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Limit on the Effective Quark Charge Radius from Inclusive ep Scattering at HERA

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Abstract

The H1 and ZEUS combined measurement of inclusive deep inelastic cross sections in neutral and charged current ep scattering, based on the final data sample corresponding to a luminosity of about 1 fb^{-1}, was used as an input to QCD analyses, providing a set of parton distribution functions HERAPDF2.0. Here the analysis is extended to take into account possible signals from physics beyond the Standard Model. The accuracy of the data requires a combined analysis, taking into account possible contributions from the Beyond Standard Model processes in the QCD fit to the data. In the presented study this approach is developed for the quark form factor model and the resulting 95% C.L. limit for the radius of the electroweak charge of quarks is $0.45 \cdot 10^{-16}$ cm.

1 Introduction

Precision measurements of deep inelastic $e^{\pm}p$ scattering (DIS) cross sections in the domain of negative four-momentum-transfer squared, Q^2, above about $10^5\,\text{GeV}^2$ allow searches for Beyond Standard Model (BSM) contributions, if such contributions are linked to processes setting in at scale of around one TeV. The search for deviations from the SM model predictions reaches beyond the center-of-mass energy of the $e^{\pm}p$ interactions, because any such BSM processes can modify the scattering cross sections via virtual effects. The cross sections would be affected by new kinds of interactions where BSM particles would be exchanged. This could be leptoquarks for which $e^{\pm}p$ scattering is particularly sensitive, because of possibly direct couplings. Another possibility are graviton exchanges in models with large extra dimensions. Many other exotic exchanges have been proposed. As we assume to be far below the scale of the actual new physics, we can approximate all such BSM interactions as contact interactions, CI. The fact that $eeqq$ CI is not renormalisable is not relevant in our kinematic domain.

The cross sections would also be influenced by a finite radius of the quarks. In all cases, one searches for a deviation of the observed from the predicted cross section for ep scattering at the highest available Q^2. The result on CI is then interpreted with respect to the model to be tested. The predictions are calculated from Parton Distribution Functions, PDFs. If those are derived from the same data which is used to search for CI, special care has to be taken. In an analysis of 1994-2000 $e^{\pm}p$ data [1], the ZEUS collaboration searched for CI using basically independent PDFs. The limit on the quark charge radius, in the classical form factor approximation, was $0.85 \cdot 10^{-16}$ cm.

The H1 and ZEUS collaborations measured inclusive $e^{\pm}p$ scattering cross sections at HERA from 1994 to 2000 (HERA I) and from 2002 to 2007 (HERA II), collecting a total integrated luminosity of about $1\,\text{fb}^{-1}$. All inclusive data were recently combined [2] to create one consistent set of NC and CC cross-section measurements for unpolarised $e^{\pm}p$ scattering. The inclusive cross sections were used as input to a QCD analysis within the DGLAP formalism resulting in a parton distribution function (PDF) set denoted as HERAPDF2.0. Additional data on charm and beauty production at HERA were used in order to constrain the heavy-quark distribution parameters. Due to the high precision and coherence of the input data HERAPDF2.0 can be used to calculate SM predictions with very small experimental uncertainties. But, when searching for BSM contributions in the data, these predictions have to be considered biased because such contributions might have been absorbed in the PDFs.

In the previous ZEUS analysis [1], the uncertainties on the PDFs used were a dominant source of systematics. Estimated uncertainties of the parton densities were used to smear model predictions in the limit setting procedure. Such an approach was valid as the CTEQ5D parameterization [3,4] used for calculating model predictions included only 1994 HERA data, less than 3% of the sample considered in the CI analysis, and the limits were dominated by statistics. For the analysis presented here, a new procedure to set limits on the BSM model contributions was developed, where BSM contributions and QCD evolution is fitted simultaneously. The search at the moment focuses on finite quark radii within the formalism of the quark form factor model [5].

