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Studies of QCD structure in high-energy collisions

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Contents

1 Executive summary

"Studies of QCD structure in high-energy collisions" is a research project in theoretical particle physics at Southern Methodist University funded by US DOE Award DE-SC0013681. The award furnished bridge funding for one year (2015/04/15-2016/03/31) between the periods funded by Nadolsky's DOE Early Career Research Award DE-SC0003870 (in 2010-2015) and a DOE grant DE-SC0010129 for SMU Department of Physics (starting in April 2016). The primary objective of the research is to provide theoretical predictions for Run-2 of the CERN Large Hadron Collider (LHC). The LHC physics program relies on state-of-the-art predictions in the field of quantum chromodynamics. The main effort of our group went into the global analysis of parton distribution functions (PDFs) employed by the bulk of LHC computations. Parton distributions describe internal structure of protons during ultrarelivistic collisions. A new generation of CTEQ parton distribution functions (PDFs), CT14, was released in summer 2015 and quickly adopted by the HEP community. The new CT14 parametrizations of PDFs were obtained using benchmarked NNLO calculations and latest data from LHC and Tevatron experiments. The group developed advanced methods for the PDF analysis and estimation of uncertainties in LHC predictions associated with the PDFs. We invented and refined a new 'meta-parametrization' technique that streamlines usage of PDFs in Higgs boson production and other numerous LHC processes, by combining PDFs from various groups using multivariate stochastic sampling. In 2015, the PDF4LHC working group recommended to LHC experimental collaborations to use 'meta-parametrizations' as a standard technique for computing PDF uncertainties. Finally, to include new QCD processes into the global fits, our group worked on several (N)NNLO calculations.

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) [3, 14, 15, 19, 21–30]. 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, CT10, and CT14 [7, 14, 19, 23, 24], consistently receive highest numbers of citations in the INSPIRE-HEP database [43]. The proposal for the current award stated the following goals: release of CT14 NNLO PDFs with LHC data; advanced applications of the meta-analysis technique [20] for combination of PDF ensembles; development of fast computations for PDF analyses based on FastNLO [51, 53] and ApplGrid [52] modules; implementation of NNLO heavy-quark DIS cross sections based on the S-ACOT-χ mass scheme [16] in the HERA Fitter program [50]; implementation in the CTEQ fitting package of N^{3}LO QCD radiative contributions to NC DIS cross sections with massive quarks in the intermediate mass factorization scheme [29]. All these goals have been achieved, the results have been documented in 4 journal papers [1–4], 8 preprints and conference contributions [5–12], and one Ph. D. thesis [13]. Below we summarize key outcomes of each research direction.

Global analysis of parton distributions

Our group leads a number of efforts aimed at development of advanced of next-to-next-to-leading order (NNLO) CTEQ parton distribution functions for general-purpose applications in high-energy

hadron scattering. Since 2010, CTEQ-TEA (Tung Et Al.) 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.

CT14 parton distributions. A new NNLO analysis, designated as **CT14** [3], was released in summer 2015 and accumulated more than 130 citations within a year. For the first time, we included 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. 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. Substantial work at SMU went into implementation of new collider experimental data, such as the combined DIS cross sections from H1 and ZEUS collaborations [44], Tevatron lepton charge asymmetry [31, 45, 46], and single-inclusive jet cross sections [40, 47]. We also invested significant effort into benchmark tests 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. In particular, the global PDF ensembles of the new generation, CT14, MMHT'2014, and NNPDF3.0, agree much better on predicted Higgs production cross sections at NNLO than the previous generation (CT10, MSTW'08, NNPDF2.3), as a result of improved procedures and new experimental constraints.

Constraints on PDFs from new experiments at the LHC and HERA. We participated in a study to identify new LHC measurements that may help constrain the PDFs in a wide kinematical range [2]. One of these measurements, of production of heavy quarks in forward regions at the LHCb, has potential to impose unique constraints on the gluon PDF at small momentum fractions. This was demonstrated in a recent paper [4] by PROSA collaboration, with **Nadolsky** as one of co-authors. Meanwhile, the H1 and ZEUS collaborations released a comprehensive data set from HERA-1 and HERA-2 measurements on neutral-current and charge-current deep inelastic scattering [48]. These data are the most extensive among all fitted experiments. It appears to indicate some discrepancies with the combined HERA-1 data set [44] used in CT14 and the earlier global analyses. To explore the impact of the legacy HERA1+2 data, we included them into an updated version of the CT14 fit that is to be released on a short time scale [11]. The HERA1+2 data probe QCD factorization across a wide kinematic region, with unprecedented precision. The study is lead by the SMU postdoc Tie-Jiun **Hou**.

