EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN–EP/90-78

8 June 1990

A Study for Intermittency in Hadronic Z^0 Decays

DELPHI Collaboration

Abstract

The correlations in rapidity in hadron production from e^+e^- annihilation near the Z^0 resonance were studied by means of the method of factorial moments, using data taken with the DELPHI detector at LEP. The parton shower hadronization model was found to be in quantitative agreement with the data, in contrast with previous results at lower energies.

(Submitted to Physics Letters B)

P.Abreu[16], W.Adam[37], F.Adami[28], T.Adye[27], G.D.Alexeev[12], J.V.Allaby[7], P.Allen[36], S.Almehed[19], F.Alted[36], S.J.Alvsvaag[4], U.Amaldi[7], E.Anassontzis[3], W-D.Apel[13], B.Asman[32], C.Astor Ferreres[30], J-E.Augustin[15], A.Augustinus[7], P.Baillon[7], P.Bambade[15], F.Barao[16], G.Barbiellini[34], D.Y.Bardin[12], A.Baroncelli[29], O.Barring[19], W.Bartl[37], M.J.Bates[25], M.Baubillier[18], K-H.Becks[39], C.J.Beeston[25], P.Beilliere[6], I.Belokopytov[31], P.Beltran[9], D.Benedic[8], J.M.Benlloch[36], M.Berggren[32], D.Bertrand[2], S.Biagi[17], F.Bianchi[33], J.H.Bibby[25], M.S.Bilenky[12], P.Billoir[18], J.Bjarne[19], D.Bloch[8], P.N.Bogolubov[12], D.Bollini[5], T.Bolognese[28], M.Bonapart[22], P.S.L.Booth[17], M.Boratav[18], P.Borgeaud[28], G.Borisov[31], H.Borner[25], C.Bosio[29], O.Botner[35], B.Bouquet[15], M.Bozzo[10], S.Braibant[7], P.Branchini[29], K.D.Brand[39], R.A.Brenner[11], C.Bricman[2], R.C.A.Brown[7], N.Brummer[22], J-M.Brunet[6], L.Bugge[24], T.Buran[24], H.Burmeister[7], C.Buttar[25], J.A.M.A.Buytaert[2], M.Caccia[20], M.Calvi[20], A.J.Camacho Rozas[30], J-E.Campagne[7], A.Campion[17], T.Camporesi[7], V.Canale[29], F.Cao[2], L.Carroll[17], C.Caso[10], E.Castelli[34], M.V.Castillo Gimenez[36], A.Cattai[7], F.R.Cavallo[5], L.Cerrito[29], P.Charpentier[7], P.Checchia[26], G.A.Chelkov[12], L.Chevalier[28], P.Chliapnikov[31], V.Chorowicz[18], R.Cirio[33], M.P.Clara[33], J.L.Contreras[36], R.Contri[10], G.Cosme[15], F.Couchot[15], H.B.Crawley[1], D.Crennell[27], M.Cresti[26], G.Crosetti[10], N.Crosland[25], M.Crozon[6], J.Cuevas Maestro[30], S.Czellar[11], S.Dagoret[15], E.Dahl-Jensen[21], B.Dalmagne[15], M.Dam[7], G.Damgaard[21], G.Darbo[10], E.Daubie[2], M.Davenport[7], P.David[18], A.De Angelis[34], M.De Beer[28], H.De Boeck[2], W.De Boer[13], C.De Clercq[2], M.D.M.De Fez Laso[36], N.De Groot[22], C.De La Vaissiere[18], B.De Lotto[34], A.De Min[20], C.Defoix[6], D.Delikaris[7], P.Delpierre[6], N.Demaria[33], L.Di Ciaccio[29], A.N.Diddens[22], H.Dijkstra[7], F.Djama[8], J.Dolbeau[6], K.Doroba[38], M.Dracos[8], J.Drees[39], M.Dris[23], W.Dulinski[8], R.Dzhelyadin[31], D.N.Edwards[17], L-O.Eek[35], P.A.-M.Eerola[11], T.Ekelof[35], G.Ekspong[32], J-P.Engel[8], V.Falaleev[31], A.Fenyuk[31], M.Fernandez Alonso[30], A.Ferrer[36], S.Ferroni[10], T.A.Filippas[23], A.Firestone[1], H.Foeth[7], E.Fokitis[23], F.Fontanelli[10], H.Forsbach[39], B.Franek[27], K.E.Fransson[35], P.Frenkiel[6], D.C.Fries[13], R.Fruhwirth[37], F.Fulda-Quenzer[15], H.Furstenau[13], J.Fuster[7], J.M.Gago[16], G.Galeazzi[26], D.Gamba[33], U.Gasparini[26], P.Gavillet[7], S.Gawne[17], E.N.Gazis[23], P.Giacomelli[5], K-W.Glitza[39], R.Gokieli[18], V.M.Golovatyuk[12], A.Goobar[32], G.Gopal[27], M.Gorski[38], Y.N.Gotra[12], V.Gracco[10], A.Grant[7], F.Grard[2], E.Graziani[29], M-H.Gros[15], G.Grosdidier[15], B.Grossetete[18], S.Gumenyuk[31], J.Guy[27], F.Hahn[39], M.Hahn[13], S.Haider[7], Z.Hajduk[14], A.Hakansson[19], A.Hallgren[35], K.Hamacher[39], G.Hamel De Monchenault[28], F.J.Harris[25], B.Heck[7], I.Herbst[39], J.J.Hernandez[36], P.Herquet[2], H.Herr[7], E.Higon[36], H.J.Hilke[7], T.Hofmokl[38], R.Holmes[1], S-O.Holmgren[32], J.E.Hooper[21], M.Houlden[17], J.Hrubec[37], P.O.Hulth[32], K.Hultqvist[32], D.Husson[8], B.D.Hyams[7], P.Ioannou[3], P-S.Iversen[4], J.N.Jackson[17], P.Jalocha[14], G.Jarlskog[19], P.Jarry[28], B.Jean-Marie[15], E.K.Johansson[32], M.Jonker[7], L.Jonsson[19], P.Juillot[8], R.B.Kadyrov[12], G.Kalkanis[3], G.Kalmus[27], G.Kantardjian[7], F.Kapusta[18], P.Kapusta[14], S.Katsanevas[3], E.C.Katsoufis[23], R.Keranen[11], J.Kesteman[2], B.A.Khomenko[12], B.King[17], H.Klein[7], W.Klempt[7], A.Klovning[4], P.Kluit[2], J.H.Koehne[13], B.Koene[22], P.Kokkinias[9], M.Kopf[13], M.Koratzinos[7], K.Korcyl[14], B.Korzen[7], C.Kourkoumelis[3], T.Kreuzberger[37], J.Krolikowski[38], U.Kruener-Marquis[39], W.Krupinski[14], W.Kucewicz[20], K.Kurvinen[11], M.I.Laakso[11], C.Lambropoulos[9], J.W.Lamsa[1], L.Lanceri[34], V.Lapin[31], J-P.Laugier[28], R.Lauhakangas[11], P.Laurikainen[11], G.Leder[37], F.Ledroit[6], J.Lemonne[2], G.Lenzen[39], V.Lepeltier[15], A.Letessier-Selvon[18], E.Lieb[39], E.Lillestol[7], E.Lillethun[4], J.Lindgren[11], I.Lippi[26], R.Llosa[36], B.Loerstad[19], M.Lokajicek[12], J.G.Loken[25], M.A.Lopez Aguera[30], A.Lopez-Fernandez[15], D.Loukas[9], J.J.Lozano[36], R.Lucock[27], B.Lund-Jensen[35], P.Lutz[6], L.Lyons[25], G.Maehlum[7], J.Maillard[6], A.Maltezos[9], F.Mandl[37], J.Marco[30], J-C.Marin[7], A.Markou[9], L.Mathis[6], C.Matteuzzi[20], G.Matthiae[29], M.Mazzucato[26], M.Mc Cubbin[17], R.Mc Kay[1], E.Menichetti[33], C.Meroni[20], W.T.Meyer[1], W.A.Mitaroff[37], G.V.Mitselmakher[12], U.Mjoernmark[19], T.Moa[32], R.Moeller[21], K.Moenig[39], M.R.Monge[10], P.Morettini[10], H.Mueller[13], H.Muller[7], G.Myatt[25], F.Naraghi[18], U.Nau-Korzen[39], F.L.Navarria[5], P.Negri[20], B.S.Nielsen[21], M.Nigro[26], V.Nikolaenko[31], V.Obraztsov[31], T.Odegaard[24], R.Orava[11], A.Ostankov[31], A.Ouraou[28], R.Pain[18], H.Palka[14], T.Papadopoulou[23], L.Pape[7], P.Pasini[5], A.Passeri[29], M.Pegoraro[26], V.Perevozchikov[31], M.Pernicka[37], M.Pimenta[16], O.Pingot[2], C.Pinori[26], A.Pinsent[25], M.E.Pol[16], G.Polok[14], P.Poropat[34], V.N.Pozdnyakov[12], P.Privitera[5], A.Pullia[20], J.Pyyhtia[11], A.A.Rademakers[22], D.Radojicic[25], S.Ragazzi[20], W.H.Range[17], P.N.Ratoff[25], A.L.Read[24], N.G.Redaelli[20], M.Regler[37], D.Reid[17], P.B.Renton[25], L.K.Resvanis[3], F.Richard[15], J.Ridky[12], G.Rinaudo[33], I.Roditi[7], A.Romero[33], P.Ronchese[26], E.I.Rosenberg[1], U.Rossi[5], E.Rosso[7], P.Roudeau[15], T.Rovelli[5], V.Ruhlmann[28], A.Ruiz[30], H.Saarikko[11], Y.Sacquin[28], E.Sanchez[36], J.Sanchez[36], E.Sanchis[36], M.Sannino[10], M.Schaeffer[8], H.Schneider[13], F.Scuri[34], A.Sebastia[36], Y.V.Sedykh[12], A.M.Segar[25], R.Sekulin[27], M.Sessa[34], G.Sette[10], R.Seufert[13], R.C.Shellard[7], P.Siegrist[28], S.Simonetti[10], F.Simonetto[26], A.N.Sissakian[12], T.B.Skaali[24], J.Skeens[1], G.Skjevling[24], G.Smadja[28], N.E.Smirnov[31], G.R.Smith[27], R.Sosnowski[38], K.Spang[21], T.Spassoff[12], E.Spiriti[29], S.Squarcia[10], H.Staeck[39], C.Stanescu[29], G.Stavropoulos[9], F.Stichelbaut[2], A.Stocchi[20], J.Strauss[37], R.Strub[8], C.J.Stubenrauch[7], M.Szczekowski[38], M.Szeptycka[38], P.Szymanski[38], S.Tavernier[2], E.Tchernyaev[31], G.Theodosiou[9], A.Tilquin[6], J.Timmermans[22], L.G.Tkatchev[12], D.Z.Toet[22], A.K.Topphol[4], L.Tortora[29], D.Treille[7], U.Trevisan[10], G.Tristram[6], C.Troncon[20], E.N.Tsyganov[12], M.Turala[14], R.Turchetta[8], M-L.Turluer[28], T.Tuuva[11], I.A.Tyapkin[12], M.Tyndel[27], S.Tzamarias[7], F.Udo[22], S.Ueberschaer[39], V.A.Uvarov[31], G.Valenti[5], E.Vallazza[33], J.A.Valls Ferrer[36], G.W.Van Apeldoorn[22], P.Van Dam[22], W.K.Van Doninck[2], N.Van Eijndhoven[7], C.Vander Velde[2], J.Varela[16], P.Vaz[16], G.Vegni[20], M.E.Veitch[25], J.Velasco[36], L.Ventura[26], W.Venus[27], F.Verbeure[2], L.S.Vertogradov[12], L.Vibert[18], D.Vilanova[28], N.K.Vishnevskiy[31], E.V.Vlasov[31], A.S.Vodopyanov[12], M.Vollmer[39], G.Voulgaris[3], M.Voutilainen[11], V.Vrba[12], H.Wahlen[39], C.Walck[32], F.Waldner[34], M.Wayne[1], P.Weilhammer[7], J.Werner[39], A.M.Wetherell[7], J.H.Wickens[2], W.S.C.Williams[25], M.Winter[8], D.Wormald[24], G.Wormser[15], K.Woschnagg[35], N.Yamdagni[32], P.Yepes[22], A.Zaitsev[31], A.Zalewska[14], P.Zalewski[38], E.Zevgolatakos[9], G.Zhang[39], N.I.Zimin[12], R.Zitoun[18], R.Zukanovich Funchal[6], G.Zumerle[26], J.Zuniga[36]

