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Limits on the effective quark radius from inclusive ep scattering and contact interactions at HERA

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The high-precision HERA data allow searches for "beyond the Standard Model" contributions to electron-quark scattering up to TeV scales. Combined H1 and ZEUS measurements of inclusive deep inelastic cross sections in neutral and charged current *ep* scattering are considered, corresponding to a luminosity of around 1 fb^{-1}. A new approach to the beyond the Standard Model analysis of the inclusive *ep* data is presented; simultaneous fits of parton distribution functions and contributions of "new physics" processes are performed. Considered are possible deviations from the Standard Model due to a finite radius of quarks, described within the quark form-factor model, and due to new electron-quark interactions in the framework of *eeqq* contact interactions (CI). The resulting 95% C.L. upper limit on the effective quark radius is $0.43 \cdot 10^{-16}$ cm. The limits on the CI mass scale extend up to 10 TeV depending on the CI scenario.

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1. Introduction

The electron[1]-proton deep inelastic scattering, DIS, measurements by the ZEUS and H1 experiments at the HERA collider have been an essential ingredient in the estimation of all recent high-precision PDFs and allow indirect searches for contributions beyond the Standard Model (BSM) up to TeV scales. About 500 pb^1 of data, divided about equally between e^+p and e^-p scattering, were collected per experiment at electron beam energy of 27.5 GeV and proton beam energies of 920, 820, 575 and 460 GeV. All final inclusive DIS measurement results from ZEUS and H1 were combined [1] into one coherent data set spanning six orders of magnitude in both, negative four-momentum-transfer squared, Q^2, and Bjorken x, x_{Bj}.

The combined $e^{\pm}p$ cross sections were used in a QCD analysis at next-to-leading order, providing a set of parton distribution functions ZCIPDF [2], and in an analysis beyond the Standard Model using a new approach, performing simultaneous fits on large sets of Monte Carlo replicas of parton distribution functions, PDFs, together with the parameters of "new physics" processes. It allowed to estimate limits on the mass scales for different contact interaction scenarios extending up to 10 TeV and evaluate an upper limit on the effective quark radius of $0.43 \cdot 10^{-16}$ cm.

2. Quark radius analysis with simultaneous fit procedure

One of the possible BSM scenarios is to assign an effective finite radius to electrons and/or quarks and to assume the SM bosons remain point-like. If the expected deviations are small, the predictions for such scenarios can be calculated by modifying the SM cross-section predictions with a semi-classical form-factor [3]:

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{\mathrm{SM}}}{dQ^2} \left(1 - \frac{R_e^2}{6} Q^2\right)^2 \left(1 - \frac{R_q^2}{6} Q^2\right)^2 , \tag{2.1}$$

where R_e^2 and R_q^2 are the mean-square radii of the electron and the quark, respectively. In the present analysis the electron was assumed to be point-like, $R_e^2 \equiv 0$, and only quarks were allowed to have finite spatial distribution.

The limits on the BSM contributions were derived in a frequentist approach [4] based on fits to large sets of Monte Carlo replicas [2]. Monte Carlo replicas are sets of cross-section values in the same (Q^2, x) grid as data, generated by randomly varying cross-section predictions according to the data uncertainties. Sets of replicas were created for different assumed true values of quark radius, $R_{\mathrm{q}}^{2\ \mathrm{True}}$, with:

$$\mu^i = \left[m_0^i + \sqrt{\delta_{i,\mathrm{stat}}^2 + \delta_{i,\mathrm{uncor}}^2} \cdot \mu_0^i \cdot r_i\right] \cdot \left(1 + \sum_j \gamma_j^i \cdot r_j\right) . \tag{2.2}$$

There, μ^i is the resulting cross-section replica, m_0^i is the cross-section prediction calculated from the ZCIPDF and modified for $R_{\mathrm{q}}^{2\ \mathrm{True}}$, μ_0^i, $\delta_{i,\mathrm{stat}}^2$, $\delta_{i,\mathrm{uncor}}^2$ and γ_j^i are cross-section value, relative statistical, uncorrelated and correlated systematic uncertainties from data, respectively, and r_i and r_j represent random numbers taken from a normal distribution.

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[1] Here and later, the word "electron" refers to both electrons and positrons, unless otherwise stated.

