Impact of ATLAS Data on Proton Structure

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Abstract

The aim of the project is on one side to analyse the impact of the ATLAS 2010 data on the proton structure, on the other side to develop the drawing tools within the framework of HERAFitter. After a short introduction about the proton structure and the physics processes of interest, the impact analysis and the Improvements on the new drawing tools of the HERAFitter program are presented.

Contents

1 Introduction

1.1 Standard Model

The standard model of particle physics is a theory which describes the electromagnetic, weak and strong interaction of particles, its particle content is shown in figure 1. The elementary particles are the six quarks (up, down, charm, strange, top, bottom) as well as the three charged leptons (electron, muon, tau) and the three neutral leptons (electron-neutrino, muon-neutrino, tau-neutrino). Besides this, there are four fundamental particles which mediate the three forces: the photon (electromagnetic interaction), the Z^0 and $W^{\pm}$ bosons (weak interaction) and the gluon (strong interaction).

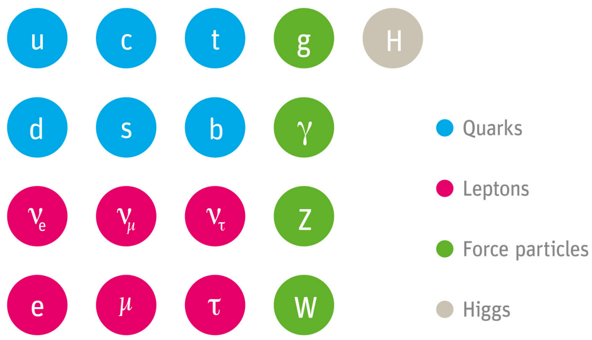


Figure 1: Particle content of the standard model of particle physics.[3]

For the impact analysis the focus was on the structure of the proton which is not elemantary. It contains two up and one down as valence quarks but also other quarks and anti-quarks (sea quarks). Furthermore gluons mediate between the quarks. To get information about the exact structure two physics processes are studied: deep inelastic scattering and W/Z production in hadron collisions.

1.2 Physics Processes

This section will take a closer look on the physics processes which are of interest to the structure of the proton. As already mentioned in section 1.1 those processes are deep inelastic scattering and W/Z production in hadron collisions.

Deep Inelastic Scattering

Deep inelastic scattering (DIS) describes the scattering of a charged lepton on a proton by exchanging a virtual particle which is schematically depicted in figure 2. On the one hand the intermediate particle can be a photon or a Z^0 boson which means a neutral current is excahnged, on the other hand a W^+ or W^- boson can mediate as a charged current. In the first case the scattered lepton is charged while in the second case the initial charged lepton will be transformed to the corresponding neutrino.

The two most important variables of this process are the Björken x which can be interpreted as a fractional momentum of the scattered quark and the squared transfered momentum Q^2 which gives the resolving power of the experiment.
Since the scattered lepton has no further substructure DIS gives a very clean appraoch to the proton structure. The dominat experiments in DIS were performed at HERA, DESY where the initial leptons have been electrons.

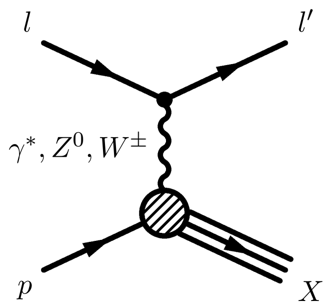


Figure 2: Feynman diagram of DIS.

W/Z Production in Hadron Collisions

Besides DIS also hadron collision processes where a $W^\pm$ or Z^0 is produced can give access to the proton structure. Although hadron collisions are not as clean as DIS since two partons are interacting with each other but still they can provide information in a complementary x and Q^2 rang which is discussed in section 2.
A schenematic representation of the process is shown in figure 3. Two quarks of two different protons get transfered to a photon or Z^0 (Drell Yan process) or a $W^\pm$. The intermediate particle desintegrates into two leptons which are a pair of particle and antiparticle of the same generation in the case of a Drell Yan process, otherwise it is a lepton and the corresponding neutrino. The important variables are the pseudorapidity y and the transfered momentum fraction Q^2 which depends on the scale of the process that means the mass of the exchanged particle.
Those kind of W/Z production processes happen today at the LHC experiments within proton proton collisions.

