Source Imaging of Two-Pion Correlations

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STAR

Experiment

Source imaging

Theory

$\text{Au} + \text{Au}$, energy $\sqrt{s_{NN}} = 200$ GeV
$\text{Cu} + \text{Cu}$, energy $\sqrt{s_{NN}} = 200$ GeV

$\pi^+ \pi^-$ scattering lengths

Theory

$\text{Au} + \text{Au}$ 40–80%, Coulomb + Strong FSI
The aim is to understand the space-time development of heavy ion collision.

Femtoscopic measurements $\Rightarrow$ probe space-time characteristics and dynamics of the particle emitting source.

Try an alternative approach to study non-Gaussian source $\Rightarrow$ Source imaging

Extract the $\pi^+\pi^-$ scattering lengths from fit to the non-identical pion correlations.
STAR experiment

- **Au+Au collisions at energy** $\sqrt{s_{NN}} = 200$ GeV
  - Data taken in 4th RHIC run (2003–04)

- **Cu+Cu collisions at energy** $\sqrt{s_{NN}} = 200$ GeV
  - Data taken in 5th RHIC run (2004–05)
Source imaging — theory basics

- Model independent technique
- Task of imaging is to determine the source $S(r)$ from data with errors $C(q)$ by inverting the Koonin-Pratt integral equation:

$$R(q) = C(q) - 1 = 4\pi \int dr \, r^2 (|\Phi_q^{-}(r)|^2 - 1) S(r)$$

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

requires inversion of kernel $K(q, r)$

$\Phi_q^{-}(r)$ → describes propagation of pion pair from source to detector

$S(r)$ → source function, distribution of relative emission points in pair CMS frame

- Inversion procedure in matrix form, expansion in $B$-spline basis:

$$S(r) = \sum_j S_j B_j(r) \quad R_i^{Th} = \sum_j K_{ij} S_j \quad K_{ij} = 4\pi \int dr \, r^2 K(q, r) B_j(r)$$

vary $S_j$ to minimize $\chi^2 = \sum_i \frac{(R_i - R_i^{Th})^2}{\Delta^2 R_i}$

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1 D. Brown, P. Danielewicz, Phys. Lett. B 398, 252 (1997); HBTprogs, brown170@llnl.gov

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Au+Au — comparing STAR data to PHENIX

**STAR**

Au+Au, 0–10% \( k_T: 0.45–0.60 \) GeV/c

**PHENIX**

Au+Au, 0–20% \( k_T: 0.48–0.60 \) GeV/c

**PHENIX**

Au+Au, 0–20% \( k_T: 0.48–0.60 \) GeV/c

2 nucl-ex/0605032
Au+Au — centrality dependence, Gaussian fit

Centrality: 0–10%

Centrality: 10–40%

Centrality: 40–80%

Source imaging

Au+Au, energy $\sqrt{s_{NN}} = 200$ GeV

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September 26, 2007
Source imaging

**Au+Au — \( k_T \) dependence, Gaussian fit**

**Centrality:**

- **0–10%**
- **10–40%**
- **40–80%**

**STAR PRELIMINARY**

Au+Au 200 GeV, Cent10%

**STAR PRELIMINARY**

Au+Au 200 GeV, Cent10%

**STAR PRELIMINARY**

Au+Au 200 GeV, Cent40%

**STAR PRELIMINARY**

Au+Au 200 GeV, Cent80%

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Source imaging of Two-Pion Correlations

Cu+Cu — centrality dependence, Gaussian fit

Centrality:

0–10%

10–40%

40–60%

Cu+Cu @ 200 GeV

STAR PRELIMINARY

Data

Restored

r (fm)

0 5 10 15 20 25

$S (\text{fm}^3)$

$\lambda = 0.296 \pm 0.001$

$R_G = 4.47 \pm 0.01 \text{ fm}$

$\lambda = 0.290 \pm 0.001$

$R_G = 3.46 \pm 0.01 \text{ fm}$

$\lambda = 0.303 \pm 0.002$

$R_G = 2.47 \pm 0.01 \text{ fm}$
Source imaging

Cu+Cu, energy $\sqrt{s_{NN}} = 200$ GeV

Cu+Cu $- k_T$ dependence, Gaussian fit

Centrality: 0–10%

Centrality: 10–40%

Centrality: 40–60%

STAR PRELIMINARY

kt1 (125,250) MeV/c

Restored kt1

kt2 (250,350) MeV/c

Restored kt2

kt3 (350,450) MeV/c

Restored kt3

kt4 (450,600) MeV/c

Restored kt4

Cu+Cu @ 200 GeV, Cent10%

Cu+Cu @ 200 GeV, Cent1040%

Cu+Cu @ 200 GeV, Cent4060%

S (fm$^{-3}$)

r (fm)

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\( \pi^+ \pi^- \) scattering lengths — theory basics

- \( \pi^+ \pi^- \) correlations \( \implies \) Coulomb and Strong FSI.
  \[ C(k^*, r^*) = A_c(\eta) \left[ 1 + 2 \frac{r^*}{a} + 2 \frac{f_0}{r^*} \right] \]

- FSI are sensitive to source size \( r^* \) and scattering amplitude \( f \)
  \[ f_0 = \frac{1}{3} (2a_0^0 + a_0^2) \approx 0.2 \text{ fm} \]

- Scattering lengths fitting code by F. Retiere, where the theoretical \( C(k^*, r^*) \) is calculated via FSI weights by R. Lednický

- Source image — distribution of relative emission points — is an input to FSI weights.