[1]Ames Laboratory and Department of Physics, Iowa State University, Ames IA 50011, USA
[2]Physics Department, Univ. Instelling Antwerpen, Universiteitsplein 1, B-2610 Wilrijk, Belgium
and IIHE, ULB-VUB, Pleinlaan 2, B-1050 Brussels, Belgium
and Service de Phys. des Part. Elém., Faculté des Sciences, Université de l'Etat Mons, Av. Maistriau 19, B-7000 Mons, Belgium
[3]Physics Laboratory, University of Athens, Solonos Str. 104, GR-10680 Athens, Greece
[4]Department of Physics, University of Bergen, Allégaten 55, N-5007 Bergen, Norway
[5]Dipartimento di Fisica, Università di Bologna and INFN, Via Irnerio 46, I-40126 Bologna, Italy
[6]Collège de France, Lab. de Physique Corpusculaire, 11 pl. M. Berthelot, F-75231 Paris Cedex 05, France
[7]CERN, CH-1211 Geneva 23, Switzerland
[8]Division des Hautes Energies, CRN - Groupe DELPHI, B.P. 20 CRO, F-67037 Strasbourg Cedex, France
[9]Greek Atomic Energy Commission, Nucl. Research Centre Demokritos, P.O. Box 60228, GR-15310 Aghia Paraskevi, Greece
[10]Dipartimento di Fisica, Università di Genova and INFN, Via Dodecaneso 33, I-16146 Genova, Italy
[11]Dept. of High Energy Physics, University of Helsinki, Siltavuorenpenger 20 C, SF-00170 Helsinki 17, Finland
[12]Joint Institute for Nuclear Research, Dubna, Head Post Office, P.O. Box 79, 101 000 Moscow, USSR.
[13]Institut für Experimentelle Kernphysik, Universität Karlsruhe, Postfach 6980, D-7500 Karlsruhe 1, FRG
[14]High Energy Physics Laboratory, Institute of Nuclear Physics, Ul. Kawiory 26 a, PL-30055 Krakow 30, Poland
[15]Université de Paris-Sud, Lab. de l'Accélérateur Linéaire, Bat 200, F-91405 Orsay, France
[16]LIP, Av. Elias Garcia 14 - 1e, P-1000 Lisbon Codex, Portugal
[17]Department of Physics, University of Liverpool, P.O. Box 147, GB - Liverpool L69 3BX, UK
[18]LPNHE, Universités Paris VI et VII, Tour 33 (RdC), 4 place Jussieu, F-75230 Paris Cedex 05, France
[19]Department of Physics, University of Lund, Sölvegatan 14, S-22363 Lund, Sweden
[20]Dipartimento di Fisica, Università di Milano and INFN, Via Celoria 16, I-20133 Milan, Italy
[21]Niels Bohr Institute, Blegdamsvej 17, DK-2100 Copenhagen 0, Denmark
[22]NIKHEF-H, Postbus 41882, NL-1009 DB Amsterdam, The Netherlands
[23]National Technical University, Physics Department, Zografou Campus, GR-15773 Athens, Greece
[24]Physics Department, University of Oslo, Blindern, N-1000 Oslo 3, Norway
[25]Nuclear Physics Laboratory, University of Oxford, Keble Road, GB - Oxford OX1 3RH, UK
[26]Dipartimento di Fisica, Università di Padova and INFN, Via Marzolo 8, I-35131 Padua, Italy
[27]Rutherford Appleton Laboratory, Chilton, GB - Didcot OX11 OQX, UK
[28]CEN-Saclay, DPhPE, F-91191 Gif-sur-Yvette Cedex, France
[29]Istituto Superiore di Sanità, Ist. Naz. di Fisica Nucl. (INFN), Viale Regina Elena 299, I-00161 Rome, Italy
and Dipartimento di Fisica, Università di Roma II and INFN, Tor Vergata, I-00173 Rome.
[30]Facultad de Ciencias, Universidad de Santander, av. de los Castros, E - 39005 Santander, Spain
[31]Inst. for High Energy Physics, Serpukow P.O. Box 35, Protvino, (Moscow Region), USSR.
[32]Institute of Physics, University of Stockholm, Vanadisvägen 9, S-113 46 Stockholm, Sweden
[33]Dipartimento di Fisica Sperimentale, Università di Torino and INFN, Via P. Giuria 1, I-10125 Turin, Italy
[34]Dipartimento di Fisica, Università di Trieste and INFN, Via A. Valerio 2, I-34127 Trieste, Italy
and Istituto di Fisica, Università di Udine, I-33100 Udine, Italy
[35]Department of Radiation Sciences, University of Uppsala, P.O. Box 535, S-751 21 Uppsala, Sweden
[36]Inst. de Fisica Corpuscular IFIC, Centro Mixto Univ. de Valencia-CSIC, Avda. Dr. Moliner 50, E-46100 Burjassot (Valencia), Spain
[37]Institut für Hochenergiephysik, Öesterreich Akad. d. Wissensch., Nikolsdorfergasse 18, A-1050 Vienna, Austria
[38]Inst. Nuclear Studies and, University of Warsaw, Ul. Hoza 69, PL-00681 Warsaw, Poland
[39]Fachbereich Physik, University of Wuppertal, Postfach 100 127, D-5600 Wuppertal 1, FRG

1 Introduction

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 [1], and immediately after in cosmic ray events [2]. Evidence of such clusters of particles in narrow (pseudo)rapidity intervals, incompatible with the predictions of many classical hadronization models, has been produced from accelerator experiments studying nucleus-nucleus [3, 4, 5] and hadron-hadron [6, 7, 8] collisions. A short review of the experimental data has been presented in Ref. [9]. Mathematical techniques and terminology which have been developed to describe such large fluctuations in non-Hamiltonian systems, turbulence in particular [10], were adapted to describe this phenomenon [11], which was given the name of *intermittency.*

Intermittency in hadron collisions has led to speculations of possible evidence for hadronic phase transitions [12], hadronic Cherenkov radiation [13], hadronic hydrodynamics [14], or simply self-similar cascading mechanisms [11, 15, 16, 17]. Recently intermittency effects have also been claimed in e^+e^- annihilation [18, 19]. This strongly favours the cascading mechanism, since hadronic reaction mechanisms, such as phase transitions, are unlikely in this case. However, presently used cascade models fail to reproduce the effect at centre of mass energies around 30 GeV. Furthermore, the predictions of various models for e^+e^- interactions differ considerably at high energies [20]. A short review of the present status of the theoretical descriptions of the phenomenon is presented in Ref. [21].

