Final Report for
Studies in Elementary Particle Physics
for the period February 1, 2010 to April 30, 2013
Virginia Tech Tasks A, B, and N

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Overview of the Virginia Tech HEP Program and Group

This final report of DOE Grant DE-FG05-92ER40709 awarded to the Virginia Tech HEP group covers the period February 1, 2010 through April 30, 2013.

The HEP program at Virginia Tech supported by this grant is organized into three tasks: A for theory (Profs. Tatsu Takeuchi and Djordje Minic), B for heavy flavor physics with the Belle and Belle II experiments (Prof. Leo Piilonen), and N for neutrino physics (Profs. Jonathan Link and Piilonen).

There are several other HEP faculty members at Virginia Tech who were not supported by this grant through April 30, 2012 with whom we collaborated. Prof. Patrick Huber works in neutrino phenomenology and is supported by a separate ECRA grant from DOE. Prof. Eric Sharpe collaborates with Minic and Takeuchi and is supported by the NSF. Prof. Camillo Mariani joined Virginia Tech in August 2012 as our newest neutrino experimentalist. Prof. Bruce Vogelaar is another neutrino experimentalist supported by the NSF; he collaborated with the late Prof. Raju Raghavan, who passed away in October 2011.

All of us are members of the Center for Neutrino Physics at Virginia Tech, an organizational unit that permits us to share our overhead funds, administrative staff, and other resources. Jon Link is the CNP Director, succeeding Leo Piilonen in February 2012 who was appointed chair of the Department of Physics in April 2012 for a three-year term.

Task A: String Theory and Quantum Field Theory

PI: Djordje Minic

I will start the discussion with the well established foundation of high energy physics: the Standard Model. The Standard Model of Particle Physics is one of the most spectacularly successful theories in the history of physics. Nevertheless the Standard Model is shrouded in many fascinating mysteries. In this exciting LHC Higgs-like discovery era, my research centers on unraveling these mysteries either in the Standard Model proper (the analytic understanding of QCD), or in string theory, the leading candidate for the fundamental theoretical framework of Standard-Model-like physics that includes quantum gravity. I also work on the applications of quantum field theory (the theoretical language of the Standard Model) and string theory, in the domain of many-body particle physics, through the reformulations and extensions of the Renormalization Group paradigm (another crucial aspect of the Standard Model and many-body physics), as implied by the modern developments in string theory, such as the gravity/conformal field theory correspondence.

My research focuses on understanding the fundamental questions in quantum field theory and string theory, and the breadth of the topics covered in my research is a clear illustration of the usefulness and strength of the techniques and ideas pursued in modern string theory and quantum field theory. My research activity in string theory and quantum field theory attempts to be as original and as deep in the choice of research topics (I work on the fundamental problems in quantum gravity, string theory, quantum field theory (gauge theory, QCD), cosmology and astrophysics, and in particular the problems of dark energy and dark matter, as well as the fundamental descriptions of the accelerating universe (de Sitter space)). Also my research activity attempts to be as creative and as broad (yet interconnected) in the subject matter: I work on the extensions of the Renormalization Group paradigm through the applications of various techniques of string theory and modern quantum field theory in many body physics, such as: high temperature superconductivity, the Aharonov-Casher and spin duals of the quantum Hall effect, topological insulators, disorder, aging in materials, stochastic field theory, foundational aspects of non-equilibrium physics (the Jarzynski identity), turbulence, the physics of the Riemann zeros as well as the foundational questions in quantum theory.

In order to cover all these multiply connected research interests, I collaborate with many physicists (I have around 50 collaborators, as it can be glanced from my publications) both from all major groups of the VT department (where I collaborate with more than a third of faculty members in the department) and with many leading researchers of our generation at various institutions around the world. In the past I have contributed to the old matrix model of string theory, the covariant formulation of Matrix theory via the quantum Nambu bracket, the group theoretic underpinnings of the AdS/CFT correspondence, non-commutative field theory, "two-time" physics, the canonical and holographic renormalizaton, the establishment of dS/CFT (independently of the seminal papers of Maldacena, Strominger and Witten), the phenomenology of the minimal length, the foundations of background independent quantum gravity, the analytic and non-perturbative QCD, the cosmological constant (or vacuum energy) problem, the invention of the Mondian dark matter, as well as to many creative contributions in different areas of the application of modern quantum field theory to many body physics.

In what follows I will explain my research efforts, and also present plans for future research. I will start from the Standard Model Physics (QCD) and then discuss my work beyond the Standard Model (sting theory, cosmology and particle physics). Due to limited space I will only refer to my own work. The 106 publications I have authored and co-authored (with around 2700 citations) can be all found on the ArXiv and INSPIRE-HEP. (Since 2008, after I have branched into many applications of string theory, my publications rate has increased rather dramatically. For example, my research activity in the last 3 years (2009-2012) has been concentrated on many of the research efforts mentioned above in 23 publications [1–23]. In the same period I have given more than 20 invited presentations on these topics.) In view of the purely theoretical nature of my work, perhaps the most surprising off-shoots of my fascination with analytic QCD and the foundations of string theory, quantum gravity, cosmology and particle physics, have happened in the areas of condensed matter and statistical physics, wherein I have made many creative contributions (see [1, 7, 9, 13, 15, 16, 18, 19, 21, 23]). This whole effort is aimed at extending the canonical QFT Wilsonian paradigm (which lies at the heart of modern effective field theory) to the realm of strongly coupled relativistic and non-relativistic many body physics and is inspired by the "Renormalization Group (RG) = General Relativity (GR)" dictionary, discovered in the domain of modern string theory. Personally, I do not distinguish between my work on the very small and very large from my interest in the very complex. Given the remarkable historical synergy between quantum field theory, condensed matter physics and statistical physics, it is perhaps not surprising that string theory should have much to say about many-body physics. Similarly, many missing ideas in string theory might come from the domain of many-body physics. That is why I consider this research as important as my research on the Standard Model physics and beyond.

In the forthcoming years I propose to continue my work on the fundamental problems in quantum field theory and string theory, especially our efforts in understanding dark energy and dark matter, the fundamental questions in string theory, quantum gravity, cosmology and particle physics and the applications of string theory techniques to analytic QCD and relativistic and non-relativistic many body physics. My research at VT has been continuously supported by the Department of Energy (DOE) since 2003. (I arrived at VT in 2001 and I had 2 summers worth of support as part of my start-up.) I continue to be supported by the DOE. The most recent competitive DOE review, under new guidelines, was successfully completed in February of 2013.

1.1 SM Physics: Analytic, Non-perturbative QCD

The analytic understanding of QCD and the elusive QCD string have been my fascinations since the graduate student days. Since 2005 I have been involved in developing a new approach to the planar limit of 2+1 and 3+1 dimensional Yang-Mills (YM) theory [24]. This whole undertaking has been motivated by a project done in collaboration with Rob Leigh [24], concerning the planar limit of the 2+1 dimensional YM theory. In the period of 2005-2008 we have discovered a new description of the vacuum of this theory, very much following the program outlined years ago by Feynman. In some sense our results answer the questions Feynman raised in 1981! Given our vacuum wave functional, the spectrum of glueballs (in the limit of the large number of colors N) can be understood and realistically compared to lattice gauge theory simulations. The comparison to the existing lattice simulations (mainly the work of Teper and collaborators) turns out to be excellent!

Together with Freidel (Perimeter) and Leigh (Urbana) [24] we have also extended our results to $3+1$ dimensions as well as provided a new understanding of the beautiful work of Karabali, Kim and Nair as well as the older work by Yang, Bars and Feynman. One can work either in the real or complex (semi-complex in the case of $3+1$) basis and thus recover all the known formal results. The important insight is that our wave functional uncovered with Leigh and Yelnikov [24] can be understood without the use of any special, local gauge invariant variables. Still a non-perturbative aspect, such as the use of the strong coupling limit of lattice gauge theory, is crucial in order to get to the desired form of the wave functional. The whole approach is general and transparent and dimension independent. That is not to say that the crucial difference between $2+1$ and $3+1$ dimensional gauge theories does not show up in the vacuum wave functional. On the contrary, the issue of a dynamical emergence of the gap is absolutely crucial in the context of the real world YM theory. Nevertheless, the formalism developed with Freidel and Leigh [24] can be used to address the question of a dynamical mass generation as well as the actual prediction of the glueball masses (in the units of the square root of the string tension) in 3+1 dimensions (published with Freidel, Leigh and Yelnikov [24]).

At the moment, we are still trying to understand what our approach means from the point of view of the large N expansion as well as from the point of view of string theory (given the phenomenally successful AdS/CFT duality). There is a claim in the literature that our $2+1$ results are exact in the large N limit, but we think that this issue has not been fully understood. The problem is even harder in the real $3+1$ dimensional case. We have new ideas how to approach this problem and perhaps also establish a connection with an effective string theory (along the lines of the AdS/QCD duality), which has been missing so far. Recently we have initated a new approach to understanding the general T-duality in string theory both in the compact and the non-compact cases. The latter is also known as the Amplitude/Wilson loop connection and is directly relevant for understanding the QCD sector of the Standard Model. One of the aims of our present research is to shed new light on some fundamental questions in string theory. Another goal is to illuminate our results concerning the spectrum of glueballs in pure QCD, hopefully thus shedding new light on the elusive QCD string. This project is in collaboration with Freidel and Leigh. We are very excited about this new view on string theory and we are preparing our first publications on this topic. We expect that this work will also have fundamental implications to our research interests in string theory, cosmology and particle physics as well as applications of string theory to many-body physics.

1.2 Beyond the SM: String Theory, Cosmology, Particle Physics

My interest in QCD and especially the analytic large N techniques has led me very naturally to think deeply about string theory. String theory is still considered as one of the most promising theoretical and methodological avenues for addressing the questions concerning the physics beyond the Standard Models of particle physics and cosmology. Yet, little is known about the true non-perturbative formulation of string theory, such as M theory. The only known direct avatar of M theory is Matrix theory, the light-cone version of M theory. Matrix theory is currently formulated in a non-covariant, background dependent way. The problem of a covariant formulation of Matrix theory as well as the issue of its background independent formulation appear crucial for understanding the fundamental physical principles of M-theory. I have performed a pioneering study of this subject in 1999 with Awata (Nagoya), Li (Beijing) and Yoneya (Tokyo). (Also, we have used this approach in our continuing work with Leigh and Petkou (Crete/Thessaloniki [20]) on the new formulation of the theory of membranes as well as my more recent work with Murat Gunaydin (Penn State) on nonassociativity in string theory.) Motivated by a study of the geometry of ordinary quantum theory we have argued, in collaboration with Tze (VT), that a background independent formulation of Matrix theory (which should shed light on holography and AdS/CFT as well) requires a natural enlargement of the geometric formulation of ordinary quantum theory. An invited review of this topic was published together with Jejjala and Kavic [25]. I am still very excited by this very original program and thus we have been vigorously pursuing its various technical and conceptual ramifications. I understand that the program does sound extremely ambitious to our skeptical colleagues and thus I have been working hard on various applications of our ideas to some of the most outstanding issues in fundamental physics.

