European Organization for Nuclear Research
Organisation européenne pour la recherche nucléaire

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Referee report of doctoral dissertation of Mr. Andrea Mauri titled "Direct and Indirect Searches for New Physics in $b \to sll$ Decays".

The doctoral dissertation of Mr. Andrea Mauri concerns one of the most important research topics that are undertaken at the Large Hadron Collider (LHC), which are searches for phenomena not described by the Standard Model (SM), often labeled as New Physics (NP). The existence of theory more general then the SM is motivated by number of experimental measurements.

Mr. Mauri has chosen to study electroweak penguin processes of $b \to sll$ type, which are particularly sensitive to large variety of NP models. In fact, in these transitions over the last five years a number of deviations from SM (called "anomalies") have been observed. Considering lack of direct observations of new particles by ATLAS and CMS collaborations these anomalies are the strongest indication of NP phenomena at the LHC. Further studies of $b \to sll$ transitions is currently the core program of the LHCb collaboration, where Mr. Mauri has performed his research. It is worth mentioning that not many such young researches as Mr. Mauri participate in such important measurements in big collaboration. This clearly shows that LHCb collaboration holds Mr. Mauri in very high esteem.

The thesis consists of eight chapters, two appendixes and together with the bibliography has 156 pages. The short introduction is followed by the chapter describing the SM and its extensions. The next two chapters describe the theoretical aspects of the $B \to K^* ll$ l transitions. Chapter 4 is devoted to describe the LHC and LHCb detector. The chapter 5 and 6 describe the direct search for a light inflaton. Chapter 7 presents the possibility direct fit of Wilson Coefficients (WC) to LHCb data. The short chapter 8 concludes the dissertation.

Chapter 1 starts by describing the experimental and theoretical problems of the SM. Mr. Mauri then moves to describe the particle context of the SM. He correctly introduces the generations and groups the particles of SM. Next the Higgs boson is introduced with its vacuum stability. Here a reader might feel a bit lack of information. It is true that the dissertation does not concern the Higgs boson itself however 4 lines of introduction of Higgs field is definitely insufficient. Especially as the author correctly noticed the Higgs gives rise to Yukawa interaction, which are a key component of flavor physics. I would also like to note that due to lack of explanation the eq. 3 is inconsistent with the eq. 15. Mr. Mauri then moves to describe the CKM structure of the quark sector. He correctly describes why only in the quark sector can have non-diagonal elements in the CKM matrix. Later the charge current interactions are introduced in the eq. 9.

Dissertation then describes the extensions of the SM and focuses on so called Inflaton models. The model chosen by Mr. Mauri can affect the $b \to s\ ll$ transitions, so its detailed description is justified. Although, reader is left with a bit of inexhaustible feeling: "Are there other NP models that relevant to $b \to s\ ll$ transitions?". The answer is of course positive and a small subsection with their brief explanation would be in place here. Going back to the Inflaton model, Mr. Mauri introduces it by extension of the SM by a new particle (called Inflaton) which mixes with the SM Higgs boson (equation 14). The model has two free parameters: the Inflaton mass and mixing angle with the Higgs. Because of the model structure, it has the same couplings as the Higgs boson. Since the $b \to s$ transition proceeds via a top loop it creates a perfect environment for the Inflaton production. Mr. Mauri discusses in details why the $B \to K$ transitions is better for looking for these particle wrt. to the $B \to K^*$. I would like to point to problems with the notations. In equation 18, the λ stands for phase space factor, while in the previous equation (17) is the Higgs self-coupling.

Chapter 2 is devoted towards the $B \to K^* \, ll$ decays and flavor anomalies. It starts by defining the effective operators, their couplings called Wilson Coefficients (WC) and a general Lagrangian for the $b \to s$ transitions. Mr. Mauri uses here a different notation compared to the literature, as he for example uses $O_{7\gamma}$ instead of what is usually known as O_7. This of course is not a mistake by any means but it creates a trap, which later the author falls in. Namely on page 25, Mr. Mauri forgets about his notation and uses a well-known O_7 operator. He later introduces the $B \to K^* \, ll$ decays, its kinematics and amplitudes in terms of WC and form factors. Here again the primed WC are not defined. The problem with the $b \to s$ transitions is the pollution of the O_{bscc} operator also known as the charm loop effect. Mr. Mauri describes the current state of the art of determining these contribution in sec. 2.2.1.1. I would like to point out that in eq. 31 the poles are not extracted as the text states but divided out. The rest of this chapter describes the observables of the $B \to K^* \, \mu\mu$ decay and anomalies that have been observed.

