CONF-900822--4

JUL 16 1990

ANL-HEP-CP--90-50

DE90 013890

STUDY OF INTERMITTENCY IN e^+e^- ANNIHILATIONS AT 29 GeV

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Abstract

Charged particle multiplicity distributions from e^+e^- annihilations at 29 GeV have been analyzed in selected rapidity and azimuthal angle intervals. The data were taken with the High Resolution Spectrometer at PEP. The factorial moments of the multiplicity distributions increase as the rapidity interval is decreased, the so-called intermittency phenomenon. These direct measurements of the moments agree with values derived from negative binomial fits to our multiplicity distributions in various central rapidity windows. The factorial moments are also given for the distribution in azimuthal angle around the beam direction and for the two-dimensional distribution in rapidity and azimuthal angle around the jet directions.

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Submitted to the XXV International Conference on High Energy Physics, August 2-8, 1990, Singapore.

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In the continuing study of multiparticle production in high energy interactions interest has recently focussed on the shape of the charged particle multiplicity distributions in selected rapidity intervals.[1] Bialas and Peschanski[2] suggested looking for a power law behavior of the variation of the factorial moments of the distributions as a function of the size of the rapidity interval (δy). Data from e^+e^- annihilation[3], πp[4], and $\bar{p}p$ collisions[5] as well as heavy ion collisions[6] exhibit such a power law behavior as δy is decreased. This behavior, in which the moments increase as the size of the interval is decreased, is called intermittency.

The word "intermittency" originally came from the field of fluid-dynamics. In an isotropic turbulent fluid of a high Reynolds number, an intermittent structure appears as tube-like regions of a high vorticity isosurface.[7] This stochastic, irregular behavior leads to a similar power-law variation of the moments as the size of the region is decreased. The properties of such fluctuations have been extensively measured and discussed in the turbulence of fluids.

The possibility of a phase transition to a quark-gluon plasma[8] motivated the study of intermittency in hadronic multiparticle production. While it is not clear whether such a phase transition exists, some cosmic ray data[9] suggests a large concentration of particles in narrow rapidity regions at very high energies. However, the totality of existing data shows that the intermittency in rapidity is strongest in e^+e^- annihilations with a hierarchy such that (e^+e^-) exhibits a stronger effect than hadron-hadron collisions which, in turn, is stronger than nucleus-nucleus collisions.

In this paper we report a study of intermittency of the charged particle multiplicity distributions in e^+e^- annihilations at 29 GeV. A high statistics data sample is used, corresponding to a total integrated luminosity of 300 pb^{-1} obtained with the High Resolution Spectrometer (HRS) at PEP. The HRS detector was a solenoidal spectrometer that measured charged particles and electromagnetic energy over 90% of the solid angle[10]. The tracking system consisted of a vertex chamber, a central drift chamber, and an outer drift chamber. The central drift chamber had 15 cylindrical layers of drift cells. Eight of the layers had stereo wires (±60 mrad) in order to measure the z position. The momentum of a 14.5 GeV/c charged particle in the 1.62 T magnetic field was measured with a resolution of about 3%. A 40-module barrel shower counter system provided electromagnetic calorimetry over 62% of the solid angle with energy resolution below 10 GeV of $\sigma_E/E \approx 0.16/\sqrt{E}$ (E in GeV). The beam pipe and the inner wall of the central drift chamber were made of beryllium so as to minimize photon conversions; the total material between the interaction point and the central drift chamber was less than 0.02 radiation lengths.

To ensure good tracking efficiency, the thrust axis of the event was selected to be within 60° of the equatorial plane of the detector, and all acceptable tracks were required to have an angle with respect to the e^+e^- beam direction (θ_{beam}) of more than 24° and to register in more than one-half of the drift chamber layers traversed. Isolated tracks were reconstructed with > 99% efficiency, but for a typical annihilation event, with several close tracks, the reconstruction efficiency was lower. For $\theta_{beam} > 30°$ and p > 200 MeV/c, the track reconstruction efficiency was 80% or better and varies slowly with dip angle; for the higher momenta, p > 2 GeV/c, this increased to 90%. In addition, ~ 7% of the found tracks were not valid. Low momentum tracks were not well reconstructed for any dip angle because of the high magnetic field of the spectrometer; a track with p < 240 MeV/c spiraled within the central drift chamber.

