Science
Life and Physics

How big is a quark?

They are the smallest things we know. But *how* do we know? A new result from an old experiment in Hamburg sets a tighter limit on the size of a fundamental particle.

Jon Butterworth
@jonmbutterworth

Thursday 7 April 2016 06.05 BST

Grains of sand in Hamburg. Because quarks are just too small.

Limits on the effective quark radius from inclusive $e^{\pm}p$ scattering at HERA

O. Turkot
On behalf of ZEUS Collaboration

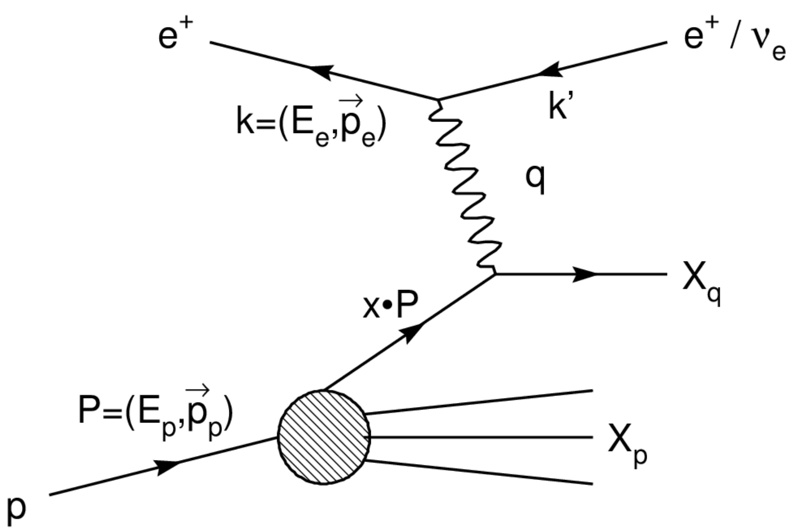
- ZEUS and H1 inclusive data combination
- Quark form factor model
- Limits-setting procedure using the simultaneous fit of quark form factor and PDFs

HERA — world only e±p collider

HERA data provides unique opportunity to study the structure of the proton.

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

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



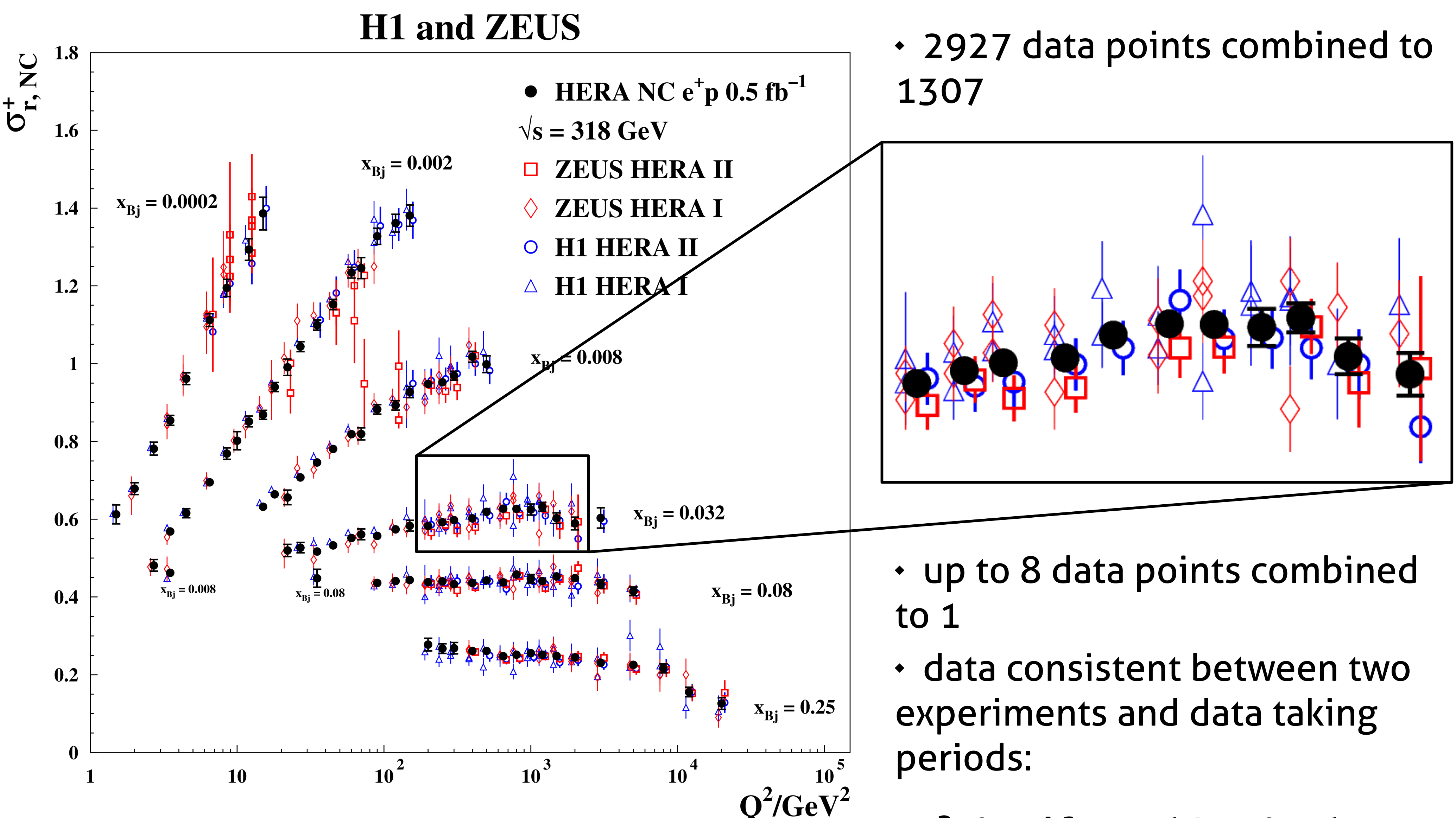
$$Q^2 = -(k-k')^2$$

$$x = \frac{Q^2}{2P\cdot q} \qquad y = \frac{P\cdot q}{P\cdot k}$$

H1 and ZEUS — two collider experiments at HERA :

