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Femtoscopy in heavy ion collisions

Wherefore, whence, and whither?

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Abstract. Non-trivial space-time geometrical effects are at the core of bulk-sector heavy ion physics, and two-particle correlations at low relative velocity are the most direct probe of this geometry at the femtometer scale. I present a brief overview of the wealth of femtoscopic measurements from the past two decades of heavy ion experiments. Essentially every conceivable "knob" at our disposal has been turned; the response of two-particle correlations to these variations has revealed much about the space-momentum substructure of the hot source created in the collisions. I discuss the present status of the femtoscopic program and questions which remain, and point to new efforts which aim to resolve them.

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1 Wherefore

High energy collisions between electrons, hadrons, or nuclei produce highly nontrivial systems. Especially in the soft (low-p_T, long spatial scale) sector, the inclusive distributions of the measured multiparticle final states are dominated by phase-space; to first order the momentum spectra and particle yields appear thermal, revealing little of the underlying physics of interest. Detailed information in this sector is obtained only through correlations; inclusive spectra tell much less than half the story.

In particular, multiparticle production is a *dynamic* process, evolving in space and time. For several decades now, small relative momentum two-particle correlations have probed the space-time structure of systems at the fermi scale. Measurements and ever-improving techniques variously called "intensity interferometry", "HBT", "GGLP", "non-identical correlations", etc., are nowadays discussed under the common rubric of femtoscopy [1].

While understanding the space-time features of the system is important to both the particle and the heavy ion physicist, in the latter case it is even vital. After all, nontrivial geometrical effects *dominate* heavy ion physics.

From the very broadest perspective, the entire heavy ion program is geared to generate and study a qualitative change in the geometric substructure of the hot system. Strongly-coupled [2] or not, the quark–gluon plasma (QGP) is a soft QCD system, in which colored degrees of freedom are relevant over large length scales. Of particular interest is the existence and nature of a deconfinement phase transition; a significant and sudden change in the degrees of freedom should be reflected in space-time aspects of the system [3]. Also of generic importance is the (often unasked) question of whether the "system" generated is, indeed, a system. Any discussion of "matter" or "bulk" properties relies on an affirmative answer.

More specifically, geometry defines each stage of the system's evolution. In the initial state, the entrance-channel geometry (impact parameter **b**) determines the subsequent collective evolution and anisotropic expansion of the system [4]; the resulting "elliptic flow" [5] has been the basis of $\sim 25\%$ of the publications from the RHIC program. In the intermediate state, also, geometry dominates: quantitative understanding of exciting parton energy loss (or "jet quenching") measurements [6, 7] requires detailed information of the evolving size and anisotropic shape of the system. If coalescence is indeed the mechanism of bulk hadronization [8], space-momentum correlations in the intermediate stage induce clustering effects which must be modeled quantitatively [9].

Clearly then, for the soft (bulk) sector in heavy ion collisions, geometrical issues dominate both the physics of interest and the system with which it is probed. No surprise, then, that since the relativistic heavy ion program began roughly two decades ago, femtoscopic studies have played a major role, and a "sub-community" has developed. Before long, erstwhile "nuclear" physicists contributed physical and technical insights to a type of measurement initially borrowed from their particle physics colleagues.

Two-particle correlations probe the space-time geometry at kinetic freezeout. In this experimental overview, I do not discuss details of the construction or fitting of

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correlation functions, nor their formal relationship to the emitting source. For this, I refer the reader to several excellent reviews which have very recently appeared in the literature [1, 10–12]. Here I touch on only the minimal details of the correlation function and what is probed.

Given the measured single-particle inclusive distributions $\mathrm{d}^3N/\mathrm{d}p^3$ for particles of type a and b, then, in the absence of correlations, the probability of measuring both particles in the same event is the product of the single-particle distributions. The correlation function is defined as the ratio of the two-particle yield for particles of type a and b, to the product of the single particle yields:

$$C(\mathbf{p}_a, \mathbf{p}_b) = \frac{\mathrm{d}^6N_2(\mathbf{p}_a, \mathbf{p}_b)/\,\mathrm{d}p_a^3\,\mathrm{d}p_b^3}{[\mathrm{d}^3N_a(\mathbf{p}_a)/\,\mathrm{d}p_a^3]\,[\mathrm{d}^3N_b(\mathbf{p}_b)/\,\mathrm{d}p_b^3]}\,. \quad (1)$$

The denominator above represents the likelihood of the two particles being measured simultaneously in the absence of any correlations, and is often estimated using mixed-event techniques [12].

Deviations of C from unity represent correlations due to two-particle quantum symmetrization effects and final-state interactions between a and b.[1] These effects are quantified in the two-particle wavefunction φ. In particular, the correlation function is related to the emission probabilities s through

$$C(\mathbf{p}_a, \mathbf{p}_b) = \frac{\int \mathrm{d}^4x_a\,\mathrm{d}^4x_b s_a(p_a, x_a) s_b(p_b, x_b) |\varphi(\mathbf{q}', \mathbf{r}')|^2}{\int \mathrm{d}^4x_a s_a(p_a, x_a) \int \mathrm{d}^4x_b s_b(p_b, x_b)}\,, \quad (2)$$

where $\mathbf{q}'$ and $\mathbf{r}'$ are the relative momentum and position in the pair rest frame, respectively. Usually, we believe we understand in detail the two-particle wavefunction φ, in which case measurement of C probes the spatial distributions of emission points $x_{a,b}$.

