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PROGRESS IN PARTICLE CORRELATION STUDIES AT NA49[1]

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Hanbury-Brown and Twiss (HBT) or intensity interferometry is now an important tool in studying the systems formed in Relativistic Heavy Ion collisions. The advances in theoretical understanding of the properties of the correlation function as well as the overwhelming statistical accuracy that large acceptance detectors are now able to provide, give a precise characterization of the source created. The limitations now, instead of being statistical, are in the understanding how the various corrections, and selection criteria affect the results. Some current experimental considerations are detailed.

1. Introduction

The application of Hanbury-Brown and Twiss (HBT) interferometry to subatomic collisions has allowed measurements of the spatial and temporal extension of reaction volumes in a wide variety of collisions from e^+e^- and pp, to those between heavy ions.[1] These measurements are believed to be very important, not only because they are able to characterize the geometric properties of the source, but also because they may be sensitive to some of the critical conditions that would occur at the onset of the deconfinement of quarks and gluons from their parent hadrons—for example an anomalously long life-time associated with a latent heat. Furthermore, the evolution of the HBT parameters with the pair's transverse momentum have shown to be sensitive to the dynamics and ordered expansion of the source.[2]

The theoretical foundations of the correlation function is best illustrated from the formalism of Pratt [3] in terms of an emission function, or Wigner phase space density—$S_i(\mathbf{x}, \mathbf{k})$. It is the probability of emission of a particle of type i at a space-time position $\mathbf{x}$, with a momentum $\mathbf{k}$. This function, in principle, completely characterizes the source in terms of its particle composition, density, degree of thermalization, dynamics, etc. Unfortunately such a function is not an observable and it must be reconstructed or modelled from experimental observables.

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HBT is one of the tools used to give insight into the character of the emission function, and it is rather unique in that it is able to quantify the spatial and temporal extension of the created fireball. The normalized two particle boson spectra, or correlation function, in terms of S, is denoted by:

$$C_i(\mathbf{q},\mathbf{K}) = 1 + \frac{|\int_{source} d^4\mathbf{x}\, S_i(\mathbf{x},\mathbf{K}) e^{i\mathbf{q}\cdot\mathbf{x}}\,|^2}{|\int_{source} d^4\mathbf{x} S_i(\mathbf{x},\mathbf{K})\,|^2} \tag{1}$$

where **x** is the space-time point of the created particle, **q** is the 4-momentum difference of the particle pair, and **K** is the average momentum of the pair. Experimentally it is specified by:

$$C_i(\mathbf{q},\mathbf{K}) = \frac{\mathbf{Y}_i(\vec{k}_1,\vec{k}_2)}{\mathbf{Y}_i(\vec{k}_1)\,\mathbf{Y}_i(\vec{k}_2)} \tag{2}$$

where $\mathbf{Y}_i(k)$ denotes the yield of the i^{th} particle species, with a momentum $\vec{k}$. Because the measurement of two particle momentum spectra, gives only three linearly independent momenta ($\vec{q}$) components, the correlation function given in Eqn. (1), has no unique Fourier transform, as the integration is carried out over four components. Because of this ambiguity, the emission function must be interpreted in the scope of some model.

In the last few years, high rate and/or large acceptance detectors have made it possible to make increasingly differential measurements of correlation functions with meaningful statistical power. These measurements have been made in small rapidity intervals over small bins in the average transverse momentum of the pair. This has allowed a mapping of the source over all regions of phase space and given additional information, not previously available, on the dynamics of the system. The radii parameters are extracted via some sort of parameterization. Currently two popular parameterizations are the Cartesian Bertsch-Pratt(BP),[4] and Yano-Koonin-Podgoretskiĭ (YKP)[5] formalisms. Although they give equivalent information in terms of the parameters extracted, it has been suggested that the YKP parameterization is preferable because its parameters do not convolute spatial and temporal information in the complicated manner of the PB formalism, and therefore have a much more intuitive interpretation.[6] However there is a trade off since the YKP parameterization populates a small region of phase space, and problems arise with the stability of the fitting procedure used to extract the radii parameters.

