Search for contact interactions in inclusive ep scattering at HERA

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Paper presentation to the collaboration

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Contact interactions (CI)

General approach to describe low-energy effects due to physics at much higher energy scales. Vector contact interactions considered in the analysis correspond to a subset of Effective Field Theory (EFT) dimension-six operators. Described by additional terms to the SM Lagrangian.

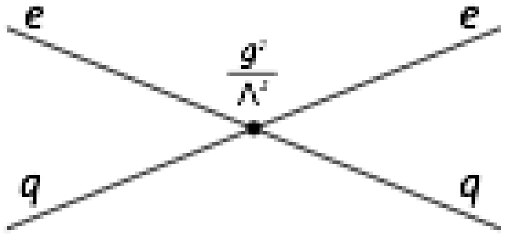
CI Lagrangian:

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

We assume all up- and down-type quarks to have the same contact-interaction couplings.

We consider one-parameter models:

$$\eta_{ij}^{eu} = \eta_{ij}^{ed} = \epsilon_{ij}\, \eta = \epsilon_{ij} \frac{4\pi}{\Lambda^2}$$



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

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

Heavy leptoquarks (LQ)

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

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

We consider 14 leptoquark scenarios from the general classification proposed by Buchmüller, Rückl and Wyler.

Same analysis framework can be used for general CI and heavy leptoquark models.

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	$a_{LL}^{ed} = -1, a_{LL}^{eu} = -2$

Reasons for the dedicated fit procedure

- We want to use combined inclusive HERA data to search/set limits on the possible BSM contributions.

  Precise and unbiased determination of SM predictions is crucial!

- Possible BSM contribution to the ep scattering 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, 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:

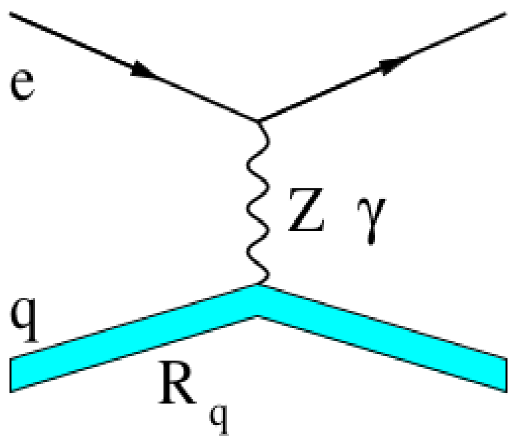
global QCD + BSM analysis

including a possible contribution from BSM processes in the cross section calculation within the PDF fitting procedure

Quark form factor

Simplest CI-like 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.

We assume $R_{e'} \equiv 0$

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

Positive and negative values of R^2_q can be considered.

This was the fist model considered in the **new analysis approach**...

Quark form factor

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

ZEUS Collaboration

New CI/LQ study follows the strategy developed for R_q analysis

Analysis procedure

The QCD analysis follows the approach adopted for the HERAPDF2.0 determination. The PDFs of the proton are described at a starting scale in terms of 14 parameters. In the QCD+CI fit, they are fit to the HERA combined data together with the CI coupling η.

The corresponding χ^2 formula is: same as in the R_q paper

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

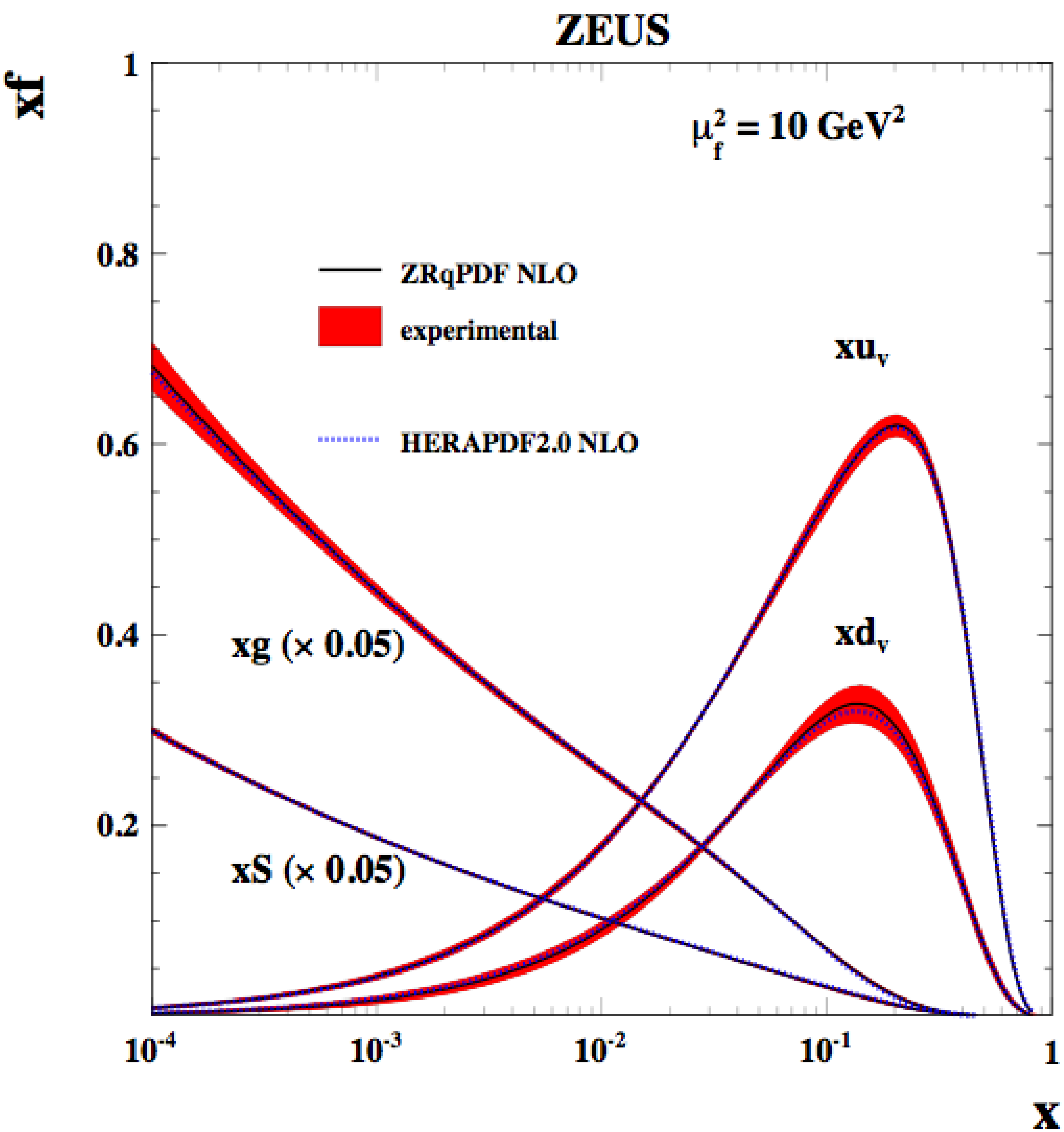
where:

μ^i_0 and m^i are the measured and predicted (SM+BSM) cross sections, ***p*** and ***s*** are vectors of PDF parameters and systematic shifts,

γ^i_j, $\delta^2_{i,stat}$, $\delta^2_{i,uncorr}$ are the relative correlated systematic, relative statistical and relative uncorrelated systematic uncertainties of the input data, respectively.

Denominator of the χ^2 formula differs from the one in HERAPDF2.0 paper...

