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1. Executive Summary (April 1, 2012 - March 31, 2015)

Title: Particle Theory, Particle Astrophysics and Cosmology

Qaisar Shafi, University of Delaware (Principal Investigator)
Stephen M. Barr, University of Delaware (Co-Principal Investigator)
Thomas K. Gaisser, University of Delaware (Co-Principal Investigator)
Todor Stanev, University of Delaware (Co-Principal Investigator)

The proposed research was carried out at the Bartol Resear included Professors Qaisar Shafi, Stephen Barr, Thomas K. Gaisser, and Todor Stanev, two postdoctoral fellows (Ilia Gogoladze and Liucheng Wang), and several graduate students. Five students of Qaisar Shafi completed their PhD during the period August 2011 - August 2014. Measures of the group's high caliber performance during the 2012-2015 funding cycle included publications in excellent refereed journals, contributions to working groups as well as white papers, and conference activities, which together provide an exceptional record of both individual performance as well as overall strength. Another important indicator of success is the outstanding quality of the past and current cohort of graduate students. The PhD students under our supervision regularly win the top departmental and university awards, and their publications records show excellence both in terms of quality and quantity.

The topics covered under this grant cover the frontline research areas in today's High Energy Theory & Phenomenology. For Professors Shafi and Barr they include LHC related topics including supersymmetry, collider physics, flavor physics, dark matter physics, Higgs boson and seesaw physics, grand unification, and neutrino physics. The LHC two years ago discovered the Standard Model Higgs boson, thereby at least partially unlocking the secrets behind electroweak symmetry breaking. We remain optimistic that new and exciting physics will be found at LHC 14, which explain our focus on physics beyond the Standard Model. Professors Shafi continued his investigations in cosmology, specifically on supergravity and GUT inflation models, primordial gravity waves, dark matter models. The origin of baryon and dark matter in the universe has been explored by Professors Barr and Shafi. The research program of Professors Gaisser and Stanev address current research topics in Particle Astrophysics, in particular atmospheric and cosmogenic neutrinos and ultra-high energy cosmic rays. Work also included use of LHC data to improve tools for interpreting cascades generated in the atmosphere by high-energy particles from the cosmos. Cosmogenic neutrinos produced by interactions of ultra-high energy cosmic rays as they propagate through the cosmic microwave background radiation provides insight into the origin of the highest energy particles in nature.

Overall, the research covered topics in the energy, cosmic and intensity frontiers.

2. Introduction

The research activities of the four faculty members on the grant fall into three broad categories:

- High Energy Theory & Phenomenology (LHC related topics such as supersymmetry, collider physics, dark matter, grand unification, flavor physics, extra dimensions, baryon and lepton number violation, and neutrino physics). Done by Professors Barr and Shafi, two postdocs and 7 graduate students.
- Cosmology (including construction of realistic inflation models, primordial gravity waves, baryogenesis). Work done by Professors Barr and Shafi and collaborators.
- Particle Astrophysics (including atmospheric and cosmogenic neutrinos, highest energy cosmic rays, dark matter). Work done by Professors Gaisser and Stanev, with postdocs and collaborators.

3 Qaisar Shafi (PI)

During the three-year period, August 2011 - August 2014, Qaisar Shafi has completed 34 papers, of which 30 have been published in refereed journals. His research primarily has been carried out in collaboration with the DOE- supported postdocs, namely Ilia Gogoladze, Tong Li, and more recently Liucheng Wang, as well as graduate students, several of whom have completed their PhD. Other collaborators include K. Babu (Oklahoma State), B.Dutta (Texas A&M), N. Okada (Alabama), C. Pallis(Valencia) and J. Valle (Valencia).

- **Energy Frontier:**

Research on Physics Beyond the Standard Model, collider and dark matter physics has largely been inspired by the successful launch of the Large Hadron Collider (LHC) at CERN and the discovery in 2012 of the SM Higgs boson. We have published some influential papers related to the SM-like boson encountered in models based on supersymmetric GUTs with third family t-b-τ (or b-τ) Yukawa unification. One paper, published in late 2011, shows that a class of Yukawa unified GUTs favor a Higgs boson mass of 122-126 GeV. The special role played by the gluino in Yukawa unified models, and its potential discovery at the LHC was emphasized in another paper. The impact of LHC searches on NLSP Stop and NLSP Gluino mass bounds was discussed in a couple of publications in 2012. Theoretical issues related to the well-known little hierarchy problem and natural supersymetry also yielded interesting results with implications for LHC and dark matter searches. The demand that the lightest (stable) neutralino provides an acceptable dark matter candidate has played an important role in several of these papers, and led to important conclusions regarding direct, indirect and LHC dark matter searches.

- **Cosmic Frontier:**

Our research efforts in the construction of inflationary scenarios based on realistic particle physics models have been successful and yielded important results regarding the abundance of primordial gravity waves generated during inflation. For instance, we have shown that the all-important quantity r (tensor to scalar ratio), a canonical measure of gravity waves, cannot exceed 0.02 in supersymmetric hybrid inflation models with supergravity and quantum corrections taken into account. [Buchmuller et.al., in a recent paper hep-ph:1404.1832, state:"Supersymmetric hybrid inflation is an exquisite framework to connect inflationary cosmology to particle physics at the scale of grand unification."] This class of extremely well motivated models, pioneered by Shafi and collaborators, can be ruled out (!) if the BICEP2 claim that $r \sim$ 0.15-0.2 is verified by the ongoing experiments.

