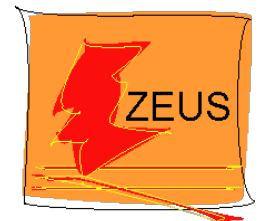




Limits on the effective quark radius from inclusive ep scattering at HERA



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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;

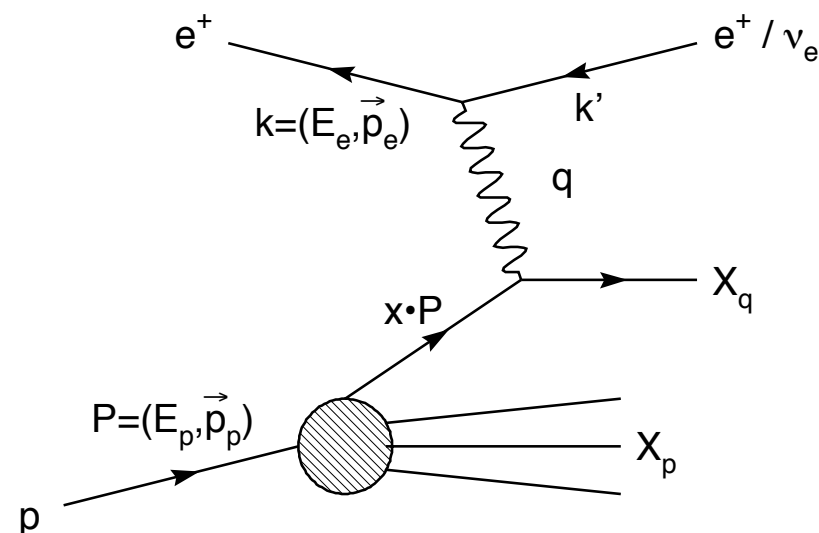
p energies of 920, 820, 575 and 460 GeV.



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

$\sim 0.5 \text{ fb}^{-1}$ of luminosity were recorded by each experiment.

