Final Report: DOE Grant No. DE-FG02-04ER41306

Oklahoma State University, Stillwater

S. Nandi (PI), K.S. Babu (Co-PI), F. Rizatdinova (Co-PI)

The Oklahoma State University (OSU) High Energy Physics program has been supported by the Department of Energy for over twenty five years. In this report we summarize the research accomplishments of the HEP group for the past three years. This DOE grant has supported three permanent faculty (S. Nandi and K. S. Babu in HEP theory, and F. Rizatdinova in HEP experiment), one theory postdoctoral fellow (Dr. S. K. Rai/Dr. K. Ghosh), one experimental postdoctoral fellow (Dr. J. Yu), and several graduate students. Five students graduated with their PhD degree during the past three years: A. Albaid, B. Grossmann, J. Julio and A. Murdock in theory, and B. Abi in experiment. The following current PhD students have received partial DOE support: S. Chakdar, D. Karabacak, S. Khan, A. Patra, S. Saad, and M. Su in HEP theory, and H. Hegab, A. Sidorov and K. Klimov in HEP experiment. Among our recent graduates, Albaid is now a faculty member at Wichita State University, Grossmann is a faculty member at University of Montana, Julio is a postdoc at the Stefan Institute, Ljubljana, Slovenia, and Murdock is on the faculty at Marymount College. Our recent postdoc Dr. Rai now holds a permanent faculty position at the Harish Chandra Research Institute in Allahabad, India.

The OSU HEP group works closely with the HEP group at the University of Oklahoma (OU) through an inter–university Center of Excellence in HEP research, the Oklahoma Center for High Energy Physics (OCHEP, http://ochep.phy.okstate.edu), which also involves Langston University. Our weekly HEP seminars are held jointly via a Talk Back TV system. We have regular interactions among the experimental groups, as well as among the theory and the experimental groups both at OSU and OU under the umbrella of OCHEP, which is helping Oklahoma make a much bigger impact in HEP research on the international scene. OSU HEP group is a members of the Quarknet program, and is contributing to educational activities involving high school teachers and students.

Currently we have two tasks, Theory (Task A) and Energy Frontier Experiment (Task B) involved in experiment and analysis in the ATLAS Collaboration at the CERN LHC, and the physics analysis at the D0 collaboration at Fermilab. In HEP experiment, in addition to PI Rizatdinova, Dr. A. Khanov is supported by a separate DOE grant for the past year, which has now been merged. The department has recently hired a third HEP experimental faculty member, Dr. Joe Haley who joined the university this Fall.

A list of students who graduated with PhD degree who were partially supported by DOE during the past three years is given below, along with the respective advisor and the year of graduation.

Student	Advisor	Year PhD granted
B. Abi	Rizatdinoa	2012
A. Albaid	Babu	2011
B. Grossmann	Nandi	2011
J. Julio	Babu	2012
A. Murdock	Nandi	2011

Below we give a brief description of the research performed by the senior investigators over the past three years supported by the DOE funding.

Theory (Task A)

The research thrust area interests of the two theory investigators (Nandi and Babu) spanned a variety of topics in the theoretical, model–building, and phenomenological aspects of elementary particle physics. The topics included unification, supersymmetry, neutrino physics and collider physics, with particular emphasis to the models that can be tested at the LHC, as well as the ongoing and upcoming neutrino experiments.

S. Nandi:

In the last 10 years of this grant, Nandi has published over 50 papers in top refereed journals, and have presented over 40 invited talks in national and international conferences. His research has been well recognized internationally, and he was regularly invited to present talks at national and international conferences. In the past ten years, Nandi was honored by being elected to be a Fellow of the American Physical Society, being appointed as a Regents Professor at OSU, and by being awarded the Regents Distinguished Research Award in its inaugural year at OSU. A brief summary of few selected papers published by Nandi published in the last three years of this grant, a selected list of his publications, and invited talks in the past ten years is given below.

1. *Top SU(5) Models: Baryon and Lepton Violating Interactions at the LHC, Shreyashi Chakdar, Tianjun Lii S. Nandi and Santosh Kumar Rai, Phys. Rev. D* **87**, *097002 (2013)*

In this work, we proposed minimal and renormalizable nonsupersymmetric top $SU(5)$ models where the $SU(5) \times SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge symmetry is broken down to the Standard Model gauge symmetry at the TeV scale. The first two families of the Standard Model fermions are charged under $SU(3)_C \times SU(2)_L \times U(1)_Y$, while the third family is charged under $SU(5)$. In the minimal top $SU(5)$ model, we show that the quark Cabibbo-Kobayashi-Maskawa mixing matrix can be generated via dimension-five operators, and the proton decay problem can be solved by fine-tuning the coefficients of the higher-dimensional operators at the order of 10^{-4}. In the renormalizable top $SU(5)$ model, we can explain the quark Cabibbo-Kobayashi-Maskawa mixing matrix by introducing vectorlike particles, and we do not have the proton decay problem. The models give rise to leptoquark and diquark gauge bosons which violate both lepton and baryon numbers involving the third-family quarks and leptons. The current experimental limits for these particles is well below the TeV scale. We also discuss the productions and decays of these new gauge bosons, and their ensuing signals, as well as their reach at the LHC.

2. *Unity of Elementary Particles and Forces and Their Interactions, Shreyashi Chakdar, Tinanjun Li, S. Nandi and Santosh Kumar Rai, Phys. Lett. B* **718**, *121 (2013)*

We proposed a non-supersymmetric $SU(5)$ model in which only the third family of fermions are unified. The model remedies the non-unification of the three Standard Model couplings in non-supersymmetric $SU(5)$. It also provides a mechanism for baryon number violation which is needed for the baryon asymmetry of the Universe and is not present in the Standard Model. Current experimental constraints on the leptoquark gauge bosons, mediating such baryon and lepton violating interactions in our model, allow their masses to be at the TeV scale. These can be searched for as a $(b\tau)$ or (tt) resonance at the Large Hadron Collider as predicted in our model.