We also revisited inflationary models with Higgs and Coleman-Weinberg type potential, as well as textbook inflationary models with quadratic and quartic potentials, taking into account quantum corrections induced by the presence of inflation couplings to additional fields required for reheating. For the (gauge singlet) Higgs model in particular, it is shown that with the scalar spectral index n_s close to the preferred value 0.96 determined by the WMAP and Planck observations, the tensor to scalar $r \geq 0.03$. This will be tested by several ongoing and planned experiments.

• **Intensity Frontier:**

Recent work in this area has been inspired by the so-called muon $g-2$ anomaly. We have explored supersymmetric models with suitably light scalar muons (smuons) which can help ameliorate the apparent disagreement between the SM prediction and experimental measurement of muon $g-2$. Being relatively light, the smuons may be accessible at the LHC. There are important implications for rare leptonic decays that are currently under investigation.

Selected Publications (Numbers refer to Q. Shafi's publications listed on page 7-11)

[2] In order to resolve the apparent muon $g-2$ anomaly encountered in the Standard Model, we explore two distinct scenarios, one in which all gaugino masses have the same sign at $M_{\rm GUT}$, and a second case with opposite sign gaugino masses. The sfermion masses in both cases are assumed to be universal at $M_{\rm GUT}$. We exploit the non universality among gaugino masses to realize large mass splitting between the colored and non-colored sfermions. Thus, the sleptons can have masses in the few hundred GeV range, whereas the colored sparticles turn out to be an order of magnitude or so heavier.

[3] We present a class of supersymmetric models in which symmetry considerations alone dictate the form of the soft SUSY breaking Lagrangian. We develop a class of minimal models, denoted as sMSSM – for flavor symmetry-based minimal supersymmetric standard model, which respect a grand unified symmetry such as SO(10) and a non-Abelian flavor symmetry H which suppresses SUSY-induced flavor violation. We discuss the parameter space of sMSSM compatible with LHC searches, B physics constraints and dark matter relic abundance. Fine-tuning in these models is relatively mild, since all SUSY particles can have masses below about 3 TeV.

[5] We propose that inflation and dark matter have a common origin, connected to the neutrino mass generation scheme. As a model we consider spontaneous breaking of global lepton number within the seesaw mechanism. We show that it provides an acceptable inflationary scenario consistent with the recent CMB B-mode observation by the BICEP2 experiment. The scheme may also account for the baryon asymmetry of the Universe through leptogenesis for reasonable parameter choices. It is important to note that there is a lower bound on r close to 0.02 in these inflationary models.

[8] We explore the upper bound on the tensor-to-scalar ratio r, a canonical measure of inflationary gravity waves, in supersymmetric hybrid inflation models with the gauge symmetry breaking scale set equal to the value 2.86×10^{16} GeV, as dictated by the unification of the MSSM gauge couplings. The upper bound on r is estimated to be of order 0.01 for subplanckian values of the inflaton, while the 'running' $|dn_s/d\ln k| \simeq 0.006$. These models will be tested by Planck and several other experiments.

[10] We study the implications for bounds on the top quark pole mass m_t in models with low scale supersymmetry following the discovery of the Standard Model-like Higgs boson. In the minimal supersymmetric standard model, we find that $m_t \geq 164$ GeV, if the light CP even Higgs boson mass $m_h = 125 \pm 2$ GeV. In particular, assuming SO(10) compatible non-universal gaugino masses, setting $m_h = 125$ GeV and requiring 5% or

better Yukawa unification, we obtain the result 172 GeV $\leq m_t \leq$ 175 GeV. Conversely, demanding 5setting $m_t = 173.2$ GeV, the Higgs boson mass is predicted to lie in the range 122 GeV $\leq m_h \leq$ 126 GeV.

[26] We identify a class of supersymmetric $SU(4)_c \times SU(2)_L \times SU(2)_R$ models in which imposing essentially perfect $t - b - \tau$ Yukawa coupling unification at $M_{\rm GUT}$ yields a mass close to 122-126 GeV for the lightest CP-even (SM-like) Higgs boson. The squark and gluino masses in these models exceed 3 TeV, but the stau and charginos in some cases can be considerably lighter.

[28] We show, contrary to previous expectations, that a gluino mass $\sim$ 0.5-3 TeV is compatible with excellent $t - b - \tau$ Yukawa coupling unification in supersymmetric models with non-universal Higgs masses (NUHM2). The gluino in such models is the lightest colored sparticle, while the squark sector displays an inverted mass hierarchy with $m_{\tilde{q}} \sim 5 - 20$ TeV. We expect gluino pair production followed by decay to final states containing four b-jets plus four W-bosons plus missing E_T to occur at possibly observable rates at LHC.