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



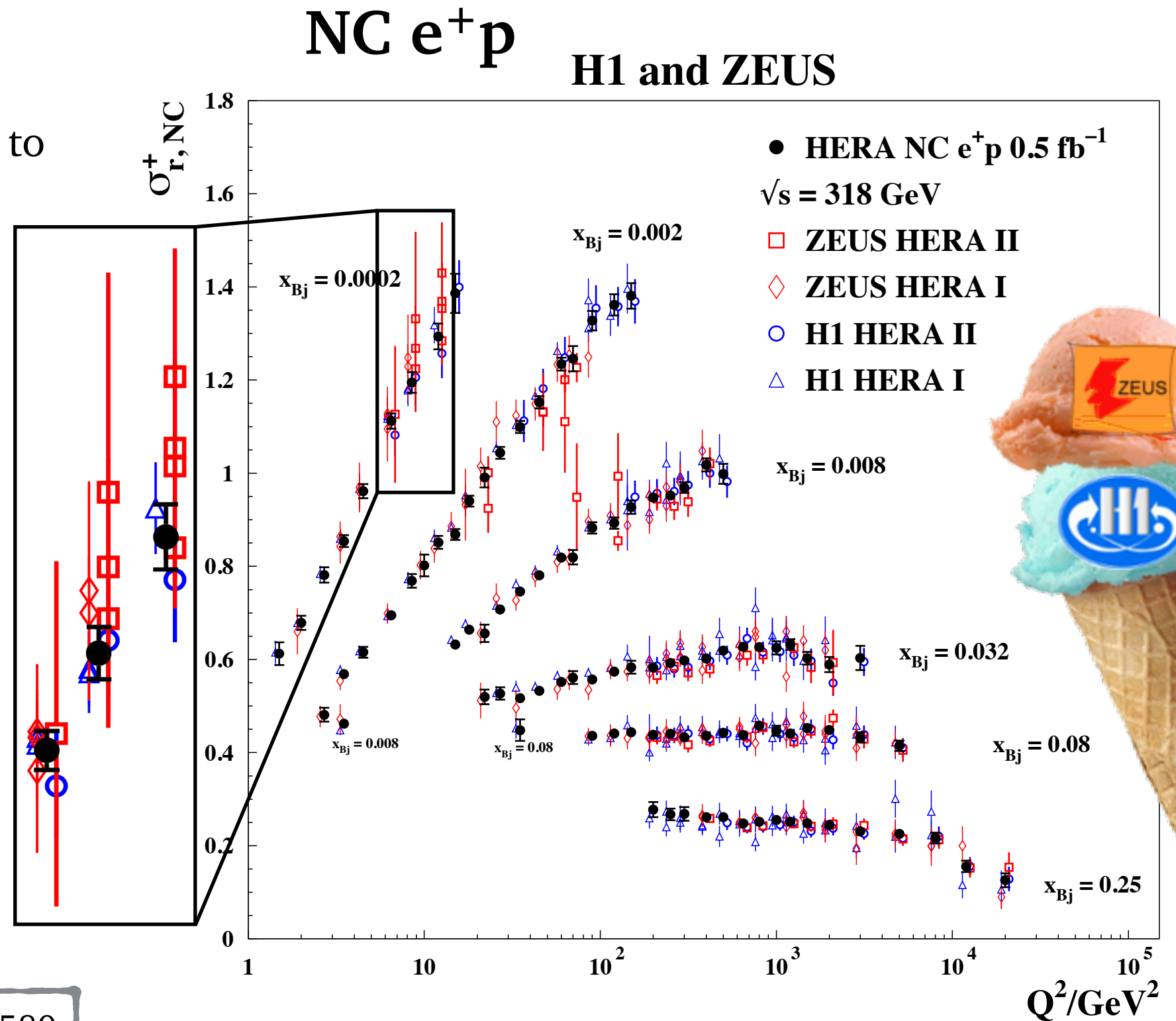
$$Q^2 = -(k - k')^2$$

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

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

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:

$$\frac{d^2\sigma_{NC}^{e^\mp p}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \cdot (Y_+ \cdot F_2 \pm Y_- \cdot xF_3 - y^2 \cdot F_L)$$

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

$$F_L \sim \alpha_s g$$

At the Quark-Parton Model:

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

$$xF_3 \sim xu_v + xd_v$$

Charged Current:

$$\frac{d^2\sigma_{CC}^{e^\mp p}}{dx dQ^2} = \frac{G_F^2}{4\pi x} \cdot \kappa^2 \cdot (Y_+ \cdot W_2^\mp \pm Y_- \cdot xW_3^\mp - y^2 \cdot W_L^\mp)$$

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

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

$$W_2^+ = x(D + \bar{U})$$

$$xW_3^- = x(U - \bar{D})$$

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

Parton Density Functions parametrisation at the starting scale $Q_0^2 = 1.9 \text{ GeV}^2$:

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

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

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

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

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

■ fixed or calculated by the sum-rules

■ set equal

Evolve to any $Q^2 > Q_0^2$ with DGLAP at NLO.

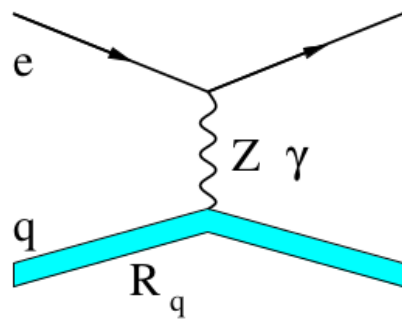
Obtained PDFs are referred to as **ZCIPDFs** and have a good agreement with the HERAPDF 2.0.

Phys. Lett. B757 (2016), 468-472

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 R_e^2 and R_q^2 are the mean-square radii of the electron and quark, respectively.

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

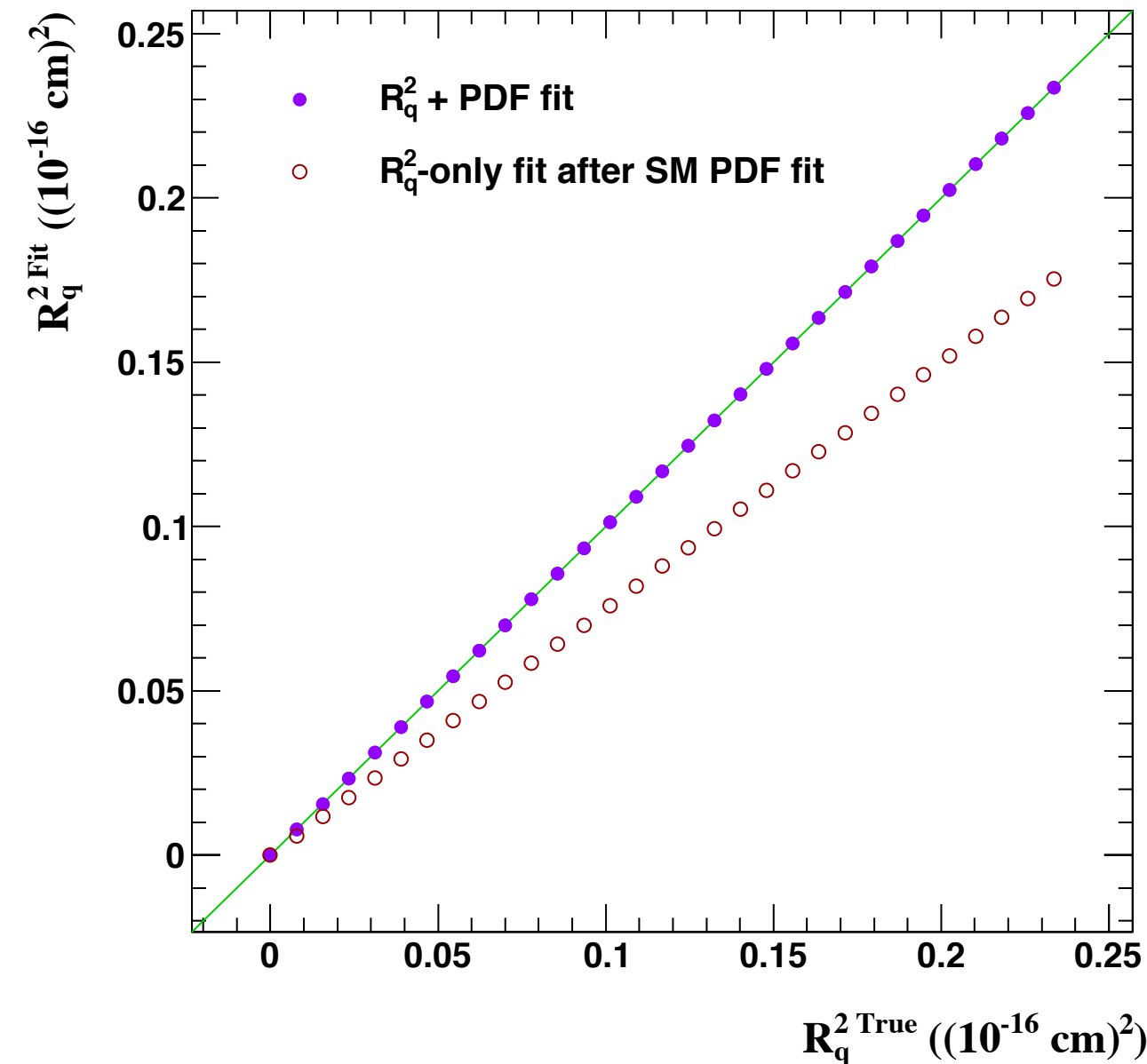
Electrons were assumed to be point-like, $R_e^2 = 0$, and both, positive and negative values of R_q^2 were considered.

