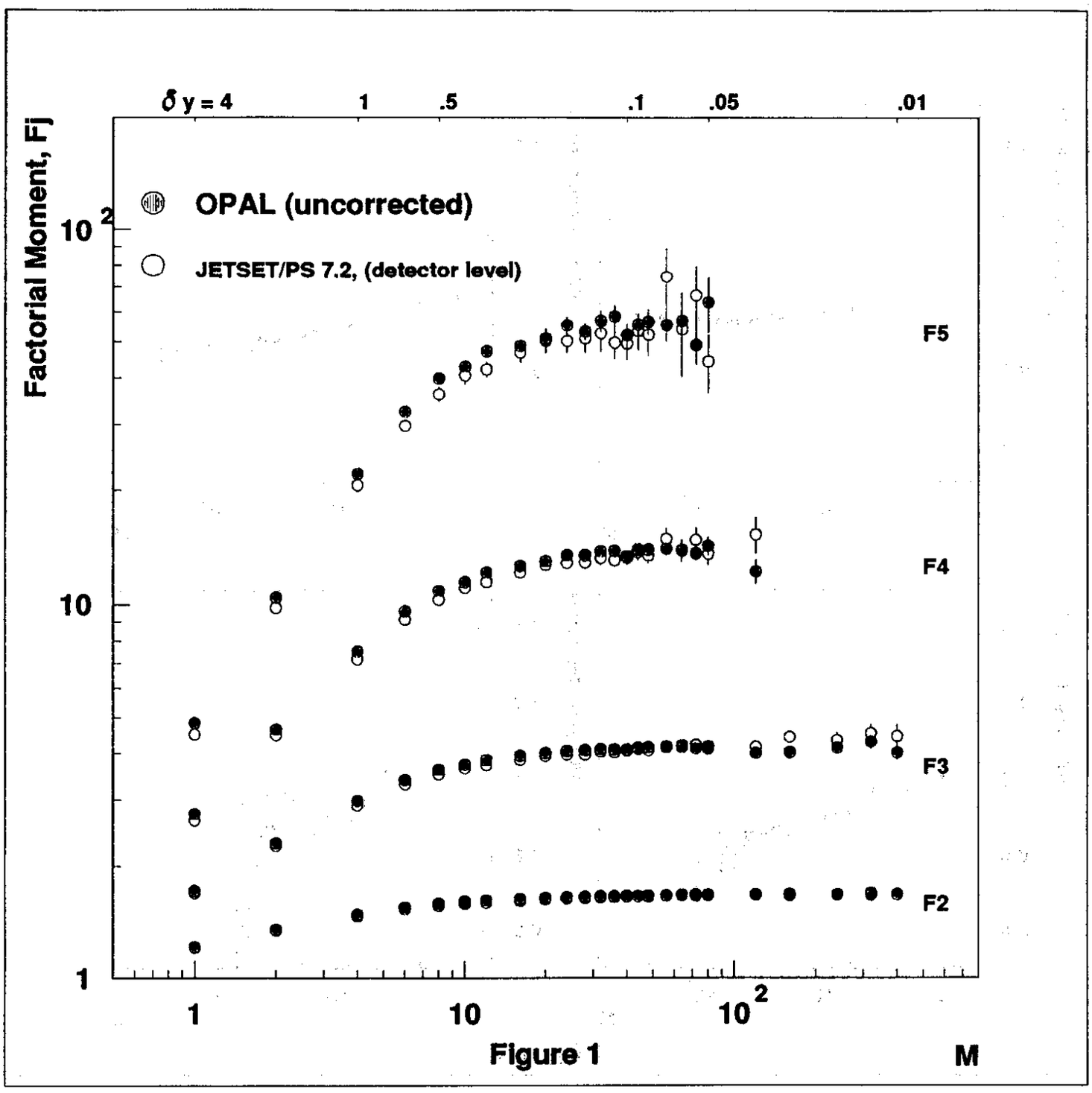
δ y = 4
1
.5
.1
.05
.01
Factorial Moment, Fj
OPAL (uncorrected)
JETSET/PS 7.2, (detector level)
F5
F4
F3
F2
10 2
10
1
1
10
10 2
M

