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Integrated analysis of particle interactions at hadron colliders

Report of research activities in 2010-2015

Pavel M. Nadolsky, PI

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Department of Physics, Southern Methodist University,
Dallas, TX, 75275-0175
Phone: (214) 768-1756
E-mail: nadolsky@smu.edu

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1 Executive summary

The report summarizes research activities of the project "Integrated analysis of particle interactions" at Southern Methodist University, funded by 2010 DOE Early Career Research Award DE-SC0003870. The goal of the project is to provide state-of-the-art predictions in quantum chromodynamics in order to achieve objectives of the LHC program for studies of electroweak symmetry breaking and new physics searches. We published 19 journal papers focusing on in-depth studies of proton structure and integration of advanced calculations from different areas of particle phenomenology: multi-loop calculations, accurate long-distance hadronic functions, and precise numerical programs. Methods for factorization of QCD cross sections were advanced in order to develop new generations of CTEQ parton distribution functions (PDFs), CT10 and CT14. These distributions provide the core theoretical input for multi-loop perturbative calculations by LHC experimental collaborations. A novel "PDF meta-analysis" technique was invented to streamline applications of PDFs in numerous LHC simulations and to combine PDFs from various groups using multivariate stochastic sampling of PDF parameters. The meta-analysis will help to bring the LHC perturbative calculations to the new level of accuracy, while reducing computational efforts. The work on parton distributions was complemented by development of advanced perturbative techniques to predict observables dependent on several momentum scales, including production of massive quarks and transverse momentum resummation at the next-to-next-to-leading order in QCD.

2 Completed studies

The SMU theory group studies strong interactions of elementary particles in the realistic environment of collider experiments. Besides providing calculations for specific scattering processes, the group participates in determination of widely used CTEQ parton distribution functions (PDFs) [1, 2, 23, 28, 29, 37, 39–46]. These nonperturbative QCD functions are indispensable for most computations for the LHC and other hadron colliders. Nadolsky's articles dedicated to the PDFs, notably CTEQ6, CTEQ6.6, and CT10 [1, 23, 39, 40], consistently receive highest numbers of citations in the INSPIRE-HEP database [87]. In 2010-2015, our group published 19 journal papers [1–4, 11–14, 23–30, 36–38] and 18 preprints and conference contributions [5–10, 16–18, 20–23, 31–35]. The efforts concentrated on the next-to-next-to-leading order analysis (NNLO) of PDFs, novel methods for multivariate statistical analysis of PDFs and their combination in LHC applications, benchmark comparisons of NNLO frameworks for PDF fits, NNLO calculations for massive quark production and transverse momentum resummation, and on various complimentary studies in the Standard Model and beyond.

Global analysis of parton distributions

Throughout the funded period, our group played the key role in development of CTEQ parton distribution functions for general-purpose applications in high-energy hadron scattering. With our direct participation, CTEQ PDFs were elevated from the next-to-leading-order (NLO) to the next-to-next-to-leading-order (NNLO) accuracy in perturbative QCD. Many new experimental measurements and new statistical techniques were implemented in the CTEQ PDF fits to better predict uncertainties in the resulting PDFs.

The first publications in this direction during the ECRA-funded period were dedicated to the **CT10 NLO global analysis** [1, 2], published in 2010. In these studies, our role was to implement and examine new experimental data sets in every category of processes used to constrain the PDFs: deep inelastic scattering (DIS), vector boson production, and inclusive jet production. These data sets include a combination of DIS cross sections by the H1 and ZEUS collaborations in HERA-1 [94], as well as measurements of W lepton asymmetry [48, 68, 95], Z rapidity distributions [93, 97], and single-inclusive jet cross sections [69, 96] by CDF and DØ collaborations at the Tevatron. **CT10 NNLO PDFs** were released for public use in June 2012 [21] and fully documented in Physical Review D in 2013 [23]. Upon their release, they were rapidly adopted for simulations by the LHC and Tevatron experimental groups. This was the first NNLO PDF set from the CTEQ collaboration, developed by a group of authors from Michigan State University (MSU) and Southern Methodist University (SMU). Although the CT10 NNLO PDFs were not fitted to the LHC data, they demonstrated excellent agreement with the LHC measurements at 7 and 8 TeV. In several instances they describe the LHC observables (lepton charge asymmetry, ratios of W and Z cross sections, high-p_T inclusive jet cross sections) better than the PDFs from competing groups (ABM'11, MSTW'08, or NNPDF2.3).

In 2015 we published the next NNLO analysis, designated as **CT14** [37]. This analysis includes several LHC data sets on production of lepton pairs and hadronic jets, as well as high-luminosity measurements of lepton asymmetry from the Tevatron and semi-inclusive charm production at HERA. CT14 is based on benchmarked (N)NLO cross sections and advanced PDF parametrization forms. In this analysis, significant effort was invested into benchmark tests and control of various effects that are comparable in their impact to the NNLO QCD corrections. As a result, the CT14 parametrizations are more reliable than CT10 NNLO. The latest PDFs from the three groups, CT14, MMHT'2014 [90], and NNPDF3.0 [89], are also in much better agreement than their respective PDFs of the previous generation, as a consequence of in-depth benchmarking comparisons.

The CTXX PDFs are obtained from a global fit of data from more than 30 experiments on DIS, vector boson production, and jet production. The final PDFs undergo multiple cross checks to validate their reliability. The SMU collaborators participate in all stages of the fits. In the CT10 NNLO study, we led implementation of theoretical cross sections for NNLO neutral-current DIS with massive quarks [4, 18] and NLO jet production [12, 13]. Substantial work at SMU went into studying sensitivity of CT10 NNLO PDFs to various theoretical and experimental inputs, especially of the gluon PDF in the range of momentum fractions typical for Higgs boson production via gluon-gluon fusion. The gluon PDF is determined from DIS at HERA and jet production at the Tevatron and LHC, and its behavior at NNLO accuracy is affected by hundreds of systematic factors from both theory and experiment. SMU's role was to study and document the impact of these factors on the final PDF error sets.

Massive-quark contributions to NNLO deep inelastic scattering

In developing the theoretical framework for NNLO global analysis of parton distributions, estimation of heavy-quark scattering contributions to DIS, including the full mass dependence, is perhaps the most arduous. This task was successfully accomplished by SMU collaborators **Guzzi** and **Nadolsky** [4, 10, 18]. The goal here is to compute DIS hard-scattering coefficient functions with up to two QCD loops without neglecting masses of heavy quarks, i.e., without making a major simplifying approximation. Mass dependence of charm quarks in DIS must be fully included at NNLO in order to reliably predict electroweak precision observables at the LHC [40, 91].

We computed these contributions in the S-ACOT-χ mass scheme [52–55], the default heavy-quark mass scheme of CTEQ studies. On the theory side, we clarified a number of issues about the heavy-quark DIS calculations raised in recent literature that had hindered improvements in the accuracy of PDFs in the past few years. We have shown that the S-ACOT-χ mass scheme offers several advantages compared to theoretical approaches adopted by other groups [51, 76]. It allows straightforward derivation from the QCD factorization theorem, transparent algorithmic formulas, and correct kinematical properties of heavy-quark production at all scattering energies. As a practical outcome, we have documented a step-by-step method to construct NNLO heavy-quark DIS cross sections for PDF analyses from the components published in literature. Such implementation allows for better control of theoretical factors affecting the accuracy of CTEQ NNLO PDFs. The SMU collaborators completed the key tasks: they derived the overall structure of NNLO DIS cross sections in the S-ACOT-χ scheme, showed that the S-ACOT-χ scheme is validated to all orders in the QCD coupling strength by the Collins' factorization theorem, implemented and tested NNLO radiative contributions in the framework of the CTEQ fitting code. They also demonstrated that the QCD factorization theorem [53], on which the S-ACOT-χ scheme is based, remains valid even when quarks with different masses contribute to Feynman diagrams. This issue becomes important when extending the general-mass scheme to the three-loop level in DIS, when diagrams with c and b propagators are present. The possibility of such extension, and hence the validity of the commonly used general-mass schemes beyond NNLO, has been recently questioned [80]. In our work, we demonstrate that these concerns are unfounded.

As a follow-up advancement, my graduate student Bowen Wang defended his Ph. D. thesis in August 2015, in which he computed approximate N^{3}LO QCD radiative contributions to NC DIS cross sections with massive quarks in the intermediate mass factorization scheme [45]. In this challenging calculation, he evaluated the leading contributions associated with the dependence on heavy-quark masses at three-loop accuracy. He classified and organized three-loop Feynman diagrams according to their flavors and mass dependence and developed the skeleton framework for their implementation in the S-ACOT-χ scheme.

Implementation of NNLO heavy-quark QCD contributions reduced theoretical uncertainties in the CTEQ global analysis and opened opportunities for new interesting studies. In [24, 31], **Gao**, **Guzzi**, and **Nadolsky** obtained constraints on the $\overline{\rm MS}$ charm quark mass $m_c(m_c)$ in a general-mass factorization scheme used by CT10 NNLO. We demonstrated that, upon the inclusion of NNLO contributions into the DIS cross sections, the CT10 NNLO fit prefers a value of $m_c(m_c)$ that is compatible with the world-average value, and that the main constraints arise from HERA data on neutral-current DIS. This study shows that, at the NNLO accuracy, the global analysis of hadronic data can be used to constrain masses of c and b quarks, opening a new avenue for measurements of quark masses. We clarified a number of theoretical issues arising in the treatment of quark masses in a variable flavor number scheme. On a related matter, **Gao** coauthored a version of the CT10 NNLO analysis that allows contributions from the nonperturbative intrinsic charm production [29]. Both studies demonstrate increased capability of the PDF analysis to probe the heavy-quark mass dependence once the NNLO contributions to DIS are included.

