Measuring the size and dynamics of heavy-ion collisions with femtoscopy

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Overview

- What is femtoscopy and what does it measure
- Femtoscopy and collectivity
- Pion femtoscopy of the p-p, p-Pb and Pb-Pb collisions
  - Lessons from RHIC
  - Pb-Pb results from the LHC
  - Azimuthally sensitive femtoscopy
  - Comparison pp, PbPb and world systematics
  - P-Pb results vs. p-p and Pb-Pb data
  - Pion coherent emission from 3-pion correlations
- Femtoscopy of heavier particles
  - What more can we learn from baryon correlations
  - Baryon-baryon and baryon-antibaryon results at the LHC
Correlation – identical particles

- Quantum interference of indistinguishable scenarios
  - We detect a pair of particles with \((p_1, p_2)\), knowing that they have been emitted somewhere from the source \((x_A, x_B)\)

\[
\Psi = \frac{1}{\sqrt{2}} \left[ \exp(-i p_1 x_A - i p_2 x_B) + \exp(-i p_1 x_B - i p_2 x_A) \right]
\]

\[
|\Psi|^2 = 1 + \frac{1}{2} \left[ \exp(-i p_1 x_A - i p_2 x_B + i p_1 x_B + i p_2 x_A) + \exp(-i p_1 x_B - i p_2 x_A + i p_1 x_A + i p_2 x_B) \right]
\]

\[
= 1 + \frac{1}{2} \left[ \exp(-i (x_A - x_B)(p_1 - p_2)) + \exp(i (x_A - x_B)(p_1 - p_2)) \right]
\]

\[
= 1 + \cos(qr)
\]

\[
q = p_1 - p_2
\]

\[
r = x_A - x_B
\]
Correlation – hadrons

- Two hadrons interact via the strong interaction after their last scattering (emission)
  - The wave function is the Bethe-Salpeter amplitude, corresponding to the standard quantum scattering problem, taken with the inverse time direction
  - For identical hadrons it must also be properly (anti-)symmetrized

\[
\Psi = \exp(-i k^* \vec{r}) + f \frac{\exp(ik^* r)}{r}
\]

\[
f^{-1} = \frac{1}{f_0} + \frac{1}{2} d_0 k^2 - ik^*
\]
Correlation – charged particles

- Two charged particles interact via Coulomb after their last scattering
  - This gives the final form of the wave-function, which must also be properly (anti-)symmetrized for identical particles

\[
\Psi_{-k^*}(r^*) = e^{i\delta_c} \sqrt{A_c(\eta)} \left[ e^{-ik^*r^*} F(-i\eta, 1, i\xi) + f_c(k^*) \tilde{G}(\rho, \eta)/r^* \right]
\]

Gamow factor \quad Coulomb part \quad Strong+Coulomb part

\[
\xi = k^* r^* + k^* r^* = \rho (1 + \cos(\theta^*)), \quad \rho = k^* r^*, \quad \eta = (k^* a)^{-1}, \quad a = (\mu z_1 z_2 e^2)^{-1}
\]

\[
F(k^*, r^*, \theta^*) = 1 + r^* (1 + \cos\theta^*)/a + (r^* (1 + \cos\theta^*)/a)^2 + i k^* r^* (1 + \cos\theta^*)^2/a + \ldots
\]

\theta^* is an angle between separation \( r^* \) and relative momentum \( k^* \)
Measuring space-time extent: femtoscopy

The Koonin-Pratt Equation

\[ C(\vec{q}) = \int S(r) |\Psi(\vec{q}, r)|^2 d^4 r = \langle |\Psi(\vec{q}, r)|^2 \rangle_{\text{pairs}} \]

- Use two-particle correlation, coming from the interaction \( \Psi \)
- Can be quantum statistics (HBT), coulomb and strong
- Try to invert the Koonin-Pratt eq. to learn \( S \) from known \( \Psi \) and measured \( C \)
What “size” do we measure?

• Source is described by $S$, which is usually taken as Gaussian:

$$S(x) \sim \exp \left( -\frac{x_o^2}{2R_o^2} - \frac{x_s^2}{2R_s^2} - \frac{x_l^2}{2R_l^2} \right)$$

• But the Koonin-Pratt (KP) equation takes the pair separations:

$$S(r) = \int S(x_1) S(r-x_1) \, d\,x_1 \sim \exp \left( -\frac{r_o^2}{4R_o^2} - \frac{r_s^2}{4R_s^2} - \frac{r_l^2}{4R_l^2} \right)$$

• For identical pions coulomb factor $K$ is factorized out, $\Psi$ is then $1+\cos(qr)$. Then KP gives the femtoscopic part of CF:

$$C_f = (1-\lambda) + \lambda K \left[ 1 + \exp \left( -R_o^2 q_o^2 - R_s^2 q_s^2 - R_l^2 q_l^2 \right) \right] B(q)$$

both $R$ and $q$ can be evaluated in several reference frames.