Nonetheless the capabilities of the large acceptance NA49 experiment[7], shown in Fig. 1. allow an investigation, with an unprecedented statistical precision, into many ystematic effects that may alter the behavior of the correlation function. Those of urrent interest are how the Coulomb correction and particle composition affect the orrelation function. Hopefully the following will illustrate how sensitive the correlation unction really is to seemingly small and insignificant changes to selection criteria and article composition.

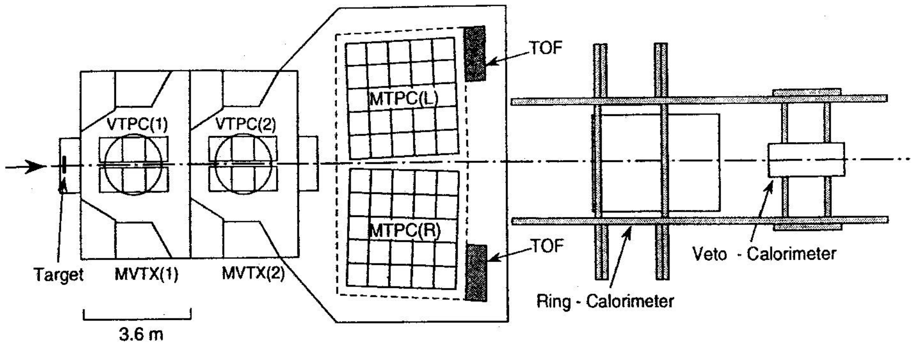

Fig. 1. The experimental set-up of NA49.

2. The Coulomb Correction

Quark Matter '96 saw a general consensus among the experiments that the Gamov correction used for the Coulomb corrections was not appropriate for the sources created in the 10.6 GeV/A Au-Au collisions at BNL AGS nor the 158 GeV/A Pb-Pb collisions at the CERN-SPS. The most important reason is simply that the Gamov factor assumes a point-like source. While perhaps adequate for those sources observed in e^+e^- or pp collisions, relativistic heavy ion collisions give source sizes with dimensions the order of 10 fm. This is definitely not justification for a point source.

However, with the demise of the Gamov correction, there has been a void created in that there is no longer a standard Coulomb correction that all experiments utilize, and a wide variety of techniques and methods are used. This has complicated the interpretations of comparisons between experiments, as no quantitative work is really available on the possible differences between the effects due to the various Coulomb corrections.

One of the more popular "post-Gamov" corrections is that of Pratt.[8] It essentially calculates two body Coulomb wave- functions and assigns weights to pairs based on their relative momentum difference (Q_{inv}).[3] There are two main concerns with this approach. First, there is no account of multi-body Coulomb effects; and second, no allowance for the possibility of source dependent effects is possible.

These are not really oversights of the model. It is simply intractable to carry out an exact many body Coulomb calculation. It is also equally difficult to evaluate source dependent effects since if one had enough source information to carry out such a calculation (essentially the emission function), there would be no need to make the measurement. The non-existence of suitable calculational tools to adequately address these questions speaks to the need to find some sort of phenomenological or effective correction.

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[3] all Coulomb corrections (that the author is aware of) are parameterized in terms of Q_{inv}.

NA35 began with a phenomenological Coulomb correction based on the measured $+-$ correlation (i.e. C^{+-}). Opposite sign pions will not exhibit the Bose-Einstein correlation, and thus any signal obtained in the construction of a $+-$ correlation function can be uniquely attributed to the Coulomb force. Thus if it is postulated:

$$C^{+-} \sim -C^{--}_{Coul} \qquad (3)$$

an effective *experimentally* deduced Coulomb correction can be used. Owing to its large acceptance coverage, NA49, like NA35, is in a unique position to simultaneously measure the positive and negative spectra, and thus to deduce a Coulomb correction from these data. Like all corrections, this procedure does have its pitfalls, and it is important to illustrate and document these problems.

