The LHC Theory Initiative:
from the Standard Model to New Physics

October 24, 2005

The LHC-TI Steering Committee

Jonathan Bagger (Johns Hopkins University)

Ulrich Baur (State University of New York at Buffalo)

R. Sekhar Chivukula (Michigan State University)

Sarah Eno (University of Maryland)

Walter Giele (Fermi National Accelerator Laboratory)

JoAnne Hewett (Stanford Linear Accelerator Center)

Ian Hinchliffe (Lawrence Berkeley National Laboratory)

Paul Langacker [*Chair*] (University of Pennsylvania)

Steve Mrenna (Fermi National Accelerator Laboratory)

Fred Olness (Southern Methodist University)

Lynne Orr (University of Rochester)

John Parsons (Columbia University)

Martin Schmaltz (Boston University)

Carlos Wagner (Argonne National Laboratory and EFI, University of Chicago)

Edward Witten (Institute for Advanced Study, Princeton)

with contributions from

Csaba Csaki (Cornell University)

David Kaplan (Johns Hopkins University)

Konstantin Matchev (University of Florida)

Maxim Perelstein (Cornell University)

David Rainwater (University of Rochester)

Ira Rothstein (Carnegie Mellon University)

Predictions are rather difficult,
especially if they concern the future.
Niels Bohr, 1885 – 1962

A Executive 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 thoroughly tested framework for describing matter particles (quarks and leptons) together with the mediators of the strong and electroweak interactions (gluon, photon, W and Z bosons). Nevertheless, 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 2007, the Large Hadron Collider (LHC) at CERN will begin operation. The LHC will collide protons at a center-of-mass energy of $\sqrt{s} = 14$ TeV with a nominal 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 what the Fermilab Tevatron has achieved so far.

With its unprecedented energy and luminosity, the LHC promises to revolutionize particle physics. It will unveil the mechanism of electroweak symmetry breaking and shed light on how matter acquires mass. Moreover, its reach for revealing new phenomena is dramatically higher than that of all previous accelerators. The LHC truly will be a discovery machine.

Accurate theoretical predictions are needed for the LHC to realize its full potential. Many of the most important signatures at the LHC are complex and contain many particles. The lowest-order predictions for such processes exhibit significant uncertainties which can be reduced by including higher orders in perturbation theory. It is important to explore signatures and strategies to make the most of the new discoveries.

The **intellectual merit** of the activities proposed here is to provide calculational tools and theoretical results necessary to fully exploit the physics potential of the LHC. Proposed activities include calculations of higher-order QCD and electroweak corrections in the SM, supersymmetric theories, and other 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 various theoretical models, such as Little Higgs, Higgsless, or Randall-Sundrum models, or extensions of the Minimal Supersymmetric Standard Model (MSSM). Much remains to be done to obtain precise calculations of SM processes and to understand the signatures of new physics. Both will be important to realize the full physics potential of the LHC data, and to allow the US theory community to benefit from the considerable investment made in the LHC experiments.

The SM calculations which are of highest priority are:

1. Improving parton distribution functions, including next-to-next-to-leading order effects, with improved uncertainties.

2. Improving calculations of basic QCD processes such as multijet production which will be used as calibration tools for the detectors. Without a detailed understanding of such processes it will not be possible to successfully search for new physics phenomena.

3. Carrying out more precise and reliable calculations of background processes which are relevant for the Higgs search. These include $t\bar{t}j$, $t\bar{t}b\bar{b}$, $t\bar{t}jj$ and $WWjj$ production.

For new physics calculations, the highest priorities are:

1. Implementing scenarios such as models with extra dimensions, Little Higgs or Higgsless models, or extensions of the MSSM involving extended Higgs sectors, new gauge bosons or exotics in Monte Carlo event generators.

2. Investigating how models can be distinguished in LHC experiments.

3. Finding ways how to determine the basic parameters of new physics, such as couplings, the spin or the electric charge of new particles.

To stimulate research on LHC related theory, and to accomplish the goals listed above, a system of named nationwide postdoctoral and graduate student Fellowships is being proposed.

- Fellowships would be awarded in open nationwide competition. Fellowship funds may be used for salary, fringe benefits, research support, and administrative fees.

- Approximately 4 postdoctoral and 6 graduate Fellowships would be awarded per year, although the actual numbers could vary from year to year based on the available funding and the pool of applicants. The program is targeted initially for a period of 5 years.

- Each Fellowship is awarded to support the research of a particular individual, and if a postdoctoral (student) Fellow is hired into a junior faculty (postdoc) position the balance of the funds will be transferred to support the Fellow's work at the new institution. The transferability of the award is predicated on the importance of the Fellow's research, and will therefore enhance the Fellow's credentials.

The **broader impact** of the proposed activities is to facilitate the development in the United States of a world-class program in collider theory, in general, and in LHC-related theory, in particular. The graduate and postdoctoral Fellows will provide a nucleus of a vital US LHC theory community over the projected twenty-year lifetime of the LHC. The nomination of women, members of underrepresented minority groups, and persons with disabilities will actively be sought.

Two annual meetings will be held to stimulate collaborative research and personal links between the Fellows, their sponsors, and the ATLAS and CMS experimental collaborations. In addition to a presentation of results, these meetings could include practical training sessions for the graduate student Fellows run by the postdoctoral Fellows or guest lecturers, and feedback from the experimental collaborations on issues arising from experimental analyses. The continuity of these links will be insured through the use of regularly-scheduled video conferences.

The proposed activities will be pursued within the framework of the LHC Theory Initiative (LHC-TI), a nationwide community effort to promote LHC-related theoretical research involving both the model building and phenomenology theory communities. The tools developed will be made publicly available and will help the experimental high-energy physics community to fully exploit the potential of the LHC. Scientific results will be published in peer-reviewed journals, via the World Wide Web, and will be presented at national and international conferences. Finally, the meetings of the Fellows will be open to the US particle theory community, and, together with the collection of Fellows, will provide a backbone for a nationwide collaborative theory network, making it possible for physicists from isolated groups and smaller institutions to participate and focus their efforts on projects that are directly relevant to the LHC.

B Project Description

B.1 Introduction and Motivation

In 2007, the Large Hadron Collider (LHC) at CERN will begin operation. The LHC will collide protons at a center-of-mass energy of $\sqrt{s} = 14$ TeV with a nominal 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 what the Fermilab Tevatron has achieved so far.

With its unprecedented energy and luminosity, the LHC promises to revolutionize particle physics. It will unveil the mechanism of electroweak symmetry breaking and shed light on how matter acquires mass. Moreover, its reach for revealing new phenomena is dramatically higher than that of all previous accelerators. The LHC truly will be a discovery machine.

Close collaboration between theorists and experimenters is extremely important for the planning and interpretation of experimental data. This is illustrated by the high precision Z pole experiments at LEP and the SLC during the 1990's [1]. These experiments showed that the SM is correct and unique to zeroth approximation, establishing the gauge principle and the standard model group and representations; that the SM is correct at the loop level, establishing the basic principles of spontaneously-broken gauge theory and leading to the successful prediction of the top quark mass; that the data is consistent with a light elementary Higgs; and that the gauge couplings are consistent with supersymmetric grand unification. None of these consequences could have been obtained from the data alone without major input from theory.

To unravel the mechanism of electroweak symmetry breaking and to discover new physics, it is necessary to have accurate theoretical calculations of SM processes and new physics signatures alike. The final states of many processes that are of interest at the LHC are complex and have high multiplicity. The lowest-order predictions for such processes in the SM exhibit a significant dependence on the unphysical renormalization and factorization scales which can be traced to the truncation of the perturbation series. The dependence on these parameters can be reduced by calculating physics observables to higher order in perturbation theory. For accurate SM predictions it is therefore necessary to calculate higher QCD and, in some cases, electroweak radiative corrections. For new physics scenarios, on the other hand, it is important to explore unique signatures and strategies to characterize the model.

However, calculating higher-order corrections and exploring the signals of new physics is not sufficient to successfully search for new phenomena at the LHC. In order to arrive at realistic predictions which can be used by the experimental community, the matrix-element based theoretical calculations have to be integrated and merged into Monte Carlo (MC) event generators, a process which, especially at higher order in perturbation theory, is not well understood yet.

While there has been much progress on both more precise calculations of SM processes and understanding the signatures of new physics in the last few years, much remains to be done in order to ensure that the full physics potential of the LHC can be utilized. We demonstrate this in Secs. B.2 and B.3. Much of the work can be accomplished in a timely fashion by a moderate increase of the number of postdocs and graduate students in the US working on LHC-related theory. We believe that an additional 4 postdocs and 6 graduate students per year over a 5 year period would be sufficient to ensure that the physics return of the LHC is optimized.

In order to stimulate more research on LHC related theory, we propose to establish graduate student and postdoctoral Fellowships, which are described in some detail in Sec. B.4. These

Fellowships require funds of approximately \$865k per year, a moderate investment in view of the price tag of the LHC and the high expectations of the physics community and the public.

B.2 Precision Calculations of Standard Model Cross Sections

The LHC is scheduled to begin operation in 2007, with the first physics run taking place in 2008. While we cannot anticipate which new physics will be discovered at the LHC, we do know that there are plenty of SM processes to be observed. In many cases, these processes offer themselves the potential for important measurements, such as the determination of the W mass, or the mass of the top quark which will make it possible to indirectly constrain the mass of the Higgs boson [2]. More in general, they provide potential backgrounds to many signals of new physics. A productive physics program at the LHC will therefore require a detailed understanding of SM processes, and of QCD in particular. *Without a detailed understanding of QCD it will be impossible to analyze LHC data.*

One of the cleanest processes in hadronic collisions, experimentally as well as theoretically, is the production of W and Z bosons. These processes may serve as luminosity monitors. Approximately $7 \cdot 10^7$ (10^7) $W \to e\nu$ ($Z \to e^+e^-$) events are expected for an integrated luminosity of 10 fb^{-1} at the LHC, which roughly corresponds to what one hopes to accumulate in the first year of running. The total cross sections for W and Z production at NNLO in QCD have been known for more than a decade [3]. More recently, a calculation of the weak boson rapidity distribution at NNLO has been performed, reducing the theoretical uncertainty for the cross section to $\mathcal{O}(1\%)$ [4]. At this level, electroweak radiative corrections become relevant [5–7], and a precise knowledge of the parton distribution functions (PDFs) becomes essential (see Sec. B.2.1).

The production of $t\bar{t}$ pairs at the LHC will occur with an inclusive rate of roughly 1 Hz. This will not only make it possible to measure the top quark mass with a precision of about $\pm 1 - 2$ GeV [8], but also to probe the couplings of the top quark to gauge bosons [9] and the Higgs boson [10–13]. To fully utilize the potential of the LHC in these measurements, the cross sections of the relevant SM processes need to be known including NLO QCD corrections, which in general reduce the dependence of cross sections on the unphysical factorization and renormalization scales. $t\bar{t}j$, $t\bar{t}jj$, $t\bar{t}b\bar{b}$, $t\bar{t}\gamma$, and $t\bar{t}Z$ production are some of the processes which are of interest for these measurements.

A SM Higgs boson, if it exists, is likely to be discovered within the first few years of LHC operation [12, 14]. For $m_H > 180$ GeV discovery will be easy thanks to the gold plated channel $H \to ZZ \to 4$ leptons. For 130 GeV $< m_H <$ 180 GeV the vector boson fusion (VBF) channel $qq' \to qq'H \to qq'WW^{(*)}$ offers the best chance. For $m_H < 130$ GeV, $qq' \to qq'H \to qq'\tau^+\tau^-$, $H \to \gamma\gamma$, and $t\bar{t}H(\to b\bar{b})$ play important roles. There has been much progress in recent years in providing reliable predictions for Higgs boson production, and also for some of the relevant backgrounds. Higgs boson production via gluon fusion is known now at NNLO [15], and a fully differential NNLO calculation of $gg \to H \to \gamma\gamma$ is available [16]. Furthermore, the continuum $\gamma\gamma$ background is known at NLO, including the $gg \to \gamma\gamma$ contribution [17], and the NLO QCD corrections to $qq' \to qq'H$ [18] and $t\bar{t}H$ [19] production have been calculated. However, a number of background reactions are still only known at leading order. Once a Higgs boson candidate has been found, the emphasis of the Higgs physics program will shift to determining the couplings of the newly found particle to fermions and gauge bosons [20], as well to the Higgs boson self-coupling, λ_{HHH} [21–23]. QCD corrections to Higgs boson pair production, and many of the backgrounds relevant for measuring λ_{HHH} are not fully known yet.

The observation of supersymmetry (SUSY) at the LHC should be relatively easy and fast, once detectors are calibrated and backgrounds are well understood [24–26]. The cross sections for the production of squarks and gluinos are very large, and the LHC experiments thus should be able to discover these particles with masses up to ~ 1.5 TeV in only one month of data taking at a luminosity of $\mathcal{L} = 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. If R-parity is conserved, the most powerful and model-independent signature is multi-jet plus missing transverse energy, $\not\!\!E_T$, production. The main backgrounds in these channels are QCD multijet events where one or several jets are badly mismeasured, $t\bar{t}$, $W+$ jets, and $Z(\to \bar{\nu}\nu)+$ jets production. A recent matrix element based calculation of the leading order (LO) $Z(\to \bar{\nu}\nu) + 4$ jet background [27] has resulted in a dramatic increase of the background to SUSY searches in this channel and underlines how important improved SUSY background calculations are. The LO multi-jet and $W/Z+ > 2$ jet cross sections depend strongly on the factorization and renormalization scales. While data for some background processes may be helpful in reducing the normalization uncertainty, this procedure is no substitute for a NLO calculation; NLO QCD corrections often affect the normalization *and* the shape of distributions. NLO calculations for (at least some of) the relevant reactions will thus be very important for supersymmetry and other searches for new physics at the LHC.

However, calculating higher-order corrections is not sufficient. In order to arrive at realistic predictions, the theoretical calculations have to be integrated into MC event generators. At higher orders, this is still a difficult task (see Sec. B.2.4).

In the remainder of this section we describe in somewhat more detail which SM physics projects the LHC Theory Initiative believes are important to pursue. The priority of a project is determined by the integrated luminosity needed for the process to become relevant.

B.2.1 Parton Distribution Functions and NNLO QCD Corrections

PDFs are essential for nearly every measurement planned for the LHC. Without the PDFs, it is impossible to relate the theoretically calculable world of quarks and gluons to the experimentally measurable world of hadrons. Specifically, LHC calculations use the parton model formula $d\sigma = f \otimes d\hat{\sigma} \otimes f$, where $d\sigma$ represents the physically measurable hadronic cross section, and $d\hat{\sigma}$ represents the theoretically calculable partonic cross section; the PDF functions (f) are the key which connects these two quantities. Since many measurements at the Tevatron were statistics limited, the precision of the current PDF sets was sufficient for most of these analyzes. However, since the LHC will have dramatically higher luminosity (and statistics), it is critical to improve the precision of the PDF so this uncertainty does not become a limiting factor.

A thorough understanding of the hadronic structure and their derived PDFs is essential to making incisive tests and identifying significant deviations from SM predictions. When the LHC begins taking data, one expects to find measurements which deviate substantially from the SM predictions. It is important that tools are developed to make discriminating comparisons between data and theory so that one can efficiently dismiss the deviations which are spurious, and focus on those that have merit. Examples of spurious deviations from the SM which occurred in the past are the excess of high E_T jets observed at the Tevatron [28], and the excess of neutral current events over the SM expectation in the large x and Q^2 region at HERA [29, 30]. Without an improved knowledge of the PDFs, we will be unprepared to make discriminating comparisons of theoretical predictions and experimental observations which advance our base of knowledge and simultaneously prepare a foundation for understanding new phenomena.

The scope of the global analysis of PDFs is necessarily very broad and relies on a diverse network of physicists—this is ultimately a community effort. It requires input from the theorists who have performed the calculations to ensure they are properly incorporated into the analysis frame work. It also requires assistance from experimentalists who are familiar with the data analysis, particularly the systematic errors, to ensure correlations are properly implemented. Finally, it requires a joint effort to assemble the pieces, evaluate the results with a balance of science and art, and extract the utmost information from the data.

In the following, we discuss several improvements to the global PDF analysis which are needed for data analysis at the LHC.

NNLO parton distribution functions and NNLO corrections to jet production As experimental precision improves, it is important that the theoretical calculations keep pace. This means that while NLO accuracy was generally sufficient at the Tevatron, NNLO precision will be necessary to reach the LHC goals for many analyzes. The NNLO evolution kernels for the PDFs have recently been computed [31–34], and these advances are now being incorporated into the various evolution programs. Additional work is still needed to integrate these programs and standardize the interface to the NNLO PDF evolution routines; such tools will allow numerical cross-checks between x-space and n-space routines (particularly at extreme values of x), and will facilitate broader use of these programs.

However, the NNLO evolution alone is not sufficient; these NNLO kernels must be matched with NNLO calculations to maximize the predictive power of the theory. Implementing the various NNLO processes in the global analysis is a formidable task. The necessary ingredients are available for the DIS structure functions [33–35] and the Drell-Yan process [36] at NNLO. However, for the other sub-processes used in the global analysis, particularly those which are less inclusive, there significant challenges remain.

Specifically, work is needed on jet production, direct photon production, and heavy quark production. For many of these sub-processes, the NNLO matrix elements have been computed [37, 38]; however, combining those with the real emission diagrams, properly taking into account soft and collinear subtractions, still requires a major collaborative effort. There are currently two promising approaches to isolate the soft and collinear singularities at NNLO: the so-called "antenna subtraction" method [39], and sector decomposition [40, 41]. The antenna subtraction method so far has only been applied to e^+e^- processes. Sector decomposition in principle is very easy to automate and gives fully differential results. For hadronic collisions, so far it has been applied to $2 \to 1$ processes, such as W/Z and Higgs boson production, [40]. Extending the method to $2 \to 2$ processes (di-jet, heavy quark and direct photon production) should be feasible.

Generalized PDFs Resummation is a technique which can be used to sum large logarithmic terms to all orders, thereby maximizing the predictive power of fixed order calculations. In many processes, it is still impossible to adequately describe differential distributions even though calculations have been carried out to NLO (and sometimes beyond). Transverse momentum distributions have been a particularly difficult problem, and this has stimulated interest in k_T-dependent PDFs (or un-integrated PDFs) which attempt to account for initial-state radiation through parton distributions that depend the parton's transverse momentum k_T (in addition to the longitudinal momentum fraction x) [42–45].

While k_T-dependent PDFs may provide an improved reorganization of the perturbation expansion, there are unresolved theoretical issues, such as the universality of the k_T-dependent parton distributions. Note that simply including a phenomenological k_T-smearing on top of a standard calculation does not yield the same information, or same results, as the full k_T-dependent PDF formalism; such differences are particularly noticeable in the tail of the distributions. Consequently, one cannot trivially factorize the k_T and x dependence separately, and a more through analysis is required.

An example of one instance where the k_T-dependent PDF formalism might be used effectively is direct photon production. While in principle this process should directly provide information on the gluon PDF, the inability to accurately calculate the initial-state radiation and resulting transverse momentum has severely limited the usefulness of this data in the past. Recent developments using resummation techniques show promise that we may now be able to overcome the previous difficulties. This fact, plus new data at higher p_T, suggest that revisiting the direct photon process may prove fruitful. Hence, it would be worthwhile to include both the updated resummed calculation and new data into the global analysis.

Gluon Distribution Because the gluon does not couple to the γ, W, and Z probes of DIS, it has been more difficult to characterize the gluon PDF; consequently, the gluon PDF has larger uncertainties than the corresponding quark distributions. The Tevatron jet production data plays 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 certainly an important process to study.

At present, we do have NLO calculations for the single jet inclusive cross section, and this information is used in the global analysis. However, there are many other observables measured at the Tevatron, such as the two jet differential cross section, which need to be both 1) included in the global analysis, and 2) extended to NLO precision. Again, many of the ingredients for this work are available, but it is essential to have the tools in place when it is time to analyze the LHC data.

Heavy Quark PDFs There are several processes of interest at the LHC which depend on the b-quark PDF's. One of these processes is t-channel single top production [8]. Other processes which critically depend on the b-quark distribution are SUSY Higgs production from $b\bar{b}$ fusion, and SUSY Hb production [46]. Subprocesses with a charm quark in the initial state contribute at the several percent level to many scattering processes at the LHC. Understanding heavy quark distributions thus will be very important for LHC physics. None of the data in the current global PDF analyzes directly measure the charm and bottom quark distributions; instead the c- and b-quark distributions are entirely derived from theoretical arguments. Tevatron data on γ/Z production in association with c- and b-quarks are becoming available [47]. These data have to be incorporated into future releases of global PDFs.

PDF Uncertainties: The Unknowns In order to decisively distinguish conventional physics signals from new phenomena, it is imperative to quantify the uncertainty originating from PDFs. The wealth of precision data available for the QCD global analysis allows extraction of highly constrained PDFs with uncertainties [48, 49]. The release of PDFs with uncertainties represents a significant advance in our ability to make quantitative estimates for the error of a particular observable. Using CTEQ6 [48] PDFs, one can re-evaluate, for any given LHC observable, the result using the 40 PDF sets to determine the inherent PDF uncertainty. This method does a good job of quantifying the inherent uncertainty of the data sets which are used in the global analysis (*"known-unknowns"*); however, there is another very important set of uncertainties arising from a variety of sources—some of which we can characterize (e.g., choice of data sets, inherent constraints of the parameterizations), and some we cannot. This latter class of uncertainties (*"unknown-unknowns"*) can in fact be larger than the first (*"known-unknowns"*). For example, the Hessian method [50], which was used in the CTEQ6 analysis, may significantly underestimate the true uncertainty in the strange quark distribution; none of the data in the global PDF analysis directly measures it. This can be overcome by using recent CCFR and NuTeV charged-current charm production ($\nu s \to c\mu \to \mu^{\pm}\mu^{\mp}X$) data. The inclusion of this data into the global analysis is in progress, however, it is limited by available resources.

Small-x broadening of the W and Z boson transverse momentum distribution is an example for *"known-unknowns"*. The LHC will span a much larger kinematic range than the Tevatron; therefore, W and Z production at the LHC will involve PDFs from an entirely different kinematic regime. In particular, W and Z bosons at the LHC will be produced with partons that carry a much smaller momentum fraction x than those at the Tevatron. Analysis of semi-inclusive DIS hadroproduction indicates a broadening of transverse momentum distribution in the small-x region below a few 10^{-3} [51]. These results imply there can be substantial small-x broadening in forward Z boson production at the Tevatron Run II; if this is observed, it will strongly affect predicted p_T distributions for $W^{\pm}$, Z, and Higgs boson production at the LHC [52]. The predicted effect may easily exceed the other uncertainties, resulting in important implications for the measurement of the W boson mass from both transverse mass and transverse momentum distributions. The selection requirements imposed on the Higgs boson candidates in the $\gamma\gamma$ decay channel may have to be reconsidered to account for the non-uniform broadening in the signal and background processes. To properly prepare for LHC data, the forward production of W and Z boson at the Tevatron should be carefully studied, and tools should be refined so that calculations can quickly be cross checked using the initial data from LHC when it begins operation.

The example of W and Z production suggests that the combination of the extended kinematic range, together with increased precision, will force us to broaden the scope of our theoretical tools at the LHC. The need for the PDFs arises within the framework of QCD factorization which is based on the DGLAP physics picture. As we go to the LHC, we have to ask if the canonically understood DGLAP picture has limitations, *e.g.*, at small x or for exclusive observables. We also must ask if an alternative framework (BFKL) [53] or hybrid DGLAP-BFKL framework (CCFM) [54] will be needed in parts of the LHC phase space; if so one has to identify the affected kinematical regions and determine the most accurate scheme to implement these calculations.

B.2.2 Standard Model Predictions

In the transition from the Tevatron to the LHC, the top quark pair production cross section increases by two orders of magnitude. Top quark pairs will be both a calibration (e.g. in setting the jet energy energy scale (JES) for the calorimeters) and a copious source of background to other searches. The JES can be determined *in situ* using the $W \to jj$ decay in

$t\bar{t} \to W^+ bW^- \bar{b} \to \ell +$ jets ($\ell = e,\, \mu$) events [8], similar to the strategy recently employed by CDF [55] and DØ [56]. This requires that QCD corrections, and in particular the radiation of extra jets in $t\bar{t}$ events, are under control. Currently, the NLO QCD corrections to $pp \to t\bar{t} \to b\bar{b} + 4f$ with $f = \ell,\, \nu,\, q$ are known in the pole approximation, ie. non-factorizable corrections are ignored [57]. Although the non-factorizable corrections are suppressed by powers of Γ_t/m_t, where Γ_t is the top quark width, it is known that non-resonant contributions to tree-level $t\bar{t} \to b\bar{b} + 4f$ production significantly modify the cross section [58], especially when cuts are imposed. For example, imposing selection cuts for $qq' \to qq'H \to qq'WW^{(*)}$, the non-resonant contributions may double the rate of the $t\bar{t}$ background for $H \to WW^{(*)}$ in VBF [58]. The non-factorizable QCD corrections to $pp \to t\bar{t} \to b\bar{b} + 4f$ may thus be relevant, not only for a precision measurement of m_t, but also for $H \to WW^{(*)}$ in VBF.

Technically, a calculation of the full NLO QCD corrections for $pp \to t\bar{t} \to b\bar{b} + 4f$ involves the calculation of massive 5- and 6-point functions. Recent advances [19, 59] have made the calculation of these classes of Feynman diagrams possible, but the complete calculation has not been done.

Top pair production is probably not the main background in $qq' \to qq'H \to qq'WW^{(*)}$; the dominant backgrounds are $t\bar{t}j$ and $\mathcal{O}(\alpha^4)$ $WWjj$ production [60]. Since $H \to WW^{(*)}$ in VBF is a major discovery mode of a light SM Higgs boson with an integrated luminosity of $10 - 30$ fb^{-1}, a calculation of the NLO QCD corrections to these processes is of high priority. $t\bar{t}j$ production is also an important background for $t\bar{t}\gamma$ production which makes it possible to probe the $tt\gamma$ couplings. Even with an integrated luminosity of only 30 fb^{-1} a measurement of the $tt\gamma$ vector and axial vector couplings with a precision of $\mathcal{O}(10\%)$ may be possible [9], provided that the SM $t\bar{t}\gamma$ rate is known to NLO accuracy. Due to the smaller cross section, the ttZ couplings can be probed only with an integrated luminosity of $\geq$ 300 fb^{-1}. A calculation of the NLO QCD corrections to $t\bar{t}Z$ production thus is less urgent.

In order to identify $qq' \to qq'H \to qq'WW^{(*)}$, one relies on the leptonic decays of the $WW^{(*)}$ system, tagging the two forward jets, and on a jet veto in the central rapidity region [60]. The central jet veto requires a detailed understanding of the jet activity in $qq' \to qq'H$ events. This is best achieved by performing a calculation of the resummed QCD corrections to $qq' \to qq'H$.

For small Higgs boson masses, $t\bar{t}H$ production with $H \to b\bar{b}$ may be an important Higgs discovery channel. In addition, it allows a measurement of the top Yukawa coupling with a precision of about $30 - 40\%$ [11, 13, 20]. The main backgrounds are $t\bar{t}b\bar{b}$ and $t\bar{t}jj$ production which are both known to LO only at present. While the normalization of these backgrounds can be obtained from data, information on its shape relies on theoretical calculations [13]. Since $pp \to t\bar{t}H \to t\bar{t}b\bar{b}$ will be observable for 30 fb^{-1}, calculations of the NLO QCD corrections for these processes have a high priority.

For 150 GeV $< m_H <$ 200 GeV, $pp \to t\bar{t}H(\to W^+W^-)$ promises a measurement of the top Yukawa coupling with a precision of $15 - 25\%$ for 30 fb^{-1} [10]. In this channel, $t\bar{t}Wjj$ production is the largest background. Its calculation involves the evaluation of several thousand Feynman diagrams and, due to insufficient computational resources, it had to be approximated in Ref. [10]. A full tree level calculation of the $t\bar{t}Wjj$ background should be feasible with current GRID resources, and is required to more accurately assess how precisely the top Yukawa coupling can be measured in $t\bar{t}H$, $H \to W^+W^-$ production.

If a Higgs boson candidate is found, emphasis will shift to determine its quantum numbers and how the new particle couples to fermions, weak bosons, and to itself (Higgs self-coupling).

These studies require an integrated luminosity of 100 fb^{-1} or more, in particular the measurement of the Higgs self-coupling which would greatly benefit from a luminosity upgrade of the LHC. For $m_H > 140$ GeV, the reaction $pp \to HH \to \ell^\pm \ell'^\pm + 4j$ offers the best prospects to measure λ_{HHH} [21]. For 300 fb^{-1} it may be possible to exclude a vanishing of λ_{HHH} if 150 GeV $<$ $m_H <$ 200 GeV, and for 3000 fb^{-1} a measurement with a precision of 30% may be feasible provided the normalization of the SM signal and the most important backgrounds, $t\bar{t}j$, $t\bar{t}W$ and $WWWjj$ production, are known to better than 30%. To achieve this, the NLO QCD corrections for these processes are needed. The NLO QCD corrections for $gg \to HH$ are currently known in the $m_t \to \infty$ limit [61], which unfortunately is not sufficient to yield accurate predictions for differential cross sections [21]. While computing the NLO QCD corrections to $gg \to HH$ and $t\bar{t}W$ production appears to be feasible with current technologies (for $gg \to HH$ this involves the evaluation of two-loop diagrams), it would require the calculation of 7-point functions for $pp \to WWWjj$, which has not been done before. Such a calculation will without doubt be technically very challenging and time consuming; however it will not be required before a luminosity upgrade of the LHC, ie. not before 2015.

For $m_H < 140$ GeV, $HH \to b\bar{b}\gamma\gamma$ offers the best chances to probe the Higgs self-coupling [23]. In this channel, the rate is so small that a luminosity upgraded LHC is needed to measure λ_{HHH}. The NLO QCD corrections of none of 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 been calculated so far.

Four jet production is also an important background for SUSY searches, and so are $pp \to W/Z + n$ jet ($n \geq 3$). The calculation of the NLO QCD corrections to $W/Z + 3$ jet production involves 6-point functions and should be feasible with current calculational techniques. For $W/Z + 4$ jet production one faces the same obstacles as for $pp \to WWWjj$.

In addition to the processes discussed above, the NLO QCD corrections to $V_1V_2 + n$ jet and $V_1V_2V_3 + n$ jet production ($V_i = W,\ Z,\ \gamma,\ i = 1, \ldots 3,\ n = 1, 2$) have been identified [62] as being important for new physics searches at the LHC where these processes often contribute to the background.

