Extracting $p\Lambda$ scattering lengths from heavy-ion collisions

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Motivation

- The strong baryon-baryon interaction can be studied in the heavy ion collision experiments using the Final State Interaction (FSI) correlation technique.
- It is based on the analysis of the momentum correlations between corresponding baryons, produced in the collision. The measured two-particle correlation functions are influenced by the final state interaction effect.
- The LHC works like "the factory of particles", producing in heavy ion collisions a great amount of various particles, including multi-strange, charmed and beauty ones, allowing one to study the fundamental interactions between different hadron species.
- Using the FSI method one can infer the parameters describing strong interaction also in such particle pairs, for which it is difficult to do in other experiments, including the traditional scattering ones.
- The extraction of this information makes it possible to check the correctness of hadron-hadron strong interaction models, constrain corresponding interaction potentials, and also improve existing cascade models (like UrQMD) by including into them the information about still unknown baryon-antibaryon annihilation cross-sections.

The STAR experiment

Baryon-baryon $p-\Lambda$, $\bar{p}-\bar{\Lambda}$ and baryon-antibaryon $p-\bar{\Lambda}$, $\bar{p}-\Lambda$ correlation functions in 10% most central RHIC $Au+Au$ collisions at $\sqrt{s_{NN}}=200$ GeV
J. Adams et. al. (STAR) Phys. Rev. C, ***74****,064906, (2006).*

- Protons and antiprotons with $0.4 < p_T < 1.1$ GeV/c and $|y| < 0.5$
- Lambdas and antilambdas with $0.3 < p_T < 2.0$ GeV/c and $|y| < 1.5$

were selected for analysis.

The correlation functions are constructed as

$$C(k^*) = \frac{D_{\text{same event}}(k^*)}{D_{\text{mixed events}}(k^*)},$$

and then are corrected for pair **purity**, defined as **the fraction of correctly identified primary particle pairs** among all the selected ones

$$\begin{aligned} \text{Particle Purity} &= P_{id} \times F_{prim}, \\ \text{Pair Purity} &= \text{Particle}_1 \text{ Purity} \times \text{Particle}_2 \text{ Purity}, \\ C_{corr}(k^*) &= \frac{C_{meas}(k^*) - 1}{\lambda(k^*)} + 1. \end{aligned}$$

The estimated mean pair purity in the experiment is $\lambda = 17.5 \pm 2.5\%$

Lednický & Lyuboshitz analytical model

R. Lednický, V. L. Lyuboshitz, Yad. Fiz. ***35****, 1316 (1982).*

$$C(k^*) = \left\langle \left| \Psi^S_{-\mathbf{k}^*}(\mathbf{r}^*) \right|^2 \right\rangle,$$

where the wave function Ψ^S represents the approximate stationary solution of the scattering problem

$$\Psi^S_{-\mathbf{k}^*}(\mathbf{r}^*) = e^{-i\mathbf{k}^*\cdot\mathbf{r}^*} + \frac{f^S(k^*)}{r^*} e^{ik^*\cdot r^*}.$$

The effective range approximation for the scattering amplitude is utilized

$$f^S(k^*) = \left(\frac{1}{f_0^S} + \frac{1}{2} d_0^S k^{*2} - ik^* \right)^{-1},$$

where f_0^S is the **scattering length** and d_0^S is the **effective radius** for a given total spin $S = 1$ or $S = 0$.

The particles are assumed to be **unpolarized** (the polarization $P = 0$) $\Rightarrow$
the fractions of pairs in the singlet and triplet states are $\rho_0 = 1/4(1 - P^2) = 1/4$, $\rho_1 = 1/4(3 + P^2) = 3/4$.

Lednický & Lyuboshitz analytical model

The pair **separation distribution** (source function) $S(\mathbf{r}^*) = d^3N/d^3r^*$ is assumed to be Gaussian

$$d^3N/d^3r^* \propto e^{-\frac{\mathbf{r}^{*2}}{4r_0^2}},$$

where r_0 is the effective **source radius**.

