Final Report

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Recipient: The University of Alabama

Project Title: Research in Theoretical High Energy Physics

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Accomplishment

1. Major goals of the project

PI Dr. Okada's research interests are centered on phenomenological aspects of particle physics. It has been abundantly clear in recent years that an extension of the Standard Model (SM), i.e. new physics beyond the SM, is needed to explain a number of experimental observations such as the neutrino oscillation data, the existence of non-baryonic dark matter, and the observed baryon asymmetry of the Universe. In addition, the SM suffers from several theoretical/conceptual problems, such as the gauge hierarchy problem, the fermion mass hierarchy problem, and the origin of the electroweak symmetry breaking. It is believed that these problems can also be solved by new physics beyond the SM. The main purpose of the Dr. Okada's research is a theoretical investigation of new physics opportunities from various phenomenological points of view, based on the recent progress of experiments/observations in particle physics and cosmology. There are many possibilities to go beyond the SM and many new physics models have been proposed. The major goal of the project is to understand the current status of possible new physics models and obtain the future prospects of new physics phenomena toward their discoveries.

2. Accomplishments under the major goals of the project

During the project period (April 01, 2015-March 31, 2017), PI Dr. Okada has investigated new physics beyond the Standard Model in a variety of aspects, such as new physics implications of the Higgs boson properties, new physics model building for neutrino mass generation, simple gauged U(1) extensions of the Standard Model with classically conformal symmetry, a right-handed neutrino dark matter in the minimal gauged U(1) extended Standard Model, and a proposal of simple inflation models that have implications to physics at the TeV scale. In the following, accomplishments of these research projects are stated with a list of publications.

A. Classically conformal extension of the Standard Model with U(1) gauge symmetry

Classical conformal extension of the SM is an interesting possibility for new physics beyond the SM, where the SM is extended with a U(1) gauge symmetry and the electroweak symmetry is dynamically broken through a radiative U(1) symmetry breaking. In the presence of the U(1) gauge symmetry, the so-called instability problem of the electroweak vacuum can be solved. With his collaborators, Dr. Okada has investigated the classically conformal U(1) extended SM and identified the allowed parameter regions which are consistent with the current LHC constraints from the search for a new gauge boson associated with the U(1) gauge symmetry, and provide the stability of the electroweak vacuum. The results are presented in the papers, [10], [18] and [20], in the list of publication attached below. Related models have been investigated in the papers, [8], [14] and [19].

B. Right-handed neutrino dark matter in the minimal U(1) extension of the SM

In the context of the minimal U(1) extended SM, Dr. Okada with his collaborator has proposed a simple dark matter scenario, where one right-handed serves as the dark matter in the present Universe. This scenario is categorized into the so-called Z'-portal dark matter scenario, where the dark matter particle communicates with the SM particles through a new gauge boson (Z'). Dr. Okada and his collaborator have figured out the parameter regions which reproduce the observed dark matter density while being consisted with the null-result from the search for the Z'-boson resonance at the Large Hadron Collider (LHC). A complementarity between the dark matter physics and the LHC physics has been pointed out in this research project. For details, see the papers, [4] and [13].

C. Cosmological inflation models

Dr. Okada and his collaborators proposed cosmological inflation scenarios in the context of well-motivated particle physics models for the neutrino mass generations and the grand unification of the SM gauge interactions. In particular, a complementarity of the inflationary predictions with physics phenomena at the TeV scale has been proposed in the model context. The search for new particles at the LHC has a correlation with the inflationary predictions that will be more precisely measured in the near future. Details are found in the papers, [1], [3], [5] and [17].

D. Models for radiative neutrino mass generation

With his collaborators, Dr. Okada has proposed models for radiative neutrino mass generation. See the papers, [7] and [21], for details. Generation of the tiny neutrino mass is one of the major research fields in particle physics. If the neutrino mass is generated only through radiative corrections, we can naturally explain the reason why the neutrinos have masses much smaller than the other fermions in the SM. In the papers, the authors have not only proposed simple models for the radiative neutrino mass, but also identified the parameter regions consistent with the current experimental data.

E. LHC phenomenology

The Majorana neutrino in type-I seesaw and the pseudo-Dirac neutrinos in the inverse seesaw can have sizable mixings with the light neutrinos in the SM, through which the heavy neutrinos can be produced at the LHC. On producing the heavy neutrinos, Dr. Okada and his collaborator in the paper [16] have studied a variety of initial states such as quark-quark, quark-gluon and gluon-gluon as well as photon mediated processes. Taking the varieties of initial states into account, the previously obtained upper bounds on the mixing angles from the LHC data have been improved. In addition, see [15] for another work by Dr. Okada and his collaborators on LHC phenomenology, where the authors have shown that some excess events recently observed by the ATLAS and the CMS collaborations can be explained simultaneously in the context of an SU(2)_L x SU(2)_R gauge extension of the SM. This model can be explored at the LHC Run-2 in the near future.

3. Opportunities for training/professional development provided by the project

The research project involves Dr. Okada's advisee graduate students (Jason Carson, Arindam Das, Nathan Papapietro, Digesh Raut, and Daisuke Takahashi), and their dissertation research subjects are included in the project. All of them have (had) been doing research toward their dissertations and have publications. Jason Carson graduated with Ph.D. in December 2015, and Arindam Das and Nathan Papapietro received their PhDs in May 2016. While Jason and Nathan got their jobs in companies, while Arindam got a postdoctoral research associate position at Korea Institute of Advanced Study (KIAS) and continues his particle physics research at KIAS since September, 2016.

With travel supports from this DOE grants, Arindam, Nathan and Digesh attended Phenomenology 2015 Symposium (May 04-06, 2015 at Univeristy of Pittsburgh) and gave oral presentations at the symposium. Arindam and Nathan also attended SUSY 2015 (Aug.

23-29, 2015 at Lake Tahoe) and presented their research. Digesh attended Dark Side of the Universe (Dec. 14-18, 2015 at Kyoto, Japan) and presented his research outcomes with Dr. Okada. Also, with summer salary supports from the DOE grant, the three students (Arindam, Nathan and Digesh) concentrated on their research projects, and they were very productive in 2016 summer. Digesh and Dr. Okada's new graduate student, Desmond Villalba, attended Phenomenology 2016 Symposium (May 07-09, 2015 at University of Pittsburgh) and gave oral presentations. Digesh's research during summer 2016 was supported by the DOE grant and his summer was very productive in particle physics research. Digesh visited University of Delaware, University of Maryland and Virginia Tech to give seminar talks in March 2017, and had useful discussions with researchers there. His travel was partly supported by the DOE grant. Digesh is expected to receive his PhD in May 2017.

4. How have the results been disseminated to communities of interest?

The results of the research project supported by the DOE have been presented in domestic/international conferences/workshops and seminar/colloquium talks by Dr. Okada, his graduate students and collaborators. Also, their research papers have been obtained from the preprint server (https://arxiv.org/) and published in scientific journals.

Impact

1. Impact on the development on the principal discipline(s) of the project

It has been clear in recent years that an extension of new physics beyond the SM is needed to explain a number of experimental observations such as solar and atmospheric neutrino oscillations and the existence of non-baryonic dark matter. Among other things, the SM suffers from a serious theoretical problem, the gauge hierarchy problem, which should be solved by new physics at the TeV scale. Therefore, one of the most important subjects in the current particle physics is to reveal new physics from both theoretical and experimental sides. This is the main theme of my research project, along which Dr. Okada has been working on a wide range of new physics, from model building to phenomenology at high energy collider experiments, cosmology and astrophysics. Examining new physics opportunities from such various phenomenological points of view, we may be able to determine a future direction of particle physics research. New physics models proposed in the project can be tested by a variety of ongoing and planned experiments in the future.

2. Impact on other disciplines

Recent results at the world largest experiments by LHC and the most precise measurements of cosmological parameters by Planck satellite experiment are key information to carry out the research. New physics opportunities are examined by various phenomenological points of view, and the future directions for particle physics phenomenology can be determined. New physics models proposed and investigated in the project can be discovered or excluded in the near future. The research project can provide new and deeper understandings of the history of the Universe, which have a great impact on any other disciplines.

List of publications

[1] ``Inflection-point inflation in hyper-charge oriented U(1)x model''
N. Okada, S. Okada and D. Raut
DOI:10.1103/PhysRevD.95.055030
Phys. Rev. D 95, no. 5, 055030 (2017)

[2] ``Thermal Inflation with Flaton Chemical Potential''
M. Arai, Y. Kobayashi, N. Okada and S. Sasaki
DOI:10.1103/PhysRevD.95.083521
Phys. Rev. D 95, no. 8, 083521 (2017)

[3] ``Non-minimal quartic inflation in supersymmetric $SO(10)$''
G. K. Leontaris, N. Okada and Q. Shafi
DOI:10.1016/j.physletb.2016.12.038
Phys. Lett. B 765, 256 (2017)

[4] ``Z'-portal right-handed neutrino dark matter in the minimal U(1)x extended Standard Model''
N. Okada and S. Okada
DOI:10.1103/PhysRevD.95.035025
Phys. Rev. D 95, no. 3, 035025 (2017)

[5] ``Inflection-point Higgs Inflation''
N.~Okada and D.~Raut
DOI:10.1103/PhysRevD.95.035035
Phys. Rev. D 95, no. 3, 035035 (2017)

[6] ``Proton decay prediction from a gauge-Higgs unification scenario in five dimensions''
N. Haba, N. Okada and T. Yamada.
DOI:10.1103/PhysRevD.94.071701
Phys. Rev. D 94, no. 7, 071701 (2016)

[7] ``A Colored KNT Neutrino Model''
T. Nomura, H. Okada and N. Okada
DOI:10.1016/j.physletb.2016.09.038
Phys. Lett. B 762, 409 (2016)

[8] ``Multiple-point principle with a scalar singlet extension of the Standard Model''}
N. Haba, H. Ishida, N. Okada and Y. Yamaguchi
DOI:10.1093/ptep/ptw186
PTEP 2017, no. 1, 013B03 (2017)

[9] ``125 GeV Higgs boson mass and muon $g-2$ in 5D MSSM''
N. Okada and H. M. Tran.
DOI:10.1103/PhysRevD.94.075016
Phys. Rev. D 94, no. 7, 075016 (2016)

[10] ``Classically conformal U(1)′ extended standard model, electroweak vacuum stability, and LHC Run-2 bounds''
A. Das, S. Oda, N. Okada and D. s. Takahashi
DOI:10.1103/PhysRevD.93.115038
Phys. Rev. D 93, no. 11, 115038 (2016)

[11] ``Higgs phenomenology in the minimal SU(3)_L×U(1)_X model''
H. Okada, N. Okada, Y. Orikasa and K. Yagyu
DOI:10.1103/PhysRevD.94.015002
Phys. Rev. D 94, no. 1, 015002 (2016)

[12] ``Radiative breaking of the minimal supersymmetric left-right model''
N. Okada and N. Papapietro
DOI:10.1016/j.physletb.2016.02.066
Phys. Lett. B 756, 47 (2016)

[13] ``Z'_BL portal dark matter and LHC Run-2 results''
N. Okada and S. Okada.
DOI:10.1103/PhysRevD.93.075003
Phys. Rev. D 93, no. 7, 075003 (2016)

[14] ``Vacuum stability and naturalness in type-II seesaw''
N. Haba, H. Ishida, N. Okada and Y. Yamaguchi.
DOI:10.1140/epjc/s10052-016-4180-z
Eur. Phys. J. C 76, no. 6, 333 (2016)

[15] ``Testing the 2-TeV Resonance with Trileptons''
A. Das, N. Nagata and N. Okada.
DOI:10.1007/JHEP03(2016)049
JHEP 1603, 049 (2016)

[16] ``Improved bounds on the heavy neutrino productions at the LHC''
A. Das and N. Okada
DOI:10.1103/PhysRevD.93.033003
Phys. Rev. D 93, no. 3, 033003 (2016)

[17] ``Running non-minimal inflation with stabilized inflaton potential''
N. Okada and D. Raut.
DOI:10.1140/epjc/s10052-017-4799-4
Eur. Phys. J. C 77, no. 4, 247 (2017)

[18] ``Electroweak vacuum stability in classically conformal B-L extension of the Standard Model''
A. Das, N. Okada and N. Papapietro.
DOI:10.1140/epjc/s10052-017-4683-2
Eur. Phys. J. C 77, no. 2, 122 (2017)

[19] ``Bosonic seesaw mechanism in a classically conformal extension of the Standard Model''
N. Haba, H. Ishida, N. Okada and Y. Yamaguchi
DOI:10.1016/j.physletb.2016.01.050
Phys. Lett. B 754, 349 (2016)

[20] ``Classically conformal U(1)′ extended standard model and Higgs vacuum stability''
S. Oda, N. Okada and D. s. Takahashi
DOI:10.1103/PhysRevD.92.015026
Phys. Rev. D 92, no. 1, 015026 (2015)

[21] ``Radiative seesaw mechanism in a minimal 3-3-1 model''
H. Okada, N. Okada and Y. Orikasa
DOI:10.1103/PhysRevD.93.073006
Phys. Rev. D 93, no. 7, 073006 (2016)

[22] ``Simple brane-world inflationary models: an update''
N.~Okada and S.~Okada.
DOI:10.1142/S0217751X16500780
Int. J. Mod. Phys. 31, no. 14n15, 1650078 (2016)