Schlussbericht

Förderinstrument:	**Sondermaßnahmen**
Impulsfonds-Förderkennzeichen	HGF-SO-072
Projekttitel	Determination of the proton structure using deep inelastic scattering and proton-proton collisions
Federführende/r Wissenschaftler/in	Dr. Katerina Lipka
Federführendes Helmholtz-Zentrum	DESY Hamburg
Weitere beteiligte Helmholtz-Zentren	
Beteiligte Universitäten u. andere Partner	
Berichtszeitraum (Förderungszeitraum)	01/2011 - 12/2014

1) Zusammenfassung (max. 1 DIN A4-Seite)

Allgemeinverständliche Darstellung der wesentlichen Ergebnisse und der erzielten Fortschritte gegenüber dem Stand des Wissens zum Zeitpunkt der Antragstellung. Ausblick auf künftige Arbeiten und Beschreibung möglicher Anwendungen.

Understanding of the matter structure is the fundamental task of particle physics. The mass of the proton and therefore of the baryonic matter in the universe is ascribed to the strong force, carried by massless gluons, acting between the quarks, the fundamental constituents of nucleons. The underlying theory of the strong force, Quantum Chromodynamics (QCD), describes the interactions of the quarks and the gluons. In QCD, the proton structure is represented by Parton Distribution Functions (PDFs), the probabilities to find a parton (a quark or a gluon) in the proton, carrying a fraction x of the proton momentum at an energy scale Q. These PDFs are the input for theoretical descriptions of processes occurring in proton-induced interactions. Precision of the PDFs is crucial for predictions for atmospheric showers, used e.g. for dark matter searches or for all the processes in proton-proton collisions at the LHC, in particular for searches for new particles produced with large masses or high momenta. While the scale dependence of the PDFs is predicted by the theory, the x-dependence can't be calculated and has to be determined experimentally. By the beginning of the project, state-of-the art precision of PDFs was not essential for precise predictions of the Standard Model (SM) processes at the LHC and was the limiting factor for the discovery potential of the LHC measurements.

The main idea of the project SO-072 was to use different semi-inclusive measurements at the LHC for improvement of the understanding of the PDFs and decreasing their uncertainty. The measurements of charge asymmetry in W-boson production at CMS experiment were used to improve precision of the valence-quark distribution at medium x range. Further, the associated production of W-boson and charm quarks at the LHC was used to determine the content of strange quark in the proton, which is of particular importance for precision of W-boson mass measurement. Charm-, beauty- and top- quark-pair production at the LHC was used to improve the constraints on the gluon distribution at low x, important for predictions for neutrino physics, and at high x, crucial for searches for new physics at the LHC. Using the associated W+c and heavy quark-pair production at the LHC for the purpose of PDF determination is novel and have never considered before. For including these data in the QCD analysis, necessary theory calculations were performed and fast computing codes were developed. As the result of the project, precision of the PDFs in the wide x range is significantly improved. All targeted milestones of the project are successfully achieved and published. The developed analysis tools are available as open-source programs. Results of the project opened the window for further high-precision QCD analyses of the proton structure in the next decades, in particular enhancing discovery potential of the LHC.

2) Arbeits- und Ergebnisbericht

Ausgangslage*:*
The aim of the project was to improve the precision of the quark and gluon distributions in the proton, in particularly in the ranges of the momentum fraction x of the proton, carried by the gluon or the quark, not probed by the data of the HERA accelerator with essential precision. The idea of the project was that the precise measurements of the electroweak boson- and heavy quarks at the LHC should provide necessary constraints. For verification of this hypothesis, precise measurements of electroweak-boson and top quark-pair production at the LHC were performed. Further, novel theory computations and the fast computing programs for the QCD analysis were developed. Due to strong and manifold correlations of the PDFs with fundamental parameters of the Standard Model like masses of heavy quarks and electroweak bosons and the strong coupling constant, as well as peculiarities in the phenomenological description of production of heavy quarks and electroweak bosons in proton-induced collisions, many experimental and theory aspects of QCD had to be addressed, making up the full consistent picture of the understanding of the proton structure. The details of each addressed issue of importance for the project are described in the following.

