Project Title: Research in Theoretical High-Energy Physics at Southern Methodist University

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Abstract

Theory: The SMU Theory group has developed a strong expertise in QCD, PDFs, and incisive comparisons between collider data and theory. The group pursues realistic phenomenological calculations for high-energy processes, the highly demanded research area driven by the LHC physics. Our field has seen major discoveries in recent years from a variety of experiments, large and small, including a number recognized by Nobel Prizes. There is a wealth of novel QCD data to explore. The SMU theory group develops the most advanced and innovative tools for comprehensive analysis in applications ranging from Higgs physics and new physics searches to nuclear scattering.

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Research in Theoretical High-Energy Physics at Southern Methodist University Report & Proposal

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Contents

Research in Theoretical Physics

Overview

SMU Theory Task

The theory task at SMU consists of faculty **Pavel Nadolsky** (Co-PI, Associate Professor) and **Fred Olness** (Co-PI, Professor). Nadolsky was supported by a DOE Early Career Research Award in 2010-2015, he is now joining the SMU umbrella grant.

The group currently has two postdocs (DOE funded) and three grad students (1 DOE and 2 SMU funded). Postdoc **Tie-Jiun Hou** joined the group in Fall 2014 and works with Nadolsky. Postdoc **Florian Lyonnet** also joined in Fall 2014 and works with Olness. Recent postdocs have been successful in finding positions after SMU. Postdoc **Jun Gao** moved from SMU to Argonne in 2014, Postdoc **Aleksander Kusina** moved from SMU to Grenoble in 2014, and Postdoc **Marco Guzzi** moved from SMU to DESY in 2012.

Graduate student **Bowen Wang** just completed his Ph.D. under Nadolsky, and will begin a postdoc at JLab in Fall 2015. Graduate students **Benjamin Clark** and **Eric Godat** are working on projects with Olness; Clark plans to graduate in 2016, and Godat in 2017. Additionally a number of junior students are interested in joining the theory group, including **Keping Xie** and **Bo-Ting Wang**. Note that, while each student selects a principal advisor, there is significant cross-communication and collaboration within the group.

SMU Theory Research Focus

The SMU Theory group has developed a strong expertise in QCD, PDFs, and incisive comparisons between data and theory. Olness and Nadolsky work on complementary aspects of these questions, and these have significant overlap with both the Energy and Intensity Frontiers.

Our field has seen major discoveries in recent years from a variety of experiments, large and small, including a number recognized with Nobel Prizes. The recent performance of the LHC has exceeded expectations and produced an unprecedented number of events to be analyzed. On the Intensity Frontier, Fermilab is advancing a number of high-precision experiments (Muon g-2, Mu2e), as well as expanding its neutrino program. Thus, there is a wealth of data to explore, and a comprehensive analysis requires the most advanced and innovative tools.

The general research focus of the SMU theory group is to develop tools that contribute to precise predictions of the SM processes. As the accuracy of the experimental measurements increases, it is essential to improve the theoretical calculations to match. If we can make detailed predictions of W/Z/Higgs production (for example), then we have the ability to distinguish a “new physics” signal from an uncertain SM background process.

For example, to determine if the massive scalar is the garden-variety Higgs boson of the Standard Model (SM), or a more exotic type, we must study both the production cross section and various decay channels to make its proper characterization. In a complementary manner, the Fermilab high-intensity high-statistics experiments force us to reexamine previous assumptions (nuclear corrections, isospin and lepton-flavor symmetries) and require us to extend our calculations to increasingly high orders including subtle electroweak corrections. The key step for all the above analyses is to make accurate predictions, including realistic estimates of the underlying theoretical uncertainty. This is the objective of the SMU theory group research program.

Pavel Nadolsky: current and future research

The SMU theory group studies strong interactions of elementary particles in the realistic environment of collider experiments. Nadolsky' group focuses on development of precise PDFs for nucleon scattering and advanced calculations combining inputs from multi-loop QCD and electroweak calculations, accurate long-distance hadronic functions, and precise numerical programs. It participates in determination of widely used CTEQ parton distribution functions (PDFs) [25–38], the nonperturbative QCD functions that 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 [25–27, 36], consistently receive highest numbers of citations in the INSPIRE-HEP database [39].

In 2010-2015, Nadolsky's research was supported by a DOE Early Career Research Award "Integrated analysis of particle interactions at hadron colliders", followed by a one-year bridge grant for the period until March 2016. During this period, our group published 20 journal papers [27, 28, 35–38, 40–53] and 17 preprints and conference contributions [13, 54–69]. 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. We review key outcomes of these studies and propose to continue funding these highly-demanded research directions.

Global analysis of parton distributions

Among various recent accomplishments by our group, I should first single out elevation of the CTEQ-TEA PDFs to the higher, next-to-next-to-leading order (NNLO) level of accuracy in perturbative QCD. This advancement required to implement new QCD radiative contributions and bring up control of other effects to a comparable level. In addition, 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 PDFs of elevated precision, dubbed "CT10 NNLO", were released in 2012 [36], following the release of the counterpart CT10 NLO ensemble [27, 35]. SMU participated in all major parts of the CT10 analysis: implementation of NNLO QCD radiative contributions, tests of the numerical program, implementation of new experimental data sets, and multivariate parameter fits. SMU postdocs and students implemented and benchmarked new collider experimental data, such as such the combined DIS cross sections from H1 and ZEUS collaborations [70], Tevatron lepton charge asymmetry [71–73], and single-inclusive jet cross sections [74, 75]. Although the CT10 NNLO PDFs were not fitted to the LHC data, they turned out to be in excellent agreement with the LHC measurements at 7 and 8 TeV.

This was followed in 2015 by another NNLO analysis, designated as **CT14** [28]. For the first time, we included 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. The CT14 ensemble is based on benchmarked (N)NLO cross sections and advanced PDF parametrization forms. It is obtained from a global fit to data on more than 30 experiments on DIS, vector boson production, and jet production. Many parts of the numerical calculation were cross checked to comply with the NNLO QCD accuracy. As a result, the CT14 parametrizations are more reliable than CT10 NNLO.

In parallel, SMU collaborators **Gao** and **Nadolsky** invented a "meta-analysis" of PDFs for LHC applications [47], realizing Monte-Carlo (stochastic) sampling of CTEQ PDFs. The meta-analysis is reviewed below. It offers a new way for combining PDF uncertainties from CTEQ and other PDF analysis groups. This approach will be adopted for estimating the PDF+α_s uncertainties in LHC simulations by the 2015 recommendation of the PDF4LHC group.

Massive-quark contributions to NNLO deep inelastic scattering

In developing the theoretical framework for CT10 NNLO, the SMU collaborators **Guzzi** and **Nadolsky** took upon the most arduous task, estimation of heavy-quark scattering contributions to DIS, including the full mass dependence [42, 57, 63]. The goal here was to compute DIS hard-scattering coefficient functions with up to two QCD loops without making a major simplifying approximation of neglecting quark masses. Mass dependence of charm quarks in DIS must be fully included in order to reliably predict LHC electroweak precision observables [26, 76].

