Project Summary

The ultimate goal of particle physics is to identify the fundamental principles that govern matter, energy, space and time. The Standard Model (SM) of particle physics provides a well tested quantitative description of the matter particles (quarks and leptons) together with the mediators of the strong and electroweak interactions (gluon, photon, W and Z bosons). An accumulating body of evidence suggests that the SM is not complete, and that it is merely the low-energy limit of a more fundamental theory.

In 2009, the CERN Large Hadron Collider (LHC) will begin operation. With its unprecedented energy and luminosity, the LHC promises to unveil the mechanism of electroweak symmetry breaking and shed light on the physical processes that are responsible for the origin of mass. The LHC holds the potential to make dark matter in the laboratory and perhaps even to reveal extra spatial dimensions. Its reach for uncovering new phenomena is dramatically higher than that of all previous accelerators. The LHC truly will be a discovery machine and, with the upgrades being planned, will likely continue to collect data through the next decade.

Accurate theoretical predictions are needed for the LHC to realize its full potential. Many of the most important signatures at the LHC are complex. For example, because of the LHCs high luminosity, it can be difficult to separate signal from background. The lowest-order predictions for such processes exhibit significant uncertainties that can be reduced by including higher orders in perturbation theory. Also, it is essential to explore signatures and strategies in depth to make the most of the new discoveries and to fully exploit the physics potential of this magnificent new experimental facility.

In response to these pressing needs and scientific opportunities, the US particle theory community has formed the LHC Theory Initiative (LHC-TI). With funding from NSF over the last three years, the LHC-TI has ramped up to fully fund a total of three postdoctoral and six graduate fellowships, and has provided travel and computing awards to a total of six postdocs and graduate students. The experience of the LHC-TI program over these first three years has demonstrated widespread interest in LHC-related theoretical issues at a variety of US institutions and the existence of a talented pool of graduate student and postdoctoral applicants. Operating the program over three years has shown the LHC-TI's ability to organize and administer the selection and award processes. And the success of this initial program has shown that even a modest investment in students and postdocs can yield impressive scientific returns, as measured by fellowship output in papers, conference proceedings, and computer code. While these successes of the LHC-TI program have been substantial, the impact on the US high-energy theory community has been limited by the financial resources available.

This proposal would renew support for LHC-TI for the next five years, and the requested funds would support the *annual* award of three postdoctoral and five graduate fellowships, as well as several travel and computation fellowships. The increased number of awards will allow the LHC-TI community of fellows to grow to a critical mass that will nucleate a vibrant LHC theory community in the US in the years to come.

The **intellectual merit** of the activities proposed here is to provide calculational tools and theoretical results necessary to fully extract physics from the LHC. Proposed activities include calculations of higher-order QCD and electroweak corrections in the SM and beyond-the-SM models, as well as the development of new, improved, shower algorithms. Also important is the development of robust and well-tested Monte Carlo tools to confront with data theoretical models. Much remains to be done in these areas.

The **broader impact** of the proposed activities is to facilitate the development in the United States of a world-class program in LHC-related theory. To stimulate research in this area, a network of nationwide postdoctoral and graduate student fellowships is being proposed. The fellows will provide the nucleus of a vital US LHC theory community over the projected twenty-year lifetime of the LHC. Annual meetings will be held to facilitate collaborative research and personal links between the fellows, their sponsors, and the LHC experimental collaborations. Professional development of the fellows will be an integral part of the program, with the expectation that they will become leaders of the field.

Project Description

1 Introduction and Motivation

In 2009, the CERN Large Hadron Collider (LHC) will begin operation. The LHC will ultimately achieve $\sqrt{s} = 14$ TeV running with a design luminosity of $\mathcal{L} = 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. This represents an increase of a factor of seven in energy and a factor of 100 in luminosity over the Fermilab Tevatron. With its unprecedented energy and luminosity, the LHC promises to unveil the mechanism of electroweak symmetry breaking (EWSB) and shed light on the physical processes that are responsible for the origin of mass. The LHC holds the potential to make dark matter in the laboratory and perhaps even to reveal extra spatial dimensions. Its reach for uncovering new phenomena is dramatically higher than that of all previous accelerators. The LHC truly will be a discovery machine and, with the upgrades being planned, will likely continue to collect data through the next decade.

To uncover the mechanism of EWSB and discover new physics, it is necessary to have accurate theoretical calculations of Standard Model (SM) processes and new physics signatures. This requires progress on several fronts. The lowest-order (LO) predictions for many SM processes exhibit a significant dependence on unphysical renormalization and factorization scales that can be traced to the truncation of the perturbation series used to calculate the relevant amplitudes. This scale dependence can be reduced by calculating observables to higher order in perturbation theory; QCD and, in some cases, electroweak (EW) radiative corrections are still needed to yield accurate SM predictions for many processes. For new physics scenarios, it is also important to identify and characterize unique signatures that can distinguish between models. Moreover, in order to arrive at realistic predictions that can be used by the experimental community, matrix-element-based theoretical calculations must be integrated into Monte Carlo (MC) event generators – a process that has only been undertaken for a few models and which, especially at higher order in perturbation theory, is not yet fully understood.

In response to these pressing needs and scientific opportunities in LHC-related theoretical physics, the US high-energy theory community has formed the LHC Theory Initiative (LHC-TI). With funding from NSF over the last three years, the LHC-TI has ramped up to fully fund a total of three postdoctoral and six graduate fellowships, and has provided travel and computing awards to a total of six postdocs and graduate students. The experience of the LHC-TI program over these first three years has demonstrated widespread interest in LHC-related theoretical issues at a variety of US institutions and the existence of a talented pool of graduate student and postdoctoral applicants. Operating the program over three years has shown the LHC-TI's ability to organize and administer the selection and award processes. And the success of this initial program has shown that even a modest investment in students and postdocs can yield impressive scientific returns, as measured by fellowship output in papers, conference proceedings, and computer code (see refs. [1]- [43]).

While these successes of the LHC-TI program have been substantial, its impact on the US high-energy theory community has been limited by the financial resources available. This proposal would renew support for the LHC-TI for the next five years; the requested funds would support the *annual* award of three postdoctoral and five graduate fellowships, as well as several travel and computation fellowships. The increased number of awards will allow the LHC-TI community of fellows to grow to a critical mass that will nucleate a vibrant LHC theory community in the US for years to come.

The following two sections of the proposal outline the kinds of SM precision calculations necessary to understand the backgrounds to new physics signatures, as well as the variety of new physics signatures that remain to be understood. The fourth section discusses the LHC-TI fellowship program in detail, including a summary of activities over the last three years and plans for the future. The fifth section contains a brief summary of results from prior NSF support.

2 Precision Calculations of Standard Model Cross Sections

The first LHC physics run will take place in late 2009 and early 2010. SM processes give rise to important measurements and are backgrounds to new physics signals. A productive LHC program will require a detailed understanding of SM processes in general, and of QCD, in particular.