[33] We employ the ATLAS search results for events containing jets and large missing transverse momentum, corresponding to an integrated luminosity of 1 fb^{-1}, to investigate the constrained minimal supersymmetric model (CMSSM) with $b - \tau$ Yukawa coupling unification. We find that the multi-jets and monojet ATLAS searches are sensitive to this scenario if the stop pair production is accompanied by a hard QCD jet. For LSP neutralino mass $\sim$ 100 GeV, the LHC constraints in some cases on the spin-dependent (spin-independent) neutralino-nucleon cross section are significantly more stringent than the current and expected bounds from Xenon, CDMS and IceCube.

Publications and Talks
(Q. Shafi, August 2011-August 2014)

- **Refereed Journals:**

1. 3.5 keV X-ray line and R-Parity Conserving Supersymmetry,
B. Dutta, I. Gogoladze, R. Khalid and Q. Shafi,
arXiv:1407.0863 [hep-ph], submitted for publication.

2. Muon $g-2$, 125 GeV Higgs and Neutralino Dark Matter in sMSSM,
K.S. Babu, I. Gogoladze, Q. Shafi and C. Salih Un,
arXiv:1406.6965 [hep-ph], submitted for publication.

3. Flavor Symmetry Based MSSM (sMSSM): Theoretical Models and Phenomenological Analysis,
K.S. Babu, I. Gogoladze, S. Raza and Q. Shafi,
arXiv:1406.6078 [hep-ph], to appear in Phys. Rev. D.

4. From Hybrid to Quadratic Inflation With High-Scale Supersymmetry Breaking,
C. Pallis and Q. Shafi,
Phys.Lett. B736 (2014) 261-266, arXiv:1405.7645 [hep-ph].

5. Inflation and majoron dark matter in the seesaw mechanism,
S. M. Boucenna , S. Morisi, Q, Shafi and J. W. F. Valle,
arXiv:1404.3198 [hep-ph], to appear in Phys. Rev. D.

6. Simple Inflationary Models in Light of BICEP2: an Update,
N. Okada, V. Nefer Senoguz and Q. Shafi,
arXiv:1403.6403 [hep-ph], submitted for publication.

7. Nonuniversal Gaugino Masses and Muon $g-2$,
I. Gogoladze, F. Nasir, Q. Shafi and C. Salih Un,
Phys.Rev. D90 (2014) 035008, arXiv:1403.2337 [hep-ph].

8. Upper Bound on the Tensor-to-Scalar Ratio in GUT-Scale Supersymmetric Hybrid Inflation,
M. Civiletti, C. Pallis and Q. Shafi,
Phys.Lett. B733 (2014) 276-282, arXiv:1402.6254 [hep-ph].

9. Split sfermion families, Yukawa unification and muon $g-2$,
M. Adeel Ajaib, I. Gogoladze, Q. Shafi and C. Salih Un,
JHEP 1405 (2014) 079, arXiv:1402.4918 [hep-ph].

10. Top Quark and Higgs Boson Masses in Supersymmetric Models,
I. Gogoladze, R. Khalid, S. Raza and Q. Shafi,
JHEP 1404 (2014) 109, arXiv:1402.2924 [hep-ph].

11. Effects of Neutrino Inverse Seesaw Mechanism on the Sparticle Spectrum in CMSSM and NUHM2,
I. Gogoladze, B. He, A. Mustafayev, S. Raza and Q. Shafi,
JHEP 1405 (2014) 078, arXiv:1401.8251 [hep-ph].

12. Observable Gravity Waves From $U(1)_{B-L}$ Higgs and Coleman-Weinberg Inflation,
N. Okada and Q. Shafi,
arXiv:1311.0921 [hep-ph], revised manuscript to be submitted.

13. Sparticle Spectroscopy from SO(10) GUT with a Unified Higgs Sector,
M. Adeel Ajaib, I. Gogoladze and Q. Shafi,
Phys.Rev. D88 (2013) 9, 095019, arXiv:1307.4882 [hep-ph].

14. Particle Spectroscopy of Supersymmetric SU(5) in Light of 125 GeV Higgs and Muon $g-2$ Data,
N. Okada, S. Raza and Q. Shafi,
Phys.Rev. D90 (2014) 015020, arXiv:1307.0461 [hep-ph].

15. SO(10) as a Framework for Natural Supersymmetry,
I. Gogoladze, F. Nasir and Q. Shafi,
JHEP 1311 (2013) 173, arXiv:1306.5699 [hep-ph].

16. Update on Minimal Supersymmetric Hybrid Inflation in Light of PLANCK,
C. Pallis and Q. Shafi,
Phys.Lett. B725 (2013) 327-333, arXiv:1304.5202 [hep-ph].

17. A Predictive Yukawa Unified SO(10) Model: Higgs and Sparticle Masses,
M. Adeel Ajaib, I. Gogoladze, Q. Shafi and C. Salih Un,
JHEP 1307 (2013) 139, arXiv:1303.6964 [hep-ph].

18. R-Symmetry Breaking in Supersymmetric Hybrid Inflation,
M. Civiletti, M. U. Rehman, E. Sabo, Q. Shafi and J. Wickman,
Phys.Rev. D88 (2013) 10, 103514, arXiv:1303.3602 [hep-ph].