We computed these contributions in the S-ACOT-χ mass scheme [77–80], and clarified a number of issues about the heavy-quark DIS calculations raised in recent literature. Our theoretical framework offers several advantages: straightforward derivation from the QCD factorization theorem, transparent algorithmic formulas, and correct kinematical properties of heavy-quark production at all scattering energies. It allows for better control of theoretical factors affecting the accuracy of CTEQ NNLO PDFs. We demonstrated that this scheme organizes NNLO DIS contributions in a very transparent manner and can be extended to an arbitrary QCD order as a consequence of the Collins' factorization theorem [78]. Even more, we show that the QCD factorization theorem, on which the S-ACOT-χ scheme is based, remains valid even if Feynman diagrams include quarks with different masses at once. 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 [81]. In our work, we demonstrate that these concerns are unfounded.

The resulting numerical implementation serves as the foundation for the precision NNLO analyses of PDFs that ensued. It controls theoretical uncertainties of QCD cross sections better than ever. Using this advanced framework, **Gao**, **Guzzi**, and **Nadolsky** obtained constraints on the $\overline{\mathrm{MS}}$ charm quark mass $m_c(m_c)$ from HERA DIS cross sections [43, 66]. We demonstrated that, upon the inclusion of NNLO contributions, the CT10 NNLO fit can determine $m_c(m_c)$ from the analysis of DIS data, 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 [37]. Both studies demonstrate increased capability of the PDF analysis to probe the heavy-quark mass dependence, once the NNLO contributions to DIS are included.

As a follow-up advancement, SMU graduate student Bowen Wang computed in 2015 approximate N^{3}LO QCD radiative contributions to NC DIS cross sections with massive quarks in the intermediate mass factorization scheme [33]. In this challenging calculation, he evaluated the leading contributions associated with the dependence on heavy-quark masses at three-loop accuracy. This calculation establishes a *systematic* skeleton framework for implementation of the S-ACOT-χ scheme at three loops, not available from previous work. It classifies multiple Feynman diagrams at this order according to their flavors and mass dependence.

Combined QCD uncertainties

Advances in our understanding of PDFs have an immediate impact on reducing theoretical uncertainties in electroweak precision observables at hadron colliders. In particular, the correlated uncertainty due to the PDFs and QCD coupling $\alpha_s(M_Z)$ is important in many of LHC measurements, e.g., Higgs boson production cross sections via gluon fusion. In [35], we derive a simple method for estimating the correlated dependence on α_s and PDF parameters. It 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, while keeping all correlated information, and became a common standard.

We also coauthored a paper [38] to estimate the correlated PDF+α_s uncertainty on Higgs production cross sections using two statistical methods, Lagrange Multiplier approach [82] and Hessian approach [83]. 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" to simplify comparison of experimental constraints from a large number of very diverse experiments. 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

Now that ABM, CT, HERAPDF, MMHT, and NNPDF groups have published their independent PDF sets including NNLO radiative contributions, it became necessary to cross validate their theoretical frameworks to resolve various discrepancies observed among the early NNLO ensembles. The SMU collaborators initiated a series of benchmark comparisons to validate the NNLO PDF-fitting frameworks and the predicted (N)NLO cross sections. Initially, predictions for W, Z, $t\bar{t}$, Higgs production at the LHC 8 TeV, were compared using PDFs from five groups and a variety of computer codes [41]. Non-negligible differences between the "nominally NNLO" predictions were identified, as well as some of the causes. For instance, we discovered that correlated systematic errors are interpreted differently by the various PDF fitting groups, producing important differences in precision observables, such as the cross sections for producing Higgs bosons via gluon fusion.

In the follow-up, inclusive DIS cross sections in the CTEQ, HERA, MMHT, and NNPDF fitting codes were compared at NNLO under coordination of SMU postdoc **Gao.** He tested our calculation of charged-current DIS cross sections with heavy quarks and corrected a numerical error, which modified the CT14 parametrizations for strangeness and gluon PDFs, as compared to the previous CTEQ PDFs.

A related effort focused on validating theoretical predictions for inclusive jet production, which is the only other process in the global QCD fits that is still known at NLO. **Nadolsky**, **Gao**, **Liang**, and **Soper** (University of Oregon) developed a new, more stable version of a program EKS for calculating NLO cross sections for jet production at hadron colliders [49, 60, 61]. The new EKS code is an alternative to the other widely used program NLOJET++; we developed it to cross validate two fast interpolation-based interfaces of NLOJet++ employed to constrain the PDFs, called Applgrid and FastNLO. MEKS 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 [60, 61] in MEKS were essential for the benchmark comparison of NLO jet cross sections at the LHC [41]. The full range of PDF uncertainty associated with factorization and renormalization scales in the jet cross sections was identified. **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 [52]. These studies helped us to build up expert understanding of the single-inclusive jet cross sections, and to minimize the associated uncertainties in the NNLO PDFs.

Largely as a result of the benchmarking comparisons, the most recent PDFs released by three global groups (CT14, MMHT'2014, NNPDF3.0) agree much better than those of the previous generation (CT10, MSTW'08, NNPDF2.3). In particular, the PDF uncertainty for Higgs production via gluon fusion at the LHC, estimated based on the PDFs of three global groups according to the 2010 PDF4LHC recommendation [54], has reduced from about 7% in 2012 [41] to about 3% now. This advancement matches the progress in the computation of hard matrix elements for Higgs production observables, which now have scale dependence of about 3% at N3LO in the gluon fusion channel [84]. All these studies contribute to the realization of the Science Drivers' objectives for the LHC, by providing the nonperturbative PDFs that are as accurate as the NNLO hard matrix elements. Now that the latest PDFs agree well, we can confidently combine them in phenomenological applications, using the novel methods described next.

Stochastic sampling and meta-analysis of PDFs

In a series of papers, we pursued in-depth statistical techniques for quantifying uncertainties on the PDFs associated with various sources. In the traditional CTEQ approach, the best-fit PDFs are found by minimization of an analytic log-likelihood function. The confidence intervals on the PDFs are determined in the quasi-Gaussian approximation by diagonalization of the Hessian matrix [83]. The alternative method to study the probability distribution for PDFs is based on stochastic sampling [85–89]. Following this alternative, we developed computer programs for generation of CT14 Monte-Carlo replicas and combination of Monte-Carlo replicas from various groups.

As one such application, Gao converted CT14 Hessian error sets into Monte-Carlo replicas using the modified Thorne-Watt method [90]. **Gao** and **Nadolsky** then proposed a method to combine PDF uncertainties from several Monte-Carlo ensembles by applying a "meta-analysis" of parton distribution functions **[47].** This method addresses a highly needed practical aspect, computing the PDF uncertainty on an LHC observable using predictions from several PDF ensembles (CT14, MMHT, etc.) that don't quite agree. The envelope combination method recommended by the PDF4LHC group in 2010 [54] is inefficient, even though widely used.

The META method offers an alternative to the 2010 PDF4LHC recommendation and simplifies many LHC simulations by reducing the number of PDF error sets. The meta-PDFs are constructed by refitting the input PDF parametrizations from CTEQ, MMHT, 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 the input PDF sets. 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 needed with the 2010 PDF4LHC prescription. In order to perform the META analysis, we developed a toolkit that combines Mathematica with multiple codes for computation of LHC cross sections (MCFM, iHixs, TOP++, FastNLO). It incorporates the Hessian method [83] used by CTEQ and MSTW groups, but also capabilities for stochastic sampling of the probability distribution in the PDF parameter space [86, 87, 90] and inclusion of new experiments by PDF reweighting [86, 91, 92].