The events were selected with the number of acceptable charged tracks between 5 and 40. Each track had to pass within 3 cm in (x,y) radius and 15 cm in z from the interaction point. In addition, the scalar sum of the charged momenta, plus the energy registered in the barrel shower counter system, was required to be greater than 12 GeV, with at least 1 GeV in the shower counter and more than 7.5 GeV/c in charged particle. The invariant mass of three-prong jets in six-prong events was required to be greater than the τ lepton mass. These cuts, which effectively removed beam-gas interactions, examples of lepton-pair production, two-photon events, and cosmic rays, produced a data sample of about 100k events. The events passing these cuts were mixtures of the two-jet and three-jet topologies. The low sphericity region ($0 < S < 0.25$) was dominated by the two-jet events, and contained 82% of the data sample; the higher sphericity region ($0.25 < S < 1$) was strongly enriched in three-jet events.

The rapidity of each charged particle was calculated from:

$$y = \frac{1}{2} \ln \frac{E + p_{\parallel}}{E - p_{\parallel}} \quad ,$$

where E is the energy of a particle assuming it to be a pion and $p_{\parallel}$ is a momentum projected onto a jet axis determined by the thrust axis determined from all charged particles.

The rapidity resolution is ~ 0.01, based on the detector track resolution. However, since there is an ambiguity in determining the true jet axis, which is the initial quark direction, a more realistic rapidity resolution is about 0.1. The rapidity distribution[11] for the inclusive data sample is relatively flat, after detector corrections, at a level of 3 charged particles per unit of y in the range between $y = -2$ and $y = +2$. The uncorrected distribution has a valley near $y = 0$, mainly because of the low tracking efficiency for slow particles as well as particles near the e^+e^- beam direction. In the following analysis, we use uncorrected variables.

An azimuthal angle (ϕ_{beam}) of each charged track around the beam axis was calculated. Although azimuthal angles for each event are clustered in narrow regions due to the jet structure of the events, the distribution averaged over many events is flat. This variable is well suited for the technical study of intermittency because it is invariant under Lorentz transformations, its distribution is flat (thus eliminating the need for detector corrections), and it is easy to visualize the intermittent structure in terms of narrowly collimated jets.

An azimuthal angle of the tracks around the jet axis (ϕ_{jet}) was also calculated and used in a two-dimensional study of the intermittency in y and ϕ_{jet}. The ϕ_{jet} distribution averaged many over many events is flat.

We first present the study in the azimuthal angle ϕ_{beam}. The total interval ($\phi_o = 2\pi$) is divided into M equal intervals of length $\delta\phi_{beam}$ =

ϕ_o/M. The normalized i^{th} factorial moment is defined as follows:

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

where k_m is the number of particles in the m^{th} bin of length $\delta\phi_{beam}$ with $1 \leq m \leq M$, N is the total number of particles in the azimuth angle interval of ϕ_o, thus $N = k_1 + k_2 + \ldots + k_M$, and $\langle\ \rangle$ means the average is taken over all events. The factorial moments in ϕ_{beam} with a total length of $\phi_o = 2\pi$ are shown in Fig. 1, where the abscissa is the number of divisions and the ordinate is the averaged factorial moments, both in log scales. All of the moments increase for low M reflecting the fact that the jets do not span the full ϕ interval. The lower moments level out for $M \gtrsim 10$. In this region, the internal structure of the jets is being probed. However, even for the largest M values, the moments are still slowly increasing, exhibiting the core structure of the particle flow in the jets.

A similar study for ϕ_{jet} (not shown) gives small moments and little variation with M indicating a uniform and relatively structureless distribution in the azimuthal angle around the jet direction.

For the rapidity study, the rapidity range is selected to be between $y = -2$ and $y = +2$ and the maximum number of divisions is $M = 40$, which corresponds to the minimum bin size of $\delta y = 0.1$. The resulting factorial moments F_i ($i = 2 - 5$) are shown in Fig. 2, where the abscissa is $-\ell n\delta y$ and the ordinate is ℓnF_i. The error bars are statistical. Again, the moments increase strongly for small M ($\delta y \sim$ 1-2 units) because of the strong two particle correlations that dominate this region. However, the moments are still increasing even for the smallest δy selection as shown by the slopes (a_i) of ℓnF_i in the small δy region (typically $-\ell n\delta y \gtrsim 0.5$), which are listed in Table 1. The table also gives the slopes from an analysis using the full rapidity scan. The values are quite similar to those measured for the central region. These slopes, which are non-zero, indicate intermittent behavior even for the smallest rapidity selection. Our results are consistent with the recent TASSO data[3]. The slopes in e^+e^- annihilations are larger than those in hadron-

hadron (hh) and nucleus-nucleus (AA) collisions with a hierarchy $a_i(e^+e^-) > a_i(hh) > a_i(AA)$.