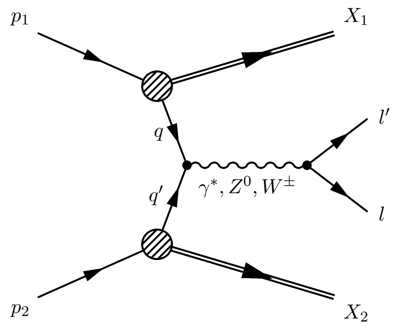


Figure 3: Feynman diagram of W/Z production.

1.3 Proton Structure

As already mentioned in section 1.1 the proton is composed of various constituents - on one side out of the valence quarks (up, up, down), on the other side out of gluons and sea quarks which can also be summarised as partons. The probability density of each parton is describted by the parton density function $f_i(\mathrm{x}, Q^2)$ (PDF) which gives the probability to find a parton i with a momentum fraction x at a given Q^2. The PDFs are be extracted by experimental data. A fairly good determination is given by the measurements of DIS but to get a better discription of the PDFs it is usefull to have a look on data from W/Z production in hadron collisions which is described in this report.
There are several groups that provide PDFs, e.g. HERAPDF, MSTW, CTEQ, JR, NNPDF and ABM.

2 Kinematic Coverage of the Measurements

The first part of the project is to determine the kinematic coverage of the measurements which are used for the impact analyses. To this purpose the variables Björken x and squared transfered momentum Q^2 of four HERA datasets from ZEUS and H1 as well as the three ATLAS datasets for W/Z production from 2010 are analysed. As a reminder the first datasets (HERA) are provided by DIS and the second datasets (ATLAS) are based on W/Z production in hadron collisions.
As brought up in section 1.2 W/Z production data is differantial in pseudorapidity y and not in Björken x. So to compare the measurements it is neccessary to convert y to x through formula 1.

$$\mathrm{x}_{1,2} = \frac{\mathrm{M}}{\sqrt{\mathrm{s}}} \exp \pm y \tag{1}$$

Whereby M is the mass of the vector bosons Z^0 (91.1876 GeV [1]) or $W^{\pm}$ (80.385 GeV [1]) and $\sqrt{\mathrm{s}}$ is the centre of mass energy of 7 TeV.
In figure 4 the combined plot of DIS and W/Z production data is shown as Q^2 in GeV over x.

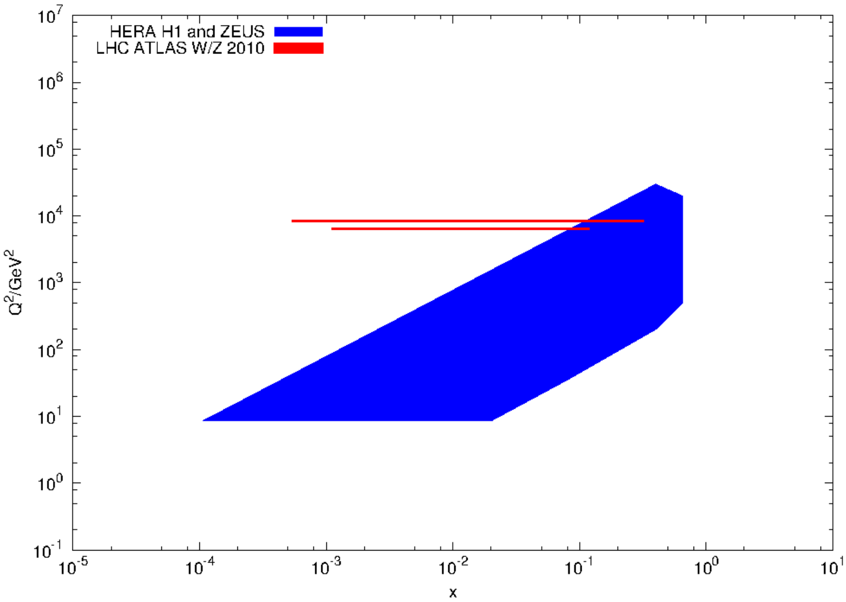


Figure 4: Kinematic coverage of the measuerements from HERA and ATLAS W/Z 2010.

The HERA data is depicted in blue and ATLAS 2010 data in red. As can be seen the addition of Z^0 and $W^{\pm}$ production measurements at ATLAS at a centre of mass energy of 7 TeV expands the range at high Q^2 ($\sim \mathrm{M}^2_{Z,W}$) to lower x. Hence improvement of the knowledge of the proton structure can be expected from the analysis of ATLAS data which is discussed in chapter 3.

