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Nuclear Physics A 982 (2019) 687–690

NUCLEAR PHYSICS A

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XXVIIth International Conference on Ultrarelativistic Nucleus-Nucleus Collisions (Quark Matter 2018)

Measurement of heavy flavor production and azimuthal anisotropy in small and large systems with ATLAS

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Abstract

Heavy-flavor hadron production and collective motion in A+A collisions provide insight into the energy loss mechanism and transport properties of heavy quarks in the QGP. The same measurements in p+A collisions serve as an important baseline for understanding the observations in A+A collisions. For example, detailed studies of heavy-flavor hadron azimuthal anisotropy in p+A collisions may help to address whether the observed long-range "ridge" correlation arises from hard or semi-hard processes, or if it is the result of mechanisms unrelated to the initial hardness scale. These proceedings summarize heavy-flavor hadron production, via their semi-leptonic decay to muons in 2.76 TeV Pb+Pb and pp collisions, non-prompt J/ψ in 5.02 TeV Pb+Pb and pp collisions, and prompt D^0 mesons in 8.16 TeV p+Pb collisions using ATLAS detector at the LHC. Azimuthal anisotropy of heavy-flavor hadrons is studied via their decay muons in 2.76 TeV Pb+Pb and 8.16 TeV p+Pb collisions, and via non-prompt J/ψ in 5.02 TeV Pb+Pb collisions. Strong suppression of heavy-flavor hadron production and azimuthal anisotropy are observed in Pb+Pb collisions, while significant azimuthal anisotropy of heavy-flavor muons is observed in p+Pb collisions, without evidence of the modification of their production rates.

1. Introduction

In heavy ion collisions, a strongly interacting state of QCD matter called the quark-gluon plasma (QGP) is created. Two of the most important features of QGP are jet quenching and the presence of bulk collectivity. Heavy quarks (c and b) are primarily produced at the early stages of heavy-ion collisions and therefore carry information about the pre-thermalization properties of the QGP. Compared with gluons and light quarks, heavy quarks are expected to lose less energy when traversing the medium due to the dead cone effect. In these proceedings, ATLAS measurements of both production rates and azimuthal anisotropies of heavy-flavor muons [1] and non-prompt J/ψ [2, 3]. In smaller systems, such as p+Pb collisions, the collective motion of charged particles has been observed. To explore the possibility of QGP formation in p+Pb

https://doi.org/10.1016/j.nuclphysa.2018.09.028
0375-9474/© 2018 Published by Elsevier B.V.

collisions, the azimuthal anisotropy of heavy-flavor muons is studied using two-particle correlations [4] and the production rate of prompt D^0 meson is measured [5].

2. ATLAS detector and event selection

The ATLAS experiment [6] consists of an inner tracking detector (ID) surrounded by a thin superconducting solenoid providing a 2T axial magnetic field, electromagnetic and hadron calorimeters, and a muon spectrometer (MS). The ID covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon micro-strip, and transition radiation tracking detectors. Lead/liquid-argon sampling calorimeters provide electromagnetic energy measurements with high granularity. A hadron (steel/scintillator-tile) calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The end-cap and forward regions are instrumented with liquid-argon calorimeters for both EM and hadronic energy measurements up to $|\eta| = 4.9$. The minimum-bias trigger scintillator (MBTS) detects charged particles over $2.07 < |\eta| < 3.86$ using two hodoscopes of 12 counters. The MS includes a system of precision tracking chambers and fast detectors for triggering. The first-level trigger is implemented in hardware and uses a subset of the detector information. This is followed by the software-based high level trigger.

Heavy-flavor muon candidates are selected as muons reconstructed in both the ID and MS with $4 < p_{\mathrm{T}}^{\mu} < 10$ GeV, in events collected by a single muon trigger. The dominant background contribution in the selected muon sample is from K and π decays-in-flight, which usually have a large imbalance between the momentum measurements based on muon segments reconstructed inside and outside the ID. Backgrounds from EW processes are found to be negligible for the measured p_{T} range. The decay-in-flight background can be subtracted statistically by performing a fit to the momentum imbalance, based on templates extracted from MC simulations. The background subtraction procedure is applied to both pp and Pb+Pb data at 2.76 TeV per nucleon, collected in 2015. For the heavy-flavor muon and hadron correlation studies in the 2016 p+Pb collisions at 8.16 TeV, a cut on the momentum imbalance is imposed to suppress the backgrounds.