b) **Darstellung der erzielten Ergebnisse:**
b.1. Improvement of light-quark distributions and flavour decomposition

b.1.1. A QCD analysis of ATLAS measurements of inclusive W and Z boson production in proton collisions at the LHC, jointly with Deep Inelastic Scattering (DIS) data from HERA, was performed. Such, sensitivity of LHC measurements of electroweak boson production to the light quark sea composition at x ~ 0.01 is tested. T**he result supported the hypothesis of a symmetric composition of the light quark sea at low x.**
Published in G. Aad et al. [ATLAS Collaboration] Phys.Rev.Lett. 109 (2012) 012001.

b.1.2*.* Measurements of the muon charge asymmetry in inclusive W-boson production in proton collisions at the LHC at 7 TeV and 8 TeV were performed. The data samples correspond to an integrated luminosity of 4.7 and 18.7 inverse femtobarn, respectively, recorded with the CMS detector. **These are the most precise data** providing additional constraints on the parton distribution functions of the proton in the kinematic range of $10^{-3}<x<10^{-1}$. These measurements and the recent CMS measurement of associated W + charm production at 7 TeV are used together with the cross sections for DIS scattering at HERA in a next-to-leading-order (NLO) QCD analysis**. The determination of the valence quark distributions is significantly improved, and the strange-quark distribution is probed for the first time directly through the leading-order process g + s → W + c in proton-proton collisions at the LHC.**
Published in S. Chatrchyan et al. [CMS Collaboration], Phys. Rew. D 90 (2014) 032004.

b.1.3*.* For the first time, a joined QCD analysis of neutrino scattering and of the proton-proton collision data was performed. **Determination of the strange sea distribution in the nucleon was improved** through constraints from the recent charm-quark production in neutrino-nucleon deep-inelastic scattering measured by the NOMAD and CHORUS experiments and from the charged current inclusive DIS at HERA. The results were demonstrated to be consistent with those obtained by using ATLAS and the CMS measurements of associated W+charm production. **Also, the consistency between ATLAS and CMS measurements was shown.**
Published in S. Alekhin et al., Phys. Rew. D. 91, 094002 (2015), arXiv:1404.6469

b.1.4 Differential cross section for the Drell-Yan process $Z/\gamma* \rightarrow ll$ as a function of the invariant mass of the two leptons was measured in proton collisions at the LHC at 7 TeV using the ATLAS detector. The measurement was performed in electron and muon channels for invariant masses between 26 GeV and 66 GeV using an integrated luminosity of 1.6 fb^{-1} and the measurements are combined. The analysis was extended to invariant masses as low as 12 GeV in the muon channel using earlier data. The cross sections are determined within

acceptance region of the detector and corrections to the full kinematic range are provided. **These measurements provide significant input for the determination of the light-quark densities in the proton.**
Published in G. Aad et al [ATLAS Collaboration], JHEP 1406 (2014) 112.

b.2. Determination of the top-quark mass, W-boson mass and of the strong coupling constant

b.2.1. The strong coupling constant was determined using ATLAS measurements of inclusive jet production in proton collisions at the LHC at 7 TeV. Several procedures for combining the statistical information from the different measurements were studied and compared. The theoretical prediction was obtained using NLO QCD, and included non-perturbative corrections. Good agreement was observed when comparing the result with the world average at the Z-boson scale, as well as with the most recent results from the Tevatron. **This was the first determination of the strong coupling constant using LHC measurements.**
Published in B. Malaescu, P. Starovoitov, Eur.Phys.J. C72 (2012) 2041.

b.2.2. **The correlation of strong coupling constant, gluon PDF and top quark mass was studied for the first time using top-quark pair production at the LHC.** Inclusive cross section for top-quark pair production measured by the CMS experiment in proton collisions at 7 TeV was confronted to the QCD prediction at next-to-next-to-leading order (NNLO) with various PDFs to determine the top-quark pole mass, or the strong coupling constant. With the PDF set NNPDF2.3, a pole mass of 176.7 +3.0 -2.8 GeV was obtained when constraining the strong coupling constant at the scale of the Z boson mass to the current world average. Alternatively, by constraining top-quark mass to the latest average from direct mass measurements, a value of strong coupling at a Z-boson mass of 0.1151 +0.0028 -0.0027 is extracted. **This was the first determination of strong coupling constant using events from top-quark production and represents the most precise measurement at a hadron collider.**
Published in S. Chatrchyan et al. [CMS Collaboration], Phys. Lett. B 728 (2013) 496.

