

Photon structure function fit with the xFitter framework

Summer Student Report

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1 Introduction

The theory of the strong interaction, Quantum Chromodynamics (QCD), is one of the main constituents of the Standard Model of elementary particle physics. Particularly interesting is the strong coupling constant α_s , the only fundamental QCD parameter, which can be only determined by experimental investigations. Therefore, the precise knowledge of α_s has been subject of many investigations, using several different methods, like for example the Z - and τ - decays at LEP. The current world average value of $\alpha_s(m_Z) = 0.1172 \pm 0.0020$, where $m_Z = 91.1876$ GeV denotes the mass of the Z -boson [1].

In terms of QCD, the photon offers particular interesting investigation possibilities, which can be shown by Deep Inelastic Scattering (DIS) of electrons and photons. Despite the assumption, that the photon is a point-like particle, hadron production can be observed. This is leading to the introduction of structure functions, as for DIS electron-nucleon scattering and can be explained by quantum fluctuations due to Heisenberg's uncertainty principle. It allows the photon for a short time period Δt , the violation of the energy conservation by the amount ΔE and ending up in the production of a fermion pair $\gamma \rightarrow f\bar{f} \rightarrow \gamma$. In the case, one of those fermions (target) interacts via a gauge boson, the parton content of the photon gets resolved. This is displayed in fig. 1 on the left-hand side and schematically compared to electron-nucleon scattering $e^- N \rightarrow e^- X$ on the right-hand side.

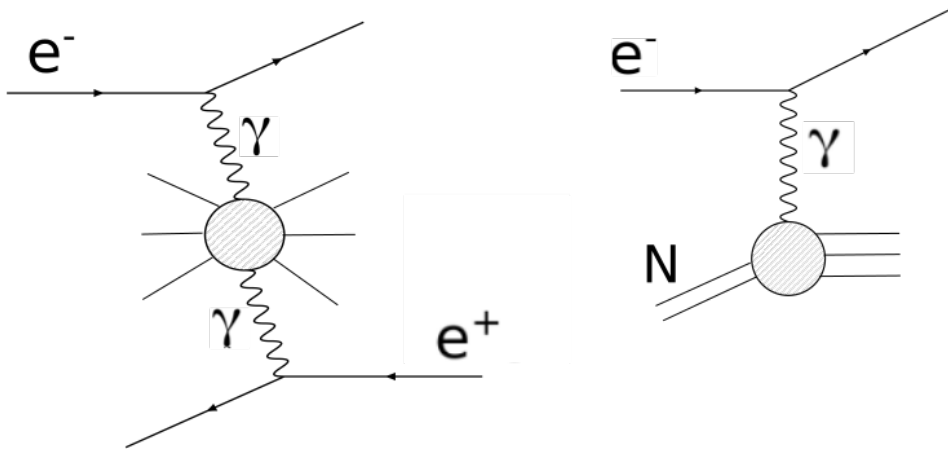


Figure 1: Comparison of the hadron production in case of photon-photon scattering (left) and electron-nucleon scattering (right). While in the later case the target is the nucleus, which gets probed by the photon, in the first case, the parton content of the target photon gets resolved by a second photon.

The photon structure function F_2^γ is determined via differential cross section measurements from e^+e^- collider data. In case of this project, only data from F_2^γ measurements from photon-photon scattering are taken into account. F_2^γ can be distinguished into a perturbative calculable point-like part, representing the production of a quark pair and a non calculable hadron-like part, describing the photon fluctuating into a hadron state, e.g. a ρ -meson. As of 2017, these processes have been calculated in leading order (LO) [2] and in next to leading order (NLO) [3], by perturbation theory. The calculations are requiring the restriction, the momentum transfer Q^2 is significant larger compared to the QCD scale parameter Λ_{QCD} .

