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A Rate/Sensitivity Study for Two-Particle Correlations in STAR

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This note describes a study of the STAR TPC's statistical sensitivity to the source parameters extracted from a two-particle correlation analysis. Using a realistic identified pion rapidity density, ($(\mathrm{dN/dy})_{\pi^-} = 200$) into the particle-identified acceptance ($|\eta| \leq 1, \mathrm{P_t} \geq 150$ MeV/c) of the STAR TPC, it is concluded that single-event two-particle correlation studies are feasible for the cases of 1 and 10 fm sources. In addition, subject to the conditions $(\mathrm{dN/dy})_{\pi^-} = 500$ and $\mathrm{p_t} \geq 40$ MeV/c, such studies are feasible for 20 fm sources. Finally, nomograms of the sensitivity to various source parameters versus number of events are provided.

I. Motivation

The technique of intensity interferometry has been historically used in nuclear and particle physics [Lor89],[Boa90] in order to infer the space-time dimensions of the source of particle production. While early work emphasized the geometrical information obtained from these so-called HBT (Hanbury-Brown–Twiss) studies, current emphasis is upon the possibilities of obtaining true dynamical information using the technique [Pad90],[Pra90]. In the field of ultrarelativistic heavy-ion collisions, this trend towards attempting to understand the impact of particular dynamical evolution scenarios upon the correlation functions resulting from an HBT analysis was spurred by early reports of anomalously large source sizes in E/A=200 GeV $^{16}\mathrm{O} + ^{197}\mathrm{Au}$ collisions [Bam88]. It is anticipated that two-particle correlation studies will continue to be an important tool as ultrarelativistic heavy-ion physics moves into the regime of RHIC energies ($\sqrt{\mathrm{s}}/\mathrm{A} = 200$ GeV) and beyond. The massive data sets envisioned for the large-acceptance major detectors at RHIC should prove well-suited to the type of high statistics, multidimensional analyses which current theoretical work indicates will be needed in order to discriminate between competing dynamical evolution scenarios for the reaction zone. However, more interesting is the possibility, due to the large expected charged particle multiplicity densities, of using single-event correlation functions as yet another variable in the event characterisation space at RHIC. Since detailed studies of the cross-correlations within this event characterisation space is a keystone of the physics program envisioned for the STAR detector, one of the purposes of this study is to determine, based purely upon the two-particle phase space accessible to the STAR detector, the feasibility of using single-event HBT as an event characterisation variable. As will be seen, due to statistics the focus is upon analysis in terms of the variable Q†, the invariant four-momentum difference. In addition, for purposes of making estimates of the level of statistics necessary for ensemble analyses of data subsets classified according to other event characterisation criteria, nomograms of source parameter sensitivity (relative error) versus number of events are provided.

II. Technique

In order to provide quantitative estimates of the dependence of the statistical sensitivity to extracted source parameters upon the number of events into the STAR acceptance, a simple procedure has been employed which permits the generation of Monte Carlo correlation functions‡ containing the fluctuations and error bars associated with a given number of events. The resulting correlation functions are then fit, using the Principle of Maximum Likelihood, and an error analysis is conducted in order to determine the confidence intervals associated with the extracted source parameters; these confidence intervals are the quoted sensitivities. In detail, the procedure has involved the following steps. First, the two-particle phase space distribution associated with a given number of events, N, is generated. This involves creating Monte Carlo events of a fixed number of single particles derived from the predicted $(\mathrm{dN/dy})_{\pi^-} = 200$ into the particle-identified rapidity acceptance of the STAR detector [Chr90]. The single-particle phase space is generated according to

