Three-Pion Interferometry Results from Central Pb+Pb Collisions at 158 A GeV/c

M.M. Aggarwal,[1] A. Agnihotri,[2] Z. Ahammed,[3] A.L.S. Angelis,[4] V. Antonenko,[5] V. Arefiev,[6] V. Astakhov,[6] V. Avdeitchikov,[6] T.C. Awes,[7] P.V.K.S. Baba,[8] S.K. Badyal,[8] C. Barlag,[9] S. Bathe,[9] B. Batiounia,[6] T. Bernier,[10] K.B. Bhalla,[2] V.S. Bhatia,[1] C. Blume,[9] R. Bock,[11] E.-M. Bohne,[9] Z. Böröcz,[9] D. Bucher,[9] A. Buijs,[12] H. Büsching,[9] L. Carlen,[13] V. Chalyshev,[6] S. Chattopadhyay,[3] R. Cherbatchev,[5] T. Chujo,[14] A. Claussen,[9] A.C. Das,[3] M.P. Decowski,[18] H. Delagrange,[10] V. Djordjadze,[6] P. Donni,[4] I. Doubovik,[5] S. Dutt,[8] M.R. Dutta Majumdar,[3] K. El Chenawi,[13] S. Eliseev,[15] K. Enosawa,[14] P. Foka,[4] S. Fokin,[5] M.S. Ganti,[3] S. Garpman,[13] O. Gavrishchuk,[6] F.J.M. Geurts,[12] T.K. Ghosh,[16] R. Glasow,[9] S. K.Gupta,[2] B. Guskov,[6] H. Å.Gustafsson,[13] H. H.Gutbrod,[10] R. Higuchi,[14] I. Hrivnacova,[15] M. Ippolitov,[5] H. Kalechofsky,[4] R. Kamermans,[12] K.-H. Kampert,[9] K. Karadjev,[5] K. Karpio,[17] S. Kato,[14] S. Kees,[9] C. Klein-Bösing,[9] S. Knoche,[9] B. W. Kolb,[11] I. Kosarev,[6] I. Koutcheryaev,[5] T. Krümpel,[9] A. Kugler,[15] P. Kulinich,[18] M. Kurata,[14] K. Kurita,[14] N. Kuzmin,[6] I. Langbein,[11] A. Lebedev,[5] Y.Y. Lee,[11] H. Löhner,[16] L. Luquin,[10] D.P. Mahapatra,[19] V. Manko,[5] M. Martin,[4] G. Martínez,[10] A. Maximov,[6] G. Mgebrichvili,[5] Y. Miake,[14] Md.F. Mir,[8] G.C. Mishra,[19] Y. Miyamoto,[14] B. Mohanty,[19] M.-J. Mora,[10] D. Morrison,[20] D. S. Mukhopadhyay,[3] H. Naef,[4] B. K. Nandi,[19] S. K. Nayak,[10] T. K. Nayak,[3] S. Neumaier,[11] A. Nianine,[5] V. Nikitine,[6] S. Nikolaev,[5] P. Nilsson,[13] S. Nishimura,[14] P. Nomokonov,[6] J. Nystrand,[13] F.E. Obenshain,[20] A. Oskarsson,[13] I. Otterlund,[13] M. Pachr,[15] S. Pavliouk,[6] T. Peitzmann,[9] V. Petracek,[15] W. Pinganaud,[10] F. Plasil,[7] U. von Poblotzki,[9] M.L. Purschke,[11] J. Rak,[15] R. Raniwala,[2] S. Raniwala,[2] V.S. Ramamurthy,[19] N.K. Rao,[8] F. Retiere,[10] K. Reygers,[9] G. Roland,[18] L. Rosselet,[4] I. Roufanov,[6] C. Roy,[10] J.M. Rubio,[4] H. Sako,[14] S.S. Sambyal,[8] R. Santo,[9] S. Sato,[14] H. Schlagheck,[9] H.-R. Schmidt,[11] Y. Schutz,[10] G. Shabratova,[6] T.H. Shah,[8] I. Sibiriak,[5] T. Siemiarczuk,[17] D. Silvermyr,[13] B.C. Sinha,[3] N. Slavine,[6] K. Söderström,[13] N. Solomey,[4] S.P. Sørensen,[7,20] P. Stankus,[7] G. Stefanek,[17] P. Steinberg,[18] E. Stenlund,[13] D. Stüken,[9] M. Sumbera,[15] T. Svensson,[13] M.D. Trivedi,[3] A. Tsvetkov,[5] L. Tykarski,[17] J. Urbahn,[11] E.C.v.d. Pijll,[12] N.v. Eijndhoven,[12] G.J.v. Nieuwenhuizen,[18] A. Vinogradov,[5] Y.P. Viyogi,[3] A. Vodopianov,[6] S. Vörös,[4] B. Wysłouch,[18] K. Yagi,[14] Y. Yokota,[14] G.R. Young[7]