19. Non-Universal Gaugino Masses and Natural Supersymmetry,
I. Gogoladze, F. Nasir and Q. Shafi,
Int.J.Mod.Phys. A28 (2013) 1350046, arXiv:1212.2593 [hep-ph].

20. Inverse Seesaw in NMSSM and 126 GeV Higgs Boson,
I. Gogoladze, and B. He and Q. Shafi,
Phys.Lett. B718 (2013) 1008-1013, arXiv:1209.5984 [hep-ph].

21. Smooth Hybrid Inflation and Non-Thermal Type II Leptogenesis,
S. Khalil, Q. Shafi and A. Sil,
Phys.Rev. D86 (2012) 073004, arXiv:1208.0731 [hep-ph].

22. Higgs Boson Production and Decay: Effects from Light Third Generation and Vectorlike Matter,

M.Adeel Ajaib, I. Gogoladze and Q. Shafi,
Phys.Rev. D86 (2012) 095028, arXiv:1207.7068 [hep-ph].

23. 125 GeV Higgs, Type III Seesaw and Gauge-Higgs Unification,
B. He, N. Okada and Q. Shafi,
Phys.Lett. B716 (2012) 197-202, arXiv:1205.4038 [hep-ph].

24. Revisiting mGMSB in Light of a 125 GeV Higgs,
M. Adeel Ajaib, I. Gogoladze, F. Nasir and Q. Shafi,
Phys.Lett. B713 (2012) 462-468, arXiv:1204.2856 [hep-ph].

25. Non-Minimal Chaotic Inflation, Peccei-Quinn Phase Transition and non-Thermal Leptogenesis,
C. Pallis and Q. Shafi,
Phys.Rev. D86 (2012) 023523, arXiv:1204.0252 [hep-ph].

26. 125 GeV Higgs Boson from t-b-τ Yukawa Unification,
I. Gogoladze, Q. Shafi and C. Salih Un,
JHEP 1207 (2012) 055, arXiv:1203.6082 [hep-ph].

27. Simplified Smooth Inflation with Observable Gravity Waves,
M. U. Rehman and Q. Shafi,
Phys.Rev. D86 (2012) 027301, arXiv:1202.0011 [hep-ph].

28. A Heavier gluino from t-b-τ Yukawa-unified SUSY,
H. Baer, S. Raza and Q. Shafi,
Phys.Lett. B712 (2012) 250-254, arXiv:1201.5668 [hep-ph].

29. Sparticle mass spectra from SU(5) SUSY GUT models with b-τ Yukawa coupling unification,
H. Baer, I. Gogoladze, A. Mustafayev, S. Raza and Q. Shafi,
JHEP 1203 (2012) 047, arXiv:1201.4412 [hep-ph].

30. Impact of LHC Searches on NLSP Top Squark and Gluino Mass,
B. He, T. Li and Q. Shafi,
JHEP 1205 (2012) 148, arXiv:1112.4461 [hep-ph].

31. Higgs Boson Mass from t-b-τ Yukawa Unification,
I. Gogoladze, Q. Shafi and C. Salih Un,
JHEP 1208 (2012) 028, arXiv:1112.2206 [hep-ph].

32. Neutralino-Sbottom Coannihilation in SU(5),
I. Gogoladze, S. Raza and Q. Shafi,
JHEP 1203 (2012) 054, arXiv:1111.6299 [hep-ph].

33. Stop-Neutralino Coannihilation in the Light of LHC,
M.Adeel Ajaib, T. Li and Q. Shafi,
Phys.Rev. D85 (2012) 055021, arXiv:1111.4467 [hep-ph].

34. θ_{13}, CP Violation and Leptogenesis in Minimal Supersymmetric $SU(4)_c \times SU(2)_L \times SU(2)_R$,
N. Okada and Q. Shafi,
arXiv:1109.4963 [hep-ph].

- **Conference Proceedings:**

1. Will Planck Observe Gravity Waves?
PoS EPS-HEP2013 (2013) 483.

2. Higgs boson mass in Yukawa unified SUSY SO(10),
J.Phys.Conf.Ser. 384 (2012) 012025.

3. Higgs boson mass and sparticle spectroscopy in Yukawa unified SUSY SO(10),
AIP Conf.Proc. 1467 (2012) 101-108.

4. Fundamental Physics at the Intensity Frontier,
ANL-HEP-TR-12-25, SLAC-R-991, FERMILAB-CONF-12-879-PPD, arXiv:1205.2671 [hep-ex].

- **White Papers & Working Group Reports:**

1. Higgs and Sparticle Masses from Yukawa Unified SO(10): A Snowmass White Paper,
C13-07-29.2, arXiv:1308.4652 [hep-ph].

2. 125 GeV Higgs Boson From Gauge-Higgs Unification: A Snowmass white paper,
C13-07-29.2, arXiv:1307.5079 [hep-ph].

3. Working Group Report: Baryon Number Violation,
C13-07-29.2, arXiv:1311.5285 [hep-ph].

4. Working Group Report: Higgs Boson,
C13-07-29.2, arXiv:1310.8361 [hep-ex].

- **Talks:**

1. 2014 Flavor Physics Workshop, June 2014, University of Sussex, UK.

