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Recent Experimental Constraints on Proton Structure

Voica Radescu*
DESY
Notkestrasse 85
D-22607 Hamburg, Germany
E-mail: voica@mail.desy.de

In the era of Higgs discovery, it is crucial to achieve higher level of precision in understanding the proton structure for obtaining the maximum possible information of Higgs' properties and to allow for most unambigous interpretations of the high energy, luminous data ahead. A tour that encapsulates the most recent measurements from past, present, and possible future experiments sensitive to the proton constituents is summarised in these proceedings.

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*Speaker.

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1. Introduction

A precice understanding of the hadron structure of the quark gluon dynamics is crucial to allow further discoveries in searches of new physics. The current precision of proton structure still represents a limiting factor of our knowledge of cross section determinations whether we deal with Standard Model (SM) or Beyond SM (BSM) formalism. Nowadays, the level of agreement among groups in extracting proton's parton distribution functions (PDFs) is of about 10% for the prediction of Higgs cross sections, which represents one of the dominant sources of uncertainties. As a consequence, there is a strong motivation to achieve a better understanding of the proton structure.

The key mechanism in extracting the proton constituents relies on the factorisable nature of the cross section that separates the partonic reaction (short distance), calculable in perturbative Quantum CromoDynamics (QCD) theory, form the proton PDFs (long distance) extracted from data. The process of Deep Inelastic Scattering (DIS) using elementary particles provides the cleanest method to probe the proton structure and extract the PDF information. The DIS experiments have been carried out either on fixed target (SLAC, BCDMS, NMC, JLAB) or using collider accelerator facilities such as the ep collider at HERA. The persistent experimental efforts blended in with the theoretical advancements over the last 40 years have provided a full coverage of precision measurements in the kinematic plane needed for the PDF extraction. PDFs can be further constrained by the measurements from the hadron colliders at Tevatron ($p\bar{p}$) and LHC (pp) for which Drell-Yan processes can be used to predict lepton pair production. At the LHC the electroweak gauge bosons Z, W are copiously produced and can provide important feedback in the area of PDF flavour decomposition, as it will be shown later.

2. Recent results from HERA

Crucial information on the proton structure comes mainly from the only ep collider HERA, located at DESY. New measurements from the HERA II running years have been presented and a selection of relevant results sensitive to PDFs are mentioned in the following.

2.1 Towards HERAPDF2.0

The H1 and ZEUS experiments at HERA have currently finalised their separate analyses of the inclusive neutral current and charged current $e^{\pm}p$ differential cross section measurements complementing the HERA I with the recent HERA II results [1], [2]. Figures 1 show selected measurements demonstrating the precision reached with the increased statistics of HERA II due to an increased luminosity compared to HERA I run. Therefore, the expected final combination of inclusive measurements from the H1 and ZEUS collaborations will improve the PDFs especially in the valence quark distribution which dominate the high x region. It is worth mentioning that by combining their measurements, H1 and ZEUS are capable to check the consistency among different sets and provide coherent and most precise data sets from HERA to be used in extraction of the PDF sets by various theory groups, as well as by the HERA community. The latter with its previous predecessors of HERAPDF series of PDFs extracted solely from ep reaction represent an important check of universality of PDFs when compared with PDFs extracted from world data.