The effects of intermittency are expected to be larger in the two-dimensional space of rapidity and azimuthal angle than in the rapidity space only.[12] To study this, we have combined y with ϕ_{jet} in a two-dimensional analysis. The total lengths of $-2 < y < 2$ and $0 < \phi_{jet} < 2\pi$ are divided into equal number of intervals, n, resulting in the total number of grid points $M = n^2$ with $n = 1, 2, 3, \ldots, 40$. The resulting factorial moments are shown in Fig. 3 where the abscissa is the total number of grid points and the ordinate is the averaged factorial moments, both with logarithmic scales. The slopes are defined as $a_i = d \ln F_i / d \ln\sqrt{M}$ so that the slopes in the two-dimensional case can be compared directly to those in the one-dimensional case with a similar bin width of δy. The a_2 value in the two-dimensional space of 0.156 ± 0.004 for $M > 100$ is about eight times larger than that in the rapidity space alone. Although a factor of 2 comes simply from the definition of a_i in the two-dimensional space, there is still a large enhancement compared to the one-dimensional rapidity result. This is the case even though the slopes in the ϕ_{jet} space only are almost zero. This may be connected with the compensation of transverse momentum, which is known to be local in rapidity.

Our data of Fig. 3 for F_2 are consistent with the TASSO results.[3] However, for F_3 our results flatten above $M \sim 100$, whereas the TASSO data suggest a continuing rise.

Indirect values of F_2 and F_3 in e^+e^- annihilations have been calculated[13] using the k-values from the negative binomial fit to the multiplicity distributions in various rapidity windows.[14] In order to compare these values with the direct measurement, we use a slightly different normalization of the factorial moments:

$$\langle F_i \rangle = \frac{\langle n(n-1) \ldots (n-i+1) \rangle}{\langle n \rangle^i} ,$$

where n is the number of charged particles in a bin of size δy at a fixed rapidity value and $\langle \; \rangle$ denotes an average over all events. The factorial moments at $y = 0$ for the inclusive sample are shown in Fig. 4, together with those from the k values of the negative binomial fits. The agreement between the calculated values and the direct measurements is generally good, although the statistical errors of the direct measurements in the small δy region are large due to the lack of "horizontal" averaging.

In conclusion, we find that the normalized factorial moments in the azimuthal angle around the beam axis show strong intermittency behavior which can be understood from the jet structure of the events. On the other hand, the factorial moments in the azimuthal angle around the jet axis show a small effect indicating that the particles are uniformly distributed around the jet axis. The normalized factorial moments in rapidity space also show a power law relation with a finite slope in the region of small rapidity intervals. The slopes of the i^{th} factorial moments F_i in the ℓnF_i - $\ell n\delta y$ plane are measured with the same normalization formula as was used by the TASSO group to facilitate comparisons. The slopes a_i increase with the index i.

The effects of intermittency are larger in the two-dimensional space of rapidity and azimuthal angle around the jet axis than in the rapidity space alone. The enhancement is about eight-fold for the slope of the F_2 moments. Although our F_2 moments are consistent with the TASSO data, there are some disagreements with the F_3 moments above $M \sim 100$.

The factorial moments at fixed rapidity position have also been measured with a slightly different normalization. They are consistent with the F_2 and F_3 calculated from the k-values in the negative binomial fits to the multiplicity distributions in various rapidity windows.

This work was supported in part by the U.S. Department of Energy, Division of High Energy Physics, under contract W-31-109-ENG-38.

