Azimuthally-Sensitive Two-Pion Interferometry in U+U Collisions

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for the STAR Collaboration
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Outline

- Shape selection in U+U
- 2\textsuperscript{nd} order femtoscopy
- Data Set
- Results
- Conclusions
Why Uranium?

Uranium's prolate shape gives a variety of initial geometries at *zero impact parameter*!

- Lead (spherical)
- Gold (slightly oblate)
- Uranium (prolate)

**Body-Body**  
Fewer nucleon-nucleon scatterings

**Tip-Tip**  
More nucleon-nucleon scatterings

**Arbitrary Orientation**  
Do not want!
Shape selection in U+U?

U+U Collision

Incoming Nuclei (Side View) Initial Geometry (Front View)

“Fully” Overlapping

# of spectator neutrons (per side)

<table>
<thead>
<tr>
<th>ZDC Centrality</th>
<th>U+U</th>
<th>Au+Au</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.125%</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>0.25%</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>0.5%</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>1.0%</td>
<td>12</td>
<td>8</td>
</tr>
<tr>
<td>2.0%</td>
<td>17</td>
<td>12</td>
</tr>
</tbody>
</table>

Use zero-degree calorimeters to cut out unwanted event classes

Non-central (Side View) Tip-on-Body (Side View) Crossed Events (Front View)

H. Wang, QM2014
Shape selection in U+U?

U+U Collision

Incoming Nuclei (Side View)  Initial Geometry (Front View)

"Fully" Overlapping

Use zero-degree calorimeters to cut out unwanted event classes

- Non-central (Side View)
- Tip-on-Body (Side View)
- Crossed Events (Front View)

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<tr>
<td>Large Flow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Multiplicity</td>
<td>0.125%</td>
<td>6</td>
</tr>
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Shape selection in U+U?

- At 1%, Au and U look similar: *impact parameter fluctuations?*
- At 0.1%, Au and U separate: *shape selection?*
Azimuthal Femtoscopy

- Femtoscopy probes 3D shape of homogeneity regions

- Determine 3 length scales: $R_{out}^2$, $R_{side}^2$, $R_{long}^2$, and the transverse correlation $R_{os}^2$

- Form correlation functions in terms of relative momentum of pairs of tracks

$$C(q) = \frac{N_{same}(q)}{N_{mixed}(q)}$$

$q = p_1 - p_2$

- Fit correlation function assuming a Gaussian emission function

$$C(q) = N((1 - \lambda) + \lambda K(q) G)$$

$$G \equiv e^{-\left(R_{out}^2 q_{out}^2 + R_{side}^2 q_{side}^2 + R_{long}^2 q_{long}^2 + 2 R_{os}^2 q_{out} q_{side}\right)}$$

- 6 Fit Parameters
  - $N$ - normalization
  - $\lambda$ – fraction of correlated pairs
  - $R_{out}^2$, $R_{side}^2$, $R_{long}^2$, $R_{os}^2$

- $K(q)$ – Coulomb correction factor

$q$ measured in Longitudinally Co-Moving System (LCMS): $p_{1,z} + p_{2,z} = 0$
Azimuthal Femtoscopy

- Length scales oscillate as source is viewed from different angles
- Magnitude of oscillation provides eccentricity

\[ \varepsilon_f \equiv \frac{R_y^2 - R_x^2}{R_y^2 + R_x^2} \approx 2 \frac{R_{s,2}^2}{R_{s,0}^2} \]
Azimuthal Femtoscopy

Look at two main observables:

\[ \varepsilon_f \sim \text{freezeout eccentricity} \]

\[ R_{\text{long}}^2 \sim \text{Tip-Tip: Longer lifetime} \to R_{\text{long}}^2 \]

\[ \varepsilon_f \equiv \frac{R_y}{R_x} \frac{R_x}{R_y + R_x} \approx 2 \frac{R_{S,2}}{R_{S,0}} \]
Time Projection Chamber
- Using for particle identification, tracking, and event plane determination
- Full $2\pi$ coverage
- Efficient tracking for $p_T > \sim 0.2 \text{ GeV}/c$

Zero-degree Calorimeters
- Using for centrality determination
- Four bins: 0 – 1.0\%
Data Set and Cuts

- 7M 1% ZDC triggered events ("fully overlapping") after basic event cuts
- Five bins in multiplicity
- Five bins in reduced flow parameter, $q_2$

### Event Cuts
- $|V_z| < 30$ cm
- $V_R < 2.0$ cm

### Track Cuts
- $|\eta| < 0.75$
- $0.15$ GeV/c < $p_T$ < $0.8$ GeV/c
- $|n\sigma_{\text{pion}}| < 2$
- $|n\sigma_{\text{other}}| > 2$
- $N_{\text{hits}} > 15$
- DCA < 3 cm

### Pair Cuts
- $0.15$ GeV/c < $k_T$ < $0.6$ GeV/c
- $-0.5 < \text{"Quality cut"} < 0.6$
- Max fraction of merged rows: 0.1

\[
q_{2,x} = \frac{1}{\sqrt{M}} \sum_{i=1}^{M} \cos 2\phi_i
\]
\[
q_{2,y} = \frac{1}{\sqrt{M}} \sum_{i=1}^{M} \sin 2\phi_i
\]
Results – Oscillating Radii

\[ 0 < q_2 < 0.5 \mid 0.00\% < Z_{dc} < 0.25\% \]

- Clear 2\textsuperscript{nd} order oscillation in \textit{transverse radii}
- Get \textit{freeze out eccentricity} from \( R_{\text{side}}^2 \)

\[ \varepsilon_f \equiv \frac{R_y^2 - R_x^2}{R_y^2 + R_x^2} \approx 2 \frac{R_{s,2}^2}{R_{s,0}^2} \]
Results – Multiplicity dependence

- No clear signal in eccentricity vs. multiplicity
- $R^2_{\text{long}}$ goes the right way, but could be trivial dependence

More initial energy density gives higher mult and larger $R^2_{\text{long}}$ without shape selection
Results – $q_2$ dependence

- No clear signal in eccentricity vs. $q_2$, though scatter decreases with tighter cuts on ZDC

- $R^2_{\text{long}}$ follows trend one might expect

Body-Body events should have more flow and smaller $R^2_{\text{long}}$
Conclusions

- Definite 2\textsuperscript{nd} order signal for femtoscopic radii
- Multiplicity:
  - No systematic trends in freeze out eccentricity
  - $R_{\text{long}}^2$ can be explained without invoking shape selection
- $q_2$:
  - No clear signal in freeze out eccentricity, though scatter decreases for tighter ZDC cuts
  - $R_{\text{long}}^2$ follows trend one might expect for shape selection
Backup

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Systematical errors are estimated by varying fitting range and efficiency correction.