- Final Scientific/Technical Report -

Searches for New Phenomena Beyond the Standard Model
Hunt for New Physics at the Large Hadron Collider

Award number:	DE-SC0007863
Project Title (04/01/2015 - 04/30/2017):	Searches for New Phenomena Beyond the Standard Model
Project Title (05/01/2012 - 03/31/2015):	Hunt for New Physics at the Large Hadron Collider
Name of Recipient:	University of Kansas Center for Research, Inc. 2385 Irving Hill Road Lawrence, KS 66045-7568
Administrative Point of Contact:	Alicia M. Reed
Telephone number:	785-864-3441
email:	kucrpropmgmt@ku.edu
Principal Investigator:	Dr. Kyoungchul Kong (K.C. Kong), Associate Professor
Institutional Affiliation:	Department of Physics and Astronomy University of Kansas Lawrence, KS 66045
Telephone number:	785-505-0951
email:	kckong@ku.edu
Research area:	Theoretical Research in High Energy Physics
Start date:	05/01/2012
Completion date:	04/30/2017
Project period end date:	04/30/2017

Searches for New Phenomena Beyond the Standard Model
Hunt for New Physics at the Large Hadron Collider

Kyoungchul (K.C.) Kong

Contents

1 Executive Summary

DOE award DE-SC0007863 supports theoretical research in high energy physics. PI and students are NOT a part of any experimental collaboration, even if some works were done in collaboration with experimental colleagues. All research products are in the form of research articles and they are publicly available under `inspirehep.net` and `arxiv.org`, which are typical publication methods in high energy physics. No invention or patent is involved with this research. No equipment or hardware is involved with the research under this award (beside a laptop purchased with PI's startup). Some of research outcome is in the form of a computer code, which is available in https://launchpad.net/maddm. This is community effort and anyone has access to the program. Its source is open and anyone can participate in the development.

Research outcomes and the code are used by colleagues in high energy physics, including both theorists and experimentalists. Therefore the outcome of research topics under this award supported the High Energy Physics experimental research program, both in understanding the data and in finding new directions for experimental exploration. The research materials are used to train undergraduate students, graduate students and postdoctoral scholars.

We summarize research activity under this award in the following section and major products are listed in section 3. Section 4 contains professional presentations given by PI. Other products developed during the award period are in section 5. Summary of expenses, and student/postdoc support are summarized in section 6 and 7, respectively.

2 Summary of research activity

Theoretical research under this award includes several major parts to support experimental effort in energy frontier, intensity frontier and cosmic frontier. Collider studies and dark matter phenomenology are summarized in section 2.1 and section 2.2. Development on models with extra dimension is presented in section 2.3. Finally, a novel dark matter tool (MadDM) is explained in section 2.4

2.1 Collider Physics

2.1.1 Development on kinematic techniques and their applications

The 750 GeV Diphoton Excess May Not Imply a 750 GeV Resonance: We discuss non-standard interpretations of the 750 GeV diphoton excess recently reported by the ATLAS and CMS Collaborations which do not involve a new, relatively broad, resonance with a mass near 750 GeV. Instead, we consider the sequential cascade decay of a much heavier, possibly quite narrow, resonance into two photons along with one or more invisible particles. The resulting diphoton invariant mass signal is generically rather broad, as suggested by the data. We examine three specific event topologies - the antler, the sandwich, and the 2-step cascade decay, and show that they all can provide a good fit to the observed published data. In each case, we delineate the preferred mass parameter space selected by the best fit. In spite of the presence of invisible particles in the final state, the measured missing transverse energy is moderate, due to its anti- correlation with the diphoton invariant mass. We comment on the future prospects of discriminating with higher statistics between our scenarios, as well as from more conventional interpretations. (Featured in physics, "Synopsis: Explaining a 750 GeV Bump" by editor.)

Resolving Combinatorial Ambiguities in Dilepton $t\bar{t}$ Event Topologies with Constrained M_2 Variables: We advocate the use of on-shell constrained M_2 variables in order to mitigate the combinatorial problem in SUSY-like events with two invisible particles at the LHC. We show that in comparison to other approaches in the literature, the constrained M_2 variables provide superior ansatze for the unmeasured invisible momenta and therefore can be usefully applied to discriminate combinatorial ambiguities. We illustrate our procedure with the example of dilepton $t\bar{t}$ events. We critically review the existing methods based on the Cambridge M_{T2} variable and MAOS-reconstruction of invisible momenta, and show that their algorithm can be simplified without loss of sensitivity, due to a perfect correlation between events with complex solutions for the invisible momenta and events exhibiting a kinematic endpoint violation. Then we demonstrate that the efficiency for selecting the correct partition is further improved by utilizing the M_2 variables instead. Finally, we also consider the general case when the underlying mass spectrum is unknown, and no kinematic endpoint information is available.

Kinematic discrimination of tW and $t\bar{t}$ productions using initial state radiation: Production of a single top quark provides excellent opportunity for understanding top quark physics and Cabibbo-Kobayashi-Maskawa structure of the quark sector in the Standard Model. Although an associated production with a b-quark has already been observed at the Tevatron in 2009, a single top production in association with a W gauge boson has not been observed till 2014 at the LHC, where pair production of the top quark serves as the dominant background. Due to the kinematic similarity between tW and the dominant background, it is challenging to find suitable kinematic variables that offer good signal-background separation, which naturally leads to the use of multivariate methods. In this paper, we investigate kinematic structure of $tW + j$ channel using M_{T2} and invariant mass variables, and find that $tW + j$ production could well be separated from $t\bar{t}$ production with high purity at a low cost of statistics when utilizing these kinematic correlations.