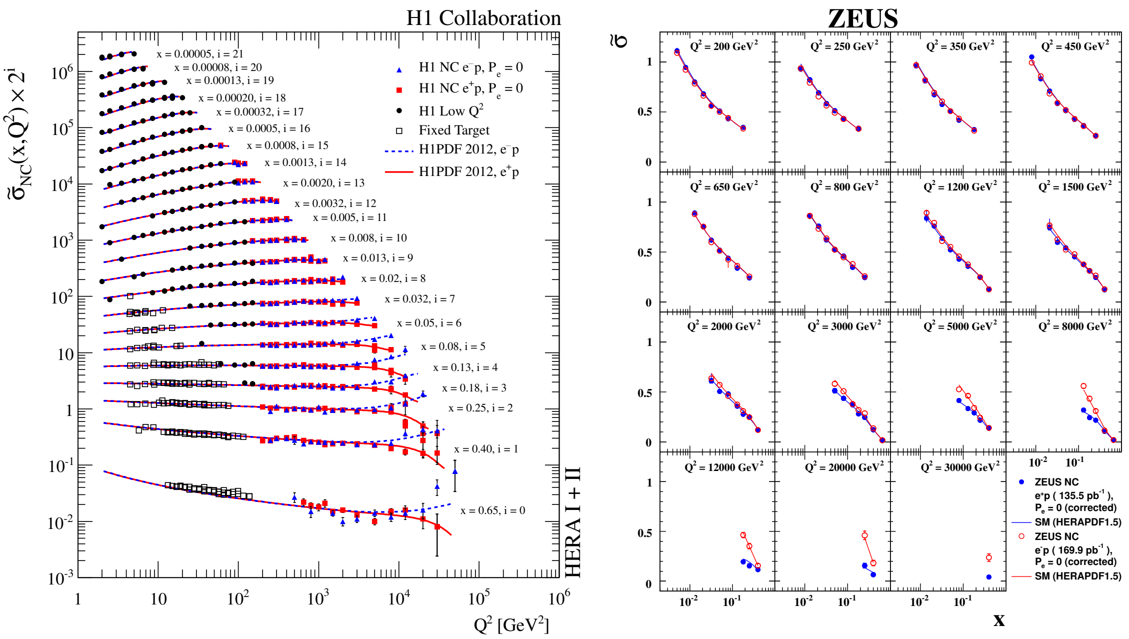

Figure 1: Figure shows on the left hand side the HERA II H1 neutral current measurements as function of Q^2 for each x bins compared to prediction extracted by fitting these data points; and on the right hand side the HERA II ZEUS charged current measurements as function of x for each available Q^2 bin is compared to predictions based on HERAPDF1.5 NLO.

2.2 Asymmetries from HERA

Additional information can be extracted by exploring the asymmetric measurements which allow either cancellation of common uncertainties, or to single out an observable of interest. For example, at HERA, the charge asymmetry has been used to extract the structure function $xF_3^{\gamma Z}$, a measurement that has benefited from an improved statistics provided by the HERA II data [1], [2]. Moreover, the use of longitudinally polarised electron beams during the HERA II period allows the extraction of the $xF_2^{\gamma Z}$ structure function by exploiting the polarisation asymmetry [1], which previously was not possible from the HERA I unpolarised run. The shapes of the distributions of these structure functions reflect their parton sensitivity as shown in Fig. 2: valence-like for $xF_3^{\gamma Z}$, and sea-like for $xF_2^{\gamma Z}$.

2.3 Charm at HERA

The charm production at HERA brings interesting impact on the gluon PDFs, but also provides an important input for the theoretical approaches that include heavy charm threshold in their calculations. This data has proved to constrain the value of charm mass chosen rather as a tuning parameter in variable flavour number of schemes (VFNS), than as a pole mass. The optimal value for M_c has been found for each of the tested VFNS schemes through a QCD fit procedure for a series of charm mass values used as input for the fits. This lead to a better agreement among predictions when they have been evaluated at their optimal value, not only for the F_2^c but also for the W and Z productions at the LHC. Figure 3 presents such a scan in the tuning parameter M_c and this information transferred to the W production. The observed large spread of the total cross section

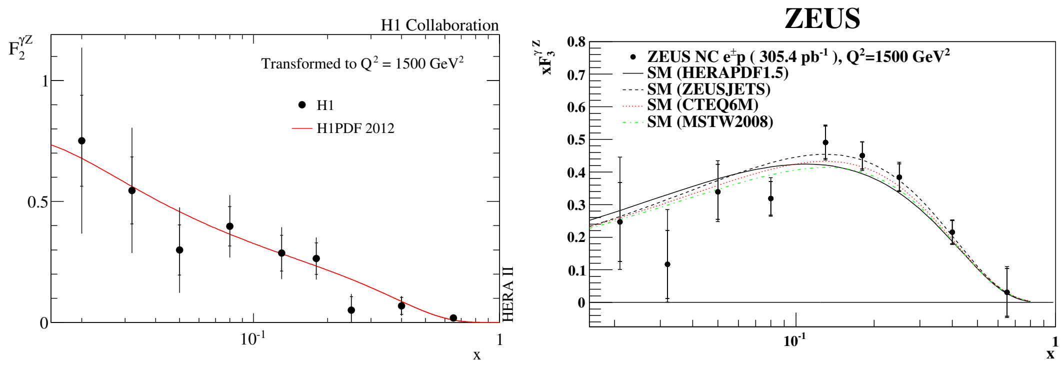

Figure 2: Figure shows on the left hand side the $xF_2^{\gamma Z}$ extracted by the H1 Collaboration compared to the prediction based on a fit to the H1 measurements, and on the right hand side the $xF_3^{\gamma Z}$ extracted by the ZEUS Collaboration compared to various predictions.

predictions is significantly reduced when predictions are compared at the optimal M_c determined from fits to F_2 charm.