These methods further evolved in the course of 2015. The PDF4LHC group decided to recommend the META analysis as a standard method for combination of PDF uncertainties in the LHC Run-2. For this purpose, we constructed a 30-member PDF4LHC-META ensemble recommended for general-purpose LHC applications. It propagated information about the central PDFs and their uncertainties from a combination of CT14, MMHT'2014, and NNPDF'3.0, using much fewer member sets.

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 [93–95] were utilized to predict QCD backgrounds in the discovery of Higgs boson in the leading $\gamma\gamma$ decay channel. Another resummation calculation for W and Z production [96, 97] is frequently used for electroweak precision measurements providing indirect constraints on the Higgs boson sector.

In 2012, **Nadolsky, Guzzi,** and **Wang** completed an enhanced transverse momentum resummation calculation for W and Z boson production at the Tevatron and LHC [44, 59]. This calculation addresses a pressing issue of comparing QCD theory to data on a novel angular variable φ^*_η in Z production [98], which showed some disagreement with resummed NNLL+"partial NNLO" predictions provided by the ResBos code [96, 99]. We demonstrated that the resummed prediction agrees well with the DØ data on φ^*_η distributions [100] 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. [48], 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. [101, 102]. 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** [40] 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, and they provided independent constraints on the QCD+SUSY sector at the beginning of the LHC operation.

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 [55]. As a contribution to this workshop [56], **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 [103–106], but so far has not been found [37, 107, 108]. 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 [50]. 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 $b\bar{b} \to H$ [45]. 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 [65]. 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 [51], **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.

Nadolsky: Proposed Research and Methods

We propose to support high-priority studies that build upon the long-term expertise reviewed above.

1. CTEQ-TEA PDFs with the new HERA and LHC data.

A variety of new data is available from the LHC to constrain the PDFs in a wide kinematical range [52]. The CT14 PDFs [28] released this year are based on the early LHC data sets that are being superseded by measurements with higher statistics. Also, the H1 and ZEUS collaborations published a comprehensive data set from HERA-1 and HERA-2 measurements [109]. It appears to indicate some discrepancies with the combined HERA-1 data set [70] adopted in CT14. It is essential to incorporate the combined HERA-2 data set in our next PDF analysis, as well as the most promising LHC experiments, including production of low-mass Drell-Yan pairs, $W + c$ pairs, inclusive b quarks, and top quarks. These data hold the promise of constraining poorly known combinations of PDFs affecting LHC measurements; e.g., they will help to achieve better separation of sea-quark PDFs, reduce the uncertainty on the gluon PDF, and better constrain all PDF flavors at momentum fractions $x > 0.1$, relevant for searches for ultra-heavy resonances.

Besides the general-purpose NNLO PDFs, various applications require specialized PDF ensembles, e.g., based on Monte-Carlo sampling, for (N)LO event generators, for Higgs boson observables, and with intrinsic charm contributions. Updates are needed on many of these PDF ensembles. To support these activities, we request funding for a postodoctoral position, currently held by Tie-Jiun Hou. Dr. Hou leads various efforts in our global analysis. He carried out the candidate CT14 fits and contributed much of the groundwork to the recent studies of PDF+α_s dependence of Higgs cross sections [38] and NNLO Intrinsic Charm PDFs [37]. He will lead the development of the fitting code and PDF fits for the next CTXX release.

2. Theoretical cross sections for CTEQ fits. We wish to develop and implement fast theoretical calculations for the new LHC processes that are going to be implemented. Examples include low-mass production of Drell-Yan pairs, $W + c$, high-p_T Z, $t\bar{t}$ production. In the recent CT studies, the SMU group took charge of implementing new radiative contributions, processes, and computational modules. We implemented NNLO radiative contributions to DIS cross sections, FastNLO [110] and ApplGrid [111] modules for vector boson and jet production. The fast calculations require to precompute a cross section grid for each process fitted. While some grids are publicly available, we plan to develop local expertise to SMU in generating ApplGrid interfaces using the aMCFast tool [112] for the processes that are still missing. In combination with Madgraph-5 and aMC@NLO [113], aMCFast provides a versatile for automated calculation of NLO cross sections. Generation of typical Applgrid files is intensive both in terms of the CPU time and computer memory. It will be done on the SMU's supercomputing cluster ManeFrame, ideally suited in terms of hardware configuration (see "Facilities and Other resources in the Energy Frontier").

For some processes with heavy quarks, we need to consistently implement mass-dependent QCD contributions, similarly to what has been done in neutral-current DIS at NNLO. Examples include charged-current DIS at NNLO and $V + Q$ production at the LHC, where $V = W$ or Z, and $Q = c$ or b. Such contributions are important for determination of precise PDFs, we have developed theoretical expertise for computing them. As mentioned above, Bowen Wang worked out a framework to extend the S-ACOT-χ scheme in neutral-current DIS to 3-loop accuracy. The only missing ingredient are the 3-loop flavor-creation contributions, currently computed in Europe by Bluemlein and collaborators. Once these last components are published, we will implement them in our calculation and explore their impact on N3LO DIS cross sections.

3. Meta-analysis and Monte-Carlo methods for parton distributions. We will continue development of the meta-analysis method [47]. Our public presentations of the META1.0 PDFs received positive feedback from the community. The meta-parametrizations simplify the computation of the PDF uncertainty in theoretical predictions, after each input parton distribution set is converted into a "meta-parametrization" based on a common functional form. We envision two near-future applications of this approach. First, the PDF4LHC group will soon release a 31-member ensemble of combined PDFs, constructed according to the meta-analysis approach from the input CT14, MMHT'14, and NNPDF3.0 PDF ensembles. This ensemble is intended for general-purpose LHC applications. Its 30 error sets essentially reproduce information about the PDF uncertainties encapsulated in 200 member sets of the input PDFs. The PDF4LHC method needs to be further extended, in particular, to explore the potential for including HERA PDFs into the combination. We plan to finish and publish a Mathematica module developed for the META analysis.

The second application concerns construction of special reduced META PDFs to evaluate the PDF uncertainty in classes of LHC processes, such as Higgs boson production in various channels. A combined PDF ensemble in this case has a greatly reduced number of PDF member sets compared to the original ensembles, after applying procedures of of "stochastic sampling" [86, 87, 90] and "data set diagonalization" [114]. For instance, about 20 PDF error sets reproduce the total PDF uncertainty and PDF-induced correlations in predictions for 50 Higgs boson observables. The META parametrizations therefore naturally shorten numerical computations by a large factor. As these PDFs are of the Hessian type, they are also naturally suited for studies of correlated uncertainties in ATLAS and CMS new physics searches, by treating the few relevant PDF degrees of freedom as nuisance parameters.

4. DIS module for HERA-Fitter. The SMU group contributes to a fitting program HERA Fitter [115]. This provides us with an opportunity to share our theoretical calculations to a broad community outside of the CTEQ collaboration. HERA Fitter is maintained by an international collaboration as an open-source platform for the PDF analysis, providing modules for QCD computations in various heavy-quark schemes, statistical analysis and Monte-Carlo sampling of PDFs. We will develop several modules for the CTEQ fitting package that could be interchangeably used with the HERA Fitter package. The module for the computation of (N)NNLO DIS cross sections in the S-ACOT-χ scheme [42] will be ported into HERA Fitter. It is important to emphasize that this module is independent and complementary to the heavy-quark module for HERA Fitter implemented by Olness' group. Our module realizes the full NNNLO calculation of massive quark contributions to neutral-current DIS used in CTEQ-TEA fits, with control of various theoretical effects. It includes exact mass-dependent contributions that have not been included in the Olness' module.