PDF uncertainties in LHC observables

Advances in our understanding of PDFs have an immediate impact on reducing theoretical uncertainties in electroweak precision observables at hadron colliders. In particular, the combined uncertainty due to the PDFs and QCD coupling $\alpha_s(M_Z)$ is important in a variety of LHC measurements, e.g., Higgs boson production cross sections via gluon fusion. In [2], we explain a simple method that is rigorously valid in the quadratic approximation normally applied in PDF fitting, and fully reproduces the correlated dependence of theoretical cross sections on α_s and PDF parameters. This method is based on a statistical relation that allows one to add the uncertainty produced by

α_s, computed with some special PDF sets, in quadrature with the PDF uncertainty obtained for the fixed α_s value (such as the CT10 NNLO PDF set). This prescription greatly simplifies the combination of the PDF and α_s uncertainties and became a common standard.

We also coauthored a paper [28] that estimated the correlated PDF+α_s uncertainty on Higgs production cross sections using two common statistical methods, Lagrange Multiplier approach [65] and Hessian approach [66]. As the Higgs cross section is mostly sensitive to gluon scattering contributions, we identified the key experiments in the CT10 NNLO fit that impose tightest constraints on the gluon PDF. For this purpose, we developed a statistical technique utilizing "effective Gaussian variables" that simplifies comparison of experimental constraints from a large number of very diverse experiments. As an upshot of the Lagrange Multiplier approach, we constructed two special CT10H NNLO PDFs for computing the total PDF uncertainty of inclusive Higgs production cross sections at the LHC 7, 8, and 14 TeV. As the estimation of the PDF+α_s uncertainty requires to compute the Higgs cross section for each error PDF set, the computational efforts are greatly reduced in the experimental analysis if the two CT10H NNLO sets are used instead of the 52 standard CT10 NNLO error sets, roughly by a factor of 25. By knowing which experiments constrain the gluon PDF, we can now outline a near-future strategy for reducing the PDF uncertainty on the Higgs cross sections.

Benchmark tests of NNLO cross sections and PDFs

With the release of recent ABM11, CT10, HERAPDF 1.5, and NNPDF2.3 PDFs, several independent PDF sets became available at the NNLO level. Consequently it became necessary to explore similarities and differences in predictions for (N)NLO collider cross sections based on various PDFs, with the eventual goal to update the 2010 PDF4LHC recommendation for the computation of PDF uncertainties in LHC cross sections [9]. The first benchmark comparison for LHC 8 TeV cross sections was carried out in Ref. [12]. Predictions for W, Z, $t\bar{t}$, Higgs production were compared using PDFs from five groups and a variety of computer codes. For example, we examined implications of the updated NNLO PDF sets for the combined PDF+α_s uncertainty in the gluon fusion Higgs production cross section. We also identified a list of factors that are comparable to NNLO radiative contributions and must be controlled for in the PDF analysis. We pointed out that correlated systematic errors published by fitted experiments are interpreted differently by the various PDF fitting groups, which leads to non-negligible differences between the PDF sets. This issue is not widely known and must be considered in the future to avoid biases in PDF fits.

The only two cross sections that are still evaluated at NLO in NNLO fits are those for inclusive jet production and charged-current DIS. It is important to reduce biases in the NNLO PDFs due to these cross sections. **Nadolsky**, **Gao**, **Liang**, and **D. Soper** (University of Oregon) developed a new, more stable version of a program EKS for calculation of NLO cross sections for jet production at hadron colliders [13, 16, 17]. The new EKS code is an alternative to the other widely used program NLOJET++ (and its fast interpolation-based interface FastNLO), and it is made public. It includes fully differential output in various formats, various jet algorithms, and possibility of parallel computations. Such program is needed both to better predict jet cross sections at NLO (e.g., to reduce the uncertainty on the large-x gluon PDF constrained predominantly by the jet data), and as a prerequisite for the anticipated full NNLO calculation for jet production. Computations based on MEKS were an essential part of the benchmark comparison of NLO jet cross sections at the LHC presented in [12]. In particular, **Gao, Liang,** and **Nadolsky** showed that EKS agrees very well with FastNLO for some, although certainly not all, combinations of input parameters [16]. The full range of PDF uncertainty associated with factorization and renormalization scales was identified.

In a parallel contribution [17], **Liang** and **Nadolsky** used the analysis of PDF-induced correlations [40] to identify other processes (besides jet production) that impose significant constraints on the gluon PDF. Finally, **Gao** and **Nadolsky** demonstrated that the residual QCD scale dependence of NLO jet cross sections only marginally increases the total PDF uncertainty of CT10 NNLO PDFs [36]. The practice of using NLO jet cross sections does not dramatically affect the NNLO PDF fits.

Similar benchmarking studies were carried out in 2013 for inclusive DIS cross sections in CTEQ, HERA, MMHT, and NNPDF fitting codes, with active leadership of Gao. **Gao** tested our calculation of charged-current DIS cross sections with heavy quarks and corrected a numerical error, which resulted in non-negligible changes in the CT14 parametrizations for strangeness and gluon PDFs, as compared to the previous CTEQ PDFs. Largely as a result of these benchmarking comparisons, the most recent PDFs released by three global groups (CT14, MMHT'2014, NNPDF3.0) agree much better than their PDFs of the previous generation (CT10, MSTW'08, NNPDF2.3). In particular, the PDF uncertainty for Higgs production via gluon fusion at the LHC, estimated according to the 2010 PDF4LHC recommendation [9] as the envelope of predictions based on the PDFs of three global groups, has reduced from about 7% in 2012 [12] to about 3% now. This advancement matches the progress in computation of hard matrix elements for Higgs production observables, which now have scale dependence of about 3% in the gluon fusion channel at N3LO [92]. All these studies contribute to the realization of the Science Drivers' objectives for the LHC, by providing the PDFs that are known as well as the NNLO hard matrix elements. Good agreement between the latest global PDF ensembles also opens door for their efficient combination in phenomenological applications, the topic to be discussed in the next subsection.

Stochastic sampling and meta-analysis of PDFs

One of the original goals of the ECRA proposal was to explore methods of stochastic (Monte-Carlo) sampling of PDF parameters in global QCD fits. In the traditional CTEQ approach, the best-fit PDFs are found by minimization of an analytic log-likelihood function. Confidence intervals on the PDF parameters are determined in the quasi-Gaussian approximation by diagonalization of the Hessian matrix [66]. There are alternative methods to study probability distributions as functions of PDF parameters, notably, stochastic sampling [49, 50, 57, 67, 84], which forms the basis of the Neural Network PDF method [63, 64, 70]. While technical implementation of stochastic sampling is challenging, it may provide additional insights when combined with the Hessian method, for instance, about the true magnitude of PDF uncertainties. We carried out studies of feasibility of stochastic sampling of multidimensional space of PDF parameters [78, 79] and developed computer programs for generation of CT14 Monte-Carlo replicas and combination of Monte-Carlo replicas from various groups.

As time progressed, our vision for the purposes of stochastic sampling evolved in light of new incoming information. In the original proposal, we planned to implement stochastic sampling primarily to study the log-likelihood function directly in the CTEQ PDF fit, by randomly probing PDF parameters in the basis of eigenvectors of the diagonalized Hessian matrix. Our expectation was that stochastic sampling might render a different estimate of the PDF uncertainty compared to that provided by the default Hessian method of CTEQ fits. However, before our method was implemented, Thorne and Watt published a similar study in [83], in which a Monte-Carlo technique was applied to study the PDF uncertainty of MSTW PDFs. Some of our initial questions were addressed in that paper. In particular, it demonstrated that the Hessian and Monte-Carlo methods produce comparable estimates of the PDF uncertainties in CTEQ and MSTW fits that assume a relatively small number (~ 20) of PDF parameters. From other new papers, we learned that the spread of the PDF uncertainty is driven by the PDF parametrization form, not so much by the sampling method. For example, the uncertainty of some CT14 PDFs is increased because of the use of a more flexible parametrization based on Bernstein polynomials [37]; it is estimated in poorly constrained x regions using the Lagrange multiplier method, which often provides similar outcomes for the PDF uncertainty as the Monte-Carlo method of NNPDF. Gao converted CT14 Hessian error sets into Monte-Carlo replicas using the modified Thorne-Watt method.

With the original questions now longer being a pressing priority, we redirected attention to an alternative application of stochastic sampling, for propagation of PDF uncertainties after the global fit. In 2013, **Gao** and **Nadolsky** published a "meta-analysis" of parton distribution functions **[26].** This study developed a new method for finding the PDF uncertainty using PDF sets from several groups that (a) offers an alternative to the widely used PDF4LHC recommendation [9] and (b) can potentially replace hundreds of PDF error sets that are currently used in the LHC kinematic range by only 10-20. The meta-PDFs are constructed by refitting the input PDF parametrizations from CTEQ, MSTW, NNPDF, etc. with the help of a common flexible parametrization based on Chebyshev or Bernstein polynomials. Hessian error sets are converted into Monte-Carlo replicas using a stochastic sampling algorithm. Then, the number of independent meta-PDF sets is reduced in a way that preserves the information about the LHC processes contained in all the input PDF sets from various groups. For the essential processes like Higgs boson production in a variety of channels, both the PDF uncertainties and PDF-induced correlations can be computed with less than 20 META PDF sets, in contrast to the hundreds of the PDFs needed with the 2010 PDF4LHC prescription. To realize this project, a new independent framework for the PDF error analysis was developed that combines Mathematica with multiple codes for computation of LHC cross sections (MCFM, iHixs, TOP++, FastNLO). It incorporates the Hessian method [66] used by CTEQ and MSTW groups, but also capabilities for stochastic sampling of the probability distribution in the PDF parameter space [50, 83, 84] and inclusion of new experiments by PDF reweighting [84–86].