(WA98 collaboration)

[1] University of Panjab, Chandigarh 160014, India
[2] University of Rajasthan, Jaipur 302004, Rajasthan, India
[3] Variable Energy Cyclotron Centre, Calcutta 700 064, India
[4] University of Geneva, CH-1211 Geneva 4,Switzerland
[5] RRC Kurchatov Institute, RU-123182 Moscow, Russia
[6] Joint Institute for Nuclear Research, RU-141980 Dubna, Russia
[7] Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6372, USA
[8] University of Jammu, Jammu 180001, India
[9] University of Münster, D-48149 Münster, Germany
[10] SUBATECH, Ecole des Mines, Nantes, France

[11] Gesellschaft für Schwerionenforschung (GSI), D-64220 Darmstadt, Germany
[12] Universiteit Utrecht/NIKHEF, NL-3508 TA Utrecht, The Netherlands
[13] Lund University, SE-221 00 Lund, Sweden
[14] University of Tsukuba, Ibaraki 305, Japan
[15] Nuclear Physics Institute, CZ-250 68 Rez, Czech Rep.
[16] KVI, University of Groningen, NL-9747 AA Groningen, The Netherlands
[17] Institute for Nuclear Studies, 00-681 Warsaw, Poland
[18] MIT, Cambridge, MA 02139, USA
[19] Institute of Physics, 751-005 Bhubaneswar, India
[20] University of Tennessee, Knoxville, Tennessee 37966, USA

Abstract

Three-particle correlations have been measured for identified π^- from central 158 A GeV Pb+Pb collisions by the WA98 experiment at CERN. A substantial contribution of the genuine three-body correlation has been found as expected for a mainly chaotic and symmetric source.

In nuclear and particle physics, the study of Bose-Einstein correlations between identical particles is widely used. It is an essential tool to obtain information on the size and time evolution of expanding systems created in heavy ion collisions [1]. In particular, two-particle Bose-Einstein interferometry has been used for a sophisticated analysis of the dynamical evolution of the freeze out volume via selection on the transverse momentum and rapidity of the correlated particles.

Three-particle interferometry measurements can provide additional information on the space-time emission which is not accessible by two-particle interferometry[2, 3, 4, 5]. In particular, if the emission is fully chaotic, the three-particle interference study gives access to the phase of the source function's Fourier transform, which is affected by the emission asymmetry. These asymmetries may be induced by source geometry, flow or resonance decays. If the source is not completely chaotic, as is likely to be the case, the interpretation is more difficult. Nevertheless, a comparison of the three-particle to the two-particle result allows to extract the relative strength of the true three-body correlation and can in principle remove obscuring effects, such as background from misidentified tracks or long-lived decay products, and therefore provide information more directly about the degree of coherence of the emission source[4]. In this letter we present first results from three-particle interferometry in central ^{208}Pb+^{208}Pb collisions at the CERN SPS.