3 Impact Analysis of ATLAS 2010 W/Z Data

The analysis which is explained in the following sections is performed on Z^0 and $W^{\pm}$ data collected with the ATLAS detector in 2010 at a centre of mass energy of 7 TeV. As a reference the combined HERA H1 and ZEUS measurements are used. In the first part of this chapter the impact of the ATLAS data on the PDFs is analysed whereas in the second part the focus is on the fitting.

3.1 Sensitivity Study

Sensitivity studies are an effective way to assess the impact of the ATLAS measurements on the proton structure. The framework used for this study is HERAFitter, it is described with more details in section 4. The aim of the sensitivity study is to evaluate the uncertainties. For that the PDFs are parametrized with 13 free parameters and as an additional parameter the strange fraction is set free. The resultant uncertainties for the output parameters are applied on the initial parameters to recalculate their uncertainties. Afterwards a second run with the same central values but adjusted uncertainties of the parameters is performed. The results of the sensitivity study are on the one hand the PDFs for each parton or parton type, on the other hand the corresponding ratio plots. In figure 5 those plots are shown for the d valence quarks.

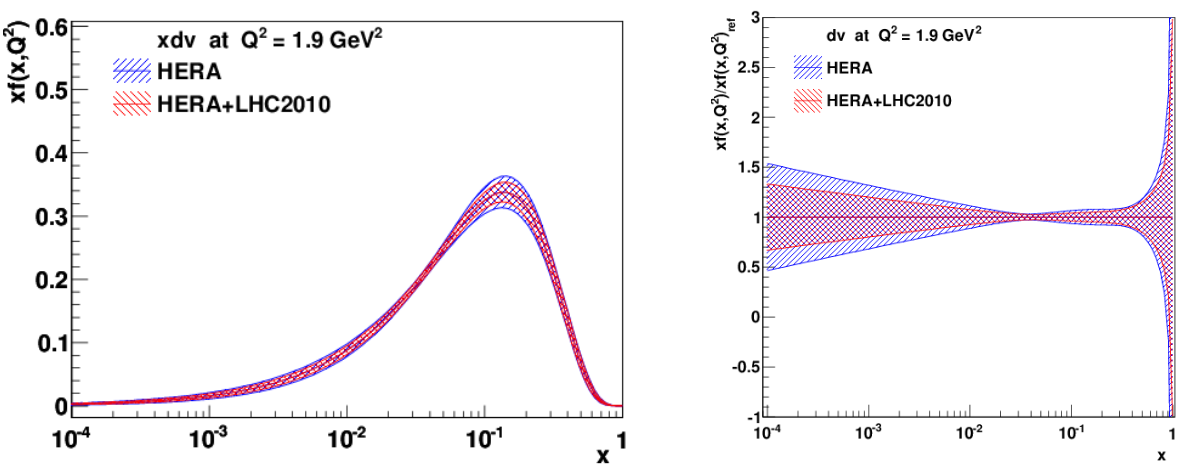


Figure 5: PDF (left) and ratio plot (right) for d valence quark with HERA and ATLAS 2010 $Z^0/W^{\pm}$ data at $Q^2 = 1.9\,\text{GeV}$.

HERA data is represented in red and ATLAS 2010 $Z^0/W^{\pm}$ data in blue. As already can be seen in the PDF plot (left) the uncertainties get smaller if ATLAS data is added which shows the ratio plot even more. Especially the measurements in the low x range have been improved.

Incidentally the results for the s sea quarks shall be presented here in figure 6 since the strange fraction is free within this analysis. However here the low as well as the central x range have been improved.

