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

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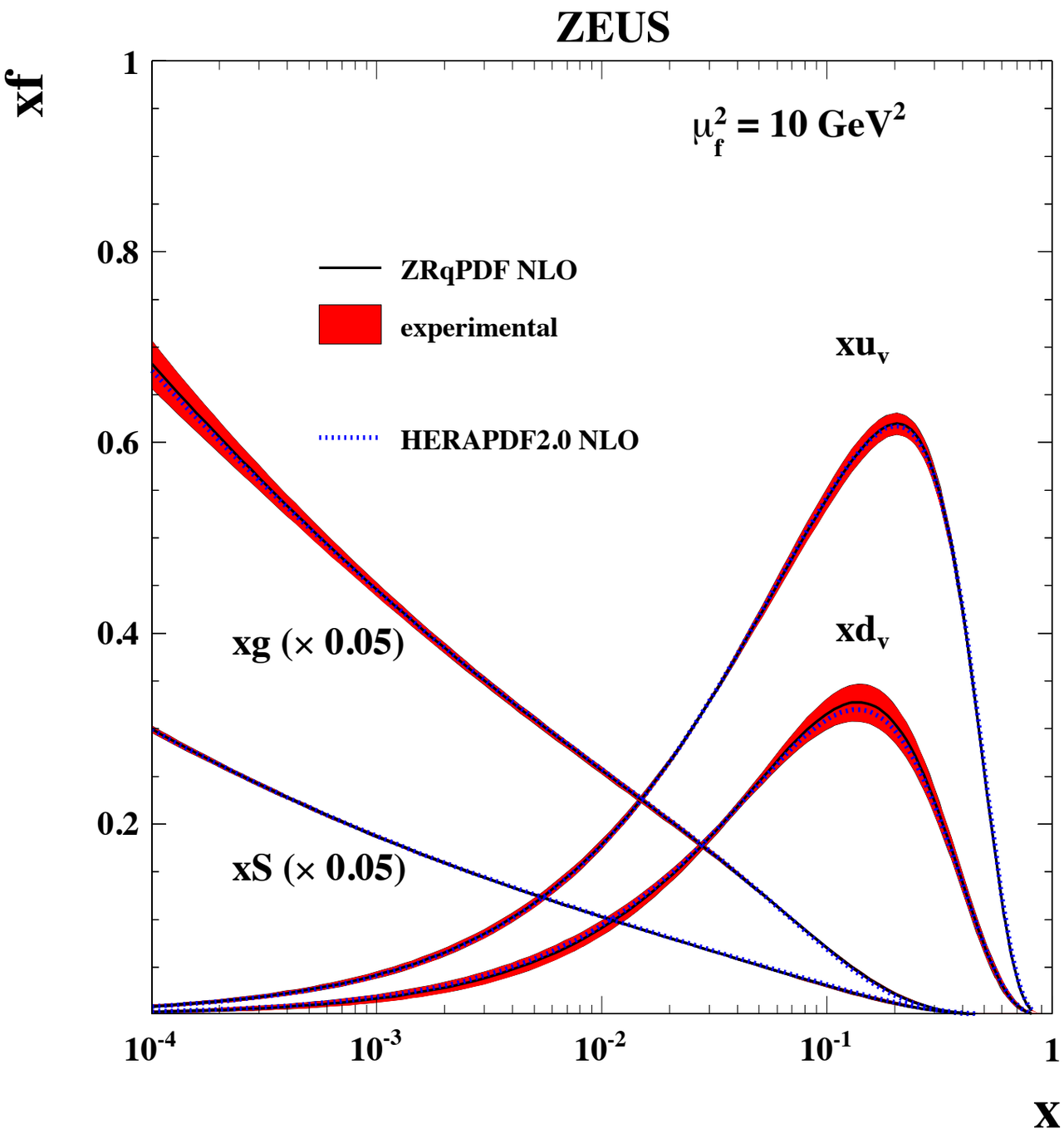
QCD analysis of the combined DIS data



Parton **D**ensity **F**unctions
Parameterised at the starting scale of $Q^2_0 = 1.9$ GeV^2:

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

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

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

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

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

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.

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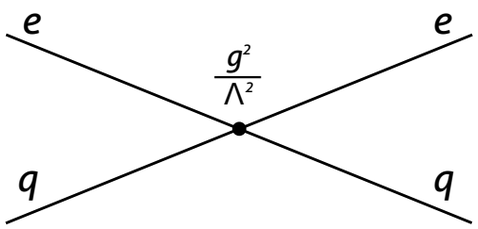
General contact interactions

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:

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



$$\eta^{eq}_{kj} = \epsilon^{eq}_{kj} \frac{g^2}{\Lambda^2}$$

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

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

$$\eta^{eu}_{kj} = \eta^{ec}_{kj} = \eta^{et}_{kt}$$

$$\eta^{ed}_{kj} = \eta^{es}_{kj} = \eta^{eb}_{kt}$$

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

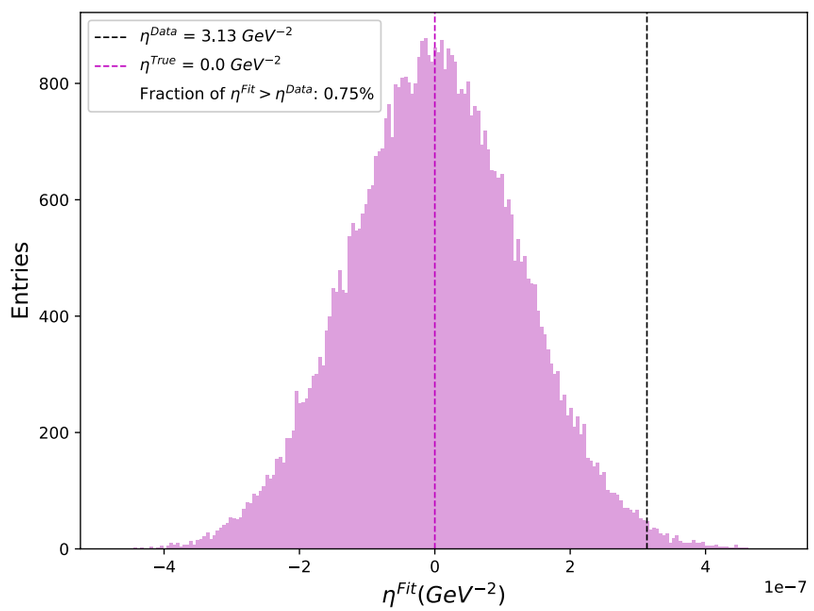
$$\mu^i = \left[m_0^i + \sqrt{\delta_{i,stat}^2 + \delta_{i,uncor}^2} \cdot \mu_0^i \cdot r_i\right] \cdot \left(1 + \sum_j \gamma_j^i \cdot r_j\right)$$