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.

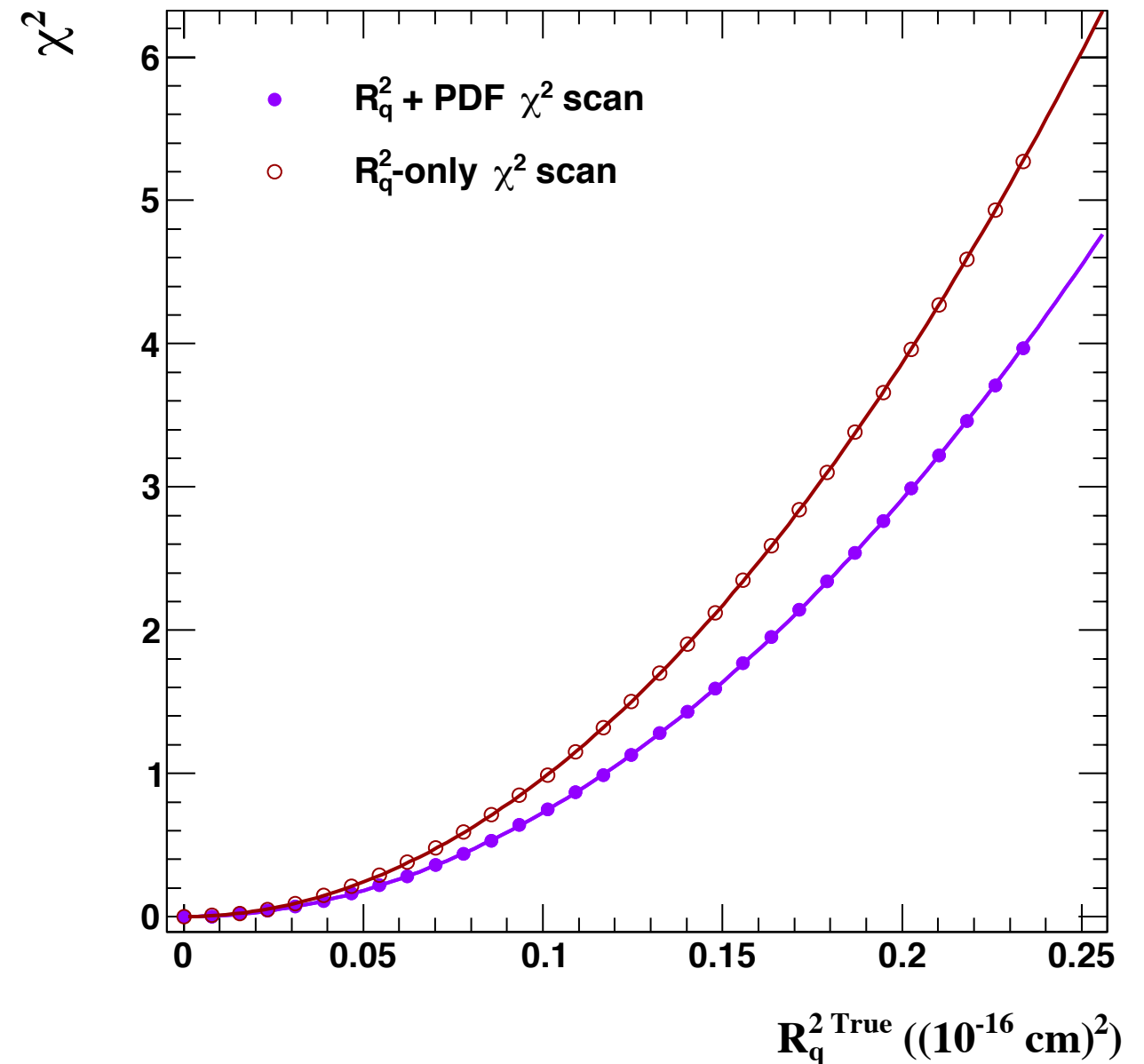
Necessity of the simultaneous fit procedure