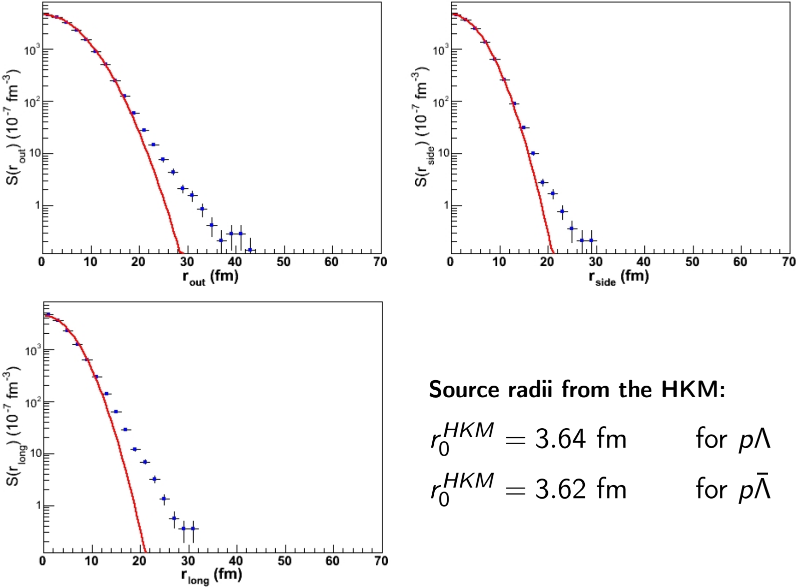
The correlation function can be calculated analytically by averaging Ψ^S over the total spin S and the distribution of the relative distances $S(\mathbf{r}^*)$

$$C(k^*) = 1 + \sum_S \rho_S \left[\frac{1}{2} \left| \frac{f^S(k^*)}{r_0} \right|^2 \left(1 - \frac{d_0^S}{2\sqrt{\pi} r_0} \right) + \frac{2\Re f^S(k^*)}{\sqrt{\pi} r_0} F_1(Qr_0) - \frac{\Im f^S(k^*)}{r_0} F_2(Qr_0) \right],$$

with $F_1(z) = \int_0^z dx e^{x^2 - z^2}/z$ and $F_2(z) = (1 - e^{-z^2})/z$.

The term $-\frac{d_0^S}{2\sqrt{\pi} r_0}$ corresponds to the correction accounting for deviation of Ψ^S from the true wave function inside the range of the strong interaction potential.

$p\Lambda$ source function projections from HKM



Source radii from the HKM:

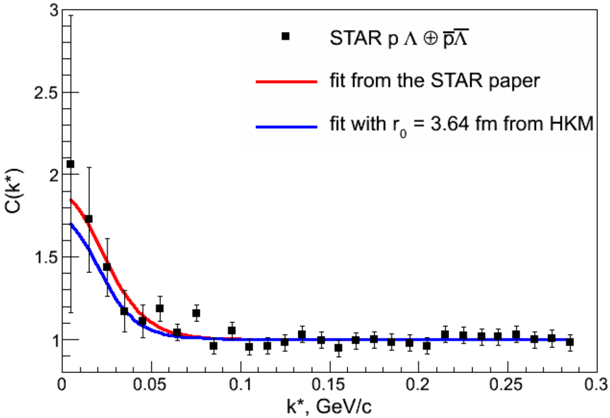
$r_0^{HKM} = 3.64$ fm for $p\Lambda$

$r_0^{HKM} = 3.62$ fm for $p\bar{\Lambda}$

Baryon-baryon $p\Lambda \oplus \bar{p}\bar{\Lambda}$ correlation function

The **scattering lengths** ($f_0^s = 2.88$ fm, $f_0^t = 1.66$ fm) and **effective radii** ($d_0^s = 2.92$ fm, $d_0^t = 3.78$ fm) for $p - \Lambda$ and $\bar{p} - \bar{\Lambda}$ interaction are taken from *F. Wang and S. Pratt, Phys. Rev. Lett. **83**, 3138 (1999).*

Source radius from HKM $r_0^{HKM} = 3.64$ fm.



Experimental source radius $r_0^{exp} = 3.09 \pm 0.30^{+0.17}_{-0.25} \pm 0.2$ fm.

Baryon-antibaryon $\bar{p}\Lambda \oplus p\bar{\Lambda}$ correlation function

Assumptions made:

- $f^s = f^t = f$
- $d_0^s = d_0^t = 0$
- $\Im f_0 > 0$

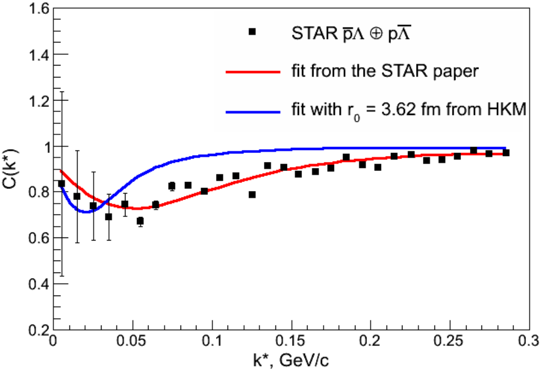
Source radius from the HKM:

$r_0^{HKM} = 3.62$ fm.

