Supervisors review of the Diploma Thesis of Jakub Češka

Title: Study of Upsilon meson production dependence on charged particle multiplicity in p+p collisions measured with the STAR experiment

Title (Czech): Studium závislosti produkce Upsilon mezonů na multiplicitě nabitych částic v p+p srážkách měřených na experimentu STAR

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The topic of the Diploma Thesis of Jakub Češka is an experimental study of the charged particle multiplicity dependence on of Upsilon meson production in p+p collisions. The purpose of these studies is to understand an interesting non-linear dependence of quarkonium production on charged particle multiplicity, which provides information about interplay of hard and soft QCD processes. A few explanations exist, which include Color Glass Condensate-like saturation effects, String Percolation or production of quarkonium in multiple parton interactions. For this purpose, Jakub analyzed data from p+p collisions at center of mass energy of 500 GeV recorded by the STAR experiment. This dataset is an order of magnitude larger than used in previous studies and will provide better precision necessary to distinguish between the models mentioned above.

The first chapter of the thesis provides an introduction to physics of relativistic hadron collisions and focuses on a detailed description of the Standard Model of particle physics. The elementary particles and interactions between them are presented. In addition, shortcomings of the standard model and its consequences for both particle physics and cosmology are mentioned. However, there is no description of proton-proton or heavy ion collisions. It would be good to mention that hadrons are complex objects and that these collisions involve both hard and soft QCD processes.

Next chapter introduces the quarkonium family of particles. Bottomonium states, their typical decays and transitions are discussed in detail. This chapter also lists the basic quarkonium production models and their features. It is important for the interpretation and motivation of this study. To put the study in the context of studies of heavy ion collisions, the author also wrote about observed quarkonium suppression and cold nuclear matter effects. These phenomena are studied to determine the properties of quark gluon plasma created in such collisions. The last section is devoted to the study of quarkonium production dependence on charged particle multiplicity created in the proton+proton collisions. Here a few theoretical models trying to explain the observed strong enhancement of quarkonium yield in high multiplicity events are mentioned: CGC Saturation model, String Percolation model and the influence of MPI. In my opinion, a more detailed description would be easier to understand for the reader. A connection between the physics represented in these models and the effect on the measured yields is not clear. It would be good to explain, which process is proportional to which yield, and which one is not.

In Chapter 3, the latest select measurements of quarkonium production in p+p collisions both at RHIC and LHC are presented. The J/ψ and Υ spectra are compared to model calculations and describe the data well, with a few exceptions. A similar comparison is performed for normalized J/ψ and Υ yields vs. charged particle multiplicity. All data show a similar trend for different states and collision energies. The only exception is when, the dependence is studied in different rapidity ranges.

The STAR experiment and the detectors used in this study are discussed in Chapter 4. The structure of the subsystems, acceptance and their principle of operation are explained. This is adequate, however there is no information on the momentum, spatial and energy resolution or detector efficiency. Thus, the reader has no way to judge the performance of these subsystems.

Chapter 5 focuses on the simulations of ϒ production vs. charged particle multiplicity using PYTHIA8 and HERWIG event generators. These studies are done to investigate the behavior of ϒ states and the effect of feed-down contributions on the charged particle multiplicity dependence. No difference is observed for the ϒ states, whether directly produced or originating from feed-down. Such study is an important guidance for the experiment.

The analysis of STAR data is presented in Chapter 6. It is described with many technical details. Some of these are not crucial like the process of submitting jobs or preparation of analysis codes but give the reader a better insight into the work. In my opinion the text could be more compact, but a longer text may be easier to understand. Event and track selection is performed in order to reconstruct ϒ signal in the dielectron channel. No information from Barrel Electromagnetic Calorimeter (BEMC) was available, which is necessary for signal reconstruction, but an attempt was made to reconstruct the signal using kinematic cuts. Still, the signal is not visible in Fig. 6.8. A question arises if there were other cuts tried besides, $p_{T1} > 3$ GeV/c and $p_{T2} > 1$ GeV/c? Because of the missing BEMC information, the author was involved in the reproduction of the data, which included tests on a small sample. Another test was performed to reconstruct J/ψ signal. This is described in Chapter 7 along with the discussion of the results. The J/ψ signal after combinatorial background subtraction is shown Fig. 7.2.

Despite the problems obtaining ϒ signal in the STAR data, an important conclusion from the simulation study is that there is no difference in charged particle multiplicity dependence of ϒ states. Similarly, the behavior does not change for directly produced ϒ compared to feed-down. This is despite the fact that additional particles are produced in the decay. Moreover, a surprisingly large yield of χ_{b2} states compared to χ_{b1} was obtained with PYTHIA8. This needs to be verified by experimental data and potentially adjusted in the event generator.

I also found a few minor errors and listed some of them:

- Page 30, bottom: "The CSM works at describing a large fraction of the quarkonium cross section" this is imprecise, it should be: "quarkonium production cross section"
- Page 31: "The perturbative part of Eq. 2.6 in the COM" it points to the wrong equation. It should point to Eq. 2.5 instead.
- Page 33, 3rd paragraph: "Multiplicity dependence dependence" – dependence is repeated
- Page 65, middle: "Around 560 million events satisfy these trigger conditions" – this number seems larger than the total 462 M events recorded by the trigger. What is the correct number?
- Page 81, bottom: "complete he ϒ signal" -> "complete the ϒ signal"

Overall, the Diploma Thesis is well written, with a few shortcomings. It represents work on a difficult to measure signal, but also contains a simulation study and a data validation work. The last part is an important contribution to the STAR experiment. However, the description of detectors and theoretical models of quarkonium production are only briefly discussed and could be expanded. On the other hand, other parts of the thesis, like the data analysis are too long and can be shortened to make it more compact. Given these factors, I recommend the mark B – very good.

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