

Status and Promise of Particle Interferometry in Heavy-Ion Collisions

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After five years of running at RHIC, and on the eve of the LHC heavy-ion program, we highlight the status of femtoscopic measurements. We emphasize the role interferometry plays in addressing fundamental questions about the state of matter created in such collisions, and present an enumerated list of measurements, analyses and calculations that are needed to advance the field in the coming years.

Keywords: Theoretical and experimental identical-particle correlations; Theoretical and experimental femtoscopy; Particle-antiparticle correlations

The first two-pion interferometric measurements of the collider era emerged within a year of RHIC becoming operational. To the surprise of many in the field, the measurements were remarkably similar to those recorded at the AGS and the SPS. The analyses were inconsistent, both qualitatively and quantitatively, with dynamic models incorporating first-order phase transitions in general. In fact, parametric explanations of the data, the forms of which are often motivated by solutions to dynamical equations, suggest that the matter explodes violently, growing from a radius of 6 fm to 13 fm in only 10 fm/c. The surprisingly strong acceleration required for such behavior and the associated failure of many of the field's most sophisticated models became known as the "HBT Puzzle".

Five years later, the field has made steady progress on a variety of fronts. Theoretically, sophisticated dynamic models have more successfully reproduced experimental results (though the very sophistication of these models has made it difficult to ascertain which aspects of the models are being validated by the comparison). New techniques have been applied to the analysis of experimental correlation functions, revealing greater detail about the size and shape of the emission region. During our discussions at the workshop, it was clear that a remarkable consensus had developed among the practitioners of the field. Although this agreement by no means represented a final conclusion, we found numerous points that could be stated without dissent. In this white paper we will first list the points concerning the current status of the field, then further below, enumerate points where participants agreed were important for further progress.

Achievements:

- Remarkable agreement has been observed between the RHIC experiments, PHENIX, PHOBOS and STAR. All three have produced high-statistics high-quality pion correlations, whose apparent source sizes are consistent to a few tenths of a fm. A similar consistency was observed among measurements performed at the top SPS energy; at lower SPS energies the maximum deviations

are on the level of 20%.

- Femtoscopic studies are highly multi-dimensional. Even the simplest and most common case of two-identical pion correlations depend on six independent variables, which have only been fully explored within the past few years. This includes extracting characteristic source sizes as function of transverse momentum, rapidity and the angle with respect to the reaction plane for off-axis collisions. Additionally, correlation functions have been analyzed as a function of beam energy, centrality and the species of the pair. This accomplishment is especially noteworthy when taking the perspective of comparing to the field 20 years ago, when extracting a single source dimension was considered state-of-the-art.
- The majority of femtoscopic investigations continues to focus on the correlations of identical pions, but analyses involving numerous other pairs (even $\Xi - \pi$ correlations) are becoming more common. Analysis of non-identical particle correlations has allowed the extraction of qualitatively new femtoscopic information about the dynamical source substructure. Thus far, the preliminary assessment is that they are consistent with the information gleaned from $\pi - \pi$ correlations. Particularly, the measured pion-proton and pion-kaon correlation asymmetries point rather directly to a strong collective flow in heavy ion collisions at SPS and RHIC.
- Advanced techniques for angular decomposition and imaging are now being applied to extract shape and size information from any measured correlation. Although these analyses are in their nascent stage, it appears they are uncovering quantitative details about the longer-time-scale aspects of particle emission, such as resonance production or surface emission.
- Without doubt, *the* dominant dynamical feature of the bulk system created at RHIC is its explosive collective

motion (flow). Flow generates a source with characteristic dynamical/geometric substructure, and has implications (e.g. spectral shapes and “ v_2 ” anisotropy) when projected onto the momentum-only space. However, with its explicit focus on the space-momentum source substructure, interferometry is the most sensitive and detailed probe of collective flow. The growth of the sideward and longitudinal sizes, along with the lack of significant extension of the outward direction, related to a short duration of the particle emission, can only be reproduced with highly explosive dynamics. Parametric descriptions based on thermal emission on the background of large collective outward flow also explain the large radial shift in emission points of different-mass particles and the dependence of the effective source sizes with transverse momentum and direction with respect to the reaction plane. Measurements of effective sizes and orientation of the source shape for non-central rapidities have also validated our space-time picture of longitudinal collective flow. Analyses with a wide range of models always come to the same conclusion, qualitatively and quantitatively, that strong longitudinal and transverse flow has developed in central collisions at the SPS and at RHIC.

