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

O. Turkot
On behalf of ZEUS Collaboration

- Combined inclusive cross sections from HERA
- Beyond-the-Standard-Model analysis simultaneously with PDFs fit
- Simplified procedure for QCD+BSM fits

5 April 2017

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

Operated during 1992 - 2007

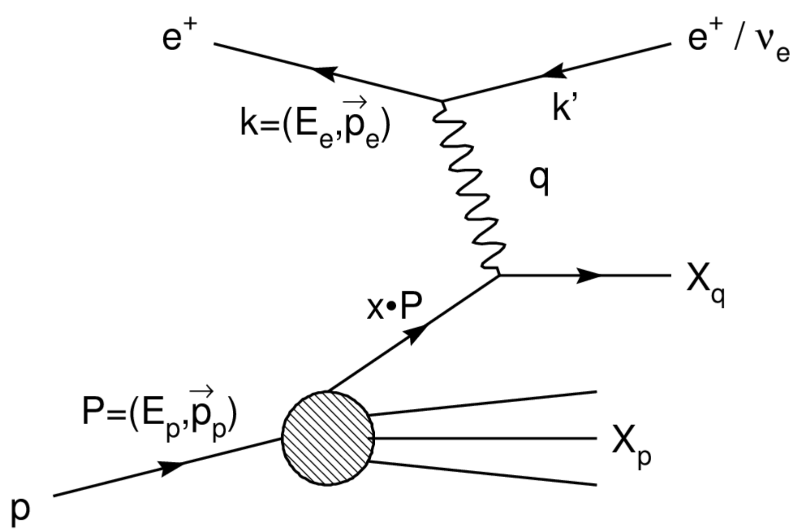
$e^{\pm}$ energy 27.5 GeV;
p energies 920, 820, 575 and 460 GeV.

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

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

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

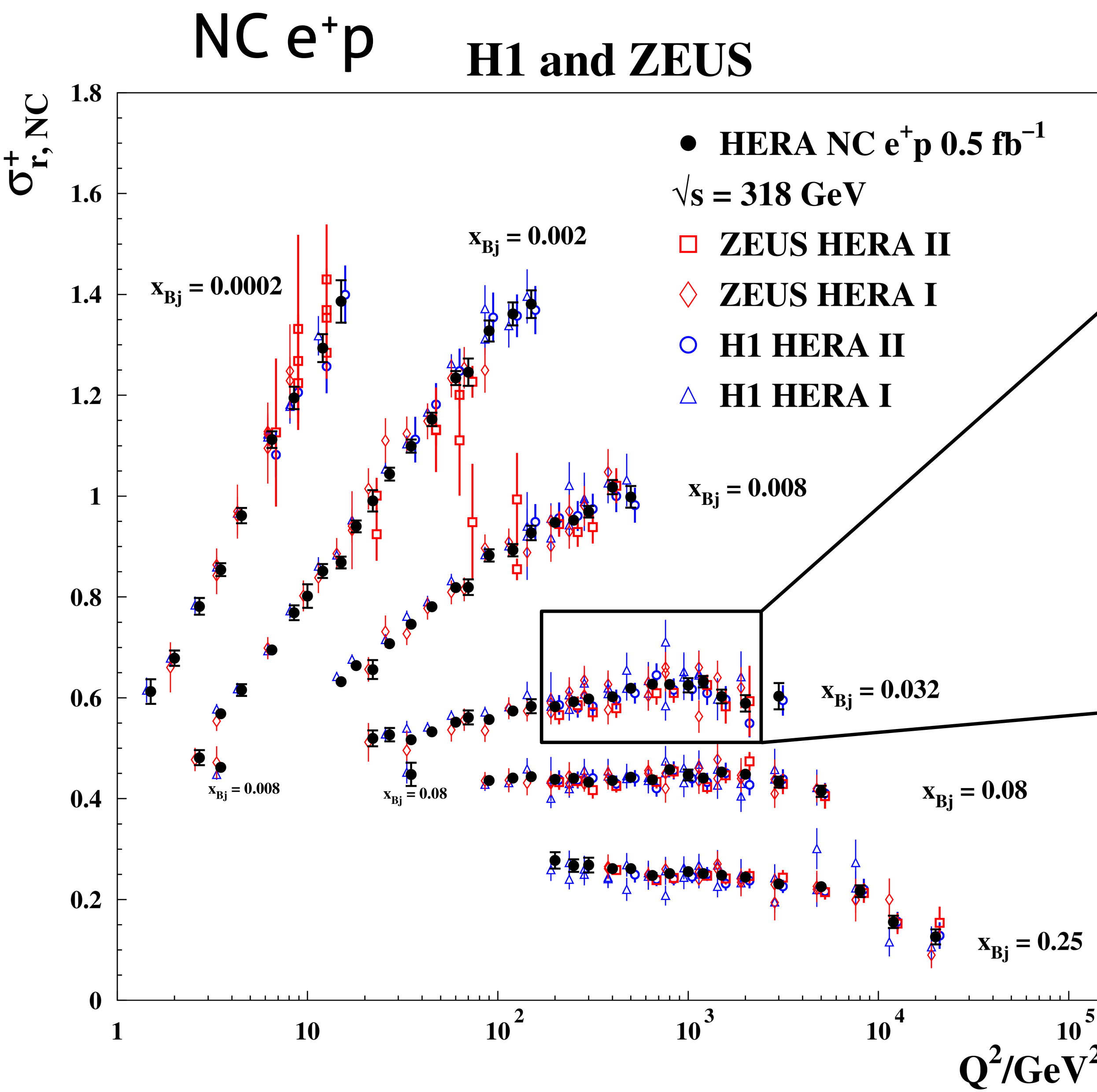
$$y = \frac{P\cdot q}{P\cdot k}$$

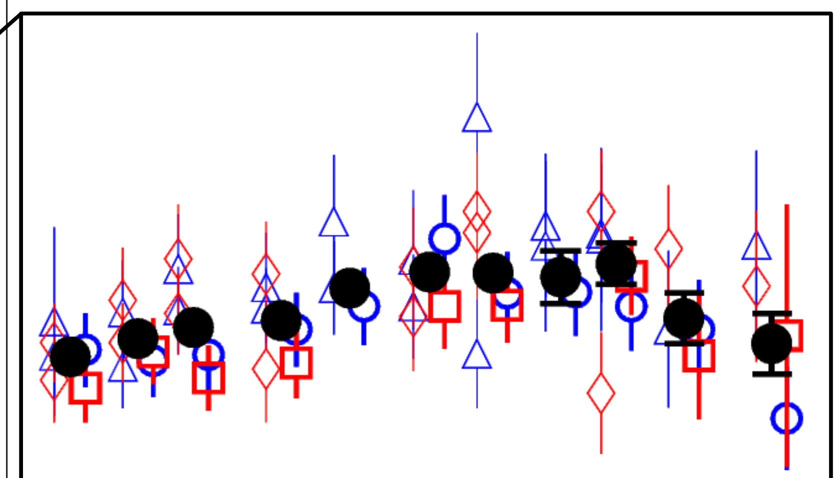


H1 and ZEUS — two collider experiments at HERA :

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

HERA inclusive data combination





- 2927 data points 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 :

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

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

$$F_L\sim\alpha_s g$$

Charged Current :

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

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

At the Quark-Partom Model:

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

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

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

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

Parton Density Functions parametrization at starting scale Q^2_0 = 1.9 GeV²:

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

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

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

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

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

- (grey) fixed or calculated by sum-rules
- (pink) set equal

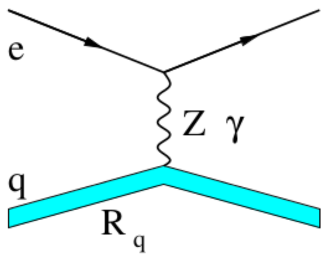
Evolve to any $Q^2 > Q^2_0$ with DGLAP.

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

How big is a quark ?

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.

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**.