While the reader is referred to the above-mentioned reviews for a fuller discussion, I simply emphasize here that the level of geometric detail possible through detailed analysis of high-statistics correlation functions is extensive. Neglecting nontrivial issues such as the ambiguity between temporal and some spatial degrees of freedom, femtoscopic measurments determine the size, shape and orientation of the emission region for particles a of momentum $\mathbf{p}_a$. An example is shown in Fig. 1. Two sets of particles, with velocities pointing to the upper right, originate from separate emission regions. The length scales in the direction of transverse motion (the "out" direction), along the beam direction ("long") and perpendicular to these ("side" direction) are measurable, as is the orientation of the emission region with respect to a global angle such as the reaction plane or jet axis. Furthermore, correlations between the two particle types shown probes the displacement (magnitude and direction) between the emission regions.

Figure 1 makes explicit that correlation functions generally do not measure the "whole" region from which all particles are emitted in a heavy ion collision; one probes only "regions of homogeneity" [16], i.e. regions emitting particles moving with a particular velocity vector. At first, this fact seems disappointing. After all, wouldn't one want to measure the "whole" source instead of a small piece? However, the answer is no! The velocity dependence of the homogeneity regions reflects the dynamically-generated *sub*-structure of the collision, revealing, for example, geometric details of collective flow.

Given the importance of geometry to heavy ion physics, and the detailed geometric information available through two-particle correlations, I hope the reader is convinced of the "wherefore" of femtoscopy. In what follows, I emphasize the breadth of systematics which has been explored so far (whence), what it has told us, and what continues to puzzle us. I then identify a few promising directions in which the field is moving (whither).

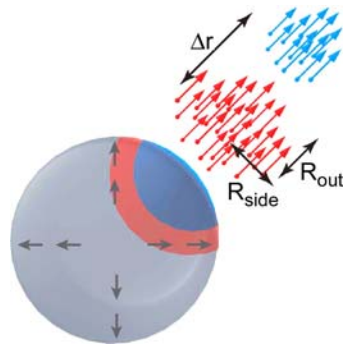

Fig. 1. Freezeout regions for particles of different species (or different transverse masses) emitted from a common source. Two-particle correlations measure the (momentum-dependent) size, shape, and orientation of the emission regions, as well as the average displacement (Δr) in the outward direction. From [12]

2 Whence

Due to their copious production and ease of detection, most femtoscopic measurements have utilized correlations between charged pions. Further, many experiments have focused on central ($|\mathbf{b}| = 0$) collisions, since (1) azimuthal symmetry simplifies the femtoscopic formalism [12, 17]; and (2) maximal energy densities and spatial extents are generated. The extent of measured femtoscopic systematics 15–20 years ago is represented in Fig. 2, showing that, in central collisions involving nuclei with mass number A, HBT radii scale approximately as $A^{1/3}$ [15, 18]. Apparently trivial, these data were at the same time comforting, confirming that pion correlations did indeed track with geometric scales.

Since then, femtoscopic data and techniques have evolved tremendously, generating an equally tremendous range of systematic femtoscopic studies. The first femtoscopic measurement in truly relativistic heavy ion collisions was reported almost twenty years ago by the NA35 Collaboration at the CERN SPS [19]. Similar measure-

[1] Other physical sources of correlation, of course, may be relevant. Accounting for these so-called "non-femtoscopic" correlations can be quite involved [13, 14].

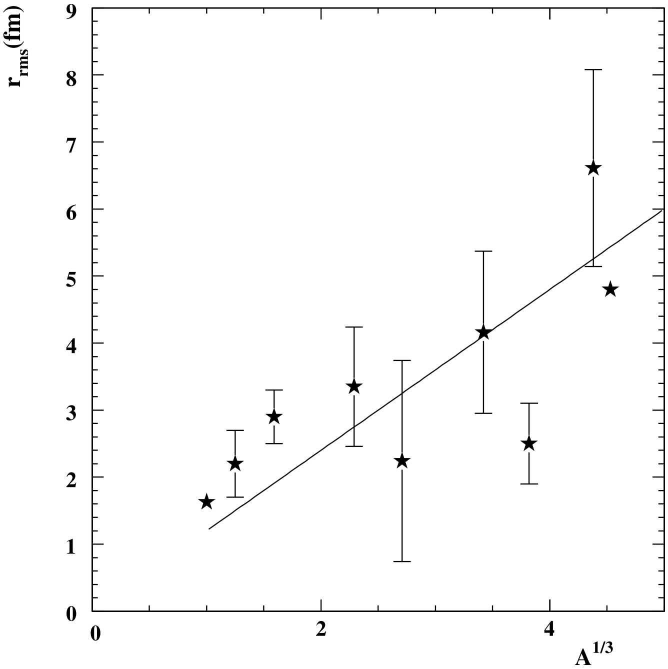

Fig. 2. Pion HBT radius versus the mass number of colliding nuclei, from Bevalac experiments ∼ 20 years ago. Compilation from [15]

