



Search for contact interactions in inclusive ep scattering at HERA

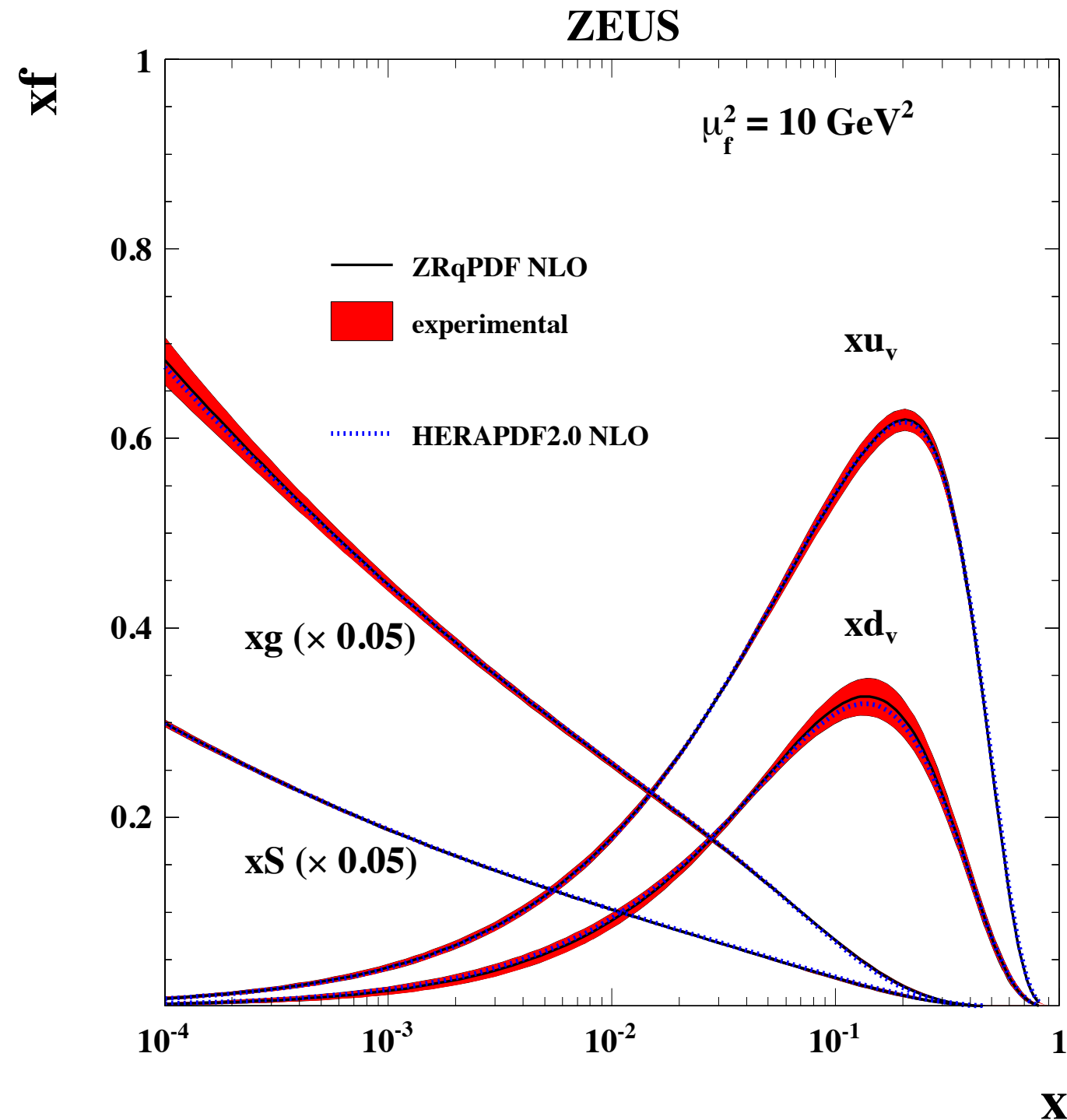


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- Beyond-the-Standard-Model analysis combined with PDFs fit
- Contact interactions and heavy leptoquarks search results

QCD analysis of the combined DIS data



Parton Density Functions

Parameterised at the starting scale of $Q^2_0 = 1.9 \text{ GeV}^2$:

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

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

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

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

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

■ fixed or calculated by the sum-rules

■ set equal

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

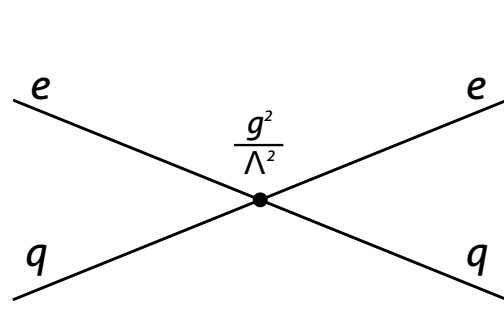
Obtained PDFs are referred to as **ZRqPDFs** and have a good agreement with the HERAPDF 2.0.

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

General contact interactions

Low-energy effects due to physics at much higher energy scales can be described with the four-fermion contact interactions (CI). Vector contact interactions considered in the analysis provide additional terms to the Standard Model Lagrangian:

$$\mathcal{L}_{\text{CI}} = \sum_{\substack{k,j=L,R \\ q=u,d,s,c,b}} \eta_{kj}^{eq} (\bar{e}_k \gamma^\mu e_k) (\bar{q}_j \gamma_\mu q_j)$$



$$\eta_{kj}^{eq} = \epsilon_{kj}^{eq} \frac{g^2}{\Lambda^2}$$

$$\epsilon_{kj}^{eq} = \pm 1; 0$$

All up- or down-type quarks were assumed to have the same contact-interaction couplings:

$$\eta_{kj}^{eu} = \eta_{kj}^{ec} = \eta_{kt}^{et}$$

$$\eta_{kj}^{ed} = \eta_{kj}^{es} = \eta_{kt}^{eb}$$

Considered CI models:

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

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.

...and HERA data allows such analysis to be performed.