The fixed target experiment WA98 [6] combined large acceptance photon detectors with a two arm charged particle tracking spectrometer. The incident 158 A GeV Pb beam impinged on a Pb target near the entrance of a large dipole magnet. The results presented here have been obtained from an analysis of the 1995 data set. These data were taken with the most central triggers corresponding to about 10% of the minimum bias cross section of 6190 mb. The π^- measurements were obtained with data from the negative particle tracking arm of the spectrometer. This tracking arm consisted of six multistep avalanche chambers with optical

readout [7]. A time of flight detector with a time resolution better than 120 ps allowed for particle identification. The rapidity acceptance ranged from $y = 2.1$ to 3.1 with an average at 2.7, close to mid-rapidity which was 2.9. The momentum resolution of the spectrometer was $\Delta p/p = 0.005$ at $p = 1.5$ GeV/c. Severe track quality cuts were applied, resulting in a final sample of 4.2×10^6 π^-, providing 7.2×10^6 pairs and 8.2×10^6 triplets. The $\pi^-\pi^-$ correlation analysis has been reported elsewhere [8].

The most common use of hadron interferometry concerns the study of pairs of identical particles. The two-particle correlation function can be defined as

$$C_2(\mathbf{p}_1,\mathbf{p}_2) = \frac{d^2N(\mathbf{p}_1,\mathbf{p}_2)/d\mathbf{p}_1 d\mathbf{p}_2}{dN(\mathbf{p}_1)/d\mathbf{p}_1 \cdot dN(\mathbf{p}_2)/d\mathbf{p}_2}$$

where $\mathbf{p}_1$ and $\mathbf{p}_2$ are the 3–momenta of the correlated particles. The product of single particle distributions in the denominator is usually obtained experimentally by a mixed event technique whereas the pair distribution in the numerator is constructed from all pair combinations of identical particles found in each event. C_2 is normalized to unity far away from the interference region. In the plane wave approximation for chaotic sources of identical particles C_2 can be written as [9]

$$C_2(\mathbf{p}_1,\mathbf{p}_2) = 1 \pm |F_{12}|^2 \tag{1}$$

with the + (-) sign for bosons (fermions). F_{12} is the Fourier transform of the space-time source function $S(x, k_{12})$

$$|F_{12}|^2 = \frac{|\int d^4x\ S(x,k_{12})\ \exp[iq_{12}x]|^2}{|\int d^4x\ S(x,k_{12})|^2} \tag{2}$$

with $q_{12} = p_1 - p_2$, the 4–momentum difference of the two particles, and $k_{12} = (p_1 + p_2)/2$. F_{12} is unity as $q_{12} \to 0$. Thus the production of identical bosons is enhanced for pairs created close together in phase space with a small momentum difference $Q_{12} \equiv \sqrt{-q_{12}^2}$.

Typically $\pi\pi$ correlation data are fit with a Gaussian form for $|F_{12}|^2$

$$C_2 = 1 + \lambda\ \exp[-Q_{12}^2 R^2] \tag{3}$$

or an exponential form

$$C_2 = 1 + \lambda\ \exp[-2Q_{12}R] \tag{4}$$

where the parameter λ is inserted to take into account the possibility that the source may not be fully chaotic and also that any wrongly reconstructed tracks, or tracks coming from decays of long-lived resonances, will dilute the correlations in the data.

The measurement of C_2 gives access to the radius R of the source, but not to the phase ϕ_{12} contained in $F_{12} \equiv |F_{12}| \exp[i\phi_{12}]$ since C_2 is only a function of the square of the Fourier transform of the source distribution S. By contrast, the three-boson interference produced by a fully chaotic source is sensitive to the phase information of the Fourier transform of the source emission function. Indeed, for a chaotic source the three-body correlation function C_3, which is

$$C_3(\mathbf{p}_1,\mathbf{p}_2,\mathbf{p}_3) = \frac{d^3N(\mathbf{p}_1,\mathbf{p}_2,\mathbf{p}_3)/d\mathbf{p}_1 d\mathbf{p}_2 d\mathbf{p}_3}{dN(\mathbf{p}_1)/d\mathbf{p}_1 \cdot dN(\mathbf{p}_2)/d\mathbf{p}_2 \cdot dN(\mathbf{p}_3)/d\mathbf{p}_3}$$

can be written [2, 3, 4, 5] as

$$C_3 = 1 + |F_{12}|^2 + |F_{23}|^2 + |F_{31}|^2 + 2 \cdot \mathrm{Re}\{F_{12} \cdot F_{23} \cdot F_{31}\} \tag{5}$$

where F_{ij} is the Fourier transform for the pair ij contained in the triplet 123. The genuine three-body correlation in C_3 is the term $2 \cdot \mathrm{Re}\{F_{12} \cdot F_{23} \cdot F_{31}\}$.