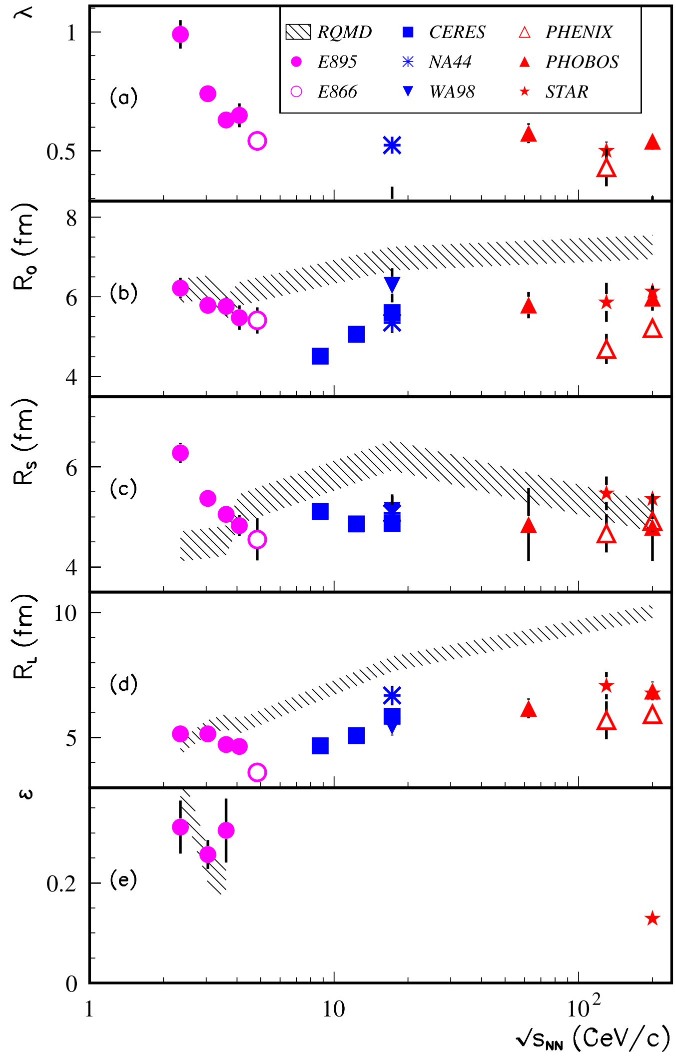

Fig. 3. World dataset of published HBT radii from central Au + Au (Pb + Pb) collisions versus collision energy. Compilation from [12]

ments have been performed at the SPS and the BNL AGS and RHIC accelerators over the collision energy range $\sqrt{s_{NN}} \approx 2.3$–200 GeV. Thus, in both energy and time, we may consider two decades' worth of systematics [12].

The original hope was to find "anomalously" large spatial and/or temporal scales, as reflected in the HBT radii, indicating large entropy generation or a long-lived QGP state. This expectation was considered rather generic [20], and, guided by quantitative predictions from hydrodynamical models [3, 21], the most commonly-discussed systematic was the excitation function (i.e. energy dependence) of pion HBT radii. This is shown in Fig. 3, where no striking features are observed in the HBT radii at any collision energy. As I discuss later, this observed contradiction of a seemingly-generic expectation may be considered the second "HBT puzzle".

Clearly, insight into geometrically-driven physics requires more detailed systematic studies than the simple excitation function. Indeed, this has always been a generic requirement for extracting physics from *any* observable in heavy ion physics, and has required development of heavy ion programs with simultaneous, complementary, large-acceptance experiments running at dedicated machines. Especially in the crucial soft sector, more is learned by varying independent variables than by long runs at the highest possible energy a given machine can deliver.

Inspired by recent "schematic equations" [22], I denote the impressive **multi**-dimensional space explored by femtoscopic experiments as

$$\text{Femtoscopy} = R\left(\sqrt{s_{NN}}; A, B, |\mathbf{b}|, \varphi, y, m_T, m_1, m_2\right) . \quad (3)$$

2.1 Global dependences

Especially in light of "puzzles", we need to perform a similar study as shown in Fig. 2, checking that femtoscopic radii track with geometric collision scales to first order. We may vary the geometric scale of the reaction zone by varying the atomic numbers of the colliding nuclei, A and B, and/or by selecting events of varying impact parameter, $|\mathbf{b}|$. Of course, fixing only one of these parameters will not define the collision scale; instead, a natural quantity would be the number of participating nucleons N_{part} [23]. Pion HBT radii corresponding to different A, B, $|\mathbf{b}|$ and $\sqrt{s_{NN}}$ are collected in Fig. 4. The left panels show that these femtoscopic lengths scale similarly to those shown in Fig. 2, replacing A by N_{part}. (Note that results for central collisions, $|\mathbf{b}| \approx 0$, are shown in Fig. 2, so that $N_{\text{part}} \sim A$.) The HBT radius R_{out}, which mixes space and time non-trivially, may be expected to violate a pure geometrical scaling; this

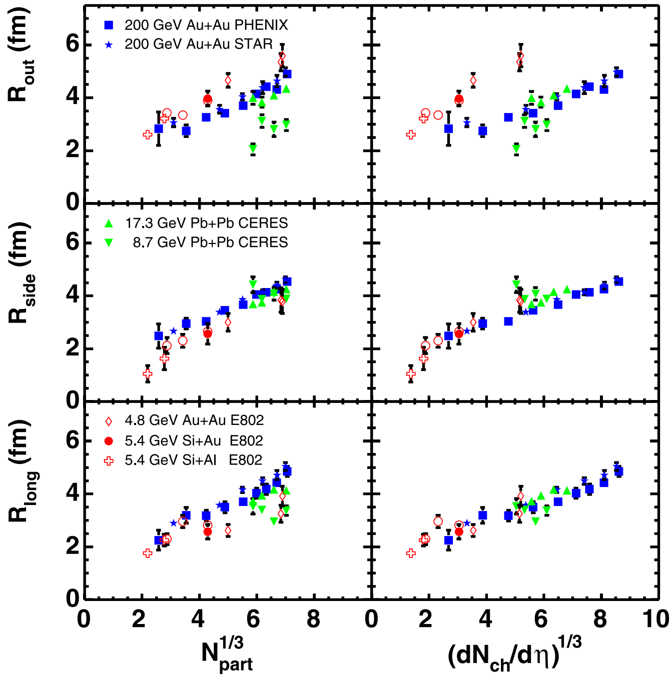

Fig. 4. Pion HBT radii plotted versus the number of participating nucleons (*left panels*), and versus the charged particle multiplicity (*right panels*). Compilation from [12]

