# SECTION C. PROJECT DESCRIPTION

## 1. Results of Prior Support

Grant: #0426272, $55,000, June 15, 2004, through June 15, 2007

Title: *Web-Based High-Energy Particle Physics Event Generation*

Summary of Results: This grant represents the original NSF funding of the MadEvent project, which had the ambitious goal of creating a web-based tool that would allow researchers to quickly and accurately run event simulations for tree-level standard model processes. To achieve this goal, many technical challenges had to be overcome. First, we needed to develop an integration technique capable of efficiently generating unweighted events from the sharply peaked matrix element amplitudes characteristic of multi-jet final states. Next, we had to select and output the appropriate spin, color, and resonance structure for each hard scattering event, so it could be passed to the showering and hadronization programs for a complete event simulation. Finally, it was necessary to develop a robust infrastructure that was simple, reliable, and flexible. We were able to complete all of these challenges successfully, and the results of this project are embodied in the MadGraph website.[1]

Using this web interface, a user can request a process of interest (e.g., W+4 jets at the LHC), and the software will identify the nearly 500 contributing subprocesses and generate the appropriate Feynman diagrams for each one. Furthermore, the user can request events to be generated via the web with both parton level and full event simulation results available on-line. The web server and computing farm supported by this grant can generate approximately 10,000 W+4 jet events/hour and has 2 terabytes of RAID disk storage, which is available to the high-energy physics (HEP) community. In addition to developing the ability to generate parton-level through fully hadronized standard model event samples, several important new models have been added to the MadGraph/MadEvent package, including the minimal supersymmetric standard model (MSSM), a Two Higgs Doublet model, as well as a Higgs effective field theory, which allows for the important generation of $gg \to H$ (a one-loop calculation) within the MadGraph/MadEvent framework.

The MadGraph and MadEvent packages have become an important resource for the HEP community. To date, 1,400 registered users have employed the web-based utility to generate tens of thousands of processes and millions of events. The original MadGraph paper [1] currently has nearly 400 citations, and the MadEvent paper [2] has already received nearly 250 citations. The 23,000 matches from a Google search of “madgraph” is further evidence of the program’s impact on the community.

List of Publications Resulting from the Award:

1. *MadGraph/MadEvent v4: The New Web Generation*. J. Alwall, P. Demin, S. DeVisscher, R. Frederix, M. Herquet, F. Maltoni, T. Plehn, D. Rainwater, T. Stelzer. **JHEP 09:028,** 1-28**, 2007**

2. *Higgs at the Tevatron in Extended Supersymmetric Models.* T. Stelzer et al. **Phys.Rev.D 75:**077701-077702**, 2007**

3. *Correlated Decays of Pair-Produced Scalar Taus.*K. Hagiwara et al. **Phys. Rev. D73:** 077701-077702**, 2006**

4. *Weak boson fusion production of supersymmetric particles at the LHC.* G.-C. Cho et al. **Phys. Rev. D73:**054002-054018**, 2006.**

5. *Tools for the Simulation of Hard Hadronic Collisions.* M.L. Mangano and T. Stelzer. **Annual Review of Nuclear and Particle Science 55:**555-588**, 2005.**

The success of this project has resulted in strong international support. Fabio Maltoni (assistant professor Université catholique de Louvain) has built a strong group, including two postdocs and six graduate students. Tilman Plehn (lecturer at University of Edinburgh), David Rainwater (research associate at Rochester University) and Johan Alwall (post doc at Stanford Linear Accelerator Center) have all joined as primary authors for the latest release of the package.

The enthusiastic reception and international support for this work has defined a clear path for continued development, which is the purpose of this request for continued and expanded funding.

