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Abstract: A sample of π^+p and K^+p non-diffractive interactions at $\sqrt{s}$=22 GeV is used to investigate factorial multiplicity moments as a function of the cms opening angle θ between particles. The angular dependence is very different for unlike-charge and like-charge particle combinations. For the latter, factorial moments increase with decreasing opening angle approximately as a power law. The θ dependence is stronger for central production-angle intervals than in the forward and backward regions. The predictions of the standard version of the FRITIOF model deviate strongly from the data, but including Bose-Einstein correlations leads to qualitative agreement.

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1 Introduction

In recent years, much attention has been paid to the possible existence of dynamical density fluctuations of particles produced in high energy collisions [1]. Such fluctuations have indeed been observed experimentally (see [2] and references therein). The effect has become known under the term *intermittency*, defined [3] as a power-law rise of normalized factorial moments F_q of order q of the (charged) particle multiplicity n,

$$F_q = \frac{\langle n(n-1)\dots(n-q+1)\rangle}{\langle n\rangle^q} \tag{1}$$

as a function of decreasing size δ of phase space cells:

$$F_q(\delta) \sim \delta^{-\phi_q}. \tag{2}$$

The positive powers ϕ_q are known as *intermittency indices.*

The primary reasons for the interest in intermittency are, on the one hand, that current models of hadron production in hadronic collisions cannot reproduce the strength of the observed fluctuations and, on the other, that perturbative QCD itself turns out to be inherently intermittent.

The first studies were performed in the kinematical variables rapidity y or pseudo-rapidity η, azimuthal angle φ and transverse momentum p_t. Later analyses [4, 5] have indicated, that the squared four-momentum difference $Q^2 = -(q_1 - q_2)^2$ or the invariant mass $M_{inv} = (Q^2 + 4m_\pi^2)^{1/2}$ of the particles are more suitable to isolate the effect.

Studies of factorial moments in terms of Q^2 and M_{inv} [4, 5, 6, 7] show, that correlations between like-charge particles and, consequently, Bose-Einstein (BE) correlations play a predominant role in the observed intermittency effect at small Q^2 or M_{inv}, while indications exist that QCD is responsible at larger Q^2. However, detailed understanding of the intermittency phenomena is still lacking and experimental data for the F_q dependence are needed in variables sensitive to these details.

In perturbative QCD, the intermittency indices ϕ_q are directly related to the anomalous multiplicity dimension $\gamma_0 = (6\alpha_s/\pi)^{1/2}$ [8, 9, 10, 11] and, therefore, to the running coupling constant α_s. In the same theoretical context, it has been argued [9, 10, 11] that the opening angle θ between particles is a suitable and sensitive variable to analyse. It is, of course, closely related to Q (or M_{inv}). The theoretical analysis in [9, 10, 11] is particularly applicable to hadron production in e^+e^- collisions. A proper interpretation of future e^+e^- data in a perturbative QCD framework requires, however, a good understanding of similar data from interactions which are *not* dominated by hard QCD effects.

In the present analysis we, therefore, investigate the opening-angle dependence of factorial moments in (soft) hadronic collisions. Use is made of the correlation (or density) strip integral method [12], a recent methodological improvement in the study of intermittency.

2 The data

The full experimental set-up of EHS, exposed to a positive meson enriched beam with momentum 250 GeV/c, is described in detail in [13, 14]. It consists of an active vertex detector (Rapid Cycling Bubble Chamber filled with H2) and a down-stream two-lever-arm spectrometer. Tracks of secondary charged particles are reconstructed from hits in the wire and drift chambers of the spectrometer and from measurement in RCBC. The momentum resolution varies from (1-2)% for tracks reconstructed in RCBC, to (1-2.5)% for tracks reconstructed in the first lever arm and to 1.5% for tracks reconstructed in the full spectrometer.

An event is accepted for analysis if the measured and the reconstructed charge multiplicity is the same, charge balance is satisfied, no electron is detected among the secondary tracks and there are no badly reconstructed (and therefore rejected) tracks. The loss of events during measurement and reconstruction is corrected for by means of the topological cross section data [14]. Elastic events are excluded. Furthermore, an event is called single-diffractive and excluded from the sample if the total charge multiplicity is smaller than 8 and at least one of the positive tracks has $|x_F| > 0.88$. After these cuts, the inelastic non-single-diffractive sample consists of 59.200 π^+p and K^+p events.

