

Violation of the elliptic flow scaling of $f_0(980)$ in p-Pb collisions at the LHC

Yili Wang^{1,*}, Wenbin Zhao^{2,3}, Che Ming Ko⁴, Feng-Kun Guo^{5,6}, Ju-Jun Xie⁷, and Huichao Song^{1,8}

¹School of Physics, Peking University, Beijing 100871, China

²Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

³Physics Department, University of California, Berkeley, California 94720, USA

⁴Cyclotron Institute and Department of Physics and Astronomy, Texas A&M University, College Station, Texas 77843, USA

⁵Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China

⁶School of Physical Sciences, University of Chinese Academy of Sciences, Beijing 100049, China

⁷Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China

⁸Center for High Energy Physics, Peking University, Beijing 100871, China

Abstract. We investigate the production and elliptic flow of the $f_0(980)$ in high-multiplicity p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV using a hadronic coalescence model with the K and \bar{K} phase-space distributions provided by the Hydro-Coal-Frag hybrid model. Our results, which agree with the ALICE and CMS measurements, support the $K\bar{K}$ molecular interpretation of the $f_0(980)$ structure and show, however, a breakdown of the simple number-of-constituent (NC) scaling of its elliptic flow. The latter is in contrast to the deuteron elliptic flow, which exhibits a significantly better NC scaling when the same coalescence width parameter is used.

Relativistic heavy-ion and light-ion collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) aim to create the quark-gluon plasma (QGP), a form of hot QCD matter that once existed in the very early universe. Near the critical temperature, the QGP undergoes hadronization, producing a variety of particles—including not only stable hadrons and resonances, but also light nuclei and exotic hadrons such as the deuteron, $X(3872)$, and $f_0(980)$. The formation of the QGP can lead to sufficiently large yields of certain light exotic hadrons, which enables systematic measurements of their transverse momentum spectra and anisotropic flows, offering a unique opportunity to probe the internal structure of exotic hadrons, e.g., to distinguish between compact tetraquark states and loosely bound molecular configurations. The $f_0(980)$, reconstructed via the decay channel $f_0(980) \rightarrow \pi^+\pi^-$ [B.R. = $(46 \pm 6)\%$], is an especially promising candidate due to its relatively low mass and abundant production. Recently, its yield, transverse momentum spectra, and elliptic flow (v_2) have been measured in p-Pb collisions at the LHC [1, 2]. Analysis of the v_2 data from the CMS Collaboration, using the number-of-constituent-quark (NCQ) scaling, suggests that the $f_0(980)$ has a conventional $q\bar{q}$ structure. This conclusion is in contrast with the hadron physics studies, which provide substantial evidence for a tetraquark or $K\bar{K}$ molecular configuration [3–7]. In this work, we employ a hadronic coalescence model,

*Speaker, e-mail: 2301110109@pku.edu.cn

which is commonly used to study the production of light nuclei, together with phase-space distributions of kaons from the Hydro–Coal–Frag hybrid model to calculate the production and elliptic flow of the $f_0(980)$ in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Our results support a molecular interpretation of the $f_0(980)$ and indicate that the hadronic coalescence process leads to a deviation from the naive NC scaling, which is more pronounced for the $f_0(980)$ than for the deuteron. This proceedings contribution is based on our work in Ref. [8].

The $f_0(980)$ is a resonance with a finite width near the $K\bar{K}$ threshold. Its $K\bar{K}$ component exhibits characteristic features of a weakly bound system, similar to the deuteron [7]. We therefore assume that it survives only after kinetic freeze-out and calculate its yield using the hadronic coalescence approach. In this model, the formation probability of a weakly bound composite is determined by the overlap of the Wigner function, ρ^W , with the phase-space distributions of its constituent particles, $f_i(\mathbf{x}_i, \mathbf{p}_i, t_i)$, at the kinetic freeze-out [9–11]:

$$\frac{dN}{d^3\mathbf{P}} = g \int p_1^\mu d^3\sigma_{1\mu} \frac{d^3\mathbf{p}_1}{E_1} p_2^\nu d^3\sigma_{2\nu} \frac{d^3\mathbf{p}_2}{E_2} \times f_1(\mathbf{x}_1, \mathbf{p}_1, t_1) f_2(\mathbf{x}_2, \mathbf{p}_2, t_2) \times \rho^W(\mathbf{x}'_1, \mathbf{x}'_2; \mathbf{p}'_1, \mathbf{p}'_2; t') \delta(\mathbf{P} - \mathbf{p}_1 - \mathbf{p}_2), \quad (1)$$