## 2. Goals and Objectives

The primary goal of the proposed project is to expand upon both the support and the scope of the MadGraph/MadEvent project for the analysis of data from the Large Hadron Collider (LHC). The support will include providing customized packages for generating important event samples, running general workshops/training for using the package, and working with individual analysts to ensure that they are generating the appropriate samples. The scope of the MadEvent package will be expanded to address the needs for all three user groups—model builders, phenomenologists, and experimentalists. For the model builders, an interface tool will be developed for adding new models, such that a user could go directly from the appropriate Lagrangian to event generation and comparison with data. For phenomenologists, improvements will include expanded control over the processes generated by allowing for specific resonant structures and decay channels, as well as the ability to project out specific color states for quarkonium production. Tools will also be developed to facilitate generation of inclusive event samples using the recently developing matching schemes. For experimentalists, infrastructure will be created to assist in using MadEvent to perform matrix element techniques for data analysis. The program format will also be modified so it can easily be assimilated into the experiments' software environment and optimized for running on the Grid.

## 3. Background and Motivation

This is an exciting time in high energy particle physics. Run II at the Fermi National Accelerator Laboratory is now underway and will collect more than 50 times the data that was used in discovering the top quark. Even while Run II progresses, the LHC at CERN is about to turn on and will soon be generating top quark events at the rate of 1/sec. Extracting new discoveries from these data requires meticulous calculations based on fundamental theory for particles and their interactions. Indeed, understanding the data that comes in will require an unprecedented level of communication between model builders, phenomonologists, and experimentalists. MadEvent can help facilitate this communication by providing a single environment in which theorists can create and test new models, phenomenologists can investigate signal signatures and mechanisms to suppress the background, and experimentalists can run complete event simulations needed to extract the physics from the data.

The ATLAS detector and physics performance Technical Design Report's analysis for the discovery of supersymmetry (SUSY) provides an excellent illustration of techniques typically employed for hadron collider analysis, as well as motivating the need for efficient communication between model builders, phenomenologists, and experimentalists if we are to fully exploit the new data. SUSY events are dominated by the production of squarks and gluinos, which decay into standard model particles and the lightest supersymmetric particle that will escape the detector. Thus the signal will be multiple jets, leptons, and missing energy. The first step is to look for deviations in the data from the standard model. Hence, it will be important to have accurate simulations of the standard model backgrounds, such as W+jet production, that can produce similar signatures. Considerable progress has been made over the past few years in simulating these multi-parton final states. In addition to producing the hard matrix elements and color connections for W+jet events, several matching schemes have been introduced to merge these events with the showering and hadronization codes to provide the most accurate simulations possible [3-6]. Once a signal has been discovered, determining the underlying model will require accurate simulation of events from numerous models of interest. These will undoubtedly include not only regions of SUSY parameter space, but also other novel theoretical models inspired by the data.

MadEvent can provide a framework in which theorists, phenomenologists, and experimentalists can efficiently communicate with one another to extract the most physics possible from the upcoming data. The following sections discuss the various enhancements being proposed and how they will facilitate communication among the various groups and contribute to understanding the data coming from the LHC.

### *Lagrangian Interface for New Models*

The current versions of MadGraph and MadEvent are capable of generating events for many new physics models. Two input files, particles.dat and interactions.dat, are all that is needed for MadGraph to generate the appropriate Feynman diagrams. A separate file to calculate the appropriate couplings is also needed for event generation. These files have already been created for several models of particular interest (MSSM, Two Higgs Double, Higgs Effective Field Theory), and can be directly accessed from the web interface. However, creating new models generally requires considerable expertise with the MadGraph system. For models having large numbers of additional particles and interactions, obtaining the appropriate couplings and phases can be a painstaking challenge. Indeed, including MSSM into MadGraph required considerable time, as a result of inconsistencies in the phases and couplings. In the end, checks using more than 500 different channels were necessary to verify proper implementation. While this effort was clearly justified for models guaranteed to be of interest, such as MSSM, it is simply too labor-intensive for a typical model builder to undertake for a potentially interesting study.

A much preferred method is to create a tool that can translate a model directly from the theorist's language (the Lagrangian) into the appropriate MadGraph/MadEvent input files. The initial investment in creating such an interface will be significant; however, the potential gains would be equally profound. Once complete, a model builder having little or no expertise in phenomenology and event generation would be able input a new model (or modify an existing model) using only the Lagrangian formalism. The tool would create a complete event generation package that phenomenologists and experimentalists could use to search for signals and analyze data. Initial investigations suggest Mathematica® would be an excellent platform for creating such a tool.