In particular, I think that there is a generic prediction of this theory with regards to the cosmological constant problem: according to our proposal the mean value of the cosmological constant is zero and the observed value is actually just the fluctuation around this mean (fixed by the "quantum diffeormorphism" symmetries of the theory). The cosmological constant is thus a pure quantum gravitational effect. The fluctuation of the cosmological constant turns out to be consistent with the size of the observable spacetime. In our approach the scale of supersymmetry breaking is related to the fundamental short distance scale as well to the Hubble scale. The preliminary results of this research have been published with Jejjala and with Kavic and Jejjala [25]. I have worked on the detailed implications of our approach to the vacuum energy problem with Chang and Takeuchi [17]. This new approach to the vacuum energy problem feeds directly into the novel approach to string theory we are advocating with Freidel and Leigh (mentioned in the previous section). This is also a continuation of the work presented in a paper written with Kavic, Jejjala and Tze [22, 26] in which the new viewpoint on the apparently very low entropy of the initial state of the universe has been addressed.

One of the most intriguing aspects of this research is the connection with a totally different field of physics: the non-equilibrium description of jammed states. (This is one of the examples of the cross-fertilizaton between fundamentals of string theory and the ideas from many-body physics!) Thus, the initial cosmological state is in our description a jammed state. The low entropy of the state is related to the "freezing by heating" transition found in (quantum!) jamming. The exponential relaxation of the initial quantum jammed state could be very well related to an inflating phase, and the long-time power law behavior of the relaxed jammed states to the FRW cosmological phase. Our work with Chang and Takeuchi [8, 17] relates this general physics of "freezing by adding energy" to the cosmological constant problem via a novel see-saw mechanism. We have also recently reviewed this proposal in our review article on the arrow of time with Jejjala, Kavic and Tze [5].

Let me also mention that I am very seriously thinking about the particle physics and astrophysics ramifications of this approach. In the realm of astrophysics I am continuing our collaboration with the VT astrophysics colleague John Simonetti that was very successfully initiated by our former student Mike Kavic [27]. In particular, new quantum gravity effects were examined in the black hole-neutron star systems in a publication with Mike Kavic and John Simonetti and John's two undergraduate students [12].

In this exciting LHC era, it behooves us to think hard about the role of the Standard Model in string theory. One project we are pursuing (called "the emergent Standard Model") has to do with the intuition that the Standard Model and its Pati-Salam generalization (which is surprisingly found in many free-fermion model realizations of stringy vacua) might point to a more fundamental role of the Standard Model than previously imagined. The aim of this project is to relate to some still not completely understood features of Connes' approach to the classical Standard Model, and the previous work (by Ne'eman et al and Fairlie) on the minimal embedding of the Weinberg-Salam gauge group in the framework of the $SU(2|1)$ superalgebra. This description does not have a direct UV completion for obvious reasons, and thus a string theoretic realization could be naturally expected to provide such short-distance definition. We have contemplated a natural embedding for this description in our approach towards non-perturbative string theory for a long time, and finally we are getting to something very specific that involves new physics at observable scales (4TeV)! The first paper on this topic was published with our postdoc Ufuk Aydemir and Tatsu Takeuchi [28]. We are currently writing a longer paper on the collider implications of this new view of the Standard Model.

I am continuing my work on the fundamental problems of quantum gravity, dark energy and dark matter as well as on the foundations of quantum gravity and its experimental manifestations. With Chang, Lewis, Takeuchi and Tze (all from VT) [11] (also [3,4]) I have examined the fundamental and previously unnoticed role of quantum supercorrelations in string theory. This work is important for the foundations of quantum theory (the super-violation of the famous Bell inequalities) as well for the central questions in quantum gravity. With Chang, Lewis and Takeuchi, I have recently reviewed [8] our pioneering work on the minimal length uncertainty relation and the dynamical momentum space in quantum gravity (argued to be crucial for the solution of the vacuum energy problem [17]). Also, together with our late VT colleague Raju Raghavan (and Takeuchi and Tze) we have studied the uses of neutrinos in relation to some foundational questions in quantum theory and in quantum gravity.

Last but note least, with Ho (Vanderbilt) and Ng (UNC) we have discovered a (holographically) dual description of Milgrom's scaling [6,10,14] associated with galactic rotation curves. Our argument was based on the recent entropic reinterpretation of Newton's laws of motion (sparked by a question from our VT particle physics colleague Leo Piilonen). We have proposed a duality between cold dark matter and modified Newtonian dynamics (MOND). We have introduced the concept of MONDian dark matter, and discussed some of its phenomenological implications. At cluster as well as cosmological scales, the MONDian dark matter would behave as cold dark matter, but at the galactic scale, the MONDian dark matter would act as MOND. We are continuing this program by concentrating on the microscopic model of this new dark matter. We are very excited about this new and quite original proposal in view of the recent experimental results, which point to more elusive forms of dark matter than previously imagined. Currently we are preparing a paper that addresses the concrete observational implications of MONDian dark matter in the context of the galactic rotation curves. This project also involves our VT astronomy colleague Duncan Farrah and Doug Edmonds, a student of another VT astronomy colleague Nahum Arav.

1.3 Applications of String Theory and QFT in Many-Body Physics

One of the most surprising off-shoots of our intense work in analytic QCD and in foundations of string theory and quantum gravity and cosmology has been in the areas of condensed matter and statistical physics wherein we have made many creative contributions. This whole effort is aimed at extending the canonical QFT Wilsonian paradigm to the realm of strongly coupled relativistic and non-relativistic many body physics and is inspired by the "Renormalization Group (RG) = General Relativity (GR)" dictionary.

First I have argued with my colleague Jean Heremans, who is a condensed matter experimentalist, that an approach involving emergent effective gravity in many body systems could play a crucial role in elucidating the properties of the high temperature superconducting materials [7]. In particular we have proposed that the high critical temperature is naturally explained in a framework constructed as a direct condensed matter analog of the Randall-Sundrum approach to a geometrization of the hierarchy problem in high-energy physics. I have continued this work with Jean Heremans and in particular we have recently discussed the gravitationally dressed Fermi liquids and the resulting quasi-unparticles in this context.

Apart from this new theory of high temperature superconductivity, together with Heremans we have introduced the spin dual of the quantum Hall effect. The crucial role in this new state of matter is played by the (Ananadan)-Aharonov-Casher phase and the spin-spin correlations. In this context, the new quantized transport quantities have been recently identified in collaboration with Jean Heremans and two of his students [29].

Our work on the spin dual of the fractional quantum Hall effect has led us to contemplate some natural field theoretic (and string theoretic) generalizations of another exciting new state of matter - topological insulators. In collaboration with out VT condensed matter colleagues, Jean Heremans and Kyungwha Park and Vito Scarola we have worked out the properties of surface states in topological insulators [15]. Currently we are looking at the chiral magnetic effect in this context.

Motivated by the general structure of AdS/CFT correspondence we have also examined the interplay between recent advances in quantum gravity and the problem of turbulence. What is most important, together with Pleimling, Staples (an expert in fluid mechanics from the Engineering Science and Mechanics department at VT) we have also proposed and tested (together with Omer San, a Ph.D. student of Staples) our new steady state distributions for fully developed turbulence [30].

With our VT colleague Michel Pleimling, who is an expert in theoretical statistical physics, we have stressed that the recent discussion of AdS/CMT correspondence has direct applications in aging phenomena [31]. We have also extended this collaboration to a fascinating relation between the AdS/CFT correspondence and the Jarzynski identity from non-equilibrium statistical physics. The concept of the aging group and its holographic dual has been investigated in collaboration with Leigh (Urbana) and Juan Jottar (Amsterdam) and Pando Zayas (Michigan). I have continued this work in our recent paper with Vaman (UVA) and Wu (Chicago). Also we have extended this program to disorder at strong coupling and to holographic duals of stochastic field theory with Leigh and Vaman. Furthermore, the covariant (holographic) renormalization group is being studied with Pando Zayas, Vaman and Leigh, in the context of the 4 d high spin theories and the 3 d critical $O(N)$ vector models.

Finally, let me mention two papers and an ongoing AdS/CFT related project on the physics of the Riemann zeros [32], conducted in collaboration with Yang-Hui He (Oxford/London) and Jejjala (an off-spring of our interest in analytic QCD and many-body physics), and a paper in preparation on the subject of emergent "quantum" theory in the context of biophysical systems, with Vijay Balasubramanian (Penn) and Sinisa Pajevic (NIH).

Task A: Phenomenology, Beyond the SM, Foundations of Quantum Mechanics & Quantum Gravity

PI: Tatsu Takeuchi

During the 2010–2013 three-year funding cycle, the phenomenology group of Task A consisted of Tatsu Takeuchi, and graduate students Yee Kao (Ph.D. Fall 2010), Zachary Lewis (Ph.D. Spring 2013), and Chen Sun (starting Fall 2012). Postdoc Ufuk Aydemir (Fall 2012–Spring 2013) worked with both the phenomenology group of Takeuchi and the string theory group of Minic. In this timeframe, we have completed 14 research papers of which 8 have been published in refereed journals [33–40], 3 are currently undergoing review [41–43], and 3 have appeared in conference proceedings [44–46]. In addition, 6 more papers are in the final stages of completion in which DOE support will be acknowledged [47–52]. Takeuchi has presented 37 talks on various topics at conferences (9), and invited seminars and colloquia (28). Graduate students Kao, Lewis, and Sun have presented their research at the annual Pheno workshop, first in Madison, and then in Pittsburgh. Our postdoc Aydemir has presented at Pheno, and has given several invited seminars.

The research of our group can be roughly classified into four categories:

(1) phenomenology at the Intensity Frontier [39, 42, 46, 49–51],

(2) phenomenology at the Cosmic Frontier [44, 47],

(3) study of models of new physics beyond the SM [40, 52], and

(4) foundations of Quantum Mechanics and Quantum Gravity [33–38, 41, 43, 45, 48].

Research in categories (2)∼(4) was conducted in close collaboration with Minic's group.

2.1 Phenomenology at the Intensity Frontier

Given the lack of new particle discoveries at the LHC, other than that of the long-anticipated Higgs-like boson, the role of Intensity Frontier experiments in uncovering new physics beyond the SM has gained added importance. The high statistics of the Intensity Frontier experiments, such as the Belle 2 project of Task B and the neutrino experiments of Task N, will allow us to determine various observables to high precision and thereby infer the presence of new physics via deviations from the SM, or detect rare processes forbidden by the SM. The role of the phenomenologist in this endeavor is to ensure that the data is squeezed for every last bit of information.

