Search for contact interactions in inclusive ep scattering at HERA: the effective quark «radius»

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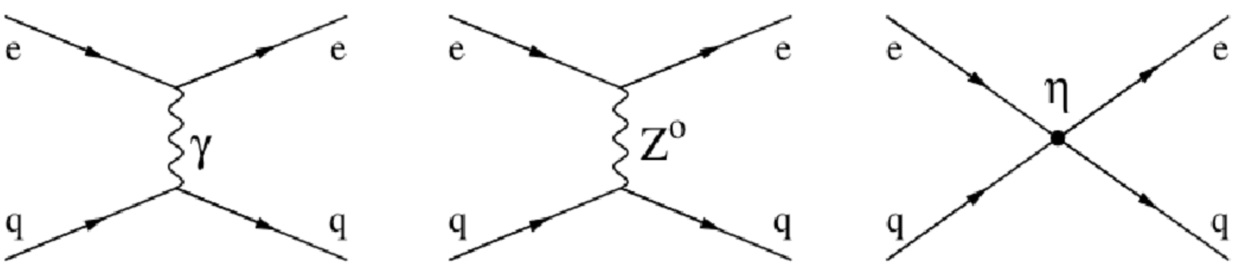
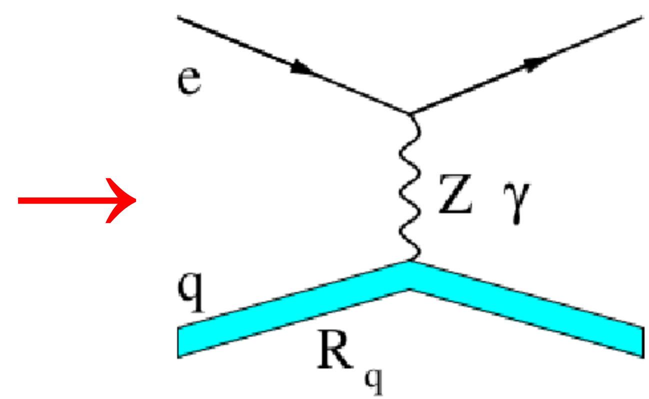
Predictions of the SM are well confirmed.
However at $Q^2 > 10^4$ GeV^2 may exist BSM effects.:
cross sections can be affected by new kinds of interactions
(new particles, a finite quark radius ...)





$$M^{eq}_{\alpha\beta}(Q^2) = \frac{e^2 e_q}{Q^2} - \frac{e^2}{sin^2\theta_W \cdot cos^2\theta_W} \cdot \frac{g^e_\alpha g^q_\beta}{Q^2 + m^2_Z} + \eta^{eq}_{\alpha\beta}$$

γ Z° ?

>100 years ago (Rutherford, 1911): α+ Au

Rutherford: Scattering charged point-like particles w/o spin.
Mott: + account relativ., recoil effects + incident particle spin (1/2)

★ $$\left(\frac{d\sigma}{d\Omega}\right)_R = \left(\frac{Z_1 Z_2 e^2}{4T}\right)^2 \frac{1}{\sin^4 \theta/2} \rightarrow \left(\frac{d\sigma}{d\Omega}\right)_{Mott}$$