The weak interaction is unlikely to produce any asymmetry in the signal as it is several orders of magnitude weaker than the electro-magnetic interaction. The strength of the Coulomb interaction does not depend on sign of the charge, but there is a problem with the length of time of the interaction. Oppositely charged particles attract, and so will be closer for a longer period of time. Like sign particles will repel and so the Coulomb force will be felt, at maximum strength, for a shorter time. Thus the length of time particles are subject to the interaction is not identical in the different channels, and this may introduce a small asymmetry. If the particles are relativistic, this should be a small affect, but it should become much more important with heavier systems (i.e. protons and kaons). Any further asymmetry must have its origins in the strong interaction—and this basically reduces to a question of charge symmetry. It is known that charge symmetry holds at the several per cent level in nuclear physics, and is broken only by the presence of the Coulomb interaction. In fact even the much stronger assumption of charge independence is not a bad one.

The strong interaction is the only other force that can introduce an asymmetry. Let us look in detail at the processes involved near freeze-out. Pion systems are weakly interacting systems, at least when compared to NN systems. This was one of the reason π correlation studies were favored over that of nucleons. π^+p and π^-n are isospin symmetric systems and interact with the same strength. Likewise so are π^+n and π^-p. Any asymmetry introduced is due to the relative populations of these channels which is introduced by the net isospin of the ^{208}Pb nuclei that contains 126 neutrons nd 82 protons. Thus the excess of neutrons will add to asymmetric behavior in the inal state interaction because of the predominance of the π^- isovector delta excitation. Vhile this may alter the Coulomb effects in the different channels, the effect should be uantifiable, at some level, in differing radii reported by the $\pi^+\pi^+$ and $\pi^-\pi^-$ channels.

Still, all the above should not be a large effect. Thus the NA49 strategy is to deterine a correction based on the correlation function of the $+-$ spectra in the variable $_{inv}$, subject to the same cuts as the identical particle spectra. Phenomenologically the rrection is in the spirit of the Yukawa potential, an exponentially damped Coulomb tential, with a finite range. Likewise in analogy the phenomenological Coulomb correction is taken as an exponentially damped Gamov factor, given in Eqn.4

$$(G(\eta) - 1)e^{-Q_{inv}/Q_{eff}} + 1 \qquad (4)$$

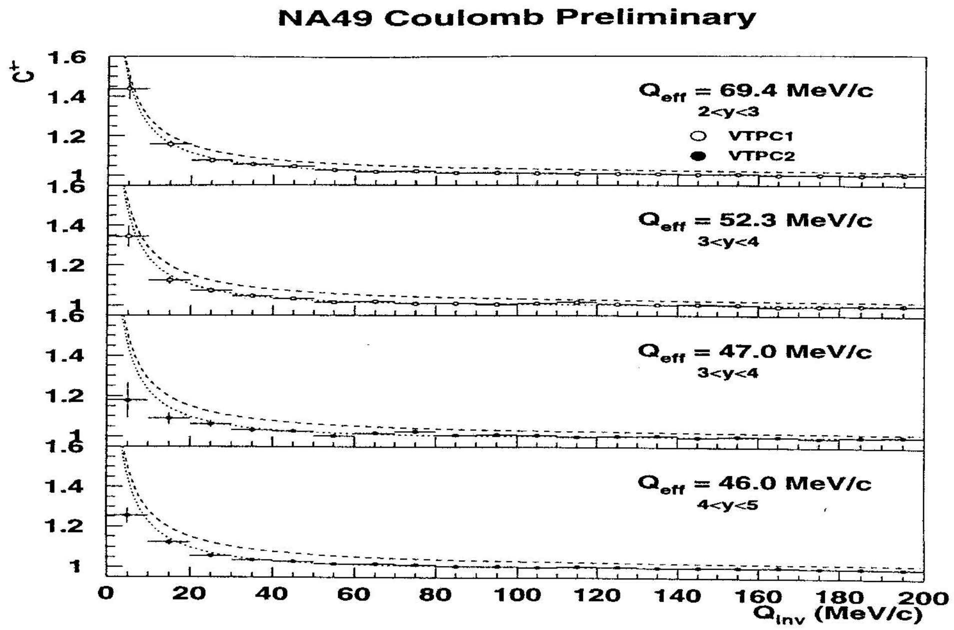

Fig. 2. The experimentally determined Coulomb correction (data) as compared to that of the Gamov correction (dashed line). Preliminary indications are that the correction varies over rapidity interval, which is not predicted by the Gamov factor, how ever before any strong conclusions are made, one should take into account the lack of identified particles.

where G(η) is the Gamov factor, and Q_{eff} is the free fit parameter. The correction thus effectively parameterizes all the two-body Coulomb effects, source effects, detector systematics (tracking systematics, asymmetries), into an effective correction. Although it mixes a myriad of effects, they are all real, and most importantly experimental observations!