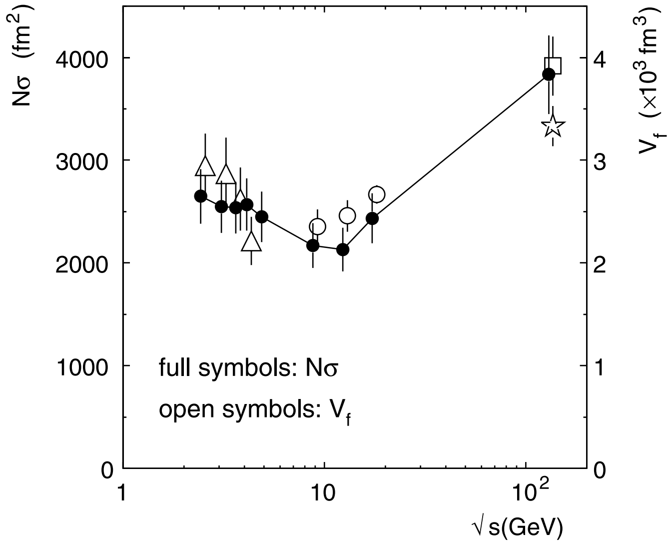

Fig. 5. The "effective pion cross-section" $N_{\mathrm{proton}}\sigma_{p\pi} + N_{\mathrm{pion}}\sigma_{\pi\pi}$ and the "freezeout volume" $\sim R_{\mathrm{long}}R^2_{\mathrm{side}}$ are plotted as a function of the collision energy, for central Au + Au (Pb + Pb) collisions. Figure and further details in [24]

may explain the increased spread in the upper panels of Fig. 4.

To good approximation, at a given $\sqrt{s_{NN}}$, total multiplicity (a final-state quantity) is a function only of N_{part} (an entrance-channel quantity), independent of A, B, or $|\mathbf{b}|$. The relationship does, however, depend on collision energy [25]. As seen in the right panels of Fig. 4, the final-state multiplicity provides a more common scaling parameter than N_{part}; recent analyses [13, 14, 26] show that this scaling persists for different m_{T} values and for lighter colliding systems at RHIC.

Several observations may be made about this multiplicity scaling. Firstly, it appears that knowledge of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ alone allows "prediction" of the HBT radii (at least R_{long} and R_{side}). This suggests that the small increase of these radii with $\sqrt{s_{NN}}$ seen in Fig. 3 is associated with increased particle production as the collision energy is raised. (Note that N_{part} is approximately constant for the data in Fig. 3.) Secondly, the finite offset d in the approximately linear relationship $R_{\mathrm{long}}R^2_{\mathrm{side}} = c(\mathrm{d}N/\mathrm{d}\eta) + d$ means that freeze-out does *not* occur at fixed density [13, 14].

Thirdly, the scaling shown in the figure breaks down dramatically for $\sqrt{s_{NN}} \lesssim 5\,\mathrm{GeV}$, as is obvious from the non-monotonic behaviour seen in Fig. 3. As the CERES Collaboration has pointed out [24], this is likely due to the dominance of baryons at lower $\sqrt{s_{NN}}$. Indeed, a quantitative connection between the number of protons and pions, and a product of HBT radii is possible, by assuming a universal ($\sqrt{s_{NN}}$-independent) mean free path at freezeout λ_{f}. In Fig. 5, the "freezeout volume" $\sim R_{\mathrm{long}}R^2_{\mathrm{side}}$ and the "effective pion cross-section" $N_{\mathrm{proton}}\sigma_{p\pi} + N_{\mathrm{pion}}\sigma_{\pi\pi}$ are seen to coincide by scaling the latter by $\lambda_{\mathrm{f}} = 1\,\mathrm{fm}$, apparently contradicting the standard assumption that freeze-out occurs when the mean free path becomes much larger than the system size.

HBT radii and the "freeze-out volume" may be connected only in the context of a model which includes dynamical effects like flow. The analysis of [24] ignores such effects; however, its bottom line remains approximately valid, as flow effects on HBT radii are expected to be small at low p_{T} [27].

2.2 Kinematic dependences

Insight on the dynamical evolution and geometric substructure of the emission region is gained by studying the dependence of femtoscopic lengths on the next three parameters in (3).

