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Partons from the LHeC

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Abstract

A brief introduction is given to the potential of the LHeC for the determination of the full set of quark distributions $xq(x, Q^2)$, $q = u_v,\ d_v,\ \bar{u},\ \bar{d},\ s,\ \bar{s},\ c,\ b,\ t$, and the measurement of the gluon distribution $xg(x, Q^2)$ for x between about 10^{-6} to 1 and Q^2 between 1 and up to 10^6 GeV^2. An initial QCD analysis of fully simulated inclusive LHeC data provides a set of PDFs with their uncertainties, which is made available at LHAPDF for the study of prospects for future measurements in *ep* and *pp*. The LHeC determines $\alpha_s(M_Z^2)$ to per mille level precision and maps xg, for solving the saturation question at low x and providing a new basis for precision Higgs measurements and searches for new physics extending to high mass at the LHC.

1 Introduction

The Large Hadron Electron Collider (LHeC) is a newly designed *ep* collider [1]. Based on the intense, high energy hadron beams of the LHC, by adding a new electron beam of typically 60 GeV energy a first TeV energy scale electron-proton and electron-ion collider [1] can be built. As the first application of energy recovery techniques for high energy particle physics, the LHeC is designed to achieve a luminosity in excess [2, 3] of $10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Very high integrated *ep* luminosities of several hundreds of fb^{-1}, i.e. around a 1000 times more than at HERA, can be collected by operating the new electron machine synchronously with the LHC. Such a huge luminosity enables measurements close to $x = 1$ and the exploitation of the full Q^2 range, up to $Q^2 \simeq 10^6\,\mathrm{GeV}^2$, exceeding the kinematic range of HERA by a factor of 20. The question of gluon saturation at low x can be expected to be settled with precision measurements of the structure functions F_2 and also F_L down to $x \geq 10^{-6}$ [1] while the large x determination of xg is crucial for the LHC Higgs and BSM program [2, 3].

With the LHeC, very precise measurements of charged currents (CC) and the exploitation of Z exchange in neutral currents (NC) become possible, in addition to photon exchange NC extending to extremely low x. A full set of NC and CC cross section measurements has been simulated and a QCD fit analysis been applied in order to study the potential for the determination of the parton distribution functions in the proton.

There are two major deficiencies of current PDF determinations, as i) they rely on too restricted or inconsistent data sets leading to a severe dependence on theoretical assumptions and rather ad hoc χ^2 tolerance criteria, and ii) they employ mostly rigid parameterisations lacking direct data input for an evolved x dependence of the individual PDFs. The LHeC, combined with HERA to fill in the medium Q^2-larger x region, provides a unique and complete DIS data set. With unprecedented precision there will be for the first time a determination possible of *all* PDFs, u_v, d_v, $\bar{u}$, $\bar{d}$, s, $\bar{s}$, c, b and even t, in furthermore a hugely extended kinematic range.

As detailed in [1], the strange quark density will be measured for the first time in an accurate way with charm tagging of Ws fusion in CC scattering. Very precise measurements are in reach of the charm and the beauty quark density, from Q^2 values below the quark masses squared up to $\sim 10^5\,\mathrm{GeV}^2$, based on the small beam spot size of $\sim 7\,\mu\mathrm{m}^2$ and a high resolution silicon detector of large acceptance. This, for example, will determine the charm mass to a precision of 3 MeV [1], an order of magnitude improved as compared to HERA, and similarly for the bottom mass. Such high precision input will certainly provide a new basis for higher order tests of the treatment of heavy quarks in the Q^2 evolution, which currently is a significant source of uncertainty in the understanding of PDFs and the predictions for LHC.

As a first step, still ignoring the heavy quark density data as well as the simulated deuteron data from the LHeC, a full simulation of LHeC inclusive NC and CC cross section measurements has been performed. Using the HERAFitter framework [5, 6, 7] with settings based on the HERAPDF NLO QCD fit analysis, a set of PDFs is generated and stored on LHAPDF for estimates of future measurement potentials. An example is the prediction of the $gg \to H$ cross section at the LHC, which will have an uncertainty from PDFs and α_s of only about 0.4 % and thus be sensitive to determinations of M_H via the cross section [3]. Another example is the importance of knowing xg for high mass searches of SUSY particles as has also been studied recently [2, 4].

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[1] As HERA never accelerated ions, nor deuterons, the kinematic range in lepton-nucleus (eA) deep inelastic scattering (DIS) is extended with the LHeC by nearly four orders of magnitude in four-momentum squared Q^2 and towards low Bjorken x. This leads to a determination of the proton but also the neutron and nuclear PDFs in a hugely extended range and with unprecedented diversity, as is described in [1].

2 Simulation and QCD Fit Procedure

The systematic uncertainties of the DIS cross sections have a number of sources, which can be classified as uncorrelated and correlated across bin boundaries. For the NC case, the uncorrelated sources, apart from event statistics, are a global efficiency uncertainty, due for example to tracking or electron identification errors, photo-production background, calorimeter noise and radiative corrections. The correlated uncertainties result from imperfect electromagnetic and hadronic energy scale and angle calibrations. In the classic ep kinematic reconstruction methods used here, the scattered electron energy E'_e and polar angle θ_e, complemented by the energy of the hadronic final state E_h can be employed to determine Q^2 and x in a redundant way. Briefly, Q^2 is best determined with the electron kinematics and x is calculated from $y = Q^2/sx$. At large y the inelasticity is essentially measured with the electron energy $y_e \simeq 1 - E'_e/E_e$. At low y the relation $y_h = E_h \sin^2(\theta_h/2)/E_e$ is used, with the hadronic final state energy E_h and angle θ_h, resulting in $\delta y_h/y_h \simeq \delta E_h/E_h$ to good approximation. There have been various refined methods proposed to determine the DIS kinematics, such as the double angle method or the so-called sigma method. For the initial estimate of the cross section uncertainty behaviour as functions of Q^2 and x, however, the simplest method using Q^2_e, y_e at large y and Q^2_e, y_h at low y is transparent and accurate to better than a factor of two. In much of the phase space, moreover, it is rather the uncorrelated efficiency or further specific errors than the kinematic correlations, which dominate the cross section measurement precision. The assumptions used in the simulation of pseudodata rely on the detector designed in [1] and are summarised in Table 1. The procedure was gauged with full H1 Monte Carlo simulations and the assumptions are corresponding to H1's achievements with an improvement where justified by at most a factor of two. The data were simulated for NC and CC scattering assuming $e^{\pm}p$ luminosities of $10\,\mathrm{fb}^{-1}$ and a 40 % polarisation. Further studies are foreseen with alterations of these assumptions. This is in view on the recent choice of the ERL racetrack configuration of the LHeC electron beam, instead of the ring-ring configuration implicitly assumed here. For the linac, the electron beam luminosity will much exceed the here assumed value while the positron luminosity will be somewhat lower.

source of uncertainty	error on the source or cross section
scattered electron energy scale $\Delta E'_e/E'_e$	0.1 %
scattered electron polar angle	0.1 mrad
hadronic energy scale $\Delta E_h/E_h$	0.5 %
calorimeter noise (only $y < 0.01$)	1-3 %
radiative corrections	0.5%
photoproduction background (only $y > 0.5$)	1 %
global efficiency error	0.7 %

Table 1: Assumptions used in the simulation of the NC cross sections on the size of uncertainties from various sources. These assumptions correspond to typical best values achieved in the H1 experiment. Note that in the cross section measurement, the energy scale and angular uncertainties are relative to the Monte Carlo and not to be confused with resolution effects which determine the purity and stability of binned cross sections. The total cross section error due to these uncertainties, e.g. for $Q^2 = 100\,\mathrm{GeV}^2$, is about 1.2, 0.7 and 2.0 % for $y = 0.84,\ 0.1,\ 0.004$.

NLO QCD fits are performed in order to study the effect of the (simulated) LHeC data on the PDF knowledge. The procedure used here is adopted from the HERA QCD fit procedure [5] with a mimim Q^2 cut of $3.5\,\mathrm{GeV}^2$ and a starting scale $Q^2_0 = 1.9\ \mathrm{GeV}^2$, chosen to be below the charm mass threshold. The fits are extended to lowest x for systematic uncertainty studies, even when at such low x values non-linear effects are expected to appear, eventually altering the evolution laws.

The parameterised PDFs are the valence distributions xu_v and xd_v, the gluon distribution xg, and the $x\bar{U}$ and $x\bar{D}$ distributions, where $x\bar{U} = x\bar{u}$, $x\bar{D} = x\bar{d} + x\bar{s}$. This ansatz is natural to the extent that the NC and CC inclusive cross sections determine the sums of up and down quark distributions, and their antiquark distributions, as the four independent sets of PDFs, which may be transformed to the ones chosen if one assumes $u_v = U - \overline{U}$ and $d_v = D - \overline{D}$, i.e. the equality of anti- and sea quark distributions of given flavour.

The following standard functional form is used to parameterise them

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

where the normalisation parameters (A_{uv}, A_{dv}, A_g) are constrained by quark counting and momentum sum rules. The parameters $B_{\bar{U}}$ and $B_{\bar{D}}$ are set equal, $B_{\bar{U}} = B_{\bar{D}}$, such that there is a single B parameter for the sea distributions. The strange quark distribution at the starting scale is assumed to be a constant fraction of $\bar{D}$, $x\bar{s} = f_s x\bar{D}$, chosen to be $f_s = 0.5$ such that $\overline{s} = \overline{d}$. In addition, to ensure that $x\bar{u} \to x\bar{d}$ as $x \to 0$, $A_{\bar{U}} = A_{\bar{D}}(1 - f_s)$. The D and E are introduced one by one until no further improvement in χ^2 is found. The best fit resulted in a total of 12 free parameters, specifically fitting B_g, C_g, D_g, B_{uv}, C_{uv}, E_{uv}, B_{dv}, C_{dv}, $C_{\overline{U}}$, $A_{\overline{D}}$, $B_{\overline{D}}$, $C_{\overline{D}}$. While the LHeC NC, CC real data, and the inclusion of further information, as of s, c, b and F_L, will certainly lead to quite a different parameterisation, it has been checked that with a more flexible set of 15 parameters very similar results on the PDF uncertainties considered here are obtained.

The PDFs are evolved using DGLAP evolution equations at NLO in the $\overline{MS}$ scheme with the renormalisation and factorisation scales set to Q^2 using standard sets of parameters as for $\alpha_s(M_Z)$. These, as well as the exact treatment of the heavy quark thresholds, have no significant influence on the estimates of the PDF uncertainties. The experimental uncertainties on the PDFs are determined using the $\Delta\chi^2 = 1$ criterion. The LHeC Design Report [1] contains a very detailed presentation of the results of the present analysis for valence and sea quarks with many remarkable features as the determination of the u/d ratio or the measurement of the valence quarks down to low $x \simeq 10^{-4}$.

3 Determination of the Gluon Distribution at the LHeC

The result on the gluon distribution is presented in Fig. 1. In the left panel, recent gluon distribution determinations and their uncertainties are shown plotted as a ratio to MSTW08. Below $x \simeq 10^{-3}$ the HERA data have vanishing constraining power due to kinematic range limitations and the gluon is just not determined at low x. At large $x \geq 0.3$ the gluon distribution becomes very small and large variations appear in its determination, differing by orders of magnitude, which is related to uncertainties of jet data, theory uncertainties and the fact that HERA had not enough luminosity to cover the high x region where, moreover, the sensitivity to xg diminishes, as the valence quark evolution is insensitive to it. The larger x situation can be expected to still improve with LHC jet and possibly top and the HERA II data. The right panel shows the experimental uncertainty of xg based on the LHeC, on HERA alone and in various combinations with further data, see the LHeC design report [1]. At small x a few per cent precision becomes possible, compare right with left. Note that the non-LHeC low x uncertainty bands (right) remain narrow below $x \simeq 10^{-3}$ solely as an artefact due to the parameterisation of xg. It is for the LHeC to discover whether xg saturates or not and whether indeed the DGLAP equations need to be replaced by non-linear parton evolution equations such as BFKL. This is important for QCD but as well for super high energy neutrino physics and low x physics at the LHC. In the region of the Higgs data at the LHC, $x \sim 0.02$, the LHeC will pin down the gluon extremely accurately and the $gg \to H$ cross section uncertainties will essentially be removed as has been discussed in [3]. At large values of e.g. $x = 0.6$ the LHeC can be expected to determine xg to $5 - 10\,\%$ precision (inner blue band). This is crucial for when the LHC operates at maximum luminosity and the searches approach the few TeV mass region, as in

$gg \to \tilde{g}\tilde{g}$ [4]. It is also important for testing QCD, as factorisation and scales, as well as electroweak effects at large x in a future critical comparison of such *ep* with LHC *pp* data as for jets, see also [2]. Similarly, surprises may result from inclusive with jet LHeC data comparisons, not considered here. PDF physics rests on controlling and testing the underlying theory.

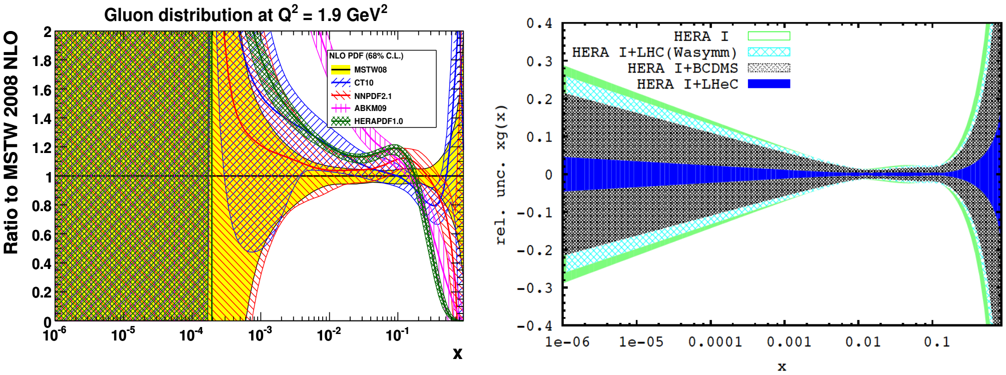

Figure 1: Uncertainty of the gluon distribution at $Q^2 = 1.9\,\mathrm{GeV}^2$ as a function of Bjorken x, see text. The LHeC PDF set, corresponding to the inner blue error band, is available on LHAPDF.

4 Strong Interaction Coupling Constant at the LHeC

Despite major efforts over the past nearly 40 years, since the discovery of asymptotic freedom, and a plethora of α_s determinations, there is no accurate value of α_s available of a precision comparable to the weak coupling constant, and a number of severe problems remains to be solved. Questions regard the (in)consistency of previous DIS data, the (in)consistency of inclusive DIS and jet based determinations, both in DIS and Drell-Yan scattering, or the treatment leading to the world average on α_s and its uncertainty [8]. As sketched above, the LHeC has the potential to provide a new, coherent data base, from neutral and charged current DIS including heavy quark parton distribution measurements, with which an order of magnitude improved experimental determination of α_s becomes possible. This is of crucial importance for QCD, for predictions of LHC cross sections, notably that of the Higgs production and for the predictions of grand unification of the electromagnetic, weak and the strong interactions at the Planck scale. It is also long time to challenge the lattice QCD α_s results, which seem to be most accurate but stand on different grounds than the classic data based measurements exhibiting variations which are non-negligible [9].

Two independent fit approaches have been undertaken in order to verify the potential of the LHeC to determine α_s. These analyses used a complete simulation of the experimental systematic errors of the NC and CC pseudo-data and higher order QCD fit analysis techniques, see the CDR [1] for details. The total experimental uncertainty on α_s is estimated to be 0.2 % from the LHeC alone and 0.1 % when combined with HERA. Relying solely on inclusive DIS *ep* data at high Q^2, this determination is free of higher twist, hadronic and nuclear corrections, unlike any of the recent global QCD fit analyses. There are known further, parametric, uncertainties in DIS determinations of α_s. These will be much reduced with the LHeC as it resolves the full set of parton distributions, u_v, d_v, $\overline{u}$, $\overline{d}$, s, $\overline{s}$, c, b and xg for the first time, providing x and Q^2 dependent constraints not "just" through the fit procedure.

5 Final Remark

It is important to emphasise that while the PDF analysis presented here serves as a valid starting point for comparison with existing PDFs, the LHeC has a unique potential to release the underlying simplifying assumptions and to provide a radically different and novel way to determine the PDFs: with the consideration of the direct measurements of the strange, charm and beauty PDFs, perhaps even the top PDF, and with the addition of tagged *eD* data, it will be possible to analyse the behaviour of not just 4 suitable combinations of PDFs but to determine the full set for the first time with crucial direct input, for example for the valence quarks at high x from high statistics CC data, at low x from electroweak structure functions or the light quarks independently of each other using *ep* and *en* and CC data. Therefore with the LHeC the world of PDFs will be radically changed. The present study of uncertainty to this extent is an illustration only and initially rather narrow in scope. It yet becomes evident that with the LHeC the development of QCD will hugely progress and the LH(e)C can be turned into a precision Higgs facility. Not excluded that electromagnetic substructure appears of the heaviest now elementary particles. Finally, the anticipated investment into highest LHC luminosity will be underpinned by the necessary precision QCD and PDF measurements by the LHeC without which highest mass limits must remain weaker and interpretations of subtle new features possibly uncertain. The LHeC appears as an impressively luminous, very important upgrade to the LHC with which the symmetry between *pp*, *ep* and may be e^+e^- can be restored at TeV energies, which appeared to be so fruitful, when the TeVatron, HERA and LEP/SLC eventually established the Standard Model of particle physics.

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