### ***Increase Limit on External Particles and Decay Chains***

The rich particle structure and decay modes of models such as MSSM motivate the need for processes having very large numbers of external particles. Consider stop pair production followed by decay into heavy quarks and the lightest supersymmetric particle as shown in Fig. 1.

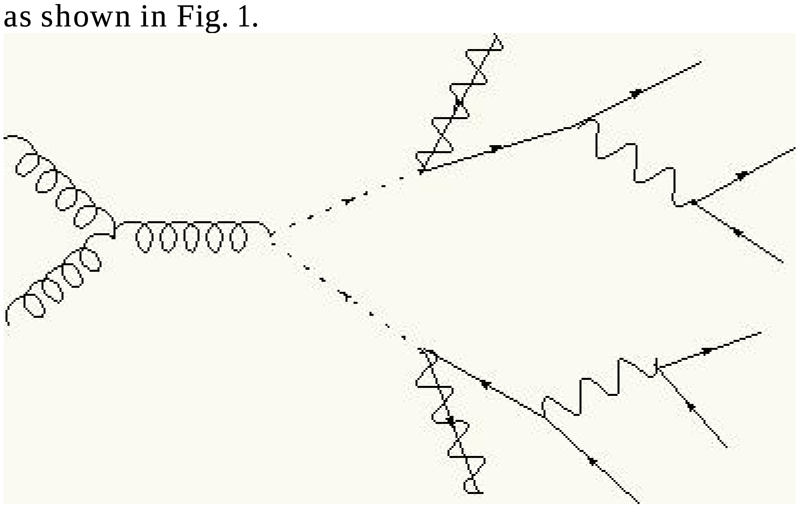

Figure 1. Feynman diagram of stop pair production,followed by decay into heavy quarks and the lightest supersymmetric particle.

The leading-order hard scattering matrix element has 10 external particles. As shown in Table I., the number of topologies that must be checked grows rapidly as external particles are included.

Table I. Requisite topologies required as external particles are included

| External Legs | Topologies |
|---|---|
| 4 | 4 |
| 5 | 25 |
| 6 | 220 |
| 7 | 2,85 |
| 8 | 34,300 |
| 9 | 559,405 |

| | |
|---|---|
| 10 | 10,525,900 |

If MadGraph were simply requested to generate all of the corresponding diagrams for the initial state (gg) and final state (e+ ve b u~ d b~ χ χ), it would have to check over 10 million topologies. This approach would not only be prohibitively slow, but most of the diagrams generated would also be irrelevant. Indeed, for a given set of MSSM parameters, the entire event structure would be dominated by a few resonant diagrams. Without knowledge of this structure, event generation would also be extremely slow, as large numbers of irrelevant diagrams would be calculated and many unimportant regions of phase space would be searched.

The solution is to have the user provide information about the production and decay channels being studied, based on the parameters of the model. MadGraph could use this information to generate only relevant topologies and diagrams. Thus, MadGraph would provide the amplitudes in the narrow width approximation for the production and decay of the MSSM particles, including all spin correlation effects. Inclusion of the spin correlation can be valuable not only for explicit correlation studies, but also for using sophisticated techniques, such as matrix element analysis, where the spin correlations can play an important role in the probability distribution.

In this scenario, users would specify a particular decay chain at the “processes request” stage. For example, a user could request stop pair production, where two stop quarks decay into top quarks and neutralinos, with the tops further decaying

$$pp \to (\tilde{t} \to (\chi(t \to b e^{+} \nu_{e}))(\bar{\tilde{t}} \to \chi(\bar{t} \to \bar{b} d \bar{u}\ ))\ .$$

MadGraph and MadEvent would use this information at three stages. First, while generating topologies, to eliminate any branches that could not provide the appropriate structure. Second, at the diagram stage, to eliminate any diagrams that did not match the required decay structure. Third, when generating events, MadEvent would force the mother particles to be on-shell, and this information would be passed through the Les Houches accord to the parton shower and hadronization.