Another planned module will allow inclusion of theoretical uncertainties in the fit (such as QCD scale uncertainties) using the method of correlation matrices. Gao and Nadolsky have formulated a procedure for including QCD scale dependence of cross sections into the PDF uncertainty by constructing a correlation matrix with additional columns for variations due to the scale dependence. This approach enables easy implementation of the scale uncertainty and other theoretical uncertainties in global fits. We plan to publish a journal paper documenting our findings.

5. Other projects. In addition to these high-priority projects, we intend to participate in the CT global analysis of NNLO PDFs with NLO electroweak contributions (led by Carl Schmidt); TMD factorization calculations for semi-inclusive DIS at COMPASS and Jefferson Lab (in collaboration with Ted Rogers); implementation of small-x and p_T resummations in CTEQ-TEA PDF fits; and development of advanced methods for estimation of PDF uncertainties, to replace the currently used method based on the "χ^2 tolerance" and "Tier-2 penalties" by CTEQ [35, 36]. Nadolsky participates in research projects of a European collaboration on Proton Structure Analyses in Hadronic Collisions (PROSA). He contributed as a coauthor to a recent PROSA analysis of the constraints on the small-x gluon PDF from single-inclusive bottom production at LHCb [53]. He plans to participate in future similar studies, in which a theoretical-experimental collaboration bands together on a short notice to explore emerging LHC results.

Nadolsky: Project Objectives

Our research program focuses on the development of common methods and tools for integrated calculations, ranging from the global QCD analysis to practical collider applications, with the priority on LHC-related studies. It pursues the following interconnected objectives:

- provide integrated description of diverse effects of perturbative and nonperturbative origin in CTEQ global analysis at next-to-next-to-leading order accuracy and beyond;
- adapt the global analysis to derive correlated constraints on the hadronic structure and parameters of non-SM interactions;

- predict LHC processes in the Standard Model and beyond with the help of advanced methods for QCD factorization and all-order resummation;
- provide experimental groups with accurate parametrizations of parton distributions and other hadronic functions, to reliably predict "standard candle" and other LHC processes;
- implement latest achievements in diverse theoretical domains into efficient computer simulation tools for HEP experimentalists.

Through a series of self-contained physics projects, we will (a) advance understanding of the structure and scattering of nucleons in a broad range of processes; and (b) develop self-consistent theoretical calculations that meet the accuracy of key collider measurements. Our results are incorporated into new parton distribution functions serving as a staple input in QCD theory. They will increase trustworthiness of HEP simulations across the board and facilitate interpretation of the upcoming collider data.

Nadolsky: Timetable of Activities

Throughout the research report, we have indicated future research topics and issues; we briefly summarize these below. Items marked "**1**"are being actively studied now, and these projects should yield results within year 1. Items marked "**2**" are projects that would take place late in year 1 or year 2. Items marked "**3**" are projects that may need to wait until year 2 or 3 depending on time-resources and other priorities.

1 Release CT14 NNLO PDFs based on Monte-Carlo replicas. Implement the combined HERA-1 and 2 DIS cross sections in the CTEQ-TEA PDF analysis [109].

2 Release a new generation of NLO and NNLO CTEQ-TEA PDFs implementing $W + c$, low-Q Drell-Yan pair, $t\bar{t}$, and other promising LHC measurements. Develop fast (N)NLO calculations for these measurements.

1 Publish the paper on N3LO contributions to neutral-current DIS in the intermediate-mass and S-ACOT-χ scheme, based on the thesis by Wang.

1 Release advanced META PDFs for Higgs boson production observables. Publish a Mathematica code for the analysis of META PDFs.

2 Implement the modules for NNLO DIS cross sections in the S-ACOT-χ scheme and analysis of correlated systematic errors in HERA Fitter.

3 Develop a new generation of CTEQ-TEA PDFs for (N)LO showering programs with PDF uncertainties. Publish CTEQ-TEA PDFs with NLO electroweak contributions. Explore new methods for estimation of the PDF uncertainty in global PDF fits. Pursue computations for new physics processes and emerging LHC results.

Fred Olness: Current (2012-15) & Future Research:

• Project Overview

The general focus of our research group is Parton Distribution Functions (PDFs) with an emphasis on multi-scale problems such as resumming heavy quark contributions using the DGLAP evolution. We have developed a number of tools for the computation, analysis, and extraction of the PDFs. Whether you are studying Higgs at the highest energies or neutrino-nucleon processes to extract the neutrino flux and energy profile, the PDFs are indispensable for all these measurements.

Improved PDFs also require improved calculations. We pioneered the ACOT formalism for computing heavy quark PDFs,[77, 116, 117] and have now extended this to N^3LO. Additionally we are working within the nCTEQ and HERA-Fitter projects to expand the range of processes included by using reweighting methods, fast grid techniques, and linking to external tools such as LHAPDF, MCFM and APPLgrid. These tools allow incisive comparisons with data as we validate our theoretical understanding of the Standard Model and search for deviations which might signal evidence of "new physics."

• Recent Research Activities:[1]

Olness is a member of the CTEQ collaboration, he served two terms as co-spokesperson (2010-2014), and he plays a lead role in organizing the CTEQ schools. The 2015 school was held in Pittsburgh, and the 2016 school will be held in Hamburg and jointly organized with DESY and MCnet.[2]

Olness is a member of the CERN LHeC Physics Programme Study Group and co-convenes the PDF & QCD working group; the study group is commissioned by the CERN International Advisory Committee to formulate a program for the future colliders.

Olness is a member of the HERA-Fitter developers team and has integrated his N^3LO ACOT program into the project code.

He serves as a member of the International Advisory Committee for the Deep Inelastic Scattering (DIS) Workshop series, and Olness hosted the 2015 workshop on the SMU campus.[3]

He participated in the 2012-13 Snowmass study,[11, 13] is a member of the Steering Committee of the LHC-Theory Initiative, and a candidate for DPF Secretary/Treasurer in the 2015 election. Locally, Olness is active with the SMU Physics QuarkNet program, and serves as the Co-Director of the Dallas Regional Science Fair.

Invited Talks: He has presented talks at conferences and workshops including: invited plenary talk at "2015 Physics Opportunities at an ElecTron-Ion Collider" (Orsay, France); the theory conference summary talk at QCD@LHC2013 (DESY, Hamburg); invited plenary talk at Recontres de Physique des Particules 2013 (Grenoble, France).

Organization: He has participated as an organizer or convener of the following: QCD@LHC2015 (London UK); CTEQ-DESY Workshop 2014 (DESY, Hamburg); 27th Texas Symposium on Relativistic Astrophysics 2013 (Dallas, TX); CTEQ/LPC Workshop (Fermilab, November 2013), LCW12 Future Linear Collider Workshop (Arlington, TX), DIS2011 (Jefferson Lab, VA).[23]

• nCTEQ Parton Distribution Functions: *Refs. [1, 5, 10, 14, 19, 24]*

The objective of the nCTEQ project is to obtain the most precise set of PDFs to facilitate measurements and interpret hadronic processes at fixed-target experiments, HERA, RHIC, Tevatron, and the

[1] Publications by Olness for the period 2012-2015 are collected in the bibliography, *cf.* Refs. [1–24].

[2] MCnet is a European Union funded collaboration dedicated to developing and supporting general-purpose Monte Carlo event generators throughout the LHC era and beyond. `http://www.montecarlonet.org/`

[3] The SMU hosted 2015 DIS Workshop: `http://www.DIS2015.org`

LHC. The project began when it was realized that a limiting factor on the proton PDF precision was the nuclear corrections used for the wealth of nuclei data—particularly the DIS data which is crucial for flavor differentiation.

As the bulk of the data used in the global analyses of the PDFs comes from Deeply Inelastic Scattering (DIS) processes, much of this is measured on heavy targets (e.g., iron or lead) where nuclear corrections must be taken into account. This data is very important for distinguishing the separate flavor components in the proton. In fact, the primary constraint on the strange quark PDF comes from neutrino-induced DIS dimuon production ($\nu N \to \mu^+ \mu^- X$) on heavy targets. Surprisingly, the strange quark PDFs have a large influence on LHC "benchmark" processes.[4]

Until recently, the data from heavy targets (both DIS and Drell-Yan) had large inherent uncertainties when used in proton PDF analyses. The nCTEQ framework allows the correction factors to be integrated *dynamically* into the fit to better identify tensions between data sets, and to extract more accurate PDF error sets.

Charged Lepton and Neutrino DIS Data Sets: [19, 24] In our first series of studies, we fit the charged lepton DIS and neutrino DIS processes separately, and extracted the nuclear correction factor for each data set. For the charged lepton DIS we obtained results compatible with the literature, while for the neutrino DIS we found different correction factors.

Note that this difference was present *only* if we imposed the full constraints of the experimental correlated systematic errors; if the systematic and statistical errors were added in quadrature, a common correction factor was obtained. This observation highlights the importance of the experimental error treatment in the fits, and resolves a number of questions regarding the compatibility of these data sets.

This work underscored the need for a detailed study to produce meaningful PDF errors including the nuclear dimension which is so important for much of the DIS data; this motivated the **nCTEQ15** fit.

nCTEQ15 PDF With Uncertainties: [1, 5, 10, 14] We have now released the **nCTEQ15** PDFs with error sets which provide our results of the global analysis for all nuclear A values; these are available on-line at the HepForge repository.

The uncertainties are determined using the Hessian method with an optimal rescaling of the eigenvectors to accurately represent the uncertainties for the chosen tolerance criteria. In addition to the Deep Inelastic Scattering (DIS) and Drell-Yan (DY) processes, we also include inclusive pion production data to help constrain the gluon PDF. Furthermore, we investigate the correlation of the data sets with specific flavor components, and asses the impact of individual experiments.

We compare with other PDF sets from the literature; while the general features are similar, we note our parameterization allows different correction factors for the up and down quarks and the fit exploits this feature to reduce the χ^2 by an additional $\sim 10\%$.

These PDFs provide a more precise analysis of the heavy target DIS and DY data which enter the fit, and thus improve the constraints on the separate flavor components of the PDF.

Ongoing & Future nCTEQ Projects:

The current **nCTEQ15** PDF release includes not only new processes and data sets, but also incorporates innovations to the nCTEQ code-base which make the program more flexible and extensible. We outline these below, along with possible future research directions.

Python Interface & Extended Functionality: We have re-used the low-level Fortran modules, but the higher level modules are now replaced with Python code; this provides a more flexible interface between the old and new routines. For example, we had to extensively revise the Hessian error analysis because the stability of the χ^2 surface can be more complex than in the proton only case. Specifically,

[4] New data from LHC are beginning to provide information the strange quark at larger Q and smaller x; *cf.* Refs. [16, 20].

we computed the Hessian using a multi-point finite difference with a step size based on our tolerance criteria (T=35) and then rescaled the eigenvectors.[1] This method improved the resulting error PDFs, and the Python interface greatly simplified the implementation.

NLO Grid Techniques: In the nCTEQ15 analysis we implemented the pion production data using a grid technique for the NLO calculation similar to that of APPLgrid. This was necessary as the calculation required a NLO matrix element convoluted first with a fragmentation function, and then with a PDF. We initially implemented this with a K-factor method, but the grid technique is preferred as it dynamically adjusts throughout the fitting procedure eliminating the need for multiple iterations. This technique was effective, and we plan to use this for other processes, possibly with the MCFM program (see below).

Markov Chain Monte Carlo (MCMC): Ideally, one would like to increase the number of parameters to allow the PDFs a more flexible form (for example, as is the case in the neural network approach). Unfortunately there is a trade off because we then encounter more flat directions which are a challenge for the standard Minuit based fitting procedure. Thus we have added Markov Chain Monte Carlo (MCMC) method which is better capable of working with flat directions and multiple minimums. At present, we are using this in a testing mode to compare with Minuit, but it appears to be a promising direction, especially for the nuclei where the data sets are limited.

MCFM & APPLgrid Interfaces: One of the next steps for the nCTEQ project is to extend the PDF fit to additional experimental processes at NLO precision including the LHC Run 2 data sets. Toward this goal we have used the Python layer to link to the MCFM (Monte Carlo for FeMtobarn processes) program which has both a variety of NLO processes and an interface to APPLgrid library which allow for fast NLO computation.[5] This will allow us to benefit from both the MCFM and APPLgrid projects and include a wide variety of NLO W/Z/Higgs processes into the fitting analysis.

Complementary CTEQ Activities: The nCTEQ framework contains the full set of machinery to fit the proton data using DIS, Drell-Yan lepton pair production and inclusive jets. In this sense it is complementary to other CTEQ efforts and we are looking into including this work to improve our hi-x description of the PDFs.[118] This, together with the new MCFM interface greatly expands the applicable region of the nCTEQ PDF studies.

• HERA-Fitter Project: *Refs. [8, 9, 17, 18]*

In a related effort, we have been participating in the HERA-Fitter project which is an open source QCD analysis framework.[6] This project grew out of the HERA-PDF efforts which have just recently released the final HERAPDF2.0, and HERA-Fitter is also used by the LHC collaborations to analyze and assess constraints on the PDFs from LHC data. The HERA-Fitter package can compare multiple PDFs with experimental data and theory predictions to identify tensions, and investigate the physics degrees of freedom ($u(x)$,$\alpha_S(\mu)$, $d\sigma$, ...) involved. Additionally, this has been linked to other programs including the LHAPDF PDF interface, APPLGRID toolbox, Hathor top production program, NNPDF reweighting tools, and the TMD unintegrated PDF packages. Thus, HERA-Fitter provides a common interface to a wide variety of tools to facilitate comparative studies. The manual is published in Ref. [9].

We have been working with members of the HERA-Fitter group (Voica Radescu, Sasha Glazov, Amanda Cooper-Sarkar, Ringaile Placakyte) to develop the heavy quark tools in the program. Olness is currently a member of the HERA-Fitter Developers Team.

ACOT Scheme at N^{3}LO:[17, 18] For the massive DIS calculation, we have implemented the complete ACOT scheme which includes a full treatment of the quark masses; comparison with data show

[5] The latest 7.0 MCFM also has OpenMP code, but the APPLgrid link is not yet working in this version.