2.1.1 Constraining Non-Standard Interactions of the Neutrino with Electrons

Non-standard interactions (NSI's) of the neutrino with the electron, putatively due to new physics beyond the SM, are expressed in the literature as

$$\mathcal{L}_{\rm NSI} \;=\; -\in\sqrt{\in}\,\mathcal{G_F}\sum_{\alpha=\rceil,\mu,\tau}\Big[\,\epsilon_{\alpha\mathcal{L}}\left(\bar{\nu}_\alpha\gamma_\mu\mathcal{P_L}\nu_\alpha\right)\left(\bar{\rceil}\,\gamma^\mu\mathcal{P_L}\rceil\right)+\epsilon_{\alpha\mathcal{R}}\left(\bar{\nu}_\alpha\gamma_\mu\mathcal{P_L}\nu_\alpha\right)\left(\bar{\rceil}\,\gamma^\mu\mathcal{P_R}\rceil\right)\Big]\,,$$

where $\epsilon_{\alpha L}$ and $\epsilon_{\alpha R}$ are dimensionless parameters to be fixed by experiment. In Ref. [39], we constrain these parameters using the data from Borexino, carefully taking into account various backgrounds due to radioactive elements in the detector. There, we point out that the reduction of the ^{85}Kr background is crucial if Borexino is to improve significantly upon existing bounds.

In Ref. [49], we analyze the potential of the proposed OscSNS experiment at Oak Ridge in constraining these parameters. The main objective of the OscSNS experiment is to use the SNS as the neutrino source to look for sterile neutrinos. By looking at the energy spectrum of the recoil electrons from νe scattering events, the same data can be used to constrain the above NSI's as well. Our preliminary results suggest that the uncertainty in the neutrino flux is the limiting factor in providing meaningful constraints. We are currently analyzing the possibility of using the interaction of the neutrino with the carbon in the detector to normalize this flux.

2.1.2 Analytical Understanding of Matter Effects on Neutrino Oscillation

In a previous funding cycle, we explored the possibility of using long-baseline (LBL) neutrino oscillation experiments to constrain new physics [54]. There, we argued that an accurate measurement of the ν_μ survival probability at a baseline of $\sim 10000\,\mathrm{km}$ could potentially constrain a certain class of new physics. In the process, we discovered a compact analytical approximation to neutrino oscillation probabilities in matter, which allowed us to calculate said probabilities to very good accuracy provided that the value of θ_{13} was of the order of $\delta m^2_{12}/|\delta m^2_{31}|$. This approximation allowed for a simple analytic derivation of the 'magic' baseline, and the conditions required to determine the mass hierarchy, as well as analytically predict the effects of new physics on the oscillation probabilities. At the time, the possibility that θ_{13} was much smaller than $\delta m^2_{12}/|\delta m^2_{31}|$ could not be ignored, and the utility of our result was limited. Corrections to our formula for small θ_{13} was worked out by Kao, but they destroyed the simplicity of the original expressions. However, with the recent measurement of a largish value of θ_{13} at Daya Bay (by Task N) and elsewhere, it turned out that our original approximation could be used as is. In Ref. [42] we present a refined version of our approximation with better accuracy, and several straightforward applications.

2.1.3 Exploring Time-Energy Uncertainty Relation with Mössbauer Neutrinos

Minic and Takeuchi had been in discussions with neutrino experimentalist Raju Raghavan (VT, deceased Oct. 2011) on the potential of using Mössbauer neutrinos to check the time-energy uncertainty relation to unprecedented accuracy. Unlike the position-momentum uncertainty relation which is derived from a commutation relation, the time-energy uncertainty relation is due to the Schrödinger equation itself and checking it would be equivalent to checking the most fundamental equation of quantum mechanics. Any deviation from the standard $\Delta t\,\Delta E \sim \hbar/2$ behavior would have profound implications for quantum mechanics and quantum gravity. A report of our investigations has been presented in Ref. [46].

2.1.4 Using Neutrinoless Double Beta Decay to Constrain R-Parity Violation

Of the various R-parity violating couplings given by

$$W_{\not R} = \frac{1}{2}\lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}_k + \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}_k + \frac{1}{2}\lambda''_{ijk}\hat{U}_i\hat{D}_j\hat{D}_k \;,$$

the coupling λ'_{111} is the best constrained by experiment with an upper bound of $O(10^{-4})$. This constraint comes from the neutrinoless double beta decay to which λ'_{111} can contribute via various processes. However, we have discovered that the formula used in the literature to calculated this bound is incorrect due to an improper accounting of color charge flow. We are working on a new bound with the corrected formula and new data from GERDA, which will be reported in Ref. [51].

2.1.5 Semi-leptonic D meson decay

The experimental values of the D-meson semi-leptonic decay branching fractions, namely:

$$R_{D^0} = \frac{\mathcal{B}(\mathcal{D}' \to \mu^+\nu_\mu\mathcal{K}^-)}{\mathcal{B}(\mathcal{D}' \to \rceil^+\nu_\rceil\mathcal{K}^-)}\ , \quad R_{D^+} = \frac{\mathcal{B}(\mathcal{D}^+ \to \mu^+\nu_\mu\overline{\mathcal{K}'})}{\mathcal{B}(\mathcal{D}^+ \to \rceil^+\nu_\rceil\overline{\mathcal{K}'})}\ , \quad R^*_{D^+} = \frac{\mathcal{B}(\mathcal{D}^+ \to \mu^+\nu_\mu\overline{\mathcal{K}^*}(\forall\exists\in)')}{\mathcal{B}(\mathcal{D}^+ \to \rceil^+\nu_\rceil\overline{\mathcal{K}^*}(\forall\exists\in)')}\ ,$$

have frequently been used in the literature to constrain new physics, *e.g.* the R-parity violating couplings λ'_{12k} and λ'_{22k} ($k = 1, 2, 3$). However, the values commonly used as their SM predictions were problematic: R_{D^0} and R_{D^+} were based on simple tree level calculations treating the mesons as point particles, while $R^*_{D^+}$ was assumed to be equal to the other two despite the fact that the mass and spin of the daughter meson were different. In the appendix of Ref. [53] (from the previous funding cycle) we correct these problems by calculating these ratios using the form-factor measurements by the FOCUS experiment (performed by Link of Task N) as input, giving the first experimental-data-based QCD predictions of these ratios. Since then, new measurements of the necessary form-factors have become available from CLEO, as well as lattice QCD calculations which are now highly accurate. We are updating our calculation which will be presented in Ref. [50].

2.2 Phenomenology at the Cosmic Frontier

2.2.1 Ratchet Model of Baryogenesis

Together with Azusa Minamizaki and Akio Sugamoto (Ochanomizu, Japan) we have proposed a new model of baryogenesis in Ref. [44]. The main idea was to separate the sector which breaks away from thermal equilibrium with that which violates the C, CP, and B symmetries. In our scenario, heavy but weakly interacting particles break away from thermal equilibrium providing a bath of these particles for other particles. Such particles exist in many extra-dimension models where Kaluza-Klein excitations can be rendered meta-stable and be given the role of a dark matter candidate. The C, CP, and B violating sector is a scalar field which is assumed to interact coherently with the heavy particle background, which provides the energy to drive B number generation. Thus, in this model, it is the dark matter particles which is responsible for driving baryogenesis. The details of the model are still in the process of being worked out.

2.2.2 Testing MONDian Dark Matter

This project is in collaboration with Minic, Chiu Man Ho (Vanderbilt), Yee Jack Ng (UNC Chapel Hill), Doug Edmonds and Duncan Farrah (VT, astrophysics group). The idea is to confront the dark matter model proposed by Ho, Minic, and Ng dubbed 'MONDian Dark Matter' [56] with astrophysical data to see whether it is viable.

MOND (MOdified Newtonian Dynamics) explains the flat galactic rotation curves by assuming the existence of a critical acceleration a_c such that $F = ma$ when $a \gg a_c$, but $F = ma^2/a_c$ when $a \ll a_c$. In the MONDian dark matter proposal of Ho, Minic, and Ng, instead of modifying $F = ma$, a particular dark matter distribution is introduced which reproduces MOND exactly at galactic scales [56]. Independently of the question whether such a distribution can be achieved dynamically, one can confront the model by comparing its mass distribution prediction with actual observation. Fits have been performed to the rotation curves of galaxies with known stellar and gas distributions. We report this in Ref. [47].

2.3 Models of New Physics Beyond the Standard Model

2.3.1 Constraints on the Superconnection Formalism

The discovery of the ∼125 GeV Higgs places a strong constraint all possible models of new physics beyond the SM. With Minic and Aydemir, Takeuchi has been studying the implications of the Higgs discovery on the model in which the electroweak sector of the SM is formulated in terms of an $SU(2/1)$ superconnection, proposed by Ne'eman, Sternberg and Fairlie [57]. It fixes the ratio of the $SU(2)_L \times U(1)_Y$ gauge couplings, as well as the quartic coupling of the Higgs. Interpreting the formalism as emergent at some new physics scale where the gauge coupling relation can be imposed, one obtains a prediction for the Higgs mass by RG running from that scale. In Ref. [40], we point out that the natural scale of the model is 4 TeV and the corresponding Higgs mass is 170 GeV. In order to fix this apparent discrepancy, we argue that new scalar degrees of freedom must be introduced into the model, which implies the extension of $SU(2/1)$ to $SU(2/2)$, which would correspond to the emergence of an $SU(2)_L \times SU(2)_R$ left-right symmetric model. The details of our observations will be presented in Ref. [52]. We are also working on a review explaining how the superconnection formalism is connected to the non-commutative geometries of Connes [58].

2.4 Foundations of Quantum Mechanics and Quantum Gravity

2.4.1 Phenomenology of the Minimal Length Uncertainty Relation

Since gravity is a theory which possesses a fundamental length scale, namely the Planck length $\ell_P = \sqrt{\hbar G_N/c^3}$, this length scale can be expected to play an essential role when gravity is quantized. Indeed, fairly generic arguments suggest that the uncertainty relation between position and momentum must be modified to

$$\Delta x \;\geq\; \frac{\hbar}{2}\left(\frac{1}{\Delta p} + \beta\Delta p\right) \quad\rightarrow\quad \Delta x \;\geq\; \hbar\sqrt{\beta} \;=\; \ell_P \;,$$

in the presence of quantum gravitational effects. This minimal length uncertainty relation (MLUR) is also suggested by perturbative string theory. Canonical QM, however, is completely oblivious of such a scale, and the uncertainty relation there is of course of the Heisenberg type with $\beta = 0$. One way to inform QM of the presence of $\ell_P = \hbar\sqrt{\beta}$ is to deform the commutation relation between the position and momentum operators to $[\,\hat{x},\,\hat{p}\,] = i\hbar(1 + \beta\hat{p}^2)$ which leads directly to the MLUR following standard arguments. In a series of papers listed in Ref. [55], we have worked out various phenomenological consequences of this deformation, including whether it was experimentally feasible to detect the deformation in some manner. See also Refs. [33, 35].

