12 December 1996

PHYSICS LETTERS B

ELSEVIER

Physics Letters B 389 (1996) 397–404

Comparison of spike production in pp and π^+p/K$^+$p interactions at 205–360 GeV/c

EHS/NA22 Collaboration

N.M. Agababyan [g], A.Kh. Argynova [h], M.R. Atayan [g], J. Czyżewski, [d,1,2], E.A. De Wolf [a,3], I.M. Dremin [i,5], K. Dziunikowska [b,2], A.M.F. Endler [e], P.F. Ermolov [c], Z.Sh. Garutchava [f], H.R. Gulkanyan [g], R.Sh. Hakobyan [g], J.K. Karamyan [g], D. Kisielewska [b,2], W. Kittel [d], A.I. Lebedev [h], A.A. Loktionov [h], S.S. Mehrabyan [g], Z.V. Metreveli [f], M.T. Nazirov [h], K. Olkiewicz [b,2], F.K. Rizatdinova [c], E.K. Shabalina [c], L.N. Smirnova [c], M.D. Tabidze [f], L.A. Tikhonova [c], A.G. Tomaradze [f,5], F. Verbeure [a], S.A. Zotkin [c]

[a] *Department of Physics, Universitaire Instelling Antwerpen, B-2610 Wilrijk, Belgium*
[b] *Institute of Physics and Nuclear Techniques of Academy of Mining and Metallurgy and Institute of Nuclear Physics, PL-30055 Krakow, Poland*
[c] *Nuclear Physics Institute, Moscow State University, RU-119899 Moscow, Russia*
[d] *High Energy Physics Institute Nijmegen (HEFIN), University of Nijmegen/NIKHEF, NL-6525 ED Nijmegen, The Netherlands*
[e] *Centro Brasileiro de Pesquisas Fisicas, BR-22290 Rio de Janeiro, Brazil*
[f] *Institute for High Energy Physics of Tbilisi State University, GE-380086 Tbilisi, Georgia*
[g] *Institute of Physics, AM-375036 Yerevan, Armenia*
[h] *Institute of High Energy Physics, Academy of Science of Kazakhstan, Alma-Ata 480082, Kazakhstan*
[i] *Lebedev Physical Institute, Moscow 117924, Russia*

Received 3 October 1996
Editor: L. Montanet

Abstract

Spike production is studied in pp and π^+p/K$^+$p collisions in the beam-momentum range of 205–360 GeV/c. The pseudorapidity distribution of spike centers exhibits two narrow peaks in pp interactions, while having one wide bump in πp and Kp interactions. The position of the peaks is consistent with the expectation from a model of coherent gluon radiation at finite length. The interference between the quark color amplitudes obtained within this model causes two off-center peaks in pp data, but only one central peak in πp and Kp data.

[1] University of Nijmegen Fellow, now at the Jagellonian University, Krakow, Poland; Fellow of the Polish Science Foundation (FNP) Scholarship for the year 1996.
[2] Supported by the Polish State Committee for Scientific Research.
[3] Onderzoeksdirecteur NFWO, Belgium.
[4] Now at UIA, Wilrijk, Belgium.
[5] Supported by the Russian Fund for Fundamental Research.

PII S0370-2693(96)01437-2

1. Introduction

The investigation of density fluctuations in multiparticle processes has been found to be conceptually useful and extremely fruitful (for a recent review see [1]). The discovery of intermittency has resulted in the application of fractal concepts which replace conventional analysis in terms of ordinary Gaussian techniques.

Hadronic multiple production events with large fluctuations in pseudorapidity have been known for a long time (see review [2]). They are called ring-like [3] or spike events, because in a single event many particles tend to be emitted with a similar polar angle, but randomly distributed in azimuthal angle. As a consequence, the event is characterized by a ring of particles in the plane perpendicular to the collision axis. Early evidence for large concentrations of particles in small pseudorapidity regions of single events has been reported for cosmic-ray experiments [4–6] and for pN collisions at 200 GeV [7]. More recently, strong fluctuations have been observed by the JACEE [8], UA5 [9] and NA22 [10] collaborations.

In recent years, the theoretical approach to this phenomenon concentrated on the scaling behavior of factorial moments as well as on ideas of intermittency and fractality. It has been recognized that similar features appear in perturbative QCD [11–14] as a consequence of parton showering. Shower evolution gives rise to a scaling law governed by the anomalous dimension of QCD.

A single gluon jet produces a spike both in pseudorapidity and azimuthal angle. Spike events with a wide azimuthal distribution, therefore, require several gluons to be emitted within a given polar-angle interval. Shower gluons are generally created in a single scattering of a parton impinging on a target-hadron constituent and provide a strong background to the effect we are looking for. No specific polar angle, however, is preferred by these gluons.

Inspired by earlier theoretical speculations [2,3] as well as by earlier experimental observations [15,16] we here present a detailed study of the ring-like spike events. Such events can result from gluons emitted between two scattering centers during a double scattering process. The effect is analogous to electromagnetic radiation from finite length and can already be deduced from the classic works of Tamm [17] on Čerenkov radiation. It is a coherent radiation off a finite-size target which is (either QCD color or QED charge) neutral. The emission angle is directly related to the target size.