2.1.2 Novel collider signatures

Monotop signature from a fermionic top partner: We investigate mono-top signatures arising from phenomenological models of fermionic top-partners, which are degenerate in mass and decay into a bosonic dark matter candidate, either spin-0 or spin-1. Such a model provides a mono-top signature as a smoking-gun, while conventional searches with $t\bar{t}$ + missing transverse momentum are limited. Two such scenarios: i) a phenomenological 3rd generation extra dimensional model with excited top and electroweak sectors, and ii) a model where only a top-partner and a dark matter particle are added to the SM, are studied in the degenerate mass regime. We find that in the case of extra dimension a number of different processes give rise to effectively the same mono-top final state, and a great gain can be obtained in the sensitivity for this channel. We show that the mono-top search can explore top-partner masses up to 630 GeV and 300 GeV for the 3rd generation extra dimensional model and the minimal fermionic top-partner model, respectively, at the high luminosity LHC.

Identifying a new particle with jet substructures: We investigate a potential of measuring properties of a heavy resonance X, exploiting jet substructure techniques. Motivated by heavy higgs boson searches, we focus on the decays of X into a pair of (massive) electroweak gauge bosons. More specifically, we consider a hadronic Z boson, which makes it possible to determine properties of X at an earlier stage. For m_X of $O(1)$ TeV, two quarks from a Z boson would be captured as a "merged jet" in a significant fraction of events. The use of the merged jet enables us to consider a Z-induced jet as a reconstructed object without any combinatorial ambiguity. We apply a conventional jet substructure method to extract four-momenta of subjets from a merged jet. We find that jet substructure procedures may enhance features in some kinematic observables formed with subjets. Subjet momenta are fed into the matrix element associated with a given hypothesis on the nature of X, which is further processed to construct a matrix element method (MEM)-based observable. For both moderately and highly boosted Z bosons, we demonstrate that the MEM with current jet substructure techniques can be a very powerful discriminator in identifying the physics nature of X. We also discuss effects from choosing different jet sizes for merged jets and jet-grooming parameters upon the MEM analyses.

Diboson Excesses Demystified in Effective Field Theory Approach: We study the collider implication of a neutral resonance which decays to several diboson final states such as W^+W^-, ZZ, and $Z\gamma$ via a minimal set of effective operators. We consider both CP-even and CP-odd bosonic states with spin 0, 1, or 2. The production cross sections for the bosonic resonance states are obtained with the effective operators involving gluons (and quarks), and the branching fractions are obtained with the operators responsible for the interactions with electroweak gauge bosons. We demonstrate that each scenario allows for a broad parameter space which could accommodate the recently-reported intriguing excesses in the ATLAS diboson final states, and discuss how the CP states and spin information of the resonance can be extracted at the LHC run II.

Probing TeV scale Top-Philic Resonances with Boosted Top-Tagging at the High Luminosity LHC: We investigate the discovery potential of singly produced top-philic resonances at the high luminosity (HL) LHC in the four-top final state. Our analysis spans over the fully-hadronic, semi-leptonic, and same-sign dilepton channels where we present concrete search strategies adequate to a boosted kinematic regime and high jet-multiplicity environments. We utilize the Template Overlap Method (TOM) with newly developed template observables for tagging boosted top quarks, a large-radius jet variable M_J and customized b-tagging tactics for background discrimination. Our results show that the same-sign dilepton channel gives the best sensitivity among the considered channels, with an improvement of significance up to 10%-20% when combined with boosted-top tagging. Both the fully-hadronic and semi-leptonic channels yield comparable discovery potential and contribute to further enhancements in the sensitivity by combining all channels. Finally, we show the sensitivity of a top-philic resonance at the LHC and HL-LHC by showing the 2σ exclusion limit and 5σ discovery reach, including a combination of all three channels.

Model-Independent Production of a Top-Philic Resonance at the LHC: We investigate the collider phenomenology of a color-singlet vector resonance, which couples to the heaviest quarks, the top quarks, but very weakly to the rest of the fermions in the Standard Model. We find that the dominant production of such a resonance does not appear at the tree level – it rather occurs at the one-loop level in association with an extra jet. Signatures like t anti-t plus jets readily emerge as a result of the subsequent decay of the resonance into a pair of top quarks. Without the additional jet, the resonance can still be produced off-shell, which gives a sizeable contribution at low masses. The lower top quark multiplicity of the loop induced resonance production facilitates its reconstruction as compared to the tree level production that gives rise to more exotic signatures involving three or even four top quarks in the final state. For all these cases, we discuss the constraints on the resonance production stemming from recent experimental measurements in the top quark sector. We find that the top-philic vector resonance remains largely unconstrained for the majority of the parameter space, although this will be scrutinized closely in the Run 2 phase of the LHC.

Dark Decay of Top Quark: We suggest top quark decays as a venue to search for light dark force carriers. The top quark is the heaviest particle in the standard model whose decays are relatively poorly measured, allowing sufficient room for exotic decay modes from new physics. A very light (GeV scale) dark gauge boson (Z') is a recently highlighted hypothetical particle that can address some astrophysical anomalies as well as the 3.6 sigma deviation in the muon $g-2$ measurement. We present and study a possible scenario that top quark decays as $t \to bW + Z'$s. This is the same as the dominant top quark decay ($t \to bW$) accompanied by one or multiple dark force carriers. The Z' can be easily boosted, and it can decay into highly collimated leptons (lepton-jet) with large branching ratio. We discuss the implications for the Large Hadron Collider experiments including the analysis based on the lepton-jets.