2 Data samples

The H1 [6–8] and ZEUS [9] detectors were general purpose instruments which consisted of tracking systems surrounded by electromagnetic and hadronic calorimeters and muon detectors, ensuring close to 4π coverage of the ep interaction point. The presented study is based on the inclusive NC and CC cross-section measurements for unpolarised $e^{\pm}p$ scattering at HERA, resulting from the combination [2] of the all available data from H1 and ZEUS experiments. The analysis included 41 different data sets collected at four different centre-of-mass energies from 1994 to 2007 (HERA I and HERA II). During the HERA I period, each experiment collected about $100\,\mathrm{pb}^{-1}$ of $e^{+}p$ and $15\,\mathrm{pb}^{-1}$ of $e^{-}p$ data, while at HERA II period, about $150\,\mathrm{pb}^{-1}$ of $e^{+}p$ and $235\,\mathrm{pb}^{-1}$ of $e^{-}p$ data were added. The original double-differential cross-section measurements, as published by the H1 and ZEUS collaborations, were averaged using the HERAverager tool [10] which is based on a χ^2 minimisation method. The 2927 published cross-section values were combined to 1307 averaged cross-section measurements. For the resulting 1620 degrees of freedom, a $\chi^2_{\mathrm{min}} = 1687$ was obtained, demonstrating very good consistency of all considered data sets. Since H1 and ZEUS used different reconstruction methods, similar systematic sources influenced the measured cross sections differently. Therefore, requiring the cross sections to agree at all x and Q^2 values resulted in significant reduction of the systematic uncertainties. For more details, see [2].

3 QCD analysis

In the following, we briefly describe the framework used in the perturbative QCD (pQCD) analysis of the combined data, as used in the HERAPDF2.0 study [2]. Only cross sections for Q^2 starting from $Q^2_{\mathrm{min}} = 3.5\,\mathrm{GeV}^2$ were used in the analysis. A fit to the data, resulting in the set of PDFs, was obtained by solving the DGLAP evolution equations at NLO in the $\overline{\mathrm{MS}}$ scheme. This was done using the programme QCDNUM [11] within the HERAFitter framework [12].

In this appoach, the PDFs of the proton, xf, are generically parameterised at the starting scale $\mu^2_{\mathrm{f}_0}$ as

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

where x is the fraction of the proton's momentum taken by the struck parton in the infinite momentum frame. The PDFs parameterised are the gluon distribution, xg, the valence-quark distributions, xu_v, xd_v, and the u-type and d-type anti-quark distributions, $x\bar{U}$, $x\bar{D}$. The PDFs parameter values were fit to the data using a χ^2 method, taking into account statistical uncertainties, as well as uncorrelated and correlated systematic uncertainties of the input experimental data.

Uncertainties of the PDFs resulting from the experimental uncertainties were determined with the criterion $\Delta\chi^2 = 1$ and verified using the Monte Carlo method based on analysing a large number of pseudo data sets called replicas. The two approaches gave consistent estimates of experimental errors. The uncertainties on HERAPDF2.0 due to the choice of model settings and the form of the parameterisation were also evaluated, and the total PDF uncertainty was obtained by adding in quadrature the experimental, the model and the parameterisation uncertainties. For more details, see [2].

4 Quark form factor

One of the possible methods to search for deviations from SM predictions in ep scattering is to assign a finite size for the radius of the electroweak charges of electrons and/or quarks while assuming the SM gauge bosons remain pointlike and their couplings are unchanged. The expected suppression of the SM cross section can be described using a semi-classical form factor approach. If the expected deviations are small, the SM predictions for the cross sections are modified, approximately, to:

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2} \left(1 - \frac{R_e^2}{6} Q^2\right)^2 \left(1 - \frac{R_q^2}{6} Q^2\right)^2 , \qquad (2)$$

where R_e and R_q are the root-mean-square radii of the electroweak charge of the electron and the quark, respectively. In the present analysis only the possible finite spatial distribution of the quark charge is considered and the electron is assumed to be point-like ($R_e \equiv 0$).

The QCD analysis described in the previous section is extended by introducing R_q as additional model parameter and modifying all $e^{\pm}p$ DIS cross-section predictions according to formula (2), to take into account possible signals from physics beyond SM. The estimate of the quark radius squared resulting from the simultaneous fit of R_q and the PDF parameters to the data is

$$R_q^{2\ Data} = -0.5\ (\pm 3.1) \cdot 10^{-6}\ \mathrm{GeV}^{-2} ,$$

in good agreement with SM expectations. However, as the resulting value is negative, outside the allowed R_q range, we use the value of $R_q^{2\ Data} = 0$ for the limit setting. This corresponds to the assumption that, within the considered model, the obtained cross section enhancement at high Q^2 could only be due to statistical fluctuations.