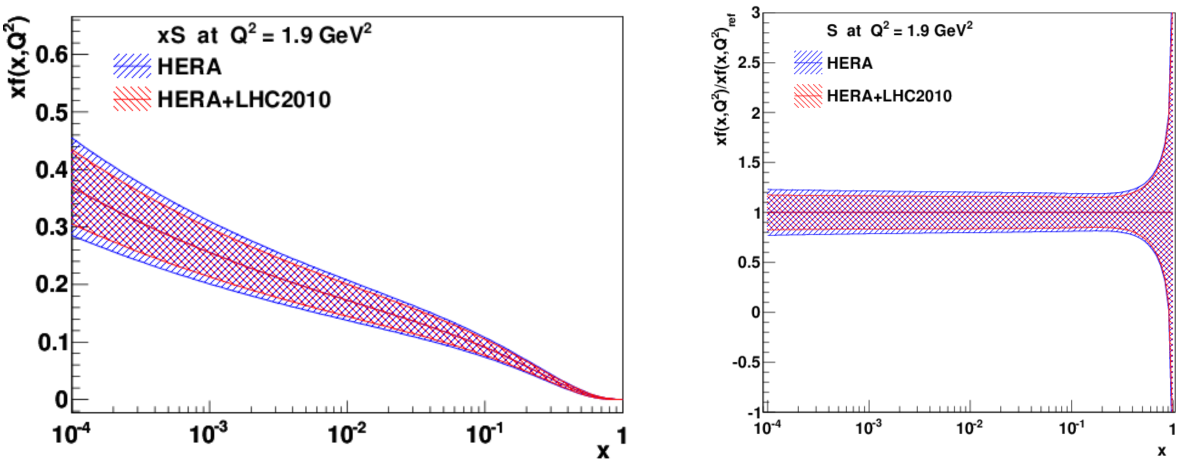


Figure 6: PDF (left) and ratio plot (right) for s sea quarks with HERA and ATLAS 2010 $Z^0/W^\pm$ data at $Q^2 = 1.9\,\text{GeV}$.

3.2 QCD Fits

The cross sections for the Z^0 and $W^\pm$ production are fitted wherby the result of the fit is shifted according to 105 correlated uncertainties treated as nuisance parameters (e.g. luminosity shift). This leads to a better description of the data.
In figure 7 the cross section for W/Z production at ATLAS in 2010 at a centre of mass energy of 7 TeV are represented. The fit is depicted as a solid red line and the fit with shifts as a dashed line. It can be seen that the fit with shifts fits the data better than than the fit without shifts.

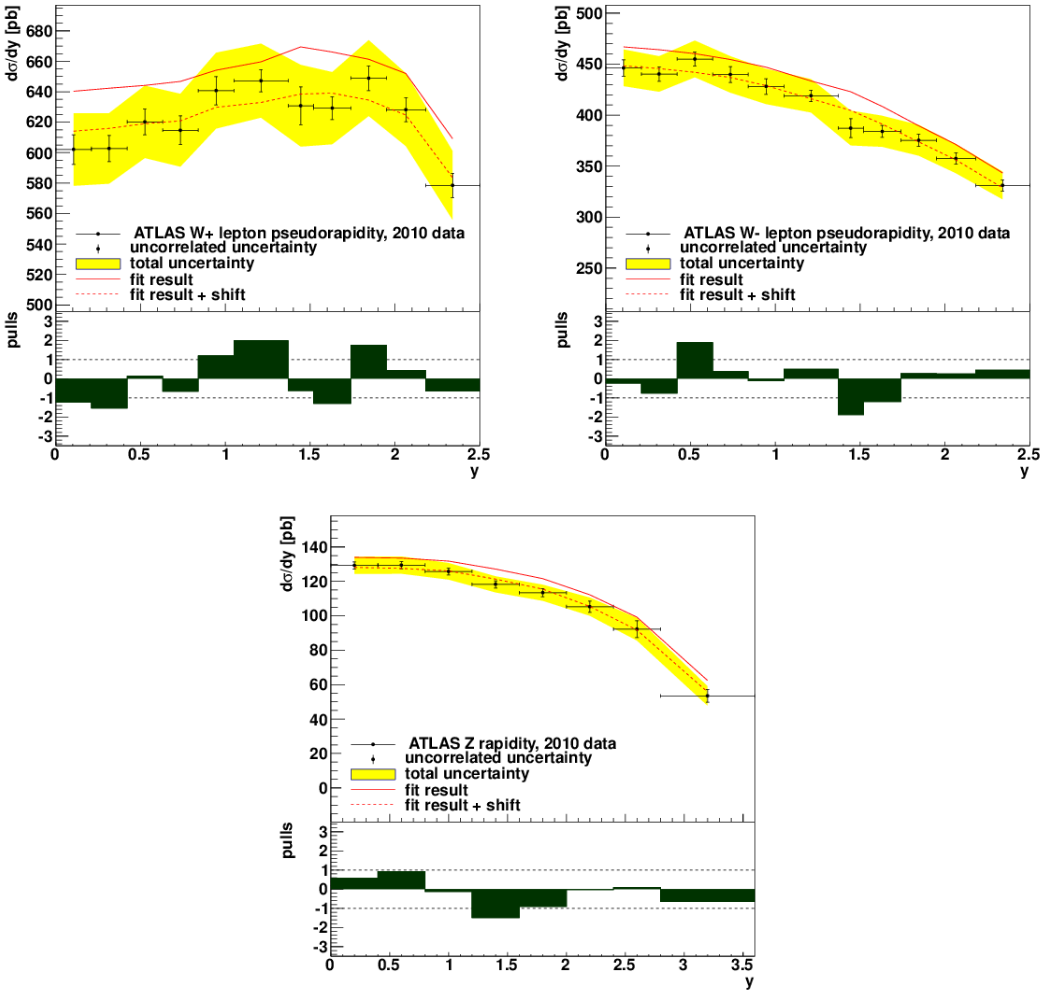


Figure 7: Cross section an pulls for Z^0(bottom), W^+(top left) and W^-(top right) production extracted by ATLAS 2010 data.

Furthermore it can be seen that the cross section for W^- production is higher than for W^-, this is due to the fact that protons are colliding at the the LHC. A W^+ is generated when one of the up valence quarks interacts with a anti-down quark of the sea quarks whereas a W^- needs a down valence quark and a anti-up quark. Since the amount of up valence quarks is higher than down valence quarks the W^+ production is more likely.
In the lower part of each plot the pulls are shown.

4 HERAFitter

HERAFitter is a QCD fitting package which was originally designed for data from electron proton collisions at the HERA experiments H1 and ZEUS and now it is extended to LHC and Tevatron data. It provides different theory predictions at next-to-leading order (NLO) as well as next-to-next-leading order (NNLO), several running schemes and parametrisation styles [2]. For the theory prediction fast techniques are employed, such as APPLGRID which relies on the factorable nature of cross sections and is in NLO. To correct from NLO to NNLO kfactors are used. Those kfactors are calculated employing CPD consuming programs as the ration of cross section in NNLO and NLO of the same PDF as shown in formula 2.

$$\text{kfactors} = \frac{\sigma_{NNLO}}{\sigma_{NLO}} \tag{2}$$

For the analysis discribed in chapter 3 the theory prediction APPLGRID with kfactors from the HERAPDF group and the Thorne-Roberts VFNS (RT) scheme are used.

4.1 Drawing Tools

The HERAFitter package also provides different tools to plot the results. As part of the project the new drawing tools has been developed.
The old tool `DrawResults` provides plots of the PDFs for up and down valence quarks, u-type, d-type as well as anti-u-type and anti-d-type sea quarks and gluons for different squared transfered momentums Q^2. An example can be seen in figure 8.
A disadvantage of this kind of depiction is that all PDFs are summarised on one page and the up and down valence even in one diagram with the corresponding typed sea quarks. Furthermore the ratio plots in those cases are only available for the total sea quarks. To improve this the new tool `DrawPdfs` was created which saves each PDF for its own and provides for each also the ratio plot. A further improvement is that the new drawing tool can compare up to six datasets and the legend can be changed by the user when executing the tool. An example is shown in figure 9.
Whereby the ratio in the new tool is calculated according to formula 3 with a reference which can be definde by the user.

$$\text{ratio} = \frac{\text{value} + \text{error}}{\text{reference}} - \frac{\text{value}}{\text{reference}} \tag{3}$$

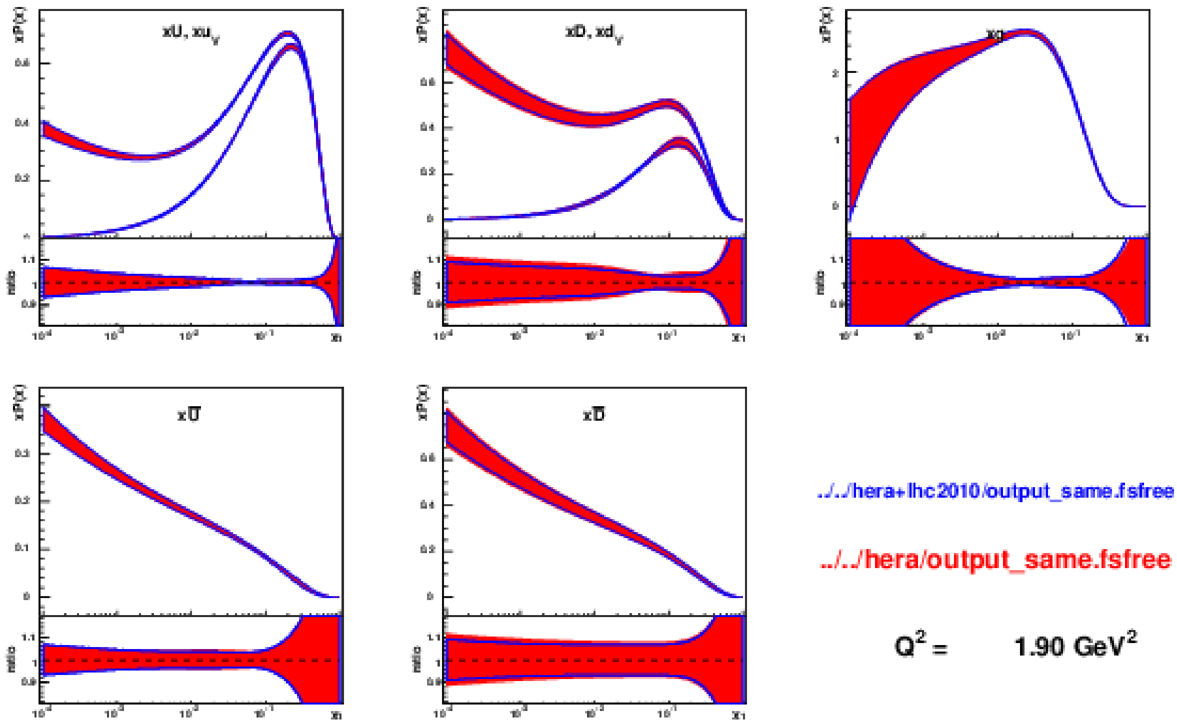


Figure 8: PDFs and ratio plots provided by the DrawResults tool.

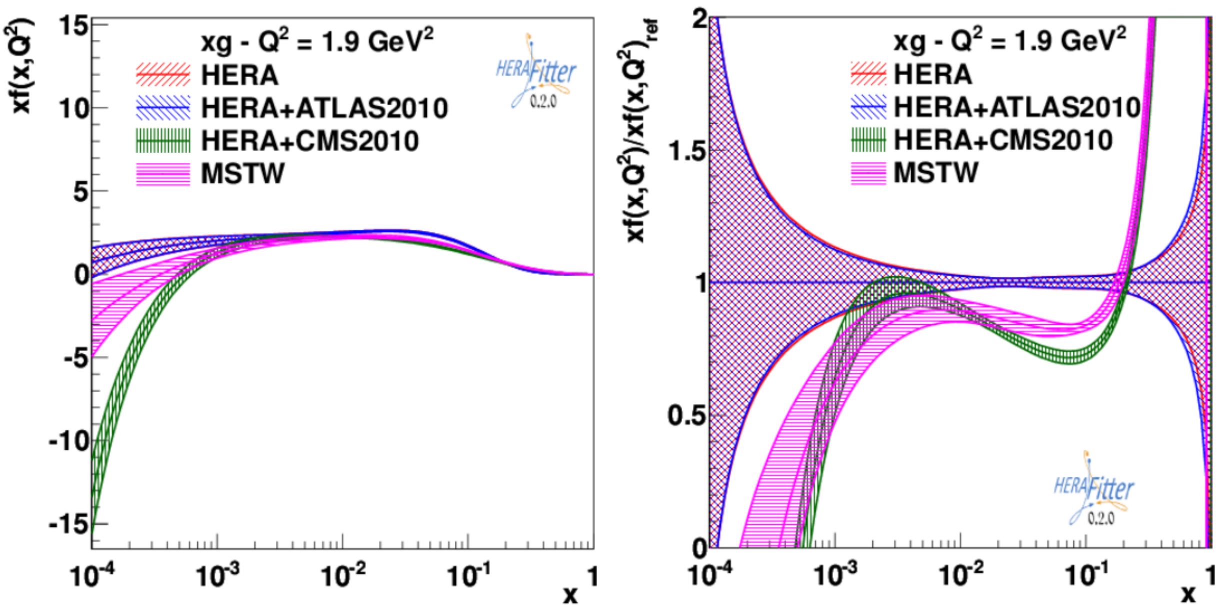


Figure 9: PDFs and ratio plots provided by the DrawPdfs tool.

