Resolving the R_{pA} and v_2 puzzle of D^0 mesons in p−Pb collisions

Chao Zhang,[a,b] **Zi-Wei Lin,**[b,*] **Liang Zheng**[c] **and Shusu Shi**[d]

[a] *School of Science, Wuhan University of Technology, Wuhan, 430070, China*
[b] *Department of Physics, East Carolina University,Greenville, North Carolina 27858, USA*
[c] *China University of Geosciences, Wuhan 430074, China*
[d] *Key Laboratory of Quark Lepton Physics (MOE) and Institute of Particle Physics, Central China Normal University, Wuhan 430079, China*

E-mail: linz@ecu.edu

It has been difficult to reconcile the experimental data on the D^0 meson nuclear modification factor and elliptic flow in p−Pb collisions at LHC energies. Here we study these observables with the string melting version of a multi-phase transport model, which has been improved with the implementation of the Cronin effect (or transverse momentum broadening) and independent fragmentation for charm quarks. Using a strong Cronin effect allows us to provide the first simultaneous description of the D^0 meson R_{pA} and v_2 data at $p_{\mathrm{T}} \leq 8$ GeV/c. The model also provides a reasonable description of the D^0 meson p_{T} spectra and the low-p_{T} (below ~ 2 GeV/c) charged hadron spectra in $p + p$ and p−Pb collisions as well as R_{pA} and v_2 in p−Pb collisions. We find that both parton scatterings and the Cronin effect are important for the D^0 meson R_{pA}, while parton scatterings are mostly responsible for the D^0 meson v_2. Our results indicate that it is crucial to include the Cronin effect for the simultaneous description of the D^0 meson R_{pA} and v_2. Since the Cronin effect is expected to grow with the system size, this work implies that the Cronin effect could also be important for heavy hadrons in large systems.

HardProbes2023
26-31 March 2023
Aschaffenburg, Germany

*Speaker

1. Introduction

The nuclear modification factors including R_{AA} and R_{pA} and elliptic flow v_2 are frequently utilized to study the hot and dense matter generated during the collision of two nuclei at high energies. Recent measurements from the experiments at the LHC have revealed a relatively flat R_{pA} [1] close to unity but a significant v_2 [2] for D^0 mesons in p−Pb collisions, which has posed a substantial challenge for the theoretical understanding. Both hydrodynamics-based models and parton/hadron transport models suggest that significant interactions between charm quarks and the quark-gluon plasma (QGP) medium is necessary to generate a substantial v_2. On the other hand, significant interactions between charm quarks and the QGP would inevitably suppress high-p_{T} charm hadrons. Therefore, it has been difficult to explain and understand simultaneously the D^0 meson R_{pA} and v_2 data.

Several theoretical studies have successfully reproduced either the heavy meson R_{pA} or the heavy meson v_2. For example, the POWLANG model [3] can successfully describe the R_{pA} of heavy flavors, but it predicts a small charm v_2. Perturbative QCD (pQCD) calculations that incorporate the cold nuclear matter effect can generally explain the data on charm R_{pA} [4], as another pQCD model that includes a parameterized k_{T} broadening. Regarding the elliptic flow of heavy flavors, the color glass condensate framework can reproduce the open and hidden charm meson v_2 in p−Pb collisions at the LHC [5], suggesting the significance of initial state correlations for heavy quarks in small systems. However, a simultaneous description of both R_{pA} and v_2 of heavy hadrons has not yet been achieved. Here we examine the R_{pA} and v_2 of D^0 mesons in p−Pb collisions at LHC energies using an improved version of a multi-phase transport (AMPT) model.

