Research in Theoretical Particle Physics

Final Report on DOE Grant Number DE-SC0010382

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Overview

This document is the final report on activity supported under DOE Grant Number DE-FG02-13ER42024. The report covers the period July 15, 2013 – March 31, 2014. Faculty supported by the grant during the period were Danny Marfatia (1.0 FTE) and Hume Feldman (1% FTE). The grant partly supported University of Hawaii students, David Yaylali and Keita Fukushima, who are supervised by Jason Kumar. Both students are expected to graduate with Ph.D. degrees in 2014. Yaylali will be joining the University of Arizona theory group in Fall 2014 with a 3-year postdoctoral appointment under Keith Dienes.

The group's research covered topics subsumed under the Energy Frontier, the Intensity Frontier, and the Cosmic Frontier. Many theoretical results related to the Standard Model and models of new physics were published during the reporting period. The report contains brief project descriptions in Section 1. Sections 2 and 3 lists published and submitted work, respectively. Sections 4 and 5 summarize group activity including conferences, workshops and professional presentations.

1 Projects

1.1 Configurations of the Long-Baseline Neutrino Experiment

Marfatia with collaborators studied the neutrino oscillation physics performance of the Long-Baseline Neutrino Experiment (LBNE) in various configurations [1]. In particular, they compared the case of a surface detector at the far site augmented by a near detector, to that with the far site detector placed deep underground but no near detector. In the latter case, information from atmospheric neutrino events is also utilized. For values of θ_{13} favored by reactor experiments and a 100 kt-yr exposure, they found roughly equivalent sensitivities to the neutrino mass hierarchy, the octant of θ_{23}, and to CP violation. They also found that as the exposure is increased, the near detector helps increase the sensitivity to CP violation substantially more than atmospheric neutrinos.

In subsequent work, the same authors extended their study to evaluate the dependencies on the precision with which θ_{13} will be measured by reactor experiments, on the detector size, beam power and exposure time, on detector magnetization, and on the systematic uncertainties achievable with and without a near detector [2]. They found that a 35 kt LBNE with a near detector will resolve the eight-fold degeneracy that is intrinsic to long baseline experiments and will meet the primary goals of oscillation physics that it is designed for.

1.2 One diagonal texture or cofactor zero of the neutrino mass matrix

In view of the recent measurement of nonzero θ_{13}, Marfatia with Kerry Whisnant and his student Jiajun Liao, carried out a systematic study of a simple class of neutrino models that has one diagonal texture or cofactor zero in the mass matrix [3]. There are seven free parameters in the model and five of them have been measured by neutrino oscillation experiments; some cases for the normal or inverted hierarchy are excluded and for the rest they obtained the preferred values for the lightest neutrino mass and Dirac CP phase. They found that there are strong similarities between one diagonal texture zero models with one mass hierarchy and one diagonal cofactor zero models with the opposite mass hierarchy. They also made predictions for neutrinoless double beta decay for these models. For the one cofactor zero models, they presented a simple realization based on a new U(1) gauge symmetry.

1.3 Dual models of the neutrino mass spectrum

Building on the above work, Marfatia *et al.* showed that any model with a homogeneous relationship among elements of the neutrino mass matrix with one mass hierarchy yields predictions for the oscillation parameters and Majorana phases similar to those given by a model with the same homogeneous relationship among cofactors of the neutrino mass matrix with the opposite mass hierarchy, except when the lightest mass is very small, or order 20 meV or less [4].

1.4 Texture and cofactor zeros of the neutrino mass matrix

The same authors then studied Majorana neutrino mass matrices that have two texture zeros, or two cofactor zeros, or one texture zero and one cofactor zero [5]. The two texture/cofactor zero conditions give four constraints, which in conjunction with the five measured oscillation parameters completely determine the nine independent real parameters of the neutrino mass matrix. They also studied the implications for neutrinoless double beta decay in these models.

1.5 Matrix element analyses of dark matter scattering and annihilation

Marfatia and Jason Kumar provided a compendium of results at the level of matrix elements for a systematic study of dark matter scattering and annihilation [6]. They identified interactions that yield spin-dependent and spin-independent scattering and specified whether the interactions are velocity- and/or momentum-suppressed. They identified the interactions that lead to s-wave or p-wave annihilation, and those that are chirality-suppressed. They also listed the interaction structures that can interfere in scattering and annihilation processes. Using these results, they pointed out situations in which deviations from the standard lore are obtained.

1.6 Isopsin-Violating Dark Matter Benchmarks for Snowmass 2013

Isospin-violating dark matter (IVDM) generalizes the standard spin-independent scattering parameter space by introducing one additional parameter, the neutron-to-proton coupling ratio f_n/f_p. In IVDM the implications of direct detection experiments can be altered significantly. Marfatia and collaborators reviewed the motivations for considering IVDM and presented benchmark models that illustrate some of the qualitatively different possibilities [7]. IVDM strongly motivates the use of a variety of target nuclei in direct detection experiments.