m_t-scaling with the canonical inverse-slope parameter of 6 GeV/c [Kin78] and a flat distribution in rapidity. In addition, p_t cutoffs of 150 and 40 MeV/c, corresponding to TPC alone and TPC with SVT information, are imposed. Then, all pair-wise combinations associated with each event are created, and the resulting relative-momentum variables are used in order to populate the desired two-particle phase space distributions (i.e. Q, (Q_0, Q), (Q_l, Q_t), etc.). Simultaneously, using the Gaussian parameterisation of a source with an assumed radius (*in the variable(s) in question*), two-particle phase space distributions pair-wise weighted with the correlation function and the di-pion Coulomb interaction are accumulated. After having amassed statistics associated with the desired number of events, the weighted two-particle phase space distributions are subjected to bin-wise Poisson fluctuations, and then the ratio of the weighted and unweighted distributions is formed in order to create the correlation function. The error associated with each bin is calculated, in the usual fashion, based upon the number of counts in each bin. In each case, the assumed chaoticity parameter, λ, is unity; no attempt has been made to include the effects of two-particle acceptance, the pair tracking efficiency at low Q.

For purposes of these calculations, the assumed source radii are 1, 10 and 20 fm; each of these choices possesses some physics motivation and poses intrinsic technical challenges. The most tangible reason for assessing the sensitivity of the STAR detector to 1 fm sources is that this is the source size which has been observed in pp, $p\bar{p}$, and pA collisions across a broad range of $\sqrt{s}$ [Lor89]. A crucial component of the STAR physics program is the accumulation of high quality pp and pA data sets to serve as reference data to which the AA data may be compared. Therefore, it is necessary to understand, in advance, the statistical sensitivity of the future STAR reference data sets to the quantities of interest. Another physics motivation for assessing the sensitivity of STAR to 1 fm sources is the possibility of observing a strong correlation between the spatial and momentum distributions of the secondaries as expected in dynamical scenarios involving collective expansion. The manifestation of this collective expansion would be a dramatic reduction in the observed source size as a function of the pair mean transverse momentum [Pra86],[Pra90]. A final physics motivation for the study of the sensitivity of the STAR detector to 1 fm sources is the possibility of observing the formation of spatial inhomogeneities during rehadronisation [RE292],[Pra92]. It should be noted that the primary technical challenge involved in measuring such a small source is having sufficient dynamic range in relative momentum space in order to reliably fit the asymptotic tail of the correlation function. The justification for exploring the sensitivity of the STAR detector to sources of size 10 fm is the approximate scale set by the Au projectile radius; lower energy heavy-ion data have been characterised as manifesting a $1.2A_p^{\frac{1}{3}}$ scaling [Bar86]. Finally, the justifications for examining the sensitivity of the STAR detector to sources of size 20 fm include the need to be able to measure the 10-15 fm sources predicted by the conjectured $0.9(dN/dy)_{\mathrm{charged}}^{\frac{1}{3}}$ scaling [Sey92] or the long-lived sources with large *outward* transverse radii predicted within various QGP formation scenarios [Pra86],[Ber88]. In the cases of each of the large radii, the primary technical challenge is having sufficient relative momentum resolution and reconstruction efficiency at low relative momentum in order to reliably fit the enhancement.

III. Results

For each radius, correlation functions associated with data samples of 1, 10, 100, and 1000 events were generated and subjected to the analysis procedure described above. In general, the fit confidence levels exceeded 25%; cases for which the fit confidence level did not exceed 25% were recomputed in order to reduce the sensitivity of the calculation to statistical fluctuations. The results for a 150 MeV/c p_t cutoff, implying TPC alone, in the one dimensional variable Q are presented in figure 1. Figure 1 provides a gauge of the number of interesting events (i.e. events with anomalously large charged multiplicity, anomalous K/π ratio, etc.) necessary in order to determine the invariant source *radius*, for purposes of correlation with other sub-sample observables, to a given level of sensitivity. It also demonstrates, within this naive calculation, that for the cases of 1 and 10 fm single-event HBT can be performed to the 20-30% level of sensitivity. Note that there is effectively no sensitivity to the invariant source *radius* for the single-event analysis of a 20 fm source. Assuming the addition of SVT information, the p_t cutoff is relaxed to 40 MeV/c; keeping $(dN/dy)_{\pi^-}$ constant the sensitivities are observed to increase slightly (lowering the curves) as depicted in figure 2. This follows from the fact that the correlation between low p_t and low relative momenta, enhances the number of pairs in the *region of interest* thereby reducing the error bars in the enhancement region.