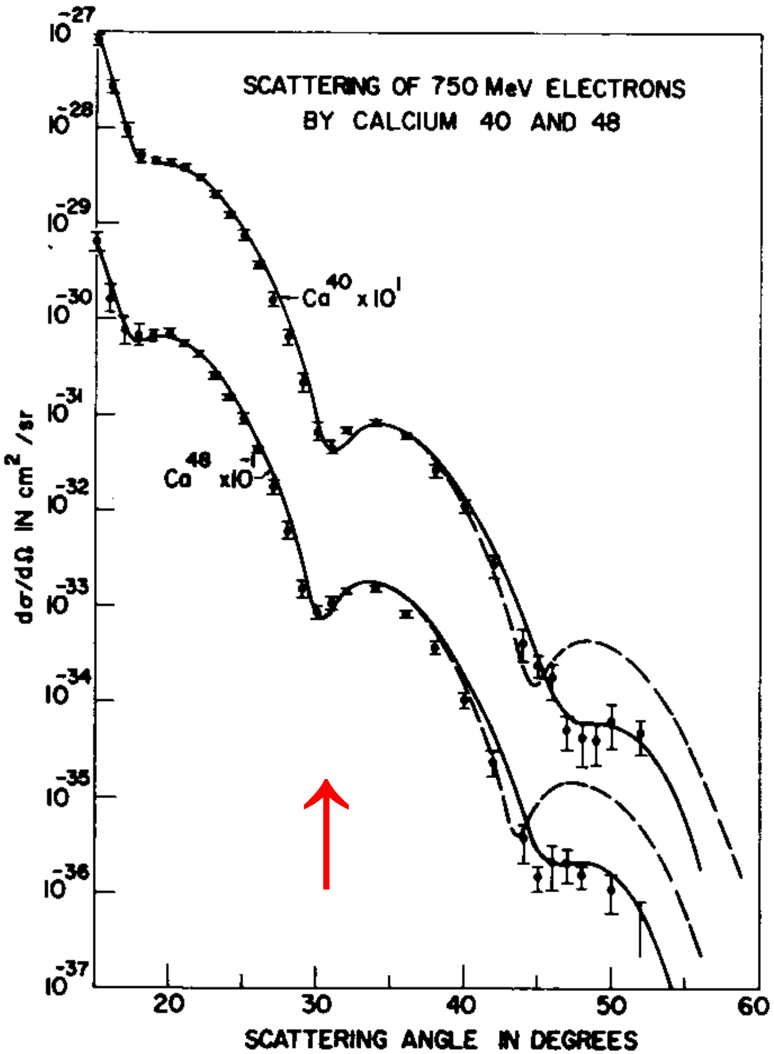
$$\tan\left(\frac{\theta}{2}\right) = \frac{r_{min}}{2b} = \frac{Z_1 Z_2 e^2}{2bT}$$

Rutherford formula describes well **α+ Au** scattering. Therefore,

$b \sim R_{Au} < 5 \cdot 10^{-12}$ cm=50 fm

Form factor

A form factor is a function describing the effect of the particle spatial extent on its interaction with other particles and fields.



★ $$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = |F(q^2)|^2 \left(\frac{d\sigma}{d\Omega}\right)_{Mott}$$