Multi-lepton signals from the top-prime quark at the LHC: We analyze the collider signatures of models with a vector-like top-prime quark and a massive color-octet boson. The top-prime quark mixes with the top quark in the Standard Model, leading to richer final states than ones that are investigated by experimental collaborations. We discuss the multi-lepton final states, and show that they can provide increased sensitivity to models with a top-prime quark and gluon-prime. Searches for new physics in high multiplicity events are an important component of the LHC program and complementary to analyses that have been performed.

2.2 Dark Matter

2.2.1 New direction in dark matter searches

Boosted Dark Matter at the Deep Underground Neutrino Experiment: We investigate the detection prospects of a non-standard dark sector in the context of boosted dark matter. We consider a scenario where two stable particles have a large mass difference and the heavier particle accounts for most of dark matter in our current universe. The heavier candidate is assumed to have no interaction with the standard model particles at tree-level, hence evading existing constraints. Although subdominant, the lighter dark matter particles are efficiently produced via pair-annihilation of the heavier ones in the center of the Galaxy or the Sun. The large Lorentz boost enables detection of the non-minimal dark sector in large volume terrestrial experiments via exchange of a light dark photon with electrons or nuclei. Various experiments designed for neutrino physics and proton decay are examined in detail, including Super-K and Hyper-K. In this study, we focus on the sensitivity of the far detector at the Deep Underground Neutrino Experiment for boosted dark matter produced in the center of the Sun, and compare our findings with recent results for boosted dark matter produced in the galactic center.

Boosted Dark Matter Signals Uplifted with Self-Interaction: We explore detection prospects of a non-standard dark sector in the context of boosted dark matter. We focus on a scenario with two dark matter particles of a large mass difference, where the heavier candidate is secluded and interacts with the standard model particles only at loops, escaping existing direct and indirect detection bounds. Yet its pair annihilation in the galactic center or in the Sun may produce boosted stable particles, which could be detected as visible Cherenkov light in large volume neutrino detectors. In such models with multiple candidates, self-interaction of dark matter particles is naturally utilized in the *assisted freeze-out* mechanism and is corroborated by various cosmological studies such as N-body simulations of structure formation, observations of dwarf galaxies, and the small scale problem. We show that self-interaction of the secluded (heavier) dark matter greatly enhances the capture rate in the Sun and results in promising signals at current and future experiments. We perform a detailed analysis of the boosted dark matter events for Super-Kamiokande, Hyper-Kamiokande and PINGU, including notable effects such as evaporation due to self-interaction and energy loss in the Sun.

Dark Matter Directionality Revisited with a High Pressure Xenon Gas Detector: An observation of the anisotropy of dark matter interactions in a direction-sensitive detector would provide decisive evidence for the discovery of galactic dark matter. Directional information would also provide a crucial input to understanding its distribution in the local Universe. Most of the existing directional dark matter detectors utilize particle tracking methods in a low-pressure gas time projection chamber. These low pressure detectors require excessively large volumes in order to be competitive in the search for physics beyond the current limit. In order to avoid these volume limitations, we consider a novel proposal, which exploits a columnar recombination effect in a high-pressure gas time projection chamber. The ratio of scintillation to ionization signals observed in the detector carries the angular information of the particle interactions. In this paper, we investigate the sensitivity of a future directional detector focused on the proposed high-pressure Xenon gas time projection chamber. We study the prospect of detecting an anisotropy in the dark matter velocity distribution. We find that tens of events are needed to exclude an isotropic distribution of dark matter interactions at 95% confidence level in the most optimistic case with head-to-tail information. However, one needs at least 10-20 times more events without head-to-tail information for light dark matter below 50 GeV. For an intermediate mass range, we find it challenging to observe an anisotropy of the dark matter distribution. Our results also show that the directional information significantly improves precision measurements of dark matter mass and the elastic scattering cross section for a heavy dark matter.

2.2.2 Dark matter anomalies

Bounds on Dark Matter Interpretation of Fermi-LAT GeV Excess: Annihilation of light dark matter of $m_{\rm DM} \approx$ (10-40) GeV into the Standard Model fermions has been suggested as a possible origin of the gamma-ray excess at GeV energies in the Fermi-LAT data. In this paper, we examine possible model-independent signatures of such dark matter models in other experiments such as AMS-02, colliders, and cosmic microwave background (CMB) measurements. We point out that first generation of fermion final states is disfavored by the existing experimental data. Currently AMS-02 positron measurements provide stringent bounds on cross sections of dark matter annihilation into leptonic final states, and e^+e^- final state is in severe tension with this constraint, if not ruled out. The e^+e^- channel will be complementarily verified in an early stage of ILC and future CMB measurements. Light quark final states ($q\bar{q}$) are relatively strongly constrained by the LHC and dark matter direct detection experiments even though these bounds are model-dependent. Dark matter signals from annihilations into $q\bar{q}$ channels would be constrained by AMS-02 antiproton data which will be released in very near future. In optimistic case, diffuse radio emission from nearby galaxy (clusters) and the galactic center might provide another hint or limit on dark matter annihilation.

X-ray line signal from 7 keV axino dark matter decay: Recently a weak X-ray emission around $E \sim 3.5$ keV was detected in the Andromeda galaxy and various galaxy clusters including the Perseus galaxy cluster but its source has been unidentified. Axino, the superpartner of axion, with a mass $2E$ is suggested as a possible origin of the line with R-parity violating decay into photon and neutrino. Moreover, most of parameter space is consistent with recent observation by the BICEP2 experiment.