Limits setting with Monte Carlo replicas

Limits are derived in a classical (frequentist) approach using the technique of Monte Carlo replicas:

First, Monte Carlo replicas of the cross-section measurements for some value of η^{True} were calculated as:

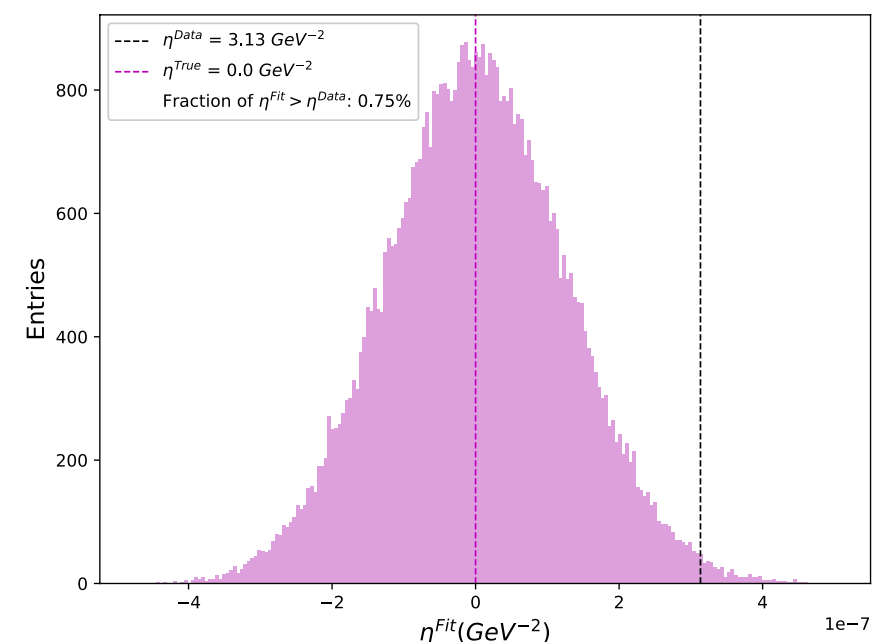
Cross-section prediction from the ZRqPDF modified with η^{True} Measured cross-section value Correlated systematic uncertainties

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

Relative statistical and uncorrelated systematic uncertainties Random numbers from a normal distribution

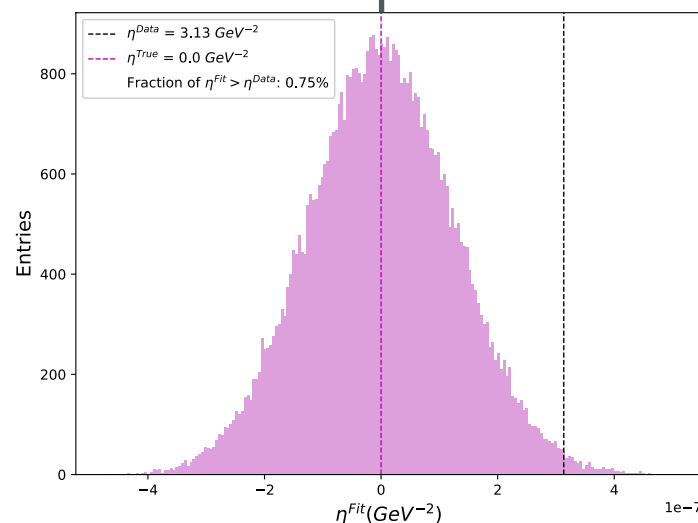
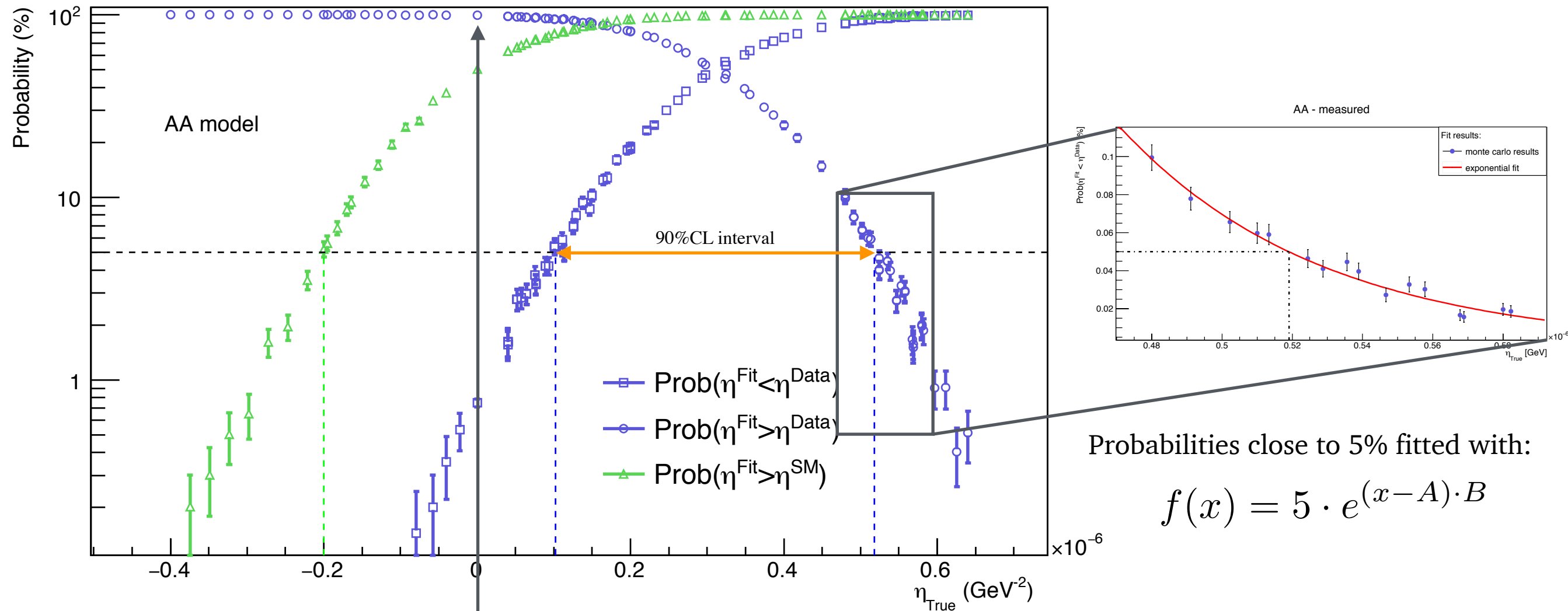
Next each Monte Carlo replica is fitted for the η^{Fit} parameter **simultaneously** with PDFs.

Lastly the fraction of η^{Fit} values less than η^{Data} obtained from the fit of data is evaluated and used further as $\text{Prob}(\eta^{\text{Fit}} < \eta^{\text{Data}})$.