$$F(\vec{q}) = \int \rho(\vec{r}) e^{i\vec{q}\vec{r}} d^3\vec{r}$$

$$\sin\theta_{min} \approx \frac{0.6}{R}\lambda$$

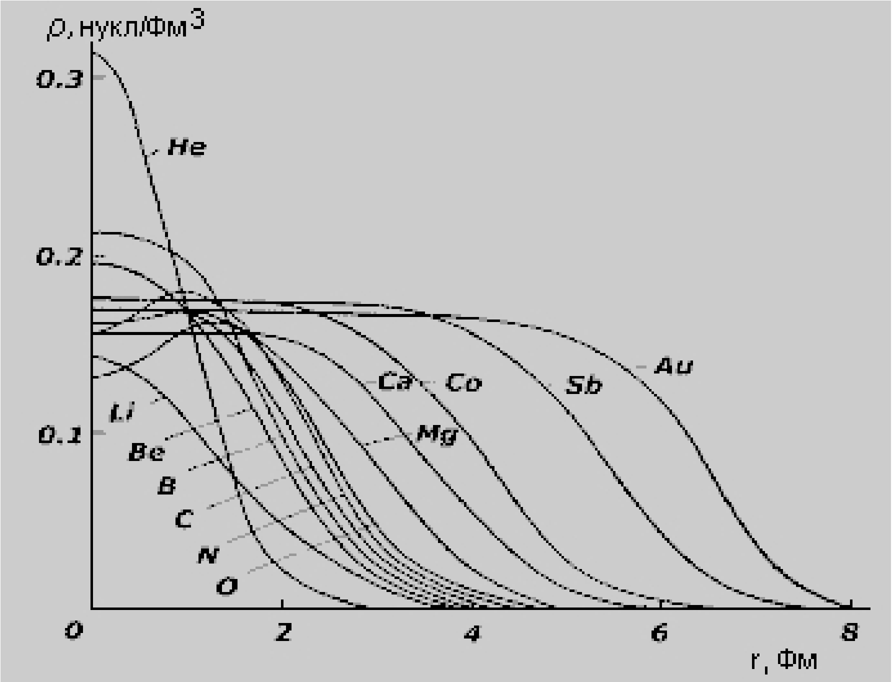
Diffractive scattering

From the position of 1-st minimum -> R of the target

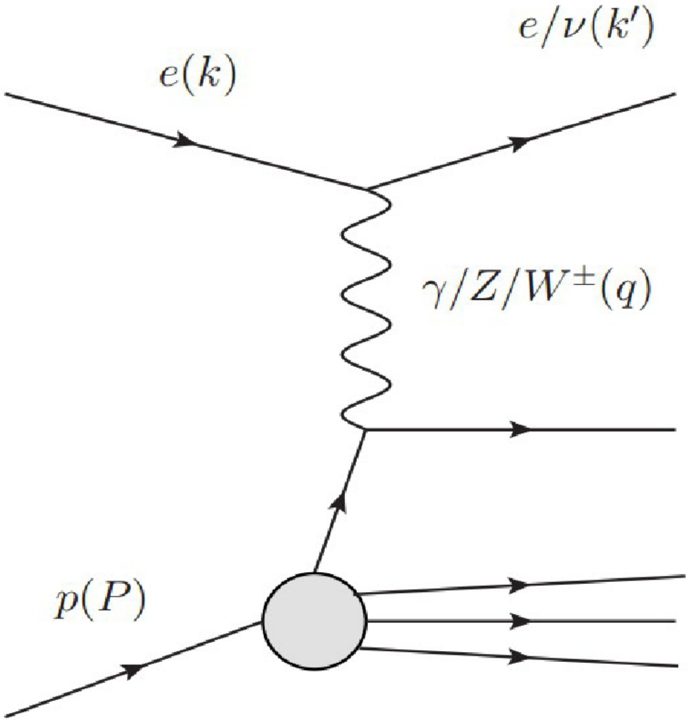
$$F(\vec{q}) = \frac{4\pi}{q}\int_0^\infty \rho(r)\sin(qr)r\,dr$$
$$= 1 - \frac{\vec{q}^{\,2}}{6}\langle r^2\rangle + \frac{\vec{q}^{\,2}}{120}\langle r^4\rangle + \ldots$$ Taylor expans.

The dipole form

$$G_D = \frac{1}{\left(1+\frac{Q^2}{0.71}\right)^2} \quad \leftrightarrow \quad \rho_D(r) = \rho_0\,\mathrm{e}^{-\sqrt{0.71}r}$$



The HERA collider



- During 1992–2007, mainly E_e = 27.5 GeV, E_p = 920 GeV giving $\sqrt{s}$ ~ 320 GeV;

Data are collected with ZEUS and H1 detectors: ~ 1 fb^{-1}

$$Q^2 = -q^2 = -(k - k')^2$$

$$x_{Bj} = \frac{Q^2}{2\,pq} \qquad y = \frac{pq}{pk}$$

$$s = (p + k)^2 \qquad Q^2 = xys$$

During 100 years the theory evolved significantly, QED, QCD, EW → Standard Model (SM)

$$\sigma^{\pm}_{r,\mathrm{NC}} = \frac{\mathrm{d}^2\sigma^{e^\pm p}_{\mathrm{NC}}}{\mathrm{d}x_{\mathrm{Bj}}\mathrm{d}Q^2} \cdot \frac{Q^4 x_{\mathrm{Bj}}}{2\pi\alpha^2 Y_+} = \tilde{F}_2 \mp \frac{Y_-}{Y_+} x\tilde{F}_3 - \frac{y^2}{Y_+}\tilde{F}_{\mathrm{L}}$$

One hundred years later,
when we again raise the question of the size of the smallest object under study (quark),
we return to the original formula.