Pseudodata generated for
values of $R_q^2 = R_q^{\text{True}}$



$R_q^2 + \text{PDF}$ procedure provides
unbiased results of $R_q^2 \text{ Fit}$

Pseudodata generated for
value of $R_q^2 = 0$



$R_q^2\text{-only}$ 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_q^{True} using **ZCIPDFs** and R_q^{Fit} parameter fitted with PDFs **fixed to ZCIPDFs**.

PDF + R_q

Monte Carlo replicas generated for R_q^{True} using **ZCIPDFs** and R_q^{Fit} parameter fitted **simultaneously** with PDFs.

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

Monte Carlo replicas

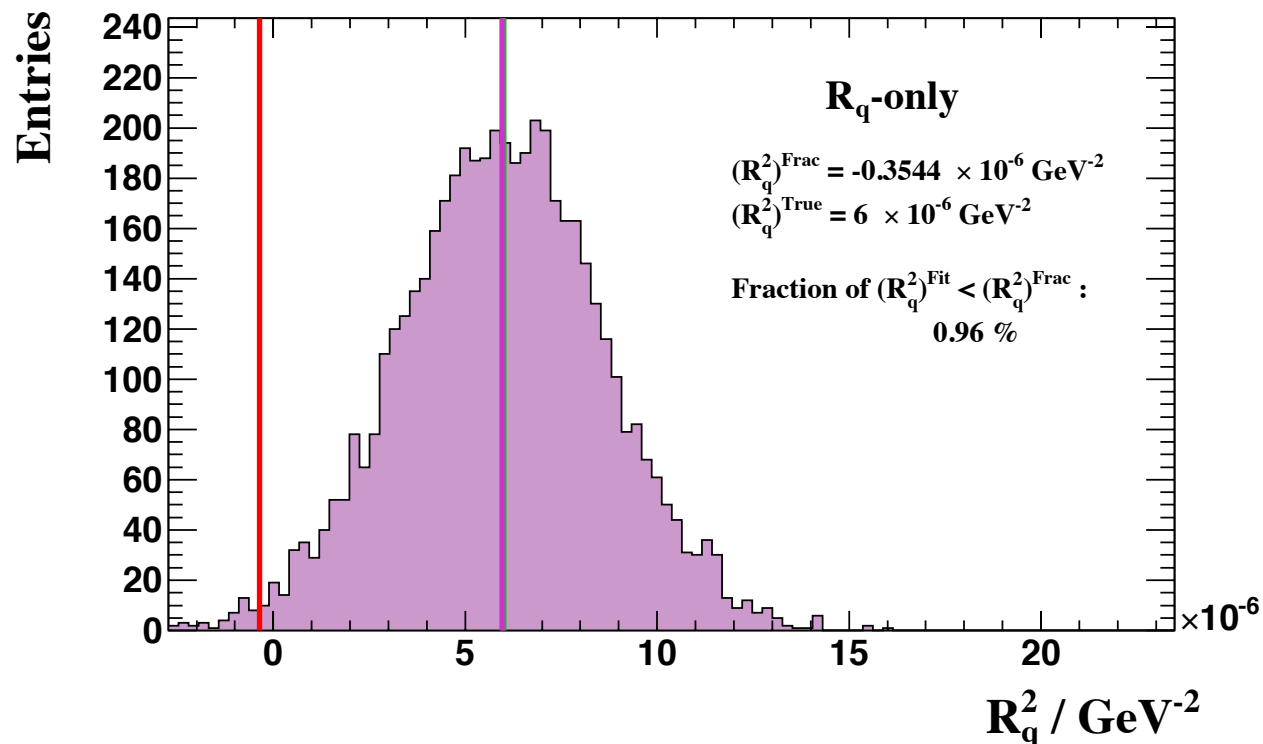
Monte Carlo replicas of the cross-section measurements were calculated with:

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

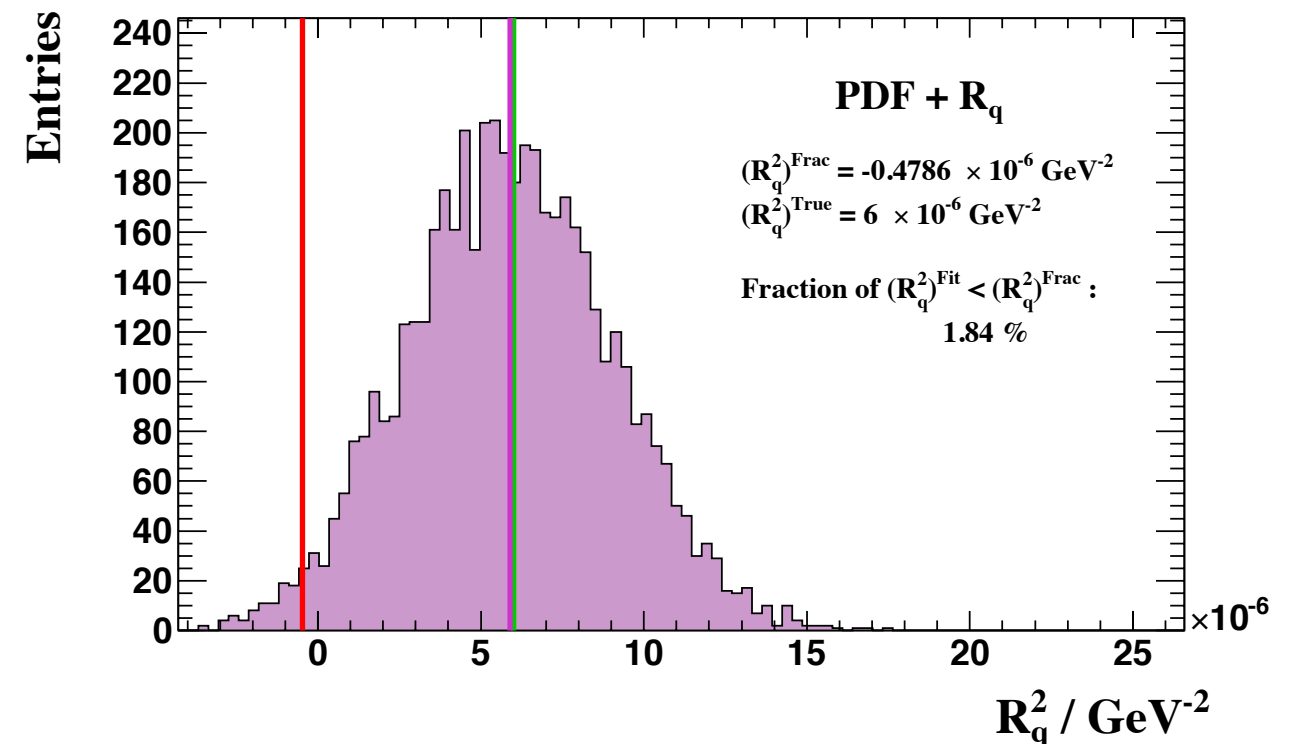
Cross-section prediction from the ZCIPDF modified with R_q^{True} (points to m_0^i)
 Measured cross-section value (points to μ_0^i)
 Correlated systematic uncertainties (points to γ_j^i)
 Relative statistical and uncorrelated systematic uncertainties (points to $\delta_{i,stat}^2 + \delta_{i,uncor}^2$)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

