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

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On behalf of ZEUS Collaboration

- ➢ Combined inclusive DIS data from HERA
- ➢ Quark form-factor model
- ➢ Beyond-the-Standard-Model analysis combined with PDFs fit

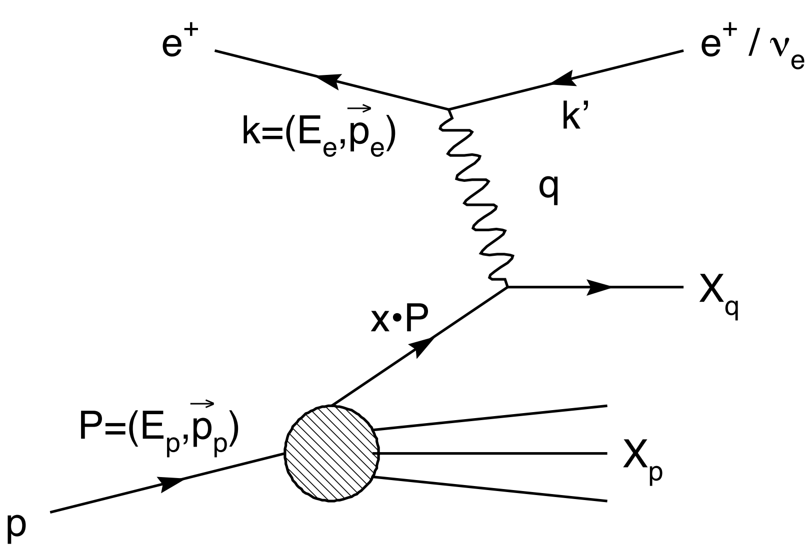
HERA - world's only $e^{\pm}p$ collider

HERA operated during 1992 - 2007 with:

$e^{\pm}$ energy of 27.5 GeV;
p energies of 920, 820, 575 and 460 GeV.

H1 and **ZEUS** - two general purpose collider experiments at HERA:

~0.5 fb^{-1} of luminosity were recorded by each experiment.



Kinematics of the $e^{\pm}p$ collisions:

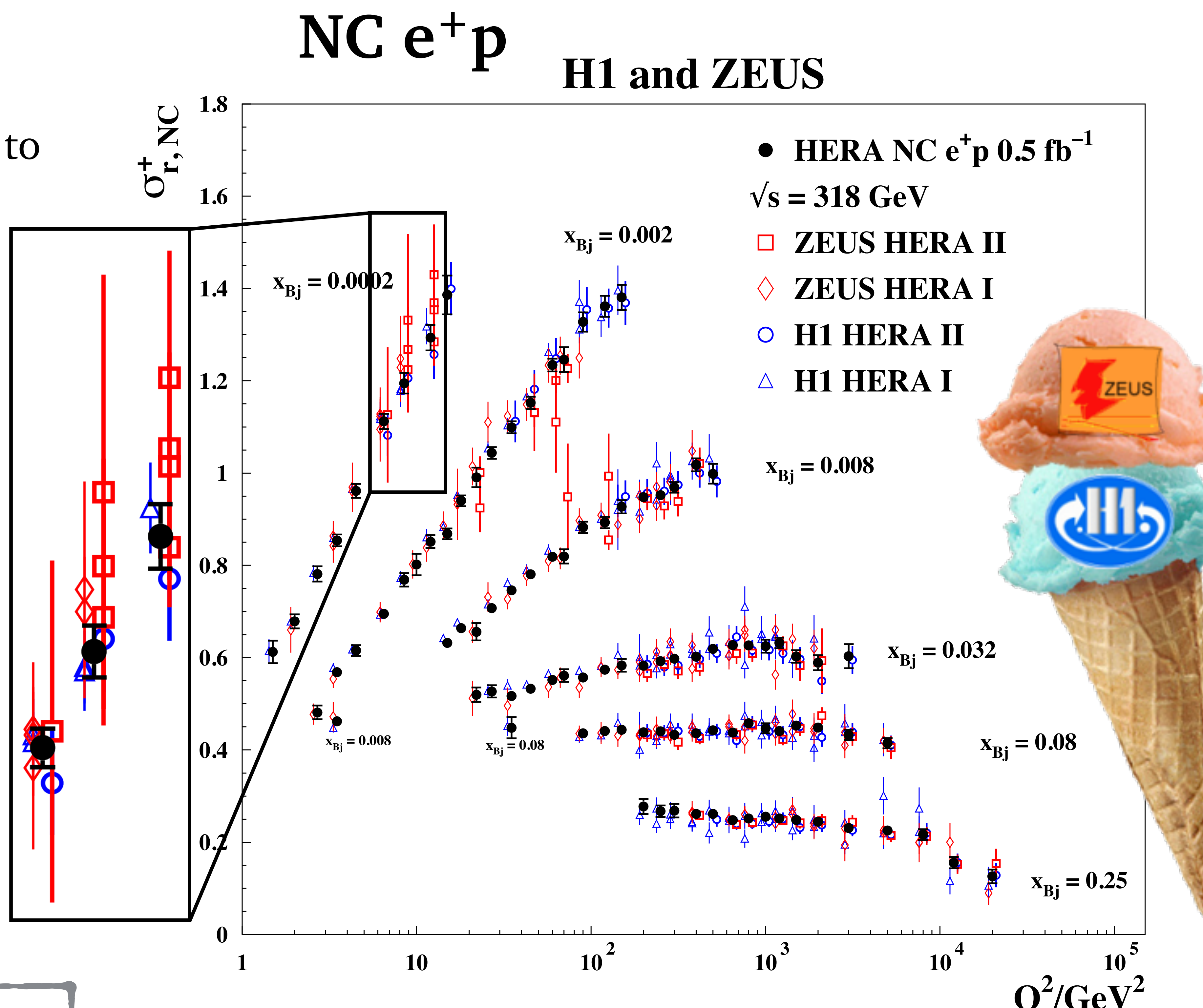
$$Q^2 = -(k - k')^2$$

$$x_{Bj} = \frac{Q^2}{2P \cdot q}$$

$$y = \frac{P \cdot q}{P \cdot k}$$

HERA inclusive data combination

- 2927 data point combined to 1307
- up to 8 data points combined to 1
- impressive improvement of precision due to:
  - increased statistics
  - better understanding of systematics
  - cross-calibration of the data from two experiments