B.2.3 Automation of Higher Order Calculations and Analytical Properties of QCD Amplitudes

For the most part, the calculations proposed in Sec. B.2.2 involve one-loop QCD diagrams. In order to achieve the goals of this project in a timely fashion, automatic, or semi-automatic, tools have to be used. Over the past few years, an automatic program for the calculation of electroweak one-loop corrections (`Grace`) has been developed [63]. Such a tool does not yet exist for QCD one-loop calculations, although several semi-automatic tools are available [64, 65] and work on extending `Grace` to include QCD corrections has begun [66]. Members of the Fermilab theory group recently have started a new approach, called `Samper`, towards developing an automatic program for evaluating one-loop QCD diagrams. The approach is based on a semi-numerical evaluation of one-loop amplitudes [67–69]. By using the Davydychev decomposition, tensor integrals can be reduced to generalized scalar integrals. These scalar integrals can be reduced to a set of analytically known base integrals using a recursion scheme derived from integration-by-part techniques (see Ref. [67] for a list of other recent semi-numerical approaches). The key point of the method developed by the Fermilab group is that a record is kept of all previously computed integrals, so that each is calculated only once. The processes calculated using this method are targeted to be included in the program MCFM [70], which already contains a number of processes at NLO which are of interest for data analysis at the LHC. For the LHC Theory Initiative, the completion of Samper, and its application to (at least some of) the processes described above, are of the highest priority and it intends to strongly support these through the proposed Fellowship program.

A promising alternative to Samper is to utilize recent progress in the analytical understanding of massless and massive tree-level [71] and massless one-loop [72] gauge theory amplitudes which was stimulated by Witten's proposal [73] of a weak-weak coupling duality between $\mathcal{N} = 4$ supersymmetric gauge theory and the topological open-string B model in twistor space. This has led to considerably more compact expressions and recursion relations which promise a much faster numerical evaluation of differential cross sections. The next steps in bringing this approach to fruition are to generalize the results for massless one-loop diagrams to the massive case, and to build parton-level MC programs for processes of interest which take full advantage of the analytical results.

B.2.4 Interface of LO and NLO QCD Calculations with Parton Showers

Parton shower MC programs, such as Pythia [74], Herwig [75], and Sherpa [76], form the bridge between hard scattering fixed order calculations and the (fully exclusive) observed final state. This is accomplished by resumming soft and collinear radiation. After the partonic shower, (parametric) hadronization models are added.

Most existing shower MC programs are based on angular/energy ordered $1 \to 2$ branching. However, in QCD, gluon radiation has a dipole structure, ie. it is based on a $2 \to 3$ branching. Developing improved shower algorithms thus is important. An example for such an improved algorithm is Vircol [77]. It is based on $2 \to 3$ branching and promises to exactly match fixed order calculations (NLO as well as LO), full phase space coverage, and a better description of hadronic radiation outside of a jet cone. The final goal is to integrate Vircol with MCFM/Samper to provide the same functionality as MC@NLO [78], however, for different processes and using a better shower approach.

Even with an improved shower MC program available, Pythia, Herwig and Sherpa will still play important roles in the LHC data analysis. Standard parton showers are based on a leading-log approximation, and must be supplemented with matrix-element (ME) corrections to accurately predict large p_T emissions. However, such corrections are only available for relatively simple cases where the kinematics of the matrix element can be mapped into those of the first or hardest splitting in a shower. It is therefore natural to attempt a more systematic merging of ME calculations with the shower MC programs to improve their accuracy in the high p_T region. There are several approaches [79–81] which lead to similar results. All approaches start by generating tree level predictions for multiparton processes using automated tools which are subject to parton-level cuts to guarantee a fixed number of cone or k_T jets satisfying a given jet criteria. One specifies minimum values of E_T and ΔR or k_T for cone or k_T jets. These parton-level jets can be thought of as *hard* jets, whose production rate is valid in the limit of hard, wide-angle emissions. If one is interested in generating an inclusive sample of Z-bosons, for example, one constructs sub-samples of Z boson + N "jets", with $N = 0, 1, 2, \ldots$. The sub-samples are then subjected to a parton shower that does not change the number of *hard* jets, but adds on additional jets and gives a realistic shape to the *hard jets* (jets are no longer infinitely narrow). The final step involves a reweighting, which is implemented by throwing away the cross section associated with events where the parton shower added or dropped a *hard* jet. This can be thought of as constructing a mock parton-shower history for the event, calculating the parton-shower probability for obtaining such an event, and then performing rejection based on random numbers.

Specific prescriptions differ in how seriously this parton-shower history is taken and in the type of parton shower that is used. In principle, the parton shower kinematics should be matched exactly to the kinematics used to define the parton-level jets. In practice, this is not the case, and there is a spurious dependence on the choice of hard jet definition. It is worth noting that, while the matching described here can be used to construct an inclusive description of W or Z boson production, the overall normalization of the various sub-samples is not corrected. This would involve the inclusion of virtual diagrams which faces problems with the current shower algorithms and is one of the motivations for the development of `Vircol`. All current hadron collider applications have been either the production of QCD singlets plus jets (W and Z bosons [81], WW pairs [82], etc.), or pure jet production. Other, more complicated final states should be considered, particularly those including heavy quarks.

Alternatively to the prescription described above, one can try to directly combine NLO QCD calculations and parton showers. So far, this has only been done for `Herwig` [78]. An extension to `Pythia` or *any* event generator is desirable. Current applications at hadron colliders have been to the production of electroweak singlets and heavy quark pairs. The case of pure jet production has not yet been handled. There is currently no understanding of how to generalize beyond NLO.

There are several other “known unknowns” in connection with MC event generators which deserve further investigation. There are indications that intra-jet logarithms may be relevant. Furthermore, electroweak logarithms may become important at high energies (see Sec. B.2.5). Neither of these effects is incorporated in current event generators.

B.2.5 Electroweak Radiative Corrections to Weak Boson Production

Electroweak (EW) radiative corrections to W and Z boson production in hadronic collisions are important for several reasons. QED corrections produce a considerable shift in the measured W and Z boson masses [83, 84]. EW corrections also change the total weak boson cross section by several percent if acceptance cuts on their decay products are imposed. Finally, the weak corrections become large and negative far above the resonance region, due to Sudakov-like logarithms. This is important for searches for new physics such as Kaluza-Klein excitations of the weak boson [85], or the production of new gauge bosons which appear eg. in Little Higgs models [86]. A heavy partner, Z' of the Z boson with a mass of 1.5 TeV may be discovered at the LHC with an integrated luminosity as small as 300 pb^{-1}.

There has been much progress in the past few years in the understanding of EW corrections to weak boson production. The complete $\mathcal{O}(\alpha)$ EW corrections to W and Z boson production are known [5]. For a consistent treatment this requires PDFs which include QED corrections. Such PDFs now exist [87]. More recently, the effects of multi-photon radiation on the W and Z masses have been calculated [6]. Nevertheless, there are two important tasks left to complete before the LHC turns on.

The experimental uncertainty on the W mass, M_W, depends significantly on the $\not\!\!E_T$ resolution, ie. on how well the transverse momentum distribution of the W is known. The p_T of the W is caused by gluon radiation. The presently available calculations [5, 6] do not include

QCD corrections. *Vice versa*, calculations of QCD corrections to weak boson production such as `RESBOS` [88], do not include any EW radiative corrections. `RESBOS` includes resummed QCD corrections, augmented by a parametrization of non-perturbative corrections at small values of p_T, and is a standard tool for experimentalists for simulating the p_T distribution of weak bosons. In order to measure M_W at the (Tevatron and) LHC with the projected accuracy of ($20-30$ MeV [89]) $10-15$ MeV [90, 91], a calculation is needed which includes resummed QCD corrections, the complete $\mathcal{O}(\alpha)$ EW corrections, and multi-photon radiation effects. A first step in this direction has been made in Ref. [7] where the authors included final state photon emission from the W decay lepton in `RESBOS`.

As mentioned before, the $\mathcal{O}(\alpha)$ weak corrections to Drell-Yan production in hadronic collisions become large at high di-lepton invariant masses [5], due to Sudakov-like logarithms of the form $\ln[m(\ell\ell)/M_V]$ ($V = W, Z$) which are associated with the exchange of soft, massive gauge bosons. A similar phenomenon occurs in $pp \to \ell\nu$. For di-lepton masses larger than about 1 TeV, these corrections have to be resummed in order to obtain an accurate prediction for the differential cross section. An all-order resummation of the weak corrections in $pp \to \ell^+\ell^-$ and $pp \to \ell\nu$ can be carried out generalizing the techniques developed in Refs. [92] and [93]. Both the leading double-logarithmic and the sub-leading single-logarithmic corrections can be resummed. Such a calculation should be carried out.

B.2.6 Prioritized List of Projects

Based on the discussion in the preceding sections, we prioritize the SM projects of the LHC-TI as follows:

1. Needed at LHC startup (2007 – 2008):
   - (a) include more data sets in PDF global analysis (e.g., $pp \to jj,\ j\gamma$), extend to NNLO accuracy, enhance PDF uncertainty analysis, and assess validity of DGLAP picture.
   - (b) apply `MCFM/Samper/Vircol` to $4j$ and $W/Z+3$ jet production at NLO and pursue other new calculational techniques, such as those based on twistors.
   - (c) resum EW Sudakov logarithms in high mass Drell-Yan production
   - (d) interface $t\bar{t}+n$ jet matrix elements, including off-shell effects, with `Pythia` and `Herwig`
2. For $10-30$ fb^{-1} (2008 – 2010):
   - (a) compute full NLO QCD corrections to $pp \to t\bar{t} \to b\bar{b}+4f$
   - (b) compute full tree level calculation of $t\bar{t}Wjj$ production
   - (c) compute NLO QCD corrections to $t\bar{t}j$, $t\bar{t}\gamma$, $t\bar{t}b\bar{b}$, $t\bar{t}jj$ and $WWjj$ production
   - (d) resum QCD corrections to $qq' \to qq'H$
   - (e) interface $H+n$ jet matrix elements with `Pythia` and `Herwig`
3. For 300 fb^{-1} (2012 – 2013): compute NLO QCD corrections to $gg \to HH$, $t\bar{t}W$ and $t\bar{t}Z$ production

4. For 3000 fb^{-1} (> 2015): compute NLO QCD corrections to $WWWjj$, $jj\gamma\gamma$ and $Q\bar{Q}\gamma j$ production

B.3 Signatures of New Phenomena at the LHC

Experiments prior to the LHC have firmly established the SM as the correct description of the laws of physics below energies of order 100 GeV. The LHC will thoroughly probe the TeV energy regime for the first time. It will allow us to discover the origin of electroweak symmetry breaking, either confirming the SM or uncovering something beyond.

Theoretically, the SM is incomplete because the scale of electroweak symmetry breaking (and the mass of the Higgs boson) is quantum mechanically unstable. Natural theories with scalar particles such as the Higgs predict the existence of new particles and couplings. The dominant source of the instability in the SM is the large coupling of the top quark to the Higgs and the quadratically divergent top loop contribution to the Higgs mass. Models which address this instability introduce new physics in the top and Higgs sectors in the form of new colored particles and deviations from SM top and Higgs couplings. This is exactly the territory that will be revealed at the LHC.

The Higgs boson also has $\mathcal{O}(1)$ couplings to electroweak gauge bosons and thus new physics in that sector is implied as well. However, electroweak precision measurements have tested W and Z interactions to the percent level with no deviations from the SM found, implying that the new physics is hidden [94]. This suggests two possibilities: One is that the new states are heavy and can be discovered in searches for Z' and W' bosons with multi-TeV masses. The other, more interesting, possibility is that the new particles carry a symmetry which suppresses contributions to precision measurements at leading order and forces them to be produced in pairs. In the latter scenario the lightest new particle would be stable and could serve as a natural dark matter candidate. Typical signatures at the LHC would then include missing energy, with or without cascade decays.

Research in model building over the last 20 years has produced a variety of possibilities for physics at the weak scale – supersymmetry, large or small extra dimensions, strong gravity, technicolor, composite and Little Higgs – with a large number of models in each category. However, all of these models are designed to address the hierarchy problem and therefore share a handful of signals that will be the focus of early LHC searches.

In the following we list these signatures and mention which classes of models give rise to them. While the detailed predictions for cross sections and branching ratios differ from model to model the basic signatures remain the same. It is the aim of this initiative to ensure that the necessary theoretical work is done in time to maximize the reach of the LHC.

- Nonstandard top physics, top partners (SUSY, composite and Little Higgs, Randall-Sundrum (RS), universal extra dimensions (UED), technicolor, and topcolor models)

- Missing energy signals with or without cascades (SUSY, composite and Little Higgs with T parity, UED)

- W' and Z' bosons (composite and Little Higgs, RS, technicolor, UED, string inspired SUSY models)

- Non-standard Higgs sectors (SUSY, composite and Little Higgs, technicolor, UED, and RS models)

In addition there are a number of signatures which are less generic but nonetheless important.

- Charged long-lived particles as seen in parts of the parameter space of SUSY or UED.
- Unique missing energy signals and black holes in theories with a low quantum gravity scale.
- Strongly coupled electroweak sectors as in technicolor or Higgsless models.

Even though many of the signals are universal, it is useful to explore them in the context of specific representative models. This also allows determining the power of the LHC in differentiating between similar models, for example through sum rules for masses and coupling constants or spin information from angular distributions. In the remainder of this section we give our list of representative models and propose specific calculations which are needed.

B.3.1 Determination of SUSY Parameters

Low energy supersymmetry provides one of the most compelling extensions of the SM. Not only does it lead a unified description of bosons and fermions, but it also allows a natural implementation of the Higgs mechanism, provides a dark matter candidate and leads to the unification of couplings at scales close to the Planck scale. Searches for supersymmetric particles are therefore a main priority of the LHC experimental program.

As mentioned before, SUSY, if it exists, is likely to be found rather quickly after the LHC begins to take physics data. After the discovery of a potential SUSY signal, emphasis will shift to a determination of the masses, spins and couplings of supersymmetric particles, their decay modes and branching fractions [95], and a measurement of the cross sections of SUSY processes. The masses of supersymmetric particles can be measured in cascade decays [96]. The spin of sleptons can be determined using lepton charge asymmetries [97]. So far, there have been no studies how the spin of other SUSY particles can be determined. Likewise, with the exception of the weak squark gauge coupling [98], whether and how the couplings of SUSY particles can be measured at the LHC remains unknown.

A large fraction of the weakly-interacting SUSY partner spectrum appears as intermediate states in cascade decays of squarks ($\tilde{q}$) and gluinos ($\tilde{g}$) at the LHC. Due to the large cross section for $\tilde{q}$ and $\tilde{g}$ production, the masses of these intermediate states can be reconstructed from edges and thresholds in the decay cascades [96]. However, most of the variables used involve jets, and it is crucial to know which jet in the event is originating from which step in the decay chain, or whether it is an additional jet due to QCD radiation. In many of the SUSY SPS benchmark points, the mass difference of squarks and gluinos is quite small, but there is a large mass gap between squarks/gluinos and neutralinos. If the mass difference is large, the cascade jets are hard. In the existing studies of mass reconstruction in cascade decays [96], `Pythia` [99] or `Herwig` [100] have been used. The shower approach used in these MC programs usually does not accurately predict the number of jets. While jet radiation is not likely to become a problem for the discovery of SUSY, it will probably soften the edges and thresholds in the cascade analysis, and the combinatorial background will make it more difficult to fit the masses of SUSY particles.

Recently, the multi-purpose event generator `MadEvent/MadGraph` [101] has been extended to the minimal supersymmetric SM (MSSM) [102]. `SUSY MadEvent` can handle up to 12 particles in the final state, contains full spin correlations, and a consistent theoretical treatment of couplings [103], thus going one step beyond the capabilities of `GRACE/SUSY` [104] and `CompHep` [105]. A calculation of $\tilde{g}\tilde{g} + n$ jet and $\tilde{u}_L\tilde{g} + n$ jet ($n = 1, 2$) production [106] using `SUSY MadEvent` shows that the p_T distribution of jets from `SUSY MadEvent` and `Pythia` can indeed be very different. Such calculations have to be carried out for many more processes.

