NCQ scaling of $f_0(980)$ elliptic flow in 200 GeV Au+Au collisions by STAR and its constituent quark content

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Abstract. Searching for exotic state particles and studying their properties have furthered our understanding of quantum chromodynamics (QCD). The $f_0(980)$ resonance is an exotic state with relatively high production rate in relativistic heavy-ion collisions, decaying primarily into $\pi\pi$. Currently the structure and quark content of the $f_0(980)$ are unknown with several predictions from theory being a $q\overline{q}$ state, a $qq\overline{qq}$ state, a $K\overline{K}$ molecule state, or a gluonium state. We report the first $f_0(980)$ elliptic flow (v_2) measurement from 200 GeV Au+Au collisions at STAR. The transverse momentum dependence of v_2 is examined and compared to those of other hadrons (baryons and mesons). The empirical number of constituent quark (NCQ) scaling is used to investigate the constituent quark content of $f_0(980)$, which may potentially address an important question in QCD.

1 Introduction

Searching for exotic state particles and studying their properties have furthered our understanding of quantum chromodynamics (QCD). Currently the structure and quark content of $f_0(980)$ are unknown with several predictions being a $q\overline{q}$ state, a $qq\overline{qq}$ state, a $K\overline{K}$ molecule state, or a gluonium state [1–6]. In contrast to the vector and tensor mesons, the identification of the scalar mesons is a long-standing puzzle [7]. Previous preliminary experimental measurements [8] on the yield of $f_0(980)$ at RHIC and theoretical calculation [9] suggest that it could be a $K\overline{K}$ stat. In this analysis, the empirical number of constituent quark (NCQ) scaling [10–12] is used to investigate the constituent quark content of $f_0(980)$ [13].

2 Experiment setup and data analysis

The data reported here are from Au+Au collisions at a nucleon-nucleon center-of-mass energy of 200 GeV, collected by the STAR experiment [14] at Brookhaven National Laboratory in 2011, 2014 and 2016. A total of 2.4 billion minimum-bias (MB) events are selected for this analysis. The main subsystem used for the data analysis is the Time Projection Chamber (TPC) [15] with 2π azimuthal coverage at mid-rapidity. The TPC dE/dx is used to select $\pi^{\pm}$ candidate with $0.2 < p_T < 5.0$ GeV/c.

The $\pi^{+}\pi^{-}$ are used to reconstruct the $f_0(980)$. The combinatorial background subtraction is based on the mixed-event technique and the like-sign method [16]. The acceptance-corrected like-sign

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pairs [16, 17] are used to subtract the combinatorial background after being normalized to unlike-sign pairs in the invariant mass (m_{inv}) range beyond 1.5 GeV/c^2 . Figure 1 (left) shows the background subtracted $\pi^+\pi^-$ invariant mass distribution. The resonance peaks are parametrized with the relativistic Breit-Wigner function [18, 19]. The total fit function is given by:

$$f(m_{inv}) = \left(\sum_{X=f_0,\rho^0,f_2} \frac{A_X m_{inv} m_X \Gamma(X)}{(m_{inv}^2 - m_X^2)^2 + m_X^2 \Gamma(X)^2} \right) \times PS + bg(m_{inv}) \tag{1}$$

where $\Gamma(X) = \frac{\Gamma_X m_X}{m_{inv}} \left(\frac{m_{inv}^2 - 4m_\pi^2}{m_X^2 - 4m_\pi^2} \right)^{J+1/2}$ [18, 19], $PS = \frac{m_{inv}}{\sqrt{m_{inv}^2 + p_T^2}} \exp\left(-\frac{\sqrt{m_{inv}^2 + p_T^2}}{T} \right)$ is the phase space correction taking into account the $\pi\pi$ scattering during the hadronic phase [19–22], and $bg(m_{inv})$ is a third order polynomial function to describe the residual background. m_X and Γ_X are the mass and width of the corresponding resonances. Γ_{ρ^0} is set to 160 MeV, and m_{f_2} and Γ_{f_2} are set according to the PDG values [7]. T is the kinetic freeze-out temperature, set to 120 MeV [20]. A_{f_0}, A_{ρ^0}, A_{f_2}, m_{f_0}, Γ_{f_0}, and m_{ρ^0} are free parameters.