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QCD analysis of the combined DIS data

Neutral Current:

$$\frac{d^2\sigma^{e^\mp p}_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\cdot\left(Y_+\cdot F_2 \pm Y_-\cdot xF_3 - y^2\cdot F_L\right)$$

$$Y_\pm = 1 \pm (1-y)^2$$

$$F_L \sim \alpha_s g$$

Charged Current:

$$\frac{d^2\sigma^{e^\mp p}_{CC}}{dxdQ^2} = \frac{G_F^2}{4\pi x}\cdot\kappa^2\cdot\left(Y_+\cdot W_2^\mp \pm Y_-\cdot xW_3^\mp - y^2\cdot W_L^\mp\right)$$

$$\kappa = \frac{M_W^2}{M_W^2+Q^2}$$

At the Quark-Parton Model:

$$F_2 = \frac{4}{9}\left(xU + x\bar{U}\right) + \frac{1}{9}\left(xD + x\bar{D}\right)$$

$$xF_3 \sim xu_v + xd_v$$

$$W_2^- = x\left(U + \bar{D}\right) \qquad W_2^+ = x\left(D + \bar{U}\right)$$

$$xW_3^- = x\left(U - \bar{D}\right) \qquad xW_3^+ = x\left(D - \bar{U}\right)$$

Parton Density Functions parametrisation at the starting scale $Q^2_0 = 1.9$ GeV^2:

$$xg(x) = A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g}$$

$$xu_v(x) = A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1 + E_{u_v}x^2\right)$$

$$xd_v(x) = A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}$$

$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}\left(1 + D_{\bar{U}}x\right)$$

$$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}$$

- fixed or calculated by the sum-rules
- set equal

Evolve to any $Q^2 > Q^2_0$ with DGLAP at NLO.

Obtained PDFs are referred to as **ZCIPDFs** and have a good agreement with the HERAPDF 2.0.

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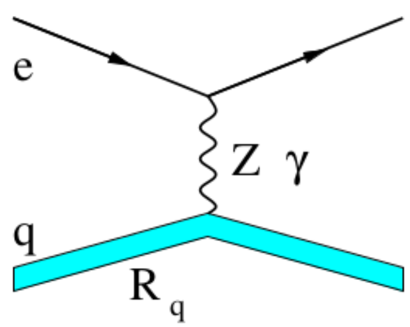
How big is a quark ?

One of the possible parameterisations of the deviations from the Standard Model - spatial distribution or substructure of electrons and/or quarks.

In a semi-classical form-factor approach cross sections are expected to **decrease** at high-Q^2:



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

There $\mathbf{R^2_e}$ and $\mathbf{R^2_q}$ are the mean-square radii of the electron and quark, respectively.

Same dependence expected for **NC** and **CC** e^+p and e^-p.

Electrons were assumed to be point-like, $\mathbf{R^2_e = 0}$, and both, positive and negative values of R^2_q were considered.

Reason for the simultaneous fit procedure

- ➢ BSM signal in the data could affect the PDF fit and result in **biased PDFs**.

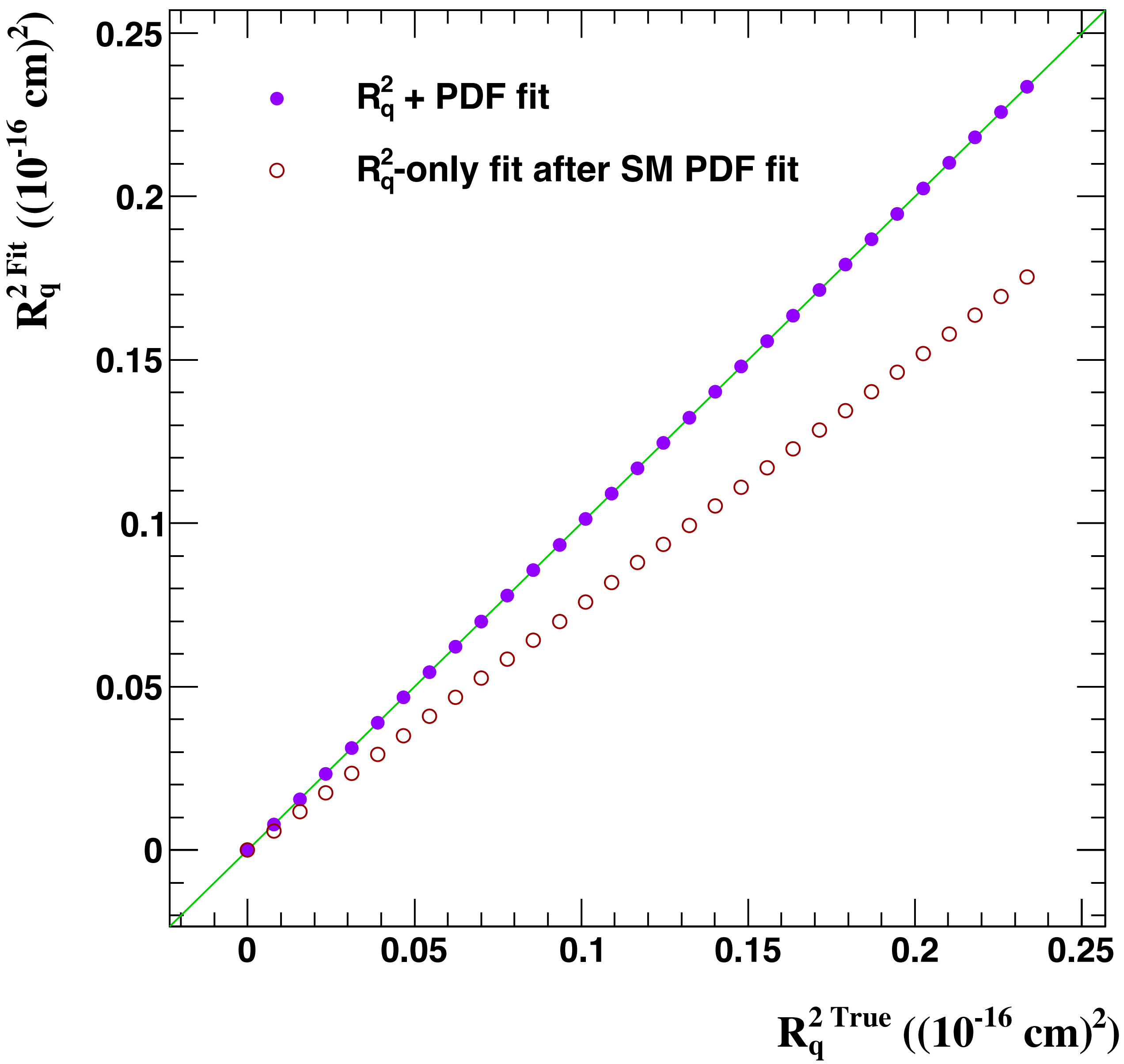
- ➢ Use of the **biased PDFs** in the BSM analysis would result in **overestimated limits**.

