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Effects of finite coverage on global polarization observables in heavy ion collisions

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ABSTRACT

In non-central relativistic heavy ion collisions, the created matter possesses a large initial orbital angular momentum. Particles produced in the collisions could be polarized globally in the direction of the orbital angular momentum due to spin–orbit coupling. Recently, the STAR experiment has presented polarization signals for Λ hyperons and possible spin alignment signals for ϕ mesons. Here we discuss the effects of finite coverage on these observables. The results from a multi-phase transport and a toy model both indicate that a pseudorapidity coverage narrower than $|\eta| <\sim 1$ will generate a larger value for the extracted ϕ-meson ρ_{00} parameter; thus a finite coverage can lead to an artificial deviation of ρ_{00} from 1/3. We also show that a finite η and p_T coverage affect the extracted p_H parameter for Λ hyperons when the real p_H value is non-zero. Therefore proper corrections are necessary to reliably quantify the global polarization with experimental observables.

1. Introduction

The dense matter created in non-central relativistic heavy ion collisions processes a large orbital angular momentum. It has been predicted that the orbital angular moment may result in a net-polarization of produced particles along the direction of the initial angular moment due to the spin–orbit coupling [1,2]. Recently, the RHIC-STAR collaboration claimed the discovery of a global Λ polarization in heavy ion collisions [3]. The estimated vorticity is much larger than all other known fluids, which suggests that the quark–gluon plasma is the most vortical fluid produced in the laboratory. Meanwhile the measured spin alignment parameter ρ_{00} of ϕ mesons is systematically larger than 1/3 [4,5]. A deviation of ρ_{00} from 1/3 indicates a spin alignment of the vector mesons, and whether ρ_{00} is greater or smaller than 1/3 depends on the hadronization mechanism [2]. More detailed measurements of polarization observables, e.g., as a function of rapidity, pseudorapidity (η), or transverse momentum (p_T), will be important to better understand the novel polarization phenomena.

The angular distribution of the Λ decay products with respect to the orbital angular momentum of system $\mathbf{L}$ can be written as [6]

$$\frac{dN}{d\cos\theta^\star} \propto 1 + \alpha_H p_H \cos\theta^\star, \tag{1}$$

where $\theta^\star$ is the angle between $\mathbf{L}$ and the momentum of the daughter proton in the rest frame of the parent Λ hyperon, and α_H is the decay parameter $\alpha_\Lambda = -\alpha_{\bar\Lambda} = 0.642 \pm 0.013$ [7]. Therefore the global polarization parameter p_H for Λ can be calculated by

$$p_H = \frac{3}{\alpha_H}\left\langle \cos\theta^\star \right\rangle. \tag{2}$$

The angle brackets above represent the averaging over all Λ decays. Assuming a perfect detector acceptance, one can also write [8]

$$p_H = \frac{8}{\pi\alpha_H}\left\langle \cos(\phi_p^\star - \phi_{\mathbf{L}}) \right\rangle, \tag{3}$$

where $\phi_p^\star$ is the azimuth of the daughter proton momentum vector in the Λ rest frame and $\phi_{\mathbf{L}}$ is the azimuth of the system angular momentum.

For vector mesons such as the ϕ meson, the polarization information including the spin alignment is described by a spin density matrix ρ. A deviation of the diagonal element $\rho_{m,m}$ ($m = -1, 0, 1$) from 1/3 is the signal of spin alignment. For a diagonal matrix ρ, since the elements $\rho_{-1,-1}$ and $\rho_{1,1}$ are degenerate, $\rho_{0,0}$ is the only independent element [9]. It can be extracted from the following

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angular distribution of the decay products of vector mesons with respect to **L** [10]:

$$\frac{dN}{d\cos\theta^\star} \propto (1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^\star. \quad (4)$$

So far lots of theoretical progresses have been made on the evolution of vorticity and polarization [11–14]. Since the experimental coverage of the phase space is always finite, in this paper we study the effects of a finite η and p_T coverage on the measured global polarization parameter p_H of Λ hyperons and spin alignment parameter ρ_{00} of ϕ mesons.

2. The simulation method

We have modified a multi-phase transport (AMPT) model [15] for this study. The string melting version of the AMPT model [16] used here consists of a fluctuating initial condition, an elastic parton cascade, a quark coalescence model for hadronization, and a hadron cascade. We use the same model parameters as those used for the top RHIC energy in an earlier study [17]. In the hadron cascade of AMPT, ϕ mesons and Λ hyperons are assumed to be uniformly polarized according to Eqs. (1) and (4) when they decay. The included channels of polarized decays are $\phi \to K + \bar{K}$ (branching ratio $\sim$ 83%) and $\Lambda \to p + \pi^-$ and $n + \pi^0$ (branching ratio $\sim$ 100%). While experimentally the direction of the angular momentum is often estimated by the normal of the reconstructed event plane [8,9], we directly calculate the initial angular momentum vector of the participant nucleons event-by-event in the AMPT calculations. All results in this study are for minimum bias (impact parameter from 0 to 15.6 fm) Au + Au collisions.