Scattering length:

$\Re f_0 = -1.0 \pm 0.5$ fm

$\Im f_0 = 2.23 \pm 0.63$ fm



Experimental source radius value:

$r_0^{exp} = 1.50 \pm 0.05^{+0.10}_{-0.12} \pm 0.3$ fm

Experimental scattering length:

$\Re f_0 = -2.03 \pm 0.96^{+1.37}_{-0.12}$ fm

$\Im f_0 = 1.01 \pm 0.92^{+2.43}_{-1.11}$ fm

Residual correlations influence

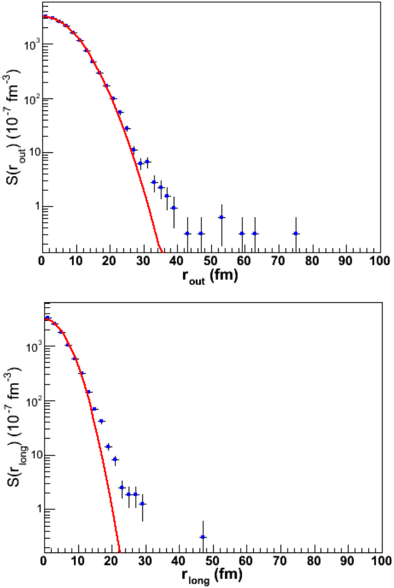
Residual correlations can exist in the pairs which include secondary particles if the secondary particle carries most of the momentum of its parent, and the parent was correlated with the second particle making the pair (or its parent).

The most particle interactions causing residual correlations are unknown, so at the moment there is no possibility to reliably account for its effect when constructing experimental correlation functions.

Fractions of different $p\Lambda$ pairs

Pairs	Fractions, %
$p_{prim} - \Lambda_{prim}$	15
$p_{\Lambda} - \Lambda_{prim}$	10
$p_{\Sigma^+} - \Lambda_{prim}$	3
$p_{prim} - \Lambda_{\Sigma^0}$	11
$p_{\Lambda} - \Lambda_{\Sigma^0}$	7
$p_{\Sigma^+} - \Lambda_{\Sigma^0}$	2
$p_{prim} - \Lambda_{\Xi}$	9
$p_{\Lambda} - \Lambda_{\Xi}$	5
$p_{\Sigma^+} - \Lambda_{\Xi}$	2
$p_{prim} - p_{prim}$	7

Baryon-baryon source radii for LHC



Source radii from the HKM:

$r_0^{HKM} = 3.96$ fm for $p\Lambda$

$r_0^{HKM} = 4.03$ fm for $\Lambda\Lambda$

$r_0^{HKM} = 3.79$ fm for pp

Residual correlations influence

We try to account for the residual correlations phenomenologically and describe the $p\bar{\Lambda}$ correlation function **not corrected for pair purity** with a modified analytical expression.

The data for uncorrected CF are taken from
*G. Renault for the STAR Collaboration, Acta Phys. Hung. A**24**, 131 (2005).*

$$C(k^*) = \lambda(k^*)C(k^*) + (1 - \lambda(k^*))(1 - \beta e^{-4k^{*2}R^2}), \tag{1}$$

$\lambda(k^*) = a\lambda_{exp}(k^*)$, where $\lambda_{exp}(k^*) = (C_{uncorr}(k^*) - 1)/(C(k^*) - 1)$

Two additional parameters:

- $\beta > 0$ – amplitude of annihilation dip in parent correlations
- $R \ll r_0$ – dip inverse width

Parameters a, $\Re f_0$, $\Im f_0$, β, and R are left to vary freely.

The extracted parameter values are:

$a = 1.28 \pm 0.84$,

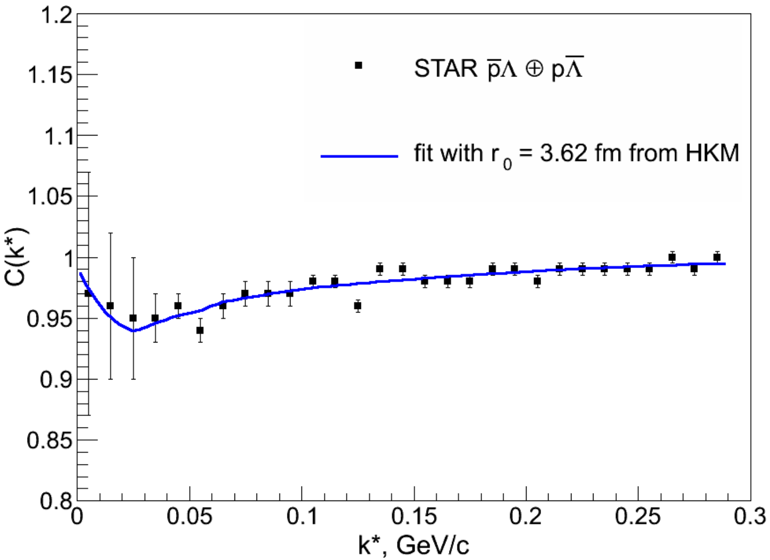
$\Re f_0 = -0.05 \pm 0.68$ fm,

$\Im f_0 = 1.41 \pm 1.07$ fm,

$\beta = 0.029 \pm 0.005$,

$R = 0.45 \pm 0.06$ fm.

Residual correlations influence



Conclusions

- Study of baryon and antibaryon correlations provides a powerful tool for measuring space-time evolution of heavy ion collisions and for extracting the parameters of strong interaction between emitted particles.
- The $p-\Lambda \oplus \bar{p}-\bar{\Lambda}$ and $\bar{p}-\Lambda \oplus p-\bar{\Lambda}$ correlation functions, measured in 10% most central Au+Au collisions by STAR at $\sqrt{s_{NN}} = 200$ GeV, were reproduced using Lednicky and Lyuboshitz analytical formalism with the source radii extracted from the hydrokinetic model (HKM)
- To take into account the residual correlations influencing baryon-antibaryon femtoscopic effects, a modified analytical approximation has been applied. The real and imaginary parts of the spin averaged scattering lenghts have been extracted for baryon-antibaryon pairs.
- New high statistics data from RHIC and LHC will provide measurements of various particle pairs, including baryon-antibaryon ones, allowing to investigate the particle interactions in these pairs.

Thank you for your attention!

HKM model

We perform computer simulations of the experiment by STAR within the HKM model. It simulates the full process of evolution of the system formed in nuclear or particle collision consisting of two stages:

- 3+1D hydrodynamical expansion of thermally and chemically equilibrated matter – *described within ideal hydrodynamics approximation (needs the equation of state)*
- Gradual decoupling after losing chemical and thermal equilibrium – *described within hydro-kinetic approach with switching to UrQMD cascade at space-like hypersurface*
  or *sudden switch to UrQMD cascade at the hadronization hypersurface*

The model gives us particle distribution functions $\frac{d^6 N}{d^3 x d^3 p}$ at the chosen switching hypersurface.

Using the Monte-Carlo procedure according to these functions we generate particles momenta and coordinates, which serve as the input to the UrQMD hadronic cascade.

To start ideal hydrodynamics stage in HKM one should specify the initial conditions at the starting proper time τ_0:

- Initial energy density (or entropy) profile $\epsilon(\mathbf{r})$
- Initial rapidity profile (initial flow) $y(\mathbf{r})$

HKM model

- We start hydrodynamics at $\tau_0 = 0.1$ fm/c (prethermal stage imitation) and work in the longitudinal boost-invariance approximation, in mid-rapidity region.
- The initial energy density profile corresponding to the MC-Glauber model is calculated using GLISSANDO code *(W. Broniowski, M. Rybczynski, P. Bozek, Comput. Phys. Commun.,* ***180****, 69 (2009))*.
- Initial flow is usually supposed to be $y_T = \alpha \frac{r_T}{R^2(\phi)}$, $y_L = \eta$ (boost-invariance), where α is another model parameter, in current analysis $\alpha = 0.45$.
- Sudden switch from hydrodynamics to UrQMD at the isotherm $T = 165$ MeV. The hadrons distribution functions are calculated using the Cooper-Frye formula

$$p_0 \frac{d^3 N_i}{p_T dp_T d\phi_p dy} = \int_{\sigma_{sw}} p^\mu d\sigma_\mu f_i^{eq}(p \cdot u(x), T(x), \mu_i(x))$$

HKM model

The HKM model gives us the source function $S(\mathbf{r}^*)$ in the pair center of mass system.

$$S(\mathbf{r}^*) = \frac{\sum_{i \neq j} \delta_\Delta(\mathbf{r}^* - \mathbf{r}_i + \mathbf{r}_j)}{\sum_{i \neq j} 1},$$

where $\delta_\Delta(x) = 1$ if $|x| < \Delta p/2$ and 0 otherwise with Δp being the size of the histogram bin.

To extract the FSI parameters we fit the obtained $S(\mathbf{r}^*)$ with the Gaussian, that gives us the source size r_0.

Then we fit the experimental correlation function with the Lednický & Lyuboshitz model, fixing the r_0 parameter and leaving the FSI parameters to vary freely.