where $g = (2J+1)/\prod_{i=1}^A(2J_i+1)$ is the statistical factor for forming a composite with angular momentum J from A constituents of spin J_i . In the above, \mathbf{x}_i and \mathbf{p}_i are the coordinates and momenta in the lab frame, while \mathbf{x}'_i and \mathbf{p}'_i are defined in the $f_0(980)$ rest frame. Assuming a Gaussian wave function for the formed composite, its Wigner function is then given by

$$\rho^W(\boldsymbol{\rho}, \mathbf{p}_\rho) = 8 \exp \left[-\frac{\boldsymbol{\rho}^2}{\sigma_\rho^2} - \mathbf{p}_\rho^2 \sigma_\rho^2 \right], \quad (2)$$

where $\boldsymbol{\rho} = \frac{1}{\sqrt{2}}(\mathbf{x}'_1 - \mathbf{x}'_2)$ and $\mathbf{p}_\rho = \frac{1}{\sqrt{2}}(\mathbf{p}'_1 - \mathbf{p}'_2)$ are the relative coordinate and momentum in the composite rest frame. The Gaussian width σ_ρ is related to the root-mean-square (RMS) radius $\sqrt{\langle r^2 \rangle}$ of the composite via $\sigma_\rho = \frac{2}{\sqrt{3}} \sqrt{\langle r^2 \rangle}$. For the deuteron, experimental data gives an RMS radius $\sqrt{\langle r^2 \rangle} = 1.96$ fm [12], while the RMS radius of the $f_0(980)$ remains uncertain due to limited data. Following the standard estimate for near-threshold hadronic molecules [7], its size can be approximated as $R \sim 1/\sqrt{2\mu E_B}$, where μ is the reduced mass and E_B the binding energy. For $E_B \approx 10$ – 20 MeV, the RMS radius of the $f_0(980)$ is estimated to be $\sqrt{\langle r^2 \rangle} \sim 1.0$ – 1.5 fm. In the following calculations in Fig. 1, we also increase the RMS radius of the $f_0(980)$ to $\sqrt{\langle r^2 \rangle} = 1.96$ fm, just for a comparison with the calculations of the deuteron. The phase-space distributions $f_i(\mathbf{x}_i, \mathbf{p}_i, t_i)$ are taken from the Hydro–Coal–Frag hybrid model, which combines hadron production at low p_T from hydrodynamics, at intermediate p_T from quark coalescence, and at high p_T from string fragmentation [13]. This model has been tuned to reproduce the p_T spectra and the elliptic flow of pions, kaons, and protons up to 6 GeV in high multiplicity p–Pb collisions at the LHC [14], relevant for the production of $f_0(980)$ and deuterons via $K\bar{K}$ and pn coalescences.

Upper panels of Fig. 1 show the p_T spectra and $v_2(p_T)$ of kaons and $f_0(980)$ in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The results of kaons are calculated from the Hydro–Coal–Frag model, which well reproduce the ALICE and CMS data up to 6 GeV. Using the K and \bar{K} phase-space distributions at the kinetic freeze-out, we compute the $f_0(980)$ production via $K + \bar{K} \rightarrow f_0(980)$ coalescence. The resulting spectra and v_2 are consistent with the ALICE and CMS measurements, with $\sqrt{\langle r^2 \rangle} = 1.0$ fm or 1.5 fm. Although the RMS radius has a noticeable effect on the yields of the $f_0(980)$, it only slightly influences its $v_2(p_T)$. A mild underestimation of the yields at high p_T is likely due to the absence of fragmentation contributions. Overall, the good agreement with the v_2 data supports the $K\bar{K}$ molecular interpretation of the $f_0(980)$. The upper right panel demonstrates, however, a breakdown of the

