Proposal:

Inclusive and Semi-Inclusive Constraints on the Parton Distributions at the LHC and the Study of Hard Processes

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1 Introduction

After a first very successful period of data taking at the LHC various inclusive reactions show an increasing sensitivity on the non-perturbative parton distributions of the proton, beyond the detailed knowledge having been gained analyzing the world deep inelastic data and notably the data from HERA. Various key-reactions, like jet-production, $W^{\pm}/Z$-boson production, the Drell-Yan process off-resonance, single top-production, and inclusive $t\bar{t}$-production, are measured at high precision and start to further constrain the PDFs. Furthermore, the final analysis of the HERA data is progressing. Higher order corrections for all these processes become available and need to be applied in these ongoing data analyses. Finally all these experimental informations have to be linked via efficient fitting tools to extract central parameters for the physics at proton colliders: the parton distribution functions, the strong coupling constant $\alpha_s(M_Z^2)$, and the quark masses.

For this reason a joint effort carried by German theory groups and experimental groups from ATLAS and CMS is proposed within the Helmholtz-Alliance to achieve a new level of precision in the knowledge of the nucleon sub-structure and the other central parameters of QCD, which is of instrumental importance for the deeper understanding of the Standard Model and possible extensions. Through this all measurements at the LHC will be greatly improved, allowing further for detailed tests of QCD. In the searches for new physics the signals will be improved and the understanding of the backgrounds is refined. We mention in particular the case of the Higgs-boson. Here these aspects are crucial, since the production cross section depends both on $\alpha_s(M_Z^2)$ and the gluon distribution function quadratically. Both these quantities have a large potential to be improved.

At the current level of precision a close cooperation of different experimental groups and theorists is needed to accompany the ongoing analyses with precision calculations and to assure the correct use of the experimental data in phenomenological analyses, such as global multi-parameter fits.

The proposing groups perform detailed research on inclusive and semi-inclusive hard scattering processes using the new LHC-data and the nearly final HERA data to improve the knowledge on the parton distribution functions. Furthermore, accompanying theoretical NNLO calculations in the sector of heavy quark processes and jet physics are performed. Packages like `OpenQCDRad` [1, 2] will be extended significantly, building in grid-analysis tools to include important experimental distributions from Tevatron and the LHC into global analyses in a very efficient form. Here the `fastNLO` [3] project forms a central link between the analyzed collider data and the global fits at NNLO, including the proper treatment of systematic errors. Ideally the results of these analyses are provided to the LHC groups to be fed into the ongoing experimental analyses at a short timescale.

2 Research Topics

The initiative will study different scattering processes at the LHC and HERA to further refine the present knowledge on the parton distribution functions. Here major tasks consists in the improvement on the gluon distribution and the resolution of the individual light sea quark distributions. The corresponding scattering cross sections are analyzed by the teams involved, who will provide the experimental distributions in a form suitable to be further analyzed in the global fit with `OpenQCDRad`. In this way also updates on the strong coupling constant $\alpha_s(M_Z^2)$ and the heavy quark masses are obtained at NNLO. Furthermore, a series of theoretical calculations will be performed to improve the analysis of several processes.

The following joint experimental and theoretical topics will be worked on:

- Integral and differential $W^{\pm}$-production and charge asymmetry; charged current DIS [DESY, CMS; U. Freiburg, ATLAS, DESY, TH]; [4, 5].
  These reactions allow stringent checks on the $u_v - d_v$ and d/u-distributions and are sensitive to the s-quark density. For the latter also the measurement of the Wc final state is of importance and complimentary to first results on the strange distribution from ATLAS [6]. The reactions have sensitivity also on the c- and b-distributions, requiring partly new calculations. Higher order corrections to charged current DIS will be provided to allow for an improved analysis of these data. The inclusive and differential $W^{\pm}$ cross sections measured at LHC will be incorporated into the fit.

- Integral and differential Z-production cross sections and off-resonance Drell-Yan data [DESY, CMS; Mainz, ATLAS, DESY, TH; Hamburg, TH]; [4, 5].
  These processes are particularly relevant for an improved determination of the $\bar{d} - \bar{u}$ distributions and the strange-quark distributions, also using the $W^{\pm}/Z$-ratios. They are of key importance since together with the known valence quark distributions an important combination can be measured for which the 2nd moment can be determined on the lattice [7], allowing for an ab-initio QCD tests. The off-resonance Drell-Yan process allows to access the yet unexplored region of larger values of x for the sea-quark distributions. Using the forward-backward asymmetry the weak mixing angle can be determined. Here the dominant experimental uncertainty is given by the PDF-errors. The respective experimental distributions will be included in the global fits in terms of grids.

- Inclusive jets, di- and multijets at LHC [Karlsruhe, CMS; Mainz, ATLAS; DESY, TH; Hamburg TH]; [8, 9].
  The measurement of single, di- and multi-jet final states will improve the present knowledge of the gluon density and $\alpha_s(M_Z^2)$ significantly. The LHC data are systematically better than those taken at Tevatron earlier and a much wider kinematic region is covered. Concerning the PDF-measurement, emphasis is laid on processes dominated by hard QCD. At present the NNLO production cross sections are not yet available. Therefore, a first goal is to calculate the Sudakov-resummation of the NLO cross sections in the region of large E_T in NNLL, to obtain first estimates beyond the NLO accuracy.

- Inclusive and differential $t\bar{t}$ production [DESY CMS, Hamburg, TH]; [10–13].
  This process is also sensitive to the gluon and inclusive sea quark densities, including larger values of x, but limited to the virtualities relevant for the $t\bar{t}$ final state. It allows to measure m_t, based on the inclusive NNLO cross sections and differential NLO distributions referring to a rigorous quantum field-theoretic treatment, at a much better precision than currently

available. The process is also sensitive to the b-quark density, which will get constrained further. The calculation of further NNLO contributions to the differential production cross sections will be performed and detailed studies of the differential distributions will be carried out.