Motivated by this work, the CMS Collaboration has searched for the leptoquark, predicted by our model, in the $b\tau$ mode, and has set a lower limit on its mass of 760 GeV.

3. *Diquark Resonance and single Top Production at the Large Hadron Collider, Durmus Karabacak, S. Nandi and Santosh Kumar Rai, Phys. Rev. D* **85**, *076010 (2012)*

New physics at the TeV scale is highly anticipated at the LHC. New particles with color, if within the LHC energy reach, will be copiously produced. One such particle is a diquark, having the quantum numbers of two quarks, and can be a scalar or a vector. It will decay to two light quarks, or two top quarks, or a top and a light quark, (up or down type depending on the quantum number of the produced diquark). If singly produced, it can be looked for as a dijet resonance, or as giving extra contribution to the single top production or tt production. In this work, we consider a color sextet vector diquark having the quantum number of (ud) type, its resonance production , and the subsequent decay to tb, giving rise to excess contribution to the single top production. Even though the diquark mass is large, its strong resonance production dominate the weak production of tb for a wide range of the diquark mass. Also its subsequent decay to tb produce a very hard b-jet compared to the usual electroweak production. In addition, the missing energy in the final state event is much larger from the massive diquark decays. Thus, with suitable cuts, the final state with $b, \bar{b}$ and a charged lepton together with large missing energy stands out compared to the Standard Model background. We make a detailed study of both the signal and the background. We find that such a diquark is accessible at the 7 TeV LHC up to a mass of about 3.3 TeV with the luminosity 1 fb^{-1}, while the reach goes up to about 4.3 TeV with a luminosity of 10 fb^{-1}.

4. *Discovering Coloron at the Early Stage of LHC, D. A. Dicus, Chung. Kao, S. Nandi and Joshua Sayre, Phys. Rev. D* **83***, 091702 (2011)*

Prospects are investigated for the discovery of massive hypergluons using data from the early runs of the Large Hadron Collider. A center of mass energy of 7 TeV and an integrated luminosity of $1 fb^{-1}$ or $5 fb^{-1}$ are assumed. A phenomenological Lagrangian is adopted to evaluate the cross section of a pair of colored vector bosons (colorons) decaying into four colored scalar resonances (hyperpions), which then decay into eight gluons. The dominant eight-jet background from the production of 8g, 7g1q, 6g2q, and 5g3q is included. We find an abundance of signal events and that realistic cuts reduce the background enough to establish a 5 signal for the coloron mass of up to 733 GeV with $1 fb^{-1}$ or 833 GeV with $5 fb^{-1}$.

5. *Non-renormalizable Yukawa Interactions and Higgs Physics, Z. Murdock, S. Nandi and Santosh Kumar Rai, Phys. Lett. B* **704***, 481 (2011)*

We explore a scenario in the Standard Model in which dimension-four Yukawa couplings are forbidden by a symmetry, and the Yukawa interactions are dominated by effective dimension-six interactions. In this case, the Higgs interactions to the fermions are enhanced in a large way, whereas its interaction with the gauge bosons remains the same as in the Standard Model. In hadron colliders, Higgs boson production via gluongluon fusion increases by a factor of nine. Higgs decay widths to fermionantifermion pairs also increase by the same factor, whereas the decay widths to photonphoton and γZ are reduced. Current Tevatron exclusion range for the Higgs mass increases to $\sim 146 - 222$ GeV in our scenario, and new physics must appear at a scale below a TeV.

6. *Natural Fermion Mass Hierarchy and Mixings in Family Unification, J. Dent, T. W. Kephart, S. Nandi, Phys. Lett. B* **697***, 397 (2011)*

We present an $SU(9)$ model of family unification with three light chiral families, and a natural hierarchy of charged fermion masses and mixings. The existence of singlet right handed neutrinos with masses about two orders of magnitude smaller than the GUT scale, as needed to understand the light neutrinos masses via the see-saw mechanism, is compelling in our model.

7. *Hidden Extra $U(1)$ at the Electroweak/TeV Scale, B. N. Grossmann, B. McElrath, S. Nandi and Santosh Kumar Rai, Phys. Rev. D* **82***, 055021 (2010)*

We propose a simple extension of the standard model (SM) by adding an extra $U(1)$ symmetry which is hidden from the SM sector. Such a hidden $U(1)$ has not been considered before, and its existence at the TeV scale can be explored at the LHC. This hidden U(1) does not couple directly to the SM particles, and couples only to new $SU(2)_L$ singlet exotic quarks and singlet Higgs bosons, and is broken at the TeV scale. The dominant signals at the high-energy hadron colliders are multilepton and multi-b-jet final states with or without missing energy. We calculate the signal rates as well as the corresponding standard model background for these final states. A very distinctive signal is 6 high

p_T b-jets in the final state with no missing energy. For a wide range of the exotic quarks masses the signals are observable above the background at the LHC.

8. *Neutrino Masses from fine tuning, B. N. Grossmann, Z. Murdock and S. Nandi, Phys. Lett. B* **693***, 274 (2010)*

We present a new approach for generating tiny neutrino masses. The Dirac neutrino mass matrix gets contributions from two new Higgs doublets with their vevs at the electroweak (EW) scale. Neutrino masses are tiny not because of tiny Yukawa couplings, or very heavy (10^{14} GeV) right-handed neutrinos. They are tiny because of a cancellation in the Dirac neutrino mass matrix (fine tuning). After fine tuning to make the Dirac neutrino mass matrix at the 10^4 GeV scale, light neutrino masses are obtained in the correct scale via the see-saw mechanism with the right-handed neutrino at the EW scale. The proposal links neutrino physics to collider physics. The Higgs search strategy is completely altered. For a wide range of Higgs masses, the Standard Model Higgs decays dominantly to $\nu_L N_R$ mode giving rise to the final state $\bar{\nu}\nu\bar{b}b$ or $\bar{\nu}\nu\tau^+\tau^-$. This can be tested at the LHC, and possibly at the Tevatron.