To obtain reliable predictions for SM processes at the LHC, (NLO) QCD corrections must be calculated. Higher-order QCD corrections reduce the dependence on the unphysical factorization and renormalization scales. In some cases, such as W and Z production [44], the effect is dramatic. Controlling EW radiative corrections [45–48] and obtaining precise knowledge of the parton distribution functions (PDFs) are also essential (see Sec. 2.1).

NLO QCD corrections are needed for top quark processes [49–51, 54–56], as well as for Higgs boson [55,57–61] and supersymmetry (SUSY) studies [62–64] (see Sec. 2.2). To arrive at realistic predictions, the theoretical calculations need to be integrated into MC event generators. At higher orders, this remains a difficult task (see Sec. 2.4).

In the remainder of this section we describe some of the SM physics projects that the LHC Theory Initiative believes are important to pursue. More details on some of the calculations described here can be found in the 2006 LHC-TI white paper [65] . (Some of the calculations described in Ref. [65] have already been completed.) The list presented here is meant to be illustrative – not exhaustive.

2.1 Parton Distribution Functions and NNLO QCD Corrections

Parton distribution functions (PDFs) are essential for nearly every measurement planned for the LHC. While NLO accuracy was sufficient at the Tevatron, NNLO precision will be needed to reach the LHC goals. Improved NNLO PDFs have recently been made available [66]. For more accurate fits of the PDFs at the NNLO level, NNLO calculations of the relevant processes are needed. The necessary NNLO ingredients are available for the DIS structure functions [67–69] and the Drell-Yan process [70]. However, for the other sub-processes used in the global analysis, significant challenges remain [71].

Specifically, work is needed on jet, direct photon, and heavy quark production. For many of these processes, the NNLO matrix elements have been computed [72, 73]; however, they need to be combined with real emission diagrams, properly accounting for soft and collinear subtractions. Several promising techniques [74–76] can be pursued to accomplish this non-trivial task.

There are a variety of other PDF-related issues that need to be investigated:

Gluon Distribution. The gluon PDF has larger uncertainties than the corresponding quark distribution functions [77]. Data from Tevatron jet production play a crucial role in constraining the gluon PDFs, particularly in the large x region. Since accurate knowledge of the gluon PDF is required for Higgs and top-quark production channels, this is an important issue to resolve.

Heavy Quark PDFs. The data in current global PDF analyses place no constraints on the charm and bottom quark distributions. Even the strange quark distribution is only weakly constrained. Dedicated efforts are needed to address this problem, using high statistics neutrino scattering data [78] and new Tevatron data on W/Z production in association with c- and b-quarks [79].

PDF Uncertainties and Validity of the DGLAP Picture. The release of PDFs with uncertainties [31, 66, 80–82] represents a significant advance in performing quantitative estimates for the errors associated with particular observables. Although the treatment of PDF uncertainties has been refined over the past few years [83], further improvements are needed to produce more accurate predictions of LHC benchmark processes [31, 77]. For the LHC, one also has to ask about limitations of the DGLAP picture, and whether an alternative framework (see eg. Refs. [84, 85]) is necessary in part of the LHC phase space.

2.2 Standard Model Predictions

There are a host of SM processes for which more accurate predictions are needed at the LHC:

Full NLO QCD Corrections to $pp \to t\bar{t} \to b\bar{b} + 4f$. Top quark pairs will provide both a calibration and a copious background at the LHC, so QCD corrections must be under control. Existing NLO QCD calculations of $pp \to t\bar{t} \to b\bar{b} + 4f$ ($f = \ell$, ν, q) do not include non-factorizable contributions [86, 87]. Since non-resonant contributions to $t\bar{t}$ production are known to be important [88], especially with cuts imposed, the non-factorizable QCD corrections to this process are likely also to be relevant. Thanks to recent advances [89], a calculation of the full NLO QCD corrections for $pp \to t\bar{t} \to b\bar{b} + 4f$ is feasible, but has not yet been done.

Resummed QCD Corrections to $qq' \to qq'H$. To identify $H \to WW^{(*)}$ in vector boson fusion (VBF) events, one relies on $WW^{(*)} \to 2\ell + 2\nu$ decays, tagging on the two forward jets, and vetoing on a jet in the central rapidity region [90]. The central jet veto requires a detailed understanding of the jet activity in $qq' \to qq'H$ events. This is best achieved by calculating the resummed QCD corrections to $qq' \to qq'H$.

NLO QCD Corrections to $t\bar{t}jj$ Production. The recent calculation of the NLO QCD corrections to $t\bar{t}b\bar{b}$ production [52, 53] has shown that these corrections may significantly affect the capabilities of ATLAS and CMS to probe the top-quark Yukawa coupling through $pp \to t\bar{t}H$ with $H \to b\bar{b}$ [54, 56, 61]. Another potentially large background in this channel is $t\bar{t}jj$ production, where the two jets are mistagged as b-quarks. Currently, $t\bar{t}jj$ production is known only to leading order. Since information on the background shape relies on theoretical calculations [56], and $pp \to t\bar{t}H \to t\bar{t}b\bar{b}$ will be observable for 30 fb^{-1}, calculations of the NLO QCD corrections for this processes are very important.

$pp \to t\bar{t}Wjj$ at LO. For m_H between 150 and 200 GeV, $pp \to t\bar{t}H(\to W^+W^-)$ promises a top Yukawa coupling measurement with $15 - 25\%$ precision for 30 fb^{-1} of data [51]. This channel's largest background, $t\bar{t}Wjj$ production, was only approximated in Ref. [51] because of its complexity. A full tree-level calculation of $t\bar{t}Wjj$ should be feasible with current GRID resources.

NLO QCD Corrections to HH, $t\bar{t}W$ and $WWWjj$ Production. Higgs pair production will make it possible to probe the Higgs self-coupling, λ_{HHH}. For $m_H >$ 140 GeV, $pp \to HH \to \ell^\pm\ell'^\pm + 4j$ offers the best prospect [57]. To measure λ_{HHH}, the cross sections for the SM signal and the most important backgrounds, $t\bar{t}j$, $t\bar{t}W$ and $WWWjj$ production, must be known to NLO precision.[1] The NLO QCD corrections for $gg \to HH$ are currently available in the $m_t \to \infty$ limit [92]; this is not sufficient for predicting differential cross sections [57]. While computing the full NLO QCD corrections to HH and $t\bar{t}W$ production appears feasible, it requires the calculation of seven-point functions for $pp \to WWWjj$, which has never been done before.

NLO QCD Corrections to $HH \to b\bar{b}\gamma\gamma$ Background Processes. For $m_H <$ 140 GeV, $HH \to b\bar{b}\gamma\gamma$ offers the best chance to probe the Higgs self-coupling [59]. The NLO QCD corrections to the main background sources for this final state, 4 jet, $\gamma + 3$ jet, $\gamma\gamma jj$, $Q\bar{Q}\gamma j$, and $Q\bar{Q}\gamma\gamma$ ($Q = b$, c) production, have yet to be calculated.