In non-central collisions, the entrance-channel geometry is naturally anisotropic; the hot source geometry approximates the overlap between target and projectile, and is characterized by a "long axis" perpendicular to the impact parameter vector $\mathbf{b}$. At RHIC, the system expands more rapidly in-plane ($\parallel \mathbf{b}$) than out ($\perp \mathbf{b}$) [29]. If it is indeed a collective *system* with finite lifetime, then the overall shape should evolve. Pion HBT radii have been measured as a function of their azimuthal angle $\varphi_{\mathrm{pair}} \equiv \angle(\mathbf{K}, \mathbf{b})$ for Au + Au collisions. The measurement at RHIC [28] is shown in Fig. 6. There, it is clear that as $|\mathbf{b}| \to 0$, the freezeout source becomes larger and rounder. In fact, there is a nice "rule of two" – the source expands to twice its original size [13, 14, 26], and its anisotropy $\varepsilon \equiv (\langle y^2\rangle - \langle x^2\rangle)/(\langle y^2\rangle + \langle x^2\rangle)$ decreases by the same factor [28]. The relatively small change in the source shape is at least semi-quantitatively [30] consistent with short timescale estimates [27] based on the longitudinal radius, and at variance with expectations from "realistic" simulations [31].

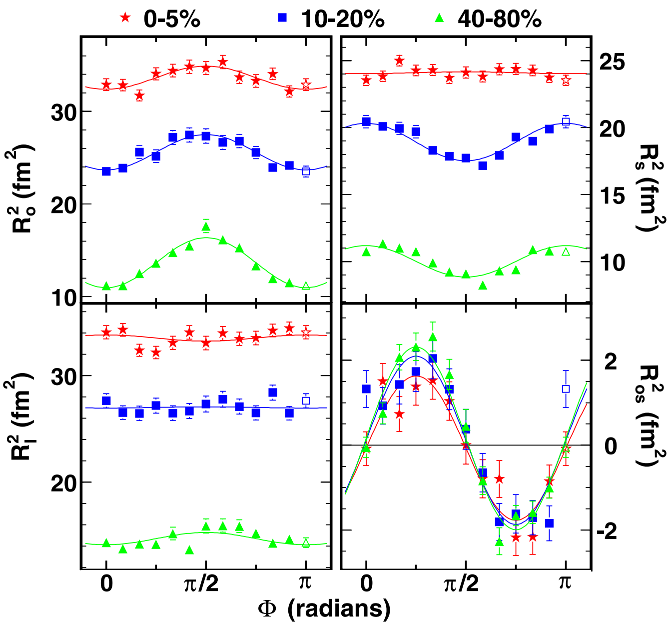

Fig. 6. Pion HBT radii measured for Au + Au collisions at $\sqrt{s_{NN}}$, plotted as a function of azimuthal emission angle relative to the reaction plane. From [28]

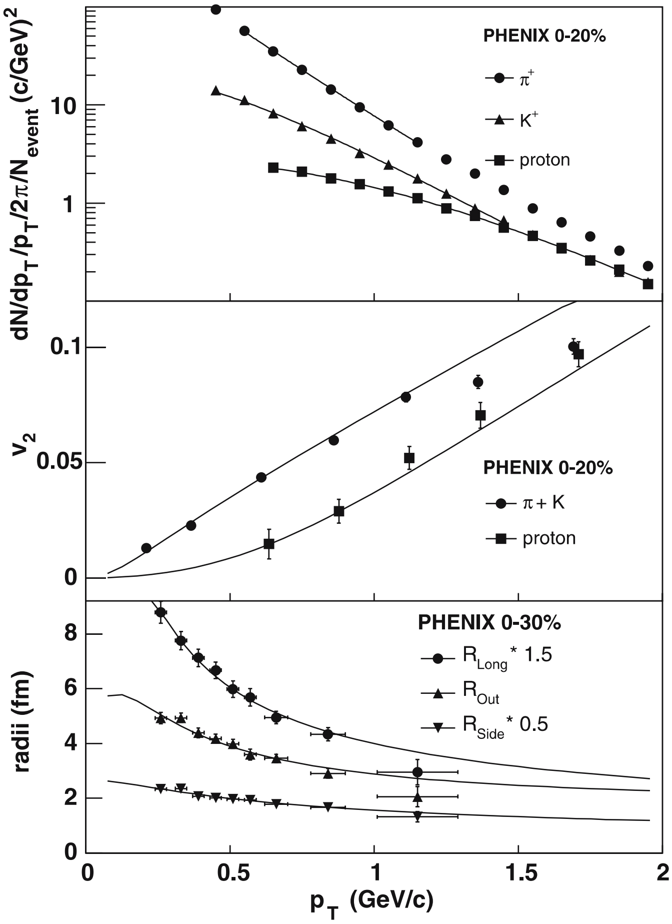

Fig. 8. A blast-wave [27] fit reproduces several observables at RHIC. See text for details. From [35]

As will become increasingly clear, the only femtoscopic systematic which might display non-trivial $\sqrt{s_{NN}}$ dependence is, in fact, the dependence on φ_p. This is clear from the bottom panel of Fig. 3, in which the relative paucity of such measurements is also clear. It will be especially interesting to see whether the flow and/or timescales at the LHC are sufficiently large to produce in-plane freeze-out configurations [32].

Experiments at a wide range of collision energies have mapped out the rapidity dependence of pion HBT radii. Of particular interest here is the so-called Yano–Koonin rapidity $Y_{\rm YK}$ [33, 34], which should approximate the rapidity of the fluid element which emits a pair of pions at some rapidity $Y_{\pi\pi}$. Here again, an approximately "universal" (independent of $\sqrt{s_{NN}}$) behaviour of $Y_{\pi\pi}$ is observed [12].

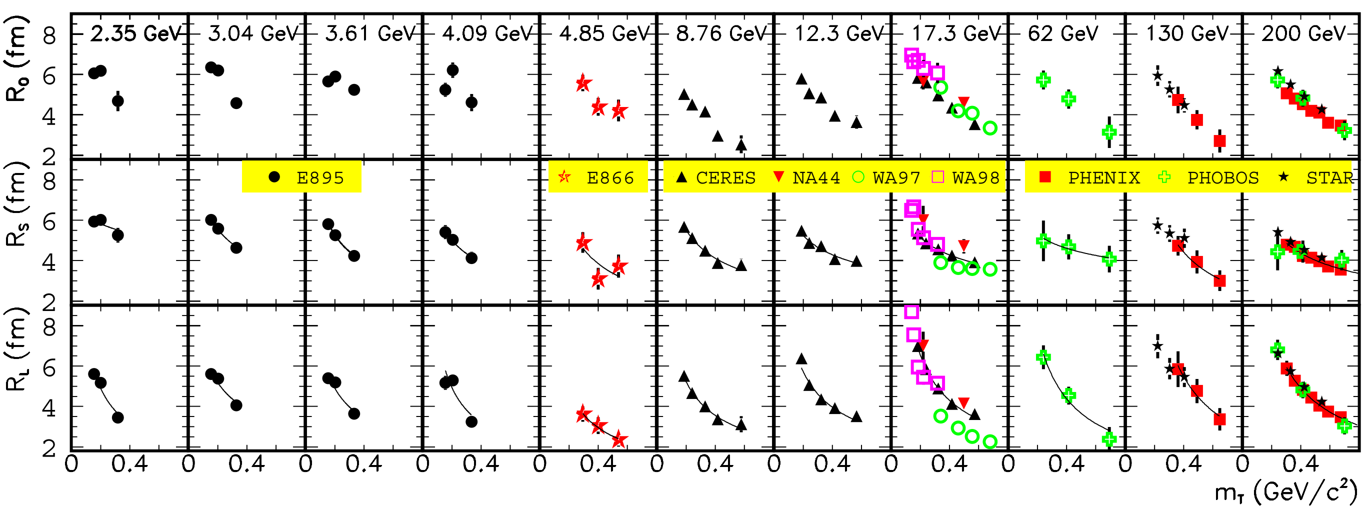

Fig. 7. Pion HBT radii plotted versus the transverse mass $m_{\rm T}$ for all published measurements of central Au + Au (Pb + Pb) collisions over two decades in $\sqrt{s_{NN}}$. Compilation from [12]

This is consistent with (but not proof of) emission from a boost-invariant system [34].

The most extensively-studied kinematic systematic has been the p_{T}-dependence of pion HBT parameters. Figure 7 shows the world dataset of published measurements for central Au + Au (Pb + Pb) collisions. The falling dependence of femtoscopic scales on transverse velocity is generally believed to arise from collective transverse and longitudinal flow (e.g. [27]). As I've mentioned, strong collective flow points to formation of a real *bulk* system.

The longitudinal radius scales approximately as $R_{\mathrm{l}} \sim m_{\mathrm{T}}^{-0.5}$, indicating strong longitudinal flow and again consistent with expectations for emission from a boost-invariant system [16, 27]. Decreasing transverse radii R_{o} and R_{s} may be due to collective transverse flow. The simplest flow-dominated models quantitatively interrelate these femtoscopic m_{T} dependences with other observations. An example is shown in Fig. 8, in which a very simple freeze-out scenario [27] – thermal motion superimposed on a collectively exploding source – can simultaneously describe a broad range of data measured at RHIC. The momentum-space distribution, quantified by the average number distribution (top panel of Fig. 8) and the number variation as a function of azimuthal angle (middle panel) give an incomplete picture by themselves. Momentum-dependent femtoscopic radii (bottom panel) probe the dynamical *sub*-structure of the collision, constraining models more stringently [12–14, 27, 36].

2.3 Particle-species dependences

Within the past several years, high-statistics datasets in experiments with good particle identification have allowed the mapping of femtoscopic systematics with the final variables in (3) – the mass (or species) of the correlated particles.

Signals of a *system's* collectivity at freeze-out should not be limited to the pions. In the simplest picture, corresponding to flow-dominated models (e.g. [27]) of Fig. 8, femtoscopic radii should approximately scale with m_{T}, independent of particle type. An impressive common scaling of radii from *all* measured particles is, indeed, observed at *all* energies explored, as seen in Fig. 9. The common scaling is particularly striking when one considers the quite different measurement systematics involved in charged pion correlations and, say, K_s^0 correlations. Even generalized nucleon separation scales, probed by relative yields of deuterons and protons (d/p in Fig. 9), follow the systematic, with the exception of one outlier point at the lowest energies.

Correlations between non-identical particles probe not only the sizes, but also the relative displacement of the particles' emission zones in space-time [47]. Any collective freeze-out scenario naturally implies a specific relationship between emission regions of the various particle types. In a flow-dominated picture, the emission zones for high-m_{T} particles are not only smaller than those for low-m_{T} particles, but are also inevitably located further from the center of the collision region [27], as suggested by the schematic in Fig. 1. As discussed in detail in the contribution of A. Kisiel [40], available measurements of these displacements at RHIC provide further support of the flow-dominated freeze-out scenario.