Figure 2. shows the results for the fitted $+-$ correlation function along with comparisons to the Gamov factor in different rapidity intervals. We see that there is a slight rapidity dependence, which is not forecast in any calculational model.

However, with its strengths and weaknesses, the overwhelming argument in favor of the $+-$ spectra as a correction is that it provides a means to present the data completely on its own, with no bias of a calculation or theoretical model for the Coulomb effect!

3. Results

Although most experiments concentrate on mid-rapidity, it is important to map the source over all rapidity. NA49 is capable of mapping the source in the rapidity region of $1.8<Y_{lab}<5.5$. The low rapidity region is covered in VTPC1 while higher regions are covered by VTPC2. In the following, results from measurements in the VTPCs are shown in three rapidity bins. The results are from multi-dimensional fits with the BP parameterization, using 10k events of 1995 data. (This is one-fifth of the data set that will be used in the final analysis.) The BP formalism is used as it is a more robust fit procedure and is fine for looking at systematics in behavior of the correlation functions, even though the YKP formalism may be preferable from a physics point of view.

The λ parameter is illustrated in Fig. 3. It is the most ambiguous parameter to interpret as many effects are convoluted in this variable. In some manner it contains information regarding the particle composition (purity) of the sample, coherence of the source, and also an indication of the stability of the fits. All these have been grouped together and given the name "correlation strength"[9]. What is immediately obvious is a large systematic offset, by a factor of two, between the two different detectors. This is also evident in the radii parameters as seen in Fig. 4. This can be interpreted as a higher contamination of non-pions (read electrons) in the VTPC1 data sample, which will dilute the correlation function . This is directly seen in λ.[4] In fact the electron population is expected to be much

higher in VTPC1 than VTPC2 just from considerations of target proximity. Electrons produced in the target through conversion will enter VTPC1. Owing to their relatively low momentum and the large bending power of the magnets, (7.8 T·m) their numbers will be greatly reduced in the chambers at a larger distance from the target. Of course there are also electrons produced in conversion processes[5] in material downstream of the target i.e. detector walls, gas etc., but these will not reconstruct to the primary vertex, and are easy to discriminate against.

A cut in the minimum Q_{inv} of the pairs is aimed at removing some of the electrons. In effect, most electron pairs reconstruct with a peak in Q_{inv} at zero. Experience with the NA35 experiment showed that a cut of $Q_{inv} > 5$ MeV/c was particularly effective in rejecting questionable pairs. Also since it is below the momentum resolution of the detector, it does not seriously degrade data quality. However, in order to get an indication of the effect of particle contamination, this cut may be tightened to $Q_{inv}>$ 35 MeV/c. As the correlation signal is of the order of 70 MeV/c wide, it appears that this cut would remove nearly half the correlation signal, and should suppress λ even more. However, with this cut a small, but systematic increase in λ is present. This is an indication that the cut is actually removing more "junk" than signal. we see the same trend. They are smaller (systematically) for VTPC1, yet increase slightly when the large Q_{inv} cut is made.

Perhaps more convincing evidence for the contamination of the "pion" sample in VTPC1, is the behavior of the cross term in the fit. This cross-term characterizes the

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[4] Non-identical particles will not correlate.

[5] there are a lot of γs from π^0 decay.