[6] The HERA-Fitter open-source PDF project: `http://www.herafitter.org/`

that this yields an improved fit, especially for the longitudinal structure function F_L. Because the leading-order contribution to F_L is small (it vanishes in the limit of zero quark mass), higher-order contributions are particularly important for this measurement. To address this issue, we have used approximation methods to extend the ACOT calculation to N^{3}LO using appropriate rescaling factors to estimate the higher-order massive contributions. These corrections have now been incorporated into the current version of the HERA-Fitter program.

ACOT Package for QCDNUM: Currently, the ACOT implementation in HERA-Fitter uses a K-factor method to speed up the calculation of the higher order contributions; this short-cut works well, but requires multiple iterations to confirm a stable minimum. A new implementation of the ACOT code has been developed in the context of the QCDNUM package using pre-computed integrand tables similar to the APPLgrid and FastNLO algorithms; this is available as a stand-along program. There is a version of this code that plugs into the QCDNUM package in a manner similar to the ZMSTF and HQSTF packages, and we are currently validating this package; this will obviate the need for the K-factor method and yield faster and more accurate calculations. Michiel Botje has been very helpful by providing us code details and some customized "hooks" that allow cross-checks at the subprocess level.

HERA-Fitter analysis of W/Z Production:[8] A recent study of W/Z boson production at the Tevatron highlights the utility of the HERA-Fitter framework. This investigation examined the W-boson charge asymmetry and of the Z-boson production cross sections from D0 and CDF to assess their impact on the proton PDFs. The data is studied using Hessian profiling and Bayesian reweighting to extract significant constraints on the d-valence quark distribution. These techniques provide powerful tools to assess the compatibility of a new data set with a previously determined PDF error set; these capabilities are built into HERA-Fitter, and we plan to use them on other processes including W/Z production at the LHC and the impact on the strange quark PDF. (See following section.)

• W/Z Production at the LHC: *Refs. [1, 2, 4, 16, 20]*

Impact of Strange Quark PDF:[16, 20] At the LHC, W and Z boson production are used as "benchmark" processes to calibrate the decay modes of the newly discovered Higgs boson, and to search for "new physics" signatures. Motivated by questions from members of the ATLAS Standard Model group, we examined the influence of the strange quark PDF on these processes. At the LHC, the strange contribution to the W/Z production processes can be as large as 30%; hence a large uncertainty in the strange quark can degrade the precision of these benchmark measurements. Additionally, we observed that because the u, d-valence quarks yield a different rapidity distribution from the s-quarks, an accurate measurement of the W/Z could constrain the relative mix of valence and sea PDFs. This experimental measurement is particularly useful as it depends only on the shape of the distribution and not the normalization.

The data used for the above ATLAS study is available in a table format compatible with the HERA-Fitter program. Thus, we can now include this new LHC data into our own global analysis, and study the interplay between the strange PDF and the W/Z measurements. Additionally, this work may help resolve some of the outstanding questions related to the neutrino-nucleon DIS data discussed above.

W/Z Production with Proton & Lead Beams: [1, 2, 4] We have computed W/Z production at the LHC for pp, pPb, and $PbPb$ reactions. These measurements can provide improved constraints over a broad x-range for the PDFs. Using our nCTEQ15 PDFs with the FEWZ program we found that the rapidity profile was significantly modified in both the pPb and $PbPb$ cases as compared to the pp case; in particular, the W^+ production channel appeared to have deviations well outside the PDF uncertainty bands. Our next step is to use the HERA-Fitter program with its Bayesian reweighting to better gauge the impact of this result on the PDFs.

• Higher Order Calculations for Heavy Quarks: *Refs. [17, 18, 21, 22]*

We developed the ACOT formalism which allows us to resum the large logarithms involving the heavy quark mass into the PDF using the DGLAP evolution formalism.[77, 116, 117] This was first implemented in the CTEQ framework, and variations of this techniques are now commonly used in other PDF analyses to compute the heavy quark PDFs.

As the standard PDF calculations are moving to higher orders, typically from NLO to NNLO, it was necessary to also extend the ACOT calculation for use in these analyses. We had previously implemented the ACOT scheme at the NLO order, and this included a full and exact treatment of the quark masses. Beyond NLO, the exact massive matrix elements are not available; but we were able to use the massless matrix elements with a massive phase-space factor to estimate the N^{2}LO and N^{3}LO results. While this is an approximation, by comparing the results for $\{$LO, NLO, N^{2}LO, N^{2}LO$\}$ throughout the kinematic range applicable for the experimental data we estimate the uncertainty due to the unknown higher-order contributions is minimal. The results of this analysis were presented in Ref. [22].

This calculation is important for the measurement of the longitudinal structure function F_L; because the Leading-Order (LO) massless contributions to F_L vanish, this quantity is very sensitive to both mass effects ($\sim m^2/Q^2$) and higher-order corrections ($\sim \alpha_s$). Recent advancements on the experimental side, in part, motivated us to increase the precision of our theoretical DIS predictions.

• N_F-dependent PDF's: Merging FFNS and VFNS. *Refs. [12, 15, 21]*

As we move to higher order (NNLO and beyond) we find that both the PDFs and the strong coupling α_S become discontinuous when matching across flavor thresholds. These are not physical thresholds, but artificial thresholds where we choose to transition from a N_F theory to a $N_F + 1$ theory. While these discontinuities decrease order by order as we improve the perturbation theory, these discontinuities can cause difficulties in the PDF analysis—especially if they happen to fall in the middle of a specific data set.

To address these discontinuities, we introduce a hybrid scheme which allows us to effectively merge the Fixed Flavor Number Scheme (FFNS) and the Variable Flavor Number Scheme (VFNS). A key ingredient of this approach is a N_F-dependent PDF, $f(x, \mu, N_F)$ which allows the user the flexibility to choose the effective number of flavors. We have released an example set of PDFs in this scheme. This method resums the heavy quark contributions and provides the freedom to choose the optimal NF for each particular data set. Thus, we can fit selected HERA data in a FFNS framework, while retaining the benefits of the VFNS to analyze LHC data at high scales.

• DGLAP Evolution Tools for Intrinsic Heavy Quarks *Refs. [6, 7]*

We derived a method to generate a matched Intrinsic Charm (IC) or Intrinsic Bottom (IB) distributions for any PDF set *without* the need for a complete global re-analysis. This allows one to easily carry out a consistent analysis including intrinsic heavy quark effects.

The key step was to demonstrate that to a very good approximation the scale-evolution of the intrinsic heavy quark content of the nucleon is governed by non-singlet evolution equations which decouples from the normal DGLAP evolution. Additionally, this means we can freely adjust the normalization of the IC/IB PDFs using this framework.

This method greatly simplifies our ability to estimate the impact of the intrinsic heavy quark effects on the new physics searches. It can also be very useful in searching for and constraining the intrinsic charm and bottom components of the nucleon by itself. In particular in the future facilities such as an

Electron Ion Collider (EIC), the Large Hadron-Electron collider (LHeC), or AFTER@LHC.

• PDF Tools and Software: *Refs. [3]*

To efficiently work with the various PDF projects described above, we have developed a number of tools and packages for examining and manipulating the PDFs and the corresponding theoretical predictions. Some of these tools are potentially useful to others, and as we develop these we post them on the HepForge site.