In order to further pursue the topic of the single-event HBT analyses for 20 fm sources, cases with $p_t \geq 40$ MeV/c and $(dN/dy)_{\pi^-} = 500$ were considered. This pion multiplicity density is exotic when compared with the predictions of conventional Monte Carlo calculations such as Fritiof, but is not at the extremes predicted by simple calculations based upon the Bjorken picture and entropy conservation throughout hadronisation [Bjo83],[Ber88]. A typical correlation function generated according to these relaxed assumptions is presented in figure 3. In order to check the stability of this result, a small ensemble (N=15) of Monte Carlo runs was generated and a histogram of the resulting sensitivities is presented in figure 4. The final observation, based upon this small ensemble of events, is that single-event HBT with sensitivity at the 30% level is feasible in the STAR detector. In order to crudely assess the impact of two-particle acceptance upon this result*, the correlation functions were refit excluding the first, and then the first and second bins. In the former case, although there was some loss of sensitivity to λ, the distribution of sensitivity to the invariant radius remained unchanged, however in the latter case there was marked loss of sensitivity to both parameters. The resulting distribution is plotted on figure 4 as a dashed curve.

In order to make the connection between the source parameter sensitivities associated with one and two dimensional analyses, a survey of the two dimensional (r, τ), and (r_l, r_t) spaces has been conducted for 10 fm source parameters. Figure 5 presents the resulting data for purposes of comparison. As a rule of thumb, the sensitivity to the averaged and transverse radii is approximately two times lower than that to the invariant radius. Meanwhile, the sensitivities to the longitudinal radius and the lifetime are markedly worse.

Finally, it should again be stressed that this study does not include the effect of two-particle acceptance or the pair tracking efficiency at low relative momenta. Any inefficiency in the reconstruction of close pairs will produce a hole in the lowest bins of the phase space distributions whose effect could be treated by either the exclusion of the affected bins or a Monte Carlo correction procedure [Alt85],[Arn86]. The above exercise performed for the 20 fm source case should provide a rough idea of the impact of the former solution.

Notes

† In the text the following convention for the definition of two-particle relative momentum variables is adopted:

$$\begin{aligned}
Q^2 &\equiv |\vec{q}|^2 - {q_0}^2 \to r_{inv} \\
\vec{q} &\equiv \vec{k}_1 - \vec{k}_2; q \equiv |\vec{q}| \to r_{avg} \\
q_0 &\equiv |E_1 - E_2| \to \tau \\
\vec{q}_t &= \vec{q} - \hat{z}(\vec{q}\cdot\hat{z}); q_t \equiv |\vec{q}_t| \to r_t \\
\vec{q}_l &= \vec{q} - \vec{q}_t; q_l \equiv |\vec{q}_l| \to r_l
\end{aligned}$$

where $\vec{k}$ is the single-particle momentum and the beam axis is $\hat{z}$. The lab frame of reference is used for the calculation of frame-dependent quantities.

‡ The formal definition of the correlation function, C2, is usually given as

$$\frac{N\dfrac{d^2n}{d\vec{k}_1 d\vec{k}_2}}{\dfrac{dn}{d\vec{k}_1}\dfrac{dn}{d\vec{k}_2}} \equiv 1 + \lambda|\tilde{\rho}(q)|^2 \equiv C_2,$$

and operationally calculated as

$$C_2 = \frac{Actual(q)}{Background(q)},$$

where *Actual*(q) represents the observed two-particle phase space distribution and *Background*(q) represents the two-particle phase space distribution in the *absence* of the effect of the Bose-Einstein correlation.