• The size $R$ measured in this way is a variance of single-particle emission function (emission probability distribution)
Refernce frames

- If statistics is sufficient (charged pions ...) the measurement can be done in 3 dimensions, giving 3 independent sizes
- The Longitudinally Co-Moving System is used
- The Bertsch-Pratt decomposition of $q$:
  - Long along the beam: sensitive to longitudinal dynamics and evolution time
  - Out along $k_T$: sensitive to geometrical size, emission time and space-time correlation
  - Side perpendicular to Long and Out: sensitive to geometrical size
- For analyses which are statistically challenged, the measurement is done in one dimension (giving only one size) in Pair Rest Frame

Longitudinally Co-Moving System (LCMS):

$$p_{1,\text{long}} = -p_{2,\text{long}}$$

The Koonin-Pratt Equation:

$$C(\vec{q}) = \int S(r) |\Psi(\vec{q}, r)|^2 d^4 r$$
Why is it called “HBT”? 

- In astronomy angular size of the star is measured via photon correlation vs. spatial separation of detectors.
- The momentum spread can be inferred, which is transformed into angular size of the star.
- The mathematical formalism is similar.
- The first measurement was done by Hanbury-Brown and Twiss – HBT!

Figure 1. Aerial photo and illustration of the original HBT apparatus. They have been extracted from Ref.[1].
Experimental procedure

- In experiment one measures the standard correlation function for pairs of **identified particles**, as a function of pair **relative momentum**:

\[
C_e(\vec{q}) = S(\vec{q})/B(\vec{q})
\]

- The “Signal” \( S \) is a distribution of pairs where both particles come from **the same event**, “background” \( B \) can be constructed in many ways. Most common is “event mixing” where the two particles come from **two different events**, similar in terms of single-particle acceptance.

- However a single “source size” is not very interesting, what really matters is the source **size dependence** on many variables: **collision system**, event **centrality**, collision **energy** and pair **transverse momentum**
How does it look like?

- Various shapes and momentum scales, depending on the pair type (interactions involved), collision system and energy, pair transverse momentum, etc.

\[ C_e(\vec{q}) = (1 - \lambda) + \lambda K(q)[1 + \exp(-R^2 q^2)] \]
Heavy Ion collision evolution

- HIC is expected to go through a QGP phase, where matter is strongly interacting – resulting in the development of collective motion.

- Radial flow dominates, with elliptic flow as azimuthal modification.

M. Chojnacki, W. Florkowski, PRC 74 (2006) 034905
Which collectivity do we seek?

- A collective component is a “common” velocity for all particles emitted close to each other.
- To that one adds “thermal” (random) velocity.
- We expect specific “common” velocity – radial direction, pointing outwards from the center.
Quantifying collectivity

Hydrodynamics produces collective flow: common velocity of all particles

\[
\langle v_{out} \rangle = \left\langle \frac{\vec{v}_T \cdot \vec{r}_T}{|\vec{r}_T|} \right\rangle, \quad \langle v_{side} \rangle = \left\langle \frac{\vec{v}_T \times \vec{r}_T}{|\vec{r}_T|} \right\rangle = 0
\]

The process drives the space-time evolution of the system

For non-central collisions differences between in-plane and out-of-plane velocities arise

Space and time azimuthal evolution closely connected.

Thermal emission from collective medium

- A particle emitted from a medium will have a collective velocity $\beta_f$ and a thermal (random) one $\beta_t$.

- As observed $p_T$ grows, the region from where such particles can be emitted gets smaller and shifted to the outside of the source.
A clear $m_T$ dependence is observed, for all femtoscopic radii and for all particle types: but is it hydrodynamic like? And can we tell?

Non-central collisions = elliptic flow

Elliptic flow is a sensitive probe of early dynamics – used as a primary evidence for hydrodynamics-like flows at RHIC.
Non-central collisions: azimuthal modulation of collectivity

anisotropic pressure gradients

• drives the emergence of elliptic flow ($v_2$)

• Space-time and momentum anisotropy connected: can they be described at the same time?