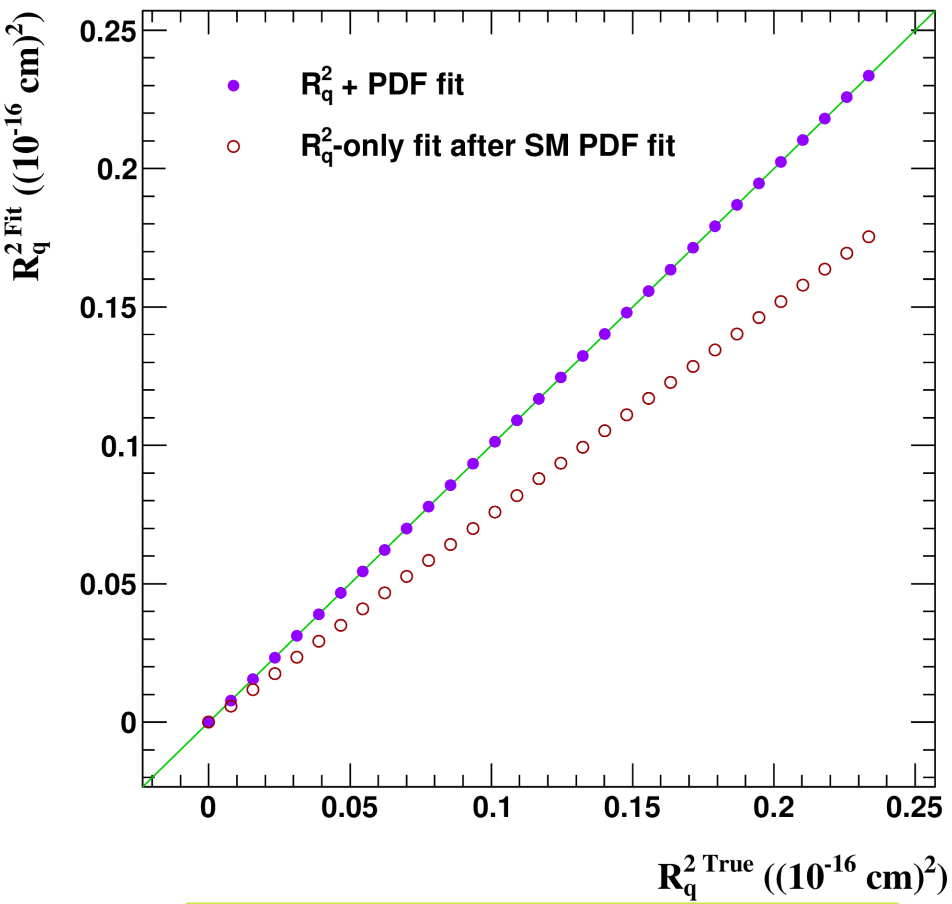
- Use of the **biased PDFs** in the BSM analysis would result in **overestimated limits**.

- 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, NNPDF3.0, etc.).

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

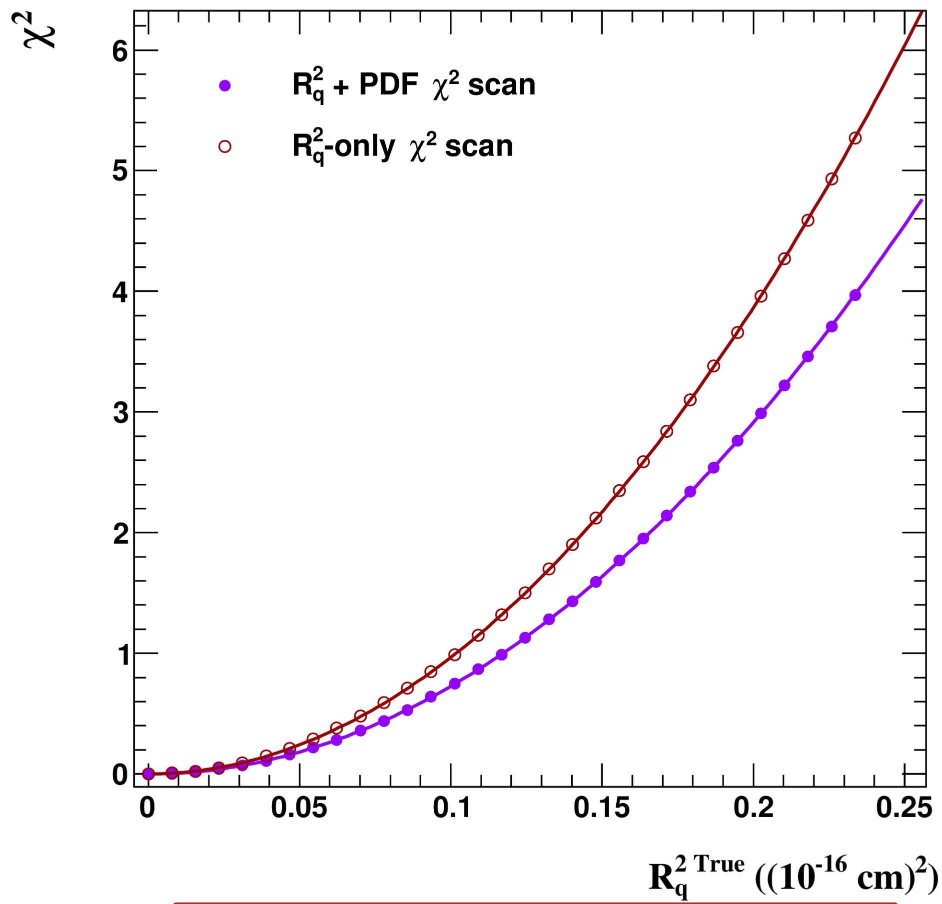
Necessity of the simultaneous fit procedure

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



R^2_q+PDF procedure provides unbiased values of $R^{2\,Fit}_q$

Pseudodata generated for $R^2_q = 0$



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

Limit setting method

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

R_q-only Monte Carlo replicas generated for R_q^{True} using **ZCIPDFs** and R_q parameter fited with PDFs **fixed to ZCIPDFs**.

R_q+PDF Monte Carlo replicas generated for R_q^{True} using **ZCIPDFs** and R_q parameter fited **simultaneously** with PDFs.

The **R_q+PDF** probability method was a main analysis method.

Monte Carlo replicas

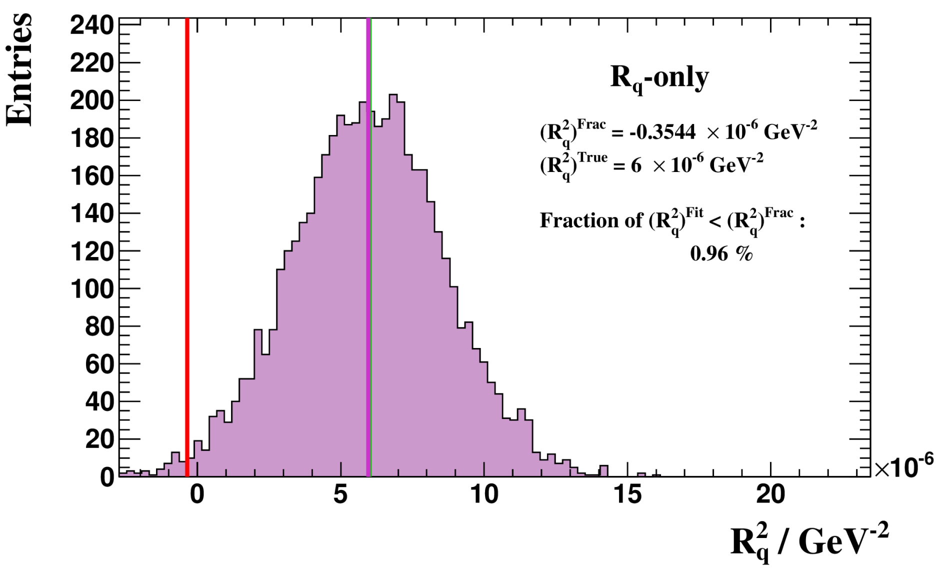
Monte Carlo replicas of cross-section measurements calculated with

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

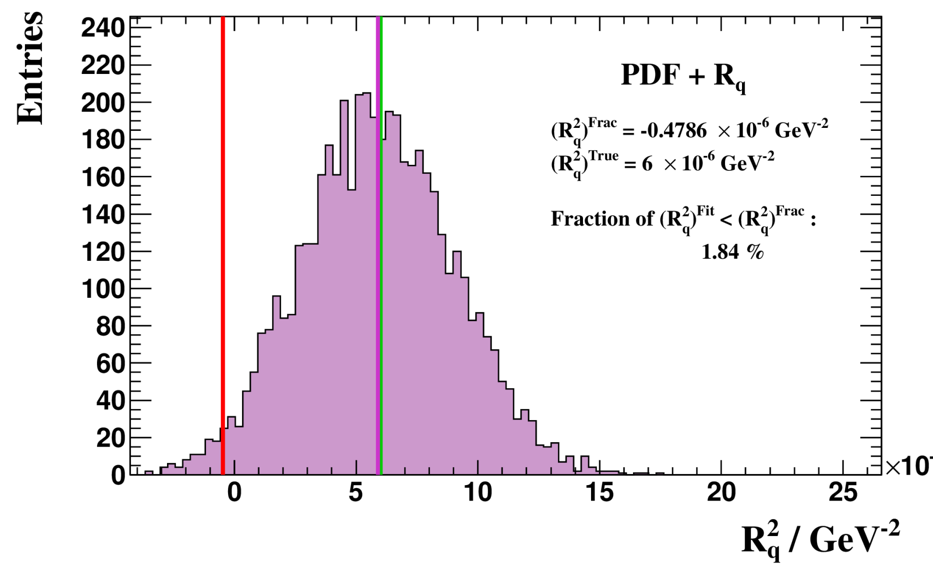
- m_0^i: Cross-section prediction from the ZCIPDF modified with R_q^{True}
- μ_0^i: Measured cross-section value
- γ_j^i: Correlated systematic uncertainties
- $\delta_{i,stat}$, $\delta_{i,uncor}$: Relative statistical and uncorrelated systematic uncertainties
- r_i, r_j: Random numbers from a normal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