2. The improved AMPT model for this study

The AMPT model [6] is a Monte Carlo event generator that contains both partonic and hadronic phases in high energy heavy ion collisions. The string melting version, which we use for this study, mainly contains four parts: the fluctuated initial conditions, partonic scatterings, quark coalescence, and hadronic scatterings. Recently, we have improved the AMPT model with a new quark coalescence [7], incorporated modern parton distribution functions of the free proton and a spatially-dependent nuclear shadowing [8], improved heavy flavor productions [9], and applied local nuclear scaling of the two key input parameters for self-consistent dependence on the system size or centrality [10]. The AMPT model used in this study [11] includes the above improvements. Regarding heavy quarks in the AMPT model, we also made further improvements by isolating the initial heavy quarks from the string melting process, including the initial state Cronin effect, and implementing the independent fragmentation process.

Since the initial charm quarks are produced from hard scatterings, not from string fragmentation, the string melting process of the AMPT model should not apply to them. In this work, we separate the initial state charm quarks produced from the HIJING model so that they enter the parton cascade (without going through the string melting process) after a formation time $\tau_f = E/m_T^2$, where E and m_T represent the charm quark energy and transverse mass, respectively. We also distinguish the cross section among light quarks (σ_{LQ}) from the cross section between a heavy quark and other quarks (σ_{HQ}). Unless specified otherwise, the default values of $\sigma_{\mathrm{LQ}} = 0.5$ mb and $\sigma_{\rm HQ} = 1.5$ mb are used; these values are determined by fitting the charged hadron v_2 data in p−Pb collisions at 5.02 TeV and the D^0 meson v_2 data in p−Pb collisions at 8.16 TeV, respectively. Furthermore, in addition to the usual quark coalescence process, we have included the independent fragmentation as another hadronization channel for heavy quarks. When a heavy quark and its coalescing partner(s) have a large relative distance or a large invariant mass, they are deemed unsuitable for quark coalescence. In such cases, the heavy quark undergoes hadronization through the independent fragmentation [11].

In addition, we include the transverse momentum broadening, known as the Cronin effect, for the heavy quarks in the initial state (before they enter the parton cascade). The broadening is implemented by introducing a transverse momentum kick $k_{\rm T}$ to each $c\bar{c}$ pair in the initial state. The value of $k_{\rm T}$ is randomly sampled from a two-dimensional Gaussian distribution characterized by a Gaussian width parameter w:

$$f\left(\vec{k_{\rm T}}\right) = \frac{1}{\pi w^2} e^{-k_{\rm T}^2/w^2}, \tag{1}$$

$$w = w_0\sqrt{1 + (n_{\rm coll} - i)\delta}. \tag{2}$$

In the above, $i = 1$ if the $c\bar{c}$ pair is produced from the radiation of one participant nucleon, $i = 2$ if the $c\bar{c}$ pair is produced from the collision between one participant nucleon from the projectile and another from the target, while $n_{\rm coll}$ is the number of primary NN collisions of the participant nucleon for the former case and the sum of the numbers of primary NN collisions of both participant nucleons for the latter case. This way, $w = w_0$ for p+p collisions. For w_0, we take the following parameterization [11] so that it depends on the Lund string fragmentation parameters $a_{\rm L}$ and $b_{\rm L}$ through the effective string tension [6]:

$$w_0 = (0.35~{\rm GeV}/c)\sqrt{\frac{b_{\rm L}^0(2 + a_{\rm L}^0)}{b_{\rm L}(2 + a_{\rm L})}}. \tag{3}$$

Details about the values of the Lund string fragmentation parameters in the above parameterization can be found in Ref. [11]. As a result, for p+p collisions, $w = 0.375$ GeV$/c$. We note that the pQCD-based HVQMNR code [12] also employs a similar approach to implement the Cronin effect for charm quarks. While we apply the broadening to each $c\bar{c}$ pair in the initial state, the HVQMNR code applies it to each charm (anti)quark. For comparisons, we have calculated the average $k_{\rm T}$ broadening to each charm quark or each $c\bar{c}$ pair. For p+p collisions at 5.02 TeV, the HVQMNR code yields $\langle k_{\rm T}^2\rangle = 1.46$ GeV^2 and 2.92 GeV^2 for a single charm quark and a $c\bar{c}$ pair, respectively. These values are higher than our corresponding values of 0.04 GeV^2 and 0.14 GeV^2. In the case of minimum bias p-Pb collisions at 5.02 TeV, the HVQMNR code gives $\langle k_{\rm T}^2\rangle = 2.49$ GeV^2 and 4.97 GeV^2 for a single charm quark and a $c\bar{c}$ pair, respectively, which are lower than our corresponding values of 3.27 GeV^2 and 13.0 GeV^2 (for $\delta = 5$).