These methods were further developed in depth in the course of 2014. We expect that the META analysis will be adopted as one of three standard methods for combination of PDF uncertainties, to be recommended by the PDF4LHC working group in 2015. The 30-member META2.0 ensemble will be recommended to compute PDF uncertainties across multiple LHC applications. It includes the same information about the PDFs as the combination of CT14, MMHT'2014, and NNPDF'3.0, while it has much fewer member sets than the input PDF ensembles. To address these needs, we are developing a public Mathematica module for META analysis applications.

Transverse momentum resummation at NNLO

Besides studying collinear PDFs such as CT14, SMU collaborators pursued in-depth studies of transverse-momentum-dependent factorization for Drell-Yan-like processes at the Tevatron and LHC. Throughout the years, Nadolsky contributed to the development of program ResBos for transverse momentum resummation in the Collins-Soper-Sterman factorization framework. His resummed predictions [60–62] were utilized to predict QCD backgrounds in the search for Higgs boson in the leading $\gamma\gamma$ decay channel for the Higgs boson discovery . Another resummation calculation for W and Z production [58, 59] required new advancements to tighten indirect constraints on the Higgs boson sector.

Nadolsky, Guzzi, and **Wang** completed an enhanced transverse momentum resummation calculation for W and Z boson production at the Tevatron and LHC [20, 27]. This calculation addresses a pressing issue of comparing QCD theory to data on a novel angular variable φ^*_η in Z production [81], which showed some disagreement with resummed NNLL+"partial NNLO" predictions provided by the ResBos code [56, 58]. We demonstrated that the resummed prediction agrees well with the DØ data on φ^*_η distributions [82] upon inclusion of subleading electroweak corrections and tuning of theoretical parameters within the range of current uncertainties. Using this calculation, we showed that the Tevatron φ^*_η data prefers a nonzero resummed nonperturbative function and estimated the uncertainty in this function. The parametrization of the nonperturbative function is used in measurements of W boson mass at the Tevatron and LHC.

In Ref. [11], the Collins-Soper-Sterman formalism for resummation of Q_T distributions was applied by **Guzzi, Guzey, Nadolsky, Strikman, and Wang** to examine prospects for studying nuclear modifications to nuclear PDFs in proton-lead and lead-lead collisions at the LHC. Specifically, we analyzed the nuclear shadowing and antishadowing corrections in production of lepton pairs from decays of neutral electroweak gauge bosons and observed a direct correlation between the predicted behavior of the transverse momentum and rapidity distributions of the produced vector bosons and the pattern of quark and gluon nuclear modifications. Our study provides detailed information for using Drell-Yan pair production in pA and AA collisions at the LHC for constraining nuclear PDFs in the small-x shadowing and moderate-x antishadowing regions.

Calculations for collider processes and new physics searches

Quantum anomalies and new particle interactions. Besides working on QCD, Guzzi has branched into physics beyond the Standard Model. In 2007-2009, he analyzed a class of models derived from a low-energy realization of string theory. These models, called "Minimal Low Scale Orientifold Models" (MLSOM), are characterized by anomalous interactions and predict existence of a light pseudoscalar particle – gauged axion, or axi-Higgs. These models offer a relatively unexplored mechanism to extend the Standard Model based on the structure of the string theory and make concrete predictions for new phenomena at TeV scales. While at SMU, Guzzi has finished a complete supersymmetric generalization of these theories, as reported in Refs. [77, 88]. It extends the minimal supersymmetry by an extra anomalous $U(1)$ group and allows for an axion and an "axino" in the particle mass spectrum. The analysis of this model is quite interesting because of its implications in astrophysics and cosmology.

Model-independent constraints on gluinos. Hadroproduction data from HERA, Tevatron, and LHC is sensitive to contributions from new physics. By incorporating these data in the global analysis, we are able to derive unique model-independent constraints on deviations from the Standard Model. **Guzzi, Berger, Nadolsky, and Olness** [42] used the global analysis to impose limits on masses of light superpartners (gluinos) as a function of gluino mass. These limits are competitive with the best (model-independent) limits available from LEP. We have completed an updated QCD+SUSY global analysis [3] on strongly interacting super-partners using the latest, most complete collider data from HERA and Tevatron. In the new work, we improved the constraints of the 2005 study by a factor of two, and we have released a corresponding set of PDFs which include the SUSY gluino degree of freedom.

Intrinsic charm production at the Electron-Ion Collider. In Fall 2010, Nadolsky and Olness attended the workshop "Gluons and the quark sea at high energies: distributions, polarization, tomography" at INT of University of Washington. This workshop aims to develop a physics program for a future Electron-Ion Collider and its complimentary to the physics program at the LHC. Our task was to identify opportunities for studies of parton distribution functions presented at the EIC [6]. As a contribution to this workshop [7], **Guzzi, Nadolsky, and Olness** have demonstrated that EIC is uniquely suited for searching for nonperturbative "intrinsic production" of charm and bottom quarks, which is predicted by a number of hadronic models [71, 72, 74, 75], but so far has not been found [47, 73]. Both contributions, on prospects for studies of parton distributions at the EIC and on the intrinsic charm at the EIC, were included in the workshop's white paper.

Top-quark decays in NNLO QCD. **Gao** and collaborators finished a complete calculation of top quark decay width at next-to-next-to-leading order in QCD, including next-to-leading electroweak corrections as well as finite bottom quark mass and W boson width effects [14]. This is the first computation of fully differential decay rates for top-quark semileptonic decay $t \to W\ell^+\nu_\ell b$ at NNLO in QCD. The calculation follows a general approach applicable to arbitrary infrared-safe observables at any perturbation order, based on the study of the invariant mass distribution of a final-state jet in the singular limit of effective field theory. It can be used to precisely predict top quark properties at both the LHC and ILC.

Ruling out Higgs impostors. **Gao** proposed a technique for distinguishing between various mechanisms for production of massive scalar particles, such as $gg \to H$, $q\bar{q} \to H$, and $b\bar{b} \to H$ [30]. In his approach, the ratios of production rates in central and forward rapidity regions distinguish between the main production channels for the scalar independently of its decay branching ratios. This analysis disfavors production of the 126 GeV Higgs boson via $q\bar{q} \to H$ by about 2 standard deviations compared to $gg \to H$.

With the discovery of the candidate Higgs boson particle, it became essential to identify its spin by observing angular distributions in its decay into photon pairs and other channels. **Dalley, Adhikari,** and **Nadolsky** proposed a method to improve determination of the spin of new particle resonances in lepton pair or photon pair production at hadron colliders by reweighting center-edge asymmetries of their decay angular distributions [19]. For example, in the diphoton decay channel, judicious selection of a reweighting factor in the center-edge asymmetry over the polar angle θ, such as $\cos^n \theta$, can improve spin discrimination by as much as 30% in production and decays of spin 0, 1, and 2 bosons. The power n can be tuned in particular cases, but $n = 2$ ($n = 1$) works well for any forward-backward symmetric (non-symmetric) decay to massless particles. With the reweighting, the number of scattering events required to determine the spin of the resonance can be reduced by a significant factor.

Contact interactions in NLO dijet production. In [15], **Gao** and coauthors presented next-to-leading order (NLO) QCD corrections to dijet production at the LHC via quark contact interactions of different color and chiral structures induced by new physics. They found that the NLO QCD corrections can lower dijet production rate due to contact interactions by several tens percent. Inclusion of NLO corrections reduced the dependence of the cross sections on factorization and renormalization scales. A program CIJET was developed for computation of new-physics contributions to jet production via effective contact interactions at NLO in QCD. The LHC collaborations employ this program to constrain contact interactions of various chiral and color structures in high-p_T inclusive jet production.

3 SMU personnel involved in the ECRA research

- The PI **Pavel Nadolsky** (CV is attached) works on computations of radiative contributions in quantum chromodynamics and multi-variate statistical analysis of experimental data probing internal structure of nucleons. He contributes to the determination of widely used CTEQ parton density functions and is an author of more than 80 research publications.

- **Tie-Jiun Hou** (CV is attached) is a postdoc working on the global analysis of parton distributions. He joined SMU in October 2014 in order to lead numerical studies of the CT14 global analysis. He contributed to the majority of recent papers dedicated to CT10 and CT14 PDFs.

- **Jun Gao** (CV is attached) was a theory postdoc at SMU in 2011-2014 and is a postdoc at the Argonne National Laboratory since September 2014. Gao received his Ph. D. from Peking University in Summer 2011 under supervision of Prof. Chong-Sheng Li. He is a winner of Asian and International Physics Olympiads, and he has published 8 research papers while at the graduate school. Gao contributed to the determination of CT10 and CT14 parton distribution functions and developed a meta-analysis method for combination of parton distribution functions.

- **Marco Guzzi** (CV is attached) held a postdoctoral appointment in our group in 2009-2012 after receiving his Ph. D. from University of Lecce. After leaving SMU, Guzzi took postdoctoral positions in particle theory at DESY (Hamburg) and University of Manchester. He was supported by ECRA between May 2010 and August 2012. Guzzi played a key role in the implementation of next-to-next-leading order (NNLO) contributions to the CTEQ PDF analysis, development of the latest CT10.X sets of parton distribution functions, and resummation calculations for W/Z boson production.

