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博士論文の要旨

氏　　名　上田　大輝

論文題目 Phenomenology of SMEFT Flavor Changing Operators

The standard model (SM) of the particle physics is a theory which describes nature very well. In 2012, the last missing piece of the SM, the Higgs boson was observed by the Large Hadron Collider (LHC) experiments. This great discovery was a culmination of the success of the SM. However, some unsolved problems, such as the hierarchy problem and an identity of the dark matter are remained in the SM. Thus, the discovery is also a beginning of searching for new physics (NP).

Without a fine-tuning between the observed Higgs mass and the bare mass of the Higgs boson, a mass of NP particle coupling to the Higgs boson is implied as 100 GeV − 1 TeV. In addition, if weakly interacting massive particles (WIMPs) dominate a density of cold non-baryonic matter in the universe, $\Omega h^2 \simeq 0.1(\langle\sigma v\rangle/10^{-26}cm^2/s)^{-1}\,\Omega$, it is expected that the mass of the WIMPs is around 100 GeV − 1 TeV. In particular, these unsolved problems indicate that the NP scale is not far from the electroweak symmetry breaking (EWSB) scale and give us a guideline for the energy scale at which the human race must aim.

However, by the LHC experiment, the NP particles with a few TeV mass have not been detected yet. At this stage, the experimental facts indicate that the NP consists either very weakly coupled particles or heavy ones well above the EWSB scale. In particular, in the second scenario which we focus in this thesis, indirect searches for the NP become important, because FCNCs and CP violating observables are sensitive to physics at the high energy scale. In the flavor-changing processes, many observables have been precisely determined in both of theoretical calculations and experimental data. In the future, the precisions in the flavor experiments will be further improved, and theoretical precise calculations become more important. Besides, in the flavor-conserving processes, several experiments are proposed to measure nucleon EDMs, whose sensitivities would be improved by 2-3 orders of magnitudes in near future. Although EDMs are flavor-conserving processes, they have a sensitivity to flavor violations through the W-boson interactions. Thus, NP effects on quark flavor-changing neutral currents can contribute to quark EDMs simultaneously by exchanging the W boson. Since the EDMs are very sensitive to NP, they can also prove flavor-changing contributions to NP.

In conventional evaluations of CP and flavor violating observables, heavy degree of freedom, such as NP particles and the heavy SM particles including the top-quark and the EW gauge boson, are simultaneously decoupled, and the NP model is matched onto the low energy effective field theory (LEFT). This is because an expectation for the NP scale is not far from the EWSB scale. The LEFT are eventually compared with experimental data. However, in the current perspective, this procedure for the evaluations of the CP and flavor violating observables are broken down. Let us focus on a class of the NP models, both of NP and SM particles appear simultaneously in a loop diagram. As mentioned before, the NP particles are likely to be much heavier than the SM ones. When there is a large mass hierarchy among the particles in a loop diagram, higher order corrections of the perturbation cannot be negligible. Then, corrections of the dynamical top quark to the low-scale effective operators can be relevant, because the top quark has a large Yukawa coupling and mass. In particular, in the conventional evaluations, it is not clear that ``in which energy scale the top quark mass (or the top Yukawa coupling) is evaluated." We call this problem as ``matching scale uncertainty" in this thesis. In addition, since the LEFT does not include the W boson as a dynamical degree of freedom, it is difficult to analyze correlations between observables with the FCNC observables and the EDMs through a model independent way. In evaluation of CP and flavor violating observables, integrating out both of NP and SM particles is no longer appropriate because of the much high NP scale, and the conventional evaluations based on the LEFT must be improved by an instead effective field theory in which the heavy SM degree of freedoms are retained.