This letter describes an investigation of intermittency effects in e^+e^- annihilation at a centre of mass energy of 91 GeV, using data collected with the DELPHI detector [22] 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). Data on intermittency are compared with 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.

2 Experimental procedure and event selection

The sample of events used in the analysis was collected by the DELPHI detector at the LEP e^+e^- collider during its first months of operation (August-December 1989). A description of the DELPHI detector can be found elsewhere [22]. Features of the apparatus relevant for the analysis of multi-hadronic final states (with emphasis on the detection of charged particles) are outlined in Ref. [23]. The present analysis relies on the information provided by:

- The Inner Detector (ID), a cylindrical drift chamber (inner radius = 12 cm, outer radius = 28 cm) covering polar angles between 29° and 151°.

- The Time Projection Chamber (TPC), a cylinder with 30 cm inner and 122 cm outer radius and a length of 2.7 m. For a polar angle θ between 22° and 158° at least 4 space points are available for track reconstruction, while for angles between 39° and 141° up to 16 space points can be used.

- The Outer Detector (OD), 5 layers of drift cells arranged in a cylinder at a radius between 198 and 208 cm, and covering the polar angle between 50° and 130°.

A quarter of the data used in this analysis were taken with a reduced magnetic field of 0.7 T, the remainder with the full field of 1.2 T.

Only charged particles fulfilling the following criteria were used:

a. Impact parameter at the nominal primary vertex less than 5 cm in radius r from the beam axis and less than 10 cm along the beam axis (z).

b. Momentum p greater than 0.1 GeV/c.

c. Measured track length greater than 50 cm.

d. Polar angle θ between 25° and 155°.

Hadronic events were then selected by requiring that α. in each of the two hemispheres, $cos\theta$ less than and greater than 0, the total energy of the charged particles $E_{ch} = \Sigma E_i$ was larger than 3 GeV, where E_i are the particle energies (assuming $\pi^{\pm}$ mass for the particles);

β. the total energy of the charged particles seen in both hemispheres together exceeded 15 GeV;

γ. there were at least 5 charged particles with momenta above 0.2 GeV/c;

δ. the polar angle θ of the sphericity axis was between 40^o and 140^o (this ensures that the selected events were largely contained inside the TPC).

A total of 2080 events from the reduced field sample and 5673 events from the full field sample satisfied these cuts. Events due to beam-gas scattering and to $\gamma\gamma$ interactions have been estimated to be less than 0.1% of the sample; background from $\tau^+\tau^-$ events was calculated to be less than 0.2%.

3 Analysis

Intermittency is usually investigated by studying the factorial moments of the (pseudo)rapidity distribution of the collision products. Factorial moments of rank q for a rapidity interval δy act as a filter for selecting events with more than q particles in at least one bin and are therefore highly sensitive to events with large density fluctuations.

The definition of the factorial moments of the experimental distribution is not unique in the literature. 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 ($m = 1...M$), most authors define the factorial moment of rank q of the distribution with respect to the partition as

$$F_q(\delta y) = \frac{M^{q-1}}{< N >^q} < \sum_{m=1}^{M} n_m(n_m - 1)...(n_m - q + 1) > \qquad (1a)$$

where the brackets indicate the average over many events. Other definitions in the literature are equivalent to (1a) in the limit of a large number of events, and/or a smooth (pseudo)rapidity distribution.

Another class of definitions used in the literature [17], using a different normalization, is *not* equivalent. This second class can be reduced to the form

$$\tilde{F}_q(\delta y) = M^{q-1} < \sum_m \frac{n_m(n_m-1)...(n_m-q+1)}{N(N-1)...(N-q+1)} > \qquad (1b)$$

The prediction from a self-similar random cascade model of hadronization inspired by turbulence theory is that for q above 1 the growth of F_q (or $\tilde{F}_q$) will asymptotically (for $\delta y \to 0$) follow a power law

$$F_q \propto (1/\delta y)^{f_q} \qquad (2)$$

with $f_q > 0$ (or, in the same way, $\tilde{F}_q \propto (1/\delta y)^{\tilde{f}_q}$ with $\tilde{f}_q > 0$). On the contrary, random uncorrelated particle production would give $F_q \approx const$ for all values of q.

Another prediction from self-similar hadronization models [15] states that the quantity

$$\alpha_q = \frac{2 \cdot f_q}{q(q-1)} \qquad (3)$$

should be independent of the rank q.

In this letter the experimental results on factorial moments will be compared with the predictions of:

1. the JETSET 6.3 [24] parton shower model (referred to as JETSET 6.3 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 7.2 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 [25, 23] to describe correctly the rapidity distribution (JETSET 7.2 ME retuned).

The essential features of these hadronization models are summarized in Ref.[20]. Both 1. and 3. (this last by construction) reproduce correctly the overall rapidity distribution as observed in the DELPHI experiment, but a disagreement is observed with model 2 [23], which predicts a significantly lower number of particles in the central region.

The Monte Carlo simulation DELSIM [26] was used to correct the data for the geometrical acceptance, kinematical cuts, resolution, particle interaction with the detector material and other detector imperfections. A sample of 10^5 hadronic Z decay events was generated with JETSET 6.3 PS. About 20% of them have been followed through this detailed simulation of the detector. From the samples of accepted and generated events, correction factors

$$C(\delta y) = \frac{F(\delta y)_{generated}}{F(\delta y)_{accepted}}$$

were computed. These factors were then used to correct the factorial moments calculated from the real data. The generated event sample contained all final state particles with a lifetime above 10^{-9} s before any tracking was done through the detector, from the sample of 10^5 events. The accepted event sample contained all final state particles observed after tracking the $2\,10^4$ fully simulated events through the DELPHI detector and processing them through the same reconstruction and analysis chain as the real data.

4 Results

The rapidity

$$y = -\frac{1}{2}\ln\frac{E - p_{||}}{E + p_{||}}$$

was calculated with respect to the sphericity axis, assuming each charged particle to have the mass of a $\pi^{\pm}$. The average resolution in rapidity, Δy, on a single track was estimated by Monte Carlo to be about 0.04 for the selected sample of charged particles. The clustering of up to 5 charged particles in a single bin can be therefore resolved down to a bin size δy as small as $\delta y \simeq 0.1$.

Factorial moments of ranks between 2 and 5 were determined from the data for y between -2 and 2, using definition (1a).

Fig. 1 compares the uncorrected factorial moments for our data sample with those calculated from the accepted events from JETSET 6.3 PS simulation, after detector simulation. The error bars take into account the correlations between numerator and denominator of Eq.(1a). Data are in reasonable agreement with the Monte Carlo. It is therefore assumed that simulated data can be used to correct for detector effects and radiative corrections. The correction factors differ from 1.0 by less than 5% on average, and decrease slightly as the bin size δy decreases.

Expression (1a) is in principle a biased estimator of the "true" value of the factorial moments. The effect of bias has been checked by comparing the factorial moments of a Monte Carlo sample (JETSET 6.3 PS at generator level) of the size of the data sample with a ten times larger sample. Results from both samples are in good agreement, indicating that present statistics is adequate to make the bias negligible.

Fig. 2 compares the corrected factorial moments with the predictions at generator level of JETSET 6.3 PS, JETSET 7.2 ME and JETSET 7.2 ME retuned. The statistical uncertainty in the correction factor was added in quadrature to the error on uncorrected data. Experimental results on factorial moments are tabulated in Table 1 (uncorrected factorial moments) and in Table 2 (corrected factorial moments).