With $F_{ij} \equiv |F_{ij}| \exp[i\phi_{ij}]$ and $W \equiv \cos(\phi_{12} + \phi_{23} + \phi_{31})$ one may rewrite

$$2 \cdot \mathrm{Re}\{F_{12} \cdot F_{23} \cdot F_{31}\} = 2 \cdot |F_{12}| \cdot |F_{23}| \cdot |F_{31}| \cdot W. \tag{6}$$

Having determined $|F_{ij}|$ from the pair correlation function C_2, the measurement of C_3 gives direct access to W, the cosine of the sum of the three phases of the Fourier transforms, and hence provides complementary information on the shape of the source. Indeed, W is related to the odd space-time moments of the source which generate the phases ϕ_{ij} [4]. For example, if the source is fully chaotic and symmetric, F_{ij} are real, $\phi_{12} = \phi_{23} = \phi_{31} = 0$, and W is equal to 1. C_3 is then fully determined by C_2, and the genuine three-particle correlation is maximum. If the source is not fully chaotic, more complicated expressions should be used, mixing the effects of fully chaotic and coherent sources [4]. Nevertheless, Eq. 6 is valid in general with W interpreted as a factor expressing the relative strength of the true three-body correlation compared to that expected for a fully symmetric chaotic source. Consequently, measuring W values less than 1 does not allow to differentiate between asymmetries or coherence in the source.

Assuming a Gaussian form of the source function, which for two bosons leads to a correlation function described by Eq. 3, one obtains

$$C_3 = 1 + \lambda \sum_{ij=12,23,31} \exp[-Q_{ij}^2 R^2] + 2\lambda^{3/2} \exp[-Q_3^2 R^2/2] \cdot W \tag{7}$$

with $Q_3^2 \equiv Q_{12}^2 + Q_{23}^2 + Q_{31}^2$. If the exponential form of the Fourier transform is assumed instead (Eq. 4), one obtains

$$C_3 = 1 + \lambda \sum_{ij=12,23,31} \exp[-2Q_{ij} R] + 2\lambda^{3/2} \exp[-(Q_{12} + Q_{23} + Q_{31})R] \cdot W \tag{8}$$

Inserting the values of λ and R obtained from the two-particle analysis into Eqs. 7 or 8, one can extract the three-particle strength information W.

The one-dimensional correlation function C_2, analyzed in terms of Q_{12}, is shown in Fig. 1. The two-track resolution of the spectrometer (2 cm) is dealt with by application of a proximity cut to each track pair. The data are corrected for the Coulomb and stong final state interactions in an iterative way [10], taking into account the source size obtained in the fit. The Gamow correction was abandoned as we found that it overcorrects the data for Q_{12} in the range of 0.1 to 0.3 GeV/c. The effect of the experimental resolution, which is estimated by a full Monte-Carlo, can be approximated in the interference region by a Gaussian of constant σ of 7 MeV/c both for Q_{12} and Q_3. It is taken into account by replacing the function $C_2(Q_{12})$ used to fit the non-corrected data by

$$C_2^{rc}(Q_{12}) = \int r(Q_{12}, Q_{12}') \, C_2(Q_{12}') \, dQ_{12}',$$

which is the convolution of $C_2(Q_{12})$ with the resolution function $r(Q_{12}, Q'_{12})$ of the spectrometer. For display purposes, Fig. 1 is obtained by multiplying each data point by $C_2^{rc}(Q_{12})/C_2(Q_{12})$. Fitting the corrected data with C_2 gives the same results as fitting the non-corrected data with C_2^{rc}. The correlation function C_2 is seen to be non-Gaussian. Instead, it is better represented by an exponential form[8]. For the C_3 analysis, an accurate description of the shape of C_2 is essential since the estimate of the W factor extracted from C_3 depends on it. The exponential fit (Eq. 4) yielding $R = 7.29 \pm 0.11$ fm and $\lambda = 0.753 \pm 0.013$ is shown in Fig. 1.