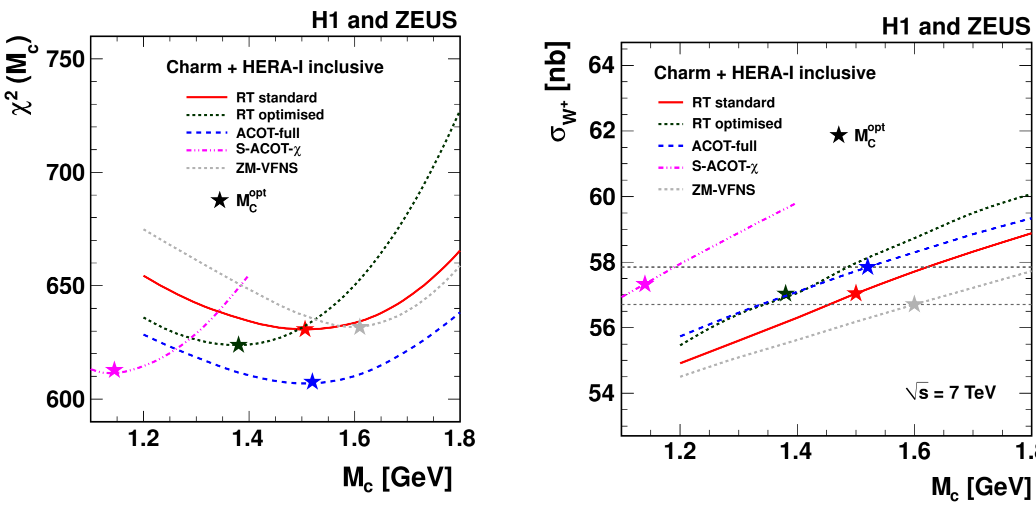

Figure 3: Figure shows on the left hand side the χ^2 scan as function of the input value for the charm mass used in the QCD fits based on various heavy flavour treatments to data which include the charm data and on the right hand side, and on the right hand side the comparison among predictions to W total cross sections at the LHC based on different theoretical schemes as function of charm mass input.

3. HERAFitter QCD Fit Framework

HERA has rightly gained its expertise in the extracting of the proton structure not only through the efforts in performing precise measurements, but also through the developments in interpreting these measurements in the context of a QCD framework. This expertise has been concreted into an open source QCD Fit Framework, HERAFitter [4]. Although it has started within the H1 and ZEUS collaborations, it has been extended successfully into the LHC community with a correspondingly large theory development.

The HERAFitter framework is built in a modular structure to allow independent developments for multiple developers ranging from various experiments and theory areas. Since its first release in September 2011 it has been successfully used by the high energy community, and successfully transferred to te LHC analysers to assess the impact of new measurements. This framework not only that it can extract the PDFs by using various set of data from different reactions, but can also provide a quantitative level of agreement between data and any theory accounting for the given sources of systematic and statistical correlations. It can also extract from the QCD fits the strong coupling by taking the correlation with gluon into account. Different available theoretical treatments can also be compared under the same conditions to assess better their differences in describing data. This framework is an asset not only to the theoretical developments, by allowing fair benchmarking exercises, but also to the experimentalists to assess and enhance the impact of new measurements.

4. Recent results from the LHC relevant to PDFs

The successful run during $2010-2012$ at the LHC has confirmed and tested the SM formalism of particle physics. LHC, with its multitude of new measurements can provide not only PDF discrimination by confronting theory with data, but also PDF improvement by using the LHC data in a QCD fit framework for the interpretation of new measurements. The following areas have shown to bring important new information sensitive to the proton structure: production of W and Z, production of W in association with charm, Drell-Yan production at low and high invariant di-lepton masses, inclusive jet and di-jet measurements, as well as single top and $t\bar{t}$ production, which will be described in further details in the next sections.