The Standard Model Effective Field Theory (SMEFT) is one of the candidates for the effective field theory above the EWSB scale. In the SMEFT, the higher dimensional operators are invariant under the SM gauge symmetries, $SU(3)_C \times SU(2)_L \times U(1)_Y$, and all the SM particles, particularly the electroweak bosons (W, Z, H) and the top quark (t), are dynamical degrees of freedom. The NP diagrams are matched onto the SMEFT, and the renormalization group equations (RGEs) in the SMEFT are solved. In this sense, we can escape the breakdown of the perturbation coming from the large mass hierarchy among the particles in a loop diagram. Since, in conventional calculations, the NP contributions are evaluated at the one-loop level, we need one-loop matching formulae to analyze the NP effects at the same order of perturbative calculations, which were provided by the author's work. By integrating out W, Z, H and t at the EWSB scale, the SMEFT effective operators are matched onto operators in the conventional LEFT. As the results, the scale uncertainty in a conventional approach is resolved by means of the RGEs and the one-loop matching condition of the SMEFT. In addition, flavor changing occurs in the matching at the one-loop level because of the decoupling the W boson, and the SMEFT $\Delta F = 1$ operators induce $\Delta F = 2$ and 0 observables. Therefore, it also becomes possible to analyze the correlations between the FCNC observables and the EDMs without specifying a NP model. In a conventional approach, however, the NP diagrams are matched directly to the low-scale effective operators, and the SMEFT effects, i.e., corrections from the dynamical t (and also W,Z,H), are discarded. Such an approximation is broken down and the scale uncertainty becomes larger, as the NP scale becomes higher than the EWSB scale.

Stimulated by the current situation in the evaluations of the low-scale observables, in this thesis, we provide the one-loop matching formulae relevant to the low-scale $\Delta F = 2$ and 0 operators with the top Yukawa couplings, and we establish a systematic way to estimate flavor and CP violating observables in the SMEFT, which are the based on the works by the author. In Chapter 3, the complete one-loop matching formula for $\Delta F = 2$ and 0 processes with the top Yukawa couplings are provided.
In Chapter 5, by using the one-loop matching formulae and solving the RGEs in the SMEFT, we investigate whether the SMEFT effects are negligible or not. In the $\Delta F = 2$ processes, we discuss the scale uncertainty, which is reduced by the one-loop matching formulae and the SMEFT RGEs. In addition, the one-loop matching formulae mediated by the Z boson contributes to $\Delta F = 1$ processes, such as $K \to \pi\nu\bar{\nu}$ which is theoretical clean and sensitive to physics at high energy scale. By using our matching formulae including the Z mediated corrections, we discuss correlations between the $\Delta F = 2$ observables and $\Delta F = 1$ ones with particular emphasis on the kaon system. We show that the constraint from ε_K is drastically changed by the right-handed NP contributions in the Z mediated corrections. Besides, through the one-loop matching formulae for $\Delta F = 0$ processes, the SMEFT $\Delta F = 1$ operators contribute to low-scale $\Delta F = 0$ observables, such as the nucleon electric dipole moments (EDM). We discuss the nucleon EDMs within the framework of the SMEFT.
In Chapter 3, we consider the one-loop matching at the EWSB scale. We provide the one-loop formulae for the SMEFT $\Delta F = 1$ operators, which contribute to the low-scale operators with the top Yukawa couplings. We show that the SMEFT $\Delta F = 1$ operators contribute to the low-scale $\Delta F = 2$ and 0 operators by decoupling the electroweak bosons (W, Z, H) and the top quark (t).
In Chapter 5, we consider the SMEFT top-quark effects on the $\Delta F = 2$ observables. We investigate model independent top-quark corrections to $\Delta F = 2$ processes within the framework of the SMEFT. Dimension-six $\Delta F = 1$ operators contribute to them through renormalization group evolutions and the one-loop matching conditions. We find that effects of the matching scale uncertainty are reduced by $O(1-100\%)$, depending on the SMEFT $\Delta F = 1$ operators. As an application of this model independent procedure, we also demonstrate these corrections on ΔM_{B_s} in the left-right symmetric model, which are compared with the conventional calculation.
In Chapter 6, we evaluate the SMEFT corrections to $\Delta F = 2$ observables with particular emphasis on the Z mediated corrections. Focusing on the matching formula mediated by the Z boson in Chapter 3, we discuss correlations of the indirect CP violation ε_K with $\Delta F = 1$ observables such as $\frac{\varepsilon'}{\varepsilon_K}$, $B(K \to \pi\nu\bar{\nu})$ and $B(K_L \to \mu^+\mu^-)$. It is