NLO QCD Corrections to SUSY Background Processes. If R-parity is conserved, the most powerful and model-independent signature for SUSY is multi-jet plus missing transverse energy production. The main backgrounds in these channels are QCD multijet events, $t\bar{t}$, $W+$ jets, and $Z(\to \bar{\nu}\nu)+$ jets production. The LO multi-jet and $W/Z+ > 2j$ cross sections depend strongly on the factorization and renormalization scales. Recently, the NLO QCD corrections to $W + 3j$ production have been calculated [37, 93] using novel techniques for one-loop calculations developed during the past few years [94, 95]. The NLO QCD corrections for $Z + 3j$ production can be calculated using the same techniques; the calculation has yet to be done. For $W/Z + 4j$ production one faces the same obstacles as for $pp \to WWWjj$.

[1]For a calculation of the NLO QCD corrections to $t\bar{t}j$ production see Ref. [91].

EW Radiative Corrections to Drell-Yan Production. These corrections become large and negative at large di-lepton invariant masses [45, 46] because of Sudakov-like logarithms. It is necessary to resum these terms for new physics searches at the LHC.

NLO QCD Corrections to VVV Production. The production of three electroweak gauge bosons, $pp \to VVV$, $V = W, Z, \gamma$ is an interesting physics signal, as well as an important background at the LHC. Several VVV production channels make it possible to probe the quartic couplings of electroweak gauge bosons [96]. The NLO QCD corrections to several three vector boson final states have recently been calculated [97]; as in the case of di-boson production [98], they are quite large. This makes it important to calculate the NLO QCD corrections for the remaining VVV channels.

2.3 Automatic Tools and Analytical Properties of QCD Amplitudes

Most calculations proposed in Sec. 2.2 involve one-loop QCD diagrams. To achieve the goals of this project in a timely fashion, automatic or semi-automatic tools must be used. However, there is no fully automatic program for calculating one-loop QCD corrections. Several semi-automatic tools are available [99, 100], and work on extending the automatic programs `Grace` and `HELAC-PHEGAS` to include QCD corrections has begun [101, 102]. Developing a fully automatic program for calculating QCD one-loop corrections also makes it necessary to numerically regularize the divergences encountered in these calculations, in particular for the real radiative corrections. Approaches to achieve this in `HELAC-PHEGAS` [104], `MadEvent` [105] and `Sherpa` [106] have recently been developed.

Recent progress in the analytical computation of tree-level [103] and massless one-loop [107] gauge theory amplitudes has led to new on-shell and generalized unitarity based approaches to calculating one-loop amplitudes efficiently and numerically [94, 95]. These techniques have been successfully applied to the calculation of the NLO QCD corrections to $W + 3j$ production. Progress has also been made in the understanding of soft and collinear functions in the SM [1] and the factorization structure of gauge theory amplitudes [2]. The next steps in bringing this approach to fruition involve integrating NLO QCD processes into parton shower Monte Carlo programs.

2.4 Interface of QCD Calculations with Parton Showers

Parton shower Monte Carlo programs, such as `Pythia` [108], `Herwig` [109], and `Sherpa` [110], form the bridge between hard-scattering fixed-order calculations and observed final states. Most shower MC programs are based on angular/energy-ordered $1 \to 2$ branching. But QCD gluon radiation has a dipole structure (i.e. $2 \to 3$ branching), so improved shower algorithms are needed. In Ref. [111] a parton shower algorithm was developed that is particularly well suited for integrating NLO calculations into Monte Carlo programs.

So far, there are two approaches to combining NLO QCD calculations with parton showers: `MC@NLO` [112] and `POWHEG` [113]. In both cases, only a limited number of processes [114, 115] have been implemented. Other, more complicated final states must also be considered, particularly those including heavy quarks. First steps have been taken to permit `MadEvent` [116] and `Sherpa` to automatically calculate one-loop corrections [105, 106]. However, both projects are far from complete. It is currently not known how to generalize this process beyond NLO.

2.5 Potential Projects

From the discussion in the previous sections, the following set of representative SM projects might be carried out by the LHC-TI fellows and their mentors:

1. Needed close to LHC startup:

(a) Complete $pp \to jj$, γj at NNLO, and improved global PDF analyses.
(b) Further application of on-shell and generalized unitarity methods to $Z + 3j$ production at NLO QCD and other relevant processes.
(c) Resummation of EW Sudakov logarithms in high-mass Drell-Yan production.
(d) Incorporation of more processes into `MC@NLO` and `POWHEG`, and development of `MadEvent` and `Sherpa` into full-fledged fully automatic NLO MC programs.

2. Needed after LHC startup:

(a) Calculation of full NLO QCD corrections to $pp \to t\bar{t} \to b\bar{b} + 4f$, including non-factorizable terms.
(b) Calculation of full tree-level $t\bar{t}Wjj$ production.
(c) Calculation of NLO QCD corrections to $t\bar{t}jj$ production.
(d) Resummation of QCD corrections to $qq' \to qq'H$.
(e) Calculation of NLO QCD corrections to $gg \to HH$ and $t\bar{t}W$ production.
(f) Calculation of NLO QCD corrections to $WWWjj$, $jj\gamma\gamma$ and $Q\bar{Q}\gamma j$ production.

3 Signatures of New Phenomena at the LHC

The LHC will revolutionize particle physics by opening the TeV energy region to direct experimental exploration. It will certainly reveal the origin of EWSB. But beyond that, it will probe a variety of possible extensions to the Standard Model – supersymmetry, large or small extra dimensions, strong gravity, technicolor, composite and Little Higgs, Lee-Wick gauge bosons, unparticles – with a large number of models in each category. These models share a common set of signals that will be the focus of early LHC searches. Generic signatures of new physics models include nonstandard top physics, top partners [SUSY, composite and Little Higgs (LH), Randall-Sundrum (RS), universal extra dimension (UED), technicolor (TC), and topcolor models], missing energy signals with or without cascades [SUSY, composite and LH with T parity, UED, unparticles], W' and Z' bosons [composite and LH, RS, TC, UED, string-inspired SUSY models, Lee-Wick models], and non-standard Higgs sectors [SUSY, composite and LH, TC, UED, and RS models]. Below we discuss some representative models and propose specific calculations that are needed. The list presented is meant to be illustrative – not exhaustive. For more details, we refer to Ref. [65].

3.1 Supersymmetry

It is possible that supersymmetry, if it exists, will be found without much difficulty after the LHC begins taking data [62]. After the discovery of a SUSY signal, the emphasis will shift to determining the masses, spins and couplings of supersymmetric particles, together with their decay modes and branching fractions [117].