The event-plane method [23] is used to study the elliptic flow (v_2) of $f_0(980)$. The event-plane is reconstructed by all charged particles in the TPC with pseudorapidity $|\eta| < 1$ and transverse momentum $0.2 < p_T < 5.0$ GeV/c. For each $\pi\pi$ pair, the two π candidates are removed from the event-plane reconstruction to avoid auto-correlation. The event-plane resolution is calculated by the correlation between two randomly divided sub-events from the full TPC [23]. Wide centrality bin effect is corrected by weighting the event-plane resolution with the $f_0(980)$ yield in each narrow centrality bin of 10% size [24]. Figure 1(right) shows the $f_0(980)$ yield as function of the azimuthal angle difference between the $\pi\pi$ pair (ϕ) and the event-plane direction (Ψ) in an example p_T bin.

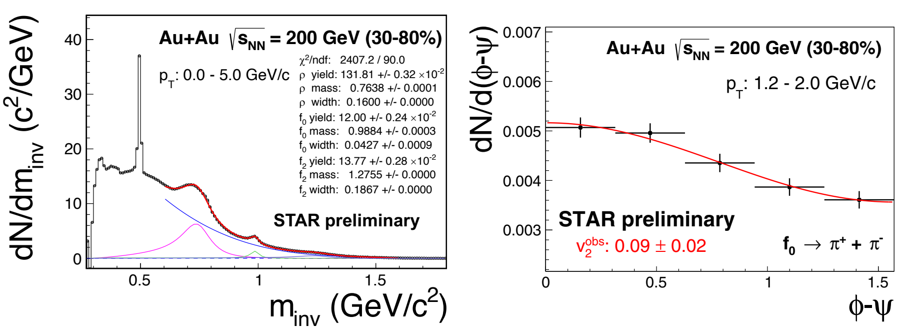

Figure 1. (Color online) (Left) The background subtracted $\pi^+\pi^-$ invariant mass distribution over the p_T range of $0 < p_T < 5.0$ GeV/c in 30–80% Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV. The red line is the result of fit. The pink, green, violet lines represent the resonance peaks of the relativistic Breit-Wigner function. The solid blue line represents the residual background using a third order polynomial function. (Right) $f_0(980)$ yield as function of $\phi - \Psi$ in a given p_T bin. Errors are statistical. The red line represents a fit ($\propto (1 + 2v_2^{obs}\cos(2\phi - 2\Psi))$) to the data.

Figure 2 shows $f_0(980)$ v_2 as a function of p_T in 30-80% centrality Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. Results are compared with other identified particles: $\pi, K, p, K_s^0, \Lambda, \Xi, \Omega, \phi$ [24]. In the low p_T region, the $f_0(980)$ v_2 seems to follow the mass ordering. In the higher p_T region, the $f_0(980)$ v_2 seems closer to the baryon band.

Figure 3 shows the number of constituent quark (n_q) scaled v_2 as function of the n_q scaled p_T (left) and $m_T - m_0$ (right). Here the $f_0(980)$ is assumed to have either 2 quarks or 4 quarks. The data are

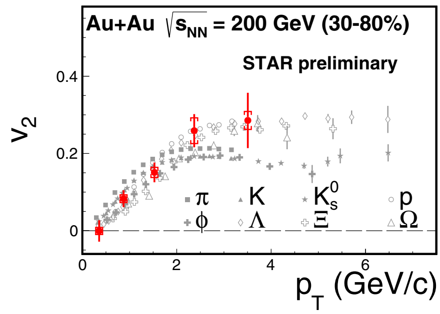

Figure 2. (Color online) $f_0(980)$ v_2 as a function of $p_{\rm T}$ in 30-80% centrality Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. Statistical uncertainties are shown by the vertical bars and systematic uncertainties are shown by the caps. Results of other particles are taken from Ref. [24].