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. We study 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. 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, we find that cosmic-ray data disfavor a heavy KK photon dark matter scenario. Also, we find these scenarios with flavor-universal bulk masses to be in conflict with dijet and dilepton searches at the LHC.

Electroweak Kaluza-Klein Dark Matter: In models with universal extra dimensions (UED), the lightest Kaluza-Klein excitation of neutral electroweak gauge bosons is a stable, weakly interacting massive particle and thus is a candidate for dark matter thanks to Kaluza-Klein parity. We examine concrete model realizations of such dark matter in the context of non-minimal UED extensions. The boundary localized kinetic terms for the electroweak gauge bosons lead to a non-trivial mixing among the first Kaluza-Klein excitations of the $SU(2)_W$ and $U(1)_Y$ gauge bosons and the resultant low energy phenomenology is rich. We investigate implications of various experiments including low energy electroweak precision measurements, direct and indirect detection of dark matter particles and direct collider searches at the LHC. Notably, we show that the electroweak Kaluza-Klein dark matter can be as heavy as 2.4 TeV, which is significantly higher than 1.3 TeV as is indicated as an upper bound in the minimal UED model.

2.3 Extra Dimensions

Radiative corrections to masses and couplings in Universal Extra Dimensions: Models with an orbifolded universal extra dimension receive important loop-induced corrections to the masses and couplings of Kaluza-Klein (KK) particles. The dominant contributions stem from so-called boundary terms which violate KK number. Previously, only the parts of these boundary terms proportional to $\ln(\Lambda R)$ have been computed, where R is the radius of the extra dimension and Λ is cut-off scale. However, for typical values of $\Lambda R \sim 10 \cdots 50$, the logarithms are not particularly large and non-logarithmic contributions may be numerically important. In this paper, these remaining finite terms are computed and their phenomenological impact is discussed. It is shown that the finite terms have a significant impact on the KK mass spectrum. Furthermore, one finds new KK-number violating interactions that do not depend on $\ln(\Lambda R)$ but nevertheless are non-zero. These lead to new production and decay channels for level-2 KK particles at colliders.

A Review on Non-Minimal Universal Extra Dimensions: We report on the current status of non-minimal universal extra dimension (UED) models. Our emphasis is on the possible extension of the minimal UED model by allowing bulk masses and boundary localized terms. We take into account the data from the Large Hadron Collider as well as direct and indirect searches of dark matter and electroweak precision measurements.

126 GeV Higgs in Next-to-Minimal Universal Extra Dimensions: Discovery of a Higgs boson and precise measurements of its properties open a new window to test physics beyond the standard model. Models with Universal Extra Dimensions are not exception. Kaluza-Klein excitations of the standard model particles contribute to the production and decay of the Higgs boson. In particular, the parameters associated with third generation quarks are constrained by Higgs data, which are relatively insensitive to other searches often involving light quarks and leptons. We investigate implications of the 126 GeV Higgs in Next-to-Minimal Universal Extra Dimensions, and show that boundary terms and bulk masses allow a lower compactification scale as compared to in Minimal Universal Extra Dimensions.

Phenomenology of Universal Extra Dimensions with Bulk-Masses and Brane-Localized Terms: We present a general model with universal extra dimensions in the presence of the bulk fermion masses and boundary localized kinetic terms, which are generically allowed by symmetries of five dimensional gauge theory. We provide a comprehensive analysis for a general UED model, including Kaluza-Klein mass spectra, their interactions with the SM particles, and constraints from LHC, electroweak tests, and dark matter experiments. Finally we show current bounds on the size of allowed universal bulk mass and universal brane-localized terms.

Bounds on the Fermion-Bulk Masses in Models with Universal Extra Dimensions: In models with extra dimensions, vectorlike Dirac masses for fermion fields are generically allowed. These masses are independent of electroweak symmetry breaking and do not contribute to the known masses for the quarks and leptons. They control the profile of the bulk wave functions, the mass spectra of Kaluza-Klein modes, and interactions that could be tested in experiments. In this article, we study the effects of bulk masses in electroweak precision measurements and in dark matter and collider searches, to set bounds on the bulk mass parameters in models with a flat universal extra dimension, namely, Split-UED. We find the current bound on the universal bulk-mass to be smaller than $(0.2 - 0.3)/R$, where R is the radius of the extra dimension. Similar but slightly relaxed bounds are obtained in the non-universal bulk mass case. The LHC is expected to play an important role in constraining the remaining parameter space.

2.4 Development of New Tools for HEP Community

Direct Detection of Dark Matter with MadDM v.2.0: We present MadDM v.2.0, a numerical tool for dark matter physics in a generic model. This version is the next step towards the development of a fully automated framework for dark matter searches at the interface of collider physics, astro-physics and cosmology. It extends the capabilities of v.1.0 to perform calculations relevant to the direct detection of dark matter. These include calculations of spin-independent/spin-dependent nucleon scattering cross sections and nuclear recoil rates (as a function of both energy and angle), as well as a simplified functionality to compare the model points with existing constraints. The functionality of MadDM v.2.0 incorporates a large selection of dark matter detector materials and sizes, and simulates detector effects on the nuclear recoil signals. We validate the code in a wide range of dark matter models by comparing results from MadDM v.2.0 to the existing tools and literature.