QCD analysis of the combined DIS data



Obtained PDFs for SM are referred to as **ZCIPDFs** and are in a good agreement with the HERAPDF 2.0

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

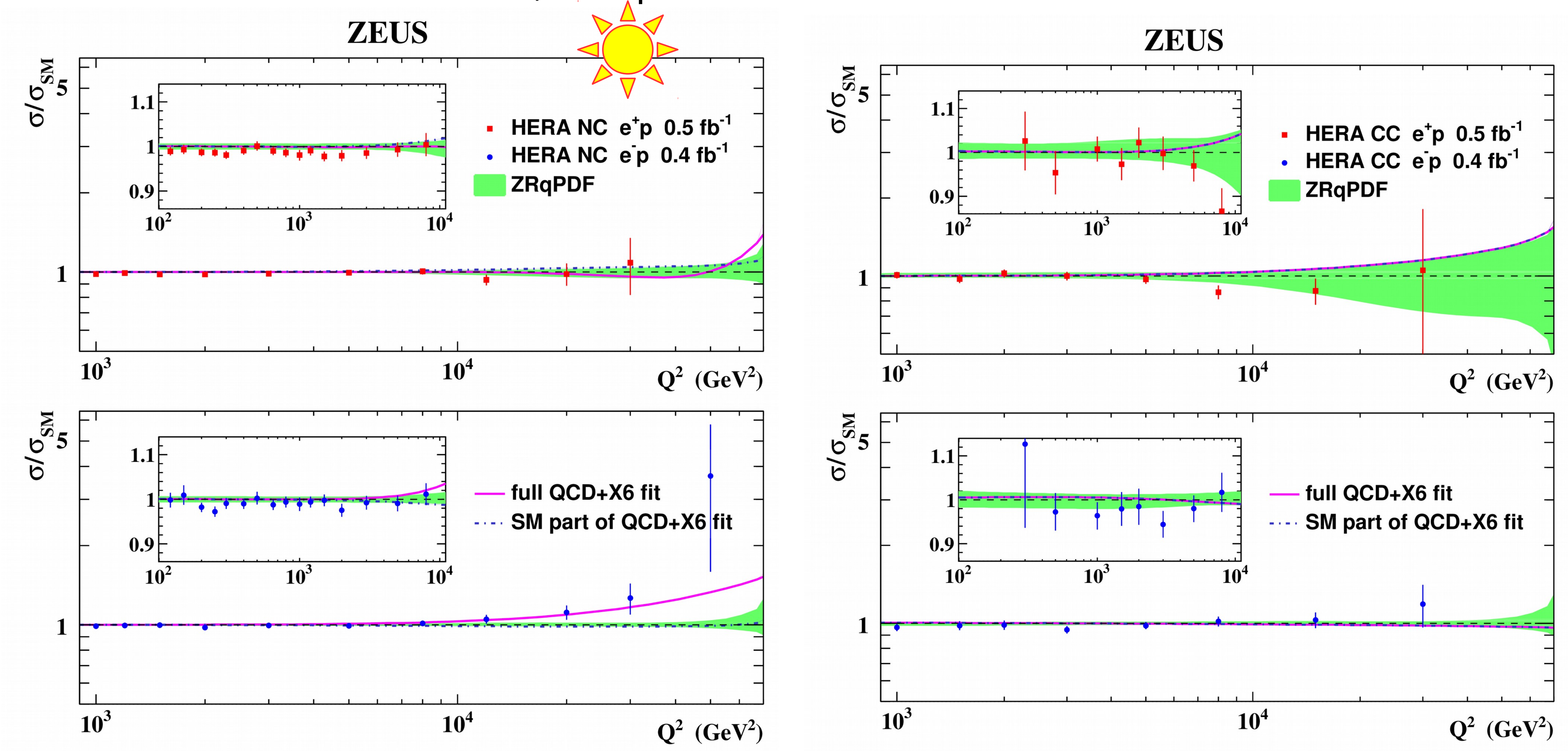
Evolve to any $Q^2 > Q^2_0$ with DGLAP at NLO.

We implement CI effects on NLO cross sections as:

$$\sigma^{SM+CI}_{NLO+LO} = \sigma^{SM}_{NLO\,QCD}\left(p_1^{NLO}\right) \times \left[\frac{\sigma^{SM+CI}_{LO\,EW}\left(p_1^{NLO}\right)}{\sigma^{SM}_{LO\,EW}\left(p_1^{NLO}\right)}\right]$$

Fit results

Result of the simultaneous QCD+CI fit to the HERA inclusive data, for X6 contact interaction model, compared to the combined HERA NC and DIS data

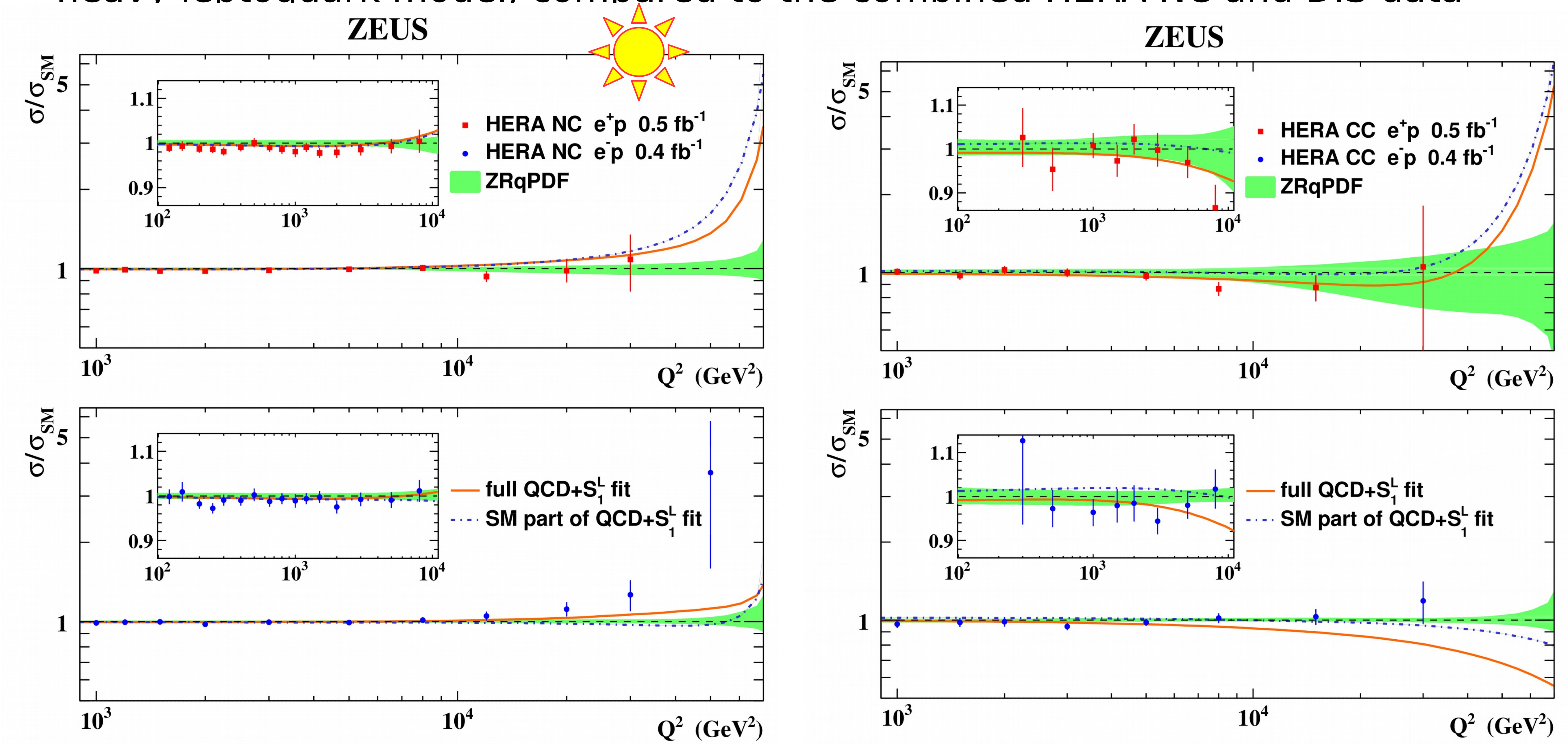


Improved description of the HERA data

$\Delta\chi^2 = \chi^2 - \chi^2_{SM} = -6.01$

Fit results

Result of the simultaneous QCD+CI fit to the HERA inclusive data, for S_1^L heavy leptoquark model, compared to the combined HERA NC and DIS data



Improved description of the HERA data $\Delta\chi^2 = \chi^2 - \chi^2_{SM} = -11.1$

Fit results

Results of the QCD+CI fits to the HERA data, for general CI models

For most model improvement is consistent with the expected $\Delta\chi^2 = -1$

Larger improvement for three models

η^{Data} uncertainties:

δ_{exp} – from statistical and systematic uncertainties of the input HERA data

δ_{mod} – from model and parameterisation uncertainties of the fit (calculated as for HERAPDF2.0)