Bremsstrahlung of a particle is known to be formed over a distance (the coherence length)

$$L \sim [\omega(1 - v\cos\theta)]^{-1} \sim 1/\omega\theta^2\,, \qquad (1)$$

where v is the particle velocity and ω and θ are the frequency and radiation angle, respectively. For usual bremsstrahlung angles $\theta \sim m/E$, this length increases without restriction as $L \sim E^2/\omega m^2$ with increasing E, where m and E are the particle mass and energy. The restriction imposed on this length due to confinement, $L = l_c$, results in an increase of the radiation angle

$$\theta \sim 1/\sqrt{\omega l_c} \gg m/E\,, \qquad (2)$$

where l_c is the characteristic size of the region of coherent quarks and gluons. A three-dimensional generalization of this simple model has been suggested in [18].

Quarks and gluons within the colliding hadrons cease to screen each other, i.e., they cease to form white objects in the course of a hadron collision. Within a certain region of space-time, finite due to confinement, quarks and gluons will, therefore, emit color bremsstrahlung gluons isotropically in the azimuthal plane, but at fixed polar angle. This polar angle is determined by the size of the space-time region. The corresponding graphs are presented in Fig. 1.

Since both the target parton and the projectile parton can emit gluons, interference between these gluons appears to be relevant. This interference is destructive for quarks of the same color but constructive or absent in the other cases [19]. Thus, pp collisions give rise to numerous destructive qq subprocesses, while these are masked by $\bar{q}q$ subprocesses in πp and Kp collisions and absent at all in $\bar{p}$p collisions. The destructive interference is expected to reveal itself as a dip at pseudorapidity $\eta_{cms} = 0$ in the spike-center pseudorapidity distribution of pp collisions. In the model, the position of the peaks depends on the choice of the coherent confinement length. In [20] it was taken as

$$l_c = x l_0/\gamma, \qquad (3)$$

where x is the fraction of the particle longitudinal momentum carried by the quark (see Fig. 1), $\gamma \simeq \sqrt{s}/2m_p$ is the Lorentz factor, and $l_0 \simeq 2/m_\pi$ is the