As shown in Fig. 2 there is a reasonable agreement between the data and the PS model, whereas 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. [27]. The retuning of the fragmentation parameters for the longitudinal and transverse momenta, such that the multiplicity and rapidity in the ME model agree with the same distributions in the PS model [25, 23], causes a drastic change both in the magnitude of the factorial moments and in the shape of their distribution for small values of δy, such that the prediction of the Monte Carlo agrees with the data within 15%. This retuning reduces the density of particles in a jet [1] and therefore reduces the probability for finding two or more particles in the same phase space volume.

In the study by the TASSO Collaboration[19] a striking disagreement has been observed between factorial moment of rank 3 and the prediction of JETSET 6.3 PS. In Fig. 3 we compare this factorial moment at $\sqrt{s}\simeq$ 35 GeV with DELPHI data at 91 GeV together with the corresponding Monte Carlo predictions [2]. As is apparent, we do not observe this disagreement, nor the increase in the factorial moments of rank 3 for large M.

[1]The variance of the Gaussian distribution for the transverse momenta was increased from 370 to 500 MeV, while the longitudinal momentum spectrum was softened until the charged multiplicity increased by about 3 units as required by the data.

[2]Here the factorial moments were calculated according to definition (1b) in order to be comparable with the TASSO 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 $\delta y < 0.4$ with a slope (f_q).

Two critical points for the determination of the slope (f_q) are:

a. fitting the factorial moments which are highly correlated;

b. choosing the interval for the fit.

The following method was used to take into account correlations in the fit. For each rank separately, the covariance matrix of the factorial moments was computed from the data. Errors shown are the square roots of the diagonal elements of this matrix. The covariance matrix was used in a standard linear least square fit.

We first have made a fit in the same range as TASSO, for δy between 0.7 and 0.12 ($6 \leq M \leq 32$) [19]. The results, plotted in Fig. 4a and tabulated in Tab. 3, are compatible with the values derived by TASSO. In contrast with TASSO, however, a fair agreement with the predictions of JETSET 6.3 PS was found for all ranks (Fig. 4 and Table 3). The values of α_q, as defined by Eq. (3), appear roughly to be independent of q, as observed previously at PETRA energies and expected in the cascade picture (Fig. 4b and Table 3).

By extending the fitting range to a larger value of M (M=40, corresponding to $\delta y = 0.1$) the values of the fitted slopes become slightly smaller. Removing from the fit the three leftmost points is enough to make the slopes compatible with 0 within two standard deviations for all ranks. Moreover, *for any choice of the fitting region*, the fitted slopes are compatible (within two standard deviations) with those predicted by JETSET 6.3 PS, again in contrast to the observation by the TASSO collaboration [19].

It has been verified that the slopes f_q (from definition (1a) of the factorial moments) and $\tilde{f}_q$ (from definition (1b)) are compatible within the experimental errors.

In order to check the influence of Bose-Einstein correlations on these results, the following analysis was made. 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}. The result of the comparison between F_{q+} and F_{qr} has been summarized in Fig. 5, where $\ln(F_{q+}/F_{qr})$ has been plotted versus the number M of subdivisions of the rapidity interval for the events with N_{i+} above 3. 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 [27].

A further study has been made on the factorial moments when rapidity y_z is defined with respect to the beam axis. The region of rapidity between -2 and +2 has been examined, and the same procedure has been followed as before. In this case small rapidities correspond to particles at a polar angle around 90°. Since the sample includes only events with sphericity axis between 40° and 140°, this study is more sensitive to intermittency effects in the core of the jets, while the previous analysis was more sensitive to the particles with large angles to the sphericity axis.

Factorial moments of rapidity defined with respect to the beam axis are plotted in Fig. 6. Their values are larger than the corresponding ones with the rapidity defined with respect to the sphericity axis, as expected from the larger density of particles in the core of a jet. Also in this case, the data are well reproduced by JETSET 6.3 PS, but not by JETSET 7.2 ME with default parameters. This discrepancy is strongly reduced after retuning.

5 Conclusions

The density fluctuations in phase space in e^+e^- annihilation, as analyzed by the dependence of the factorial moments on the size of the rapidity window δy, were found to contain features expected by cascade models. The detailed behaviour shows a strong increase of the reduced factorial moments with decreasing resolution δy, and a flattening off for δy below 0.4. This is well described by JETSET 6.3 PS with default parameters, in contrast with the situation at lower energies [19].

Tuning the fragmentation parameters of JETSET 7.2 ME (based on the second order QCD matrix element followed by string fragmentation) to obtain a correct description of the density of particles in a jet makes the results from this model to agree with the data to within 15%.

6 Acknowledgements

We are greatly indebted to our technical staffs and collaborators and funding agencies for their support in building the DELPHI detector and to the many members of the LEP division for the speedy commissioning and superb performance of the LEP machine.

We are grateful to A. Bialas, A. Giovannini, L. Van Hove and T. Sjöstrand for many helpful discussions and suggestions.

References

[1] P. Carlson (UA5 Collaboration), in 4^{th} Topical Workshop on $p\bar{p}$ Collider Physics, Bern, March 1983.
J. Rushbrooke (UA5 Collaboration), in Proceedings of Workshop on $p\bar{p}$ Options for the Supercollider, Argonne and Chicago, February 1984.

[2] T.H. Burnett et al. (JACEE Collaboration), Phys. Rev. Lett. **50** (1983) 2062.
F. Takagi, Phys. Rev. Lett. **53** (1984) 427.

[3] R. Holinski et al. (KLM collaboration), Phys. Rev. Lett. **62** (1989) 733.

[4] I. Derado (NA35 Collaboration), Invited Talk at the Meeting on Multiparticle Dynamics, La Thuile, Valle d'Aosta, Italy, March 1989.

[5] R. Albrecht et al. (WA80 collaboration), Phys. Lett. **B221** (1989) 427.

[6] I.V. Ainenko et al. (NA22 Collaboration), Phys. Lett. **B222** (1989) 306.
M. Adamus et al. (NA22 Collaboration), Phys. Lett. **B185** (1987) 200.

[7] C. Albajar et al. (UA1 Collaboration), Intermittency Studies in $\bar{p}p$ Collisions at $\sqrt{s}$ = 630 GeV, CERN-EP/90-56, Submitted to Nucl. Phys. B.

[8] G.J. Alner et al. (UA5 Collaboration), Phys. Rep. **154** (1987) 247.
R.E. Ansorge et al. (UA5 Collaboration), Z. Phys. **C43** (1989) 357.

[9] B. Buschbeck and P. Lipa, Mod. Phys. Lett. **A4** (1989) 1871.

[10] G. Paladin and A. Vulpiani, Phys. Rep. **56** (1987) 147.

[11] A. Bialas and R. Peschanski, Nucl. Phys. **B273** (1986) 703.

[12] R.C. Hwa, Phys. Lett. **B201** (1988) 165.
N.G. Antoniou et al., "Intermittency, Kadanoff scaling and hadronization", CERN-TH 5625/90, January 1990.

[13] I.M. Dremin, JETP Lett **30** (1980) 152.
I.M. Dremin, Sov. J. Nucl. Phys. **33** (1981) 726.

[14] J. Dias de Deus, Phys. Lett. **B194** (1987) 297.
J. Dias de Deus, Sov. J. Nucl. Phys. **33** (1981) 726.

[15] A. Bialas and R. Peschanski, Nucl. Phys. B308 (1988) 857.

[16] W. Ochs and J. Wosiek, Phys. Lett. **B214** (1988) 617.
W. Ochs and J. Wosiek, Phys. Lett. **B232** (1989) 271.

[17] I. Sarcevic and H. Satz, Phys. Lett. **B233** (1989) 251.

[18] B. Buschbeck et al., Phys. Lett. **B215** (1988) 788. Based on data of the HRS collaboration, assuming that multiplicity follows the negative binomial distribution [28].

[19] W. Braunschweig et al. (TASSO Collaboration), Phys. Lett. **B231** (1989) 548.

[20] QCD generators for LEP, Proc. of the 1989 Workshop on Z Physics at LEP 1, B. Bambah et al., CERN 89-08, Vol. 3, p.143, Eds. G. Altarelli, R. Kleiss and C. Verzegnassi.

[21] L. Van Hove, Mod. Phys. Lett. **A4** (1989) 1867.

[22] P. Aarnio et al. (DELPHI Collaboration), "DELPHI Technical Proposal", DELPHI 83/66/1, Geneva 1983.
The DELPHI Collaboration, "The DELPHI Detector", to be submitted to Nucl. Instr. and Meth. A.

[23] P. Aarnio et al. (DELPHI Collaboration), "Study of hadronic decays of the Z boson", CERN-EP/90-19, 9 February 1990, submitted to Phys. Lett. B.

[24] T. Sjöstrand, Comp. Phys. Comm. **27** (1982) 243, ibid. **28** (1983) 229.
T. Sjöstrand and M. Bengtsson, Comp. Phys. Commun. **43** (1987) 367.

[25] W. de Boer, H. Furstenau and J. Kohne, in preparation.

[26] DELSIM User Manual, DELPHI 87-96 PROG-99, Geneva, July 1989.
DELSIM Reference Manual, DELPHI 87-98 PROG-100, Geneva, July 1989.