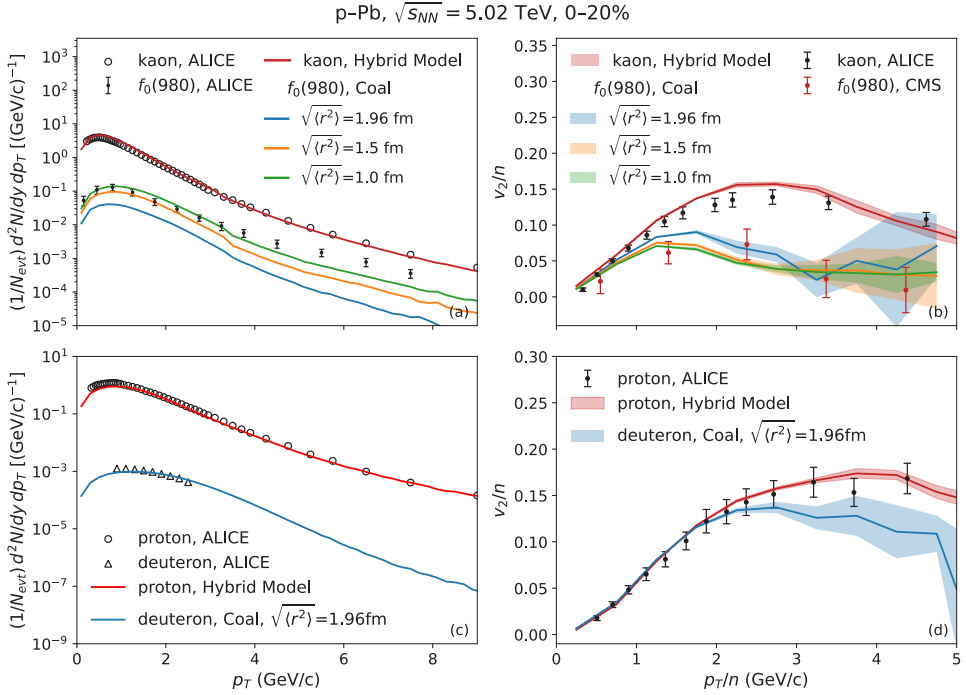


Figure 1. p_T -spectra and $v_2(p_T)$ of $f_0(980)$ and deuterons calculated from the coalescence model, using the phase-space distributions of kaons and protons from the Hydro-Coal-Frag Hybrid model [13, 14]. Data are from [1, 2, 15–17].

NC scaling of v_2 for the $f_0(980)$ because its Wigner function depends on both coordinate and momentum separations. A small σ_ρ (with $\sqrt{\langle r^2 \rangle} = 1.0$ fm or 1.5 fm) broadens the momentum width, allowing recombination of constituents with unequal momenta and leading to the violation of the NC scaling of v_2 [8].

For comparison, we also compute deuteron production via $p+n \rightarrow d$ coalescence with the coalescence parameter $\sigma_\rho = 2.26$ fm ($\sqrt{\langle r^2 \rangle} = 1.96$ fm). As shown in lower panels of Fig. 1, the p_T -spectra and $v_2(p_T)$ of protons are well reproduced, and the deuteron spectra from the coalescence model fit the measured data well. The upper and lower right panels also show that, with the same RMS radius $\sqrt{\langle r^2 \rangle} = 1.96$ fm, a substantially better NC scaling of v_2 for the deuteron than for the $f_0(980)$. This difference can be attributed to the much higher density of kaons than that of protons and neutrons at the kinetic freeze-out, which increases the coalescence probability of kaons with mismatched spatial coordinates and momenta associated with the NC scaling violation [8].

In summary, we have calculated the p_T -spectra and elliptic flow $v_2(p_T)$ of the $f_0(980)$ in high-multiplicity p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, using a hadronic coalescence model with $K + \bar{K} \rightarrow f_0(980)$ coalescence. Our calculations reproduce the measured data well, which supports the $f_0(980)$ being a loosely bound $K\bar{K}$ molecule. We further show that, with reasonable values for the RMS radius of $f_0(980)$, the Wigner function in the $K\bar{K}$ coalescence allows recombination of kaons with unequal momenta, leading to a breakdown of the hadronic NC scaling of v_2 for the $f_0(980)$. In contrast, the deuteron exhibits a significantly better NC scaling behavior of v_2 , due to the lower densities of its constituent protons and neutrons at the kinetic freeze-out than those of kaons.