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Table 1

The intermittency slopes (a_i) of the $-\ell n\delta y$ vs. ℓnF_i plot in the small δy region ($-\ell n\delta y \gtrsim 0.5$).

a_i	Flat Rapidity Region $Y_o = 4$	Full Rapidity Region $Y_o = 10$
a_2	0.021 ± 0.002	0.025 ± 0.003
a_3	0.063 ± 0.009	0.073 ± 0.010
a_4	0.202 ± 0.080	0.245 ± 0.100
a_5	0.469 ± 0.250	0.623 ± 0.340

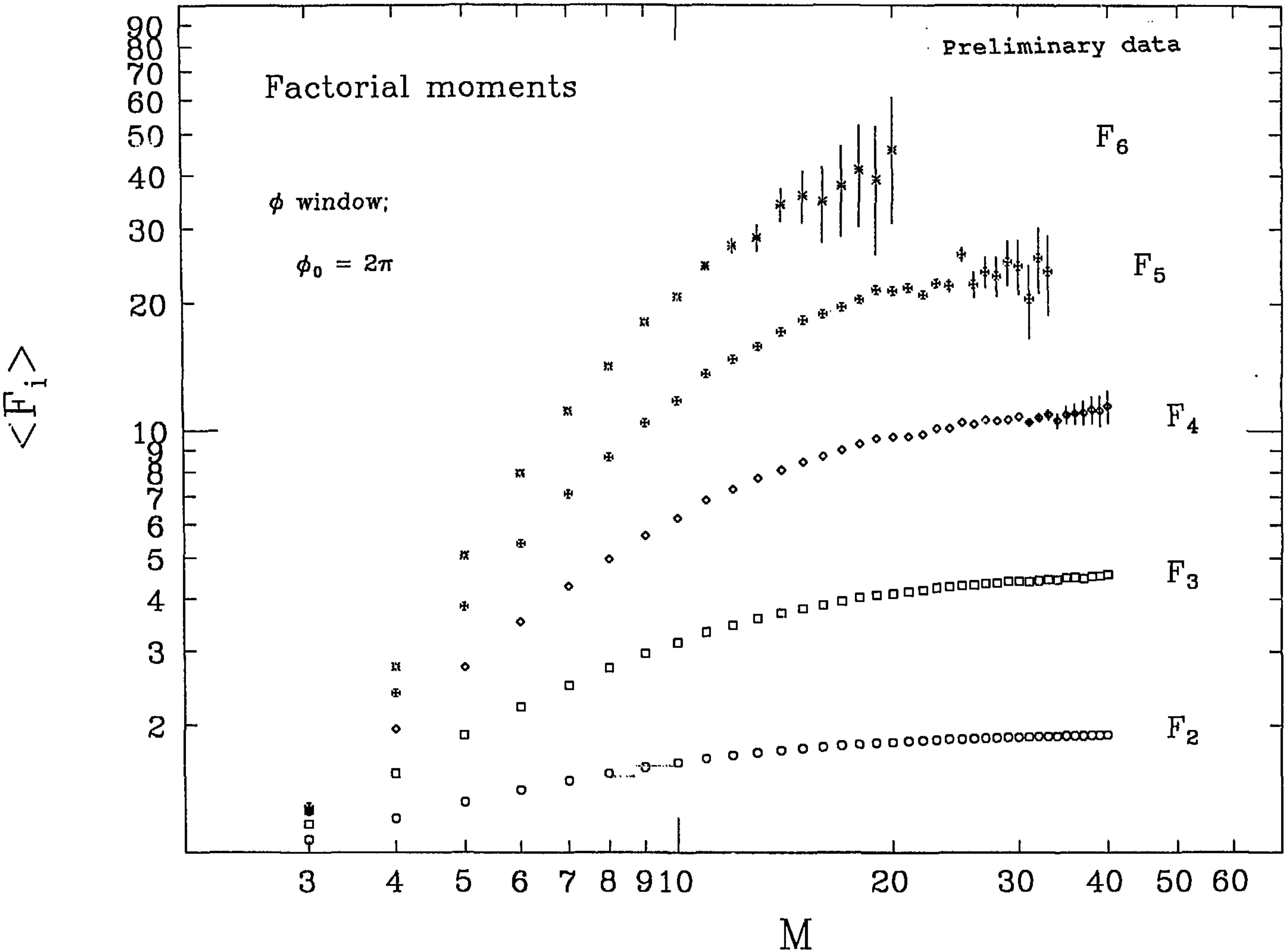
Figure Captions

1. The normalized factorial moments of charged particles in the full azimuthal angle range between $\phi_{beam} = 0$ and $\phi_{beam} = 2\pi$. The abscissa is the number of divisions of the total length ϕ_o.

2. The normalized factorial moments (F_i) of charged particles in the rapidity range between $y = -2$ and $y = +2$ for the inclusive sample. The abscissa is $-\ln\delta y$, where δy is a rapidity window Y_o/M ($M = 1, 2, 3, \ldots, 40$).