The results for $\tilde{g}\tilde{g} + n$ jet and $\tilde{u}_L\tilde{g} + n$ jet ($n = 1, 2$) production indicate the necessity of a full NLO SUSY-QCD MC generator for squark and gluino production, including cascade decays and, where appropriate, spin correlations. SUSY-QCD corrections for many SUSY production processes [107] are already known. They increase cross sections by typically $30 - 40\%$ for squarks and more than 80% for gluinos, and significantly reduce the sensitivity to the unphysical renormalization and factorization scales. However, cascade decays of the SUSY particles and the effects of realistic acceptance cuts were not taken into account in these calculations. The NLO SUSY-QCD corrections to the relevant decay processes are also known [95]. Using these building blocks, together with `Vircol`, the goal of developing a full NLO SUSY-QCD MC generator for squark and gluino production, including cascade decays, should be feasible.

For the LHC-TI, studies of how the spin and the couplings of SUSY particles can be measured at the LHC are of the highest priority and it intends to strongly support these through the proposed Fellowship program and activities related to it. ME-based calculations of the jet activity in SUSY events and the development of a full NLO SUSY-QCD MC generator for squark and gluino production are also considered to be very important.

Cascade decays of gluinos and squarks assume that there is no hierarchy in masses between the fermions and scalars in SUSY. If the scalars are much heavier than the fermions, as in split supersymmetry (SpS) [108], the signatures for supersymmetry may be very different. In this case, stable charged R-parity carrying hadrons may exist [109], and the lifetime of the gluino may be very long.

B.3.2 Other SUSY Projects

In addition to the measurement of the spin and the couplings of SUSY particles, there are a number of issues which need to be addressed before the LHC reaches its design luminosity.

1. **Including CP-violating phases in supersymmetric production and decay processes** These phases have been already implemented in `CPsuperH` [110] and `FeynHiggs` [111] which calculate Higgs production and decay processes, but still need to be taken into account in other supersymmetric particle production cross sections.

2. **Including various versions of the NMSSM and R-parity violating models in event generators** This should be fairly straightforward for the NMSSM, which contains an extra singlet in addition to particle spectrum of the MSSM. R-parity violation for SUSY particle decays is included in `Pythia` and `Herwig`. However, this is not the case for the production of these particles.

3. **Incorporating NLO QCD corrections in SUSY Higgs production processes** Currently, there are separate programs that deal with the production and decays of SUSY Higgs par-

ticles. The decays of Higgs particles, including the possibility of CP-violation, are calculated by `CPsuperH`, `FeynHiggs` and `HDECAY` [112]. The LO Higgs production cross sections are calculated in `Higlu` [113]. A complete, NLO SUSY QCD calculation of the Higgs radiation off bottom and top quarks [46, 114], and via VBF is still lacking.

B.3.3 Introduction to New Models of Electroweak Symmetry Breaking and of TeV Scale Physics

In the MSSM, at tree-level, the lightest Higgs mass is bound by the mass of the Z-boson. The only way the Higgs boson can be significantly heavier is if the loop corrections from the top-stop sector are significant. This implies that the stop mass has to be in the range of 500 GeV – 1 TeV in order to raise the Higgs mass above the LEP2 lower limit of 114 GeV [115]. However, this will imply that there has to be a tuning of order 1 – 5 percent in order for electroweak symmetry breaking to give a sufficiently low Z-mass. This problem is referred to as the "little hierarchy" problem, which basically means that if supersymmetry solves the "big hierarchy" problem, we would have expected it to be already discovered. This issue got many theorists to reexamine the question whether there could be other mechanisms for electroweak symmetry breaking (some of which could naturally avoid this problem). This has been one of the main themes of particle phenomenology over the past five years, and many interesting new alternatives for electroweak symmetry breaking have emerged over this period.

One of the promising novel approaches to electroweak symmetry breaking is the "Little Higgs" (LH) mechanism [116]. This mechanism describes the Higgs field as a pseudo-Goldstone boson associated with the spontaneous breaking of a global symmetry. The explicit breaking of global symmetries by gauge and Yukawa interactions generates a potential for the Higgs field, leading to electroweak symmetry breaking. A number of explicit models based on the LH mechanism have been constructed. The generic main feature of such models is that new particles with the same spin will cancel the one loop quadratically divergent contributions to the Higgs mass. Since the cancellation happens only at the one loop order, it is a good solution to the little hierarchy problem, but needs a UV completion beyond energies of about 10 TeV to solve the full hierarchy problem. For example, one could imagine a supersymmetric theory with superpartners at the 10 TeV scale, and below that scale the model would look like a little Higgs theory rather than a generic supersymmetric model. Phenomenological studies of some of these models have been published [117], indicating that at least some of the predicted new particles should be observable at the LHC. A more detailed study of a specific model by the ATLAS collaboration has also appeared [86]. However, some of the more promising models (such as the recently proposed models with T-parity [118]) have not yet been studied in detail, and deserve more attention. More importantly, none of the LH models has yet been incorporated into standard Monte Carlo packages in a systematic way. This needs to be done before the LHC turns on to enable the experiments to conduct dedicated searches for these models.

Another interesting direction is to utilize the properties of extra dimensional theories to find new mechanisms for electroweak symmetry breaking. In one interesting class of models electroweak symmetry breaking happens via the boundary conditions of the gauge fields without the appearance of a physical Higgs scalar in the spectrum [119]. These models are called Higgsless models. In another class of models there is a Higgs boson in the spectrum, however it is not a fundamental scalar, but rather a scalar component (A_5) of a higher dimensional gauge field [120].

This mechanism is sometimes referred to as models with gauge-Higgs unification. The more successful versions of these models build on the properties of the well-known Randall-Sundrum [121] geometries (a single extra dimension with warped spacetime, that is a slice of AdS_5 space). The nice feature of this setup is that it has an alternative description in terms of an ordinary four dimensional conformal field theory, where conformality is broken at low energies spontaneously due to strong dynamics. Using this interpretation [122] the ordinary Randall-Sundrum model (where electroweak symmetry breaking happens via an elementary Higgs) is explained as a theory where strong dynamics produces a composite Higgs boson [123], which is weakly coupled and then breaks the electroweak symmetry. In the model with gauge-Higgs unification [124] there is also a composite Higgs boson, however it is also a pseudo-Goldstone boson, which then explains why it is much lighter than other bound states in the theory. Finally, in the Higgsless models electroweak symmetry breaking is directly triggered by the strong dynamics like in technicolor models, except that the 5D theory may be in the weakly coupled regime. The common feature of all these models is that they predict a Kaluza-Klein (KK) tower for both the SM gauge bosons and the SM fermions. Depending on the actual model, the KK tower for the gauge bosons could start at around 500 GeV (as in Higgsless models) or at 2 – 3 TeV (as in the RS model or the model with gauge-Higgs unification). The phenomenological studies in the LH and Higgsless models which need to be carried out so that these models can be tested at the LHC are described in more detail in Sec. B.3.4. As for the realistic Randall-Sundrum model and the version with gauge-Higgs unification, not even preliminary collider studies have been performed to find out the discovery reach of the LHC, even though these models are extremely exciting and pass all current experimental bounds.

We have learned from string theory that supersymmetry and extra spatial dimensions are the price for unifying the Standard Model with gravity. Yet we are practically ignorant about how these extra symmetries are broken. The hierarchy problem provides a tantalizing clue that supersymmetry or extra dimensions (or both!) could be realized at the TeV scale, in which case the LHC is destined for momentous discoveries. Supersymmetry has been the traditional, and perhaps best motivated, candidate for new physics at the TeV scale. However, recent developments in string theory have spurred a revival of interest in the phenomenology of theories with extra spatial dimensions. The realization that consistency of string theory requires new non-perturbative soliton-like objects called branes opened new avenues for model building in extra dimensions.

For example, branes allowed a simple way to localize the Standard Model particles in the extra dimension, leaving only gravity to propagate in the bulk. Within this construction, which became known as the ADD model [125], one could understand the feebleness of gravity in terms of a volume suppression due to the "largeness" of the extra dimensions. The generic collider signal of the ADD scenario is the production of gravitons, which would appear as missing energy in the detector. In order to be able to trigger on such events, the gravitons must be accompanied by an observable object, e.g. a photon or a jet [126]. These missing energy signatures are very challenging experimentally, and require very good understanding of the detector as well as the physical and instrumental backgrounds.

Of course, some or even all of the Standard Model particles could also propagate in the bulk. This translates into a rich and exciting phenomenology at the LHC, since quantization of the particle momentum along the extra dimension necessarily implies the existence of a whole tower of massive particles, called Kaluza-Klein (KK) modes or partners. The KK particles within each tower are nothing but heavier versions of their Standard Model counterpart. A discovery of a compact extra dimension at a collider can only be made through the discovery of the KK particles and measurement of their properties. The mass spectrum of the KK partners even encodes information about the space-time geometry: if the extra dimension is flat, the KK masses are roughly equally spaced, and if the extra dimension is warped (i.e. has a non-trivial metric), the KK mass spectrum follows a non-trivial pattern.

Consider, for example, the most "democratic" scenario (which has become known as Universal Extra Dimensions [127]) in which all Standard Model particles propagate in the bulk. Its simplest incarnation has a single extra dimension of size R, which is compactified on an S_1/Z_2 orbifold. A peculiar feature of UED is the conservation of Kaluza-Klein number at tree level, which is a simple consequence of momentum conservation along the extra dimension. However, bulk and brane radiative effects [128] break KK number down to a discrete conserved quantity, called KK parity. KK parity adorns the UED scenario with many of the virtues typically associated with supersymmetry: for example, the lightest KK-partners (those at level 1) must always be pair-produced in collider experiments, which leads to relatively weak bounds from direct searches [127]. KK parity conservation also implies that the contributions to various precisely measured low-energy observables only arise at the loop level and are small [129]. Finally, KK-parity guarantees that the lightest KK partner is stable, and thus can be a cold dark matter candidate [130]. A detailed list of issues which need to be addressed to enable the LHC experiments to successfully search for extra dimensions is given in Section B.3.5.

The above summary is by no means an exhaustive list of all possible LHC signatures pertaining to extra dimensions. Notable other scenarios of interest are radions [131], deconstructed models [132] and the more speculative production of mini-black holes [133], to name a few.

B.3.4 Little Higgs and Higgsless Models: Specific Projects

While the SM is able to describe EW symmetry breaking, it does not explain why the Higgs field develops a vacuum expectation value. This requires going beyond the SM. One can either add structure to make the theory predictive, or one can eliminate the Higgs field altogether. Examples for the first type of models are SUSY with radiative EW symmetry breaking and Little Higgs models [134]. Technicolor [135] and so-called Higgsless models [136] are prototypes for models where EW symmetry breaking is achieved without a scalar field.

In the SM, the Higgs boson is a remnant of spontaneous breaking of the EW symmetry. In many scattering processes, such as weak boson scattering, it ensures S-matrix unitarity. Without the Higgs boson, unitarity is violated at an energy of about 1 TeV. In Higgsless models, new weakly coupled vector bosons appear at the TeV scale and postpone unitarity violation in WW and WZ scattering if the couplings of the new vector bosons fulfill certain sum rules. These sum rules are independent of model building details and a generic prediction of Higgsless models. The phenomenology of the new vector bosons appearing in Higgsless models has been studied in Ref. [137]. The charged vector boson, $V^{\pm}$, can be discovered at the LHC in VBF, $qq' \to V^{\pm}qq'$ with $V \to WZ \to 3\ell + \nu$ ($\ell = e, \mu$) with a mass $m_V < 550$ GeV for 10 fb^{-1}. However, there are other final states such as $V \to WZ \to \ell^+\ell^- jj$ or $V \to WZ \to \ell\nu jj$ which have larger branching fractions, but also potentially more dangerous backgrounds ($W/Z + 4$ jet production). Whether these modes are observable, and perhaps have a better discovery potential than the $3\ell+\nu+jj$ final state, has not been investigated yet. Likewise, it has not been studied yet whether $VW \to WWZ$ and $VZ \to WZZ$ production can be observed at the LHC. For $m_V < 400$ GeV, the VW and VZ

production rates are about as large as the $qq' \to V^{\pm}qq'$ cross section. In order to have a sufficient number of VW or VZ events, it may be necessary to require that at least one of the weak bosons decays hadronically. In this case, $WZjj$, $WWjj$ or $ZZjj$ production are potentially dangerous backgrounds.

As stated before, sum rules for the couplings of the new vector bosons are a characteristic feature of Higgsless models. They are expected to hold at the few-percent level. To test these sum rules, m_V and the VWZ coupling, g_{VWZ}, have to be measured. g_{VWZ} can be determined from the observed cross section and a measurement of the total V-width, Γ_V. The observed cross section, together with the theoretical prediction of the production cross section of the processes chosen, determines the branching fraction for $V \to WZ$. Once Γ_V is known, g_{VWZ} can then be extracted. For a measurement of m_V and Γ_V, the $V \to WZ \to \ell^+\ell^- jj$ channel is suited best. Since V bosons should be narrow resonances, a detailed simulation of the invariant mass resolution in the $\ell^+\ell^- jj$ channel is needed in order to find out how well Γ_V can be determined. The remaining uncertainties are then in the V production cross section, and likely arise from PDF uncertainties and NLO QCD corrections. Finding out how well the sum rule in Higgsless models can be tested at the LHC is a project the LHC-TI believes should have high priority.

As mentioned in Sec. B.3.3, in Little Higgs models, additional massive fermions and vector bosons are introduced to cancel the quadratic divergences which destabilize the Higgs mass. The phenomenology of these particles at the LHC has been studied in Ref. [86]. Common features of all Little Higgs models are a global symmetry which is broken at a scale f, and the prediction of a new heavy top like quark, T. In order for the cancellation of the quadratic divergences to m_H to work, the mass of the T-quark, m_T, the $TtH/TtZ/TbW$ coupling (H is the Higgs boson), λ_T, the top quark Yukawa coupling and the scale f need to fulfill a sum rule. All four quantities can in principle be measured. The scale f is related to the masses and widths of new vector bosons which commonly appear in these models. m_T can be measured by reconstructing $T \to bW$ and $T \to tZ$ decays using techniques which have been developed for the measurement of the top quark mass at the Tevatron and LHC. Finally, λ_T can be determined in single T production, $qb \to q'T$, similar to V_{tb} in single top quark production. The LHC-TI plans to investigate how well the relation between these four quantities can be tested at the LHC.

The best known Little Higgs model is the so-called "Littlest Higgs" model [138]. Precision electroweak constraints favor a value of $f = 5 - 10$ TeV for the scale where the global SU(5) symmetry of the model is broken to SO(5). This is about a factor 10 higher than what one normally assumes to avoid a reincarnation of the hierarchy problem. To solve this problem, one can introduce a new conserved quantum number, T-parity, which ensures that there are no contributions from new states to the precision EW observables. The phenomenology of the Littlest Higgs model with T-parity has recently been studied in Ref. [139]. The model predicts T-even and T-odd partners of the top quark, t_+ and t_-, and four new vector bosons, $W_H^{\pm}$, Z_H, and A_H. The A_H is the lightest particle with T-parity and thus is stable. It is a dark matter candidate. The main production channels for the new vector bosons are $W_H^+W_H^-$, $W_H^{\pm}Z_H$ and $W_H^{\pm}A_H$ production. The subsequent decays $W_H \to WA_H$ and $Z_H \to HA_H$ then lead to $W_H^+W_H^- \to \ell^+\ell^- + \not{p}_T$ and $W_H^{\pm}Z_H \to \ell^{\pm}b\bar{b} + \not{p}_T$ final states if $W \to \ell\nu$ and $H \to b\bar{b}$. These final states suffer from a potentially large SM background (eg. $pp \to W^+W^-$ and $pp \to Wb\bar{b}$), although the large $\not{p}_T$ expected for the signal events may help to suppress the background. A detailed study of signal and background for these and other final states has not been carried out yet. The LHC-TI is planning to fill this gap.

