IL NUOVO CIMENTO **48 C** (2025) 20
DOI 10.1393/ncc/i2025-25020-7

Colloquia: WPCF-Resonance 2023

Measurement of azimuthal anisotropy of $\mathrm{f}_0(980)$ and D^0 in heavy ion collisions at CMS

Nihar Ranjan Saha for the CMS Collaboration
Indian Institute of Technology - Madras, India

received 23 July 2024

Summary. — We present novel insights into the elusive $\mathrm{f}_0(980)$ hadron's quark composition and the interaction of heavy charm quarks with the quark-gluon plasma (QGP) through the anisotropic flow measurement of D^0 in Heavy-Ion collisions. The $\mathrm{f}_0(980)$, whose precise configuration has remained controversial, is reconstructed for the first time via its dominant decay channel, $\mathrm{f}_0(980) \to \pi^+\pi^-$, using data from proton-lead collisions at 8.16 TeV, as collected by the CMS experiment. The azimuthal angle anisotropy v_2 of $\mathrm{f}_0(980)$ relative to the event plane is also investigated, allowing us to extract the v_2 parameter for the $\mathrm{f}_0(980)$ and compare it with other hadrons. In addition, we also investigate how heavy quarks interact with QGP by measuring the coefficients of azimuthal anisotropy (v_n) of D^0 mesons in lead-lead collisions at 5.02 TeV with CMS experiment. The measurements cover a wide range of transverse momentum and thus reveal the flow formation mechanisms of heavy charm quarks, illuminating the diffusion and path-dependent parton energy loss.

1. – Introduction

Exotic hadrons, characterized by configurations diverging from the conventional $\mathrm{q\bar{q}}$ and $\mathrm{qqq(\bar{q}\bar{q}\bar{q})}$ formations, have long captivated researchers due to their potential insight into the realm of quantum chromodynamics (QCD). The $\mathrm{f}_0(980)$ stands as a prime example of such exotic candidates, initially detected amidst $\pi\pi$ scattering investigations during the 1970s. Despite decades of scrutiny, its definitive configuration remains contentious, with proposed identities ranging from a conventional $\mathrm{S\bar{S}}$ meson to a tetraquark $\mathrm{s\bar{s}q\bar{q}}$ amalgamation or a composite $\mathrm{K\bar{K}}$ molecular structure [1-3].

Conversely, the final state correlations between heavy and light flavor hadrons emitted from high-energy nuclear collisions offer a unique avenue for unraveling the mass-dependent parton energy loss and diffusion within quark-gluon plasma (QGP) that may be elucidated through azimuthal anisotropy Fourier coefficients such as v_2 (elliptic flow) and v_3 (triangular flow). Studies on the behavior of charm (c) quarks reveal strong similarities with lighter quarks with their transverse momentum (p_T) and centrality dependences. However, the magnitude of flow coefficients for c quarks, especially within the

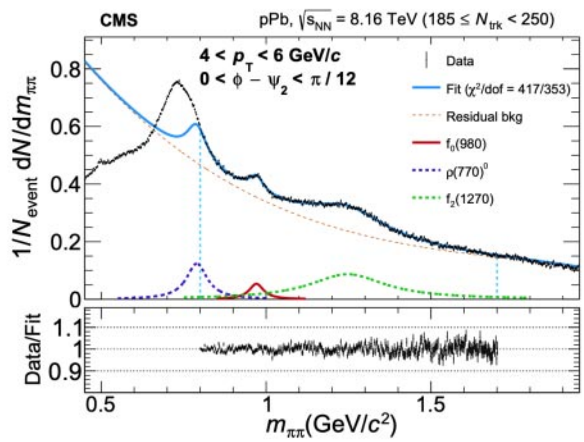

Fig. 1. – The same sign combinatorial background subtracted invariant mass spectrum for pair transverse momentum $4 < p_T < 6$ GeV/c and azimuthal angle $0 < \phi - \psi_2 < \pi/12$ in high-multiplicity ($185 \leq N_{\text{offline}} < 250$) pPb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV. The figure is taken from ref. [5]

low and intermediate p_{T} regime ($p_{\text{T}} < 15$ GeV/c), suggests a distinct thermalization process. Given the significantly greater mass of bottom (b) quarks relative to charm quarks, analyzing azimuthal anisotropy of b hadrons presents a promising avenue for gaining deeper insights into the interactions between heavy quarks and the QGP medium.