Coupling structure		Coupling fit results (TeV^{-2})				
Model	$[\epsilon_{LL}, \epsilon_{LR}, \epsilon_{RL}, \epsilon_{RR}]$	η^{Data}	δ_{exp}	δ_{mod}	δ_{tot}	$\Delta\chi^2$
LL	[+1, 0, 0, 0]	0.305	0.206	$^{+0.017}_{-0.037}$	$^{+0.207}_{-0.209}$	-2.06
RR	[0, 0, 0, +1]	0.338	0.210	$^{+0.019}_{-0.038}$	$^{+0.210}_{-0.213}$	-2.30
LR	[0, +1, 0, 0]	-0.084	0.247	$^{+0.212}_{-0.060}$	$^{+0.325}_{-0.254}$	-0.12
RL	[0, 0, +1, 0]	-0.040	0.241	$^{+0.198}_{-0.057}$	$^{+0.312}_{-0.248}$	-0.03
VV	[+1, +1, +1, +1]	0.041	0.061	$^{+0.024}_{-0.009}$	$^{+0.066}_{-0.062}$	-0.45
AA	[+1, −1, −1, +1]	0.326	0.161	$^{+0.250}_{-0.175}$	$^{+0.297}_{-0.238}$	-4.67
VA	[+1, −1, +1, −1]	-0.594	0.225	$^{+0.028}_{-0.120}$	$^{+0.227}_{-0.255}$	-1.21
		0.676	0.200	$^{+0.078}_{-0.019}$	$^{+0.215}_{-0.201}$	-3.25
X1	[+1, −1, 0, 0]	0.682	0.267	$^{+0.339}_{-0.243}$	$^{+0.432}_{-0.361}$	-5.52
X2	[+1, 0, +1, 0]	0.089	0.121	$^{+0.046}_{-0.017}$	$^{+0.129}_{-0.122}$	-0.52
X3	[+1, 0, 0, +1]	0.158	0.108	$^{+0.009}_{-0.019}$	$^{+0.109}_{-0.110}$	-2.09
X4	[0, +1, +1, 0]	-0.029	0.116	$^{+0.098}_{-0.026}$	$^{+0.151}_{-0.119}$	-0.06
X5	[0, +1, 0, +1]	0.079	0.123	$^{+0.052}_{-0.018}$	$^{+0.133}_{-0.124}$	-0.41
X6	[0, 0, +1, −1]	-0.786	0.274	$^{+0.192}_{-0.295}$	$^{+0.334}_{-0.402}$	-6.01

Fit results

Results of the QCD+CI fits to the HERA data, for heavy leptoquarks

For most model improvement is consistent with the expected $\Delta\chi^2 = -1$

Larger improvement for S_1^L model

(V_0^L – unphysical, only positive η allowed)

Model	Coupling Structure	Coupling fit results (TeV^{-2})				$\Delta\chi^2$
		η_{LQ}^{Data}	δ_{exp}	δ_{mod}	δ_{tot}	
$S_\circ^L$	$a_{LL}^{eu} = +\frac{1}{2}$	-0.258	0.196	$^{+0.034}_{-0.036}$	$^{+0.199}_{-0.199}$	-1.56
$S_\circ^R$	$a_{RR}^{eu} = +\frac{1}{2}$	0.533	0.331	$^{+0.034}_{-0.061}$	$^{+0.332}_{-0.336}$	-2.53
$\tilde{S}_\circ^R$	$a_{RR}^{ed} = +\frac{1}{2}$	-2.561	1.115	$^{+0.323}_{-0.221}$	$^{+1.161}_{-1.137}$	-3.98
$S_{1/2}^L$	$a_{LR}^{eu} = -\frac{1}{2}$	0.054	0.341	$^{+0.075}_{-0.280}$	$^{+0.349}_{-0.441}$	-0.02
$S_{1/2}^R$	$a_{RL}^{ed} = a_{RL}^{eu} = -\frac{1}{2}$	0.112	0.491	$^{+0.118}_{-0.412}$	$^{+0.505}_{-0.641}$	-0.05
$\tilde{S}_{1/2}^L$	$a_{LR}^{ed} = -\frac{1}{2}$	0.464	1.371	$^{+0.925}_{-0.264}$	$^{+1.654}_{-1.396}$	-0.10
S_1^L	$a_{LL}^{ed} = +1,\ a_{LL}^{eu} = +\frac{1}{2}$	0.974	0.203	$^{+0.043}_{-0.337}$	$^{+0.207}_{-0.393}$	-11.10
$V_\circ^L$	$a_{LL}^{ed} = -1$	-0.325	0.116	$^{+0.030}_{-0.101}$	$^{+0.120}_{-0.154}$	-6.17
$V_\circ^R$	$a_{RR}^{ed} = -1$	1.280	0.558	$^{+0.111}_{-0.163}$	$^{+0.568}_{-0.581}$	-3.98
$\tilde{V}_\circ^R$	$a_{RR}^{eu} = -1$	-0.267	0.165	$^{+0.030}_{-0.017}$	$^{+0.168}_{-0.166}$	-2.53
$V_{1/2}^L$	$a_{LR}^{ed} = +1$	-0.232	0.685	$^{+0.132}_{-0.460}$	$^{+0.698}_{-0.825}$	-0.10
$V_{1/2}^R$	$a_{RL}^{ed} = a_{RL}^{eu} = +1$	-0.056	0.246	$^{+0.206}_{-0.059}$	$^{+0.320}_{-0.253}$	-0.05
$\tilde{V}_{1/2}^L$	$a_{LR}^{eu} = +1$	-0.027	0.171	$^{+0.139}_{-0.038}$	$^{+0.220}_{-0.175}$	-0.02
V_1^L	$a_{LL}^{ed} = -1,\ a_{LL}^{eu} = -2$	0.029	0.077	$^{+0.015}_{-0.013}$	$^{+0.079}_{-0.079}$	-0.14

Statistical analysis with Monte Carlo replicas

Corresponding to classical (frequentist) definition of confidence intervals and limits

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

Cross-section prediction from the ZCIPDF modified with η^{True}

Measured cross-section value

Correlated systematic uncertainties

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

Relative statistical and uncorrelated systematic uncertainties

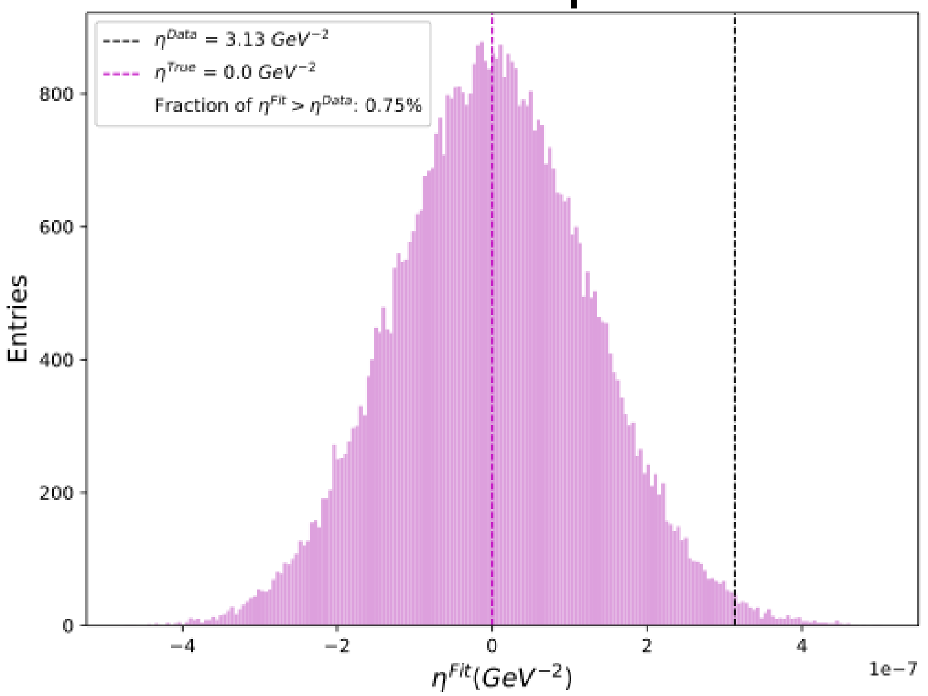
Random numbers from a normal distribution

Simultaneous QCD+CI fit is repeated for each Monte Carlo replica resulting in the distribution of η^{Fit} values.