The masses of supersymmetric particles can be reconstructed from edges and thresholds in cascade decays [118, 119]. Most such analyses involve jets; hence understanding the jet activity in SUSY events is critical. Existing studies [118] have used `Pythia` [120] and `Herwig` [121]. But a recent study [122] shows that the p_T distributions of jets from a matrix-element-based calculation [123] and `Pythia` can be very different. This indicates the need for a full NLO SUSY-QCD MC generator for squark and gluino production and decay (with spin correlations where appropriate). SUSY-QCD corrections for many SUSY production [124] and decay [117] processes are already known. Using these building blocks, the development of a full NLO SUSY-QCD MC generator, including cascade decays, should be feasible.

Once SUSY is discovered, it will be important to measure the spins and couplings of the SUSY particles. The spin of sleptons can be determined using lepton charge asymmetries [125], but there are no similar studies for the spins of other SUSY particles. Likewise, whether and how the couplings of SUSY particles can be measured at the LHC remains unknown, except for the weak squark gauge boson coupling [126]. Finally, it is necessary to study alternatives to and extensions of the MSSM, and in the light of recent progress in the calculation of possible SUSY backgrounds [37, 93], to reconsider early LHC SUSY signatures.

Other SUSY issues need to be addressed before the LHC reaches its design luminosity. For example, CP-violating phases must be included in general SUSY production and decay processes. Various versions of the NMSSM, and R-parity violating SUSY production processes, must be incorporated in event generators. NLO QCD corrections to Higgs production off bottom and top quarks [127, 128] and via VBF also need to be calculated.

A great deal of work has been devoted to developing "semi-realistic" string constructions[2] that contain the gauge group and particles of the SM or the MSSM. So far, no construction is fully complete. One major issue involves supersymmetry breaking and its mediation. Almost all existing constructions suggest new TeV-scale physics beyond the MSSM. For these reasons, physics at the LHC could well be much more complicated than the SM or the MSSM. It is important to work out a variety of examples, together with their signatures, and then implement the physics in event generators.

3.2 Models of Electroweak Symmetry Breaking

Motivated by precision measurements, theorists have developed many other intriguing models for EWSB. One of the most promising new approaches is the "Little Higgs" (LH) mechanism [136], in which the Higgs field is a pseudo-Goldstone boson associated with the spontaneous breaking of a global symmetry. In such models, new particles with the same spin cancel the one-loop quadratically divergent contributions to the Higgs mass. Some of the predicted new particles should be observable at the LHC [137, 138]. Cancellation of the quadratic divergences implies a sum rule, which can in principle be tested at the LHC; it is currently not known how well. Other aspects of LH models also warrant more detailed investigation. For example, recently proposed models with supersymmetry [139] and pseudo-axions [140] have yet to be studied in detail. LH models have yet to be incorporated into standard MC packages in a systematic way.

Extra-dimensional theories represent another promising direction. In Higgsless models, EWSB occurs via the boundary conditions of gauge fields without the appearance of a physical Higgs boson [141]. These models predict a Kaluza-Klein (KK) tower for both the SM gauge bosons and the SM fermions. Some phenomenological aspects of the KK excitations of the SM gauge bosons have been studied in Ref. [142]. However, many properties of Higgsless models have not been explored. For example, the couplings of the new vector bosons fulfill certain model-independent sum rules that can be tested at the LHC. Furthermore, no LHC studies have been performed for the Higgsless RS model or the version with gauge-Higgs unification [143].

Unparticles [144] are based on the hypothesis that there could be an exact scale-invariant hidden sector that leads to similar collider signatures as extra-dimensional models [145]. Many phenomenological consequences of unparticles, such as signatures of unparticle self-interactions [146], still need to be worked out.

The Lee-Wick (LW) extension of the SM offers another intriguing possibility to solve the hierarchy problem [147]. Phenomenologically, the model predicts the existence of heavy, negative-norm copies of the usual SM fields. These particles have ghost-like propagators and negative decay widths. It is difficult to distinguish these states from those appearing in models based on flat TeV-scale extra dimensions with localized quarks and leptons [148]. Vertex displacements offer a possibility to uniquely identify LW leptons at the LHC [149]; however, much more work is needed to identify unique signatures for other LW particles.

String theory suggests that extra spatial dimensions may be the price for unifying the SM with gravity.

[2] See, for example, Refs. [129–132]; for reviews, see Refs. [133–135].

The fact that string theory contains new non-perturbative soliton-like objects is opening new avenues for model building. Several classes of such extra dimension (ED) models have been developed [150–153]. Remarkably, the so-called universal extra dimension (UED) models [153] have many of the same discovery signatures as SUSY; it is difficult to discriminate between the two possibilities [154]. Although much work on ED models has already been done [155], there are a number of issues that need to be addressed. In particular, the implementation of ED and other BSM models in event generators has to be completed; constraints on the ED parameter space from current data have to be determined; and representative ED benchmark points have to be developed.

3.3 Flavor Physics

LHC-b will produce an astonishing 10^{12} bottom quark pairs a year, with which it will be possible to test the CKM sector of the SM in extremely rare channels that have branching ratios of $\mathcal{O}(10^{-9} - 10^{-10})$ [156]. Of particular interest is the B_s meson, whose decays are sensitive to multiple CKM parameters. The extraction of the CKM parameters in heretofore unstudied modes will allow strong consistency checks whose violation would signal new physics.

3.4 Potential Projects

Based on the discussion above, some or all of the following projects might be carried out by the LHC-TI fellows and their mentors:

1. Needed close to LHC startup:
   (a) Studies of jet activity in cascade events, and determinations of how SUSY-particle spins and couplings can be measured. Studies of CP-violating phases in SUSY production and decay processes, and investigations of how kinematic observables such as $MT2$ can be used to identify supersymmetry.
   (b) Studies of how well the sum rules of Little Higgs and Higgsless models can be tested.
   (c) Calculations of the search reach for UED.
   (d) Establishment of benchmark points for ED models and determination of the parameter space that is consistent with existing data.
   (e) Studies of the LHC discovery reach in Randall-Sundrum and Higgsless models with gauge-Higgs unification.
   (f) Implementation of new physics models in MC event generators.
2. Needed after LHC startup:
   (a) Implementation of a full NLO SUSY QCD event generator and calculation of SUSY QCD corrections to Higgs production in association with t- and b-quarks.
   (b) More complete studies of the phenomenology of new particles in Little Higgs and Higgsless models, as well as in Lee-Wick models and unparticle theories.
   (c) Incorporation of new physics from string constructions into event generators.
   (d) Development of techniques to distinguish KK gauge boson excitations from heavy Z' production in GUT theories.
   (e) Calculation of NLO QCD corrections for processes in models with extra dimensions.

Of course, the priorities will be determined by LHC results. The overall program targets both phenomenology and model-building because of the close interconnections between the two fields. Indeed, the postdoctoral and graduate student fellows will build bridges between the two communities. A tighter coupling would work to the benefit of each.