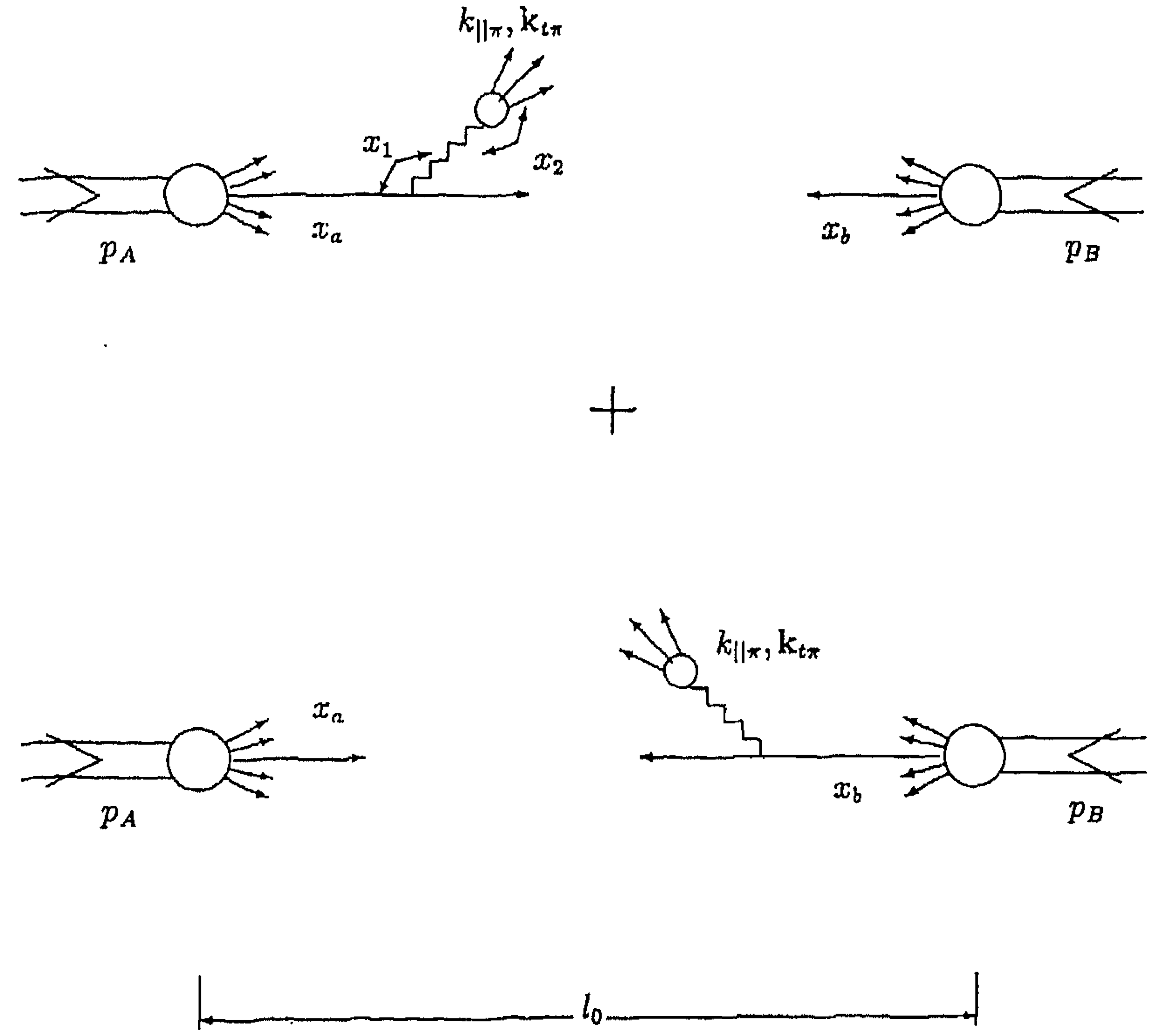

Fig. 1. Diagrams representating of coherent gluon-jet emission off projectile and target particles within the length l_0. The momentum of the colliding particles is denoted by p_A and p_B, respectively. The fractional momentum carried by the quarks is x_a and x_b, respectively. The gluon-jet carries a fraction x_1 of the quark momentum, the final pion a fraction x_2 of the gluon momentum.

finite size (in the target proton rest system) of the region where free color currents exist. Theoretical estimates based on these assumptions predict peaks positioned at $\langle\eta_g^{cms}\rangle \approx \pm 0.3$ with an interpeak distance of $D(\langle\eta_1\rangle, \langle\eta_2\rangle) \approx 0.6$ [19,20]. We, therefore, expect to observe a double-peak structure in pp collisions, but only a single peak one in $p\bar{p}$ and πp/Kp data.

The first indication of a double-peak structure in the spike-center distribution of pp interactions came from [20], where it was interpreted as evidence for the coherent gluon radiation from finite length as discussed above.

In this paper, we compare the spike production in pp collisions with that in πp and Kp collisions in the same cms energy region. The experimental sample consists of 5024 pp interactions at 205 GeV/c (FNAL Bubble Chamber filled with H_2 [21]), 33 228 pp interactions at 360 GeV/c (EHS [22]) and of 6082 pp, 36 317 K^+p and 102 079 π^+p interactions at 250 GeV/c (EHS, this experiment [23]). An event was accepted for analysis if the measured and reconstructed charge multiplicity was the same, charge balance was satisfied and the total charge multiplicity was $n_{ch} \geq 8$.

The spike-search algorithm is described in Section 2, the results are presented in Section 3 and the conclusions are summarized in Section 4.

2. The method

For the spike analysis we need to discriminate between the dynamical fluctuations with an unknown density distribution and the statistical ones which always exist in systems with small internal correlations and are governed by the Gaussian law. In other words, we need to define selection criteria to remove the Gaussian statistical noise from the data without distorting the density distribution in the strongly fluctuating region.

An iterative procedure to find dense, isolated, homogeneous groups of particles is proposed in [20]. For each individual event, with charged particle multiplicity n_{ch} the following variables are calculated in each iterative step j:

1. the (target-proton rest-frame) pseudorapidity interval covered by a particle group

$$\Delta\eta(j) = \eta_{max}(j) - \eta_{min}(j), \tag{4}$$

2. the number of particles $k(j)$ in that group,
3. the average pseudorapidity

$$\langle\eta(j)\rangle = \frac{1}{k(j)} \sum_{i=1}^{k(j)} \eta_i, \tag{5}$$

4. the density of particles

$$DN(j) = k(j)/\Delta\eta(j), \tag{6}$$

5. the gradient of density

$$GDN(j) = DN(j) - DN(j-1), \tag{7}$$

6. the maximum interval between neighboring tracks within the particle group

$$GAP(j) = \max_i |\eta_i - \eta_{i-1}| , \quad i = 2,3\ldots k(j) . \tag{8}$$

For each track i in the group, the deviation from the average pseudorapidity $\langle\eta(j)\rangle$ is calculated and the particle with the largest deviation is rejected. After that, a new iteration $j \to j+1$ is started until $j_{max} = n_{ch} - 2$ is reached. In the first step, $k(1)$ is equal to the charge multiplicity n_{ch} of the whole event, and $\Delta\eta(1)$ is the interval covered by the whole event.

The experimental two-dimensional distributions $DN(j)$ vs. $GDN(j)$ obtained from pp data at 360 GeV/c for groups of k particles ($3 < k < 9$) contain a large Gaussian-like peak at low DN and GDN and a long non-Gaussian tail at high DN and GDN (not shown here). The major peak is formed by low-density groups corresponding to statistical density fluctuations. We significantly suppress the statistical noise by assuming two standard deviations from the DN (GDN) peak position as a threshold TDN for the particle density (for the $TGDN$ density gradient) and removing groups with

Table 1
Threshold values as a function of spike multiplicity k

k	TDN	$TGDN$	$TGAP$
3	5.50	3.00	0.291
4	5.75	2.75	0.291
5	6.00	2.50	0.291
6	7.00	2.25	0.291
7	8.00	2.25	0.291
8	9.00	2.25	0.291
9	10.00	2.25	0.291

$$DN(j) < TDN, \tag{9}$$

$$GDN(j) < TGDN \tag{10}$$

from further analysis.

To select homogeneous groups from this sample, an upper limit was further set on the maximum interval $TGAP$ between the tracks within the group. The experimental distribution of the maximum gap in dense groups peaks at $TGAP = 0.291$. The distribution in the second largest gap between tracks in dense groups peaks at about half that value. The significant difference between these two peak values allows us to consider the first one as a definition of a homogeneous group.

The analysis of different experimental data samples has shown that the thresholds are neither sensitive to the type of interacting hadrons nor to the initial-particle energy within the energy range under study. The threshold values used in the analysis are given in Table 1 as a function of the spike multiplicity k.

Expressions (9) and (10) can be modified and rewritten in terms of the interval $\Delta\eta(k+1)$ for $k+1$ particles from which k belong to the spike:

$$\Delta\eta(k+1) > \Delta\eta(k) + n\delta\eta, \tag{11}$$

where $\delta\eta$ is the average inner gap within the spike and n is an integer. Physically, n is related to the distance from the spike to the nearest track and characterizes the group isolation from other tracks in the event. As two options of a final selection, we require (11), therefore, to be fulfilled with $n = 2$ and 4, respectively. As expected [15], the contribution of dynamical fluctuations tends to increase with increasing n.

Events were processed sequentially using the algorithm described above. The tracks forming the spikes found first were removed from the data set and the spike-finding algorithm is applied to the remaining tracks of the event. Using a loop over all tracks in the current event, all possible spikes were considered.

3. The results

The $\langle\eta\rangle$ distribution of spike centers was first studied in [16] on a combined sample of pp interactions at 205 and 360 GeV/c. The spikes were selected according to the method described above. Narrow peaks were observed at 75° and 105° in the center of mass system and interpreted as a manifestation of coherent gluon jet emission that revealed itself in the form of ring-like spikes, even at low particle-multiplicity within the spike ($k = 3$). Further analysis of the transverse-momentum distribution of spikes and the transverse-momentum, azimuthal-angle and energy distribution of particles within the spikes [20] supported the model of coherent gluon-jet emission as a possible, although certainly not dominant, mechanism of multiparticle production.

The number of spikes in the event decreased rapidly with the increase of the number of particles k in the spike, following an exponential law [18]

$$dN/dk \sim \exp(-bk), \qquad (12)$$

where the parameter b depends on the spike selection procedure and the selection criteria. Therefore, a meaningful statistical significance of the effect under study is expected only for the sum over spike multiplicities from low ($k = 3$) to the highest ones ($k > 6$), even though low-k spikes contain a fairly strong background from statistical noise.

The analysis presented in this paper is based on both pp and π^+p/K$^+$p data. That allows a comparison of quark-quark and quark-antiquark initial states expected to produce different gluon jet spectra.

Dense groups with $k \geq 3$ are selected according to the procedure described in the previous section, with the isolation criterion $n = 4$. The pseudorapidity bin-width was chosen to be 0.1 unit, more than 10 times the experimental track resolution in the backward cms hemisphere and 5 to 10 times that in the forward one.