Limits setting with Monte Carlo replicas

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Procedure is repeated for different η^{True} and central 90% CL coupling interval is evaluated:

$$0.10 \cdot 10^{-6} \text{ GeV}^{-2} < \eta < 0.52 \cdot 10^{-6} \text{ GeV}^{-2}$$

$$\Lambda^+ < 11.1 \text{ TeV}$$

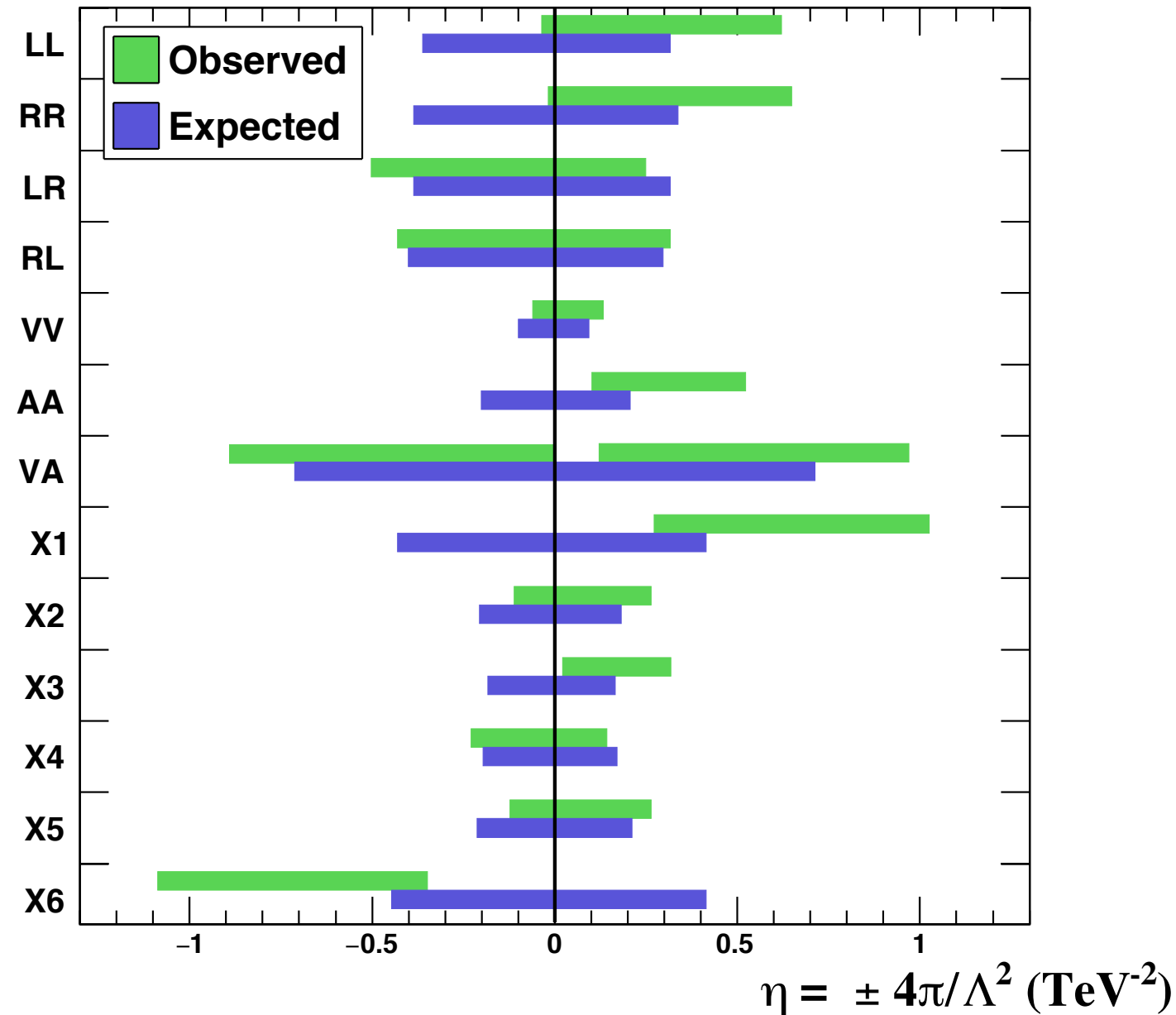
$$\Lambda^+ > 5.0 \text{ TeV}$$

General contact interactions limits

95% C.L. limits (TeV)

	Measured		Expected		ρ_{SM} [%]
	Λ^-	Λ^+	Λ^-	Λ^+	
LL	18.9	4.5	5.9	6.3	7.0
RR	27.2	4.4	5.7	6.1	5.9
LR	5.0	7.1	5.7	6.3	34
RL	5.4	6.3	5.6	6.5	42
VV	14.7	9.7	11.2	11.4	25
AA	-	5.0 - 11.1	7.9	7.8	0.8
VA	3.76	3.6 - 10.2	4.2	4.2	5.8 2.8
X1	-	3.5 - 6.8	5.4	5.5	0.4
X2	10.1	6.9	7.8	8.3	23
X3	24.4	6.3	8.3	8.7	7.3
X4	7.4	9.4	8.0	8.6	39
X5	10.1	6.9	7.7	7.7	26
X6	3.4 - 6.0	-	5.3	5.5	0.3