b.2.3. **The precision of the top-quark pole mass measurement is further improved by exploring top-quark decay properties.** The distribution of the invariant mass, m_{lb}, of the lepton and the b-quark originating from top-quark decays was investigated. The analysed data set was recorded at the CMS experiment at the LHC in proton-proton collisions at a center-of-mass energy of 8 TeV, and corresponds to a luminosity of 19.7 fb^{-1}. A high-purity top-quark pair event sample with one electron, one muon and two jets was selected. The observed invariant mass distribution is confronted to theory predictions using a Monte Carlo simulation and a fixed-order calculation at leading and next-to-leading-order QCD. A top-quark mass of 172.3±1.3 GeV is obtained. **This result is the most precise determination of the pole mass of the top quark to date.**
Published in [CMS Collaboration], CMS-PAS-TOP-14-014.

b.2.4. The measurement of the mass of the W boson at the LHC requires control of both theoretical and experimental uncertainties. The extraction of the W-boson mass from the transverse momentum spectrum of electrons and muons produced in the leptonic decay of the W boson is limited by theoretical uncertainties. **Uncertainties arising from the incomplete knowledge of the PDFs and from the modeling of the low transverse momentum of the W boson were estimated**, accounting for the resolution effects of the ATLAS detector. Emphasis was given to the study of the physical origin of the uncertainties, so as to providing useful information for reduction of the uncertainties in the future.
Published in [ATLAS Collaboration], ATL-PHYS-PUB-2014-015.

b.3. Phenomenology of the Nucleon Structure and global QCD analysis

b.3.1. Nuclear modifications of parton distributions are analyzed, notably, the nuclear

shadowing and antishadowing corrections, in production of lepton pairs from decays of neutral electroweak bosons in proton-lead and lead-collisions at the LHC. Using the Collins-Soper-Sterman resummation formalism that was extended to the case of nuclear parton distributions, 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 is observed. **This makes Drell-Yan pair production in pA and AA collisions at the LHC a useful tool for constraining nuclear PDFs in the small-x shadowing and moderate-x antishadowing regions.**
Published in M. Guzzi et al, Eur. Phys. J. A49 (2013) 35.

b.3.2. PDFs were determined at next-to-next-to-leading order (NNLO) in the framework of the CTEQ-TEA group. The CT10NNLO PDF fit was based on the global data sets used in the CT10 and CT10W NLO PDF analyses. After exploring the goodness of the fits to the HERA combined data and the Tevatron jet data, various predictions at NNLO accuracy for both existing and forthcoming precision measurements from the LHC were provided. The range of variations in the gluon distribution introduced by correlated systematic effects in inclusive jet production was also examined. **The resulting CT10 PDF set is currently the basic input in the most Monte-Carlo simulations of the detector effects, used in all analyses the LHC experiments.**
Published in J. Gao, M. Guzzi et al, Phys. Rev. D 89, 033009 (2014).

b.3.3. Nonperturbative contributions to the transverse momentum distribution of Z/γ^* bosons produced at hadron colliders were analyzed. The new TEVATRON measurements the angular distribution $\phi^*\eta$ of Drell-Yan pairs were shown to be in excellent agreement with a perturbative QCD prediction, based on the Collins-Soper-Sterman (CSS) resummation formalism at next-to-next-to leading log (NNLL) accuracy. Using these data, **the nonperturbative component of the CSS resummed cross section was determined and its dependence on arbitrary resummation scales and other factors was estimated**. With the scale dependence included at the NNLL level, a significant nonperturbative component is needed to describe the angular distribution.
Published in M. Guzzi, P. M. Nadolsky, B. Wang, Phys. Rev. D 90, 014030 (2014).

b.3.4. *Sets of PDFs of the proton are provided for the leading (LO), next-to-leading (NLO) and next-to-next-to leading order (NNLO) QCD calculations. The PDFs were determined with the HERAFitter program using the data from the HERA experiments and preserving correlations between uncertainties for the LO, NLO and NNLO PDF sets. These PDF sets were used to study cross-section ratios and their uncertainties when calculated at different orders in QCD.* ***A reduction of the overall theoretical uncertainty was observed if correlations between the PDF sets are taken into account*** *for the ratio of WW di-boson to Z-boson production cross sections at the LHC.*
Published in P. Belov et al. [HERAFitter Collaboration], Eur. Phys. J. C74, 10, 3039 (2014).