Chapter 3 describes phenomenological work done by the author during his PhD. He tried to determine if in the future using LHCb data there will be a possibility to distinguish the non-local effects from NP in the $b \to s \, \mu\mu$ transitions. Mr. Mauri performed an extensive number of pseudo-experiments to determine if with 50fb^{-1}, LHCb will have power to disassemble the two effects. The work described in this chapter is published as two preprints. The idea of Mr. Mauri is to build on the previous description of the non-local correlator but in its parametrization, use directly the $B \to K^* \, \mu\mu$ data. With this approach, a single fit will determine whether the non-local correlator or WC modification describes the data better. Mr. Mauri prepared the pseudo-experiments with great detail, sampling them accordingly to what was observed in Run1 $B \to K^* \, \mu\mu$ analysis. Clearly these approach shows the meticulousness of Mr. Mauri as a researcher. Mr. Mauri then discuss the truncation of the Taylor expansion of the correlator and model dependence it creates on the future analysis. All conclusions made by the author are supported by the results of pseudo-experiments. In section 3.3 he introduced an additional idea to include in the studies the Lepton Universality Violating observables. These observables are insensitive to the non-local correlator, which gives the fit an additional handle in disentangling the two effects.

Chapter 4 describes the LHC accelerator with LHCb detector and is a standard part of the experimental dissertations like the reviewed one. Writing these kind of chapters is not an easy task. Modern detectors are extremely complex systems and selecting important details to describe causes a problem for unexperienced students. In this case Mr. Mauri shown an excellent knowledge about LHCb detector. The subdetectors which are important for the analysis performed by him are described in more details then the others. As a result, the chapter is very easy to read even by people outside the LHCb collaboration. In addition, Mr. Mauri has performed studied of the Silicon Tracker, which is documented in the sec. 4.2.2.

Chapter 5 describes the date selection for the $B \to K/K^* \, \mu\mu$ decays. It consists standard elements of typical LHCb analysis, such as trigger selection, vetos against specific background and multivariate training. Each of this step is known and has been performed many times by other students in LHCb, however successfully performing all the selection chain by Mr. Mauri demonstrates his skill as experimental physicists. Furthermore, Mr. Mauri in this chapter describes (in sec. 5.4.1) the corrections that are applied to Monte Carlo simulation. The multivariate selections use the k-Folding technique which is the state of the art in terms of High Energy Physics Machine Learning. It allows for more optimal usage of the training samples.

Chapter 6 documents the search for the Inflaton performed by Mr. Mauri in LHCb experiment using Run1 pp data. The search for such a particle is not a simple one. One does not know its mass and lifetime. Mr. Mauri knowing these difficulties designed the whole selection in a way to cover all the possible variations of the Inflaton model parameters. Furthermore, he boosts the sensitivity of the Inflaton search by looking in several ranges of lifetime ranges. The first one is the short-lived inflation. This bin contains all of the irreducible SM background of $B \to K \, \mu\mu$. The second one for middle lifetime of Inflaton and the third one which is essentially background free. The number and ranges of these bins have been determined with extensive pseudo-experimental studies. In addition, one has to optimize the search mass window for the Inflaton and the sideband fit. Here Mr. Mauri faced a classical variance vs bias problem. Again, using a pseudo-experiment study, he determines the best possible k parameter (eq. 62).

Mr. Mauri finally sets the limits on the branching fraction of $B \to K \, \chi(\mu\mu)$ as a function of Inflation mass and its lifetime. Furthermore, the branching fraction limits are translated into Inflaton model parameters (Fig. 60). The obtained limits supersede the previous analysis and are the most constraining limits at the presented model. The limits obtained by Mr. Mauri are calculated with the CL_s method described in section 6.1.1. Unfortunately, the section does not describe how the systematic uncertainty enter the CL_s limit setting procedure.

In chapter 7 Mr. Mauri studies the sensitivity to direct determination of WC from Run2 data of LHCb. In order to estimate these sensitivity Mr. Mauri has developed from scratch his own fitting framework using TensorFlow library. They pseudo-experiments prepared by Mr. Mauri are again with great attention to details. All the acceptance corrections and background have been taken into account. What is even more important the S-wave of the $K\pi$ system is taken into account. In this chapter, an extensive list of potential systematic has been explored. The last chapter concludes the dictation results.

In summary, the dissertation of Mr. Mauri presents results from wide spread of areas. Starting from detector development, going through the experimental data analysis, finishing on the phenomenological research. It is rather a rare that a PhD student conducts such a wide spectrum of research. My comments about the dissertation are of editorial nature and do not change any of the result or the conclusions of this dissertation.

Concluding, the doctoral dissertation of Mr. Mauri fulfills all the necessary legal and social requirements of such document and I recommend to allow its public defense. In addition, I consider the review dissertation and research conducted by Mr. Mauri to be in the top 5% of students I have encountered during my postdoctoral time at UZH.

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