For momenta $p_{lab} < 0.7$ GeV/c, the range in the bubble chamber and/or the change of track curvature is used for proton identification. In addition, a visual ionization scan has been performed for $p_{lab} < 1.2$ GeV/c on the full K^+p and on 62% of the π^+p sample. A positive particle with $p_{lab} > 150$ GeV/c is given the identity of the beam particle. Other particles with momenta $p_{lab} > 1.2$ GeV/c are not identified in the present analysis and are treated as pions. The π^+p and K^+p samples are combined and only particles in the cms rapidity window $-2 < y < 2$ are used.

3 The method

The phase space variable used for the present analysis is the center of mass opening angle θ_{ij} between two particles

$$\theta_{ij} = \arccos[(\vec{p}_i \cdot \vec{p}_j)/|\vec{p}_i||\vec{p}_j|] \quad , \tag{3}$$

with $\vec{p}_i$ and $\vec{p}_j$ being the three-momenta of particles i and j. An angular distance measure for more than two particles is defined as:

$$\mathrm{dist}\,(p_{i_1}, \ldots, p_{i_q}) = \max_{\substack{all\ pairs\\ k_1,k_2}} \theta_{i_{k_1}, i_{k_2}} \quad . \tag{4}$$

In terms of the density strip integral, the numerator of F_q can be determined by counting, for each event, the number of q-tuples that have a pairwise angular opening smaller than a given value θ and then averaging over all events. Using the Heaviside unit step function Θ, this can mathematically be expressed as

$$F_q(\theta) = \frac{1}{\text{norm}} \langle q! \sum_{i_1 < \ldots < i_q} \prod_{\substack{allpairs \\ k_1, k_2}} \Theta(\theta - \theta_{i_{k_1}, i_{k_2}}) \rangle \quad , \tag{5}$$

where the factor $q!$ takes into account the number of permutations within a q-tuple.

The normalization is obtained from "mixed" events constructed by random selection of tracks from different events in a track pool [5]. The multiplicity of a mixed event is taken to be a Poissonian random variable, thereby ensuring that no extra correlations are introduced. The mixed events are treated in the same way as real events. A correction factor is applied for the difference in average multiplicity of the Poissonian and the experimental distribution.

4 The results

In Fig. 1, the data for $\ln F_q$ are plotted as a function of $-\ln\theta$ for all charges combined and, separately, for positive, negative and unlike-charge particle combinations. Factorial moments are plotted for order $q = 2$ to 5 in the four sub-figures, respectively. On the double logarithmic plot used, the increase should be linear if (2) was strictly applicable. For our data, this holds at most in limited θ regions. Nevertheless, as a rough indication for the θ dependence, intermittency indices ϕ_q are given in column 3 of table 1, as obtained from a fit by

$$\ln F_q = a - \phi_q \cdot \ln\theta \tag{6}$$

in the θ range given in column 1 and indicated by arrows in Fig. 1.

From Fig. 1 and table 1 it can be seen that:

- for all-negative particle combinations, the $\ln F_q$ (for all orders) rise for all values of $-\ln\theta$;
- for all-positive particle combinations, the F_q first decrease when $-\ln\theta$ increases, have a minimum and then increase for high $-\ln\theta$ values;
- for mixed-charge combinations F_2 increases at high $-\ln\theta$, but no strong θ dependence is observed in the higher orders.

As in our previous analyses [4, 5], we conclude that the rise of the factorial moments at small phase-space distances is caused by like-charge combinations, not only for $q = 2$, but also for orders up to 5. The increase of F_2 at small distances for the $(+-)$ combination is difficult to interpret because of contamination from Dalitz decay, γ conversions and η or η' decays.

A comparison of the data has been performed with the FRITIOF Monte-Carlo model versions 2.0 [15] and 7.0 [16]. Events generated with these models are subject to the same selection criteria as the real data. Since version 2.0 is better tuned to our data [5] and the results obtained from both versions are very similar, we show the comparison for version 2.0 . To include BE-correlations, we use the algorithm developed for JETSET 7.3 [17] with exponential parametrization[1] in Q and measured parameters r and λ [5].

Fig. 2 and Fig. 3 show, respectively, the FRITIOF 2.0 predictions without and with BE-correlations. The intermittency indices are given in columns 4 and 5 of table 1.