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

R_q-only

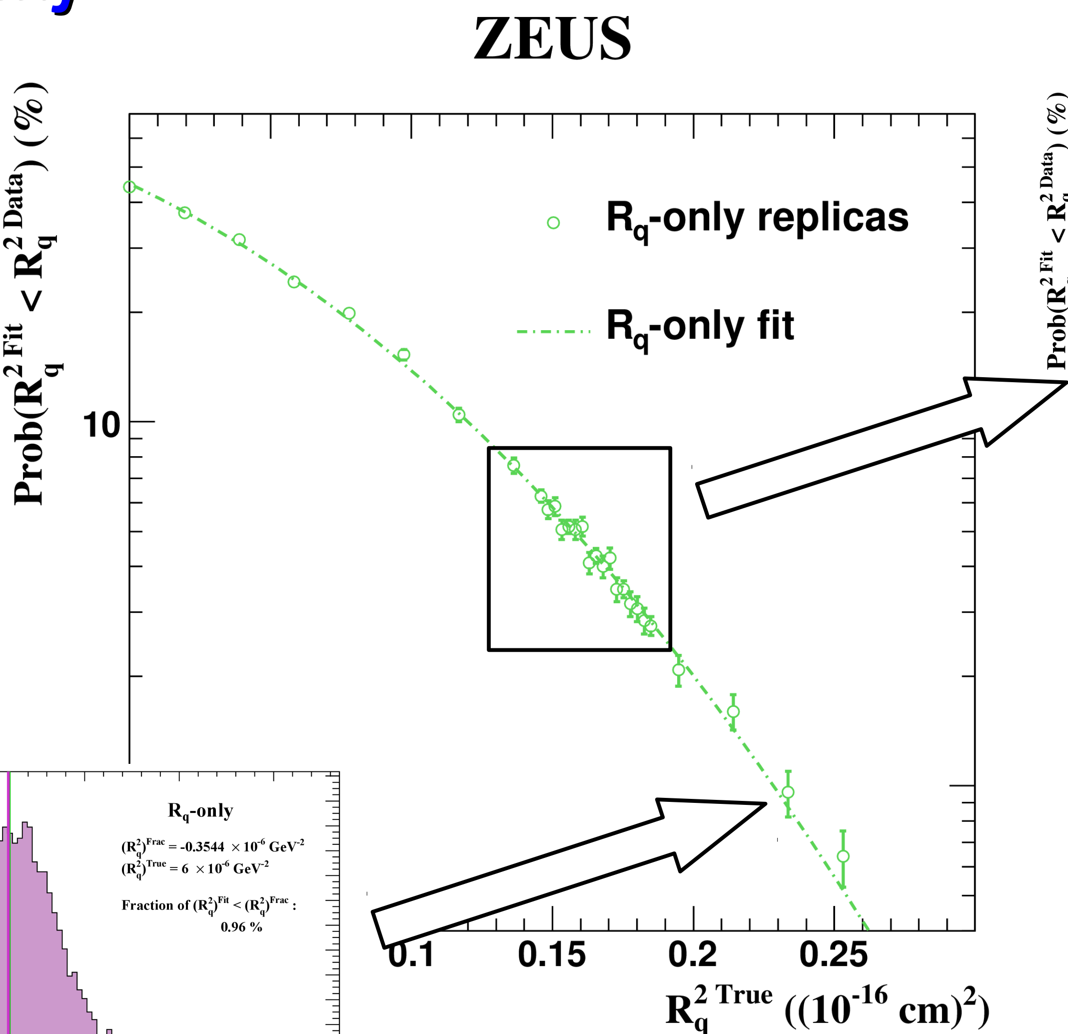


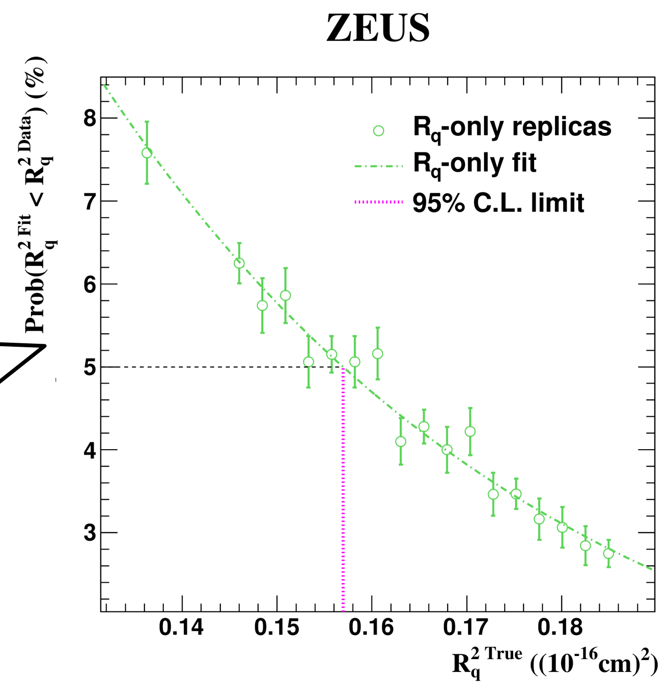
R_q+PDF

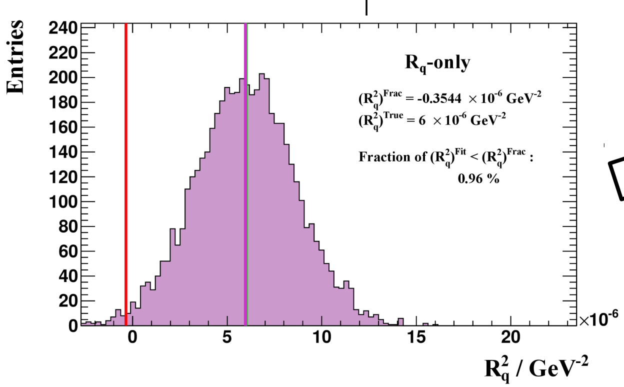


R_q limits with the MC replicas

R_q-only







Fractions close to 5% fitted with:

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

$$-[0.42 \times 10^{-16}\,\mathrm{cm}]^2 \leq \mathrm{R}_q^2 \leq [0.40 \times 10^{-16}\,\mathrm{cm}]^2$$

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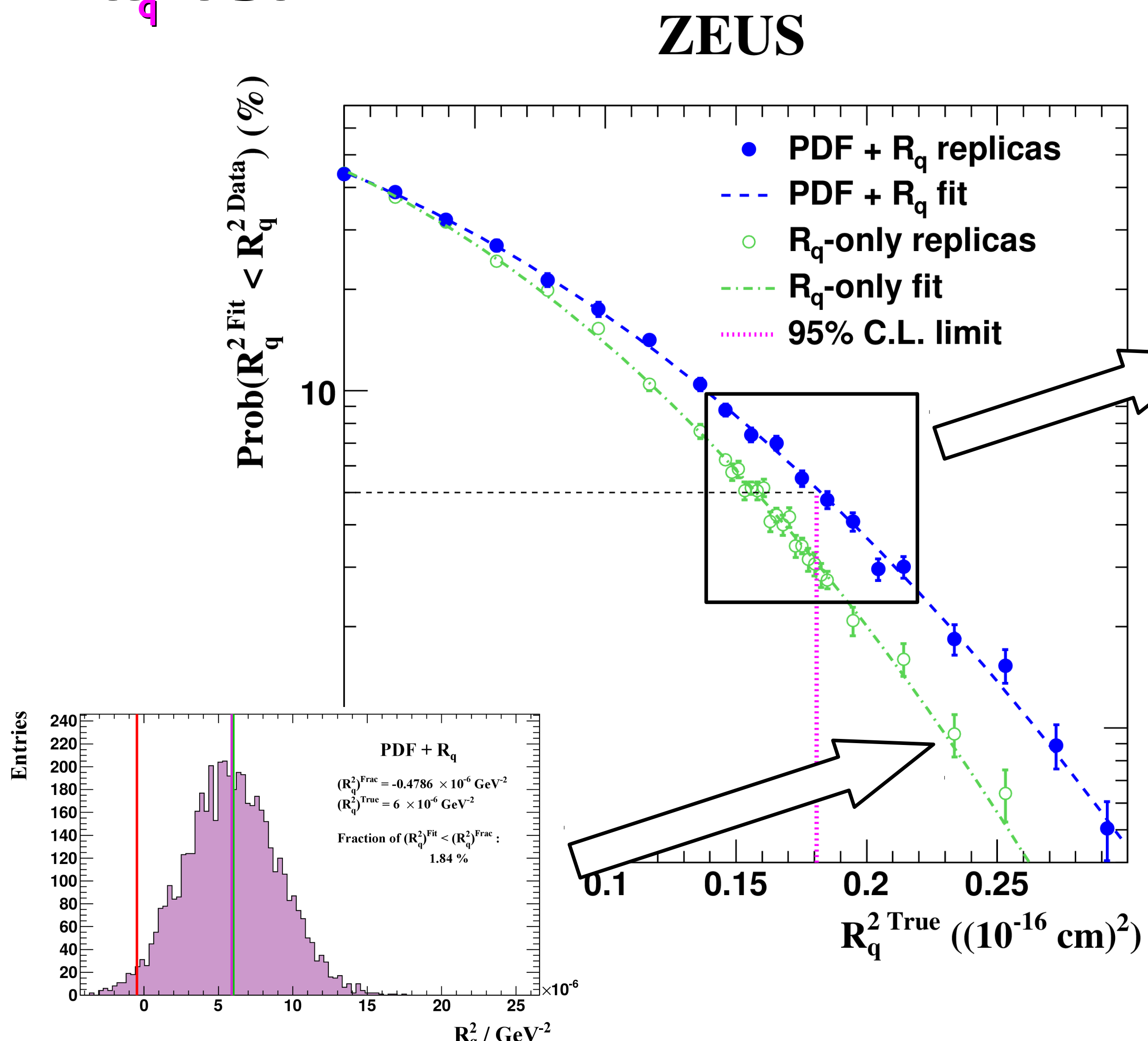
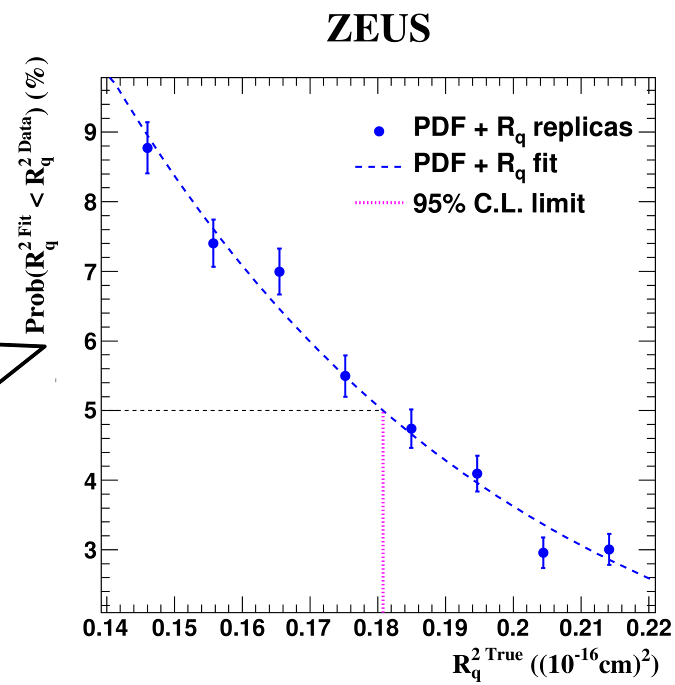
R_q limits with the MC replicas

