Limits on contact interactions and leptoquarks at HERA

Aleksander Filip Żarnecki

Faculty of Physics, University of Warsaw

on behalf of the ZEUS collaboration

The European Physical Society Conference on High Energy Physics

Searches for New Physics parallel session

PDF description in BSM analysis

Precise knowledge of the parton densities inside the proton is crucial, in particular, for the full exploitation of the physics potential of the LHC.

Parametrizations of the parton distribution function (PDF) of the proton are based on the QCD (DGLAP) analysis of the available data.

H1 and ZEUS measurements of deep inelastic $e^{\pm}p$ scattering (DIS) cross sections at HERA are the crucial input to all available PDF sets.

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HERA measurements can be sensitive to BSM contributions even at scales far beyond the center-of-mass energy of 320 GeV.

If BSM physics effects existed in the HERA data, the current PDF sets would have been biased by absorbing unrecognized BSM contributions.

Also, PDF uncertainties estimated with the SM analysis would have been significantly underestimated...

Motivation

PDF description in BSM analysis

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H1 and ZEUS me... ering (DIS) cross sections at HERA ... DF sets.

New approach needed!

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Outline

For details refer to:

H. Abramowicz et al. (ZEUS Collaboration),
Limits on contact interactions and leptoquarks at HERA,
Phys. Rev. D 99, 092006 (2019), arXiv:1902.03048

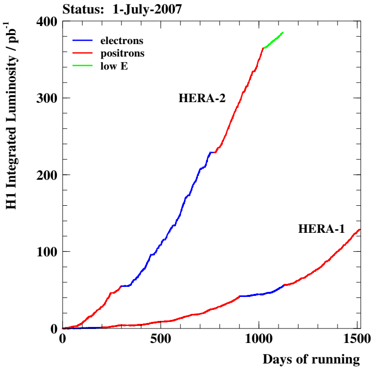
HERA

electron(positron)-proton collider at DESY

HERA I 1994-2000

about $100 pb^{-1}$ collected per experiment

mainly e^+p data, unpolarised



HERA II 2002-2007

about $400 pb^{-1}$ per experiment

similar amount of e^-p and e^+p data

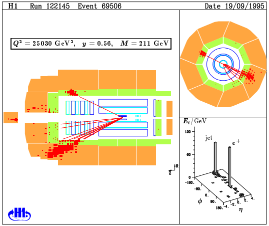
with longitudinal polarization of $e^\pm$ beams (30-40%)

and small samples collected at reduced proton beam energy

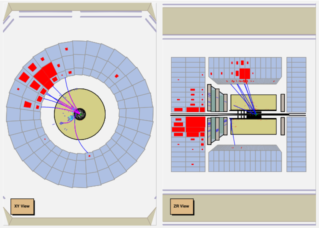
Deep Inelastic $e^{\pm}p$ Scattering

Main process studied by H1 and ZEUS

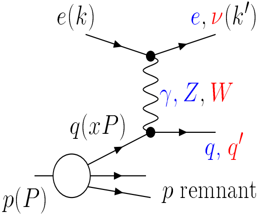
NC DIS



CC DIS



Kinematic variables:



$$Q^2 = -(k - k')^2$$ |virtuality| of the exchanged boson

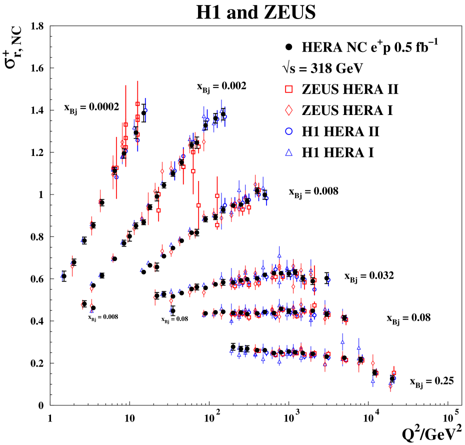
$$x = \frac{Q^2}{2P \cdot (k - k')}$$ fraction of proton momenta carried by stuck quark

$$y = \frac{P \cdot (k - k')}{P \cdot k}$$ fraction of lepton energy transfered in the proton rest frame

QCD analysis of HERA measurements

All DIS data from H1 and ZEUS combined into one set of cross section measurements.

