π-Ξ correlations at RHIC

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Physics motivation

**Quark Gluon Plasma:** Deconfined and thermalized state of quarks and gluons

- Equilibration:
  - hadron yields

- Partonic Collectivity:
  - Spectra of multi-strange baryons

- Thermalization:
  - heavy-quark flow
  - (thermal photons, di-leptons)

**nucleus**

**Compress**

**Heat**

**nucleon boundary irrelevant**

**QGP**
Experiments at RHIC
• Solenoidal field
• TPC’s, ToF, SVT, PMD, EMC’s

• Measurements of hadronic observables using a large acceptance
• Event-by-event analyses of hadrons
• Jets
STAR event

Central event of

Au+Au at $\sqrt{s_{NN}} \approx 130$ GeV

Particle identification via energy loss in TPC
Ultra-relativistic Au-Au collision

Pre-Equilibrated

QGP ?

Hadronization

Chemical Freeze-out

Thermal Freeze-out

Equilibrated ?

Thermalized ?

Partonic dof

Partonic Collectivity ?

Hadron Interactions
The Phase Transition in the Laboratory

Hydrodynamic Evolution

- Hadron Formation
- Pre-Hadronic Phase
- Hadron Gas
- Mixed Phase
- QGP
- Pre-Equilibrium Phase ($< \tau_0$)
- Freezing Out
- Chemical Freezing Out

a) without QGP
b) with QGP

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Expansion of the fireball:
higher pressure gradient in the reaction plane
ellipsoidal to spherical shape evolution

\[ \tau - \tau_0 = 3.2 \text{ fm/c} \]

\[ \tau - \tau_0 = 8 \text{ fm/c} \]
Femtoscopy in heavy ion collisions

• Measuring size, shape and life-time
• Long lifetime – sign of phase transition
• Learn about dynamics from the freeze-out shape

\[ \tau - \tau_0 = 3.2 \text{ fm/c} \]

\[ \tau - \tau_0 = 8 \text{ fm/c} \]

d hyper evolution

later hadronic stage?
Two particle correlations

relating correlation in p-space of final products to source space-time properties

\[ \vec{k} = \frac{\vec{p}_1 + \vec{p}_2}{2} \]

\[ \vec{k}_1^* = -\vec{k}_2^* \]

particle momenta in pair rest frame

Small \( k^* \) coincides with small relative velocity

\[
C(k^*, k) = \frac{P(p_1, p_2)}{P(p_1)P(p_2)} = \frac{\text{real event pairs}}{\text{mixed pairs}}
\]

Final-state effects (Coulomb, strong) will cause correlations
HBT in Au+Au at $\sqrt{s} = 200$ GeV

Significant dependence of HBT radii on $m_T$
Results from azimuthally sensitive two-pion HBT

- Clear oscillations observed at all $k_T$

Even at freeze-out source remains elongated in the out of plane direction. Evolution time not long enough to make the source round.
Non central collisions: Interaction between constituents $\Rightarrow$ pressure gradient $\Rightarrow$ spatial asymmetry converted in an asymmetry in the momentum phase space.

Anisotropy parameter, $v_2$

$$v_2 = \langle \cos 2\phi \rangle, \quad \phi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

$$\mathcal{E} = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

$$\frac{d^3N}{dp_t\ dy\ d\phi} = \frac{d^2N}{dp_t\ dy} \frac{1}{2\pi} (1 + 2v_1 \cos(\phi) + 2v_2 \cos(2\phi) + \ldots)$$

$v_2$ sensitive to the initial stage of the collision so to parton rescattering in the hot and dense medium.
small hadronic cross-section, yet...

- Rapidly expanding source - “fireball” explosion
- Multi-strange baryons decouple earlier
- If flow created at an early partonic stage, MSB must show significant elliptic flow (v_2)

π, K, p: common thermal freeze-out:

T~90 MeV, <β⊥>~0.60 c

Ξ, Ω: Different thermal FO behavior:

T~150 MeV, <β⊥>~0.47c
Non-identical particle correlations

alternative way to “classical HBT” of studying space-time properties of the emission source relative to other particle species.

study effects of flow for different particles.

learn about dynamics via source properties at freeze-out

study final state effects - Coulomb and strong interaction
Final state interaction in $\pi-\Xi$