- **Zhihua Liang, Bowen Wang, and Ben Clark** are graduate students in our theoretical physics group. **Liang** defended his Ph. D. thesis in September 2012 and currently holds a postdoctoral position in medical physics at University of Houston. His thesis is dedicated to a new program MEKS for computation of NLO jet production cross sections at hadron colliders. The work that he and Jun Gao carried out helped to reduce theoretical uncertainties affecting determination of the gluon distribution from collider jet production cross sections. ECRA paid for his research assistantship for three months in Summer 2010. **Wang** defended his Ph. D. in 2015 and is currently a postdoc at Jefferson Laboratory. His thesis developed a framework to classify implement massive quark contributions in neutral-current DIS cross sections at NNNLO. He also worked with Nadolsky and Guzzi on applications of transverse momentum resummation to electroweak boson production at the LHC. **Wang** was supported by ECRA between June 2013 and August 2015. **Clark** is a graduate student supervised by Fred Olness. In 2014, he was supported with ECRA funds for one month during his collaboration with Bowen Wang on the development of a Mathematica module for the analysis and plotting of PDFs.

- **Simon Dalley** is an SMU senior lecturer who collaborated with **Nadolsky** and undergraduate student **Adhikari** on a study of angular dependence of heavy particle decays at the LHC. **Fredrick Olness** is an SMU professor of theoretical physics and our frequent collaborator. **Olness and Dalley** were supported by the DOE grant DE-FG02-04ER41299. **Adhikari** was supported by an SMU Undergraduate Research Assistantship and a Hamilton Scholarship.

4 Talks and research-related activities

The research of our group received significant international attention. Our group members were invited to present invited talks at international meetings and participate in collaborative efforts with theorists and experimentalists. ECRA was used to support travel to these occasions and was supplemented by SMU funds.

In 2011, Nadolsky attended HEP research workshops at Snowmass, Colorado (February); Jefferson Lab, Newport News, Virginia (DIS'2011, April); Les Houches, France (June); DESY Zeuthen (June); INFN, Florence, Italy (September); and Ringberg, Germany (September). He was invited to these workshops to present the latest work on CTEQ PDFs, and he also actively participated in the analysis of the latest collider data with theorists and experimentalists. He also participated in in the Les Houches workshop "Physics at TeV Colliders" in the summer, where he worked closely with CMS experimentalists on the implementation of a resummation calculation [60–62] for photon pair production in Higgs boson searches. In addition to traveling to these workshops, Nadolsky gave colloquia about his latest work at University of Texas (Arlington) and University of Baylor, gave a lecture on "Vector boson production" at CTEQ school for young physicists and organized a discussion of PDFs at the CTEQ-LPC workshop at Fermilab. Guzzi gave talks about our work on CT10 PDFs at the Winter QCD Les Houches Workshop in February and on the NNLO computations for DIS at the DIS'2011 workshop in Newport News in April.

In 2012, ECRA supported Nadolsky's travel to give invited talks at the LoopFest workshop at University of Pittsburgh (Pittsburgh, PA); workshop "QCD @ LHC" at Michigan State University (E. Lansing, MI); and workshop "LHC physics in the Higgs era" at University of Chicago (Chicago, IL). Gao participated in the LoopFest workshop in May and SUSY 2012 Conference at Peking University (Beijing, China) in August. Guzzi was invited to give a talk about our study of resummation for angular variables [20, 27] at the DØ workshop on W boson physics at SUNY (Stony Brook, NY) in April.

In 2013, ECRA-supported travel include Nadolsky's invited participation in the XXI International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS'2013) in Marseille, France; the APS DPF meeting at University of California (Santa Cruz); and QCD Frontier 2013 meeting at Newport News, VA in October. Nadolsky was a convener of the Structure Functions Working Group at the DIS'2013 workshop. Gao presented his research on top quarks at the Pheno'2013 Symposium in Pittsburgh, PA in May and gave an invited review talk about LHC studies of the gluon parton distribution at the CTEQ-LPC workshop "QCD Tools for LHC Physics: From 8 to 14 TeV" at Fermilab in November. Remote participation by Vidyo/Skype was increasingly used in 2013 as an alternative to physical travel to collaborative meetings. Gao remotely presented the results of our meta-analysis of PDFs at the Les Houches workshop "Physics at TeV colliders" in June and the PDF4LHC meeting at CERN in December.

In FY2014-2015, Nadolsky traveled to the DOE PI meeting in Washington, DC; LoopFest Symposium in New York; Terascale PDF workshop at DESY (Hamburg); PDF4LHC meeting at CERN; High-x workshop in Frascati, Italy; and collaborative visit at Michigan State University (E. Lansing, MI). Gao was paid by ECRA to give an invited talk at the LoopFest workshop in New York. Wang was supported by ECRA to present his results at PHENO'2014 symposium in Pittsburgh, PA.

5 Cost status

The final project grant expense summary for May 31, 2015 is attached.

6 SMU publications in 2010-2015

In this section, we report recent publications of our group supported by the ECRA grant DE-SC0003870. The ECRA funds were used to support the PI's summer salary, postdoc salaries and benefits, travel, and operational expenses. Support of research-related activities were supplemented by Nadolsky's startup fund and Lightner-Sams Foundation, which paid for HEP seminars and some operational expenses in the SMU Department of Physics.

[1] H.-L. Lai, M. Guzzi, J. Huston, Z. Li, P. Nadolsky, J. Pumplin, and C.-P. Yuan, *New parton distributions for collider physics*, *Phys.Rev.* **D82** (2010) 074024.

[2] H.-L. Lai, J. Huston, Z. Li, P. Nadolsky, J. Pumplin, D. Stump, and C.-P. Yuan, *Uncertainty induced by QCD coupling in the CTEQ global analysis of parton distributions*, *Phys. Rev.* **D82** (2010) 054021.

[3] E. L. Berger, M. Guzzi, H.-L. Lai, P. M. Nadolsky, and F. I. Olness, *Constraints on color-octet fermions from a global parton distribution analysis*, *Phys.Rev.* **D82** (2010) 114023.

[4] M. Guzzi, P. M. Nadolsky, H.-L. Lai, and C.-P. Yuan, *General-Mass Treatment for Deep Inelastic Scattering at Two-Loop Accuracy*, *Phys.Rev.* **D86** (2012) 053005, [arXiv:1108.5112].

[5] M. Guzzi, P. Nadolsky, E. Berger, H.-L. Lai, F. Olness, and C.-P. Yuan, *CT10 parton distributions and other developments in the global QCD analysis*, arXiv:1101.0561.

[6] M. Guzzi, P. Nadolsky, and F. Olness, *Unpolarized parton distribution functions: questions to be addressed at an EIC*, in *Gluons and the quark sea at high energies: Distributions, polarization, tomography* (D. Boer, M. Diehl, R. Milner, R. Venugopalan, and W. Vogelsang, eds.), p. 27, 2011. arXiv:1108.1713.

[7] M. Guzzi, P. Nadolsky, and F. Olness, *Intrinsic charm production at the Electron-Ion Collider*, in *Gluons and the quark sea at high energies: Distributions, polarization, tomography* (D. Boer, M. Diehl, R. Milner, R. Venugopalan, and W. Vogelsang, eds.), p. 44, 2011. arXiv:1108.1713.

[8] D. Boer, M. Diehl, R. Milner, R. Venugopalan, W. Vogelsang, et al., *Gluons and the quark sea at high energies: Distributions, polarization, tomography*, 2011. arXiv:1108.1713.

[9] M. Botje, J. Butterworth, A. Cooper-Sarkar, A. de Roeck, J. Feltesse, et al., *The PDF4LHC Working Group Interim Recommendations*, arXiv:1101.0538.

[10] M. Guzzi, P. M. Nadolsky, H.-L. Lai, and C.-P. Yuan, *Heavy-flavor contributions at NNLO in CTEQ PDF analysis*, arXiv:1108.4008.

[11] V. Guzey, M. Guzzi, P. M. Nadolsky, M. Strikman, and B. Wang, *Massive neutral gauge boson production as a probe of nuclear modifications of parton distributions at the LHC*, *Eur.Phys.J.* **A49** (2013) 35, [arXiv:1212.5344].

[12] R. D. Ball, S. Carrazza, L. Del Debbio, S. Forte, J. Gao, et al., *Parton Distribution Benchmarking with LHC Data*, *JHEP* **1304** (2013) 125, [arXiv:1211.5142].

[13] J. Gao, Z. Liang, D. E. Soper, H.-L. Lai, P. M. Nadolsky, and C.-P. Yuan, *MEKS: a program for computation of inclusive jet cross sections at hadron colliders*, *Comput.Phys.Commun.* **184** (2013) 1626–1642, [arXiv:1207.0513].

[14] J. Gao, C. S. Li, and H. X. Zhu, *Top Quark Decay at Next-to-Next-to Leading Order in QCD*, *Phys.Rev.Lett.* **110** (2013) 042001, [arXiv:1210.2808].

[15] J. Gao, C. S. Li, and C.-P. Yuan, *NLO QCD corrections to dijet production via quark contact interactions*, *JHEP* **1207** (2012) 037, [arXiv:1204.4773].