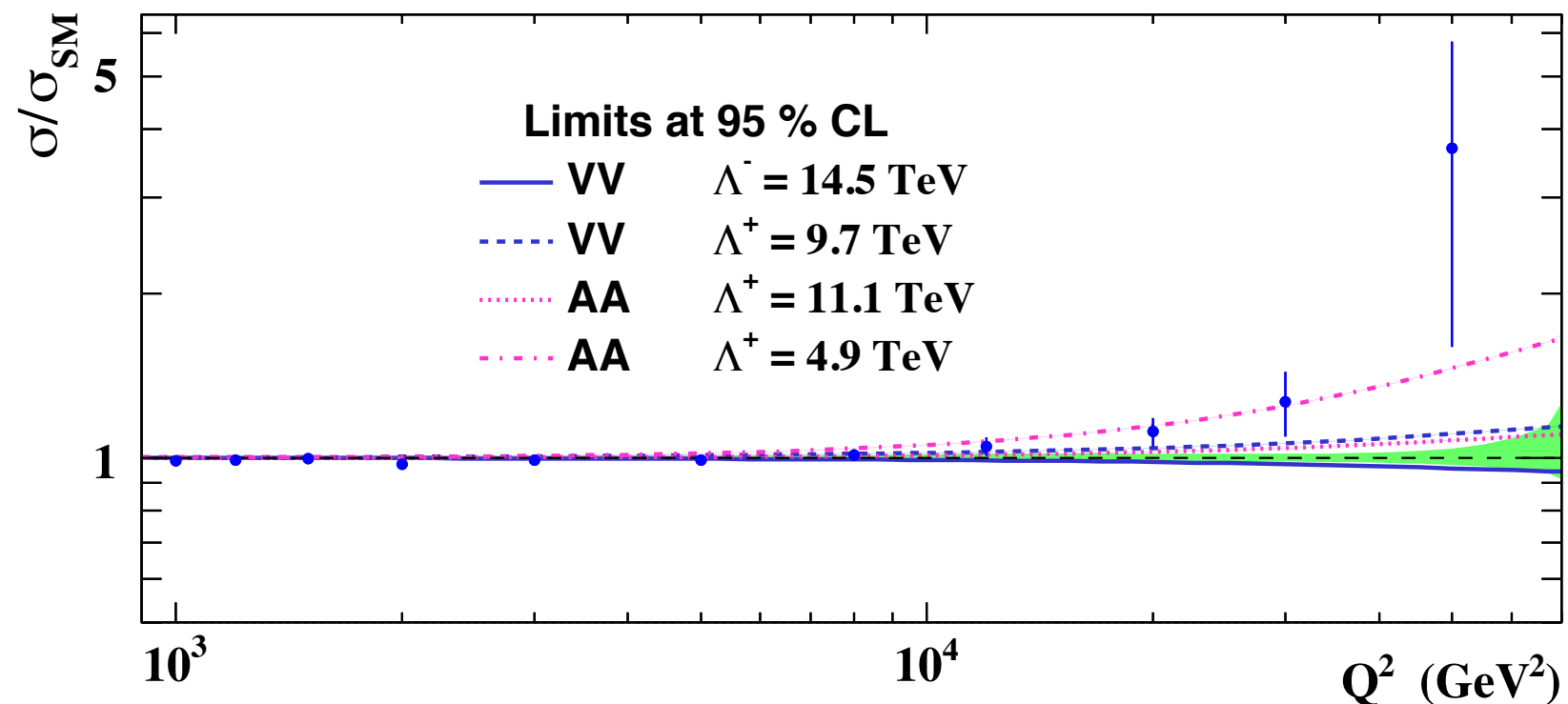
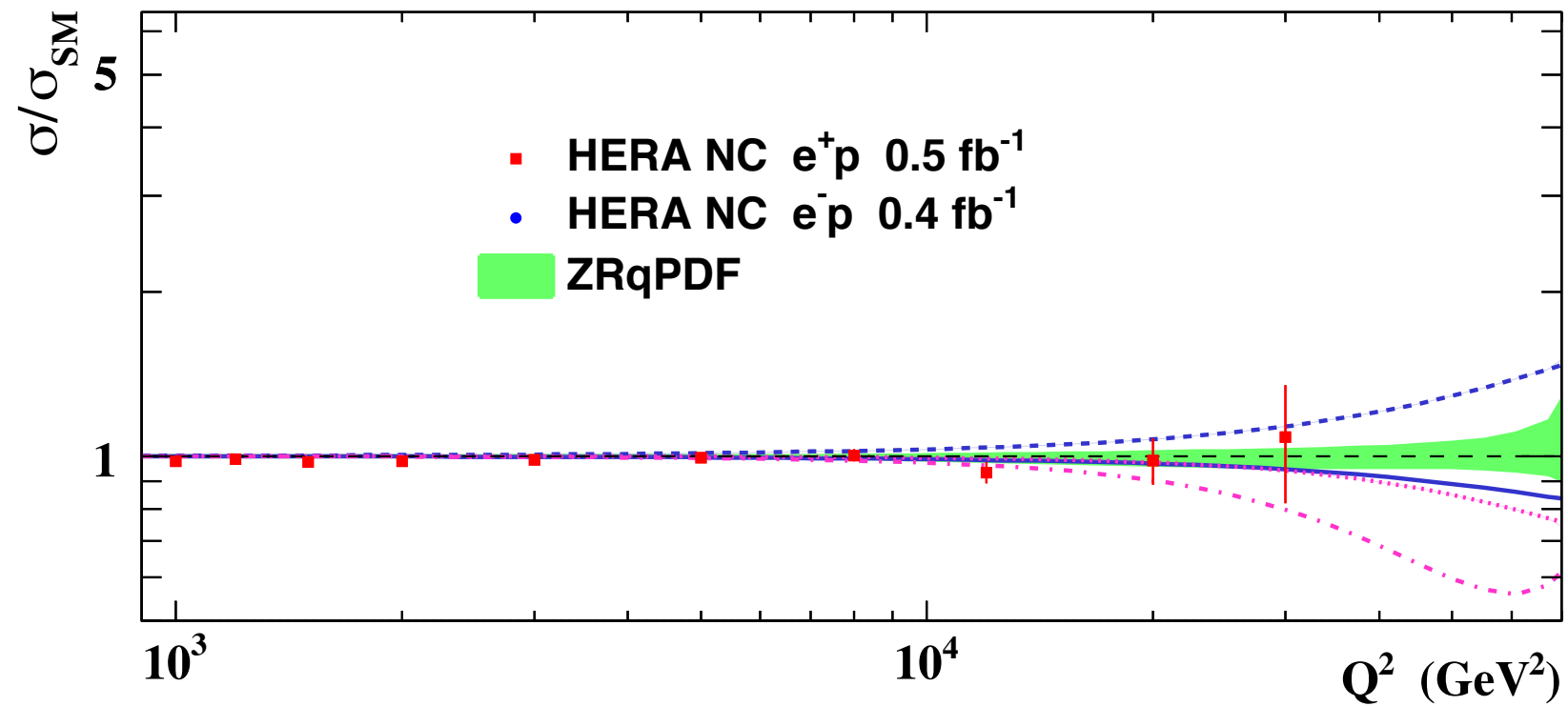
ZEUS Preliminary HERA $e^\pm p$ 1994-2007 95% C.L.



Comparison to Data

Neutral Current:

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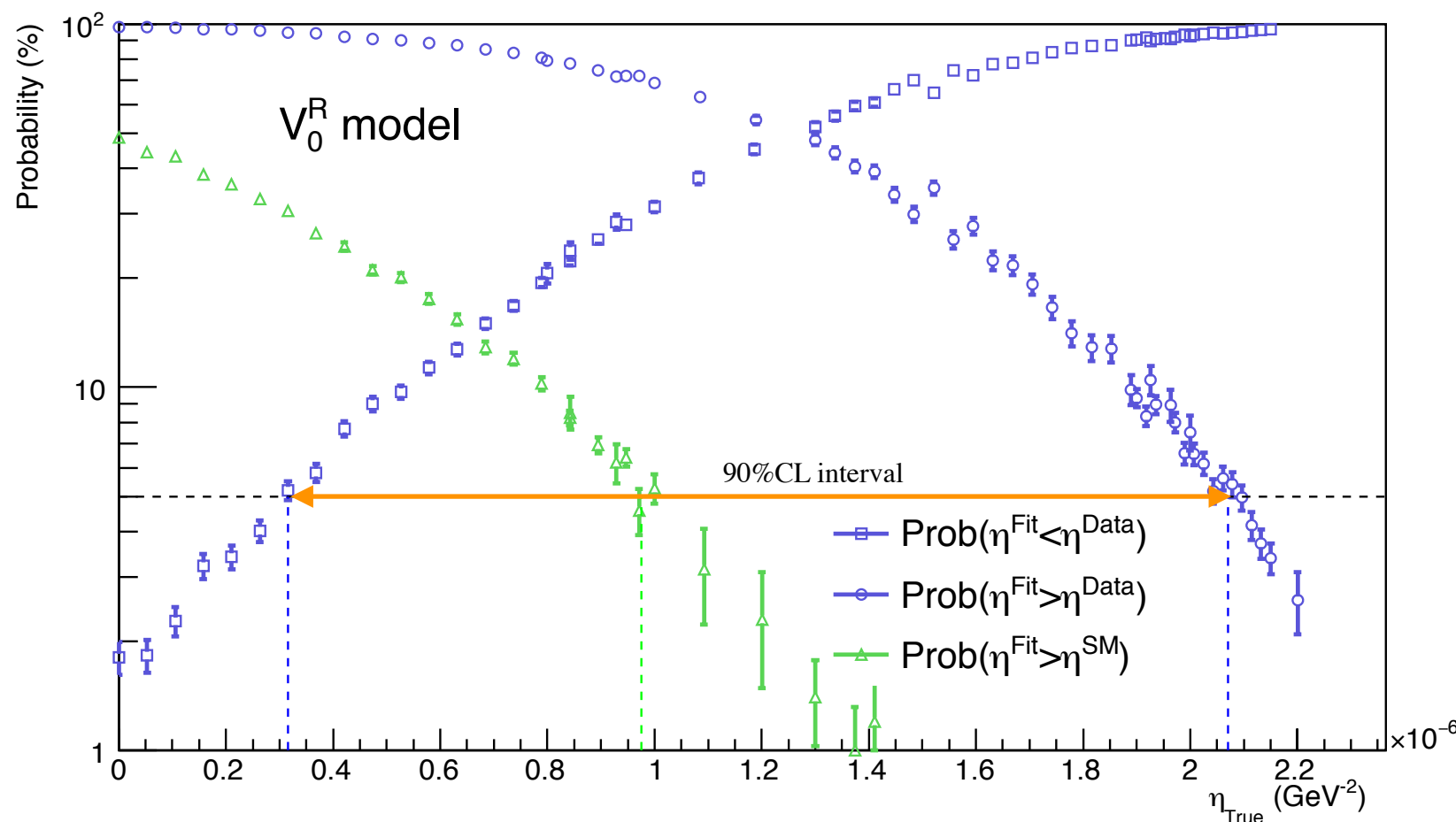
Heavy leptoquarks