Good consistency between experiments and different data sets



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

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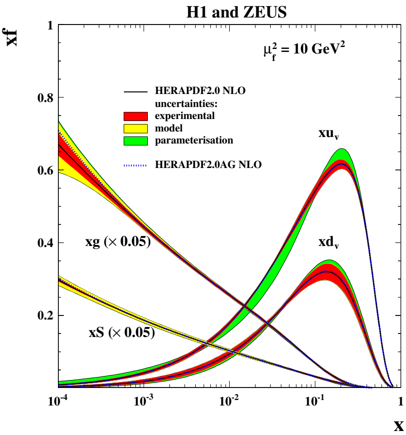
Parton Density Functions (PDFs) parametrised at a starting scale of $Q^2 = 1.9$ GeV^2.

Fit to combined H1+ZEUS data using QCD evolution equations to evolve them to arbitrary Q^2 scale.

⇒ **HERAPDF2.0**



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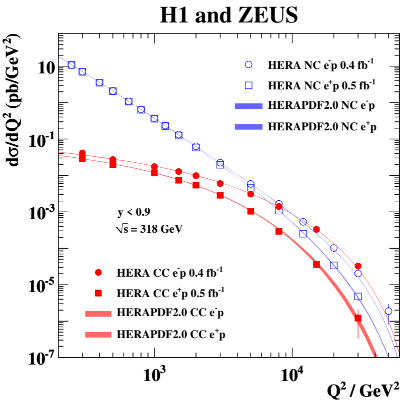
SM predictions from HERA



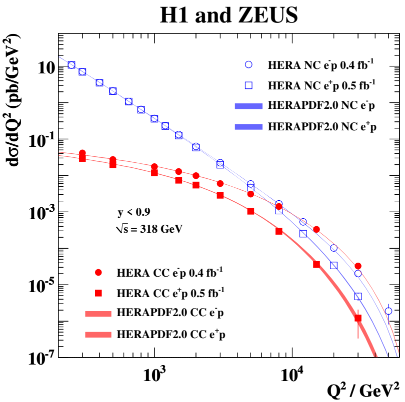
NC and CC DIS cross sections comparable for the highest Q^2 values

$$Q^2 \sim M_Z^2,\ M_W^2$$

Combined QCD+EW analysis shows good agreement with SM predictions

Phys. Rev. D 93 (2016) 092002, arXiv:1603.09628

SM predictions from HERA



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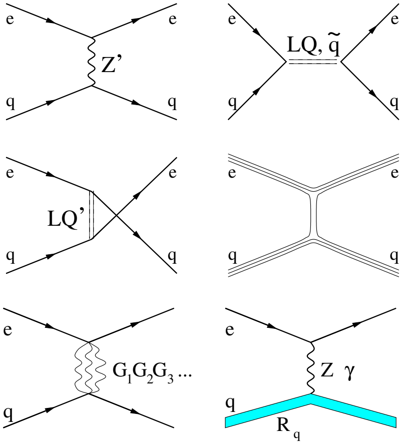
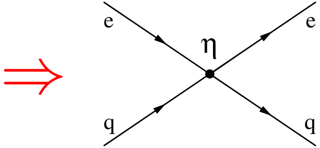
High precision data could also be used to look for possible BSM effects...

However, new approach to PDF analysis is then needed...

Framework

For many scenarios of “new physics” at much larger energy scale, BSM interactions can be approximated as *eeqq* Contact Interactions (CI)





eeqq contact interactions (CI)

Framework

For many scenarios of "new physics" at much larger energy scale, BSM interactions can be approximated as *eeqq* Contact Interactions (CI)

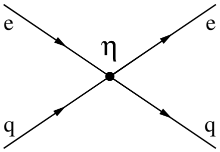
Effective Lagrangian for vector *eeqq* contact interactions:

$$\mathcal{L}_{CI} = \sum_{\substack{\alpha,\beta=L,R \\ q}} \eta^{eq}_{\alpha\beta} \cdot (\bar{e}_\alpha \gamma^\mu e_\alpha)(\bar{q}_\beta \gamma_\mu q_\beta)$$