More recently [36], Takeuchi and Lewis have discovered that when $\hat{x}$ and $\hat{p}$ obey the above commutation relation, the harmonic oscillator Hamiltonian

$$\hat{H} \;=\; \frac{\hat{p}^2}{2m} + \frac{k}{2}\,\hat{x}^2\;,$$

can have discrete positive eigenvalue eigenstates even when $m < 0$. Furthermore, we find that $\Delta x \sim 1/\Delta p$ when $m > 0$ while $\Delta x \sim \Delta p$ when $m < 0$, with Δx reaching its minimum in the limit $1/m \to 0$. To see if these properties are generic, we have recently worked out the energy eigenvalues and eigenstates of the Hamiltonian

$$\hat{H} \;=\; \frac{\hat{p}^2}{2m} + F|\hat{x}|\;,\qquad |\hat{x}| \;\equiv\; \sqrt{\hat{x}^2}\;.$$

Here, too, we discover discrete energy eigenstates for both positive and negative mass. Thus the existence of the negative mass bounds states may be a generic feature of the MLUR. However, in contrast to the harmonic oscillator case, while $\Delta x \sim 1/\Delta p$ for the positive mass states, both Δx and Δp diverge for the negative mass states. Thus the $\Delta x \sim \Delta p$ behavior, which one would naively think characterizes the MLUR, is not realized. This result will be presented in Ref. [48].

2.4.2 Construction of Mutant Quantum Mechanics

One of the features which characterizes QM are correlations which violate Bell's inequality. In the formulation of Clauser, Horne, Shimony, and Holt (CHSH), Bell's inequality is expressed as

$$\bigl|\langle AB\rangle + \langle Ab\rangle + \langle aB\rangle - \langle ab\rangle\bigr| \;\le\; 2\;, \tag{2.1}$$

where A and a are observables of particle 1, while B and b are observables of particle 2. All four observables are assumed to take on the values ± 1 upon measurement. Since each of the four correlators that appear in the above expression take on values in the range $[-1, 1]$, the absolute maximum value of the left-hand-side is 4. For classical hidden variable theories, the left-hand-side cannot exceed 2. Quantum correlations, on the other hand, are bounded by $2\sqrt{2}$. The question we asked was why QM correlations were bounded in this way, and whether super-quantum theories whose correlations saturate the absolute maximum bound of 4 existed. In Refs. [34, 43], we argued that 'doubly' quantizing a theory may saturate the 4 bound and conjectured that Witten's open string field theory may be precisely such a theory.

We then searched for toy models for which the CHSH bound was different from the quantum value of $2\sqrt{2}$. Existence of such models, and how they are different from canonical QM would shed light on the properties of canonical QM itself. To find these models we adopted what we call the 'geneticist's approach' to QM. The idea was to introduce 'mutations' into the mathematical structure of QM and look at how the resulting theory had changed. In Refs. [37, 38, 41, 45] we introduce a 'mutation' by replacing the complex number field $\mathbb{C}$ over which the vector space of states is defined by the finite Galois field $GF(p^n)$, where p is a prime number and $n \in \mathbb{N}$. The simplest of these fields is $GF(2) = \mathbb{Z}/2\mathbb{Z} = \{\underline{0}, \underline{1}\}$. While the vector space resulting from this replacement is finite and discrete, this 'mutation' is not so innocuous since this vector space lacks an inner product. The inner product in the canonical formulation of QM is indispensable if one wishes to define norms of vectors, dual vectors as hermitian conjugates of vectors, and observables as hermitian operators. All these concepts must be redefined on the vector space over $GF(p^n)$.

Refs. [37, 38] and Ref. [41] take different approaches to this problem. In Refs. [37, 38] we define a quantum-like theory by retaining the following expression for probabilities from canonical QM:

$$P(\alpha|\psi) \;=\; \frac{|\langle\alpha|\psi\rangle|^2}{\sum_\beta |\langle\beta|\psi\rangle|^2}\;. \tag{2.2}$$

For this expression to make sense, the dual-vectors $\langle\alpha|$ need not be paired with any vector via the inner product. Rather, all one needs is for each of the dual vectors to be associated with a particular outcome of a measurement, and for the set of dual-vectors in the sum to span the dual-vector space. The result of a dual-vector $\langle\alpha|$ acting on a vector $|\psi\rangle$, namely the bracket $\langle\alpha|\psi\rangle$, is an element of $GF(p^n)$ and is converted into a real number as follows: $|\underline{k}| = 0 \; if \; \underline{k} = \underline{0}$ and $|\underline{k}| = 1$ otherwise. Using this construction, spin-like observables can be defined on a two-dimensional vector space over $GF(p^n)$. The resulting model has the interesting property that while its CHSH bound is the 2, its probabilities cannot be reproduced by any classical hidden variable theory.

In Ref. [41], a different approach is adopted in which we retain the canonical expression for expectation values, namely $\langle\psi|\hat{A}|\psi\rangle$. Vectors and dual-vectors are paired via biorthogonal systems, namely, a set of bases for the vector and dual-vector spaces which satisfy the relation $\langle\alpha|\beta\rangle = \underline{\delta}_{\alpha\beta}$. Observables are defined via $\hat{A} = \sum_\alpha \underline{\alpha}|\alpha\rangle\langle\alpha|$. The expression $\langle\psi|\hat{A}|\psi\rangle$, which is an element of $GF(p)$, is mapped to an element of $\mathbb{R}$ via a product preserving map so that it can be interpreted as an expectation value of a physical observable. In the absence of an inner product, this approach leads to a different model from what was constructed in Refs. [37, 38]. Indeed, in the model constructed over $GF(9)$, we show that its CHSH bound is the maximal 4. To our knowledge, this is the first time that such a simple model with super-quantum correlations has been constructed.

The discovery of these models is much more than just of academic interest. The lack of an inner product divorces the vector and dual-vector spaces, allowing for separate physical interpretations of the two: the vector space is the space of possible states of the system, while the dual-vector space is the space of possible outcomes of a measurement. The constructions used in Refs. [37,38,41,45] can be applied as is to any vector space without an inner product, e.g. Banach spaces. Construction of quantum-like theories on Banach spaces would be quite interesting since the Hilbert space of canonical QM is just a special case in which the space is isomorphic to its dual. Thus, such theories could allow for a continuous deformation away from canonical QM to either a sub-quantum (classical?) or super-quantum theory. This question is currently under intense investigation.

2.5 Summary

We believe that we have made some very basic contributions to phenomenology at the intensity frontier, as well as a few speculative ones to phenomenology at the cosmic frontier. Our work on the superconnection formulation of the SM suggests the possibility of constructing an entirely new class of models of new physics beyond the standard model, perhaps with connection to the non-commutative geometries of Connes. We have made some very interesting discoveries pertaining to the minimal length uncertainty relation, and in the search for mutant quantum mechanical models.

Task B: Heavy Flavor Physics

PI: Leo Piilonen

Our research program is directed entirely to the study of heavy quarks and leptons at the Belle and Belle II experiments at the High Energy Accelerator Research Organization (KEK) in Japan.

When it ended data-taking operations in June 2010, Belle had recorded about $1\,\mathrm{ab}^{-1}$ of data. We have continued to exploit this data set to publish new papers on CP asymmetries in B- and D-meson decays, searches for new states of charmonium-like and bottomonium-like matter, studies of the properties of τ leptons, and insights into QCD via two-photon and fragmentation physics.

The Belle II and SuperKEKB project were approved by the Japanese government in 2010. The aim of Belle II is to accumulate about $50\,\mathrm{ab}^{-1}$ of data over its lifetime, with SuperKEKB accelerator commissioning starting in 2015 and physics data-taking in 2016. This enormous data set will permit us to study in greater detail the hints of physics beyond the Standard Model that appeared in Belle in several channels but always at the statistically-limited $\sim 2\sigma$ level. In Belle II, we focused on the upgrade of the barrel KLM.

The personnel associated with these activities are Piilonen (PI), research associates Yousuke Yusa, Debabrata Mohapatra (part-time) and Xiao Long Wang, and graduate students Kimberly Williams, Yao Li, and Curtis Ogle (spring 2013 only).

In April 2012, Piilonen was elected co-spokesperson of Belle for a renewable two-year term (together with Yoshihide Sakai of KEK and Hisaki Hayashii of Nara Women's University). In this role, Piilonen has the shared responsibility to see that the exploitation of Belle's data continues unabated before the start of Belle II operation in 2015. He referees each physics paper internally prior to its submission for publication. Also, he is guiding the long-term preservation of the Belle data in a format that is accessible to the Belle II software suite so that this data can continue to be used in future years for performance studies and baseline comparisons by Belle II physicists. Prior to this role, Piilonen served on Belle's Executive Board and was the long-standing chair of the Institutional Board. He continues to serve on the Publication Council (the internal editorial board) and to manage Belle's somewhat unique authorship confirmation process, whereby each author must explicitly affirm his/her intent to be an author on each physics publication. At the request of the founding Belle management team, Piilonen implemented this online system in 2001 that has been used for every Belle physics paper.

Piilonen was the elected chair of the Belle II Institutional Board from April 2009 to April 2011 (for a non-renewable term according to the IB by-laws). He has served on the Belle II Executive Board as the IB Chair (ex officio) and as the Barrel KLM subsystem manager and is the Level 2 Manager for the US Belle II Project's Barrel KLM task.

3.1 Belle Experiment

The Belle experiment concluded operations on June 30, 2010, having accumulated over $1\,\mathrm{ab}^{-1}$ of data over its decade-long lifetime, with about $0.71\,\mathrm{ab}^{-1}$ at the $\Upsilon(4\mathrm{S})$ resonance, $0.12\,\mathrm{ab}^{-1}$ at the $\Upsilon(5\mathrm{S})$ resonance, and the remainder just below the $\Upsilon(4\mathrm{S})$ or at lower-mass Υ resonances.

Since then, the Belle collaboration has been in its Intense Analysis Phase, wherein the fully re-processed data are being mined for our final set of publications. To date, Belle has published 375 refereed physics papers, with several more in the queue. We have been publishing about 25 papers per year during the project period and we expect to publish about 30 papers annually for the next three years. Our published results are being compiled with those from the BaBar collaboration in a comprehensive paper known informally as the B Factory Physics Book. We are in the final stages of editing the book's chapters, with Piilonen providing some editorial assistance to the two chief Belle editors, Bostjan Golob and Bruce Yabsley. (Yabsley was a VT postdoctoral associate.) This 850-page document will be published in 2013.

3.1.1 Belle Physics

Highlights of Belle's recent results are (1) the world's most precise measurement of the CP-sensitive parameter $\sin 2\phi_1$ (where ϕ_1 is one of the angles of the CKM quark mixing matrix) [59], (2) the first observation of the h_b(1P) and h_b(2P) charmonium resonances [60], (3) evidence for the η_b(2S) charmonium resonance and observation of the h_b(nP) decays to η_b(1S) γ [61], (4) the observation of new charged and neutral bottomonium-like four-quark states dubbed Z_b [62, 63], and (5) a more precise measurement of $B \to \tau\nu$ using hadronic-tag events [64]. The conventional h_b and η_b bottomonium states were expected, but the Z_b bottomonium-like states complement our earlier observations of similar charmonium-like states, starting with the $X(3872)$ in 2003 [65]. The $B \to \tau\nu$ decay exemplifies our ability to probe physics beyond the Standard Model—charged Higgs bosons, in this case—through the interference of SM amplitudes with those in which new particles appear in the internal loop(s); such "missing-energy" modes are not accessible in the LHCB experiment.