3. The normalized factorial moments in the two-dimensional space of y and ϕ_{jet}. The abscissa is the total number of grids with $M = 1, 4, 9, 16, \ldots, 1600$.

4. The normalized factorial moments at the rapidity center of $y = 0$ (without horizontal averaging) averaged over all events for the inclusive sample. The normalization factor is described in the text. Superimposed are the data derived from the k-values in negative binomial fits to the distributions in various rapidity windows.



Preliminary data
Factorial moments
ϕ window;
$\phi_0 = 2\pi$
F_6
F_5
F_4
F_3
F_2
$\langle F_i \rangle$
M

Fig. 1

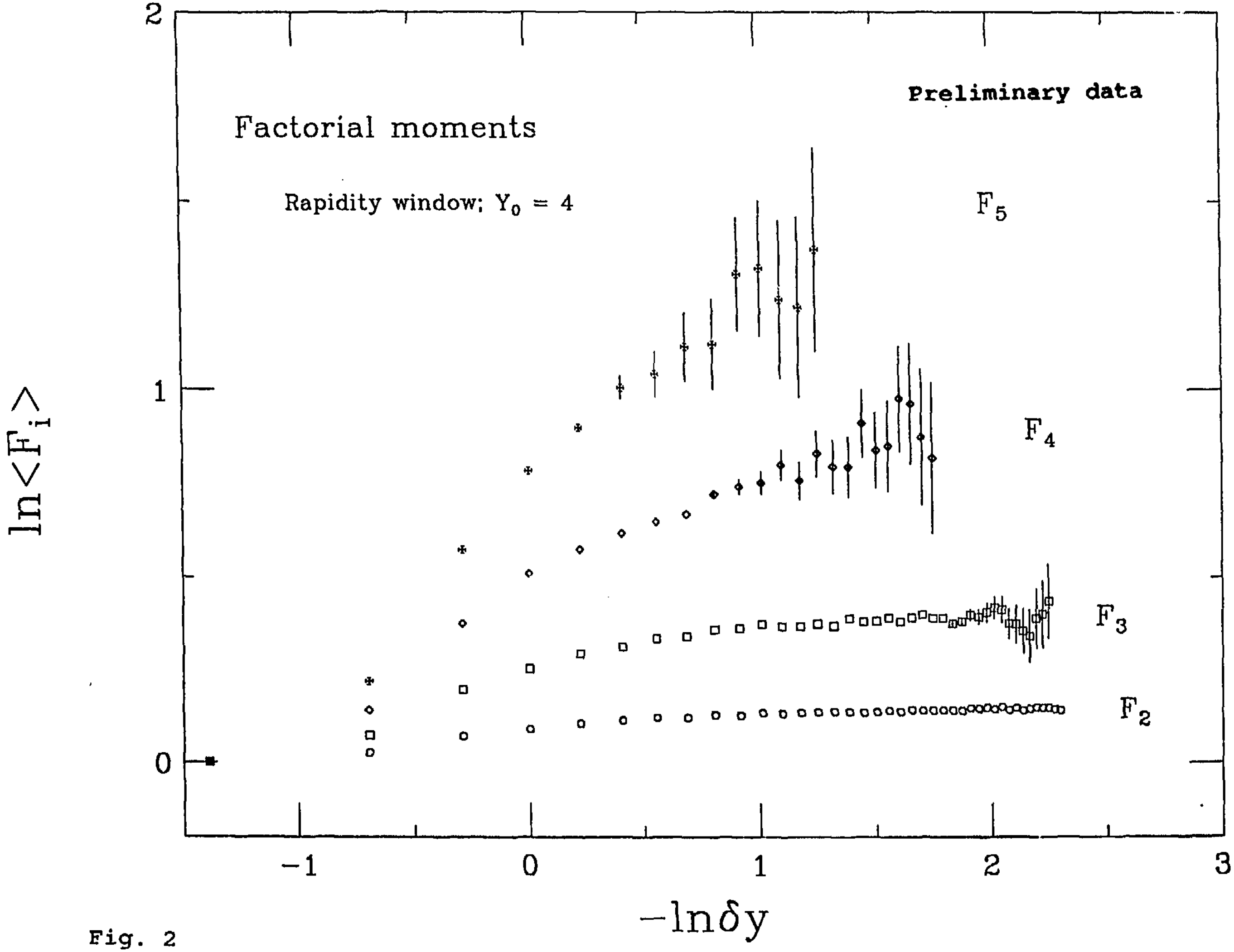

Preliminary data
Factorial moments
Rapidity window; $Y_0 = 4$
F_5
F_4
F_3
F_2
$\ln\langle F_i \rangle$
$-\ln\delta y$
2
1
0
−1
0
1
2
3