MadDM v.1.0: Computation of Dark Matter Relic Abundance Using Mad- Graph5: We present MadDM v.1.0, a numerical tool to compute dark matter relic abundance in a generic model. The code is based on the existing MadGraph 5 architecture and as such is easily integrable into any MadGraph collider study. A simple Python interface offers a level of user-friendliness characteristic of MadGraph 5 without sacrificing functionality. MadDM is able to calculate the dark matter relic abundance in models which include a multi-component dark sector, resonance annihilation channels and co-annihilations. We validate the code in a wide range of dark matter models by comparing the relic density results from MadDM to the existing tools and literature.

3 Major Products Developed Under the Award

3.1 Publications in Refereed Journals

24. **Radiative corrections to masses and couplings in Universal Extra Dimensions** (with A. Freitas, D. Wiegand), **JHEP 1803 (2018) 093**, e-Print: arXiv:1711.07526 [hep-ph] (major work done before the project end date)

23. **Monotop signature from a fermionic top partner** (D. Goncalves, K.Sakurai, M. Takeuchi, **Phys. Rev. D97 (2018) no.1, 015002**, e-Print: arXiv:1710.09377 [hep-ph] (major work done before the project end date)

22. **Resolving Combinatorial Ambiguities in Dilepton $t\bar{t}$ Event Topologies with Constrained M_2 Variables** (with D. Debnath, D. Kim, J. Kim, K. Matchev), **Phys. Rev. D96 (2017) no.7, 076005**, e-Print: arXiv:1706.04995 [hep-ph] (major work done before the project end date)

21. **Electroweak Kaluza-Klein Dark Matter** (with T. Flacke, D. Kang, G. Mohlabeng, S. Park), **JHEP 1704 (2017) 041**, e-Print: arXiv:1702.02949 [hep-ph]

20. **Boosted Dark Matter at the Deep Underground Neutrino Experiment** (with H. Alhazmi, G. Mohlabeng, J. Park), **JHEP 1704 (2017) 158**, e-Print: arXiv:1611.09866 [hep-ph]

19. **Identifying a new particle with jet substructures** (with S. Lim, C. Han, D. Kim, M. Kim, M. Park), **JHEP 1701 (2017) 027**, e-Print: arXiv:1609.06205 [hep-ph]

18. **Probing TeV scale Top-Philic Resonances with Boosted Top-Tagging at the High Luminosity LHC** (with J. Kim, S. Lee, G. Mohlabeng), **Phys. Rev. D94 (2016) no.3, 035023**, e-Print: arXiv:1604.07421 [hep-ph]

17. **The 750 GeV Diphoton Excess May Not Imply a 750 GeV Resonance** (with W. Cho, D. Kim, S. Lim, K. Matchev, J. Park, M. Park), **Phys. Rev. Lett. 116, 151805 (2016)**, e-Print: arXiv:1512.06824 [hep-ph], (Featured in physics, "Synopsis: Explaining a 750 GeV Bump" by editor.)

16. **ATLAS Diboson Excesses Demystified in Effective Field Theory Approach** (with D. Kim, H. Lee, S. Park), **JHEP 1511 (2015) 150**, e-Print: arXiv:1507.03683 [hep-ph]

15. **Direct Detection of Dark Matter with MadDM v.2.0** (with M. Backovic, A. Martini, O. Mattelaer, G. Mohlabeng), **Phys. Dark Univ. 9-10 37-50**, e-Print: arXiv:1505.04190 [hep-ph]

14. **Dark Matter Directionality Revisited with a High Pressure Xenon Gas Detector** (with G. Mohlabeng, J. Li, A. Para, J. Yoo), **JHEP 1507 (2015) 092**, e-Print: arXiv:1503.03937 [hep-ph]

13. **Kinematic discrimination of tW and $t\bar{t}$ productions using initial state radiation**, **Phys.Lett. B751 (2015) 512-524**, e-Print: arXiv:1503.03872 [hep-ph]

12. **Boosted Dark Matter Signals Uplifted with Self-Interaction** (with G. Mohlabeng, J. Park), **Phys. Lett. B743 (2015) 256-266**, e-Print: arXiv:1411.6632 [hep-ph]

11. **Model-Independent Production of a Top-Philic Resonance at the LHC** (with N. Greiner, J. Park, S. Park, J. Winter), **JHEP 1504 (2015) 029**, arXiv:1410.6099 [hep-ph]

10. **A Review on Non-Minimal Universal Extra Dimensions** (with T. Flacke, S. Park), invited article in **Mod. Phys. Lett. A30 (2015) 05, 1530003** , arXiv:1408.4024 [hep-ph]

9. **Bounds on Dark Matter Interpretation of Fermi-LAT GeV Excess** (with J. Park), **Nucl.Phys. B888 (2014) 154-168**, arXiv:1404.3741 [hep-ph]

8. **X-ray line signal from 7 keV axino dark matter decay** (with J. Park, S. Park), **Phys.Lett. B733 (2014) 217-220**, arXiv:1403.1536 [hep-ph]

7. **AMS-02 and Next-to-Minimal Universal Extra Dimensions** (with Y. Gao, D. Marfatia), **Phys. Lett. B732 (2014) 269-272**, arXiv:1402.1723 [hep-ph]

6. **Dark Decay of Top Quark** (with H. S. Lee, M. Park), **Phys. Rev. D89 (2014) 074007**, arXiv:1401.5020 [hep-ph]

5. **126 GeV Higgs in Next-to-Minimal Universal Extra Dimensions** (with T. Flacke, S. Park), **Phys. Lett. B728 (2014) 262-267**, e-Print: arXiv:1309.7077 [hep-ph]