In Little Higgs models pseudo-axions appear as remnants of the broken global symmetries. The production and decays of these states, which we generically denote by η, has been explored in Ref. [140] for several models. However, the pseudo-axions also affect the signatures of the T-quark through the decay $T \to t\eta$. The phenomenology of T-quark decays involving axions, in particular whether these decay modes are visible above the background at the LHC, has not been studied yet. Furthermore, the phenomenological consequences of the ηZH coupling which exists in Little Higgs models have not been explored yet. The LHC-TI believes that it is very important to investigate these questions.

In order to perform detailed simulations for the type of models described in this section, it is necessary to interface the calculations for the new physics signals with MC event generators. Thanks to the Les Houches accord [141], this can be done for most new physics models. However, instead of attempting this for all existing models, the LHC-TI proposes a targeted approach:

1. Identify the best-motivated models,

2. Identify the most promising LHC signatures within each class of models, and

3. Incorporate those into MC generators.

A joint working group of MC event generator experts and model builders should be formed to address these issues.

B.3.5 Search for Extra Dimensions at the LHC: Specific Projects

The possible existence of additional dimensions beyond our usual 3 spatial $+1$ time dimensional world would dramatically alter our view of the universe. Extra spatial dimensions at very short distances are a prediction of string theory and theorists have studied the effects of higher dimensional space-times for decades. New theories, developed to address the hierarchy problem, propose that the effects of extra dimensions may be visible at larger distances, comparable to the TeV energy scale. These theories utilize the geometry of additional spatial dimensions to resolve the hierarchy, *i.e.*, the disparity between the electroweak scale (~ 1 TeV) where electroweak symmetry breaking takes place and the traditional scale of gravity defined by the Planck scale ($M_P \approx 10^{19}$ GeV). These ideas make use of the fact that gravity has yet to be probed at energy scales much above 10^{-3} eV in laboratory experiments, admitting for the possibility that gravity behaves differently than expected at higher energies.

If new dimensions are indeed related to the source of the hierarchy, then they should provide detectable signatures in experiments at the electroweak scale. Particles which propagate in compactified extra dimensions behave similarly to a particle-in-a-box; each quanta of momentum in the compactified volume appears as an excited state in 4-d, thus building an entire Kaluza-Klein tower (KK) of states. The collider signature for the existence of additional dimensions is the observation of these KK states. The detailed properties of the KK states are determined by the geometry of the compactified space and their measurement would reveal the underlying geometry of the higher dimensional spacetime, or bulk. A review of extra dimensional models and their experimental signatures can be found in Ref. [142]. Several classes of models have been developed in recent years, including:

- *Large Extra Dimensions* [125] (ADD). In this model, which was discussed already briefly in Sec. B.3.3, the hierarchy problem is solved by lowering the fundamental scale of gravity in higher dimensional spacetime. This results in extra dimensions as large as a submillimeter, in which gravity alone may propagate. The three classes of collider signatures are (i) the emission of graviton KK states in association with a gluon, photon, or Z-boson, where the KK state does not interact and appears as missing energy, (ii) the virtual exchange of graviton KK states in the pair production of any two particles, and (iii) the production of TeV-scale black-holes.

- *Warped Extra Dimensions* [121] (RS). This scenario consists of a single extra dimension which is of order M_P^{-1} in size and has a very large curvature. This strong curvature relates the Planck and Electroweak scales. There are many variants of this model and all SM fields are allowed to propagate in the bulk. The mass of the first graviton KK state is expected to be $\sim$ a TeV and has weak-scale couplings.

- *TeV Scale Extra Dimensions* [143] (TeV). This scenario is not related to the hierarchy problem, but can arise naturally from string models. The SM gauge fields and Higgs boson propagate in the bulk and have TeV-scale KK excitations.

- *Universal Extra Dimensions* [127] (UED). As mentioned in Sec. B.3.3, in this case, all the SM fields propagate in a $\sim$ TeV^{-1}-sized bulk. Translational invariance is thus maintained in the bulk, resulting in a conserved quantum number, KK-parity. The KK excitations must then be produced in pairs and decay via cascade chains to the lightest KK particle. The phenomenology of this scenario clearly resembles that of supersymmetry.

Although much work on models with extra dimensions (ED) has already been done, there are a number of issues which need to be addressed before the LHC reaches its design luminosity. Specifically, the LHC-TI intends to address the following points:

1. Implement the ADD model in a general purpose event generator. At this moment, only the simplest signatures, which have the largest rates (but also the largest backgrounds), jet plus missing energy and single photon plus missing energy, have been implemented in ISAJET [144] and PYTHIA [145]. While the complete ADD model is currently also available within the fully automated `AMEGIC` platform [146], its interface to parton shower Monte Carlo programs is still lacking and needs to be developed. The LHC-TI would perform a more systematic inclusion of these signatures in various generators. Radion production is also not included.

2. Develop techniques to determine the fundamental parameters of the ADD model (*i.e.*, fundamental Planck scale, number of extra dimensions, and brane tension) at the LHC.

3. Explore techniques to distinguish large extra dimensions from other missing energy signatures.

4. Compute combined search reaches from different final states for graviton KK exchange.

5. Although the RS model is included in `Pythia` and `Herwig`, it is still necessary to complete spin correlations in `Pythia`.

6. Extensions of the RS model, such as the introduction of brane kinetic terms or additional dimensions, result in a distortion of the expected graviton KK spectrum. The states may become extremely narrow or closely spaced. Studies need to be performed to determine the observability of such states at the LHC.

7. Develop the phenomenological signatures of SM fermions propagating in the warped RS bulk.

8. Perform further studies of radion effects in measurements of the Higgs properties.

9. Develop methods for distinguishing KK gauge boson production in TeV extra dimension scenarios from heavy Z' production in ordinary GUT models.

10. Include branon production [147] and transplanckian effects [148] in MC generators.

11. Collect information on the parameter space that is consistent with current data.

12. Develop a number of representative ED benchmark points and use them for detailed studies.

13. NLO QCD corrections to Drell-Yan production in the ADD and RS models are significantly larger than in the SM [149]. This changes the sensitivity limits at the LHC by about 50%. The result of Ref. [149] raises the question of how large NLO QCD corrections are in other processes, such at $\gamma\gamma$ production via graviton exchange. This issue needs to be resolved.

14. Compute search reaches for UED.

15. How can one discriminate between UED and SUSY? The analogy between UED and R-parity conserving supersymmetry runs so deep that discriminating the two at hadron colliders is a very challenging enterprise [150]. The two scenarios have identical discovery signatures and the only fundamental distinction is related to the spins of the new particles — the KK partners have identical spin quantum numbers as their SM counterparts, while the spins of the superpartners differ by $1/2$ unit. Unfortunately, none of the general purpose event generators currently incorporates both supersymmetry and UED with proper spin correlations. In fact UED so far has only been implemented at the parton level in CompHEP [151], while supersymmetry with spin correlations is only available in HERWIG [152]. While certain methods for measuring spin correlations have already been proposed [97], they need to be tested within detailed, fully realistic studies. This requires complete implementation of the models and their relevant features in an event generator.

B.3.6 Searching for New Physics from String Constructions at the LHC

There has been a great deal of work in developing "semi-realistic" string constructions[1] which at least contain the gauge group and particles of the standard model or the MSSM, including both open and closed string constructions and using a variety of compactifications, including Calabi-Yau and toroidal orbifolds.

So far, no construction has been fully realistic, and it is unlikely that any uniquely "correct" construction will emerge in the near future. Nevertheless, continued vigorous exploration

[1] see, for example, Refs. [153–156]; for reviews, see Refs. [157–159].

of top-down constructions is very important, because they may suggest the form of physics that is likely to emerge from classes of string theories. For example, they may provide frameworks for discussing the origins of fermion families, hierarchies of Yukawa couplings, and small neutrino masses; for the possibility of grand unification in four or more dimensions; and for exotic phenomena such as possible large extra dimensions, fractional electric charges, etc.

String constructions may also suggest the form of new physics at the TeV scale. One major issue involves the form and scale of supersymmetry breaking and its mediation and the related issues of moduli stabilization and the smallness or absence of the cosmological constant. Much work has been done on these topics, including the exploration of hidden sector dynamics, work on the role of chiral fluxes, and recent speculations concerning a vast landscape of string vacua [160]. While such studies are in their infancy, they suggest that supersymmetry breaking or realization may be much more complicated that the usually studied minimal supergravity scenario with four real parameters. Similarly, almost all existing constructions suggest new TeV scale physics beyond the MSSM, such as extended Higgs sectors involving additional Higgs doublet pairs or (standard model) singlets, the associated extended neutralino and chargino sectors, exotic particles (such as heavy quarks that are vectorlike with respect to the SM interactions), or extended gauge groups (especially new $U(1)$ factors). These could be flaws of specific constructions or could be hints that such things really exist.

For these reasons, as well as for the possibility of entirely different extensions of the SM (such as strong dynamics or the previously discussed Little Higgs models), physics at the LHC could well be much more complicated than the SM or the MSSM. In this case it will be very difficult to unravel what is happening, and a close collaboration between theory and experiment will be essential. It is critical for theorists and experimenters to work out a variety of examples of likely new scenarios, their signatures, and how they are related to the underlying string constructions; and to develop the tools needed to study them. Unfortunately, there is currently a severe shortage of tools for studying the implications of such extended new physics scenarios. For example, there are a number of excellent programs for studying the renormalization-group connection between supersymmetry breaking and other parameters at the Planck or GUT scale and those at low energy. However, none of them are sufficiently general to allow the incorporation of CP-violating phases (expected in most generalized models of supersymmetry breaking; see also Sec. B.3.2) and of new particles and interactions beyond the MSSM. Similarly, none of the event generators needed for serious simulation of new physics signals and backgrounds at the LHC allow for the easy addition of extended Higgs/neutralino sectors, new gauge interactions, new exotic particles, or general supersymmetry breaking scenarios. This lack of tools is seriously hindering the community from preparing for the more complicated physics that is likely to be encountered at the LHC. The extensive study of the TeV-scale implications of string constructions, the development of the needed analysis tools, and their use in studying new physics scenarios is a large and critical need.

B.3.7 Flavor Physics at the LHC

Flavor physics will drive research at the LHC in two important directions.

- Direct discovery of new physics at LHCB:

  LHCB is a dedicated B physics experiment which will use the detuned mainline beam to study CP violation and rare decays [161]. The ability of the DØ and CDF experiments to do precision B physics shows that LHCB, which will produce 10^{12} bottom quark pairs a year, will be able to test the SM CKM sector in new extremely rare channels with branching ratios of $\mathcal{O}(10^{-9} - 10^{-10})$. In addition, LHCB has the advantage, relative to the B factories, that it will produce all bottom hadrons. Of particular interest will be the B_s meson, whose decays are sensitive to multiple CKM parameters. The extraction of these parameters in heretofore unstudied modes will allow for strong consistency checks whose violation would signal the existence of new physics. A sampling of some of the crucial measurements will be:

1. A five sigma observation for B_s oscillations will be possible for $\Delta m_s < 68\ p.s.^{-1}$, which given the previous data on the unitarity triangle from the B factories, will be a strong test for new physics.
2. $B_s \to \mu^+\mu^-$ which has a branching ratio of $\mathcal{O}(10^{-9})$ in the SM but is strongly enhanced in most SUSY models.
3. ϕ_s, the phase in B_s oscillations, which is small in the SM, and thus sensitive to new physics.
4. The exclusive decay $B_s \to D_s + K$, which can be used to extract the angle γ.

Our ability to make new physics claims will be bounded by our handle on theoretical errors, thus there needs to be a concerted effort to support young theorists who work in flavor physics. There has been significant progress made in understanding power corrections using new effective field theory techniques, and it seems that further progress is possible given sufficient effort.

- Flavor physics puts very stringent constraints on models of new physics:

  Given the chiral nature of the standard model, electroweak symmetry breaking (EWSB) is inextricably linked to fermion mass generation. In fact, it might be hoped that uncovering the mechanism for EWSB will shed light on the puzzle of the family hierarchy. In any case, it is clear that flavor physics will be an extremely sharp tool with which to distinguish models. Since the LHC will most likely not have access to the entire spectrum of heavy states, flavor physics constraints arising from B decays, bounds on electric dipole moments and lepton number violating processes, will play the role of guide in attempts to uncover organizing principles.

  Each class of models has a distinct mechanism of generating fermion masses the nature of which encapsulates information on the status of flavor symmetries. In minimal SUSY models the puzzle of fermion mass generation is related to the nature of SUSY breaking. Thus the strong constraints stemming from flavor changing neutral currents and the lack of lepton number violation in muon decay enforce the need for some organizing flavor principle in the soft SUSY breaking terms.

  In the Little Higgs models and strongly coupled models, the third generation plays a special role. The former are motivated by the fact that the scale of "flavor physics" is well above the weak scale and in order the preserve the hierarchy between these two scale additional heavy quarks tied to the top are needed to cancel potentially dangerous quadratic divergences. In strongly coupled models precision electro-weak measurements present a challenge to generating a large top quark mass. Models of extra dimensions, on the other hand, have the ability to generate hierarchies by placing families on disparate hyper-surfaces in the extra dimensions. In all three classes of models, the constraints from flavor physics will play a crucial role.

It is clear that fitting any new physics into a model will need theorists conversant in the cross-pollination between model building and flavor physics as well as skilled personnel in calculating the effects of new heavy physics on flavor observables. The prioritization of heavy flavor projects, however, will very much depend on the results which are expected from the B-factories in the coming years.

B.3.8 Prioritized List of Projects

Based on the discussion in the preceding sections, we prioritize the new physics projects of the LHC-TI as follows:

1. Needed at LHC startup (2007 – 2008):

   (a) study how the spin of SUSY particles and their couplings can be measured.

   (b) study the jet activity in cascade events.

   (c) include CP-violating phases in supersymmetric production and decay processes.

   (d) examine how well the sum rules of Little Higgs and Higgsless models can be tested as a function of the integrated luminosity available.

   (e) complete spin correlations in the RS model in `Pythia` and fully implement the UED in `Pythia` and `Herwig`. Calculate search reaches for UED.

   (f) develop benchmark points for models with extra dimensions and gather information on the parameter space which is consistent with existing data.

   (g) study the discovery reach of the LHC in Higgsless models with gauge-Higgs unification and Randall-Sundrum type models.

   (h) learn how well SUSY and UED can be discriminated.

2. For $10 - 30$ fb^{-1} (2008 – 2010):

   (a) implement a full NLO SUSY QCD event generator.

   (b) compute SUSY QCD corrections to Higgs production in association with top and bottom quarks.

   (c) include branon production and transplanckian effects in MC generators.

   (d) carry out more complete studies of the production of new vector bosons in Little Higgs and Higgsless models.

   (e) perform more complete studies of the phenomenology of heavy fermions and pseudo-axions in Little Higgs models.

   (f) implement new physics from string constructions, such as general SUSY breaking scenarios in event generators.

(g) develop techniques to distinguish KK gauge boson excitations from heavy Z' production in GUT theories.

3. For 300 fb^{-1} (2012 – 2013): compute NLO QCD corrections for processes in models with extra dimensions (if still relevant)

B.4 Fellowships

The projects described in the previous sections demonstrate that a significant amount of work remains to be done to ensure that the full physics potential of the LHC can be realized. (Many more calculations and studies that are important for the LHC could be listed.) Currently, the number of US theorists working on LHC related projects is limited. In particular, there are very few people working on event generator related calculations. This shortage is evident at the faculty, the postdoc and the graduate student levels alike. Furthermore, those working on traditional phenomenology (ie. higher order calculations, PDFs, MC event generators, etc.) have little contact with theorists working on model building, and *vice versa*. In order to stimulate theoretical research on LHC related physics in general, and on the projects described earlier, we propose to establish a system of Fellowships at the graduate student and postdoctoral levels. There is general agreement in the theory community that this is the most efficient mechanism to stimulate LHC related theory research and to rebuild a world-class hadron collider theory program. The collection of Fellows will form the backbone of a nation-wide collaborative theory network. This is described in more detail in Sec. B.4.1.