Relative statistical and uncorrelated systematic uncertainties

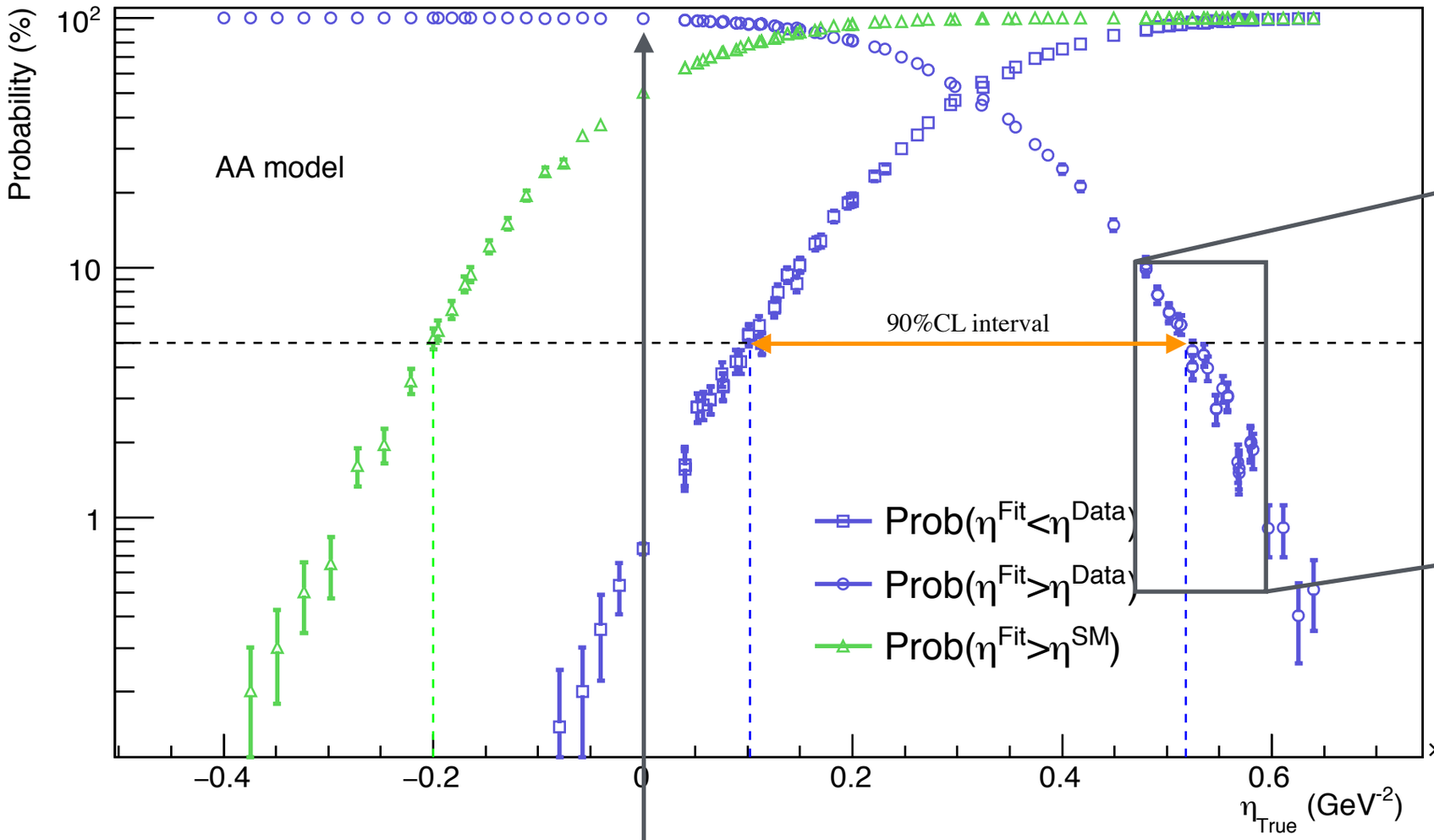
Random numbers from a normal distribution

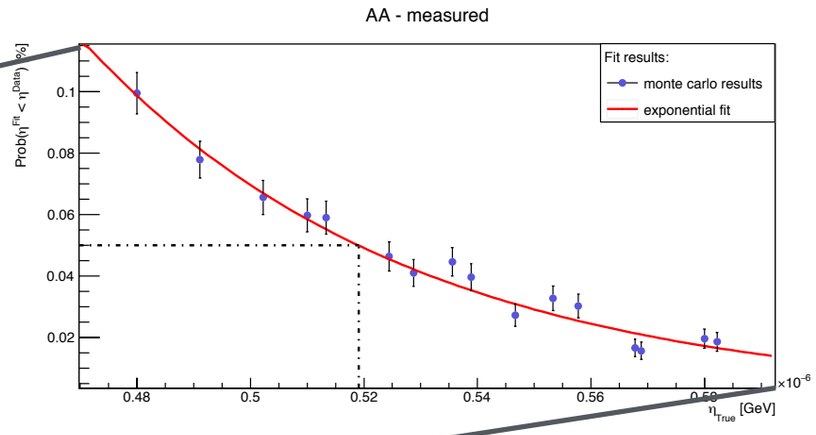
Next each Monte Carlo replica is fitted for the η^{Fit} parameter **simultaneously** with PDFs.