4.1 W and Z production

At the LHC, unlike as at HERA, the Drell-Yan and jet measurements probe a bi-linear combination of quarks (as we deal with proton - proton collision). The decomposition in quark distribution of the charged current $W^{\pm}$s and neutral current Z and γ^{*} as function of the rapidity of the boson (or pseudo-rapidity of the lepton) are different: while for $W^{+(-)}$ the dominant contribution comes from the $u\bar{d}(d\bar{u})$ quarks, for Z there is rather a similar weight for each of the quark as shown in Fig. 4. Therefore, by exploiting these differences further, new information on light sea decomposition can be achieved, proving that the measurements of W and Z production differentially in rapidity y can bring an important feedback to PDFs.

As for HERA, the interplay between the flavour asymmetries can be also enhanced at LHC via the ratio measurements such as W charge asymmetry. This measurement has been performed by the CMS [6], ATLAS[5] and LHCb [7] collaborations. The CMS has chosen to measure directly the electron asymmetry from the 2011 data, while the ATLAS has translated the separate differential measurements of W^{+} and W^{-} into charge asymmetry by careful consideration of common correlations. The LHCb extends the measurements into forward region, an interesting region where distribution changes sign due to Vector-Axial structure. These measurements as shown in Fig.5 can not be directly compared among eachother as they are presented in their fiducial volume, where selection criteria are optimized for each experiment. It is clearly observed that prediction based on the MSTW08 PDF [25] fails to describe this measurement [1].

[1] This finding was addressed by the authors in [26].

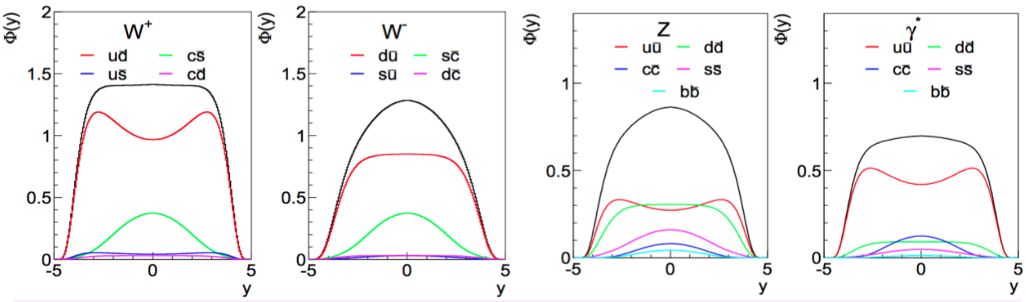

Figure 4: Figure shows the flavour decomposition at LO of the $W^{\pm}$, Z and γ^{*} distribution as function of rapidity. Different colors represent the different quark distribution.

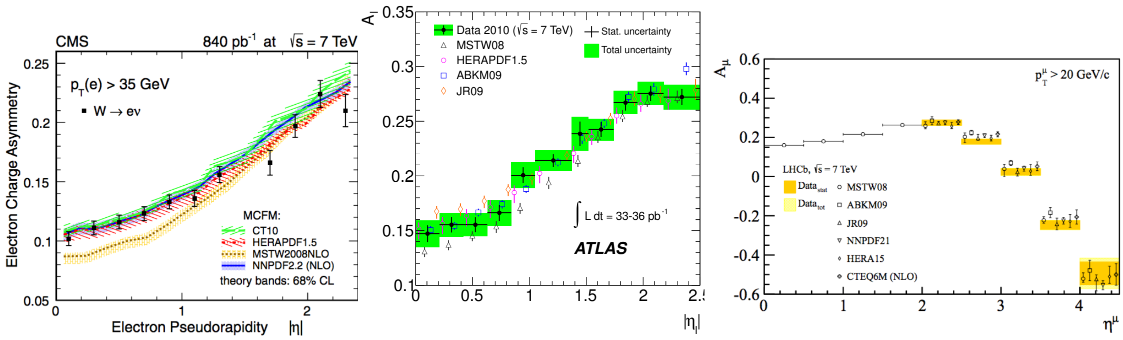

Figure 5: Figure shows the W charge asymmetry measurement extracted by the three experiments at the LHC: CMS (left), ATLAS (middle), LHCb(right). The measurements are confronted with predictions based on various PDF sets.

The neutral current Drell-Yan di-lepton measurements have the potential to bring additional constraints on the sea quark PDFs. ATLAS [8], CMS [12] and LHCb [10] have provided beautiful Drell-Yan measurements in the invariant mass spectrum (in the combined di-electron and di-muon channels, or in the separate channels) in an extended range from 5 GeV to 1500 GeV. A good agreement with the SM predictions is observed. However, the differential measurements in the rapidity distributions are of more interest for PDFs as they provide shape information. These differential measurements are provided by ATLAS, CMS, LHCb and a good agreement is found among them after extrapolating to a common region [9]. When ATLAS measurements are confronted with theoretical predictions based on different PDFs some tensions are observed, in particular with the ABM[20] and JR[21] sets, as seen in Fig.6.

The strange quark is one of the least constrained PDFs and the current PDF groups rely on the information coming from the neutrino dimuon data [27] which favours a suppressed strange as compared to light quarks $xu(x)$ and $xd(x)$. At the LHC, the Z differential cross sections in y_Z can provide a constraint on strange quark density, enhanced by the use of W data to fix the normalisation uncertainty. The LHC measurements are in the kinematic region of $x \sim 0.01$. ATLAS has determined the strange quark density by performing a NNLO QCD fit to both W and Z differential data collected in 2010. The advantage of using both measurements is to cancel out the common systematic sources, of which in this particular case, the dominant one arises from the luminosity uncertainty of 3.4%. The ATLAS results indicate a flavour symmetric sea with an enhanced

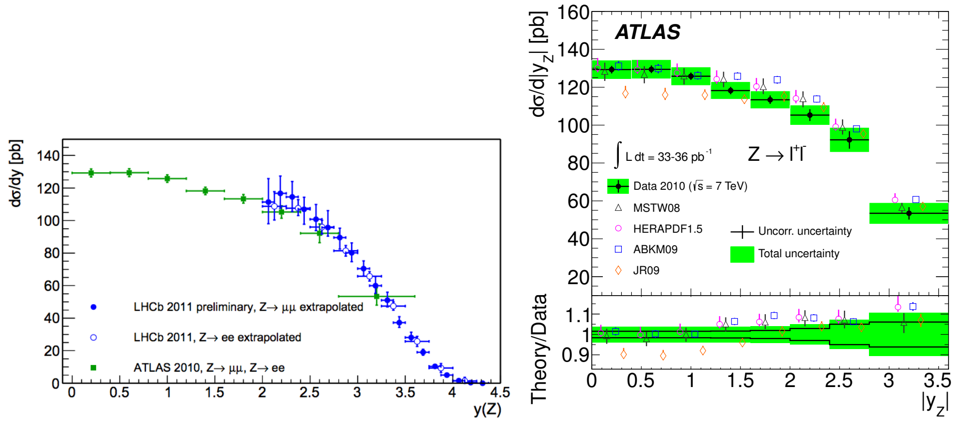

Figure 6: Figures show the differential cross section for Z boson production as a function of the rapidity of the Z boson. The LHCb results in the muon chanel are extrapolated to the fiducial volume of the ATLAS measurement (left), while the Z differential cross section from ATLAS (right) is compared with predictions based on various PDFs (shown in different symbols).

strangeness which is found to be in agreement with the predictions from [22] and above the ones from [25], [20], [24] evaluated at NNLO. Figure 7 visualises this result, with r_s defined as $r_s = \bar{s}/\bar{d}$.