b.4. Phenomenology of the Heavy Quark Production in the context of PDF determination

b.4.1. The effect of the charm quark mass in the global QCD analyses were studied. Constraints on the MS-bar running mass of the charm quark are examined at the NLO and NNLO in the Fixed-Flavor-Number scheme and S-ACOT-χ factorization scheme. **The values of the charm quark mass from the hadronic scattering data in the CT10 NNLO fit, including semi-inclusive charm production in DIS at HERA collider, are determined.**
Published in S. Alekhin, K. Daum, K. Lipka, S. Moch, Phys. Lett. B 718 (2012) 550;
S. Alekhin, J. Bluemlein, K. Daum, K. Lipka, S. Moch, Phys.Lett. B 720 (2013) 172-176;
J. Gao, M. Guzzi, P. Nadolsky, Eur. Phys. J. C73 (2013) 2541.

b.4.2. **Detailed phenomenological studies of top-quark pair production in proton-proton collisions were performed for the first time.** Differential cross sections are calculated in perturbative QCD at approximate NNLO by using methods of threshold resummation beyond

the leading logarithmic accuracy. Predictions for the single-particle inclusive kinematics were provided for transverse momentum and rapidity distributions of final-state top quarks**. For the first time, uncertainties related to the description of proton structure, top-quark mass and strong coupling constant are investigated in detail.** The results are compared to the available measurements at the LHC. The calculation is implemented in the computer code Difftop and can be applied to the general case of heavy-quark pair production at hadron-hadron colliders. For the first time, the PDF fit at NNLO is performed by using the differential cross sections of top-quark pair production together with other data sets. **The impact of the top-pair production on the precision of the gluon distribution at high scales is expressed by significant change of the gluon distribution at high x, and reduction of the gluon PDF uncertainty.** This result is of particular importance for the searches for new particles, produced with high mass or high transverse momenta.
Published in M. Guzzi, K. Lipka, S.-O. Moch, DESY-14-077, JHEP 1501 (2015) 082.

b.4.3. The impact of recent measurements of heavy-flavour production in deep inelastic electron-proton scattering and in proton collisions on PDFs is studied in a QCD analysis in the fixed-flavour number scheme at NLO. Differential cross sections of charm- and beauty-hadron production measured by LHCb experiment at the LHC are used together with inclusive and heavy-flavour production cross sections in DIS at HERA. The heavy-flavour data of the LHCb experiment impose additional constraints on the gluon and the sea-quark distributions at low x down to 5 x 10^{-6}. This kinematic range is currently not covered by other experimental data in perturbative QCD fits**. As a result, the uncertainty on the gluon distribution at low x is reduced by a factor of 3. This result is of particular importance for calculation of atmospheric neutrino showers.**
Published in O. Zenaiev et al. [PROSA Collaboration], [arXiv:1503.04581], in review by EPJC.

b.5. Development of phenomenological computing tools

b.5.1. **In the scope of the project, the unique open-source QCD analysis program HERAFitter was developed.** HERAFitter is a package that provides a framework for the determination of the proton PDFs and for many different kinds of analyses in QCD. It encodes results from a wide range of experimental measurements in lepton-proton DIS and proton-proton (proton-antiproton) collisions at hadron colliders. These are complemented with a variety of theoretical options for calculating PDF-dependent cross section predictions corresponding to the measurements. The framework covers a large number of the existing methods and schemes used for PDF determination. The data and theoretical predictions are brought together through numerous methodological options for carrying out PDF fits and plotting tools to help visualize the results. While primarily based on the approach of collinear factorization, HERAFitter also provides facilities for fits of dipole models and transverse-momentum dependent PDFs. The package can be used to study the impact of new precise measurements from hadron colliders. **HERAFitter is the only open-source program available for PDF fits and is widely used by experiments at the LHC and beyond in mutli-purpose analyses.**
Published in S. Alekhin et al. [HERAFItter Group], [arXiv:1410.4412], accepted by EPJC,
HERAFitter is available at https://wiki-zeuthen.desy.de/HERAFitter.