2. – Datasets and analysis details

To study the configuration of $\text{f}_0(980)$ we used high multiplicity data sample collected from pPb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV with CMS [4] in 2016, with integrated luminosity of 186 nb^{-1}. The standard triggers, event, and track selections for CMS pPb at the given energy were applied. The $\text{f}_0(980)$ is reconstructed via the invariant mass spectrum through its dominant decay channel, $\text{f}_0(980) \to \pi^+\pi^-$. Each pair of tracks is corrected for the track efficiencies using HIJING model simulation and detector response with GEANT4 as a function of p_{T} and η. The mass spectrum fig.1 is fitted with a function composed of three Breit-Wigner functions for the $\rho(770)$, $\text{f}_0(980)$, and $f_2(1270)$ peaks and a third order polynomial to model the residual background. The mass fit range is chosen to be $0.8 - 1.7$ GeV/c^2, with the upper limit to exclude the $\rho(1770)$ peak and the lower limit to avoid the low mass region not well described by the polynomial function.

In order to compare the nonflow-subtracted v_2 of $\text{f}_0(980)$, v_2^{sub} to the established NCQ scaling by other hadrons, the $v_2^{\text{sub}}/n_{\text{q}}$ of K_{S}^0, Λ, Ξ^-, and Ω measured in the same high-multiplicity range is fitted by $f(E_{\text{T}}/n_{\text{q}}) = E_{\text{T}}/n_{\text{q}}(p_0 + p_1 E_{\text{T}}/n_{\text{q}})e^{-p_2 E_{\text{T}}/n_{\text{q}}}$ as a function of transverse kinetic energy per constituent quark, $E_{\text{T}}/n_{\text{q}}$. Here $E_{\text{T}} = \sqrt{q_{\text{m}}^2 + \langle p_{\text{T}} \rangle^2} - m$ and the $\text{f}_0(980)$ mass is taken to be $m = 0.99$ GeV/c^2.

On the other hand, to measure the azimuthal anisotropy of D^0, we utilized the PbPb collisions data at $\sqrt{S_{\text{NN}}} = 5.02$ TeV collected with the CMS detector with a total integrated luminosity of 0.58 pb^{-1} . Inclusive D^0 meson candidates reconstruction is done via decay channel $D^0 \to \pi^+ + K^-(D^0 \to \pi^- + K^+)$ by pairing particles of opposite charge. A

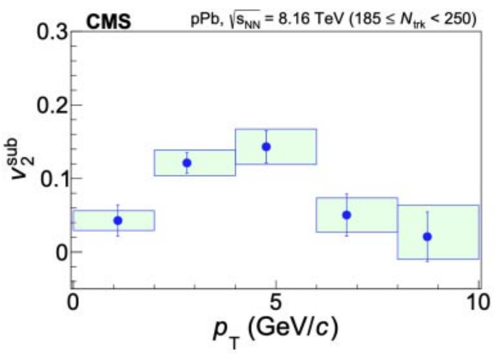

Fig. 2. – The nonflow-subtracted elliptic flow v_2^{sub} of the $f_0(980)$ as functions of p_T within pseudorapidity $|\eta| < 2.4$ in high-multiplicity $185 \leq N_{\mathrm{offline}} < 250$ pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV. The figure is taken from ref. [5]

boosted decision tree algorithm, from the TMVA package [6], is applied in order to suppress the background (both combinatorial background and prompt D^0 component).The fraction of nonprompt D^0 mesons is extracted from the template fit of the distribution of the distance of closest approach between the collision point and the direction of the D^0 momentum vector.