- Fit theoretical \( \pi^+ \pi^- \) correlation function to measured data
  \( \implies \) vary \( a_0^0, a_0^2 \) to minimize
  \[ \chi^2 = \sum_i \frac{(C_i - C_{i}^{\text{Th}})^2}{\Delta^2 C_i} \]
Summary of experimental situation for $a_0^0$, $a_0^2$

- DIRAC ($A_{2\pi} : \pi^+\pi^- \rightarrow \pi^0\pi^0$) $\Rightarrow \frac{1}{\tau_{A_{2\pi}}} \sim (a_0^0 - a_0^2)^2$
- NA48/2 ($K_{3\pi} : K^\pm \rightarrow \pi^0\pi^0\pi^\pm$) $\Rightarrow (a_0^0 - a_0^2)$
- E865, NA48/2 ($K_{e4} : K^\pm \rightarrow \pi^+\pi^-e^\pm\nu) \Rightarrow a_0^0$
- TRIUMF ($\pi^+p \rightarrow \pi^+\pi^+n$) $\Rightarrow a_0^2$

ChPT prediction
(Colangelo, Gasser, Leutwyler, hep-ph/0007112)

$$a_0^0 = 0.220 \pm 0.005 [m_\pi^{-1}]$$
$$a_0^2 = -0.0444 \pm 0.0010 [m_\pi^{-1}]$$
$$a_0^0 - a_0^2 = -0.265 \pm 0.004 [m_\pi^{-1}]$$
$\pi^+ \pi^-$ scattering lengths

Au+Au, energy $\sqrt{s_{NN}} = 200$ GeV

$\pi^+ \pi^-$ correlations — Au+Au, 40–80%

$k_T$: 0.125–0.250 GeV/c

- PRELIMINARY results
- Coulomb + Strong FSI fit to data
- vary $a_0^0, a_0^2$ $\rightarrow$ $\chi^2$ map

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$\pi^+\pi^-$ scattering lengths

Au+Au, energy $\sqrt{s_{\text{NN}}} = 200$ GeV

$\pi^+\pi^-$ correlations — Au+Au, 40–80%

$k_T$: 0.250–0.350 GeV/c

- PRELIMINARY results
- Coulomb + Strong FSI fit to data →
- vary $a_0^0$, $a_0^2$ → $\chi^2$ map

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$\pi^+\pi^-$ scattering lengths

$\sqrt{s_{NN}} = 200$ GeV

$\pi^+\pi^-$ correlations — Au+Au, 40–80%

$k_T$: 0.350–0.450 GeV/c

- PRELIMINARY results
- Coulomb + Strong FSI fit to data $\rightarrow$
- vary $a_0^0$, $a_0^2$ $\rightarrow$ $\chi^2$ map

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\[ \pi^+ \pi^- \text{ scattering lengths} \quad \text{Au+Au, energy } \sqrt{s_{\text{NN}}} = 200 \text{ GeV} \]

**\[ \pi^+ \pi^- \text{ correlations — Au+Au, 40–80\%} \]**

\[ k_T: 0.450–0.600 \text{ GeV/c} \]

- PRELIMINARY results
- Coulomb + Strong FSI fit to data ➔
- vary \( a_0^0, a_0^2 \) ➔ \( \chi^2 \) map

\[ C \text{ (GeV/c)}^{-1} q \]

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Summary

- Source imaging provides close fit to measured correlation $C(q_{\text{inv}})$ of identical charged pions produced in $\text{Au}+\text{Au}$ and $\text{Cu}+\text{Cu}$ collisions at energy $\sqrt{s_{\text{NN}}} = 200$ GeV.
- Centrality and $k_T$ dependence of source functions is studied with useful accuracy in relative pion separation out to about 20 fm.
- Source functions cannot be described by a simple Gaussian due to the substantially wider tail of relative pion separation distribution.
- The origins of the non-Gaussian source tail need to be examined by comparing different systems, $\text{Au}+\text{Au}$ and $\text{Cu}+\text{Cu}$.
- Small and compact source seen at high-$k_T$ in $\text{Au}+\text{Au}$ peripheral collisions seems to be a good candidate to fit scattering lengths $a_0^0, a_0^2$.

Thank you.
Event and Track selection criteria

- **Event cuts**
  - Centrality = \{0–10, 10–40, 40–80(60)\}\% of total hadronic cross-section

- **Track cuts**
  - Select pion \( dE/dx \) band \( \pm 2\sigma \)
  - \( p_T = \{0.125, 1.000\} \text{ GeV/c} \)
  - \( y = \{-0.8, 0.8\} \)

- **Pair cuts**
  - Identical pions \( \{\pi^+\pi^+, \pi^-\pi^-\} \)
  - \( k_T = \frac{1}{2}(p_{T1} + p_{T2}) = \{0.125, 0.600\} \text{ GeV/c} \)
  - anti-splitting, anti-merging