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

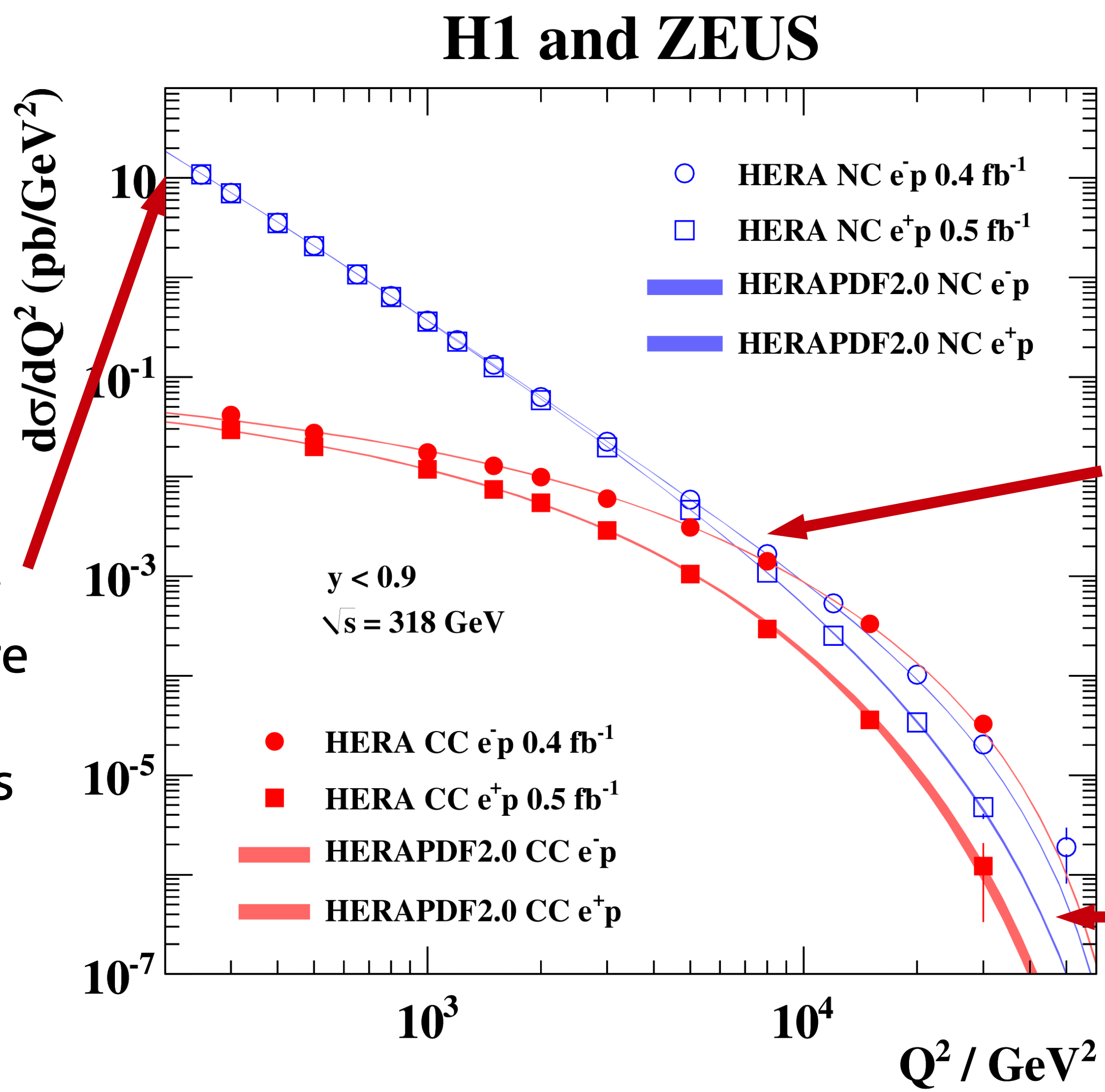
Combined Inclusive DIS



- 2927 data points combined to 1307
- up to 8 data points combined to 1
- data consistent between two experiments and data taking periods:

$$\chi^2 / \text{ndf} = 1685 / 1620$$

Combined Inclusive DIS



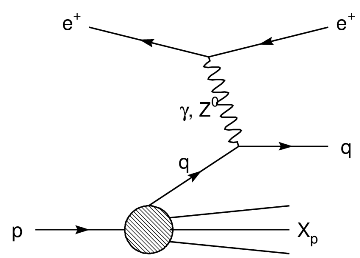
at low Q^2
γ exchange
(NC DIS)
dominates

NC and CC DIS cross sections become comparable at $Q^2 \sim M_Z^2, M_W^2$

γZ^0 interference
difference in NC e^+ and e^-

Effects of electroweak unification clearly seen.

QCD analysis of combined DIS data



Neutral Current :

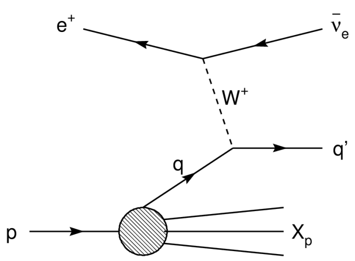
$$\frac{d^2\sigma_{NC}^{e\mp p}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\cdot\left(Y_+\cdot F_2 \pm Y_-\cdot x\cdot F_3 - y^2\cdot F_L\right)$$

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

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

$$x\cdot F_3 \sim xu_v + xd_v$$

Similar equation for CC DIS.



Parton Density Functions parametrization at starting scale Q^2 = 1.9 GeV^2:

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

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

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

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

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

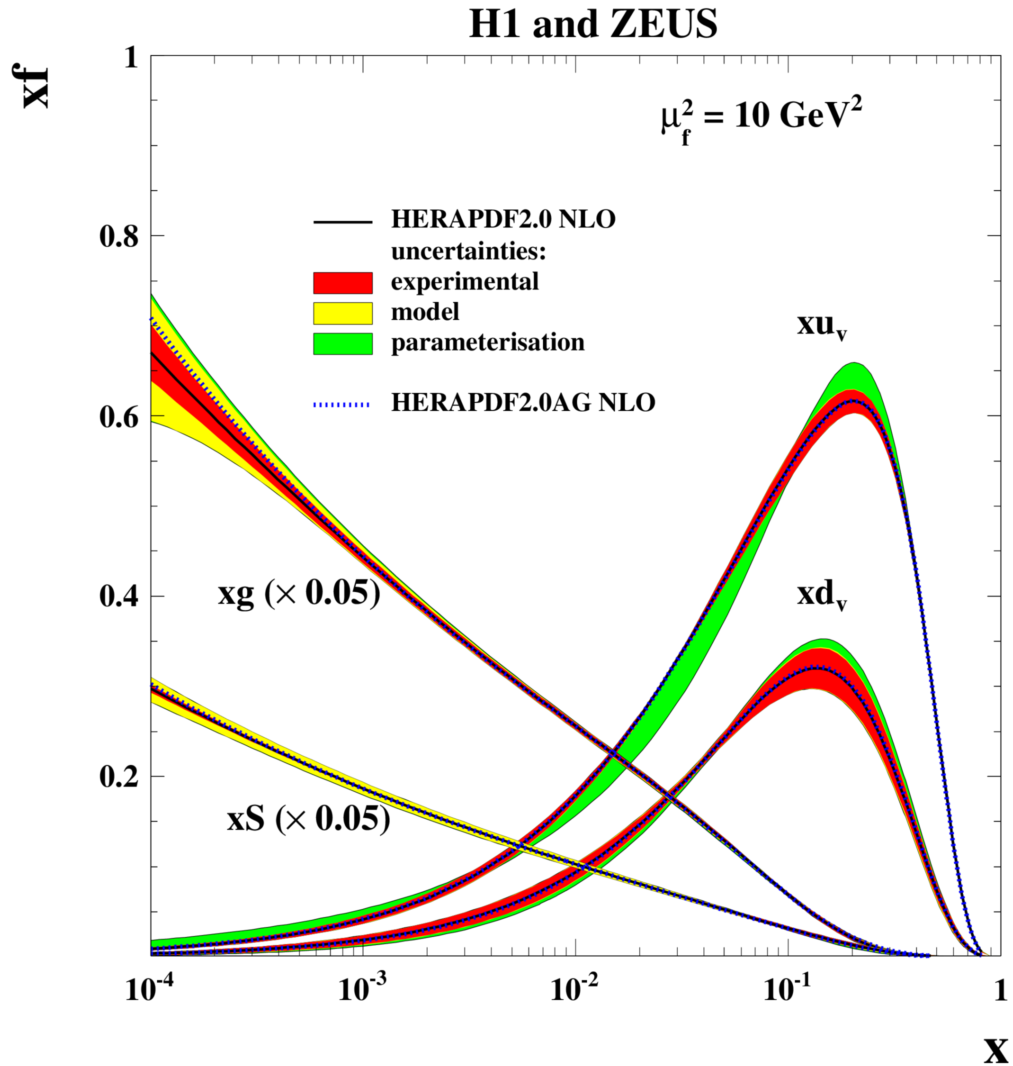
fixed or calculated by sum-rules

set equal

- Evolve to any Q^2 with DGLAP at NLO.
- Use Thorne-Roberts GMVFN scheme for Heavy quarks.

QCD analysis of combined DIS data

Eur. Phys. J. C 75 (2015) 580
arXiv:1506.06042

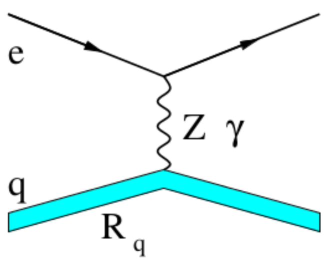


More information on HERAPDF2.0 analysis you might have seen in the plenary talk "The HERA Legacy" by Paul Newman on Monday.

Quark form factor

One of the possible parameterisations of deviations from SM – 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:



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

R_e, R_q – root mean square radii of the electroweak charge distributions in the electron and quark.

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

We assume electron to be point-like, $\mathbf{R^2_e = 0}$.

We consider both, positive and negative values of R^2_q.

ZEUS QCD + BSM analysis of combined DIS data

HERA data is a core of any PDF extraction, and thus simultaneous fit, PDF+BSM, is necessary for any BSM analysis.

By minimazing the χ^2 function:

$$\chi^2_{\exp}(\boldsymbol{p},\boldsymbol{s},\boldsymbol{R_q^2})=\sum_i \frac{\left[m^i(\boldsymbol{p},\boldsymbol{R_q^2})+\sum_j \gamma_i^j s_j m^i(\boldsymbol{p},\boldsymbol{R_q^2})-\mu_0^i\right]^2}{\delta^2_{i,tot.uncor.}(\mu_0^i)^2}+\sum_j s_j^2$$

$\boldsymbol{p}$ – PDF parameters
$\boldsymbol{s}$ – systematic shifts
m^i – model expectations
γ, δ – relative systematic and total uncorrelated uncertainties
μ^i_0 – measured cross sections

PDF parameters $\boldsymbol{p}$ were fitted on data simultaneously with quark form factor $\boldsymbol{R^2_q}$:

$$R^{2\ \mathrm{Data}}_q = -[0.14 \cdot 10^{-16}\ \mathrm{cm}]^2$$

in agreement with SM expectation of $R_q^{\mathrm{Data}} = 0$.

Frequentist approach

Monte Carlo replicas of the whole data set were generated as:

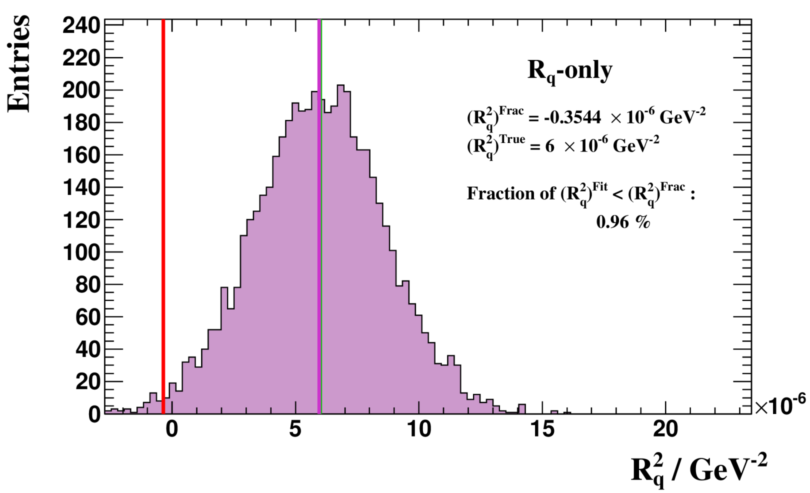
$$\mu^i = [m_0^i + \delta^i_{tot.uncor.} \cdot r^i_{tot.uncor.} \cdot \mu_0^i] \cdot (1 + \sum_j \gamma^j \cdot r^j_{sys.sh.})$$