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



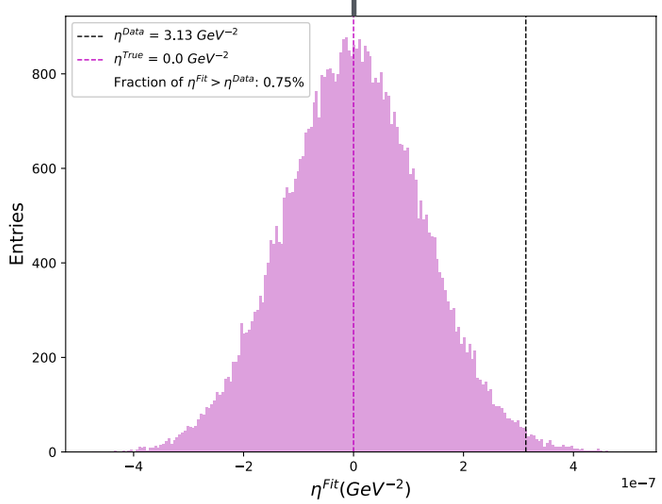
Limits setting with Monte Carlo replicas





Probabilities close to 5% fitted with:

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



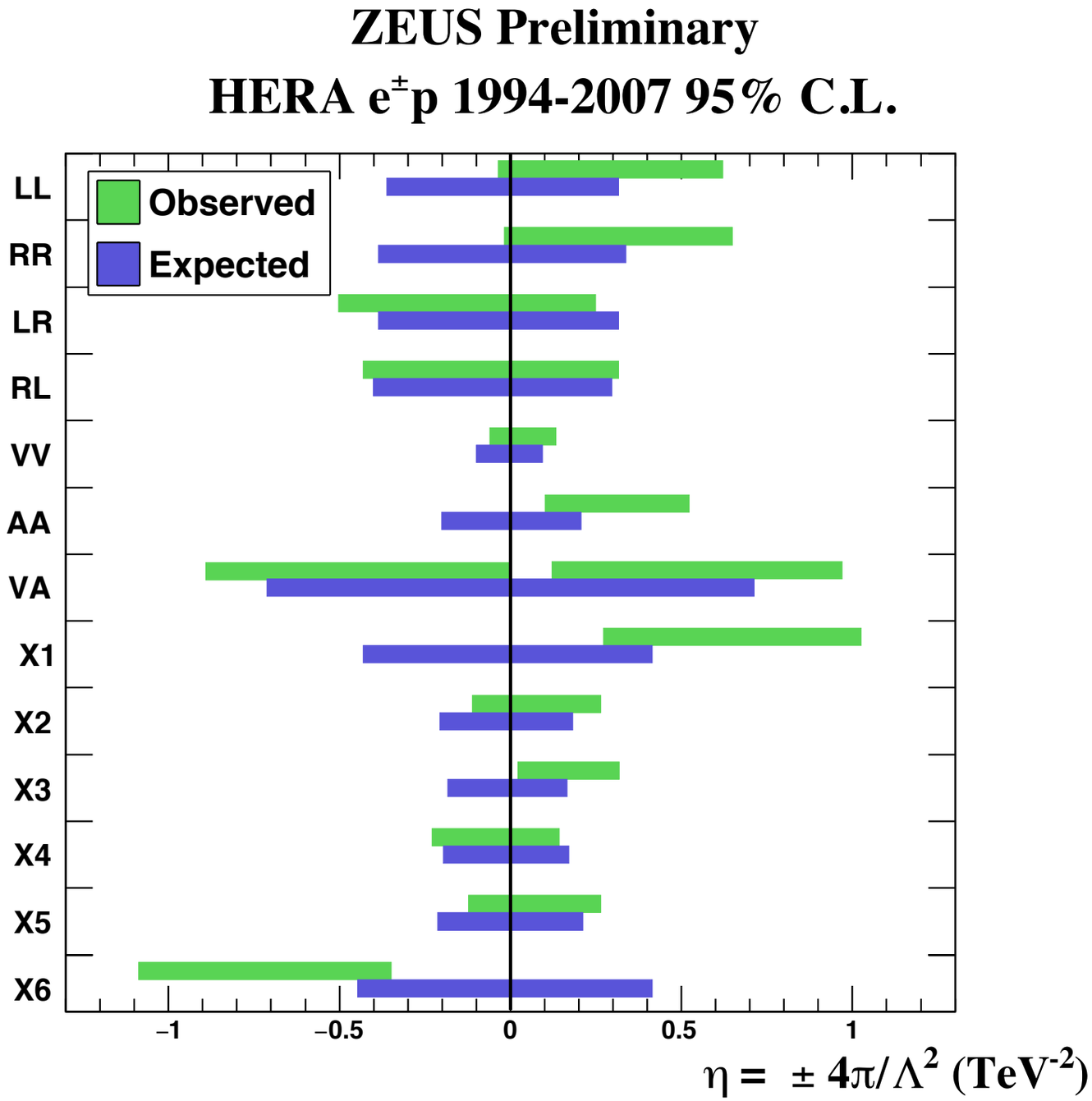
Procedure is repeated for different η^{True} and central 90% CL coupling interval is evaluated:

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

$\Lambda^+ < 11.1$ TeV $\Lambda^+ > 5.0$ TeV

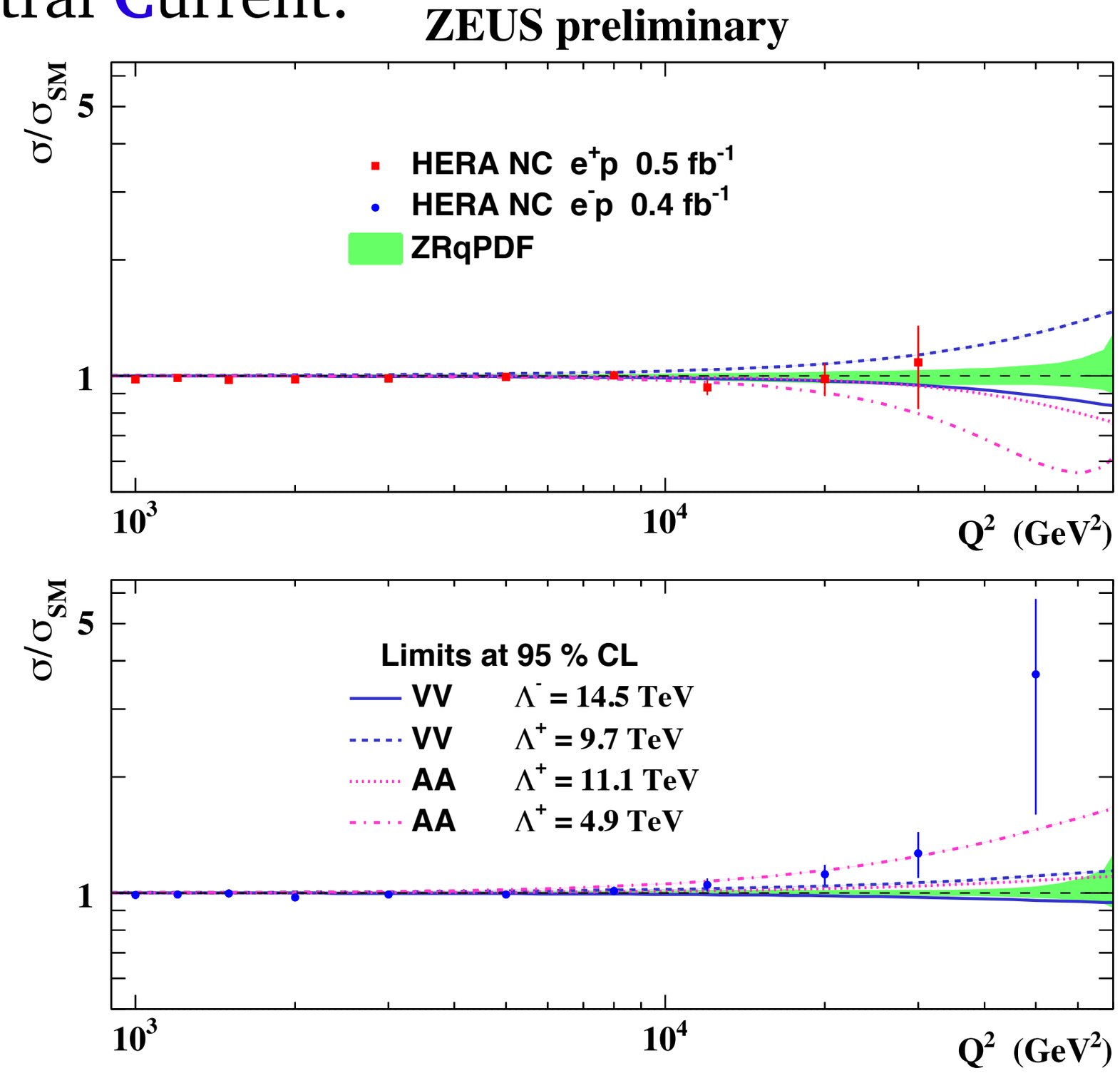
General contact interactions limits

	95% C.L. limits (TeV)				
	Measured		Expected		p_{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



Comparison to Data

Neutral Current:

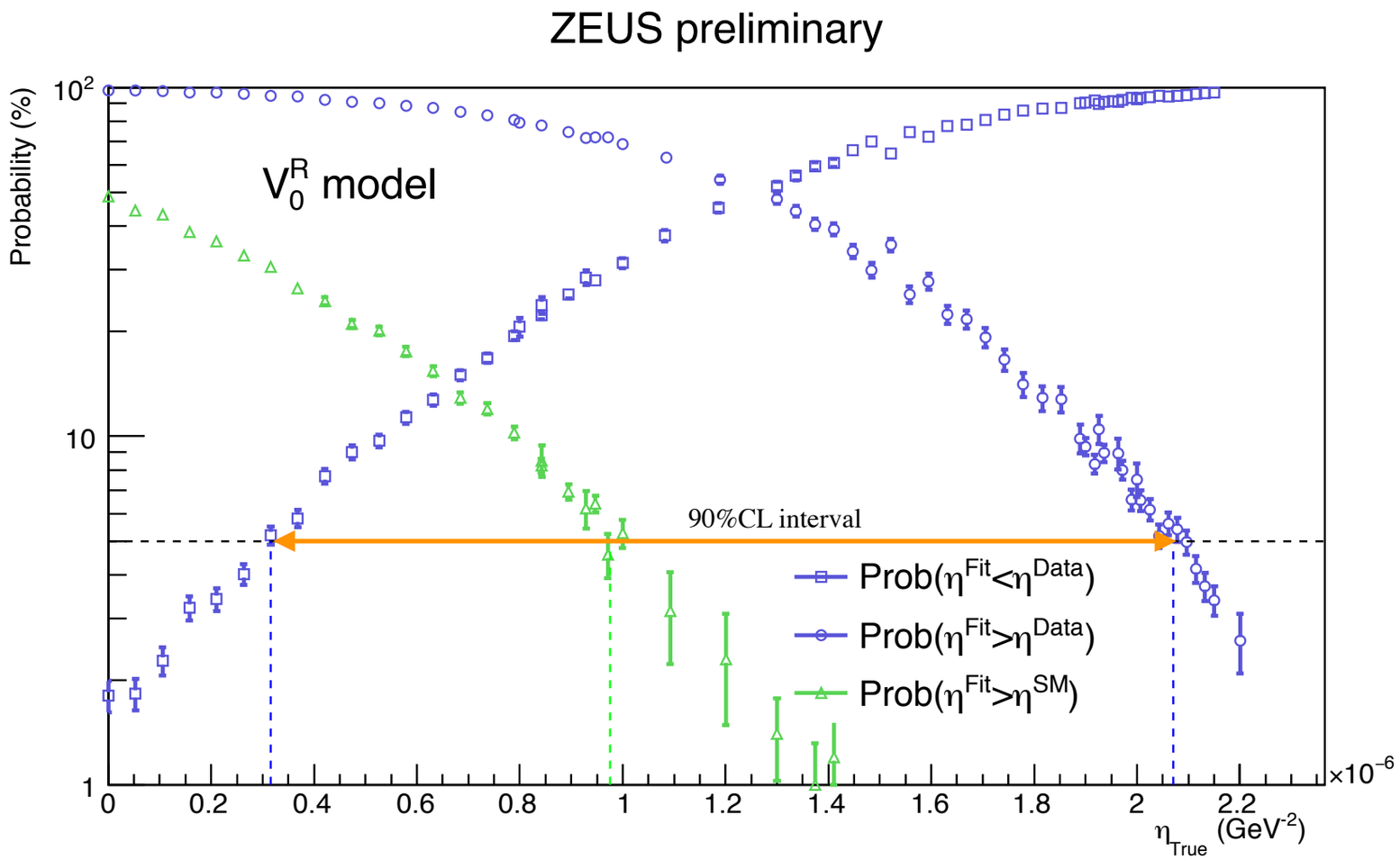


Heavy leptoquarks

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:



LQ species:

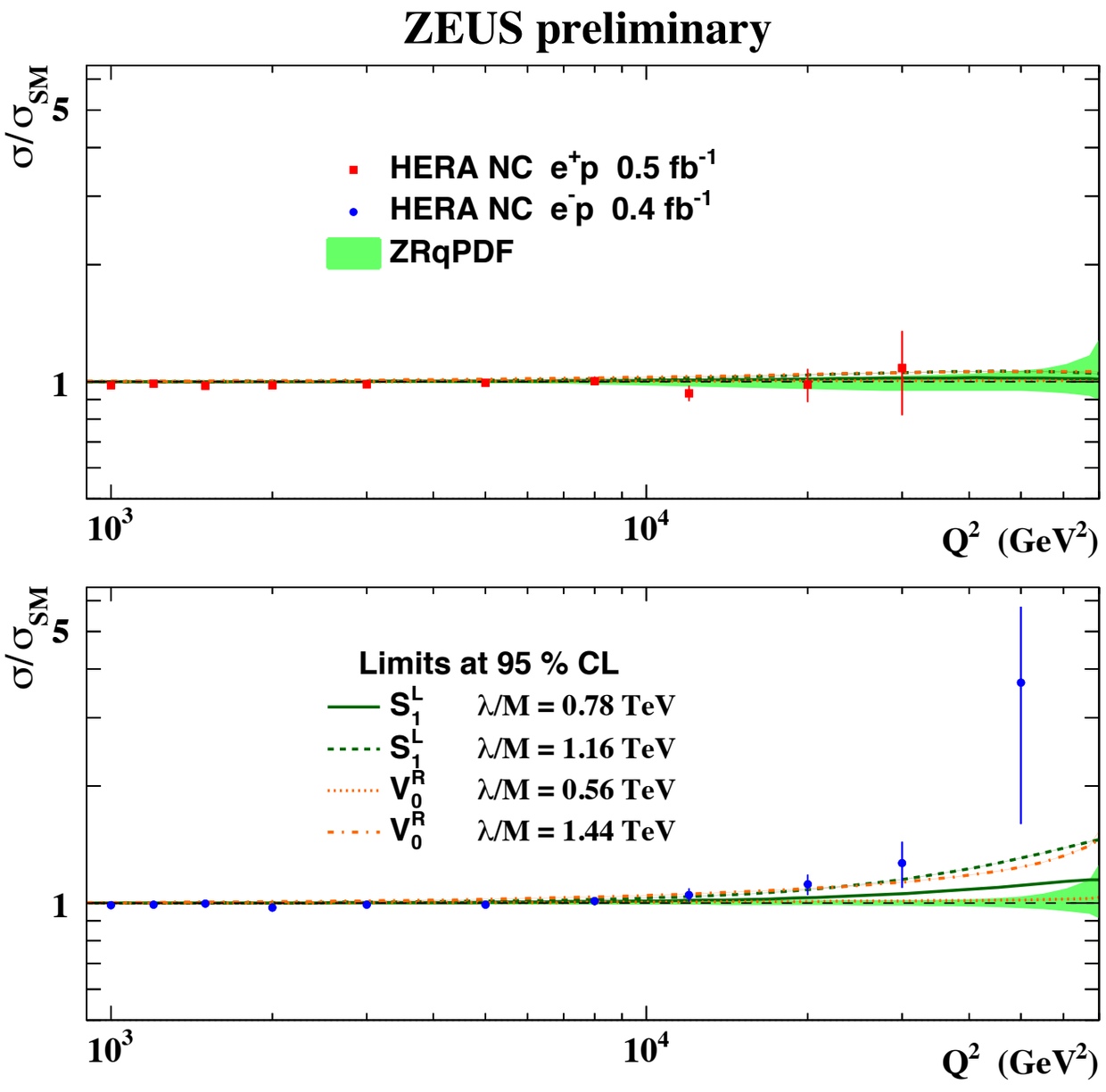
Model	Coupling Structure
S_o^L	$a_{LL}^{eu} = +\frac{1}{2}$
S_o^R	$a_{RR}^{eu} = +\frac{1}{2}$
$\widetilde{S}_o^R$	$a_{RR}^{ed} = +\frac{1}{2}$
$S_{\frac{1}{2}}^L$	$a_{LR}^{eu} = -\frac{1}{2}$
$S_{\frac{1}{2}}^R$	$a_{RL}^{ed} = a_{RL}^{eu} = -\frac{1}{2}$
$\widetilde{S}_{\frac{1}{2}}^L$	$a_{LR}^{ed}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