9. *New Mechanism for Neutrino Mass Generation and triply Charged Higgs Boson at the LHC, K. S. Babu, S. Nandi and Z. Tavartkiladze, Phys. Rev. D* **80***, 071702 (2009)*

We propose a new mechanism for generating small neutrino masses which predicts the relation $m_\nu\ v^4/M^3$, where v is the electroweak scale, rather than the conventional seesaw formula $m_\nu\ v^2/M$. Such a mass relation is obtained via effective dimension seven operators $LLHH(H^\dagger H)/M^3$, which arise when an isospin 3/2 Higgs multiplet Φ is introduced along with iso-triplet leptons. The masses of these particles are naturally in the TeV scale. The neutral member of Φ acquires an induced vacuum expectation value and generates neutrino masses, while its triply charged partner provides the smoking gun signal of this scenario. These triply charged bosons can be pair produced at the LHC and the Tevatron, with Φ^{+++} decaying into $W^+l^+l^+$ or $W^+W^+W^+$, possibly with displaced vertices. The leptonic decays of Φ^{+++} will help discriminate between normal and inverted hierarchies of neutrino masses. This scenario also allows for raising the standard Higgs boson mass to values in excess of 500 GeV.

10. *A Light Scalar as the Messenger of Electroweak and Flavor Symmetry Breaking, J. Lykken, Z. Murdock and S. Nandi, Phys. Rev. D* **D9***, 075014 (2009)*

We propose a new framework for understanding the hierarchies of fermion masses and mixings. The masses and mixings of all Standard Model (SM) charged fermions other than top arise from higher dimensional operators involving a messenger scalar S and flavon scalars F_i. The flavons spontaneously break SM flavor symmetries at around the TeV scale. The SM singlet scalar S couples directly to the Higgs H and spontaneously breaks another $U(1)$ at the electroweak scale. At the TeV scale, SM quarks and charged leptons have renormalizable couplings to S, but not to H or F_i. These couplings involve new heavy vectorlike fermions. Integrating out these fermions produces a pattern of higher dimensional operators that reproduce the observed hierarchies of the SM masses and mixings in terms of powers of the 'little hierarchy': the ratio of the electroweak scale to the flavor-breaking scale. The framework has important phenomenological implications. Flavor-changing neutral currents are within experimental limits but D^0 mixing and $B_s \to \mu^+\mu^-$could be close to current sensitivities. The neutral scalar s of the messenger field mixes with the light Higgs of the SM, which can have strong effects on Higgs decay branching fractions. The s mass eigenstate may be lighter than the Higgs, and could be detected at the Tevatron or the LHC.

S. Nandi: List of Selected Publications during the last three years

1. "Top $SU(5)$ models: Baryon and Lepton Number Violating Interactions at the LHC," S. Chakdar, T. Li, S. Nandi and Santosh Kumar Rai, Phys. Rev. D **87**, 096002 (2013).
2. "Search for spin-3/2 quark at the Large Hadron Collider," D. Karabacak, D. A. Dicus, S. Nandi and Santosh Kumar Rai, Phys. Rev. D **87**, 0125023 (2013).
3. "True unification of elementary particles and forces for the third family," Shreyashi Chakdar, Tianjun, Li, S. Nandi and Santosh Kumar Rai, Phys. Lett. B **718**, 121 (2012).
4. "Quark lepton unification in higher dimensions," Tianjun Li, Z. Murdock, S. Nandi andSantosh Kumar Rai, Phys. Rev. D **85** 076010 (2012).
5. "Diquark resonance and single top production at the Large Hadron Collider," Durmus Karabacak, S. Nandi, And Santosh Kumar Rai, Phys. Rev. D **85**, 075011 (2012).
6. "Searching for Coloron at the Large Hadron Collider," Joshua Sayre, Duane A. Dicus, Chung Kao, S. Nandi, Phys. Rev D **84**, 015011 (2011).
7. "Supersymmetry Signals at the LHC under the most favorable SUGRA Scenario," Subhaditya Bhattacharya, S. Nandi, e-Print: arXiv: 1101.3301[hep-ph] (submitted to Phys. Rev. D).
8. "Discovering Colorons at the Early Stage LHC," Duane A. Dicus, Chung Kao, S. Nandi, Joshua Sayre, Phys. Rev. D **83**, 091702 (2011).
9. "New Mechanism for Neutrino mass Generation and Triply Charged Higgs Boson at the LHC," PoS ICHEP2010, 311 (2010).
10. "Fermion Mass Hierarchy from symmetry breaking at the TeV Scale," B. N. Grossmann, Z. Murdock , S. Nandi, (submitted to Phys. Rev. D).
11. "Non-renormalizable Yukaa interactions and Higgs Physics," Z. Murdock, S. Nandi and Santosh Kumar Rai, Phys. Lett. B **704**, 481-485 (2011).
12. "Hidden Extra U(1) at the Electroweak/TeV scale," B. N. Grossmann, B. MCElrath, S. Nandi and Santosh KumamRai, Phys. Rev. D **82**, 055021 (2010).
13. "Neutrino masses from fine tuning," B. N. Grossmann, Z. Murdock, S. Nandi, Phys. Lett. B **693**, 274-280 (2010).
14. "Fermion mass hierarchy and new physics at the TeV scale," AIP Conf. Proc. 1200, 93-102 (2010).
15. "Natural fermion mass hierarchy and mixings in family unification," James B. Dent, T.W. Kephart and S. Nandi and R. Feger, Phys. Lett. B **697**, 367-369 (2011).
16. "New mechanism for neutrino mass generation, and triply charged Higgs boson at the LHC," K. S. Babu, S. Nandi and Z. Tavartkiladze: Phys. Rev. D **80**, 071702 (2009).
17. "Three family unification in higher dimensional models," Y. Mimura and S. Nandi, Phys. Rev. D **79**, 095021 (2009).
18. "A light scalar as the messenger of electroweak and flavor symmetry breaking," J. Lykken, Z. Murdock and S. Nandi, Phys. Rev. D **79**, 075014 (2009).