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x_{Bj}\mathrm{d}Q^2} = \frac{\mathrm{d}^2\sigma^{\mathrm{SM}}}{\mathrm{d}x_{Bj}\mathrm{d}Q^2} \cdot \left[1 - \frac{\langle R_q^2 \rangle}{6} Q^2\right]^2$$

← the dipole form of FF

R_q provides the effective scale

Before to start: Estimations based on the uncertainty principle

$$q_0 = (k - x_{Bj} P)\frac{Q^2}{x_{Bj} s}, \quad |\vec{q}| = \sqrt{q_0^2 + Q^2}$$

The virtual photon momentum components

$$\Delta x = \frac{\hbar \cdot c}{|\vec{q}|}$$

In space units

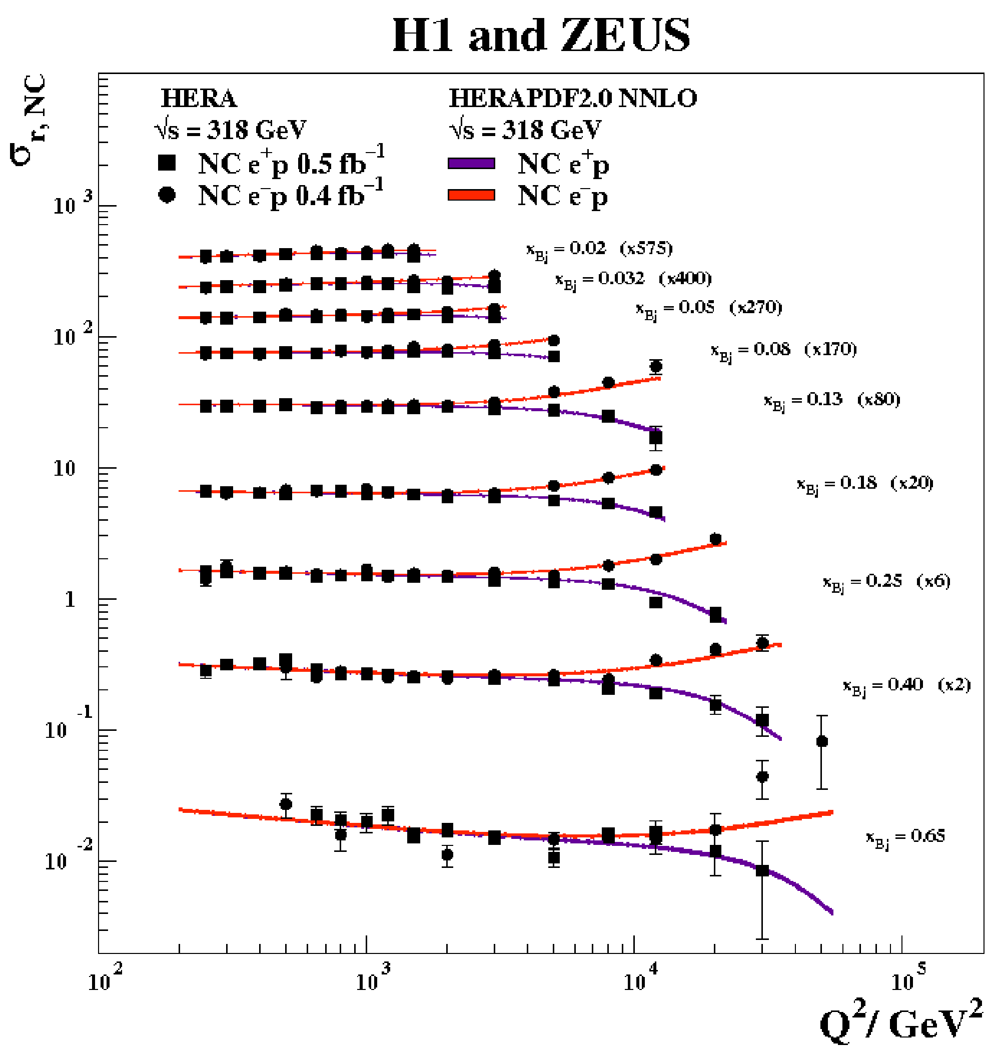
At a point from the comb. data set

Q^2 =50000 GeV^2, x_{Bj}=0.65

$$\Delta x = 0.41 * 10^{-3}\,\mathrm{fm}$$

Reduced cross sections

$$\sigma^{\pm}_{r,\mathrm{NC}} = \frac{d^2\sigma^{e^{\pm}p}_{\mathrm{NC}}}{dx_{\mathrm{Bj}}dQ^2} \cdot \frac{Q^4 x_{\mathrm{Bj}}}{2\pi\alpha^2 Y_+} = \tilde{F}_2 \mp \frac{Y_-}{Y_+} x\tilde{F}_3 - \frac{y^2}{Y_+}\tilde{F}_{\mathrm{L}}$$



{QCD, DGLAP}→HERAPDF2.0

14 fit parameters

In this analysis BSM contributions (R_q^2) and the QCD evolution are fitted simultaneously.