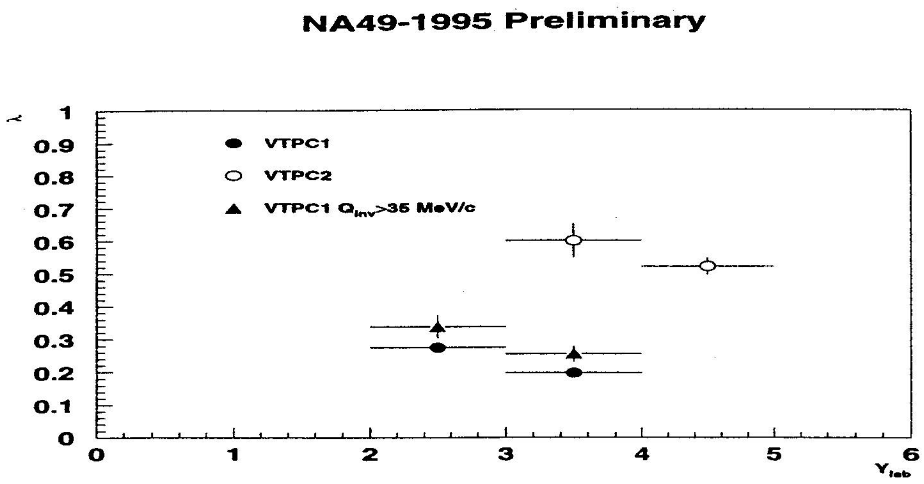

Fig. 3. The λ parameter from multi-dimensional Pratt-Bertsch fit. The discontinuity between the two chambers is the most striking feature. The circles illustrate the correlation function deduced requiring a minimum Q_{inv} of 5 MeV/c, whi le the triangles illustrate a correlation function, constructed from the same events with a minimum Q_{inv} of 35 MeV/c. After this cut, the correlation strength actually increases, suggesting that the low Q_{inv} pairs are actually contaminants.

asymmetry of the source in the transverse and longitudinal direction.[10] It disappears exactly at mid-rapidity and is expected to disappear everywhere if the source is longitudinally boost invariant. Strictly speaking a finite source is never *exactly* boost invariant as is evident by the finite value for this term in the forward rapidity region. It does approach zero at mid-rapidity, but should change sign as one goes to the backward region (i.e. the cross term is odd in z). However, as shown in Fig. 5., this is not the case until the $Q_{inv} > 35$ MeV/c cut is made in the data sample. Taken together, this is strong evidence that "non-correlating" particles are diluting the correlation function, and this dilution can have a large consequences modifying any physics conclusion!

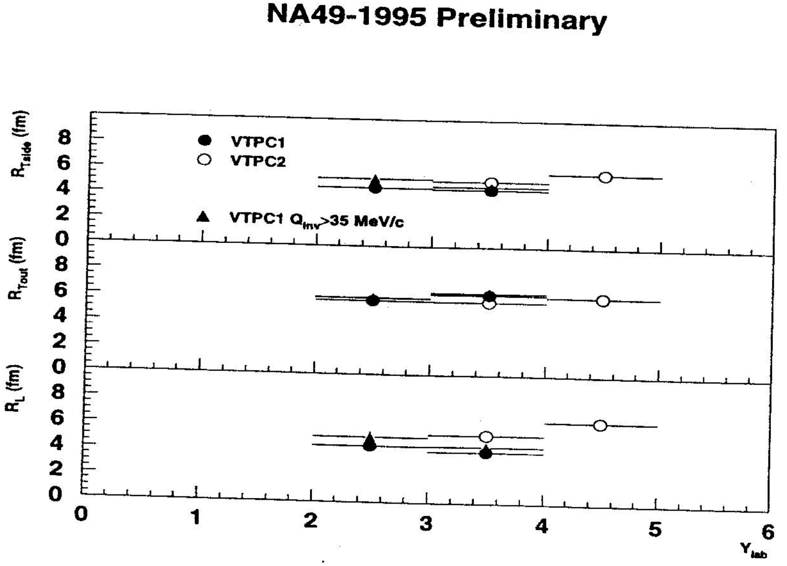

Fig. 4. The radii parameters from multi-dimensional Pratt-Bertsch fit. The discrepancy between the two chambers is at the 20% level and improves slightly with the strong requirement of Q_{inv}.

A cut in Q_{inv} is not something that anyone would advocate for reducing particle contamination. NA49 was constructed with the goal of utilizing the ionization information in the TPCs to identify particles. As presented in Fig. 6., particle identification in the low momentum region, as measured by VTPC1, is feasible using the dE/dx information in the TPC, but also that the electron contamination is as high as 20%. With these capabilities electrons will be removed quite effectively, such that uncontaminated spectra may be utilized. It is also feasible to do identified $\pi^+\pi^+$ correlations, previously untouched because of the fear of proton contamination.

4. Event-by-Event Possibilities

It is perhaps interesting to look at the first indications of correlation analyses at he Event-by-Event level, since such analyses, was the primary design goal of NA49.[11]

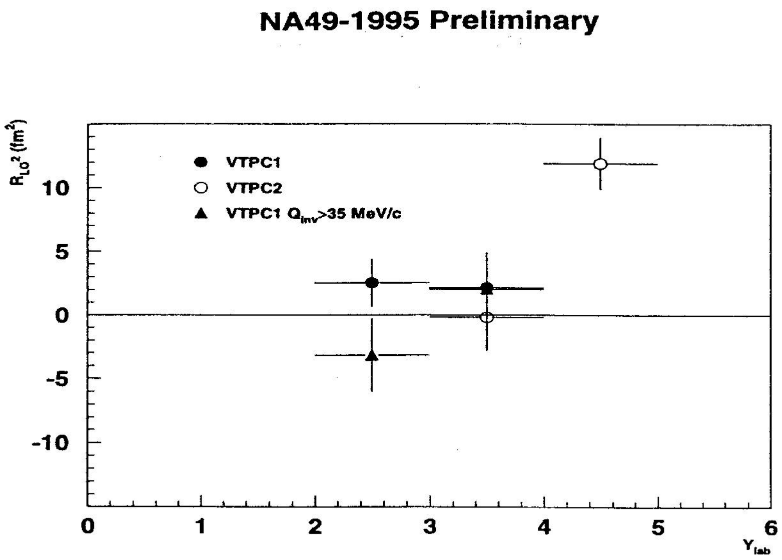

Fig. 5. The cross term for the above fits. The cross term as seen in VTPC1 is of the right magnitude but the sign is not correct until the large cut in Q_{inv} is made.

Up until now, Event-by-Event studies have been restricted to simulated data. Fig. 7. presents, a first attempt at constructing a correlation function with real data.

The most pressing question regarding correlation functions on an Event-by-Event level is how to construct the background. There is always the possibility of constructing a generic background from an ensemble of mixed events, but this seems to violate the spirit of such physics. In Fig. 7., the correlation function is constructed as the total yield of all negative pairs, over the total yield of opposite sign pairs in the NA49 Vertex TPCs[6] as a function of Q_{inv}. Thus the background *and* Coulomb correction are deduced from the same event. Although the "ensemble background" may reduce the statistical uncertainty in the denominator, one cannot discount the possibility that this method may be more sensitive to smaller effects because either the signal (numerator),

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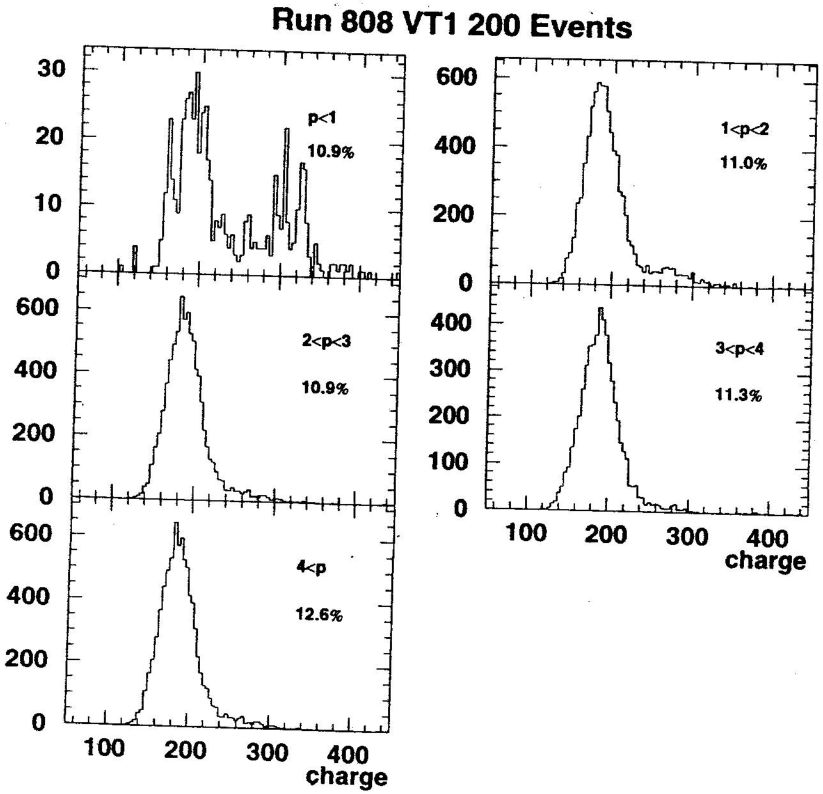
[6] This is a precaution to avoid double counting of tracks that overlap between VTPC2 and MTPCs.