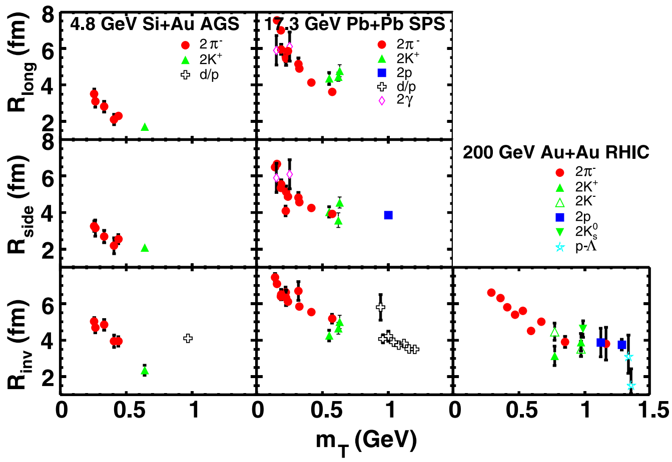

Fig. 9. Femtoscopic radii for various similar-mass particle pairs, plotted as a function of m_{T}. Compilation from [12]

Table 1. A very incomplete table of published or ongoing femtoscopic studies at RHIC for various particle combinations. "Traditional" identical-particle interferometry lies along the lowest diagonal line of cells

	π^+	π^-	K^+	K^-	K_s^0	p	$\bar{p}$
$\bar{\Xi}$	[37, 38]	[37, 38]					
Ξ	[37, 38]	[37, 38]					
$\bar{\Lambda}$						[39]	[39]
Λ						[39]	[39]
$\bar{p}$	[40]	[40]	[40]	[40]		[41]	[41]
p	[40]	[40]	[40]	[40]		[41, 42]	
K_s^0					[43]		
K^-	[44]	[44]		[42]			
K^+	[44]	[44]	[42]				
π^-	[26, 41]	[26, 45, 46]					
π^+	[26, 45, 46]						

Non-identical particle correlations are today a growth industry. Table 1 lists only a sampling of recently-published or ongoing analyses at RHIC energies. Similar studies have been performed at lower energies [12, 48]. The diagonal axis corresponds to identical-particle correlations, the "traditional" focus of HBT interferometry.

3 Whither

Excluding aficionados attending workshops such as this one, in the minds of most heavy ion (or high energy) physicists, the term "femtoscopy" brings to mind only the single, rather uninspiring systematic plotted in Fig. 3; indeed, some may be tempted toward the dismissive view that "the measured radius is always 5 fm".

As we have just discussed, this is grossly unfair: the systematics are tremendously richer, with femtoscopic length scales varying with almost every parameter in (3). Furthermore, these strong systematic trends are found consistently by experiments separated by decades and using quite different measurement and correction techniques; indeed, especially at RHIC, the data are almost embarrassingly consistent (cf. Fig. 7). Yet further, it appears that these systematics may be well understood in the commonly-accepted framework of *system* evolution due to strong flow quantitatively consistent with momentum-space observables [27]. Clearly, there is much more to femtoscopy than its most notorious figure.

On the other hand, the trends shown in Figs. 4, 7, and 9 suggest that the notorious Fig. 3 quite correctly summarizes the situation after all. At any $\sqrt{s_{NN}}$, the systematics of (3) are quite rich and may well be reconciled with a reasonable physical picture. However, in more ways than expressed by Fig. 3, those systematics are essentially independent of $\sqrt{s_{NN}}$! Without resorting to agreement or disagreement with particular models, this second[2] femtoscopic puzzle is startling, suggesting that the space-time consequences of the physical processes are the same at RHIC as they are near the pion production threshold. Often, "universal" behaviour is a key to deeper physical insight. Heavy ion femtoscopy, however, might display a bit *too* much universality.

3.1 Whither... or wither?

Given the prominence of nontrivial geometry to the physics of heavy ion collisions in general, and the rather generic [20] expectation of significant changes in spacetime evolution with $\sqrt{s_{NN}}$, understanding this universality remains urgent. What future efforts might shed some light?

Today, one almost reflexively points to the impending heavy ion program at the LHC for new observations generating fresh insights. While anything might happen in an unexplored energy domain, we may venture a prediction. Instead of a crystal ball, however, we use a mirror to gaze over our shoulder at twenty years of systematics in heavy ions. The $\sqrt{s_{NN}}$-dependence of the global multiplicity (per participant pair) has been significantly extended at RHIC and summarized by the PHOBOS collaboration [25]. Boldly and probably naively extending this systematic leads to the expectation that multiplicities at the LHC will be $\sim 60\%$ higher than they are at RHIC [50, 51].

As discussed in the previous section, femtoscopic length scales – for any $m_{\rm T}$, y, $N_{\rm part}$, or particle species – depend primarily on event multiplicity. Taken together, the PHOBOS-based extrapolation and Fig. 4 suggest that radii[3] in central collisions at RHIC will simply be $\sim 17\%$ higher than they are at RHIC ($(1.6)^{1/3} = 1.17.$).

Notably, evidence is mounting that perhaps *all* soft-sector observables are determined primarily by total multipilcity, independent of $\sqrt{s_{NN}}$. Properly-scaled elliptic flow [52] and even strangeness enhancement [50, 51] appear to show universal multiplicity scalings. Whether this is a trivial implication of entropy-driven phasespace dominance in bulk observables is unclear. However, nontrivial new phases of *matter* should have signatures in the long-distance (soft momentum) sector; dependence only on multiplicity (and not energy) would be intriguing.