4 Fellowships

To stimulate work on LHC-related theory, and in particular on the questions raised in the previous sections, LHC-TI instituted a program of national postdoctoral and graduate student fellowships with support from the NSF. This fellowship program was the result of a collaborative community effort; it arose out of a series of open meetings to discuss how best to proceed.[3]

By awarding fellowships through a nationwide competition, the LHC-TI program supports the best qualified individuals at any US institution working on the highest priority LHC issues. By focusing on student and postdoctoral support, it attracts highly qualified young particle theorists to collider physics, and – especially important given the current economic climate – helps retain them in the field. Finally, by encouraging nominations for LHC fellowships from all institutions engaged in elementary particle physics research, the program creates a higher profile for LHC-related physics nationwide – not just at those institutions already emphasizing collider physics.

Over time, the fellowships will help create and sustain a vital LHC theory community in the United States, with most fellows eventually pursuing a career as tenure-track faculty. There is proof that this approach can succeed: Out of the twenty SSC Postdoctoral Fellowships awarded by the Texas National Research Laboratory Commission to theorists from 1990-93, thirteen led to tenured positions at research universities or national laboratories. These theorists have formed a nucleus of the US collider theory community over the last decade – indeed, two are members of the LHC-TI Steering Committee.[4] Similarly, we expect that the graduate and postdoctoral LHC fellows will become attractive candidates for tenure-track faculty positions and that they will help sustain a vital US LHC theory community over the projected twenty-year lifetime of the LHC. Although statistics from the initial three-years are limited, the indications are promising: two LHC-TI winners, Victoria Sanz-Gonzalez and Pavel Nadolsky, have now begun tenure-track faculty positions.

At the instigation of the Screening Committee, and with the support and approval of the NSF, the LHC-TI has created two classes of awards: full postdoctoral or graduate fellowships, and travel and computing awards.[5] Full fellowships include salary support, while all awards cover research expenses – something that enables the fellows to be more productive and more independent than ordinary postdocs or graduate students. The research funds allow the fellows to play highly visible roles in conferences or workshops. They also help to cover the computing needs of the fellowship projects, enable the fellows to invite collaborators for visits, or visit other institutions for collaborative purposes.

The LHC-TI fellowship program aims to provide financial support to young scientists, and support for their career development as well. Scientific mentoring is an integral part of the fellowship selection process, and all applications must include descriptions by the sponsors of the support and mentoring to be provided. This mentorship plan is explicitly evaluated by the Screening Committee; it satisfies the postdoctoral mentoring requirement set by NSF.

To grow a network of fellows, and foster collaboration between fellows, the Steering Committee is organizing annual meetings patterned after the successful SSC Fellows meetings organized by the Texas

[3] A timeline and cumulative set of documents developed during this process may be found at the LHC-TI website, `http://www.pas.rochester.edu/~orr/LHC-TI.html`.

[4] Giele and Orr are former SSC Postdoctoral Fellows. For an exposition of Steering Committee's role, see Sec. 4.4.

[5] Details of these awards are given in Sec. 4.2 below.

National Research Laboratory Commission. The first fellows meeting was held for a half day in conjunction with PHENO2008, with gracious organizational help from the University of Wisconsin high-energy physics group. The meeting featured presentations by senior scientists as well as by the fellows themselves. Now that more fellowships have been awarded, there are enough fellows to expand these annual meetings into two-day stand-alone workshops. They will include talks by the fellows, as well as practical training sessions offering exposure to the broad array of LHC-related physics topics and technical tools being developed. They will also provide advice on professional development, such applying and interviewing for faculty positions, teaching and outreach strategies, writing grants, and giving seminars or colloquia. The next meeting will be held October 29-30, 2009, hosted by the Fermilab Theory group. Many of the tutorials planned for this workshop will be conducted by the fellows themselves.

4.1 LHC-TI Fellowships Awarded

The LHC-TI program has awarded Graduate Fellowships ($40K each), Graduate Travel/Computing Awards ($5K each), Postdoctoral Fellowships ($150K each), and Postdoctoral Travel/Computing Awards ($15K each), to the following individuals. The number of fellowships was determined by the available funding.

- 2007: 2 Graduate Fellowships and 4 Graduate Travel/Computing Awards.
    1. Randall Kelley, Graduate Fellow, UC San Diego. Advisor: Aneesh Manohar.
    2. Jonathan Walsh, Graduate Fellow, Washington. Advisor: Matt Strassler.
    3. Dai De Chang, Graduate Travel/Computing Award, Case Western Reserve. Advisor: Glenn Starkmann.
    4. Wei Gong, Graduate Travel/Computing Award, Oregon. Advisor: Davison Soper.
    5. David Krohn, Graduate Travel/Computing Award, Princeton. Advisor: L.-T. Wang.
    6. Keith Rehermann, Graduate Travel/Computing Award, Johns Hopkins. Advisor: David E. Kaplan.
- 2008: 1 Postdoctoral Fellowship, 1 Graduate Fellowship, 2 Postdoctoral Travel/Computing Awards, and 2 Graduate Travel/Computing Awards.
    1. Alexander Mitov, Postdoctoral Fellow, SUNY Stony Brook. Host: George Sterman.
    2. Pavel Nadolsky, Postdoctoral Travel/Computing Award, Michigan State. Host: C.-P. Yuan.
    3. Veronica Sanz-Gonzalez, Postdoctoral Travel/Computing Award, Boston. Host: M. Schmaltz.
    4. Catherine Bernaciak, Graduate Fellow, SUNY Buffalo. Advisor: Doreen Wackeroth.
    5. Duff Neill, Graduate Travel/Computing Award, Carnegie Mellon. Advisor: Ira Rothstein.
    6. Rob Putman, Graduate Travel/Computing Award, Illinois. Advisor: Scott Willenbrock.
- 2009: 2 Postdoctoral Fellowships and 3 Graduate Fellowships.
    1. Neil Christensen, Postdoctoral Fellow, Wisconsin. Host: Tao Han.
    2. Harald Ita, Postdoctoral Fellow, UCLA. Host: Zvi Bern.
    3. Andrew Horning, Graduate Fellow, UC Berkeley. Advisor: Christian Bauer.
    4. William Link, Graduate Fellow, Illinois. Advisor: Scott Willenbrock.
    5. Benjamin Thayer, Graduate Fellow, Florida State. Advisor: Laura Reina.

The LHC-TI experience shows that the quality of the applicant pool is excellent; those who won awards were extremely well qualified. The fellows' research interests span a broad set of skills, including calculations of higher-order corrections both within and beyond the Standard Model, as well as the development of new, improved, simulation tools to confront with data theoretical models. Many of the candidates participated in various LHC-related workshops (LHC Olympics, TeV4LHC Workshops, etc.). These activities helped focus their research on LHC-related topics and jump-start direct collaboration with experimentalists. Such collaborative efforts will be essential for a proper interpretation of LHC data.

The LHC-TI Screening Committee (described in the following section) was encouraged to see strong applications from groups and institutions that have traditionally been more "formal" and less "experimentally" driven. They saw this as a sign that the US community is beginning to respond to the upcoming LHC project; new LHC fellows can help catalyze this process.