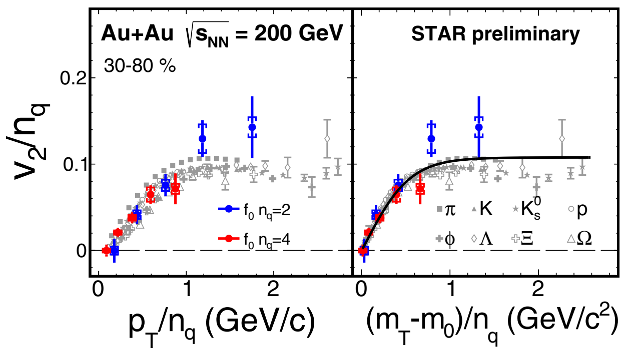

Figure 3. (Color online) $f_0(980)$ v_2 divided by n_q as a function of $p_{\rm T}/n_q$ (left) and $(m_T - m_0)/n_q$ (right) in 30-80% centrality Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. Results of other particles are taken from Ref. [24]. Black line in the right panel represents a fit to results of other particles using a NCQ scaling inspired function (Eq. 2).

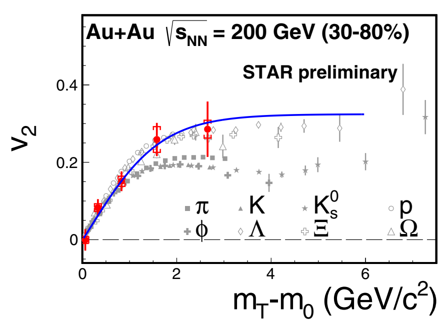

Figure 4. (Color online) $f_0(980)$ v_2 as a function of $m_T - m_0$ in 30-80% centrality Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. The blue curve represents the NCQ inspired fit (Eq. 2), where the only free parameter is the n_q of $f_0(980)$ and all other parameters are fixed according to the fit in the right panel of the Fig. 3.

compared to the fit of other particles [24] using a NCQ scaling inspired function [25]:

$$f_{v_2}(n_q) = \frac{a n_q}{1 + \exp(-((m_T - m_0)/n_q - b)/c)} - d n_q. \quad (2)$$

The 2-quarks (4-quarks) scaled $f_0(980)$ v_2 seems to deviate from the fit, above (below) the fit by $\sim 1\sigma$ for the last one or two points at high $(m_T - m_0)/n_q$.

Figure 4 shows $f_0(980)$ v_2 as a function of $m_T - m_0$ with a fit according to the function shown in Eq. 2. In the fit, only the n_q of $f_0(980)$ is treated as a free parameter and all other parameters are fixed according to the fit in the right panel of the Fig. 3. This NCQ scaling fit of the $f_0(980)$ v_2 yields $n_q = 3.0 \pm 0.7$ (stat) $\pm$ 0.5 (syst).

With the current uncertainty, our result is not able to determine whether $f_0(980)$ is a $q\overline{q}$, $qq\overline{qq}$, $K\overline{K}$ molecule, gluonium state, or produced through $\pi\pi$ coalescence. It could also be given by some combined states as well. Future measurements, e.g. the $f_0(980)$ yields, could also provide different aspect to understand it.

3 Summary

Preliminary results on the $f_0(980)$ v_2 in 30-80% centrality Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV are presented. In the low $p_{\rm T}$ region ($p_{\rm T}$<2 GeV/c), the $f_0(980)$ v_2 seems to follow the mass ordering. In the higher $p_{\rm T}$ region ($p_{\rm T}$>2 GeV/c), the $f_0(980)$ v_2 seems closer to the baryon band. A NCQ scaling inspired function was used to fit the $f_0(980)$ v_2. The extracted quark content of $f_0(980)$ is n_q = 3.0 ± 0.7 (stat) ± 0.5 (syst). More data are needed to understand whether $f_0(980)$ is a $q\overline{q}$, $qq\overline{qq}$, $K\overline{K}$ molecule, gluonium state, or produced through $\pi\pi$ coalescence. Our study indicates that heavy-ion collisions can be a useful place to examine the quark content of scalar mesons. The isobar data taken in 2018 at RHIC and the 8-fold increase in Au+Au data expected in 2023-2025 would provide more insights.

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