Baryon-(anti-)baryon interaction cross-section measurement with femtoscopy technique in HIC

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Heavy-ion collision evolution

- HIC is expected to go through a QGP phase, from which particles are produced (freeze-out) thermally.
- Matter moves collectively in explosive manner (radial flow).

M. Chojnacki, W. Florkowski, PRC 74 (2006) 034905
Particle production in HIC

- At RHIC and LHC – several thousand particles per event
- STAR, ALICE – excellent PID at low $p_T$
(Anti-)Baryon production in HIC

- Similar no. of baryons and anti-baryons produced at RHIC and LHC, at low-$p_T$, PID needed (STAR, ALICE)

- HIC are matter-antimatter pair factories ($p$, $\Lambda$, $\Xi$, $\Omega$, ...)

Data/Model

$\frac{dN}{dy}$

ALICE Preliminary

$\chi^2$/NDF

Model

T (MeV)

THERMUS 2.3

155 ± 2

24.5/9

GSI-Heidelberg

156 ± 2

18.4/9

SHARE 3

156 ± 3

15.1/9

BR = 25%
Baryon femtoscopy

- Femtoscopy: use two-particle correlation function $C$ and known interaction $\Psi$ to extract information on the source emission function $S$

$$C(\vec{q}) = \int S(\vec{r}) |\Psi(\vec{q}, \vec{r})|^2 d^4 r$$  \hspace{1cm} \text{(Koonin-Pratt equation)}

measured correlation \hspace{1cm} \text{emission function (radius)} \hspace{1cm} \text{cross-section}

- The procedure can be reversed: study $\Psi$ with known $S$
Correlation from Strong interaction

- Femtoscopy: correlation $C$ connects interaction $\Psi$ and source $S$

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

- Strong interaction after hadrons' last scattering (freeze-out)
  - $\Psi$ is the Bethe-Salpeter amplitude, (solution of the quantum scattering problem, taken with the inverse time direction)

$$ \Psi = \exp(-i k^* \vec{r}) + f \frac{\exp(i k^* \vec{r})}{r} \quad \text{(s-wave approximation)} $$

$$ f^{-1} = \frac{1}{f_0} + \frac{1}{2} d_0 k^{*2} - ik^* \quad \text{(effective range approximation)} $$

- Cross-section $\sigma$ (at low relative momentum $k^*$) is simply:

$$ \sigma = 4\pi |f|^2 $$

\[ x_A \quad \rightarrow p_1 \]
\[ x_B \quad \rightarrow p_2 \]
\[ + \]
**Lednicky & Lyuboshitz formula**

- For the case of pure strong interaction, the integral equation for $C$ performed analytically for a Gaussian source $S$:

$$C(k^*) = 1 + \sum_s \rho_s \left[ \frac{1}{2} \left| \frac{f^S(k^*)}{R} \right|^2 \left(1 - \frac{d_0^S}{2 \sqrt{\pi R}}\right) + \frac{2 \Re f^S(k^*)}{\sqrt{\pi R}} F_1(2k^*R) - \frac{3 f^S(k^*)}{R} F_2(2k^*R) \right]$$

where $\rho_s$ are the pair spin fractions, $F_1$ and $F_2$ are known functions, $R$ is the Gaussian source width (variance)

- Scattering length $f_0$ and effective range $d_0$ appear directly in the correlation function form, real and imaginary part of $f$ have distinctly different contributions

- Not realistic to fit $R$ and interaction parameters ($f_0$, $d_0$) simultaneously, at least one must be fixed

Real and imaginary part of $f$

- A sharp peak (depression) at low $k^*$, for positive (negative) value of $\text{Re}(f_0)$ (width – up to 100 MeV/c)

- A broad depression at larger $k^*$ for non-zero values of $\text{Im}(f_0)$ (baryon annihilation) (width – several hundred MeV/c)

- Dependence of the CF on the system size and scattering length non-trivial, may be difficult to distinguish
Has it been done? $p\Lambda$ and $p\overline{\Lambda}$ in STAR

- Data fitted with Lednicky&Lyuboshitz formula
- $p\Lambda$ radius is 3.09 fm, predictions from hydrodynamics ($m_T$ or $k_T$ scaling) also give a "large" radius
- Unrealistically low radius obtained for $p\overline{\Lambda}$ from the fit (should be similar)
  $R=1.50 +/- 0.05 +/- 0.3$ fm

- Effective range fixed to 0
- Residual correlations explicitly not taken into account

