Elliptic flow of $\Lambda$, $\Xi$ and $\Omega$ in 2.76 A TeV Pb+Pb collisions

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Abstract. The elliptic flow $v_2$ for strange and multi-strange baryons in 2.76 A TeV Pb+Pb collisions is investigated with VISHNU hybrid model that connects 2+1-d viscous hydrodynamics with a hadron cascade model. It is found that VISHNU nicely describes $v_2(p_T)$ data for $\Lambda$, $\Xi$ and $\Omega$ at various centralities. Comparing with the ALICE data, it roughly reproduces the mass-ordering of $v_2$ among $\pi$, $K$, $p$, $\Xi$ and $\Omega$ within current statistics, but gives an inverse $v_2$ mass-ordering between $p$ and $\Lambda$.

1. Introduction

The QGP viscosity is a hot research topic. Viscous hydrodynamic simulations showed that elliptic flow $v_2$ is very sensitive to the QGP shear viscosity to entropy density ratio $\eta/s$. Even the minimum value $1/4\pi$ from the AdS/CFT correspondence could lead to 20-25% suppression of $v_2$ [1, 2]. Generally, the QGP viscosity is extracted from the integrated $v_2$ for all charged hadrons, since it is directly related to the fluid momentum anisotropy and varies monotonously with $\eta/s$ [3, 4]. The anisotropy flow for common hadrons (pions, kaons and protons) are developed in both QGP and hadronic stages. A precise extraction of the QGP viscosity from these soft hadron data requires a sophisticated hybrid model that nicely describes the kinetics and decoupling of the hadronic matter. In contrast, hadrons contain multiple strange quarks ($\Xi$, $\Omega$ and etc.) are predicted to decouple earlier from the system due to their smaller hadronic cross sections [5, 6]. They may directly probe the QGP phase and can be used to test the QGP viscosity extracted from the elliptic flow of common hadrons [7].

Recently, the ALICE collaboration measured the multiplicity, $p_T$ spectra and elliptic flow for strange and multi-strange hadrons [8, 9], so this is the right time to perform a careful theoretical investigation of these data. In this article, we will briefly report VISHNU calculations of the elliptic flow for $\Lambda$, $\Xi$ and $\Omega$ hyperons in 2.76 A TeV Pb+Pb collisions. Detailed investigation of these strange and multi-strange hadrons can be found in the incoming article [10]. The VISHNU predictions for the elliptic flow of $\phi$ meson are documented in Ref [11].

2. Set-ups

The theoretical tool used here is VISHNU hybrid model [12]. It connects 2+1-d hydrodynamics for the viscous QGP fluid expansion to a hadron cascade model for the kinetic evolution of the hadronic matter. For simplicity, we neglect the net baryon density, heat flow and bulk viscosity. The equation of state (EOS) s95p-PCE used for the hydrodynamic evolution is constructed from...
Figure 1. (Color online) Differential elliptic flow for $\Lambda$, $\Xi$ and $\Omega$ in 2.76 A TeV Pb+Pb collisions. Experimental data are from ALICE [9], theoretical lines are from VISHNU simulations with $(\eta/s)_{QGP} = 0.16$ and MC-KLN initial conditions.

Recent lattice data [13]. The hyper-surface switching between hydrodynamics and the hadron cascade is constructed by a switching temperature at 165 MeV, which is close to the QCD phase transition and chemical freeze-out temperature at top RHIC energy. Following Ref [14], we use MC-KLN initial conditions. The initial entropy density profiles for selected centralities are generated from MC-KLN model through averaging over a large number of fluctuating entropy density distributions with recentering and aligning the reaction plane. The QGP specific shear viscosity $(\eta/s)_{QGP}$ is set to 0.16, which gives a nice description of $v_2(p_T)$ for pion, kaon and protons at the LHC [11]. For $(\eta/s)_{QGP} = 0.16$, the starting time $\tau_0$ is 0.9 fm/c, which is obtained from fitting the slope of the $p_T$ spectra for all charged hadrons below 2 GeV [14]. With these inputs and parameters fixed, we predict the elliptic flow for strange and multi-strange baryons in 2.76 A TeV Pb+Pb collisions.

3. Results

VISHNU hybrid model is a successful tool to describe and predict the soft hadron productions at RHIC and the LHC. Using VISHNU [12], we extracted the QGP specific shear viscosity from the integrated elliptic flow for all charged hadrons in 200 A GeV Au+Au collisions and found $1/(4\pi) < (\eta/s)_{QGP} < 2.5/(4\pi)$ (0.08 < $(\eta/s)_{QGP} < 0.20$), where the uncertainties are dominated by the undetermined initial conditions from MC-Glauber and MC-KLN models [3]. With that extracted QGP viscosity, VISHNU gives a nice description of the $p_T$ spectra and elliptic flow for all charged and identified hadrons at RHIC [4].