3. Results

The left and right panels of Fig. 1 show the transverse momentum spectra of D^0 mesons and charged hadrons, respectively, in $p + p$ and minimum bias p−Pb collisions at 5.02 TeV from the

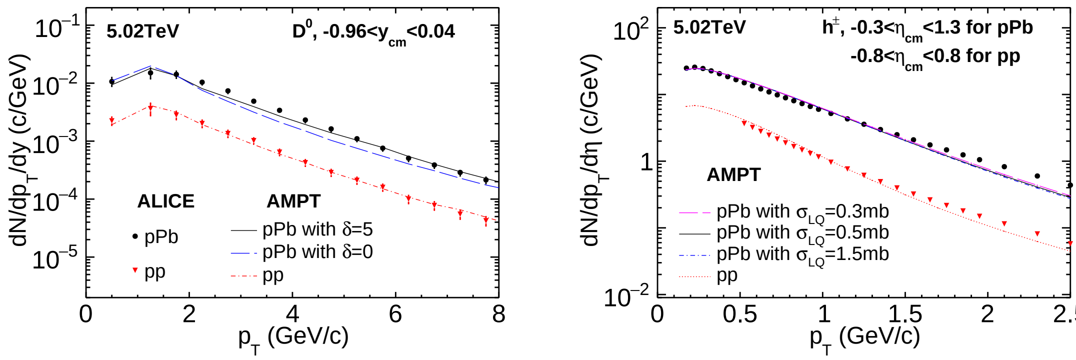

Figure 1: Left panel: AMPT model results on the transverse momentum spectra of D^0 mesons at mid-rapidity in $p+p$ collisions and minimum bias p−Pb collisions (with $\delta = 5$ or 0) at 5.02 TeV in comparison with the experimental data. Right panel: transverse momentum spectra of charged hadrons around mid-rapidity in $p+p$ collisions and p−Pb collisions at 5.02 TeV from the AMPT model in comparison with the experimental data. The AMPT spectra for p−Pb collisions are shown for three values of σ_{LQ}: 0.3, 0.5, and 1.5 mb.

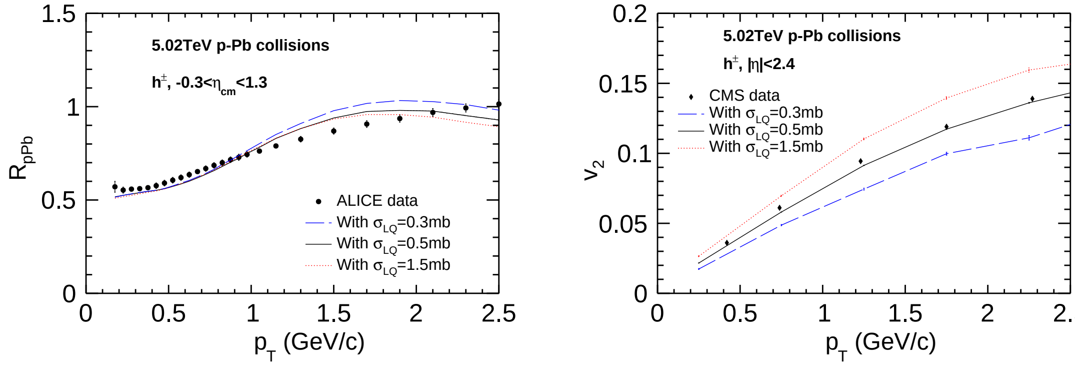

Figure 2: Charged hadron R_{pPb} (left panel) in minimum bias p−Pb collisions at 5.02 TeV and v_2 (right panel) in high multiplicity p−Pb collisions at 5.02 TeV from the AMPT model with $\sigma_{\text{LQ}} = 0.3$, 0.5, and 1.5 mb in comparison with the experimental data.