[16] J. Gao, Z. Liang, and P. Nadolsky, "*A NLO benchmark comparison for inclusive jet production at hadron colliders*." Preprint SMU-HEP-12-02 (2012), in Proceedings of the 2011 Workshop "Physics at TeV Colliders", Les Houches, France, 2011; arXiv:1203.6803 [hep-ph], pages 77-88.

[17] Z. Liang and P. Nadolsky, "*What constrains the gluon PDF in a global fit?*." Preprint SMU-HEP-12-03 (2012), in Proceedings of the 2011 Workshop "Physics at TeV Colliders", Les Houches, France, 2011; arXiv:1203.6803 [hep-ph], pages 36-44.

[18] P. M. Nadolsky and M. Guzzi, *DIS heavy-flavor contributions at two loops in a general-mass scheme*, *Nucl.Phys.Proc.Suppl.* **222-224** (2012) 35–40. In Proceedings of the Workshop *New Trends in HERA physics*, Ringberg, Germany, September 25-28, 2011.

[19] S. Dalley, S. Adhikari, and P. Nadolsky, *Optimizing Polar Angle Asymmetry Observables at Colliders*, *Acta Phys.Polon.Supp.* **6** (2013) 213–218, [arXiv:1211.4003].

[20] M. Guzzi and P. M. Nadolsky, *Nonperturbative contributions to a resummed leptonic angular distribution in inclusive Z/γ^* boson production*, arXiv:1209.1252. In Proceedings of the Workshop on QCD evolution, Jefferson Laboratory, May 2011.

[21] P. Nadolsky, J. Gao, M. Guzzi, J. Huston, H.-L. Lai, Z. Li, J. Pumplin, D. Stump, and C.-P. Yuan, *Progress in CTEQ-TEA PDF Analysis*, arXiv:1206.3321. In Proceedings of the XX Workshop on Deep Inelastic Scattering and Related Subjects, Bonn, Germany, 26-30 March, 2012.

[22] S. Dittmaier, S. Dittmaier, C. Mariotti, G. Passarino, R. Tanaka, et al., *Handbook of LHC Higgs Cross Sections: 2. Differential Distributions*, arXiv:1201.3084.

[23] J. Gao, M. Guzzi, J. Huston, H.-L. Lai, Z. Li, et al., *The CT10 NNLO Global Analysis of QCD*, arXiv:1302.6246. In print in Physical Review D.

[24] J. Gao, M. Guzzi, and P. M. Nadolsky, *Charm quark mass dependence in a global QCD analysis*, *Eur.Phys.J.* **C73** (2013) 2541, [arXiv:1304.3494].

[25] J. Gao, *CIJET: A program for computation of jet cross sections induced by quark contact interactions at hadron colliders*, *Comput.Phys.Commun.* **184** (2013) 2362–2366, [arXiv:1301.7263].

[26] J. Gao and P. Nadolsky, *A meta-analysis of parton distribution functions*, *JHEP* **07** (2014) 035, [arXiv:1401.0013].

[27] M. Guzzi, P. M. Nadolsky, and B. Wang, *Nonperturbative contributions to a resummed leptonic angular distribution in inclusive neutral vector boson production*, *Phys. Rev.* **D90** (2014), no. 1 014030, [arXiv:1309.1393].

[28] S. Dulat, T.-J. Hou, J. Gao, J. Huston, P. Nadolsky, J. Pumplin, C. Schmidt, D. Stump, and C. P. Yuan, *Higgs Boson Cross Section from CTEQ-TEA Global Analysis*, *Phys. Rev.* **D89** (2014), no. 11 113002, [arXiv:1310.7601].

[29] S. Dulat, T.-J. Hou, J. Gao, J. Huston, J. Pumplin, C. Schmidt, D. Stump, and C. P. Yuan, *Intrinsic Charm Parton Distribution Functions from CTEQ-TEA Global Analysis*, *Phys. Rev.* **D89** (2014), no. 7 073004, [arXiv:1309.0025].

[30] J. Gao, *Differentiating the production mechanisms of the Higgs-like resonance using inclusive observables at hadron colliders*, *JHEP* **02** (2014) 094, [arXiv:1308.5453].

[31] J. Gao, M. Guzzi, and P. M. Nadolsky, *Charm quark mass dependence in the CTEQ NNLO global QCD analysis*, arXiv:1306.5319. In Proceedings of the XXI Workshop on Deep Inelastic Scattering and Related Subjects, Marseille, France, 22-26 April, 2013.

[32] S. Hoche, L. Reina, M. Wobisch, C. Bauer, Z. Bern, et al., *Computing for Perturbative QCD - A Snowmass White Paper*, arXiv:1309.3598.

[33] J. Campbell, K. Hatakeyama, J. Huston, F. Petriello, J. R. Andersen, et al., *Report of the Snowmass 2013 Energy Frontier QCD Working Group*, arXiv:1310.5189.

[34] C. Schmidt, S. Dulat, J. Gao, M. Guzzi, T.-j. Hou, J. W. Huston, P. Nadolsky, J. Pumplin, D. Stump, and C. P. Yuan, *Uncertainties on H and $t\bar{t}$ predictions at the LHC (and update on intrinsic charm)*, *PoS* **DIS2014** (2014) 146.

[35] J. R. Andersen et al., *Les Houches 2013: Physics at TeV Colliders: Standard Model Working Group Report*, arXiv:1405.1067.

[36] J. Rojo et al., *The PDF4LHC report on PDFs and LHC data: Results from Run I and preparation for Run II*, arXiv:1507.0055.

[37] S. Dulat, T. J. Hou, J. Gao, M. Guzzi, J. Huston, P. Nadolsky, J. Pumplin, C. Schmidt, D. Stump, and C. P. Yuan, *The CT14 Global Analysis of Quantum Chromodynamics*, arXiv:1506.0744.

[38] O. Zenaiev et al., *Impact of heavy-flavour production cross sections measured by the LHCb experiment on parton distribution functions at low x*, arXiv:1503.0458.

7 Other publications

[39] J. Pumplin et al., *New generation of parton distributions with uncertainties from global QCD analysis*, *JHEP* **07** (2002) 012.

[40] P. M. Nadolsky et al., *Implications of CTEQ global analysis for collider observables*, *Phys. Rev.* **D78** (2008) 013004.

[41] F. Olness et al., *Neutrino dimuon production and the strangeness asymmetry of the nucleon*, *Eur. Phys. J.* **C40** (2005) 145.

[42] E. L. Berger, P. M. Nadolsky, F. I. Olness, and J. Pumplin, *Light gluino constituents of hadrons and a global analysis of hadron scattering data*, *Phys. Rev.* **D71** (2005) 014007.

[43] H.-L. Lai et al., *The strange parton distribution of the nucleon: global analysis and applications*, *JHEP* **04** (2007) 089.

[44] J. Pumplin et al., *Collider Inclusive Jet Data and the Gluon Distribution*, *Phys. Rev.* **D80** (2009) 014019.

[45] P. M. Nadolsky and W.-K. Tung, *Improved Formulation of Global QCD Analysis with Zero-mass Matrix Elements*, *Phys. Rev.* **D79** (2009) 113014.

[46] H.-L. Lai et al., *Parton Distributions for Event Generators*, *JHEP* **04** (2010) 035.

[47] J. Pumplin, H.-L. Lai, and W.-K. Tung, *The charm parton content of the nucleon*, *Phys. Rev.* **D75** (2007) 054029.

[48] **CDF** Collaboration, D. Acosta et al., *Measurement of the forward-backward charge asymmetry from $w \to e\nu$ production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ tev*, *Phys. Rev.* **D71** (2005) 051104.

[49] W. T. Giele, S. A. Keller, and D. A. Kosower, *Parton distribution function uncertainties*, `hep-ph/0104052`.

[50] W. T. Giele, S. Keller, and D. A. Kosower, "*Parton distributions with errors*." Prepared for 13th Les Rencontres de Physique de la Valle d'Aoste: Results and Perspectives in Particle Physics, La Thuile, Valle d'Aoste, Italy, 28 Feb - 6 Mar 1999.

[51] R. S. Thorne, *A variable-flavour number scheme for NNLO*, *Phys. Rev.* **D73** (2006) 054019.

[52] M. A. G. Aivazis, J. C. Collins, F. I. Olness, and W.-K. Tung, *Leptoproduction of heavy quarks. 2. A Unified QCD formulation of charged and neutral current processes from fixed target to collider energies*, *Phys. Rev.* **D50** (1994) 3102.

[53] J. C. Collins, *Hard-scattering factorization with heavy quarks: a general treatment*, *Phys. Rev.* **D58** (1998) 094002.

[54] W.-K. Tung, S. Kretzer, and C. Schmidt, *Open heavy flavor production in QCD: Conceptual framework and implementation issues*, *J. Phys.* **G28** (2002) 983–996.

[55] M. Kramer, F. I. Olness, and D. E. Soper, *Treatment of heavy quarks in deeply inelastic scattering*, *Phys. Rev.* **D62** (2000) 096007.

[56] C. Balazs and C.-P. Yuan, *Soft gluon effects on lepton pairs at hadron colliders*, *Phys. Rev.* **D56** (1997) 5558.

[57] W. Giele *et al.*, *The QCD/SM working group: Summary report*, 2002, ch. 1.12; `[hep-ph/0204316]`.

[58] F. Landry, R. Brock, P. M. Nadolsky, and C.-P. Yuan, *Tevatron Run-1 Z boson data and Collins-Soper-Sterman resummation formalism*, *Phys. Rev.* **D67** (2003) 073016.

[59] A. V. Konychev and P. M. Nadolsky, *Universality of the Collins-Soper-Sterman nonperturbative function in gauge boson production*, *Phys. Lett.* **B633** (2006) 710–714.