Fig. 2

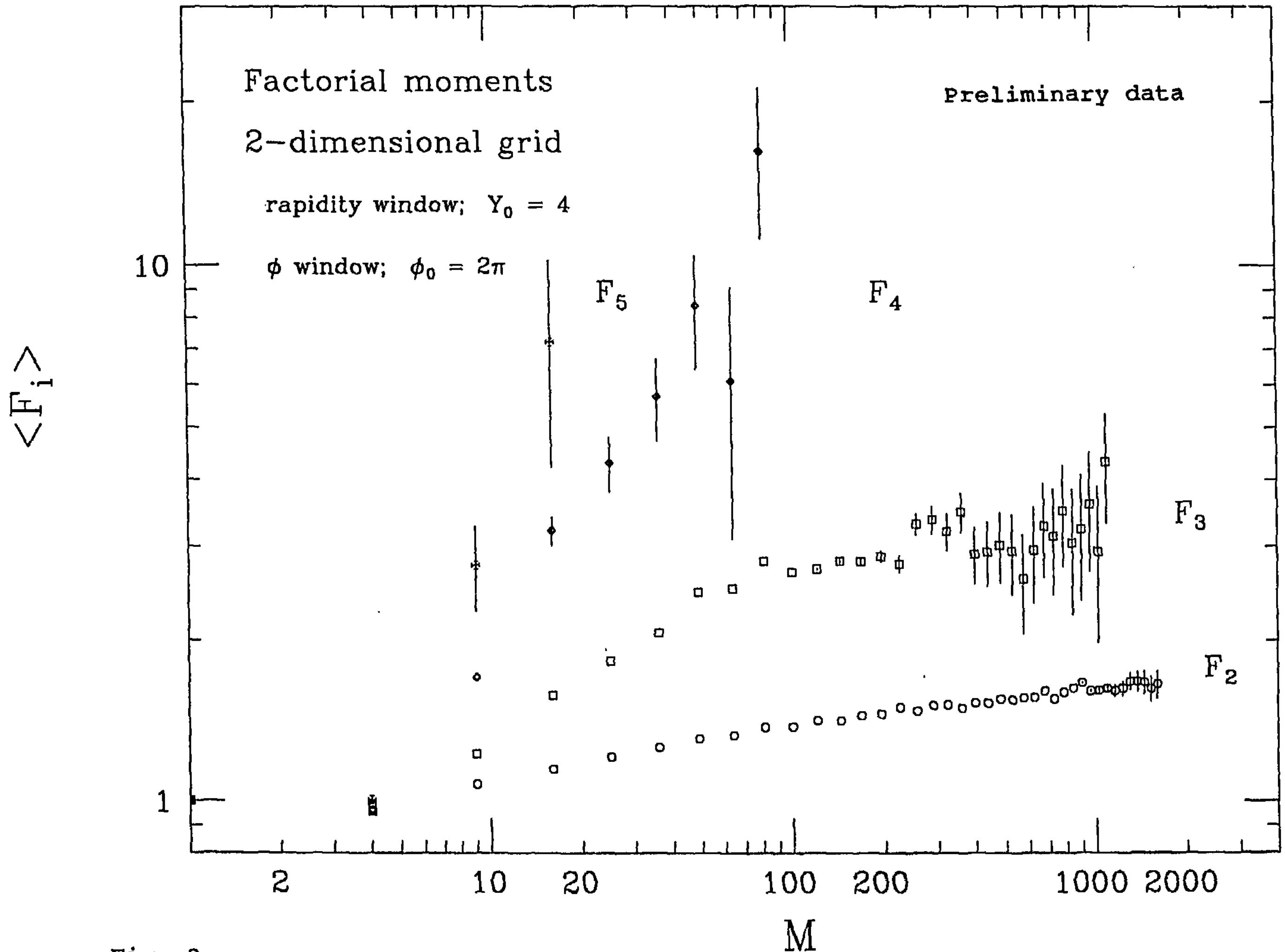

Factorial moments
2–dimensional grid
rapidity window; $Y_0 = 4$
ϕ window; $\phi_0 = 2\pi$
Preliminary data
F_5
F_4
F_3
F_2
10
1
2
10
20
100
200
1000
2000
M
$<F_i>$