2. University of Valencia, March 2014, Spain.

3. Dark Matter Workshop, March 2014, Valencia, Spain.

4. ASU-Tufts 2014 Cosmic String Workshop, February 2014, Phoenix, AZ, USA.

5. Seminar talk, January 2014, University of Nottingham, UK.

6. UK Cosmology Workshop, January 2014, King's College, London, UK.

7. Miami 2013, December 2013, Miami, USA.

8. European Physical Society, July 2013, Stockholm, Sweden.
9. 2013 BCVSPIN Advanced Study Institute, Hangzhou, China.
10. University of Cyprus, March 2013, Nicosia, Cyprus.
11. University of Thessaloniki, March 2013, Greece.
12. Imperial College, March 2013, London, UK.
13. Miami 2012, December 2012, Miami, USA.
14. 2012 GUT Workshop, March 2012, Kyoto, Japan.
15. University of Lancaster, October 2011, UK.
16. Southampton University, October 2011, UK.
17. DSU 2011, September 2011, Beijing, China.

4 Stephen M. Barr (Co-PI)

4.1 Overview of Research of S.M. Barr (August 2011-August 2014)

Prof. Barr's research in high energy theory, model building, and cosmology during this period was carried out with graduate student Heng-Yu Chen and with Professors Jihn E. Kim (Kyung Hee Univ.), X. Calmet (Univ. Sussex), and T. Kephart (Vanderbilt Univ.).

Much of this work concerned the development of new mechanisms for the genesis of dark matter, non-standard ideas about proton decay, models that relate quark and lepton properties and precisely predict neutrino parameters, low-energy consequences of Planck-scale physics, and axion cosmology. The models that were developed have interesting implications for LHC physics (such as predicting new scalar particles and vectorlike fermions), for experiments that will attempt to measure the neutrino parameters θ_{13} and δ_{CP}, and for proton decay and dark matter searches.

- **Cosmic Frontier**

Barr and his collaborators have recently developed several new ideas concerning dark matter and its origin. The idea of "cogeneration" of dark matter and baryonic matter has attracted much recent interest as a way to explain the "cosmic coincidence" of their similar cosmic densities. In a paper published in 2012, Barr suggested that that grand unified models based on groups larger than $SU(5)$ are a natural context for "cogeneration". In a 2013 paper Barr and his student Heng-Yu Chen showed that "sphaleron processes" of a non-Standard Model interaction provide a simple cogeneration mechanism that allows for precise (model-dependent) predictions of the ratio of baryon number to dark matter number. Another idea for dark matter was developed by Barr in collaboration with Kephart based on the idea that Higgs fields come in families, analogous to quark and lepton families. The extra Higgs in these schemes can act like "inert dark matter."

Invisible axions lead to a variety of interesting cosmological consequences, including being one of the most promising candidates for dark matter. Barr and Jihn Kim (the originator of the invisible axion idea) published a paper in 2014 that showed a novel way to avoid one of the potential cosmological problems of axion theories.

- **Intensity Frontier**

In the period covered by this review, Barr and his collaborators have developed some new ideas in the theory of proton decay. With Calmet, Barr showed that Planck-scale physics can give observable proton (and neutron) decay with very distinctive signatures. Another question is how stable the proton can be. In a 2013 paper, Barr showed that in certain simple unified schemes proton decay at the tree level can be forbidden. In a subsequent paper, with Calmet, they showed that the proton can be made absolutely stable even with respect to gravitational and non-perturbative effects.

With his student Heng-Yu Chen, Barr has developed an extremely predictive model that explains all flavor mixing and violation from a single source. The model predicts several as yet unknown (or poorly known) neutrino properties. In a follow-up paper, they showed that the model also has distinctive predictions for proton decay branching ratios.

• **Energy Frontier**

Several of the models developed by Barr and his collaborators predict the existence of new particles that could be seen at the LHC. The dark matter cogeneration models and the predictive model of flavor mixing both predict the existence of vectorlike fermions. The Model of "Higgs families" give a rich structure of new scalar fields in the multi-TeV range. The model in which the proton is made absolutely stable, predicts a large number of new chiral leptons, with masses near the weak scale, which though consistent with present precision electroweak tests should show up soon.

Selected Publications (Numbers refer to the list of S.M. Barr's publications in refereed journals)

[1] This paper showed that grand unified models with groups larger than $SU(5)$ have several features that make them a natural context for "cogeneration" of dark matter. The multiplets of such groups almost always have Standard-Model-singlet fermions that could play the role of dark matter particles. Just as $B - L$ is an "accidental global symmetry of the minimal $SU(5)$ model, unified models based on larger groups can have other such global $U(1)$ symmetries that could stabilize dark matter particles. And such models have new gauge interactions that can provide co-generation mechanisms. A specific model was presented illustrating all these features.