Consistency with SM: for $\eta^{Data}>0$

$$p_{SM} = \text{Prob}(\eta^{Fit} < \eta^{Data}; \eta^{True}=0)$$

where η^{Data} : result of the QCD+CI fit to HERA data



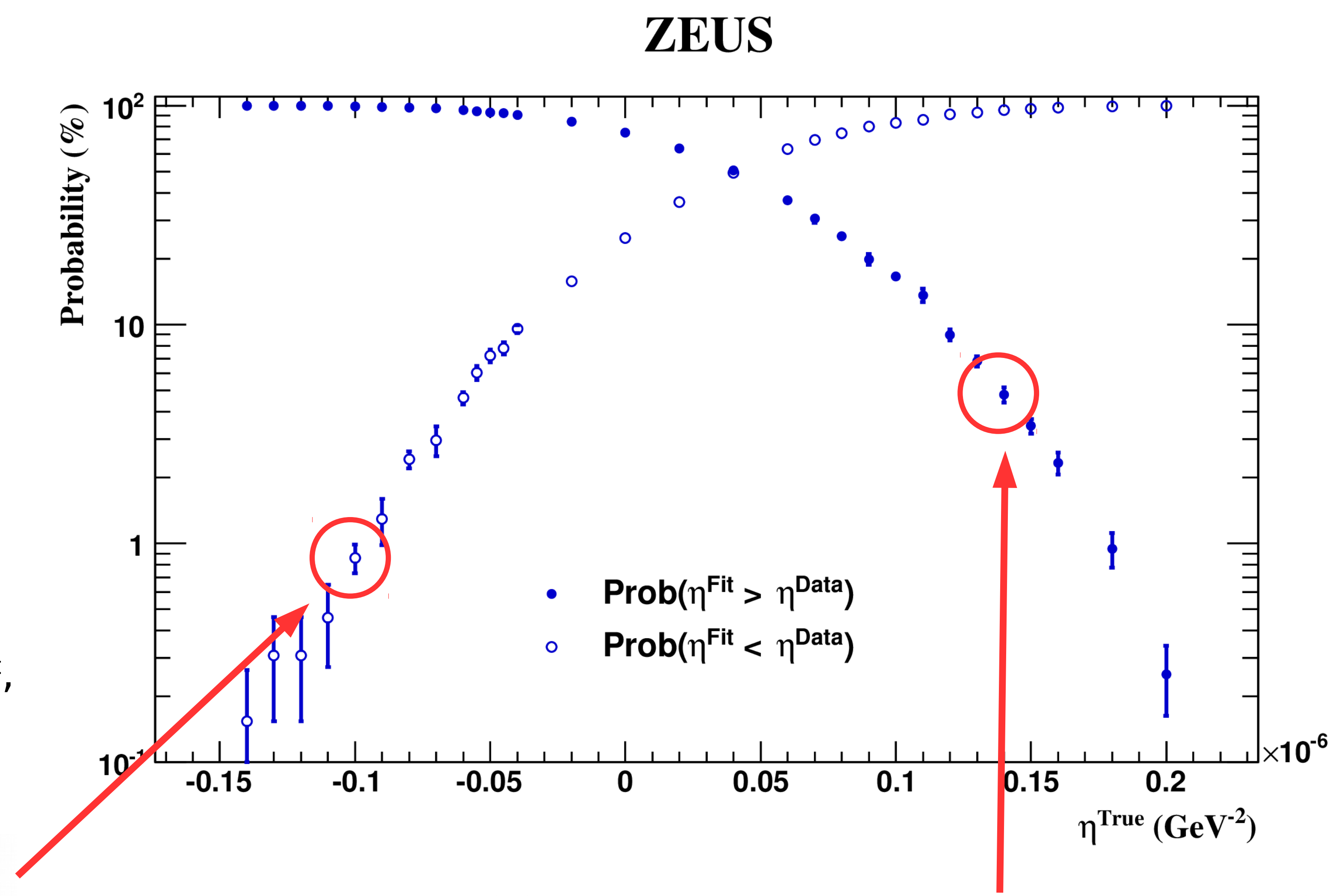
Confidence interval for the coupling based on the probability

$$p(\eta^{True}) = \text{Prob}(\eta^{Fit} < \eta^{Data}; \eta^{True})$$

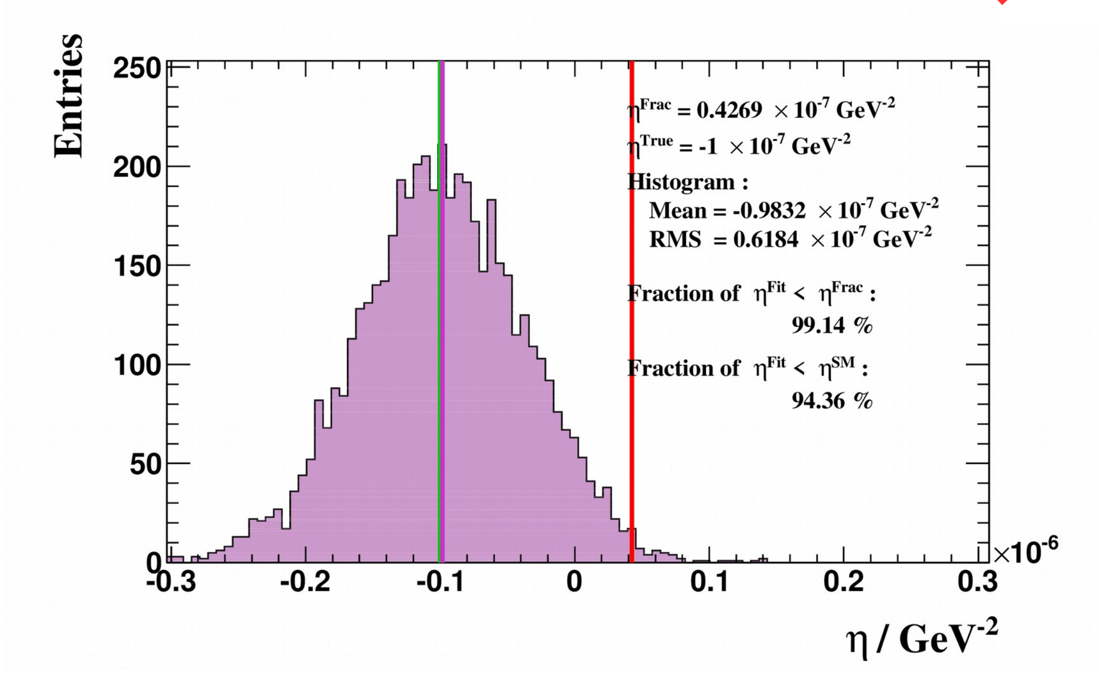
Replicas scan example

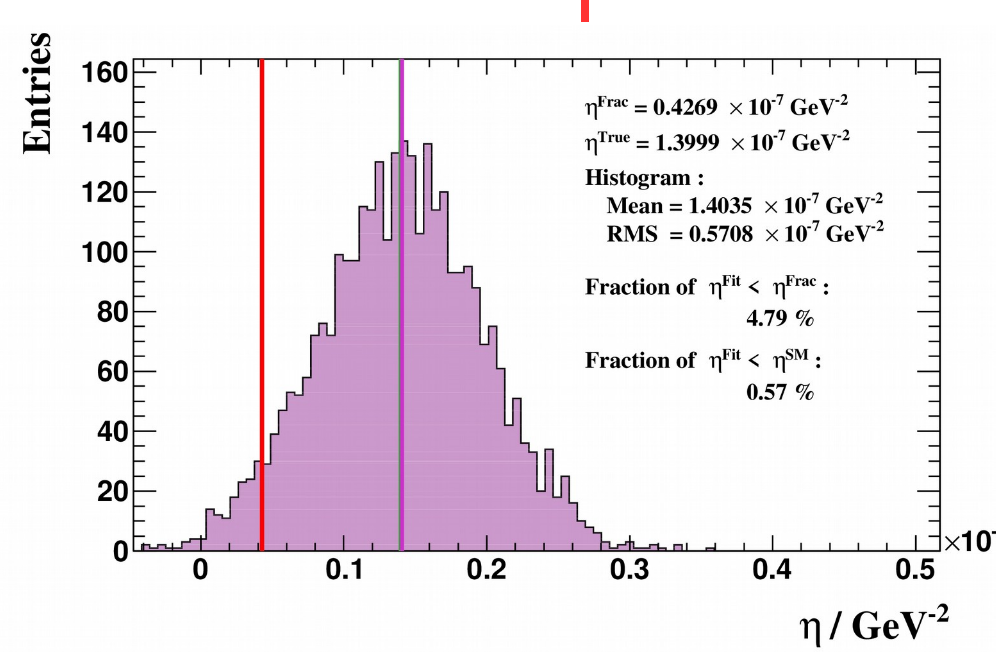
VV model

$\eta^{Data} = 0.041\ TeV^{-2}$



Distributions of fitted coupling values, η^{Fit}, for single replica sets (given η^{True}):