Over the past three years, Piilonen and research associates Yousuke Yusa, Debabrata Mohapatra and now Xiao Long Wang have given Belle conference talks at the 7th Workshop on the CKM Unitarity Triangle (CKM 2012), the 10th International Workshop on Hyperons, Beauty and Charm Hadrons (BEACH 2012), the 5th International Workshop on Charm Physics (CHARM 2012), the APS DPF meeting (DPF2011), the 23rd Rencontres de Blois Particle Physics and Cosmology Conference (2011), the XIX International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS 2011), the 10th International Conference on Heavy Quarks and Leptons (HQL 2010), the annual fall meeting of the Japanese Physical Society (JPS 2010), the 12th International Conference on Meson-Nucleon Physics and Brookhaven Forum (BF 2010), the annual Lake Louise Winter Institute (LLWI 2010), Physics in Collision (2009), and the SLAC Summer Institute (2009).

Research associate Yusa was the key contributor to the first recent physics highlight that was mentioned above—the measurement of the CP-sensitive parameter $\sin 2\phi_1$ in $b \to c\bar{c}s$ decays [59]. Yusa's analysis used three CP-odd decay modes of the neutral B meson ($J/\psi K_S$, $\psi(2S)K_S$, and $\chi_{c1}K_S$) and one CP-even mode ($J/\psi K_L$), using all of the Belle data. Yusa prepared new Monte Carlo simulations of B decays to charmonium; these new simulations used the latest event-generator decay tables and the most up-to-date reconstruction codes. Yusa, as the coordinator of the charmonium subgroup, was charged with filtering and categorizing all of the recorded events that contain charmonium(-like) states. Finally, he updated the software tools that were used to extract the value of $\sin(2\phi_1)$ in the global fit to the afore-mentioned CP-sensitive modes and he used these to finalizing the modeling of the resolution functions that are ingredients in this extraction. Yusa's reanalysis of the systematic uncertainties was a tour de force. We are now finalizing a detailed paper on this analysis, to complement the PRL, that will provide an archival description of this measurement. Piilonen was one of the internal referees on the PRL and continues in this role on this new paper. Prior to this analysis, Yusa spearheaded a novel study of $B^0 \to K_L \pi^0$ to fill in a missing piece of the so-called $K\pi$ puzzle. In $B \to K\pi$, a contribution from the color-suppressed tree diagram shifts the direct CP asymmetry from the zero value expected in the typical single-diagram-dominated $sq\bar{q}$ transition by an amount that depends on the specific $K\pi$ final state; these shifts can be related precisely by applying an SU(2) flavor symmetry sum rule [66]. This paper was published in 2010 [67]. Yusa is now a tenure-track faculty member at Niigata University.

Until his departure in early 2012, research associate Debabrata Mohapatra—formerly Piilonen's graduate student—worked primarily on the Daya Bay neutrino experiment under Jon Link's supervision. Capitalizing on his heavy-flavor expertise from his earlier work, Mohapatra spent a small fraction of his time on Belle activities: assisting our graduate students, refereeing papers, and presenting Belle talks at several conferences. Mohapatra worked briefly at Pacific Northwest National Laboratory (on Belle and Belle II) before taking a permanent position at Intel Corporation.

Our newest research associate, Xiao Long Wang, worked as a Belle graduate student at the Institute for High Energy Physics in Beijing on the study of charmonium(-like) production in e^+e^- collisions with initial state radiation. At Virginia Tech, he is completing this analysis and has recently released a paper for final internal review prior to its submission for publication. In this paper, the states $\psi(4040)$ and $\psi(4160)$ are observed as resonances for the first time in the $\eta\, J/\psi$ final state, using 98% of the Belle data. Fitting the mass spectrum with the coherent sum of two Breit-Wigner functions, Wang obtains two equally valid solutions for which the products of branching fraction and width are $\mathcal{B}(\psi(4040) \to \eta\, J/\psi) \cdot \Gamma^{\psi(4040)}_{e^+e^-} = (4.8 \pm 0.9 \pm 1.4)\,\mathrm{eV}/c^2$ and $\mathcal{B}(\psi(4160) \to \eta\, J/\psi) \cdot \Gamma^{\psi(4160)}_{e^+e^-} = (4.0 \pm 0.8 \pm 1.4)\,\mathrm{eV}/c^2$ in solution I $\mathcal{B}(\psi(4040) \to \eta\, J/\psi) \cdot \Gamma^{\psi(4040)}_{e^+e^-} = (11.2 \pm 1.3 \pm 2.0)\,\mathrm{eV}/c^2$ and $\mathcal{B}(\psi(4160) \to \eta\, J/\psi) \cdot \Gamma^{\psi(4160)}_{e^+e^-} = (13.8 \pm 1.3 \pm 2.1)\,\mathrm{eV}/c^2$ in solution II. Wang has recently begun to study inclusive $B \to X_c \ell \nu$ semileptonic decays as a probe of the CKM matrix element V_{cb}.

Graduate students Yao Li and Kimberly Williams are pursuing analyses in $B^+ \to \pi^+\pi^+\pi^-$ (CP nonconservation and the measurement of the CKM angle ϕ_2 or α) and $B^0 \to \ell^+\ell^-$ (search for new physics beyond the Standard Model), respectively. Li and Williams have skimmed all of the reprocessed Belle data as well as all of the generic Monte Carlo data (B decay as well as continuum background) to select events that contain tracks likely to have originated from a parent B meson. Using signal Monte Carlo events that they have generated and simulated in combination with tagged real data, real sideband data, and a fraction of the generic Monte Carlo data, they have tuned their analysis codes to optimize their cuts on the event topology and other characteristics (particle identification information, vertexing information, etc.) so as to maximize the significance of their signal over the irreducible backgrounds from continuum and misreconstructed B mesons. Both analyses will be completed and published in 2013.

3.1.2 Service Work

The KLM (K_L–muon) subsystem of Belle performed very well throughout its lifetime and most of the barrel KLM—designed and built at Virginia Tech—will be used in Belle II. During Belle operation up to June 2010, Virginia Tech continued to be responsible for KLM operation, monitoring and maintenance. Yusa managed the on-call staff at KEK, responsible for troubleshooting any intermittent problems with the KLM's high voltage distribution or signal recording system. We have contributed to the continual improvement of KLM-related software for data acquisition, monitoring, reconstruction, analysis, and simulation.

Yusa successfully completed the transition of the KLM's RPC readout from the original system based on LeCroy FASTBUS TDCs to a KEK-designed custom readout system ("COPPER II"). He developed new software for the data unpacking, monitoring, hardware access, and analysis (online and offline) and these were used up to the end of Belle operations in mid-2010.

In addition to taking expert experimental shift assignments, Yusa was the on-call KLM expert who troubleshoots any issues that shifters find in the KLM hardware or data monitors. Piilonen has taken expert shifts as well, in conjunction with his travel to KEK for Belle meetings. Williams and Li took non-expert shifts in Fall 2009 and trained to become expert shifters; thereafter, they took expert shifts until Summer 2010.

Yusa made substantial contributions to the determination of the muon-identification efficiency through the study of two-photon decays $e^+e^- \to (e^+e^-)\mu^+\mu^-$. Piilonen rewrote the K_L meson identification algorithm to improve the signal to noise ratio (the latter originating primarily from beam-background neutrons) by improving the timing resolution and by refining the charged-track veto criteria. These algorithms, updated efficiency tables and systematic contributions to higher-level analyses have been incorporated into the grand reprocessing of Belle's data set in 2010.

Virginia Tech was the top non-KEK producer of Monte Carlo simulation events for the Belle experiment. (KEK produced about 40% of the MC data, while outside institutions produced the remainder.) The bulk of our production was devoted to generic $e^+e^- \to \Upsilon(4S) \to B\overline{B}$ events. Altogether, Belle's MC data set contains ten times the number of real $B\bar{B}$ events and six times the number of real $q\bar{q}$ ($q = u$, c, s, d) events. We have also produced event samples for specific decays such as $B \to \rho\gamma$ and $B \to \omega\gamma$, $B \to K^*\gamma$, and $D \to K\pi$. We have also produced single-track muon and hadron event samples for use in tuning the muon and K_L reconstruction codes and likelihood/efficiency tables.

We have established a new dedicated computer cluster devoted entirely to OpenScienceGrid operations, with the support of our College of Science (hardware purchase) and the Department of Physics (Computer Systems Engineer Roger Link as the system manager for this cluster). Since 2010, Roger Link has worked closely with the OSG personnel at Fermilab to install, troubleshoot, and maintain the grid middleware on our new cluster. We created a new "Belle" virtual organization in OSG that is affiliated with the existing Belle VO in the European/Asian grid (EGI). We have continued to develop our OSG site to accommodate its new purpose as an element in the Belle II grid strategy for data analysis and Monte Carlo event production.

3.2 Belle II Experiment

In 2010, the Japanese government approved the SuperKEKB project that includes the Belle II experiment. This project aims to increase the recorded data set in heavy-quark and -lepton physics by a factor of 50 over that of Belle, starting in 2016 and running into the early 2020's. The $50\,\text{ab}^{-1}$ data set expected by 2022 will enable us to make sensitive measurements in b, c, and τ interactions that are complementary to those that are being pursued by the LHCb experiment.

The Belle II Technical Design Report [68] describes the detector that will be implemented in conjunction with this project. Piilonen co-wrote the KLM chapter of the TDR and worked closely with the general editors on the remainder of this document. In late 2010, several US groups including

Virginia Tech presented an Intensity Frontier proposal to the DOE for the Belle II experiment. After DOE's statements of support in 2011 for US participation in Belle II, the CD-0 milestone for the physics of a super B factory was reached in late 2011. Pacific Northwest National Laboratory will oversee the US Belle II Project for DOE. We have since gone through several reviews: PNNL Director's Review in December 2011, Conceptual Design Review at KEK in March 2012, pre-CD-1 Director's Review at PNNL in March 2012, and a successful CD-1 review at DOE in June 2012. At the CD-1 review, the reviewers and DOE indicated that an early CD-3A approval for the project component that is led by Virginia Tech would be forthcoming in 2012, decoupled from the more lengthy follow-up reviews for the remainder of the project. This component, encoded in Work Breakdown Schedule element 1.4, involves the fabrication of new detector elements based on extruded scintillator strips to replace the inner two (of fifteen) layers of resistive plate counters in the barrel KLM. (We built the glass-electrode RPCs at Virginia Tech for Belle's KLM barrel and will continue to maintain and operate the remaining thirteen RPC layers in Belle II.)

Piilonen wrote the KLM chapter of the Conceptual Design Report and the corresponding sections of the WBS for the US Belle II construction project (WBS 1) and the subsequent installation and commissioning stage (WBS 2), and provided additional documentation to the PNNL project management team on hazard analysis and safety protocols in place at Virginia Tech.

3.2.1 Belle II Physics

The Belle II experiment is part of a broad-based search for new physics. The Large Hadron Collider (LHC), which is now operating with high luminosity at a center of mass energy of 7 TeV, is designed to search for new physics at the *energy* frontier: its high center-of-mass energy may allow it to produce heavy, as-yet-undiscovered particles such as the recently announced Higgs(-like) boson and supersymmetric partners of quarks and leptons or new particles linked to extra dimensions. At SuperKEKB, Belle II will search for new physics using the very high luminosity of the *intensity* frontier by precisely measuring and comparing with theory the measured branching fractions, angular distributions, CP asymmetries, forward-backward asymmetries, and a host of other observables that are difficult or infeasible to measure at the LHC.