Figure 1

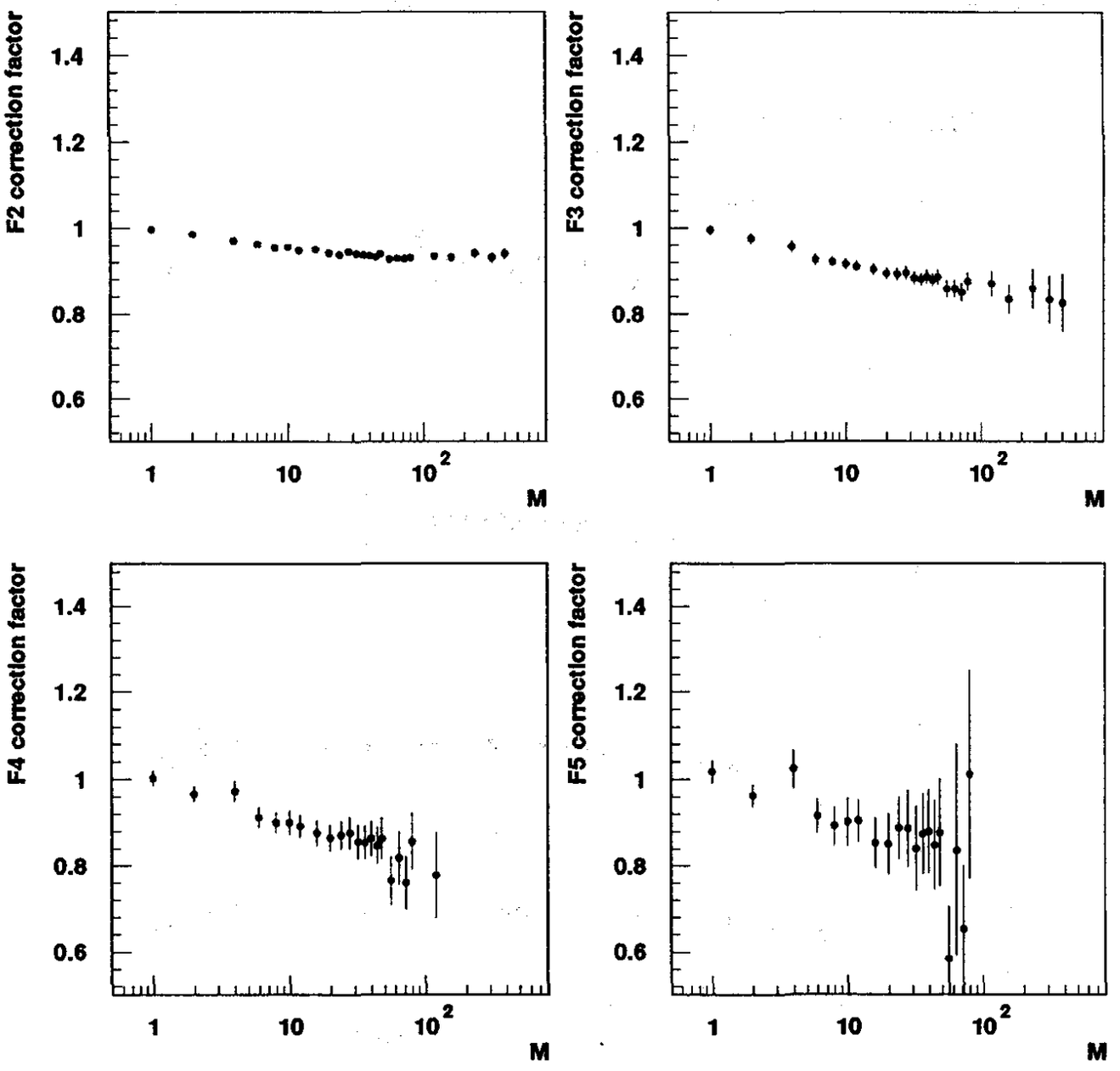
F2 correction factor
F3 correction factor
F4 correction factor
F5 correction factor
1.4
1.2
1
0.8
0.6
1
10
10^2
M