Details of the Fellowships include:

- The Fellowships would be named, and carry salary support (including fringe benefits) and research funds. They would be awarded in an open nation-wide competition. For postdoctoral Fellows, the funds could be spent over a period of two or three years; for graduate students the Fellowships would be for one year. Allowed expenses for research would include travel, equipment, and collaborative efforts such as hosting visitors.

- The nomination of women, members of underrepresented minority groups, and persons with disabilities would actively be sought.

- The postdoctoral (graduate student) Fellowships would be for a fixed amount of \$150k (\$40k).

- Four postdoc and 6 graduate student Fellowships would be awarded each year, although the individual numbers could vary from year to year. The program is targeted for a period of 5 years.

- Student Fellowships would include support for tuition up to \$6k.

- Fellowships would awarded in an open nationwide competition. A short proposal describing the proposed project, which must directly relate to LHC physics, would be required. The proposal would have to be accompanied by an endorsement letter from the institution which plans to host the Fellow. The institution must agree to limit the administrative fee to \$10k (\$5k) for postdocs (students). A faculty member or other eligible member of the scientific staff of the host institution would serve as the faculty for scientific purposes and be the Principal Investigator of the Fellow's grant for administrative purposes.

- For postdoctoral Fellowships, the funds could be spent as the proposing institution and its nominee see fit, so long as it is specified in the proposal. However, a minimum of \$4k per year for research funds must be allocated. Two sample scenarios how the money could be spent are given in the table below. The proposing institution would guarantee all other resources necessary for the proposed project to proceed.
- If a postdoctoral (student) Fellow is hired on a junior faculty (postdoc) position during the Fellowship period, the balance of funds would stay with the recipient.

The prestige of the Fellowships, together with the balance of funds that would stay with the Fellow in case he/she is hired on a junior faculty position, would add substantial value beyond a regular postdoc position. The research funds should enable the Fellow to play a highly visible role in international conferences and workshops, help covering the computing needs of the Fellow, and should make it possible for the Fellow to invite collaborators for visits, or to visit other institutions and laboratories, such as Fermilab or CERN, for collaborative purposes.

The following table gives a breakdown of the graduate student award, and gives two examples how the funds for a postdoctoral award could be spent (many other scenarios are possible!). The first scenario assumes a duration of two years, and that the Fellowship pays full salary (\$50k/year). The second example assumes that the duration is three years with full salary support of \$55k for one year from the Fellowship, and a salary of \$40k from the sponsoring institution for the second and third year. The Fellowship provides a salary supplement of \$15k in the second and third year. The table assumes that Fellowships are awarded as subcontracts, and that a flat administrative fee of \$10k (\$5k) is charged for each postdoctoral (graduate student) Fellowship. Furthermore, it is assumed that the institution which administers the grant charges a flat administrative fee of \$25k per year. Fringe benefits are assumed to be 31% (11%) for postdoctoral (graduate student) Fellowships. The graduate student stipend is taken to be \$21k per year.

	postdoctoral Fellowship		graduate student
	example 1	example 2	Fellowship
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

This results in a total cost of the Fellowship program of about \$865k per year for 4 postdoctoral and 6 student Fellowships, plus the \$25k administration fee.

The proposed guidelines for selecting recipients for the Fellowships are:

- Recipients are selected by a committee with 5-7 members. Members of the committee serve for one year. The selection committee should be representative of the US high energy theory community in LHC-related physics.

- Members of the selection committee cannot nominate.
- In order to ensure the full consideration of women, members of underrepresented minority groups, and persons with disabilities, the selection committee will apply the best practices developed for the unbiased review of applicants[2]. The selection committee will also, to the best of its ability, keep track of the diversity of the nomination pool, and two members of the Fellowship selection committee will be specifically charged to provide a report to the steering committee on the status of women, underrepresented minorities, and people with disabilities in the Fellowship selection process.
- Members of the selection committee are appointed by the LHC-TI Steering Committee.
- To avoid an excessive concentration of Fellows at any one institution, only one new post-doctoral and one new graduate student Fellow every other year will be approved for any single institution. Each faculty sponsor may nominate at most one graduate Fellow and new postdoctoral Fellow in a given year of institutional eligibility.
- For a given individual, only one Fellowship nomination will be accepted per year and there is a lifetime limit of two graduate and one postdoctoral Fellowship.
- Postdoctoral Fellowship awards will be made the December prior to the beginning of the Fellowship year, so as to coordinate with the annual postdoctoral hiring cycle.
- The following criteria are used to select recipients:
    1. quality of the candidate,
    2. quality of the proposal,
    3. relevance of the proposed work for the LHC, using the projects listed in Secs. B.2.6 and B.3.8 as guidelines,
    4. support committed by the recipient's institution, in particular the synergy of the proposed work with the theoretical and experimental groups at the sponsoring institution, and the quality of students, postdocs and faculty to collaborate,
    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.

B.4.1 Workshops and Theory Network

Close collaboration among the Fellows, and of the Fellows with the rest of the theory community working on LHC related physics, is essential in order to accomplish the goals. In order to foster the exchange of ideas, and to improve the knowledge basis of the Fellows, in particular the graduate student Fellows, we propose to hold a yearly symposium ("ColliderFest") where the new Fellows are introduced to the community. We also propose to hold in addition one workshop of the Fellows and the LHC theory and experimental communities which features tutorials and

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

practical training sessions on MC event generators, automated calculational tools, model building and detector simulation. The practical training sessions are taught by postdoctoral recipients of Fellowships and by guest instructors. The meetings should give the Fellows an opportunity to interact and collaborate with LHC experimenters. The symposia and workshops could be hosted by National Laboratories, or other institutions, such as KITP or the Aspen Center for Physics.

As part of its activities, the LHC-TI plans to initiate monthly, largely informal, videoconferenced meetings which, together with the collection of Fellows, are intended to form the backbone of a nationwide theory network. These meetings are open to the whole community, thereby involving a broad range of LHC related topics and participants. Fellows are expected to participate in the videoconferenced meetings and to play a leadership role in the theory network. The goal is to create an environment similar to that of the physics analysis working groups of the Tevatron and LHC experiments. From time to time the meetings should contain a formal component, such as tutorials on new theoretical or experimental developments. Holding videoconferenced meetings has the advantage of attracting physicists from isolated groups and smaller institutions, and makes it possible for them to coherently focus their efforts on projects that are directly relevant to LHC physics.

In particular, the theory network should bring together Fellows and other members of the theory community working on diverse topics. The most interesting and arguably the most productive collaborative efforts are those that bring together specialists from various subfields to attack a global problem. For example, modeling of global event properties with MC programs has improved recently because of a collaboration between experts in NLO QCD calculations and MC event generators. The theory network will be organized in projects and/or working groups which follow these guidelines. Projects/working groups can organize their own separate series of videoconferenced meetings if this is deemed to be advantageous.

The videoconferenced meetings are intended to play an important role in the theory network. Communication is vital to the success of such a network where groups and individuals are separated by distance as well as by discipline. Using web-based forms of communication through the LHC-TI web page (`http://www.pas.rochester.edu/~orr/LHC-TI.html`), such as wikis, skype, or electronic logbooks for all projects will be important.

Members of the LHC-TI Steering Committee will organize the yearly symposia and workshops, as well as the projects/working groups of the theory network, and maintain the LHC-TI web page with links to the individual project/working group pages.

References

[1] S. Eidelman *et al.* [Particle Data Group], Phys. Lett. B **592**, 1 (2004).

[2] U. Baur *et al.* [The Snowmass Working Group on Precision Electroweak Measurements], in *Proc. of the APS/DPF/DPB Summer Study on the Future of Particle Physics (Snowmass 2001)* ed. N. Graf, eConf **C010630**, P1WG1 (2001) [arXiv:hep-ph/0202001].

[3] R. Hamberg, W. L. van Neerven and T. Matsuura, Nucl. Phys. B **359**, 343 (1991) [Erratum-ibid. B **644**, 403 (2002)].

[4] C. Anastasiou, L. J. Dixon, K. Melnikov and F. Petriello, Phys. Rev. D **69**, 094008 (2004) [arXiv:hep-ph/0312266].

[5] U. Baur, S. Keller and W. K. Sakumoto, Phys. Rev. D **57**, 199 (1998) [arXiv:hep-ph/9707301]; U. Baur, S. Keller and D. Wackeroth, Phys. Rev. D **59**, 013002 (1999) [arXiv:hep-ph/9807417]; U. Baur, O. Brein, W. Hollik, C. Schappacher and D. Wackeroth, Phys. Rev. D **65**, 033007 (2002) [arXiv:hep-ph/0108274]; S. Dittmaier and M. Krämer, Phys. Rev. D **65**, 073007 (2002) [arXiv:hep-ph/0109062]; U. Baur and D. Wackeroth, Phys. Rev. D **70**, 073015 (2004) [arXiv:hep-ph/0405191].

[6] W. Placzek and S. Jadach, Eur. Phys. J. C **29**, 325 (2003) [arXiv:hep-ph/0302065]; C. M. Carloni Calame, G. Montagna, O. Nicrosini and M. Treccani, Phys. Rev. D **69**, 037301 (2004) [arXiv:hep-ph/0303102] and JHEP **0505**, 019 (2005) [arXiv:hep-ph/0502218].

[7] Q. H. Cao and C. P. Yuan, Phys. Rev. Lett. **93**, 042001 (2004) [arXiv:hep-ph/0401026].

[8] M. Beneke *et al.*, arXiv:hep-ph/0003033.

[9] U. Baur, A. Juste, L. H. Orr and D. Rainwater, Phys. Rev. D **71**, 054013 (2005) [arXiv:hep-ph/0412021].

[10] F. Maltoni, D. L. Rainwater and S. Willenbrock, Phys. Rev. D **66**, 034022 (2002) [arXiv:hep-ph/0202205].

[11] V. Drollinger, T. Müller and D. Denegri, arXiv:hep-ph/0111312.

[12] S. Abdullin *et al.*, Eur. Phys. J. C **39S2**, 41 (2005);

[13] J. Cammin and M. Schumacher, ATL-PHYS-2003-024.

[14] S. Asai *et al.*, Eur. Phys. J. C **32S2**, 19 (2004) [arXiv:hep-ph/0402254].

[15] R. V. Harlander and W. B. Kilgore, Phys. Rev. Lett. **88**, 201801 (2002) [arXiv:hep-ph/0201206]; C. Anastasiou and K. Melnikov, Nucl. Phys. B **646**, 220 (2002) [arXiv:hep-ph/0207004].

[16] C. Anastasiou, K. Melnikov and F. Petriello, Phys. Rev. Lett. **93**, 262002 (2004) [arXiv:hep-ph/0409088]; and arXiv:hep-ph/0501130.

[17] Z. Bern, L. J. Dixon and C. Schmidt, Phys. Rev. D **66**, 074018 (2002) [arXiv:hep-ph/0206194].

[18] T. Han, G. Valencia and S. Willenbrock, Phys. Rev. Lett. **69**, 3274 (1992) [arXiv:hep-ph/9206246]; T. Figy, C. Oleari and D. Zeppenfeld, Phys. Rev. D **68**, 073005 (2003) [arXiv:hep-ph/0306109].

[19] W. Beenakker, S. Dittmaier, M. Krämer, B. Plümper, M. Spira and P. M. Zerwas, Phys. Rev. Lett. **87**, 201805 (2001) [arXiv:hep-ph/0107081]; and Nucl. Phys. B **653**, 151 (2003) [arXiv:hep-ph/0211352]. L. Reina and S. Dawson, Phys. Rev. Lett. **87**, 201804 (2001) [arXiv:hep-ph/0107101]; L. Reina, S. Dawson and D. Wackeroth, Phys. Rev. D **65**, 053017 (2002) [arXiv:hep-ph/0109066]; S. Dawson, L. H. Orr, L. Reina and D. Wackeroth, Phys. Rev. D **67**, 071503 (2003) [arXiv:hep-ph/0211438]; S. Dawson, C. Jackson, L. H. Orr, L. Reina and D. Wackeroth, Phys. Rev. D **68**, 034022 (2003) [arXiv:hep-ph/0305087].

[20] M. Dührssen, S. Heinemeyer, H. Logan, D. Rainwater, G. Weiglein and D. Zeppenfeld, Phys. Rev. D **70**, 113009 (2004) [arXiv:hep-ph/0406323] and references therein.

[21] U. Baur, T. Plehn and D. L. Rainwater, Phys. Rev. Lett. **89**, 151801 (2002) [arXiv:hep-ph/0206024] and Phys. Rev. D **67**, 033003 (2003) [arXiv:hep-ph/0211224].

[22] U. Baur, T. Plehn and D. L. Rainwater, Phys. Rev. D **68**, 033001 (2003) [arXiv:hep-ph/0304015].

[23] U. Baur, T. Plehn and D. L. Rainwater, Phys. Rev. D **69**, 053004 (2004) [arXiv:hep-ph/0310056].

[24] S. Abdullin *et al.* [CMS Collaboration], J. Phys. G **28**, 469 (2002) [arXiv:hep-ph/9806366].

[25] J. G. Branson, D. Denegri, I. Hinchliffe, F. Gianotti, F. E. Paige and P. Sphicas [ATLAS and CMS Collaborations], Eur. Phys. J. directC **4**, N1 (2002).

[26] I. Hinchliffe and F. E. Paige, Phys. Rev. D **61**, 095011 (2000) [arXiv:hep-ph/9907519].

[27] F. Gianotti and M. L. Mangano, arXiv:hep-ph/0504221.

[28] F. Abe *et al.* [CDF Collaboration], Phys. Rev. Lett. **77**, 438 (1996).

[29] C. Adloff *et al.*, [H1 Collaboration], Z. Phys. C **74**, 191 (1997).

[30] J. Breitweg *et al.* [ZEUS Collaboration], Z. Phys. C **74**, 207 (1997).

[31] W. L. van Neerven and A. Vogt, Nucl. Phys. B **568**, 263 (2000) [arXiv:hep-ph/9907472].

[32] W. L. van Neerven and A. Vogt, Nucl. Phys. B **588**, 345 (2000) [arXiv:hep-ph/0006154].

[33] A. Vogt, S. Moch and J. A. M. Vermaseren, Nucl. Phys. B **691**, 129 (2004) [arXiv:hep-ph/0404111].

[34] S. Moch, J. A. M. Vermaseren and A. Vogt, Nucl. Phys. B **688**, 101 (2004) [arXiv:hep-ph/0403192].

[35] S. Moch, J. A. M. Vermaseren and A. Vogt, Phys. Lett. B **606**, 123 (2005) [arXiv:hep-ph/0411112].

[36] J. Blümlein and V. Ravindran, Nucl. Phys. B **716**, 128 (2005) [arXiv:hep-ph/0501178].

[37] E. W. N. Glover, C. Oleari and M. E. Tejeda-Yeomans, Nucl. Phys. B **605**, 467 (2001) [arXiv:hep-ph/0102201]; C. Anastasiou, E. W. N. Glover, C. Oleari and M. E. Tejeda-Yeomans, Nucl. Phys. B **605**, 486 (2001) [arXiv:hep-ph/0101304]; Phys. Lett. B **506**, 59 (2001) [arXiv:hep-ph/0012007]; Nucl. Phys. B **601**, 341 (2001) [arXiv:hep-ph/0011094]; Nucl. Phys. B **601**, 318 (2001) [arXiv:hep-ph/0010212]; C. Anastasiou, E. W. N. Glover and M. E. Tejeda-Yeomans, Nucl. Phys. B **629**, 255 (2002) [arXiv:hep-ph/0201274].