$\eta^{eq}_{\alpha\beta}$ - 4 possible couplings per flavor q related to the coupling strength η or the "new physics" mass scale Λ by:

$$\eta_{\alpha\beta} = \varepsilon_{\alpha\beta} \cdot \eta = \varepsilon_{\alpha\beta} \cdot \frac{4\pi}{\Lambda^2}$$

where $\varepsilon_{\alpha\beta} = \pm 1$



eeqq contact interactions (CI)

Different CI scenarios assume different helicity structure of new interactions, given by set of $\varepsilon_{\alpha\beta}$

General models

Also referred to as compositeness models
(Λ - compositeness scale)

Family universality assumed:

$$\eta^{eu}_{\alpha\beta} = \eta^{ed}_{\alpha\beta} = \eta^{es}_{\alpha\beta} = \eta^{ec}_{\alpha\beta} = \eta^{eb}_{\alpha\beta} = \eta^{et}_{\alpha\beta}$$

Parity conservation require:

$$\eta^{eq}_{LL} + \eta^{eq}_{LR} - \eta^{eq}_{RL} - \eta^{eq}_{RR} = 0$$

Models violating parity:

Model	ε_{LL}	ε_{LR}	ε_{RL}	ε_{RR}
LL	$+1$			
LR		$+1$		
RL			$+1$	
RR				$+1$

Models conserving parity:

Model	ε_{LL}	ε_{LR}	ε_{RL}	ε_{RR}
VV	$+1$	$+1$	$+1$	$+1$
AA	$+1$	-1	-1	$+1$
VA	$+1$	-1	$+1$	-1
X1	$+1$	-1		
X2	$+1$		$+1$	
X3	$+1$			$+1$
X4		$+1$	$+1$	
X5		$+1$		$+1$
X6			$+1$	-1

Heavy leptoquarks

For high mass leptoquarks

$$M_{LQ} \gg \sqrt{s}$$

virtual LQ production/exchange results in an effective LQ coupling:

$$\eta_{LQ} = \left(\frac{\lambda_{LQ}}{M_{LQ}}\right)^2$$

λ_{LQ} - leptoquark Yukawa coupling

CI couplings can be then written as:

$$\eta^{eq}_{\alpha\beta} = a^{eq}_{\alpha\beta} \cdot \eta_{LQ}$$

14 LQ types considered based on general classification by Buchmüller, Rückl and Wyler

Scalar leptoquark models:

Model	Coupling structure
S_0^L	$a^{eu}_{LL} = +\frac{1}{2}$
S_0^R	$a^{eu}_{RR} = +\frac{1}{2}$
$\tilde{S}_0^R$	$a^{ed}_{RR} = +\frac{1}{2}$
$S_{1/2}^L$	$a^{eu}_{LR} = -\frac{1}{2}$
$S_{1/2}^R$	$a^{ed}_{RL} = a^{eu}_{RL} = -\frac{1}{2}$
$\tilde{S}_{1/2}^L$	$a^{ed}_{LR} = -\frac{1}{2}$
S_1^L	$a^{ed}_{LL} = +1,\ a^{eu}_{LL} = +\frac{1}{2}$

Vector leptoquark models:

Model	Coupling structure
V_0^L	$a^{ed}_{LL} = -1$
V_0^R	$a^{ed}_{RR} = -1$
$\tilde{V}_0^R$	$a^{eu}_{RR} = -1$
$V_{1/2}^L$	$a^{ed}_{LR} = +1$
$V_{1/2}^R$	$a^{ed}_{RL} = a^{eu}_{RL} = +1$
$\tilde{V}_{1/2}^L$	$a^{eu}_{LR} = +1$
V_1^L	$a^{ed}_{LL} = -1,\ a^{eu}_{LL} = -2$

QCD+CI fit procedure

Approach used for HERAPDF2.0 determination extended to take into account the possible BSM contribution

$$\chi^2(\boldsymbol{p}, \boldsymbol{s}, \eta) = \sum_i \frac{\left[m^i + \sum_j \gamma_j^i m^i s_j - \mu_0^i\right]^2}{\left(\delta_{i,\mathrm{stat}}^2 + \delta_{i,\mathrm{uncor}}^2\right)\,(\mu_0^i)^2} + \sum_j s_j^2$$

$\boldsymbol{p}$ and $\boldsymbol{s}$ are vectors of PDF parameters p_k and systematic shifts s_j,
η is the parameter describing BSM contribution (η or η_{LQ})

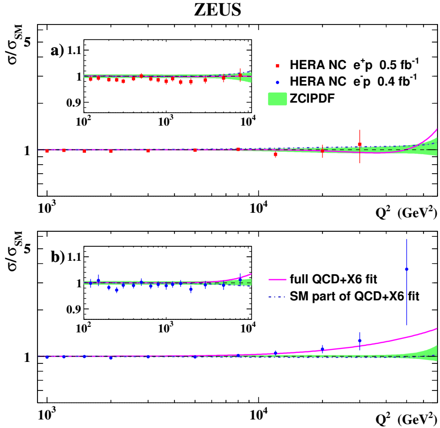
⇒ we **fit them simultaneously** to the combined HERA data

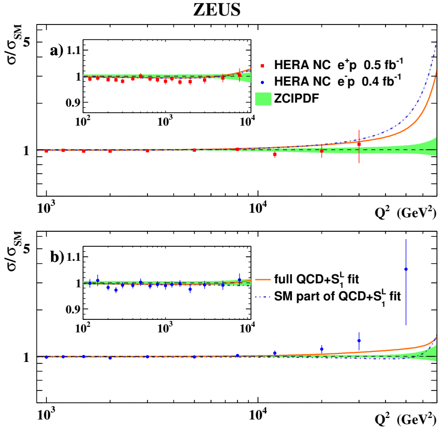
⇒ coupling value resulting in best description of the data, η^{Data}

μ_0^i and $m^i(\boldsymbol{p}, \eta)$ are measured and predicted (SM+BSM) cross sections,
γ_j^i, $\delta_{i,\mathrm{stat}}$ and $\delta_{i,\mathrm{uncor}}$ are the relative correlated systematic, relative statistical and relative uncorrelated systematic uncertainties of the input data point i

QCD+CI fit results

Improved description of the data for four models (3CI+1LQ): $\Delta\chi^2 < -4$.





X6: change dominated by CI contribution
$\Delta\chi^2 = -6.01$

S_1^L: significant change in proton PDF !
$\Delta\chi^2 = -11.1$

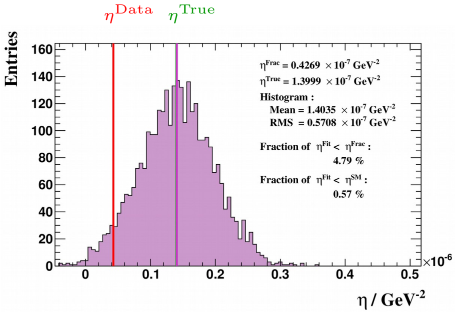
Limit setting

Limits derived using the technique of MC replicas (frequentist approach).

Replicas are generated sets of cross-section values that are calculated for given η^{True} and varied randomly according to the statistical and systematic uncertainties (including correlations) of the input data.

Each replica is then used as an input to QCD+BSM fit
$\Rightarrow \eta^{\mathrm{Fit}}$

Number of replicas for each considered η^{True} value
$\Rightarrow$ distribution of η^{Fit}



η^{True} is tested by comparing η^{Fit} distribution with the value of η^{Data}

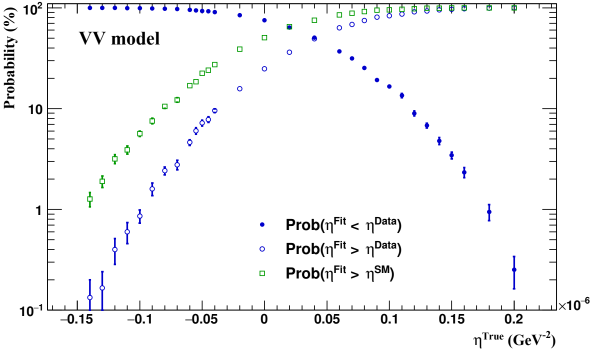
Limit setting

Use replicas to calculate:

$$\text{Prob}(\eta^{\text{Fit}} < \eta^{\text{Data}}) \quad \text{for} \quad \eta > \eta^{\text{Data}}$$