Working with SMU graduate students Benjamin Clark and Eric Godat we have been developing a Mathematica program that can read and interpolate PDF tables in the standard CTEQ "PDS" table format, as well as the new Les Houches Accord PDF (LHAPDF6) format; this is currently available on the web. Additionally, we are extending this program so it will also be capable of writing (and thus, interchanging) these formats.

We also have a Mathematica add-on package to the above which computes PDF luminosities, correlations, and uncertainties. For combining the individual PDF error sets to evaluate the uncertainty, there are a number of options (add in quadrature, take maximal values, use a Monte Carlo technique), and these are implemented in the PDF error package.

Additionally, under the leadership of postdoc Florian Lyonnet we have designed some Python utilities to manipulate and combine PDF grids. This allows us to covert between PDS and LHAPDF6 format directly (without any interpolation). Furthermore, we are able to construct specific PDF grid tables for nuclei; this is useful for the LHC heavy ion group as they can just swap in a lead PDF table in place of the proton PDF table to generate their cross sections.

• Future Facilities:

It is certainly an exciting time in the field as the LHC Run 2 prepares to extend our kinematic reach by nearly a factor of two; however this will be the last significant increase in energy for a long time. Thus, the key factor will no longer be energy, but precision—both for the energy frontier at the LHC and the Intensity Frontier at Fermilab. There are two future facilities which are on the horizon (hopefully before a Future Circular Collider) that could provide vital new information on the PDFs, and hence on those processes involving hadronic interactions, namely the Large Hadron electron Collider (LHeC) and the Electron Ion Collider (EIC).

I have joined the LHeC Physics Programme Study Group and am serving as Co-Convener of the Parton Distribution Functions (PDFs) working group. This study group is commissioned by the CERN International Advisory Committee to formulate a program for the future colliders. lhec.web.cern

As we move to higher precision, a number of new features enter. For example, if we extend our calculations to NNLO in the strong coupling α_S, these corrections can be comparable to the NLO Electroweak corrections which are proportional to α_{EW}. Note that the electroweak interactions **do not** respect isospin symmetry; this means our simple relations between proton and neutron PDFs are no longer valid. Additionally, the QCD and EW corrections do not simply factorize, so a proper calculation at this order requires a full QCD+EW calculation—this is significantly more complex than even a straight QCD NNLO calculation. These precise measurements, and the corresponding calculations are essential if we are looking for lepton flavor violation, charge symmetry violations, extra dimensions, extra vector bosons, or other new physics signals within high precision measurements.

As part off these studies, we are extrapolating from current calculations to quantify the ability of different machines designs to constrain the PDFs, thereby improving SM predictions and increasing our "resolution" as we search for new physics signals.

• Project Milestones:

The following project milestones have been completed within the recent period.

- The **nCTEQ15** PDFs with errors sets are now computed and available on the web.[1]
- The HERA-Fitter examination of the W/Z production data from the Tevatron explicitly demonstrates the utility of this analysis framework.[8]
- The ACOT calculation has been extended to N^{2}LO and N^{3}LO so we can include heavy quark production processes higher-order PDF analyses.[22]
- The N^{2}LO and N^{3}LO ACOT contributions have been implemented in the HERA-Fitter program (using the $HF\_SCHEME = ACOT$ and $nord = 2, 3$ switches).[9]
- We have extended our previous PDF Mathematica interface to work with both the PDS and LHAPDF6 formats. Additionally, we provide an error PDF package.[3]
- We have a set of Mathematica and Python tools which can generate the intrinsic charm or bottom distributions for any given PDF set **without** need to regenerate the global analysis.[6]

• Project Timetable:

Throughout the research report, we have indicated future research topics and issues; we briefly summarize these below. Items marked "**1**" are being actively studied now, and these projects should yield results within year 1. Items marked "**2**" are projects that would take place late in year 1 or year 2. Items marked "**3**" are projects that may need to wait until year 2 or 3 depending on time-resources and other priorities.

1 Validate the MCFM interface to the nCTEQ program so we have access to the wider range of NLO processes. Additionally, explore options for using the APPLgrid tools to allow for fast NLO calculations.

2 Extend our current work on W/Z production using the reweighting techniques built into HERA-Fitter. Additionally, the ATLAS W/Z data sets are available as a plug-in to HERA-Fitter, so we can easily reproduce and extend this analysis to investigate the impact on the strange quark PDF.

3 Extend the nCTEQ analysis to include the extreme $\{x, Q^2\}$ regions being explored by the CTEQ-CJ analysis.

3 Continue development of the N_F-Dependent PDF framework to automatically handle the discontinuities in the PDFs and α_S and allow for different transition points for separate experimental data sets.

1 Validate the stand-alone ACOT grid program with the QCDNUM ACOT package so this can be released.

2 Continue the development of the PDF Mathematica tools, and provide web updates. Also, if there is an interest for the Python tools, we can test and distribute these also.

3 Use the HERA-Fitter program to assess the N^{2}LO and N^{3}LO ACOT contributions.

Appendix 1: Biographical Sketches

Contents

Pavel Nadolsky

Education and training

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

Research and professional experience

Southern Methodist University	Associate Professor in theoretical physics	06/2013-present
	Assistant Professor	2008-05/2013
Michigan State University	High energy physics	Postdoc
Argonne National Laboratory	High energy physics	Postdoc
Southern Methodist University	High energy physics	Postdoc

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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
- Lecturer, CTEQ summer school on QCD Analysis and Phenomenology, 2007, 2009, 2014
- Convener of working groups, XIII and XXI International Workshops on DIS, QCD @ LHC workshops (2012, 2013)
- Referee for JHEP, Nuclear Physics B, Physics Letters B, and Physical Review D

Potential conflicts of interest

1. **Collaborators and coeditors**

   Richard Ball (Edinburgh), Amanda Cooper-Sarkar (Oxford), Sayip Dulat (Xinxian), Stefano Forte (Milan), Jun Gao (Argonne), Achim Geiser (DESY), Vadim Guzey (JLab), Marco Guzzi (Manchester), Joey Huston (Michigan State University), Hung-Liang Lai (Taiwan), Zhao Li (Peking U.), Katerina Lipka (DESY), Mark Strikman (Penn State University), Jon Pumplin (Michigan State University), Voica Radescu (DESY), Ted Rogers (JLab), Juan Rojo (CERN), Carl Schmidt (Michigan State), Davison Soper (Oregon), Mark Strikman (Penn State University), Daniel Stump (Michigan State University), Robert Thorne (University College, London), C.-P. Yuan (Michigan State University)

2. **Graduate and postdoctoral advisors and advisees**

   Postdocs: Marco Guzzi, 2010-2012, at Univ. of Manchester; **Jun Gao**, 2012-2014, postdoc at ANL; **Tie-Jiun Hou**, postdoc at SMU.

   Graduate students: Major advisor: **Zhihua Liang** (2012), **Bowen Wang** (2015). Committee member: **Renat Ishmukhametov** (2012), **Kamile Dingdar-Yagci** (2012), **Huanzhao Liu** (2015).

3. **Advisory committees**

   None

Fredrick Olness

Education and Training

- Ph.D. Theoretical Particle Physics. **University of Wisconsin**–Madison, 1985.
- M.S. Physics. **University of Wisconsin**–Madison, 1982.
- B.S. Physics. **Duke University,** 1980. Honors Research with Distinction.