In the limit of heavy leptoquarks ($M_{LQ} \gg \sqrt{s}$), the effect of s - and t -channel LQ exchange is equivalent to a vector-type $eeqq$ contact interaction with the coupling of:

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

Analysis performed similarly to the general CI:

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LQ species:

Model	Coupling Structure
S_o^L	$a_{LL}^{eu} = +\frac{1}{2}$
S_o^R	$a_{RR}^{eu} = +\frac{1}{2}$
$\tilde{S}_o^R$	$a_{RR}^{ed} = +\frac{1}{2}$
$S_{\frac{1}{2}}^L$	$a_{LR}^{eu} = -\frac{1}{2}$
$S_{\frac{1}{2}}^R$	$a_{RL}^{ed} = a_{RL}^{eu} = -\frac{1}{2}$
$\tilde{S}_{\frac{1}{2}}^L$	$a_{LR}^{ed} = -\frac{1}{2}$
S_1^L	$a_{LL}^{ed} = +1, a_{LL}^{eu} = +\frac{1}{2}$
V_o^L	$a_{LL}^{ed} = -1$
V_o^R	$a_{RR}^{ed} = -1$
$\tilde{V}_o^R$	$a_{RR}^{eu} = -1$
$V_{\frac{1}{2}}^L$	$a_{LR}^{ed} = +1$
$V_{\frac{1}{2}}^R$	$a_{RL}^{ed} = a_{RL}^{eu} = +1$
$\tilde{V}_{\frac{1}{2}}^L$	$a_{LR}^{eu} = +1$
V_1^L	$a_{LL}^{ed} = -1, a_{LL}^{eu} = -2$

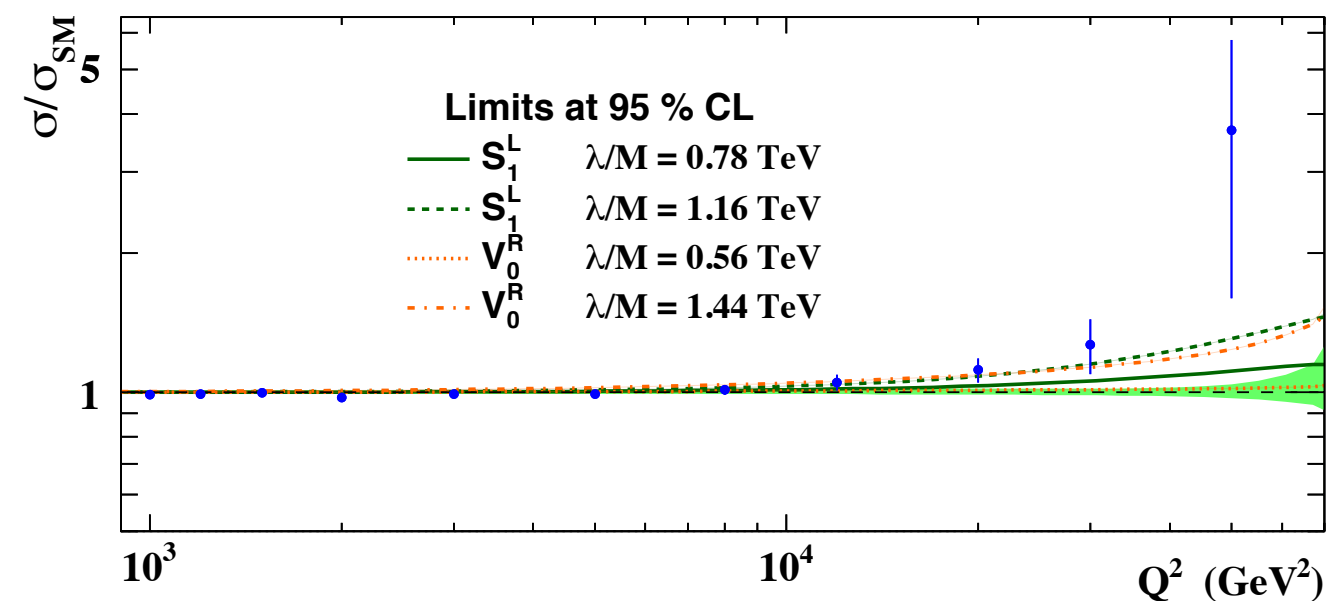
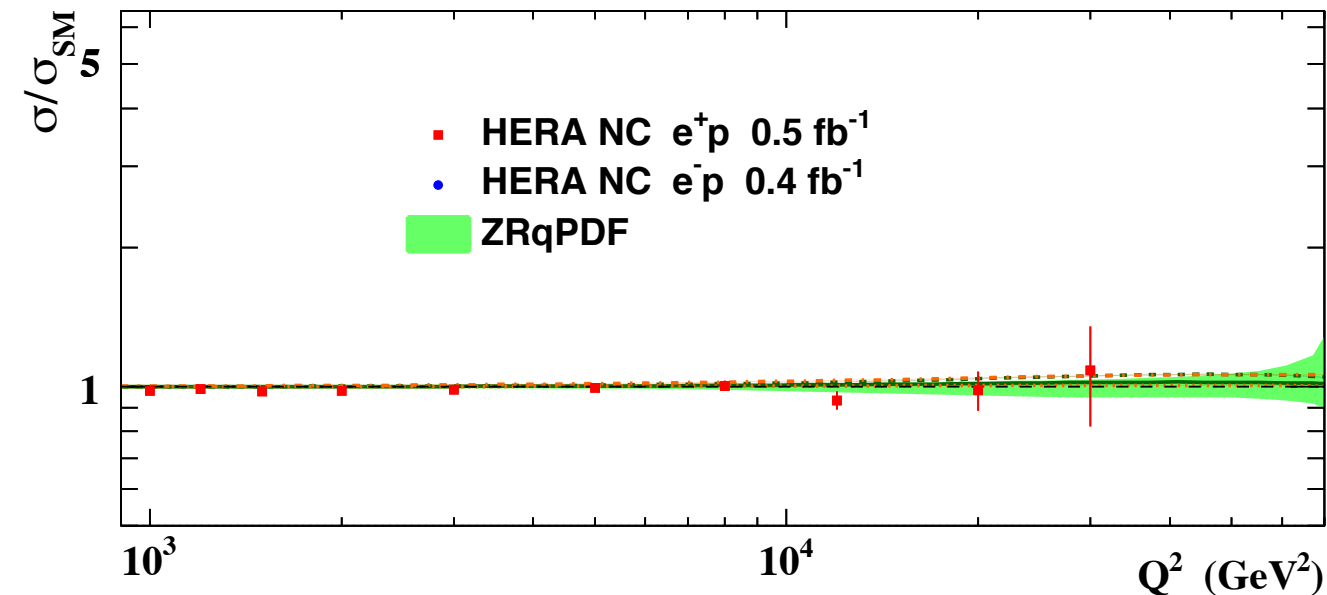
Heavy leptoquarks limits

