Response to Opponent Review

Opponent: Máté Csanád, PhD
Title of thesis: Fragmentation through Heavy and Light-flavor Measurements with the LHC ALICE Experiment
PhD candidate: Zoltán Varga

First of all, I would like to thank the Opponent for agreeing to review my thesis on such a short notice. I would also like to thank him for thoroughly examining my doctoral dissertation and giving a positive evaluation. There have been important questions raised about the results, for which my answers can be found below.

Questions

1.) There are many types of observables shown from both data and simulations. What would be one of the final, global goal of these investigations? In other words, ultimately what physical property of the strong interaction can be determined from these, and how? Is it the coupling constant of QCD, the quark-hadron transition temperature, or some kind of a transport property of the Quark-Gluon Plasma?

My studies are not aimed at obtaining a direct value of a particular QCD observable. The ultimate goal is to understand the non-perturbative regime of QCD. Several competing models and mechanisms are utilized to describe the physics of this regime. My results approach this unexplored territory from various directions, and with the results applied to experimental data, it will become possible to differentiate between these models.

Refining the models will naturally lead to a better understanding of the QCD coupling and jet formation mechanisms. However, there will be no answer regarding the transition temperature or QGP transport, because I have been primarily focusing on vacuum QCD effects, in particular the phenomena of hadronization and jet formation.

It is an intriguing question whether the quark-gluon plasma may be created in small collision systems and what are the limiting parameters of this transition. For instance, POWLANG transport-model calculations **[J. High Energy Phys. 03 (2016) 123]**, which assume the formation of deconfined medium in p-Pb collisions, may be able to describe the ALICE measurement of R_{pPb} of D-mesons **[Phys. Rev. C 94, 054908 (2016)]**. While gaining fundamental insight into this subject is very challenging, the multiplicity-based studies and the testing of different models is a step in this direction.

Another important aspect of my studies was to test the limits of PYTHIA 8 in describing high-energy hadron collisions and pinpoint areas where the observable deviations between particular tunes can be used to improve existing models or build new ones. A more technical aspect was to study the physics at the soft-hard boundary of hadron collisions and study what kind of mechanisms are at play. Fragmentation is a challenging non-perturbative problem which we currently describe with phenomenological models. It is crucial to understand this mechanism properly as it affects almost every measurement we do. My research, such as studying heavy-flavor correlations, helps to better understand our models.

2.) For many results, Pythia 8 was used, with a given set of settings (a "tune"). How much would the obtained results depend on the particularities of these settings, and is this dependence (or does it have to be) incorporated in the final systematic uncertainties?

One of the main goals was exactly to find variables that help with the fine tuning of PYTHIA. In Chapter 3, I showed in my jet shape analysis that differential observables can lead to significant tensions between otherwise well-established tools. This way I also motivated experimental measurements. In the studies of the KNO-like scaling (Chapter 4.) the main tunes (Monash and 4C) did not affect the conclusions regarding the multiplicity scaling.

In the heavy-flavor studies of Chapter 7. the decay kinematics are not much affected by the choice of widely used tunes such as Monash or 4C. However, the tunes that incorporate color string junctions (color-reconnection beyond leading order, CR-BLC modes) significantly differ from Monash and from each other as well. My results provide observables that can be extracted from future data to effectively distinguish between these models. There is still much needed improvement to be done for the CR-BLC modes, as the Λ_b/B ratios require a different tuning than the Λ_c/D ratios, as we have recently shown in **[arXiv:2408.16447]**.

3.) While Chapter 3 utilizes the jet "radius" (R parameter) of 0.7 (as in the corresponding CMS analysis), for Chapter 5, R = 0.4 was used. Both analyses are in pp collisons. What is the reason behind this difference? How much do the results depend on this parameter?

The choice of the jet resolution parameter is always a pragmatic decision. If the jet cone is too large, we pick up a lot of background, and also reduce the acceptance. If the jet cone is too small, we lose the large-angle parton radiation.

The ALICE acceptance ($|\eta| < 0.9$) limits the practical jet cone size and for many analyses the R=0.4 is a standard choice (it still captures most of the parton shower). The CMS experiment chose R=0.7 in their jet structure studies **[*JHEP* 06 (2012) 160]**, because these wider jets capture the majority of the p_T profile of the jets, including the tail of the jet shape distributions. Furthermore, the background contribution is relatively low and easy to account for in p-p collisions **[Phys. Rev. D 103, 051503 (2021)]**. Since the CMS experiment can study jets with higher p_T than the ALICE experiment, I chose the same jet resolution parameter to be able to do a complete comparison between my simulations and the CMS data.

4.) In Section 5.3, the usage of RooUnfold is mentioned. How were uncertainties, in particular bin-by-bin correlations treated in this case, when estimating the uncertainties of the unfolded result? Furthermore, the author mentions that a 4D response matrix was created. Is this really still a 2D matrix, for which each "supercolumn" is a matrix, flattened?

The unfolding process only uses the point-by-point uncorrelated errors, the systematic errors were handled after the unfolding. The unfolding process handles the problem as a multidimensional problem and takes it into account if the points are correlated, based on the assumption that the prior distribution is smooth (due to the problem being underdetermined).

The 2D histogram of the true distribution T_{kl} ($k = 0, 1, .., N_t - 1; l = 0, 1, .., M_t - 1$) can be treated as a 1D histogram T_j ($j = 0, 1, .., N_t \times M_t - 1$). The same can be done for the measured distribution M_{mn}. The only considerable difference between 1D and 2D comes from the definition of the regularization term of the selection criteria.

5.) Subtracting the baseline from angular correlations, as indicated in Section 6.4, needs a good control of angular event shapes, in particular higher-order flow coefficients. Based on that, would such a measurement, as the one shown in Figure 6.3 or 6.4, be also possible in PbPb collisions? This was once a highlight of jet-suppression measurements, as shown in Figure 2.9. What are the challenges in such a measurement, going from pp to pPb and PbPb?

In p-Pb collisions the flow was observed not to be significant when the heavy-flavor decay electrons had a high energy **[Phys.Rev.Lett. 122 (2019) 7, 072301]**. In Pb-Pb collisions we have to determine the flow in different centrality and p_T bins and fit the azimuthal distributions in a region far from the jet regions. The non-heavy flavour electron background can be removed using a selection on the $e^{\pm}$ invariant mass distribution. Detector acceptance effects can be corrected for using mixed event correlation distributions. The jet-like correlation distributions are then obtained after baseline and flow subtraction. The correlation measurements in Run 3 will extend to heavy-ion collisions and will take these into account.

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Zoltan Varga

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