b.5.2*.* One of the major tasks of the project was providing the community with the possibility to include measurements of the differential top quark-pair cross sections in proton-proton and proton-antiproton collisions into QCD analyses. These data are the only possibility to constrain the high-x gluon distribution, which is of key importance for searches for new physics. **In the scope of the project, the necessary theory was developed and integrated into an open-source program Difftop.** DiffTop is the Fortran-based package, which allows the user to calculate the differential and total cross section for heavy-quark pair production at hadron colliders in one-particle inclusive kinematics. The cross sections are calculated in perturbative QCD at approximate NNLO by using methods of threshold resummation beyond the leading logarithmic accuracy. The code is interfaced to the QCD analysis package HERAfitter via

FastNLOToolKit and is used in the QCD analysis using TEVATRON and LHC measurements of top-quark pair production. **For the first time, and only realized in the scope of the project, such analysis is possible.**
Published in M. Guzzi, K. Lipka, S.-O. Moch, JHEP 1501 (2015) 082,
Difftop is available at https://difftop.hepforge.org.

c) Fortschritt der durchgeführten Arbeiten:

Milestones:
All the milestones targeted in the original project were achieved in time: the measurements of the main processes at the LHC probing the proton structure were performed and were used together with the measurements of HERA in order to significantly improve the precision of the valence quark distributions, get insight into the flavour separation in the light-quark sea of the proton and decrease uncertainty of the gluon distribution. Necessary theory developments were performed and made public, novel computing programs were created as open-source and are available. Furthermore, novel ideas were developed, like determination of the gluon distribution in the kinematic region of low x, important for calculation of the atmospheric showers, necessary for the dark matter searches.

Deviations from the financial plan:
The original proposal serving originally as a proof-of-principle for the application for a HGF Virtual Institute (VI). This VI was expected to provide a scope a long-term cooperation of several theory and experimental groups with the world-leading expertise in QCD. The aim of VI was the improvement of understanding the proton structure and reducing the dominant uncertainty for the interpretation of the LHC results in the future decades. 12 German Universities and 4 international institutions committed their investment into this Virtual Institute. The VI application “Proton Structure Analyses in hadronic collisions (PROSA)” was planned for 2012 with DESY as the leading organisation. However, according to priorities in the Helmholtz center in 2012, another application was submitted and succeeded in 2012. The PROSA application was postponed, however the termination of the VI instrument was known by that time. A very small part of the planned activities in the planned PROSA Virtual Institute could be funded through an Analysis Project VH-HA-101 in 2013-2014.

With the absence of the Virtual Institute, the long-term perspective for the involvement of non-permanent experts within SO-072 became critical. As a result, one post-doc terminated his contract before the planned end of the project to start a longer-term position in the theory group of the University of Manchester.
Another postdoc applied for the Helmholtz Nachwuchsgruppe in 2013 (S. Naumann-Emme). The father of 2 preschool kids was disqualified for the interview since his several months of stay at CERN and experience as convenor of an international group of about 60 members for 1 year were not acknowledged by the Helmholtz association as international experience. Without a long-term perspective in the absence of a VI, he left physics before the end of the project.
These personnel changes in the group lead to deviation of about 40KEuro from the basis DESY resources, since each of the postdocs was a unique expert in his field and refilling the positions by new personnel with similar qualification without a long-term contract perspective was not possible.

d) Besonderheiten der Sondermaßnahme:

The originality of the project was the multi-experimental-theory cooperation on the topic of the proton structure determination, which did not exist before. The important role in the success of this excellence initiative was played by DESY being the host of HERA, both LHC experiments and of the QCD-expert theory groups. The project gained its added value in the daily close collaboration of members of ATLAS and CMS, theory experts and inherited the expertise of HERA. This construction is unique among German LHC groups and could only exist in the

environment provided by Helmholtz Association. Also close contact to the German universities in the framework of the Helmholtz Alliance “Physics at the Terascale” was of advantage. As a result, high-level scientific work could be performed, fully exploiting the developed synergies between the experimental analyses within large international collaborations and developments of theory calculations as well as of phenomenological tools. Group members played leading roles in the main Standard-Model (SM) analyses in LHC experiments ATLAS and CMS, having strong impact on precise determination of the proton structure, and are involved the development of QCD analysis tools.