R_q+PDF





Fractions close to 5% fitted with:

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

$$-[0.47\times10^{-16}\,\text{cm}]^2 \leq R_q^2 \leq [0.43\times10^{-16}\,\text{cm}]^2$$

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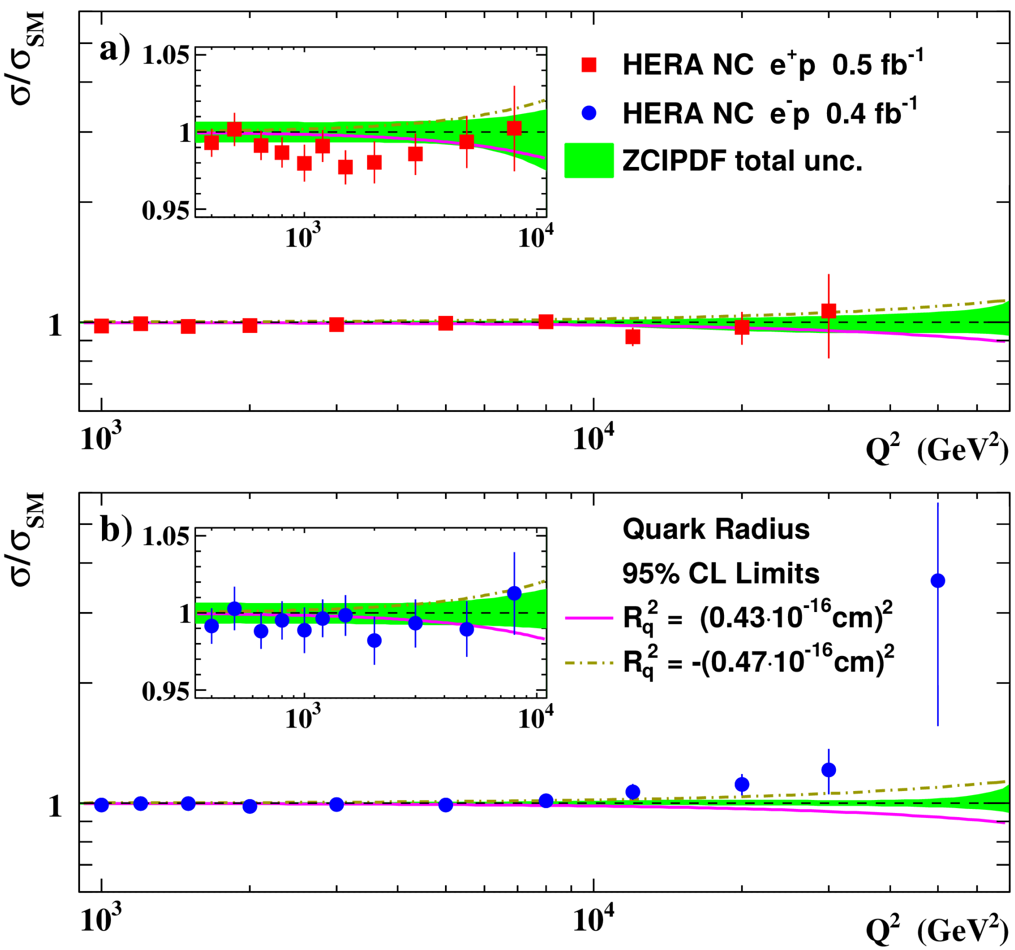
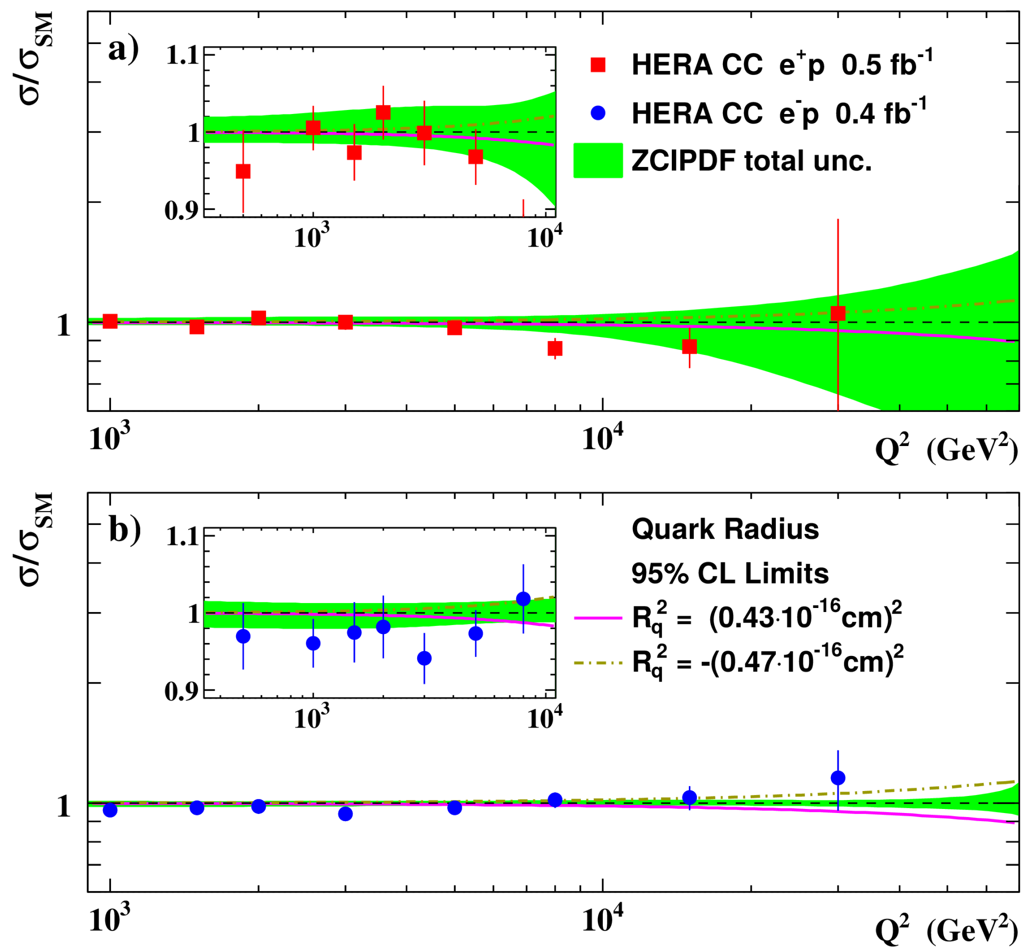
Comparison to Data

NC $e^{\pm}p$



CC $e^{\pm}p$



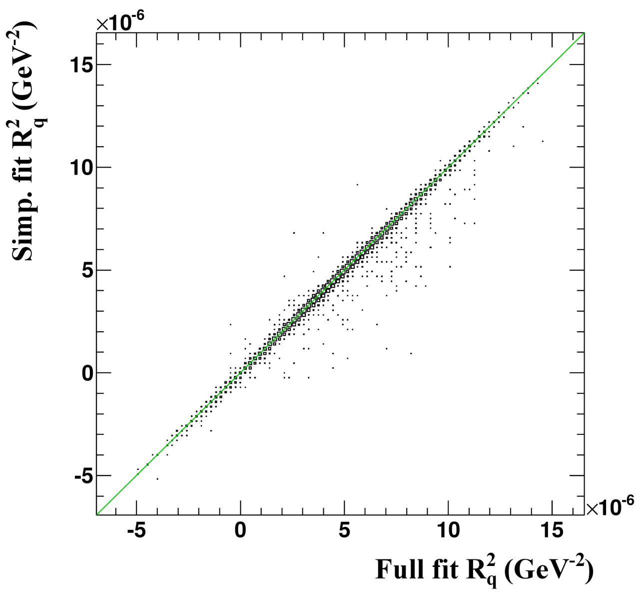
Simplified fit procedure

On average every CI+PDF fit takes **~1.5 hours** of cpu time.