In the past, measurements of processes involving internal loops have given access to high mass scales. To continue this paradigm-shifting pursuit of flavor physics, about two orders of magnitude more data will be collected by Belle II to permit us to say whether the CP-violation effects observed in B decays are consistent with the Standard Model and to search for other evidence of physics beyond the Standard Model in, for example, flavor-changing neutral-current (FCNC) processes, which would probe a new-physics mass range of 1-100 TeV. If supersymmetry were discovered at the LHC, Belle II could help determine how the supersymmetry is broken [69]. Other probes at Belle II include the search for right-handed currents that might contribute to the time-dependent CP asymmetry in $B \to K^{*0}\gamma$ and related modes, the triple-product CP asymmetry in $B \to VV$ decays, and the forward-backward asymmetry as a function of q^2 of the dilepton pair in $b \to s\ell^+\ell^-$ decays. We will cooperate with our Task A phenomenologists (Takeuchi *et al*) to identify interesting new research topics that exploit the Belle II data.

3.2.2 Barrel KLM subsystem upgrade

Extrapolations from Belle/KEKB to the Belle II/SuperKEKB environment have concluded that the dominant background in the barrel KLM is expected to be from neutrons associated with Touschek scattering in the positron beam, with a rate of $\mathcal{O}(10\,\mathrm{Hz/cm^2})$. The resistive plate counters used in the Belle KLM detector (and in the outer thirteen of fifteen layers of the Belle II barrel KLM) are rate-limited due to the very high resistivity ($\sim 10^{12}\,\Omega\cdot\mathrm{cm}$) of the glass electrode, so their efficiency for muons would sag to below 50% under the expected ambient neutron rate.

The endcap RPCs and the innermost two layers of the barrel RPCs will be replaced with a scintillator-based design that would provide comparable—or better—information for muon tracking and K_L meson detection. The scintillators can operate efficiently at background rates at least two orders of magnitude larger than those in Belle, well above the rates expected at the SuperKEKB design luminosity. The detection efficiency of the remaining thirteen barrel RPC layers in this hybrid configuration is 90% or higher at the design luminosity. As part of the US Belle II Project, Virginia Tech is responsible for the barrel upgrade.

Two rectangular detector modules are placed in each octant of the Belle II barrel (32 modules total in the two innermost layers). Within each module, two orthogonal layers of scintillator strips are placed inside an aluminum frame made of extruded U-channels. The module is enclosed by a protective aluminum sheath. The 37.7-mm thick modules are between $1581 \times 1542\,\mathrm{cm}^2$ and $2217 \times 1716\,\mathrm{mm}^2$ in area and contain between 75 and 97 scintillator strips.

Photons from each scintillator strip are collected by an embedded wavelength-shifting optical fiber and detected by a Multi-Pixel Photon Counter (MPPC)—an avalanche photodiode operated in Geiger mode. The MPPC, which is immune to a magnetic field of up to 1.5 T, is glued directly to the scintillator strip at one end of the WLS fiber. The fiber's other end is mirrored. Preamplifier carrier cards inside the detector module, with 15 channels per card, deliver power at $\sim 70\,\mathrm{V}$ to each MPPC (externally tunable per MPPC) and deliver the preamplified MPPC signal to the front-end readout electronics (FEE) mounted on the periphery of the magnet yoke. For a layer 0 (1) module, six (seven) pairs of twist-n-flat ribbon cables, each approximately 6 meters long, run between the module's service panel and the external FEE card; one cable in each pair carries power from the FEE to the MPPCs while the other carries signals from the MPPCs to the FEE.

The module frame is assembled from four extruded aluminum U-channels joined to form the perimeter. The frames are cut to length and prepared for assembly in the Virginia Tech machine shop. The module is enclosed in protective aluminum sheathing riveted to the U-channels; the seams between adjacent sheaths are taped together. An extruded PVC edge cover is then fitted along the perimeter to protect the rivets.

The R&D phase for the barrel KLM scintillator modules at Virginia Tech extended from mid-2010 into late 2012, funded by contracts from PNNL as part of the US Belle II Project. Final test assemblies before the start of module production were carried out at Virginia Tech in spring 2013, near the end of this grant period.

3.3 Task N: Experimental Neutrino Physics

3.3.1 Overview

In the period covered by this grant, the Virginia Tech DOE Task N group was comprised of four professors (Patrick Huber, Jonathan Link, group leader, Camillo Mariani, and Leo Piilonen) a revolving cast of postdoctoral researchers (Sanjib Agarwalla, Pilar Coloma, Chun-Min Jun, and Deb Mohapatra), four graduate students (Joseph Hor, Evan Guarnaccia, Patrick Jaffke, and Yue Meng) and one technician (Jo Ellen Morgan), but only Link, Piilonen, Mohapatra, Hor, Guarnaccia, and Meng were funded all or in part by this grant.

The Virginia Tech neutrino group was involved in a number of projects during the period of this grant. The primary focus of our effort was in measuring $\sin^2 2\theta_{13}$ with the Daya Bay reactor neutrino experiment. This goal was achieved when Daya Bay released its first measurement of the parameter in April 2012 [72]. While the initial success of Daya Bay bodes well for its ability to provide a high precision measurement of $\sin^2 2\theta_{13}$ as well as Δm^2_{ee}, the reactor flux distribution and overall flux normalization (addressing the reactor anomaly), we nonetheless expect that the Daya Bay physics program will be complete by 2016. So during this grant period we also participated in the development of the future programs LBNE and nuSTORM. Additionally, we were wrapping up our effort on the MiniBooNE experiment, publishing an additional 7 papers on cross section physics [73–77], oscillation searches [78], and a search for CPT and Lorentz violations [79].

During the period of this grant, Link spend a significant amount of time helping to chart the future of the field, first as an organizer of a workshop on sterile neutrinos titled "Sterile Neutrinos at the Crossroads," then as the editor of "Light Sterile Neutrinos: A White Paper" [80] and finally as convener of the "anomalies and New Physics" subgroup of the Neutrinos working group for Snowmass [81].

3.3.2 Daya Bay

The Virginia Tech Daya Bay group consists of Profs. Link, Piilonen and Huber; postdoctoral researcher Mohapatra; technician Morgan, and graduate students Hor (advised by Link), Jaffke (advised by Huber), and Meng (advised by Link).

The Daya Bay Experiment

The Daya Bay experiment [82] is located at the Daya Bay Nuclear Reactor facility in Guangdong Province, China. This site has six active reactor cores with a combined operational thermal power of 17.4 GW. The mountainous terrain around the plant provides significant cosmic ray shielding for the 8 detectors located deep underground. Because the three pairs of reactor cores are spread out over more than a kilometer, the layout includes two near detector sites. The near detector sites measure the reactor flux prior to significant oscillations, while the far detector site, which is located close to the oscillation maximum, is sensitive to oscillations. Oscillations appear as a deficit of electron antineutrino interactions at the far site compared to the expectation based on the observed rate at the two near sites. The near and far sites are connected by a system of

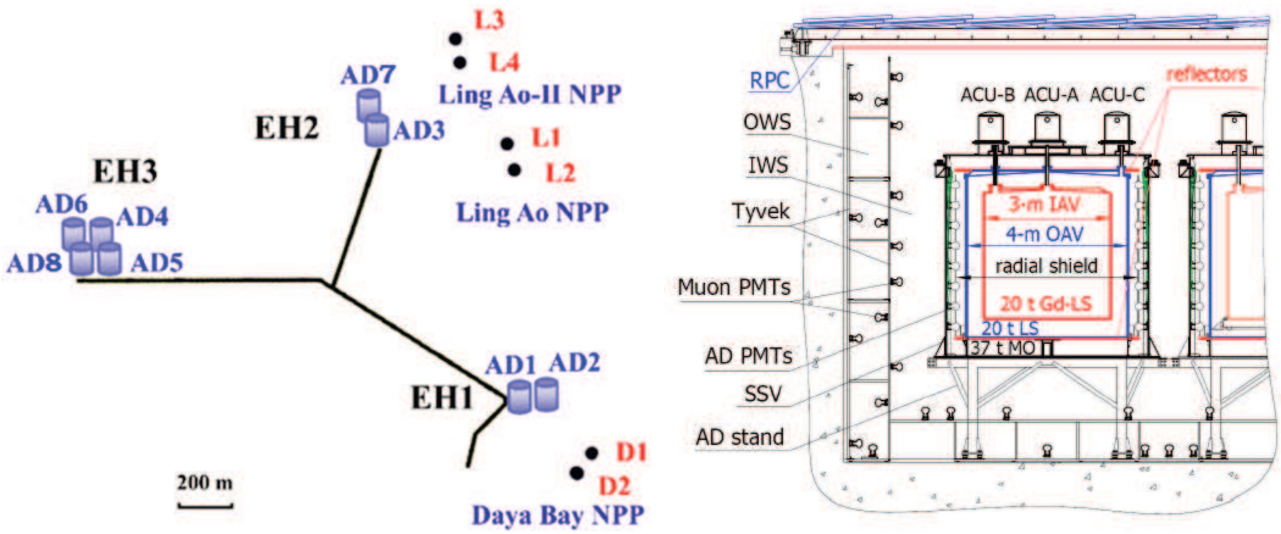


Figure 3.1: (Left) Layout of the Daya Bay experiment showing locations of the 8 detector and 6 reactors. (Right) Schematic of a Daya Bay detector showing the three zone antineutrino detector, inner and outer water pools, and RPCs.

tunnels (Figure 3.1 (left) shows the layout of the experiment). Each near site has two 20 ton target mass detectors while the far site has four such detectors. All detectors were constructed using the identical design and every effort was made to ensure that detector and target materials are consistent (Figure 3.1 (right) shows a schematic of an antineutrino detector and the muon veto). The use of multiple detectors has several advantages: it allows for a larger detector mass at the far site, where rates are lower, while maintaining a common detector design; and it provides for direct comparisons of relative normalization and calibration between detectors using reactor neutrinos at the same site [83].

Data taking on Daya Bay data began on September 23, 2011, with the first pair of detectors installed and fully commissioned in the first near hall. The first two months of data from these side-by-side detectors was used to make a precision comparison of detector response to reactor antineutrino interactions and absolute events rates [83]. This comparison demonstrated that the relative event rates between two Daya Bay detectors could be predicted from the target mass calculations and the differences in weighted baselines to an accuracy matching the available statistics. In this two detector comparison the difference between the measured to expected relative events rates mas smaller than the experiment's specifications.

On December 24, 2011, four additional detectors where brought on line for physics data taking, one in the second near hall and three in the far hall. The first oscillation result [72] is based on the first 55 days of data (through February 17, 2012) in this configuration. The value of $\sin^2 2\theta_{13}$ was determined with a significance of 5.2 σ. The analysis was updated with data extending out to May 11, 2012 [84] and again with the full 6 detector data set (including data through July 28, 2012) including a fit to the energy spectra for both $\sin^2 2\theta_{13}$ and Δm^2_{ee} [85]. Figure 3.2 shows the energy spectra relative to expectation in the three detector halls, and the fit contours in Δm^2_{ee} vs.