### *Inclusive Samples and Matching*

Before any new physics can be discovered at the LHC, standard model analysis must be completed. This analysis is essential not only to validate the functioning of the collider and detector, but also to provide a basis for the background from which the signal will be detected. To provide the most accurate model of this background, the matrix element calculation should be used for the production of “hard” radiation, and the resumed parton showers for soft and collinear radiation. Significant work has been done over the past several years to develop a formalism to combine the matrix element calculation with the parton showers without double counting. Catani et al. [3] developed a formalism for combining the hard matrix element with the showering code that is accurate up to next-to-leading log. Mangano [6] and Mrenna [4] have also developed techniques that provide similar levels of accuracy. Work continues in this area, and new frameworks are being studied that may allow for even higher accuracy.

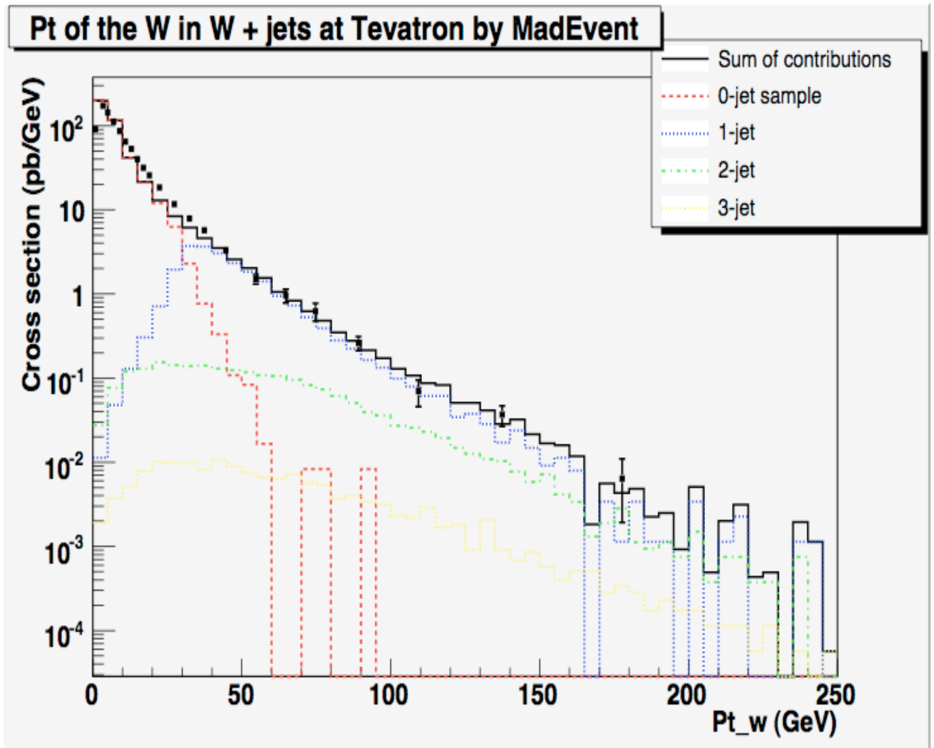


Figure 2. Contributions of the various hard scattering amplitudes to the transverse momentum distribution of the W using matrix element calculation combined with parton showers.

Experts in MadEvent and event matching have already demonstrated the effectiveness of these techniques [5]. Figure 2 shows contributions of the various hard scattering amplitudes to the transverse momentum distribution of the W at the Tevatron using this technique. The enhancements proposed here will increase the range of analysis that can utilize this essential physics in three important ways. First, an event library of important inclusive standard model background processes will be created. Reasonable parameters for the parton distribution functions, factorization, and renormalization scales, as well as matching, will be chosen. This library will be an important benchmark resource that theorists and experimentalists can easily access to perform feasibility analyses as well as comparisons with their own event samples. MadEvent will also be expanded in two important ways to facilitate the generation of custom inclusive data sets. The first enhancement will allow for the automatic generation of inclusive parton level samples. Currently each of the contributing processes (e.g., pp > W+, pp > W+j, pp > W+jj, pp > W+jjj) must be specified, which are then combined with the appropriate number of events and relative weighting. The proposed new format would allow the user to simply specify the maximum number of hard jets, (e.g. pp > W+jjjj *), and MadEvent would generate events for all of the contributing subprocesses and combine them in the appropriate weights.