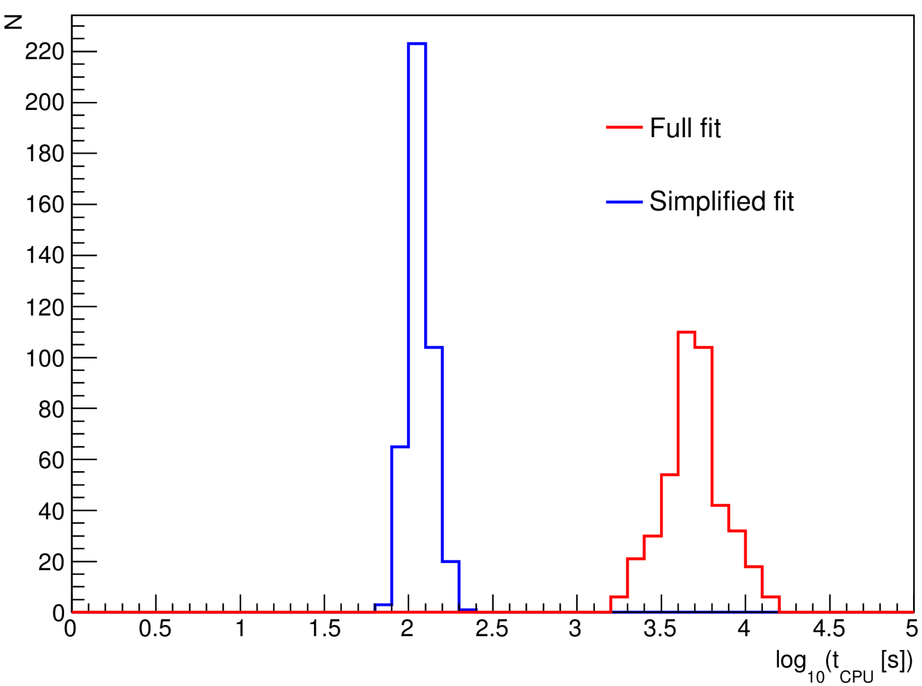
For final R_q analysis 215000 replicas were fitted, taking **~36.8** years of cpu time.

To proceed with other BSM models a simplified fit procedure based on the approximation of the cross-section predictions with a Taylor expansion have been developed and implemented, reducing the average fit duration to **~2 minutes** of cpu time.

For $R_q^{True} = 0.43 \cdot 10^{-16}$ cm:

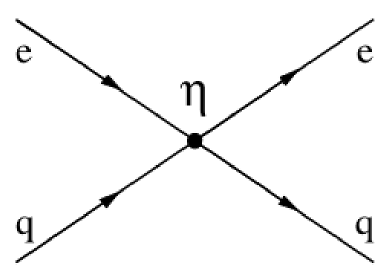


CPU time for single replica fit



Contact interactions

Four-fermion *eeqq* contact interactions provide a convenient method to search for possible effects due to the virtual exchange of new particles with mass much higher than center of mass energy.



$$\mathscr{L}_{CI} = \sum_{\substack{i,j=L,R \\ q=u,d}} \eta_{ij}^{eq} (\bar{e}_i \gamma^{\mu} e_i)(\bar{q}_j \gamma_{\mu} q_j)$$

$$\eta_{ij} = \epsilon_{ij} \cdot \frac{4\pi}{\Lambda^2}$$

$$\epsilon_{ij} = \pm 1; 0$$

Considered models:

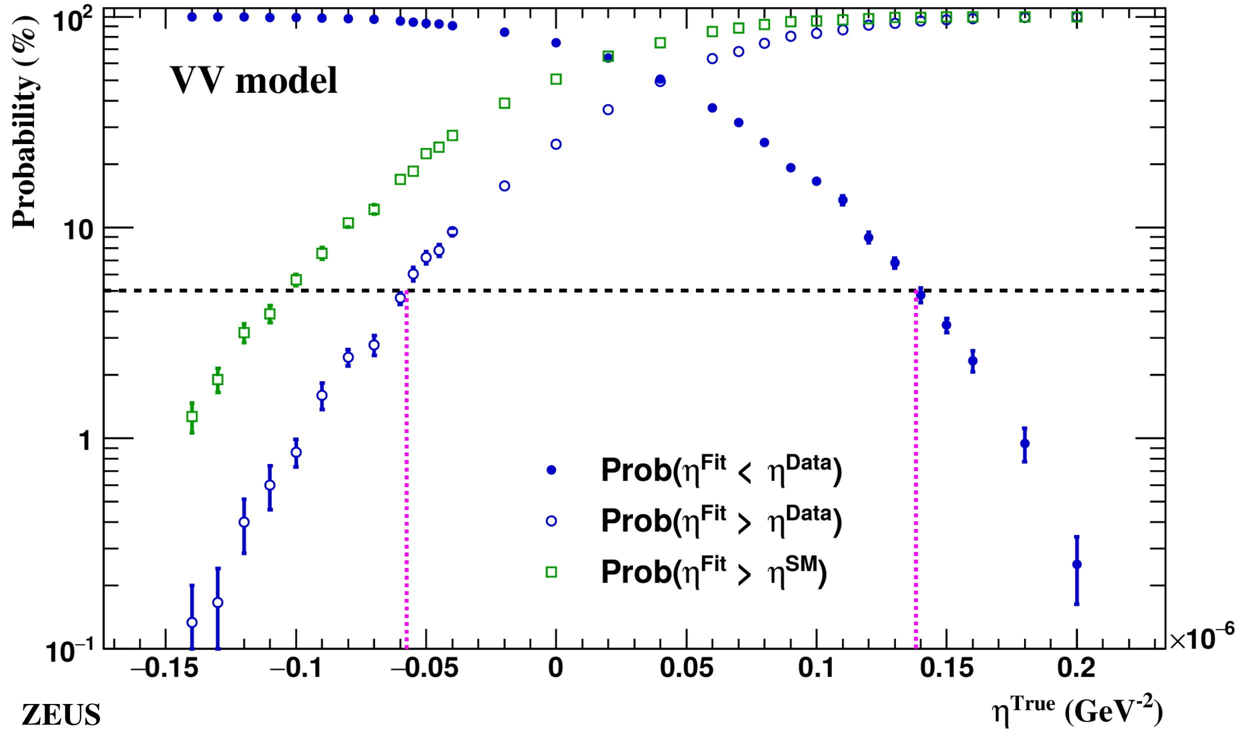
Model	η_{LL}^{eq}	η_{LR}^{eq}	η_{RL}^{eq}	η_{RR}^{eq}
LL	$+\eta$			
RR				$+\eta$
VV	$+\eta$	$+\eta$	$+\eta$	$+\eta$
AA	$+\eta$	$-\eta$	$-\eta$	$+\eta$
VA	$+\eta$	$-\eta$	$+\eta$	$-\eta$
X1	$+\eta$	$-\eta$		
X2	$+\eta$		$+\eta$	
X4		$+\eta$	$+\eta$	