	95% C.L. limits		
	$\lambda_{\text{LQ}} / M_{\text{LQ}} \text{ (TeV}^{-1}\text{)}$		ρ_{SM}
Model	Measured	Expected	[%]
S_o^L	0.27	0.56	8.4
S_o^R	1.02	0.72	5.9
$\tilde{S}_o^R$	-	1.71	1.8
$S_{\frac{1}{2}}^L$	0.8	0.76	42
$S_{\frac{1}{2}}^R$	0.99	0.92	37
$\tilde{S}_{\frac{1}{2}}^L$	1.51	1.39	41
S_1^L	0.78 - 1.16	0.62	<0.01
V_o^L	-	0.44	0.4
V_o^R	0.56 - 1.44	0.99	1.8
$\tilde{V}_o^R$	0.16	0.53	6.3
$V_{\frac{1}{2}}^L$	1.11	1.29	38
$V_{\frac{1}{2}}^R$	0.53	0.57	39
$\tilde{V}_{\frac{1}{2}}^L$	0.47	0.49	42
V_1^L	0.39	0.35	31

Comparison to Data

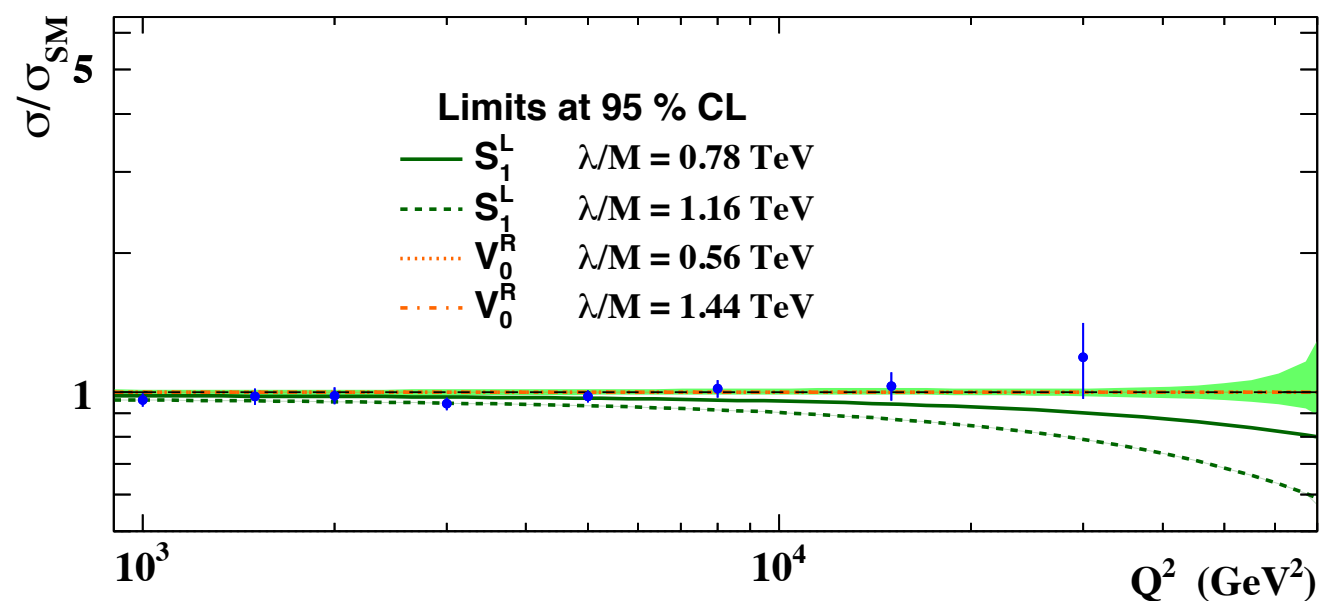
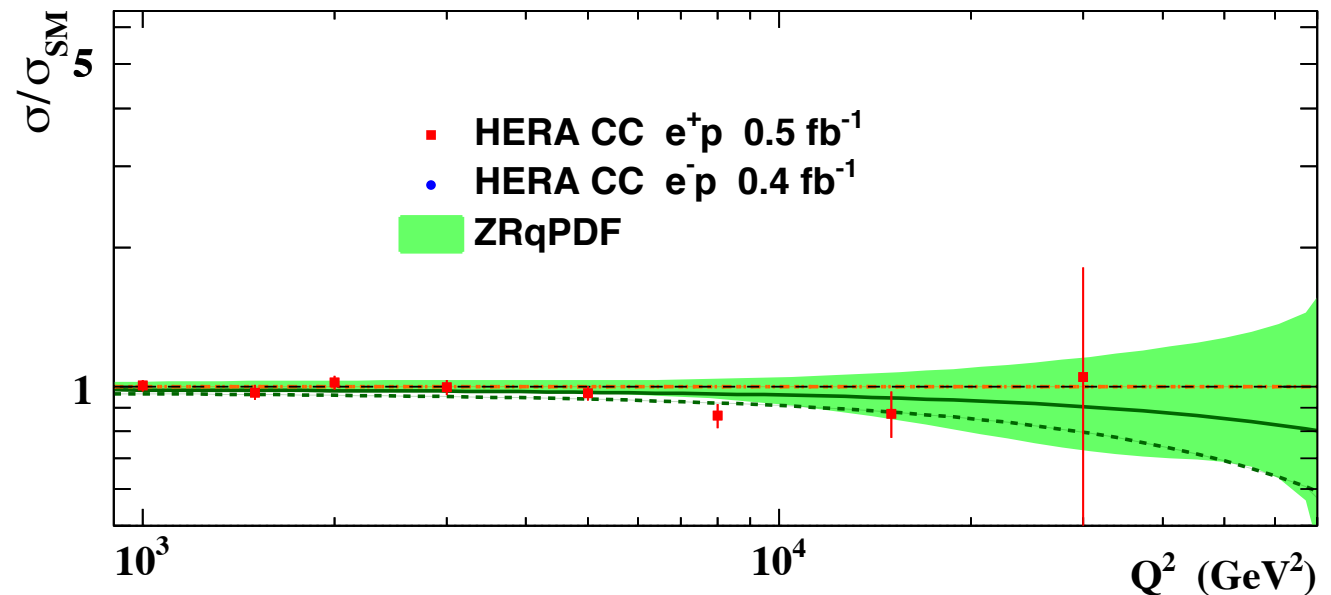
Neutral Current:

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Charged Current:

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1D fits: deviation from SM

The χ^2 values obtained in the CI+PDF fits:

Model	η^{Data} (TeV ⁻²)	p_{SM} (%)	χ^2
SM	0	50	1363.9
LL	0.30	6.6	1361.9
RR	0.33	5.5	1361.7
LR	-0.09	34	1363.7
RL	-0.05	41	1363.8
VV	0.04	26	1363.5
AA	0.33	0.6	1359.2
VA	0.67	2.8	1360.7
X1	0.68	0.4	1358.4
X2	0.08	24	1363.4
X3	0.15	6.7	1361.9
X4	-0.03	38	1363.8
X5	0.07	27	1363.5
X6	-0.79	0.3	1357.9

Model	η^{Data} (TeV ⁻²)	p_{SM} (%)	χ^2
S_o^L	-0.27	8.4	1362.2
S_o^R	0.52	5.9	1361.5
$\tilde{S}_o^R$	-2.51	1.8	1360.1
$S_{\frac{1}{2}}^L$	0.06	42	1363.8
$S_{\frac{1}{2}}^R$	0.13	37	1363.8
$\tilde{S}_{\frac{1}{2}}^L$	0.42	41	1363.8
S_1^L	0.97	< 0.01	1352.5
V_o^L	-0.33	0.4	1357.6
V_o^R	1.26	1.8	1360.1
$\tilde{V}_o^R$	-0.26	6.3	1361.5
$V_{\frac{1}{2}}^L$	-0.21	38	1363.8
$V_{\frac{1}{2}}^R$	-0.07	39	1363.8
$\tilde{V}_{\frac{1}{2}}^L$	-0.03	42	1363.8
V_1^L	0.03	31	1363.7

Outlook

- Check the effects of possible fit parameters variations.
- Extend the study with the simultaneous fits of 2 / 4 / 8 contact-interaction couplings.

SM PDFs fit χ^2 value: 1363.9

8 couplings + PDFs fit χ^2 value: 1325.0

Coupling	Value (TeV ⁻²)	Unc.
$\eta^{\text{eu}}_{\text{RR}}$	0.22	1.18
$\eta^{\text{eu}}_{\text{LR}}$	-1.17	0.62
$\eta^{\text{eu}}_{\text{RL}}$	-0.66	0.67
$\eta^{\text{eu}}_{\text{LL}}$	-1.85	1.06
$\eta^{\text{ed}}_{\text{RR}}$	-4.94	1.68
$\eta^{\text{ed}}_{\text{LR}}$	-1.24	1.29
$\eta^{\text{ed}}_{\text{RL}}$	-1.28	1.58
$\eta^{\text{ed}}_{\text{LL}}$	-1.41	1.06

	$\eta^{\text{ed}}_{\text{LL}}$	$\eta^{\text{ed}}_{\text{RL}}$	$\eta^{\text{ed}}_{\text{LR}}$	$\eta^{\text{ed}}_{\text{RR}}$	$\eta^{\text{eu}}_{\text{LL}}$	$\eta^{\text{eu}}_{\text{RL}}$	$\eta^{\text{eu}}_{\text{LR}}$
$\eta^{\text{eu}}_{\text{RR}}$	-0.75	-0.06	-0.14	0.92	-0.77	-0.10	-0.10
$\eta^{\text{eu}}_{\text{LR}}$	-0.07	0.10	0.33	-0.14	-0.07	-0.58	
$\eta^{\text{eu}}_{\text{RL}}$	-0.06	0.16	0.24	-0.13	-0.06		
$\eta^{\text{eu}}_{\text{LL}}$	0.99	0.03	-0.07	-0.53			
$\eta^{\text{ed}}_{\text{RR}}$	-0.52	-0.09	-0.28				
$\eta^{\text{ed}}_{\text{LR}}$	-0.06	-0.31					
$\eta^{\text{ed}}_{\text{RL}}$	0.03						

4 CI parameters fit

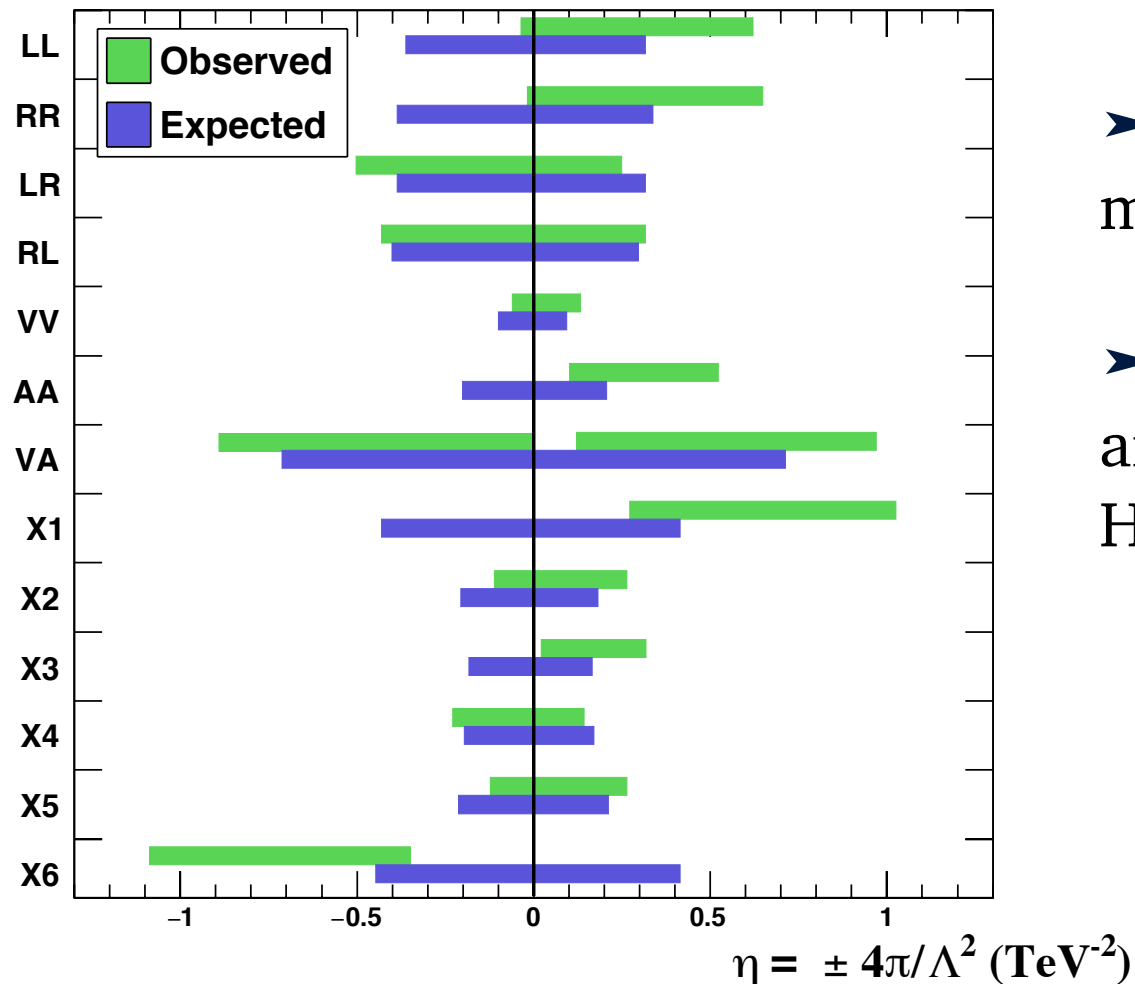
SM PDFs fit χ^2 value: 1363.9

4 CI parameters + PDFs fit χ^2 value: 1325.0

Couplings	Value (TeV ⁻²)	Unc.				
$\eta^{\text{eu}}_{\text{RR}} + \eta^{\text{ed}}_{\text{RR}}$	-3.00	1.49		$\eta^{\text{eu}}_{\text{LL}} - \eta^{\text{ed}}_{\text{LL}}$	$\eta^{\text{eu}}_{\text{LL}} + \eta^{\text{ed}}_{\text{LL}}$	$\eta^{\text{eu}}_{\text{RR}} - \eta^{\text{ed}}_{\text{RR}}$
$\eta^{\text{eu}}_{\text{RR}} - \eta^{\text{ed}}_{\text{RR}}$	2.48	0.22	$\eta^{\text{eu}}_{\text{RR}} + \eta^{\text{ed}}_{\text{RR}}$	-0.003	-0.88	-0.41
$\eta^{\text{eu}}_{\text{LL}} + \eta^{\text{ed}}_{\text{LL}}$	-2.22	1.32	$\eta^{\text{eu}}_{\text{RR}} - \eta^{\text{ed}}_{\text{RR}}$	-0.07	0.02	
$\eta^{\text{eu}}_{\text{LL}} - \eta^{\text{ed}}_{\text{LL}}$	-0.16	0.06	$\eta^{\text{eu}}_{\text{LL}} + \eta^{\text{ed}}_{\text{LL}}$	0.01		

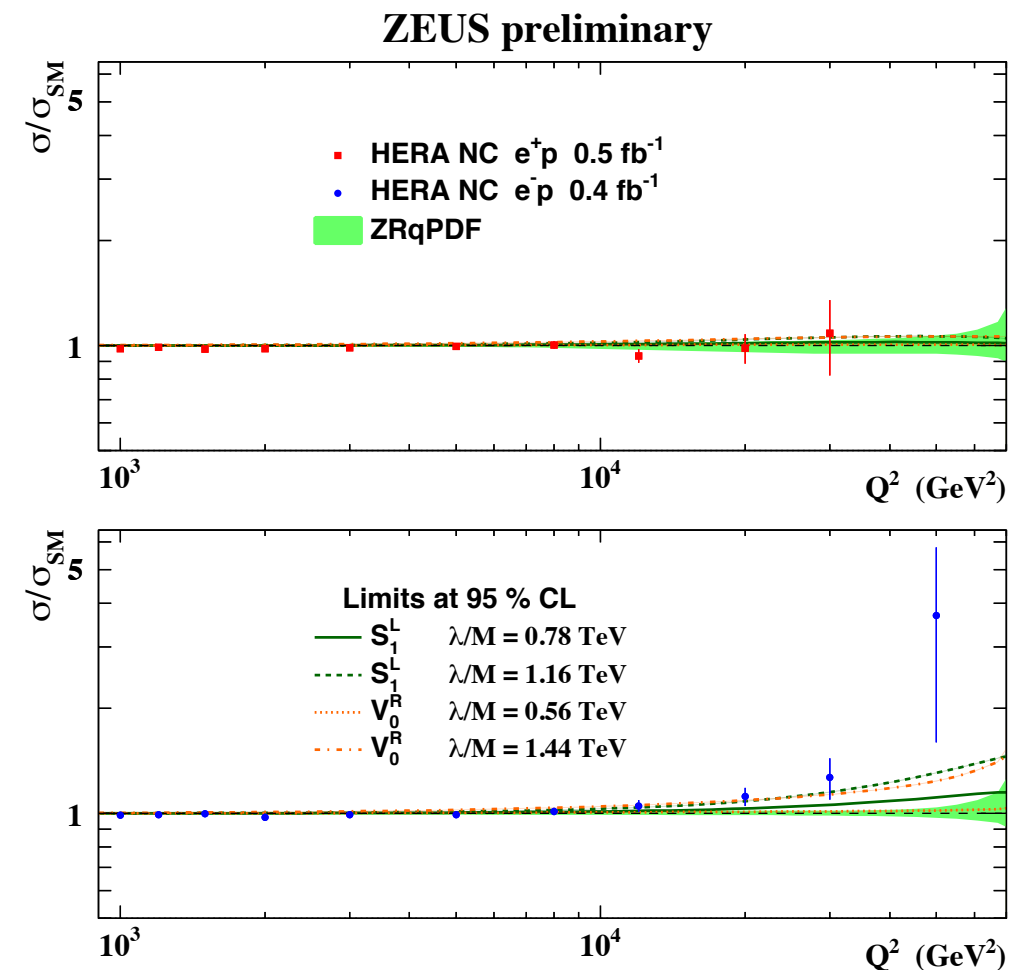
Summary

ZEUS Preliminary
HERA $e^\pm p$ 1994-2007 95% C.L.



- Combined HERA inclusive DIS cross-section measurements allow BSM searches up to TeV scales.
- New method - simultaneous fit of PDF parameters and BSM contribution deployed for BSM analysis of HERA data

- Some of the general contact interactions and heavy leptoquarks models provide significantly improved description of the data.
- Analysis is ongoing to understand the nature of the effect.



Backup

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