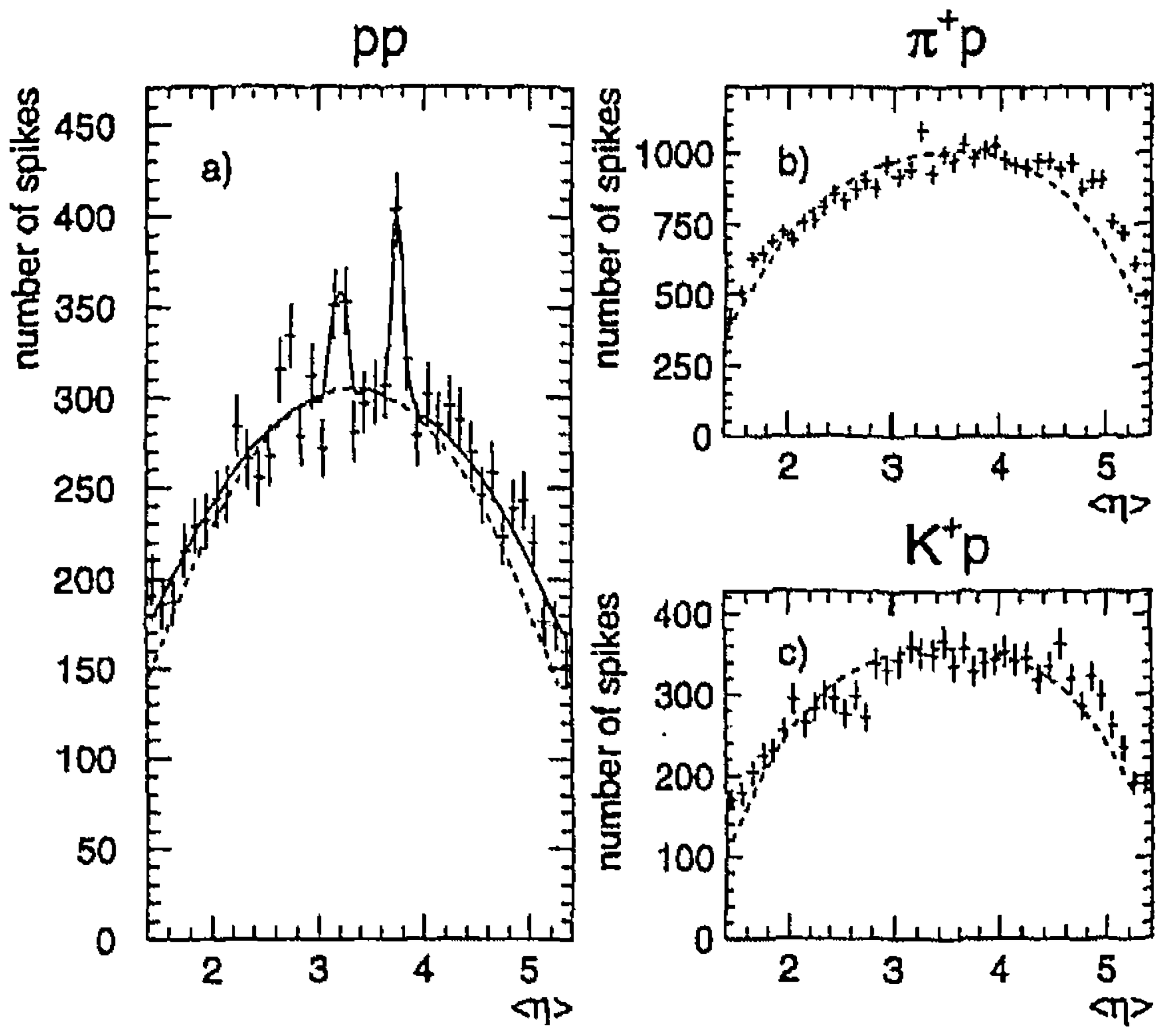

Fig. 2. Spike-center pseudorapidity distribution for pp interactions at 205, 250 and 360 GeV/c (Fig. 2a), for π^+p interactions at 250 GeV/c (Fig. 2b) and for K$^+$p interactions at 250 GeV/c (Fig. 2c). The solid line in Fig. 2a is a result of the fit (see text), the dashed lines are the FRITIOF predictions.

The inclusive $\langle\eta\rangle$ distribution of the spike centers for the combined pp data at 205, 250 and 360 GeV/c is presented in Fig. 2a and that for the π^+p and the K$^+$p data at 250 GeV/c in Figs. 2b and 2c, respectively. A complicated structure revealing a number of peaks over a fairly strong background can be observed in the distribution of the pp data in Fig. 2a. To parametrize the background we fit it by a second-order polynomial. The two peaks with the largest statistical significance are parametrized by Gaussians. The solid curve shows the result of a fit of signal and background. The peaks with the largest statistical significance ($S/\sqrt{S+B}$) are found to be those at $\langle\eta\rangle = 3.2$ and 3.8, corresponding to cms production angles of 72° ± 3° and 108° ± 3°. These positions are in agreement with the theoretical prediction for the gluon jet emission angles $\langle\eta_g^{\rm cms}\rangle = \pm 0.3$. The fit yields 101 and 120 groups in the peaks above a background of 603 and 605, corresponding to a statistical significance of 3.8 and 4.4 standard deviations, respectively.

The distance $D(\langle\eta_1\rangle, \langle\eta_2\rangle)$ between these peaks is

$$D(\langle\eta_1\rangle, \langle\eta_2\rangle) = 0.57 \pm 0.03(\text{stat}) \pm 0.12(\text{syst}), \qquad (13)$$

also in agreement with the theoretical estimate above. The ratio of such spikes to the full data sample of events with multiplicity $n_{ch} \geq 8$ is $(0.85 \pm 0.04(\text{stat}))\cdot 10^{-2}$ spikes/event.

In contrast to that for the pp interactions, the spike-center distribution for the π^+p (K^+p) data presented in Fig. 2b(c) is rather smooth, showing no particular peaks in the pseudorapidity region $3.0 < \langle\eta\rangle < 4.0$. In this case, including a Gaussian for a possible signal does not improve the quality of the fit.

In order to study the origin of the peaks observed in the pp data, we generated 100000 Monte Carlo events of each type (pp, π^+p and K^+p) using the FRITIOF7.02 model. The pp sample was generated as a mixture of events with the same composition of beam energies as the experimental pp data sample under consideration. The spike-center distribution for the simulated events, normalized to the background in the experimental distribution, is shown as the dashed curve in Figs. 2(a–c). No peaks are seen in the model. The shape of the theoretical curves is close to that of the experimental distributions for π^+p and K^+p interactions. For pp data the theoretical curve follows the shape of the background.