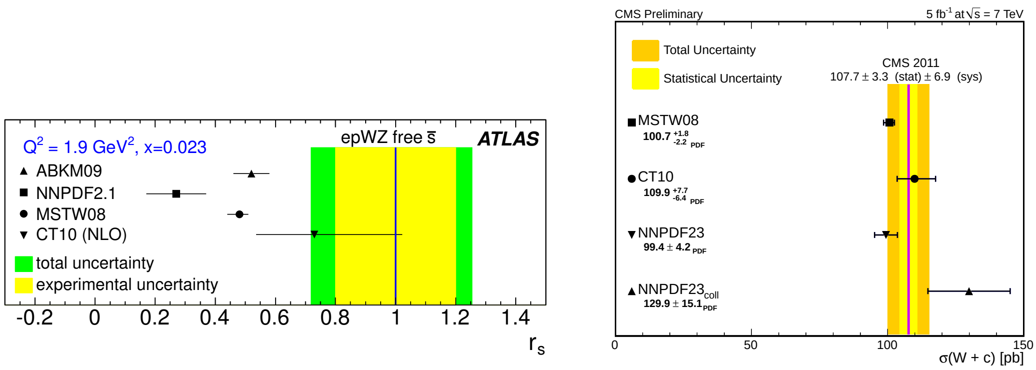

Figure 7: Figure shows on the left hand side the theoretical predictions compare to the experimental measurement from ATLAS, and on the right hand side the comparison of the theoretical predictions for $W+c$ total cross section for several sets of PDFs with the averaged measurements from CMS.

The impact of the fit results is observed as the cross section for the Z is increased and its shape is affected by the enhancement of the strange, while for the W's there is in fact little difference observed. This result can be cross checked with a complementary measurement of W production in association with heavy charm which is directly sensitive to the strange content in the proton. CMS has released a preliminary result[2] which shows best agreement with the predictions based on CT10 PDFs [22] which has rather larger strange content as shown in Fig. 7.

4.2 Inclusive Jet and Di-Jet Production

It is already known that the jet measurements are directly correlated to the gluon density,

[2] ATLAS has also released by now a preliminary result [14] that confirms the enhanced strangeness observation.

therefore measurements at the LHC with their extended kinematic reach are sensitive to gluon at high x. ATLAS and CMS have both released measurements of inclusive jet and di-jet cross sections differential in p_T (or invariant mass) and rapidity y [15], [16]. These measurements are provided with full information on correlated systematic sources which are crucial in extracting the strong coupling of QCD. Since the dominant uncertainty of these measurements are arising from the jet energy scale, there is a clear advantage of using the ratio measurements, for which common systematic uncertainties cancel out. Moreover, LHC has provided two beam energies of 2.76 and 7 TeV which probe different x and Q^2 values for the same p_T and y ranges so that the theoretical uncertainties due to PDFs do not cancel out in these ratios providing therefore more impact on PDF determination than from the separate data sets. ATLAS has employed the HERAFitter framework to study the impact of these ratio measurements to the gluon PDFs [16]. This is shown in Fig.8, where the results are compared using as a reference sample the HERA I data alone. The results indicate that gluon becomes harder in shape and its uncertainties are reduced especially in the high x region which improves the level of agreement between data and theory in the most forward region.

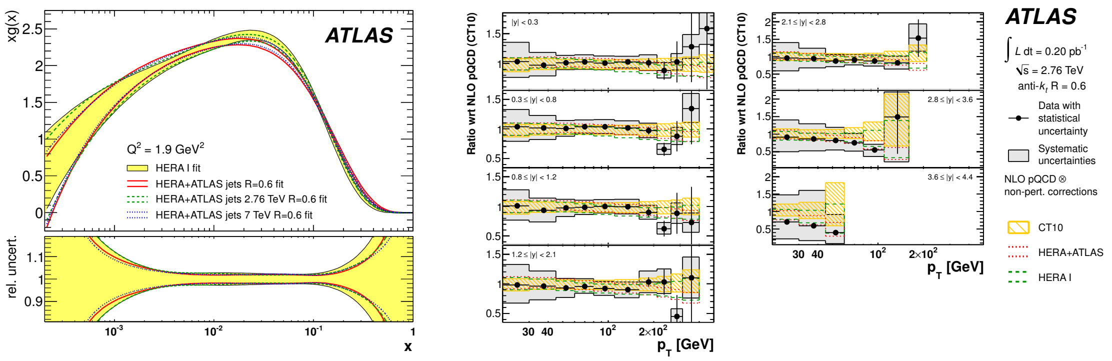

Figure 8: Figure shows on the left hand side the gluon $xg(x)$ together with their relative experimental uncertainty as a function of x for $Q^2 = 1.9\text{GeV}^2$. The filled area indicates a fit to HERA data only. The bands show fits to HERA data in combination with both ATLAS jet data sets, and with the individual data sets (each for jets of $R = 0.6$ size). On the right hand side comparison of NLO pQCD predictions of the jet cross-section at $\sqrt(s) = 2.76$ TeV is shown. The predictions are normalised to the one using the CT10 PDF set. Also shown is the measured jet cross-section. The 2.7% uncertainty from the luminosity measurement is not shown

4.3 Sensitivity to PDFs from the top production

The top production at LHC is a promising new input in constraining PDFs, especially for the gluon distribution at high x. The recent unfolded distribution from the top pair production provided differentially in various variables at CMS from 8 TeV data [19] has been compared with various theoretical predictions. It is important to note that the availability of higher order calculations makes this a compelling measurement, as the dominant theoretical uncertainties arising from the scales are significantly reduced. Figure 4.3 shows the normalised differential $t\bar{t}$ production cross section as a function of invariant mass and rapidity of the top quark.

