Three-dimensional Kaon Source Extraction from STAR experiment at RHIC

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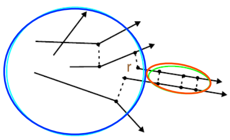
Abstract

Three-dimensional source imaging techniques in conjunction with detailed model comparisons have shown the viability of disentangling the spatio-temporal information contained in two-pion interferometric measurements from ultra-relativistic heavy ion collisions. This has led to the observation of non-Gaussian tails in the 3D pion source function and the extraction of finite pion emission duration at RHIC energies [1]. The STAR Collaboration has recently extracted the 3D kaon source function from a high statistics two-kaon interferometric measurement from Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. Such measurement offers a window into the fireball freeze-out dynamics with a much cleaner probe with smaller resonance decay contributions than for the pion case. The extracted space-time characteristics are compared with those obtained from pion analysis. Kaon emission is inferred to be instantaneous from a freeze-out hypersurface bearing no space-time correlation.

Motivation

Source imaging:
Model-independent femtoscopic technique of emission source shape extraction (beyond Gaussian assumption). D. Brown and P. Danielewicz [2].



Inversion of linear integral equation to obtain source function

1D Koonin-Pratt equation:

$$R(q) \equiv C(q) - 1 = 4\pi \int dr\, r^2 K(q,r) S(r)$$

- **Correlation function**
- **Kernel** (Encodes FSI)
- **Source function** (Distribution of pair separations in pair rest frame)

Freeze-out occurs after last scattering
⇒ Only Coulomb & QS effect included in the kernel: $K(q,r) = \frac{1}{2}\int d\cos\theta_{\vec{q},\vec{r}} \left[|\phi(\vec{q},\vec{r})|^2 - 1 \right]$

Inversion procedure: $S(r) = \sum_j S_j \cdot B_j(r)$ *Expansion into B-spline basis*

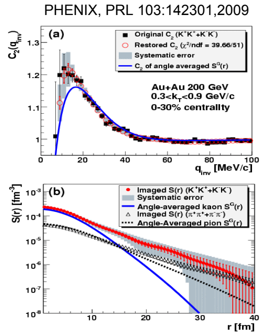
$$C^{Th}(q_i) = \sum_j K_{ij} \cdot S_j$$

$$K_{ij} = \int dr \cdot K(q_i,r) B_j(r)$$

$$\chi^2 = \frac{\left(C^{Expt}(q_i) - \sum_j K_{ij} \cdot S_j\right)^2}{\left(\Delta C^{Expt}(q_i)\right)^2}$$

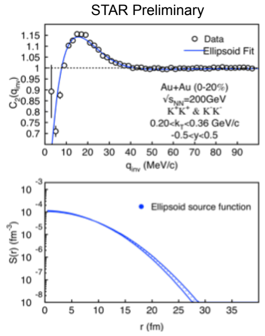
Kaon 1D source shape results

PHENIX, PRL 103:142301,2009



"… non-Gaussian tail in the kaon source reaffirms that the particle emission region … is extended, and that similar measurements with pions are not solely due to the decay of long-lived resonances." [3]

STAR Preliminary



STAR data are well described by Gaussian. Contrary to PHENIX result [3], no non-Gaussian tails are observed. Disagreement is probably due to a differenet k_T-range: STAR k_T-bin is about 4x narrower.

3D source shape analysis

Expansion of R(q) and S(r) in Cartesian Harmonics basis [4]

$$R(\vec{q}) = \sum_l \sum_{\alpha_1 \ldots \alpha_l} R^l_{\alpha_1 \ldots \alpha_l}(q)\, A^l_{\alpha_1 \ldots \alpha_l}(\Omega_q) \quad (1)$$

$$S(\vec{r}) = \sum_l \sum_{\alpha_1 \ldots \alpha_l} S^l_{\alpha_1 \ldots \alpha_l}(r)\, A^l_{\alpha_1 \ldots \alpha_l}(\Omega_r) \quad (2)$$

α_i = x, y or z
x = out-direction
y= side-direction
z = long-direction

- Cartesian surface-spherical harmonic are based on the products of unit vector components, $n_{\alpha 1}\, n_{\alpha 2}, \ldots, n_{\alpha \ell}$.
- Unlike the spherical harmonics they are real.
- Due to the normalization $n^2_x + n^2_y + n^2_z = 1$, at a given $\ell \geq 2$, the different component products are not linearly independent as functions of spherical angle.
- At a given ℓ, the products are spanned by spherical harmonics of rank $\ell' \leq \ell$, with ℓ′ of the same evenness as ℓ.

$$R(\vec{q}) = C(\vec{q}) - 1 = 4\pi \int dr^3 K(\vec{q},\vec{r}) S(\vec{r}) \quad (3)$$ 3D Koonin-Pratt eq.