S. Nandi: Conference and workshop presentation during the last three years

1. *Baryon and Lepton Number Violation at the TeV Scale*, Talk presented at Miami 2012: A Topical Conference in Elementary Particles, Astrophysics and Cosmology, Ft. Lauderdale, FL, December 13–20, 2012.

2. *Lepto-quark and di-quark at the LHC*, invited talk presented at the PLHC 2012 conference in Vancouver, Canada, May 6–11, 2012.

3. *Unification of quarks and leptons at the TeV scale*, talk presented at the PHENO 2012 Symposium, in Pittsburgh, PA, May 6–9, 2012.

4. *Quark lepton unification in higher dimensions*, Invited plenary talk presented at the "Topical conference on elementary particles, astrophysics and cosmology", Miami 2010, at Fort Lauderdale, Florida, December 14–19, 2010.

5. *Fermion mass hierarchy and new physics at the TeV scale*, Invited talk presented at the International Conference on High Energy Physics, ICHEP 2010, Paris, France, July 22–28, 2010.

6. *New mechanism for neutrino mass generation and triply charged Higgs boson at the LHC*, Invited talk presented at the International Conference on High Energy Physics, ICHEP 2010, Paris, France, July 22–28, 2010.

7. *SU(9) family unification*, Talk presented at Phenomenology 2010 Symposium, at Madison, Wisconsin, May 10–12, 2010, also chaired a session.

8. *New mechanism for neutrino mass generation*, Invited plenary talk at Topical Conference on Elementary Particles, Astrophysics and Cosmology, Miami 2009, Fort Lauderdale, Florida, December 15–20, 2009.

9. *Fermion mass hierarchy and new physics at the TeV scale*, Invited plenary talk at SUSY 09: 17th International Conference on Supersymmetry and Unificatio of Fundamental Interactions, Boston, MA, June 5–10, 2009.

10. *New mechanism for neutrino mass generation*, Invited talk at the International Conference in Theoretical Physics, Matter to the Deepest: Recent Developments in Physics of Fundamental Interactions, USTRON 09, Ustron, Poland, September 11–16, 2009.

11. *New mechanism for neutrino mass generation*, Talk presented at the SM and BSM Physics at the LHC, CERN, Geneva, Switzerland, August 3–28, 2009.

12. *New mechanism for neutrino mass generation*, Talk presented at the PHENO 2009 Symposium: LHC Alive!, University of Wisconsin, Madison, May 11–13, 2009, also chaired a session.

13. *Fermion mass Hierarchy and new physics at the TeV scale*, Invited plenary talk at the 2009 BSM LHC Workshop at the Indian Association for the Cultivation of Science, Kolkata, India, January 14–16, 2009.

K.S. Babu

I. Awards and recognitions during the past three years (K.S. Babu)

- Appointed Regents Professor, OSU (2012)
- Elected Fellow of the American Physical Society (2009)

III. List of Research Publications: K.S. Babu (past three years)

1. "New Ways to Leptogenesis with Gauged B-L Symmetry," K. S. Babu, Y. Meng and Z. Tavartkiladze, Phys. Lett. B **681**, 37 (2009).
2. "New Mechanism for Neutrino Mass Generation and Triply Charged Higgs Bosons at the LHC," K. S. Babu, S. Nandi and Z. Tavartkiladze, Phys. Rev. D **80**, 071702 (2009) (Rapid Communication).
3. "Flavor Violation in Supersymmetric Q_6 Model," K. S. Babu and Y. Meng, Phys. Rev. D **80**, 075003 (2009).
4. "Constraining Proton Lifetime in SO(10) with Stabilized Doublet-Triplet Splitting," K. S. Babu, J. C. Pati and Z. Tavartkiladze, JHEP **1006**, 084 (2010).
5. "Topics in Flavor Physics," K. S. Babu, published in *The Dawn of the LHC era*, ed. Tao Han, pages 49–124, World Scientific (2010).
6. "Semidirect Product Groups, Vacuum Alignment and Tribimaximal Neutrino Mixing," K. S. Babu and S. Gabriel, Phys. Rev. D **82**, 073014 (2010).
7. "Two-Loop Neutrino Mass Generation through Leptoquarks," K. S. Babu and J. Julio, Nucl. Phys. B **841**, 130 (2010).
8. "Radiative neutrino mass generation and its experimental signals", K. S. Babu, arXiv:1103.1338 [hep-ph], Proc. Sci., ICHEP2010, 291 (2011).
9. "Recent Progress in SUSY GUTs," K. S. Babu, arXiv:1103.3491 [hep-ph], Proc. Sci., ICHEP2010, 379 (2011).
10. "Variations on the Q_6 model of flavor", K. S. Babu, K. Kawashima and J. Kubo, Phys. Rev. D **83**, 095008 (2011).
11. "Top quark asymmetry and Wjj excess at CDF from gauged flavor symmetry," K. S. Babu, M. Frank and S. K. Rai, Phys. Rev. Lett. **107**, 061802 (2011).
12. "Perturbative unitarity constraints on general W' models and collider implications," K. S. Babu, J. Julio and Y. Zhang, Nucl. Phys. B **858**, 468 (2012).
13. "Variety of SO(10) GUTs with Natural Doublet-Triplet Splitting via the Missing Partner Mechanism," K. S. Babu, I. Gogoladze, P. Nath and R. M. Syed, Phys. Rev. D **85**, 075002 (2012).
14. "Radiative Neutrino Mass Generation through Vector-like Quarks," K. S. Babu and J. Julio, Phys. Rev. D **85**, 073005 (2012).
15. "$B-L$ violating nucleon decay and GUT scale baryogenesis," K.S. Babu and R.N. Mohapatra, Phys. Rev. D **86**, 035018 (2012).
16. "Fundamental Physics at the Intensity Frontier," J. L. Hewett, H. Weerts *et al.*, arXiv:1205.2671 [hep-ex].

