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$\pi\Xi$ CORRELATIONS: MODEL COMPARISON AND $\Xi^*(1530)$ PUZZLE*

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Predictions of hydrodynamics-parametrized statistical hadronization model HYDJET++ are compared to the STAR Collaboration preliminary $\pi\Xi$ data. We demonstrate how decay of resonances and collective flow affect shift between the average freeze-out space-time points of Ξ and π. We study how different freeze-out scenarios: *single freeze-out* at $T_{\rm th} = T_{\rm ch} = 0.165$ GeV; *thermal freeze-out* at $T_{\rm th} = 0.1$ GeV; *combined scenario* when Ξ and $\Xi^*(1530)$ are emitted at chemical freeze-out while all other particles are emitted at the thermal freeze-out influence this shift. We study influence of the relative contribution of Ξ from $\Xi^*(1530)$ resonance decay on the $\pi\Xi$ emission asymmetries. We show that the best description of $m_{\rm t}$-spectra and space-time differences is achieved within the *combined scenario.*

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1. Introduction

Femtoscopic measurements provide important insight into the space-time evolution of the system created in collisions of ultra-relativistic nuclei. The high-statistics data accumulated at RHIC and SPS allow to conclude that space-time structure of the source is strongly affected by collective expansion

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of the hot and dense matter. In particular, final state interactions (FSI) between pairs of non-identical particles provide information about the average relative space-time separation between the emission points of two particle species in the pair rest frame [1]. Preliminary results for $\pi^{\pm}\Xi^{\pm}$ system are available from STAR Collaboration [2, 3]. Following important observation were made:

- Decomposition of the correlation function $C(\boldsymbol{k}^*) \equiv C(k^*, \cos\theta, \varphi)$ from 10% most central Au + Au collision into spherical harmonic provided first preliminary values of $R = (6.7 \pm 1.0)$ fm and $\Delta_{\rm out} = (-5.6 \pm 1.0)$ fm. The negative value of the shift parameter $\Delta_{\rm out}$ indicates that average emission point of the Ξ is positioned more to the outside of the fireball than the average emission point of the pion.
- In addition to the Coulomb interaction seen in previous non-identical particle analyses the $\pi^{\pm}\Xi^{\mp}$ correlations at small relative momenta provide sufficiently clear signal of the strong FSI that reveals itself in a peak corresponding to a $\Xi^*(1530)$ resonance. Peak's centrality dependence shows a high sensitivity to the source size.
- Comparison with the FSI model confirms that theoretical calculations in the Coulomb region are in a qualitative agreement with the data. In the strong $\Xi^*(1530)$-region they over-predict both the size and the shift coefficients.

Our goal in this study is to clarify influence of collective flow and resonances on the shift between average freeze-out space time points of Ξ and π. For this we employ hydrodynamics-parametrized statistical hadronization model HYDJET++ [4]. We analyze particle ratios and $m_{\rm t}$-spectra and then the space-time differences of the Ξ and π emission points. We compare different freeze-out scenarios implemented in HYDJET++: *single freeze-out* at $T_{\rm th} = T_{\rm ch}$ and *thermal freeze-out* at $T_{\rm th} < T_{\rm ch}$. In addition to this we introduce into HYDJET++ *combined* scenario when Ξ and $\Xi^*(1530)$ are emitted already at chemical freeze-out while other particles π, K, p are emitted later at the thermal freeze-out.

2. The HYDJET++ generator

HYDJET++ [4] is a further development of its predecessors: the HYDJET [5] and FASTMC [6, 7] MC generators. In this study we neglect the hard processes option implemented in the model because of a small influence of the high-$p_{\rm t}$ part processes on the femtoscopy data at RHIC energies and use the soft part only. Later is based on a hydrodynamical parametrization of the initial state providing the thermal hadronic state generated on the chemical (*single freeze-out* scenario) or thermal (*thermal freeze-out* scenario) freeze-out hypersurfaces represented by a parametrization of relativistic hydrodynamics with given freeze-out conditions [6, 7]. The mean multiplicity of hadron species crossing the space-like freeze-out hypersurface is calculated using effective thermal volume approximation. Let us note that unlike FASTMC in HYDJET++ the value of effective volume of the fireball $V_{\rm eff}$ is generated for each event separately. $V_{\rm eff}$ is proportional to the mean number of participating nucleons at the considered centrality (impact parameter b) which is calculated from the generalization of Glauber multiple scattering model to the case of independent inelastic nucleon–nucleon collisions. In the case of the *thermal freeze-out* scenario the system expands hydrodynamically with frozen chemical composition, cools down and finally decays at a thermal freeze-out hypersurface [7]. The two- and three-body decays of the resonances with branching ratios are taken from the SHARE particle decay table [8].