- ➢ This cannot be avoided for the analysis of HERA data by using another available PDF set, since all high-precision PDF fits include the DIS data from HERA (MMHT2014, NNPDF 3.0, etc.).

- ➢ The proper procedure for a BSM analysis of the HERA data - global **QCD analysis which includes a possible contribution from BSM** processes.

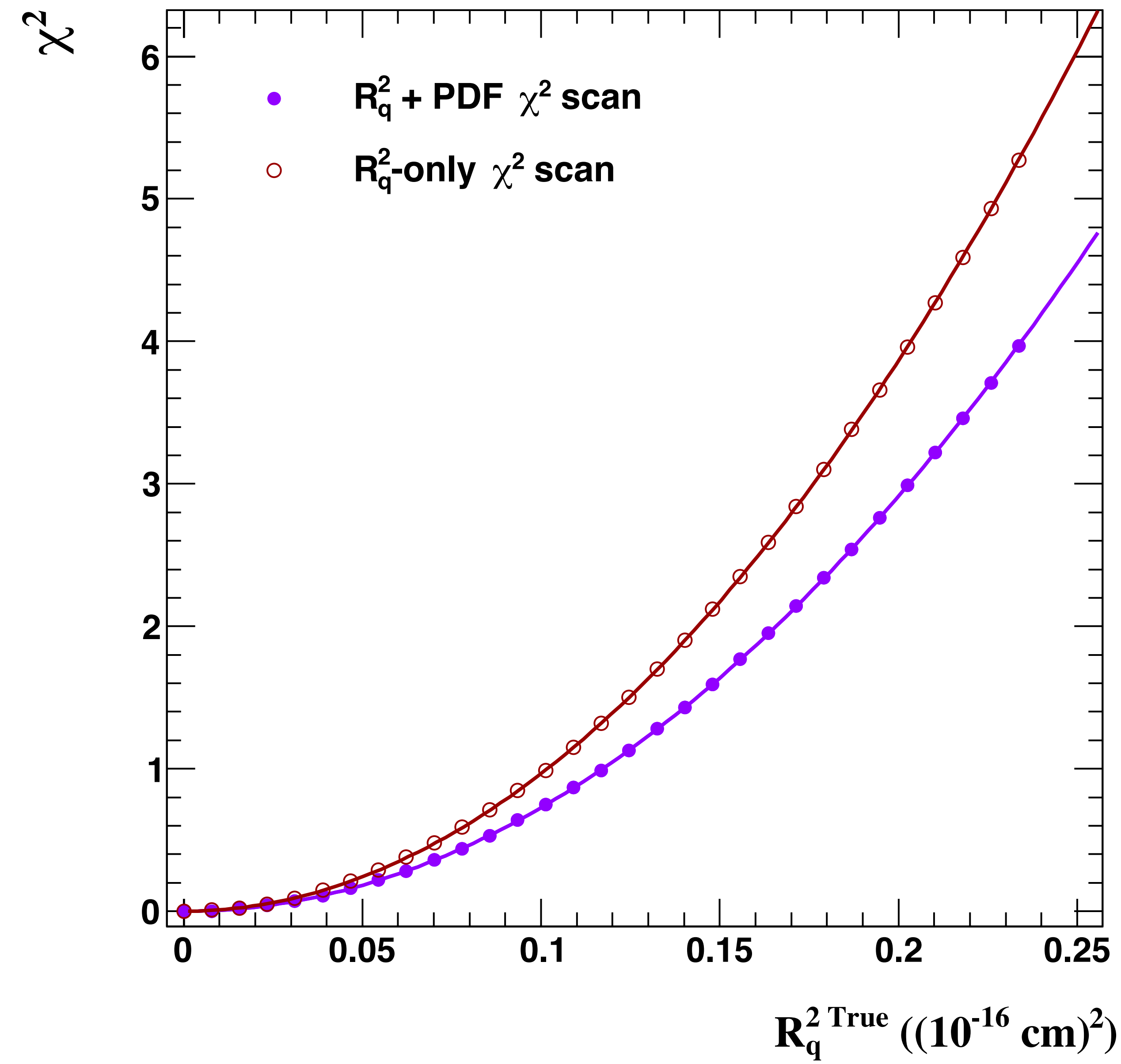
Necessity of the simultaneous fit procedure

Pseudodata generated for values of $R^2_q = R^2_q{}^{True}$



R^2_q+PDF procedure provides unbiased results of $R^2_q{}^{Fit}$

Pseudodata generated for value of $R^2_q = 0$



R^2_q-only procedure results in too strong limits

Limits setting method

Limits are derived in a frequentist approach using the technique of Monte Carlo replicas. Two procedures were used:

R_q-only Monte Carlo replicas generated for $R^2_q{}^{True}$ using **ZCIPDFs** and $R^2_q{}^{Fit}$ parameter fitted with PDFs **fixed to ZCIPDFs**.