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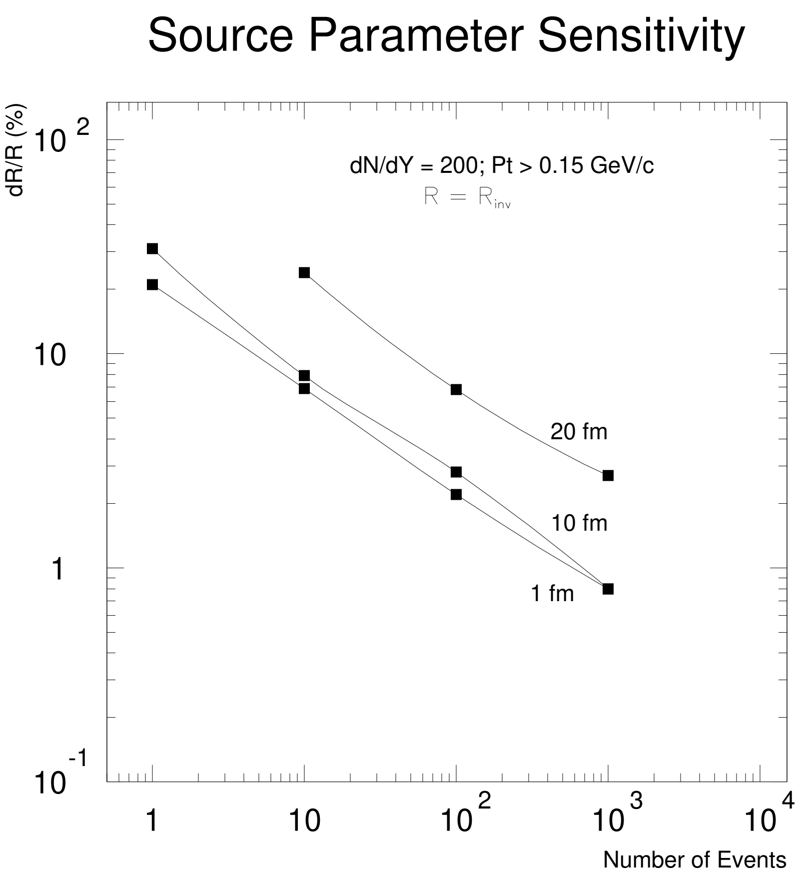

Fig. 1. Sensitivity to extracted source parameters versus number of events.