The SO-072 was leading determination of parton distribution functions (PDFs) at HERA and the LHC experiments and in the global QCD analyses within the international CTEQ collaboration through common activities of DESY and the Southern Methodist University (SMU) in Dallas, USA. The group represents the origin and the core of the international, multi-institute network “Proton Structure Analyses in Hadronic Collisions (PROSA)”, an initiative between theoretical and experimental groups, aiming in enhancing of the LHC discovery potential through increased precision of the fundamental SM parameters. The group members received significant visibility in the large international collaborations through taking the coordination responsibilities at the LHC experiments and HERA, PROSA and HERAFitter collaborations. Due to expertise collected in the group, the level of the scientific results obtained in the project is remarkable. Most of the performed work is pioneering, which is acknowledged by the LHC experiments and clearly beneficial for the Helmholtz Association.

e) **Ausblick auf zukünftige Arbeiten, Nachhaltigkeit***: Geplante weiterführende Arbeiten/Kooperationen, ggf. auch mit weiteren Partnern. (max. 2 DIN A4-Seiten)*

The theory-experimental collaboration, established within SO-072 will be further preserved within the expert network PROSA.

Performed measurements at HERA and the LHC are published and will be used by other international phenomenology groups investigating the proton structure.

Phenomenological studies performed within SO-072 are pioneering and have opened the novel aspects of proton structure analyses. Those attracted high interest in the community and developments of theory and phenomenology tools performed within SO-072 are already in use and will be further used by the international high-energy-physics institutions.

f) Verwertungspotenzial:

The results of the project are of key importance for the high energy and high-luminosity upgrade of the LHC. The uncertainty of the description of the proton structure – PDF, strong coupling constant, heavy-quark masses and W-boson mass will be limiting factors in high-precision Higgs-boson physics of for searches for new phenomena. The aim of the current project was the significant reduction of these limiting factors using the present and future LHC data. The unique expertise collected and preserved within the SO-072 is immediately used and absorbed within the international theory and LHC experimental community.
The prospects for achieving the ultimate goal of understanding the proton structure to unprecedented precision go far beyond the duration of the SO-072 project, since new data of the LHC, restarting in 2015, would provide more significant constraints on the proton structure than currently available. The results of the SO-072 are of extraordinary benefit for efforts going into many LHC measurements in the whole next running period. It would be of high importance to keep this expertise within the Helmholtz association. In this case, long-term career perspectives for the key members of the project would be necessary. The insights achieved in the scope of SO-072 will be the basis of relevant investigations by the international community.

3) Qualifikation des wissenschaftlichen Nachwuchses:

The goals of the project demanded specific and unique expertise, which sets particular requirements to the personnel in the group. The major tasks were addressed by experienced post-doctoral researchers, well known in the community for their expertise in data analysis, theory developments and determination of PDFs.

Therefore, only 2 Ph.D. students were involved in the project. During the mandate of the project, the Ph.D. degree is assigned to O. Zeniaev for his thesis **"Charm Production and QCD Analysis at HERA and LHC"** by the University of Hamburg with the mark **"summa cum laude".** Dr. Zenaiev is applying for the Helmholtz Postdoktorandenprogramm 2015.

The second Ph.D. student is expected to finish his thesis in 2015.

4) **Publikationen***:*

Peer-reviewed publications:

- *S. Alekhin, K. Daum, K. Lipka, S. Moch, Phys. Lett. B 718 (2012) 550, arXiv:1209.0436*
- *S. Alekhin, J. Bluemlein, K. Daum, K. Lipka, S. Moch, Phys.Lett. B 720 (2013) 172-176 arXv:1212.2355*
- *G. Aad et al. [ATLAS Collaboration] Phys.Rev.Lett. 109 (2012) 012001, arXiv:1203.4051.*
- *B. Malaescu, P. Starovoitov, Eur.Phys.J. C72 (2012) 2041, arXiv:1203.5416*
- *S. Chatrchyan et al. [CMS Collaboration], Phys. Lett. B 728 (2013) 496, arXiv:1307.1907*
- *M. Guzzi et al, Eur. Phys. J. A49 (2013) 35, arXiv:1212.5344.*
- *J. Gao, M. Guzzi, P. Nadolsky, Eur. Phys. J. C73 (2013) 2541, arXiv:1304.3494.*
- *S. Chatrchyan et al. [CMS Collaboration], Phys. Rew. D 90 (2014) 032004 arXiv:1312.6283.*
- *S. Alekhin et al., Phys. Rew. D. 91, 094002 (2015), arXiv:1404.6469*
- *J. Gao, M. Guzzi et al, Phys. Rev. D 89, 033009 (2014), arXiv:1302.6246*
- *G. Aad et al. [ATLAS Collaboration], JHEP1406, 112 (2014), arXiv:1404.1212*
- *M. Guzzi, P. M. Nadolsky, B. Wang, Phys. Rev. D 90, 014030 (2014), arXiv:1309.1393*
- *P. Belov et al. [HERAFitter Collaboration], Eur. Phys. J. C74,10, 3039 (2014) arXiv:1404.4234*
- *M. Guzzi, K. Lipka, S.-O. Moch, DESY-14-077, JHEP 1501 (2015) 082, [arXiv:1406.0386]*
- *O. Zenaiev et al. [PROSA Collaboration], arXiv:1503.04581, in review by Eur. Phys. J.*
- *S. Alekhin et al. [HERAFItter Group], arXiv:1410.4412, in review by Eur. Phys. J.*

NB: in high energy physics, the publications by members of experimental collaborations have the author lists including all the authorized members of the collaboration, ordered alphabetically with respect to participating organisation. PROSA collaboration orders the authors in order of their contribution to the paper. The listed journal publications represent only papers with major contribution by the SO-072 group members.

Public results reviewed by collaborations:

- J. Kieseler, K. Lipka, S. Naumann [CMS Collaboration], *CMS-PAS-TOP-14-014*
- O. Zenaiev, A. Geiser, K. Lipka [PROSA Collaboration] *PROSA-14-001*
- *A. Vargas, K. Lipka, R. Placakyte* [CMS Collaboration] *CMS-SMP-12-021*
- *K. Lipka,, R. Placakyte* [CMS Collaboration] *CMS-SMP-14-022*
- *P. Starovoitov, V. Radescu et al* [ATLAS Collaboration] *ATL-PHYS-PUB-2014-015*
- J. Kieseler, S. Naumann [CMS Collaboration] *CMS-PAS-TOP-13-007*
- S. Naumann [CMS Collaboration] *CMS-PAS-FTR-13-017*
- V. Radescu, P. Starovoitov [ATLAS Collaboration] *ATLAS-CONF-2012-159*

- V. Radescu, P. Starovoitov [ATLAS Collaboration] ATL-CONF-2012-128
- S. Naumann, K. Lipka [CMS-PAS-12-022]

Conference contributions
In 2012-2014 the group reported the achieved results in 54 public presentations at major international conferences and in invited seminars and lectures.

5) Öffentlichkeitsarbeit

Results of the project are reported in the public DESY annual brochure on highlights of particle physics:
Particle Physics 2011 (Highlights):
Electrons and jets at HERA by A. Geiser and C. Diaconu
CMS: Physics of the top quark by M. Aldaya
Strange sea quarks in the proton at the LHC by A. Glazov and V. Radescu

Particle Physics 2012 (Highlights):
QCD and Proton Structure from HERA to the LHC by K. Lipka and H. Jung
The charm of HERA by A. Geiser and S. Schmitt

Particle Physics 2014 (Highlights):
Proton anatomy by K. Lipka
Proton under the LHC microscope by K. Lipka and H. Jung
HERAFitter by V. Radescu, R. Placakyte, A. Glazov, H. Pirumov

Organisation of schools/workshops

International school "Proton structure in the LHC era" 28.09 – 02.10.2014 at DESY,
A common project of SO-072 and the CTEQ collaboration. The school was addressing young scientists (masters, Ph.D students and young postdocs) and included lectures and hand-on tutorials on the project-specific topics.

The project has the own webpage with further links to the Projects publications and open-source programs: https://www.desy.de/~knegod/sofi/so072.html

The PROSA Collaboration is represented by its own website http://prosa.desy.de