Non-prompt J/ψ mesons from B-hadron decays are reconstructed via the decay channel of $J/\psi \to \mu^+\mu^-$ in dimuon triggered events in pp and Pb+Pb collisions at 5.02 TeV per nucleon, both collected in 2015. Muons with opposite charges are refitted to a common vertex, from which the pseudo-proper lifetime from a primary vertex, $\tau_{\mu\mu} = L_{xy}/p_{\mathrm{T}}^{\mu\mu}$, is calculated for each refitted J/ψ candidate. Contributions from prompt J/ψ, including direct production and feed-down from the direct production of excited charmonium states, and fake J/ψ background, are subtracted by performing a two-dimensional fit in dimuon invariant mass and $\tau_{\mu\mu}$.

Prompt D^0 mesons are reconstructed via the decay $D^0 \to K + \pi$ in p+Pb collisions collected in 2016 at 8.16 TeV. A minimum bias trigger based on the MBTS is used to collect the candidate events. Pairs of tracks with opposite charges that are successfully refitted to common vertices are selected. The K and π masses are assigned in turn to each track to account for all possible combinations due to the lack of PID. Topological cuts on the decay length significance, goodness of vertex fit, and pointing angle are applied to further suppress background contributions from random combinations. Residual background is subtracted statistically by performing fits to the $K\pi$ invariant mass distribution. The contribution of D^0 from B-hadron decays is removed based on the expected yield from FONLL calculations.

3. Heavy flavor production and flow in Pb+Pb collisions

The nuclear modification factor, R_{AA}, of heavy-flavor muons is reported as a function of muon p_{T} and Pb+Pb event centralities in the left panel of Fig. 1. The production rates of heavy-flavor muons in Pb+Pb collisions are found to be strongly suppressed with respect to that in pp collisions. The suppression is stronger in more central collisions with $R_{\mathrm{AA}} \approx 0.4$ in 0−10% centrality, rising to ≈ 0.7 in 40−60% centrality. According to FONLL calculations, the selected heavy-flavor muon sample is dominated by decays from charm mesons at low p_{T}, with the contribution from bottom mesons increasing with p_{T} and becoming comparable with charm mesons at $p_{\mathrm{T}} \approx 14$ GeV. Thus the flat p_{T} dependence of the heavy-flavor muon R_{AA} indicates suppressions of both charm and bottom meson production in Pb+Pb collisions.

The elliptic flow coefficient, v_2, of heavy-flavor muons is obtained using the event-plane method. The measured v_2 values are presented as a function of muon p_T in five centrality slices in the right panel of Fig. 1. Significant elliptic flow of heavy-flavor muons up to $p_T \sim 14$ GeV is observed in all centralities. The measured heavy-flavor muon R_{AA} and v_2 are compared to TAMU and DABMod calculations. The TAMU calculation is able to describe both the magnitude and p_T dependence of the measured muon R_{AA}, but slightly underestimates the magnitude of v_2. The DABMod calculation, incorporating event-by-event fluctuations, is able to describe the measured heavy flavor muon v_2. However, DABMod is not able to reproduce R_{AA} at low p_T , due to its incomplete modeling of low p_T heavy-flavor meson production.

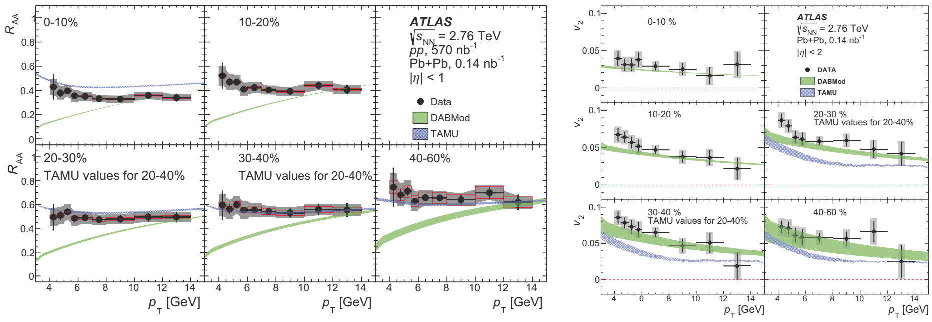

Fig. 1. Left: Heavy-flavor muon nuclear modification factor, R_{AA}, as a function of muon p_T for five different centrality intervals. Right: Heavy-flavor muon v_2, as a function of muon p_T for five different centrality intervals. The measured quantities in data are compared to the DABMod and TAMU model predictions [1].