PDF+R_q Monte Carlo replicas generated for $R^2_q{}^{True}$ using **ZCIPDFs** and $R^2_q{}^{Fit}$ parameter fitted **simultaneously** with PDFs.

The **PDF+R_q** frequentist method was the main analysis method.

Monte Carlo replicas

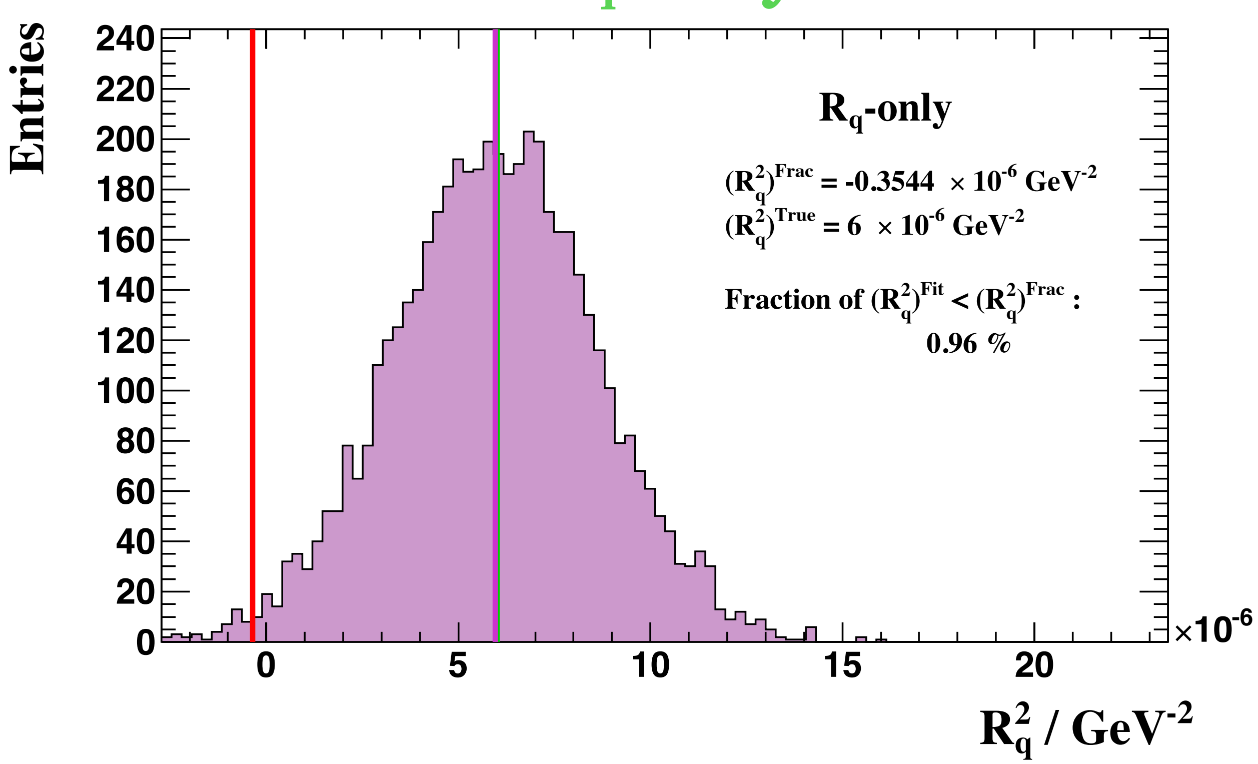
Monte Carlo replicas of the cross-section measurements were calculated with:

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

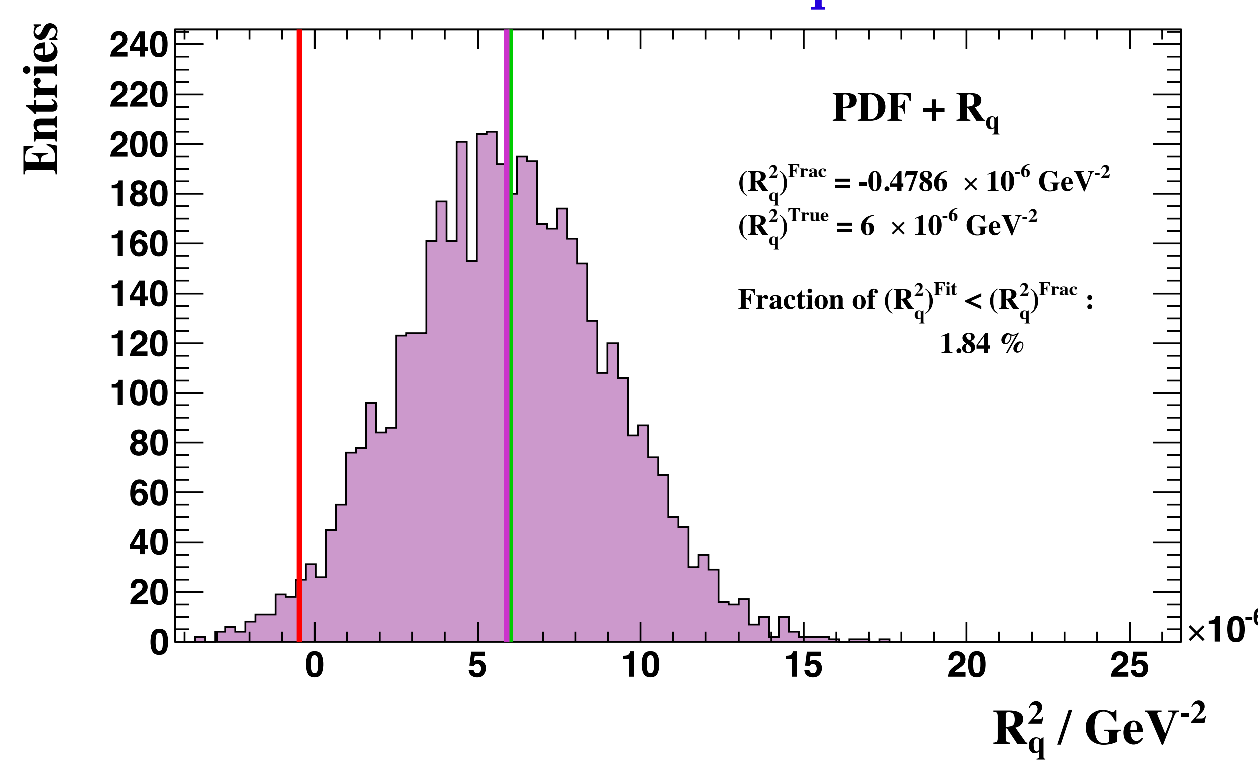
- m_0^i: Cross-section prediction from the ZCIPDF modified with $R_q^{2\,True}$
- μ_0^i: Measured cross-section value
- γ_j^i: Correlated systematic uncertainties
- $\delta_{i,stat}$, $\delta_{i,uncor}$: Relative statistical and uncorrelated systematic uncertainties
- r_i, r_j: Random numbers from a normal distribution