[60] C. Balazs, E. L. Berger, P. Nadolsky, and C.-P. Yuan, *All-orders resummation for diphoton production at hadron colliders*, *Phys. Lett.* **B637** (2006) 235.

[61] P. Nadolsky, C. Balazs, E. L. Berger, and C.-P. Yuan, *Gluon-gluon contributions to the production of continuum diphoton pairs at hadron colliders*, *Phys. Rev.* **D76** (2007) 013008.

[62] C. Balazs, E. L. Berger, P. M. Nadolsky, and C.-P. Yuan, *Calculation of prompt diphoton production cross sections at Tevatron and LHC energies*, *Phys. Rev.* **D76** (2007) 013009.

[63] S. Forte, L. Garrido, J. I. Latorre, and A. Piccione, *Neural network parametrization of deep-inelastic structure functions*, *JHEP* **05** (2002) 062.

[64] **NNPDF** Collaboration, L. Del Debbio, S. Forte, J. I. Latorre, A. Piccione, and J. Rojo, *Neural network determination of parton distributions: the nonsinglet case*, *JHEP* **03** (2007) 039.

[65] D. Stump et al., *Uncertainties of predictions from parton distribution functions. I: The Lagrange multiplier method*, *Phys. Rev.* **D65** (2002) 014012.

[66] J. Pumplin et al., *Uncertainties of predictions from parton distribution functions. II: The Hessian method*, *Phys. Rev.* **D65** (2002) 014013.

[67] The Fermi 2002 PDF sets are publicly distributed as a part of the LHAPDF library, available at http://projects.hepforge.org/lhapdf/pdfsets.

[68] **D0** Collaboration, V. M. Abazov et al., *Measurement of the electron charge asymmetry in $p\bar{p} \to W + X \to e\nu + X$ events at $\sqrt{s}$ = 1.96 TeV*, .

[69] **CDF** Collaboration, T. Aaltonen et al., *Measurement of the inclusive jet cross section at the Fermilab Tevatron $p\bar{p}$ collider using a cone-based jet algorithm*, *Phys. Rev.* **D78** (2008) 052006.

[70] **NNPDF** Collaboration, R. D. Ball et al., *A determination of parton distributions with faithful uncertainty estimation*, *Nucl. Phys.* **B809** (2009) 1–63.

[71] S. J. Brodsky, P. Hoyer, C. Peterson, and N. Sakai, *The Intrinsic Charm of the Proton*, *Phys. Lett.* **B93** (1980) 451–455.

[72] S. J. Brodsky, C. Peterson, and N. Sakai, *Intrinsic Heavy Quark States*, *Phys. Rev.* **D23** (1981) 2745.

[73] B. W. Harris, J. Smith, and R. Vogt, *Reanalysis of the EMC charm production data with extrinsic and intrinsic charm at NLO*, *Nucl. Phys.* **B461** (1996) 181–196, [hep-ph/9508403].

[74] B. Z. Kopeliovich, I. K. Potashnikova, and I. Schmidt, *Penetrating intrinsic charm: evidence in data*, arXiv:1003.3673.

[75] J. Pumplin, *Light-Cone Models for Intrinsic Charm and Bottom*, *Phys. Rev.* **D73** (2006) 114015, [hep-ph/0508184].

[76] S. Forte, E. Laenen, P. Nason, and J. Rojo, *Heavy quarks in deep-inelastic scattering*, *Nucl. Phys.* **B834** (2010) 116–162.

[77] C. Coriano, M. Guzzi, G. Lazarides, and A. Mariano, *Cosmological Properties of a Gauged Axion*, *Phys. Rev.* **D82** (2010) 065013.

[78] B. Bertoni, "Comparison of algorithms for Monte-Carlo integration of a multi-dimensional Gaussian function." Preprint SMU-HEP-10-13 (2010), http://www.physics.smu.edu/web/research/preprints/SMU-HEP-10-13.pdf.

[79] B. Bertoni, "Multi-dimensional ellipsoidal fitting." Preprint SMU-HEP-10-14 (2010), http://www.physics.smu.edu/web/research/preprints/SMU-HEP-10-14.pdf.

[80] J. Ablinger, J. Bluemlein, A. Hasselhuhn, S. Klein, C. Schneider, et al., *New Heavy Flavor Contributions to the DIS Structure Function $F_2(x, Q^2)$ at $O(\alpha_s^3)$*, arXiv:1202.2700.

[81] A. Banfi, S. Redford, M. Vesterinen, P. Waller, and T. Wyatt, *Optimisation of variables for studying dilepton transverse momentum distributions at hadron colliders*, *Eur.Phys.J.* **C71** (2011) 1600, [arXiv:1009.1580].

[82] **D0** Collaboration, V. M. Abazov et al., *Precise study of the Z/γ^* boson transverse momentum distribution in $p\bar{p}$ collisions using a novel technique*, *Phys.Rev.Lett.* **106** (2011) 122001, [arXiv:1010.0262].

[83] G. Watt and R. Thorne, *Study of Monte Carlo approach to experimental uncertainty propagation with MSTW 2008 PDFs*, *JHEP* **1208** (2012) 052, [arXiv:1205.4024].

[84] W. T. Giele and S. Keller, *Implications of hadron collider observables on parton distribution function uncertainties*, *Phys.Rev.* **D58** (1998) 094023, [hep-ph/9803393].

[85] **NNPDF Collaboration** Collaboration, R. D. Ball et al., *Reweighting NNPDFs: the W lepton asymmetry*, *Nucl.Phys.* **B849** (2011) 112–143, [arXiv:1012.0836].

[86] R. D. Ball, V. Bertone, F. Cerutti, L. Del Debbio, S. Forte, et al., *Reweighting and Unweighting of Parton Distributions and the LHC W lepton asymmetry data*, *Nucl.Phys.* **B855** (2012) 608–638, [arXiv:1108.1758].

[87] INSPIRE-HEP topcites, http://inspirehep.net/info/hep/stats/topcites/index.

[88] C. Coriano, M. Guzzi, and A. Mariano, *Relic Densities of Dark Matter in the U(1)-Extended NMSSM and the Gauged Axion Supermultiplet*, *Phys.Rev.* **D85** (2012) 095008, [arXiv:1010.2010].

[89] **NNPDF** Collaboration, R. D. Ball et al., *Parton distributions for the LHC Run II*, *JHEP* **04** (2015) 040, [arXiv:1410.8849].

[90] L. A. Harland-Lang, A. D. Martin, P. Motylinski, and R. S. Thorne, *Parton distributions in the LHC era: MMHT 2014 PDFs*, *Eur. Phys. J.* **C75** (2015), no. 5 204, [arXiv:1412.3989].

[91] W. K. Tung, H. L. Lai, A. Belyaev, J. Pumplin, D. Stump, and C. P. Yuan, *Heavy Quark Mass Effects in Deep Inelastic Scattering and Global QCD Analysis*, *JHEP* **02** (2007) 053, [hep-ph/0611254].

[92] C. Anastasiou, C. Duhr, F. Dulat, F. Herzog, and B. Mistlberger, *Higgs Boson Gluon-Fusion Production in QCD at Three Loops*, *Phys. Rev. Lett.* **114** (2015) 212001, [arXiv:1503.0605].

[93] **CDF** Collaboration, T. A. Aaltonen et al., *Measurement of $d\sigma/dy$ of Drell-Yan e^+e^- pairs in the Z Mass Region from $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV*, *Phys. Lett.* **B692** (2010) 232–239, [arXiv:0908.3914].

[94] **ZEUS, H1** Collaboration, F. D. Aaron et al., *Combined Measurement and QCD Analysis of the Inclusive e+- p Scattering Cross Sections at HERA*, *JHEP* **01** (2010) 109, [arXiv:0911.0884].

[95] **CDF** Collaboration, T. Aaltonen et al., *Direct Measurement of the W Production Charge Asymmetry in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV*, *Phys. Rev. Lett.* **102** (2009) 181801, [arXiv:0901.2169].

[96] **D0** Collaboration, V. M. Abazov et al., *Measurement of the inclusive jet cross-section in $p\bar{p}$ collisions at $s^{(1/2)}$ =1.96-TeV*, *Phys. Rev. Lett.* **101** (2008) 062001, [arXiv:0802.2400].

[97] **D0** Collaboration, V. M. Abazov et al., *Measurement of the shape of the boson rapidity distribution for $p\bar{p} \to Z/gamma^* \to e^+e^- + X$ events produced at $\sqrt{s}$ of 1.96-TeV*, *Phys. Rev.* **D76** (2007) 012003, [hep-ex/0702025].

