When the LHC begins operation, particle physics will enter an exciting new era of discovery. My research is aimed at calculating some of the most important Standard Model processes observed in accelerator experiments at high precision, using new advances in the methods of applying quantum field theory to phenomenology. Future discoveries may suggest new directions of research which cannot be predicted at this time. My wide range of research experience, encompassing both phenomenology and earlier work in string theory, provides the background needed to make valuable contributions to the theoretical study of any new phenomena which may be uncovered.

The physics of the LHC, as well as the proposed ILC, will place unprecedented precision requirements on the calculations of the hadronic and electroweak processes measured at those colliders. Such precision will be needed to fully test the validity of the Standard Model, to probe its Higgs sector, and to search for hints of new physics beyond the Standard Model.

My work, which is was funded by Department of Energy grant DE-FG02-05ER-41399 in 2005, is directed in several key areas where new calculations will be needed to bring theoretical predictions to the anticipated precision level of the upcoming experiments. These can be separated into two main categories: W and Z production at hadron colliders (LHC), and Bhabha scattering or fermion pair production at next-generation electron-positron colliders (ILC). New methods of computing Feynman diagrams are expected to be fruitful in both of these projects, and I have also been engaged in some attempts to develop new methods based on hypergeometric functions for the reduction of high-order diagrams.

W and Z Boson Production

The production of W and Z bosons is one of the most basic processes observed in a hadron collider. This process is identified as the leading choice for the luminosity monitor at the LHC. In addition, studying these interactions is of interest on its own, since precision data on them will provide important tests of the Standard Model. A fully exclusive calculation, implemented in a Monte Carlo program at the 1% precision level, will be needed to meet the requirements of LHC physics.

I have been working with B.F.L. Ward at Baylor University toward the construction of a MC program for vector boson production at the LHC, to be used in the later stages of data analysis when high precision is essential. S. Jadach and other collaborators in Cracow are also involved in related projects. This new program is intended to be a step beyond state-of-the-art tools such as MC@NLO and HORACE. This year, I am visiting the Princeton CMS group, which includes D. Marlow and V. Halyo, and is working on the experimental side of the luminosity measurement. This should be a fruitful exchange both for developing the program and for assisting the Princeton group in assessing available MC tools. For example, I have been running tests to assess the importance of NNLO QCD for relevant experimental cuts on the outgoing fermions in Z production using the FEWZ program.

Our MC program will be based on a nonabelian generalization of the YFS exponentiation approach which had great success in the programs BHLUMI and $\mathcal{KK}$ MC developed for leptonic physics. This procedure has significant advantages in treating multiple photon and gluon emission, allowing an exact representation of the phase space and exponentiation of the infrared singularities. The IR structure of QCD is clearly more complicated than for QED, but our work so far suggests that the YFS paradigm can be adapted to this case, with due attention to the uniquely nonabelian contributions which appear at each order. The parton-level matrix element can then be combined with an existing shower generator, or with a newer one which may be developed, in a way that avoids double counting of effects. Both gluon and photon emission must be considered to reach the desired precision level.

In fact, the kernels used to construct the showers can themselves be exponentiated, and experience with the QED analog at LEP as well as new calculations by Ward suggest that such exponentiation should be an important contribution to a precision MC. We anticipate testing exponentiated kernels in both HERWIG and PYTHIA in the near future.

The large number of diagrams appearing in the parton-level processes needed at the 1% level, and large number of terms which may be generated per diagram, lead to some challenges for MC implementation. It is important to insure that the results are numerically stable, and represented in a sufficiently compact manner to be practical for use in an event generator. We are presently working on new representations for the relevant integrals and testing various ways of evaluating them to avoid these problems. My collaborators and I have been developing hypergeometric function techniques in the hope of creating a new set of algorithms for reducing high-order Feynman diagrams. These algorithms are based on recursion relations among hypergeometric functions which can be derived using a differential equation representation.