Fitted MC replicas for $\mathbf{R_q^{True} = 0.48 \cdot 10^{-16}}$ **cm**:

R_q-only

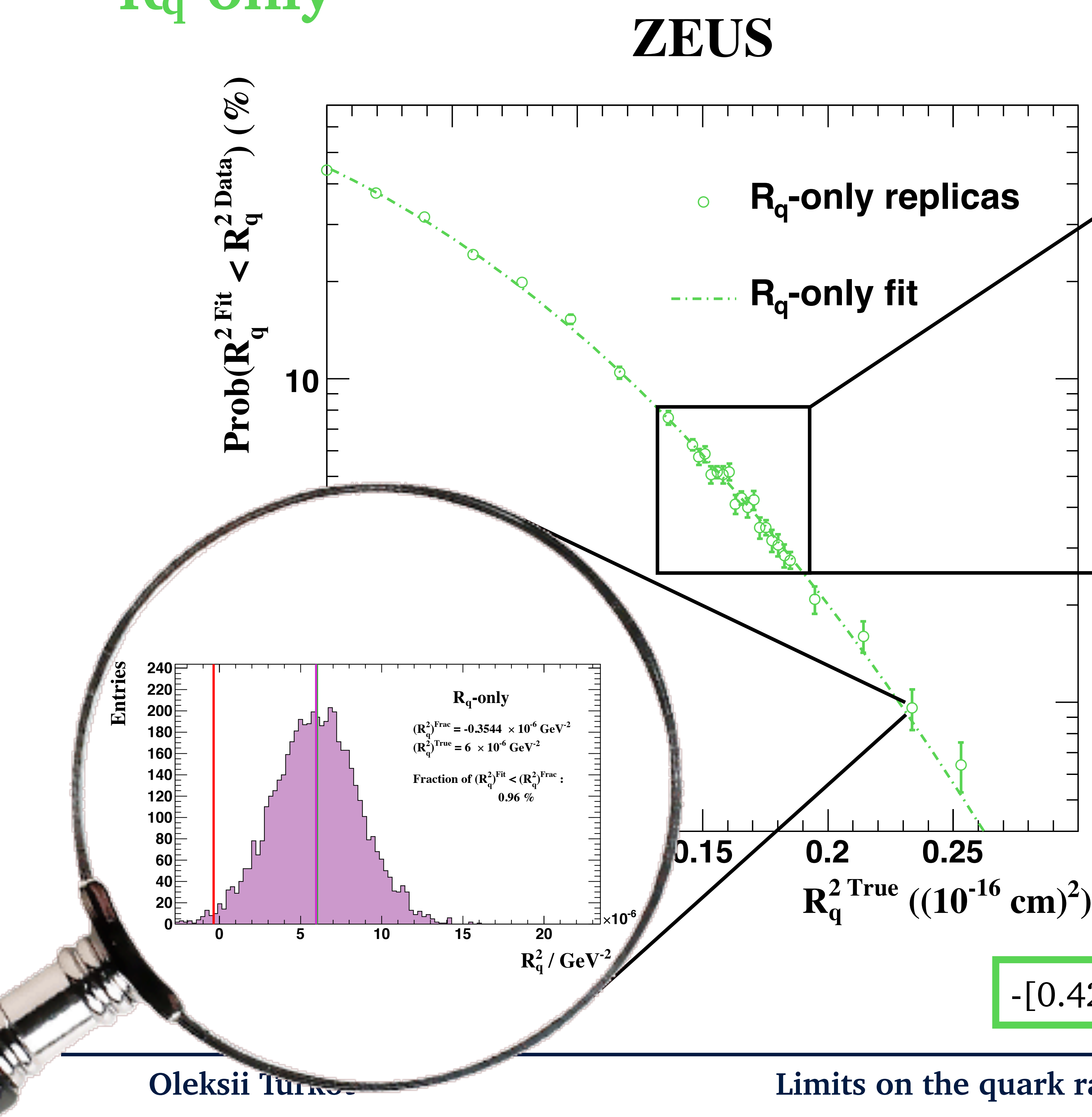


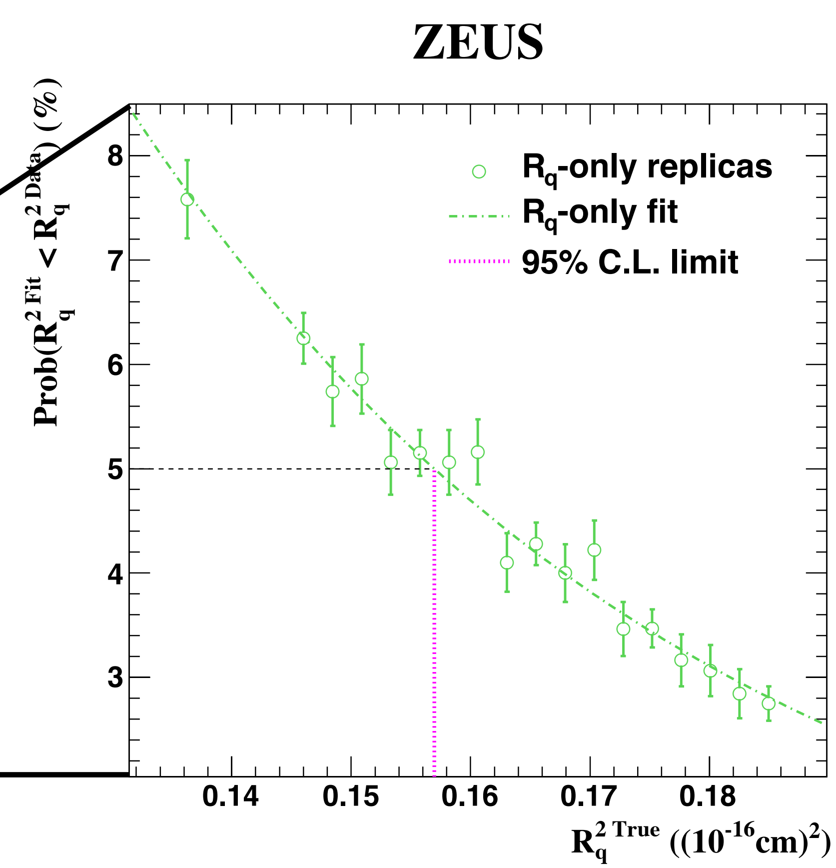
PDF+R_q



R_q limits with the MC replicas

R_q-only





Probabilities close to 5% fitted with:

$$f(x) = 5 \cdot e^{(x-A)\cdot B}$$

$-[0.42 \cdot 10^{-16}\ \text{cm}]^2 \leq R^2_q \leq [0.40 \cdot 10^{-16}\ \text{cm}]^2$

R_q limits with the MC replicas

PDF+R_q

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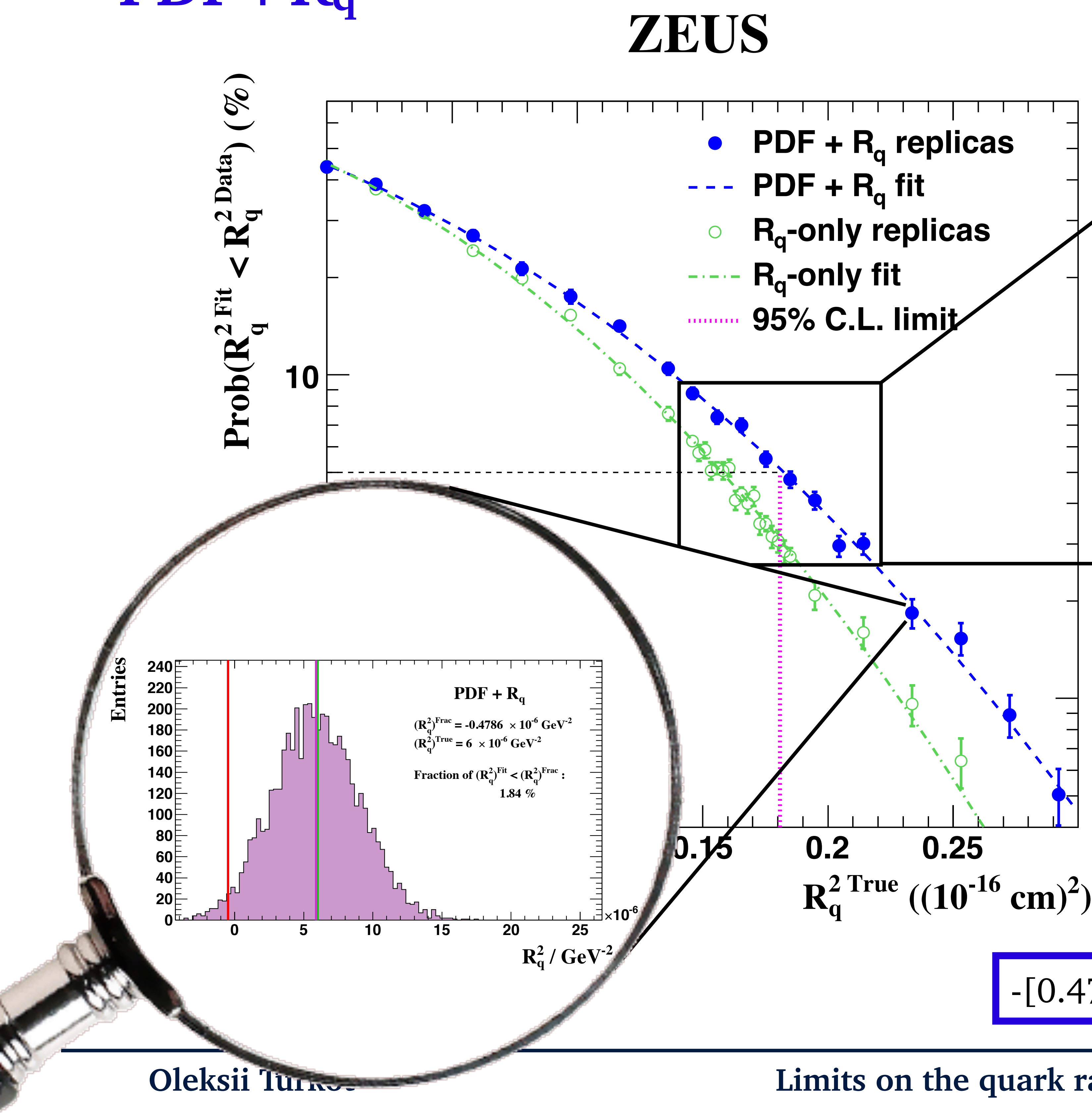
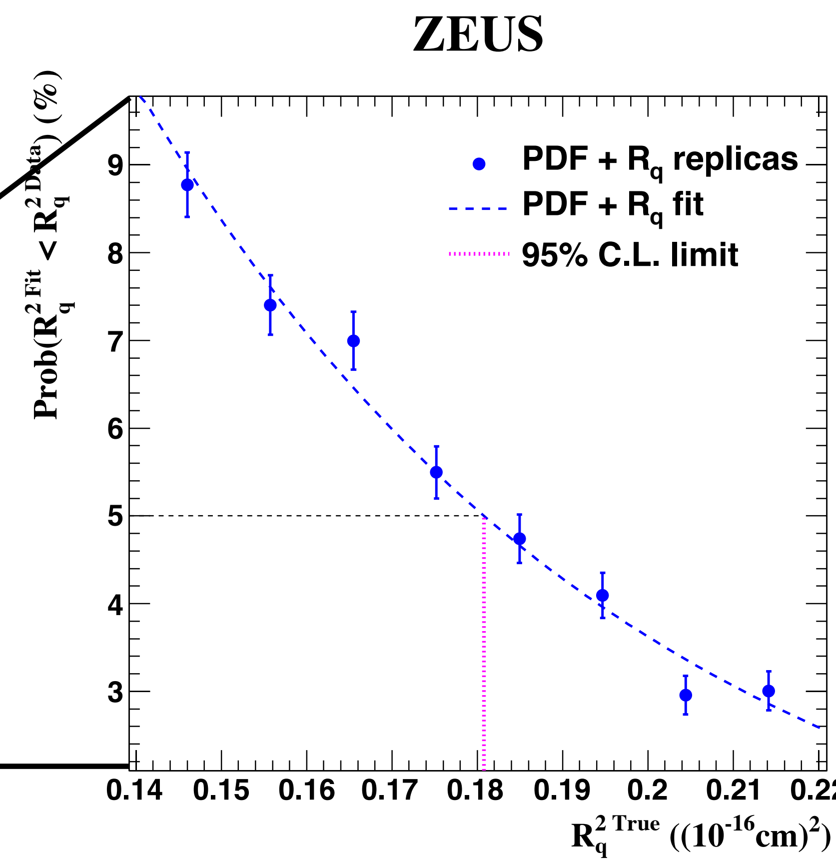