[27] T. Sjöstrand, Proc. of Multiparticle production, Eds. R. Hwa, G. Pancheri and Y. Srivastava, World Scientific, Singapore 1989, p.327.

[28] A. Giovannini and L. Van Hove, Z. Phys. **C30** (1986) 391.

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. Factorial moment F_3 from definition (1b) versus the number M of subdivisions of the rapidity interval. DELPHI uncorrected data (circles) and JETSET 6.3 PS with detector simulation (solid line). TASSO data (black circles) and TASSO simulation with JETSET 6.3 PS (dashed line) (both from Ref. [19]).

4. (a) The slope f_q (white circles) as a function of the rank q of the moment.
   (b) Dependence of the quantity $\alpha_q = 2f_q/[q(q-1)]$ (white circles) on the rank q of the moment. In both cases, JETSET 6.3 PS predictions are superimposed as a solid line.

5. Comparison between the factorial moments of rank 2 (a), 3 (b) and 4 (c) for like sign particles in an event and an equal number of charged particles chosen at random. $\ln(F_{q+}/F_{qr})$ (see text) is plotted versus the number M of subdivisions of the rapidity interval.

6. Dependence of the factorial moments of rank 2 (a), 3 (b), 4 (c) and 5 (d) on the on the number M of subdivisions of the rapidity interval, when rapidity is calculated with respect to the beam axis. DELPHI corrected data (white circles), compared withthe 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).

M	F_2	F_3	F_4	F_5
1	1.20 ± 0.02	1.68 ± 0.05	2.7 ± 0.1	4.6 ± 0.2
2	1.34 ± 0.02	2.25 ± 0.04	4.4 ± 0.1	9.7 ± 0.4
4	1.48 ± 0.02	2.97 ± 0.09	7.6 ± 0.3	22.9 ± 1.8
6	1.54 ± 0.02	3.35 ± 0.07	9.3 ± 0.5	31.8 ± 2.5
8	1.57 ± 0.02	3.63 ± 0.11	11.1 ± 0.6	39.3 ± 3.5
10	1.59 ± 0.01	3.74 ± 0.11	11.7 ± 0.7	44.3 ± 4.4
12	1.60 ± 0.01	3.82 ± 0.11	12.2 ± 0.6	46.5 ± 4.7
14	1.61 ± 0.01	3.94 ± 0.12	13.1 ± 0.8	51.4 ± 5.7
16	1.62 ± 0.01	4.06 ± 0.12	13.7 ± 0.8	56.3 ± 5.6
18	1.63 ± 0.01	3.97 ± 0.12	13.2 ± 0.8	52.5 ± 6.3
20	1.63 ± 0.01	4.01 ± 0.12	13.2 ± 0.9	51.9 ± 7.3
22	1.63 ± 0.01	4.06 ± 0.12	13.3 ± 0.9	49.4 ± 5.9
24	1.63 ± 0.01	4.10 ± 0.12	13.7 ± 1.0	51.9 ± 6.2
26	1.63 ± 0.01	4.01 ± 0.12	13.1 ± 0.9	49.4 ± 7.4
28	1.63 ± 0.01	4.01 ± 0.12	14.0 ± 1.1	59.1 ± 9.5
30	1.63 ± 0.01	4.06 ± 0.12	13.9 ± 1.2	59.1 ± 11.2
32	1.63 ± 0.01	4.01 ± 0.12	13.7 ± 1.1	55.7 ± 9.5
34	1.62 ± 0.01	4.01 ± 0.12	13.9 ± 1.2	58.6 ± 11.7
36	1.63 ± 0.01	4.18 ± 0.17	15.3 ± 1.5	70.1 ± 16.1
38	1.64 ± 0.01	4.18 ± 0.13	15.0 ± 1.5	68.7 ± 15.1
40	1.62 ± 0.01	4.01 ± 0.12	13.9 ± 1.2	54.6 ± 10.4

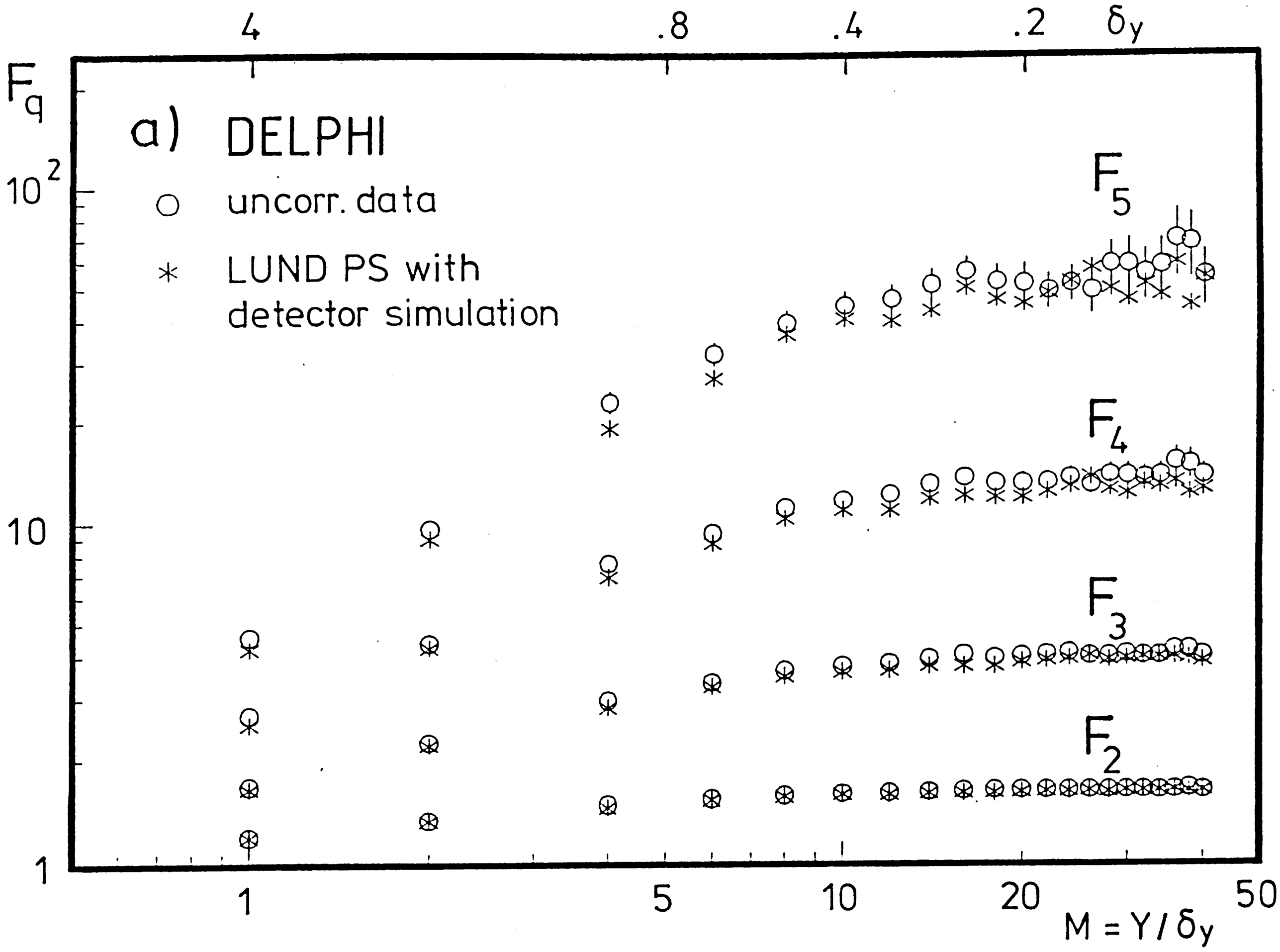
Table 1: Uncorrected factorial moments

M	F_2	F_3	F_4	F_5
1	1.23 ± 0.03	1.82 ± 0.07	3.0 ± 0.2	5.6 ± 0.4
2	1.38 ± 0.03	2.41 ± 0.10	5.1 ± 0.3	11.7 ± 0.9
4	1.50 ± 0.03	3.16 ± 0.13	8.8 ± 0.6	29.7 ± 3.6
6	1.55 ± 0.02	3.49 ± 0.14	10.2 ± 0.7	38.9 ± 4.3
8	1.57 ± 0.02	3.60 ± 0.14	11.0 ± 0.9	37.7 ± 4.9
10	1.59 ± 0.02	3.78 ± 0.15	11.8 ± 1.1	44.3 ± 7.1
12	1.60 ± 0.02	3.94 ± 0.16	12.9 ± 1.0	52.0 ± 8.8
14	1.60 ± 0.02	3.90 ± 0.16	12.3 ± 1.0	47.5 ± 7.6
16	1.61 ± 0.02	3.97 ± 0.16	13.1 ± 1.3	45.6 ± 8.2
18	1.62 ± 0.02	3.97 ± 0.16	13.2 ± 1.2	52.4 ± 8.9
20	1.61 ± 0.02	4.01 ± 0.16	13.6 ± 1.4	55.0 ± 12.7
22	1.60 ± 0.02	3.85 ± 0.15	12.7 ± 1.3	45.3 ± 8.2
24	1.60 ± 0.02	3.97 ± 0.16	12.8 ± 1.3	48.4 ± 9.7
26	1.60 ± 0.02	3.82 ± 0.15	11.9 ± 1.2	43.8 ± 8.8
28	1.62 ± 0.02	4.02 ± 0.20	14.4 ± 1.6	72.6 ± 18.1
30	1.61 ± 0.02	3.97 ± 0.20	13.6 ± 1.8	54.6 ± 15.3
32	1.59 ± 0.02	3.86 ± 0.19	12.9 ± 1.6	52.5 ± 13.6
34	1.59 ± 0.02	3.90 ± 0.19	14.0 ± 1.7	66.6 ± 19.3
36	1.60 ± 0.02	3.93 ± 0.20	13.0 ± 1.8	52.6 ± 15.8
38	1.63 ± 0.02	4.14 ± 0.21	15.8 ± 2.4	81.5 ± 27.7
40	1.60 ± 0.02	3.93 ± 0.24	13.3 ± 1.9	49.5 ± 16.3