[2] This paper proposed the idea of non-abelian "Higgs flavor" groups, under which only the Higgs fields transform, not the quarks and leptons. This idea has no problems with excessive flavor-changing neutral current processes, as multi-Higgs models typically do, but leads to a very rich phenomenology of extra scalar fields. Some of the new scalars act as "sequential Higgs", i.e. with couplings to quarks and leptons proportional to those of the Standard Model Higgs. Others have no direct couplings to fermions, and act like "inert Higgs". Some are exactly stable and would be dark matter. These models and aspects of their phenomenology were classified in this paper according to the possible Higgs-flavor groups.

[4] Barr and Calmet gave a general operator analysis of proton decay (and B-violating neutron decay) coming from Planck-scale physics. It showed that if certain colored scalar fields exist that have mass at or near the weak scale (and with the SM quantum numbers of either Q, u^c, or d^c), then gravity-induced proton-decay amplitudes exist that are suppressed by only one power of the Planck mass rather than two and that are of a detectable magnitude. Interestingly, in all these cases $B - L$ is violated and $B + L$ conserved, giving unusual modes such as $p \to \pi^+ \pi^+ e^-$. The proton decay rate can be tied to the mass and certain partial decay rates of the new colored scalar, which could be measured at LHC or future colliders.

[5] In this paper, Barr and Heng-Yu Chen developed a model with a very simple structure that gives a close relationship between quark mixing (the CKM matrix) and lepton mixing (the MNS matrix). The key feature is that all fermion mixing is controlled

by a single hermitian matrix. This matrix describes the mixing of the $\overline{\mathbf{5}}$ multiplets in the "ordinary" three families to those in "extra" vectorlike $\mathbf{5} + \overline{\mathbf{5}}$ multiplets. This simple scheme yields predictions of all the neutrino properties in terms of the quark mass ratios and quark mixing angles (which are known) and three parameters. a single overall neutrino mass scale. There are predictions of as-yet unmeasured neutrino properties (the Dirac and Majorana CP phases of the neutrinos, and the lightest neutrino mass), as well as sharp "post-dictions" of some as-yet poorly determined quantities, such as the atmospheric and solar neutrino angles, the real and imaginary parts of V_{ub}, and m_s/m_d.

[6] This paper extended the work of paper [5], by showing that the same model predicts the values of certain flavor mixing angles that can only be seen in proton (or neutron) decay. These angles determine how the leptons of one family are placed in $SU(5)$ multiplets with quarks of a different family.)

[7] The idea has long been discussed that proton decay could be "rotated away", i.e. suppressed by fermion mixing angles (of the same type discussed in paper [5]). It has long been known that this could happen, but only if some mixing angles were precisely and unnaturally tuned to certain values. In this paper, it was shown that in schemes based on "flipped" unification, proton decay from tree-level processes (both gauge-boson and scalar-boson exchange) can be rotated away in a simple and natural way.

[8] The first suggestion that baryonic matter and dark matter could have a common origin was made in a 1990 paper by Barr, Chivukula, and Farhi, which is also one of the first to propose the idea of asymmetric dark matter (other than neutrinos). In that paper, the cogeneration mechanism was electroweak (EW) "sphalerons processes" that convert baryons, leptons, and dark matter into each other. A drawback of that is that dark matter must be chiral under the EW $SU(2)$, which raises thorny model building difficulties. In this paper of Barr and Heng-Yu Chen it was shown that cogeneration is done much more simply by sphalerons of a non-Standard Model gauge interaction. Moreover, it was shown that in such a scheme, the conditions for equilibrium of the two kinds of sphalerons (EW and non-EW) determine the two ratios among baryon number, lepton number, and dark matter number, thus determining the mass of the dark matter particle.

[9] In this paper, barr and Calmet go beyond paper [7] to show that there exist models in which protons can be made absolutely stable, to all orders in perturbation theory, and including also non-perturbative and gravity effects. They showed that this is only possible if new leptons exist that are chiral under the EW interactions, whose existence is highly testable through precision EW tests, through their effect on the Higgs-to-two-gamma amplitude, and by direct searches.

[10] In this paper, Barr and Jihn E. Kim discuss a new mechanism for suppressing axion domain walls, whose possible existence is one of the well-known cosmological difficulties that face axion models.

4.3 Publications and Talks (Stephen M. Barr, August 2011 – August 2014)

- **Refereed Journals:**

1. The Unification and Cogeneration of Dark Matter and Baryonic Matter,
   S.M. Barr, Phys. Rev. D85, 013001 (2012). arXiv:1109.2562[hep-ph]

2. A Classification and Analysis of Higgs-flavor Models,
   S.M. Barr and T.W. Kephart, Phys. Rev. D85, 035010 (2012). arXiv:1111.0963 [hep-ph]

3. Grand Unification without Higgs Bosons,
   S.M. Barr and Xavier Calmet, Int. J. Mod. Phys. Conf. Ser. 13, 20 (2012). arXiv:1202.1752 [hep-ph]

4. Observable Proton Decay from Planck Scale Physics,
   S.M. Barr and Xavier Calmet, Phys. Rev. D86, 116010 (2012). arXiv:1203.5694 [hep-ph]

5. A Simple Grand Unified Relation between Neutrino Mixing and Quark Mixing,
   S.M. Barr and Heng-Yu Chen, JHEP 1211, 092 (2012). arXiv:1208.6546 [hep-ph]

6. Proton Decay and the Origin of Quark and Lepton Mixing,
   S.M. Barr and Heng-Yu Chen, JHEP 1310, 049 (2013) arXiv:1307.5755 [hep-ph]

7. Rotating Away Proton Decay in Flipped Unification,
   S.M. Barr, Phys. Rev. D88, 057702 (2013). arXiv:1307.5770 [hep-ph]

8. Cogeneration of Dark Matter and Baryons by Non-Standard-Model Sphalerons in Unified Models,
   S.M. Barr and Heng-Yu Chen, JHEP 1310, 129 (2013). arXiv:1309.0020 [hep-ph].