5 Limit setting procedure

The limit on the effective quark radius R_q is derived by using a frequentist approach. We compare the most likely value of the quark radius squared, determined from the χ^2 minimization, for the actual input data and for a large number of equivalent replicas. Excluded at the 95% C.L. are R_q values which, in more than 95% of the replicas, result in the fitted radius squared value, $R_q^{2\,Fit}$, greater than that obtained for the data, $R_q^{2\,Data}$.

To set the limit, distribution of $R_q^{2\,Fit}$ values had to be reconstructed from QCD fits to multiple replicas, for different values of the assumed true radius, R_q^{true}. However, the assumed value of R_q^{true} needs to be taken into account in replicas generation as well. Therefor, for each R_q^{true} value considered, a dedicated QCD fit to the combined data was first performed (with R_q fixed to R_q^{true}) to obtain the corresponding PDF parametrization. These PDFs were then used to generate multiple data replicas for given R_q^{true}. Replica data-sets were created by taking the reduced cross sections calculated from PDFs and fluctuating their values randomly within given statistical and systematic uncertainties taking into account correlations. All uncertainties were assumed to follow the Gaussian distribution. For each replica, the generated value of the cross section at the point i was calculated as:

$$\mu^i = \left[m_0^i + \sqrt{\delta_{i,\text{stat}}^2 + \delta_{i,\text{uncor}}^2} \cdot D_i \cdot r_i \right] \cdot (1 + \sum_j \gamma_j^i \cdot r_j) \quad , \tag{3}$$

where D_i is the measured cross section value at the point i and m_0^i is the expected cross section at this point for the considered R_q^{true} value. γ_j^i, $\delta_{i,\text{stat}}$ and $\delta_{i,\text{uncor}}$ are the relative correlated systematic, relative statistical and relative uncorrelated systematic uncertainties of the input data, respectively. r_i and r_j are random numbers generated from normal distribution for each data point i and for each source of correlated systematic uncertainty j, respectively.

Finally, the full QCD fit was performed on the generated replica set to reconstruct the $R_q^{2\,Fit}$ distribution. The χ^2 formula used for fitting R_q and PDF parameters, and possible correlated systematic shifts in the input data is:

$$\chi^2(\boldsymbol{m}, \boldsymbol{s}) = \sum_i \frac{\left[m^i + \sum_j \gamma_j^i m^i s_j - \mu^i \right]^2}{\left(\delta_{i,\text{stat}}^2 + \delta_{i,\text{uncor}}^2 \right)^2 D_i^2} + \sum_j s_j^2 \quad , \tag{4}$$

where the vector $\boldsymbol{m}$ represents the set of cross section predictions m_i and the components s_j of the vector $\boldsymbol{s}$ represent correlated shifts of the cross sections in units of sigma of the respective correlated systematic uncertainties; the summations over j extend over all correlated systematic uncertainties. It was checked that the usage of fixed statistical and uncorrelated systematic uncertainties in the denominator of the first r.h.s term of eq. (4,) taking the values from the data, minimizes the biases in the fit results.

In the last step, the probability of obtaining the $R_q^{2\,Fit}$ value smaller than that obtained for the actual data, Prob($R_q^{2\,Fit} < R_q^{2\,Data}$), was plotted as a function of R_q^{true}, as shown in Fig. 1. Points with error bars represent replica sets generated for subsequent R_q^{true} values. The errors are statistical only, calculated assuming binomial probability distribution for Prob($R_q^{2\,Fit} < R_q^{2\,Data}$). Blue dashed line, drawn to guide the eye, represents the dependence expected for gaussian distribution of $R_q^{2\,Fit}$. For comparison, the dependence obtained with PDF parameters fixed to HERAPDF2.0 values (both in replica generation and in R_q fits to replica sets based on χ^2 minimization), is indicated by the green dash-dotted line. The probability distribution is interpolated to calculate the R_q value corresponding to the 95% C.L. limit. The interpolation is done with a fit of an exponential function to the points with an estimated probability between 2.5 and 8.5%, as illustrated in Fig. 2.

6 Results

The limit setting procedure described above was repeated for different model and parameter settings considered as systematic checks in the QCD fitting procedure (see [2] for details). The resulting variations of the R_q limit values are very small, of the order of 1%. The obtained 95% C.L. upper limit on the effective quark-charge radius is:

$$R_q \quad < \quad 0.45 \cdot 10^{-16}\,\text{cm} \quad .$$

This result is about 10% weaker than the limit obtained without taking into account possible R_q influence on the PDF fit result. As a cross check the limit on R_q was also determined from the simultaneous PDF and R_q fit to the data (see Sec. 4 and 5), looking at the variation of the χ^2 value minimized with respect to the PDF parameters when changing the R_q value. The estimated limit was in a good agreement with the result presented here.

Cross section deviations corresponding to the 95% C.L. exclusion limit for the effective radius, R_q, of the electroweak charge of the quark are compared with the combined H1 and ZEUS high-Q^2 NC DIS data in Fig. 3.

7 Conclusions

The H1 and ZEUS combined measurement of inclusive deep inelastic cross sections in neutral and charged current $e^{\pm}p$ scattering, was used to set limit on the possible physics beyond SM in the classical quark form factor approximation. This model, describing possible effects due to quark substructure or finite spatial distribution of the quark charge, was used as a test scenario to demonstrate the improved limit setting procedure. The QCD analyses of HERA data, providing a set of parton distribution functions HERAPDF2.0, was extended to take into account possible cross section modification due to a finite quark charge radius. As the same data are used to calculate PDFs and to set limit on BSM scenario, the limit setting procedure was based on a simultaneous fit of PDF parameters and R_q, properly taking into account possible contributions from the BSM processes in the QCD fit to the data.

The quark-charge radius larger than $0.45 \cdot 10^{-16}$ cm has been excluded on 95% C.L., which is almost a factor of two improvement compared to the published ZEUS limit of $0.85 \cdot 10^{-16}$ cm, based on the HERA I data [1]. The present result improves the limit set in ep scattering by the H1 collaboration [13] ($R_q < 0.65 \cdot 10^{-16}$ cm) and is similar to the limit presented by the L3 collaboration ($R_q < 0.42 \cdot 10^{-16}$ cm, assuming $R_e = 0$), based on quark-pair production measurement at LEP2 [14].

References

[1] ZEUS Coll., S. Chekanov et al., Phys. Lett. **B 591**, 23 (2004). doi:10.1016/j.physletb.2004.03.081.

[2] H1 ans ZEUS Collaborations, *Combination of Measurements of Inclusive Deep Inelastic $e^{\pm}p$ Scattering Cross Sections and QCD Analysis of HERA data.* DESY-15-039, arXiv:1506.06042, submitted to EPJS, 2015.

[3] CTEQ Coll., H.L. Lai et al., Eur. Phys. J. **C 12**, 375 (2000). doi:10.1007/s100529900196.

[4] H.L. Lai et al., Phys. Rev. **D 55**, 1280 (1997). doi:10.1103/PhysRevD.55.1280.

[5] Kopp, G. and Schaile, D. and Spira, M. and Zerwas, P. M., Z. Phys. **C65**, 545 (1995). doi:10.1007/BF01556142.

[6] Abt, I. and others **386**, 310 (1997).

[7] Abt, I. and others **386**, 348 (1997).

[8] Appuhn, R. D. and others, *H1 backward upgrade with a SPACAL calorimeter: The Hadronic section.* DESY, 1996.

[9] ZEUS Collaboration, U. Holm (editor). The ZEUS Detector. Status Report (unpublished), DESY (1993).

[10] The documentation and the package can be found at: `https://wiki-zeuthen.desy.de/HERAverager`.

[11] Botje, M., Comp. Phys. Comm. **182**, 490 (2011).

[12] Alekhin, S. and others, *HERAFitter, Open Source QCD Fit Project.* arXiv:1410.4412, 2014.

[13] Aaron, F. D. and others, Phys. Lett. **B705**, 52 (2011). doi:10.1016/j.physletb.2011.09.109.

[14] L3 Coll., M. Acciarri et al., Phys. Lett. **B 489**, 81 (2000).

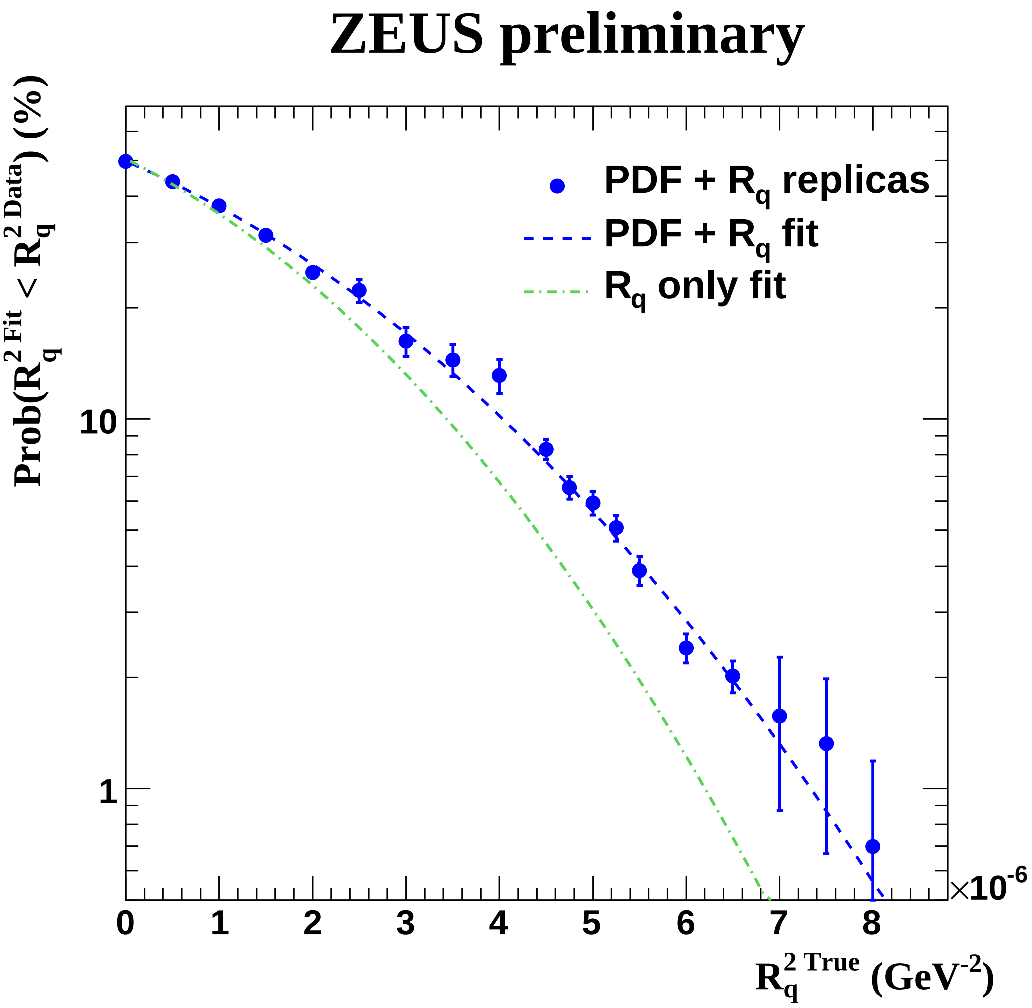

Figure 1: *The probability of obtaining the $R_q^{2\,Fit}$ value smaller than that obtained for the actual data, $R_q^{2\,Data}$, calculated from multiple Monte Carlo replicas, as a function of the assumed value for the quark radius, R_q^{true}. Points represent Monte Carlo replica sets generated for different values of R_q^{true}, with error bars indicating statistical uncertainty of the probability estimated assuming binomial probability distribution. The $R_q^{2\,Fit}$ values were estimated from the simultaneous fit of the R_q and PDF parameters. Blue dashed line represents the dependence expected for gaussian probability distribution for $R_q^{2\,Fit}$. For comparison, green dash-dotted line represents the dependence obtained when fixing PDF parameters in replica generation and R_q fits to HERAPDF2.0 values.*