R_q^2 was treated as a test statistic

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Combined (H1+ZEUS) reduced NC cross sections (small fraction)

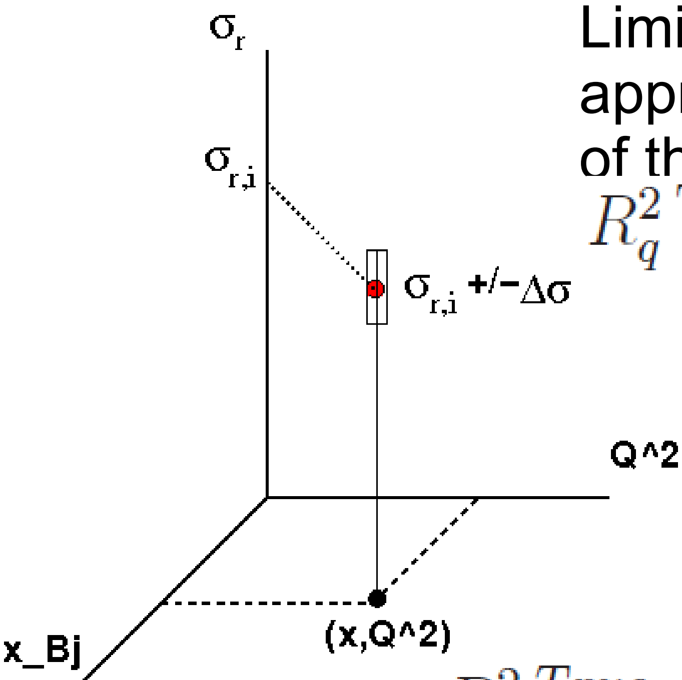
Q^2 GeV^2	x_{Bj}	$\sigma^+_{r,NC}$	δ_{stat} %	δ_{uncor} %	δ_{cor} %	δ_{rel} %	$\delta_{\gamma p}$ %	δ_{had} %	δ_1 %	δ_2 %	δ_3 %	δ_4 %	δ_{tot} %
3.5	0.406×10^{-4}	0.806	6.14	4.17	1.18	1.09	−0.25	−0.46	−0.04	−0.75	−0.01	−0.15	7.65
3.5	0.432×10^{-4}	0.881	3.08	2.83	3.31	0.70	−4.07	0.56	−2.62	−0.18	−0.01	−0.05	7.26
3.5	0.460×10^{-4}	0.965	3.05	2.99	1.10	0.35	−0.21	−0.41	−0.05	−0.15	−0.01	−0.22	4.45
3.5	0.512×10^{-4}	0.940	2.16	2.25	1.53	0.52	−1.61	0.05	−1.16	−0.07	0.01	0.01	4.04
3.5	0.531×10^{-4}	0.880	3.10	2.64	0.91	0.48	−0.20	−0.30	−0.03	−0.01	−0.01	−0.21	4.22
3.5	0.800×10^{-4}	0.952	1.25	1.55	0.88	0.43	−0.26	−0.09	−0.08	−0.09	0.01	0.03	2.24
3.5	0.130×10^{-3}	0.918	0.66	0.86	0.80	0.45	−0.13	−0.28	0.18	0.00	0.02	0.06	1.46
3.5	0.200×10^{-3}	0.854	0.68	0.83	0.81	0.44	0.09	−0.22	0.26	0.00	0.01	0.08	1.46
3.5	0.320×10^{-3}	0.791	0.72	0.88	0.86	0.50	−0.21	−0.01	0.11	0.00	0.01	0.07	1.53