Bhabha Scattering and Fermion Pairs

In 1991, I began work on a series of projects designed to improve the accuracy of the luminosity process calculation for electron-positron colliders, in which scattering rates are normalized by measuring the Bhabha scattering cross section, $e^+e^- \to e^+e^- + n\gamma$. It was recognized that to reduce the accuracy of BHLUMI below the 0.25% level, it would be necessary to compute the exact two-photon radiative corrections, which previously had been incorporated at leading logarithm level.

In collaboration with S. Jadach and B.F.L. Ward, I began addressing this problem by calculating the exact two-photon radiative corrections for Bhabha scattering. This work made use of helicity spinor methods which have been valuable in all successive work in this direction.

All two-photon bremsstrahlung contributions (real and virtual) were included to the extent that they were applicable to LEP physics, and used to verify a 0.061% precision tag for BHLUMI in LEP1 physics and 0.122% in LEP2 physics. Including the exact effects is an important step in upgrading BHLUMI for ILC physics, where a 0.01% precision tag is requested for the Bhabha process.

It is also necessary to check whether a certain class of diagrams involving two virtual photons exchanged between the electron and positron lines ("up-down interference") can become significant in ILC physics. These contributions are suppressed at small angles, but it is important to verify that they remain negligible at the higher precision level, and possibly larger angles, of the ILC, and to incorporate them if they are needed. There have turned out to be many numerical issues relating to the accurate calculation of the four and five-point box diagrams needed for this result, but we expect to be able to report on the details shortly. A postdoctoral associate, S. Majhi, is providing crucial assistance in these efforts.

A related project which has occupied much of my attention has been to calculate all second-order photonic radiative corrections to the pair production process $e^+e^- \to \gamma, Z \to f\overline{f}$. The results have been implemented in the $\mathcal{KK}$ Monte Carlo program. Recently, another expression for the initial state real + virtual photon radiation has become available via the leptonic tensor used in the PHOKHARA Monte Carlo for radiative return studies (in which emission of a high-energy photon from the incoming particles is used to reduce the energy of the ensuing collision).

The calculations use different techniques, and significantly, different approximations for calculating the collinear electron-mass effects. A comparison will lead to a better understanding these collinear mass effects. An anticipated outgrowth of these comparisons is the extension of the $\mathcal{KK}$ MC to the lower energy regime of Φ and B factories, providing an alternative tool for the analysis of radiative return experiments.

Earlier Accomplishments

Before entering the field of elementary particle phenomenology in 1991, I worked on other topics. Following some early investigations of the status of dibaryons in the Skyrme model and related chiral soliton models of nucleons, I began work on superstring theory, focusing primarily on various aspects of open strings. At the time, the newly-discovered heterotic string was receiving much more attention, but this work became very influential following the discovery of dualities between the various forms of string theory, when open string theories proved to be equally important as the other models, which were all seen as limiting cases of some underlying "M-theory". In particular, open strings play an important role in brane-world scenarios, in which an end of the string is confined to a "brane" where the gauge interactions live.

A study of open strings in background gauge fields led to a derivation of the nonlinear Born-Infeld action from the conditions of conformal invariance. Investigating the interaction of open and closed strings through degenerating holes in the string worldsheet led a series of papers with C. Callan, C. Lovelace, and C. Nappi, which clarified the role of string loop effects on the symmetries and equations of motion of the classical theory. The effect of a gauge field background on the closed string sector was investigated using a combination of worldsheet and boundary operator techniques.

Later work included various other topics relating to open string physics. C. Preitchopf, C. Thorn and I developed a cubic action for open superstring field theory in Witten's non-abelian geometry formalism which avoided certain technical problems (divergences and gauge anomalies) which had been discovered the original formulation. In the process, we found a novel gauge for constructing the tree-level processes from Witten's string field theory. M. McGuigan, C. Nappi, and I studied charged black holes in two-dimensional open string theory. I also presented an analysis of supermatrix models, an extension of the matrix models studied in connection to conformal field theory and low-dimensional string theory.