FRITIOF without BE-correlations (Fig. 2) strongly deviates from the data. FRITIOF with BE-correlations (Fig. 3) can reproduce the rise of F_q, but, as already noted in [17], the effect is overestimated, particularly for high-order factorial moments.

In a more differential analysis, we study the angular dependence of factorial moments in intervals of the cms production angle Θ_0 defined as

$$\Theta_o = \arccos[(\vec{p} \cdot \vec{p}_{beam})/|\vec{p}||\vec{p}_{beam}|] \quad . \tag{7}$$

Fig. 4 shows a strong Θ_0-dependence of the intermittency indices ϕ_2 and ϕ_3, with the largest values obtained in Θ_0 intervals close to 90^0. For this Θ_0 region, the effect is even stronger in θ than in Q^2 (not shown). For like-charge combinations, FRITIOF without BE-correlations does not reproduce the data (dashed lines in Fig. 4a,b). Including BE-effects in the model leads to reasonable agreement with the data (full lines in Fig. 4a,b).

5 Conclusions

In this paper we present the first results on the opening-angle dependence of factorial multiplicity moments F_q for various charge combinations. For like-charge particle combinations, the F_q rise with decreasing cms opening angle θ between particles, for $q = 2 \ldots 5$. Only a weak dependence is observed for unlike-charge combinations. The intermittency indices ϕ_q depend strongly on the production angle Θ_0 of the particles. For the region close to $\Theta_0 = 90^0$, the dependence of factorial moments is even stronger in θ than in Q^2. The standard version of the Monte Carlo program FRITIOF is unable to reproduce the data. When Bose-Einstein correlations are included, the model reproduces the rise of the factorial moments, but the effect is overestimated in particular for higher orders. Because of its relevance in a perturbative-QCD treatment of intermittency, the angular variable would be particularly well suited for an analysis of e^+e^- data at LEP. A comparison to the present (soft) NA22 results might help in clarifying the importance of perturbative and non-perturbative contributions to hadron production in e^+e^- annihilation at high energies.

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[1] FRITIOF 2.0 with BE describes the shape of the Q^2 dependence of the second order factorial moment, but overestimates the increase with increasing $-\ln Q^2$ of the third order factorial moment [5].

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Table 1. Intermittency indices ϕ_q according to (6) for the various charge combinations.

		Data	FRITIOF	FRITIOF+BE
$q = 2$	$++$	0.024 ± 0.004	-0.033 ± 0.003	0.038 ± 0.003
$4^0 < \theta < 47^0$	$+-$	0.002 ± 0.003	-0.055 ± 0.003	-0.067 ± 0.003
	$--$	0.048 ± 0.006	-0.035 ± 0.004	0.067 ± 0.004
	cc	0.018 ± 0.003	-0.044 ± 0.002	-0.011 ± 0.002
$q = 3$	$+++$	0.08 ± 0.02	-0.18 ± 0.02	0.34 ± 0.03
$7^0 < \theta < 51^0$	$++-$	-0.07 ± 0.01	-0.22 ± 0.01	-0.10 ± 0.01
	$+--$	-0.06 ± 0.02	-0.16 ± 0.01	-0.07 ± 0.01
	$---$	0.33 ± 0.03	-0.17 ± 0.03	0.40 ± 0.03
	ccc	-0.01 ± 0.01	-0.19 ± 0.01	0.02 ± 0.01
$q = 4$	$++++$	0.32 ± 0.10	-0.44 ± 0.11	1.81 ± 0.16
$18^0 < \theta < 51^0$	$+++-$	-0.02 ± 0.06	-0.35 ± 0.05	0.00 ± 0.05
	$++--$	-0.26 ± 0.06	-0.31 ± 0.04	-0.06 ± 0.04
	$+---$	0.02 ± 0.08	-0.26 ± 0.07	-0.01 ± 0.07
	$----$	0.95 ± 0.18	-0.68 ± 0.21	1.36 ± 0.19
	cccc	-0.05 ± 0.05	-0.31 ± 0.04	0.22 ± 0.05
$q = 5$	$+++++$	0.6 ± 0.4	0.0 ± 0.6	4.4 ± 0.6
$27^0 < \theta < 51^0$	$++++-$	-0.2 ± 0.2	-0.3 ± 0.3	0.6 ± 0.3
	$+++--$	-0.5 ± 0.2	-0.5 ± 0.2	0.2 ± 0.2
	$++---$	-0.4 ± 0.2	-0.3 ± 0.2	0.2 ± 0.2
	$+----$	0.6 ± 0.4	-1.0 ± 0.4	0.9 ± 0.5
	$-----$	1.8 ± 0.6	-1.9 ± 2.0	3.4 ± 0.7
	ccccc	0.6 ± 0.4	-0.4 ± 0.2	0.8 ± 0.2