The set of thermodynamical parameters determining the *single freeze-out* scenario covers chemical potentials: $\widetilde{\mu_{\rm B}} = 0.0285$ GeV, $\widetilde{\mu_{\rm S}} = 0.007$ GeV, $\widetilde{\mu_{\rm Q}} = -0.001$, strangeness suppression factor $\gamma_{\rm s} = 0.8$, chemical freeze-out temperature $T_{\rm ch} = 0.165$ GeV, and the parameters determining fireball size: $R = 9.0$ fm, $\tau = 7.0$ fm$/c$, $\Delta\tau = 2.0$ fm$/c$, $\rho_u^{\rm max} = 0.65$. The set of parameters determining the *thermal freeze-out* scenario: $T_{\rm th} = 100$ MeV, $\mu^{\rm th}_{{\rm eff}\pi} = 0.105$ GeV, $R = 10.0$ fm, $\tau = 8.0$ fm$/c$, $\Delta\tau = 2.0$ fm$/c$, $\rho_u^{\rm max} = 1.0$.

3. $\pi\Xi$ correlations study with HYDJET++

3.1. *Ratios of hadron abundances and* $m_{\rm t}$*-spectra*

It is well known that the particle abundances in heavy ion collisions in a wide energy range can be reasonably described by statistical hadronization models based on the assumption that the produced hadronic matter reaches thermal and chemical equilibrium. The thermodynamical parameters $\widetilde{\mu_{\rm B}} = 0.0285$ GeV, $\widetilde{\mu_{\rm S}} = 0.007$ GeV, $\widetilde{\mu_{\rm Q}} = -0.001$, the strangeness suppression factor $\gamma_{\rm s} = 0.8$ and the chemical freeze-out temperature $T_{\rm ch} = 0.165$ GeV have been successfully used [6] to describe the RHIC data on various particle ratios produced in central Au + Au collisions near mid-rapidity at $\sqrt{s_{\rm NN}}$=200 GeV: π^-/π^+, $\bar{p}/\pi^-$, K^-/K^+, K^-/π^-, $\bar{p}/p$, $\bar{\Lambda}/\Lambda$, $\bar{\Lambda}/\Lambda$, $\bar{\Xi}/\Xi$, ϕ/K^-, Λ/p, Ξ^-/π^-.

First preliminary measurements of the $\Xi^*(1530)$ spectra and their yields [9] have shown substantially higher $\Xi^*(1530)/\Xi^-$ ratio when compared to statistical model calculations. This is also true for our HYDJET++ calculations using above mentioned parameters. Our model underestimates this ratio (>2 times) as well.

In Fig. 1 the $m_{\rm t}$-spectra of π^+ and $\Xi^{\pm}$ for *single freeze-out* at $T_{\rm th} = T_{\rm ch} = 0.165$ GeV and for *thermal freeze-out* at $T_{\rm th} = 0.1$ GeV, $T_{\rm ch} = 0.165$ GeV scenarios are compared with STAR data [10,12]. One can see that π, K, p spectra are better described within the *thermal freeze-out* scenario (Fig. 1(b)) while the Ξ spectrum is better described within the *single freeze-out* scenario (Fig. 1(a)). The slope of the $p_{\rm t}$-spectra $\Xi^*(1530)$ [9] is also much better described within the *single freeze-out* scenario. Let us note that in the HYDJET++ model the particle freeze-out conditions, temperature, maximal transverse flow rapidity, freeze-out time and fireball radii are the same for all particle species. However, Fig. 1 indicates that the $m_{\rm t}$-spectra of different particle species cannot be described with the same set of parameters. To solve this problem we have introduced in the model the third, *combined freeze-out* scenario: Ξ, $\Xi^*(1530)$ are emitted at the chemical freeze-out, the other particles are emitted later at the thermal freeze-out.