So, perhaps the choice of collider facility (LHC versus RHIC) is unimportant, and heavy ion femtoscopists should focus on filling in the holes of Table 1? Most evidence thus far indicates that flow-dominated freezeout scenarios (e.g. [27]) fitted to identical π correlations essentially "predict" femtoscopic data using other particle combinations. The data is yet scant, however, so ongoing studies [40] to further explore this table are quite important. There are even preliminary reports [37, 38], with exotic particle combinations, of inconsistencies with these freezeout models. If confirmed, strong theoretical focus should come to bear on this result. If, on the other hand, varying the particle combination repeatedly yields results "predicted" by blast-wave models, continually filling in cells of Table 1 risks becoming a stamp-collecting exercise.

Even if all of the particle combinations in Table 1 follow simple blast-wave calculations, and so reveal no new femtoscopic information, this can actually be turned to good use. In particular, one may turn around the traditional approach in which one uses the known two-particle final state interaction (FSI) to extract geometric information, to extract the FSI itself [48, 53]. Finalized results from STAR on $p-\Lambda$ correlations [39] have extracted previously inaccessible scattering length information for low-energy baryon–antibaryon scattering, severely constraining theoretical calculations of such; cf. Fig. 10. While not QGP-related physics, such studies can make a unique contribution to low-energy QCD and hadronic physics.

We have said that HBT-like correlations were initially studied in very small systems. Only with the advent of RHIC has it been possible to compare directly at a fixed energy and using identical detector and analysis techniques, correlation data from the heaviest ion collisions to that from $p+p$ collisions [13, 14]. As has been observed previously in high energy experiments, femtoscopic radii from identical pion correlations measured in p+p collisions decrease with increasing $p_{\rm T}$, qualitatively similar to the dependence shown in Fig. 7. The preliminary STAR data shows, however, that in all three HBT radii, the $p_{\rm T}$ dependence is *quantitatively identical* in $p+p$ and $A+A$ collisions! Since the heavy ion and high energy communities

[2] In this experimental overview, I have not discussed what has come to be known as "the" HBT puzzle [49] which, simply put, is that otherwise-successful and apparently reasonable models like hydrodynamics do not reproduce femtoscopic measurements [12]. To all but the novice heavy ion physicist, however, the initial failure of dynamical models to reproduce *diverse* observations is hardly puzzling. The experience at lower energies is that such initial failure is more the rule than the exception. In light of other, more generic puzzles, I call this problem only the "*first* HBT puzzle" [13, 14].

[3] Precise expectations $R_{\rm out}$ or φ-dependent radii at the LHC are, admittedly, less certain, as the former does not scale exactly with multiplicity (cf. Fig. 4), and the multiplicity-dependence of the latter has not been extensively mapped (cf. Figs. 3 and 6).

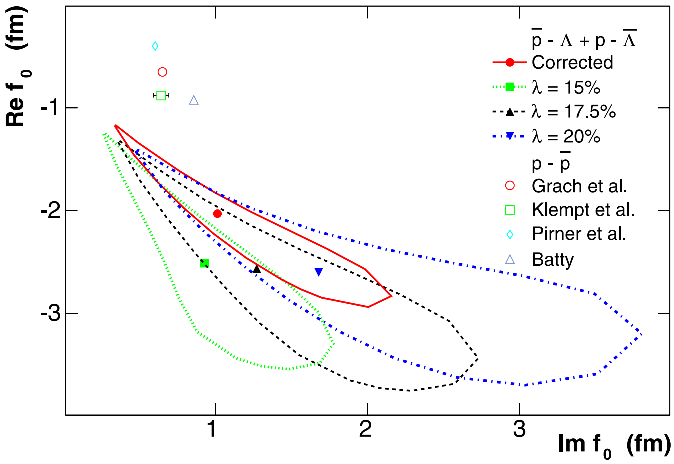

Fig. 10. Constraints on the complex scattering length for the $p-\bar{\Lambda}$ system (*contours*) versus theoretical calculations (*open symbols*). From [39]

have traditionally used very different physics mechanisms to explain this dependence, this observation potentially throws the explanations of both communities into doubt. If this result is confirmed, it ranks as the third (and perhaps more important) "HBT puzzle".

Unexplained long-range structure in the correlation functions for the lowest-multiplicity collisions, however, presently cloud the interpretation of the HBT radii for $p+p$ collisions [13, 14]. Partly in an effort to understand this, a new representation of the data in terms of spherical harmonic amplitudes in **q**-space was developed as an experimental diagnostic tool [54]. In fact, a similar harmonic decomposition method was earlier already developed by Danielewicz and collaborators [55, 56], not as a diagnostic, but as a direct link to the detailed geometry (beyond simply length scales) of the emitting source. This representation has a natural connection to source imaging [57], and, indeed, first applications to PHENIX data have been reported [56].

Harmonic decompositions as an improved representation of the correlation function and source imaging as an improved, generalized fit to the data are, in a sense, merely technical improvements, but they are quite significant ones. Just as femtoscopic studies have explored the systematic landscape of (3), so should they probe the "microscape" of fine details of the measured data.

The femtoscopy of heavy ion collisions can be an addicting endevour. Systematics make sufficient sense that we are convinced that we are probe geometry at the femtometer scale. Spacetime geometry at that scale is sufficiently important to the physics that the measurements must be done well. Such measurements are sufficiently challenging that it is enjoyable to do them well and to develop improved techniques. However, for now, the overall results are sufficiently puzzling that there is plenty more to do.

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