9. Absolutely Stable Proton and Lowering the Gauge Unification Scale,
   S.M. Barr and Xavier Calmet, JHEP 1407, 159 (2014). arXiv:1404.4594 [hep-ph]

10. New Confining Force Solution of QCD Axion Domain Wall Problem,
    S.M. Barr and Jihn E. Kim, Phys. Rev. Lett. 113, 241301 (2014). arXiv:1407.4311 [hep-ph]

• Invited and Contributed Talks (by S.M. Barr or his graduate student Heng-Yu Chen):

1. The Unification and Cogeneration of Dark Matter,
   Third International Workshop on Baryon and Lepton Number Violation BLV2011 Workshop, Gatlinburg, TN, Sept. 22-24, 2011.

2. Relating Quark Mixing, Neutrino Mixing and δ_{lep},
   CETUP2012 Workshop (Center for Theoretical Underground Physics and Related Areas), Lead, South Dakota, July 19-29, 2012.

3. A Simple Grand Unified Relation between Quark and Lepton Mixing,
   Theory Seminar at Carnegie Mellon University, April 26, 2013.

4. Relating CKM and MNS Mixing and Predicting the Neutrino CP Phases,
   (Heng-Yu Chen), PHENO2013 Workshop, Pittsburgh, PA, May 6-8, 2013.

5. Relating CKM and MNS Mixing and Predicting the Neutrino CP Phases,
   (Heng-Yu Chen), BVSPIN2013 Workshop, Hangzhou, China, June 7-15, 2013.

6. A simple Grand Unification Relation between Neutrino Mixing and Quark Mixing,
   (Heng-Yu Chen) Workshop on Strings, Particles and Cosmology 2013, Sichuan University, Chengdu, China, June 17-21, 2013.

7. Cogeneration of Dark Matter and Baryons by Non-Standard Model Sphalerons in Grand Unified Models,
   MIAMI2013, Ft. Lauderdale, FL, Dec 11-17, 2013.

8. Cogeneration of Dark Matter and Baryons by Non-Standard Model Sphalerons in Grand Unified Models,
   PHENO2014 Workshop, Pittsburgh, PA, May 5-7, 2014.

9. Cogeneration of Dark Matter and Baryons by Non-Standard Model Sphalerons in Grand Unified Models,
   (Heng-Yu Chen) Tri-Institute Summer School on Elementary Particles 2014, SNOLAB, Sudbury, Canada, June 10 2014.

5 Thomas K. Gaisser & Todor Stanev (Co-PIs)

5.1 Research accomplishments, August 2011-August 2014

Our work supported by DOE includes the following topics:

- Atmospheric neutrinos at high energy;
- Cosmogenic neutrinos as a probe of origin and propagation of ultra-high energy cosmic rays;
- Hadronic interactions at high energy for interpretation of cosmic-ray cascades in the atmosphere; and
- Spectrum and composition of high-energy cosmic radiation.

For many years we have been co-authors of the article on cosmic rays in *Review of Particle Physics* (see item 17 in our list of publications for the most recent versions). We are co-authors of the event generator SIBYLL, which is widely used as an event generator for fast simulation of cosmic-ray air showers. In this period we have worked with Ralph Engel (Karlsruhe Institute of Technology) and his graduate students, Felix Riehn and Anatoli Fedynitch to upgrade the SIBYLL event generator in light of results from the LHC.

The upgrade of SIBYLL and the work on atmospheric neutrinos are closely related. In particular, the new version of SIBYLL provides an improved set of spectrum weighted moments that synthesizes the hadronic interaction data into a form appropriate for numerical calculations of atmospheric neutrino fluxes to very high energy. Preliminary results of the work were reported at the International Cossmic ray Conference in Rio de Janeiro. One paper (item 11) describes the result of incorporating LHC data into the new (not yet released) version of Sibyll 2.3 The other (item 10) shows the atmoepheric neutrino fluxes predicted by the new version of SIBYLL, which includes the production of charm mesons and baryons. The new version of SIBYLL is nearly complete and was presented at the recent ISVHECRI meeting at CERN (August, 2014). SIBYLL is currently the only model for cosmic-ray interactions in the atmosphere that provides a good description of the latest LHC data on production of charm.

It is known that the primary cosmic-ray spectrum steepens at the "knee", which is around 3 PeV total energy per particle. Important for the atmospheric lepton fluxes is instead the spectrum of nucleons per GeV/nucleon, including nucleons bound in helium and other nuclei, as well as free protons. We have studied the energy-dependence of the primary composition systematically in items 6 and 8. Implications for the fluxes of atmospheric muons and neutrinos were presented in items 2, 3, 12, 13, 20 and 21. Implications for the energy-dependence of the charge ratio of atmospheric muons are worked out in item 19.