$$\text{Prob}(\eta^{\text{Fit}} > \eta^{\text{Data}}) \quad \text{for} \quad \eta < \eta^{\text{Data}}$$

for different η^{True}



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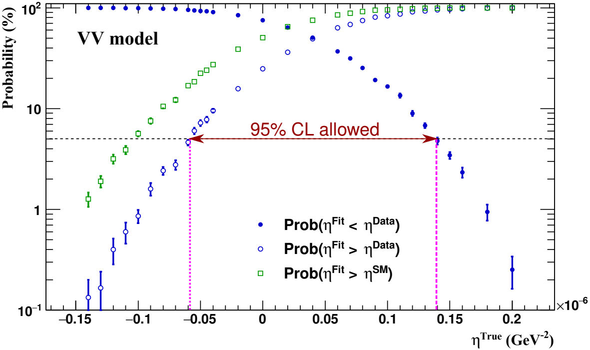
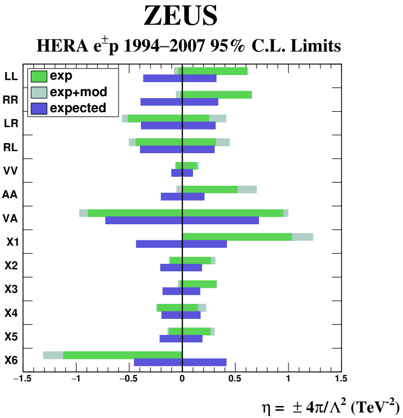


Excluded on 95% C.L. are η^{True} resulting in probability below 5%.

The limit-calculation procedure was repeated for systematic variations considered. The weakest of the obtained coupling limits was taken as the result of the analysis and used to calculate the final mass-scale limits.

Contact Interaction limits



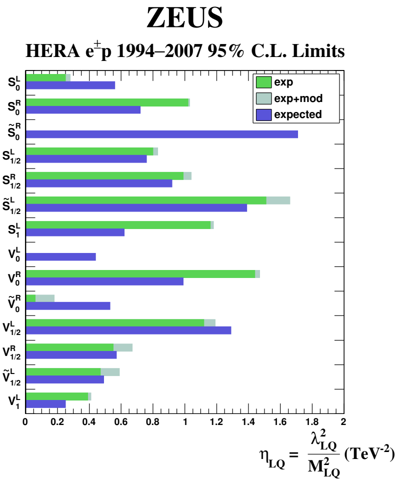
limits calculated without and with modeling uncertainties compared with the expected ones

ZEUS

HERA $e^{\pm}p$ 1994-2007 95% C.L. limits (TeV)

Model	Observed (exp+mod) Λ^-	Observed (exp+mod) Λ^+	Expected Λ^-	Expected Λ^+	p_{SM} (%)
LL	12.8	4.5	5.9	6.3	7.0
RR	14.7	4.4	5.7	6.1	5.9
LR	4.7	5.5	5.7	6.3	34
RL	5.0	5.3	5.6	6.5	42
VV	13.9	9.0	11.2	11.4	25
AA	15.7	4.2	7.9	7.8	0.6
VA	3.6	3.5	4.2	4.2	5.8
X1		3.2	5.4	5.5	0.4
X2	10.4	6.4	7.8	8.3	24
X3	17.9	6.2	8.3	8.7	7.3
X4	7.2	7.5	8.0	8.6	39
X5	9.5	6.4	7.7	7.7	27
X6	3.1		5.3	5.5	0.3

Heavy Leptoquark limits



ZEUS

λ_{LQ}/M_{LQ} 95% C.L. limits (TeV^{-1})

Model	Observed (exp+mod)	Expected	p_{SM}
S_0^L	0.28	0.56	9.0
S_0^R	1.03	0.72	5.5
$\tilde{S}_0^R$		1.71	1.8
$S_{1/2}^L$	0.83	0.76	43
$S_{1/2}^R$	1.04	0.92	39
$\tilde{S}_{1/2}^L$	1.66	1.39	38
S_1^L	1.18	0.62	< 0.01
V_0^L		0.44	0.5
V_0^R	1.47	0.99	1.8
$\tilde{V}_0^R$	0.18	0.53	5.5
$V_{1/2}^L$	1.19	1.29	38
$V_{1/2}^R$	0.67	0.57	39
$\tilde{V}_{1/2}^L$	0.59	0.49	43
V_1^L	0.41	0.25	32

Conclusions

High-precision HERA inclusive data allow searches for "new physics" effects up to TeV scales.