17. "Coupling Unification, GUT-Scale Baryogenesis and Neutron-Antineutron Oscillation in SO(10)," K.S. Babu and R.N. Mohapatra, Phys. Lett. B **715**, 328 (2012).

18. "B-L Violating Proton Decay Modes and New Baryogenesis Scenario in SO(10)," K.S. Babu and R.N. Mohapatra, Phys. Rev. Lett. **109**, 091803 (2012).

19. "Realistic Fermion Masses and Nucleon Decay Rates in SUSY SU(5) with Vector-Like Matter," K. S. Babu, B. Bajc and Z. Tavartkiladze, Phys. Rev. D **86**, 075005 (2012).

20. "B-L Violating Nucleon Decay and GUT Scale Baryogenesis in SO(10)," K.S. Babu, AIP Conf. Proc. **1467**, 21 (2012).

21. "New scenario for GUT scale baryogenesis and novel nucleon decay modes in $SO(10)$," K. S. Babu, AIP Conf. Proc. **1534**, 202 (2012).

22. "Expectations for neutron-antineutron oscillation time from TeV scale baryogenesis," K. S. Babu, P. S. Bhupal Dev, E. C. F. S. Fortes and R. N. Mohapatra, AIP Conf. Proc. **1534**, 211 (2012).

23. "Higgs boson of mass 125 GeV in GMSB models with messenger-matter mixing," A. Albaid and K. S. Babu, Phys. Rev. D **88**, 055007 (2013).

24. "New Signals for Doubly-Charged Scalars and Fermions at the Large Hadron Collider," K. S. Babu, A. Patra and S. K. Rai, Phys. Rev. D **88**, 055006 (2013).

25. "Post-Sphaleron Baryogenesis and an Upper Limit on the Neutron-Antineutron Oscillation Time," K. S. Babu, P. S. B. Dev, E. C. F. S. Fortes and R. N. Mohapatra, Phys. Rev. D **87**, 115019 (2013).

26. "New scenario for GUT scale baryogenesis and novel nucleon decay modes in $SO(10)$," K.S. Babu, AIP Conf. Proc. **1534**, 202 (2012).

27. "Expectations for neutron-antineutron oscillation time from TeV scale baryogenesis," K. S. Babu, P. S. Bhupal Dev, E. C. F. S. Fortes and R. N. Mohapatra, AIP Conf. Proc. **1534**, 211 (2012).

28. "Predictive Model of Radiative Neutrino Masses," K. S. Babu and J. Julio, arXiv:1310.0303 [hep-ph].

29. "Neutrinos," A. de Gouvea *et al.* [Intensity Frontier Neutrino Working Group Collaboration], arXiv:1310.4340 [hep-ex].

30. "The future of US particle theory: Report of the DPF Theory Panel", M. Dine, K. Babu, C. Csaki, S. Dawson, L. Dixon, S. Gottleib, J. Harvery, D. Whiteson, arXiv:1310.6111 [hep-ph].

31. "Baryon Number Violation," K. S. Babu, E. Kearns, U. Al-Binni, S. Banerjee, D. V. Baxter, Z. Berezhiani, M. Bergevin and S. Bhattacharya *et al.*, arXiv:1311.5285 [hep-ph].

32. "Flavor Physics Constraints on TeV Scale Color Sextet Scalars," E. C. F. S. Fortes, K. S. Babu and R. N. Mohapatra, arXiv:1311.4101 [hep-ph], to be published in CHARM 2013 Proceedings.

IV. Invited talks at major Conferences: K.S. Babu (past three years)

1. *Progress in Radiative Neutrino Mass Models*, Invited Talk at the Workshop "Neutrinos: From Majorana to LHC", ICTP, Trieste, Italy, October 2013.

2. *Baryon Number Violation*, Invited Grand Plenary Talk, Community Planning Study, Minneapolis, August 2013.

3. *Charged Lepton Flavor Physics*, Invited plenary talk at Energy Frontier Workshop, University of Washington, Seattle, July 2013.

4. B-L Violating Nucleon Decay, Invited talk at the Intensity Frontier Workshop, Argonne National Lab, Chicago, April 2013.

5. *Neutron-antineutron oscillations and baryogenesis*, Invited talk at the Project X workshop, Fermilab, Batavia, October 2012.

6. *Radiative neutrino masses and its experimental signals*, Invited plenary talk at BeNe 2012: International Workshop on Models of Neutrino Mass, ICTP, Trieste, September 2012.

7. *Radiative neutrino masses and its experimental signals*, Invited plenary talk at Neutrino and New Physics Workshop, TRIUMF, Vancouver, November 2012.

8. *New GUT scale baryogenesis and novel nucleon decay modes in $SO(10)$*, Invited talk at the CETUP* Workshop on Neutrino physics and unification, July 2012.

9. *Higgs boson mass in GMSB with messenger–matter mixing*, Invited talk at the International Conference on High Energy Physics, ICHEP 2012, Melbourne, Australia, July 2012.

10. *Large θ_{13} and minimal $SO(10)$ unification*, Invited talk at the International Conference on High Energy Physics, ICHEP 2012, Melbourne, Australia, July 2012.

11. *Top quark forward–backward asymmetry from gauged flavor symmetry*, Invited talk at the International Conference on High Energy Physics, ICHEP 2012, Melbourne, Australia, July 2012.

12. *Radiative neutrino mass generation and its experimental signals*, Invited talk at the LHC Theory Workshop, University of Melbourne, Australia, July 2012.