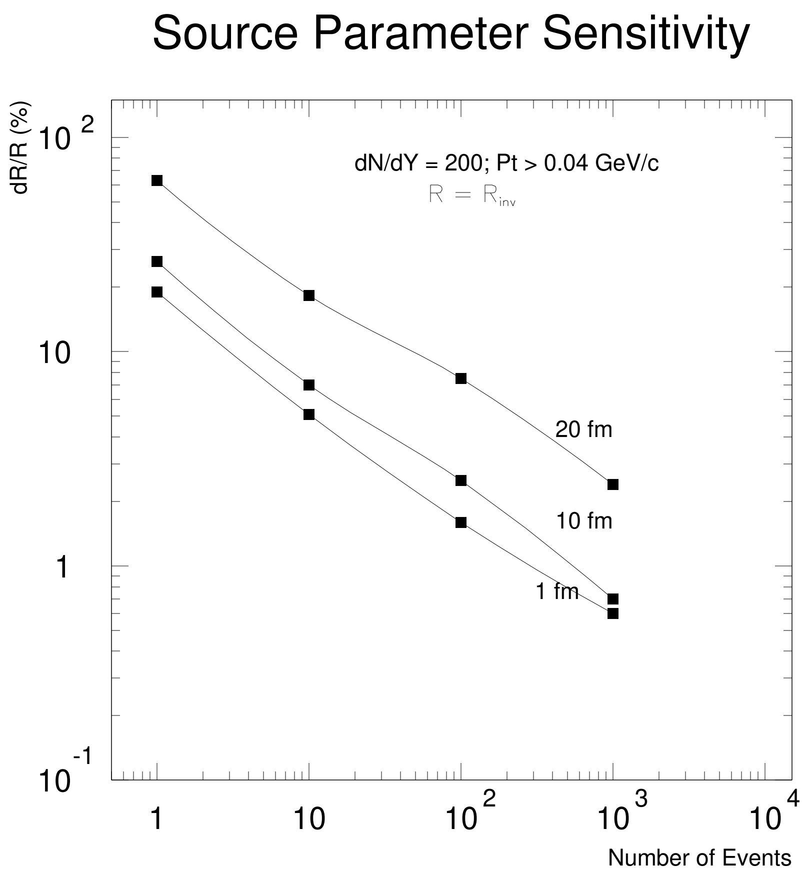

Fig. 2. Sensitivity to extracted source parameters versus number of events.

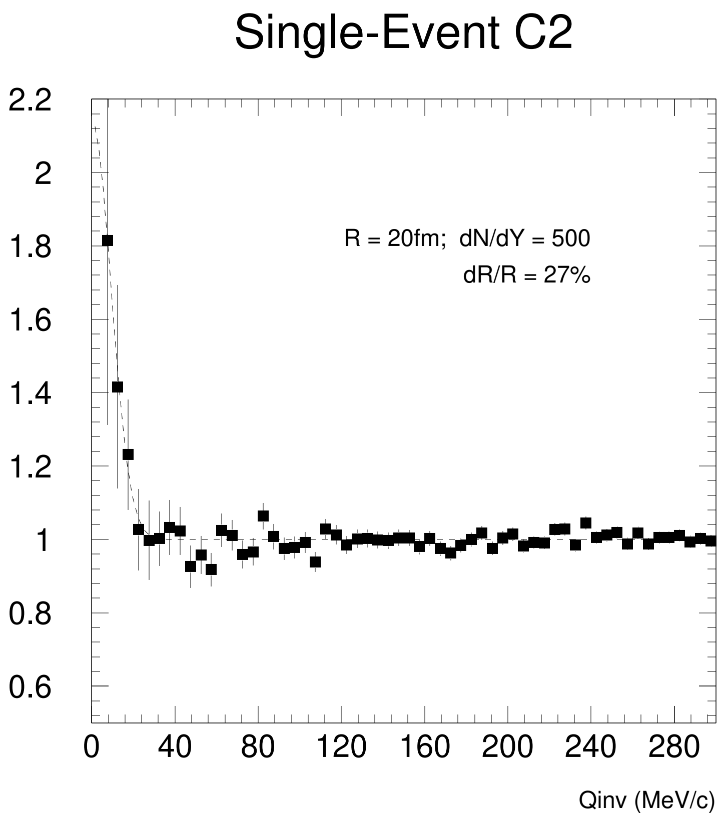

Fig. 3. Single-event correlation function for 20 fm source.