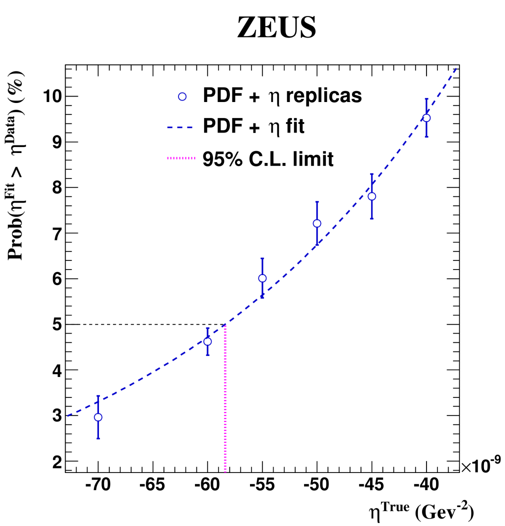
Contact interactions

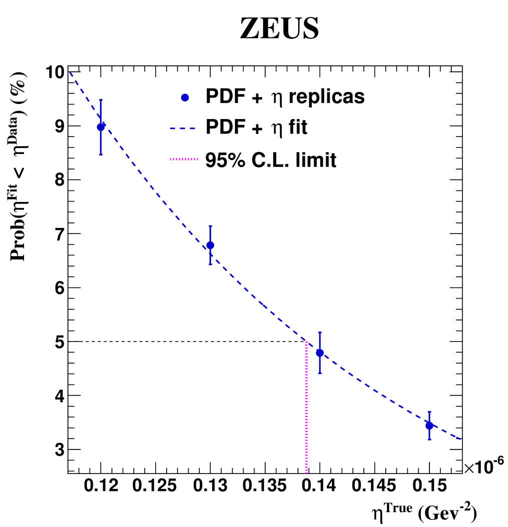
Following approach from the R_q analysis:

VV model

(highest sensitivity)







Evaluated 95% C.L. limits:

$$-5.8\cdot 10^{-8}\,GeV^{-2} < \eta < 13.9\cdot 10^{-8}\,GeV^{-2}$$

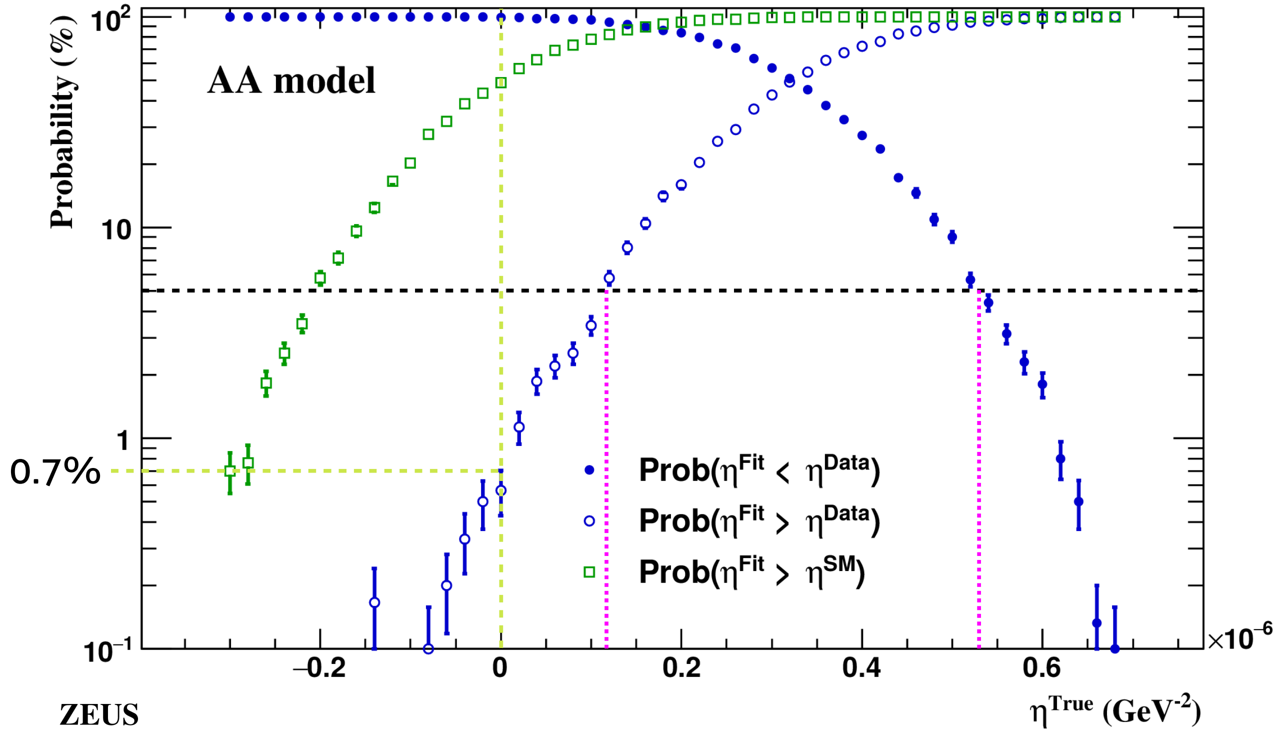
$$\Lambda^{-} > 14.7\ Tev \qquad \Lambda^{+} > 9.5\ Tev$$

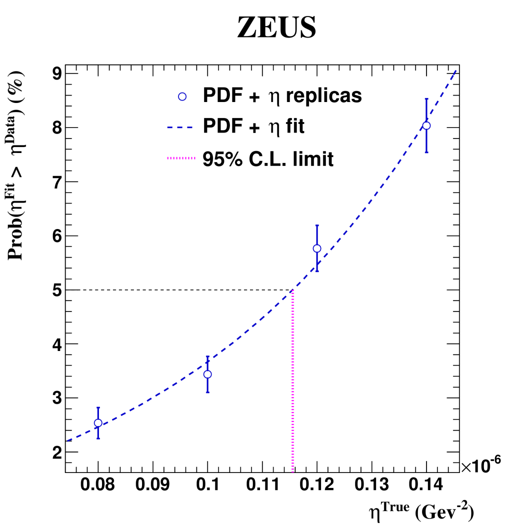
Contact interactions

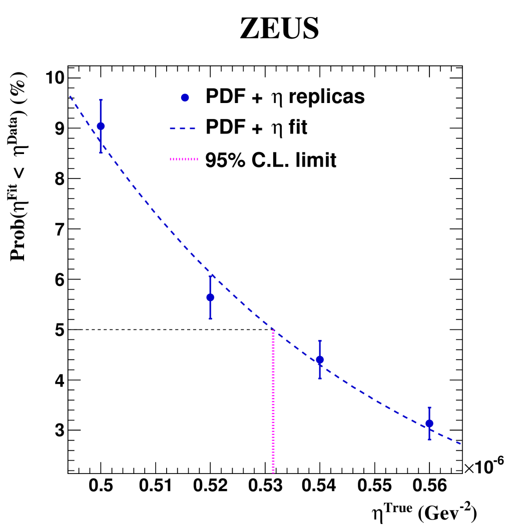
Following approach from the R_q analysis:

AA model

(deviation from SM 2.5 σ)





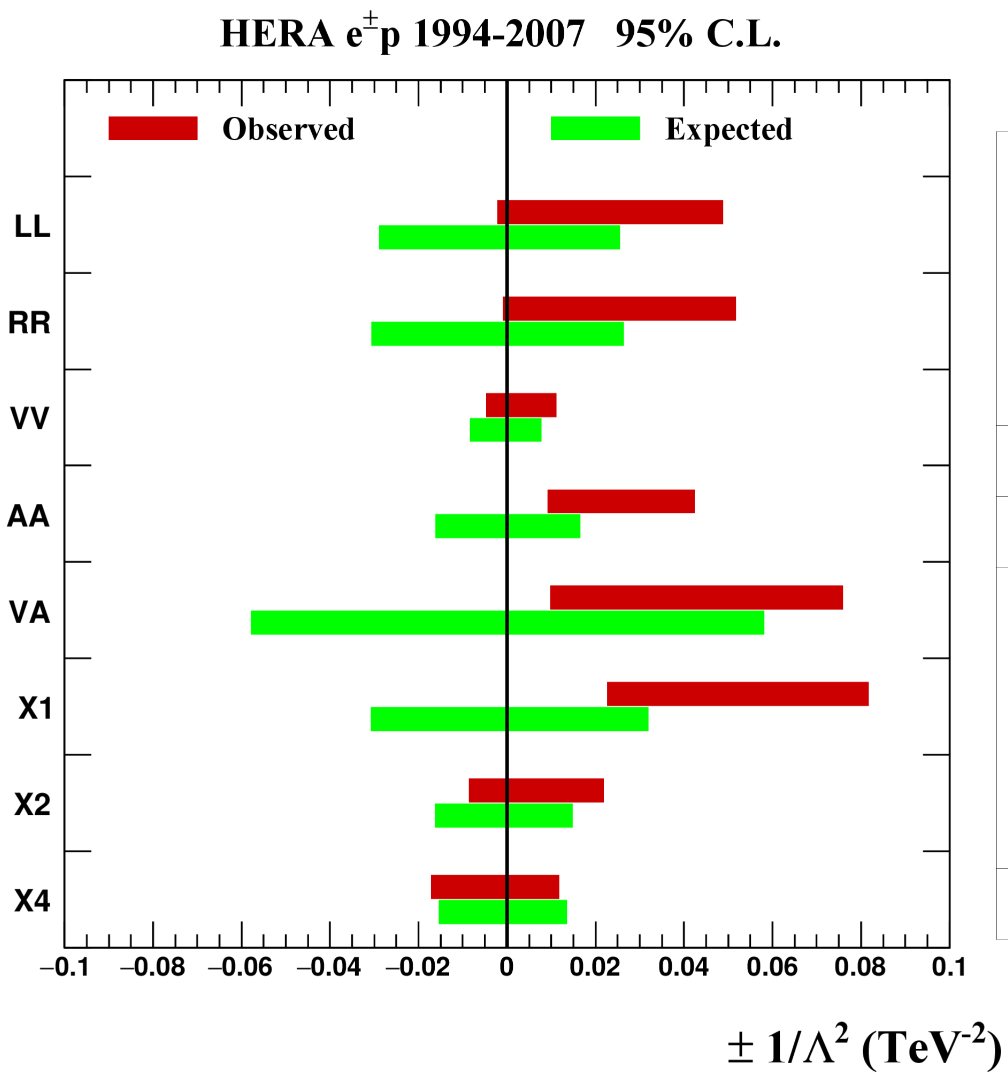


Evaluated 95% C.L. limits:

$$11.6\cdot 10^{-8}\,\mathrm{GeV}^{-2} < \eta < 53.1\cdot 10^{-8}\,\mathrm{GeV}^{-2}$$

$$\Lambda^{+} < 10.4\ \mathrm{Tev} \qquad \Lambda^{+} > 4.8\ \mathrm{Tev}$$

Evaluated CI limits



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

Summary

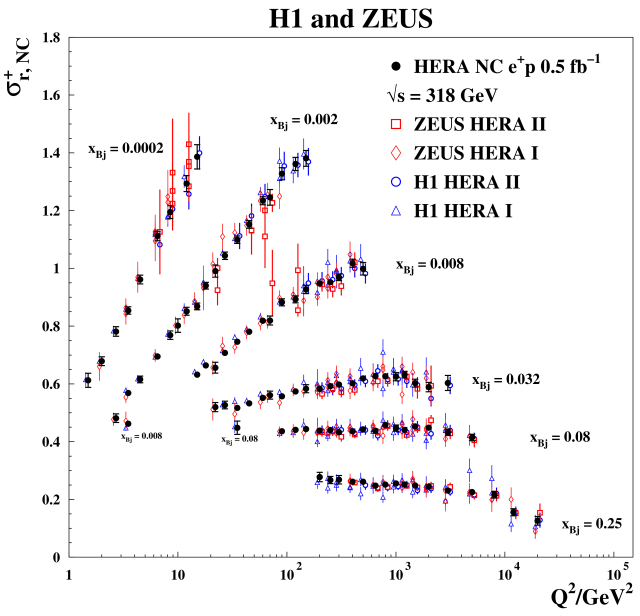
➔ Combined HERA inclusive DIS cross sections allow BSM searches up to TeV svales

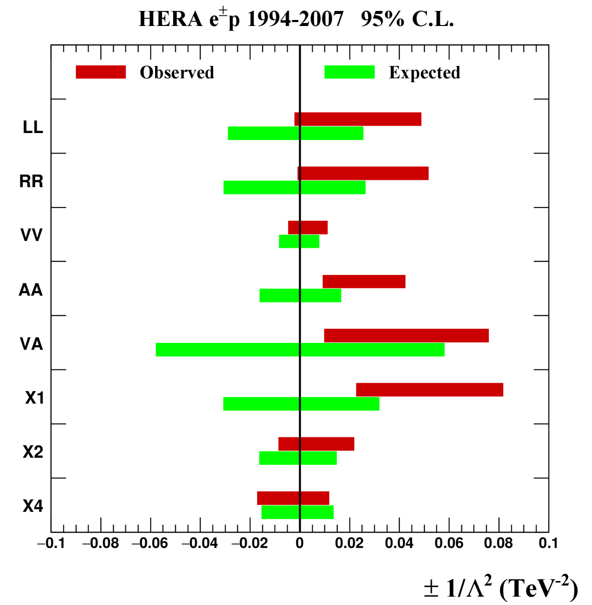
➔ Limits on the quark form factor:

$$-[0.47\times10^{-16}\,\mathrm{cm}]^2 \le R_q^2 \le [0.43\times10^{-16}\,\mathrm{cm}]^2$$

➔ Simultaneous fit procedure is necessary since limits obtained with fixed PDFs are too strong

➔ Some of the contact interactions models provide improved description of the data





BackUp

Determination of ZCIPDFs

The QCD analysis done with the HERAFitter, ancestor of the xFitter.
(available at www.xfitter.org/xFitter/).

The procedure established for HERAPDF 2.0 was closely followed:

- Q^2_{min} = 3.5 GeV² → 1145 data points used
- Renormalisation and factorisation in the $\overline{\text{MS}}$ scheme, with $\mu^2_R = \mu^2_F = Q^2$
- NLO calculations and DGLAP evolution
- Heavy quarks evaluated in RTOPT scheme with M_c = 1.47 GeV and M_b = 4.5 GeV
- Starting scale Q^2_0 = 1.9 GeV²
- $\alpha_s(M^2_Z) = 0.118$, $f_s = 0.4$

The χ^2 definition for ZCIPDF was different from HERAPDF 2.0:

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

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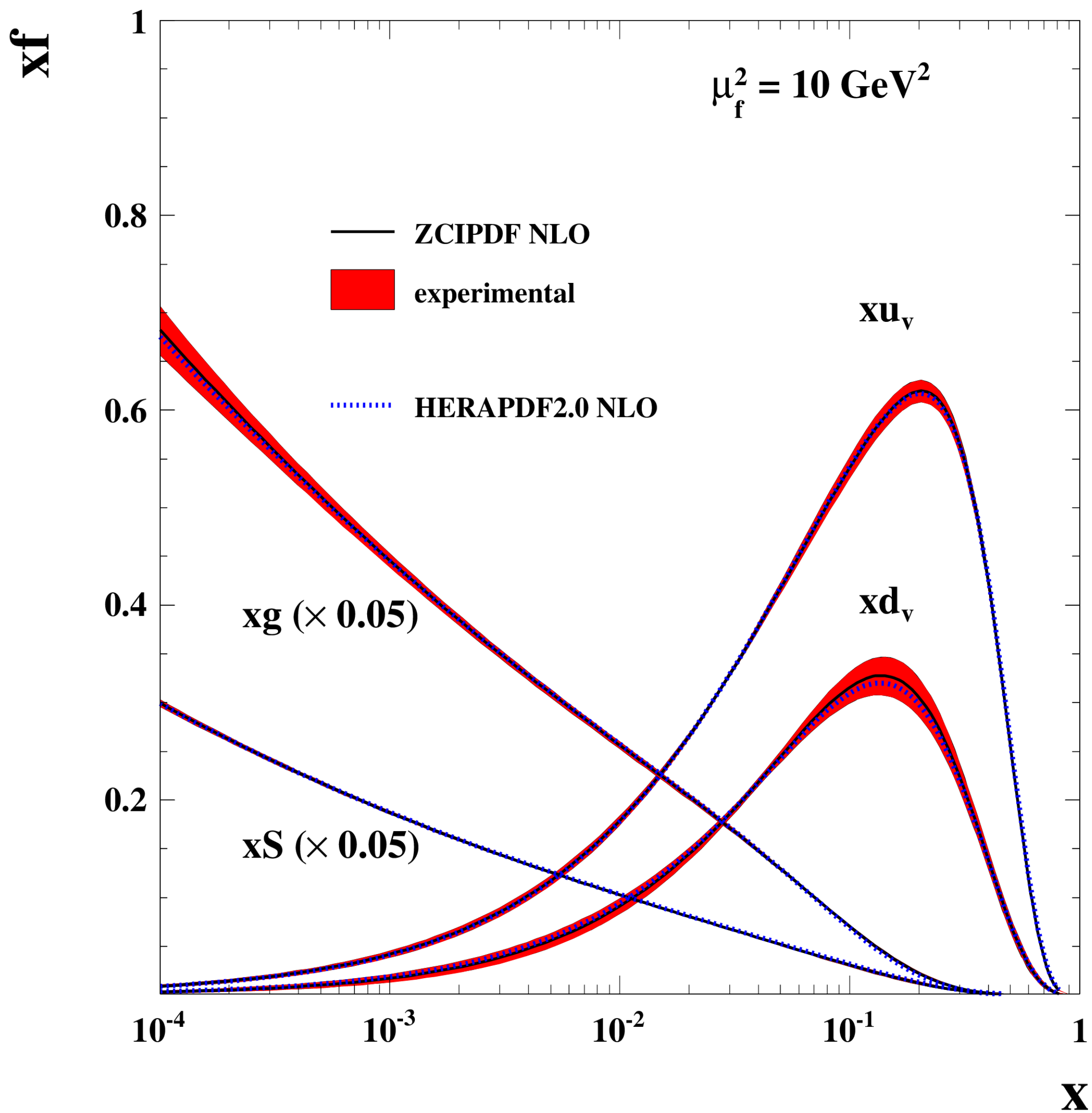
ZCIPDFs