3. – Results

We measured the elliptic anisotropy v_2 and the nonflow-subtracted v_2^{sub} of the $f_0(980)$. A significant positive v_2 signal is observed, with a clear trend of rising and declining with p_T, achieving a v_2 and v_2^{sub} maximum at $4 < p < 6$ GeV/c. Also, a comparison of $v_2^{\mathrm{sub}}/n_{\mathrm{q}}$ to those of K_{S}^0, Λ, Ξ^- , and Ω as functions of p_T/n_{q} (left panel) and $E_{\mathrm{T}}/n_{\mathrm{q}}$ (right panel). Two sets of the $f_0(980)$ data points are depicted in fig. 3, one with the $n_{\mathrm{q}} = 2$ hypothesis and the other with the $n_{\mathrm{q}} = 4$ hypothesis. It indicates that the $n_{\mathrm{q}} = 2$ ($\mathrm{q\bar{q}}$ state) hypothesis is favored over $n_{\mathrm{q}} = 4$ ($\mathrm{qq(\bar{q}\bar{q})}$ or $\mathrm{K\bar{K}}$ states) in the $p_{\mathrm{T}} < 10$ GeV/c range.

Moreover, we measured v_2 and v_3, the azimuthal anisotropy coefficients for nonprompt

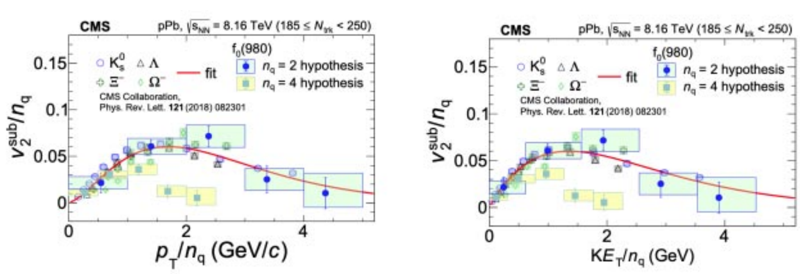

Fig. 3. – The $v_2^{\mathrm{sub}}/n_{\mathrm{q}}$ of $f_0(980)$ (with $n = 2$ and 4) as functions of p_T/n_{q} (left panel) and $E_{\mathrm{T}}/n_{\mathrm{q}}$ (right panel), compared with those of other hadrons (K_S^0, Λ, Ξ^-, and Ω strange hadrons) in high-multiplicity $185 \leq N_{\mathrm{offline}} < 250$ pPb collisions at $\sqrt{S_{\mathrm{NN}}} = 8.16$ TeV. The figure is taken from ref. [5]

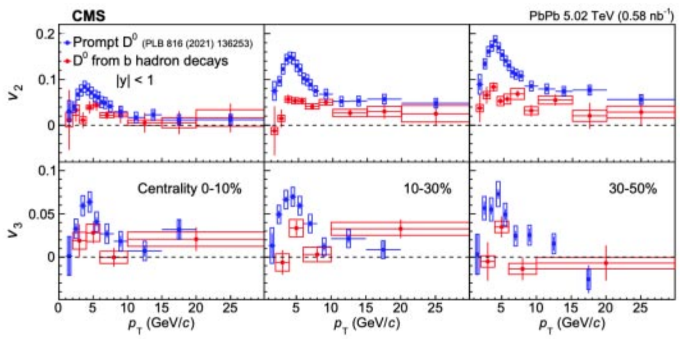

Fig. 4. – The elliptic, v_2 (top panel), and the triangular, v_3 (bottom panel), flow coefficients of nonprompt and prompt D^0 mesons as functions of p_{T} and in three bins of centrality. The figure is taken from ref. [8]

D^0 mesons, compared with previously published prompt D^0 from ref. [7], are shown in fig.4. The results show non-zero values of the elliptic flow of b hadron daughters, although the flow magnitude is significantly smaller than the prompt D^0 case. The difference is more evident in the low and intermediate p_{T} range and it follows the mass ordering. At larger D^0 transverse momentum, elliptic flow values from c and b quarks start converging. The v_2 coefficients of nonprompt D^0 mesons exhibit very weak dependence on centrality and p_{T}, unlike flow of promptly produced D^0 mesons where those dependencies are strongly expressed.

The comparison between the measured nonprompt D^0 v_n coefficients and theoretical calculations that have different modeling of the b quark flow is shown in fig.5. While all models show qualitative agreement with the measured p_{T} dependence of the elliptic flow, quantitative discrepancies could constrain the description of b quark interactions with the medium.

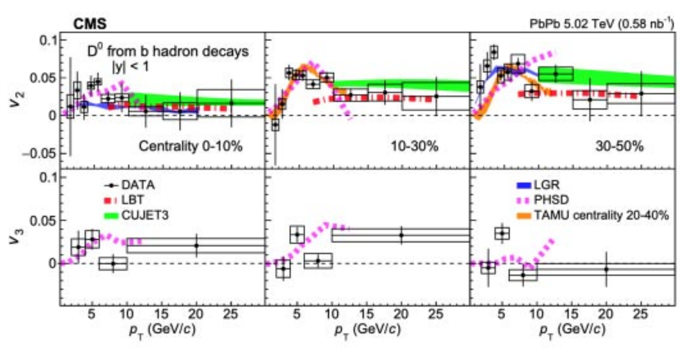

Fig. 5. – The elliptic, v_2 (top panel), and the triangular, v_3 (bottom panel), flow coefficients of non-prompt D0 mesons as functions of transverse momentum and in three bins of centrality. The colored bands show theoretical predictions. The figure is taken from ref. [8]

4. – Summary

In summary, the $f_0(980)$ yields are extracted at rapidity ($|\eta| < 2.4$) from the invariant mass spectra of its main $\pi^+\pi^-$ decay channel in high-multiplicity pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV by the CMS experiment at the LHC. The elliptic flow anisotropy v_2 of the $f_0(980)$ is measured as a function of p_{T} up to 10 GeV/c, with respect to the second-order harmonic plane reconstructed from forward/backward energies. Nonflow contamination is estimated from K^0_{S} measurements and is subtracted. By comparing the nonflow-subtracted v_2^{sub} of the $f_0(980)$ to those of K^0_{S}, Λ, Ξ^- , and Ω under the NCQ scaling hypothesis, we found evidence that the $f_0(980)$ hadron is a normal quark-antiquark state.

On the other hand, the elliptic (v_2) and triangular (v_3) Fourier harmonics of D^0 mesons that come from b hadron decays (non-prompt D^0) are measured in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The v_2 results suggest a transverse momentum dependence and a slight increase for less central collisions, while the magnitudes are lower comparing with the promptly produced D^0 mesons. An indication of non-zero triangular flow is found in the transverse momentum range $4 < p_{\mathrm{T}} < 6$ GeV/c.

REFERENCES

[1] Bugg D. V., *Phys. Rep.*, **397** (2004) 257.
[2] Klempt E. and Zaitsev A., *Phys. Rep.*, **454** (2007) 1.
[3] Peláez J. R., *Phys. Rep.*, **658** (2016) 1.
[4] The CMS Collaboration (Tytgat M. *et al.*), *J. Instrum.*, **3** (2008) S08004.
[5] CMS Collaboration, *Elliptic anisotropy measurement of the* $f_0(980)$ *hadron in proton-lead collisions and evidence of its quark-antiquark composition*, arXiv:2312.17092 (2023).
[6] Voss H., Höcker A., Stelzer J. and Tegenfeldt F., *PoS*, **ACAT** (2009) 040.
[7] The CMS Collaboration (Canelli M. F. *et al.*), *Phys. Lett. B*, **816** (2021) 136253.
[8] CMS Collaboration, *Azimuthal anisotropy of nonprompt* D^0 *mesons in PbPb collisions at* $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, arXiv:2212.01636 (2022).