found that the Z mediated SMEFT corrections by the right-handed NP effects make experimental bounds coming from the $\Delta F = 2$ observables drastically change. As an application of this model independent procedure, we also discuss Z mediated gluino contributions. For simplified scenarios, we discuss that the Z mediated SMEFT corrections may make the constraint for the SUSY scale be changed by $O(100\%)$. It is found that gluino mediated contributions are consistent with the experimental data by taking into account the Z mediated SMEFT corrections, if the squark mass is smaller than 5.2 TeV.

In Chapter 7, we investigate model independent flavor changing operators effects on the nucleon EDMs within the framework of the SMEFT. We focus on contributions of dimension-six $\Delta F = 1$ operators of the down-type quarks to EDM with particular emphasis on the top quark effects. In addition, we demonstrate correlations between the neucleon EDMs and $\Delta F = 2$ observables, such as ε_K and ΔM_{B_d}. It is found that some of the SMEFT operators are already excluded for the NP scale, $M_{NP} \lesssim 1 - 2$ GeV by the neutron EDM, and future experiments may be able to probe those in $M_{NP} \lesssim 2 - 10$ TeV. We also discuss correlations of these effects with $\Delta F = 2$ observables such as ε_K and ΔM_{B_d}.

As summaries of these studies, it becomes clear that the SMEFT is essential to reduce the scale uncertainty, the constraint for the right-handed NP effects are tightly constrained in the Z mediated SMEFT corrections, and the nucleon EDMs can provide an complementary information on the $\Delta F = 1$ effective operators in future. We will conclude that the SMEFT effects are essential rather than negligible as the results of these studies.

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（様式８・別紙）

Results of the doctoral thesis screening

博士論文審査結果

Name in Full
氏　名　上田　大輝

Title
論文題目　Phenomenology of SMEFT Flavor Changing Operators

上田大輝氏の学位論文は、素粒子標準理論を拡張した有効理論（SMEFT）においてクォークフレーバーを変える演算子が引き起こす素粒子現象の研究成果をまとめたものである。素粒子標準理論を超える新しい物理理論の探索は現代の素粒子研究の主要なターゲットである。これまでに LHC 実験などで発見に至っておらず、その正体を探るためには、フレーバーや CP を破る素粒子反応を精密に探ることが有力な手段になっている。

これらの素粒子反応に対する新しい物理理論の効果は低エネルギー有効理論を用いて研究されてきた。しかし、これまでの有効理論には、素粒子標準理論の W ボソンやトップクォークなど重い素粒子の効果は近似的にしか取り入れられてこなかった。このような近似は、1TeV を超えるような高いエネルギースケールにおける新しい物理理論では成り立たない。上田氏は、有効理論として SMEFT を導入することでこの問題を解決した。

W ボソンやトップクォークの量子効果は、とくに新しい物理理論から予言されるフレーバーや CP の破れの大きさに影響を与える。上田氏は SMEFT を用いることで、これらの重い素粒子の量子効果が定性的、定量的に重要な影響を与えることを示した。とくに、電弱エネルギースケール以下の有効理論との適切な接続条件を新たに導入することで、フレーバーや CP を破る素粒子反応に対する新しい物理理論の効果を精密に評価した。従来のアプローチでは未解決であったスケール不定性の問題を解決して、さらに K 中間子や B 中間子の素粒子反応や、電気双極子モーメントに対する SMEFT 特有の効果を特定して、それらを定量的に評価した。

以上の研究の成果は海外の論文誌 Journal of High Energy Physics に掲載されており、複数の国際研究会において発表されている。博士論文審査会では、論文の内容をわかりやすくまとめた発表を行い、出席者からの質問にも適切に対応した。博士論文は英語で記述されており、英語による研究発表も行なっていることから、英語による十分な研究遂行能力を持っていることも確認された。

本論文は上田氏が高い研究能力を備えていることを示しており、審査員は全員一致で博士論文を合格とすることを決定した。