New method developed for BSM analysis of HERA data:
simultaneous fit of PDF parameters and BSM contribution.

Even small BSM contribution can significantly modify PDF fit results!!!

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Limits for CI compositeness scales in the 10 TeV range obtained.
Limits for LQ mass scales are in the TeV range.

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simultaneous fit of PDF parameters and BSM contribution.

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Limits for CI compositeness scales in the 10 TeV range obtained.
Limits for LQ mass scales are in the TeV range.

For some of the considered CI and LQ scenarios QCD+BSM fits provide improved descriptions of the HERA inclusive data!
Difference from the SM at the level of up to 2.7σ (X6) and 4σ (S_1^L)

Unlikely to result from statistical fluctuations alone.
Might be explicable by a combination of modeling uncertainties in the fitting procedure and statistical fluctuations.

Physics Letters B 757 (2016) 468–472

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

CrossMark

ZEUS Collaboration

Thank you!

PHYSICAL REVIEW D **99,** 092006 (2019)

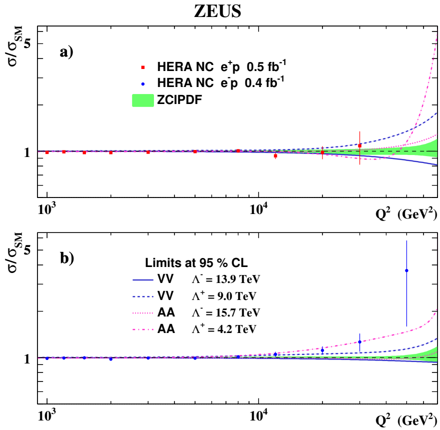
Limits on contact interactions and leptoquarks at HERA

H. Abramowicz,[26,q] I. Abt,[21] L. Adamczyk,[7] M. Adamus,[33] R. Aggarwal,[3,b] S. Antonelli,[1] V. Aushev,[18] O. Behnke,[9] U. Behrens,[9] A. Bertolin,[23] I. Bloch,[10] I. Brock,[2] N. H. Brook,[31,r] R. Brugnera,[24] A. Bruni,[1] P. J. Bussey,[11] A. Caldwell,[21] M. Capua,[4] C. D. Catterall,[35] J. Chwastowski,[6] J. Ciborowski,[32,t] R. Ciesielski,[9,e] A. M. Cooper-Sarkar,[22] M. Corradi,[1,a] R. K. Dementiev,[20] R. C. E. Devenish,[22] S. Dusini,[23] J. Ferrando,[9] B. Foster,[13,j] E. Gallo,[13,k] A. Garfagnini,[24] A. Geiser,[9] A. Gizhko,[9] L. K. Gladilin,[20] Yu. A. Golubkov,[20] G. Grzelak,[32] C. Gwenlan,[22] O. Hlushchenko,[18,o] D. Hochman,[34] Z. A. Ibrahim,[5] Y. Iga,[25] N. Z. Jomhari,[9] I. Kadenko,[18] S. Kananov,[26] U. Karshon,[34] P. Kaur,[3,c] D. Kisielewska,[7] R. Klanner,[13] U. Klein,[9,f] I. A. Korzhavina,[20] A. Kotański,[8] N. Kovalchuk,[13] H. Kowalski,[9] B. Krupa,[6] O. Kuprash,[9,g] M. Kuze,[28] B. B. Levchenko,[20] A. Levy,[26] V. Libov,[9] M. Lisovyi,[9,h] B. Löhr,[9] E. Lohrmann,[13] A. Longhin,[24] O. Yu. Lukina,[20] I. Makarenko,[9] J. Malka,[9] S. Masciocchi,[12,l] F. Mohamad Idris,[5,d] N. Mohammad Nasir,[5] V. Myronenko,[9] K. Nagano,[15] J. D. Nam,[27] M. Nicassio,[14] J. Onderwaater,[14,m] Yu. Onishchuk,[18] E. Paul,[2] I. Pidhurskyi,[18]