Table 2: Corrected factorial moments

q	f_q (data)	α_q (data)	f_q (JETSET 6.3 PS)
2	0.024 ± 0.005	0.024 ± 0.005	0.025 ± 0.001
3	0.087 ± 0.020	0.029 ± 0.007	0.090 ± 0.005
4	0.195 ± 0.054	0.032 ± 0.009	0.196 ± 0.011
5	0.298 ± 0.116	0.030 ± 0.012	0.336 ± 0.024

Table 3: Fitted slopes in the range $6 \leq M \leq 32$ (corresponding to δy between 0.7 and 0.12) for corrected data


4
.8
.4
.2
δy
Fq
a) DELPHI
10²
○ uncorr. data
* LUND PS with
detector simulation
F5
F4
10
F3
F2
1
1
5
10
20
50
M = Y/δy

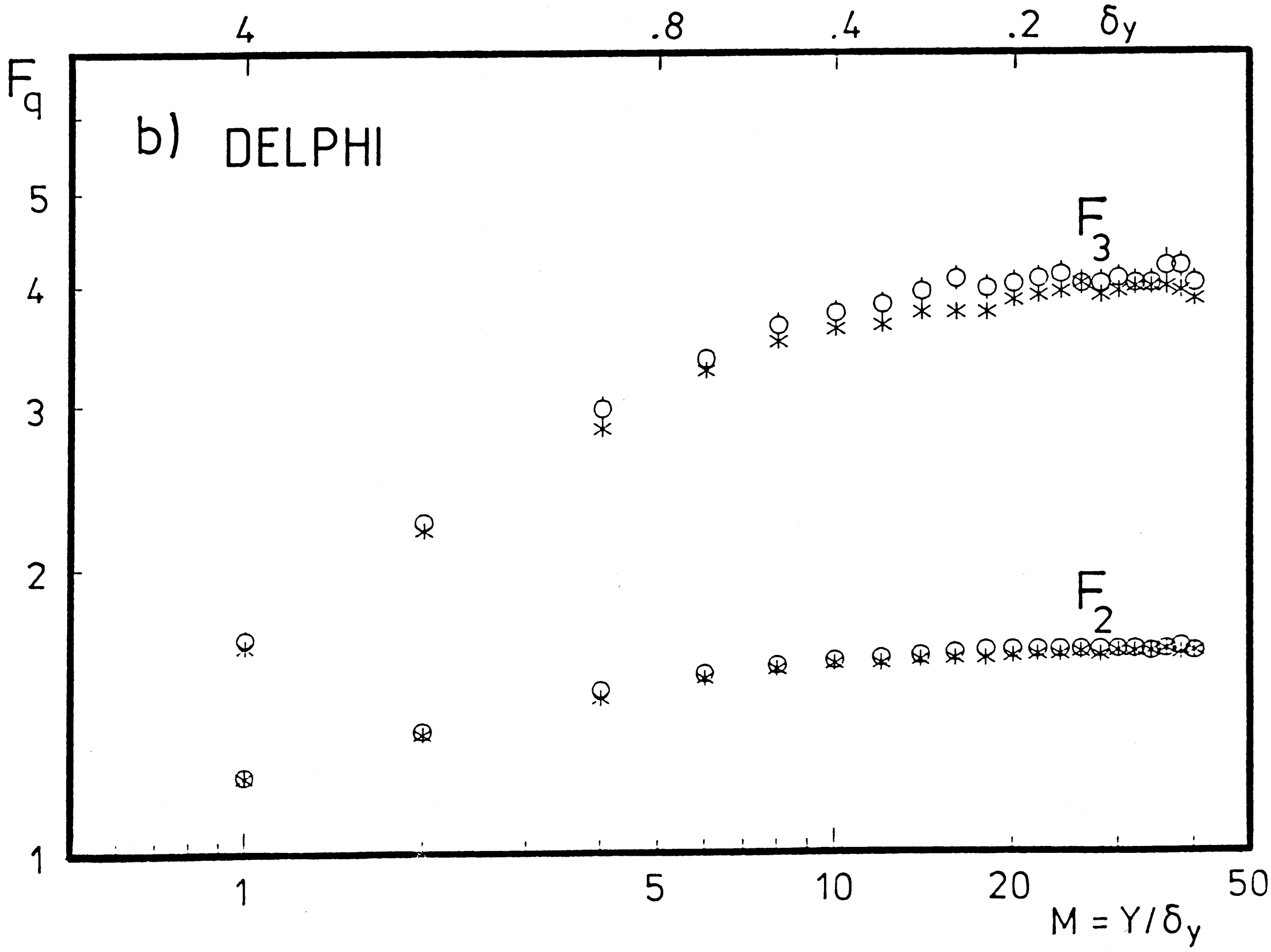
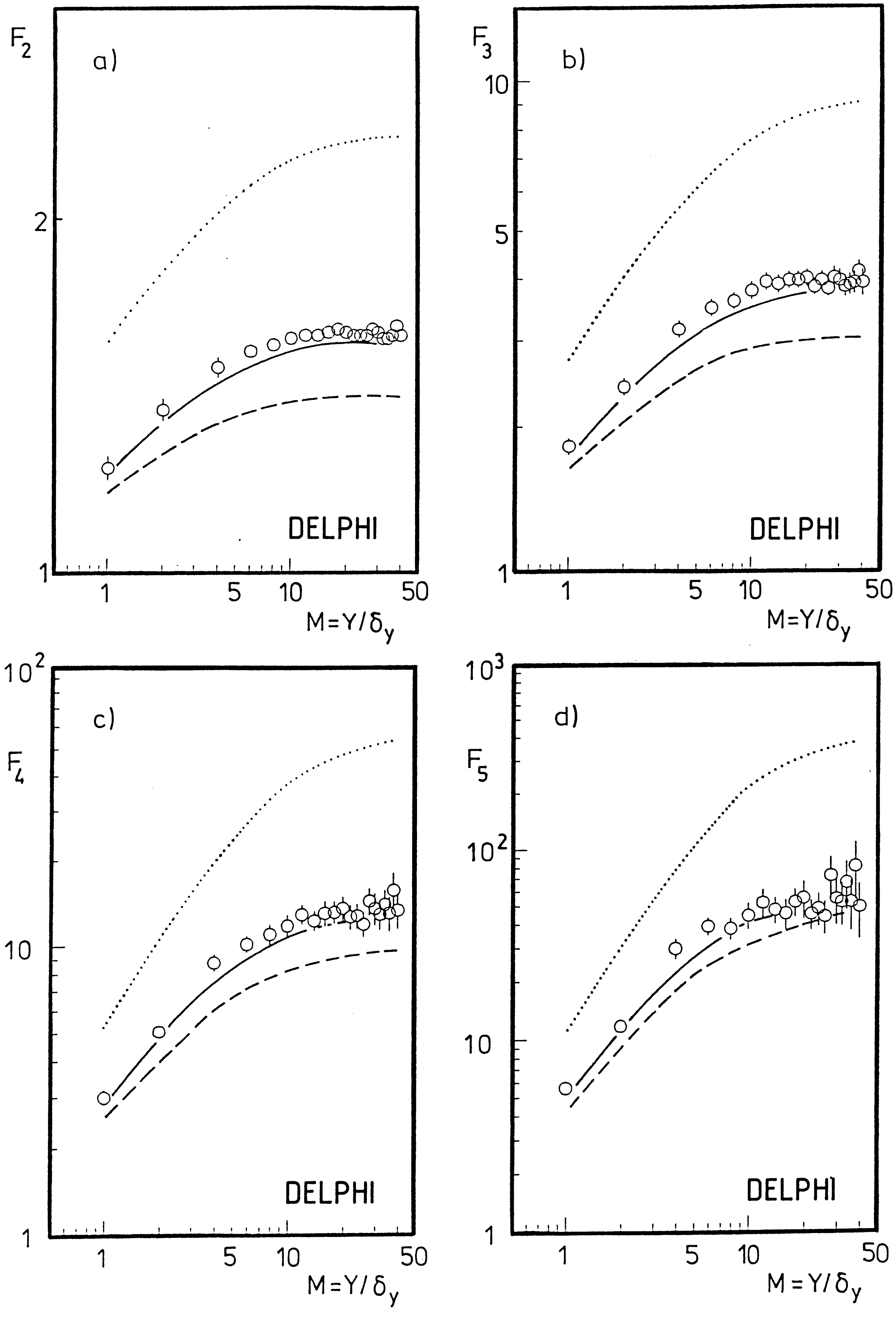
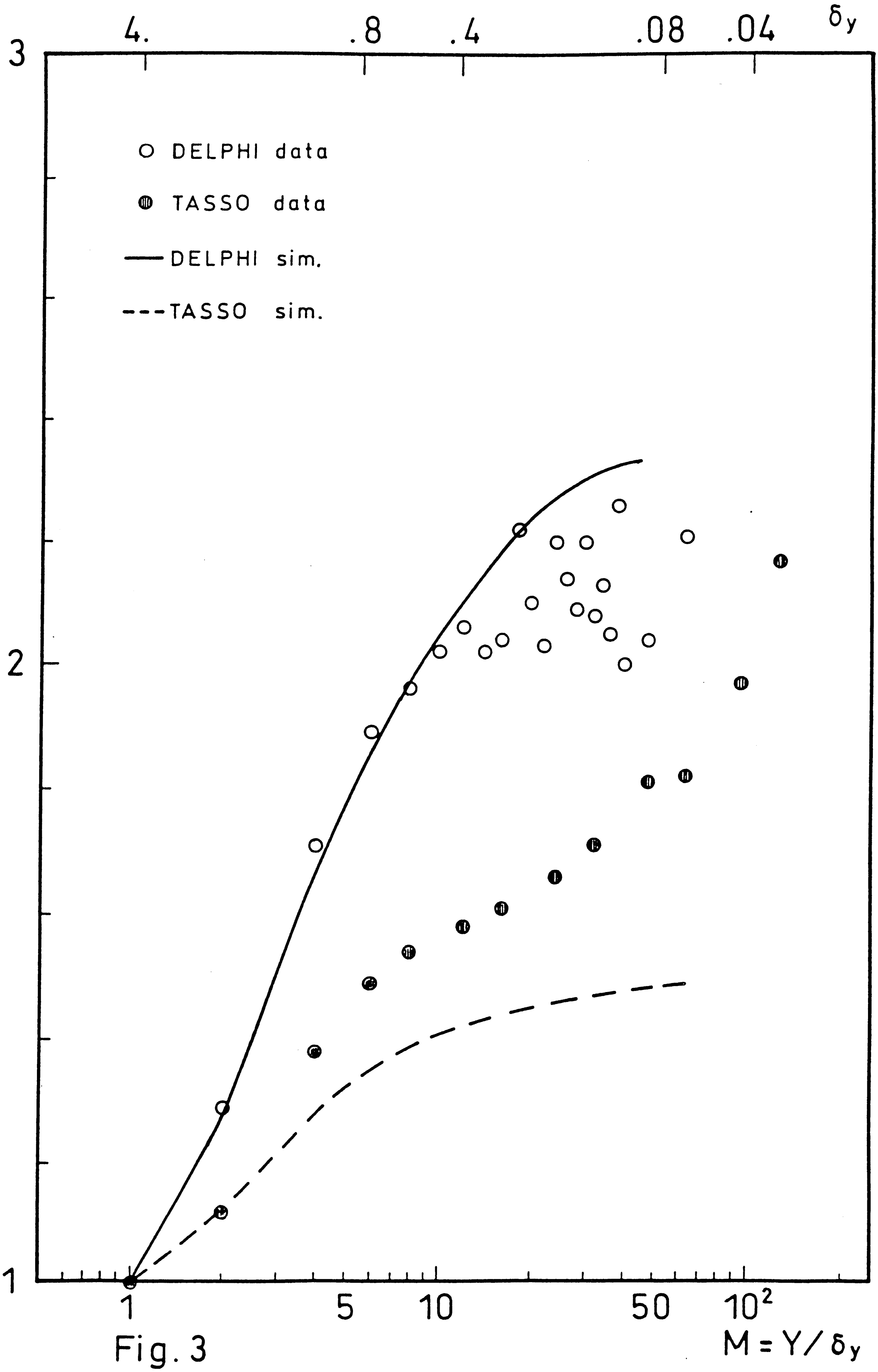