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References

- [1] S. Acharya et al. (ALICE), Observation of abnormal suppression of $f_0(980)$ production in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, *Phys. Lett. B* **853**, 138665 (2024), 2311.11786. [10.1016/j.physletb.2024.138665](https://doi.org/10.1016/j.physletb.2024.138665)
- [2] A. Hayrapetyan et al. (CMS), Elliptic anisotropy measurement of the $f_0(980)$ hadron in proton-lead collisions and evidence for its quark-antiquark composition (2023), 2312.17092
- [3] R.L. Jaffe, Multi-Quark Hadrons. 1. The Phenomenology of (2 Quark 2 anti-Quark) Mesons, *Phys. Rev. D* **15**, 267 (1977). [10.1103/PhysRevD.15.267](https://doi.org/10.1103/PhysRevD.15.267)
- [4] R.L. Jaffe, Multi-Quark Hadrons. 2. Methods, *Phys. Rev. D* **15**, 281 (1977). [10.1103/PhysRevD.15.281](https://doi.org/10.1103/PhysRevD.15.281)
- [5] J.D. Weinstein, N. Isgur, K anti-K Molecules, *Phys. Rev. D* **41**, 2236 (1990). [10.1103/PhysRevD.41.2236](https://doi.org/10.1103/PhysRevD.41.2236)
- [6] V. Baru, J. Haidenbauer, C. Hanhart, Y. Kalashnikova, A.E. Kudryavtsev, Evidence that the $a_0(980)$ and $f_0(980)$ are not elementary particles, *Phys. Lett. B* **586**, 53 (2004), hep-ph/0308129. [10.1016/j.physletb.2004.01.088](https://doi.org/10.1016/j.physletb.2004.01.088)
- [7] F.K. Guo, C. Hanhart, U.G. Meißner, Q. Wang, Q. Zhao, B.S. Zou, Hadronic molecules, *Rev. Mod. Phys.* **90**, 015004 (2018), [Erratum: *Rev.Mod.Phys.* 94, 029901 (2022)], 1705.00141. [10.1103/RevModPhys.90.015004](https://doi.org/10.1103/RevModPhys.90.015004)
- [8] Y. Wang, W. Zhao, C.M. Ko, F. Guo, J. Xie, H. Song, Probing the structure of light exotic hadron $f_0(980)$ with elliptic flow in p-Pb collisions at the LHC (2025), in preparation.
- [9] L.W. Chen, C.M. Ko, B.A. Li, Light cluster production in intermediate-energy heavy ion collisions induced by neutron rich nuclei, *Nucl. Phys. A* **729**, 809 (2003), nucl-th/0306032. [10.1016/j.nuclphysa.2003.09.010](https://doi.org/10.1016/j.nuclphysa.2003.09.010)
- [10] W. Zhao, L. Zhu, H. Zheng, C.M. Ko, H. Song, Spectra and flow of light nuclei in relativistic heavy ion collisions at energies available at the BNL Relativistic Heavy Ion Collider and at the CERN Large Hadron Collider, *Phys. Rev. C* **98**, 054905 (2018), 1807.02813. [10.1103/PhysRevC.98.054905](https://doi.org/10.1103/PhysRevC.98.054905)
- [11] W. Zhao, C. Shen, C.M. Ko, Q. Liu, H. Song, Beam-energy dependence of the production of light nuclei in Au + Au collisions, *Phys. Rev. C* **102**, 044912 (2020), 2009.06959. [10.1103/PhysRevC.102.044912](https://doi.org/10.1103/PhysRevC.102.044912)
- [12] C. Rappold et al. (HypHI), Search for evidence of ${}^3_{\Lambda}n$ by observing $d + \pi^-$ and $t + \pi^-$ final states in the reaction of ${}^6Li + {}^{12}C$ at 2A GeV, *Phys. Rev. C* **88**, 041001 (2013). [10.1103/PhysRevC.88.041001](https://doi.org/10.1103/PhysRevC.88.041001)
- [13] W. Zhao, C.M. Ko, Y.X. Liu, G.Y. Qin, H. Song, Probing the Partonic Degrees of Freedom in High-Multiplicity p – Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, *Phys. Rev. Lett.* **125**, 072301 (2020), 1911.00826. [10.1103/PhysRevLett.125.072301](https://doi.org/10.1103/PhysRevLett.125.072301)
- [14] Y. Wang, W. Zhao, H. Song, Exploring the partonic collectivity in small systems at the LHC (2023), 2401.00913.

- [15] J. Adam et al. (ALICE), Multiplicity dependence of charged pion, kaon, and (anti)proton production at large transverse momentum in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, Phys. Lett. B **760**, 720 (2016), 1601.03658. [10.1016/j.physletb.2016.07.050](https://doi.org/10.1016/j.physletb.2016.07.050)
- [16] S. Acharya et al. (ALICE), Observation of partonic flow in proton-proton and proton-nucleus collisions (2024), 2411.09323.
- [17] S. Acharya et al. (ALICE), Multiplicity dependence of light (anti-)nuclei production in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, Phys. Lett. B **800**, 135043 (2020), 1906.03136. [10.1016/j.physletb.2019.135043](https://doi.org/10.1016/j.physletb.2019.135043)