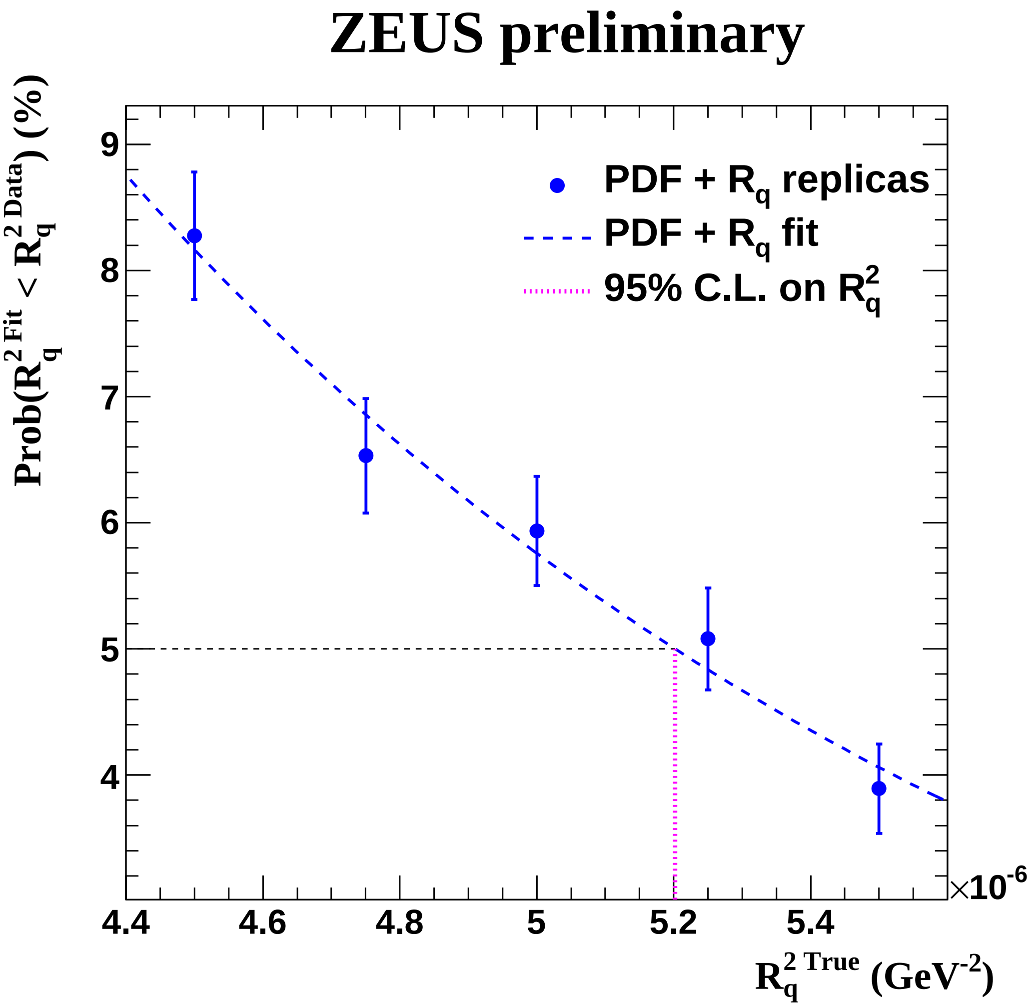

Figure 2: *The probability of obtaining the $R_q^{2\ Fit}$ value smaller than that obtained for the actual data, $R_q^{2\ Data}$, calculated from multiple Monte Carlo replicas, as a function of the assumed value for the quark radius, R_q^{true}. Points represent Monte Carlo replica sets generated for different values of R_q^{true}, with error bars indicating statistical uncertainty of the probability estimated assuming binomial probability distribution. Shown are the results selected for the final limit evaluation. Dashed blue line represents the fitted exponential dependence used to interpolate simulation results to probability of 5%. Resulting 95% C.L. limit on R_q^2 value is indicated by the vertical dotted line.*