Heavy leptoquarks limits

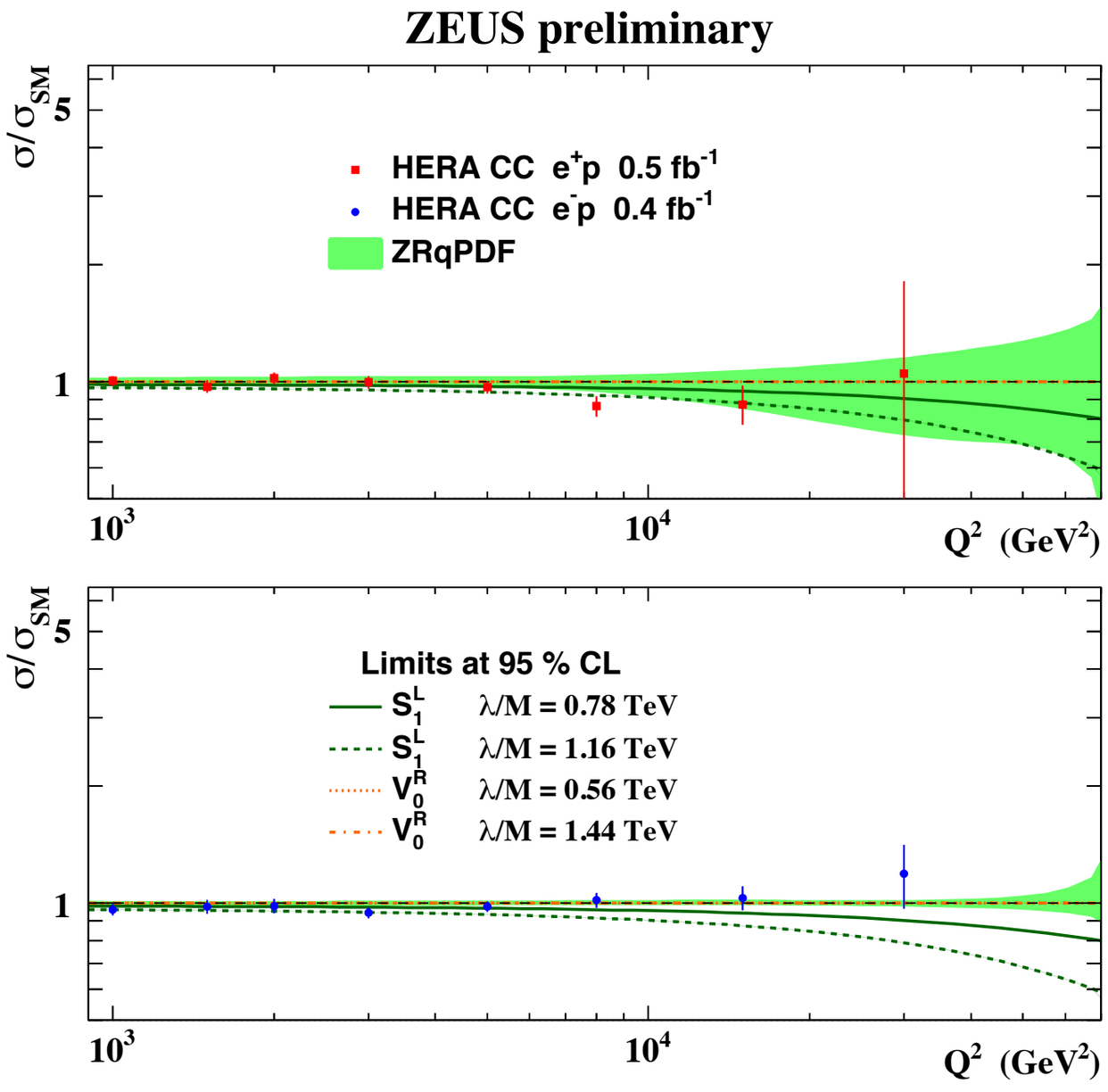
	95% C.L. limits		
	λ_{LQ} / M_{LQ} (TeV^{-1})		p_{SM} [%]
Model	Measured	Expected	
S_o^L	0.27	0.56	8.4
S_o^R	1.02	0.72	5.9
$\widetilde{S}_o^R$	-	1.71	1.8
$S_{\frac{1}{2}}^L$	0.8	0.76	42
$S_{\frac{1}{2}}^R$	0.99	0.92	37
$\widetilde{S}_{\frac{1}{2}}^L$	1.51	1.39	41
S_1^L	0.78 - 1.16	0.62	<0.01
V_o^L	-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

Comparison to Data

Neutral Current:



Charged Current:



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
$\widetilde{S}_o^R$	-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
$\widetilde{S}_{\frac{1}{2}}^L$	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
$\widetilde{V}_o^R$	-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
$\widetilde{V}_{\frac{1}{2}}^L$	-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.
η^{eu}_{RR}	0.22	1.18
η^{eu}_{LR}	-1.17	0.62
η^{eu}_{RL}	-0.66	0.67
η^{eu}_{LL}	-1.85	1.06
η^{ed}_{RR}	-4.94	1.68
η^{ed}_{LR}	-1.24	1.29
η^{ed}_{RL}	-1.28	1.58
η^{ed}_{LL}	-1.41	1.06