Figure 2

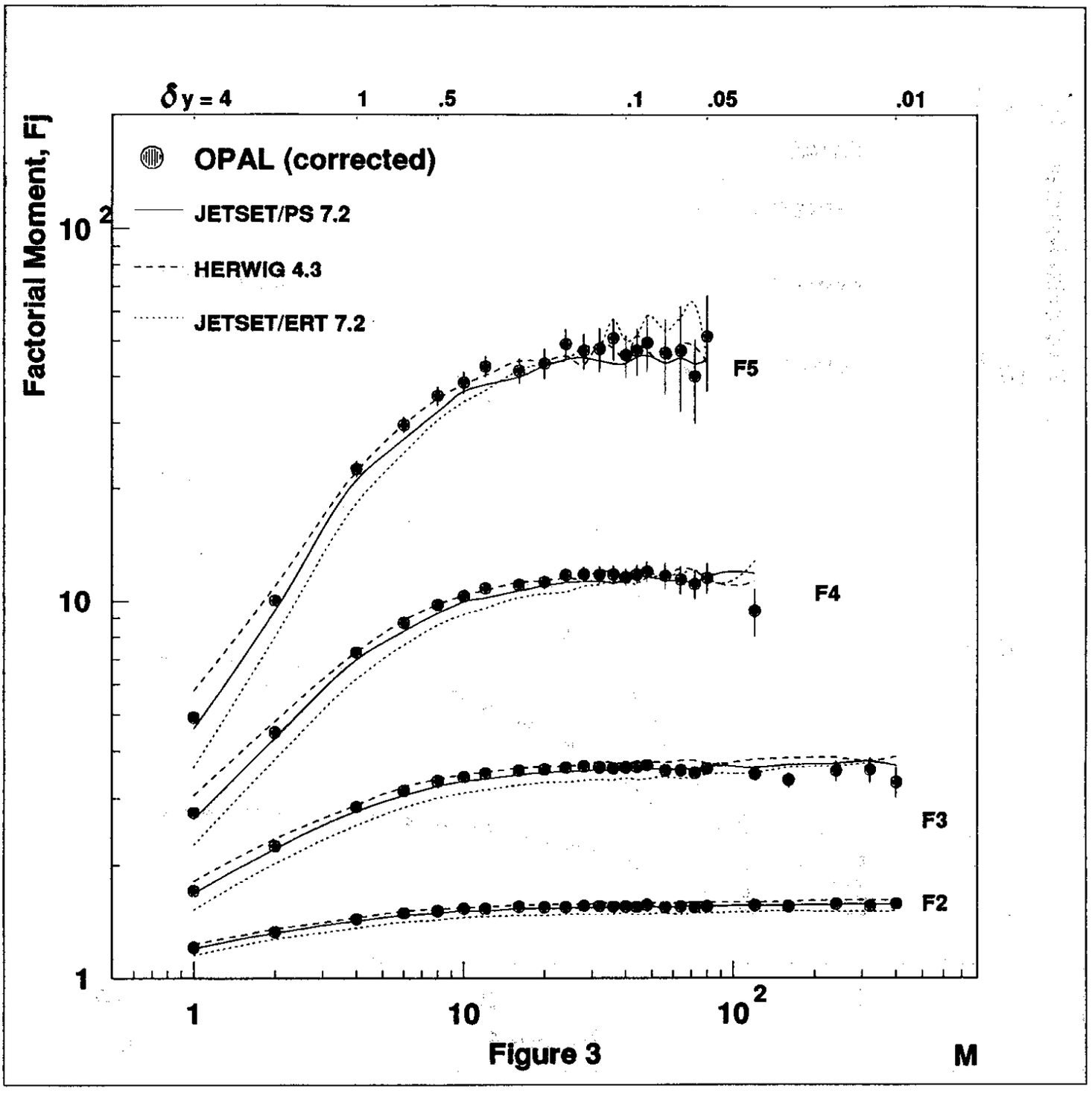
δy = 4
1
.5
.1
.05
.01
OPAL (corrected)
JETSET/PS 7.2
HERWIG 4.3
JETSET/ERT 7.2
Factorial Moment, Fj
10 2
10
1
F5
F4
F3
F2
1
10
10 2
M