Interaction dominated by Coulomb $\Rightarrow$ can be calculated Using Scott Pratt's algorithm (Phys.Rep. C68, 054901(2003))

$$C(\vec{v}, \vec{k}^*) = \int g(\vec{v}, \vec{r})|\psi(\vec{k}^*, \vec{r})| \, d^3r$$

$$g(\vec{v}, \vec{r}) = \int S_\pi(\vec{v}, x_\pi) S_\Xi(\vec{v}, x_\Xi) \delta^3(\vec{x}_\pi - \vec{x}_\Xi - \vec{r}) \, d^4x_\pi d^4x_\Xi$$

$\vec{v}$ ...pair's center of mass velocity

$\vec{r}$ ...particle separation distance in pair's center of mass frame

$S(\vec{v}, x)$ ...single particle emission function

We must know the two-particle wave function $\psi(\vec{k}^*, \vec{r})$

Final correlation function depends on relative source sizes and space-time shift of the sources.
\( \Xi \) reconstruction

- **STAR** detects charged hadrons, using dE/dx for PID.

- **allows to reconstruct** \( \Xi^- , \Xi^+ \) **using topological cuts**, decaying into charged particles:

\[
\Xi^- \rightarrow \pi^- + \Lambda^0 ; \quad \Lambda^0 \rightarrow \pi^- + p
\]

\[
\Xi^+ \rightarrow \pi^+ + \Lambda^0 ; \quad \Lambda^0 \rightarrow \pi^+ + p
\]
Data from RHIC's year 2004 high statistics AuAu run.

Data corrected for $\pi$ and $\Xi$ sample purities.

Coulomb and strong ($\Xi^* 1530$) final state interaction effects present.

Centrality dependence observed, particularly strong in the $\Xi^*$ region.
\( \pi - \Xi \) systematics

\( \pi - \Xi \) CF measured for the first time in 62GeV AuAu and 200GeV dAu collisions

No significant energy dependence

Strong system dependence

No significant energy dependence

Strong system dependence
Effects of transverse flow (explosion)

Correlation between momentum and emission point

Effective reduction of source size and shift in average emission point

Effect increases with $m_T$

Non-identical correlations can test flow by measuring sizes and shifts of the sources

Emission points from Blastwave

$\beta t = 0.73$ for all species

Pion

$pt = 0.15$ GeV/c

Proton

$pt = 1.0$ GeV/c

$\Xi^-$

$pt = 1.4$ GeV/c

$\Omega^-$

$pt = 1.8$ GeV/c
Shifts in average emission point between two particle-species

- Study emission asymmetries with final-state interactions
  - Strong radial flow induces species-dependent x-p correlations

<table>
<thead>
<tr>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle emitted closer to center is <strong>slower</strong></td>
<td>Particle emitted closer to center is <strong>faster</strong></td>
</tr>
<tr>
<td>- Effective interaction time <strong>shorter</strong></td>
<td>- Effective interaction time <strong>larger</strong></td>
</tr>
<tr>
<td>- Weaker correlation</td>
<td>- Stronger correlation</td>
</tr>
</tbody>
</table>

- The two cases can be discriminated
  - Two correlation functions: “lighter particle faster”, “lighter particle slower”
  - Compare correlation strength of two CF’s
Spherical harmonics decomposition

\[
A_{l,m}(|\vec{k}^*|) = \frac{\Delta \cos \theta \Delta \phi}{\sqrt{4\pi}} \sum_{i}^{} Y_{l,m}(\theta_i, \phi_i) C(|\vec{k}^*|, \cos \theta_i, \phi_i)
\]

Testing symmetry in \( k^* \) space by decomposition of CF into spherical harmonics

Different \( A_{lm} \) coefficients correspond to different symmetries of the source

\( A_{00} \) - angularly averaged CF

\( A_{11} \) to study shift in \( R_{out} \) direction
Accessing shift between sources

$A_{11} \neq 0$ in Coulomb and strong region

Shift in the average emission point between $\pi - \Xi$

STAR preliminary
Model comparison

Model:
- \textit{Emission points from:}
  - Blastwave: constrained by $\pi-\pi$ HBT
  - RQMD

Difference between measured and calculated CF under investigation
- Observed \textit{shift agrees qualitatively with flow scenario}. 
Remaining technical challenges

- Non-flat baseline issue
- Wide $k^*$ structure in CF
  - possible source: flow, detector
  - effects currently being investigated
- Using fake $\Xi$s to construct correlation function with similar baseline behaviour for corrections

![Graph 1](image1.png)

$$C(k^*)$$

![Graph 2](image2.png)

$$\pi^+\pi^- 200\text{GeV AuAu}$$

10-40% central
- true CF
- fake CF

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fake $\Xi$s

![Graph 3](image3.png)

$$C(k^*)^{-1}$$

$$\pi^+\pi^- 200\text{GeV AuAu} \text{- subtracted}$$

10-40% central
- $k^*\text{sign}(k_{out}) > 0$
- $k^*\text{sign}(k_{out}) < 0$

STAR preliminary
Conclusions

- **First high statistics measurements of** $\pi$−$\Xi$ **correlations in 200 and 62 GeV AuAu and 200 GeV dAu collisions were presented.**

- **Coulomb and strong FSI were observed.**

- **Very good sensitivity to source size in $\Xi^*$ peak was found.** Theoretical input needed.