The second new drawing tool is `DrawDataPulls`. It can be used to create plots with cross sections and pulls like those in figure 7 in section 3.2. With this tool up to two datasets can be compared. Formula 4 gives the calculation for the pulls.

$$\text{pulls} = \frac{\text{data} - \text{theory}}{\text{error}} \tag{4}$$

Whereby the theory value is taken according to the fit with shifts. All plots which were shown in section 3 of this report were created with this new drawing tools with HERA data as reference for the ratio plots.

5 Summary

The impact of the ATLAS data on the proton structure has been successfully investigated within the project. The addition of ATLAS data improves the description of the proton structure since it gives access to a wider x and Q^2 range. Furthermore the drawing tools of the HERAFitter package have been improved and are now also more user-friendly.
Still there are possibilities to do further sensitivity studies, e.g. by fitting with more parameters and also the drawing tools can be enhanced by adding more options or by simplifying it.
The studies which are shown here are based on publicly available data. However the impact analysis were performed on internal 2011 W/Z ATLAS data as well but cannot be presented here.

References

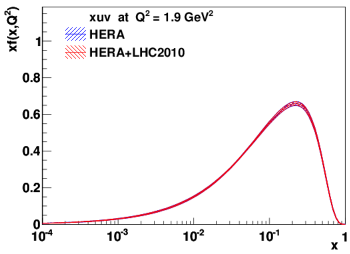
[1] *Particle Physics Booklet*, Particle Data Group, 2012

[2] *HERAFitter - PDF Fitting package*, HERAFitter developers, 2013

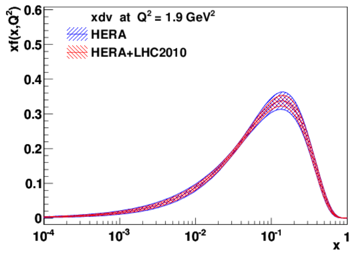
[3] `http://www.weltmaschine.de/news/07102010/`, 11:05 am, September 3, 2013

Appendix

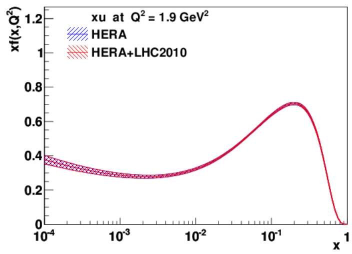
PDFs and ratio plots for all partons for HERA and ATLAS 2010 data at $Q^2 = 1.9\,\mathrm{GeV}$.



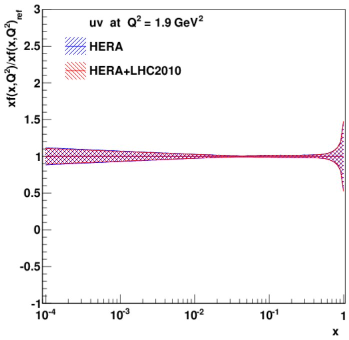
PDF for the up valence quark.



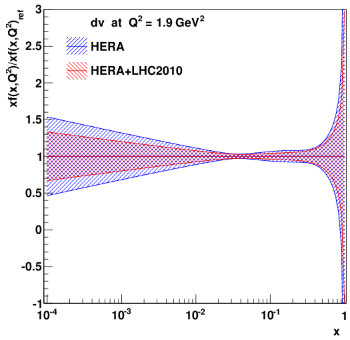
PDF for the down valence quark.



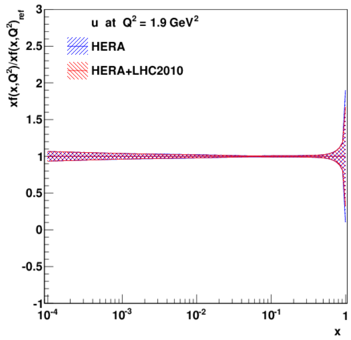
PDF for up quarks.



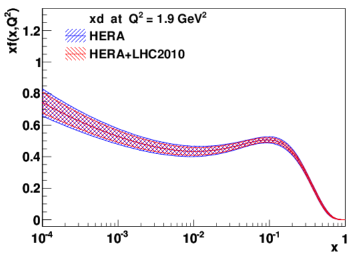
Ratio plot for the up valence quark PDF.



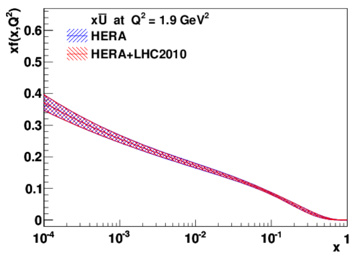
Ratio plot for the down valence quark PDF.