4
.8
.4
.2
δy
Fq
b) DELPHI
5
F3
4
3
2
F2
1
1
5
10
20
50
M = Y/δy

Fig. 1



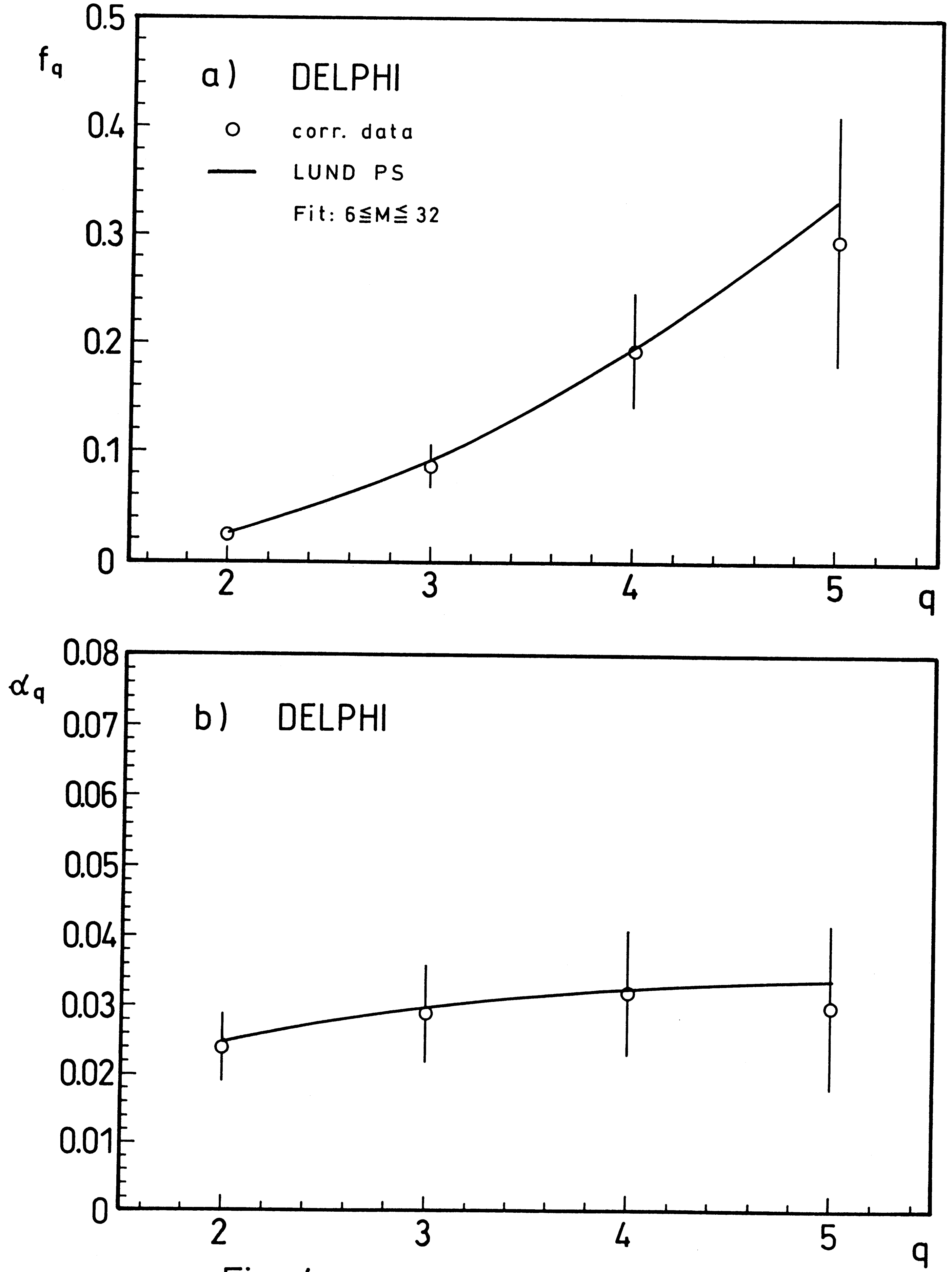
a)
F_2
2
1
1
5
10
50
$M=Y/\delta_y$
DELPHI
b)
F_3
10
5
1
1
5
10
50
$M=Y/\delta_y$
DELPHI
c)
F_4
10^2
10
1
1
5
10
50
$M=Y/\delta_y$
DELPHI
d)
F_5
10^3
10^2
10
1
1
5
10
50
$M=Y/\delta_y$
DELPHI