To reduce the statistical background, we further limit the analysis to events containing at least two dense groups. In this sample, a large contribution of spikes is observed from diffractive processes in the regions of $\langle\eta\rangle < 1.9$ and $\langle\eta\rangle > 4.9$. In order to discard these processes, we restrict the analysis to the pseudorapidity interval $1.9 < \langle\eta\rangle < 4.9$.

The corresponding spike-center distributions are shown in Figs. 3(a–c). Again, a double-peak structure can be observed in the pp data (Fig. 3a), but with peaks more dominant over the background than those in Fig. 2a. The same fitting procedure as applied above gives 73 and 63 spikes in the peaks above a background of 150 and 147, corresponding to a statistical significance of 4.9 and 4.3 standard deviations, respectively. The $\langle\eta\rangle$ values for the left and the right peaks are commensurate with those obtained for the full sample. The distance $D(\langle\eta_1\rangle, \langle\eta_2\rangle)$ between the peaks is estimated to be

$$D(\langle\eta_1\rangle, \langle\eta_2\rangle) = 0.77 \pm 0.04(\text{stat}) \pm 0.12(\text{syst})\,. \quad (14)$$

The ratio of two-spike events to the full data sample with $n_{ch} \geq 8$ is $(0.26 \pm 0.03(\text{stat}))\cdot 10^{-2}$.

The shape of the spike-center distribution for

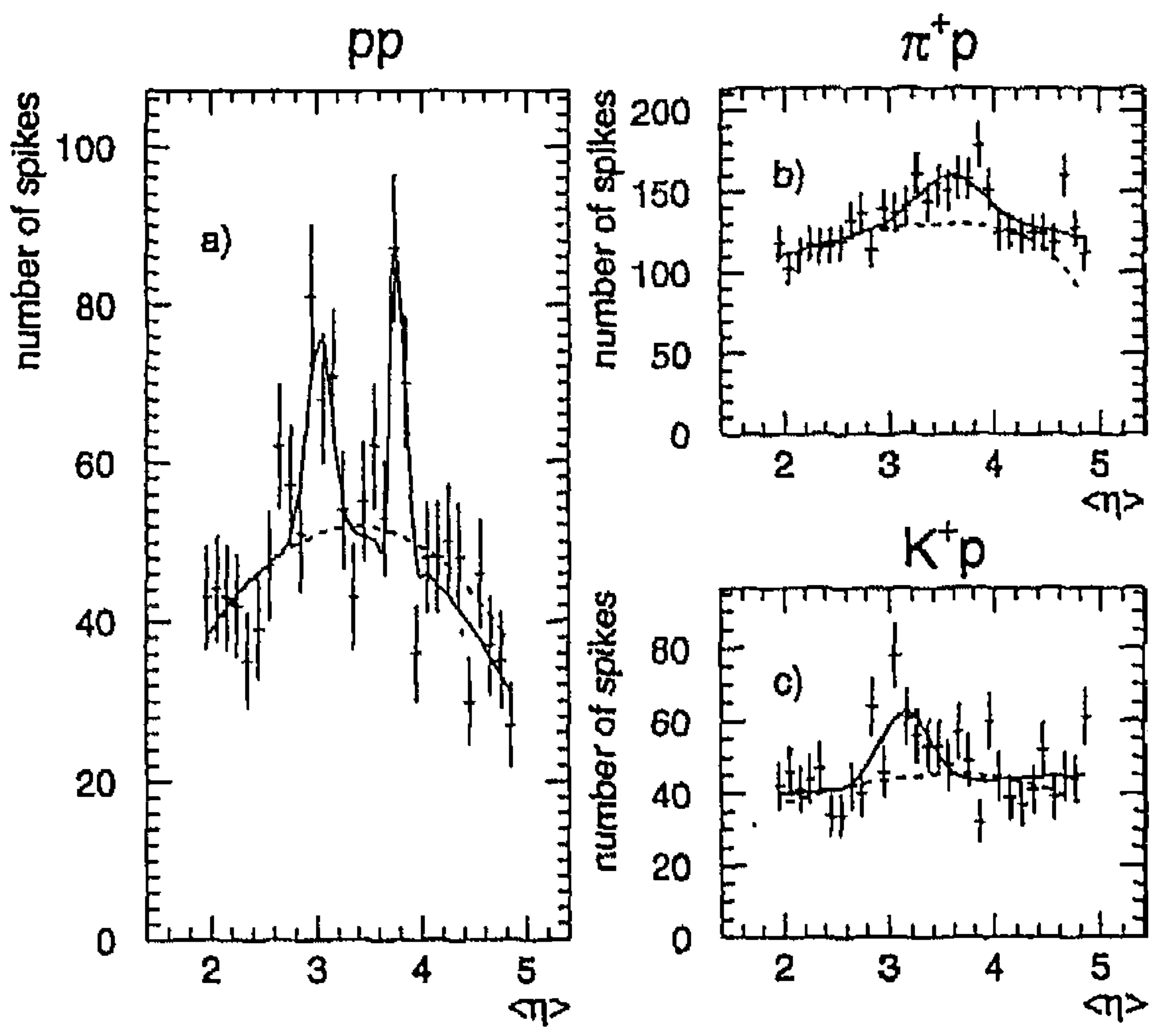

Fig. 3. Spike-center pseudorapidity distribution in events with associated spike-spike production a) for pp interactions at 205, 250 and 360 GeV/c, b) for π^+p interactions at 250 GeV/c, c) for K^+p interactions at 250 GeV/c. The solid lines show the results of fits. The dashed lines are the FRITIOF predictions.