AMPT model in comparison with the experimental data. The improved AMPT model provides a good description of the experimental data for both collision systems. We find that the Cronin effect is very important for the D^0 meson p_{T} spectra in p−Pb collisions, where the AMPT model without the Cronin effect (i.e., at $\delta = 0$) underestimates the yield of D^0 meson at relatively high p_{T}, while using $\delta = 5$ leads to a significant enhancement of the D^0 meson yield at relative high p_{T}. The effect of parton scatterings on the charged hadron p_{T} spectra is also investigated. We see that the parton scatterings will suppress the charged hadron yield at relative high p_{T} due to the parton energy loss or jet quenching.

In Fig. 2 we investigate the nuclear modification factor R_{pPb} and elliptic flow v_2 of charged hadrons around mid-rapidity in p−Pb collisions at 5.02 TeV. The AMPT model can reasonably describe these observables up to $p_{\text{T}} \sim 2$ GeV$/c$. Consistent with Fig. 1, we see that a larger parton cross section results in a lower (or a moderate reduction of) nuclear modification factor R_{pPb} for charged hadrons at relatively high p_{T}. On the other hand, a larger parton cross section leads to a substantial increase in the elliptic flow (v_2) of charged hadrons.

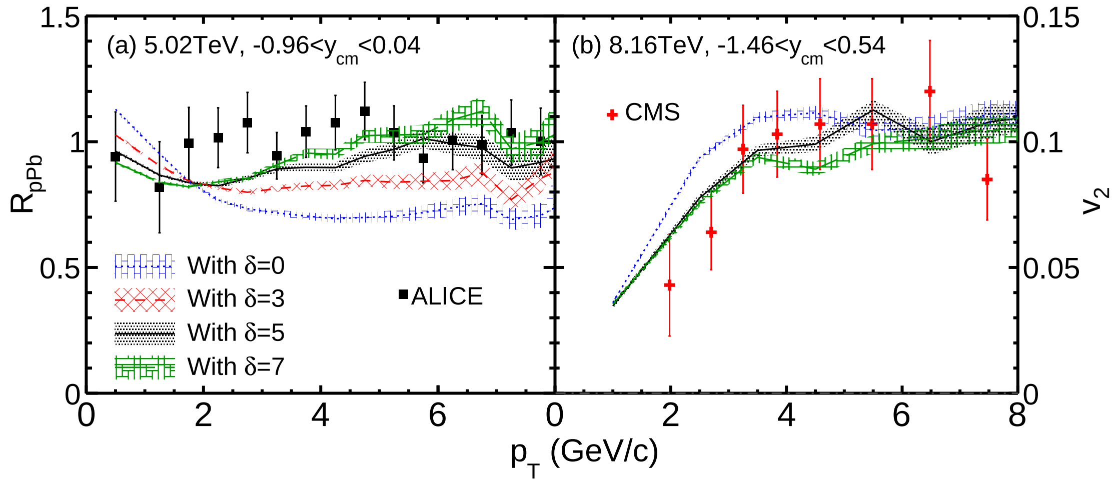

Figure 3: D^0 meson (a) $R_{\rm pPb}$ in minimum bias p–Pb collisions at 5.02 TeV and (b) v_2 in high multiplicity p–Pb collisions at 8.16 TeV from the AMPT model with different strengths of the Cronin effect (δ) in comparison with the experimental data (symbols).

We now examine the nuclear modification factor ($R_{\rm pPb}$) of D^0 mesons in p–Pb collisions at 5.02 TeV and their elliptic flow (v_2) in p–Pb collisions at 8.16 TeV. Figure 3(a) compares the D^0 meson $R_{\rm pPb}$ data with the model results for different strengths of the Cronin effect (via the δ parameter). Figure 3(b) shows the v_2 of D^0 mesons from the AMPT model in comparison with the data. We see that the AMPT model with a strong Cronin effect (at $\delta = 5$ or $\delta = 7$) provides a reasonable description of both the $R_{\rm pA}$ and v_2 observables. A large value of δ or a strong Cronin effect is found to result in a significant enhancement of the D^0 meson $R_{\rm pPb}$ at relatively high $p_{\rm T}$, while it leads to a small decrease of the D^0 meson v_2.