- The relative success and failure of various dynamic descriptions to provide sources that match those observed with interferometry has significantly constrained our understanding of the equation of state at high temperature. Twenty years ago, bag-model descriptions of the equation of state with latent heats of many GeV/fm³ were common. It is now clear that extremely soft equations of state, i.e., those that have large latent heats, are grossly inconsistent with interferometric measurements. Although smaller latent heats are not yet ruled out (cross-over or second order transitions are also possible), the range of acceptable equations of state would be much broader if not for femtoscopic analyses.
- The pion source sizes, when analyzed as a function of the collision energy, seem to follow the mean pion cross section for scattering on surrounding particles in the collision fireball. This indicates that the freeze-out happens when the pion mean free path exceeds a certain critical value, in a quantitative analysis estimated to be 1-2 fm. The interferometry data favors the fixed mean free path freeze-out criterion over a freeze-out at a fixed spatial density, or at a fixed phase-space density, or when the mean free path exceeds the system size.
- In addition to hints about the equation of state that would manifest themselves through dynamics, and thus through observables such as R_{out}/R_{side} , correlations have provided a quasi-model-independent measure of the phase space density and the total entropy observed in heavy ion collisions. Although the first estimates are rather rough, this already has provided a significant constraint on the equation of state.
- The connection between the source emission probability, which is given in coordinate space, and the correlation function, measured as a function of relative momentum, is contingent on the assumption of chaotic uncorrelated emission sources, whose correlations arise principally from final-state two-body interactions. This presumption has been verified by measurements of three-pion correlations, which have been shown theoretically to be sensitive to coherent emission.
- A parallel direction has developed, distinct from the study of heavy ion collisions, *per se*. Extracted knowledge of the space-time substructure of the emitting source also allows the femtoscopic program to be run “in reverse.” Assuming known geometries from other correlations analyses, correlations for pairs where the interactions are not well understood (e.g. $\Lambda\Lambda$) are being used to determine details of the interaction between unstable particles. Since correlation analyses naturally involve low-relative momentum pairs, scattering lengths are especially accessible.

Despite the enormous progress listed above, significant hurdles have yet to be overcome and numerous opportunities have not yet been exploited. Workshop participants felt that enumeration of a “to-do” list for the field would be enormously helpful, both for informing the greater heavy-ion community of our plans, and for clarifying, in our own minds, the important needs for our immediate future. These needs encompass both new experimental equipment, measurements, and analyses, along with needed development in theory, and with better integrating interferometric analyses with other families of observables.

Opportunities and Challenges:

- Coherent phenomena are intimately associated with correlations. This includes novel Bose effects as well as coherent emission from classical fields, such as what is often described in dynamic models of the chiral condensate. In nearly all such cases, the phenomena are expected to be strongest at low \mathbf{p}_T . Since the momentum scale can be estimated as the inverse characteristic source size, measurements at $\mathbf{p}_T \sim 50$ MeV/c are required to best explore such possibilities. Such measurements might require experiments to either run at low magnetic field settings or to install special detectors.
- Back-to-back correlations (BBC) have recently been shown to arise if hadronic masses are modified by interactions in a dense medium. These quantum mechanical correlations are induced by a non-zero overlap between the in-medium states and free states, which are observed. In particular, medium-modified bosonic or fermionic fields can be represented in terms of two-mode squeezed states of the corresponding asymptotic fields. Both the fermionic and the bosonic BBC lead to positive correlations of unlimited strength. They are more pronounced for large absolute values of the particles’ back-to-back momenta and might survive the ef-

fect of collective flow. A joint experimental and theoretical effort will be essential for effectively observing and understanding such correlations, by looking for both an optimized form of the signal and the most promising experimental conditions for measuring it.