- Single top-production [Wuppertal, ATLAS; DESY, CMS]; [14].
  The scattering cross section is sensitive to the gluon distribution in a mass range similar to the one for the present Higgs-boson search [15]. This process will help to set direct experimental constraints on the gluon distribution in this important region. By measuring the single top-quark and single top-antiquark cross sections separately and forming their ratio R_t (expected to be roughly equal to two) one is sensitive to the u-quark and d-quark PDFs in the intermediate x region between 0.02 and 0.5. A preliminary measurement of this kind has been performed by ATLAS [16]. In the frame of the proposed project it is intended to extend the measurement to be differential in certain sensitive variables. The cross section is rather sensitive to the b-distribution and at high luminosities also differential distributions can be studied.

- Improved values for the heavy quark masses m_c and m_b [DESY, CMS; Wuppertal, ATLAS, DESY, TH; Hamburg, TH]; [17–20].
  Further to the processes having been mentioned already inclusive HERA data and data on $F_2^{c\bar{c}}, F_2^{b\bar{b}}$ will allow to measure m_c and m_b at a higher precision. This also applies to the planned analyses of the $Wb\bar{b}$ and $Zb\bar{b}$ final states at the LHC. Note that the more accurate values of m_c and m_b will reduce the present uncertainties of the W- and Z-boson production cross sections.

- Global PDF-fits, including DIS and LHC data [DESY, TH; Hamburg, TH], [2].
  The code `OpenQCDRad` will be steadily extended to allow for the grid-processing of the various sets of the LHC data mentioned. In the first year, mainly the W, Z- and Drell-Yan data and various samples of the jet-data from ATLAS and CMS will be processed. Here an important issue consists in the thorough account for the systematic errors. All analyses of this kind will be performed in close contact to the experimental groups. The newly obtained PDFs and α_s-values, including correlated errors, will be made available to the participating groups continuously.

- Measurement of α_s [all groups]; [2, 21].
  The strong coupling constant, as one of the fundamental parameters of the Standard Model, is still not known to the precision actually being provided experimentally by individual precision measurements. The initiative aims to understand the systematics of all processes used to such detail that a consistent determination of $\alpha_s(M_Z^2)$ is possible. This is essential to trace remaining, yet uncovered systematics and missing parts in the theoretical description. In particular, it has to be clarified whether or not the central value of $\alpha_s(M_Z^2)$ is low as found in the DIS analyses. For this the measurement of α_s at TeV-scales is crucial.

3 Resources and Networking

To fund the present initiative we ask for **four half positions/year** to be paid by the Helmholtz Alliance for a duration of the project of two years in total, amounting to

EUR 120.000.-/year.

All these positions will be co-funded by the participating institutions to **eight full positions** for one year each. The fund will be shared equally between the participating nodes, i.e. four half positions per year. Furthermore, the participating institutions will dedicate own funds to allow for continuous work on the named topics for the period of two years. PhD students and some of the Post-Docs working in the different sub-groups will join the effort. Travel- and networking allowances are provided by the participating groups.

The time lines of the project concerning the global analysis somewhat depend on the availability of the corresponding data both from ATLAS and CMS. They will be processed by to `OpenQCDRad` providing new fits of the PDFs, $\alpha_s(M_Z^2)$, m_c and m_b. Here we will discuss optimal strategies with the partners involved. On the theoretical and phenomenological side we will provide the most complete descriptions for the cross sections to be analyzed on time. Furthermore, longer term calculations are performed in parallel. A major issue at the phenomenological side consists in the stepwise perfection and automation of the analysis chain of `OpenQCDRad`.

The final goal of the initiative after two years is to reach improved and mutually consistent PDF-sets, a better value of $\alpha_s(M_Z^2)$, more precise values on m_c, m_b and m_t, and a deeper theoretical and phenomenological understanding of the experimental processes analyzed.

4 Participating Groups

The following teams are involved in the planned initiative :

- Prof. J. Blümlein, Dr. S. Alekhin, Deutsches Elektronen-Synchrotron, DESY, Zeuthen, TH
- Prof. K. Jakobs, Dr. K. Lohwasser, Universität Freiburg, ATLAS
- Dr. K. Lipka, Dr. A. Geiser, and collab., Deutsches Elektronen-Synchrotron, DESY, Hamburg, CMS
- Prof. S.-O. Moch, Universität Hamburg, TH
- Dr. K. Rabbertz, Karlsruhe Institute of Technology, KIT, CMS
- Prof. S. Tapprogge, Dr. F. Ellinghaus, Johannes Gutenberg-Universität Mainz, ATLAS
- Prof. W. Wagner, Dr. D. Hirschbühl, Bergische Universität Wuppertal, ATLAS

As has been lined out, the present task can only be achieved within a very close cooperation between the experimental and theoretical groups and will naturally form a new vivid network acting on various levels of research. The quality of the LHC data will improve the present constraints on the PDFs significantly and will contribute to a much better understanding of the strong coupling constant. Based on the LHC data taken in the present run period at $\sqrt{s} = 7$ and 8 TeV very stringent QCD tests will be possible and major inclusive and semi-inclusive scattering processes will be understood at a much better precision enhancing the discovery potential in the respective channels.

In this way, the planned network will strengthen the physics analysis of the LHC experiments significantly and is supposed to lead to a visible contribution from Germany inside the LHC physics community as a whole.

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