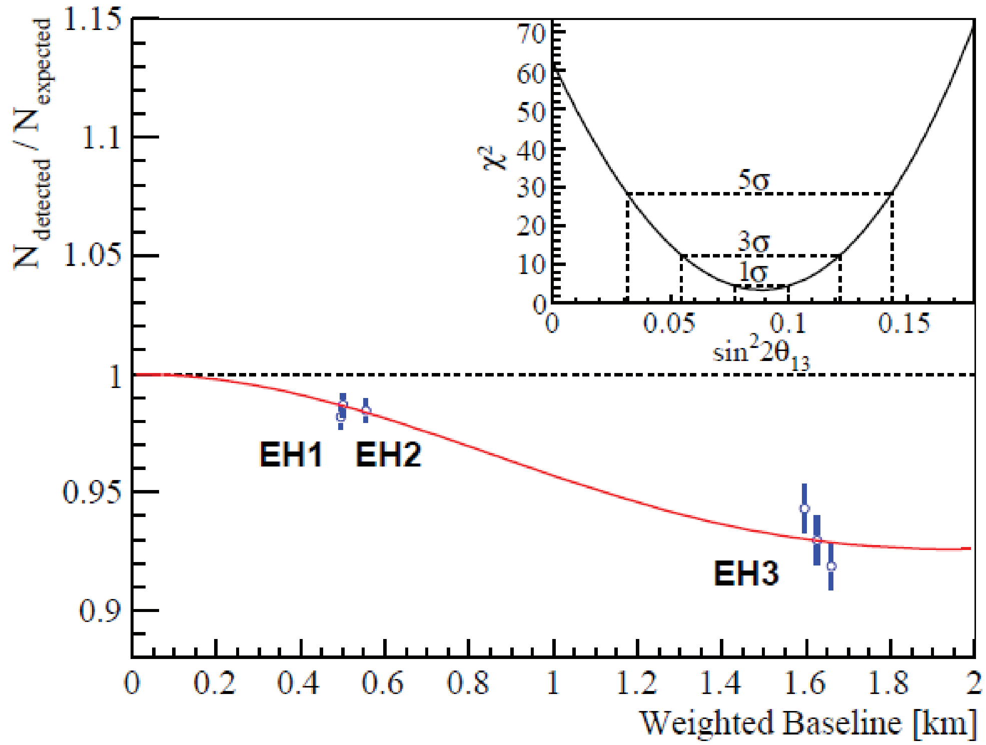


Figure 3.2: Ratio of the measured to expected (assuming no oscillations) energy spectra with the best fit oscillation hypothesis for experimental halls: (a) EH1, (b) EH2 and (c) EH3. (d) The fit contours in Δm^2_{ee} and $\sin^2 2\theta_{13}$.

$\sin^2 2\theta_{13}$. The best fit values are:

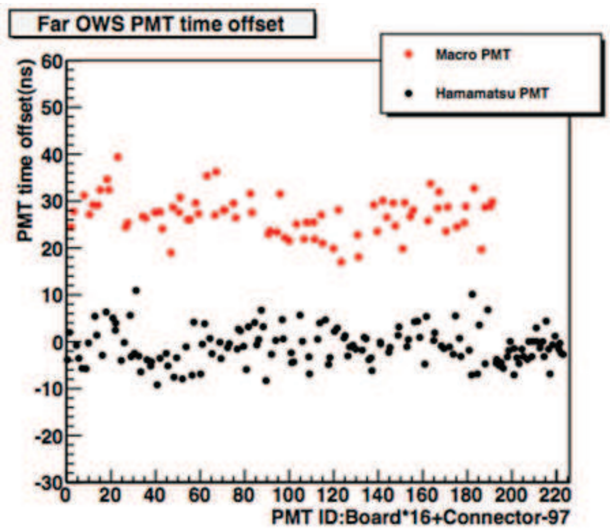
$$\sin^2 2\theta_{13} = 0.090 \pm 0.009 \text{ and } \Delta m^2_{ee} = (2.59 \pm 0.020) \times 10^{-3}.$$

In October 2012, after a brief shutdown, the final 2 detectors were brought online. The experiment will continue to take data in this configuration through the end of 2015 at which point the precision on the $\sin^2 2\theta_{13}$ and Δm^2_{ee} will most likely be limited by irreducible systematic uncertainties.

Virginia Tech at Daya Bay

The Virginia Tech group is one of the largest university groups on Daya Bay. We took a leading role in the design and construction of the muon tagging and veto system. We built and installed a calibration system for the muon pool water (Link is the level three manager for muon calibration), and high voltage distribution system for the resistive plate chambers (RPC). We are responsible for the weekly muon calibration. We are actively participating in the analysis.

Muon Calibration: VT designed and built the calibration system for the muon water pool. In Daya Bay the muon tagging system consists of two parts. The primary system is water pool for



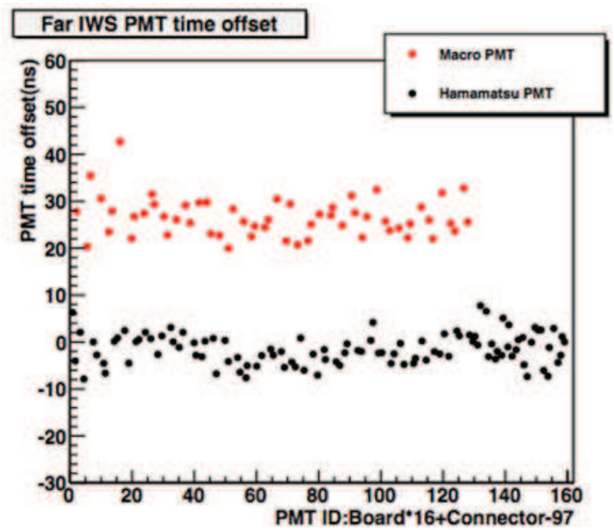


Figure 3.3: PMT timing offset distributions determined by analysis of the calibration data. In this example from the far hall water pool one can see that the offsets fall into two bands corresponding to the Macro and Hamamatsu PMTs. This band structure is due to differences in the cable length and the number of dynodes between the two types of PMTs.

detecting Čerenkov light, segmented into inner and outer zones by a layer of white Tyvek. The antineutrino detectors sit in the middle of the inner water pool. The secondary system is four layers of resistive plate chambers (RPCs) which cover the top of the water pool. The water pool calibration system is a network of LED flashers embedded in a Teflon diffuser ball. There are 50 flashers in each near pool and 76 on the far pool. The custom designed, miniature flasher circuit produces a short flash (5 ns FWHM) of adjustable intensity. Up to 30 LEDs are controlled by a custom build controller board. The controller board also provides a trigger output and a timing pulse which is readout by a PMT TDC channel.

The VT group monitors the weekly muon pool calibration runs and analyzes the data. The muon calibration data is used to time in the water pool PMTs and track water clarity. The timing calibration algorithm developed by Prof. Link and Yue Meng minimizes a χ^2 formed of terms involving the difference of light arrival times for tube pairs from individual LEDs. Figure 3.3 shows a distribution of PMT time offsets determined in this analysis. When the analysis was first run, the time offsets were observed to fall into two bands. It was later discovered that these bands had a complete correlation with the two PMT types (Hamamatsu and Macro). Graduate student Joseph Hor is working with Prof. Link on a water attenuation length analysis. This analysis is complicated by a large degeneracy between the water attenuation and the Tyvek reflectivity, but preliminary studies can differentiate between clean water and relatively less clean water as measured from the resistivity of the water flowing from the pool into the filtration system.

The VT group is continuing to maintain the muon water pool calibration system and monitor the weekly calibration runs. The timing calibration algorithm work is complete and the timing offsets are available for use in the muon reconstruction.

Resistive Plate Chamber High Voltage: VT designed and built the high voltage distribution system for the resistive plate chambers (RPCs). The system is installed and in operation. The VT group is responsible, as the system experts, for maintaining the system and responding to any operational issues.

Analysis: The initial Daya Bay analysis represents a tour de force of a central core of mostly postdoctoral or more senior researchers, which resulted in the first and still world's best measurement of the neutrino mixing angle θ_{13}. As complex and well executed as that analysis was, it was statistics limited and could tolerate systematic errors which were larger than the projected final systematic errors. As the experiment accumulates more data, the systematic errors will have to improve, and this is when the real hard work of Daya Bay analysis will begin. VT graduate students Meng and Hor, in collaboration with Profs. Link and Huber, and with the postdoctoral researcher to be named, are working to help lower the systematic errors in specific areas of the analysis. These areas include: reactor fluxes, the reconstructed energy scale, and muon induced backgrounds.

Yue Meng is studying muon induced isotope production, especially ^{12}B, as a tool to measure non-linearity in the antineutrino detector's energy response to $\beta^{\pm}$. Gamma ray sources of known energy are often used to calibrate detectors like Daya Bay, but they have drawbacks: 1) it's very hard to get them everywhere inside the detector, and 2) gamma rays, which loose energy by producing multiple ionizing particles and are therefore quenched in the scintillator multiple times unlike positrons and electrons which are quenched only once. ^{12}B, which is produced in the process ^{12}C(n,p)^{12}B, is the most common isotope made in muon induced hadronic showers. It is produced uniformly throughout the detector, it β-decay direct to the ground state 97% of the time, and it has a well understood energy distribution. As a pure electron final state, ^{12}B can be used, in combination with the ^{68}Ge positron annihilation source as a proxy for positron energy deposition. Following the detection of a showing muons, there is a window from 200 ns to 50 ms where about 95% of all events detected are ^{12}B decays. Meng's analysis will use these shower tagged ^{12}B decays to calibrate the positron energy scale and track its variation throughout the detector volume. This work was used will be a critical input to the oscillation analysis using spectral distortion.

The near detectors are intended to mitigate the systematic uncertainty coming from the reactor neutrino flux model, yet as the experiment pushes for its ultimate precision, the residual flux effects from the far/near ratio will eventually contribute as a limiting factor. Additionally, there is an intrinsic interest in improved measurements of reactor neutrino fluxes which may be useful, for example, in designing neutrino based reactor safeguard protocols. Prof. Huber, one of the world's leading experts in reactor neutrino fluxes, is interested in using the Daya Bay data, which will be the largest reactor neutrino data set ever, to measure the neutrino flux with unprecedented precision. Joseph Hor is working on an analysis to characterize the energy spectrum of the reactor flux and relate it to the operational reactor data on the fuel burn-up cycle.. Prof. Huber's graduate student, Patrick Jaffke, is working on an estimate of the neutrino flux from spent fuel on the Daya Bay site. His calculation is based on publicly available data on the operational history of the cores.

Other Service Work and Responsibilities:

- After serving as a member of the Talks Committee since 2006, Prof. Link was asked to serve as Talks Committee chair starting in 2012.