Pavel M. Nadolsky

Associate Professor
Department of Physics
Southern Methodist University
Dallas, TX 75275, USA

Phone: (214) 768-1756
Fax: (214) 768-4095
E-mail: nadolsky@mail.physics.smu.edu
Web page: http://www.physics.smu.edu/nadolsky

Education and training

Michigan State University	High energy physics	Postdoc	2007-2008
Argonne National Laboratory	High energy physics	Postdoc	2004-2007
Southern Methodist University	High energy physics	Postdoc	2001-2004
Michigan State University	Physics	Ph. D.	1996-2001
Institute for HEP (Russia)	Physics/Math	Researcher	1992-1996
Moscow State University	Physics	M. Sc. with Honors	1986-1992

Appointments

Southern Methodist University	Associate Professor in theoretical physics	06/2013-present
	Assistant Professor	2008-05/2013

Grants and financial support

	Grants	Awarded by	Grant No.	Time period
1.	Early Career Research Award	US Dept. of Energy	DE-SC0003870	04/2010-04/2015
2.	Studies of QCD structure...	US Dept. of Energy	DE-SC0013681	04/2015-03/2016
3.	LHC Theory Initiative Travel & Computing Fellowship	US Natl. Science Foundation	PHY-0705862	01/2008-07/2010

Postdoctoral research associates

	Name	Time period	Supported by
1.	Tie-Jiun Hou	10/2014-present	ECRA, DE-SC0013681
2.	Jun Gao	09/2011-09/2014	ECRA
3.	Marco Guzzi	09/2009-08/2012	ECRA

Graduate studentsdesy

	Name	University	Degree	Awarded in
1.	Bowen Wang	SMU	Ph. D.	2015
2.	Zhihua Liang	SMU	Ph. D.	2012
3.	Sophia Chabysheva	SMU	Ph. D.	2009
4.	Anton Konychev	Indiana University	Ph. D.	2006

Synergistic Activities

- Member of the Coordinated Theoretical-Experimental Project on QCD (CTEQ, www.cteq.org)
- Convener of the Integrated Physics Analysis, PROSA collaboration, prosa.desy.de
- Convener of working groups, XIII and XXI International Workshops on DIS, 2005 and 2013
- Referee for Annals of Physics, JHEP, Nuclear Physics B, Physics Letters B, and Physical Review D

Curriculum Vitae

Jun Gao

Department of High Energy Physics,
Argonne National Laboratory,
Lemont, IL 60439, USA
Tel: 630-252-7405 (office)

E-mail: jgao@anl.gov

[redacted]

Gender: Male
Nationality: P. R. China

Education and training

- Postdoc in Theoretical Physics, Argonne National Laboratory, 2014-present.
- Postdoc in Theoretical Physics, Southern Methodist University, 2011-2014.
- Ph.D. in Theoretical Physics, Peking University, 2006-2011.
- B.Sc. in Physics, Peking University, 2002-2006.

Research interests

My research concentrates on phenomenology of particle physics, especially at the LHC, including pQCD calculations, global analyses of QCD, Higgs physics, top quark physics, dark matter search, developments of various Monte Carlo tools. I am particularly interested on precise theoretical predictions for the LHC studies and searches for new physics beyond the standard model.

Honors and awards

- 2011 Excellent PhD Thesis Award, Peking University
- 2011 Excellent Graduate Student Award, Peking University

- 2010 LiaoKaiYuan Scholarship, Peking University
- 2009 WuSi Scholarship, Peking University
- 2002-2005 MingDe Scholarship, Peking University
- 2002 Silver Medal of the 33rd International Physics Olympiad
- 2002 Gold Medal of the 3rd Asian Physics Olympiad

Conference & Seminar Talks

1. Searching for anomalous top quark production at the early LHC, at Joint Fall 2011 Meeting of the Texas Sections of the APS, AAPT, and Zone 13 of the SPS, Texas A&M University-Commerce, Commerce, Texas, USA, October 2011
2. NLO QCD corrections to dijet production via quark contact interactions, at Pheno 2012 Symposium, University of Pittsburgh, Pittsburgh, Pennsylvania, USA, May 2012
3. Jet data from hadron colliders and correlated uncertainties, PDF section of 2012 QCD4LHC meeting, online, May 2012
4. Gluon PDF and jet data in the CT10 global fit, at 2012 CTEQ fall meeting, Jefferson Lab, Newport News, Virginia, November 2012
5. Precise predictions of top quark fully differential decay, seminar at Michigan State University, East Lansing, Michigan, USA, April 2013
6. Precise predictions of top quark fully differential decay, at Pheno 2013 Symposium, University of Pittsburgh, Pittsburgh, Pennsylvania, USA, May 2013
7. A meta analysis of parton distribution functions for LHC applications, PDF section of Les Houches 2013, online, June 2013
8. Constraining the gluon PDF for LHC physics, invited talk at the PDF session of the mini-workshop on "QCD Tools for LHC Physics: From 8 to 14 TeV - What's needed and why?", Fermilab, Batavia, Illinois, USA, November 2013
9. A meta analysis of parton distribution functions, Moriond QCD and High Energy Interactions, La Thuile, Italy, March 2014
10. Parton Distribution Function benchmarking and LHC applications, seminar at Northwestern University, Evanston, Illinois, USA, April 2014

11. Less Houches Higgs PDF study, PDF4LHC meeting, online, May 2014
12. Top-quark forward-backward asymmetry in e+e- annihilation at NNLO in QCD, workshop on "QCD and beyond", University of Pittsburgh, Pittsburgh, Pennsylvania, USA, November 2014
13. Higher-order QCD corrections to the Higgs-boson qT distribution, DIS workshop 2015, Southern Methodist University, Dallas, Texas, USA, April 2015
14. Higher-order QCD corrections to the Higgs-boson qT distribution, Radcor/Loopfest workshop 2015, University of Califonia at Los Angeles, Los Angeles, Califonia, USA, June 2015

High energy physics code maintained

1. MEKS, http://meks.hepforge.org/
2. CIJET, http://cidijet.hepforge.org/
3. NNTopDec, http://nntopdec.hepforge.org/
4. METAPDF, http://metapdf.hepforge.org/

Other Related

Program Skills	Experienced programming in Fortran, C/C++, Python. Knowledgeable about common program package in high energy physics: FeynArts/FormCalc/LoopTools, FeynCalc, FORM, GoSam, MadGraph, ALPGEN, Pythia, PGS, MCFM, ROOT, CERNLIB.

Curriculum vitae

Marco Guzzi

July, 2015

Personal Informations

- First Name: Marco
- Last Name: Guzzi
- Nationality: Italy
- [redacted]
- Current Adress: 16 Tarleton Street, Manchester, United Kingdom.
- marital status: married
- cell. phone: +44 (0)7437 513631
- Work Phone: +44 (0) 161 30 66473
- current e-mail adress: marco.guzzi@manchester.ac.uk
- previous e-mail contacts: marco.guzzi@desy.de, mguzzi@physics.smu.edu, marco.guzzi@le.infn.it
- Work address:
  University of Manchester,
  School of Physics and Astronomy,
  Particle Physics Group,
  Brunswick Street, Schuster building,
  Manchester M13 9PL, United Kingdom.
- Office number : 6.28
- Office Phone : +44 (0) 161 30 6647

Foreign Languages

- English

Knowledge of informatics

- Operative systems: Linux and Windows
- C/C++ and Fortran programming
- Mathematica
- tools for High Energy Physics: FeynCalc

List of all colleges and Universities attended

- University of Lecce
  Grade: Laurea (Theoretical Physics)
  date: July 24 2002
  Thesis title:"Perturbative aspects of QCD in the presence of supersymmetry".
  Advisor: Prof. Claudio Corianò.

- Mar 2003 - Sep 2006 Ph.D. University of Salento, Lecce, Italy.
  Graduation date: Sep. 28 2006
  Ph.D. Thesis Title: "QCD Studies at Hadron Colliders and in Deeply Virtual Neutrino Scattering". e-Print: hep-ph/0612355
  Advisor: Prof. Claudio Corianò.

- I.N.F.N. Research Fellow: 2-year position at I.N.F.N. and Salento U. (Mar 1 2007 - Feb 28 2009), Lecce, Italy.
  with: Prof. Claudio Corianò.

- Postdoc: Research associate, 3-year position at Southern Methodist University (Sep 1 2009 - Aug 31 2012) , Dallas, USA.
  with: Prof. Pavel Nadolsky.

- Postdoc: Research associate, 2-year position at DESY Hamburg (Oct 1 2012 - Oct 31 2014), Hamburg Germany
  with: Dr. Katerina Lipka (CMS group at DESY Hamburg), Prof. Sven-Olaf Moch (DESY Hamburg and University of Hamburg).

- Postdoc: Research associate, 2-year position at the Elementary Particle Theory Group of the University of Manchester (Nov 1 2014 - Nov 1 2016), Manchester, UK
  with: Prof. Michael H. Seymour.

Activities during the Ph.D.

- "IX Meeting of theoretical Physics", Univ. of Parma, Parma, Italy. Sep 2-13 2002.
- "International School of High Energy Physics", Heraklion, (Crete), Greece. Sep 1 - Oct 6 2003.
- CERN Geneva Nov 26-30 2003.
- International School of Advanced Study of University of Turin: "QGP and Relativistic Heavy Ions: Past, Present, Future". Turin, Italy, Dec 1-5 2003.
- Italo Hellenic School of Physics 2004 "The Physics of LHC: Theoretical tools and experimental challeges" Martignano, (Lecce), Italy. May 20-25 2004.
- University of Ioannina, for a Collaboration with Prof. K. Tamvakis. Nov 2004.
- Italo Hellenic School of Physics 2005 "The Physics of LHC: Theoretical tools and experimental challeges" Martignano (Lecce), Italy June 9-14 2005
- Italo Hellenic School of Physics 2006 "The Physics of LHC: Theoretical tools and experimental challeges" Martignano, (Lecce), Italy, June 12-18 2006.
- "MCWS", I Monte Carlo Workshop, Physics and Simulations at the LHC. INFN Frascati National Laboratories, Italy 27-28 Feb. 2006.
- "MCWS", II Monte Carlo Workshop, Physics and Simulations at the LHC. INFN Frascati National Laboratories, Italy 22-23 May 2006.
- "NOW 2006" Neutrino Oscillation Workshop, Conca Specchiulla Otranto Lecce Italy, Sep 9-16 2006.
- Scientific association at the I.N.F.N. (Istituto Nazionale di Fisica Nucleare) Lecce, Italy, from Feb 1 - Aug 31 2005.
- Scientific association at the I.N.F.N. (Istituto Nazionale di Fisica Nucleare) Lecce, Italy, from Mar 1 2007 to Feb 28 2009.