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

4 CI parameters fit

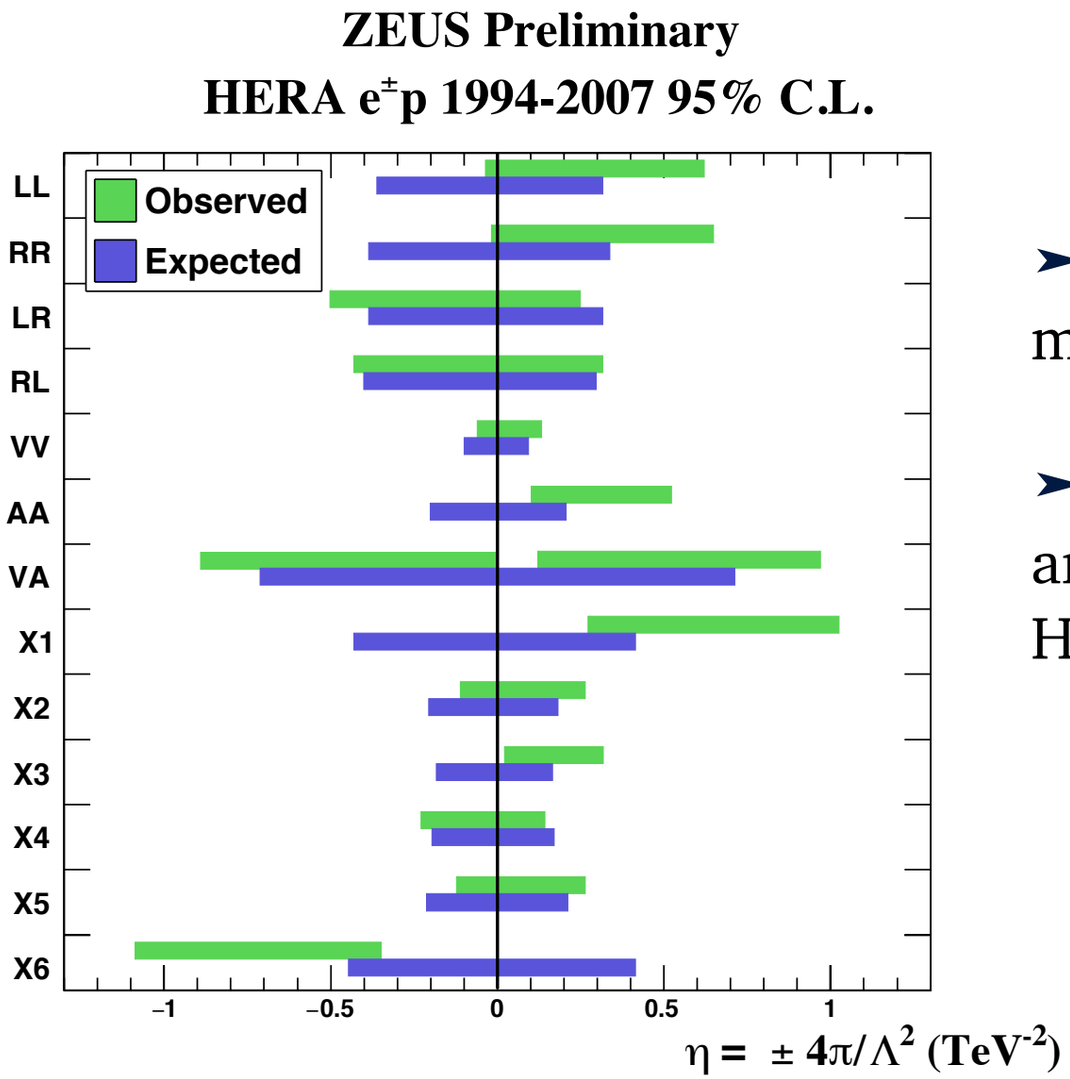
SM PDFs fit χ^2 value: 1363.9

4 CI parameters + PDFs fit χ^2 value: 1335.5

Couplings	Value (TeV^{-2})	Unc.
$\eta^{eu}_{RR} + \eta^{ed}_{RR}$	-3.00	1.49
$\eta^{eu}_{RR} - \eta^{ed}_{RR}$	2.48	0.22
$\eta^{eu}_{LL} + \eta^{ed}_{LL}$	-2.22	1.32
$\eta^{eu}_{LL} - \eta^{ed}_{LL}$	-0.16	0.06

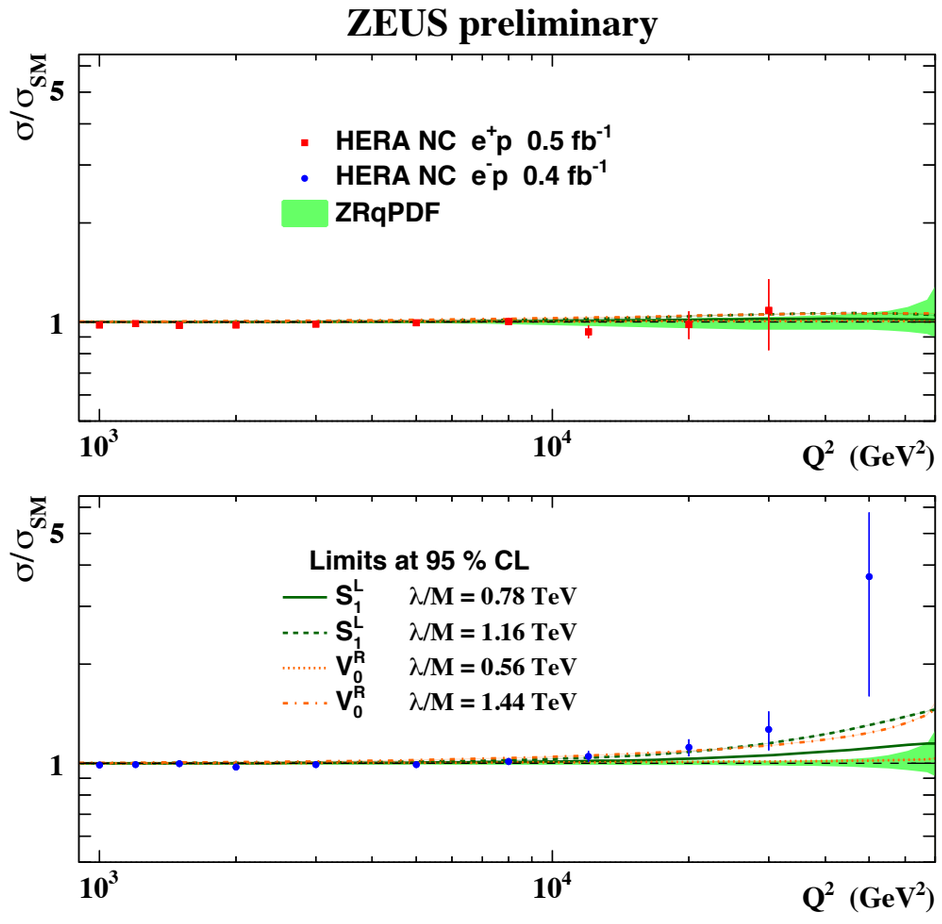
	$\eta^{eu}_{LL} - \eta^{ed}_{LL}$	$\eta^{eu}_{LL} + \eta^{ed}_{LL}$	$\eta^{eu}_{RR} - \eta^{ed}_{RR}$
$\eta^{eu}_{RR} + \eta^{ed}_{RR}$	-0.003	**-0.88**	-0.41
$\eta^{eu}_{RR} - \eta^{ed}_{RR}$	-0.07	0.02	
$\eta^{eu}_{LL} + \eta^{ed}_{LL}$	0.01		