Research and Professional Experience

- **Southern Methodist University**, Department of Physics. Assistant Prof. 1991-96; Associate Prof. 1996-2003; Professor 2003-Present; Chair 2001-07, & 2010-15; 2010 Dedman Family Distinguished Professor.
- **CERN**, Theoretical Physics Group: Visiting Scientist 2007 - 2008.
- **Fermilab**, Visiting Scientist, Theoretical Physics Group. Sept. 1997 - Aug. 1998.
- **TNRLC/Superconducting SuperCollider Laboratory**, SSC Fellow 1993-94. Physics Research Group, Guest Scientist. 1991 to 1994.
- **University of Oregon**, Institute of Theoretical Science, Theoretical Particle Physics. Postdoctoral Research Fellow. September 1988 to August 1991.
- **Universität Dortmund**, Institut für Theoretische Physik. Visiting faculty, Apr.-May 1989.
- **Illinois Institute of Technology**, Theoretical Particle Physics Group. Postdoctoral Research Fellow. September 1985 to August 1988.

Selected Publications

1. **nCTEQ15** - Global analysis of nuclear parton distributions with uncertainties in the CTEQ framework. K. Kovarik et al., arXiv:1509.00792 [hep-ph]
2. (ACOT) Leptoproduction of heavy quarks. M. Aivazis, et al., Phys.Rev.D50:3102,1994. *[450+ citations]*
3. Global QCD analysis of parton structure of the nucleon. H.L. Lai, et al., Eur.Phys.J.C12:375,2000. *[1900+ citations]*
4. CTEQ: Handbook of perturbative QCD. R. Brock, et al., Rev.Mod.Phys.67:157,1995. *[350+ citations]*
5. HERAFitter. HERAFitter developers' Team Collaboration: (S. Alekhin et al.) Eur.Phys.J. C75 (2015) 7, 304.
6. QCD analysis of W- and Z-boson production at Tevatron. HERAFitter developers' Team Collaboration (S. Camarda et al.). arXiv:1503.05221.
7. (nCTEQ) Nuclear corrections in neutrino-nucleus DIS and their compatibility with global NPDF analyses. K. Kovarik, et al., Phys.Rev.Lett. 106 (2011) 122301. *[50+ citations]*

8. Heavy Quark Production in the ACOT Scheme at NNLO and N^3LO.
   A. Kusina, et al., Phys.Rev. D85 (2012) 114014

9. Hybrid scheme for heavy flavors: Merging the fixed flavor number scheme and variable flavor number scheme
   A. Kusina, et al., Phys.Rev. D88 (2013) 7,

10. Gluons and the quark sea at high energies: Distributions, polarization, tomography.
    Daniel Boer et al. [arXiv:1108.1713] *A report on the joint BNL/INT/Jlab program on the science case for an Electron-Ion Collider, September 13 to November 19, 2010, Institute for Nuclear Theory, Seattle.* *[250+ citations]*

Synergistic Activities

1. CTEQ Member; Collaboration Co-Spokesperson (2010-2014)
   Summer School organizer (2011-2016).

2. HERA-Fitter Development Team: `www.herafitter.org`

3. Member, LHeC Physics Programme Study Group, Co-Convener: Parton Distribution Functions (PDFs) working group. This study group is commissioned by the CERN International Advisory Committee to formulate a program for the future colliders. `lhec.web.cern.ch`

4. DIS International Advisory Committee (2010-Present)
   Hosted DIS2015 on the SMU campus, April 2015.

5. LHC Theory Initiative Steering Committee (2006-Present);
   Chair, Fellowship Selection Committee (2006-08).

Potential Conflicts of Interest

1. **Collaborators and Co-Editors:**

   O. Behnke (DESY), S. Berge (Aachen), S. Hoeche (SLAC), T. Jezo (Milan), C. Keppel (JLab), K. Kovarik (Muenster), A. Kusina (Grenoble), J.G. Morfin (Fermilab), P. Nadolsky (SMU), J.F. Owens (FSU), V. Radescu (DESY), I. Schienbein (LPSC), D. Soper (Oregon), T. Stavreva (Grrenoble), J.Y. Yu (Grenoble), C.P. Yuan (MSU)

2. **Graduate and Postdoctoral Advisors and Advisees:**

   Postdocs: Stefan Berge (2003-2006) lecturer at RWTH Aachen U; **Ingo Schienbein** (2005-2006) now faculty at LPSC and Universite Joseph Fourier in Grenoble; **Ji Young Yu** (2006-2009) now researcher at LPSC; **Zack Sullivan** (2007-2008) now faculty at Illinois Institute of Technology; **Kwangwoo Park** (2008-2011) now lecturer at Yonsei University, Korea; **Aleksander Kusina** (2011-2014) now postdoc at University of Grenoble; **Florian Lyonnet** (2014-Present).

   Graduate Students: Major Advisor: **Benjamin Clark** (2011-Present); **Eric Godat** (2013-Present); Committee Member: **Bowen Wang** (2009-Present), **Zhihua Liang** (2006-2012); *(Previous Advisees listed on my full CV, available online.)*

3. **Advisory Committees:**:

   None.

Appendix 4: Bibliography and References Cited

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Theoretical Physics

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Appendix 5: Facilities and Other Resources

Not applicable

Appendix 6: Equipment

Not applicable.

Appendix 8: Data Management Plan

Contents

Data Management Plan for the Theory Program

SMU Theory Data Preservation Policy

The principal intent of this document is to describe the SMU Theory policy ensuring that its data are maintained reliably in a form accessible to the HEP community.

We are committed to preserving the final results of our analyses and computations so that they can be reprocessed and reanalysed for future studies.

The Repositories

There are two primary long-term repositories where this work is stored.

- Hepforge: `https://www.hepforge.org/`
  HepForge is a development environment for any sort of academic software projects related to high-energy physics. The site hosts a variety of ready-made, easy-to-use set of Web based tools. This provides a long-term repository for a variety of tools and programs.

- LHAPDF `https://lhapdf.hepforge.org/`
  The LHAPDF project collects PDF sets from different collaborations in a common format which can then be accessed by a standard set of routines. This project is maintained by the Durham IPPP and hosted on Hepforge. This provides a long-term repository for our PDF table files.

- `http://hep.pa.msu.edu/cteq/public/index.html`
  Public repository of CTEQ PDFs and related computer programs

The PDF sets and programs.

One of the primary outputs of the SMU group is the PDF data tables such as CT14 and nCTEQ15. These are submitted to the LHAPDF project. where they are stored in a common format. Any user with access to the web can download and use these PDF data tables using the LHAPDF tools.

In addition to the PDF parametrizations, we distribute auxiliary programs and tools for HEP computations via the Hepforge website. On this website, we keep public versions of the program MEKS for computation of jet production cross sections, C++/Mathematica/Fortran package MP4LHC for the meta-analysis of PDFs, and sample Fortran programs to read the PDF data files and perform simple calculations, such as computations of basic structure functions. Additionally, we have developed a Mathematica module that reads PDF data files (both in the LHAPDF and propriertary CTEQ formats) and gives the user full access for the analysis of PDFs within the Mathematica framework; these are available on Hepforge within the nCTEQ project space.

We will continue to use these long-term repositories to archive and distribute these tools and data sets.

Appendix 9: Other Attachments

Not applicable.