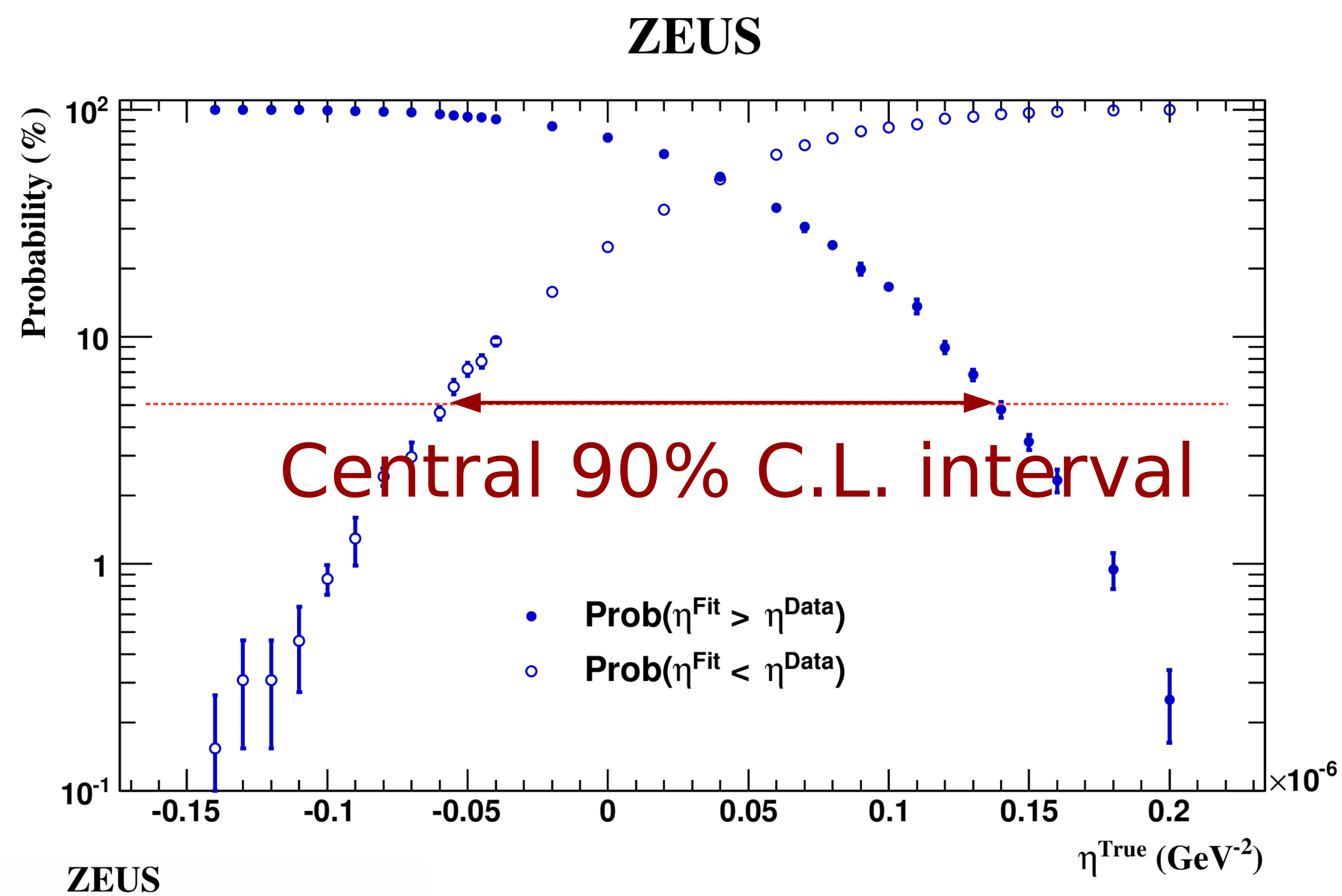


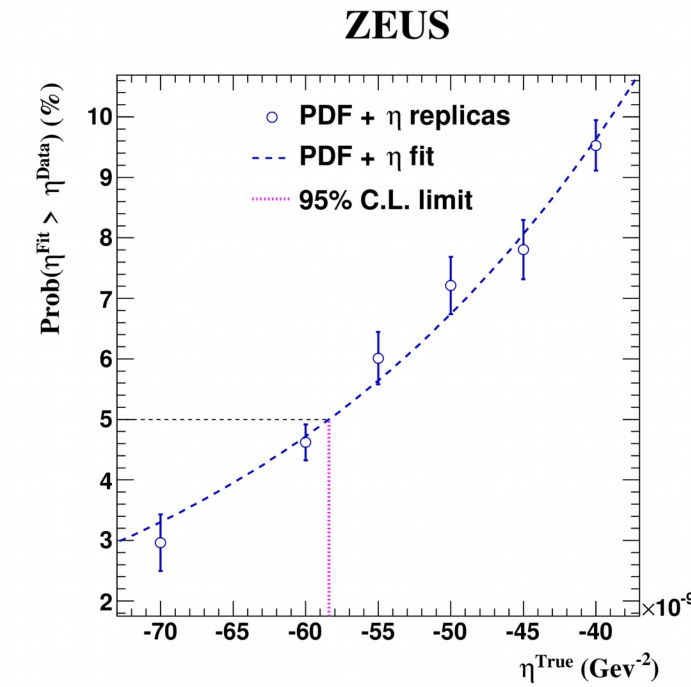


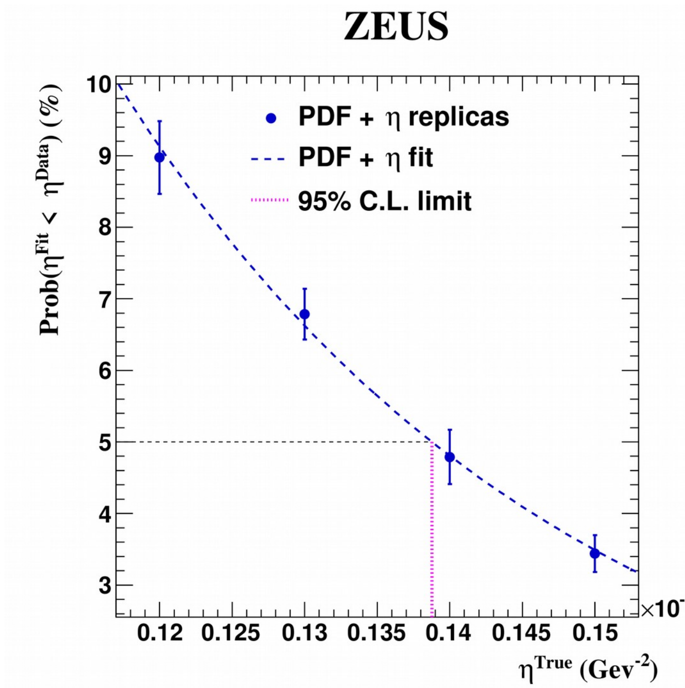
Replicas scan example

VV model

$\eta^{Data} = 0.041\ TeV^{-2}$







Coupling interval (90% C.L.):