However, the point-like part rises a power singularity for Bjorken-scale variable x [4, 5], which can be regularized with the introduction of a cut-off [6, 7], ending up in reducing the sensitivity towards α_s and

a unphysical cut-off dependences [8]. Therefore, the fit of α_s and of the cut-off to the experimental data has to be done. A different approach to get rid of the singularity, is the cancellation of every order of the perturbation calculations, resulting in a hadronic boundary condition at low static scale Q_0 [9], where the hadronic input has also be fitted to the experimental data. The hadronic input evolution with Q^2 is given by perturbation calculations [10].

The main results of F_2^γ data has been determined via e^+e^- colliders, like LEP over the last decades and already been used for the determination of α_s in NLO [11]. In this context, F_2^γ data from the last decades from the different e^+e^- experiments from LEP, KEK, PETRA and SLAC [12–35], obtained in the process $\gamma\gamma \rightarrow X$, is used in the following. The latest published measurements [14, 15, 22] make a repeat determination of α_s very interesting, especially if one takes next to next to leading order (NNLO) evolution into account. For the achievement of that long term goal, this project aims to implement the fit of the photon structure function inside the xFitter framework [36, 37]. xFitter is a parton density function (PDFs) fit program and will be introduced later in more detail.

In the following a short introduction to xFitter is given, explaining its basic structure and the output. The first preparations and changes introduced in xFitter will be discussed afterwards. Closing with a discussion of the results and a short summary.

2 The xFitter framework

xFitter is an open-source program for the determination of the parton distribution functions of the proton. Furthermore, it provides many different kinds of QCD analysis tools. Theoretical predictions and experimentally determined data are handled by several methodological options, resulting in PDF fits. These results can be easily visualized by the internal plotting tools. xFitter has been used in many different analysis and areas, for example in case of QCD analyses for inclusive [38] and heavy flavour production measurements [39], as well as for the investigation of Standard Model processes at LHC, like the determination of the strange quark density of the proton with W and Z decays [40].

The basic structure of xFitter is displayed in fig. 2. Inside the framework, the measurements from various processes including their uncertainties, are provided and are the starting point of any proton PDF determination. The data input-files, have standard ASCII form, where in the header all data information is provided about the data table content below. The data include Q^2 , the Bjorken- x , the measured cross section and the available information of the uncertainties. These input PDFs are parametrized with a functional form at a starting scale Q_0^2 . There are several functional forms for the different parametrizations for the quark and gluon distributions available. The standard parametrization for example is of the form:

$$xf(x) = Ax^B(1-x)^C(1+Dx+Ex^2), \quad (1)$$

which is used in case of PDF distributions at HERA, for the valence quarks xu_v and xd_v , the gluon xg and the sea quarks $x\bar{U}$ and $x\bar{D}$. Several constraints are applied on the fit parameters (A-E), e.g. the momentum sum-rules.

In the second step of the analysis process, the PDFs get evolved towards increasing Q^2 correspondent to the measurements uses the DGLAP [41–45] evolution by default, other options are available. The cross section prediction, for a particular process, is given by the convolution of the evolved PDF with the corresponding scattering cross section of the parton.

