Space-time picture of the source in heavy-ion collisions from non-identical particle correlations

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Outline

- Extracting information from non-id femtoscopy: emission asymmetries and system size
- Importance of measuring asymmetries: direct evidence for collective matter behavior - radial flow aka space-momentum correlations
- Experimental results from RHIC
  - Analysis details – important corrections
  - Results for pion-kaon, pion-proton and kaon-proton
  - Comparing to hydrodynamics + statistical hadronization models
Non-identical particle correlations via the coulomb wave-function

\[ S(r) = \int S_a(r_1)S_b(r_2)\delta(r-(r_1-r_2))d^4r_1d^4r_2 \]

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

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

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

\( A_c(\eta) \) is the Gamow factor, and \( G \) is the combination of the regular and singular s-wave Coulomb func., \( f \) is the scattering amplitude

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

note the asymmetry with respect to \( \theta^* \).
Accessing asymmetry

Only particle momenta are measured

- One selects pairs basing on the angle \( \Psi \) between pair relative \((k^*)\) and average \((v)\) momenta

- Angles \( \Psi \) and \( \theta^* \) are connected through \( \phi \) - angle between pair velocity and space separation

- The average \( r^* \| v \) is the result of the asymmetry analysis

\[
k_{out}^* \equiv k^* \cos(\Psi)
\]
\[
k_{side}^* \equiv k^* \sin(\Psi)
\]

\[
\Psi = \phi + \theta^*
\]

\[
\cos(\Psi) = \cos(\phi) \cos(\theta^*) + \sin(\phi) \sin(\theta^*)
\]

\[
\text{sign}\left\langle \cos(\Psi) \right\rangle = \text{sign}\left\langle \cos(\phi) \right\rangle \text{sign}\left\langle \cos(\theta^*) \right\rangle
\]
Sensitivity to size and shift

- Coulomb correlation function shows sensitivity to the source size both in width and height of the effect (unlike identical particle correlations, where only width is affected).

- The “double ratio” shows monotonic sensitivity to the shift in average emission points: $\langle r^* \rangle$

$$C(\text{for } \cos(\Psi > 0))/C(\text{for } \cos(\Psi < 0))$$
CorrFit – getting quantitative

- One starts from two-particle emission function, which includes a possibility of non-zero mean separation (shift):
  \[ S(\hat{r}, \hat{K}) \sim \exp \left( -\frac{(r_{\text{out}} - \mu_{\text{out}})^2}{\sigma_{\text{out}}^2} - \frac{r_{\text{side}}^2}{\sigma_{\text{side}}^2} - \frac{r_{\text{long}}^2}{\sigma_{\text{long}}^2} \right), \]

- Then one numerically integrates it with particle momenta taken from the experiment, assuming a range of values of source radii. Best-fit radii are selected by finding which calculated CF describes the experimental one best.

\[ S(\hat{r}, \hat{K}) \sim \exp \left( -\frac{(r_{\text{out}}^* - \mu_{\text{out}})^2}{\sigma_{\text{out}}^2} - \frac{r_{\text{side}}^*}{\sigma_{\text{side}}^2} - \frac{r_{\text{long}}^*}{\sigma_{\text{long}}^2} \right), \]

\[ \chi^2 = \text{map} \]

\[ \text{best fit} \]
Advantages of binning in SH

- No need to keep a 3D histogram in memory – each function is kept as a vector of 1D histograms.
- More robust determination of the correlation function, because the method does not rely on the symmetries of the correlation function, which are valid for identical particles, but not for non-identical.
- Immune to the problem of “holes” in the 3D relative momentum acceptance. No need to fit a 3D correlation function to get a correlation in SH.
CF directly in spherical harmonics

- We have true pairs $T$ and mixed pairs $M$, which together give the correlation function $C$:
  \[ T(q) = C(q) M(q) \]
  where $T$, $M$ and $C$ can be represented as vectors of spherical harmonics components:
  \[ T_{lm}(q_n) = \frac{1}{N} \sum_{i=1}^{N} Y_{lm}^*(\Omega_{q_i}) \quad \text{for} \quad q_i \in \text{bin} \ q_n \]

- We want to minimize $\chi^2$:
  \[ (T - \tilde{M} C)^T (\Delta^2 T)^{-1} (T - \tilde{M} C) \]

- Which produces correlation function:
  \[ C = \Delta^2 C \tilde{M}^T (\Delta^2 T)^{-1} T \]
  and the covariance matrix
  \[ \Delta^2 C = (\tilde{M}^T (\Delta^2 T)^{-1} \tilde{M})^{-1} \]
CF representations: SH vs. traditional

correlation function in spherical harmonics

\[ c_0 \quad c_2^0 \quad c_2^1 \quad c_2^2 \quad c_3^0 \quad c_3^1 \quad c_3^2 \quad c_3^3 \]

real part \quad imaginary part

Must vanish

STAR preliminary double ratio(s)

correlation function

out
side
long

double ratio(s)
Space asymmetry from flow

- Transverse momentum of particles is composed of the thermal (randomly distributed) and flow (directed "outwards") components.
- For particles with large mass thermal motion matters less – they are shifted more in "out" direction. The difference is measured as emission asymmetry.
- Flow makes the source smaller ("size"-p correlation) AND shifted in outwards direction (x-p correlation).
- With no flow average emission point is at center of the source and the length of homogeneity is the whole source.
Origins of asymmetry – time shift

- Measures asymmetry in pair rest frame is a combination of time and space shifts in source frame
  \[
  \langle r_{out}^* \rangle = \gamma \left( \langle r_{out} \rangle - \beta t \langle \Delta t \rangle \right)
  \]

- In heavy-ion collisions one expects difference in emission time from resonance decays
Lhyquid+Therminator at RHIC

- Dynamical model with hydrodynamical evolution and strong resonance propagation
- Reproduces spectra, elliptic flow and HBT
- Includes all effects important for proper non-id asymmetry predictions

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Pion-Kaon correlation functions

- Correlation functions show expected correlation pattern
- Functions for same charge combinations are in very good agreement
- The agreement within the charge combination points to a very similar $K^+$ and $K^-$ emission mechanism

Size: $12.5 \pm 0.4 \pm 2.2$ syst. $-3.0$ syst. fm

Shift: $-5.6 \pm 0.6 \pm 1.9$ syst. $-1.3$ syst. fm

Fit assumes source is a gaussian in $r^*_{out}$

$k^* = |k^*_\pi| = |k^*_K|$ (GeV/c)
Double ratios

- Clear deviation from unity for Out – sign of asymmetry: pions are emitted closer to the center and/or later

- Side and Long – flat as expected (experimental cross-check)
STAR data at 200 AGeV

- We present STAR data from AuAu collisions at $\sqrt{s_{NN}}=200$ AGeV
- Only central data (0-10% total hadronic cross-section) ~ 1.8M events for two field orientations (important systematic cross-check)
- Pt range: pions 0.1 – 0.5 GeV, kaons: 0.3-0.9 GeV, protons 0.5-1.2 GeV, only primary tracks
- Anti-merging and anti-gamma-conversion cuts applied at pair level for all systems
Purity correction

- Pair purity consists of probabilities that:
  - given particle is correctly identified in the TPC
  - given particle is a primary particle
- The correlation function is corrected with:
  \[ C_{corrected} = \frac{(C_{raw} - 1)}{P + 1} \]
- Purity correction is critical, since the extracted radius is directly sensitive to it.
Momentum resolution

- Momentum resolution washes out correlation effect at small $k^*$
  - It is difficult to “unsmear” the experimental CF
  - Instead an experimental parameterization of the MR is introduced into model calculations
  - CF is affected only in first 2 bins, asymmetry in first 5
Pion-Kaon asymmetry – 200 AGeV

- Data: 1.8M central Au+Au events at $\sqrt{s_{NN}} = 200$ AGeV
- Clear emission asymmetry signal
- All charge combinations consistent
- Data with all corrections applied

The correlation function

The asymmetry signal

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Pion-Kaon vs. Therminator

- Data quantitatively consistent with the Therminator prediction
- Calculation done with momentum resolution taken into account

points: STAR data
tlines: calculations from Therminator model

\[ \pi^+ K^+ \quad \pi^- K^- \]
\[ \pi^+ K^- \quad \pi^- K^+ \]

STAR preliminary

Therminator predictions

**Re(C^2)**

**Re(C^2)**
Asymmetries in other directions

- CF asymmetries consistent with expectations:
  - physics effect: $\text{Re}\{C_1\}$ consistent and as expected
  - Cross-checks: $\text{Im}\{C_1\}$ and $\text{Re}\{C_1\}$ with trend consistent with remnants of pair merging and $e^+e^-$ pair from gamma conversions

Example pion-kaon C11 component of the CF for one field orientation

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Pion-proton correlations Year2

- Pion-proton shows consistent correlation effect
- Asymmetry qualitatively consistent with the flow picture
- Visible lambda peak, as expected both in correlation effect and asymmetry
**Pion-proton – comparing to Therminator**

STAR preliminary

**points:** STAR data
**lines:** calculations from Therminator model

Same sign

Opposite sign
Kaon-Proton at 200 AGeV

- Kaon-proton shows consistent correlation effect, including one coming from non-trivial strong interaction potential for opposite charge pairs
- Asymmetry does not show a definite trend, statistically limited
Kaon-proton fits

- STAR preliminary
- strong interaction effect understood

CF can be described by known interaction potentials
Kaon-proton – comparing to Therminator

- Relatively good agreement but measurement of asymmetry statistically limited

points: STAR data
lines: calculations from Therminator model
(only same sign due to model CF calculation limitations)
Summary

- Non-identical particle correlations provide crucial cross-check of the consistency of system evolution modeling, through the unique feature of measuring emission asymmetries.

- Corrections in data under control: purity, momentum resolution. New analysis techniques used (spherical harmonics) consistent with traditional representation.

- Clear asymmetry signal seen for pi-K and pi-p, asymmetry for K-p smaller, possibly consistent with 0.

- All systems are consistent with the hydrodynamics + statistical hadronization model.