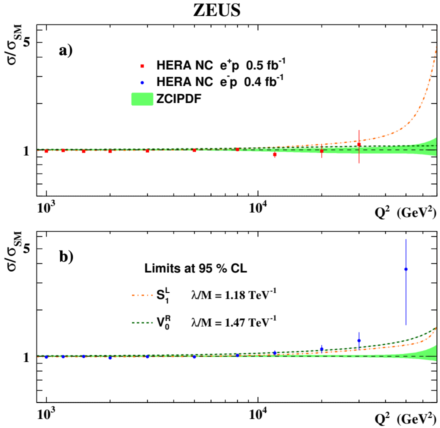
HERA limits

Cross section deviations corresponding to the coupling limits for selected

Contact Interaction scenarios



Heavy Leptoquarks



Modeling uncertaintie

Input parameter variations considered to evaluate model and parametrization uncertainties of the fit

Variation	Nominal Value	Lower Limit	Upper Limit
$Q^2_{\rm min}$ [GeV^2]	3.5	2.5	5.0
charm mass parameter M_c [GeV]	1.47	1.41	1.53
beauty mass parameter M_b [GeV]	4.5	4.25	4.75
sea strange fraction f_s	0.4	0.3	0.5
starting scale $\mu^2_{f_0}$ [GeV^2]	1.9	1.6	2.2

Comparison with LHC

ZEUS

Model	Coupling structure $[\epsilon_{LL}, \epsilon_{LR}, \epsilon_{RL}, \epsilon_{RR}]$	HERA Λ^-	HERA Λ^+	ATLAS Λ^-	ATLAS Λ^+	CMS Λ^-	CMS Λ^+
		95%C.L. limits (TeV)					
LL	[+1, 0, 0, 0]	12.8	4.5	24	37	13.5	18.3
RR	[0, 0, 0, +1]	14.7	4.4	26	33		
LR	[0, +1, 0, 0]	4.7	5.5	26	33		
RL	[0, 0, +1, 0]	5.0	5.3	26	33		

M. Aaboud et al. (ATLAS Collaboration), J. High Energy Phys. 10 (2017) 182.
A. M. Sirunyan et al. (CMS Collaboration), J. High Energy Phys. 04 (2019) 114.

Simplified fit procedure

Limit setting in the replica method is very time consuming.
Full fit of HERA data: QCD evolution of PDFs repeated at each iteration.

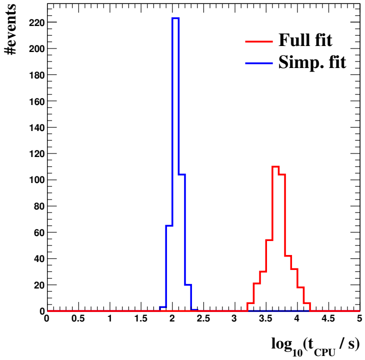
R_q analysis: 3000–5000 Monte Carlo replicas for each value of $R_q^{2\ \mathrm{True}}$
$\Rightarrow$ over 200'000 fits to set final limits

Processing time was a limiting factor for including more models

Simplified fit method, based on the Taylor expansion of the cross section predictions in terms of PDF parameters

$\Rightarrow$ reduce the limit calculation time by almost two orders of magnitude.

For details see arXiv:1606.06670

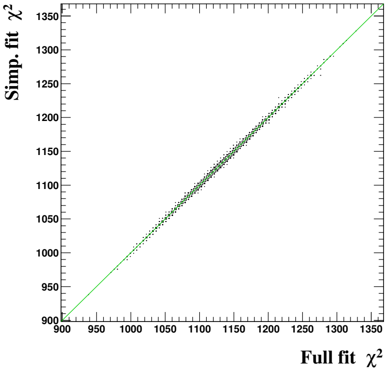


Simplified fit procedure

New procedure was validated by repeating R_q^2 limit setting procedure.

Comparison of results for replicas generated with $R_q^{2\ \mathrm{True}} = (R_q^{\mathrm{Limit}})^2$.

χ^2 of the fit



Fitted value of R_q^2