$$-0.058\,TeV^{-2} < \eta < 0.135\,TeV^{-2}$$

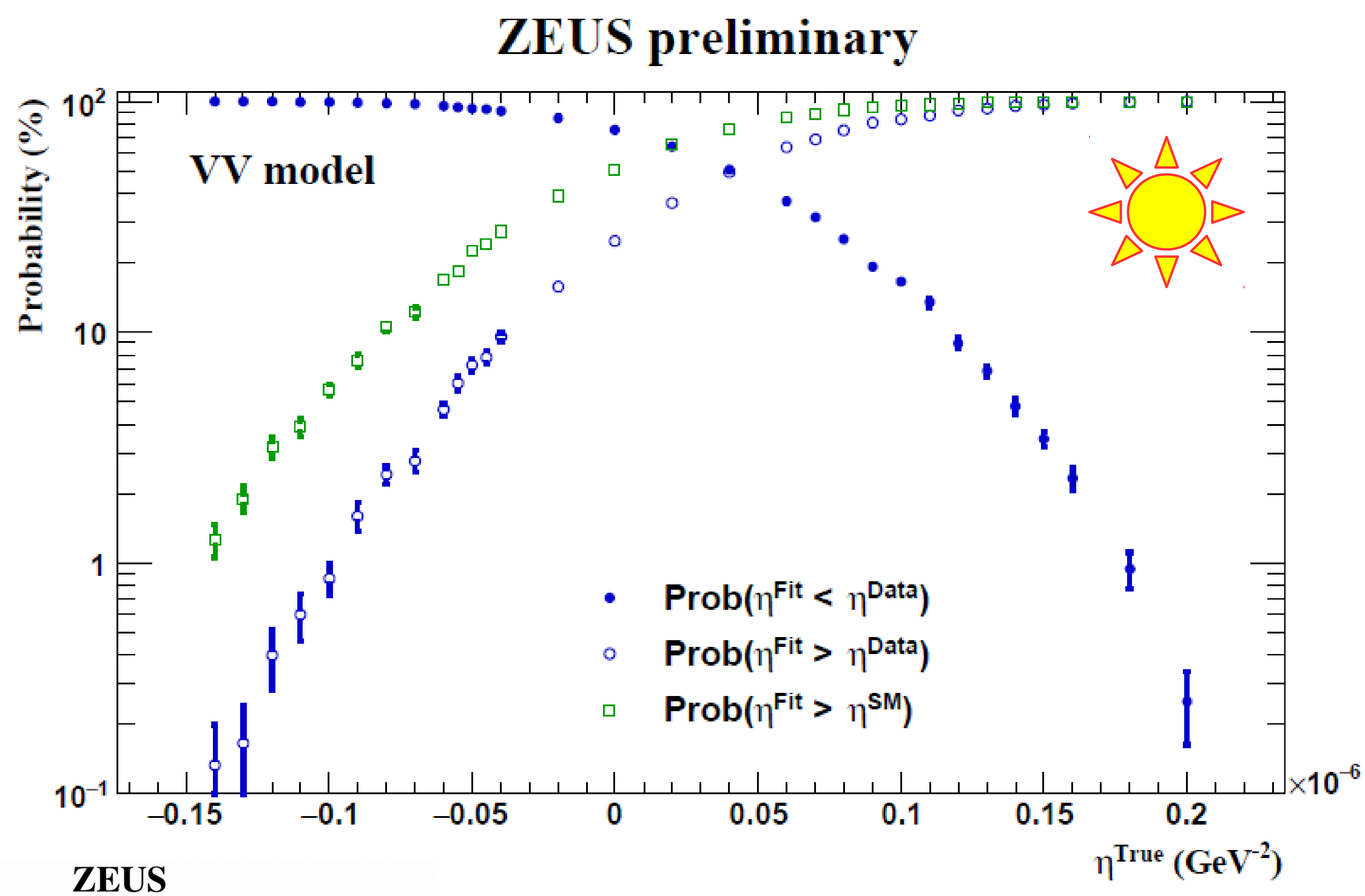
Corresponding to 95% C.L. limits:

$$\Lambda^{-} > 14.7\,Tev$$

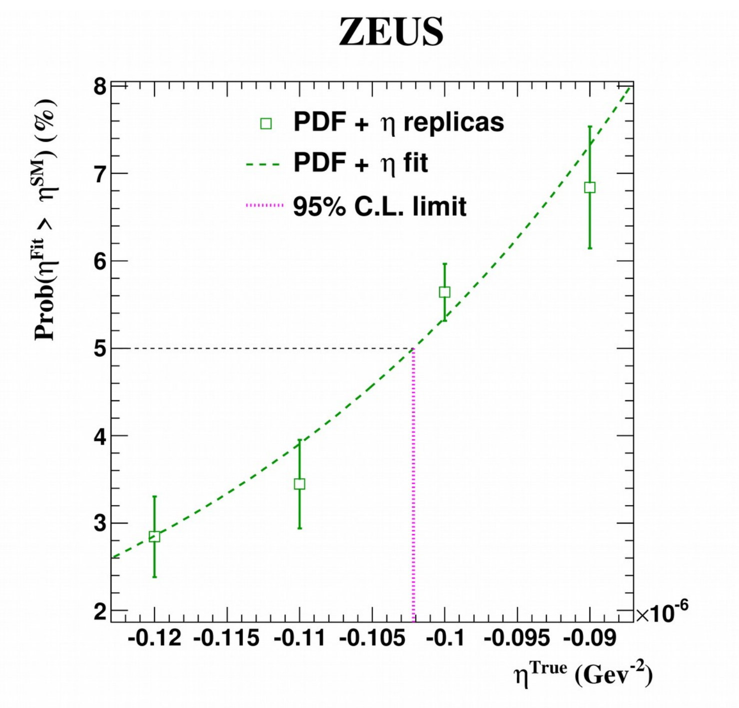
$$\Lambda^{+} > 9.5\,Tev$$

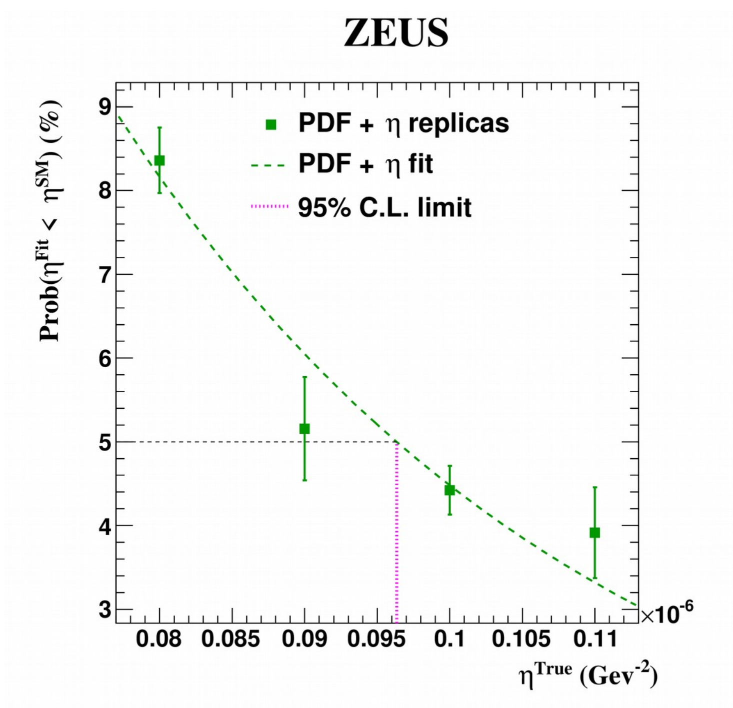
Replicas scan example

VV model



Expected limits can be calculated by comparing replica fit results with $\eta^{SM}=0$ (expected median of SM replica fits).





Coupling interval (90% C.L.):

$$-0.058\, TeV^{-2} < \eta < 0.135\, TeV^{-2}$$

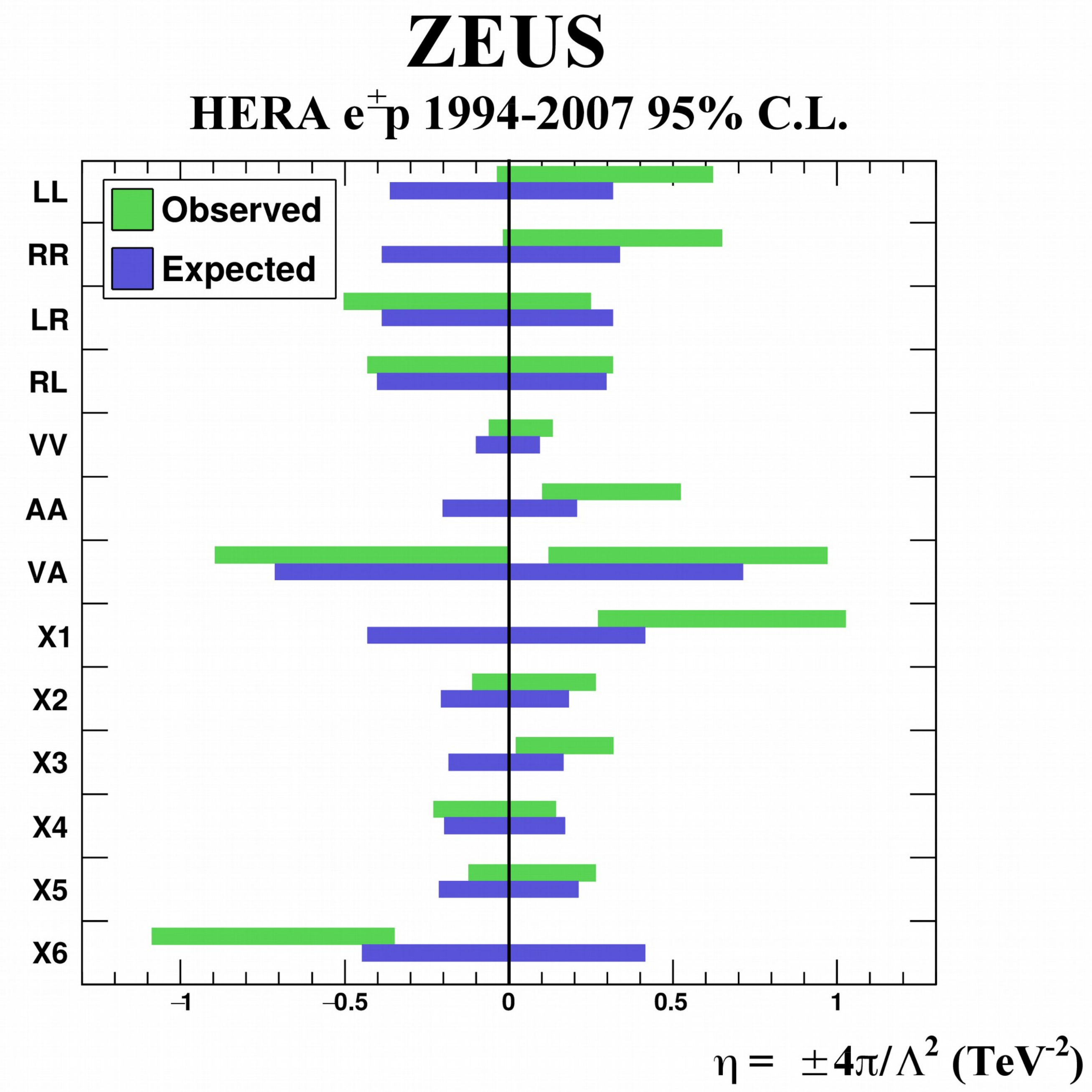
Expected interval (90% C.L.):