Plug (1) & (2) into (3) ⇒ $R^l_{\alpha_1 \ldots \alpha_l}(q) = 4\pi \int dr\, r^2 K_l(q,r) S^l_{\alpha_1 \ldots \alpha_l}(r) \quad (4)$

Invert (1) ⇒ $R^l_{\alpha_1 \ldots \alpha_l}(q) = \frac{(2l+1)!!}{l!} \int \frac{d\Omega_q}{4\pi} A^l_{\alpha_1 \ldots \alpha_l}(\Omega_q) R(\vec{q})$

Invert (2) ⇒ $S^l_{\alpha_1 \ldots \alpha_l}(r) = \frac{(2l+1)!!}{l!} \int \frac{d\Omega_r}{4\pi} A^l_{\alpha_1 \ldots \alpha_l}(\Omega_r) S(\vec{r})$

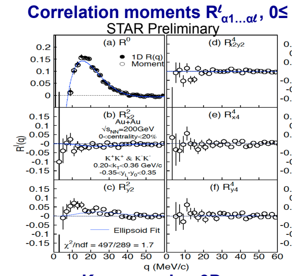
Fit to the 3D correlation function with a trial functional form for S(r).
Trial function: 4-parameter ellipsoid (3D Gaussian):

$$S^G(x,y,z) = \frac{\lambda}{(2\pi)^3 r_x r_y r_z} \exp\left[-\left(\frac{x^2}{4r_x^2} + \frac{y^2}{4r_y^2} + \frac{z^2}{4r_z^2} \right) \right]$$

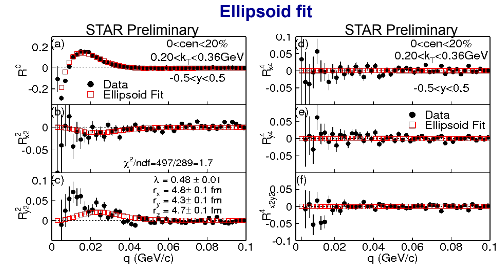
Since the 3D correlation function has been decomposed into its independent moments this is equivalent to a simultaneous fit of 6 independent moments with the trial functional form.

Kaon and pion 3D source shape results

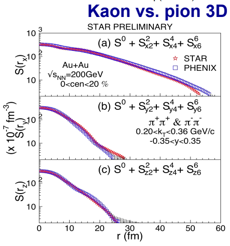
Correlation moments $R^{\ell}_{\alpha 1 \ldots \alpha \ell}$, $0 \leq \ell \leq 4$



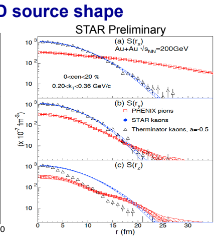
Ellipsoid fit



Kaon vs. pion 3D source shape



Good agreement on 3D pion source shape between PHENIX [1] and STAR.

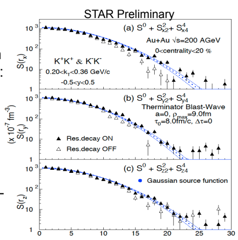


Pion [1] and kaon source shapes are very different: Is it due to different dynamics?

Comparison to the Thermintor model [5]

Model main ingredients:

1. Boost invariance in z.
2. Blast-wave expansion in transverse radius ρ: $v_r(\rho) = (\rho/\rho_{max})/(\rho/\rho_{max} + v_t)$. v_t =0.445: $\langle v_r \rangle \approx 0.6$ [6].
3. Thermal emission at proper time τ, from a cylinder of infinite length and finite transverse dimension ρ_{max}.
4. Emission duration included via $\Delta\tau$.



Freeze-out occurs at $\tau = \tau_0 + a\rho$. Particles which are emitted at (z, ρ) have LAB emission time $t^2 = (\tau_0 + a\rho)^2 + z^2$.

Reference

[1] S. Afanasiev et al. (PHENIX Collaboration), Phys. Rev. Lett.100:232301, 2008.
[2] D. Brown and P. Danielewicz, Phys. Lett. B398:252, 1997; Phys. Rev. C57:2474,1998.
[3]] S. Afanasiev et al. (PHENIX Collaboration) Phys. Rev. Lett. 103:142301, 2009.
[4] P. Danielewicz and S. Pratt, Phys. Lett. B618:60, 2005.
[5] A. Kisiel *et al.*, Phys. Rev. C 73:064902 2006).
[6] B. I. Abelev et al. (STAR Collaboration), Phys. Rev. C79:034909, 2009.

Summary

1. STAR high-statistics measurements allowed first model-independent extraction of kaon three dimensional source function.
2. The source function of mid-rapidity, low-momentum kaons from central Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV obtained via Cartesian surface-spherical harmonic decomposition method is essentially ellipsoidal in shape. No long-range non-Gaussian tails are observed.
3. Comparison with Therminator model calculations indicates that kaons are emitted from a fireball whose transverse dimension and lifetime are consistent with those extracted with two-pion interferometry.
4. Contrary to a substantial emission duration and a negative ρ−τ correlation observed for pions [1], kaons are emitted instantaneously in the source element rest frame from a freeze-out hypersurface with no ρ−τ correlation.
5. Kaons and pions may be subjected to different dynamics owing to their emission over different timescales.