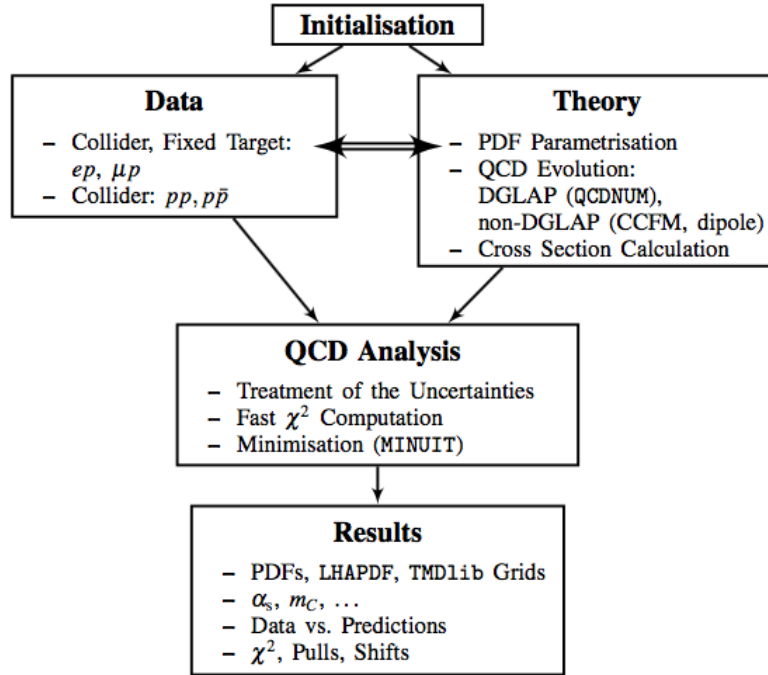


Figure 2: Illustration of the xFitter workflow, taken from [36]. Input data is fitted at starting scale Q_0^2 , following the PDF evolution. The final distributions are extracted via minimization afterwards.

The provided input data and the theoretical predictions, are compared to determine the PDFs in the fit, which is performed using MINUIT [46]. xFitter provides a lot of output information, in fig. fig. 3, one can see the results for the distributions of the valance quark xu_v and the gluon xg , fitted as an example from HERA data at a starting scale of $Q_0^2 = 1.9 \text{ GeV}^2$.

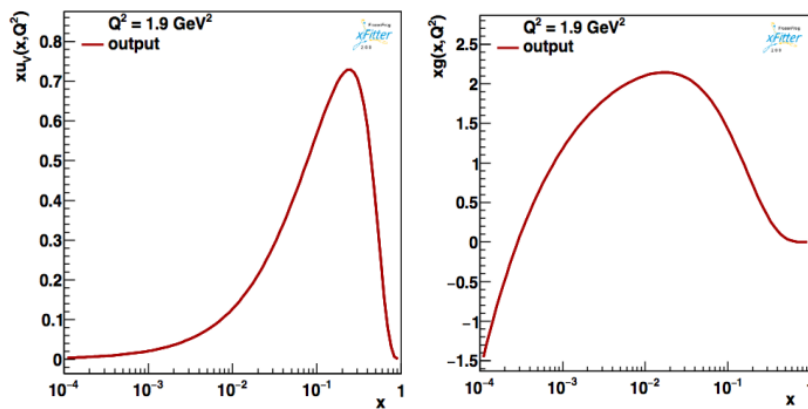


Figure 3: Example for partron distributions, determined with xFitter using DIS data from HERA. Left: valance u-quark distribution. Right: gluon distribution.

The fit is displayed in fig. 4. The solid line shows the fit to the data with systematics, while the dashed line shows the result with switched of systematics. Typically, the starting scale is displayed and if evolved, the results show the scale. The theoretical predictions are compared with the data in the plot below. Additionally, xFitter provides several details of the fit to judge its quality, e.g. χ^2 or the number of degrees of freedom.

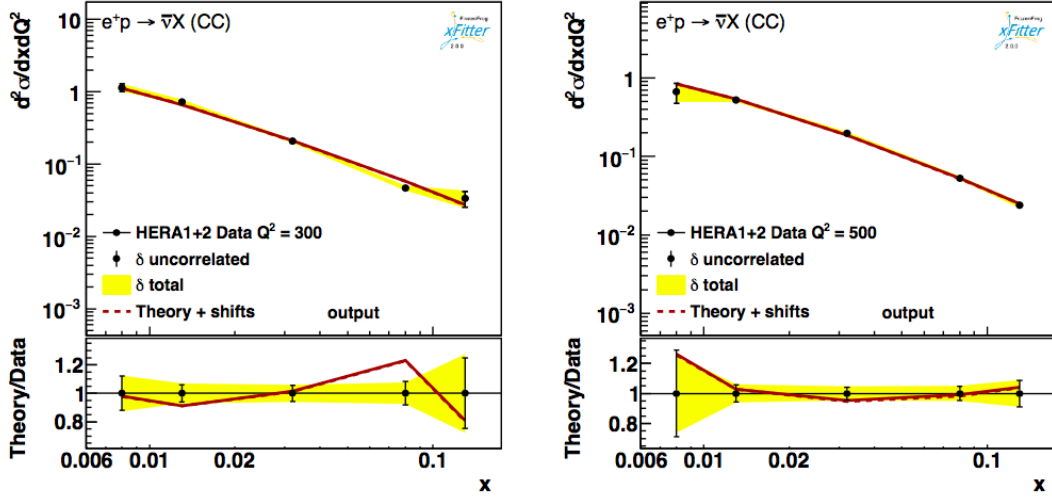


Figure 4: Fit result for HERA data. The plots display the result of the differential cross section fit for evolve scales Q^2 .

While photon and proton share common characteristic in case of hadron production, the main work to include the PDF extraction of photons from F_2^γ data, consist in the change of the functional form of the parametrization and the PDF decomposition. Additional changes regarding evolution, driven by an sub program like QCDNUM [47], where the NNLO calculations have to be implemented, have to be taken into account. In the next section of this report, the implementation of the F_2^γ fit will be introduced, regarding the changes, which have to be done inside xFitter and discussing first results.

3 Implementation of the F_2^γ fit

In order to perform the analysis of F_2^γ data with xFitter, several changes inside the program were made, including the input data, the PDF parametrizations, the PDF decomposition and the evolution. Therefore, different changes and options have been implemented in xFitter.

3.1 Input data

In terms of this project, only measured F_2^γ data from e^+e^- colliders with the process

$$e^+e^- \rightarrow e^+e^-\gamma\gamma \rightarrow e^+e^-X, \quad (2)$$

are taken into account. All data input files are created specifically for this project, following the xFitter standard input files format. In the header, the main information about the data is provided, the number of data points, the reaction type and the content of the different data table columns (*bin, x, sigma* or *error*). The data table consists of different columns for Q^2, x , the cross section and the errors. For the photon fit, the cross section is just replaced with the F_2^γ data points, without any further changes. In all data files, just one statistical and one systematic error are provided. The Q^2 values cover a range starting from 1.9 GeV^2 till 390 GeV^2 . In terms of consistency, for the Bjorken- x , the bin center is used, since this is the original value used for the proton fit.

3.2 Photon PDF parametrization

The parametrization is one of the most important parts in this project since it has to be chosen wisely in order to get a proper description of the photon PDFs. The first step is the analysis of the above mentioned F_2^γ data files with the xFitter default setup called HERAPDF. The main change, which has been made here, is to set the valence quark distributions to zero since they don't contribute in case of the photon. For this purpose, a new PDFstyle inside xFitter is implemented. Both setups will be described in the following more precise.

3.2.1 Photon fit with HERAPDF style

The parametrized PDFs included in the HERAPDF style, are the valence quarks xu_v and xd_v , the xg distribution for the gluon, as well as the sea quark distributions $x\bar{U}$, $x\bar{D}$. Equation 1 is used as the functional form, where the parameters are constrained by the sum-rules. In HERAPDF fits, the strange sea quark density is assumed to have an identical shape as the down quark density. Furthermore, the strange quark distribution itself is already present at the starting scale of the evolution. A more detailed description of this PDFstyle can be found in the xFitter manual.

In order to get a preliminary results of the photon PDFs, described with the xFitter default HERAPDF style, only data points at the starting scale of $Q_0^2 = 1.9 \text{ GeV}^2$ are analysed. Therefore a separated input file created, containing 19 data points inclusive their statical and systematic uncertainties. The systematic uncertainties are assumed to be uncorrelated, setting them *uncor* in the header of the data file. All five parameters, describing the valance distributions, are set to zero and fixed, leaving 11 free parameters for the fit. Fig. 5 displays some important results, one gets using this setup. In the first line, one can see that the valance distributions xu and xd are fixed at very small values $\sim 10^{-6}$, while as one would expect, the gluon distribution xg shows a totally different behaviour, compared with the result from a proton fit fig. 3 right hand side. However, the last distribution in fig. 5 contains the most interesting information. As one can see on the right side, the fit is described quite good by the functional form at starting scale. However, the χ^2 value is quite high and the fit contains only 5 degrees of freedom, as it is displayed by the table next to the fit. It has been observed, that with additional parameter, the result improved a lot. In future tasks, this could be useful to optimize the description of the PDFs, while using the HERAPDF parametrization.