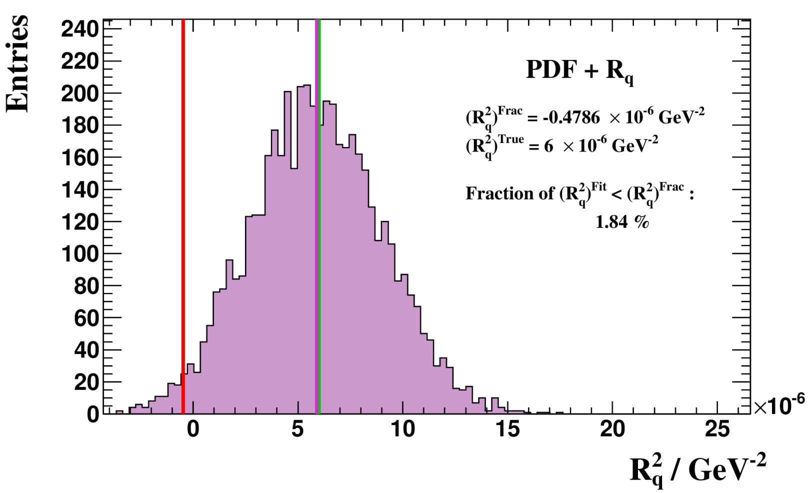
r^i, r^j – Gaussian random numbers.

Two different procedures were tested:

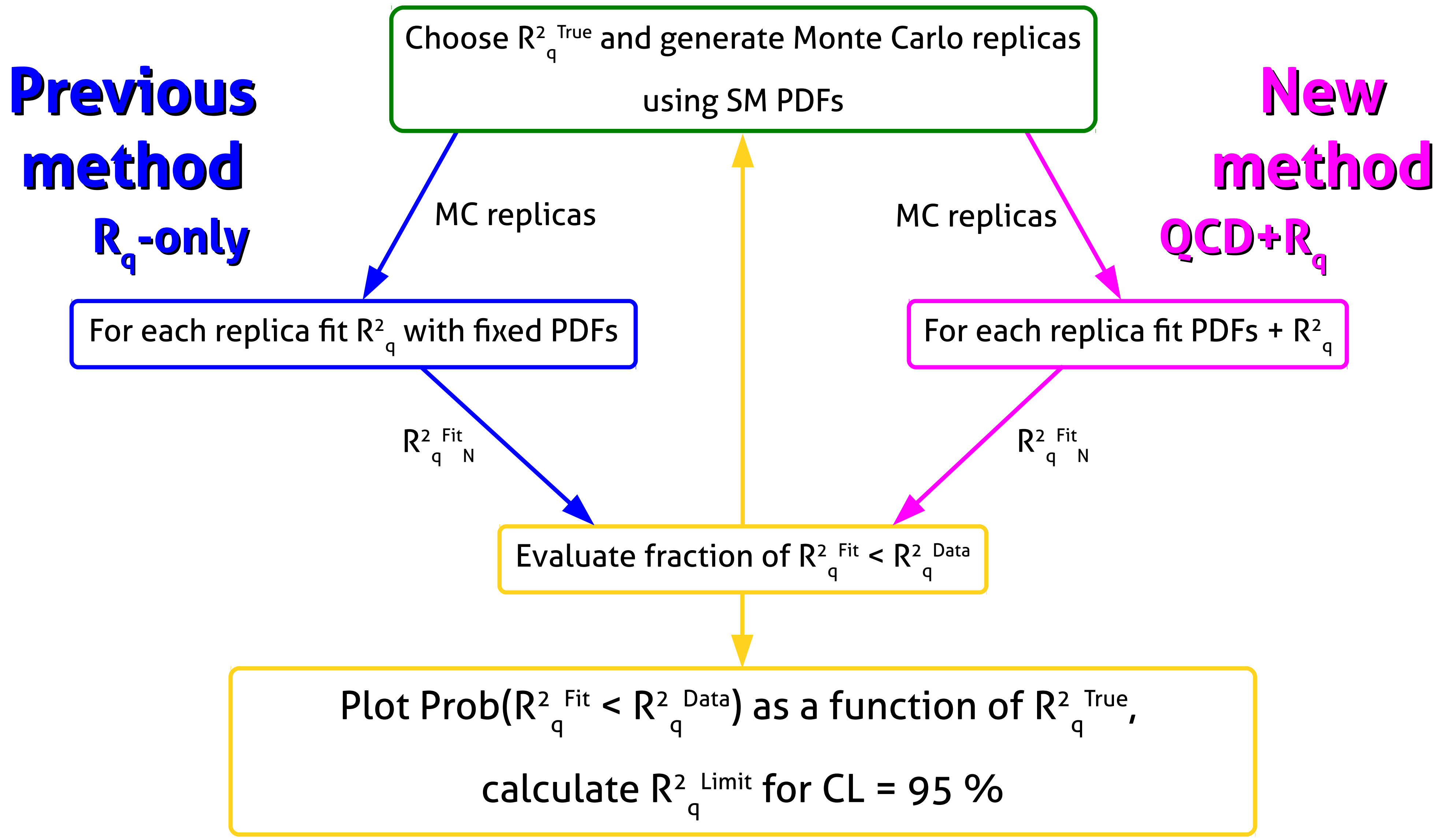
Previous method: R_q-only	New method: PDF+R_q
R^2_q parameter fited with PDFs **fixed to SM PDFs**.	R^2_q parameter fited **simultaneously** with PDFs.

For example, for $R_q^{True} = 0.48 \cdot 10^{-16}$ cm:

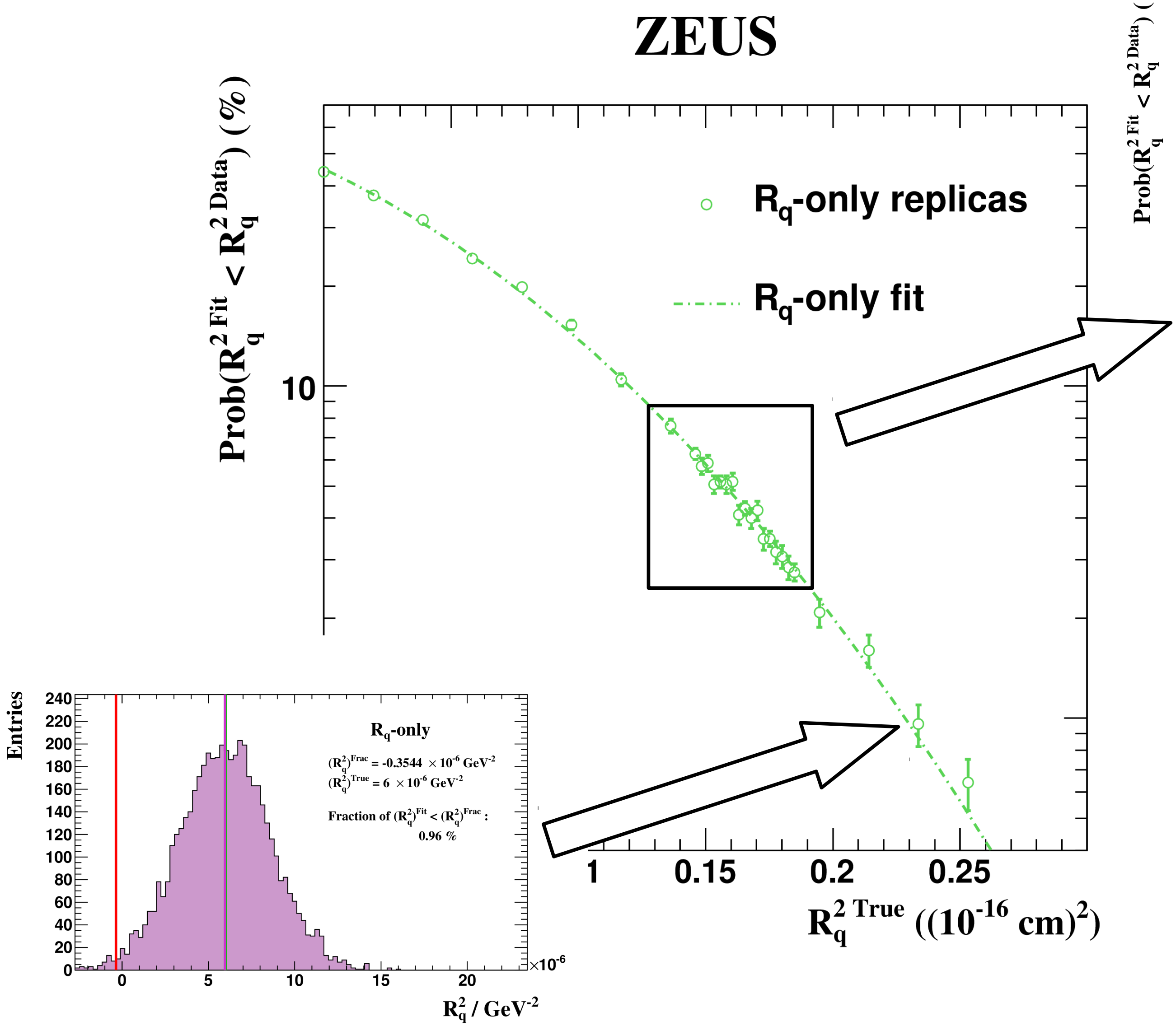


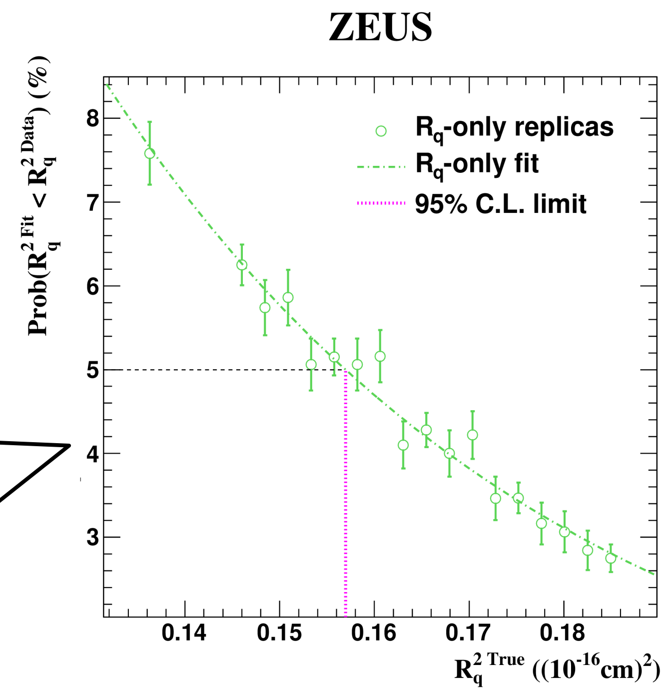


Analysis flowchart



R_q-only





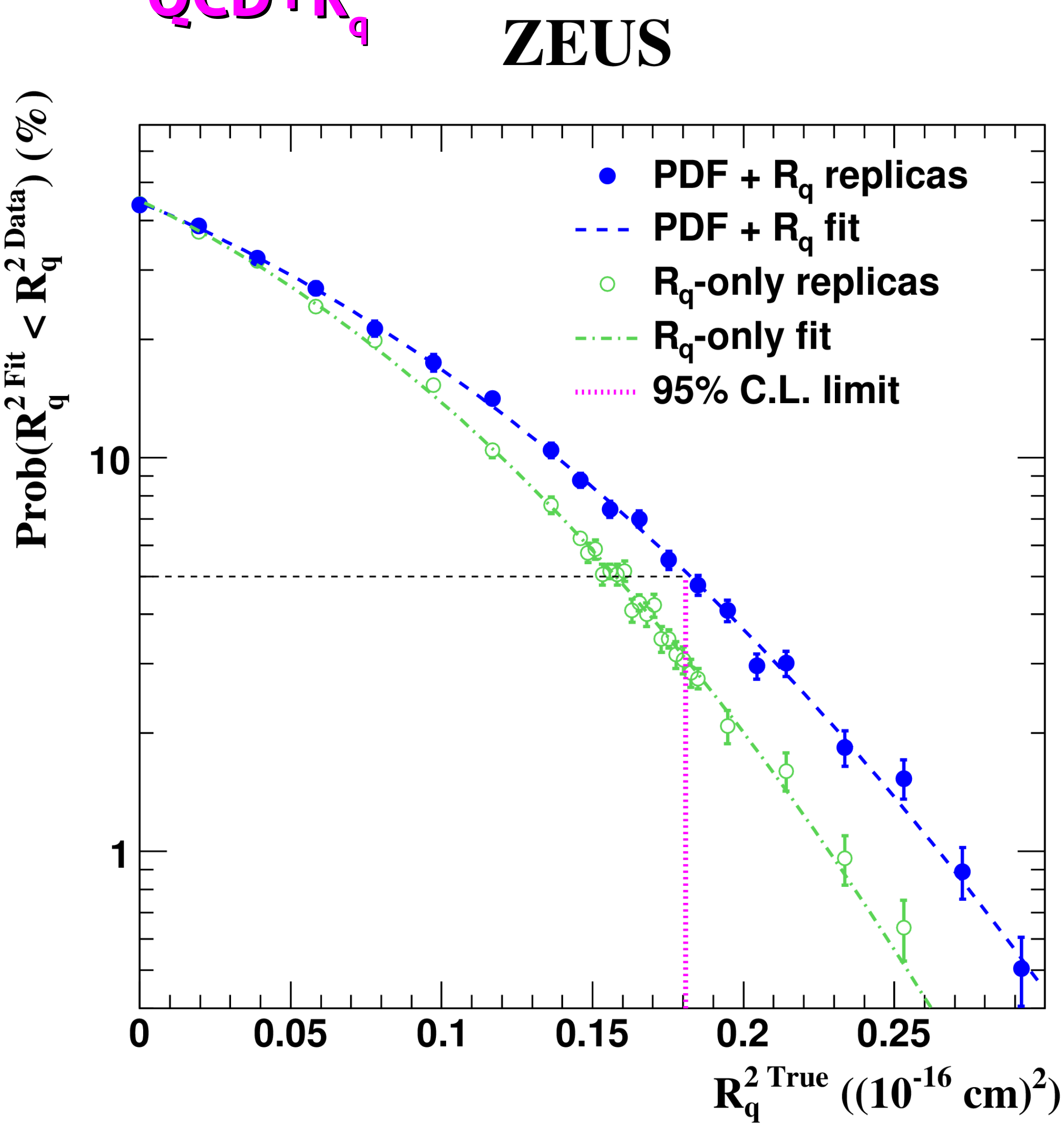
Fractions close to 5% fitted with:

$$f(x) = 5 \cdot \exp((x - A) \cdot B)$$

$$R_q^{Limit} = 0.40 \cdot 10^{-16}\ \text{cm}$$

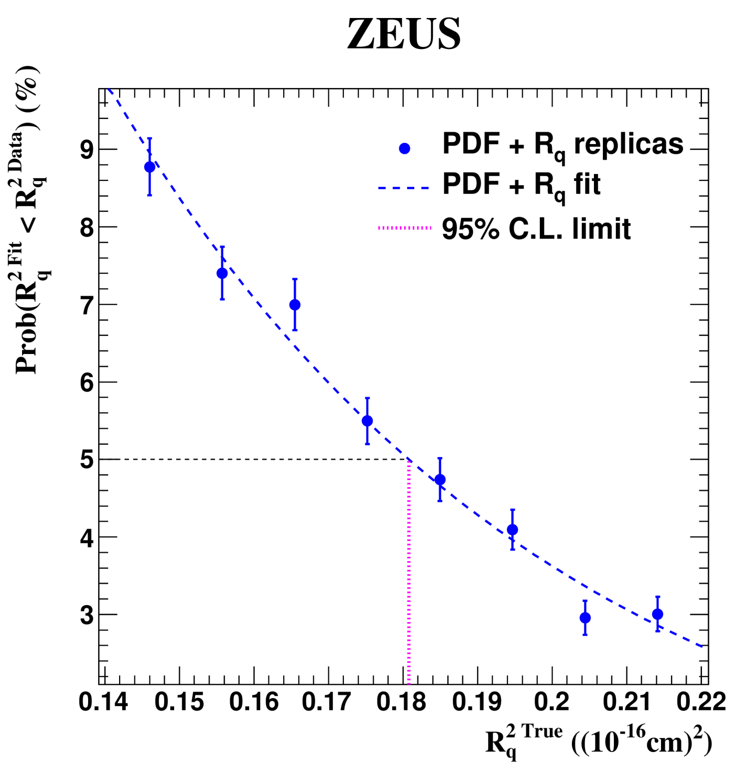
DESY-16-035
Accepted for publication in Phys. Lett. B

QCD+R_q



Fractions close to 5% fitted with:

$$f(x) = 5 \cdot \exp((x - A) \cdot B)$$

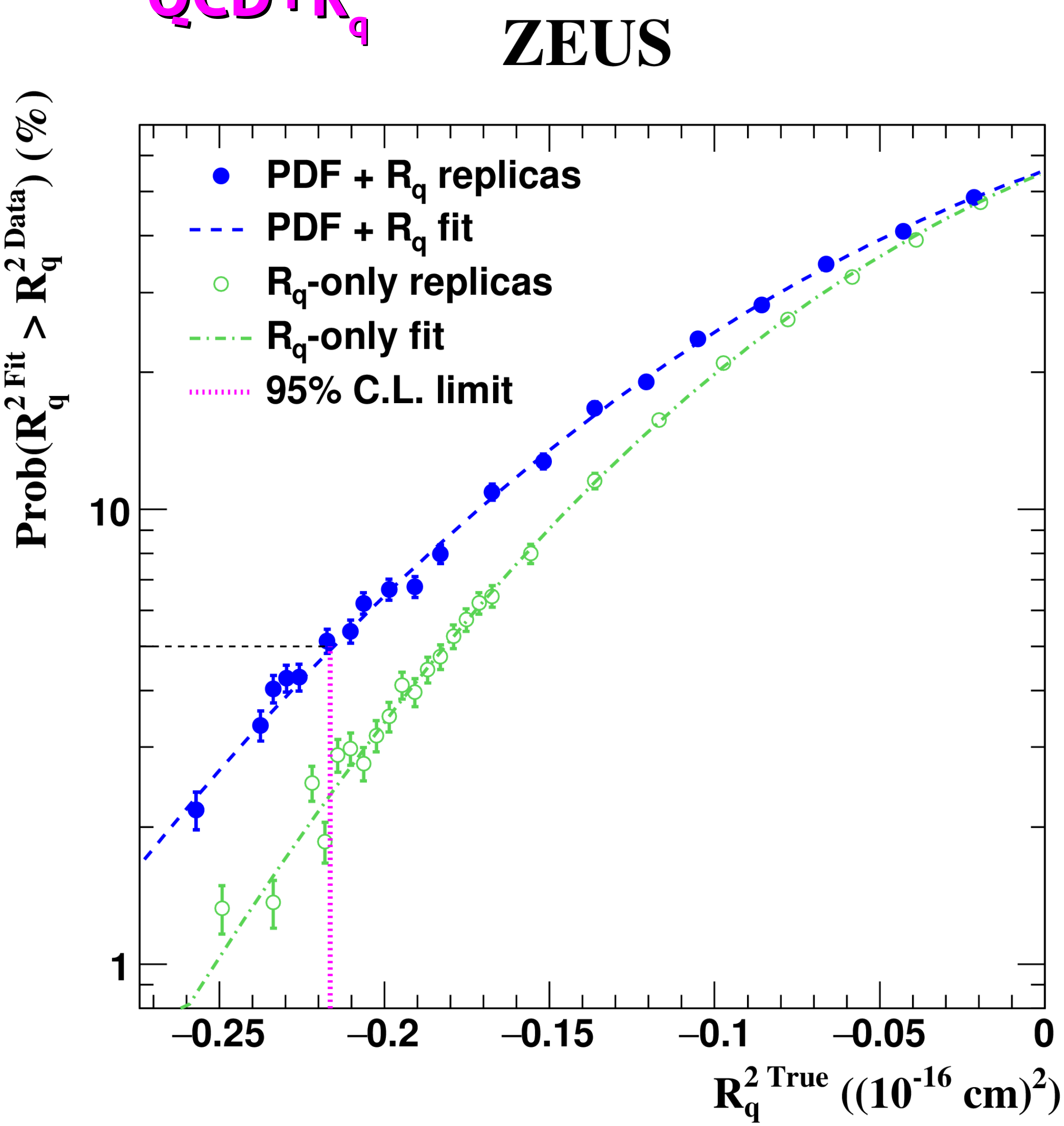


$$R_q^{Limit} = 0.43 \cdot 10^{-16}\ \text{cm}$$

Negative R^2_q limit:

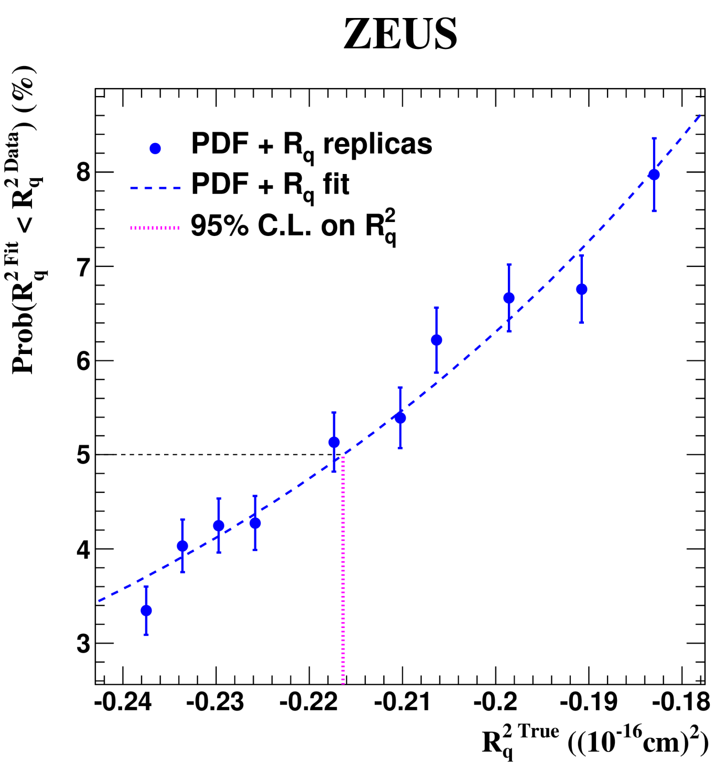
DESY-16-035
Accepted for publication in Phys. Lett. B

QCD+R_q



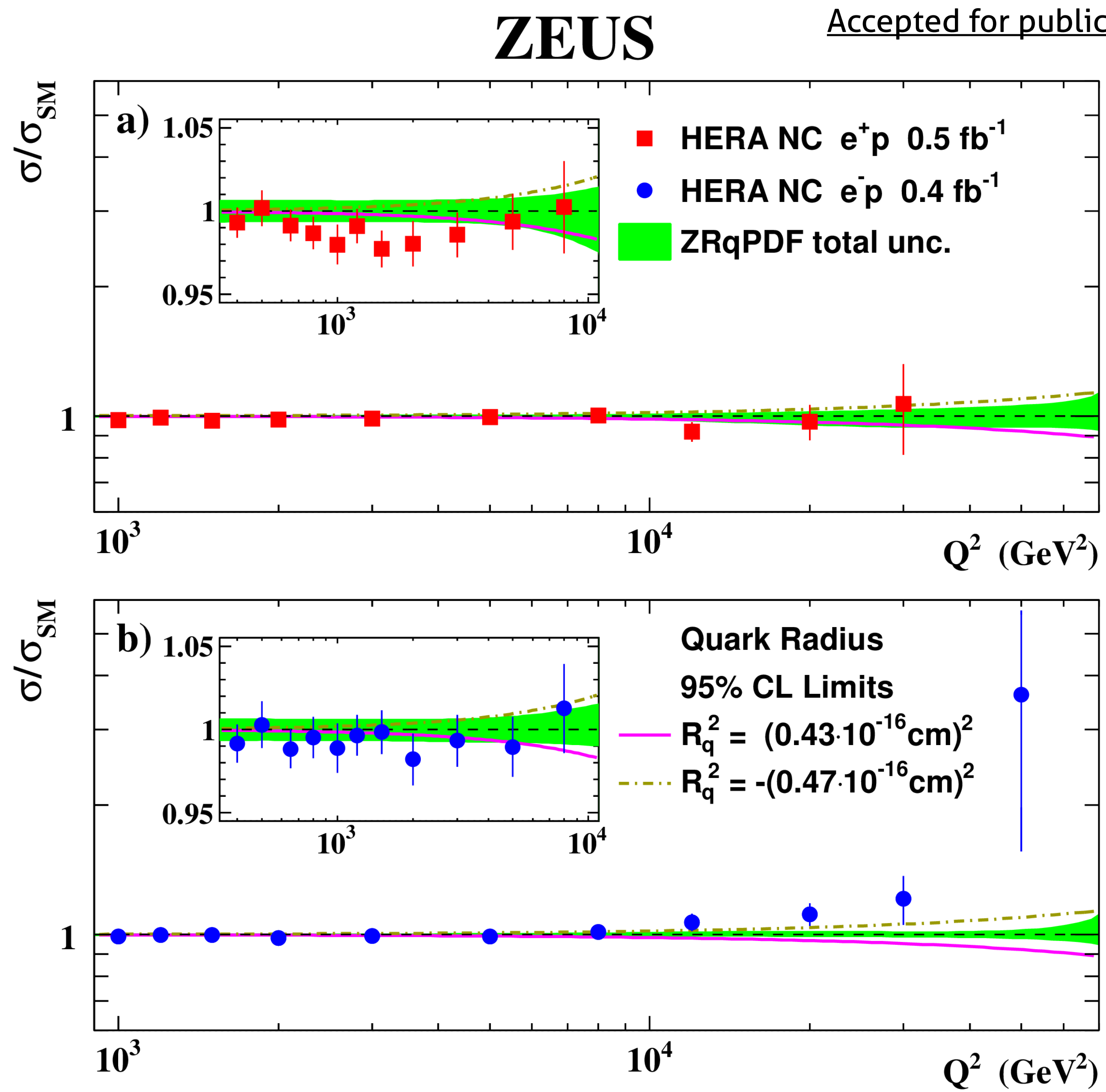
Fractions close to 5% fitted with:

$$f(x) = 5 \cdot \exp((x - A) \cdot B)$$



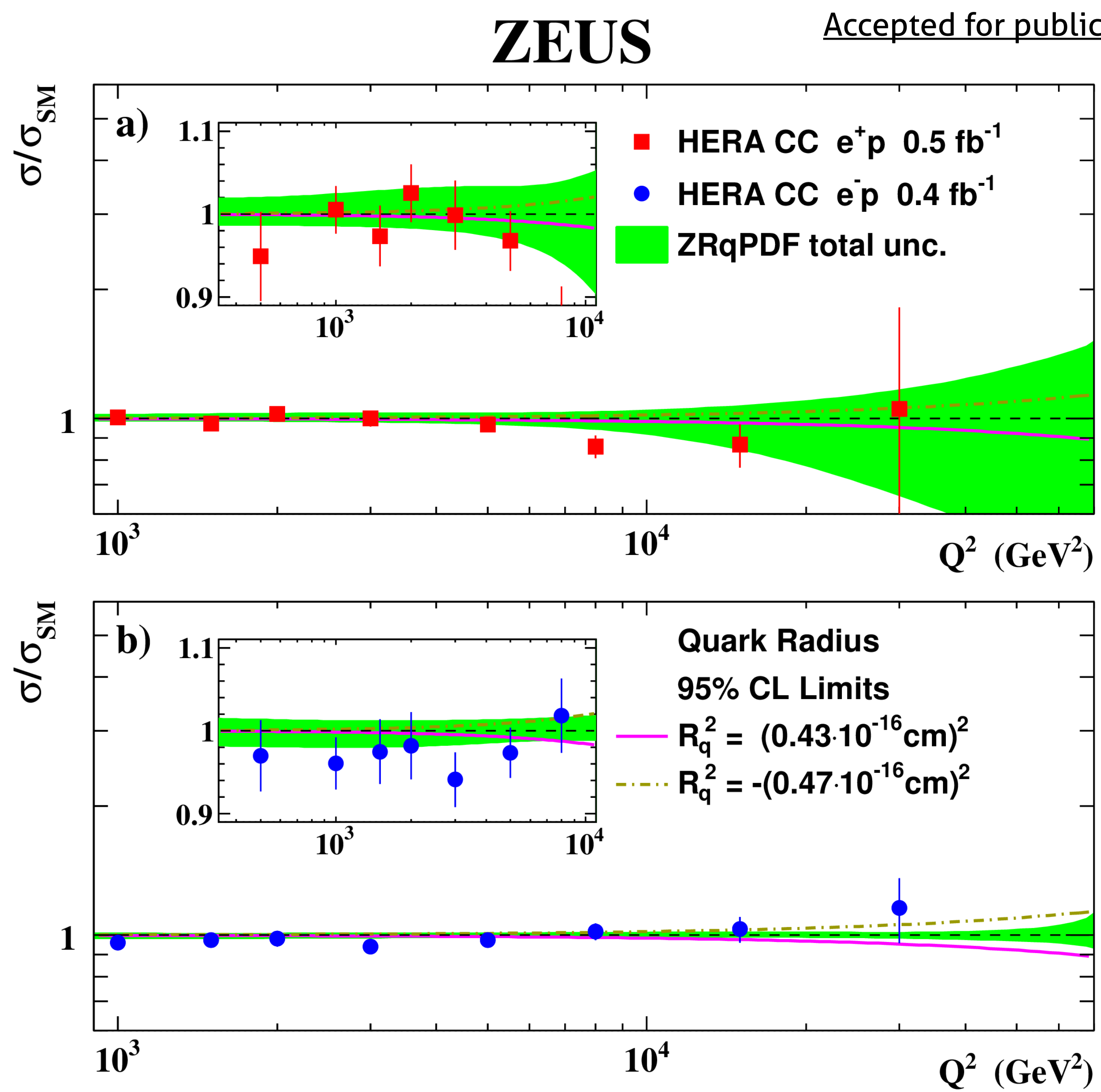
$$R_q^{2\ \mathrm{Limit}} = -\,[0.47 \cdot 10^{-16}\ \mathrm{cm}]^2$$

DESY-16-035
Accepted for publication in Phys. Lett. B



Comparison of R^2_q exclusion limits to HERA NC ep DIS data.

DESY-16-035
Accepted for publication in Phys. Lett. B



Comparison of R^2_q exclusion limits to HERA CC ep DIS data.

Summary

- First BSM analysis based on the final HERA inclusive data:

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

provides us with limit on quark radius ~2000 times smaller than proton

- Limits consistent with expected sensitivity:

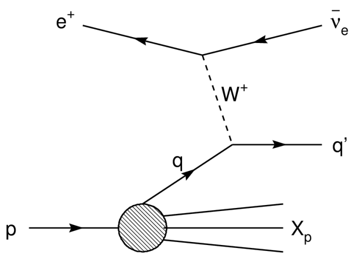
$$R_q^{sens} = 0.45 \cdot 10^{-16}\ \mathrm{cm}$$

- Limits based on the new approach: simultaneous fit of PDF and BSM contribution; limits obtained with "previous" method ~10-20 % too strong.

- Paper (DESY-16-035) accepted for publication in Physics Letters B, arXiv:1604.01280 .

Backup

QCD analysis of combined DIS data



Charged Current :

$$\frac{d^2\sigma_{CC}^{e\mp p}}{dxdQ^2} = \frac{G_F^2}{4\pi x} \cdot \kappa^2 \cdot \left(Y_+ \cdot W_2^{\mp} \pm Y_- \cdot x \cdot W_3^{\mp} - y^2 \cdot W_L^{\mp} \right)$$

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

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

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

QCD analysis of combined DIS data

ZRqPDF set compared to HERAPDF2.0: