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

Jie Zhao¹·⋆ (for the STAR collaboration)

¹Department of Physics and Astronomy, Purdue University

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 $qq$ state, a $qqq\bar{q}$ state, a $KK$ 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 $qq$ state, a $qqq\bar{q}$ state, a $KK$ molecule state, or a gluonium state [1–5]. 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 $KK$ 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 $2\pi$ 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
pairs [16] [17] are used to subtract the combinatorial background after being normalized to unlike-sign pairs in the invariant mass \( m_{\text{inv}} \) 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:

\[
f(m_{\text{inv}}) = \left( \sum_{X=f_0, \phi} \frac{A_X m_{\text{inv}} m_X \Gamma(X)}{(m_{\text{inv}}^2 - m_X^2)^2 + m_X^2 \Gamma(X)^2} \right) \times PS + bg(m_{\text{inv}})
\]

where \( \Gamma(X) = \Gamma_X m_X \left( \frac{m_{\text{inv}}^2 - 4m_X^2}{m_X^2 - 4m_{\text{inv}}^2} \right)^{J+1/2} \) [18] [19], \( PS = \sqrt{m_{\text{inv}}^2 + p_T^2} \exp \left( -\frac{m_{\text{inv}}^2 + p_T^2}{T} \right) \) is the phase space correction taking into account the \( \pi \pi \) scattering during the hadronic phase [19] [22], and \( bg(m_{\text{inv}}) \) is a third order polynomial function to describe the residual background. \( m_X \) and \( \Gamma_X \) are the mass and width of the corresponding resonances. \( \Gamma_{f_0} \) is set to 160 MeV, and \( m_{f_2} \) and \( \Gamma_{f_2} \) are set according to the PDG values [7]. \( T \) is the kinetic freeze-out temperature, set to 120 MeV [20]. \( A_{f_0}, A_{\rho}, A_{f_2}, m_{f_0}, \Gamma_{f_0} \), and \( m_{f_2} \) 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 \( 0.2 < p_T < 5.0 \text{ GeV/c} \). For each \( \pi\pi \) pair, the two \( \pi \) 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 \( (\phi) \) and the event-plane direction \( (\Psi) \) in an example \( p_T \) bin.

![Figure 1](image-url) (Color online) (Left) The background subtracted \( \pi^+\pi^- \) invariant mass distribution over the \( p_T \) range of \( 0 < p_T < 5.0 \text{ GeV/c} \) in 30-80% Au+Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \). 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 \( (\propto (1 + 2v_2^{\text{obs}} \cos(2(\phi - 2\Psi))) \) 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 \( \sqrt{s_{NN}} = 200 \text{ GeV} \). Results are compared with other identified particles: \( \pi, K, p, K^0, \Lambda, \Xi, \Omega, \phi \) [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 $p_T$ 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 $p_T/n_q$ (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]:

$$f_v(n_q) = \frac{a n_q}{1 + \exp(-(m_T - m_0)/n_q - b)/c} - d n_q.$$  \hspace{1cm} (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 $q\bar{q}$, $qq\bar{q}\bar{q}$, $K\bar{K}$ 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 $\sqrt{s_{NN}} = 200$ GeV are presented. In the low $p_T$ region ($p_T<2$ GeV/c), the $f_0(980)$ $v_2$ seems to follow the mass ordering. In the higher $p_T$ region ($p_T>2$ 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 $n_q = 3.0 \pm 0.7$ (stat) $\pm 0.5$ (syst). More data are needed to understand whether $f_0(980)$ is a $q\bar{q}$, $qq\bar{q}\bar{q}$, $K\bar{K}$ 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.

Acknowledgments

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References

[1] J.D. Weinstein, N. Isgur, Phys. Rev. D 27, 588 (1983)
[2] J.D. Weinstein, N. Isgur, Phys. Rev. D 41, 2236 (1990)
[3] F. Kleefeld, E. van Beveren, G. Rupp, M.D. Scadron, Phys. Rev. D 66, 034007 (2002)
[4] V. Baru et al., Phys. Lett. B 586, 53 (2004)
[5] M. Ablikim et al. (BESIII), Phys. Rev. D 92, 052003 (2015)
[6] N.N. Achasov et al., Phys. Rev. D 103, 014010 (2021)
[7] P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 083C01 (2020)
[8] P. Fachini, J. Phys. G 30, S735 (2004)
[9] S. Cho et al. (ExHIC), Phys. Rev. Lett. 106, 212001 (2011)
[10] D. Molnar, S.A. Voloshin, Phys. Rev. Lett. 91, 092301 (2003)
[11] S.S. Adler et al. (PHENIX), Phys. Rev. Lett. 91, 182301 (2003)
[12] J. Adams et al. (STAR), Phys. Rev. Lett. 92, 052302 (2004)
[13] A. Gu, T. Edmonds, J. Zhao, F. Wang, Phys. Rev. C 101, 024908 (2020)
[14] K.H. Ackermann et al. (STAR), Nucl. Instrum. Meth. A499, 624 (2003)
[15] M. Anderson et al., Nucl. Instrum. Meth. A499, 659 (2003)
[16] L. Adamczyk et al. (STAR), Phys. Rev. C 92, 024912 (2015)
[17] L. Adamczyk et al. (STAR), Phys. Rev. Lett. 113, 022301 (2014)
[18] C. Adler et al. (STAR), Phys. Rev. Lett. 89, 272302 (2002)
[19] J. Adams et al. (STAR), Phys. Rev. Lett. 92, 092301 (2004)
[20] E.V. Shuryak, G.E. Brown, Nucl. Phys. A 717, 322 (2003)
[21] P.F. Kolb, M. Prakash, Phys. Rev. C 67, 044902 (2003)
[22] R. Rapp, Nucl. Phys. A 725, 254 (2003)
[23] A.M. Poskanzer, S.A. Voloshin, Phys. Rev. C 58, 1671 (1998)
[24] L. Adamczyk et al. (STAR), Phys. Rev. Lett. 116, 062301 (2016)
[25] X. Dong, S. Esumi, P. Sorensen, N. Xu, Z. Xu, Phys. Lett. B 597, 328 (2004)