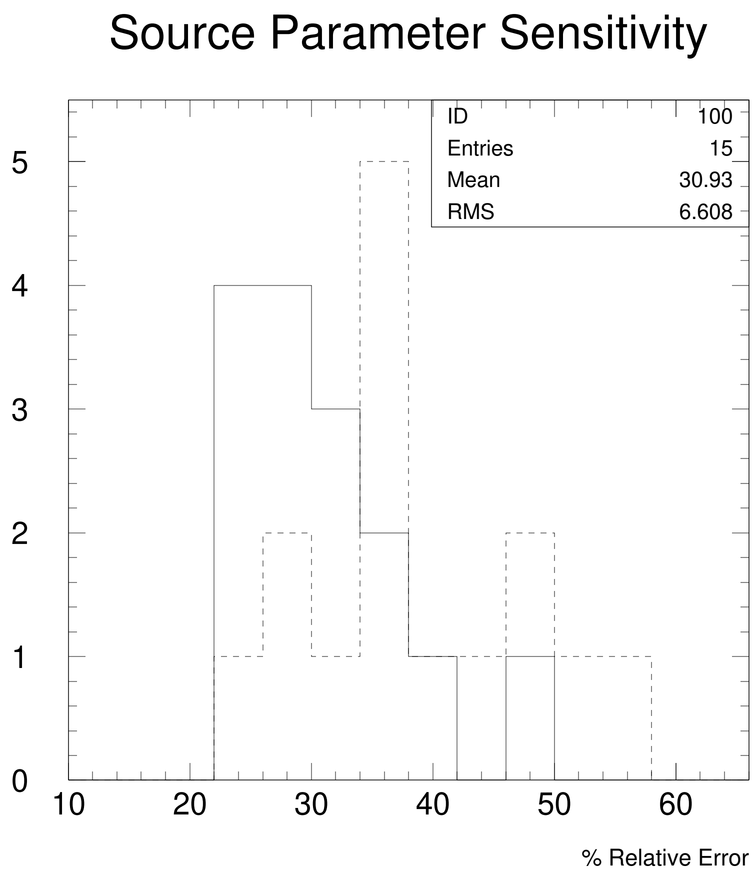

Fig. 4. Distribution of sensitivities to 15 events from 20 fm sources. The solid line represents the distribution obtained for all correlation function bins included in the fit. The dashed line represents the distribution obtained when the first 2 bins, representing the first 10 MeV/c in relative momentum, are excluded from the fit.

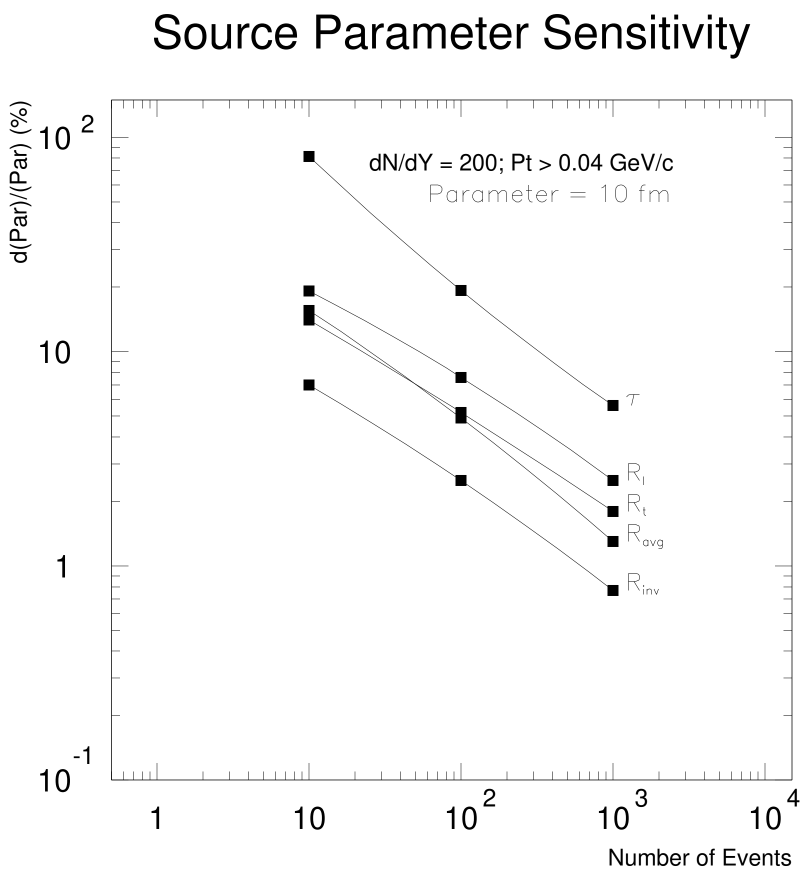

Fig. 5. Sensitivity to extracted source parameters versus number of events.