4. **MadDM v.1.0: Computation of Dark Matter Relic Abundance Using MadGraph5** (with M. Backovic, M. McCaskey), **Physics of the Dark Universe 5-6 (2014) 18-28**, e-Print: arXiv:1308.4955 [hep-ph]

3. **Phenomenology of Universal Extra Dimensions with Bulk-Masses and Brane-Localized Terms** (with T. Flacke, S. Park), **JHEP 1305 (2013) 111**, e-Print: arXiv:1303.0872 [hep-ph]

2. **Bounds on the Fermion-Bulk Masses in Models with Universal Extra Dimensions** (with G. Huang, S. Park), **JHEP 1206 (2012) 099**, e-Print: arXiv:1204.0522 [hep-ph]

1. **Multi-lepton signals from the top-prime quark at the LHC** (with M. McCaskey, G. Wilson), **JHEP 1204 (2012) 079**, e-Print: arXiv:1112.3041 [hep-ph] (published after the project start date)

3.2 Working Group Reports, Proceedings, and Lecture Articles

10. **The unexplored landscape of two-body resonances** (with N Craig, P. Draper, Y. Ng, D. Whiteson), e-Print: arXiv:1610.09392 [hep-ph]

9. **MadDM: New Dark Matter Tool in the LHC era** (with M. Backovic, A. Martini, O. Mattelaer, G. Mohlabeng), e-Print: arXiv:1509.03683 [hep-ph]

8. **Charged Higgs Probes of Dark Bosons at the LHC** (with H. Lee, M. Park), arXiv:1408.4021 [hep-ph]

7. **New Particles Working Group Report of the Snowmass 2013 Community Summer Study** (with New Physics Working group), e-Print: arXiv:1311.0299 [hep-ex]

6. **Dark Matter in the Coming Decade: Complementary Paths to Discovery and Beyond** (with Dark Matter Complementarity working group), e-Print: arXiv:1310.8621 [hep-ph]

5. **Measuring Properties of Dark Matter at the LHC**, Submitted to the proceedings of PPC 2013, e-Print: arXiv:1309.6936 [hep-ph]

4. **Discovery potential of Kaluza-Klein gluons at hadron colliders: A Snowmass whitepaper** (with F. Yu), e-Print: arXiv:1308.1078 [hep-ph]

3. **Kaluza-Klein Dark Matter: Direct Detection vis-a-vis LHC (2013 update)** (with S. Arrenberg, L. Baudis, K. Matchev, J. Yoo), e-Print: arXiv:1307.6581 [hep-ph]

2. **Weighing Dark Matter the at the LHC**, invited article in Association of Korean Physicists in America (AKPA), September 2012

1. **TASI 2011: CalcHEP and PYTHIA Tutorials**, e-Print: arXiv:1208.0035 [hep-ph] (invited lecture article) (submitted after the project start date)

3.3 Books and Review Articles

2. **A Review on Non-Minimal Universal Extra Dimensions** (with T. Flacke, S. Park), invited article in **Mod. Phys. Lett. A30 (2015) 05, 1530003**, arXiv:1408.4024 [hep-ph]

1. **The Dark Secrets of the Terascale** (edited by Konstantin T. Matchev and Tim M. P. Tait), invited contribution to CalcHEP and PYTHIA Tutorials, World Scientific Publishing Company, **ISBN-10: 9814390151, ISBN-13: 978-9814390156**

4 Professional talks given by PI

4.1 Talks at conferences and workshops

19. *"Unexplored landscape of N-body resonances"*, (October 24-28, 2016), Durham-Kavli-IPMU-KEK-KIAS workshop, KIAS, Korea **(plenary/invited)**

18. *"Searches for New Physics at the LHC Run II"*, (August 12, 2016), Physics Symposium, UKC2016, Dallas, TX **(invited)**

17. *"Non-standard resonance searches at the LHC"*, (July 25-August 28, 2016), Charting the Unknown: interpreting LHC data from the energy frontier, CERN **(plenary/invited)**

16. *"Searches for New Physics at the LHC Run II"*, (July 4-8, 2016), LHC Run 2, Santa Fe 2016 Summer Workshop **(plenary/invited)**

15. *"MadDM: New Dark Matter Tool at the LHC Era"*, (April 26-28, 2016), QUC workshop: QCD and DM at the LHC, KIAS, Korea **(invited)**

14. *"Looking for Resonances under the LHC Lamppost"*, (December 14-18, 2015), Non-conventional searches at the LHC (IBS-CTPU Focused workshop), Daejon, Korea **(invited/plenary)**

13. *"Model-Independent Production of a Top-Philic Resonance at the LHC"*, (August 4-8, 2015), The Meeting of the American Physical Society Division of Particles and Fields, Ann Arbor, Michigan **(contributed)**

12. *"MadDM: New Dark Matter Tool in the LHC era"*, PPC workshop 2015, Deadwood, SD **(contributed)**

11. *"Looking for resonances under the lamppost at the LHC"*, (September 8-10, 2014), Searches for New Phenomena at the Upgraded LHC, Theory Workshop, TRIUMF, Vancouver, Canada **(invited/plenary)**

10. *"Charged Higgs probes of dark bosons"*, (June 11-13, 2014), Dark Interactions: Perspectives from Theory and Experiment, Brookhaven National Laboratory, Upton, NY **(invited/plenary)**

9. *"Charged Higgs probes of dark bosons"*, (June 2-7, 2014), Large Hadron Collider Physics Conference, New York, NY **(contributed)**