4.2 Fellowship Details

The fellowships are formally structured as subawards from Johns Hopkins University to the institutions hosting fellowship winners. Details of the LHC fellowships are as follows:

- Each LHC postdoctoral fellowship totals $150K, to be spent over two or three years. A fellowship can be awarded to an existing postdoc, or to a new postdoc whose position would be made possible by the award. Applications are initiated by the prospective postdoctoral fellow, and sponsored by a host institution. The funds can be used for salary support (including fringe benefits), research support (of at least $4K per year), and an administrative fee of up to $10K. The precise distribution of funds is left to the applicant, but the allocation must be specified in the applicant's proposal. Two examples are given in Table 1.
- Each LHC graduate fellowship totals $40K for one year. The funds can be used to provide a graduate stipend (including fringe benefits), research support (of at least $4K), tuition support, and an administrative fee of up to $5K. The fellowship frees the student from other responsibilities, allowing full-time effort on LHC research. The precise distribution of funds is left to the applicant, but the allocation must be specified in the applicant's proposal. An example is given in Table 1. Individuals are eligible for a total of two graduate fellowships, thereby deriving support for two years; they must be nominated for the second year of support. Such nominations will be considered during the selection process (see Sec. 4.3) in competition with other graduate student nominations.
- Each LHC-TI postdoctoral travel/computing award totals $15K over two years, and each graduate travel/computing award totals $5K for one year. These funds are intended to support the research expenses of the fellow, and cannot be used for salary, fringe benefits, or tuition.[6] Winners are selected from the applicants for the full fellowship awards.
- The number of postdoctoral and graduate LHC fellowships may vary from year to year based on the pool of applicants and the availability of funds. The budget included with this proposal anticipates the annual award of 3 postdoctoral and 5 graduate LHC fellowships, and 2 postdoctoral and 4 graduate travel/computing awards, for each of five years. (This is a small step up from the 2 postdoctoral and 5 graduate student fellowships being offered in 2010. The Screening Committee believes that the applicant pool is sufficiently deep to merit the additional awards.)

  All told, the proposed budget supports a total of 15 postdoctoral fellowships and 10 postdoctoral travel/computing awards, and 25 graduate fellowships and 20 graduate travel/computing awards over five years – providing a substantial impact on the number and profile of young physicists working in

[6]Financially, the travel/computing award funds are reimbursed directly from Johns Hopkins University and no separate administrative fee is paid to the institution hosting the award winner.

	Postdoctoral Fellowship		Graduate Fellowship
	Example 1 (2-year)	Example 2 (3-year)	
salary/stipend	$50K+$50K	$55K+$15K+$15K	$21K
fringe benefits	$15.5K+$15.5K	$17K+$4.7K+$4.7K	$2.3K
tuition			$6K
research funds	$9K	$28.6K	$5.7K
adm. fee	$10K	$10K	$5K
total	$150K	$150K	$40K

Table 1: An illustration of the possible distribution of award funds for a two- or three-year postdoctoral fellowship and a graduate fellowship.

LHC-related theory in the United States.[7] The program is designed so that it can be scaled based on the availability of funds.

- Postdoctoral fellowships are intended to begin in September each year, to coincide with the usual particle theory postdoctoral appointments, while graduate fellowships may cover any year-long period as proposed in the nomination letter.
- To avoid an excessive concentration of fellows, each institution may host only one new postdoctoral and one new graduate student fellow every other year.
- For a given individual, only one fellowship nomination is accepted per year; there is a lifetime limit of two graduate fellowships and one postdoctoral fellowship per individual.
- Nominees need not currently be resident at the nominating institution, although in most cases graduate nominees will be continuing students.

Johns Hopkins University has agreed to administer the overall grant for a flat administrative fee of $5K per postdoctoral fellowship and $2.5K per graduate student fellowship (plus off-campus F&A on travel/computing awards and meeting expenses). Each subaward is limited to $10K or $5K of administrative expenses. We expect recipient universities will continue to accept this arrangement because of the prestige and visibility that such a fellow brings. Indeed, this is the model behind the very successful Hubble Fellowships in Astronomy, and the recently initiated Astronomy and Astrophysics Postdoctoral Fellowships at NSF.

The yearly cost of the fellowship program is $650K for 3 postdoctoral and 5 graduate fellowships, and $50K for 2 postdoctoral and 4 graduate travel/computing awards. In addition we anticipate a nominal amount ($4K per year) of additional expenses to support advertising the fellowship as well as extraneous costs associated with the annual fellows' meetings (see Sec. 4.3).

4.3 Fellowship Nomination and Selection

LHC postdoctoral and graduate fellowships are advertised in the early autumn, and the fellows selected by early December, in line with the annual postdoctoral hiring cycle. The fellowships are awarded in an open nationwide competition:

- The applicant submits an application to the LHC-TI Steering Committee (see Sec. 4.4). The application must include:

[7] By way of comparison, as noted above, a total of 20 SSC Postdoctoral Fellowships were awarded to particle theorists during the four-year period from 1990-1993.

1. A nomination letter from a faculty member or other eligible scientific staff member who would serve as the fellow's sponsor and scientific mentor. The letter should briefly describe the fellowship project, its relation to existing or planned theoretical collaborations, the nominee's qualifications, and the mentoring activities that the sponsor plans on behalf of the nominee. Each faculty sponsor may nominate at most one graduate fellow and one postdoctoral fellow in a given year of institutional eligibility.
2. An institutional endorsement letter specifying the financial and other support being committed by the host institution to ensure the success of the fellow's research, along with a budget explaining how the fellowship funds would be spent over the period of the award (two or three years for postdoctoral fellowships and one year for graduate fellowships). The faculty sponsor would serve as Principal Investigator for the fellowship subaward.
3. For a postdoctoral fellowship nomination, a short research plan (of no more than five pages) written by the nominee, and two additional letters of recommendation. For a graduate fellowship, only one additional letter of recommendation is necessary, and a research plan is not required.
4. Graduate fellowship nominations should specify the start date of the award.
5. Collaborative nominations from two institutions are encouraged, in which case the nomination should include institutional endorsements from both institutions.
6. Postdoctoral and graduate travel/computing award winners are chosen from the pool of fellowship nominees; separate applications for travel/computing awards are not accepted.
7. Nominations are submitted online, through academicjobsonline.org.

- The fellowship announcement encourages the nomination of women, members of under-represented minority groups, and persons with disabilities. The announcement is distributed widely to reach these groups – e.g. by using the WIPHYS e-mail list.