σ_r «surface» in (x,Q^2)-space with > 10^3 points

$$\chi^2(\boldsymbol{m},\boldsymbol{s}) = \sum_i \frac{\left[m^i + \sum_j \gamma^i_j m^i s_j - \mu^i_0\right]^2}{\left(\delta^2_{i,\mathrm{stat}} + \delta^2_{i,\mathrm{uncor}}\right)\,(\mu^i_0)^2} + \sum_j s_j^2$$

μ^i_0 is the measured cross-section value at the point i

Limits setting with Monte Carlo replicas



Limits are derived in a classical (frequentist) approach using the technique of Monte Carlo replicas of the cross-section measurements for some value of $R_q^{2\,\mathrm{True}}$ (~5000 replicas for each)

Next each Monte Carlo replica is fitted for the $R_q^{2\,\mathrm{True}}$ parameter simultaneously with PDFs.

200000 fits

$$R_q^{2\,True} \longrightarrow \quad R_q^{2\,Fit} \quad \longleftrightarrow \quad R_q^{2\,Data}$$

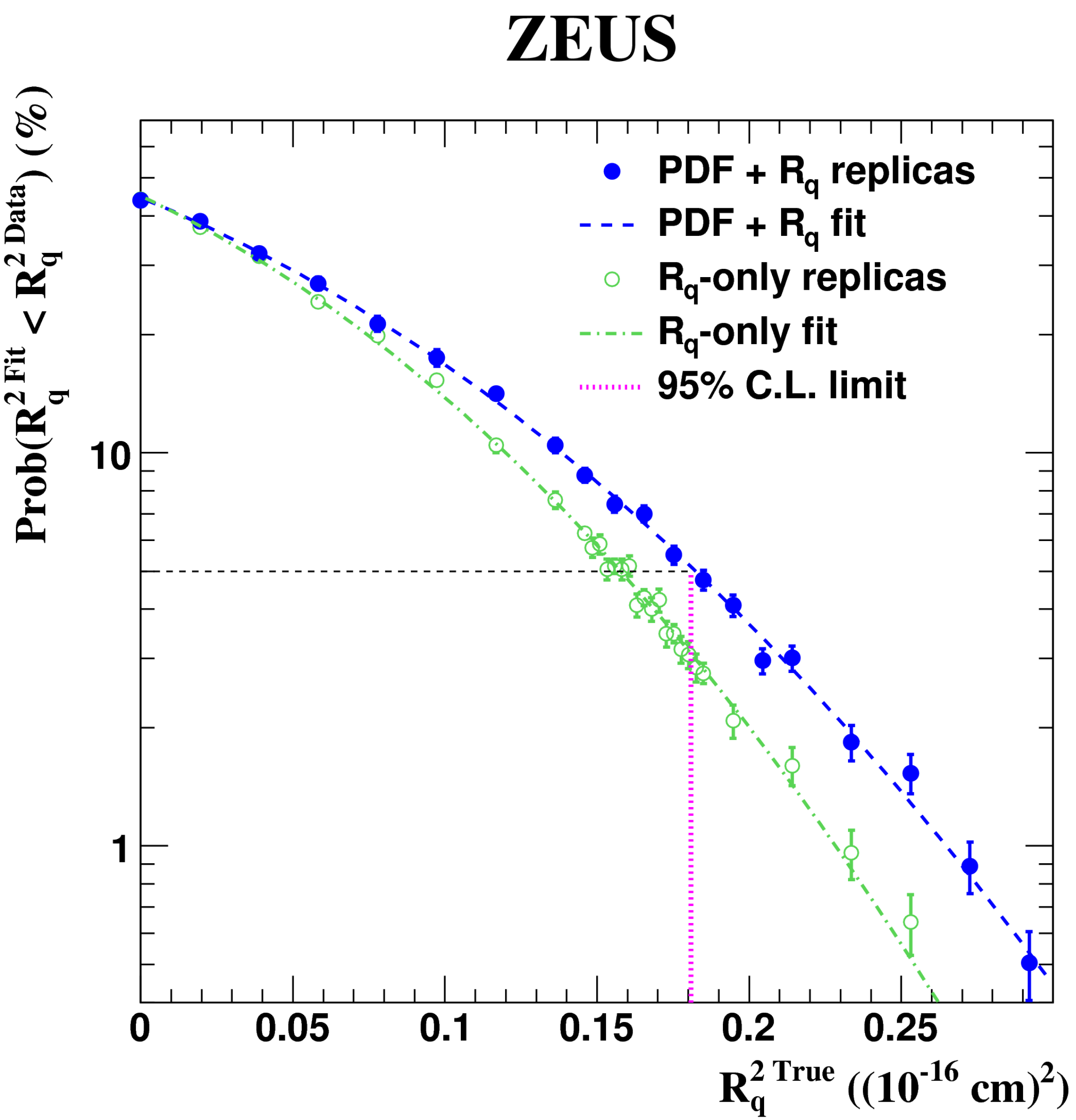
$R_q^{2\,True}$	$\sigma_r^{\mathrm{ZR_q}} \cdot \left[1 - \frac{R_q^{2\,True}}{6} Q^2\right]^2 = m_0^i$	Varied randomly
$R_q^{2\,Fit}$	$\sigma_r^{\mathrm{ZR_q}} \cdot \left[1 - \frac{R_q^{2\,Fit}}{6} Q^2\right]^2 = \mu^i$	Fit replicas
$R_q^{2\,Data}$	$\sigma_r^{\mathrm{ZR_q}} \cdot \left[1 - \frac{R_q^{2\,Data}}{6} Q^2\right]^2 = \sigma_r$	Fit to data