Fig. 3

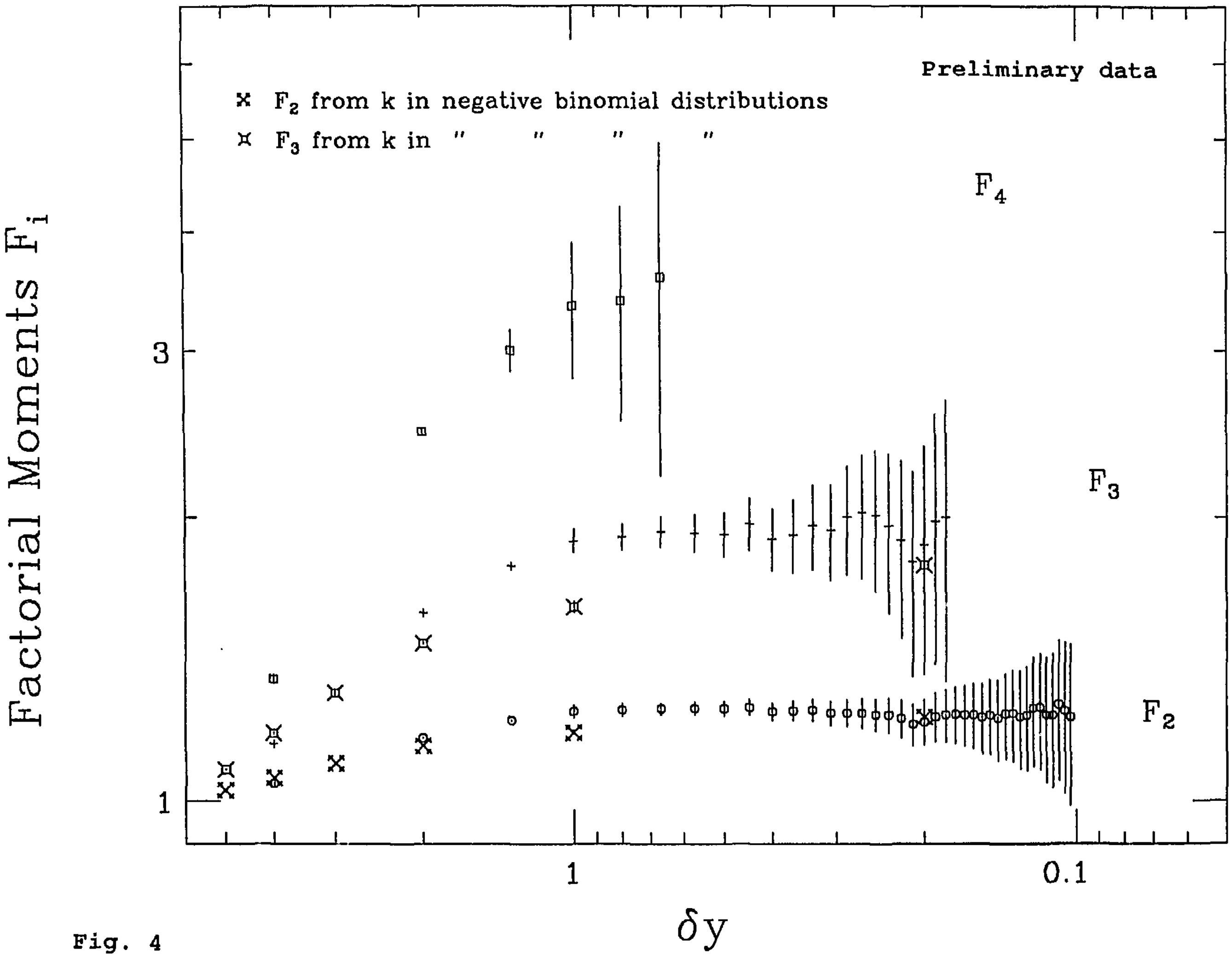

Preliminary data
× F2 from k in negative binomial distributions
⌑ F3 from k in " " " "
F4
F3
F2
Factorial Moments Fi
3
1
1
0.1
δy

Fig. 4