- Nominations are screened by a committee with five members chosen by the LHC-TI Steering Committee (see Sec. 4.4), and to ensure fairness, subsequently vetted by the cognizant NSF Program Officer (currently Dr. Keith Dienes):

  1. The Screening Committee, chosen by the Steering Committee, examines the applications. Members typically serve for one or two years; the Screening Committee is representative of the US particle theory community in LHC-related physics, and includes representatives from US CMS and ATLAS.[8] To avoid conflicts of interest, members of the Screening Committee are not eligible to nominate a fellow during the time of their service on the committee.
  2. The Screening Committee produces a rank-ordered list of all nominations, and a recommendation on the number of postdoctoral and graduate fellowships and travel/computing awards to be conferred. These recommendations and all nomination materials are forwarded to NSF as a reallocation request involving a "change of scope" (see sections 311.1 and 322b of the NSF Grant Policy Manual, NSF-05-131).
  3. The cognizant NSF Program Officer reviews the screening process and recommendations.
  4. This information is returned to the LHC-TI Steering Committee; the final (sub-)awards are processed by Johns Hopkins University.

- The following criteria are used by the Screening Committee to rank nominations:

[8] Prof. Fred Olness has served as Chair of the Screening Committee during 2007-2009; additional members included Bogdan Dobrescu (2009), Steve Ellis (2009), Sarah Eno (2007-2008), Joey Huston (2008), Greg Landsberg (2009), Tom LeCompte (2009), Steve Mrenna (2007-2008), John Parsons (2007), and Martin Schmaltz (2007-2008).

1. Quality of the candidate.
2. Quality of the fellowship project.
3. Relevance of the proposed work to the LHC, using the projects listed in Secs. 2 and 3 (updated appropriately) as guidelines.
4. Support committed by the recipient's institution, in particular the synergy with the theoretical and experimental groups at the sponsoring institution, as well as the availability of students, postdocs and faculty for collaboration.
5. Potential for impact on the recipient institution as a center of excellence for LHC-related theoretical research.
6. Potential for the proposed project to nucleate an active theoretical working group.

- In order to ensure the full consideration of women, members of underrepresented minority groups, and persons with disabilities, the Screening Committee applies the best practices developed for the unbiased review of applicants.[9] The Screening Committee also, to the best of its ability, keeps track of the diversity of the nomination pool, and provides a report to the Steering Committee on the status of the nominations of women, underrepresented minorities, and people with disabilities.

- If a postdoctoral (graduate) fellow is hired into a junior faculty (postdoctoral) position during the fellowship period, the balance of funds stays with the fellow to continue the support of his or her project.

4.4 Management Structure

As with all grant proposals, formal scientific management rests with the PI and co-PIs. However, in order for the LHC fellowship program to be responsive to the array of issues discussed in the previous sections, it is crucial to have broad-based community input. A Steering Committee, chaired by Paul Langacker, and including representatives of US ATLAS and CMS, as well as the model building and string theory communities, oversees the LHC-TI process. The current members of the Steering Committee are:

Jonathan Bagger*† (Johns Hopkins)	Ulrich Baur*† (SUNY Buffalo)
R. Sekhar Chivukula*† (MSU)	Csaba Csaki (Cornell)
Sarah Eno (Maryland)	Walter Giele (Fermilab)
JoAnne Hewett† (SLAC)	Ian Hinchliffe† (LBNL)
Paul Langacker [*Chair*] (IAS Princeton)	Steve Mrenna (Fermilab)
Fred Olness (SMU)	Lynne Orr*† (Rochester)
Carlos Wagner (Argonne and Chicago)	Edward Witten (IAS, Princeton)

* (co-)PI of this proposal
† Executive Committee member

All members of the LHC-TI Steering Committee have agreed to serve for at least one more year. The Steering Committee selects the Screening Committee, and ensures that the fellowship program is "done right." It constructs the fellowship Screening Committee and advises on any policy issues not specified in this proposal.

In addition, a smaller Executive Committee handles the execution of the fellowship program – for example, constructing and distributing a suitable fellowship solicitation, ensuring that fellowship meetings are scheduled and that programs are arranged, etc. The Executive Committee is a subset of the Steering

[9]See, for example, `http://wiseli.engr.wisc.edu/initiatives/hiring/Bias.pdf`.

Committee of about 7 members. The current Executive Committee members are indicated by a dagger. Lynne Orr and Ulrich Baur have agreed to serve as co-chairs of the Executive Committee. The (co)-PIs of the proposal (who are indicated by an asterisk) are committed to serve on the Executive Committee for the duration of the grant. The additional members have agreed to serve through at least two more years. The LHC-TI Steering Committee has overall oversight responsibility for this group.

Finally, as replacements on the Executive or Steering Committees are needed, the LHC-TI Steering Committee will solicit and endorse replacement members – while maintaining broad-based representation in terms of research interests and diversity.

5 Results from Prior NSF Support

Principal Investigator: Jonathan Bagger (PI), Ulrich Baur, R. Sekhar Chivukula, and Lynne Orr (Co-PIs), NSF-PHY-0705682 ($689,538, 11/01/2007 – 10/31/2009)

This grant provides the primary support for the LHC Theory Initiative fellowship program. The present proposal is intended to extend this project an additional five years.[10] In this section we highlight work carried out by the class of 2008, the first set of fellows supported by this grant. A complete list of LHC-TI publications is given in the references [1]- [43].

Three postdoctoral awards were given in 2008: Alexander Mitov (Stony Brook, Fellowship), Pavel Nadolsky (Michigan State, Travel/Computing), and Veronica Sanz-Gonzalez (Boston, Travel/Computing). Mitov is still a postdoc, but Nadolsky and Sanz-Gonzalez have moved into junior faculty positions, at Southern Methodist and York, respectively.

Mitov focussed his work on achieving substantial improvements in the theoretical predictions for top-pair production in hadronic collisions. In [25] and [24] he completed calculating the NLO corrections and NLL resummation for the top-pair total production cross-section. His results have important implications for the threshold behavior of that observable.

Mitov also worked to understand the IR singularities of massive gauge amplitudes at higher orders. In [23] he derived general properties of the two-loop anomalous dimension matrix that controls the single IR poles of any massive two-loop amplitude, and proved some general properties of these matrices that are needed in soft gluon resummation in top-pair production at NNLL. In [21] he determined how NNLL resummation for heavy flavor production in hadronic collisions should be performed, and derived the required two-loop anomalous dimensions that control the NNLL soft logarithms. He clarified the relation between the resummation in the total inclusive cross-section and the resummation in the differential pair production cross-section.

Nadolsky focussed his attention on PDFs. In refs. [27, 31], he explored the implications of charm and bottom quark masses for global PDF analyses. He showed that heavy-quark mass effects arise primarily in DIS at low energies, yet their impact survives at higher energies and leads to phenomenologically significant shifts in "standard candle" W and Z production cross sections at the LHC. He assessed the heavy-quark effects using the "general-mass" factorization scheme for heavy quarks and in a simplified effective theory that captures the heavy-quark kinematical dependence while operating with zero-mass matrix elements.