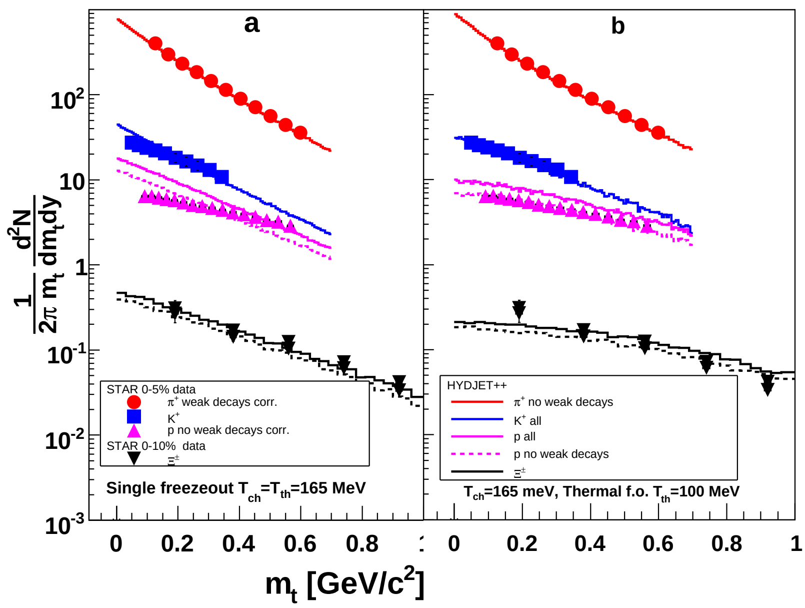

Fig. 1. The $m_{\rm t}$-spectra of π^+, K^+, p and $\Xi^{\pm}$ calculated with HYDJET++ within (a) single freeze-out scenario and (b) thermal freeze-out scenario. The experimental data of STAR collaboration are shown by the solid points, the HYDJET++ calculations by the lines.

3.2. Space-time differences of the Ξ and π emission points

Let us note that FSI between two particles is non-negligible if they are close in the local pair rest frame (PRF) (the system where the center-of-mass of the pair is at rest). In that case they have close velocities in the laboratory frame. For the particles with such a different masses as Ξ and π the corresponding laboratory momenta will be very different. Large momentum of Ξ corresponds a small momentum of π. Big shift induced by hydro-type evolution is thus expected, even larger than in the πp case since the mass difference is larger. The shift may also be affected by different decoupling conditions and/or emission of Ξ from the long-lived $\Xi^*(1530)$ resonance. Indeed some model-dependent analyses have indicated that multistrange baryons decouple earlier because of their small hadronic cross-sections [11].

In the following we will study the separation between particles emission points in PRF using standard parametrization of the 3D projections on the axes: *long* — along the beam axes, *out* — along the pair transverse momentum, *side* — perpendicular to the pair transverse momenta. For a symmetric system $\langle \Delta r^*_{\rm out}\rangle = 0$ and $\langle \Delta r^*_{\rm side}\rangle = 0$, and the asymmetry appears only in *out* direction,

$$\Delta\langle r^*_{\rm out}\rangle = \gamma_t(\Delta r_{\rm out} - \beta_t \Delta t)\,. \tag{1}$$

The separations $\Delta r^*_{\rm out}$ between the emission points of π and Ξ in the PRF are displayed in Fig. 2. The best description of the data [2] is obtained within the *combined freeze-out* scenario. Since thermal smearing is maximal