$$-0.101\, TeV^{-2} < \eta < 0.097\, TeV^{-2}$$

General CI coupling intervals

Results from the Monte Carlo replica scan analysis

Model	$\eta^{\rm Data}$ (TeV^{-2})	p_{SM} (%)	Central 90% C.L. intervals (TeV^{-2}) $\eta^{\rm min}$	$\eta^{\rm max}$
LL	0.305	7.0	-0.033	0.610
RR	0.338	5.9	-0.017	0.649
LR	-0.084	34	-0.514	-0.25
RL	-0.040	42	-0.464	0.299
VV	0.041	25	-0.058	0.135
AA	0.326	0.6	0.116	0.530
VA	-0.594	5.8	-0.888	0
	0.676	2.5	0.092	0.949
X1	0.682	0.4	0.292	1.020
X2	0.089	24	-0.113	0.269
X3	0.158	7.3	-0.018	0.320
X4	-0.029	39	-0.230	0.144
X5	0.079	27	-0.129	0.263
X6	-0.786	0.3	-1.130	-0.369



Two intervals calculated for the VA model correspond to two minima observed in the χ^2 distribution for the HERA data.

Heavy LQ effective coupling intervals

Results from the Monte Carlo replica scan analysis

Model	Coupling Structure	η_{LQ}^{Data} (TeV^{-2})	p_{SM} (%)	λ_{LQ}/M_{LQ} 95% C.L. limits (TeV^{-1})
$S_\circ^L$	$a_{LL}^{eu} = +\frac{1}{2}$	-0.258	9.0	0.27
$S_\circ^R$	$a_{RR}^{eu} = +\frac{1}{2}$	0.533	5.5	1.02
$\tilde{S}_\circ^R$	$a_{RR}^{ed} = +\frac{1}{2}$	-2.561	1.8	-
$S_{1/2}^L$	$a_{LR}^{eu} = -\frac{1}{2}$	0.054	43	0.8
$S_{1/2}^R$	$a_{RL}^{ed} = a_{RL}^{eu} = -\frac{1}{2}$	0.112	39	0.99
$\tilde{S}_{1/2}^L$	$a_{LR}^{ed} = -\frac{1}{2}$	0.464	38	1.51
S_1^L	$a_{LL}^{ed} = +1, \ a_{LL}^{eu} = +\frac{1}{2}$	0.974	< 0.01	0.78-1.16
$V_\circ^L$	$a_{LL}^{ed} = -1$	-0.325	0.5	-
$V_\circ^R$	$a_{RR}^{ed} = -1$	1.280	1.8	0.56-1.44
$\tilde{V}_\circ^R$	$a_{RR}^{eu} = -1$	-0.267	5.5	0.16
$V_{1/2}^L$	$a_{LR}^{ed} = +1$	-0.232	38	1.11
$V_{1/2}^R$	$a_{RL}^{ed} = a_{RL}^{eu} = +1$	-0.056	39	0.53
$\tilde{V}_{1/2}^L$	$a_{LR}^{eu} = +1$	-0.027	43	0.47
V_1^L	$a_{LL}^{ed} = -1, \ a_{LL}^{eu} = -2$	0.029	32	0.27

Monte Carlo replica study confirms earlier observations based on the fit results.

For three CI and one LQ model, discrepancies between the HERA data and the SM predictions are not likely to be due to statistical fluctuations **only**

Before any conclusions on the BSM contribution to the HERA data can be drawn, we need to take into account model and parameterisation uncertainties.

Modelling uncertainties

The analysis is based on the HERA data combined in the HERAPDF2.0 framework.

The framework has its limitations, but we can not avoid using it without going back to raw ZEUS and H1 data. All results are valid within this framework.

We consider uncertainties due to model parameters and parameterisation form, as defined in the HERAPDF2.0 analysis.

Following variation were used to estimate modelling uncertainties:

- Variation of heavy quark mass parameters, M_b and M_c
- Variation of the strange see contribution, f_s
- Choice of the minimum value of Q^2 for considered data, Q^2_{min}
- Choice of the parameterisation starting scale, Q^2_0
- Additional parameters in the PDF parameterisation, in the description of:
  - gluon density, D_g and E_g
  - valence u and d quark densities, D_{Uv}, D_{Dv} and E_{Dv}
  - see quark densities, $D_{\bar{D}}$ and $E_{\bar{D}}$

Modelling uncertainties

The QCD+CI fit to the HERA data is repeated for each model parameter and parameterisation form variation considered.

Modelling uncertainties, δ_{mod} , on the nominal coupling values, η^{Data} , are calculated from the η^{Fit} variations (from the fits to nominal HERA data).

For each model we take variations resulting in largest shift in η^{Data} (up and down) and repeat confidence interval calculation with MC replicas for these variation.

Final confidence interval for the CI or LQ coupling is defined as the sum of nominal 90% C.L. coupling interval and the two intervals corresponding to the largest modelling variations (up and down)

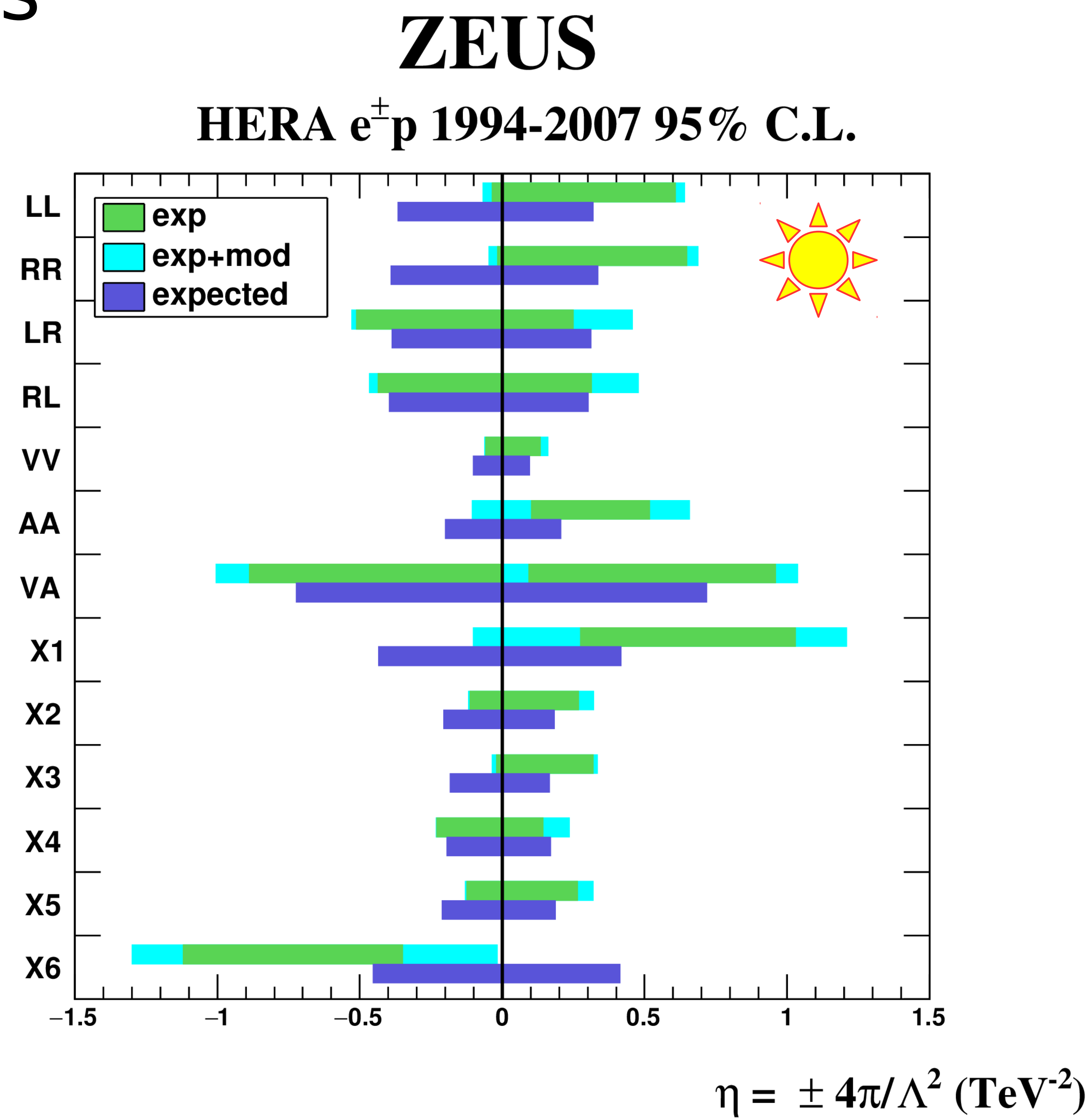
This procedure does not require any assumption about the underlying probability distributions for the systematic variations. In fact, one can not give any such estimate for most of the considered variations...