13. *Insight into proton decay modes of interest from a theorist's perspective*, Invited Plenary Talk at International Conference on Next Generation Nucleon Decay and Neutrino Physics, NNN12, Fermilab, October 2012.

14. *Muon physics: Theoretical Overview*, Invited Plenary Talk at the Project X Physics Study Workshop, Fermilab, June, 2012.

15. *Baryogenesis and neutron–antineutron oscillations*, Invited talk at the Project X Physics Study Workshop, Fermilab, June 2012.

16. *Probing new physics in neutrino oscillations*, Invited Plenary Talk at the Phenomenology 2012 Symposium, University of Pittsburgh, Pittsburgh, May 2012.

17. *$B-L$ violating nucleon decay and GUT scale baryogenesis in $SO(10)$*, Invited talk at the International Workshop on Grand Unification, Kyoto, Japan, March 2012.

18. *Theory of charged lepton flavor violation*, Invited talk at the Intensity Frontier Workshop, Rockville, MD, December 2011.

19. *Upper limit on proton lifetime in realistic SUSY $SU(5)$*, Invited talk at the Intensity Frontier Workshop, Rockville, MD, December 2011.

20. *Grand unification and θ_{13}*, Invited talk at the CETUP Workshop, Center for Theoretical Physics and Related Areas, Lead, South Dakota, June 2011.

21. *Baryogenesis and neutron–antineutron oscillations*, Invited talk at the mini-workshop on neutron–antineutron oscillations, Washington University, St. Louis, February 2011.

22. *Predictive theories of neutrino mixing*, Invited talk at the 2010 Workshop on major DUSEL physics topics, South Dakota School of Mines & Technology, Rapid City, SD, October 2010.

23. *Recent progress in SUSY GUTs*, Invited talk presented at the 35th International Conference in High Energy Physics, ICHEP 2010, Paris, July 2010.

24. *Radiative generation of neutrino masses and its experimental signals*, Invited talk presented at the 35th International Conference in High Energy Physics, ICHEP 2010, Paris, July 2010.

25. *Radiative neutrino mass generation and experimental signals*, Invited talk presented at Goran-Fest, the Joy of Making Physics, Split, Croatia, June 2010.

26. *Radiative neutrino mass generation and its experimental signals*, Invited talk presented at the Santa Fe – Los Alamos Workshop in particle physics, July 2010.

27. *Family symmetries for fermion masses and mixings and SUSY flavor*, Talk presented at the PHENO 2010 Symposium, Madison, WI, May 2010.

28. *The fermion mass puzzle and physics beyond the standard model*, Invited plenary talk at the XI Workshop on High Energy Physics Phenomenology, WHEPP XI, Ahmedabad, India, January 2010.

29. *Resonant leptogenesis*, Invited talk at the XI Workshop on High Energy Physics Phenomenology, WHEPP XI, Ahmedabad, India, January 2010.

30. *Grand Unification, nucleon decay and the flavor puzzle*, Invited talk at the 2nd PROMETEO Workshop, Valencia, Spain, December 2009.

31. *Weak scale baryogenesis and neutron–antineutron oscillations*, Invited talk presented at the Workshop on baryon and lepton number violation, Madison, WI, September 2009.

32. *New mechanisms for neutrino mass generation and their implications for LHC*, Invited plenary talk at the Summer Institute in Phenomenology, Fujiyoshida, Japan, August 2009.

33. *Recent progress in SUSY GUTs*, Invited Plenary talk at the International Workshop on Supersymmetry and Unification (SUSY09), Boston, July 2009.

34. *Left–right symmetry and its implications for LHC*, Talk presented at the PHENO 09 Symposium, Madison, WI, May 2009.

V. Synopses of 5 significant publications: K.S. Babu

1. *Constraining Proton Lifetime in SO(10) with Stabilized Doublet-Triplet Splitting, K.S. Babu, J.C. Pati and Z. Tavartkiladze, JHEP* **1006**, *084 (2010)*

In this paper we present a class of realistic unified models based on supersymmetric $SO(10)$ wherein issues related to natural doublet-triplet (DT) splitting are fully resolved. Using a minimal set of low dimensional Higgs fields which includes a single adjoint, we show that the Dimopoulos–Wilzcek mechanism for DT splitting can be made stable in the presence of all higher order operators without having pseudo-Goldstone bosons and flat directions. The μ term of order TeV is found to be naturally induced. A Z_2-assisted anomalous $U(1)_A$ gauge symmetry plays a crucial role in achieving these results. The threshold corrections to $\alpha_3(M_Z)$, somewhat surprisingly, are found to be controlled by only a few effective parameters. This leads to a very predictive scenario for proton decay. As a novel feature, we find an interesting correlation between the $d = 6$ ($p \to e^+\pi^0$) and $d = 5$ ($p \to \bar{\nu}K^+$) decay amplitudes which allows us to derive a constrained upper limit on the inverse rate of the $e^+\pi^0$ mode. Our results show that both modes should be observed with an improvement in the current sensitivity by about a factor of five to ten.

2. *B-L Violating Proton Decay Modes and New Baryogenesis Scenario in SO(10), K.S. Babu and R.N. Mohapatra, Phys. Rev. Lett.* **109***, 091803 (2012)*

Here we show that grand unified theories based on $SO(10)$ generate quite naturally baryon number violating dimension seven operators that violate $(B-L)$, and lead to novel nucleon decay modes such as $n \to e^- K^+$, $e^- \pi^+$ and $p \to \nu \pi^+$. We find that in two-step breaking schemes of non-supersymmetric $SO(10)$, the partial lifetimes for these modes can be within reach of experiments. The interactions responsible for these decay modes also provide a new way to understand the origin of matter in the universe via the decays of GUT scale scalar bosons of $SO(10)$. Their $(B-L)$-violating nature guarantees that the GUT scale induced baryon asymmetry is not washed out by the electroweak sphaleron interactions. In minimal $SO(10)$ models this asymmetry is closely tied to the masses of quarks, leptons and the neutrinos.