CT14 replica distributions. Ensembles of error PDF sets are constructed in two common formats, based on the Hessian [38] and Monte-Carlo replica [32–34, 42] techniques. The CTEQ-TEA PDF ensembles are usually given in the Hessian format. In Ref. [12], we developed an advanced method for conversion of Hessian PDFs into the Monte-Carlo format. It generalizes previously available results [20, 41] and, contrary to the other techniques, generates MC replicas that reproduce asymmetry in the Hessian PDF errors and lead to positive-definite PDFs and cross sections. In this study we developed a C++ code MCGEN [49] to generate Monte-Carlo replicas according to several probability distributions. A user can run this code to convert Hessian PDFs for such purposes as combination of PDF ensembles or PDF reweighting.

DIS module for xFitter. The SMU group contributes to a fitting program xFITTER (formerly HERA FITTER) [50]. xFITTER 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. In early 2016, the module for the computation of (N)NNLO DIS cross sections in the S-ACOT-χ heavy-quark scheme [16] has been ported into xFITTER by the SMU postdoc T.-J. **Hou** and Dr. Marco **Guzzi** from the University of Manchester. Now outside users can use the NNLO DIS cross sections in the S-ACOT-χ scheme in

such applications as the HERAPDF fits. The implementation increases interoperability of xFitter and CTEQ-TEA global analysis platform.

Massive-quark contributions to NNLO deep inelastic scattering

In 2010-2012, SMU collaborators **Guzzi** and **Nadolsky** computed DIS hard-scattering coefficient functions with up to two QCD loops, and including full dependence on masses of heavy quarks [16–18]. As a follow-up advancement, the SMU graduate student **Bowen Wang** computed in 2015 approximate N^3LO QCD radiative contributions to NC DIS cross sections with massive quarks in the intermediate mass factorization scheme [29]. 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 the flavors of quark propagators and developed a skeleton framework for implementing three-loop massive coefficient functions in the S-ACOT-χ scheme. At this QCD order, new topologies of Feynman diagrams arise that need to be classified according to their flavor composition [39]. This classification is applicable in all heavy-quark schemes. Bowen documented the calculation in his Ph. D. thesis [13]. His results were cross checked by **Xie**, our student, and a journal paper is now in preparation with full details. [9].

Meta-analysis of PDFs and combination of PDF ensembles

A question is often raised about the proper method for estimating uncertainties due to the PDFs, when predictions based on various PDF ensembles are not identical. In 2013 we proposed a solution that employs "meta-parametrizations" of PDFs **[20].** In many cases it can replace hundreds of input PDF error sets by only 10-30, and yet reproduce the full uncertainty predicted by the original sets. In 2015, the PDF4LHC working group recommended [1] to use the meta-analysis as one of three standard methods for combination of PDF uncertainties. The 30-member PDF4LHC-2015 ensemble was released last year and utilizes the META technology to include the same information as the combination of CT14, MMHT'2014, and NNPDF'3.0, while having much fewer member sets. This ensemble is sufficient for the majority of LHC applications. We co-authored a PDF4LHC recommendation document [1], in which various existing PDF ensembles were compared, and techniques for combination of PDF uncertainties were summarized. As a follow-up, we wrote a contribution to the Standard Model Working Group report of the 2015 Les Houches workshop "Physics at TeV Colliders" [5, page 13], which documented technical details for the construction of the 30-member PDF4LHC15 ensemble and compared predictions for benchmark LHC cross sections based on the PDF4LHC15 ensembles.

This work builds up on a series of our papers that developed new statistical techniques for quantifying various sources of PDF uncertainties. As mentioned above, for practical applications, it is necessary to come up with convenient methods for propagating the PDF uncertainty into QCD cross sections. We developed tools for converting the Hessian representation for CT error PDFs [38] into the Monte-Carlo representation [32–34, 42], and back [20]. The two representations have complementary strengths, their development enabled combination of Hessian (CT, MMHT) and Monte-Carlo (NNPDF) ensembles in the form recommended by the 2015 PDF4LHC document.

Transverse momentum resummation at NNLO

In winter 2016, Nadolsky and Xie computed resummed NNLL/NLO predictions for background QCD production of $\gamma\gamma$ pairs in the mass region relevant to search for the 750 GeV candidate resonance [10]. This work has updated an earlier prediction from ResBos for $\gamma\gamma$ production [35–37]

in an extended kinematic region accessible at the LHC. We also include contributions from $\gamma\gamma$ radiation off top quark pairs, not been considered in the earlier work. This calculation provides latest resummed predictions for the QCD background in Higgs boson production and searches for heavy resonances in the essential diphoton decay channel.