4. Summary

We have studied the nuclear modification factor $R_{\rm pPb}$ of D^0 mesons and charged hadrons in minimum bias p–Pb collisions as well as the elliptic flows v_2 in high multiplicity p–Pb collisions at LHC energies with a multi-phase transport model. The model has been improved with the inclusion of transverse momentum broadening (i.e., the Cronin effect) and independent fragmentation for charm quarks. When invoking a strong Cronin effect, we are able to provide the first simultaneous description of both the $R_{\rm pPb}$ and v_2 data of D^0 mesons below the transverse momentum of 8 GeV/c. Our results show that both parton scatterings and the Cronin effect significantly affect the $R_{\rm pPb}$ of D^0 mesons. On the other hand, the v_2 of D^0 mesons is primarily generated by parton scatterings, while the Cronin effect leads to a modest reduction of the charm v_2. In particular, we demonstrate that the Cronin effect could resolve the $R_{\rm pPb}$ and v_2 puzzle of D^0 mesons at LHC energies.

References

[1] S. Acharya *et al.* [ALICE], "Measurement of prompt D^0, D^+, D^{*+}, and D_S^+ production in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV," JHEP **12**, 092 (2019)

[2] A. M. Sirunyan *et al.* [CMS], "Elliptic flow of charm and strange hadrons in high-multiplicity pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV," Phys. Rev. Lett. **121**, no.8, 082301 (2018)

[3] A. Beraudo, A. De Pace, M. Monteno, M. Nardi and F. Prino, "Heavy-flavour production in high-energy d-Au and p-Pb collisions," JHEP **03**, 123 (2016)

[4] Z. B. Kang, I. Vitev, E. Wang, H. Xing and C. Zhang, "Multiple scattering effects on heavy meson production in p+A collisions at backward rapidity," Phys. Lett. B **740**, 23-29 (2015)

[5] C. Zhang, C. Marquet, G. Y. Qin, Y. Shi, L. Wang, S. Y. Wei and B. W. Xiao, "Collectivity of heavy mesons in proton-nucleus collisions," Phys. Rev. D **102**, no.3, 034010 (2020)

[6] Z. W. Lin, C. M. Ko, B. A. Li, B. Zhang and S. Pal, "A Multi-phase transport model for relativistic heavy ion collisions," Phys. Rev. C **72**, 064901 (2005)

[7] Y. He and Z. W. Lin, "Improved Quark Coalescence for a Multi-Phase Transport Model," Phys. Rev. C **96**, no.1, 014910 (2017)

[8] C. Zhang, L. Zheng, F. Liu, S. Shi and Z. W. Lin, "Update of a multiphase transport model with modern parton distribution functions and nuclear shadowing," Phys. Rev. C **99**, no.6, 064906 (2019)

[9] L. Zheng, C. Zhang, S. S. Shi and Z. W. Lin, "Improvement of heavy flavor production in a multiphase transport model updated with modern nuclear parton distribution functions," Phys. Rev. C **101**, no.3, 034905 (2020)

[10] C. Zhang, L. Zheng, S. Shi and Z. W. Lin, "Using local nuclear scaling of initial condition parameters to improve the system size dependence of transport model descriptions of nuclear collisions," Phys. Rev. C **104**, no.1, 014908 (2021)

[11] C. Zhang, L. Zheng, S. Shi and Z. W. Lin, "Resolving the R_{pA} and v_2 puzzle of D^0 mesons in p−Pb collisions at the LHC," arXiv:2210.07767 [nucl-th].

[12] R. Vogt, "Limits on Intrinsic Charm Production from the SeaQuest Experiment," Phys. Rev. C **103**, no.3, 035204 (2021)