The second enhancement would be to provide an additional option at the event-generation point to perform the appropriate matching scheme and pass these events for showering, such that a fully inclusive event sample would be generated for further analysis. Ideally, a choice would be offered among the different formalisms to identify systematic effects. These new features would dramatically improve the typical user's ability to obtain accurate simulations of important processes, both for initial tests of the collider and detector, as well as for new physics discoveries.

### *Quarkonia*

Quarkonium phenomenology at hadron colliders typically involves leading order calculations using the non-relativistic QCD factorization approach (NRQCD) [7]. This formalism allows production cross sections and annihilation decay rates to be expressed in terms of the nonperturbative functions multiplied by coefficients calculated from perturbative matrix elements. The nearly 1000 citations to this work and hundreds of references to papers using this technique are evidence of its value to the field. Currently, the evaluation of the coefficients from the perturbative matrix elements is done "by hand" and remains a labor-intensive exercise, thereby limiting both the number of physicists capable of performing the analysis and the processes that can be investigated. Modifications to MadGraph and MadEvent could dramatically change this situation, and will proceed in two phases. The first phase will expand MadGraph to allow for the projection of quark pairs in color octet and singlet states to automate the calculation of the perturbative coefficients, which can then be combined with the nonperturbative functions needed for calculating quarkonium production cross sections and annihilation decay rates. The second phase will be to modify MadEvent such that it can perform event generation based on these calculations, including all of the color information needed to pass the event to PYTHIA of HERWIG for showering and hadronization. This capability would dramatically change the landscape for calculating quarkonium processes, just as tools such as MadGraph changed the way parton-level calculations are performed.

### *Matrix Element Technique*

In principle, the matrix element technique is the ideal analysis tool for distinguishing signal from background or determining the model that best describes the data. Instead of relying on a discrete set of cuts in one or two dimensions, the matrix element technique utilizes the full differential cross section of the model at the parton level. Theoretically, this method provides the optimal possible discrimination. Although hadronization and detector resolution effects limit the actual discrimination achieved, the matrix element technique has proven to be a powerful tool for analyzing data, as illustrated by its use for the top quark mass measurement [8].

At the core of these analyses is the minimization of the likelihood that the observed experimental data could be produced by the model. This likelihood function is of the form

$$L = \prod_{i=1}^{N} P(\vec{x}_i).$$

Here, $P$ represents the probability that the observed experimental event would be produced by the model

$$P(\vec{x}_i) = \frac{1}{\sigma}\int d\sigma(\vec{y})W(\vec{x},\vec{y}).$$

The parton-level differential cross section must be convoluted with a transfer function $W$, which gives the probability that the parton-level event $y$ would result in the detector-level event $x$. Evaluating $P$ is technically very challenging, as both the differential cross section and the transfer function are sharply peaked, making them difficult to integrate. MadGraph can currently generate the differential cross section for both standard model as well as beyond-the-standard-model processes. The single-diagram enhanced technique developed for MadEvent effectively maps the peaks of the differential cross section to integration variables so that they can be efficiently calculated. However, in general, the peaks are in different variables from those of the cross section, limiting the range of studies that can utilize the matrix element analysis. Extending MadEvent such that it could combine the known peaking structure of the processes being studied with the structure of the transfer function would dramatically extend the range of studies that could employ the matrix element analysis. If successfully implemented, the matrix element technique will likely be a primary analysis method for the LHC data.