• Azimuthally sensitive femtoscopy measures the space-time asymmetry by measuring radii vs. reaction plane

• Specific oscillations are expected
Emission from the source vs. time

- Azimuthal anisotropy is self-quenching – evolving towards a spherical shape
- Observed shape is a multiplicity-weighted average


Time slices of 1 fm/c
Radii vs. reaction plane orientation

- Separate CFs are constructed for each orientations of pair $k_T$ vs. reaction plane

- Radii are extracted vs this angle, total dependence can be characterized by 7 parameters:

$$\begin{align*}
R_{\text{out}}^2 &= R_{\text{out},0}^2 + 2R_{\text{out},2}^2 \cos(2\phi_p) \\
R_{\text{side}}^2 &= R_{\text{side},0}^2 + 2R_{\text{side},2}^2 \cos(2\phi_p) \\
R_{\text{long}}^2 &= R_{\text{long},0}^2 + 2R_{\text{long},2}^2 \cos(2\phi_p) \\
R_{\text{out-side}} &= 2R_{\text{side-out}}^2 \sin(2\phi_p)
\end{align*}$$

- Experiment clearly sees an anisotropic source shape

\textit{e-Print Archives (nucl-ex/0312009)}
RHIC Hydro-HBT puzzle

First hydro calculations struggled to describe femtoscopic data: predicted too small $R_{\text{side}}$, too large $R_{\text{out}}$ – too long emission duration

No evidence of first order phase tr.

T. Hirano, K. Tsuda, nucl-th/0205043

U. Heinz, P. Kolb, hep-ph/0204061
Revisiting hydrodynamics assumptions

- Data in the momentum sector ($p_T$ spectra, elliptic flow) well described by hydrodynamics, why not in space-time?
- Usually initial conditions do not have initial flow at the start of hydrodynamics (~1 fm/c) – they should.
- Femtoscopy data rules out first order phase transition – smooth cross-over is needed.
- Resonance propagation and decay as well as particle rescattering after freeze-out need to be taken into account: similar in effects to viscosity.
Expectations for the LHC

- **Lessons from RHIC:**
  - "Pre-thermal flow": strong flows already at $\tau_0 = 1$ fm/c
  - EOS with no first-order phase transition
  - Careful treatment of resonances important

- **Extrapolating to the LHC:**
  - Longer evolution gives larger system $\rightarrow$ all of the 3D radii grow
  - Stronger radial flow $\rightarrow$ steeper $k_T$ radii dependence
  - Change of freeze-out shape $\rightarrow$ lower $R_{out}/R_{side}$ ratio
Comparing LHC to RHIC

• 30% increase in homogeneity lengths between most central RHIC and LHC
• Strong dependence of all radii on pair momentum, consistent with strong collective radial and longitudinal flow
• The $R_{\text{out}}/R_{\text{side}}$ ratio comparable or smaller than at RHIC: gives discriminating power to challenge models
• Only models tuned to reproduce RHIC data continue to work at the LHC
• All features expected from hydrodynamics extrapolation observed

ALICE Pb-Pb


$<k_T>$

$R_{\text{out}}/R_{\text{side}}$

$R_{\text{long}}$

$R_{\text{long}}/R_{\text{side}}$

$k_T$

$R_{\text{out}}$

$R_{\text{side}}$

$<k_T>$
Radii vs. centrality and $k_T$

Femtoscopic radii vs. $k_T$ for 7 centrality bins

Radii scaling factorizes into linear in multiplicity and power-law in $k_T$

Both dependencies in agreement with predictions from collective models (hydrodynamics)

Scaling similar to this seen at lower energies
Collectivity with heavier particles

- The $k_T$ dependence should be equally valid for heavier particles.
- The 3D $K^0_S$ results in central Pb-Pb consistent with collectivity (hydro) expectations.
Azimuthally sensitive HBT

- Measurement of pion radii vs. reaction plane orientation – important cross-check of azimuthal evolution. Directly comparable to STAR.
Clocking the evolution

• Final eccentricity comparable but smaller than at RHIC, as expected for longer evolution duration
• Qualitatively confirms hydro
pp collisions: radii vs. $k_T$

- $R_{\text{long}}$ falls with $k_T$ for all multiplicities
- $R_{\text{side}}$ flat with $k_T$ at lowest mult, develops dependence as mult increases
- $R_{\text{out}}$ dependence on $k_T$ evolves strongly with multiplicity and is steeply falling at top mult
- $R_{\text{out}}/R_{\text{side}}$ falls with multiplicity, goes significantly below 1.0
- Behavior in heavy-ions is not a simple scaling of pp, as suggested at RHIC
Looking for scaling variables

- 3D LCMS correlation decomposed into Spherical Harmonics, first 3 non-vanishing components shown

- Correlations vary with $dN_{ch}/d\eta$ and $k_T$, independent of $\sqrt{s}$

arXiv:1101.3665

![Graphs showing correlations with $q_{LCMS}$](image)
Comparison LHC vs. world

- $\langle k_T \rangle = 0.4$ GeV/c

ALICE preliminary

- pp and AA linear scaling clearly different, no simple pp/AA scaling
- ALICE PbPb $R_{\text{long}}$ in perfect agreement with world data
- ALICE PbPb $R_{\text{side}}$ in reasonable agreement with world data
- ALICE $R_{\text{out}}$ clearly below the linear scaling
- Behavior of all 3 radii in PbPb @ 2.76 TeV in qualitative agreement with hydrodynamical model expectations.
p-Pb like pp or PbPb?