Curriculum Vitae

Tie-Jiun Hou

Address :	Dedman College of Humanities and Sciences Department of Physics Southern Methodist University Dallas, Texas 75275-0175
Phone Number :	1-214-768-4839
Email :	tiejiun.hou@gmail.com

[redacted]

Education

2003–2010	Ph.D	National Tsing Hua University, Taiwan. Advisor: Kingman Cheung.
2000–2003	M.S.	National Central University, Taiwan. Advisor: Hsiang-Kuang Tseng.
1996–2000	B.S.	National Central University. Taiwan.

Experience

2014-present	Post Doctoral Fellow at Southern Methodist University.
2011-2014	Postdoctor at Academia Sinica.
2010-2011	Postdoctoral Researcher at National Tsing Hua University.
2006-2010	Research assistant at National Tsing Hua University.

Thesis

1. *The Higgs Sector of NMSSM with CP Violation*, Ph.D Thesis, National Tsing Hua University;
   Thesis advisor: Kingman Cheung.

2. *The Polarization Correlations in Atomic Field Bremsstrahlung at High Frequency Limit*, Unpublished master dissertation, National Central University, Jhong-li;
   Thesis advisor: Hsiang-Kuang Tseng.

Publications

1. "*The CT14 Global Analysis of Quantum Chromodynamics,* "
S. Dulat, T. -J. Hou, J. Gao, M. Guzzi, J. Huston, P. Nadolsky, J. Pumplin and C. Schmidt *et al.*, arXiv:1506.07443 [hep-ph].

2. "*On the Momentum Dependence of the Flavor Structure of the Nucleon Sea,* "
J. -C. Peng, W. -C. Chang, H. -Y. Cheng, T. -J. Hou, K. -F. Liu and J. -W. Qiu, Phys. Lett. B **736**, 411 (2014) [arXiv:1401.1705 [hep-ph]].

3. "*Higgs Boson Cross Section from CTEQ-TEA Global Analysis,* "
S. Dulat, T. -J. Hou, J. Gao, J. Huston, P. Nadolsky, J. Pumplin, C. Schmidt and D. Stump *et al.*, Phys. Rev. D **89**, 113002 (2014) [arXiv:1310.7601 [hep-ph]].

4. "*Intrinsic Charm Parton Distribution Functions from CTEQ-TEA Global Analysis,* "
S. Dulat, T. -J. Hou, J. Gao, J. Huston, J. Pumplin, C. Schmidt, D. Stump and C. -P. Yuan, Phys. Rev. D **89**, 073004 (2014) [arXiv:1309.0025 [hep-ph]].

5. "*Singlino-driven Electroweak Baryogenesis in the Next-to-MSSM,* "
K. Cheung, T. -J. Hou, J. S. Lee and E. Senaha, Phys. Lett. B **710**, 188 (2012) [arXiv:1201.3781 [hep-ph]].

6. "*Higgs Mediated EDMs in the Next-to-MSSM: An Application to Electroweak Baryogenesis,* "
K. Cheung, T. -J. Hou, J. S. Lee and E. Senaha, Phys. Rev. D **84**, 015002 (2011) [arXiv:1102.5679 [hep-ph]].

7. "*The Higgs Boson Sector of the Next-to-MSSM with CP Violation,* "
K. Cheung, T. -J. Hou, J. S. Lee and E. Senaha, Phys. Rev. D **82**, 075007 (2010) [arXiv:1006.1458 [hep-ph]].

8. "*Light Pseudoscalar Higgs boson in Neutralino Decays in the Next-to-Minimal Supersymmetric Standard Model,* "
K. Cheung and T. -J. Hou, Phys. Lett. B **674**, 54 (2009) [arXiv:0809.1122 [hep-ph]].

9. "*Associated production of a light pseudoscalar Higgs boson with a chargino pair in the NMSSM,* "
A. Arhrib, K. Cheung, T. -J. Hou and K. -W. Song, JHEP **0703**, 073 (2007) [hep-ph/0606114].

Manager: **Nadolsky,Pavel M**
Start Date: **2014-04-01**
End Date: **2015-04-14**
Award No: **DE-SC0003870**
Fund Src: **DOE**

SOUTHERN METHODIST UNIVERSITY
Project (Grant) Expense Summary
G001350 Integrated Analysis Particle
2015-05-31
Budget Authorization: Expanded

		BUDGET		ACTUAL			OPEN	REMAINING	%
		ORIGINAL	REVISED	THIS MONTH	YEAR TO DATE	PROJ TO DATE	COMMIT	BUDGET BAL	SPENT
6112	FT Faculty Extra Compensation	16,357.00	17,512.00	0.00	17,511.12	17,511.12	0.00	0.88	99.99
6165	Graduate Research Assistants	15,750.00	18,900.00	0.00	18,818.18	18,818.18	0.00	81.82	99.57
6181	Post Doctoral Employee - Base	50,000.00	35,018.00	3,750.00	36,767.05	40,642.05	0.00	(5,624.05)	116.06
SALARY		**82,107.00**	**71,430.00**	**3,750.00**	**73,096.35**	**76,971.35**	**-**	**(5,541.35)**	**107.76**
C/S SALARY		-	###	-	-	-	-	-	
AGY SALARY		82,107.00	71,430.00	3,750.00	73,096.35	76,971.35	-	(5,541)	107.76
6201	Fringe Benefits - FT Faculty	3,778.00	4,045.00	0.00	4,640.44	4,640.44	0.00	(595.44)	114.72
6207	Fringe Benefits - Post Doc	6,000.00	4,202.00	168.75	1,654.54	2,197.04	0.00	2,004.96	52.29
6210	Graduate Tuition Remission	5,040.00	6,048.00	0.00	6,021.82	6,021.82	0.00	26.18	99.57
BENEFITS		**14,818.00**	**14,295.00**	**168.75**	**12,316.80**	**12,859.30**	**-**	**1,435.70**	**89.96**
C/S BENEFITS		-	###	-	-	-	-	-	
AGY BENEFITS		14,818.00	14,295.00	168.75	12,316.80	12,859.30	-	1,436	89.96
SUPPLIES & SERVICES		-	###	-	-	-	-	-	
6600	Domestic Travel	4,245.00	9,260.00	0.00	3,611.87	5,183.87	0.00	4,076.13	55.98
6605	Foreign Travel	3,499.00	9,999.00	0.00	7,971.59	7,971.59	0.00	2,027.41	79.72
TRAVEL		**7,744.00**	**19,259.00**	**-**	**11,583.46**	**13,155.46**	**-**	**6,103.54**	**68.31**
SUBCONTRACTS		-	###	-	-	-	-	-	
C/S SUPPLIES & SERVICES		-	###	-	-	-	-	-	
C/S THIRD PARTY		-	###	-	-	-	-	-	
AGY SUP/SERV		7,744.00	19,259.00	-	11,583.46	13,155.46	-	6,104	68.31
EQUIPMENT		-	###	-	-	-	-	-	
C/S EQUIPMENT		-	###	-	-	-	-	-	
C/S THIRD PARTY		-	###	-	-	-	-	-	
AGY EQUIP		-	###	-	-	-	-	-	
SMU DIRECT COSTS		-	###	-	-	-	-	-	
SMU INDIRECT COSTS		-	###	-	-	-	-	-	
TOTAL SMU EXPENSE		-	###	-	-	-	-	-	
6112	FT Faculty Extra Compensation	16,357.00	17,512.00	0.00	17,511.12	17,511.12	0.00	0.88	99.99
6165	Graduate Research Assistants	15,750.00	18,900.00	0.00	18,818.18	18,818.18	0.00	81.82	99.57
6181	Post Doctoral Employee - Base	50,000.00	35,018.00	3,750.00	36,767.05	40,642.05	0.00	(5,624.05)	116.06
6201	Fringe Benefits - FT Faculty	3,778.00	4,045.00	0.00	4,640.44	4,640.44	0.00	(595.44)	114.72
6207	Fringe Benefits - Post Doc	6,000.00	4,202.00	168.75	1,654.54	2,197.04	0.00	2,004.96	52.29
6210	Graduate Tuition Remission	5,040.00	6,048.00	0.00	6,021.82	6,021.82	0.00	26.18	99.57
6600	Domestic Travel	4,245.00	9,260.00	0.00	3,611.87	5,183.87	0.00	4,076.13	55.98
6605	Foreign Travel	3,499.00	9,999.00	0.00	7,971.59	7,971.59	0.00	2,027.41	79.72
AGY DIRECT COSTS		**104,669.00**	**104,984.00**	**3,918.75**	**96,996.61**	**102,986.11**	**-**	**1,997.89**	**98.10**
7600	On Campus F&A - Agency	45,331.00	45,016.00	1,783.03	41,393.53	44,118.75	0.00	897.25	98.01
AGY INDIRECT COSTS		**45,331.00**	**45,016.00**	**1,783.03**	**41,393.53**	**44,118.75**	**-**	**897.25**	**98.01**
TOTAL AGY EXPENSE		150,000.00	150,000.00	5,701.78	138,390.14	147,104.86	-	2,895	98.07
COSTS NEEDING EXPLANATION		0.00	0.00	0.00	0.00	0.00	0		