Cosmogenic neutrinos are generated in interactions of ultra-high energy cosmic rays with the cosmic microwave background and other universal cosmic photon backgrounds. Classic calculations such as that of Engel, Seckel and Stanev (Phys. Rev. D64 (2001) 093010) need updating to account for new estimates of emissivity and spectrum at the sources and to consider the indications of a larger fraction of heavy nuclei at high energy. Items 1, 4, 7, 14 and 16 address these issues. A reassessment of cosmic photon backgrounds is addressed in item 5.

5.2 Publications and Talks Related to this Grant (Thomas Gaisser, Todor Stanev and collaborators, August 2011 – August 2014)

1. Cosmogenic neutrinos and gamma rays Todor Stanev, Comptes Rendus Physique 15, 349 (2014)
2. Atmospheric lepton fluxes, T. K. Gaisser, invited talk at ISVHECRI 2014 (CERN, August 2014).
3. Atmospheric neutrinos at High Energy, T. K. Gaisser, invited talk in the particle astrophysics session of ICHEP 2014 (Valencia, July 2014)
4. Cosmogenic Neutrinos T. Stanev. PoS Neutel2013:060 (2013)
5. Cosmic backgrounds due to the formation of the first generation of supermassive black holes, Peter L. Biermann, Biman B. Nath, Laureniu I. Caramete, Benjamin C. Harms, Todor Stanev, Julia Becker Tjus, MNRAS, 441.1147B (2014) e-Print: arXiv:1403.3804
6. High energy cosmic rays: sources and fluxes, Todor Stanev, Thomas K. Gaisser, and Serap Tilav Nucl.Instrum.Meth. A742, 42 (2014)
7. Ultrahigh energy cosmic ray fluxes and cosmogenic neutrinos Todor Stanev, Nucl.Phys.Proc.Suppl. 237-238, 233 (2013)
8. Cosmic Ray Energy Spectrum from Measurements of Air Showers Thomas K. Gaisser, Todor Stanev, Serap Tilav, 2013. 11 pp. Front.Phys.China 8, 748 (2013)
9. Simulating hadronic interactions with Sibyll, F. Riehn, R. Engel, T.K. Gaisser and T. Stanev, Talk at the 2013 APS, T8009R
10. Atmospheric neutrinos at high energy, E.-J. Ahn, R. Engel, A. Fedynitch, T. Gaisser, F. Riehn & T. Stanev, Proc. 33rd Int. Cosmic Ray Conf. 1144 (Rio de Janeiro, July, 2013)
11. LHC Update of the Hadronic Interaction Model SIBYLL 2.1, E.-J. Ahn, Ralph Engel, Thomas K. Gaisser, Paolo Lipari, Relix Riehn & Todor Stanev, Proc. 33rd Int. Cosmic Ray Conf. 0803 (Rio de Janeiro, July, 2013)
12. Very high energy photons and neutrinos: Implications for UHECR. T. K. Gaisser, EPJ Web Conf. **53**, 01012 (2013)
13. Atmospheric leptons. T. K. Gaisser, EPJ Web Conf. **52**, 09004 (2013)
14. Cosmogenic Neutrinos, T. Stanev, Proceedings of the XV Workshop on Neutrino Telescopes, 2013iwnt.workE..60S
15. Ultrahigh Energy Cosmic Rays: Review of the current situation, T. Stanev, AcPol,53: 692S (2013)

16. , Neutrinos and Cosmic Rays, T.K. Gaisser and T. Stanev, Astropart. Phys. 39, 120G (2012); arxiv:1202.0310

17. Review of Particle Physics (RPP) Particle Data Group Collaboration (J. Beringer (LBL, Berkeley) et al Phys.Rev. D86:010001 (2012) and (K.A. Olive et al.) Chinese Physics C38 (2014)

18. The Centaurus A Ultrahigh-Energy Cosmic Ray Excess and the Local Extragalactic Magnetic Field, Hasan Yuksel, Todor Stanev, Matthew D. Kistler, P. Kronberg, Astrophys.J. 758 (2012) 16 (2012)

19. Spectrum of cosmic-ray nucleons, kaon production, and the atmospheric muon charge ratio. T. K. Gaisser, Astropart. Phys. **35**, 801 (2012)

20. High Energy Neutrinos from Space. T. K. Gaisser, arXiv:1201.6651 [astro-ph.HE] (invited talk at Lepton-Photon 2011).

21. Catching the highest energy neutrinos, Todor Stanev, Nucl.Phys.Proc.Suppl. 217, 263 (2011)

22. Ultrahigh Energy Cosmic Rays, Antoine Letessier-Selvon, Todor Stanev, Rev.Mod.Phys. 83, 907, (2011), arXiv:1103.0031

23. Sibyll with charm, Eun-Joo Ahn, Ralph Engel, Thomas K. Gaisser, Paolo Lipari, Todor Stanev. Talk at ISVECRI 2011; arXiv:1102.5705