The R_{AA} and v_2 of B-hadrons are probed by using non-prompt J/ψ mesons as shown in Fig. 2 as a function of J/ψ p_T. Strong suppression of the production rates of non-prompt J/ψ in Pb+Pb collisions with respect to pp collisions is observed. The elliptic flow of non-prompt J/ψ mesons is measured using the event-plane method. Based on simulation studies, the p_T of non-prompt J/ψ mesons is typically $4-5$ GeV smaller than its parent B-hadron, and has a small angular smearing. Thus the flow of non-prompt J/ψ is expected to be a probe of the flow of B-hadrons at slightly higher p_T. The resulting non-prompt J/ψ v_2 has a non-zero central value with no observable p_T dependence within sensitivity. However, the limited statistical precision prevents a stronger conclusion from being drawn.

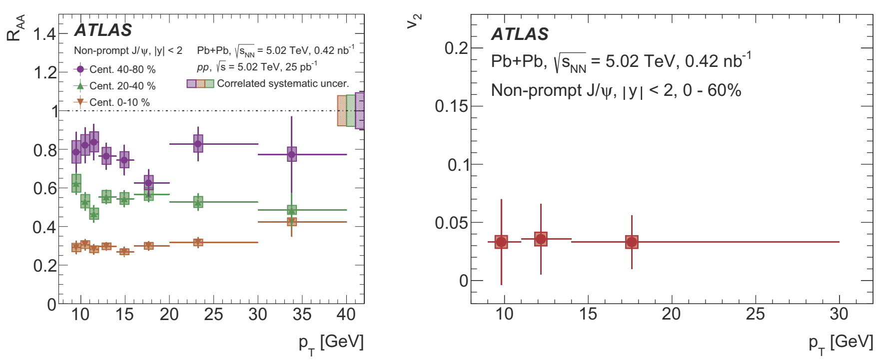

Fig. 2. Left: Non-prompt J/ψ nuclear modification factor, R_{AA}, as a function of p_T for three different centrality intervals in 5.02 TeV Pb+Pb collisions [2]. Right: Non-prompt J/ψ v_2, as a function of p_T in $0-60\%$ centrality Pb+Pb collisions [3].

4. Heavy flavor production and flow in p+Pb collisions

To explore the collective motion and energy loss of heavy quarks in a smaller collision system, the production rates of prompt D^0 mesons and azimuthal anisotropy of heavy-flavor muons are studied in 2016 8.16 TeV p+Pb collisions. The cross section of prompt D^0 meson production as a function of its center-of-mass rapidity, y^*, is shown in the left panel of Fig. 3, in comparison to FONLL calculations for pp collisions at 8 TeV scaled by a factor of 208. The measured prompt D^0 production is comparable to the scaled FONLL calculations, indicating relatively small modification due to nuclear effects. The v_2 of heavy-flavor muons is extracted from angular correlation between muons and charged hadrons via a template fit method as shown in the right panel of Fig. 3 as a function of multiplicity. The observed heavy-flavor muon v_2 is significant, albeit smaller than the inclusive hadron v_2, and has a weak multiplicity dependence.

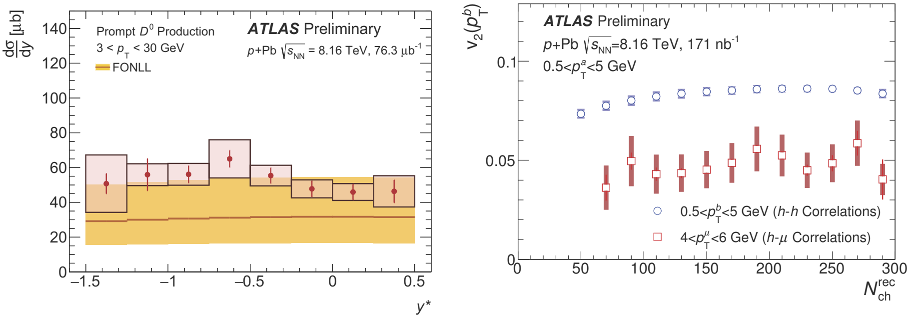

Fig. 3. Left: D^0 meson production cross section as a function of center-of-mass rapidity, y^*, in 8.16 TeV p+Pb collisions. The data are compared to FONLL calculations for pp collisions at 8 TeV scaled by a factor of 208 [5]. Right: Heavy-flavor muon v_2 as a function of multiplicity in 8.16 TeV p+Pb collisions, in comparison to that for inclusive hadrons [4].

5. Summary

These proceedings present ATLAS measurements of heavy flavor hadron production and azimuthal anisotropy in Pb+Pb and p+Pb collisions systems. Different probes, including heavy-flavor decay muons, non-prompt J/ψ, and prompt D^0 mesons are used as probes of how heavy flavor quarks interact with the QGP. Strong suppression and elliptic flow of heavy flavor quarks are observed in Pb+Pb collisions. A significant v_2 of heavy flavor quarks is observed in p+Pb collisions, while no obvious modification compared to the theoretical predictions is observed.

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