3. *Higgs boson of mass 125 GeV in GMSB models with messenger-matter mixing, A. Albaid and K.S. Babu, Phys. Rev. D* **88***, 055007 (2013)*

With his PhD student A. Albaid, Babu investigated the effects of messenger-matter mixing on the lightest CP-even Higgs boson mass m_h in gauge-mediated supersymmetry breaking models. It was shown that with such mixings m_h can be raised to about 125 GeV, even when the superparticles have sub-TeV masses, and when the gravitino has a cosmologically preferred sub-keV mass. In minimal gauge mediation without messenger-matter mixing, realizing $m_h = 125$ GeV would require multi-TeV SUSY spectrum. The increase in m_h due to messenger-matter mixing is maximal in the case of messengers belonging to $10 + \bar{10}$ of $SU(5)$ unification, while it is still significant when they belong to $5 + \bar{5}$ of $SU(5)$. Our results are compatible with gauge coupling unification, perturbativity, and the unification of messenger Yukawa couplings. We embed these models into a grand unification framework with a $U(1)$ flavor symmetry that addresses the fermion mass hierarchy and generates naturally large neutrino mixing angles. While SUSY mediated flavor changing processes are sufficiently suppressed in such an embedding, small new contributions to $K^0 - \bar{K}^0$ mixing can resolve the apparent discrepancy in the CP asymmetry parameters $\sin 2\beta$ and ϵ_K.

4. *New Signals for Doubly-Charged Scalars and Fermions at the Large Hadron Collider, K.S. Babu, A. Patra, S. Rai, Phys. Rev. D* **88***, 055006 (2013)*

With his student Patra and postdoc Rai, Babu studied the production and decay of doubly charged scalars which arise in several extensions of the Standard Model. The supersymmetric versions of these models introduce fermionic superpartners of these doubly-charged Higgs bosons, the Higgsinos, which also remain light. In this work we analyze a new collider signal resulting from the pair production and decay of a light doubly-charged Higgsino to an even lighter doubly-charged Higgs boson. We focus on the minimal left-right supersymmetric model with automatic R-parity conservation, which predicts such a light doubly-charged Higgs boson and its Higgsino partner at the TeV scale, which are singlets of $SU(2)_L$. We investigate the distinctive signatures of these particles with four leptons and missing transverse energy in the final state at the Large Hadron Collider and show that the discovery reach for both particles can be increased in this channel.

5. *Baryon Number Violation, K. S. Babu, E. Kearns, U. Al-Binni, S. Banerjee, D. V. Baxter, Z. Berezhiani, M. Bergevin and S. Bhattacharya et al., arXiv:1311.5285 [hep-ph]*

This is a comprehensive study of baryon number violation prepared for the Snowmass Community Planning Study – Snowmass 2013 – led by Babu and E. Kearns. It summarizes the theoretical motivations and the experimental efforts to search for baryon number violation, focussing on nucleon decay and neutron-antineutron oscillations. Present and future nucleon decay search experiments using large underground detectors, as well as planned neutron-antineutron oscillation search experiments with free neutron beams are highlighted.

OSU experimental HEP group (Task B)

The OSU experimental group includes two faculty members, Dr. Rizatdinova and Dr. Alexander Khanov, one post-doctoral fellow Dr. Jie Yu, part-time engineer Mr. Steven Welch and four graduate students, B. Abi, H. Hegab, K. Klimov and D. Sidorov. OSU group is a member of two collaborations, ATLAS at CERN and DØ at Fermi National Laboratory. Currently the research of the group is focused on the ATLAS experiment. During the period of the grant, graduate student Babak Abi has graduated using data collected with the ATLAS detector. His research was partially supported by the DOE grant. Postdoctoral fellow Jie Yu was also partially supported by DOE grant. Members of the group presented their results on 18 international conferences and meetings during the 2011–2013 grant period.

Impact of the OSU group on the ATLAS research program is significant in the following areas: top quark physics, calibration of the b-tagging algorithms, and pixel detector upgrade. In the last three years, the group has performed three measurements related to the top quark pair ($t\bar{t}$) production, which resulted in one publication and two conference notes. Our group is among the strongest contributors to the top quark physics in the ATLAS. As a service work for the experiment, we took responsibility to regularly provide the mistag rate calibration for all b-tagging algorithms that are in use by various physics groups. For the upcoming pixel detector upgrade, when the IBL will be installed, we are responsible for the construction of optoboxes and their integration in the readout chain of the IBL. In DØ, one graduate student (Hegab) under Rizatdinova's supervision is in the stage of completing his Ph.D. thesis on search for a Higgs boson in WH channel. In addition, Rizatdinova serves as the chair of the Editorial Board on searches for non-Standard Model (SM) Higgs boson in multijet final states. Below are highlights of results of the group during the last three years.

Rizatdinova, her graduate student Abi, Khanov and postdoc from OU Saleem have performed $t\bar{t}$ inclusive production cross section measurement at 7 TeV using 35 pb^{-1} data set. The measurement was done in lepton+jets final state using the multivariate technique (likelihood), which exploits the difference in the kinematics between $t\bar{t}$ and backgrounds. The measured cross section was found to be in a good agreement with next-to-leading order theoretical calculations. This result has been published in Phys. Lett. B . The OSU group also performed the measurement of the cross section for $t\bar{t}$+jets production cross section using kinematic fit method on the data set corresponding to 4.7 fb^{-1} integrated luminosity at 7 TeV. This measurement is the first measurement of $t\bar{t}$+jets production at the LHC. The results are summarized in conference note ATLAS-CONF-2012-083, and have been shown at all major conferences starting from ICHEP 2012. Rizatdinova, Khanov, Abi and Yu have completed the inclusive $t\bar{t}$ production cross section measurement at 8 TeV on a data set corresponding to an integrated luminosity of 5.8 fb^{-1}. It is documented in conference note ATLAS-CONF-2012-149 and has been shown on major international conferences. Multivariate technique and b-jet identification were employed to separate the signal $t\bar{t}$ events from various backgrounds. The inclusive $t\bar{t}$ production cross section was found in a good agreement with the current theoretical prediction.