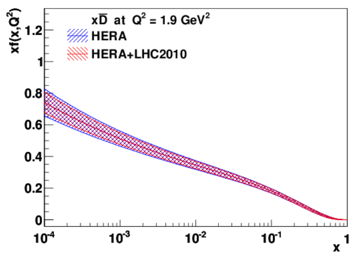
Ratio plot for the up quarks PDF.



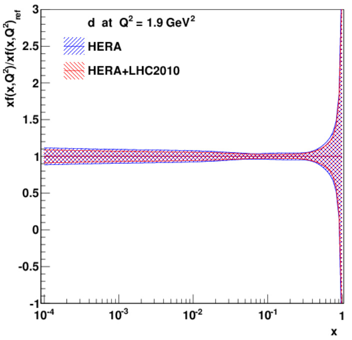
PDF for down quarks.



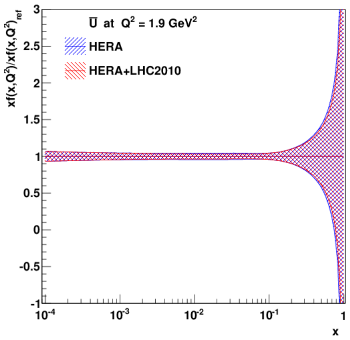
PDF for anti-up quarks.



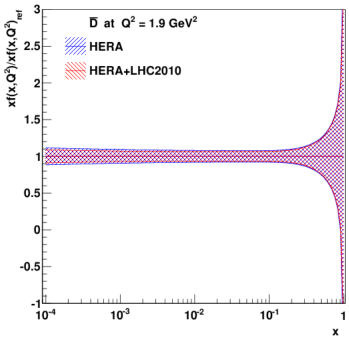
PDF for anti-down quarks.



Ratio plot for the down quarks PDF.



Ratio plot for the anti-up quarks PDF.



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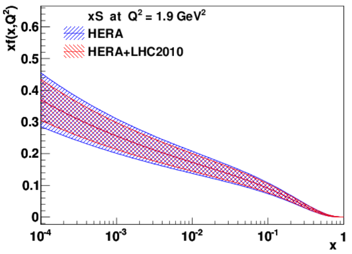
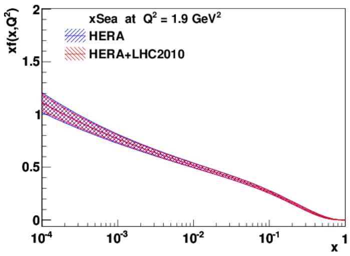
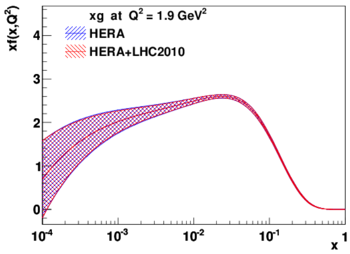


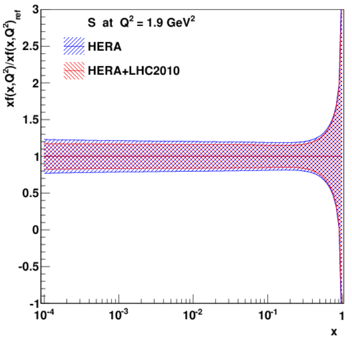
PDF for the strange quarks.



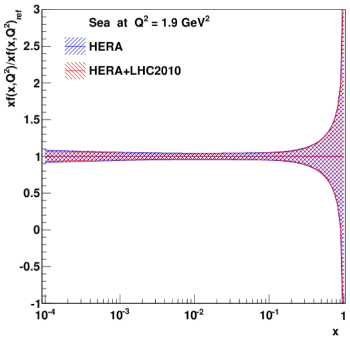
PDF for sea quarks.



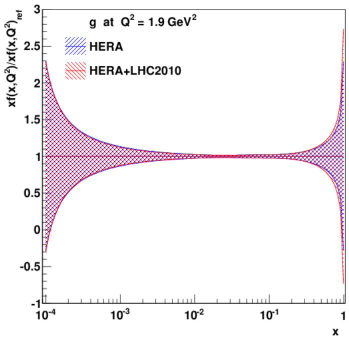
PDF for gluons.



Ratio plot for the strange quarks PDF.



Ratio plot for the sea quarks PDF.



Ratio plot for the gluon PDF.