Fig. 2 shows the three-pion correlation as a function of Q_3, after correction for resolution. A very strong $\pi^-\pi^-\pi^-$ correlation is observed, which is robust under all tracking criteria. The result shown is obtained for the same sample and the same cuts applied on the three pair combinations contained in each triplet as used for the two-pion interference analysis. For the C_3 result, the Coulomb correction applied to a particular triplet is the product of the Coulomb corrections used for the three pair combinations contained in that triplet. The resolution is taken into account using the same procedure as in the two-pion analysis. The resolution has a tiny effect compared to the Coulomb correction and it has been checked that the results are not affected by the order in which these corrections are applied to the data. The dashed line is a fit to a double exponential function

$$C_3 = 1 + \lambda_1 \exp[-2Q_3R_1] + \lambda_2 \exp[-2Q_3R_2] \tag{9}$$

with fitted parameters $R_1 = 5.01 \pm 0.38$ fm, $\lambda_1 = 2.79 \pm 0.32$, $R_2 = 1.72 \pm 0.12$ fm, $\lambda_2 = 0.343 \pm 0.072$ and $\chi^2/d.o.f. = 0.88$. The three-pion correlation data cannot be well fitted by a Gaussian or a single exponential as a function of Q_3. Such non-Gaussian behaviour has been predicted by a final-state rescattering model [11].

In Fig. 2, the three-pion correlation data are compared to an estimate using Eq. 8 with $W = 1$ (upper line) and $W = 0$ (lower line). This estimate is made using triplets from mixed events with the λ and R parameters extracted from the two-pion interferometry analysis. Although the calculated contribution to C_3 from the genuine three-pion correlation is rather small and becomes insignificant for $Q_3 > 60 - 80$ MeV/c, the experimental results clearly indicate a W factor which lies between 0 and 1.

As proposed in Refs. [4, 12], a method to extract the experimental value of W as a function of Q_3 is to invert Eqs. 5 and 6 and rewrite $|F_{ij}|$ in terms of C_2 using Eq. 1 to obtain

$$W = \frac{\{C_3(Q_3) - 1\} - \{C_2(Q_{12}) - 1\} - \{C_2(Q_{23}) - 1\} - \{C_2(Q_{31}) - 1\}}{2 \cdot \sqrt{\{C_2(Q_{12}) - 1\}\{C_2(Q_{23}) - 1\}\{C_2(Q_{31}) - 1\}}} \tag{10}$$

In this method, the analysis must be performed in two steps. First, the λ and R parameters are determined both for the two-pion and three-pion correlations with a fit to the data of Eqs. 4 and 9 as previously explained. Then the data are analyzed again, and, for each triplet found, characterized by the value Q_3, W is determined using Eqs. 4, 9, and 10 with the values Q_{12}, Q_{23}, and Q_{31} corresponding to the three pair combinations contained in the triplet. For each bin in Q_3 containing N triplets, the statistical error on the mean value $\langle W \rangle$ is $\sigma/\sqrt{N}$, where σ^2 is the variance of the W distribution in this particular bin. The estimate of systematic errors is done by varying the different analysis cuts in the two and three-pion interference studies. It includes in particular the cuts used to identify the pions with the time of flight system. The systematic error on the Coulomb correction due to the error on the

determination of the R parameter in the two-pion fit, as well as a possible 10% systematic error on the evaluation of the Q_{12} and Q_3 resolution are also taken into account. The effects on W of the statistical errors in the determination of C_2 and C_3 are treated as systematic errors by changing C_2 and C_3 respectively by $\pm\sigma_{C_2}$ and $\pm\sigma_{C_3}$. All of these variations are then added in quadrature.

Fig. 3 shows the W values obtained for five bins of 10 MeV/c in Q_3. The error bars are the sum of statistical and systematic errors. The statistical errors (not shown separately in Fig. 3) are nearly negligible. The slight Q_3 dependence observed is not significant in view of the errors. The genuine three-body correlation is substantial with a weighted mean $\langle W \rangle = 0.606 \pm 0.005 \pm 0.179$ for $Q_3 < 60$ MeV/c. [1] This result should be compared to the lower $\pi^+\pi^+\pi^+$ result of $\langle W \rangle = 0.20 \pm 0.02 \pm 0.19$ observed by the NA44 collaboration [12] in S+Pb minimum bias collisions at 200 GeV per nucleon.

In conclusion, we have studied the $\pi^-\pi^-\pi^-$ interference of pions produced in central Pb+Pb collisions at 158 GeV per nucleon. Although its contribution is small, the genuine three-pion correlation, the portion of the correlation not trivially due to the two-pion interference, has been extracted and found to be substantial. The genuine three-pion correlation is greater than reported for S+Pb minimum bias collisions [12], but not as large as expected for a fully chaotic and symmetric source.

We would like to thank the CERN-SPS accelerator crew for providing an excellent Pb beam. This work was supported jointly by the German BMBF and DFG, the U.S. DOE, the Swedish NFR, the Dutch Stichting FOM, the Swiss National Fund, the Humboldt Foundation, the Stiftung für deutsch-polnische Zusammenarbeit, the Department of Atomic Energy, the Department of Science and Technology and the University Grants Commission of the Government of India, the Indo-FRG Exchange Programme, the PPE division of CERN, the INTAS under contract INTAS-97-0158, the Polish KBN under the grant 2P03B16815, the Grant-in-Aid for Scientific Research (Specially Promoted Research & International Scientific Research) of the Ministry of Education, Science, Sports and Culture, JSPS Research Fellowships for Young Scientists, the University of Tsukuba Special Research Projects, and ORISE. ORNL is managed by UT-Battelle, LLC, for the U.S. Department of Energy under contract DE-AC05-00OR22725.

References

[1] U.A. Wiedemann and U. Heinz, Phys. Rep. **319** (1999) 145 and references therein.

[2] I.V. Andreev, M. Plümer, and R.M. Weiner, Int. J. Mod. Phys. **A8** (1993) 4577.

[3] B. Lörstad, Int. J. Mod. Phys. **A4** (1989) 2861.

[4] U. Heinz and Q.H. Zhang, Phys. Rev. **C56** (1997) 426.

[5] H. Heiselberg and A.P. Vischer, Phys. Rev. **C55** (1997) 874.

[6] WA98 collaboration, Proposal for a large acceptance hadron and photon spectrometer, 1991, Preprint CERN/SPSLC 91-17, SPSLC/P260.

[1] The weighted systematic error is obtained by calculating the weighted average over the five Q_3 bins separately for each kind of systematic error. These errors are then added in quadrature. On the contrary, adding quadratically the systematic errors of the five Q_3 bins as done for weighted statistical errors, or as done in [12], would give ± 0.097 instead of ± 0.179 for the systematic uncertainty.

[7] J.M. Rubio et al., Nucl. Instr. and Meth. **A367** (1995) 358.
A.L.S. Angelis et al., Nucl. Phys. **A566** (1994) 605c.
M. Iżycki et al., Nucl. Instr. and Meth. **A310** (1991) 98.

[8] M.M. Aggarwal et al., hep-ex/0003009, to be published in Eur. Phys. J. **C**.
S. Vörös et al., Nucl. Phys. **A661** (1999) 427c.

[9] G.F. Bertsch, P. Danielewicz, and M. Herrmann, Phys. Rev. **C49** (1994) 442.
E. Shuryak, Phys. Lett. **B44** (1973) 387; Sov. J. Nucl. Phys. **18** (1974) 667.
S. Pratt, T. Csörgő and J. Zimányi, Phys. Rev. **C42** (1990) 2646.
S. Chapman and U. Heinz, Phys. Lett. **B340** (1994) 250.

[10] S.Pratt et al., Phys. Rev. **C42** (1990) 2646; these calculations were made with a Fortran program supplied by S. Pratt.

[11] T.J. Humanic, Phys. Rev. **C60** (1999) 014901.

[12] H. Bøggild et al., Phys. Lett. **B455** (1999) 77.

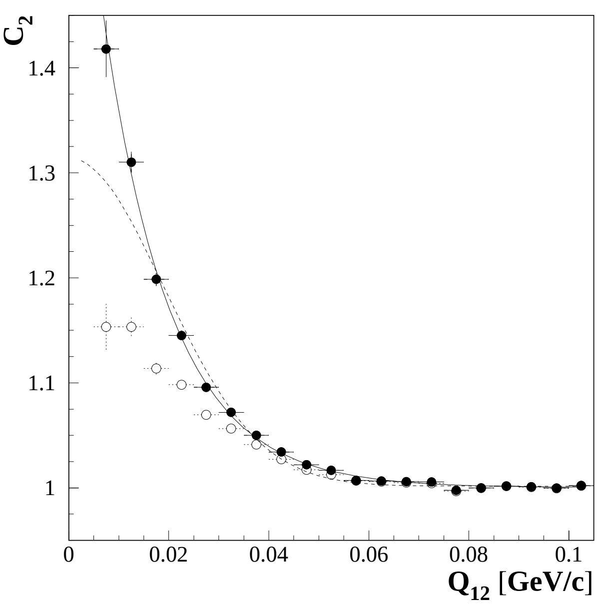

Figure 1: The measured $\pi^-\pi^-$ correlation function C_2 (full symbols) fit with an exponential (solid curve) or Gaussian form (dashed curve) corrected for resolution. The empty symbols show the data before Coulomb and resolution corrections. Only statistical errors are shown.

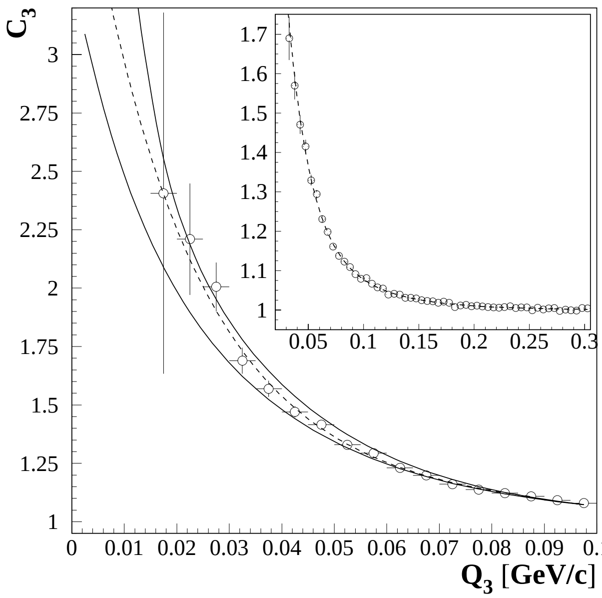

Figure 2: The three-pion correlation function C_3 as a function of Q_3 with a fit to a double exponential form (dashed line–see text). The result is also compared to an estimate of C_3 with $W = 1$ (upper solid line) and $W = 0$ (lower solid line). The inset shows C_3 over a larger Q_3 range.

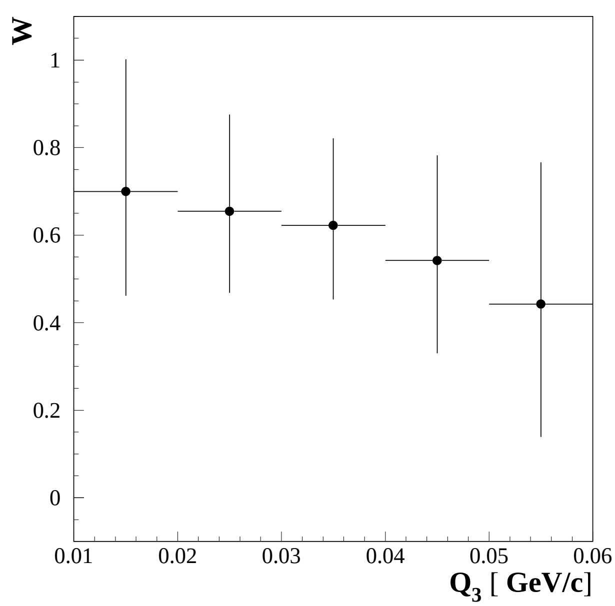

Figure 3: The factor W as a function of Q_3. The error bars include statistical and systematic errors. The statistical errors alone (not shown) are contained within the size of the symbols except for the first bin where it amounts to twice the size of the symbol. The horizontal bars indicate the bin width.