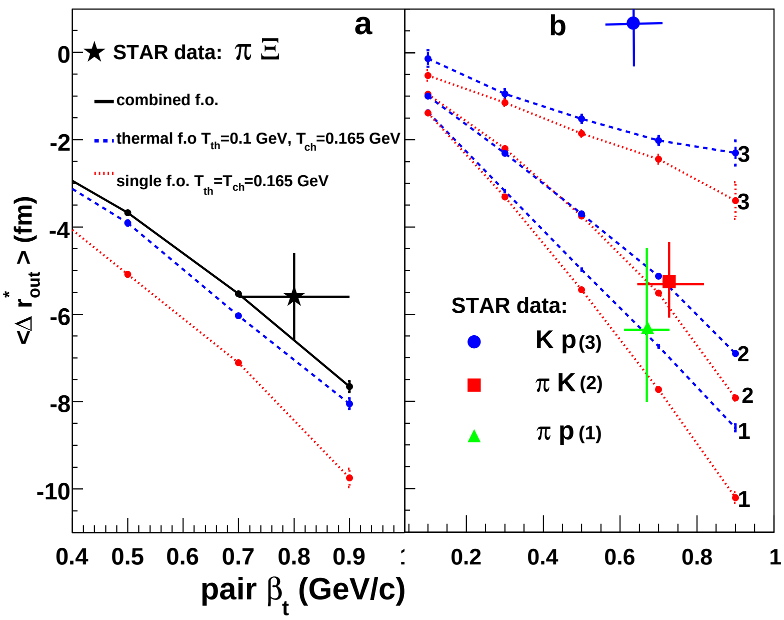

Fig. 2. The total space-time shift in pair rest frame for (a) $\pi\Xi$ and (b) $\pi p, \pi K, \pi p$ for *combined freeze-out* (solid line), *thermal freeze-out* (dashed line) and *single freeze-out* (dotted line) scenarios in comparison with STAR collaboration data $\pi\Xi$ (stars), Kp (circles), πK (squares), πp (triangles). The HYDJET++ calculations are shown by numbers in (b): (1)πp , (2)πK, (3)Kp.

for particle with low mass and momentum the region emitting particles with given momentum shrinks and moves to edge of the system as mass and/or momentum increases. The pion smearing is maximal for the *single freeze out*, so its shift is smaller than in the case of the *thermal freeze out* (*combined freeze-out*). The value of Ξ space shift is larger than that of the pion. Due to larger value of the maximal flow rapidity and larger system size the Ξ space shift is larger for the *thermal freeze-out* than for the *single freeze-out* (*combined freeze-out*). The smallest value of the shift between π and Ξ occurs for the *combined freeze-out* scenario because the pion shift is maximal (coincides with *thermal freeze-out*) and Ξ shift is minimal (coincides with *single freeze-out* scenario). The time shift for *combined freeze-out* scenario is maximal, but its contribution to the total shift is smaller than the spacial one. Therefore the minimal value of total shift takes place for the *combined freeze-out* scenario (see Fig. 2(a)), which is also closest to the data.

The space-time differences of the systems: πp, πK, Kp are plotted in Fig. 2(b). The best description of the πp, πK data [13] is obtained within the *thermal freeze-out* scenario. The Kp space-time emission asymmetry is not described well by the model.

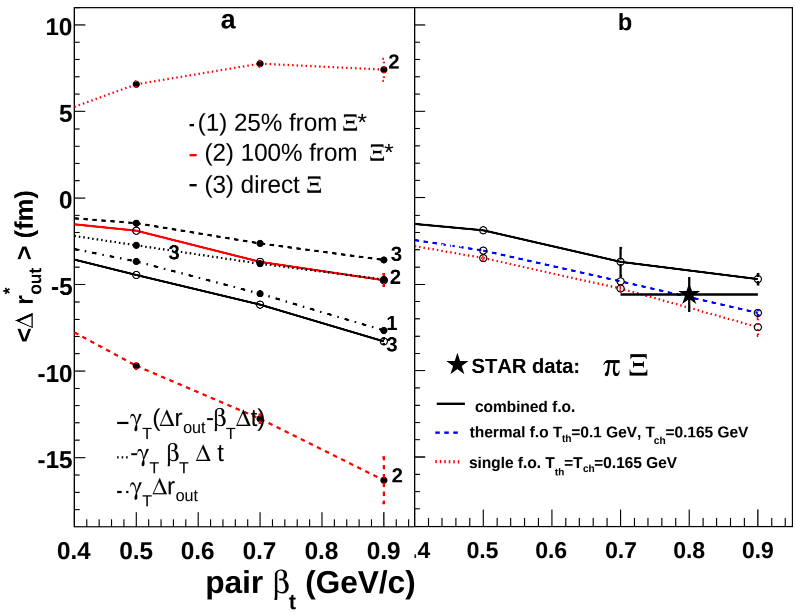

Fig. 3. (a): The space $\gamma_t \Delta r_{\rm out}$ (dash-dotted lines) and time $-\gamma_t \beta_t \Delta t$ (dotted lines) relative contributions in the separations $\Delta r^*_{\rm out}$ (solid lines) between the emission points of π and Ξ in PRF for direct Ξ and Ξ from $\Xi^*(1530)$ decays within *combined freeze-out* scenario; (b): the same as Fig. 2(a) for the case of all Ξ coming from $\Xi^*(1530)$ decays.

For the case of *combined freeze-out* the space ($\gamma_t \Delta r_{\rm out}$) and time ($-\gamma_t \beta_t \Delta t$) relative contributions to the total space-time shift $\Delta r^*_{\rm out}$ between the emission points of π and Ξ in the PRF are shown in Fig. 3(a) for direct Ξ and Ξ from $\Xi^*(1530)$ decays. Fig. 3 demonstrates that $\Xi^*(1530)$ decay increases the time and space shifts between $\pi\Xi$. The resulting total shift is maximal for the direct Ξ, and minimal for Ξ coming only from Ξ^* decays. The shift obtained by HYDJET++ with ratio $\Xi^*/\Xi \sim 0.25$ considered above (Fig. 2(a), solid line) is closer to the direct Ξ case (Fig. 3(a), dash-dotted line). The separations $\Delta r^*_{\rm out}$ between the emission points of π and Ξ in the PRF are displayed on Fig. 3(b) for the extreme case when all Ξ come from Ξ^* decays. The total shifts obtained within different scenario are higher than in Fig. 2(a).

4. Conclusions

Preliminary STAR measurements of the $\pi\Xi$ correlations [2, 3] and $\Xi^*(1530)$ spectra [9] provide an interesting information about the space-time interval between chemical and thermal freeze-outs. Combined comparison of the m_t-spectra and space-time differences between HYDJET++ and real data was performed. The best agreement with the data was achieved within the *combined* scenario with the following parameters: $T_{\rm ch} = 165$ MeV, $T_{\rm th} = 100$ MeV, $R_{\rm th} = 10$ fm, $\tau_{\rm th} = 8$ fm/c and $R_{\rm ch} = 9$ fm, $\tau_{\rm ch} = 7$ fm/c. We have demonstrated that an increase of the relative contribution of Ξ from $\Xi^*(1530)$ decays decreases the $\pi\Xi$ emission asymmetry making an unambiguous interpretation of the results complicated. More precise measurement of Ξ^*/Ξ ratio and $\pi\Xi$ correlation function is thus necessary.

REFERENCES

[1] R. Lednicky, V.L. Lyuboshits, B. Erazmus, D. Nouais, *Phys. Lett.* **B373**, 3034 (1996).

[2] M. Šumbera [STAR Collaboration], *Braz. J. Phys.* **37**, 925 (2007) [nucl-ex/0702015].

[3] P. Chaloupka [STAR Collaboration], *J. Phys. G* **32**, S537 (2006); *Nucl. Phys.* **A774**, 603 (2006); *Nucl. Phys.* **A749**, 283 (2005); *Int. J. Mod. Phys.* **E16**, 2222 (2007).

[4] I.P. Lokhtin, L.V. Malinina, S.V. Petrushanko, A.M. Snigirev, I. Arsene, K. Tywoniuk, arXiv:0809.2708 [hep-ph], accepted by *Comput. Phys. Commun.*, program can be downloaded from http://cern.ch/lokhtin/hydjet++

[5] I.P. Lokhtin, A.M. Snigirev, *Eur. Phys. J.* **C45**, 211 (2006).

[6] N.S. Amelin *et al.*, *Phys. Rev.* **C74**, 064901 (2006).

[7] N.S. Amelin *et al.*, *Phys. Rev.* **C77**, 014903 (2008).
[8] G. Torrieri *at al.*, *Comput. Phys. Commun.* **167**, 229 (2005).
[9] R. Witt, *J. Phys. G* **34**, S921 (2007) `[arXiv:nucl-ex/0701063]`.
[10] J. Adams *et al.* [STAR Collaboration], *Phys. Rev. Lett.* **92**, 112301 (2004).
[11] S. Soff, S. Bass, D. Hardtke, S. Panitkin, *Nucl. Phys.* **A715**, 801 (2003).
[12] J. Adams *et al.* [STAR Collaboration], *Phys. Rev. Lett.* **98**, 062301 (2007) `[nucl-ex/0606014]`.
[13] A. Kisiel [STAR Collaboration], *J. Phys. G* **30**, S1059 (2004).