Figure Captions

1. Dependence of factorial moments of order $q = 2$ to $q = 5$ on the opening angle θ for various charge configurations.

2. Same as in Fig. 1, but for FRITIOF 2.0 without Bose-Einstein effect.

3. Same as in Fig. 1, but for FRITIOF 2.0 with Bose-Einstein effect in exponential parametrization.

4. Intermittency indices ϕ_2 and ϕ_3 for angular dependence of factorial moments in different production angle Θ_0 intervals. The range in θ corresponds to that given in table 1. Dashed lines show FRITIOF 2.0 without BE correlations. Full Lines are FRITIOF 2.0 with Bose-Einstein correlations.

NA22

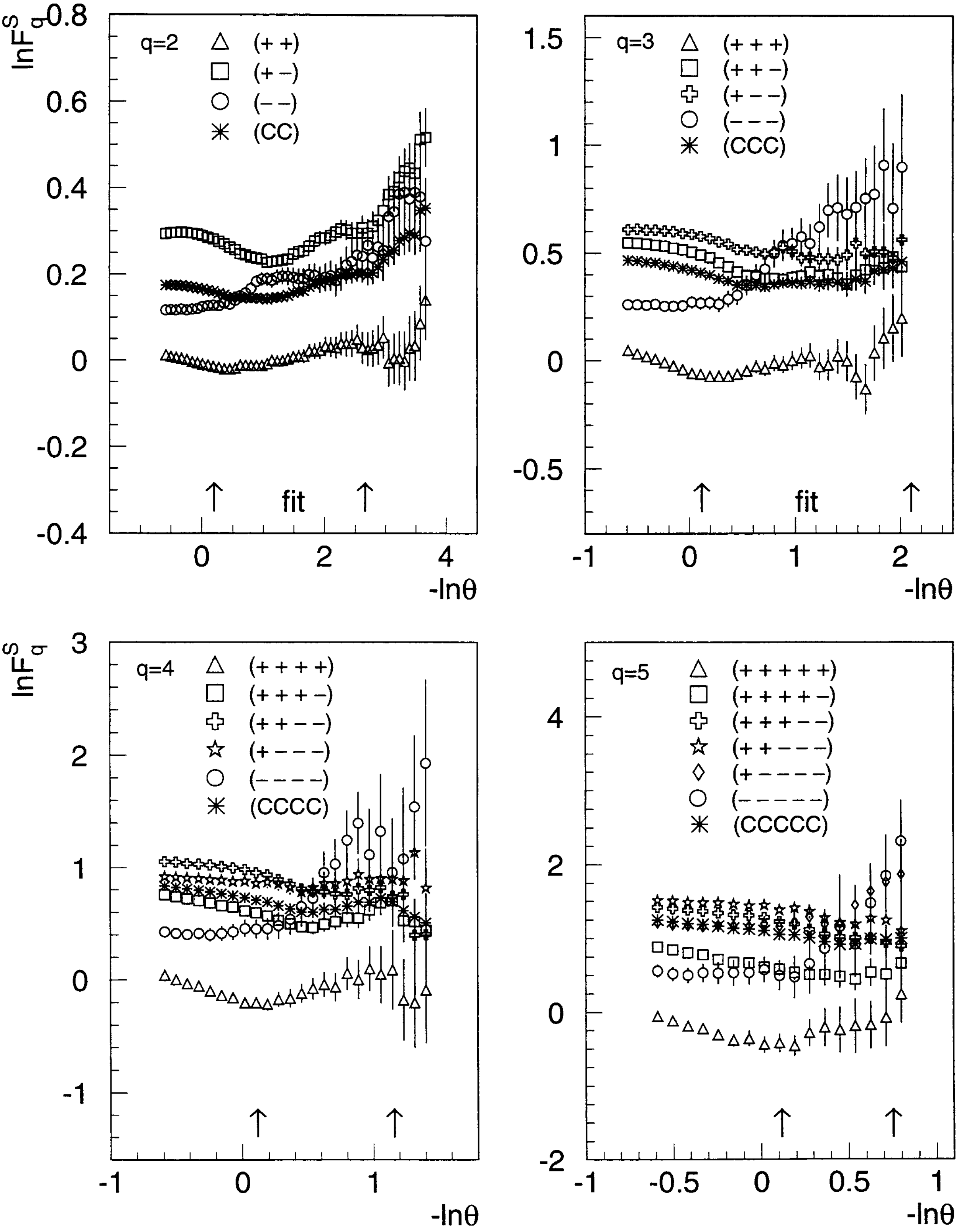

lnF^S_q
q=2
(+ +)
(+ −)
(− −)
(CC)
fit
-lnθ
-0.4
-0.2
0
0.2
0.4
0.6
0.8
0
2
4
q=3
(+ + +)
(+ + −)
(+ − −)
(− − −)
(CCC)
fit
-lnθ
-0.5
0
0.5
1
1.5
-1
0
1
2
q=4
(+ + + +)
(+ + + −)
(+ + − −)
(+ − − −)
(− − − −)
(CCCC)
-lnθ
-1
0
1
2
3
-1
0
1
q=5
(+ + + + +)
(+ + + + −)
(+ + + − −)
(+ + − − −)
(+ − − − −)
(− − − − −)
(CCCCC)
-lnθ
-2
0
2
4
-1
-0.5
0
0.5
1