We follow the experimental procedure to extract the ρ_{00} parameter of ϕ mesons: pairs of $K\bar{K}$ from each event are used to reconstruct the ϕ-meson candidates, while pairs from different events are constructed to estimate the background; these same event pairs and mixed event pairs are both divided into multiple $\cos\theta^\star$ bins. We then extract the ρ_{00} parameter by using Eq. (4) to fit the $|\cos\theta^\star|$ distribution of the ϕ-meson signal, i.e., the difference between the same event and mixed event pairs. For Λ hyperons, we found that the systematic uncertainty of background subtraction (up to a fraction of a percent) is too large when the input p_H is small or zero; it is also not straightforward to apply topological cuts to decays from the AMPT model as done in the experimental analysis. Therefore we use the Λ decay information from the AMPT model directly to extract the p_H parameter. We have found that hadronic rescatterings have negligible effects on the value of the extracted p_H parameter for Λ hyperons or the ρ_{00} parameter for ϕ mesons; this is expected due to their long lifetimes before decay. We have also used the ϕ decay information directly to extract the ρ_{00} parameter from the AMPT model and obtained consistent values as those extracted from the background subtraction method.

When there are no phase space cuts on particles (i.e. when we have full coverage), we have found that the extracted ρ_{00} or p_H value is consistent with the input value as expected. However, the experimental acceptance is always limited. The detected η range for finial state particles is typically from ± 0.5 to ± 2, e.g., the STAR experiment covers $|\eta| < 1$; and the p_T of detected particle tracks is typically larger than 0.1–0.2 GeV/c. Not only are the candidate decay daughters for ϕ and Λ reconstructions within a certain η and p_T coverage, but additional y (or η) and p_T cuts are also often applied to the reconstructed parent particles (ϕ and Λ). Therefore we need to investigate whether and how the phase-space cuts may influence the extracted value of the global polarization/spin-alignment parameters. Note that the vorticity in a nuclear collision depends on the transverse position and pseudorapidity in principle [14], thus the real polarization may depend on the phase space variables such as η and p_T; but that is outside the scope of this study.

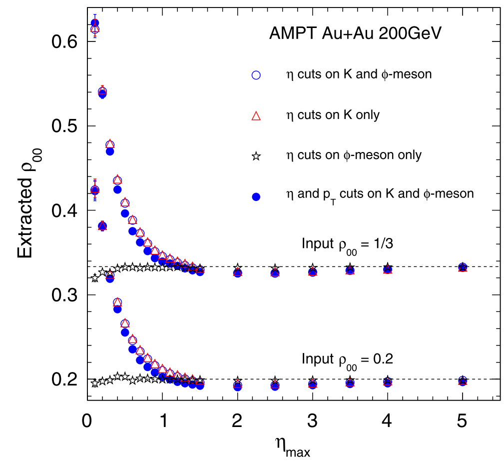

Fig. 1. (Color online.) The extracted ρ_{00} as a function of the upper limit of the $|\eta|$ coverage from AMPT for minimum bias Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV, where dashed lines represent the input ρ_{00} value of 0.2 or 1/3. Results for η cuts applied to both kaons and ϕ mesons, only kaons, and only ϕ-mesons are shown, in addition to results with both the η cuts and the STAR p_T cuts on kaons and ϕ-mesons.

3. Results

Fig. 1 shows the AMPT model results for the extracted ρ_{00} of ϕ mesons as a function of the upper limit of the $|\eta|$ coverage, $\eta_{\max}$, for Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Results are shown for two input ρ_{00} values, 0.2 and 1/3, where we study the η-cut effects by applying the cut $|\eta| < \eta_{\max}$ to both kaons and ϕ mesons (open circles), only kaons (triangles), or only ϕ mesons (stars). We see that, when the $|\eta|$ cut is only applied to the parent ϕ mesons, the extracted ρ_{00} has almost no deviation from the input value for any η cut. On the other hand, the extracted ρ_{00} strongly depends on the η cut applied to the decay daughter candidates, where an η coverage narrower than ~ 1 gives a significantly larger extracted ρ_{00} than the input value. This is because, with the angular momentum **L** in the transverse plane, a narrow η cut on kaons tends to exclude some kaons along the beam directions and thus excludes those ϕ-meson decays with daughter kaons around $\theta^\star \sim 90°$. Note that such loss of decay daughters close to the beam direction due to finite acceptance and its effect on the hyperon global polarization parameter p_H have been pointed out earlier for Lambda decays [8]. Also shown in Fig. 1 are the results where both the η cuts and the STAR p_T cuts ($p_T^K > 0.1$ GeV/c and $0.4 < p_T^\phi < 3$ GeV/c) are applied to the kaons and ϕ mesons (filled circles), where we see that the p_T cuts lead to a small reduction of the extracted ρ_{00} values. We also see in Fig. 1 that the extracted ρ_{00} value converges to the input value at large $\eta_{\max}$ for all the considered cuts.

To further illustrate the η-cut effect on ρ_{00}, we also use a toy model, where we sample the p_T, η and azimuth distributions of ϕ mesons according to the AMPT results and decay the hadrons with PYTHIA [18]. As shown in Fig. 2a, the effects of η cuts from the toy model are essentially the same as those from the AMPT model. Fig. 2b shows the two-dimensional distribution (in $\cos\theta^\star$ and p_T) of kaons within $|\eta| < 0.3$ from ϕ decays. We can clearly observe that the η cut excludes more kaons from ϕ decays around $\theta^\star \sim 90°$, i.e., around $\cos\theta^\star \sim 0$. The figure also demonstrates that the η-cut mostly affects the low p_T region. Furthermore, a differ-