3 Participating SMU personnel

- The PI **Pavel Nadolsky** (CV is attached) works on computations of radiative contributions in quantum chromodynamics, multi-variate statistical analysis of experimental data probing internal structure of nucleons, and determination of CTEQ-TEA parton distributions.

- **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.

- **Bo Ting Wang, Bowen Wang, and Keping Xie** are graduate students in our theoretical physics group, partly supported by the DOE grant and SMU Department of Physics. **Bowen Wang** defended his Ph. D. in August 2015 and is currently a postdoc at Jefferson Laboratory. His thesis developed a framework to classify 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. **Xie** made essential contributions to a transverse momentum calculation for $\gamma\gamma$ production, a journal paper on N3LO heavy-quark contributions to DIS, and phenomenological predictions based on PDF4LHC15 and CT14MC PDFs. **Bo Ting Wang** joined the theory group in Winter 2016 and works on the PDF analysis.

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 to participate in collaborative efforts with theorists and experimentalists. Travel to these occasions was paid from the DOE award and SMU funds.

During the award period, **Nadolsky** gave invited seminars at LAL Orsay (France), Universities of Oxford and Manchester (UK); an invited talk at the RadCor/LoopFest symposium (UCLA); 9 remote video presentations to the PDF4LHC working group, 2015 Les Houches workshop "Physics at TeV Colliders", CMS Top/Electroweak working group, and CMS PDF forum. **Nadolsky** was a member of the Local Organizing Committee of the 23rd International workshop on Deep Inelastic Scattering and Related Subjects (DIS'2015) in Dallas, TX in April 2015. He was an instructor at the CTEQ summer school in Pittsburgh in July 2015 and attended the MHV@30 workshop at Fermilab in March 2016. In November 2015 **Nadolsky** was elected a theory co-spokesperson of CTEQ collaboration. In 2015, **Nadolsky** was also a co-convener of the Integrated Physics Analysis working package of the Proton Structure Analyses in Hadronic Collisions (PROSA) collaboration.

Hou gave a seminar at Michigan State University and an invited talk about the PDFs at the APS DPF meeting in Ann Arbor in August 2015. **Xie** gave a talk about N3LO DIS corrections at the meeting of the APS Texas session in Fall 2015 (supported by the SMU physics department). **Xie** attended the MHV@30 workshop at Fermilab in March 2016.

5 SMU publications in 2015-2016

In this section, we report recent publications of our group supported by the DOE award.

[1] J. Butterworth et al., *PDF4LHC recommendations for LHC Run II*, *J. Phys.* **G43** (2016) 023001, [arXiv:1510.0386].

[2] J. Rojo et al., *The PDF4LHC report on PDFs and LHC data: Results from Run I and preparation for Run II*, *J. Phys.* **G42** (2015) 103103, [arXiv:1507.0055].

[3] S. Dulat, T.-J. Hou, J. Gao, M. Guzzi, J. Huston, P. Nadolsky, J. Pumplin, C. Schmidt, D. Stump, and C.-P. Yuan, *New parton distribution functions from a global analysis of quantum chromodynamics*, *Phys. Rev.* **D93** (2016) 033006, [arXiv:1506.0744].

[4] **PROSA** Collaboration, O. Zenaiev et al., *Impact of heavy-flavour production cross sections measured by the LHCb experiment on parton distribution functions at low x*, *Eur. Phys. J.* **C75** (2015) 396, [arXiv:1503.0458].

[5] J. R. Andersen et al., *Les Houches 2015: Physics at TeV Colliders Standard Model Working Group Report*, in *9th Les Houches Workshop on Physics at TeV Colliders (PhysTeV 2015) Les Houches, France, June 1, 2015*. arXiv:1605.0469.

[6] F. I. Olness, R. Kehoe, and P. Nadolsky, *Report on the DIS2015 International Workshop*, *PoS* **DIS2015** (2016) 018.

[7] S. Dulat, T.-J. Hou, J. Gao, M. Guzzi, J. W. Huston, P. Nadolsky, J. Pumplin, C. R. Schmidt, D. Stump, and C.-P. Yuan, *Progress in CT PDF Analysis*, *PoS* **DIS2015** (2015) 059.

[8] T.-J. Hou, S. Dulat, J. Gao, M. Guzzi, J. W. Huston, P. Nadolsky, J. Pumplin, C. R. Schmidt, D. Stump, and C.-P. Yuan, *Heavy Flavors in CT14*, *PoS* **DIS2015** (2015) 166.

[9] P. Nadolsky, B. Wang, and K. P. Xie, "*Heavy-quark mass treatment for deep inelastic scattering at N3LO level*." Preprint SMU-HEP-16-01.

[10] P. Nadolsky and K. P. Xie, "*Resummed background for heavy diphoton resonances*." Preprint SMU-HEP-16-08.

[11] T.-J. Hou, S. Dulat, J. Gao, M. Guzzi, J. Huston, P. Nadolsky, J. Pumplin, C. Schmidt, D. Stump, and C.-P. Yuan, "*CTEQ-TEA PDFs and HERA I+II Combined Data*." Preprint SMU-HEP-16-07.

[12] P. Nadolsky, S. Dulat, J. Gao, M. Guzzi, T.-J. Hou, J. Huston, P. Nadolsky, J. Pumplin, C. Schmidt, D. Stump, B. T. Wang, K. P. Xie, and C.-P. Yuan, "*Reconstruction of Monte Carlo replicas from Hessian parton distributions*." Preprint SMU-HEP-16-06.

[13] B. Wang, *Applications of QCD factorization in multi-scale hadronic scattering*. PhD thesis, Southern Methodist University, 2015. Full text at http://www.physics.smu.edu/web/research/preprints/SMU-HEP-15-14.pdf.

6 Other publications

[14] 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.

[15] 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.

[16] 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].

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

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

[19] J. Gao, M. Guzzi, J. Huston, H.-L. Lai, Z. Li, P. Nadolsky, J. Pumplin, D. Stump, and C.-P. Yuan, *CT10 next-to-next-to-leading order global analysis of QCD*, *Phys. Rev.* **D89** (2014) 033009, [arXiv:1302.6246].

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

[21] 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) 113002, [arXiv:1310.7601].

[22] 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) 073004, [arXiv:1309.0025].

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

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

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

[26] 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.

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

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

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

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

[31] **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.

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

[33] 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.

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

[35] 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.

[36] 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.

[37] 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.

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

[39] S. Moch, J. A. M. Vermaseren, and A. Vogt, *The three-loop splitting functions in QCD: the non-singlet case*, *Nucl. Phys.* **B688** (2004) 101.

[40] **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.

[41] 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`].

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

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

[44] **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`].

[45] **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`].

[46] **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*, *Phys. Rev. Lett.* **101** (2008) 211801, [arXiv:0807.3367].

[47] **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].

[48] **ZEUS, H1** Collaboration, H. Abramowicz et al., *Combination of Measurements of Inclusive Deep Inelastic $e^{\pm}p$ Scattering Cross Sections and QCD Analysis of HERA Data*, arXiv:1506.0604.

[49] http://metapdf.hepforge.org/mcgen/.

[50] https://wiki-zeuthen.desy.de/xFitter/.

[51] T. Kluge, K. Rabbertz, and M. Wobisch, *FastNLO: Fast pQCD calculations for PDF fits*, in *Deep inelastic scattering. Proceedings, 14th International Workshop, DIS 2006, Tsukuba, Japan, April 20-24, 2006*, p. 483, 2006. hep-ph/0609285.

[52] T. Carli, D. Clements, A. Cooper-Sarkar, C. Gwenlan, G. P. Salam, F. Siegert, P. Starovoitov, and M. Sutton, *A posteriori inclusion of parton density functions in NLO QCD final-state calculations at hadron colliders: The APPLGRID Project*, *Eur. Phys. J.* **C66** (2010) 503, [arXiv:0911.2985].

[53] http://fastnlo.hepforge.org/.

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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.	Research in High-Energy Physics at SMU	US Dept. of Energy	DE-SC0010129	04/2016-present
2.	Studies of QCD structure...	US Dept. of Energy	DE-SC0013681	04/2015-03/2016
3.	Early Career Research Award	US Dept. of Energy	DE-SC0003870	04/2010-04/2015
4.	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, SC0010129
2.	Jun Gao	09/2011-09/2014	ECRA
3.	Marco Guzzi	09/2009-08/2012	ECRA

Graduate students

	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

- Co-spokesperson, 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
- Local organizing committee, XXIII Workshop on Deep Inelastic Scattering and related subjects, SMU, Dallas, April 2015
- Referee for Annals of Physics, JHEP, Nuclear Physics B, Physics Letters B, and Physical Review D

Curriculum Vitae

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Education

2003–2010	Ph.D	National Tsing Hua University, Taiwan. Advisor: Kingman Cheung. Thesis topic: *The Higgs Sector of NMSSM with CP Violation*
2000–2003	M.S.	National Central University, Taiwan. Advisor: Hsiang-Kuang Tseng. Thesis topic: *The Polarization Correlations in Atomic Field Bremsstrahlung at High Frequency Limit.*
1996–2000	B.S.	National Central University. Taiwan.

Experience

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

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].