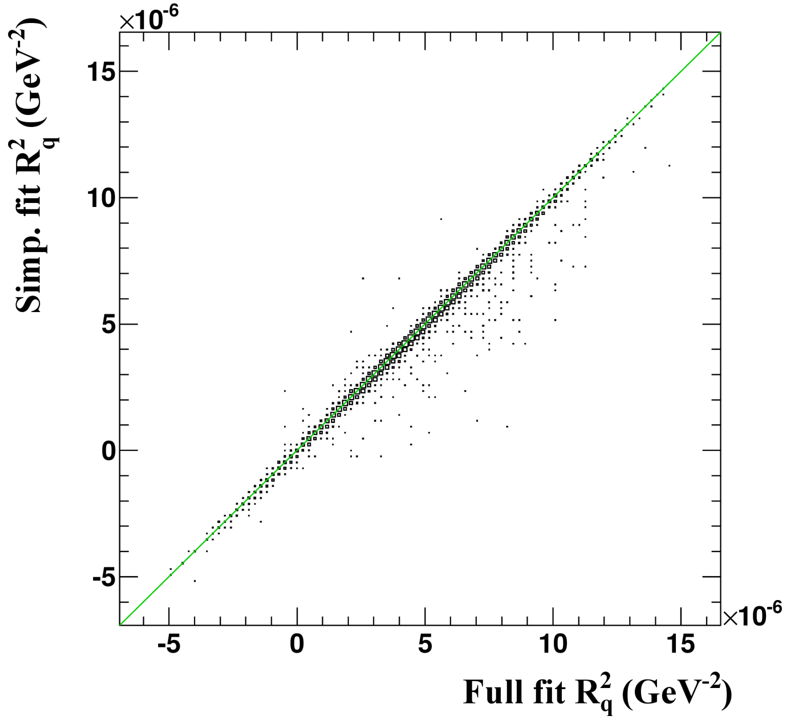
Good agreement with HERAPDF 2.0

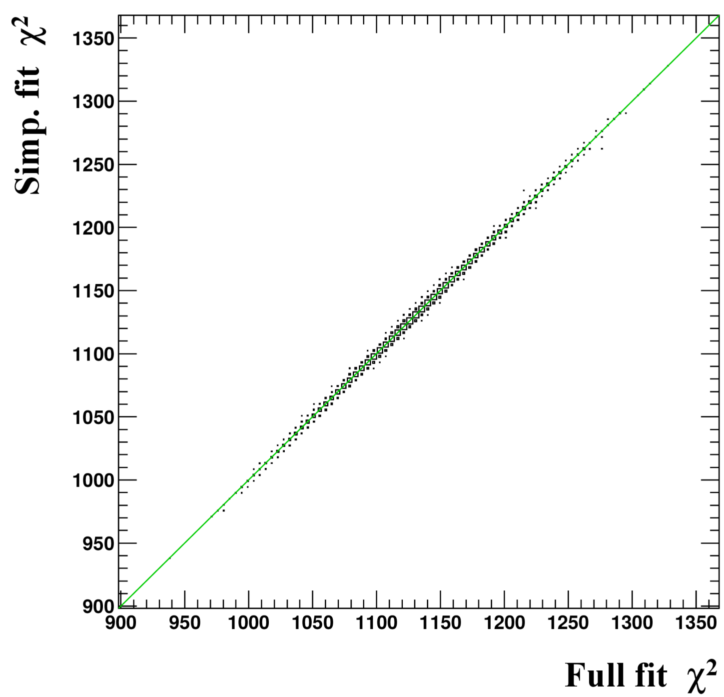
Simplified fit procedure

In simplified procedure cross-section predictions were approximated by first-order Taylor expansion in PDFs $\vec{p}$ and second-order expansion in BSM parameter η:

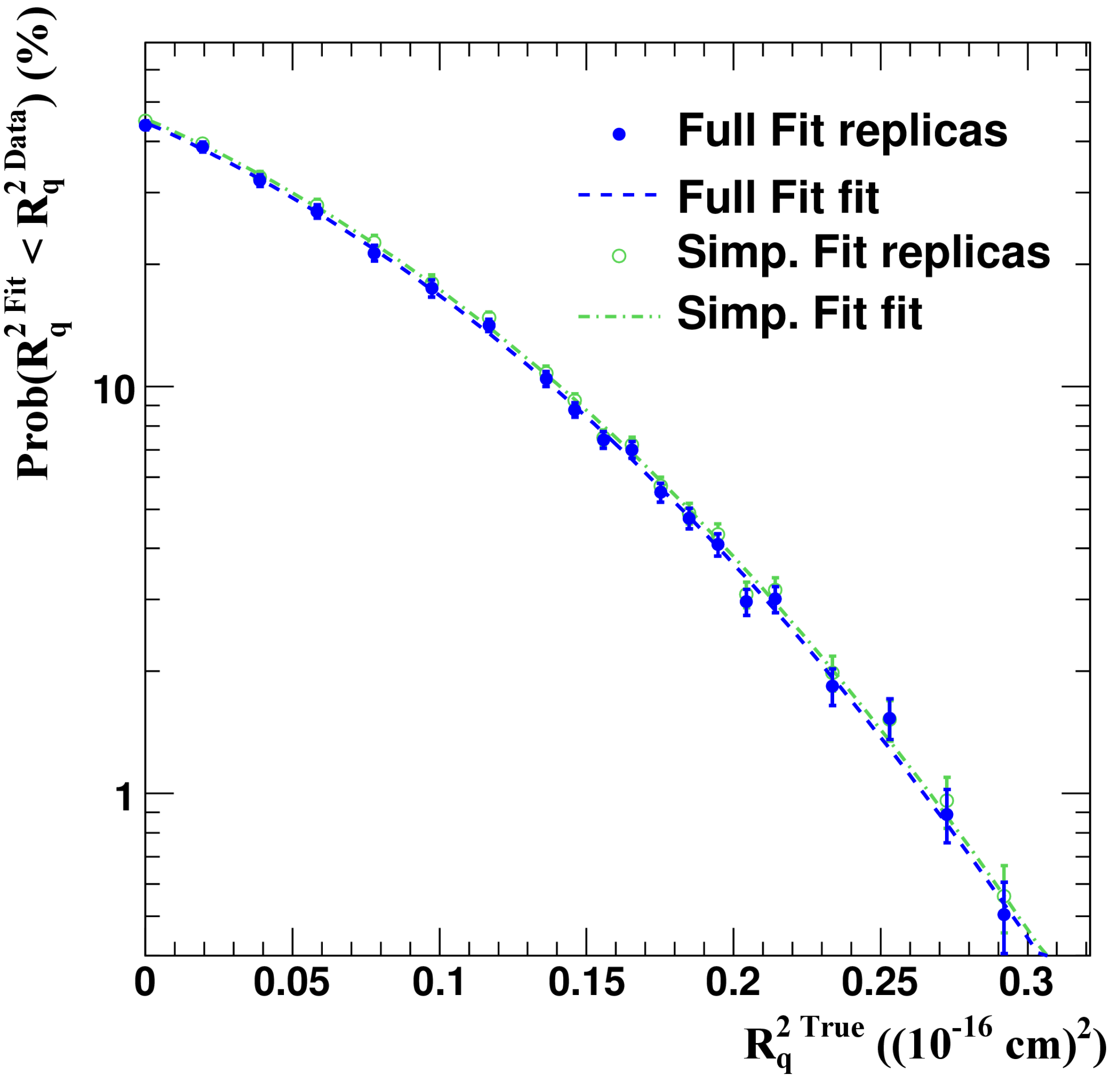
$$m(x_i, Q_i^2, \vec{p}, \eta) = m_0^i + \sum_k \Theta_{0,k}^i \Delta p^k + (m_1^i + \sum_{k'} \Theta_{1,k'}^i \Delta p^{k'}) \cdot \eta + (m_2^i + \sum_{k''} \Theta_{2,k''}^i \Delta p^{k''}) \cdot \eta^2$$

Comparing simplified and full fit results for $R_q^{True} = 0.43 \cdot 10^{-16}$ cm:





R_q limits with simplified procedure



Very good agreement of the analyses results

Comparison to other experiments

Measured 95% C.L. limits ($\times 10^{-16}$ cm)							
HERA combined		LEP 2		ZEUS 2004		H1 2011	
R_q^-	R_q^+	R_q^-	R_q^+	R_q^-	R_q^+	R_q^-	R_q^+
0.47	0.43		0.42	1.06	0.85		0.65

	Measured 95% C.L. limits (TeV)											
	HERA combined		Atlas		CMS		ALEPH		ZEUS 2004		H1 2011	
	Λ^-	Λ^+	Λ^-	Λ^+	Λ^-	Λ^+	Λ^-	Λ^+	Λ^-	Λ^+	Λ^-	Λ^+
LL	22.0	4.5	20.7	16.4	18.3	13.5	7.2	12.9	1.7	2.7	4.0	4.2
RR	32.9	4.4	20.2	16.6			5.3	10.2	1.8	2.7	3.9	4.4
VV	14.7	9.5					8.3	16.9	6.2	5.4	7.2	5.6
AA	—	4.8 - 10.4					9.6	15.9	4.7	4.4	5.1	4.4
VA	—	3.6 - 10.1							3.3	3.2	3.6	3.8
X1	—	3.5 - 6.6							3.6	2.6		
X2	10.8	6.8							3.9	4.0		
X4	7.6	9.2	25.2	19.2			6.8	3.7	5.1	4.8	4.8	5.4