Fig. 2



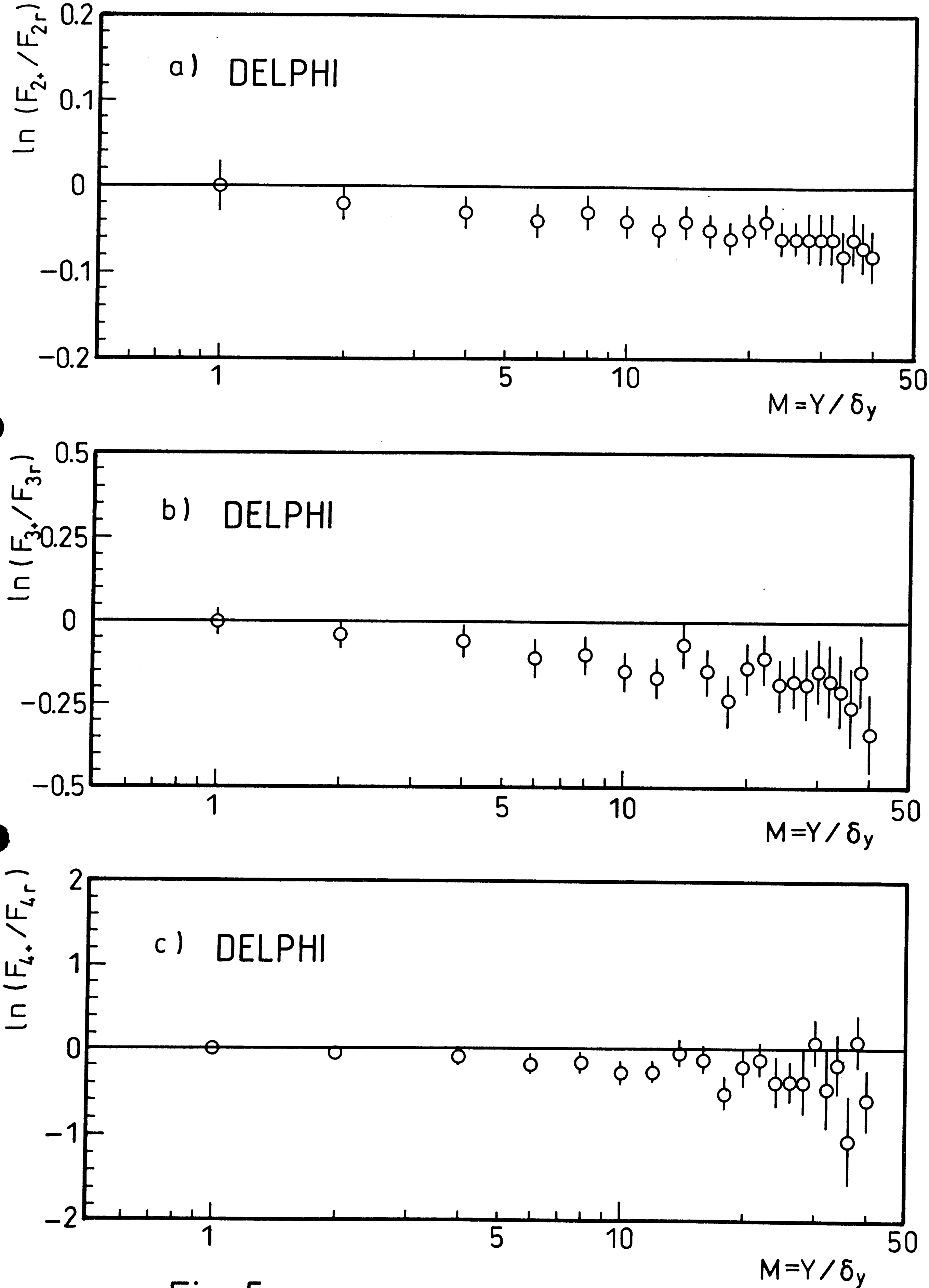
δy
4.
.8
.4
.08
.04
3
F3
2
1
DELPHI data
TASSO data
DELPHI sim.
TASSO sim.
1
5
10
50
10²
M = Y/δy

Fig. 3



0.5
f_q
a) DELPHI
0.4
corr. data
LUND PS
Fit: 6≦M≦32
0.3
0.2
0.1
0
2
3
4
5
q
0.08
α_q
0.07
b) DELPHI
0.06
0.05
0.04
0.03
0.02
0.01
0
2
3
4
5
q

Fig. 4



a) DELPHI
$\ln(F_{2+}/F_{2r})$
0.2
0.1
0
−0.1
−0.2
1
5
10
50
$M = Y/\delta_y$
b) DELPHI
$\ln(F_{3+}/F_{3r})$
0.5
0.25
0
−0.25
−0.5
1
5
10
50
$M = Y/\delta_y$
c) DELPHI
$\ln(F_{4+}/F_{4r})$
2
1
0
−1
−2
1
5
10
50
$M = Y/\delta_y$

Fig. 5

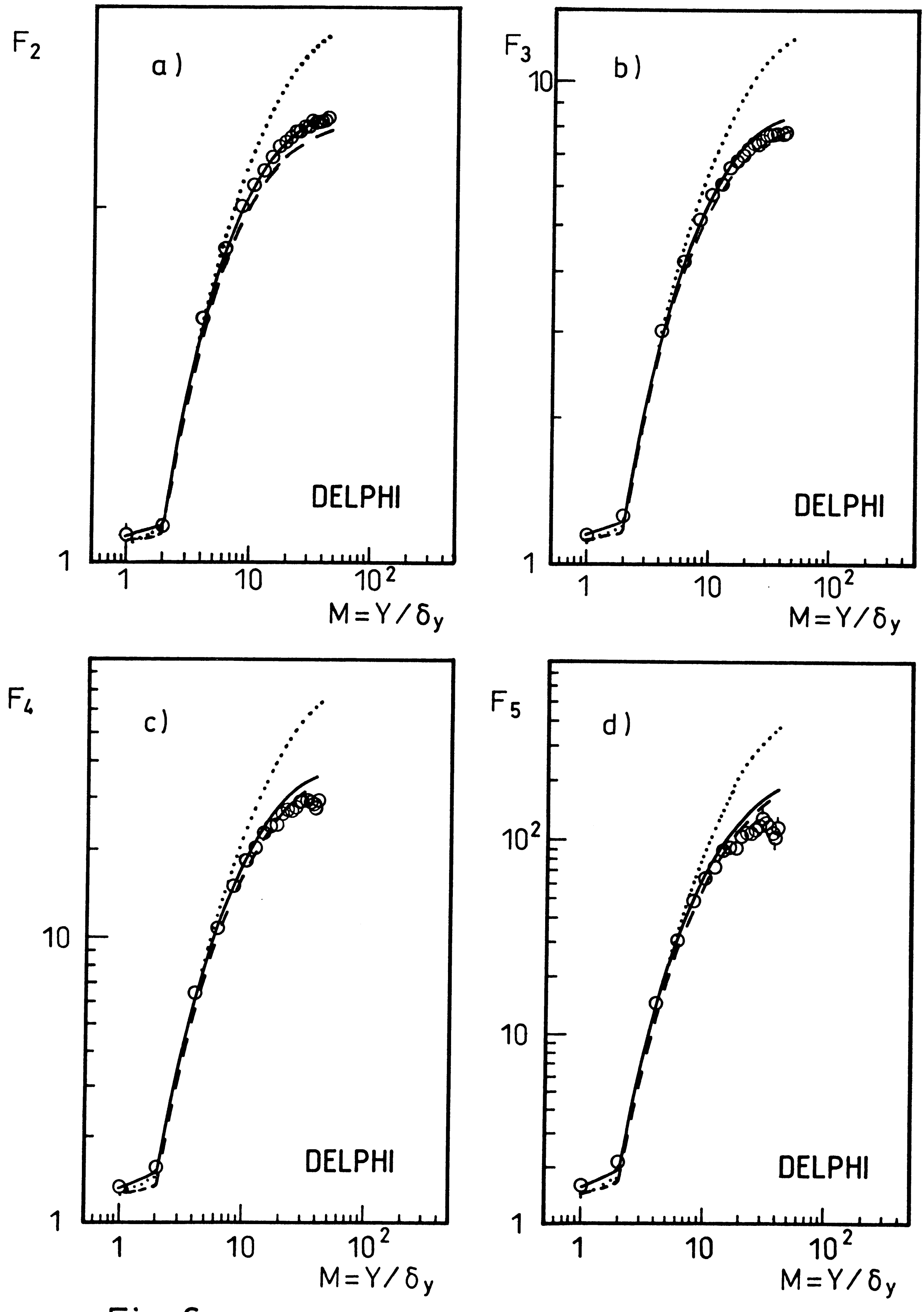


Fig. 6

Imprimé au CERN   Prix : 0.50 Fr