In case the same data are used first in the determination of PDFs within the Standard Model and afterwards in the BSM parameter-limit evaluation a possible contribution from BSM processes to the high-Q^2 DIS data could affect the PDF fit and result in biased PDF distributions. Results of such two-step fits for different sets of pseudodata $\mu^i = m_0^i\left(R_\mathrm{q}^{2\ \mathrm{True}}\right)$ are presented in Fig. 1 (left) with open red circles. They show a bias in fitted quark-radius values. The Standard Model predictions obtained with biased PDFs would include some BSM contribution, providing good agreement with the data but thereby overestimating BSM parameter limits. The proper procedure for a BSM analysis of the HERA data would be a global QCD analysis which simultaneously includes a possible contribution from BSM processes in the QCD fit. The quark-radius values estimated simultaneously with PDF parameters are displayed in Fig. 1 (left) as solid blue circles. There the fitted value $R_\mathrm{q}^{2\ \mathrm{Fit}} \approx R_\mathrm{q}^{2\ \mathrm{True}}$ and the bias is not observed. The χ^2 values evaluated on a set of pseudodata $\mu^i = m_0^i\left(R_\mathrm{q}^2 = 0\right)$ for different values of $R_\mathrm{q}^{2\ \mathrm{True}}$ with fixed PDFs are shown in Fig. 1 (right) with open red circles, and χ^2 values obtained in fits with PDFs used as free fit parameters are presented with solid blue circles. The distribution for the procedure with fixed PDFs can be described with a narrower parabola and thus would result in stronger limits than the combined procedure.

To set limits, each of the Monte Carlo replica sets prepared for some $R_\mathrm{q}^{2\ \mathrm{True}}$ using Eq. 2.2 was fitted using the combined QCD fit simultaneously estimating PDF parameters and the quark-radius value $R_\mathrm{q}^{2\ \mathrm{Fit}}$. The value of quark radius fitted on data, $R_\mathrm{q}^{2\ \mathrm{Data}}$, was taken as a test statistic, to which the values of $R_\mathrm{q}^{2\ \mathrm{Fit}}$ were compared and probability P to obtain $R_\mathrm{q}^{2\ \mathrm{Fit}} < R_\mathrm{q}^{2\ \mathrm{Data}}$ was evaluated. The procedure was repeated for different values of $R_\mathrm{q}^{2\ \mathrm{True}}$ and the quark-radius values corresponding to $P = 5\%$ provided the 95% C.L. limits of

$$-(0.47 \cdot 10^{-16}\ \mathrm{cm})^2 < R_\mathrm{q}^2 < (0.43 \cdot 10^{-16}\ \mathrm{cm})^2 \ . \tag{2.3}$$

Deviations of the cross sections corresponding to these limits are compared to the combined HERA high-Q^2 NC and CC DIS data integrated over x in Fig. 2 (left) and Fig. 2 (right), respectively.

3. Simplified fit procedure and contact interactions limits

In the quark-radius analysis, about 5000 Monte Carlo replicas were generated and fitted for each value of the true quark-radius squared, $R_q^{2\ \mathrm{True}}$. In total about 200 000 combined fits of PDF parameters and $R_\mathrm{q}^{2\ \mathrm{Fit}}$ were performed, taking more than 30 years of CPU time for setting the final limits in the single BSM scenario. This makes the processing time a limiting factor for the extension of the analysis to other models. To reduce the processing time a simplified approach, based on the Taylor expansion of the cross section predictions in terms of PDF parameters, was developed [5]. It allowed to reduce the calculation time for the BSM limits by about a factor of 50. The simplified fit procedure was tested on the combined PDFs and quark-radii form-factor fits of the Monte Carlo replicas generated for the quark-radius limit of $R_\mathrm{q}^{\mathrm{True}} = 0.43 \cdot 10^{-16}$ cm and the obtained $R_\mathrm{q}^{2\ \mathrm{Fit}}$ values are compared to the result of the full fit in Fig. 3.