1.7 Isospin-Violating Dark Matter at the LHC

Marfatia and collaborators considered a toy model of dark matter (DM) with a gauge singlet Dirac fermion that has contact interactions to quarks that differ for right-handed up and down quarks [8]. This is motivated by the isospin-violating dark matter scenario mentioned above. They discussed how the effects of isospin violation in these couplings can be observed at the LHC. By studying events with large missing transverse momentum ($\not{E}_T$), they showed that the ratio of the mono-photon and mono-jet events is sensitive to the ratio of the absolute values of the couplings to the up and down quarks, whereas a dedicated study of di-jet plus $\not{E}_T$ events can reveal their relative sign. They also considered how their results are modified if instead of a contact interaction, a particle that mediates the interaction is introduced. Their methods have broad applicability to new physics that involves unequal couplings to up and down quarks.

1.8 AMS-02 and Next-to-Minimal Universal Extra Dimensions

The anomaly detected by AMS-02 and PAMELA in the cosmic-ray positron flux when interpreted as arising from dark matter annihilation suggests that dark matter may interact differently with hadrons and leptons so as to remain compatible with cosmic-ray antiproton data. Such a scenario is readily accommodated in models with extra spatial dimensions. Marfatia, Gao and Kong studied indirect detection of Kaluza-Klein (KK) dark matter in Universal Extra Dimensions with brane-localized terms and fermion bulk masses: Next-to-Minimal Universal Extra Dimensions [9]. So that an excess of antiprotons is not produced in explaining the positron anomaly, it is necessary that the KK bulk masses in the lepton and hadron sectors be distinct. Even so, they found that cosmic-ray data disfavor a heavy KK photon dark matter scenario. Also, they found these scenarios with flavor-universal bulk masses to be in conflict with dijet and dilepton searches at the LHC.

1.9 Cosmic Neutrino Pevatrons: A Brand New Pathway to Astronomy, Astrophysics, and Particle Physics

The announcement by the IceCube Collaboration of the observation of cosmic neutrino candidates has been greeted with a great deal of justified excitement. The data reported so far depart by more than 4σ from the expected atmospheric neutrino background, which raises the obvious question: "Where in the Cosmos are these neutrinos coming from?" Marfatia and collaborators reviewed the many possibilities that have been explored in the literature to address this question, including origins at either Galactic or extragalactic celestial objects [10]. They also briefly discussed new physics processes which may either explain or be constrained by IceCube data.

1.10 End of the cosmic neutrino energy spectrum

There may be a high-energy cutoff of neutrino events in IceCube data. In particular, IceCube does not observe the Standard Model Glashow-resonance events expected at 6.3 PeV. There are also no higher-energy neutrino signatures in the ANITA and Auger experiments. This absence of high-energy neutrino events motivated Marfatia and collaborators to study models with a fundamental restriction on neutrino energies above a few PeV [11]. The simplest scenario to terminate the neutrino spectrum is Lorentz-invariance violating with a limiting neutrino velocity that is smaller than the speed of light. If the limiting velocity of the neutrino applies also to its associated charged lepton, then a significant consequence is that charged pions are stable above two times the maximum neutrino energy; such stabilized pions may serve as cosmic ray primaries.

1.11 S-dual Inflation: BICEP2 data without unlikeliness

Marfatia *et al.* showed that S-dual inflationary potentials solve the unlikeliness problem manifested in Planck data and explain the excess B-mode power observed by the BICEP2 experiment as arising from primordial tensor fluctuations [12].

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[1] V. Barger, A. Bhattacharya, A. Chatterjee, R. Gandhi, D. Marfatia and M. Masud, Phys. Rev. D **89**, 011302 (2014) [arXiv:1307.2519 [hep-ph]].

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4 Talks by Marfatia

1. *Perturbations to $\mu - \tau$ symmetry in neutrino mixing*
   PASCOS 2013: The 19^{th} International Symposium on Particles, Strings and Cosmology, Taipei, Taiwan, November 2013.

2. *Aspects of Isospin-Violating Dark Matter*
   KITP Program, Hunting for Dark Matter: Building a cross-disciplinary multi-pronged approach, Santa Barbara, California, June 2013.

5 Conferences and Workshops attended by Marfatia

1. PASCOS 2013: The 19^{th} International Symposium on Particles, Strings and Cosmology
   November 20–26, Taipei, Taiwan.

2. CosPA 2013: International Symposium on Cosmology and Particle Astrophysics
   November 12–15, Honolulu, Hawaii.

3. KITP Program, Exploring TeV Scale New Physics with LHC Data
   April 29–July 26, 2013, Santa Barbara, California.

4. KITP Program, Hunting for Dark Matter: Building a cross-disciplinary multi-pronged approach
   April 22–June 28, 2013, Santa Barbara, California.