two-spike events from the π^+p sample (Fig. 3b) is essentially different from that for the pp sample. It shows one wide bump centered at $\langle\eta\rangle = 3.57 \pm 0.08(\text{stat}) \pm 0.15(\text{syst})$. The bump consists of 204 spikes above a background of 1107, corresponding to a statistical significance of 6.1 standard deviations. The distribution of the K^+p data (Fig. 3c) has a similar wide bump centered at $\langle\eta\rangle = 3.15 \pm 0.07(\text{stat}) \pm 0.15(\text{syst})$. It consists of 116 spikes above a background of 411, corresponding to a statistical significance of 5.7 standard deviations.

The width of the bump observed in π^+p interactions is about twice that of the peaks in pp interactions. This result agrees qualitatively with the prediction of the coherent gluon radiation model. The shift of the bump in $\langle\eta\rangle$ for K^+p, with respect to that for π^+p collisions, can be explained by the large mass of the s-quark in the K^+.

The dashed lines in Figs. 3(a–c) show the FRITIOF predictions for the spike-center distributions normalized to the background. The theoretical curves do not reproduce the structure of the experimental distribution for any of the three types of interactions.

The two-spike event analysis, therefore, confirms the existence of two distinct peaks in the spike-center distribution for pp interactions and gives evidence for