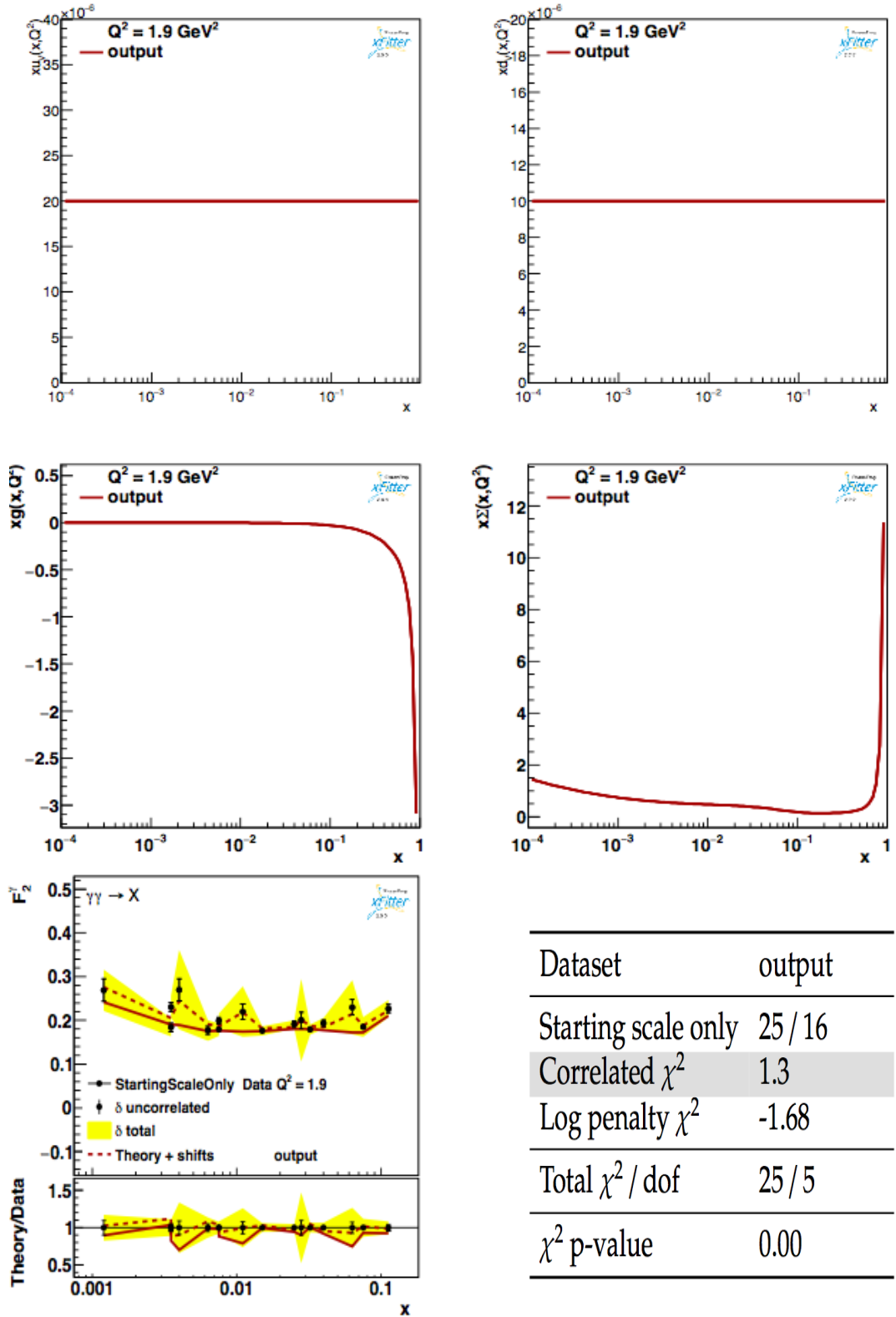


Figure 5: xFitter output of starting scale fit. Only 19 data points for $Q_0^2 = 1.9 \text{ GeV}^2$ are fitted with HERAPDF style and switched off valance quarks. The top line shows the xu_v and xd_v valance distributions, followed by the distribution of the gluon xg and the quark singlet distribution $x\Sigma$. The last plot displays the fit. solid line: fit with systematic uncertainties. dashed line: without systematic uncertainties.