### *Optimization for HEP Grid Computing*

The web interface and 40-node computing farm currently hosted at the University of Illinois can generate nearly 10,000 unweighted partonic W+4jet events per hour. The rate is certainly sufficient for phenomenological and model-building analysis. However, for experimentalists to fully exploit MadEvents capabilities, it must be optimized to run in their environment, i.e., the Grid.

The current MadEvent structure assumes a local file structure that is available for reading and updating by all running processes. Optimizing MadEvent for Grid running would require restructuring the jobs so that they are self-contained packages that can be deployed remotely and then report back the generated events. Furthermore, a new driver function must be created for submitting the jobs, assembling their results, and resubmitting “lost” jobs. Although such changes will take some effort to implement, the result fully justifies this additional work. The vast computing resources of the Grid will allow for the feasible generation of the millions of unweighted events required for an experimental analysis in a short amount of time. Perhaps even more important, by moving to a Grid-compatible format, experimentalists will be able to fully incorporate MadEvent into their analysis environments. This improvement lies at the heart of the MadEvent philosophy, of providing a truly unified framework in which model builders, phenomenologists, and experimentalists can efficient perform their analyses and communicate their results with each other using the same tools.

### *Maximizing the US Impact on LHC Physics*

Thus far the project has described important upgrades to the MadGraph/MadEvent tools that will be useful throughout the high energy physics community. This last segment is a strategy to take advantage of the expertise at the University of Illinois to fully exploit these tools in the analysis of LHC data. Our European collaborators on the LHC understand the essential role event simulation will play in the discovery of new physics at the LHC. Fabio Maltoni has supported two postdocs and six graduate students working on this issue, and they have now officially joined the CMS experiment. The US has also identified importance of funding the development of expertise necessary for analysing data from the LHC. The DOE/NSF High Energy Physics Advisory Panal Report[9] identified “Funding directed at university-based theoretical particle physics for the purpose of increasing the number of HEP-grant-supported graduate students should be given a higher priority in the overall HEP program. Support for students and postdocs doing calculations related to upcoming experiments is particularly urgent." The Department of Physics at Illinois would be an excellent location to house a similar effort for ATLAS in the US. The department has a strong experimental group who played a significant role in CDF at the Tevatron and are now applying their expertise and experience to the ATLAS experiment at the LHC. The department's theory group includes Professor Scott Willenbrock, an expert on the top quark and Higgs phenomenology. Thus the foundation exists for a strong local analysis team, but fully exploiting this potential will require the resources of graduate students and a post doc.

This proposal requests funding for a graduate student and partial funding from the NSF for the post-doc. The post doc will be fully literate in the MadEvent tools and will become an expert in event simulation, working closely with experimental groups to provide the support necessary for the MadEvent tools to be assimilated into the ATLAS environment. The result will be a very strong US-based team having expertise in theory, event simulation, and experiment and the resources to respond immediately to the challenges and opportunities that the LHC will provide. The LHC has created considerable interest in high energy physics, and the University of Illinois is fortunate to have some of the best graduate students in the country seeking to join the theory group. It is an exceptional time in the field, but accepting students requires a financial commitment to at least cover their summer salary. This proposal would provide funding for a graduate student to fully participate in the analysis, actively participating in conversations with both experimentalists and theorists to understand all of the complexities and gain the skills necessary to complete an analysis.

### *Timetable*

A three-year project is proposed, although if the project is as useful as anticipated, the plan would be to continue and expand its range as demand dictates.

**Activities for the *first year* include:**

- Develop decay chain formalism for MadGraph/MadEvent.
- Develop Lagrangian interface for adding new models to MadEvent.
- Enhance MadEvent interface to allow for inclusive samples (W+jets).
- Promote adoption of MadGraph and MadEvent by HEP community through training user communities.
- Present results at appropriate fora.
- Prepare first annual report for NSF.

**Activities for the *second year* include:**

- Expand and enhance web server based on demand and feedback.
- Add color projection to MadGraph for quarkonia studies.
- Optimize MadEvent for Grid running
- Develop tools for using MadEvent with matrix element Analysis
- Support use of MadGraph© and MadEvent by HEP community.
- Present results at appropriate fora.