- As the seventh largest group on Daya Bay, VT is responsible for about 3% of all shifts.
- Prof. Link served on the paper review committee for the collaboration's third major paper, which appeared in Chinese Physics C [84], and as a physics reviewer for the first oscillation analysis [72].
- Prof. Huber helped to implement his reactor neutrino fluxes [86] into the Daya Bay analysis and will continue to update the flux as necessary.
- VT postdoc Deb Mohapatra lead the muon system commissioning effort. Deb has since moved on to a permanent position at Intel.

3.3.3 Long-Baseline Neutrino Experiment (LBNE)

The Virginia Tech LBNE group consists of Profs. Link and Camillo Mariani, postdoctoral researchers Deb Mohapatra and Chun-Min Jen, and graduate student Evan Guarnaccia.

Graduate student Guarnaccia completed a calculation of muon rates and energy spectra as a function of angle at the 4850 foot level in the Homestake mine. His work has been presented as a note in the LBNE Document database (DocDB 4155).

Mohapatra and Link calculated long-baseline sensitivity to θ_{13}, CP violations and mass hierarchy using GLoBES [87]. One focus of this work has been on comparing various beam configurations. These calculation were included in the recent LBNE Physics Working Group Report [88]. Additionally, Link and Mohapatra collaborated with Huber and Sanjib Agarwalla on a study of an alternative approach to antineutrino running using stopped pion beams [89].

Mariani and Jen are working on an implementation spectral functions in the cross section model of the neutrino interaction generator code Genie. This work is supported out of Mariani's start-up.

3.3.4 Neutrinos from Stored Muons (nuSTORM)

Virginia Tech is a charter member of the nuSTORM collaboration and has taken a leading role in the effort. In April, 2013 we hosted a meeting of the nuSTORM collaboration and Link organized a collaboration building session on nuSTORM at the Snowmass on the Mississippi meeting this past summer. The Center for Neutrino Physics funded an engineering study to outfit the DO hall for the far detector location and contributed to the FESS study of the required new facilities and infrastructures. We have initiated an effort to study the possible light collection technologies for the SuperBIND detector design.

Appendix 1: Biographical Sketches

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08/2010 – present:	William E. Hassinger, Jr. Senior Faculty Fellow in Physics, Virginia Tech
08/2002 – present:	Professor of Physics, Virginia Tech
08/1993 – 08/2002:	Associate Professor of Physics, Virginia Tech
08/1987 – 08/1993:	Assistant Professor of Physics, Virginia Tech
01/1985 – 07/1987:	Postdoctoral Fellow, Los Alamos National Laborarory

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Publications most closely connected to proposed activity:

S.K. Choi *et al.* (Belle Collaboration), *Observation of a new narrow charmonium state in exclusive* $B^+ \to K^+\pi^+\pi^- J/\psi$ *decays*, Phys. Rev. Lett. **91, 262001**, 1–6 (2003). [689 citations]

K. Abe *et al.* (Belle Collaboration), *Observation of large CP violation in the neutral B meson system*, Phys. Rev. Lett. **87, 091802**, 1–7 (2001). [573 citations]

M. Nakao *et al.* (Belle Collaboration), *A measurement of the branching fraction for the inclusive* $B \to X_s\gamma$ *decays with the Belle detector*, Phys. Lett. **B511**, 151–158 (2001). [370 citations]

K. Abe *et al.* (Belle Collaboration), *Improved measurement of mixing-induced CP violation in the neutral B meson system*, Phys. Rev. D **66, 071102**, 1–6 (2002). [315 citations]

P. Koppenburg *et al.* (Belle Collaboration), *Inclusive measurement of the photon energy spectrum in* $b \to s\gamma$ *decays*, Phys. Rev. Lett. **93, 061803**, 1–6 (2004). [259 citations]

K. Abe *et al.* (Belle Collaboration), *Observation of double* $c\bar{c}$ *production in* e^+e^- *annihilation at* $\sqrt{s} \simeq 10.6$ *GeV*, Phys. Rev. Lett. **89, 142001**, 1–7 (2002). [254 citations]

P. Krokovny *et al.* (Belle Collaboration), *Observation of D_{sJ}(2317) and D_{sJ}(2457) in B decays*, Phys. Rev. Lett. **91, 262002**, 1–6 (2003). [247 citations]

Synergistic Activities:

None.

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(Note: 301 Belle Collaboration members outside the US not listed). D. M. Asner (PNNL), M. Barrett (Hawaii), M. Belhorn (Cincinnati), G. Bonvicini (Wayne State), T. E. Browder (Hawaii), J. Crnkovic (UIUC), S. Esen (Cincinnati), H. Farhat (Wayne State), J. E. Fast (PNNL), R. Gillard (Wayne State), M. Grosse Perdekamp (UIUC and RIKEN-BNL), I. Jaegle (Hawaii), M. Jones (Hawaii), K. Kinoshita (Cincinnati), R. T. Kouzes (PNNL), M. Leitgab (UIUC and RIKEN-BNL), Y. Liu (Cincinnati), D. Marlow (Princeton), D. Mohapatra (PNNL), K. Nishimura (Hawaii), A. Ogawa (RIKEN-BNL), T. K. Pedlar (Luther), M. Peters (Hawaii), J. Rorie (Hawaii), H. Sahoo (Hawaii), D. Santel (Cincinnati), A. J. Schwartz (Cincinnati), R. Seidl (RIKEN-BNL), G. Tatishvili (PNNL), S. E. Vahsen (Hawaii), G. Varner (Hawaii), A. Vossen (Indiana), E. White (Cincinnati), J. Yamaoka (Hawaii), P. Zhou (Wayne State).

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Publications most closely connected to proposed activity:

- L. N. Chang, Z. Lewis, D. Minic, and T. Takeuchi, *Biorthogonal Quantum Mechanics: Super-Quantum Correlations and Expectation Values without Definite Probabilities*, arXiv:1208.5189, submitted to Communications in Mathematical Physics (2012).

- S. K. Agarwalla, F. Lombardi, and T. Takeuchi, *Constraining Non-Standard Interactions of the Neutrino with Borexino*, arXiv:1207.3492, submitted to JHEP (2012).

- L. N. Chang, Z. Lewis, D. Minic, and T. Takeuchi, *Galois Field Quantum Mechanics*, arXiv:1205.4800, submitted to Physics Letters A (2012).

- Z. Lewis and T. Takeuchi, *Position and Momentum Uncertainties of the Normal and Inverted Harmonic Oscillators under the Minimal Length Uncertainty Relation*, Phys. Rev. D **84**, 105029 (2011).

- L. N. Chang, Z. Lewis, D. Minic, and T. Takeuchi, *On the Minimal Length Uncertainty Relation and the Foundations of String Theory*, Adv. in High Energy Physics 2011, 493514 (2011).

- L. N. Chang, Z. Lewis, D. Minic, T. Takeuchi, and C. H. Tze *Bell's Inequalities, Superquantum Correlations, and String Theory*, Adv. in High Energy Physics 2011, 593423 (2011).

- Y. Kao and T. Takeuchi, *Single-Coupling Bounds on R-parity violating Supersymmetry, an update*, arXiv:0910.4980 (2009).

- T. Adams et al. (VT authors A. Pronin and T. Takeuchi), *Terascale Physics Opportunities at a High Statistics, High Energy Neutrino Scattering Experiment: NuSOnG*, Int. J. Mod. Phys. A24, 671-717 (2009).

- M. Honda, Y. Kao, N. Okamura, A. Pronin and T. Takeuchi, *Constraints on New Physics from Long Baseline Neutrino Oscillation Experiments*, arXiv:hep-ph/0707.4545 (2007).

- M. Honda, Y. Kao, N. Okamura, and T. Takeuchi, *A Simple Parameterization of Matter Effects on Neutrino Oscillations*, arXiv:hep-ph/0602115 (2006).

Synergistic Activities:

None.

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Publications most closely connected to proposed activity:

- R. G. Leigh, D. Minic and A. Yelnikov, *On the Glueball Spectrum of Pure Yang-Mills Theory in 2+1 Dimensions*, Phys. Rev. D **76**, 065018 (2007).
- L. Freidel, R. G. Leigh and D. Minic, *Towards a solution of pure Yang-Mills theory in 3+1 dimensions*, Phys. Lett. B **641**, 105 (2006).
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- V. Jejjala, M. Kavic and D. Minic, *Time and M-theory*, Int. J. Mod. Phys. A **22**, 3317 (2007).
- V. Jejjala, M. Kavic, D. Minic and C. H. Tze, *On the Origin of Time and the Universe*, Int. J. Mod. Phys. A **25**, 2515 (2010).
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- C. M. Ho, D. Minic and Y. J. Ng, *Cold Dark Matter with MOND Scaling*, Phys. Lett. B **693**, 567 (2010).
- J. H. Simonetti, M. Kavic, D. Minic, U. Surani and V. Vejayan, *A Precision Test for an Extra Spatial Dimension Using Black Hole–Pulsar Binaries*, Astrophys. J. Lett. **737**, L28 (2011).
- L. N. Chang, Z. Lewis, D. Minic, T. Takeuchi and C. H. Tze, *Bell's Inequalities, Superquantum Correlations, and String Theory*, Adv. High Energy Phys. **2011**, 593423 (2011).

- L. N. Chang, Z. Lewis, D. Minic and T. Takeuchi, *On the Minimal Length Uncertainty Relation and the Foundations of String Theory*, Adv. High Energy Phys. **2011**, 493514 (2011).

Synergistic Activities (Conferences and Workshops Organized and Hosted):

- Aspen Center of Physics Working group 2012 [with Rob Leigh (Urbana), Diana Vaman (UVA) and Leo Pando Zayas (Michigan)]
- Miami International Winter Conferences [with Thomas Curtright (Miami), Luca Mezincescu (Miami), Pierre Ramond (U of Florida) and others]
- Sterile Neutrinos at the Crossroads [with Patrick Huber, Jonathan Link and Raju Raghavan (deceased) - all from VT]
- Perimeter Institute International Conference on Quantum Gravity [with Laurent Freidel, Bianca Dittrich and Lee Smolin - all from Perimeter Institute]
- Virginia-Maryland meetings on particle physics and string theory [with Jim Gates (U of Maryland), Tristan Hubsch (Howard U) and Diana Vaman (UVA)]

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Publications most closely connected to proposed activity:

- F. P. An, *et al.* (Daya Bay Collaboration), *Observation of electron-antineutrino disappearance at Daya Bay*, Phys. Rev. Lett. **108**, 171803 (2012).
- F. P. An, *et al.* (Daya Bay Collaboration), *A side-by-side comparison of Daya Bay antineutrino detectors*, Nucl.Instrum.Meth. **A685**, 78-97 (2012).
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Synergistic Activities:

- Sterile Neutrinos at the Crossroads workshop (2011) [with Patrick Huber, Djordje Minic, and Raju Raghavan (deceased) - all from VT]
- 4th International Neutrino Summer School (2012) [with Patrick Huber]

Identification of Potential Conflicts of Interest or Bias in Selection of Reviewers:

US Collaborators and Other Affiliations

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