$$R_q^{2\,True} \longrightarrow R_q^{2\,Fit} \longleftrightarrow R_q^{2\,Data}$$

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

- m_0^i: Cross-section prediction from the ZRqPDF modified with η^{True}
- μ_0^i: Measured cross-section value
- γ_j^i: Correlated systematic uncertainties
- $\delta_{i,stat}$, $\delta_{i,uncor}$: Relative statistical and uncorrelated systematic uncertainties
- r_i, r_j: Random numbers from a normal distribution

If $R_q^{2\,Fit} > R_q^{2\,Data}$ in 95% replicas, then excluded at the 95% C.L.



The solid circles correspond to the results obtained from the simultaneous fit of R_q^2 and PDF parameters (PDF+Rq).

The open circles represent the dependence obtained when fixing the PDF parameters to the ZRqPDF values (Rq-only).

The effective quark radius limits

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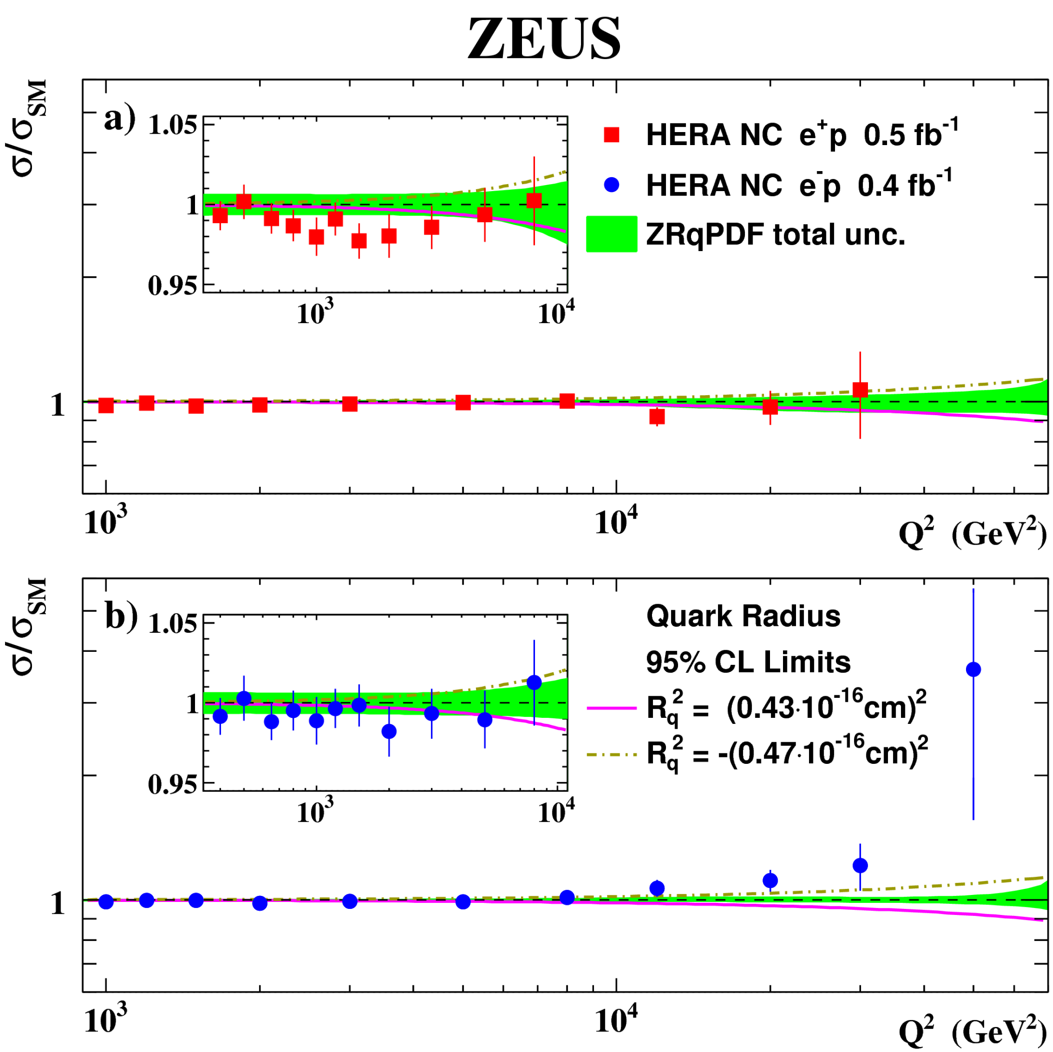
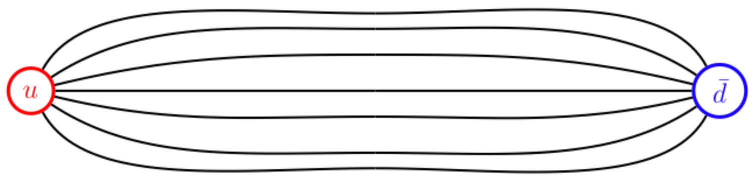
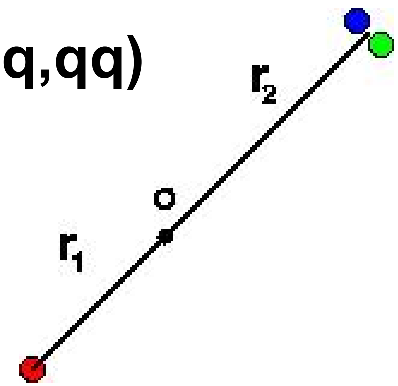