Figure 3

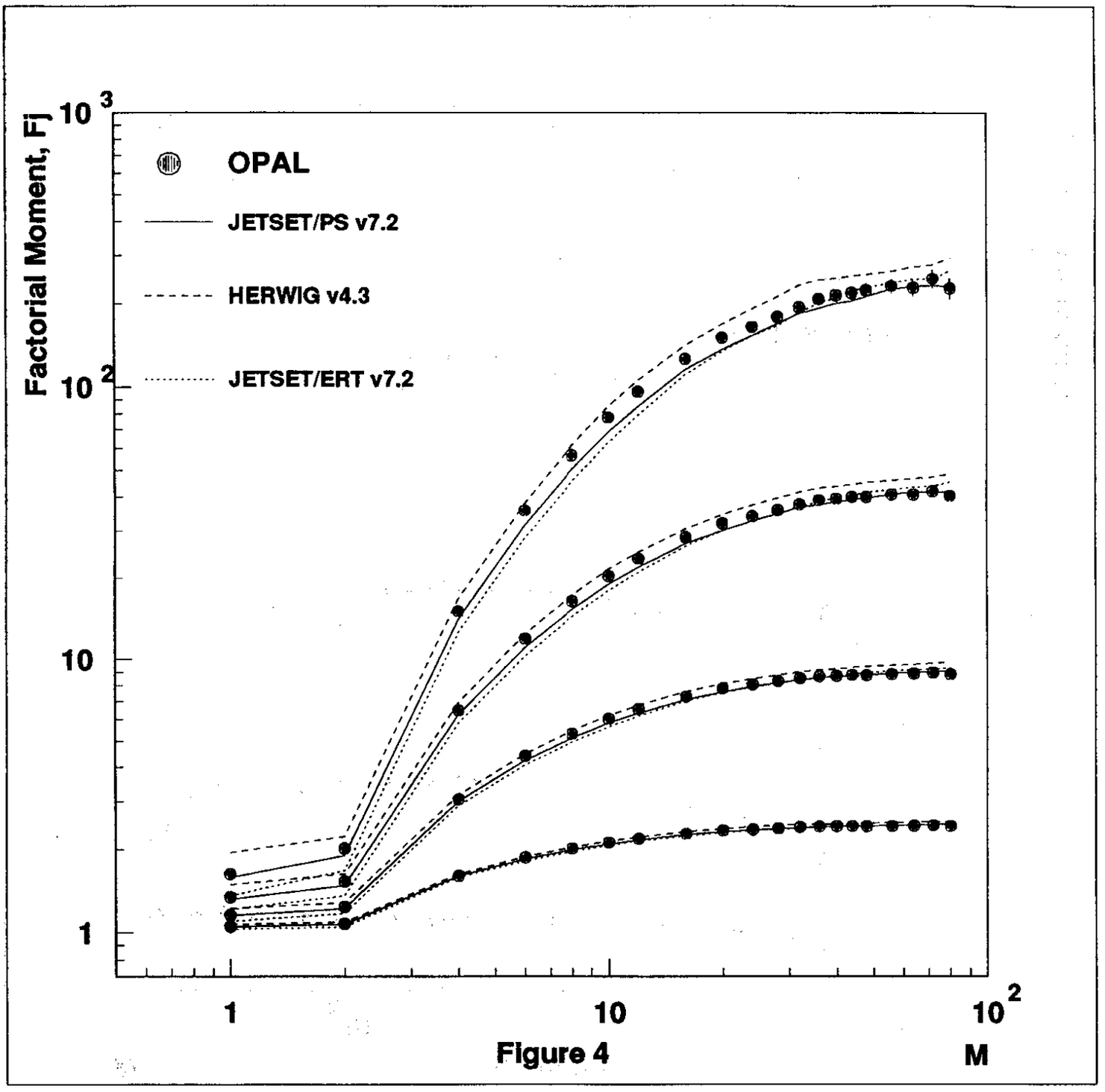
Factorial Moment, Fj
10^3
10^2
10
1
OPAL
JETSET/PS v7.2
HERWIG v4.3
JETSET/ERT v7.2
1
10
10^2
M

