Bose-Einstein or HBT correlations in high energy reactions

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DOI: http://dx.doi.org/10.3204/DESY-PROC-2009-01/46

Abstract
Concepts of thermalization and hydrodynamical behavior are applied from time to time to e$^+$+ e$^-$, hadron+hadron and heavy ion collisions. These applications are scrutinized paying attention to particle multiplicities, spectra, and Bose-Einstein correlations in particular. Can hydrodynamics describe these data?

1 Introduction

In 2008, the speakers of the International Symposium on Multiparticle Dynamics were given a quiz of 18 questions, that were compiled by Hannes Jung and Gösta Gustafson, the Chair and the Co-Chair of this meeting [1]. My goal is to discuss three of these problems:

1. Can thermal & hydrodynamical models describe e^++e^-, h+p and A+B reactions? [1]
2. What heavy ion physics can learn from e^++e^-, h^-+p and p+p collisions?
3. How can correlations be used to determine the size of the interaction region and the characteristics of phase transitions?

These questions are related to Bose-Einstein correlations, that appear due to the symmetrization of hadronic final states for the interchange of identical bosons, and are also known by other names, for example Hanbury Brown – Twiss or HBT correlations in heavy ion collisions, intensity interferometry, or intensity correlations [2]. These correlations are also tools of femtoscopy, because they are used to measure length scales on the femtometer scale [3–5].

2 The shortest film ever made: e^+ e^- collisions at LEP

In e^+ e^- collisions, Bose-Einstein correlations were used to record the fastest film ever made: the formation of a ring-like, *non-thermal* source in the transverse plane of jet production, a process that ends in less than 10^{-23} seconds [6, 7]. Can *thermal* models describe multiplicities, spectra and correlations in these collisions?

A number of recent papers consider the possibility of thermal particle production in e^+ e^- reactions. Two recent, interesting examples are refs. [8] and [9], that present thermal model fits to these data with similar level of statistical significance but with very different physics conclusions. A model cannot be excluded with the help of mathematical statistics if its confidence level is CL$\geq 0.1\%$, thus the probability that the model describes the data is at least one in thousand.

Fig. 1 of ref. [8] is a very beautiful plot indicating intriguing similarities between particle abundances in e^+ e^- at $\sqrt{s_{NN}}$ = 91 GeV and thermal model calculations. The fit quality is

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[1]Instead of the originally given e^-+p problem, let me discuss soft hadron-proton collisions, for clarity.

characterized by a χ^2/NDF = 631/30. The corresponding confidence level is CL = 1.1 10^{-111} %. This confidence level is an extremely small positive number and so the probability that the thermal particle production describes this data set is practically zero [8] . These authors also observe and point out correctly that the statistical or thermodynamical description of these data fails completely at the high level of present experimental precision. Approximate qualitative agreement between thermal particle production and data can only be obtained if the relative errors on these data are magnified to about 10 % [8]. Their conclusion can be contrasted to other manuscripts, that claim that a thermodynamical or statistical description of particle multiplicities in $e^+ \ e^-$ reactions is possible. For example, the same data set was analyzed in ref. [9] , using a slightly different thermal model description and the quality of their fit is given in their Table V as χ^2/NDF = 215./27 . The corresponding confidence level is CL = 3.4 10^{-29} % hence the probability that this thermal model describes particle abundances in electron-positron annihilation is practically zero. When the analysis is restricted to include only those 15 resonances in the fitting, whose width is less than 10 MeV, the same thermal model description yields χ^2/NDF = 39./12 . The confidence level of this fit is still CL = 1.1 10^{-2} % , which is many orders of magnitude improvement, but still an order of magnitude less than the conventional threshold of acceptance, CL = 0.1 %. Thus thermal particle production models do not describe the multiplicities of elementary particles of $e^+ \ e^-$ at $\sqrt{s_{NN}}$ = 91 GeV in an acceptable manner.

Two important and well known features of hadronic spectra also disagree with a thermal, statistical picture of particle production. The observation of jets (2 and 3 jet events at this energies) can be contrasted to the lack of preferred direction in the initial conditions and in a thermal picture of particle production. Perhaps the thermal picture can be limited to the transverse direction? The power-law tail the transverse momentum spectra, which can be explained in terms of perturbative QCD processes and jets decaying to jets to jets and in particular the correlations among these jets are inconsistent with a thermal and/or a hydrodynamical interpretation, that lead typically to exponential spectra. Furthermore, generalized thermal models that describe the spectra cannot naturally interpret the correlation structures observed in two and three jet events which are basically energy momentum conservation laws and have a trivial interpretation in partonic picture, the emission of quark and gluon jets in perturbative QCD.

Bose-Einstein correlations are more subtle features of two-particle distributions. They carry information on the space-time structure and on the chaotic or coherent nature of particle emitting sources. Recently measured Bose-Einstein correlations disagree qualitatively with the hypothesis that the produced particles are emitted from a thermal or hydrodynamical source in $e^+ + e^-$ reactions, because in thermal models the two-particle Bose-Einstein correlation function is always given by a 1 + positive definite function, and this constraint is violated by a recent analysis of L3 data [7,10].With other words, there is no region of two-particle relative momentum space, where a chaotic (or thermal) picture of particle production would lead to anti-correlations. However, recently analyses L3 data as detailed in ref. [7, 10] indicate very clearly the existence of a region of anti-correlation: if the correlation functions are measured as a function of the Lorentz invariant relative momentum variable $Q = \sqrt{-(k_1 - k_2)^2}$, where k_i stands for the four-momentum of particle i, a dip is found experimentally in the region of 0.6 GeV $< Q <$ 1.5 GeV, as indicated in Fig. 1. In this kinematic range the errors are small. This feature is shown in greater details in Fig 1. L3 data from ref. [7] are compared to a Gaussian fit, $C(Q) =$

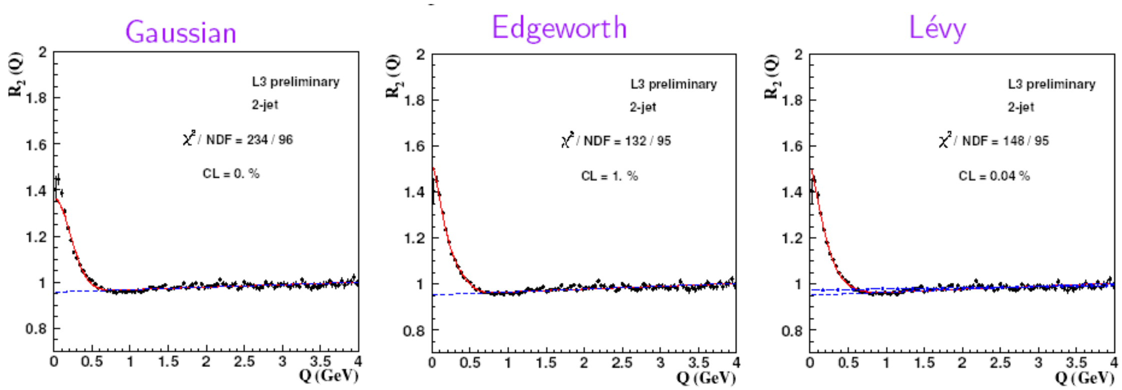

Fig. 1: Comparison of Gaussian (left), Edgeworth (middle) and Lévy fits to L3 Bose-Einstein correlation functions. The 1+ positive definite forms, Gaussian and Lévy do not have a statistically acceptable level, CL < 0.1%. The Edgeworth expansion has an acceptable CL = 1 % and describes the dip using a 1+ non-positive definite expression.

$1 + \lambda \exp(-Q^2R^2)$, $\chi^2/NDF = 234./96$ and the corresponding confidence level is practically zero. A generalization of the Gaussians is given by the symmetric Lévy form $C(Q) = 1 + \lambda \exp(-Q^\alpha R^\alpha)$, $\chi^2/NDF = 148./95$, CL = 0.04 %. This is only a factor of 2.5 below the conventional domain of acceptable results, but the chance that this form represents the data is only 4 in 10000. This form however is 1 + a positive definite function. The right panel also indicates a linear fit to the long range, $Q > 1.5$ GeV correlations, shown with a dot-dashed line. It describes the data in the fitted $Q > 1.5$ GeV region, and it clearly cuts into the "dip" region of the data, located at $0.6 < Q < 1.5$ GeV . When a Lévy fit form is enforced, these long range correlations get distorted, pushed below the dip region by the fit, as indicated by the dashed line in the right panel, and the overall fit quality is decreased below the limit of acceptability, CL < 0.1 %. The best fit is achieved using an Edgeworth expansion, $C(Q) = 1+\lambda \exp(-Q^2R^2)[1+\kappa_3 H_3(QR)]$, where $H_3(x)$ is the third order Hermite polynomial, see ref. [7] for details. This Edgeworth fit has a statistically acceptable CL = 1 % and describes the dip using 1 + a non-positive definite expression, in a model and interpretation independent manner.

The τ-model of ref. [11] also predicted the existence of such anti-correlated regions, based on the assumption that $e^+ + e^-$ annihilations indeed correspond to point-like collisions hence the produced particles with a given momentum k^μ appear in a direction parallel to their momentum, $x^\mu \propto k^\mu$, however with a broad proper-time distribution $H(\tau)$. This model leads to simple fitting forms, that improve the description of the data as compared to the model-independent Edgeworth expansion method, CL is increased from 1 % to 40 % , and when the fit parameters are required to satisfy the model constraints, CL is slightly increased to 42 % , see ref. [7] for details. The parameters of the proper-time distribution are determined from detailed fits to the L3 Bose-Einstein correlation functions. This way the proper-time evolution of particle production is reconstructed in these reactions, and the following points can be made: in 2-jet events, particle emission starts just after the collision, so that the most probable value for τ is 0.3 fm/c, but this one-sided proper-time distribution has a power-law tail, corresponding to a one-sided Lévy distribution with an index of stability of $\alpha = 0.42 \pm 0.01$. Using a recently developed method based on the τ-model [12], even a movie of the space-time evolution of particle emission can be

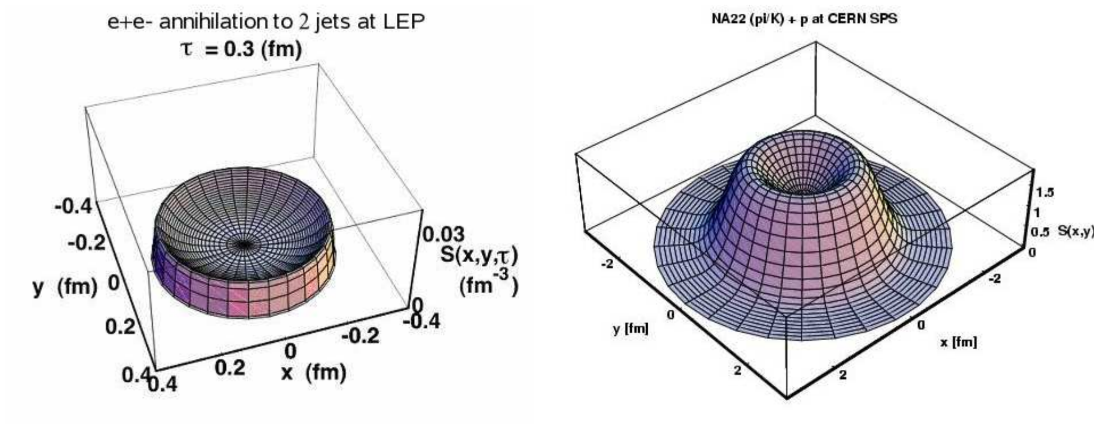

Fig. 2: Left panel: A snapshot picture from the reconstructed video of jet formation in the transverse plane of 2-jet events in e^+ + e^- annihilation at LEP at $\tau = 0.3$ fm/c. A non-thermal, expanding ring is observed, the amplitude of the ring diminishes very quickly, while its radius grows nearly with the speed of light. Right panel: The reconstructed transverse part of the particle emission function in h+p reactions at CERN SPS as inferred from Bose-Einstein correlations and single particle spectra as measured by the NA22 collaboration, describing a tiny ring of fire.

reconstructed. This movie – the shortest film ever recorded – practically ends in about 0.3 fm/c.

3 The smallest ring of fire: h+ p and p+p collisions

In hadron-proton collisions, Bose-Einstein correlations have been used to make a snapshot picture of the smallest ring of fire, ever detected: the diameter is less than 1 fm or 10^{-15} m, but the source seems to be thermal. The ring formation here is a hydrodynamical effect, the temperature drops from $T \approx 140$ MeV in the center to nearly zero within about 1 fm radial distance, hence a strong pressure gradient builds up. However, the experimentally seen transverse flow is too week to move the matter away from the surface, hence a pile-up at the surface, a fire-ring is found [2, 13]. A similarly hydrodynamical ring of fire formation due to large temperature gradients and small transverse flows can be inferred from a simultaneous analysis of single particle spectra of pions, kaons, protons and STAR preliminary Bose-Einstein or HBT correlation radii of pion pairs in $\sqrt{s_{NN}} = 200$ GeV p+p collisions at RHIC [14].

4 The hottest and most perfect fluid: $Au + Au$ collisions at RHIC

In Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV at the RHIC accelerator at BNL, Bose-Einstein correlation measurements also yield snapshot pictures of the hottest and most perfect fluid, ever made in a laboratory experiment.

The following milestones lead to this important discovery: PHENIX was the first to observe a *new phenomena* in 0-10 % central Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV at RHIC: the suppression of particle production with high transverse momentum, the first RHIC discovery that made it to the cover page of The Physical Review Letters in January 2002. However, it was not clear initially if this effect is due to the nuclear modification of the structure functions (initial conditions) at such a high energies, or if this is indeed a hadronic final state effect. As a control, $d + Au$ measurement was performed and all the four RHIC collaborations: BRAHMS, PHENIX, PHOBOS and STAR reported the absence of suppression in these reactions. This discovery implied that the suppression in Au+Au reaction is a final state effect, due to the formation of *a new form of matter*, that also made its way to the cover page of the Physical Review Letters in August 2003. The third milestone was the publication of the so called “White Papers” or review papers by all the four RHIC experiments. After several year’s worth of high energy collisions, and from a detailed analysis of the elliptic flow data, a consensus interpretation emerged that the fireball made in Au+Au collisions at RHIC behaves like a liquid of strongly interacting constituents, also known as “the perfect fluid”. This discovery became also known as the Top Physics Story for 2005 by the American Institute of Physics. This discovery has been considerably sharpened when STAR and PHENIX pointed out that the observed elliptic flow patterns scale with the number of constituent quarks and strange and even charm quarks participate in the flow. Although the theoretical interpretation of this effect is still open for discussions in particular because the unsolved problem of quark confinement in QCD prevents the application of first principle QCD calculations for this phenomena, in my opinion the experimental evidence is very clear, it is irrefutable that quark degrees of freedom are active and the perfect fluid seen in Au+Au collisions is a fluid of quarks [16]. (The role of gluons is less clear and less directly measurable from the experimental point of view.) The fifth milestone was the quantification, how perfect is the perfect fluid at RHIC? Answers were obtained by measuring the so called kinematic viscosity η/s, which is the ratio of the shear viscosity to the entropy density. Two theoretical analyses were published in 2007 based on elliptic flow patters, a third measurement was based on the transverse momentum correlations, while PHENIX studied the energy loss and flow of heavy (charmed) quarks and based on a charm diffusion picture, found that $\eta/s = (1.3-2.0)\frac{1}{4\pi}$ [16]. Even more recently, PHENIX was able to put a lower limit on the initial temperature of the fireball at RHIC from the analysis of direct photon data [17], $T_i > 220$MeV. These numbers can be compared to similar characteristics of other known fluids, like water, liquid nitrogen or helium, see Fig. 3, based on refs. [18, 19].

Note that ^{4}He becomes superfluid at extremely low temperatures and its kinematic viscosity η/s reaches a minimum at the onset of superfluidity, so for superfluid ^{4}He $\eta/s \geq 10\frac{1}{4\pi}$. The matter created in Au+Au collisions at RHIC has temperatures larger than 2 Terakelvin, nevertheless its kinematic viscosity is the lowest value ever produced in laboratory: it is at least a factor of 4 smaller than that of superfluid ^{4}He. We may thus refer this property of the matter created in Au+Au collisions at RHIC as *high temperature superfluidity* [20]: the matter created in Au+Au collisions at RHIC is the most perfect fluid ever made by humans.

We gain information on the type of transition from hadronic matter to quark matter with the help of the Bose-Einstein correlations. By now, circumstantial evidence is obtained that this transition is either a cross-over or, a non-equilibrium transition. This consensus opinion is based on important and highly selective constraints given by Bose-Einstein correlations and particle interferometry data in Au+Au collisions at RHIC [5].