In Ref. [31] Nadolsky introduced a new technique to evaluate PDF-induced correlations between pairs of cross sections or other physical observables, based on an extension of the widely used error matrix method for computing PDF uncertainties. This technique can reveal regularities in the PDF dependence that are not obvious with the other approaches. For instance, the correlations clarify previously unexplained relations

[10] The 2007 graduate fellowships were funded as a supplement to the Johns Hopkins particle theory grant, NSF-PHY-0401513. The 2008 and 2009 postdoctoral and graduate fellowships were supported by the present grant, NSF-PHY-0705682. The 2010 fellowship competition is presently underway.

between the PDF dependences of W, Z, $t\bar{t}$, single-top, and Higgs production cross sections. They link the PDF uncertainties of physical observables to PDFs for physical flavors at well-defined (x, μ) values.

Sanz-Gonzalez spent her fellowship year working on LHC signatures for supersymmetry, technicolor, and extra-dimensional models. She is presently working on with experimentalists on early signatures simulations (discovery potential below 10 fb^{-1} of 10 TeV data), carrying out a signature-based study of 4 leptons + X, which encompasses a variety of possible models.

In particular, Sanz-Gonzalez is studying Lepto-SUSY [33], a theory that she co-developed, whose signatures contain 2 or more leptons, 2 heavy stable sleptons, and 2 hard jets. The sleptons are quite boosted and usually mistagged as muons. Therefore, all Lepto-SUSY signals contain at least 4 "leptons" – including the Higgs. This attracted the attention of the ATLAS Higgs coordinator Ketevi Assamagan (BNL), who has proposed a full simulation study of this model. Sanz-Gonzalez, in collaboration with experimentalists Simona Rolli (Tufts) and Assamagan, carried out the validation study; she is now working with Shlomit Tarem (Technion) and her group in the GEANT implementation of the model – especially the correct implementation of long-lived sleptons.

In collaboration with experimentalist Piyali Barnejee (Montreal), Sanz-Gonzalez and Adam Martin (Fermilab) are investigating di-lepton resonances as a way to distinguish different models of strong interactions. They have simulated several scenarios in ATLFAST and are preparing a full simulation of this process.

Three graduate student awards were given in 2008: Catherine Bernaciak (Buffalo, Fellowship), Duff Neill (Carnegie Mellon, Travel/Computing), and Rob Putman (Illinois, Travel/Computing). All three are still students, working towards their Ph.D. degrees.

Bernaciak is studying final-state photon radiation and mixed EW + QCD higher-order corrections in the process $p\overset{(-)}{p} \to W^{\pm} \to \ell^{\pm}\nu$. She has been extending the Monte Carlo program WGRAD, which includes the complete $\mathcal{O}(\alpha)$ electroweak (EW) radiative corrections to $p\overset{(-)}{p} \to W^{\pm} \to \ell^{\pm}\nu$, to include multiple soft final-state photon radiation (mFSR) from a final state lepton using the QED structure function approach. She is currently studying the combined effects of EW and QCD higher-order corrections to this process by including initial-state QCD corrections at next-to-leading-order (NLO). In addition to mFSR and QCD NLO corrections, she plans to model initial-state parton shower effects using the POWHEG parton shower generator. She will then study effects on the W boson mass and other observables from mixed EW + QCD corrections up to NNLO, initial-state parton showering, and final-state multiple soft-photon radiation.

Neill calculated the two-loop matching coefficients for the dimension-eight operators that contribute to Higgs production via gluon fusion [36]. The coefficients can be used to calculate the first correction to the infinite-top-mass limit to Higgs production with large transverse momentum at two loops. To date such processes have been studied at two-loop order only for the leading term in the top mass expansion. These corrections become enhanced in processes with large final-state invariant mass, typical of multijet processes. Neill is also using extended effective theory to study the real and virtual corrections to processes producing the Higgs with large transverse momentum, such as $pp \to H + j + X$. He has also begun investigating issues of Higgs production in bottom quark fusion using SCET. Questions of interest include precise determination of role of the b-quark PDFs, the resummation of mass logarithms, and also possible non-perturbative corrections from higher twist operators.

During his time as a LHC-TI fellow, Putman has worked on developing the collinear factorization scheme that factorizes into the PDFs all terms that arise from the universal collinear limit. Comparing this factorization scheme to MS-bar reveals that it factorizes logarithmic terms that arise from the d-dimensional phase space, as well as polynomial terms that arise from the d-dimensional splitting functions. The logarithmic terms are at times quite large and can contribute a large fraction of the higher-order correction. Putman has generated a set of collinear scheme PDFs and tested his factorization scheme and scale choice on the Drell-Yan process, as well as Higgs production from gluon fusion. In both cases the collinear scheme shows advantages over the MS-bar factorization scheme, producing much smaller explicit corrections.

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Postdoctoral Mentoring Plan

Fostering postdoctoral professional and scientific development is *the* primary rationale for the LHC-TI Postdoctoral Fellowship program. Postdoctoral mentoring is specifically incorporated into the selection criteria and in the annual fellows meetings.

Selection Process

As described in section 4.3 of this proposal, the faculty sponsor is expected to serve as the scientific mentor for the postdoctoral nominee, and not simply as a scientific collaborator. To this end, the sponsor's nomination letter must describe:

- The fellowship project and its relation to existing or planned theoretical collaborations.
- The mentoring activities that the sponsor plans on behalf of the nominee.

This information allows the Screening Committee to judge whether the faculty sponsor is likely to provide the support and scientific mentorship necessary to successfully complete the fellowship project, as well as to foster the fellow's professional development. The Screening Committee's evaluation criteria will follow those used by NSF in evaluating postdoctoral mentoring plans in grant proposals (see sec. II.C.j of NSF-09-29).

Fellows Meetings

As described in section 4, the Steering Committee is organizing annual meetings patterned after the successful SSC Fellows meetings run by the Texas National Research Laboratory Commission. The meetings will allow the fellows to:

- Receive feedback on their work from their peers (other LHC-TI fellows), as well as from senior scientists (including host laboratory personnel and Steering Committee members, as well as other interested members of the community).
- Participate in practical training sessions offering in-depth exposure to a broad array of LHC-related technical tools being developed.
- Attend sessions devoted to professional development, including information on applying and interviewing for faculty positions, teaching and outreach strategies, writing grants, and giving seminars or colloquia.

The meeting will be open to present and past LHC-TI fellows; all current and newly appointed fellows will be expected to attend. All current and newly appointed postdoctoral fellows will be required to speak. All fellows will be given the opportunity to run tutorial sessions for the graduate and postdoctoral fellows attending the meeting.

It is expected that the fellows will form the nucleus of an active LHC theory community in the US over the coming decades. Therefore the workshops will provide ample opportunity for the fellows to interact among themselves. In this way the LHC-TI will facilitate the formation of collaborative networks between particle theorists that will be vital to answering the scientific questions raised in sections 2 and 3 of this proposal.

The next fellows meeting will be held October 29-30, 2009, hosted by the Fermilab theory group.