5. Future prospects

There are several projects formulated for future large facilities: LHeC [29] an ep collider to

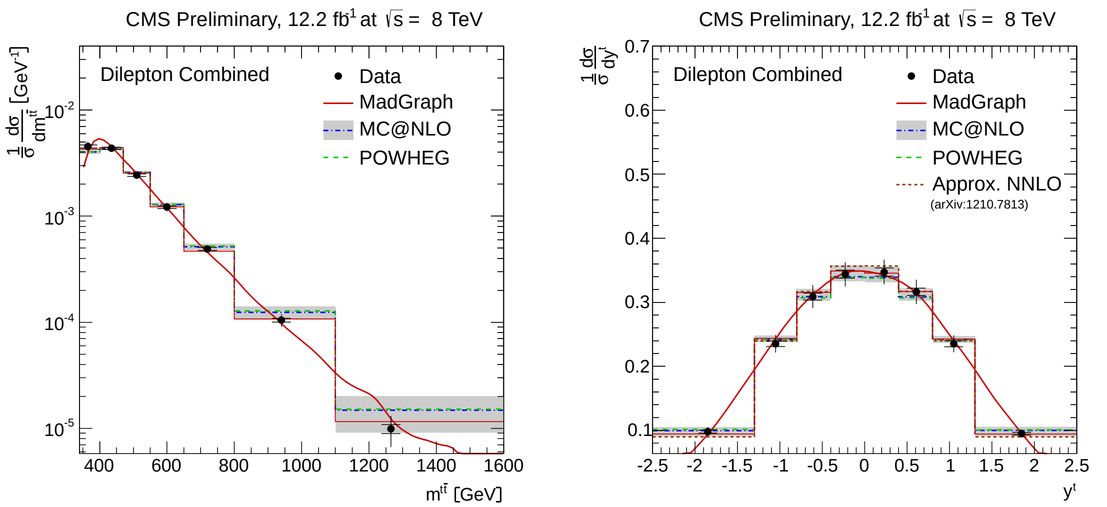

Figure 9: Figures show the differential cross section for $t\bar{t}$ production as a function of the rapidity of the invariant mass (left) and rapidity distribution of the top quark (right) from CMS). The measurements are confronted with the most accurate available theoretical predictions.

complement LHC at CERN, EIC [28] an *eA* collider to address the spin structure, and ILC [30] an e^+e^- linear collider. The LHeC promises to provide a complete precise PDF set which would enhance then the measurements at the LHC. In addition, the LHeC promises per mille accuracy on the strong coupling, fundamental parameter of QCD. The LHeC has also the potential to access a clean and complementary channel the Higgs Production, through di-boson fusion rather than gluon-gluon fusion at *pp* collider.

6. Summary

PDFs are an important ingredient needed to be understood to facilitate possible new discoveries at the LHC. There are huge efforts from different experiments to produce further measurements to constrain even better the PDFs. HERA has finalised its separate measurements relevant to PDFs and their current ongoing efforts are on combining final measurements to reach its ultimate precision. Standard Model LHC measurements can themselves contribute to PDF discrimination and PDF improvement. LHC data suggest that the light quark sea is flavour symmetric: the results on strange density from the W, Z inclusive measurements are being cross checked against the $W+c$ production. Exploiting different energy beams for inclusive jets brings forward sensitivity to the gluon PDFs. The gluon PDF can also be improved in the future also through the photon-jet measurements. Top measurement is becoming an interesting ground to bring impact on gluon PDFs (and alphas). Many more valuable measurements are already available, but not covered in these proceedings. More precision measurements from the LHC are still to come from Run I and in the future from Run 2. LHeC project has the potential to represent a natural extension to LHC by providing an accurate and complete PDF set and an access to a clean channel in Higgs production.

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