Ref. [14] extrapolates the VISHNU calculations to the LHC and shows that VISHNU could nicely describe the $p_T$ spectra and elliptic flow for all charged hadrons with MC-KLN initial conditions and $(\eta/s)_{QGP} = 0.20 - 0.24$, a slightly higher value than the one extracted at RHIC with MC-KLN initial conditions. With the identified soft hadron data becoming available, we
Further calculated the multiplicity, $p_T$ spectra and differential elliptic flow for pions kaons and protons and found these $v_2(p_T)$ prefer $(\eta/s)_{QGP} = 0.16$ for MC-KLN [11, 15]. It is noticed that the integrated and differential elliptic flow for all charged hadrons are measured by 4 particle cumulants method ($v_2\{4\}$), while the elliptic flow for identified hadrons are measured by scalar product method ($v_2\{sp\}$) based on 2 particle correlations. Comparing with $v_2\{4\}$, non-flow and fluctuations raise the flow signal of $v_2\{sp\}$, leading to a slightly lower value of $(\eta/s)_{QGP}$ to fit $v_2\{sp\}$ data for identified hadrons.

Recently, the ALICE collaboration measured the elliptic flow for $\Lambda$, $\Xi$ and $\Omega$ in 2.76 A TeV Pb+Pb collisions using scalar product method [9]. Using VISHNU hybrid model, we calculate the differential elliptic flow $v_2(p_T)$ for these strange and multi-strange hadrons. Here we choose $(\eta/s)_{QGP} = 0.16$, MC-KLN initial conditions and other parameter sets as used in early calculations [11] that nicely describe the soft hadron data for pions kaons and protons at the LHC. Fig. 1 shows that VISHNU nicely describes $v_2(p_T)$ data for $\Xi$ and $\Omega$ from central to peripheral collisions and nicely describes $\Lambda$ data at 10% and 40% centralities as measured by ALICE. Due to the very low particle yields, the elliptic flow for $\Omega$ has large error bars in ALICE data and the VISHNU results. For better comparisons, the statistics for $\Omega$ should be further increased in both experimental and theoretical sides.

Fig. 2 further explores the mass-ordering of elliptic flow among various hadrons in 2.76 A TeV Pb+Pb collisions. Radial flow tends to push low $p_T$ hadrons to higher transverse momenta. Such effects are more efficient for heavier particles, leading to the mass-ordering of $v_2$ as predicted in hydrodynamics [16]. Comparing with $v_2(p_T)$ for all charge hadrons, the mass-splitting of $v_2$ among various hadrons reflects the interplay of the radial and elliptic flow during hadronic evolution, which is more sensitive to details of theoretical calculations. Fig. 2 shows that, within current statistics, VISHNU roughly reproduces the $v_2$ mass ordering among $\pi$, $K$, $p$, $\Xi$ and $\Omega$ in semi-central collisions, but gives an inverse mass-ordering between $p$ and $\Lambda$ for the two selected (10-20% and 40-50%) centralities. Early OSU calculations [17], using pure viscous hydrodynamics VISH2+1, nicely predicts the mass ordering among $\pi$, $K$, $p$, $\Xi$, $\Omega$ and $\Lambda$ as measured in experiments later on, but over-predicts the elliptic flow for proton and $\Lambda$ at 10-20% centrality bin. With the microscopic description of hadronic rescatterings and evolution, VISHNU hybrid...
model improves the descriptions of the elliptic flow for proton and Λ, while the slightly under-predicts of the proton $v_2(p_T)$ below 2 GeV lead to an inverse mass ordering of $v_2$ between $p$ and Λ. To improve the description of $v_2(p_T)$ for proton as well as for Ξ and Ω, the related hadronic cross sections in UrQMD need to be improved. On the other hand, to further understand these rare multi-strange hadrons and to test theoretical models, the statistics for Ξ and Ω need to be increased in both experimental and theoretical sides.

4. Summary
In this proceeding, we present VISHNU hybrid model calculations of the elliptic flow for Λ, Ξ and Ω in 2.76 A TeV Pb+Pb collisions. VISHNU nicely describes $v_2(p_T)$ for these strange and multi-strange hadrons at various centralities measured by ALICE. It roughly reproduce the mass-ordering of $v_2$ among $π$, $K$, $p$, Ξ and Ω within current statistics, but gives an inverse mass-ordering between $p$ and Λ. For a better comparison and understanding of the elliptic flow data for the rare multi-strange hadrons like Ξ and Ω, high statistic runs are needed in both experimental and theoretical sides.

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