Fig. 1

FRITIOF 2.0

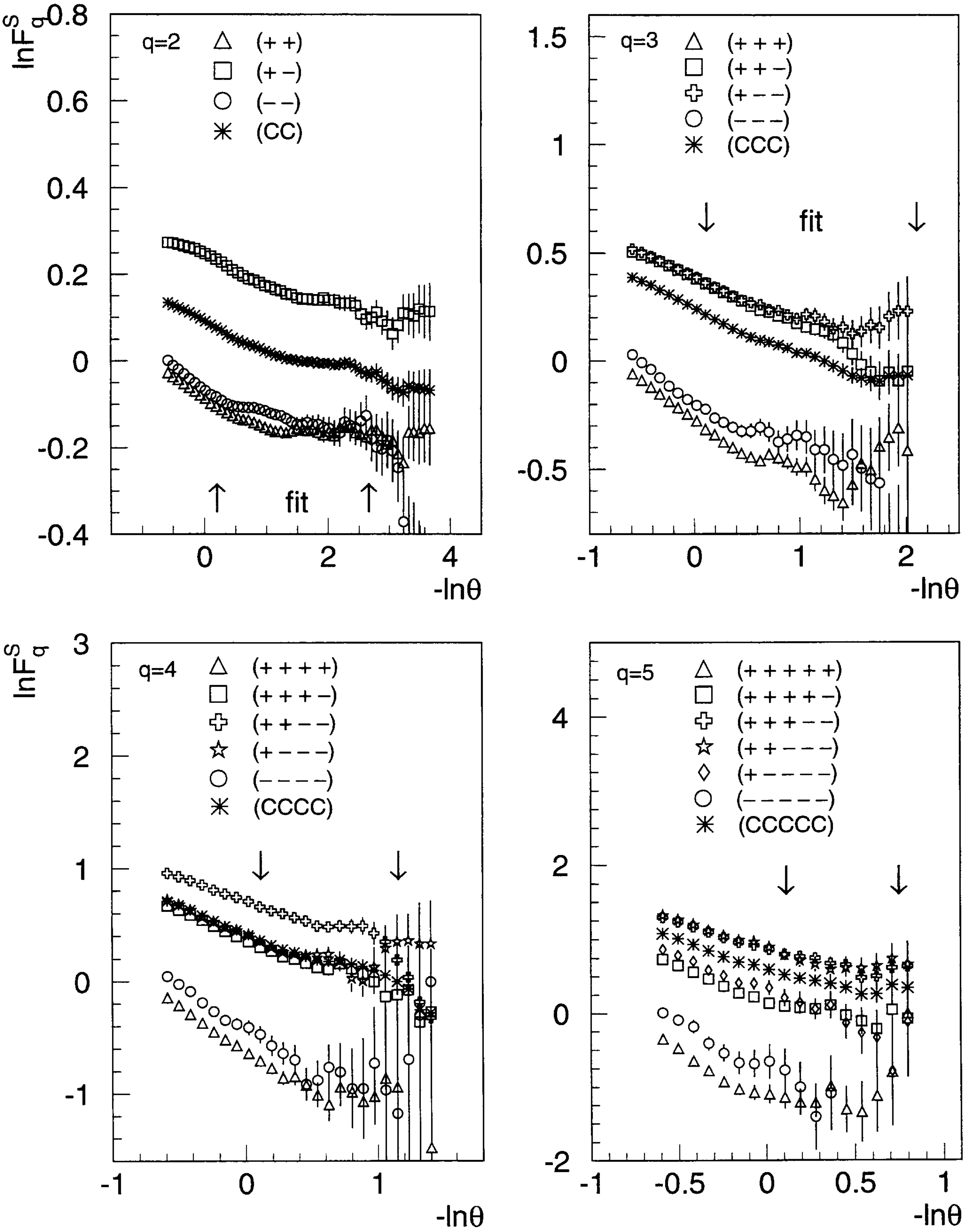


Fig. 2

FRITIOF 2.0 + B.E.