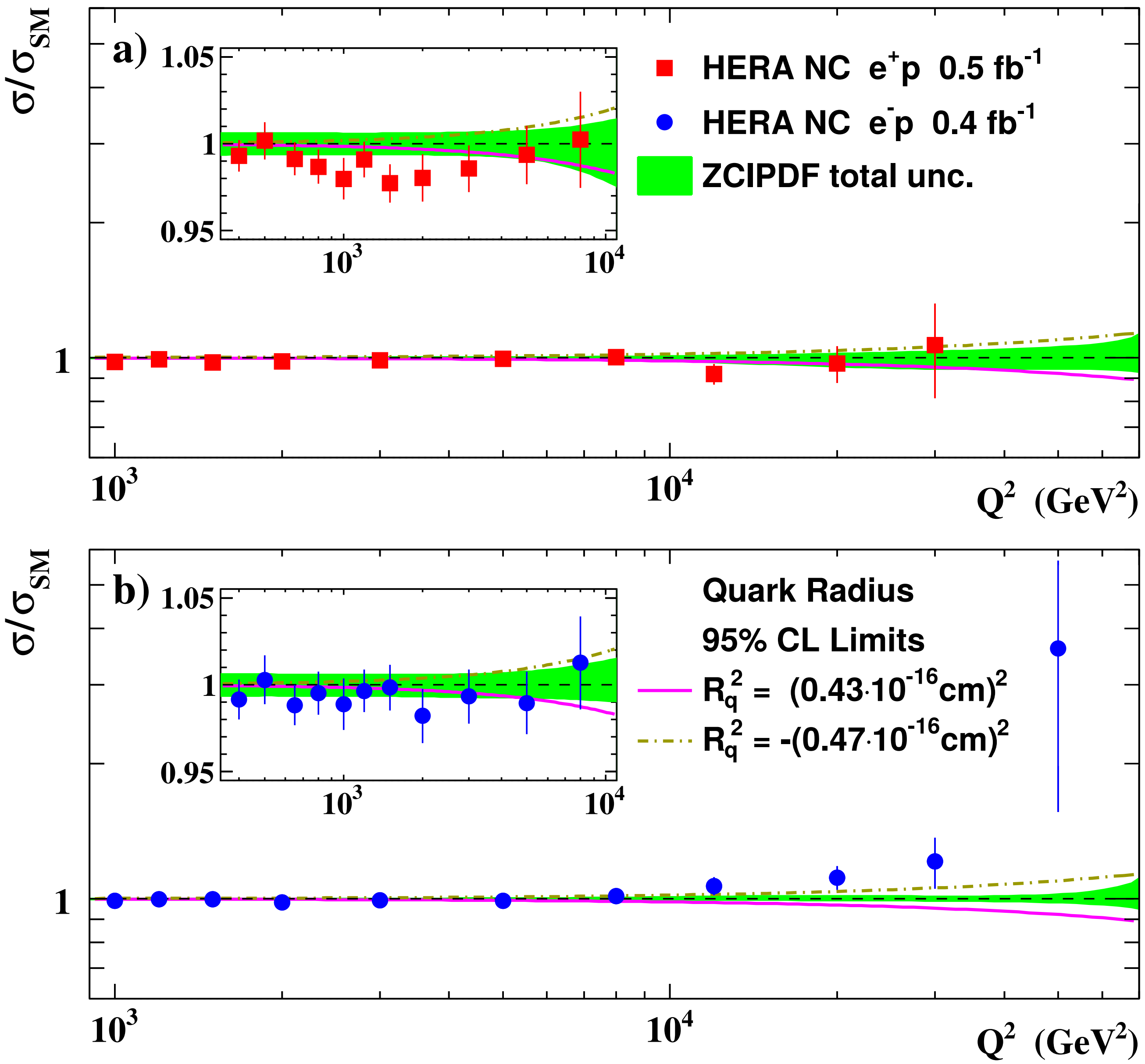
Probabilities close to 5% fitted with:

$$f(x) = 5 \cdot e^{(x-A)\cdot B}$$

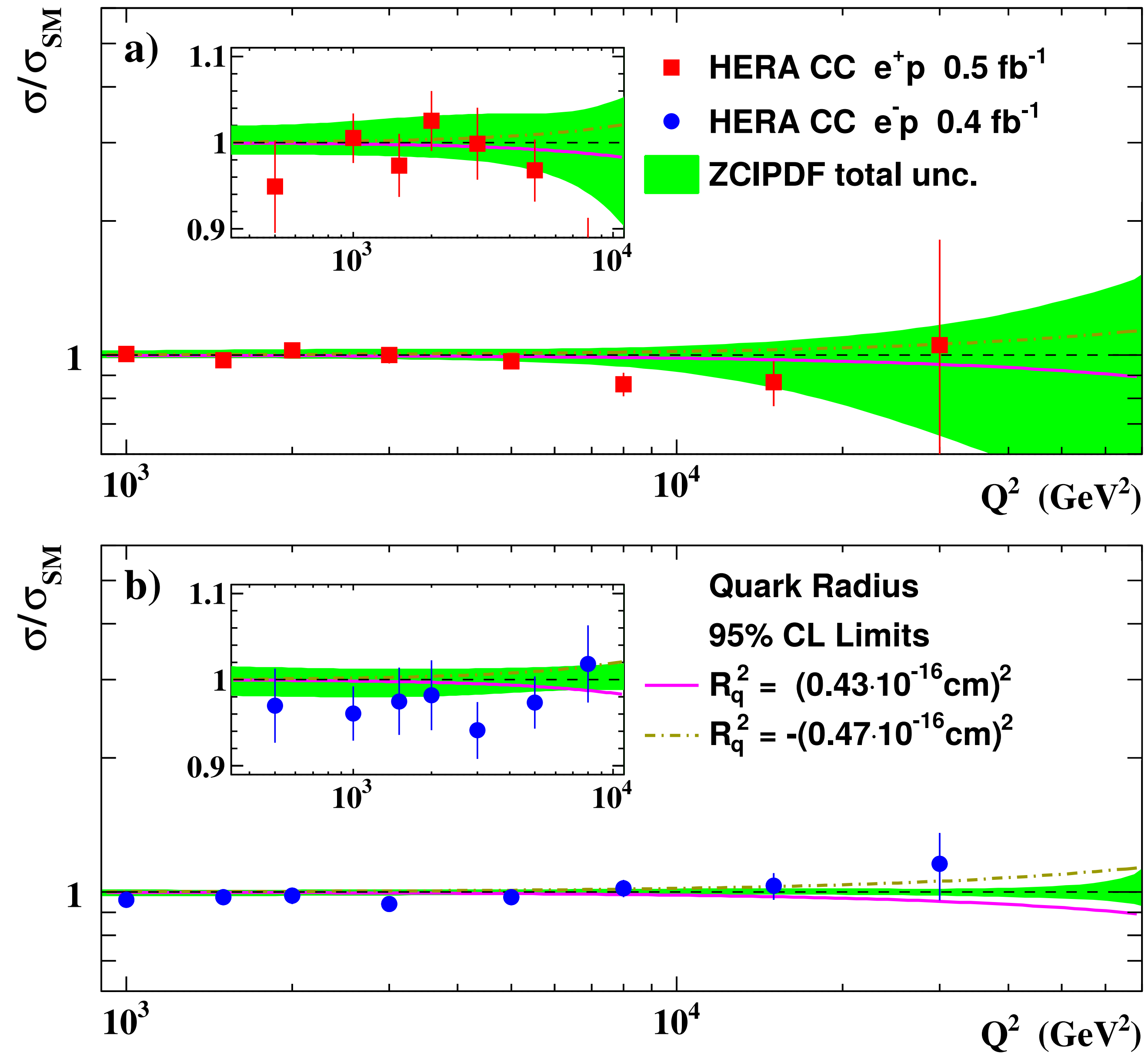
$-[0.47 \cdot 10^{-16}\ \mathrm{cm}]^2 \leq R^2_q \leq [0.43 \cdot 10^{-16}\ \mathrm{cm}]^2$

Comparison to Data

Neutral Current:



Charged Current:



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Summary

➢ Combined HERA inclusive DIS cross-section measurements allow to study the proton substructure at the scales down to 10^{-17} cm.

➢ The simultaneous analysis of PDFs and quark form factor yield the 95% C.L. limits of the effective quark radius of

$$-[0.47 \cdot 10^{-16}\ \mathrm{cm}]^2 \leq R^2_q \leq [0.43 \cdot 10^{-16}\ \mathrm{cm}]^2$$

➢ The simultaneous analysis is necessary since the limits that would be obtained otherwise are too strong by about 10%.

More results of the combined PDFs and BSM analysis were presented by K. Wichmann today at 9:45.