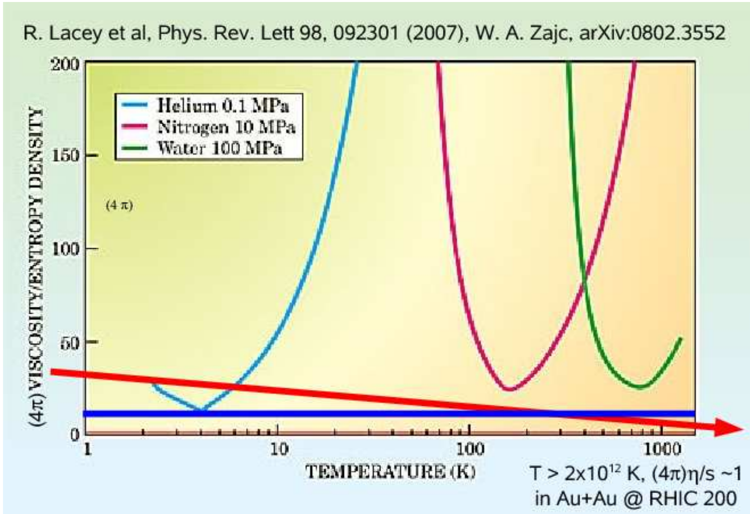

Fig. 3: Comparison of the properties of the perfect fluid created in $\sqrt{s_{NN} = 200}$ GeV Au+Au collisions with less extraordinary materials like water, nitrogen or helium.

5 Conclusions

After having discussed e^+ e^-, hadron-proton and heavy ion reactions one after the other, and based on the presented evidence let me attempt to give answers to the questions discussed in the Introduction, keeping in mind that these answers were worked out predominantly from the point of view of Bose-Einstein correlations and their models in these reactions.

Can thermal & hydrodynamical models describe e^++e^-, h+p and A+B reactions? It seems that thermal models cannot interpret particle multiplicities, spectra and Bose-Einstein correlations in e^+ + e^- reactions at the present level of experimental precision, and using the conventional threshold for acceptable confidence levels (99.9 % $\geq$ CL $\geq$ 0.1 %). However, hydrodynamical and thermal models are remarkably successful in describing soft ($p_t < 1.5$ GeV) hadron-proton, proton-proton and heavy ion reactions. At higher values of the transverse momenta, jet physics and interaction of jets and the hydrodynamical medium opens up new research directions at the intersection of particle and nuclear physics.

What heavy ion physics can learn from e^++e^-, h^-+p and p+p collisions? One lesson that I presented was to take statistical analysis and confidence level determinations seriously. Based on detailed and precision analysis of Bose-Einstein correlations in two-jet events and a simultaneous analysis of single particle spectra, the time evolution, a movie or a video like film of particle emission has been already reconstructed in e^+ e^- reactions at LEP. In heavy ion physics, only snapshot like pictures can be reconstructed at present. Further developments of the femtoscopic tools are needed to allow for a video like reconstruction of the time evolution of particle emission in heavy ion reactions. Based on Bose-Einstein data in e^+ + e^- reactions, it seems that the most probable value of the proper-time parameter of particle production is $\tau =$ 0.3 fm/c, a surprisingly short value. It would be interesting to consider the phenomenological consequences of this number in heavy ion reactions, and if possible, to extract similar numbers for jets that are produced in a nuclear medium.

How can correlations be used to determine the size of the interaction region and the characteristics of phase transitions? Of course a complete answer to this question goes well beyond the scope of this conference contribution. Let me just emphasize here, that correlations are routinely used to take a snapshot picture of the interaction region [2–5]. The resolution of these snapshot pictures has been increased recently and more detailed information about structures (like a ring of fire) or heavy tails (non-Gaussian behavior) are seen in all kind of reactions [5]. Recent progress even allowed for the determination of the time evolution of the region of particle production in $e^+ e^-$ reactions, based on a non-thermal description. Similar techniques are not yet developed for soft hadron-proton, proton-proton and heavy ion collisions, where the thermodynamical and hydrodynamical models can readily be applied. However, in heavy ion reactions matter formation and also a transition to a perfect fluid of quarks has been experimentally proven (although with open theoretical issues). Bose-Einstein correlations have been proven to constrain models in an extremely efficient manner. At present, models with a strong first order QCD phase transition or with a second order phase transition point disagree with Bose-Einstein correlation data in heavy ion collisions at RHIC, however, models with a cross-over transition or with non-equilibrium rehadronization scenario cannot be excluded at present [5, 21].

Acknowledgments: It is my pleasure to thank the Organizers for a most professionally organized conference. This research was supported by the OTKA grants NK73143, T49466 as well as by a Senior Scholarship Award of the Hungarian-American Enterprise Scholarship Fund.

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