3.2.2 GRV parametrization

Additionally to the HERAPDF style, different parametrizations are considered, to get the best possible description of the photon PDFs. The Literature already provides several examples of parametrizations for the photon structure function F_2^γ . A summary can be found in [48]. One particular interesting example, is the parametrization of Glück et.al. [49] (GRV), who performed LO and HO analysis of the F_2^γ distributions, using vector-meson dominance (VMD). For the light quarks and the gluon

$$xf(x, Q^2) = x^{a_1}(a_2 + a_3 \sqrt{x} + a_4 x^{a_5}) + s^{a_6} \exp(-a_7 + \sqrt{a_8 s^{a_9} \ln(1/x)})(1-x)^{a_{10}}, \quad (3)$$

with $s = \ln(\ln((18.58 * Q^2)/(1.53)))$ and 10 fit parameters a_i .

The heavy quarks s, c and b are described with 12 parameters and functional form:

$$xf(x, Q^2) = (s - a_1)x^{a_2}(a_3 + a_4 \sqrt{x} + a_5 x^{a_6}) + (s - a_7)^{a_8} \exp(-a_9 + \sqrt{-a_{10} s^{a_{11}} \ln(x)})(1 - x)^{a_{12}}. \quad (4)$$

This parametrization can be used inside xFitter, switching the PDFStyle in the steering.txt to the new introduced style 'F2_GAMMA'. This PDFStyle uses the same PDF_Decomposition like the HERAPDF style. However, not the same distributions are used, because this step of the analysis should be more understand, as a way to find how one can implement new functional forms inside the framework. The composition of distributions, which are part in case of the photon PDFs, have to be optimized in the future.

However, for a first impression of the GRV parametrization, a fit is performed with the same condition as in sec. 3.2.1. Again, 19 data points at the evolution starting scale $Q_0^2 = 1.9 \text{ GeV}^2$ are used for the fit, as well as the same setup of the minuit input parameters and constrains. The valance quarks are switched off again, by setting the corresponding parameters to small values ($\sim 10^{-20}$) and fix them. This can be seen in the results fig. ??, where xu_v and the xd_v distributions are obviously fixed at very small scales, like for the HERAPDF before. Regarding the fit informations, one can clearly see that the data is not described very good by the parametrization. Also the number of degrees of freedom is quit unreal. This leads to the conclusion, that obviously the chosen configuration inside xFitter is not flexible for the description of the data points. A solution could be, to fix the PDF composition, implemented inside xFitter for this new PDFStyle and also to add additional parameters. This might give the fit more freedom and might result in a more precise description.