Figure 4

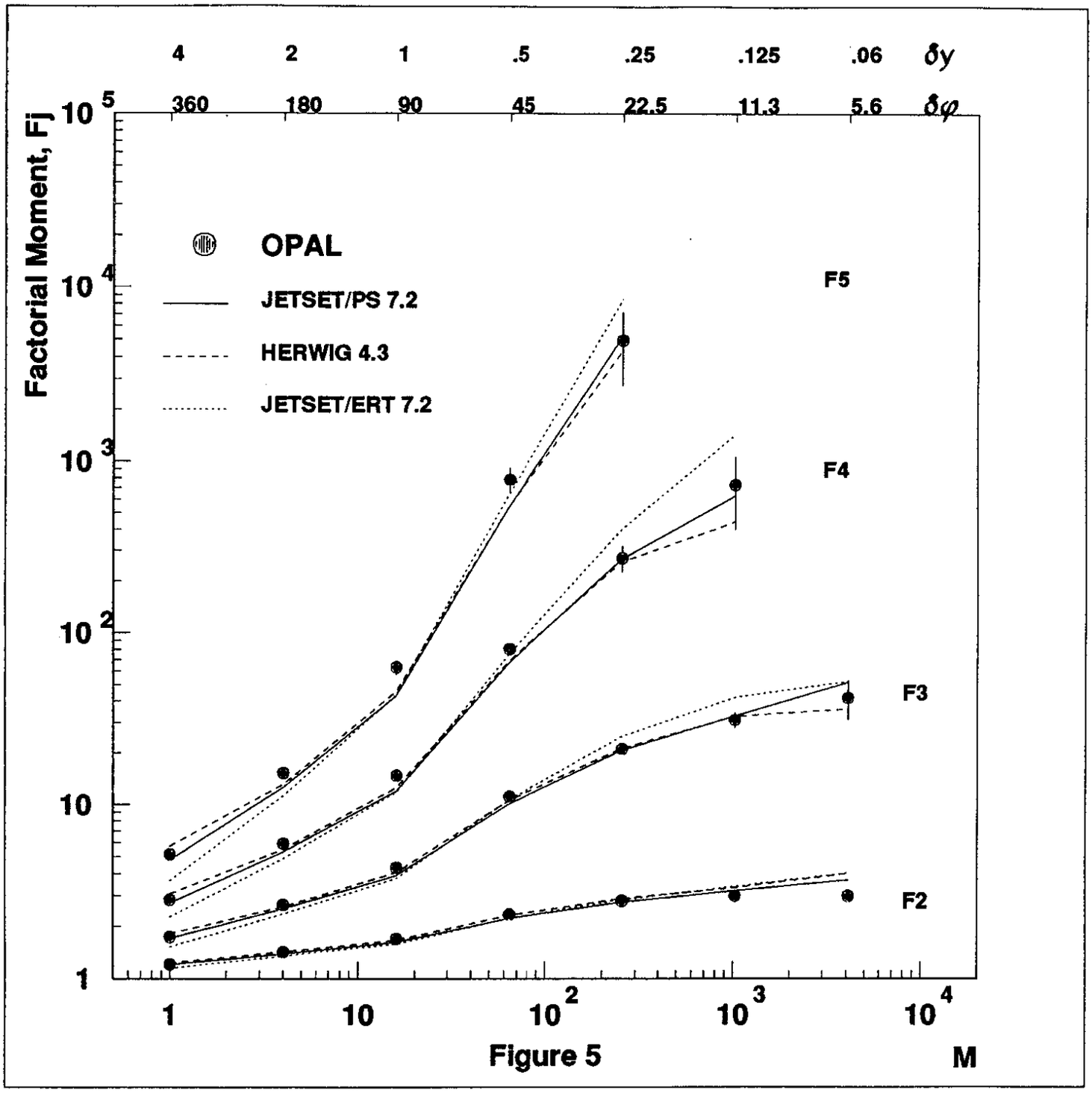

Figure 5

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