ig. 6. The specific ionization of tracks, or dE/dx, (denoted as charge) in five momentum bins n VTPC1. Electrons are higher ionizing at low momentum than any other particle and are dentified with the second (smaller) peak. The resolution is give n as σ/mean and is at the 10% evel. Electrons account for nearly 10% of the total number of tracks in the low momentum egions.

r background (denominator) may exhibit fluctuations. To keep a the maximum number f pairs, no other restrictions are imposed.

The conclusions one can draw from the above is that CERN SPS energies do not rovide high enough multiplicities to facilitate the construction of a multi-dimensional rrelation function. This is a concern because it is an issue whether or not meaningful

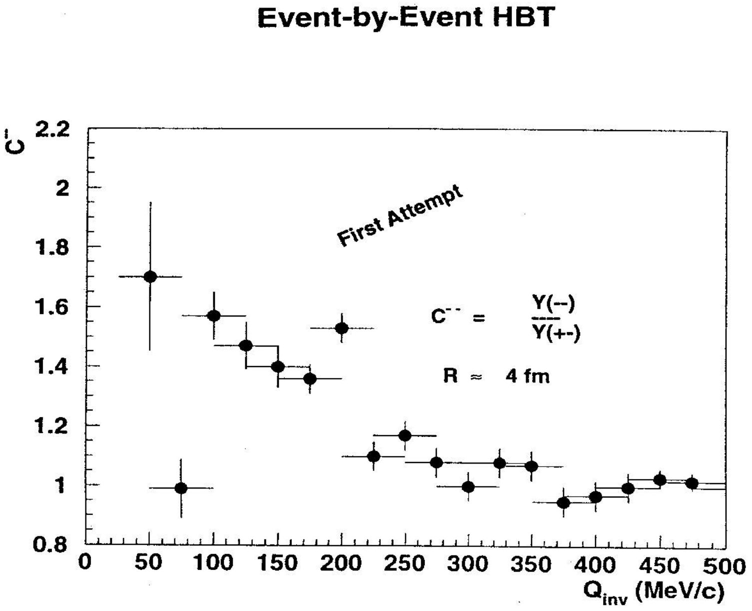


Fig. 7. Correlation function constructed from the tracks within the VTPCs of a single NA49 event. The multiplicity is of the order of~ 700 tracks (~ 450k pairs). Although the statistics are very marginal, the correct shape and somewhat re asonable radius, R_{inv}, is extracted.

information can be extracted from a Q_{inv} spectrum. This is a question that will have to be considered in future theoretical studies.

5. Conclusion

It is evident that the correlation function is an observable that is very sensitive to small details of the source. It is also clear that this sensitivity can be reduced by the cuts or corrections that are not well understood. Measurements of +− spectra allow use of experimental data to parameterize the Coulomb correction which reduces the model dependence in the construction of the correlation function. Furthermore, it appears that the HBT parameters are quite sensitive to the particle composition, and purity of the sample. To address this, future correlation studies at NA49 will center on identified particles, while also looking for methods to extract meaningful parameters out of Event-by-Event studies.

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