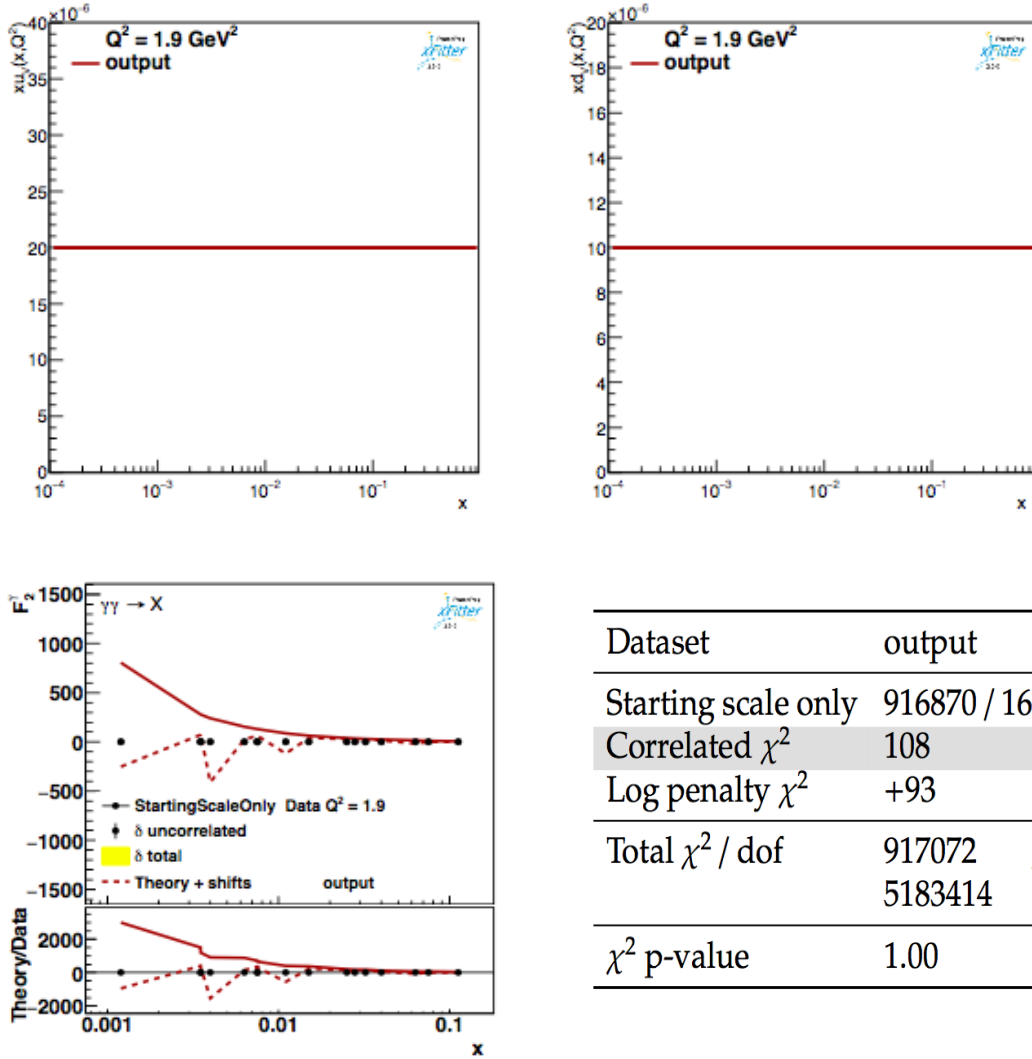


Figure 6: xFitter output of starting scale fits with GRV parametrization. For $Q_0^2 = 1.9 \text{ GeV}^2$ data with switched off valance quarks. The plots at the top show the xu_v and xd_v valance distributions, followed by the fit results.

4 Summary

In case of this summer student project, F_2^γ measurements obtained from e^+e^- collider over the last decades, was collected and converted into a data format, which can be used by the xFitter framework. It has been shown, that xFitter is able to analyse the collected F_2^γ data in general, although the framework itself has to be optimized, to get useful output. Furthermore, there are signs, that the F_2^γ can be fitted with xFitter, leading to reasonable results, with the default setup HERAPDF style. This can be huge advantage, since it reduces the number of changes, which have to be implemented for the photon fit, compared to the introduction of a completely new fit setup for photons. However, in order to get proper fit results further changes of the HERAPDF style have to be made. Adding additional parameters seem to be a promising way, giving the fit process more freedom and therefore make it easier to parametrize the distributions.

Additionally, an alternative functional form for the parametrization has been implemented. Even that the first fit trials with the GRV parametrization are not satisfying, it gives a first impression how a new parametrization has to be implemented inside the xFitter program.

The main step for the near future, should be to find the best parametrization of the photon PDFs. Therefore, the fit at starting scale has to be optimized first. Afterwards, one should consider the evolution, first working with the implemented proton evolution in the xFitter framework, to perform a good fit as a starting point for the next step, which is the implementation of the NNLO photon evolution. Once this is implemented inside xFitter and the results are satisfying, the extraction of α_s can be taken into account.

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