Four-fermion contact interactions (CI) provide the most general method for indirect searches of BSM physics at the scales higher than the centre-of-mass energy. CI approach is only valid in the low-energy limit and vector-like contact interactions considered here can be represented as an

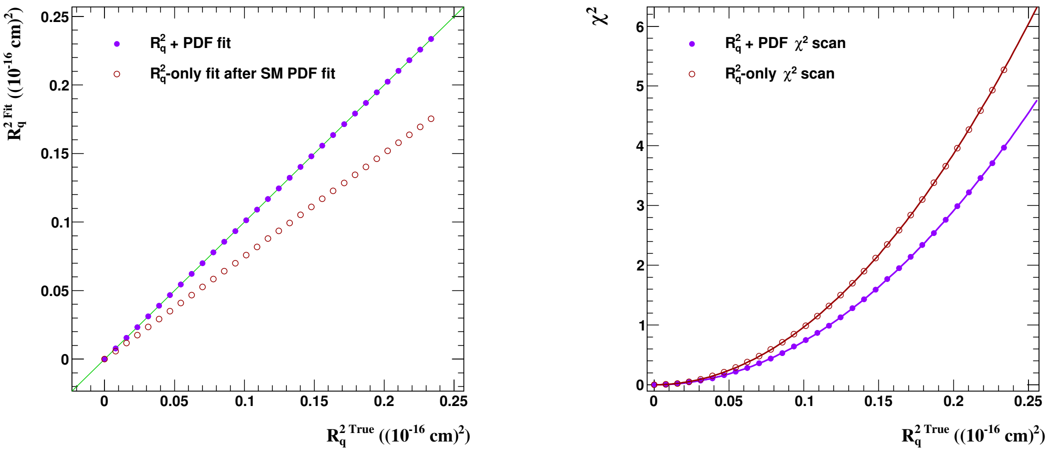

Figure 1: $R_q^{2\ \mathrm{Fit}}$ results of pseudodata fits (left) and χ^2 distributions for the least-squares method (right) with the combined procedure (solid blue circles) and the procedure with fixed PDFs (open red circles). The pseudodata for the fits are obtained from the Standard Model cross-section predictions (right) and by modifying the Standard Model predictions with the quark-radius form-factor $R_q^{2\ \mathrm{True}}$ (left).

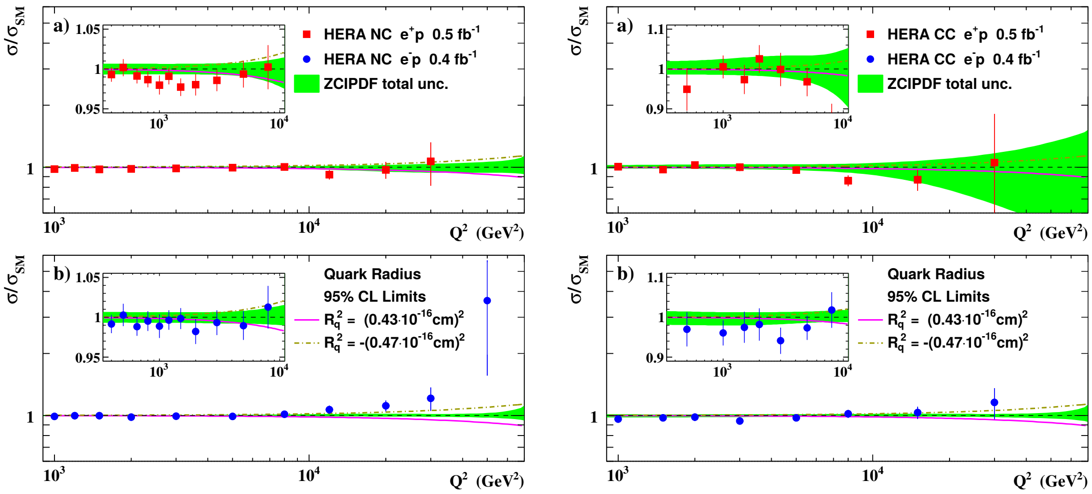

Figure 2: Combined HERA (a) e^+p and (b) e^-p NC (left) and CC (right) DIS data divided by the cross-section expectations from ZCIPDF and compared to the 95% C.L. exclusion limits on the effective mean-square radius of quarks. The bands on the ZCIPDF predictions represent the total uncertainty. The insets show the comparison in the $Q^2 < 10^4$ GeV^2 region with a linear ordinate scale.

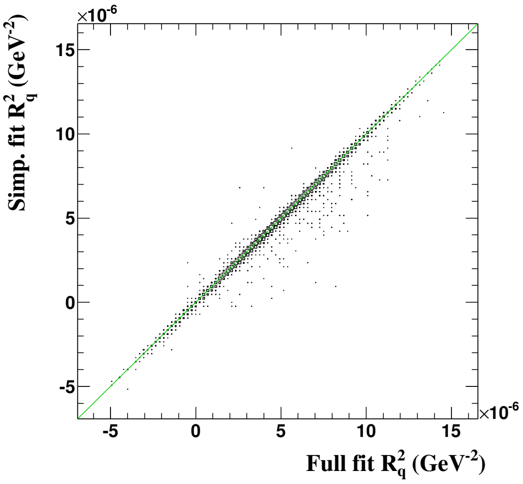

Figure 3: Comparison of the quark-radius squared, $R_\mathrm{q}^{2\ \mathrm{Fit}}$, resulting from the simplified and full combined PDFs and R_q^2 fits on Monte Carlo replicas generated for $R_\mathrm{q}^\mathrm{True} = 0.43 \cdot 10^{-16}$ cm.

extra term $\mathscr{L}_\mathrm{CI}$ added to the Standard Model Lagrangian:

$$\mathscr{L}_\mathrm{CI} = \sum_{\substack{k,j=L,R \\ q=u,d,s,c,b}} \eta_{kj}^{eq} (\bar{e}_k \gamma^\mu e_k)(\bar{q}_j \gamma_\mu q_j) \quad . \tag{3.1}$$

Here the sum runs over electron and quark helicities and quark flavours, and η_{kj}^{eq} are coupling coefficients. It was assumed that the same coupling structure applies to all quarks. The coupling coefficients describe the helicity and flavour structure of the contact interactions:

$$\eta_{kj}^{eq} = \varepsilon_{kj}^{eq} \frac{g^2}{\Lambda^2} \quad . \tag{3.2}$$

The coefficients ε_{kj}^{eq} can be equal to ± 1 or 0 and are listed in the first column of the Table 1, g is the coupling strength which was assumed to be equal to $2\sqrt{\pi}$, and Λ is the mass scale of the contact interactions.

The same analysis procedure as for the quark radius has been followed for each CI model [6]. Estimated 95% C.L. limits on the compositeness scales Λ^+ and Λ^-, as well as the probabilities p_{SM} that an experiment, assuming validity of the Standard Model, would produce a value of $\eta^\mathrm{Fit} > \eta_\mathrm{CI+PDF}^\mathrm{Data}$, are presented in Table 1.

For the VV, X2 and X4 models, no significant deviation from the Standard Model has been observed. The probabilities p_{SM} for these scenarios range from 23.1% to 60.3% and measured limits are close to the expected values. The LL and RR models have p_{SM} equal to 6.5 and 5.6, respectively, and large values of the compositeness scale in the negative direction of the CI coupling. The AA model, as well as VA and X1, have negative coupling values excluded at 95% C.L. The probability p_{SM} for AA model is equal to 0.7%, which means a 2.5 σ deviation from the Standard Model.

HERA $e^{\pm}p$ 1994-2007 data

		95% C.L. limits (TeV)				
Coupling structure		Measured		Expected		p_{SM}
Model	$[\varepsilon_{LL}, \varepsilon_{LR}, \varepsilon_{RL}, \varepsilon_{RR}]$	Λ^-	Λ^+	Λ^-	Λ^+	(%)
LL	$[+1, \ 0, \ 0, \ 0]$	22.0	4.5	5.9	6.2	6.5
RR	$[\ 0, \ 0, \ 0, +1]$	32.9	4.4	5.7	6.1	5.6
VV	$[+1, +1, +1, +1]$	14.7	9.5	11.0	11.4	24.8
AA	$[+1, -1, -1, +1]$	-	4.8 - 10.4	7.9	7.8	0.7
VA	$[+1, -1, +1, -1]$	-	3.6 - 10.1	4.1	4.1	2.1
X1	$[+1, -1, \ 0, \ 0]$	-	3.5 - 6.6	5.7	5.6	0.3
X2	$[+1, \ 0, +1, \ 0]$	10.8	6.8	7.8	8.2	23.1
X4	$[\ 0, +1, +1, \ 0]$	7.6	9.2	8.0	8.6	60.3

Table 1: Coupling structure parameters ε_{ij}^{eq} and 95% C.L. limits on the compositeness scale, Λ, for the considered general contact-interactions models. Also listed are the expected limits and probabilities p_{SM} of the Standard Model to result in the best-fit coupling value greater than (or less than, in case of the negative value) $\eta_{\mathrm{CI+PDF}}^{\mathrm{Data}}$. The compositeness scale Λ^+ corresponds to positive and Λ^- to negative values of the coupling η. The same coupling structure applies to all quarks.

References

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