$$-(0.47 \cdot 10^{-16} \mathrm{cm})^2 < R_q^2 < (0.43 \cdot 10^{-16} \mathrm{cm})^2$$

For comparison

QCD string model: Proton as a quark-diquark (q,qq)





$$\bar{r_p} = 0.25\,\text{fm}$$

PDG

$$r_p = 0.875\ (7)\ \text{fm}$$

Present analysis (ZEUS): effective quark «size»

$$\bar{r_q} = \sqrt{|\langle R_q^2 \rangle|} < 0.43 \cdot 10^{-3}\,\text{fm}$$

Rutherford, (1911)

$R_{Au} < 5 \cdot 10^{-12}$cm=50 fm

$2.9\ \text{GeV}^2 < Q^2 < 10^5\ \ \text{GeV}^2$

Summary

- A new approach to the BSM analysis of the inclusive ***ep*** data is presented; simultaneous fits of parton distribution functions together with contributions of *"new physics"* processes were performed.

- Results are presented considering a finite radius of quarks within the quark form-factor model.

-The resulting 95% C.L. upper limit on the effective quark radius is $4.3 \cdot 10^{-17}$ cm ($4.3 \cdot 10^{-4}$ fm) .

-The term "quark radius" is only one possible interpretation of BSM effects parameterised as form factors.