[38] Z. Bern, A. De Freitas and L. J. Dixon, JHEP **0203**, 018 (2002) [arXiv:hep-ph/0201161]; JHEP **0306**, 028 (2003) [arXiv:hep-ph/0304168]; JHEP **0109**, 037 (2001) [arXiv:hep-ph/0109078]; A. De Freitas and Z. Bern, JHEP **0409**, 039 (2004) [arXiv:hep-ph/0409007].

[39] A. Gehrmann-De Ridder, T. Gehrmann and E. W. N. Glover, arXiv:hep-ph/0505111.

[40] C. Anastasiou, K. Melnikov and F. Petriello, Phys. Rev. D **69**, 076010 (2004) [arXiv:hep-ph/0311311].

[41] T. Binoth and G. Heinrich, Nucl. Phys. B **693**, 134 (2004) [arXiv:hep-ph/0402265].

[42] For a review see B. Andersson *et al.* [Small x Collaboration], Eur. Phys. J. C **25**, 77 (2002) [arXiv:hep-ph/0204115].

[43] G. Watt, A. D. Martin and M. G. Ryskin, Eur. Phys. J. C **31**, 73 (2003) [arXiv:hep-ph/0306169].

[44] G. Watt, A. D. Martin and M. G. Ryskin, Phys. Rev. D **70**, 014012 (2004) [Erratum-ibid. D **70**, 079902 (2004)] [arXiv:hep-ph/0309096].

[45] J. Collins and H. Jung, arXiv:hep-ph/0508280.

[46] J. Campbell *et al.*, arXiv:hep-ph/0405302; S. Dawson, C. B. Jackson, L. Reina and D. Wackeroth, Phys. Rev. D **69**, 074027 (2004) [arXiv:hep-ph/0311067]; Phys. Rev. Lett. **94**, 031802 (2005) [arXiv:hep-ph/0408077]; arXiv:hep-ph/0508293; S. Dittmaier, M. Krämer and M. Spira, Phys. Rev. D **70**, 074010 (2004) [arXiv:hep-ph/0309204].

[47] The CDF Collaboration, CDF/PHYS/CDF/PUBLIC/7072 and `http://www-cdf.fnal.gov/physics/new/qcd/zbjets/zbjet/zbjet_prelim.html`

[48] J. Pumplin, D. R. Stump, J. Huston, H. L. Lai, P. Nadolsky and W. K. Tung, JHEP **0207**, 012 (2002) [arXiv:hep-ph/0201195].

[49] A. D. Martin, R. G. Roberts, W. J. Stirling and R. S. Thorne, Eur. Phys. J. C **28**, 455 (2003) [arXiv:hep-ph/0211080]; Eur. Phys. J. C **35**, 325 (2004) [arXiv:hep-ph/0308087].

[50] D. Stump, J. Huston, J. Pumplin, W. K. Tung, H. L. Lai, S. Kuhlmann and J. F. Owens, JHEP **0310**, 046 (2003) [arXiv:hep-ph/0303013].

[51] P. M. Nadolsky, D. R. Stump and C. P. Yuan, Phys. Rev. D **64**, 114011 (2001) [arXiv:hep-ph/0012261].

[52] S. Berge, P. Nadolsky, F. Olness and C. P. Yuan, Phys. Rev. D **72**, 033015 (2005) [arXiv:hep-ph/0410375].

[53] L. N. Lipatov, Sov. J. Nucl. Phys. **23**, 338 (1976); E. A. Kuraev, L. N. Lipatov and V. .S. Fadin, Sov. Phys. JETP **45**, 199 (1977); Ya. Ya. Balitsky and L. N. Lipatov, J. Nucl. Phys. **28**, 822 (1978).

[54] M. Ciafaloni, Nucl. Phys. B **296**, 49 (1988); S. Catani, F. Fiorani and G. Marchesini, Phys. Lett. B **234**, 339 (1990); Nucl. Phys. B **336**, 18 (1990).

[55] A. Bhatti *et al.* [CDF Collaboration], arXiv:hep-ex/0510047; A. Abulencia *et al.* [CDF Collaboration], arXiv:hep-ex/0510048.

[56] The DØ Collaboration, DØ note 4874-CONF (July 2005); `http://www-d0.fnal.gov/Run2Physics/top/public/public.html`

[57] W. Bernreuther, A. Brandenburg, Z. G. Si and P. Uwer, Nucl. Phys. B **690**, 81 (2004) [arXiv:hep-ph/0403035].

[58] N. Kauer and D. Zeppenfeld, Phys. Rev. D **65**, 014021 (2002) [arXiv:hep-ph/0107181]; N. Kauer, Phys. Rev. D **67**, 054013 (2003) [arXiv:hep-ph/0212091].

[59] A. Denner, S. Dittmaier, M. Roth and L. H. Wieders, arXiv:hep-ph/0505042 and Phys. Lett. B **612**, 223 (2005) [arXiv:hep-ph/0502063].

[60] N. Kauer, T. Plehn, D. L. Rainwater and D. Zeppenfeld, Phys. Lett. B **503**, 113 (2001) [arXiv:hep-ph/0012351]; see also M. Dührssen and J. Huston, talks given at the "TeV4LHC Workshop", Fermilab, 20 – 22 October 2005, `http://agenda.cern.ch/fullAgenda.php?ida=a056155`.

[61] S. Dawson, S. Dittmaier and M. Spira, Phys. Rev. D **58**, 115012 (1998) [arXiv:hep-ph/9805244].

[62] G. Heinrich, talk given at the "Physics at TeV Colliders" Workshop, Les Houches, May 2005, `http://agenda.cern.ch/fullAgenda.php?ida=a052819`.

[63] G. Belanger, F. Boudjema, J. Fujimoto, T. Ishikawa, T. Kaneko, K. Kato and Y. Shimizu, arXiv:hep-ph/0308080.

[64] T. Hahn and M. Perez-Victoria, Comput. Phys. Commun. **118**, 153 (1999) [arXiv:hep-ph/9807565].

[65] P. Nogueira, J. Comput. Phys. **105**, 279 (1993).

[66] Y. Kurihara, talk at *LoopFest IV*, Snowmass, CO, August 2005, `http://agenda.cern.ch/fullAgenda.php?ida=a053785`.

[67] W. T. Giele and E. W. N. Glover, JHEP **0404**, 029 (2004) [arXiv:hep-ph/0402152].

[68] R. K. Ellis, W. T. Giele and G. Zanderighi, Phys. Rev. D **72**, 054018 (2005) [arXiv:hep-ph/0506196].

[69] R. K. Ellis, W. T. Giele and G. Zanderighi, arXiv:hep-ph/0508308.

[70] `http://mcfm.fnal.gov` and references therein.

[71] F. Cachazo, P. Svrček and E. Witten, JHEP **0409**, 006 (2004) [arXiv:hep-th/0403047]; C. J. Zhu, JHEP **0404**, 032 (2004) [arXiv:hep-th/0403115];G. Georgiou and V. V. Khoze, JHEP **0405**, 070 (2004) [arXiv:hep-th/0404072]; J. B. Wu and C. J. Zhu, JHEP **0407**, 032 (2004) [arXiv:hep-th/0406085]; J. B. Wu and C. J. Zhu, JHEP **0409**, 063 (2004) [arXiv:hep-th/0406146]; D. A. Kosower, Phys. Rev. D **71**, 045007 (2005) [arXiv:hep-th/0406175]; G. Georgiou, E. W. N. Glover and V. V. Khoze, JHEP **0407**, 048 (2004) [arXiv:hep-th/0407027]; Y. Abe, V. P. Nair and M. I. Park, Phys. Rev. D **71**, 025002 (2005) [arXiv:hep-th/0408191]; L. J. Dixon, E. W. N. Glover and V. V. Khoze, JHEP **0412**, 015 (2004) [arXiv:hep-th/0411092]; S. D. Badger, E. W. N. Glover and V. V. Khoze, JHEP **0503**, 023 (2005) [arXiv:hep-th/0412275]; Z. Bern, D. Forde, D. A. Kosower and P. Mastrolia, Phys. Rev. D **72**, 025006 (2005) [arXiv:hep-ph/0412167]; R. Roiban, M. Spradlin and A. Volovich, Phys. Rev. Lett. **94**, 102002 (2005) [arXiv:hep-th/0412265]; R. Britto, F. Cachazo and B. Feng, Nucl. Phys. B **715**, 499 (2005) [arXiv:hep-th/0412308]; R. Britto, F. Cachazo, B. Feng and E. Witten, Phys. Rev. Lett. **94**, 181602 (2005) [arXiv:hep-th/0501052]; M. Luo and C. Wen, JHEP **0503**, 004 (2005) [arXiv:hep-th/0501121]; Phys. Rev. D **71**, 091501 (2005) [arXiv:hep-th/0502009]; R. Britto, B. Feng, R. Roiban, M. Spradlin and A. Volovich, Phys. Rev. D **71**, 105017 (2005) [arXiv:hep-th/0503198]; S. D. Badger, E. W. N. Glover, V. V. Khoze and P. Svrček, JHEP **0507**, 025 (2005) [arXiv:hep-th/0504159].

[72] A. Brandhuber, B. Spence and G. Travaglini, Nucl. Phys. B **706**, 150 (2005) [arXiv:hep-th/0407214]; R. Britto, F. Cachazo and B. Feng, Phys. Rev. D **71**, 025012 (2005) [arXiv:hep-th/0410179]; Z. Bern, V. Del Duca, L. J. Dixon and D. A. Kosower, Phys. Rev. D **71**, 045006 (2005) [arXiv:hep-th/0410224]; R. Britto, F. Cachazo and B. Feng, Nucl. Phys. B **725**, 275 (2005) [arXiv:hep-th/0412103]; Z. Bern, L. J. Dixon and D. A. Kosower, Phys. Rev. D **72**, 045014 (2005) [arXiv:hep-th/0412210]; arXiv:hep-ph/0507005; C. Quigley and M. Rozali, JHEP **0501**, 053 (2005) [arXiv:hep-th/0410278]; J. Bedford, A. Brandhuber, B. Spence and G. Travaglini, Nucl. Phys. B **706**, 100 (2005) [arXiv:hep-th/0410280]; Nucl. Phys. B **712**, 59 (2005) [arXiv:hep-th/0412108]; S. J. Bidder, N. E. J. Bjerrum-Bohr, L. J. Dixon and D. C. Dunbar, Phys. Lett. B **606**, 189 (2005) [arXiv:hep-th/0410296]; S. J. Bidder, N. E. J. Bjerrum-Bohr, D. C. Dunbar and W. B. Perkins, Phys. Lett. B **608**, 151 (2005) [arXiv:hep-th/0412023]; Phys. Lett. B **612**, 75 (2005) [arXiv:hep-th/0502028]; R. Britto, E. Buchbinder, F. Cachazo and B. Feng, Phys. Rev. D **72**, 065012 (2005) [arXiv:hep-ph/0503132].

[73] E. Witten, Commun. Math. Phys. **252**, 189 (2004) [arXiv:hep-th/0312171].

[74] T. Sjostrand, L. Lönnblad, S. Mrenna and P. Skands, arXiv:hep-ph/0308153.

[75] G. Corcella *et al.*, arXiv:hep-ph/0210213.

[76] T. Gleisberg, S. Hoche, F. Krauss, A. Schalicke, S. Schumann and J. C. Winter, JHEP **0402**, 056 (2004) [arXiv:hep-ph/0311263].

[77] P. Skands, talk at *LoopFest IV*, Snowmass, CO, August 2005, `http://agenda.cern.ch/fullAgenda.php?ida=a053785`

[78] S. Frixione and B. R. Webber, arXiv:hep-ph/0506182.

[79] F. Krauss, JHEP **0208**, 015 (2002) [arXiv:hep-ph/0205283].

[80] S. Catani, F. Krauss, R. Kuhn and B. R. Webber, JHEP **0111**, 063 (2001) [arXiv:hep-ph/0109231].

[81] S. Mrenna and P. Richardson, JHEP **0405**, 040 (2004) [arXiv:hep-ph/0312274].

[82] F. Krauss, A. Schalicke, S. Schumann and G. Soff, Phys. Rev. D **70**, 114009 (2004) [arXiv:hep-ph/0409106].

[83] F. Abe *et al.* [CDF Collaboration], Phys. Rev. Lett. **75**, 11 (1995) and Phys. Rev. D **52**, 4784 (1995); T. Affolder *et al.* [CDF Collaboration], Phys. Rev. D **64**, 052001 (2001).

[84] S. Abachi *et al.* [DØ Collaboration], Phys. Rev. Lett. **77**, 3309 (1996), B. Abbott *et al.* [DØ Collaboration], Phys. Rev. D **58** 012002 (1998); Phys. Rev. D **58** 092003 (1998); Phys. Rev. Lett. **80**, 3008 (1998); Phys. Rev. Lett. **84**, 222 (2000); Phys. Rev. D **62** 092006 (2000); V. M. Abazov *et al.* [DØ Collaboration], Phys. Rev. D **66**, 012001 (2002).

[85] G. Azuelos and G. Polesello, Eur. Phys. J. C **39S2**, 1 (2005).

[86] G. Azuelos *et al.*, Eur. Phys. J. C **39S2**, 13 (2005) [arXiv:hep-ph/0402037].

[87] A. D. Martin, R. G. Roberts, W. J. Stirling and R. S. Thorne, Eur. Phys. J. C **39**, 155 (2005) [arXiv:hep-ph/0411040].

[88] C. Balazs and C. P. Yuan, Phys. Rev. D **56**, 5558 (1997) [arXiv:hep-ph/9704258].

[89] R. Brock *et al.*, arXiv:hep-ex/0011009.

[90] S. Haywood *et al.*, arXiv:hep-ph/0003275.

[91] A. Schmidt, CMS thesis, University of Karlsruhe, Germany.

[92] M. Ciafaloni, P. Ciafaloni and D. Comelli, Nucl. Phys. B **589**, 359 (2000).

[93] V. S. Fadin, L. N. Lipatov, A. D. Martin and M. Melles, Phys. Rev. D **61**, 094002 (2000); J.H. Kühn, A.A. Penin and V.A. Smirnov, Eur. Phys. J. C **17**, 97 (2000); M. Melles, Phys. Rept. **375**, 219 (2003).

[94] [LEP and SLD Collaborations], arXiv:hep-ex/0509008.

[95] M. Mühlleitner, A. Djouadi and Y. Mambrini, arXiv:hep-ph/0311167 and references therein.

[96] H. Bachacou, I. Hinchliffe and F. E. Paige, Phys. Rev. D **62**, 015009 (2000) [arXiv:hep-ph/9907518]; B. C. Allanach, C. G. Lester, M. A. Parker and B. R. Webber, JHEP **0009**, 004 (2000) [arXiv:hep-ph/0007009].

[97] A. J. Barr, Phys. Lett. B **596**, 205 (2004) [arXiv:hep-ph/0405052].

[98] D. Berdine and D. Rainwater, arXiv:hep-ph/0506261.

[99] S. Mrenna, Comput. Phys. Commun. **101**, 232 (1997) [arXiv:hep-ph/9609360].

[100] S. Moretti, K. Odagiri, P. Richardson, M. H. Seymour and B. R. Webber, JHEP **0204**, 028 (2002) [arXiv:hep-ph/0204123].

[101] F. Maltoni and T. Stelzer, JHEP **0302**, 027 (2003) [arXiv:hep-ph/0208156].

[102] G.-C. Cho, K. Hagiwara, J. Kanzaki, T. Plehn, D. Rainwater and T. Stelzer, in preparation.

[103] D. Rainwater, talk given at SUSY05, Durham, England, July 2005.

[104] J. Fujimoto *et al.*, Comput. Phys. Commun. **153**, 106 (2003) [arXiv:hep-ph/0208036].

[105] E. Boos *et al.* [CompHEP Collaboration], Nucl. Instrum. Meth. A **534**, 250 (2004) [arXiv:hep-ph/0403113].

[106] T. Plehn, D. Rainwater and P. Skands, arXiv:hep-ph/0510144.