8. *"Review on Kinematics"*, (May 19-23, 2014), MC4BSM workshop, Center for Theoretical Physics of the Universe, Daejeon, South Korea **(invited/plenary)**

7. *"Dark Matter at the LHC"*, (July 7-13, 2013), PPC workshop 2013, Deadwood, SD **(invited/plenary)**

6. *"Next-to-Minimal Universal Extra Dimensions"*, APS April Meeting (April 13-16, 2013), Denver, CO **(contributed)**

5. *"Universal Extra Dimensions"* (remotely with Lian-Tao Wang), BNL Energy Frontier Workshop (April 5, 2013), Brookhaven National Laboratory, Upton, NY **(invited)**

4. *"Dark Matter Complementarity: UED Review"*, Cosmic Frontier Workshop (March 6-8, 2013), SLAC National Accelerator Laboratory, Menlo Park, CA **(invited)**

3. *"Benchmark models for Universal Extra Dimensions"*, Energy Frontier Workshop on BSM Physics (January 14-16, 2013), University of California, Irvine, CA

2. *"A new Dark Matter tool in the LHC era"*, Santa Few 2012 Summer Workshop (July 9-13, 2012), Santa Fe, NM **(contributed)**

1. *"Multi-leptons in non-supersymmetric theories'*, Chicago 2012 Workshop on LHC Physics (May 2-4 2012), The University of Chicago, Chicago, IL **(invited/plenary)**

4.2 Invited Public Talks

6. *"What is the Universe Made of?"*, (December 22, 2016), 6th grade science class, Ingomar Middle School, Pittsburgh, PA

5. *"Implication of Modern Physics and Future"*, (March 27, 2016), Department of Physics, Pusan National University

4. *"Cursory Look at Special Relativity"*, (December 19, 2015), three hour long lecture on special relativity for high school students, Geumseung high school, Pusan, South Korea

3. *"Cursory Look at Special Relativity"*, (January 26, 2015), three hour long lecture on special relativity for high school students, Geumseung high school, Pusan, South Korea

2. *"Cursory Look at Special Relativity"*, (January 27, 2014), three hour long lecture on special relativity for high school students, Geumseung high school, Pusan, South Korea

1. *"Shining light on dark matter at the LHC"*, (October 4, 2013), a public talk for high school students, Geumseung high school, Pusan, South Korea

4.3 Invited Seminars and Colloquium

18. *"Non-standard resonance searches at the LHC"*, (February 9, 2017), Harish-Chandra Research Institute, India

17. *"Searches for New Physics at the LHC Run II"*, (December 7, 2016), colloquium, Physics, University of Texas, Arlington, TX

16. *"Non-standard resonance searches at the LHC"*, (September 13, 2016), PITT PACC, Physics and Astronomy, University of Pittsburgh

15. *"Search for New Physics at the LHC Run II"*, (June 28, 2016), Theory Seminars, Fermilab

14. *"Searches for New Physics at the LHC Run II: Copernican Approach"*, (March 23, 2016), colloquium, Physics Department, Yonsei University

13. *"Searches for New Physics at the LHC Run II: Copernican Approach"*, (March 2, 2016), colloquium, Physics Department, Wichita State University

12. *"Copernican Approach for LHC RUN II"*, (September 29, 2014), colloquium, Physics and Astronomy, KU

11. *"What's the Matter?"*, (May 15, 2014), colloquium, Department of Physics, Inha University, Korea

10. *"What's the Matter?"*, (May 13, 2014), colloquium, Department of Physics, Pukyong University, Korea

9. *"Tprime and Higgs: a model for Tprime deays to tHq and studies of kinematics variables"* (with E. Smith), (May 1, 2014), High Energy Physics Seminar, Physics and Astronomy, KU

8. *"Extra Dimensions: Where Do We Stand?"*, (April 16, 2014), Physics Department, University of Virginia, Charlottesville

7. *"How to look for resonances under the lamppost at the LHC"*, (February 28, 2014), Theory Seminar, Physics and Astronomy, KU

6. *"Next-to-Minimal Universal Extra Dimensions"*, Cosmology, Phenomenology, and Experiment Seminars (December 5, 2013), Mitchell Institute for Fundamental Physics and Astronomy, Texas A&M

5. *"(Flat) Extra Dimensions: Where Do We Stand?"*, (November 7, 2013), High Energy Physics Seminar, Physics and Astronomy, KU

4. *"Shining light on dark matter at the LHC"*, (October 2, 2013), colloquium, Physics department, Sungkyunkwan University, South Korea

3. *"Dark Matter at the LHC: how to measure their properties"*, (September 30, 2013), Physics and Astronomy, Seoul National University

2. *"Next-to-Minimal Universal Extra Dimensions"*, Fermilab theory seminar (July 23, 2013)

1. *"The latest and greatest tricks in studying missing energy events"*, HEP/Astro Seminar, Kansas State University (September 26, 2012)

5 Other Products Developed Under the Award

5.1 Other professional activities

Invited Lectures at Schools

March 21-April 1, 2016 :	Introduction to Collider Physics, Yonsei University, Korea
January 18-24, 2015 :	Open KIAS winter school, KIAS, Korea
January 19-25, 2014 :	Open KIAS winter school, KIAS, Korea
February 17-22, 2013 :	Open KIAS winter school on Collider Physics, KIAS, Korea
June 2011 :	Graduate level, Theoretical Advanced Studies Institute (TASI 2011), University of Colorado, Boulder, CO