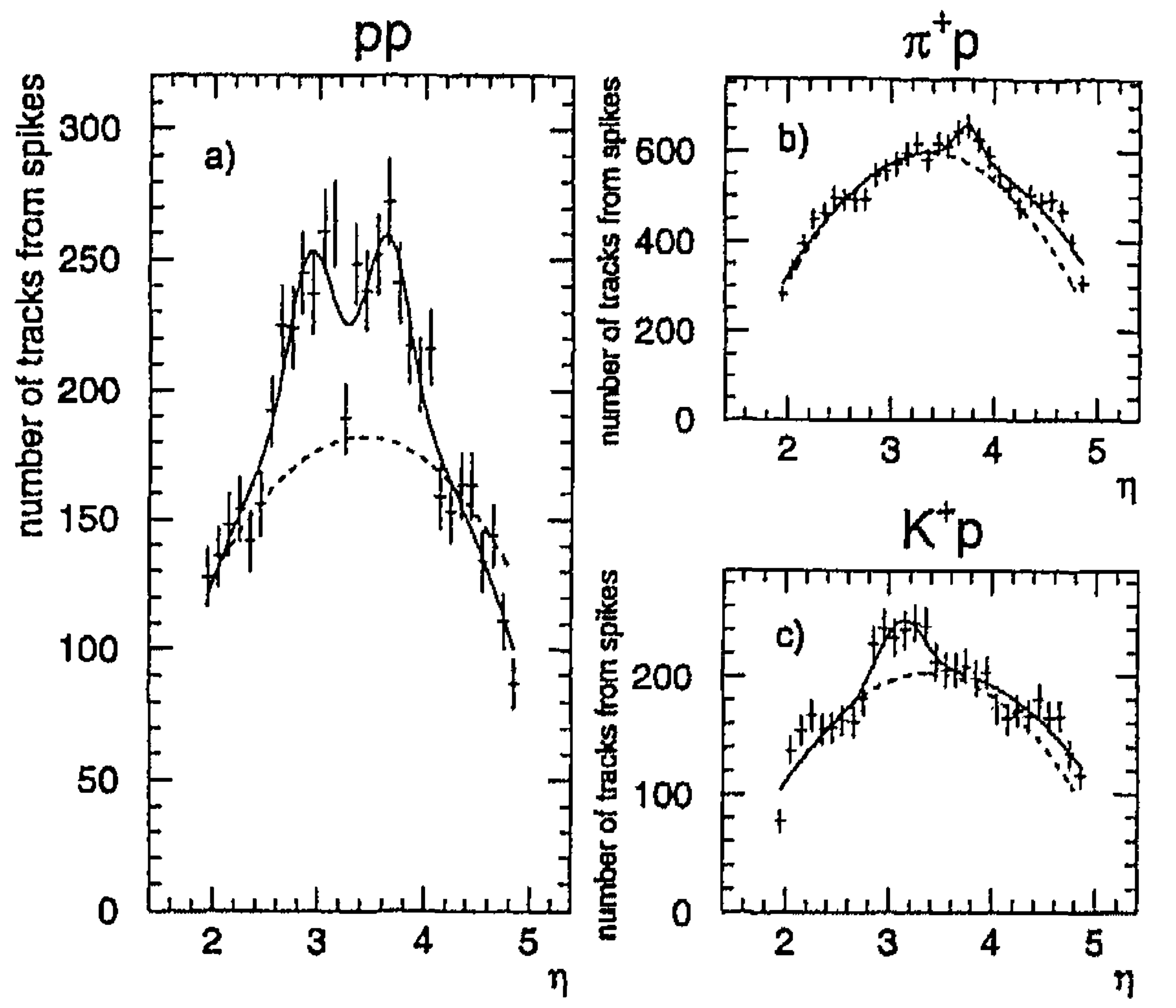

Fig. 4. The pseudorapidity distribution of tracks from spikes in events with associated spike-spike production (a) for pp interactions at 205, 250 and 360 GeV/c, (b) for π^+p interactions at 250 GeV/c, (c) for K$^+$p interactions at 250 GeV/c. The solid lines show the results of fits. The dashed lines are the FRITIOF predictions.

one wide bump in π^+p and K$^+$p interactions.

The pseudorapidity distribution of individual tracks originating from the spikes (Fig. 4) follows the shape of the corresponding spike-center distribution. In pp interactions, in particular, two peaks are observed at a distance of

$$D(\langle\eta_1\rangle, \langle\eta_2\rangle) = 0.77 \pm 0.06(\text{stat}) \pm 0.12(\text{syst}) \quad (15)$$

from one another, while π^+p interactions produce a bump at $\langle\eta\rangle = 3.75 \pm 0.04(\text{stat}) \pm 0.15(\text{syst})$, K$^+$p interactions at $\langle\eta\rangle = 3.15 \pm 0.05(\text{stat}) \pm 0.15(\text{syst})$.

Figs. 2a, 3a, 4a and expressions (13)–(15) demonstrate a stability of the pseudorapidity position of the peaks in the pp data. The most probable values of the enhancements extracted from the different versions of the analysis are close to the polar angles 72°±3°(stat) and 108° ± 3°(stat) in the center-of-mass frame of the colliding protons.

4. Conclusions

Using tools that provide direct spike identification on the one hand, and a model of coherent gluon emission over a finite length on the other, we come to the following conclusions:

- The spike-center pseudorapidity distribution for pp interactions reveals two prominent peaks. The most probable values of the polar angle of the peaks are 72° ± 3°(stat) and 108° ± 3°(stat) in the cms system of the colliding protons. The distance between the peaks agrees with the choice of the cms coherence length (the cms longitudinal size of the colliding hadrons) $l_c = xl_0/\gamma$. A similar distribution is observed for spikes from events with at least one spike and those with at least two spikes, as well as for tracks originating from spikes.
- The π^+p data show one wide bump in the middle of the spike-center pseudorapidity distribution, at $\langle\eta\rangle = 3.57 \pm 0.08(\text{stat}) \pm 0.15(\text{syst})$. The bump width is nearly twice that for pp interactions. It becomes observable with a sample of two-spike events.
- The K$^+$p data are similar to the π^+p data, but the bump center is shifted to a lower pseudorapidity, $\langle\eta\rangle = 3.15 \pm 0.07(\text{stat}) \pm 0.15(\text{syst})$.
- The increase in statistical significance of the peaks observed when more stringent selection criteria are used, and the stability of their positions for the various versions of the analysis suggest a dynamical nature of the peaks. The FRITIOF model neither reproduces the two-peak structure of the experimental spike-center pseudorapidity distribution for the pp sample, nor the wide bumps in the same distribution for two-spike events in the π^+p and K$^+$p samples. The shape of the spike-center pseudorapidity distribution for pp, πp and Kp interactions is in agreement with the predictions of the coherent gluon radiation model, i.e., a double-peak structure for pp interactions and a single-peak one for πp or Kp interactions.
- The effect of ring-like events in hadroproduction is somewhat similar to the ring-like structure of accompanying radiation of short-lived particles (the "dead-cone effect") predicted in [24] and observed in integral form in [25].

Acknowledgements

It is a pleasure to thank the FNAL (205 GeV/c pp) and CERN EHS/NA23 collaborations for the permis-

sion to use their experimental data.

We are grateful to the III. Physikalisches Institut B, RWTH Aachen, Germany, the DESY-Institut für Hochenergiephysik, Berlin-Zeuthen, Germany, the Department of High Energy Physics, Helsinki University, Finland, the Institute for High Energy Physics, Protvino, Russia, and the University of Warsaw and Institute of Nuclear Problems, Poland, for early contributions to this experiment.

One of the authors (J.C.) was supported by the Polish KBN grant No. 2 P03B083 08 and by the Polish-German Collaboration Foundation grant FWPN No. 1441/LN/94.

This work is part of the research program of the "Stichting voor Fundamenteel Onderzoek der Materie (FOM)", which is financially supported by the "Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO)". We further thank NWO for support of this project within the program for subsistence to the former Soviet Union (07-13-038). The Yerevan group activity is financially supported, in the framework of the theme No. 94-496, by the Government of the Republic of Armenia.

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