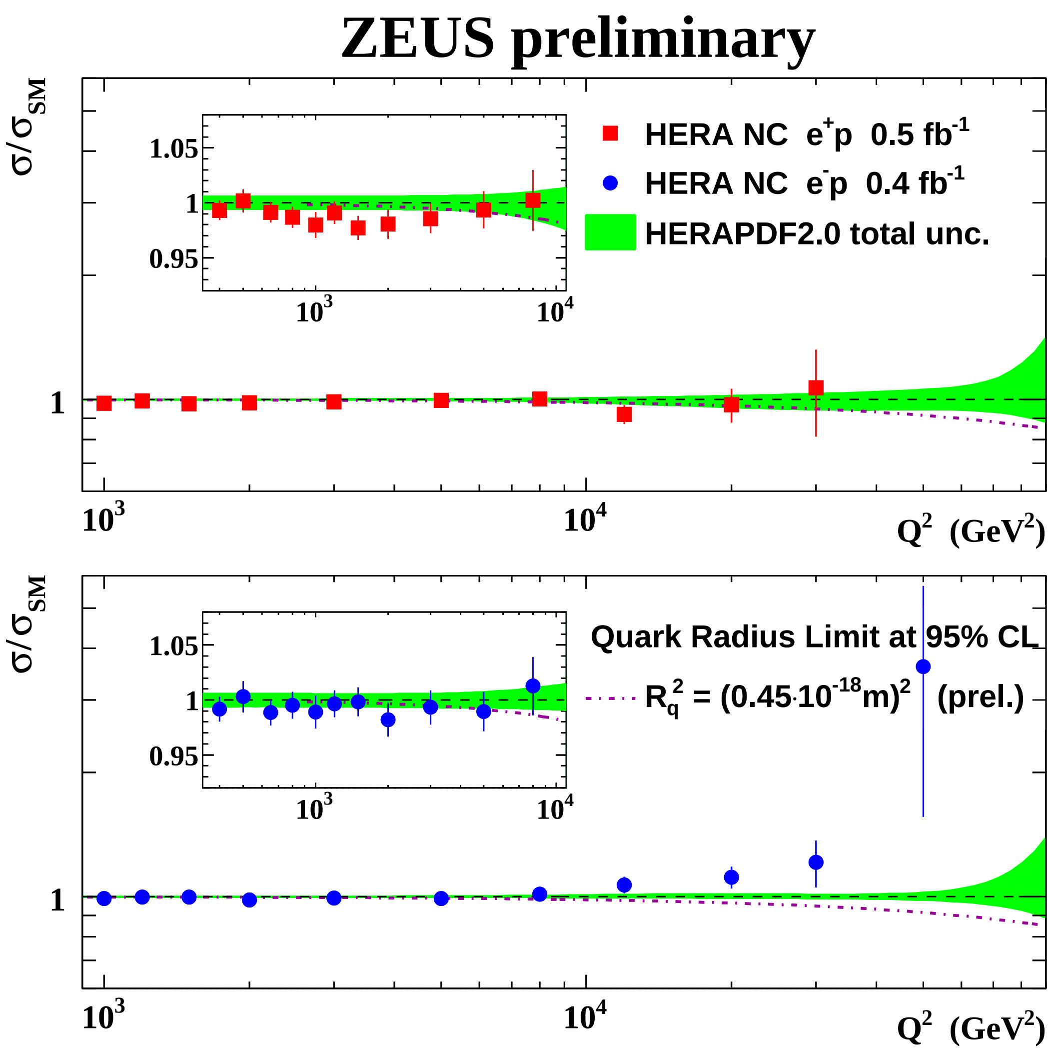

Figure 3: *Combined H1 and ZEUS e^+p data (top plot) and e^-p data (bottom plot) compared with the 95% C.L. exclusion limit for the effective mean-square radius of the electroweak charge of the quark. Results are compared to the Standard Model expectations calculated using the HERAPDF2.0 parton distributions. The green bands represent the total uncertainty on the HERAPDF2.0 predictions. The insets show the comparison in the $Q^2 < 10^4$ GeV^2 region, with a linear ordinate scale.*