DEPARTMENT OF PHYSICS
INDIANA UNIVERSITY
College of Arts and Sciences
Bloomington

Emilie Passemar
812-855-5422
e-mail: epassema@indiana.edu

Professor Jan Kratochvíl
Dean
Faculty of Mathematics and Physics
Charles University Prague
Ke Karlovu 3
12116 Praha 2
Czech Republic

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Evaluation of the thesis of Mr. Tomáš Husek: Some aspects of low-energy QCD at the precision frontier.

The thesis submitted by Tomáš Husek is an impressive compilation of high quality, original results. It is clear that the author has demonstrated ability for creative scientific work. Many of the key results of this thesis have already gone through peer review and are published in high-impact scientific journals. They provide the basis for future scientific investigations in the area of low-energy particle physics.

Recent measurements at kaon and pion flavour factories [NA48 (CERN), KLOE (LNF) and KTeV (Fermilab)], B factories [BaBar (SLAC) and Belle (KEK)], Tevatron (Fermilab) and LHCb (CERN), as well as the muon g-2 experiment (BNL) have yielded a wealth of data that could allow us to test the Standard Model – the theory describing strong, weak and electromagnetic interactions – at low energy with an unprecedented precision. The main challenge in this quest is to obtain correspondingly precise theoretical predictions for the measured observables within the Standard Model, especially in the hadronic sector. In this thesis, the author has carried out this task at the cutting edge of the field, focusing on improving the treatment of the electromagnetic corrections and of hadronic quantities (form factors) for certain rare meson decays never considered before.

The thesis is divided into four chapters that serve as an introduction and overview of the scientific work presented as three publications appended to it.

In Chapter I a cogent introduction of Chiral Perturbation Theory (ChPT), the effective theory used to describe strong interaction at low energy is given. This framework provides a quantitative description of low-energy meson decays considered later. The presentation is clear and emphasizes important concepts such as the Wess-Zumino-Witten Lagrangian related to the chiral anomaly.

In Chapter II, the large-N (color) framework is presented and its use in phenomenology is outlined.

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Chapter III introduces radiative corrections in quantum electrodynamics (QED) and one of its difficulties, namely the treatment of the infrared divergences. The discussion then specializes to the decays $\pi^0 \to e^+e^-\gamma$ and $\pi^0 \to e^+e^-$ measured by the experimental collaboration NA62 at CERN. The thesis emphasizes the challenges of such calculations as well as the strategy adopted to tackle them. This chapter together with the appended publications develops an original method of computing the radiative decays of the pion. The method combines ChPT with electromagnetic effects.

In Chapter IV, this method is then applied to the radiative decays of η and η'. These calculations are very important for ongoing new physics searches for dark forces at Jefferson Laboratory (Newport News, USA), MAMI (Mainz, Germany), LNF (Frascati, Italy) and BESS-III (Beijing, China). The challenges of computing the radiative decays of η and η' are discussed. Particular attention is paid to their strange-flavor content and the mixing between these two states. A strategy for addressing these difficulties is developed.

Finally, five appendices supply all the relevant mathematical details.

Following this, three papers are presented. In Paper I, the radiative corrections to the process $\pi^0 \to e^+e^-$ beyond leading order are computed. This calculation is motivated by a 3.3σ discrepancy between the earlier theoretical prediction and the experimental measurement by the KTeV collaboration. Paper I shows that by accurately computing the two-loop virtual corrections together with the bremsstrahlung contribution beyond the soft-photon approximation the discrepancy is reduced to only a 2σ level. This explicitly illustrates the importance of accurate theoretical calculations of the radiative corrections when one reaches a high level of precision in the experimental measurements. I would like to point out that the inclusion of the bremsstrahlung contribution beyond the soft-photon approximation was performed for the first time here and was shown to be important.

In Paper II, the rare pion decay $\pi^0 \to e^+e^-\gamma$ is considered. This process is essential for measuring the double virtual pion form factor, an important input for the light-by-light scattering contribution of the anomalous magnetic moment of the muon (g-2). The state-of-the-art theoretical predictions for the muon g-2 are 3.5σ away from the measured value, raising the possibility of a new physics contribution. The process $\pi^0 \to e^+e^-\gamma$ is under measurement at NA48/NA62 at CERN. This paper recomputes the radiative corrections to this Dalitz decay improving on the original work of Mikaelian and Smith. The new analysis goes beyond the soft-photon approximation, i.e. applies over the whole range of the Dalitz plot and with no restrictions on the radiative photon. Moreover the one-photon irreducible contribution, which was for a long time considered to be negligible was added here for the first time. Additionally, no approximation regarding masses of the involved particles was used throughout the calculation. A C++ code, which returns the correction for any point of the Dalitz plot and which became a part of the simulation software of NA62 experiment, was developed.

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In Paper III, motivated by the remaining discrepancy in the rare pion decay $\pi^0 \to e^+e^-$ an improved model of the pion transition form factor was proposed. In this model all low- and high-energy constraints were carefully implemented improving the theoretical description of this form factor. The result is a more accurate theoretical calculation of the rare pion decay $\pi^0 \to e^+e^-$, but also of $\pi^0 \to e^+e^-\gamma$. Such a model promises a better theoretical description of other transition form factors, such as for the mesons η, η' or for hyperons. Improving the hyperon transition form factor description is crucial for the new PANDA experiment at FAIR (Darmstadt, Germany) in order to allow the scientific community to unveil the properties of strong interaction in the baryon sector.

In summary the thesis of Tomáš Husek develops an original, well-motivated, and accurate approach for studying radiative decays of mesons at low energies. The work is highly relevant for many experimental programs in Europe (NA48/NA62 at CERN and MAMI in Mainz) as well as in the US (JLab in Virginia). It contains a lot of new material, which is presented in a clear and transparent way. The work developed here has already resulted in important theoretical predictions, superseding earlier results and ameliorating a discrepancy with experiment. Moreover, the methods developed and presented in this thesis could be applied to many other processes improving their theoretical descriptions. Some examples have been given in the thesis. This thesis documents in a convincing way the ability of Tomáš Husek for creative scientific work. I strongly recommend that it be accepted by the faculty of Mathematics and Physics of Charles University.

Sincerely yours,

Emilie Passemar
Assistant Professor
Department of Physics
Indiana University

Swain Hall West 117
Bloomington, Indiana
47405-4202

812-855-3977
Fax: 812-855-5533
http://www.physics.indiana.edu