- Interferometric and flow analyses at RHIC have suggested that the average speed of sound is in the neighborhood of $c_s \sim 0.3 - 0.4$. It is expected that the LHC region will explore much further above T_c where the matter is predicted to stiffen and the speed of sound approaches $c_s \sim 1/\sqrt{3} \approx 0.58$. It is imperative that experiments at the LHC have the capability for making high quality correlation measurements for particles with $100 \text{ MeV}/c \lesssim \mathbf{p}_T \lesssim 1 \text{ GeV}/c$ if this fundamental property of hot matter is to be explored.
- In the last few years, lattice calculations have begun to suggest that the QCD phase transition is a cross-over for nearly zero chemical potentials, probed at RHIC with $\sqrt{s_{NN}} = 200 \text{ GeV}$ collisions, and that it becomes a second order phase transition at a critical end point in the phase-diagram (T_{CEP}, μ_{CEP}). Beyond this critical value, and for higher chemical potentials, $\mu > \mu_{CEP}$, the transition becomes first order. The critical point might be reached for energies just above the AGS range, in low energy runs at the CERN SPS and at the RHIC accelerators. As this range will also be covered by the upcoming FAIR facility at GSI and at the planned NICA facility at JINR, it is important that proper detectors are installed for high-resolution measurements of correlations in the critical region.
- An analysis of the energy dependence of the averaged particle phase-space density, which is directly related to femtoscopy measurements in current and future experiments, is of great interest. This quantity is approximately conserved during the hadronic stage of evolution and therefore is connected with the initial phase-space density of hadronic matter. It provides information about the states of the matter at the end of hadronization stage, or at chemical freeze-out, and thus allows one to search for phase transitions or a limiting Hagedorn temperature in relativistic nucleus-nucleus collisions.
- Femtoscopy for high \mathbf{p}_T particles would provide stringent tests of theoretical pictures of recombination and fragmentation models such as coalescence. However, femtoscopic measurements have thus far only been made for pairs with low relative momentum, as it is inherently difficult to gather statistics at high \mathbf{p}_T , where the phase space density is low. Specialized measurements or intensity upgrades might be required for high-quality interferometric measurements in the relevant \mathbf{p}_T range of several GeV/c .
- Analyses of correlations for pairs of particles other than identical pions, such as pp , pK , πp , $p\Lambda \dots$, are in a nascent stage, with new imaging techniques having been recently developed for extracting detailed size and shape information. It would be of tremendous importance to quantitatively verify, using different classes of final-state interactions, the space-time picture of the breakup stage that has emerged from the analysis of identical-pion correlations. Such analyses might require experimental upgrades, such as the STAR time-of-flight wall, which by expanding the range of particle identification would allow particles of much different mass to be correlated at low relative velocity.
- The interferometry of penetrating probes has just recently become possible. In addition to potentially providing space-time information about pre-breakup stages, $\gamma\gamma$ correlations can reveal the fraction of low \mathbf{p}_T photons that do not originate from π^0 decays, thus providing a direct photon spectrum at sufficiently low \mathbf{p}_T to yield robust insight into the temperature during earlier stages of heavy-ion collisions. Also, recently there has been some theoretical development of correlation functions for lepton pairs, which reiterates the need for measuring correlation data of other penetrating probes, such as lepton-lepton femtoscopy.
- Meticulous experimental analysis of the structure of the correlation function at very small relative momentum appears to show details of longer-time components of the emission function. Given the connection between long-lived emission and the equation of state, it is important to vigorously pursue such analyses. In some cases, this might require detector upgrades to achieve the $\sim 2 \text{ MeV}/c$ resolution necessary to resolve low relative momentum features in the correlation function.
- The primary motivation of heavy ion experiments is the determination of bulk properties of matter. To achieve this ultimate goal, all relevant observables, including flow and spectra, must be simultaneously analyzed by comparing comprehensive dynamical models with data. Analyses of parametric models have already illustrated the importance of a coordinated study of both correlations and spectra. Although numerous dynamic descriptions have been tested for their interferometric predictions, many models remain untested, or are only tested through rather primitive breakup criteria. The femtoscopic community needs to improve our link with theorists developing dynamical models such as hydrodynamics. Furthermore, the theory community should be strongly encouraged to develop models which are better tested, better documented and are more flexible. In particular, femtoscopic conclusions about the equation of state (EoS) have been complicated by the need, in many cases, to compare to the data one group's calculation using a given EoS, and *another* group's calculation using a different EoS. Firmer conclusions about this crucial feature of the matter will be much helped if all groups will produce predictions using a variety of EoS. Similar treatment should be adopted with other important factors, such as initial conditions, the list of free parameters considered in each model, etc. Such a

development is crucial if interferometric data are to be fully exploited.

- Extracting source functions from hydrodynamic models should be better accommodated, which might entail providing interfaces between hydrodynamic models and microscopic hadronic codes used for modelling the final breakup. Given the possible importance of mean fields in driving the dynamics or in refracting outgoing trajectories, mean fields should be included in transport codes. Such codes should be made available to the hydrodynamic community, along with support for interfacing the descriptions.
- Given the increasing sophistication and subtlety of femtosopic studies, some collaboration between experimentalists and theorists *on the data analysis itself* might be beneficial. Experimental collaborations may consider incorporating more flexibility into rules related to propriety of data, either in general or on a case-by-case basis.
- A large fraction of practicing femtoscopists, now focusing on relativistic heavy ion collisions, initially worked at lower (sub-AGS) energies. Frequent interactions and exchanges of ideas and techniques has always benefited both communities. However, these interactions may be becoming less frequent due to two factors: (i) the increasing fraction of young people who already began their career at the highest energies, and (ii) the increasingly self-referential nature of relativistic heavy ion physics in general. Continued and enhanced collaboration between high- and lower-energy femtoscopy should be an explicit consideration in the organization of femtoscopy-oriented symposia and workshops.
- The heavy-ion and the high-energy femtosopic communities should make greater efforts towards communicating. Advancing the understanding of small source (~ 1 fm) interferometry will require more careful analysis of numerous effects which challenge the assumption

of chaotic independent emission. In particular, common research projects between heavy ion physicists and experts working on interferometry studies in elementary particle collisions, such as in pp , hp , $\bar{p}p$, e^+e^- , should be strongly encouraged. By better understanding the $\mathbf{p_T}$ dependence of source sizes in pp collisions, we should attain a quantitative understanding of the effects in AA collisions and provide a systematic error to the underlying theory.

A unifying theme of all the points, both in the list of accomplishments and in the list of upcoming challenges, is the importance of collaboration. This includes sharing knowledge, expertise and ideas between collaborations, between experimentalists and theorists, between various segments of the theoretical community, and between different fields. To that end, there was unanimous consent that the WPCF series of workshops has already been enormously useful. Evidence of discussions and collaborations during the 2005 meeting in Kroměříž was already evident in the results shown in 2006. The continuation of the workshop was enthusiastically endorsed by all participants.

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