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

R_q -only



PDF + R_q

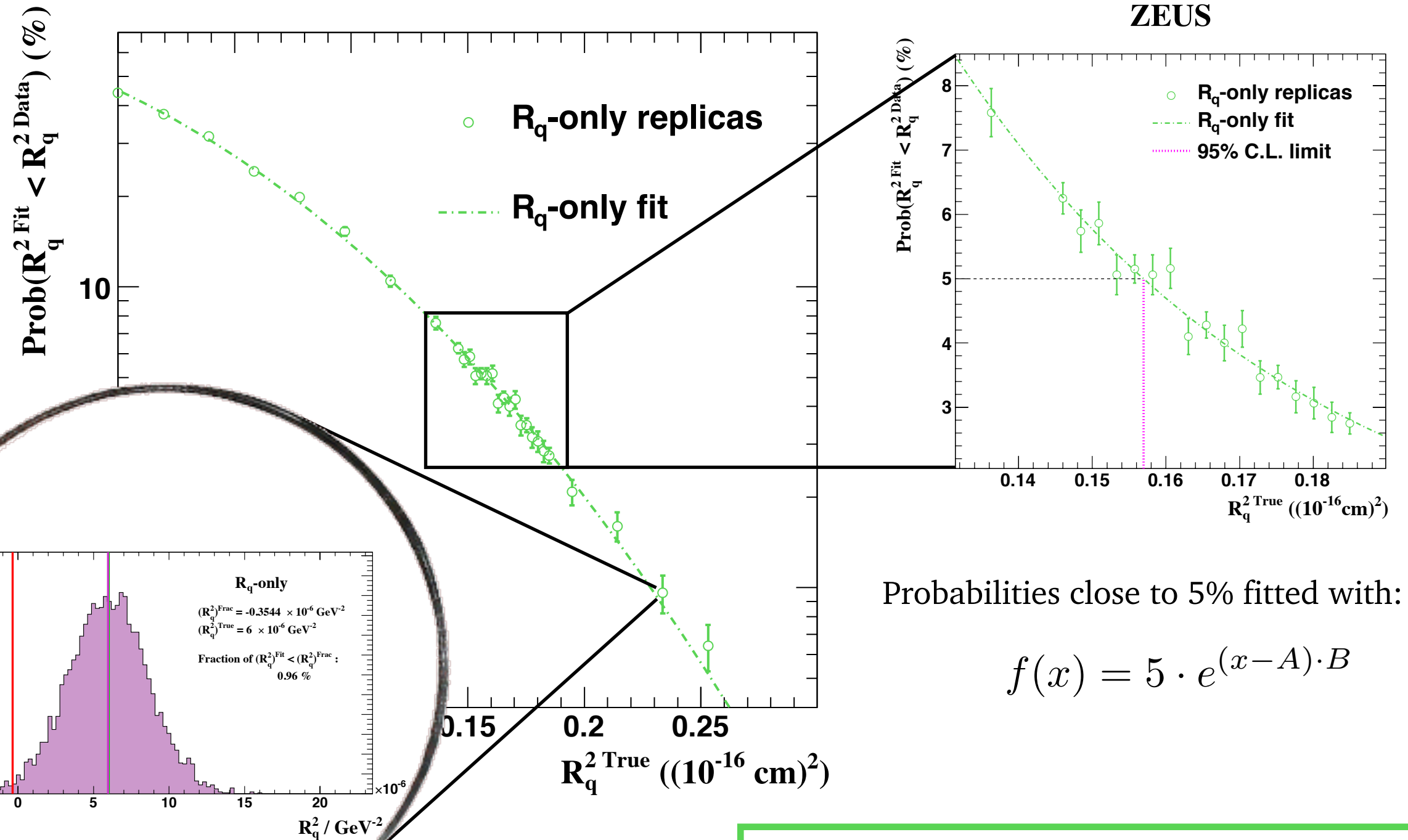


R_q limits with the MC replicas

R_q -only

ZEUS

ZEUS



Probabilities close to 5% fitted with:

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

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

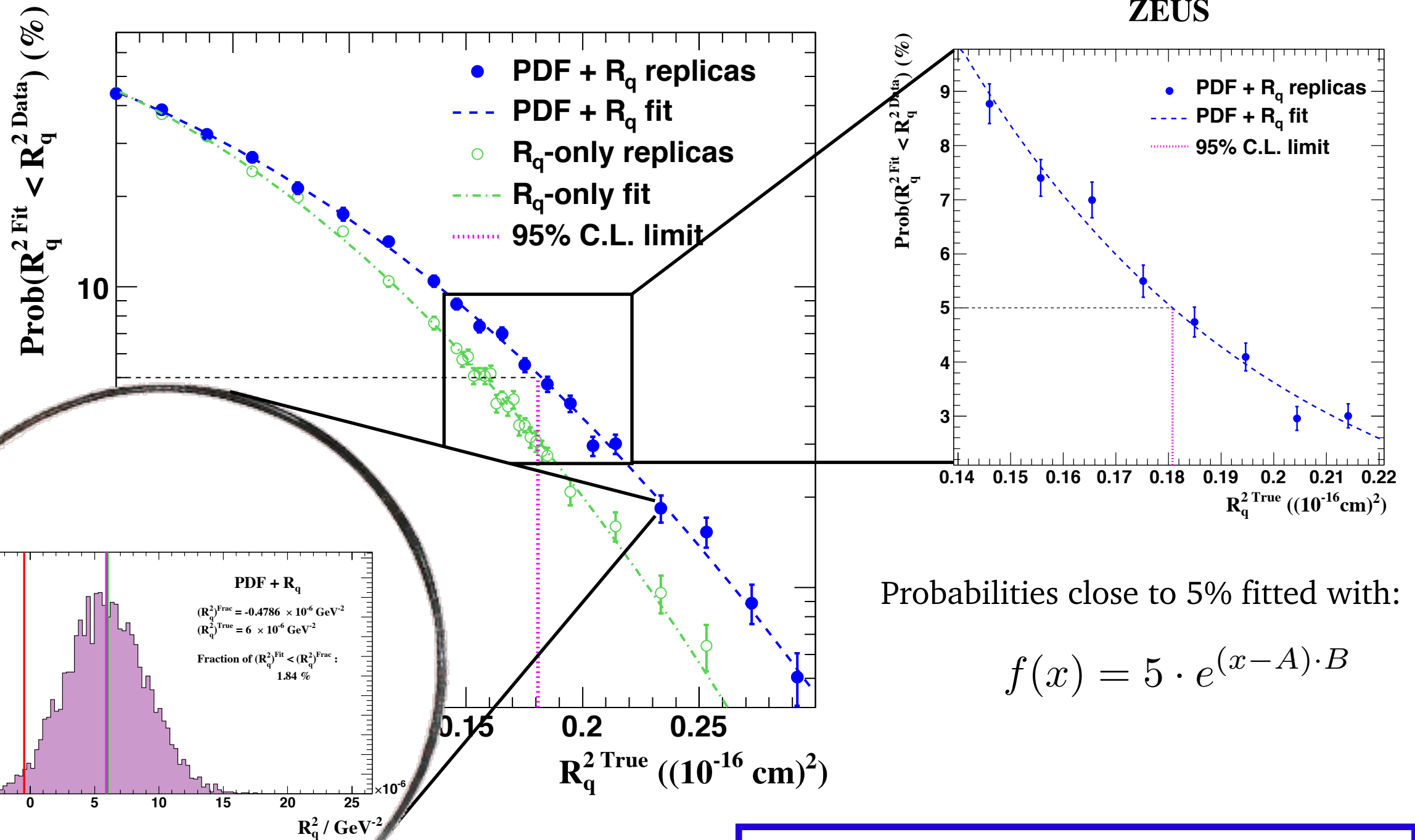
R_q limits with the MC replicas

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PDF + R_q

ZEUS

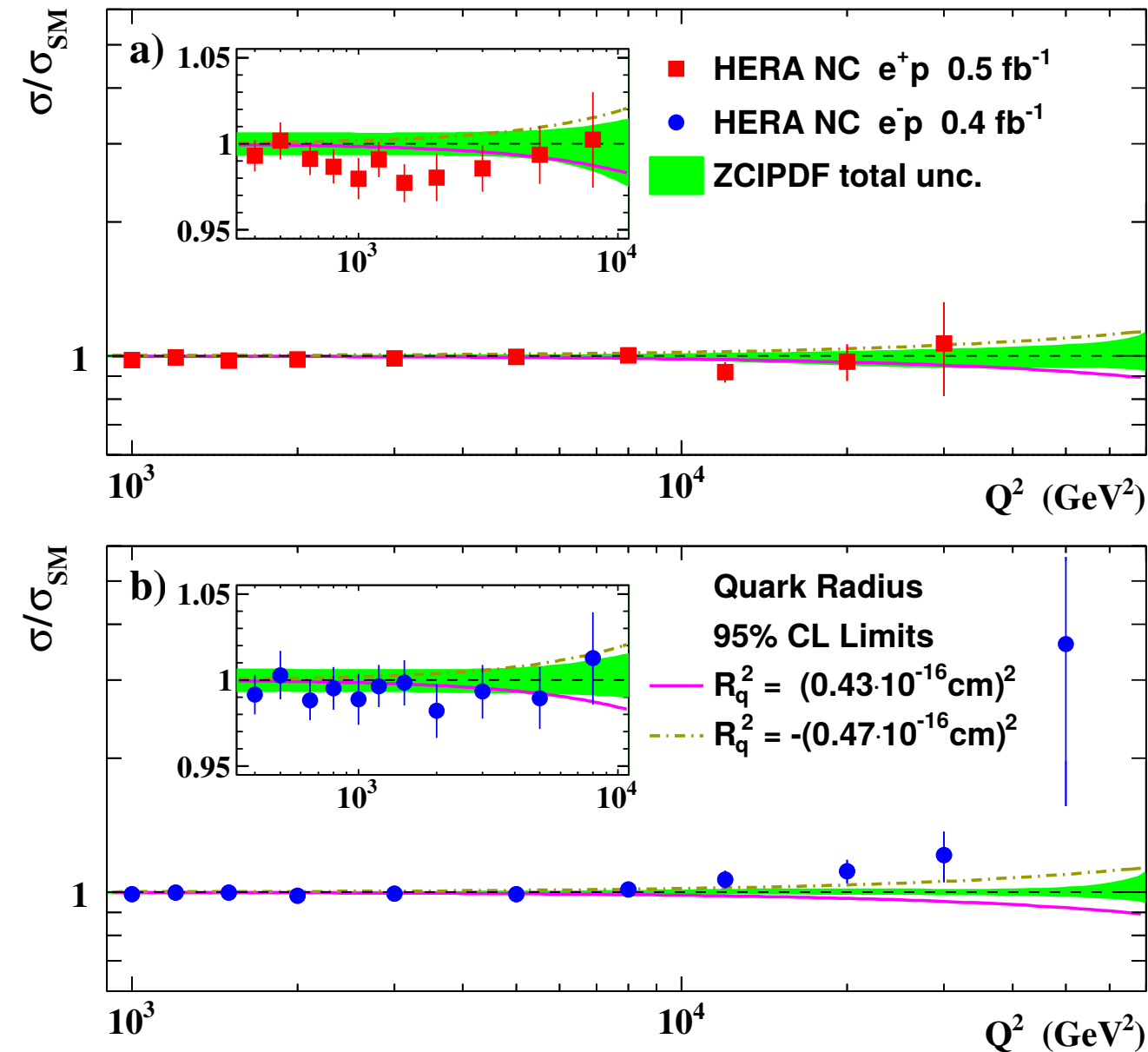
ZEUS