[107] W. Beenakker, R. Höpker, M. Spira and P. M. Zerwas, Phys. Rev. Lett. **74**, 2905 (1995) [arXiv:hep-ph/9412272]; Z. Phys. C **69**, 163 (1995) [arXiv:hep-ph/9505416]; Nucl. Phys. B **492**, 51 (1997) [arXiv:hep-ph/9610490]; W. Beenakker, M. Krämer, T. Plehn, M. Spira and P. M. Zerwas, Nucl. Phys. B **515**, 3 (1998) [arXiv:hep-ph/9710451]; W. Beenakker, M. Klasen, M. Krämer, T. Plehn, M. Spira and P. M. Zerwas, Phys. Rev. Lett. **83**, 3780 (1999) [arXiv:hep-ph/9906298]; M. Spira, arXiv:hep-ph/0211145; E. L. Berger, M. Klasen and T. M. P. Tait, Phys. Rev. D **62**, 095014 (2000) [arXiv:hep-ph/0005196]; Phys. Rev. D **67**, 099901 (2003) [arXiv:hep-ph/0212306].

[108] N. Arkani-Hamed, S. Dimopoulos, G. F. Giudice and A. Romanino, Nucl. Phys. B **709**, 3 (2005) [arXiv:hep-ph/0409232]; J. D. Wells, Phys. Rev. D **71**, 015013 (2005) [arXiv:hep-ph/0411041].

[109] S. P. Martin, K. Tobe and J. D. Wells, Phys. Rev. D **71**, 073014 (2005) [arXiv:hep-ph/0412424]; M. Toharia and J. D. Wells, arXiv:hep-ph/0503175; W. Kilian, T. Plehn, P. Richardson and E. Schmidt, Eur. Phys. J. C **39**, 229 (2005) [arXiv:hep-ph/0408088]; K. Cheung and J. Song, Phys. Rev. D **72**, 055019 (2005) [arXiv:hep-ph/0507113]; P. Gambino, G. F. Giudice and P. Slavich, Nucl. Phys. B **726**, 35 (2005) [arXiv:hep-ph/0506214]; J. L. Hewett, B. Lillie, M. Masip and T. G. Rizzo, JHEP **0409**, 070 (2004) [arXiv:hep-ph/0408248].

[110] J. S. Lee, A. Pilaftsis, M. Carena, S. Y. Choi, M. Drees, J. R. Ellis and C. E. M. Wagner, Comput. Phys. Commun. **156**, 283 (2004) [arXiv:hep-ph/0307377].

[111] S. Heinemeyer, Eur. Phys. J. C **22**, 521 (2001) [arXiv:hep-ph/0108059].

[112] A. Djouadi, J. Kalinowski and M. Spira, Comput. Phys. Commun. **108**, 56 (1998) [arXiv:hep-ph/9704448].

[113] M. Spira, arXiv:hep-ph/9510347.

[114] W. Beenakker, S. Dittmaier, M. Krämer, B. Plümper, M. Spira and P. M. Zerwas, Phys. Rev. Lett. **87**, 201805 (2001) [arXiv:hep-ph/0107081]; Nucl. Phys. B **653**, 151 (2003) [arXiv:hep-ph/0211352]; L. Reina and S. Dawson, Phys. Rev. Lett. **87**, 201804 (2001) [arXiv:hep-ph/0107101]; L. Reina, S. Dawson and D. Wackeroth, Phys. Rev. D **65**, 053017 (2002) [arXiv:hep-ph/0109066]; S. Dawson, L. H. Orr, L. Reina and D. Wackeroth, Phys. Rev. D **67**, 071503 (2003) [arXiv:hep-ph/0211438]; S. Dawson, C. Jackson, L. H. Orr, L. Reina and D. Wackeroth, Phys. Rev. D **68**, 034022 (2003) [arXiv:hep-ph/0305087];

[115] R. Barate *et al.* [ALEPH Collaboration], Phys. Lett. B **565**, 61 (2003) [arXiv:hep-ex/0306033].

[116] N. Arkani-Hamed, A. G. Cohen, E. Katz and A. E. Nelson, JHEP **0207**, 034 (2002) [arXiv:hep-ph/0206021]; N. Arkani-Hamed, A. G. Cohen, E. Katz, A. E. Nelson, T. Gregoire and J. G. Wacker, JHEP **0208**, 021 (2002) [arXiv:hep-ph/0206020]; D. E. Kaplan and M. Schmaltz, JHEP **0310**, 039 (2003) [arXiv:hep-ph/0302049]; M. Schmaltz, JHEP **0408**, 056 (2004) [arXiv:hep-ph/0407143]; M. Schmaltz and D. Tucker-Smith, arXiv:hep-ph/0502182.

[117] G. Burdman, M. Perelstein and A. Pierce, Phys. Rev. Lett. **90**, 241802 (2003) [Erratum-ibid. **92**, 049903 (2004)] [arXiv:hep-ph/0212228]; T. Han, H. E. Logan, B. McElrath and L. T. Wang, Phys. Rev. D **67**, 095004 (2003) [arXiv:hep-ph/0301040]; M. Perelstein, M. E. Peskin and A. Pierce, Phys. Rev. D **69**, 075002 (2004) [arXiv:hep-ph/0310039].

[118] H. C. Cheng and I. Low, JHEP **0408**, 061 (2004) [arXiv:hep-ph/0405243]; I. Low, JHEP **0410**, 067 (2004) [arXiv:hep-ph/0409025].

[119] C. Csaki, C. Grojean, H. Murayama, L. Pilo and J. Terning, Phys. Rev. D **69**, 055006 (2004) [arXiv:hep-ph/0305237]; C. Csaki, C. Grojean, L. Pilo and J. Terning, Phys. Rev. Lett. **92**, 101802 (2004) [arXiv:hep-ph/0308038].

[120] N. S. Manton, Nucl. Phys. B **158**, 141 (1979).

[121] L. Randall and R. Sundrum, Phys. Rev. Lett. **83**, 3370 (1999) [arXiv:hep-ph/9905221].

[122] N. Arkani-Hamed, M. Porrati and L. Randall, JHEP **0108**, 017 (2001) [arXiv:hep-th/0012148].

[123] K. Agashe, A. Delgado, M. J. May and R. Sundrum, JHEP **0308**, 050 (2003) [arXiv:hep-ph/0308036].

[124] K. Agashe, R. Contino and A. Pomarol, Nucl. Phys. B **719**, 165 (2005) [arXiv:hep-ph/0412089].

[125] N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Lett. B **429**, 263 (1998) [arXiv:hep-ph/9803315]; I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Lett. B **436**, 257 (1998) [arXiv:hep-ph/9804398]; N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Rev. D **59**, 086004 (1999) [arXiv:hep-ph/9807344].

[126] G. F. Giudice, R. Rattazzi and J. D. Wells, Nucl. Phys. B **544**, 3 (1999) [arXiv:hep-ph/9811291]; E. A. Mirabelli, M. Perelstein and M. E. Peskin, Phys. Rev. Lett. **82**, 2236 (1999) [arXiv:hep-ph/9811337].

[127] T. Appelquist, H. C. Cheng and B. A. Dobrescu, Phys. Rev. D **64**, 035002 (2001) [arXiv:hep-ph/0012100]; C. Macesanu, C. D. McMullen and S. Nandi, Phys. Lett. B **546**, 253 (2002) [arXiv:hep-ph/0207269].

[128] H. Georgi, A. K. Grant and G. Hailu, Phys. Lett. B **506**, 207 (2001) [arXiv:hep-ph/0012379]; G. von Gersdorff, N. Irges and M. Quiros, Nucl. Phys. B **635**, 127 (2002) [arXiv:hep-th/0204223]; H. C. Cheng, K. T. Matchev and M. Schmaltz, Phys. Rev. D **66**, 036005 (2002) [arXiv:hep-ph/0204342].

[129] K. Agashe, N. G. Deshpande and G. H. Wu, Phys. Lett. B **511**, 85 (2001) [arXiv:hep-ph/0103235]; Phys. Lett. B **514**, 309 (2001) [arXiv:hep-ph/0105084]; T. Appelquist and B. A. Dobrescu, Phys. Lett. B **516**, 85 (2001) [arXiv:hep-ph/0106140]; T. Appelquist and H. U. Yee, Phys. Rev. D **67**, 055002 (2003) [arXiv:hep-ph/0211023]; D. Chakraverty, K. Huitu and A. Kundu, Phys. Lett. B **558**, 173 (2003) [arXiv:hep-ph/0212047]; A. J. Buras, M. Spranger and A. Weiler, Nucl. Phys. B **660**, 225 (2003) [arXiv:hep-ph/0212143]; A. J. Buras, A. Poschenrieder, M. Spranger and A. Weiler, Nucl. Phys. B **678**, 455 (2004) [arXiv:hep-ph/0306158].

[130] G. Servant and T. M. Tait, Nucl. Phys. B **650**, 391 (2003) [arXiv:hep-ph/0206071]; H. C. Cheng, J. L. Feng and K. T. Matchev, Phys. Rev. Lett. **89**, 211301 (2002) [arXiv:hep-ph/0207125].

[131] G. F. Giudice, R. Rattazzi and J. D. Wells, Nucl. Phys. B **595**, 250 (2001) [arXiv:hep-ph/0002178]; U. Mahanta and A. Datta, Phys. Lett. B **483**, 196 (2000) [arXiv:hep-ph/0002183]; C. Csaki, M. L. Graesser and G. D. Kribs, Phys. Rev. D **63**, 065002 (2001) [arXiv:hep-th/0008151]; M. Chaichian, A. Datta, K. Huitu and Z. h. Yu, Phys. Lett. B **524**, 161 (2002) [arXiv:hep-ph/0110035]; J. L. Hewett and T. G. Rizzo, JHEP **0308**, 028 (2003) [arXiv:hep-ph/0202155].

[132] N. Arkani-Hamed, A. G. Cohen and H. Georgi, Phys. Rev. Lett. **86**, 4757 (2001) [arXiv:hep-th/0104005]; C. T. Hill, S. Pokorski and J. Wang, Phys. Rev. D **64**, 105005 (2001) [arXiv:hep-th/0104035].

[133] S. B. Giddings and S. Thomas, Phys. Rev. D **65**, 056010 (2002) [arXiv:hep-ph/0106219]; S. Dimopoulos and G. Landsberg, Phys. Rev. Lett. **87**, 161602 (2001) [arXiv:hep-ph/0106295].

[134] N. Arkani-Hamed, A. G. Cohen and H. Georgi, Phys. Lett. B **513**, 232 (2001) [arXiv:hep-ph/0105239].

[135] S. Dimopoulos and L. Susskind, Nucl. Phys. B **155**, 237 (1979); S. Weinberg, Phys. Rev. D **19**, 1277 (1979).

[136] C. Csaki, C. Grojean, H. Murayama, L. Pilo and J. Terning, Phys. Rev. D **69**, 055006 (2004) [arXiv:hep-ph/0305237]; C. Csaki, C. Grojean, L. Pilo and J. Terning, Phys. Rev. Lett. **92**, 101802 (2004) [arXiv:hep-ph/0308038]; C. Csaki, C. Grojean, J. Hubisz, Y. Shirman and J. Terning, Phys. Rev. D **70**, 015012 (2004) [arXiv:hep-ph/0310355]; Y. Nomura, JHEP **0311**, 050 (2003) [arXiv:hep-ph/0309189].

[137] A. Birkedal, K. Matchev and M. Perelstein, Phys. Rev. Lett. **94**, 191803 (2005) [arXiv:hep-ph/0412278].

[138] N. Arkani-Hamed, A. G. Cohen, E. Katz and A. E. Nelson, JHEP **0207**, 034 (2002) [arXiv:hep-ph/0206021].

[139] J. Hubisz, P. Meade, A. Noble and M. Perelstein, arXiv:hep-ph/0506042.

[140] W. Kilian, D. Rainwater and J. Reuter, Phys. Rev. D **71**, 015008 (2005) [arXiv:hep-ph/0411213].

[141] E. Boos *et al.*, arXiv:hep-ph/0109068.

[142] J. Hewett and M. Spiropulu, Ann. Rev. Nucl. Part. Sci. **52**, 397 (2002) [arXiv:hep-ph/0205106].

[143] I. Antoniadis, Phys. Lett. B **246**, 377 (1990); J. D. Lykken, Phys. Rev. D **54**, 3693 (1996) [arXiv:hep-th/9603133]; I. Antoniadis and M. Quiros, Phys. Lett. B **392**, 61 (1997) [arXiv:hep-th/9609209].

[144] F. E. Paige, S. D. Protopescu, H. Baer and X. Tata, arXiv:hep-ph/0312045.

[145] L. Vacavant and I. Hinchliffe, J. Phys. G **27**, 1839 (2001); J. Lykken and K. Matchev, unpublished.

[146] T. Gleisberg, F. Krauss, K. T. Matchev, A. Schalicke, S. Schumann and G. Soff, JHEP **0309**, 001 (2003) [arXiv:hep-ph/0306182].

[147] J. A. R. Cembranos, A. Dobado and A. L. Maroto, Phys. Rev. D **70**, 096001 (2004) [arXiv:hep-ph/0405286].

[148] G. F. Giudice, R. Rattazzi and J. D. Wells, Nucl. Phys. B **630**, 293 (2002) [arXiv:hep-ph/0112161].

[149] P. Mathews, V. Ravindran, K. Sridhar and W. L. van Neerven, Nucl. Phys. B **713**, 333 (2005) [arXiv:hep-ph/0411018].

[150] H. C. Cheng, K. T. Matchev and M. Schmaltz, Phys. Rev. D **66**, 056006 (2002) [arXiv:hep-ph/0205314]; J. M. Smillie and B. R. Webber, arXiv:hep-ph/0507170; M. Battaglia, A. K. Datta, A. De Roeck, K. Kong and K. T. Matchev, arXiv:hep-ph/0507284.

[151] M. Battaglia, A. Datta, A. De Roeck, K. Kong and K. T. Matchev, JHEP **0507**, 033 (2005) [arXiv:hep-ph/0502041].

[152] P. Richardson, JHEP **0111**, 029 (2001) [arXiv:hep-ph/0110108]; S. Moretti, K. Odagiri, P. Richardson, M. H. Seymour and B. R. Webber, JHEP **0204**, 028 (2002) [arXiv:hep-ph/0204123].

[153] G. Cleaver, M. Cvetic, J. R. Espinosa, L. L. Everett, P. Langacker and J. Wang, Phys. Rev. D **59**, 055005 (1999) [arXiv:hep-ph/9807479].

[154] M. Cvetic, G. Shiu and A. M. Uranga, Nucl. Phys. B **615**, 3 (2001) [arXiv:hep-th/0107166].

[155] V. Braun, Y. H. He, B. A. Ovrut and T. Pantev, JHEP **0506**, 039 (2005) [arXiv:hep-th/0502155].

[156] T. P. T. Dijkstra, L. R. Huiszoon and A. N. Schellekens, Nucl. Phys. B **710**, 3 (2005) [arXiv:hep-th/0411129].

[157] F. Quevedo, *Prepared for ICTP Spring School on Superstrings and Related Matters, Trieste, Italy, 18-26 Mar 2002*.

[158] A. E. Faraggi, C. Kounnas, S. E. M. Nooij and J. Rizos, Nucl. Phys. B **695**, 41 (2004) [arXiv:hep-th/0403058].

[159] R. Blumenhagen, M. Cvetic, P. Langacker and G. Shiu, [arXiv:hep-th/0502005].

[160] See, for example, S. Kachru, R. Kallosh, A. Linde and S. P. Trivedi, Phys. Rev. D **68**, 046005 (2003) [arXiv:hep-th/0301240].

[161] For an overview see M. Calvi, arXiv:hep-ex/0506046 and J. Rademacker [LHCb Collaboration], arXiv:hep-ex/0503001.