- **Using new spherical harmonics representation of data we observe clear shift between average emission points of** $\pi$ **and $\Xi$ sources in qualitative agreement with transversally expanding source.**

- **Results presented at Quark Matter 2005 in Budapest**
Analyzed data

200GeV AuAu

10.7M minimum bias + central events

Three centrality bins:

0-10%  ~ 60k Ξ
10-40% ~ 17k Ξ
40-80% ~ 5k Ξ

62GeV AuAu

12.7M minimum bias events

Three centrality bins:

0-10%  ~ 24k Ξ
10-40% ~ 68k Ξ
40-80% ~ 24k Ξ

Statistics insufficient for constructing $C_+(k^*)/C_-(k^*)$ ratio to directly compare π and Ξ source shifts. Available only $C(k^*)$. 

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STAR preliminary
"pion faster" shows stronger correlation
pions on average emitted nearer to source center
Arises naturally in collective expansion picture

Similar studies are underway for many particle combinations

Exotic correlations like $\Xi$-$\pi$ can yield information about nature of $\Xi$ flow
Little summary

• System undergoing rapid expansion ~ 0.6c.

• Single particle $p_T$ spectra well reproduced within hydro model.

• Suggesting collective behaviour is built on partonic as well as hadronic level

• Multistrange particles seem to decouple early after chemical freezeout

• !! Hydro models need time to build the collective behaviour, predicting long emission time and large sources.
Hydrodynamics and Description of Thermal Spectra

- Final state spectra at Thermal Freeze-Out can be modeled by ideal hydrodynamics.

Especially mass dependence with:

- "temperature" $T_{\text{kin}}$
- collective radial (transverse) flow $\beta_T$

purely thermal source

explosive source

$m_T$ $dN/dm_T$

light

1/$m_T$ $dN/dm_T$

heavy

$1/m_T dN/dm_T$

Central Au+Au
\[ \sqrt{s} = 200 \text{ GeV} \]
Coalescence: possible mechanism at intermediate $p_T$

- The **in vacuo fragmentation** of a high momentum quark to produce hadrons competes with the **in medium recombination** of lower momentum quarks to produce hadrons.

Example:

- **Fragmentation: $D_q \rightarrow h(z)$**
  - produces a 6 GeV/c $\pi$ from a 10 GeV/c quark

- **Recombination:**
  - produces a 6 GeV/c $\pi$ from *two* 3 GeV/c quarks
  - produces a 6 GeV/c proton from *three* 2 GeV/c quarks

...requires the assumption of a thermalized parton phase... (which) may be appropriately called a quark-gluon plasma.

Particle identification

- Charged particles at mid-rapidity via dE/dx in TPC
  \[ \pi: y=\{-0.5, 0.5\} \]
  \[ p_t=\{150, 800\} \text{ MeV/c} \]

- Topological reconstruction of \( \Xi^\pm \)
  \[ \Xi\Xi \rightarrow \pi\pi + \Lambda \; ; \; \Lambda\Lambda \rightarrow \pi + p \]
  \[ \Xi: p_t=\{1, 3\} \text{ GeV/c} \]
Early freeze-out?

- Is this due to early freeze-out? (Could we tell?)

- Competing changes – small overall effect

- Assumed early freeze-out scenario – small effect on CF

<table>
<thead>
<tr>
<th>BW parameters</th>
<th>$\pi$</th>
<th>$\Xi$</th>
<th>$\Xi$ early freeze-out</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$ [MeV]</td>
<td>103</td>
<td>103</td>
<td>150</td>
</tr>
<tr>
<td>$\rho$</td>
<td>0.93</td>
<td>0.93</td>
<td>0.75</td>
</tr>
<tr>
<td>$R$ [fm]</td>
<td>10.3</td>
<td>10.3</td>
<td>9</td>
</tr>
<tr>
<td>$\tau$ [fm]</td>
<td>6.9</td>
<td>6.9</td>
<td>5</td>
</tr>
<tr>
<td>$\Delta \tau$ [fm]</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
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