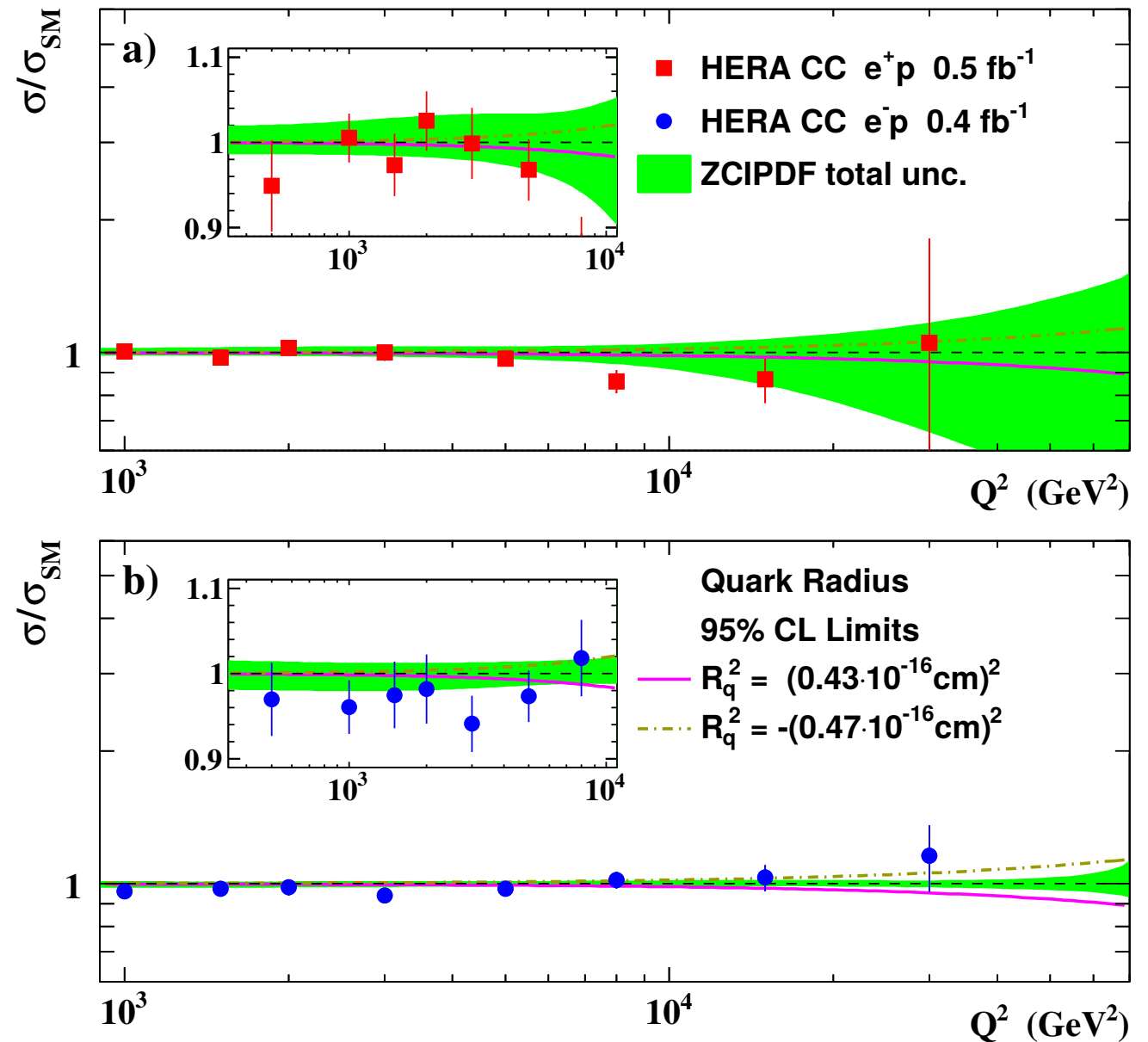
$$-[0.47 \cdot 10^{-16} \text{ cm}]^2 \leq R_q^2 \leq [0.43 \cdot 10^{-16} \text{ cm}]^2$$

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

$$-[0.47 \cdot 10^{-16} \text{ cm}]^2 \leq R_q^2 \leq [0.43 \cdot 10^{-16} \text{ cm}]^2$$

- 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.