The OSU group is committed to service work for the ATLAS experiment in two areas. The first one is the detector operations. Khanov took responsibility for creation of the CORA COOL database for pixel detector. He wrote this database, which is part of the ATLAS software now. The database provides necessary online calibration information for pixel detector for the offline track reconstruction software. His work is documented in several ATLAS notes. The other area of our service work for the Collaboration is the measurement of mistag rate for all tagging algorithms for all their operating points. OSU group is one of only two groups in the Collaboration, which performs this important calibration for the tagging algorithms. All physics analyses that use b-tagging are using the calibrations provided by our group. Khanov and Rizatdinova developed methods for the measurement of mistag rates of b-tagging algorithms and performed the first mistag measurement using 3 pb^{-1} of data. This result is described in conference note ATLAS-CONF-2010-099. Since that time, our group regularly updated the calibration of initial and more sophisticated tagging algorithms (based on use of the neural networks). The corresponding conference notes are ATLAS-CONF-2011-089, ATLAS-CONF-2011-102. The latest results were obtained with the active participation of newly hired postdoc Yu and graduate student Sidorov and published as conference note ATLAS-CONF-2012-040.

OSU HEP group is involved in the pixel detector upgrade project since it has joined the ATLAS Collaboration. OSU has hired a part-time engineer S. Welch, who is stationed at CERN. Welch participates in the new Services Quarter Panels (nSQP) project and in the IBL. The main goals of nSQP project are to replace the electrical and mechanical services for the ATLAS pixel detector, move failing components to lower humidity environment and provide a better access to pixel detectors services. OSU responsibilities in nSQP include design of nSQP optobox, which has several printed circuit boards (PCB) in it, overview the production of all these PCBs and perform the reliability assurance for PCBs. At this moment, prototypes of optoboxes have been manufactured and went through extensive testing. Tests have demonstrated reliability of the designed optoboxes. Next step is the production of the optoboxes and their installation in the ATLAS detector.

List of international conference/workshop presentations by the group members

Rizatdinova:

1. Measurements of differential tt cross sections at the LHC, 7th International Workshop on the CKM Unitarity Triangle, Cincinnati, OH, September 28–October 2, 2012.
2. Measurement of top properties at DØ, XI Conference on the Intersections of Particle and Nuclear Physics, St. Petersburg, FL, May 2012.
3. Top Physics at the Tevatron, XV Lomonosov Conference, Moscow, August 2011.
4. Top Cross Section Measurement, 22nd Rencontres de Blois, Blois, France, July 2010.

Khanov:

1. Top quark couplings: tt+jets, Snowmass Energy Frontier Workshop (April 2013), Brookhaven National Laboratory.
2. Top physics with ATLAS, 15th Lomonosov Conference on Elementary Particle Physics (August 2011), Moscow, Russia.
3. Summary of recent physics results from the Tevatron, Hadron Structure and QCD (July 2010), Gatchina, Russia.

Yu:

1. Measurements of Top Properties in ATLAS, La Thuile, Italy, February 2013.

Babak:

1. Measurement of the cross section in $t\bar{t}$+jets using a multivariate kinematics fit method with the ATLAS detector, American Physical Society (APS) April Meeting 2012, March 31–April 3, Atlanta, GA, USA.
2. Measurement of the top quark pair production cross section with early ATLAS data, American Physical Society (APS) April Meeting 2011, April 30–May 3 2011, Anaheim, California, USA.
3. Top quark pair production Cross Section in ATLAS with early data, The Hadron Collider Physics Symposium 2010, August 23–27, University of Toronto, Toronto, Canada.

Hegab:

1. Search for associated production of a W and a Higgs Boson in $\ell\nu b\bar{b}$ final states at DØ, American Physical Society (APS) April Meeting 2011, April 30–May 3 2011, Anaheim, California, USA.

Welch:

1. The ATLAS Pixel nSQP readout chain, TWEPP 2012, September 2012, Oxford University, UK.

Publications

The Group members are co-authors of 483 publications for the last three years as members of the DØ and ATLAS Collaborations.

Papers with major contributions are:

1. G. Aad et al. [ATLAS Collaboration], Measurement of the top quark pair production cross-section with ATLAS in the single lepton channel, Phys. Lett. B **711**, 244 (2012).

2. V. M. Abazov et al. [D0 Collaboration], Search for Higgs bosons of the minimal supersymmetric standard model in pp collisions at $\sqrt{s} = 1.96$ TeV, Phys. Lett. B **710**, 569 (2012).

3. G. Aad et al. [Atlas Collaboration], Measurement of the top quark-pair production cross section with ATLAS in pp collisions at $\sqrt{s} = 7$ TeV, Eur. Phys. J. C **71**, 1577 (2011).

4. S. N. Ahmed et al. [D0 Collaboration], The DØ Silicon Microstrip Tracker, Nucl. Instrum. Meth. A **634**, 8 (2011).

5. T. Aaltonen et al. [CDF and D0 Collaboration], Combined CDF and DØ Upper Limits on Standard Model Higgs Boson Production with up to 8.2 fb^{-1} of Data, arXiv:1103.3233 [hep-ex].

6. V. M. Abazov et al. [D0 Collaboration], Search for neutral Higgs bosons in the multi-b-jet topology in 5.2 fb^{-1} of ppbar collisions at $\sqrt{s} = 1.96$ TeV, Phys. Lett. B **698**, 97 (2011).

7. V. M. Abazov et al. [D0 Collaboration], b-Jet Identification in the DØ Experiment, Nucl. Instrum. Meth. A **620**, 490 (2010).