Summary



➤ Combined HERA inclusive DIS cross-section measurements allow BSM searches up to TeV scales.

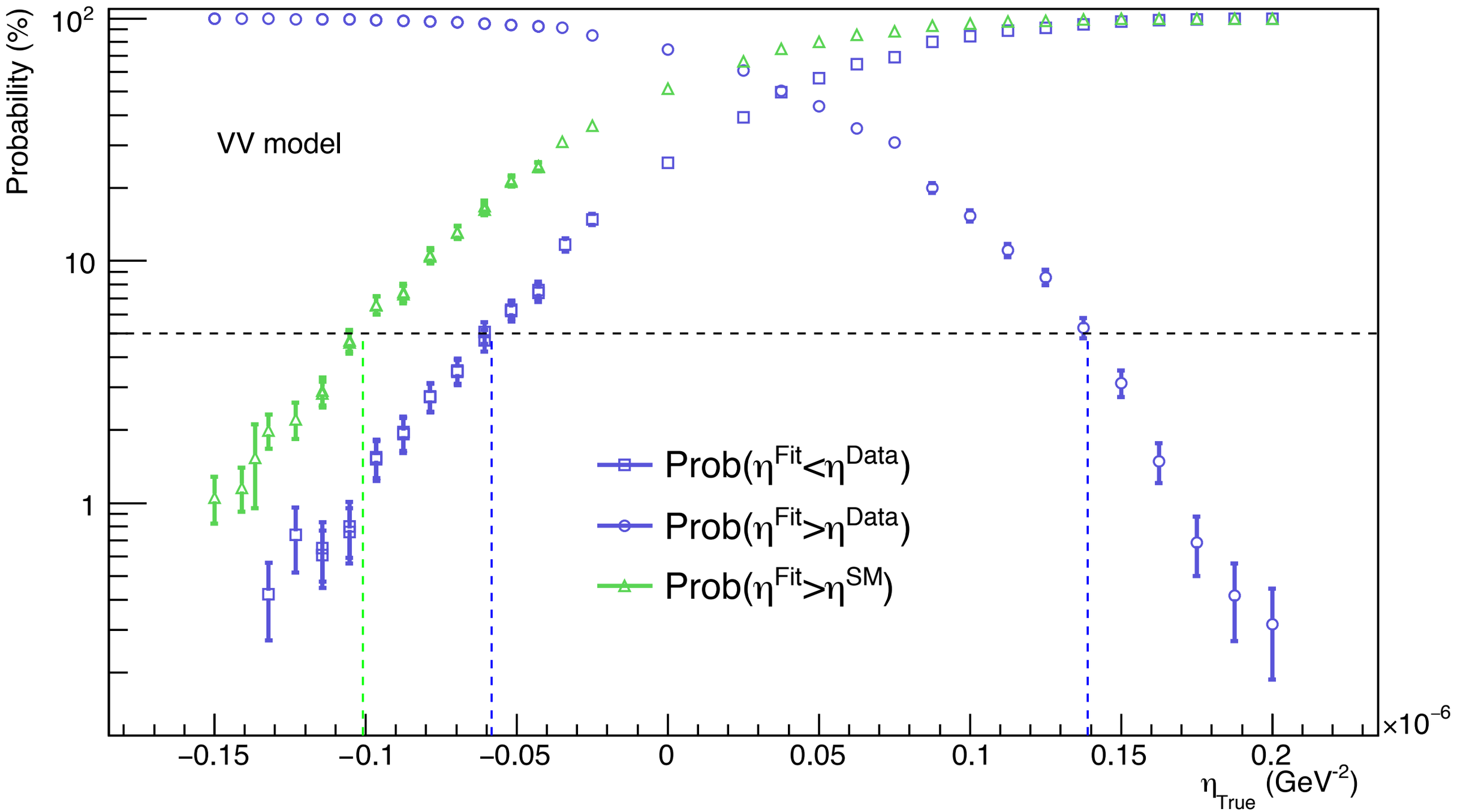
➤ New method - simultaneous fit of PDF parameters and BSM contribution deployed for BSM analysis of HERA data



➤ 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


ZEUS preliminary
Probability (%)
10^2
10
1
VV model
Prob($\eta^{Fit}<\eta^{Data}$)
Prob($\eta^{Fit}>\eta^{Data}$)
Prob($\eta^{Fit}>\eta^{SM}$)
−0.15
−0.1
−0.05
0
0.05
0.1
0.15
0.2
×10⁻⁶
η_{True} (GeV^{-2})