Community Service

2015 - present :	member, Newsletter Editorial Board, Association of Korean Physicists in America (AKPA)
2018 :	Organizing committee, Particle Physics on the Plains, KU
2017 :	Organizing committee, Dark Matter Day event, KU
2012 - 2017 :	member, Award Committee for Outstanding Young Research Award, AKPA
2016 :	Organizing committee, QCD and DM at the LHC (QUC workshop), KIAS
2013 - 2016 :	Organizing committee, KIAS winter school on collider physics
2014 :	Co-convener, 'Beyond Standard Model/Cosmology', The 2014 Americas Linear Collider Workshop, Fermilab, May 12-16, 2014
2012 - 2013 :	Sub-convener, 'Extra Dimensions working group', Snowmass 2013: Energy Frontier Workshop on BSM Physics
2012 - 2013 :	Sub-convener, 'Dark Matter Complementarity', Snowmass 2013: Cosmic Frontier

5.2 Web site or other Internet sites that reflect the results of this project

All publications (main research activity) are found in the web sites, `inspirehep.net` and `arxiv.org`, which are typical publication methods in high energy physics. Specifically, the following link include all publications `https://inspirehep.net/search?p=exactauthor%3AK.Kong.1+`. A couple of research papers are on development of dark matter tool, `MadDM`, which is a computer code and is available in `https://launchpad.net/maddm`. The code is developed as a part of community effort and anyone has access to the program. Its source is open and anyone can participate in the development.

5.3 Networks or collaborations fostered

Collaborators/coeditors during 05/01/2012 - 04/30/2017

Mr. H Alhazmi (U of Kansas),
Dr. S. Arrenberg (Zürich, Switzerland),
Dr. M. Backovic (CP3, UCL),
Prof. P. Baringer (KU, CMS),
Prof. A. J. Barr (Oxford, ATLAS),
Prof. L. Baudis (Zürich, XENON),
Prof. G. Bertone (Paris University, France),
Prof. AseshKrishna Datta (Harish-Chandra, India),

Dr. W. Cho (Seoul U, Korea),
Prof. N. Craig (UCSB),
Dr. D. Debnath (U of Florida),
Prof. P. Draper (Amherst),
Dr. T. Flacke (IBS, Korea),
Prof. A. Freitas (U of Pittsburgh),
Dr. Y. Gao (Wayne State U),
Dr. D. Goncalves (U of Pittsburgh), Dr. N. Greiner (Zürich),
Dr. C. Han (Tokyo U., IPMU),
Mr. D. Kang (IBS, Korea),
Mr. T. J. Jian Khoo (Cambridge, ATLAS),
Dr. P. Konar (Physical Research Laboratory, India),
Prof. C. G. Lester (Cambridge, ATLAS),
Dr. D. Kim (CERN),
Dr. J. Kim (U of Kansas),
Prof. H-S. Lee (KAIST, Korea),
Prof. H. Lee (Chungang U, Korea),
Prof. S. Lee (Korea U, Korea),
Dr. J. Li (IBS, Korea),
Dr. S. Lim (Tokyo U., IPMU),
Mr. A. Martini (CP3, UCL),
Dr. M. McCaskey (NASA),
Prof. D. Marfatia (Hawaii),
Mr. A. Martini (CP3, UCL),
Prof. K. T. Matchev (University of Florida, CMS),
Dr. O. Mattelaer (U. of Louvain, Belgium),
Dr. G. Mohlabeng (BNL),
Dr. Y. Ng (UC, Irvine),
Dr. M. McCaskey (Industry),
Dr. D. Noonan (CMS),
Dr. A. Para (Fermilab),
Prof. J.-C. Park (Chungbuk U, Korea),
Prof. M. Park (IBS, Korea),
Prof. S. Park (Yonsei U, Korea),
Prof. K. Sakurai (Warsaw U.),
Dr. S. Shin (Yonsei U, Korea),
Dr. M. Takeuchi (Tokyo U., IPMU),
Prof. D. Whiteson (UC, Irvine),
Dr. D. Wiegand (U of Pittsburgh),
Prof. G. Wilson (KU, CMS),
Dr. J. Winter (Michigan State U),
Dr. J. Yoo (IBS, Korea),
Dr. F. Yu (Mainz).

5.4 Inventions/Patent Applications, licensing agreements

None available.

6 Summary of Budget and Expenses

PI Salaries	\$35,138.49
Postdoc Salaries	\$67,002.18
Student Salaries	\$20,038.23
Fringe for all Salaries	\$26,661.87
Visitors	\$2,602.80
Domestic Travel	\$25,439.49
International Travel	\$13,674.90
Tuition	\$92,327.10
Indirect cost	\$3,010.90
Total Expense	\$285,895.96
Total Budget	\$286,000.00

7 Summary of Students and Postdocs Support

This DOE fund did NOT include postdoctoral scholar in the budget and all postdocs are supported by PI's start up and some internal sources. However whenever possible, PI used his research fund to support postdocs. DOE DID support their professional trips to conferences and meeting. It also supported graduate students and their travels.

Placement of Graduate Students under Supervision

Name	Duration	Position after KU
Gopolang Mohlabeng	2011-2017	research associate, BNL
Haider Alhazmi	2014-	

Placement of Postdocs under Supervision

Name	Duration	Position after KU
Mathew McCaskey	2010-2013	NASA
Gyu-Yu Huang	2011-2013	Industry
Jong-Chul Park	2014-2015	faculty, Chungnam National University, Korea
Jeong Han Kim	2016-	