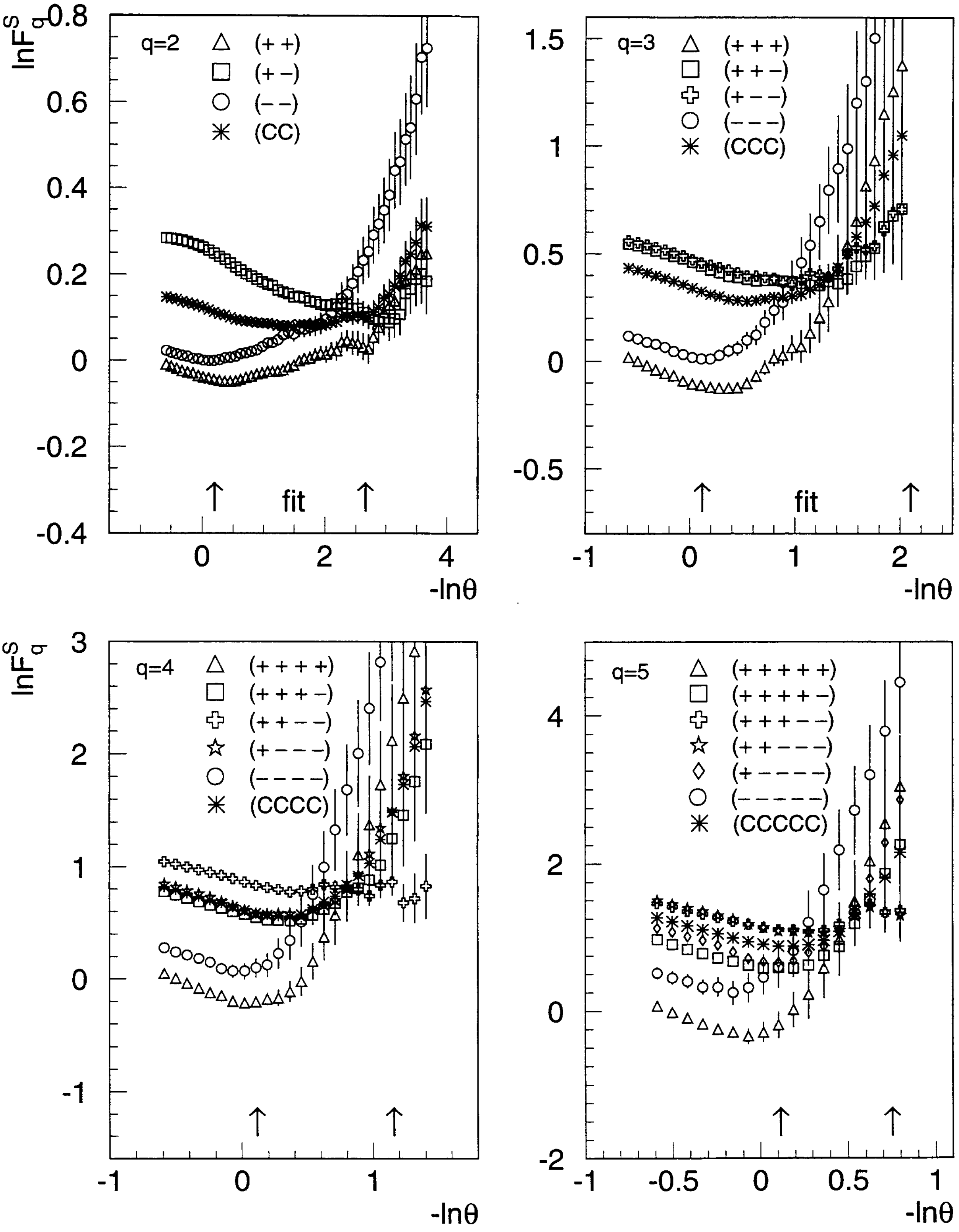


Fig. 3

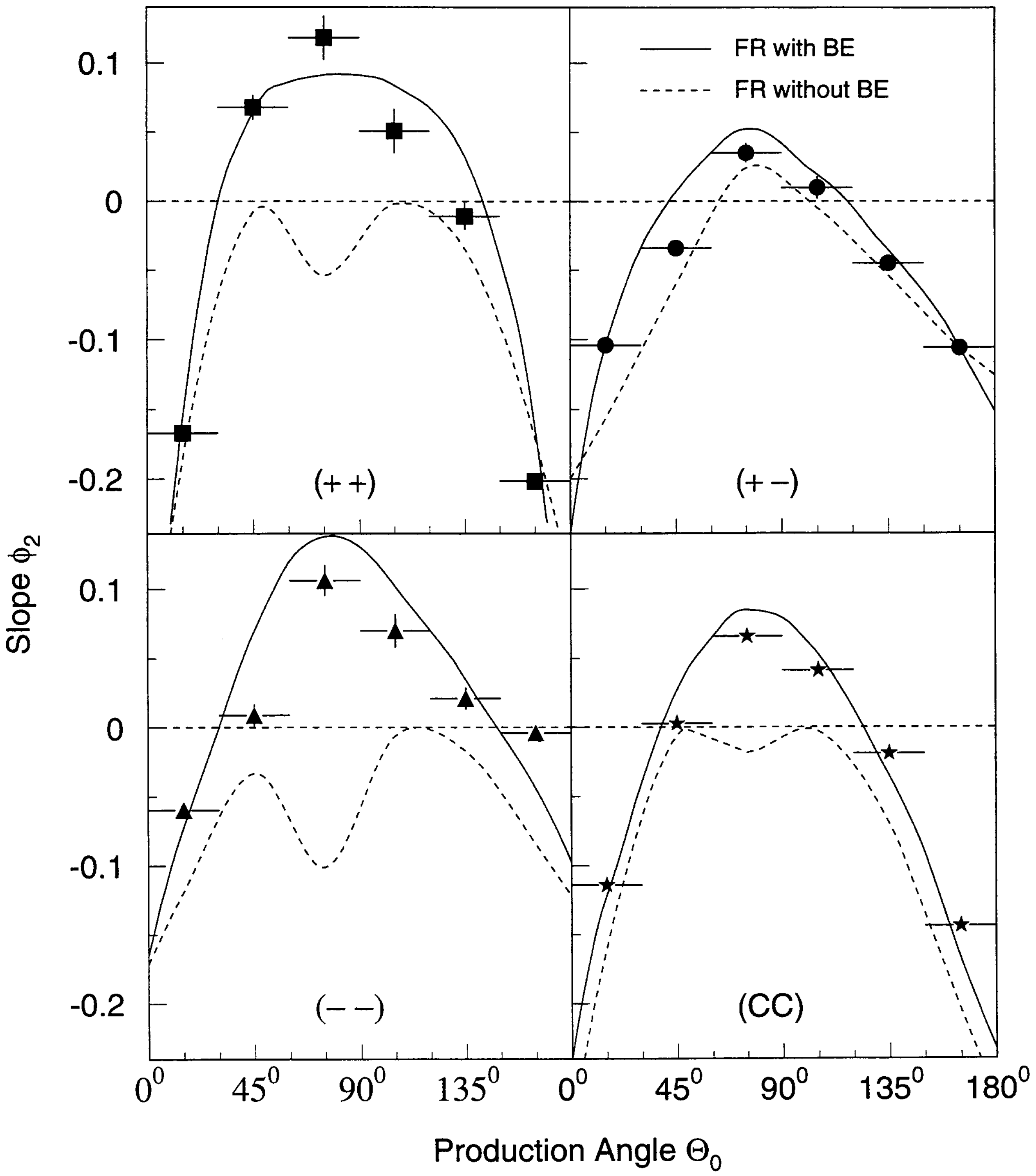
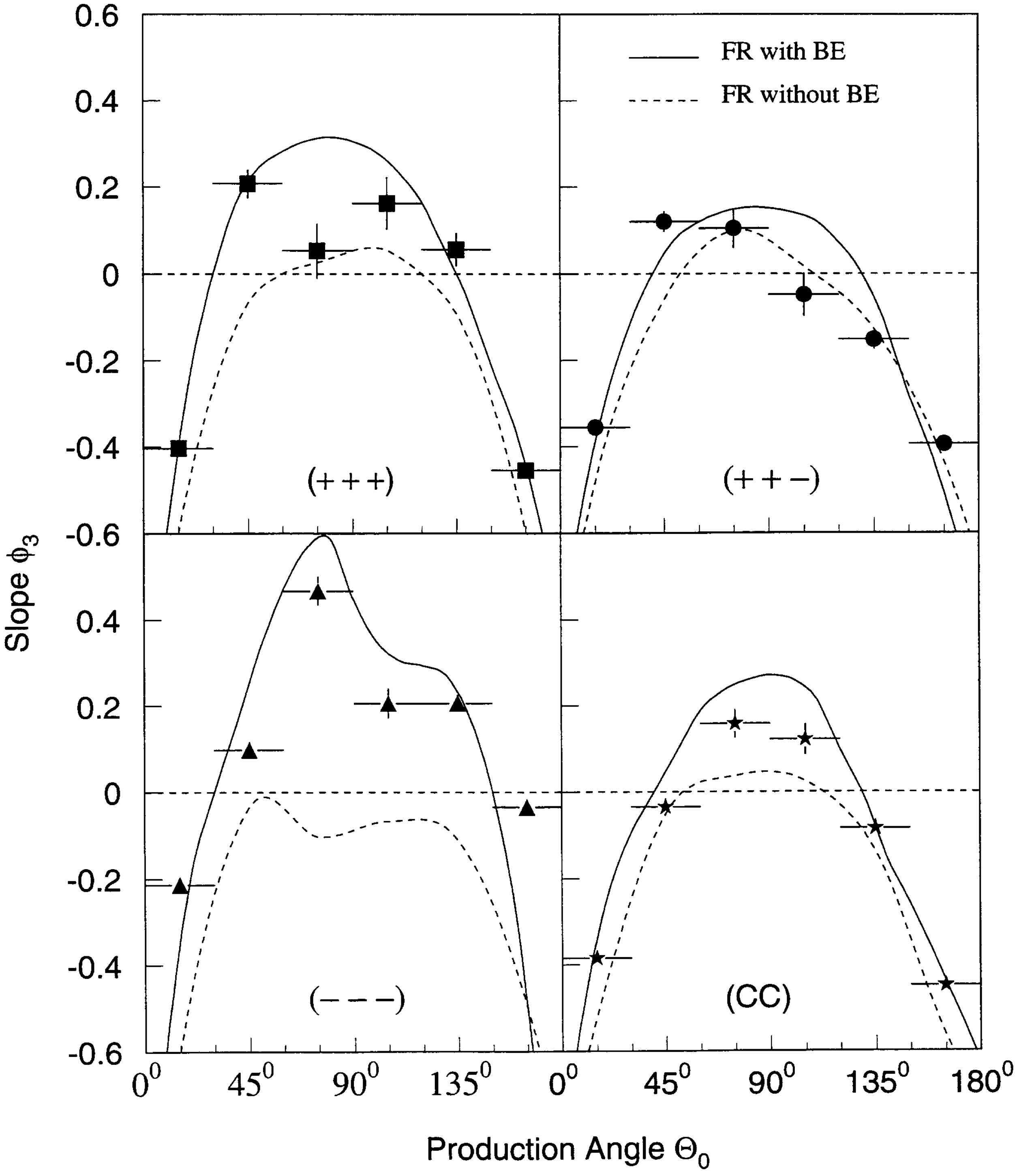

FR with BE
FR without BE
Slope ϕ_2
0.1
0
-0.1
-0.2
(++)
(+−)
(−−)
(CC)
0^0
45^0
90^0
135^0
180^0
Production Angle Θ_0

Fig.4a



FR with BE
FR without BE
Slope ϕ_3
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
(+ + +)
(+ + −)
(− − −)
(CC)
0⁰
45⁰
90⁰
135⁰
180⁰
Production Angle Θ_0

Fig.4b