- Hydrodynamics predicts that radii for pPb are consistent with PbPb scaling
- Important to compare the pp, pPb and PbPb results at similar multiplicity
- The GCG-type calculations predict size in pPb generally similar to that observed in pp
1D pPb from ALICE

- 1D analysis performed for pp, pPb and PbPb
- Uses 2-pion and 3-pion formalism, with different sensitivity to backgrounds
- pPb results approximately 10% higher than pp at similar multiplicity, up to 40% smaller than PbPb
- Comparing only LHC results, not “AA line” from lower energies
- No $k_T$ dependence, so hard to conclude on collectivity
3D pPb in ALICE

- Analysis in 3D is also sensitive to collectivity signatures
- pPb radii are 10% larger than pp at similar multiplicity in Side and Long, Out shows larger difference
- Hydro predictions are comparable to high-multiplicity pPb in Side and Long and overestimate Out
- $k_T$ dependence similar in models and data
3-pion correlations

- 3-pion cumulant extracts the genuine 3-particle correlation
- Has higher signal/background ratio
- Is sensitive to source size
- Is much more sensitive to coherent pion production than the 2-pion correlation

$0.16 < K_{T,3} < 1.0 \text{ GeV/c}$

$|\eta| < 0.8, 0.16 < p_T < 1.0 \text{ GeV/c}$

$\pi^+\pi^+\pi^+ \& \pi^-\pi^-\pi^-$ combined
Extracting coherent fraction

- The $r_3$ variable should approach 2 for $Q_3 \to 0$ for fully chaotic emission
- At low triplet momentum the extrapolated intercept is below 2, does not depend strongly on centrality
- At high triplet momentum the intercept is consistent with 2
- Deviation from theoretical limit of 2 consistent with up to 20% coherent pion production
Interpretation of 3-particle results

Biegun, Florkowski, Rybczyński; arXiv:1312.1487

- Other possible effect of coherent pion production: increase of pion multiplicity at low momentum
- Preliminary model calculations show intriguing effects in the low-$p_T$ region
- Are the two effects consistent and/or connected?
**Baryon femtoscopy**

\[ C(\vec{q}) = \int S(\vec{r}) |\Psi(\vec{q}, \vec{r})|^2 d^4 r \]

- For protons, cross-sections known, only radius can change
- For other (e.g. p\(\Lambda\), \(\Lambda\Lambda\)), the radius and the cross-section not known (or known with large uncertainties) → only one can be a free parameter
**pp and pp correlation functions**

- Correlation effect increases for more peripheral events - size decreases with decreasing multiplicity
- QS, Coulomb and Strong FSI – all contribute to measured correlations
- Possible to extract the source radius for heavy particles
$R_{inv}$ from proton femtoscopy

- Radii increase with multiplicity, higher $k_T$ gives smaller radii, consistent with hydro collectivity.
Annihilation in baryon-antibaryon correlations

- Deviation of proton yields from chemical models expectations
  - “rescattering” phase should be taken into account while determining yields
  - Steinheimer, Aichelin, Bleicher; arXiv:1203.5302
  - Karpenko, Sinyukov, Werner; arXiv:1204.5351
  - If true, annihilation must be seen in baryon-antibaryon correlations

(...switching $B\bar{B}$-annihilation on suppresses baryon yields, in the same time increases pion yield, thus lowering $p/\pi$ ratio to the value 0.052, which is quite close to the one measured by ALICE(...)

pp correlation functions

- Shape dominated by Coulomb and Strong FSI
- Wide negative correlation consistent with annihilation in the strong FSI
- Femtoscopic effect very wide, better statistical handle on the system size (compared to pp)
• Wide negative correlation observed, consistent with annihilation in the strong FSI
• Annihilation not limited to particle-antiparticle systems!
• Correlation strength increases with decreasing multiplicity (consistent with decrease of the system size)
• Quantitative analysis requires careful consideration of the residual correlations (feed-up from $pp$, correlations with $\Sigma^0$ and others)
Summary

• Femtoscopy is sensitive to system size (lengths of homogeneity) and collision dynamics

• Femtoscopy provides important constraints on system dynamics and Equation of State at RHIC and at the LHC

• Pion femtoscopy at the LHC consistent with predictions from hydrodynamics, constrained by RHIC data

• Radii in pp scale linearly with multiplicity, depend on momentum in non-trivial way, do not depend on energy, are different from PbPb

• Radii in pPb more similar to pp rather than PbPb, transverse momentum dependence similar to hydro

• Significant annihilation for BB systems observed (not limited to particle-antiparticle!), should provide better data on cross-sections for the rescattering codes and other fields