- Prepare second annual report for NSF.

**Activities for the *third year* include**:

- Expand and enhance MadGraph/MadEvent based on demand and feedback.
- Develop tools for using MadEvent with matrix element analysis.
- Include Quarkonia event generation in MadEvent
- Continue to support use of MadGraph and MadEvent by HEP community.
- Present results at appropriate fora.
- Prepare final report for NSF.

### *3.5 Broader Impacts*

The MadEvent project will play an important role in providing accurate simulations of high-energy particle interactions essential for the expert analysis of LHC data. However, the intuitive nature of the web interface also makes MadGraph/MadEvent an excellent tool for education and outreach. Several faculty have commented on how they have incorporated MadGraph/MadEvent activities into their educational efforts for advanced undergraduate and new graduate students.

Indeed, the PI for this project has held MadGraph workshops for the last three summers as part of the CERN Summer Programme. In these workshops, advanced undergraduates are introduced to the standard model and the anatomy of a hadronic collision through an animated recreation of a top quark production event. They are then introduced to the basic idea of Feynman diagrams and allowed to explore several standard model processes using the web interface to MadGraph and MadEvent. As the sophistication of MadGraph/MadEvent has developed over the past several years, we have also been able to increase the sophistication of this workshop. This past summer it even included an LHC Olympic-type contest where the students where given “data” and had to use the MadEvent tools to determine which model it came from. These workshops have been very popular, with more than 150 students attending in the past three years.

The PI understands the importance of conveying the enthusiasm for physics and the scientific process to society. This is accomplished through several mechanisms, that although not directly funded by this grant, are enabled by the support of his research. These include in-class “Science Thursdays,” where the PI created a series of workshops he performed in a local elementary school. The children are engaged in hands-on activities to reinforce fundamental ideas of physics and enjoyment of scientific discovery. These activities were extremely popular, with many students citing them as the best activities of the entire year.

## 4. Available Resources and Facilities

The NSF investment in this project will be enhanced by the substantial research infrastructure existing in the Department of Physics at the University of Illinois at Urbana-Champaign. On the physical side, significant computational resources and expertise already exist in the high energy group. The group has extensive experience in maintaining its own PBS computing farm in a climate-controlled environment. The MadGraph farm is housed in the same facility and mirrors its structure. Furthermore, the Department of Physics at Illinois has a strong experimental physics group active in the CDF and ATLAS experiments. They provide important guidance and feedback for optimizing MadGraph and MadEvent for experimentalists. One of the strengths of the high energy group at the University of Illinois is the collaboration between the theorists and experimentalists. The reputation of the Department of Physics at the University of Illinois attracts some of the best graduate students in the country, and it is from this select cohort that we would choose a graduate student to participate in the project.

## 5. Experience and Capability of Principal Investigator

**Timothy J. Stelzer** is a research associate professor at the University of Illinois. He received his Ph.D. from the University of Wisconsin in high energy particle theory, doing research on a range of topics from using neutrino detectors for dark matter searches, to rapidity gap analysis for finding the Higgs at high-energy hadron colliders. Since then Stelzer has worked primarily on hadron collider physics with an emphasis on the top quark. To assist in his own research, Stelzer created the MadGraph program to automatically calculate tree-level helicity amplitudes. This program has subsequently become an important tool for phenomologists across the world, and the original paper describing it currently has nearly 400 citations. To expand the scope of the program, Stelzer developed the method of single-diagram-enhanced integration, which allowed for the expansion of MadGraph to include event generation. This expanded package (MadEvent) and the web interface created with prior NSF support (NSF PHY-0426272) has been very popular. The paper has over 200 citations, and there are more than 1,500 registered users of the web interface. The popularity of this package has led to a significant expansion of the MadEvent team, most notably including Fabio Maltoni at Université catholique de Louvain (Belgium). As the principal author of the MadGraph and MadEvent codes, Stelzer plays a crucial role in the support and expansion of these important tools.

## SECTION D. REFERENCES CITED


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