Residual correlations

For colliders weak decay baryons with momentum in similar direction as parent – decay momentum is small with respect to the baryon mass (e.g. $\Lambda \rightarrow p$: 101 MeV/c)

The femtoscopic correlation of the parent pair is smeared by the decay, but can still be significant – if:

- (A) Parent correlation is strong (large cross-section)
- (B) Secondaries are numerous with respect to primordial baryons
- (C) Decay momentum is small
The transformation matrix

- The transformation matrix $T$ from parent pair $k^*$ to the daughter pair $k^*$ determined by random decay, bound by decay momenta.
- When only one particle decays, it has a rectangular shape, for pairs when both particles decay it is smeared more.

Smearing by decay

- By how much is the correlation smeared in the decay?
- At low momentum the shape changes significantly and is smoothed out, but is not trivial
- At large momentum the contribution is very similar to the original one

\[
C^{\bar{X} \rightarrow \bar{p} \Lambda}(k^*) = \int \frac{C^{\bar{X} Y}(k^*_{\bar{p} \Lambda}) W(k^*_{\bar{p} \Lambda}, k^*_Y) dk^*_Y}{\int W(k^*_{\bar{p} \Lambda}, k^*_Y) dk^*_Y}
\]

\( r_0 = 3.0 \text{ fm} \)
\( \text{Re}(f_0) = 0.2 \text{ fm} \)
\( \text{Im}(f_0) = 0.88 \text{ fm} \)
Correcting STAR $p\bar{\Lambda}$ for residual corr.

- The correlation is fitted with:
  \[
  C_{XY}^{p\Lambda}(k_{p\Lambda}^*) = 1 + \lambda_{p\Lambda}(C_{p\Lambda}^{p\Lambda}(k_{p\Lambda}^*) - 1) + \sum_{XY} \lambda_{XY}(C_{XY}^{XY}(k_{p\Lambda}^*) - 1)
  \]

- Radius comparable to the expectations is obtained
- All pairs provide a significant contribution to the correlation
- $\text{Im}(f_0)$ assumed the same for all pairs – consistent with $pp$

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Measuring $B\bar{B}$ in ALICE

• Recent ALICE measurement of baryon-(anti-)baryon correlations
  - 6 centralities, 2 collision energies, 3 baryon-antibaryon systems (+3 baryon-baryon as well, not shown here)

• Employed dedicated PID procedures of ALICE
  - Protons measured directly in TPC, also used TOF for PID
  - Lambdas measured via V0 decay topology with TPC, PID enhanced by TOF as well

• Complete set of $p\bar{p}$, $p\Lambda$, $\Lambda\bar{\Lambda}$ correlation functions
  - In fitting – used spin-averaged $(f_0, d_0)$, separate sets for $p\bar{\Lambda}$, $\Lambda\bar{\Lambda}$ and a separate set for all higher-mass residual pairs
Residual correlation web

• Significant interlinks between many pair combinations
Baryon-Antibaryon in ALICE

- All combinations of baryon-antibaryon correlation functions with pairs containing protons and lambdas
- Fit fully including the web of residual correlations
- Combined fit to 6 centralities x 2 collision energies x 3 systems
- Interaction parameters free in the fit (3 sets)
- Sizes constrained to $m_T$ scaling predictions
Measurement of strong $B \bar{B}$ interaction

- Estimation of the scattering length and effective range
- Assumption of $d_0=0$ not necessary
- Non-zero negative value of the real part of $f_0$
- Non-zero value of imaginary part of $f_0$ (annihilation), comparable for all pair types
Comparison to other measurements

- ALICE measurement competitive in accuracy to world data on baryon-antibaryon interaction
- Real part of $f_0$ for baryon-antibaryon – comparable value but opposite sign to baryon-baryon
Conclusions

- RHIC and LHC are baryon-antibaryon pair factories, provide unique measurement opportunities
- The correlations are sensitive to the strong interaction potential parameters, including the annihilation
- Residual correlations are especially relevant for baryon pairs due to the ratio of decay momenta to particle momenta
- Residual correlations are particularly important for annihilation due to the large $k^*$-width of the effect
- STAR data on proton-antilambda correlations is reanalyzed taking into account residual correlations, giving realistic results
- Combined fit for 3 pair types done for the first time in ALICE
- ALICE provides world-class data on all parameters of the baryon-antibaryon strong scattering parameters, with more potentially in the future, also for baryon-baryon, including (multi-)strange baryons