How to estimate the probability that there is an additional parameter in the gluon density description?...

Results

Modelling uncertainties significantly widen the coupling intervals

Only for X6 model, Standard Model (η = 0) is (just) outside the central 90% C.L. interval.



Results

Coupling intervals calculated with modelling variations (exp+mod) and the corresponding mass scale limits

ZEUS

HERA $e^{\pm}p$ 1994-2007 data

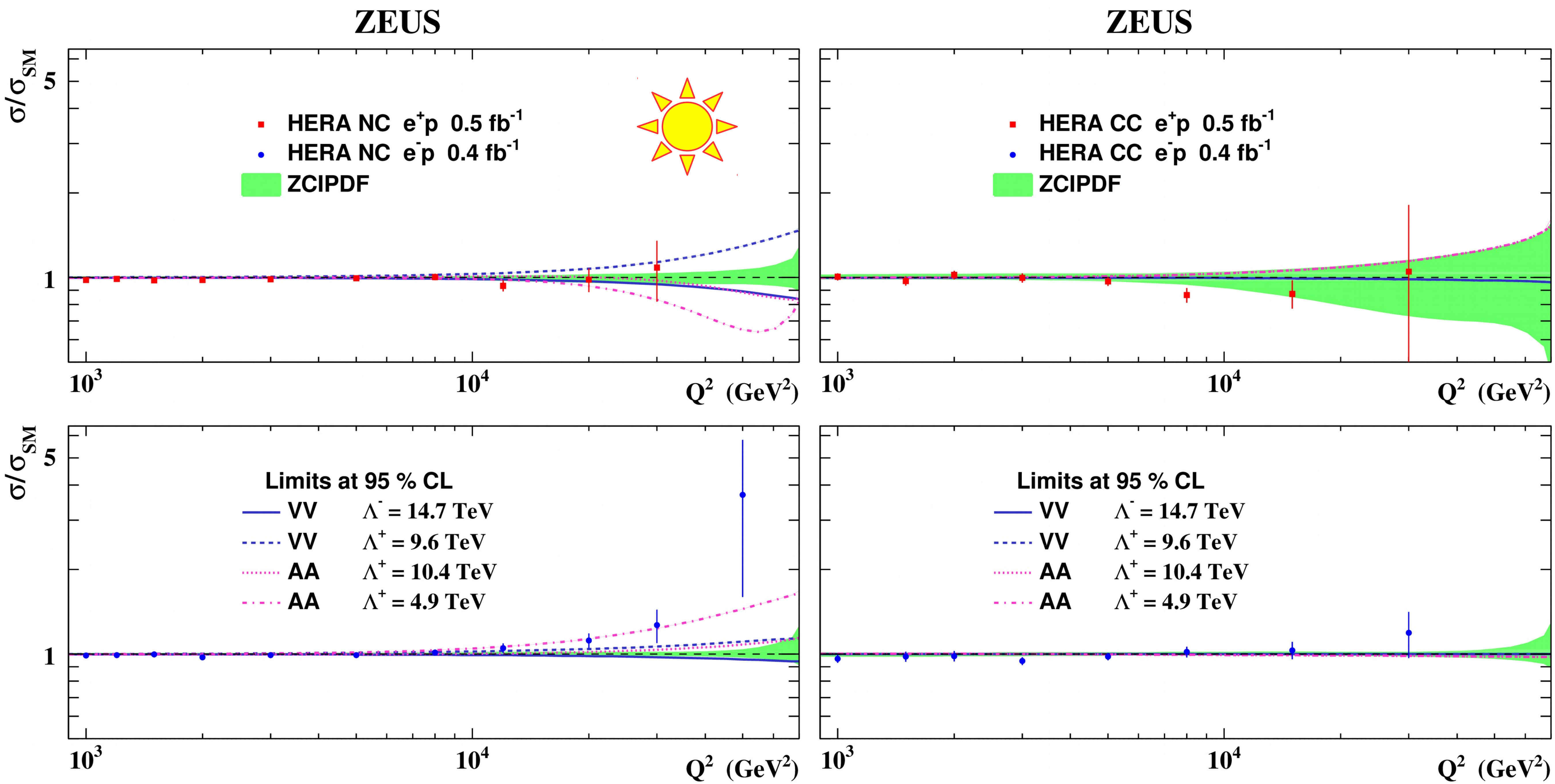
Model	η^{Data}	p_{SM}	Central 90% C.L. intervals (TeV^{-2})						95% C.L. limits (TeV)			
			Measured (exp)		Measured (exp+mod)		Expected		Measured (exp+mod)		Expected	
	(TeV^{-2})	(%)	η^{min}	η^{max}	η^{min}	η^{max}	η^{min}	η^{max}	Λ^-	Λ^+	Λ^-	Λ^+
LL	0.305	7.0	-0.033	0.610	-0.07	0.64	-0.367	0.319	13.6	4.4	5.9	6.3
RR	0.338	5.9	-0.017	0.649	-0.05	0.69	-0.390	0.337	16.5	4.3	5.7	6.1
LR	-0.084	34	-0.514	0.250	-0.53	0.46	-0.388	0.313	4.9	5.2	5.7	6.3
RL	-0.040	42	-0.464	0.299	-0.47	0.48	-0.397	0.302	5.2	5.1	5.6	6.5
VV	0.041	25	-0.058	0.135	-0.06	0.16	-0.101	0.097	14.2	8.8	11.2	11.4
AA	0.326	0.6	0.116	0.530	-0.11	0.66	-0.200	0.207	10.9	4.4	7.9	7.8
VA	-0.594 0.676	5.8 2.5	-0.888 0.092	0 0.949	-1.01	1.04	-0.723	0.719	3.5	3.5	4.2	4.2
X1	0.682	0.4	0.292	1.020	-0.10	1.23	-0.435	0.418	11.1	3.2	5.4	5.5
X2	0.089	24	-0.113	0.269	-0.12	0.32	-0.206	0.184	10.3	6.2	7.8	8.3
X3	0.158	7.3	-0.018	0.320	-0.04	0.33	-0.183	0.166	18.8	6.1	8.3	8.7
X4	-0.029	39	-0.230	0.144	-0.23	0.24	-0.194	0.170	7.4	7.3	8.0	8.6
X5	0.079	27	-0.129	0.263	-0.13	0.32	-0.212	0.188	9.9	6.3	7.7	7.7
X6	-0.786	0.3	-1.130	-0.369	-1.30	-0.02	-0.454	0.415	3.1		5.3	5.5

All exp+mod numbers preliminary, to be updated !!!

Results

Comparison of general CI limits with SM predictions

Plots to be updated for final (exp+mod) limits



Results

Smaller influence of modelling variations for fits of heavy leptoquark models

Deviation observed for S1L model persists...

All exp+mod numbers preliminary, to be updated !!!

ZEUS

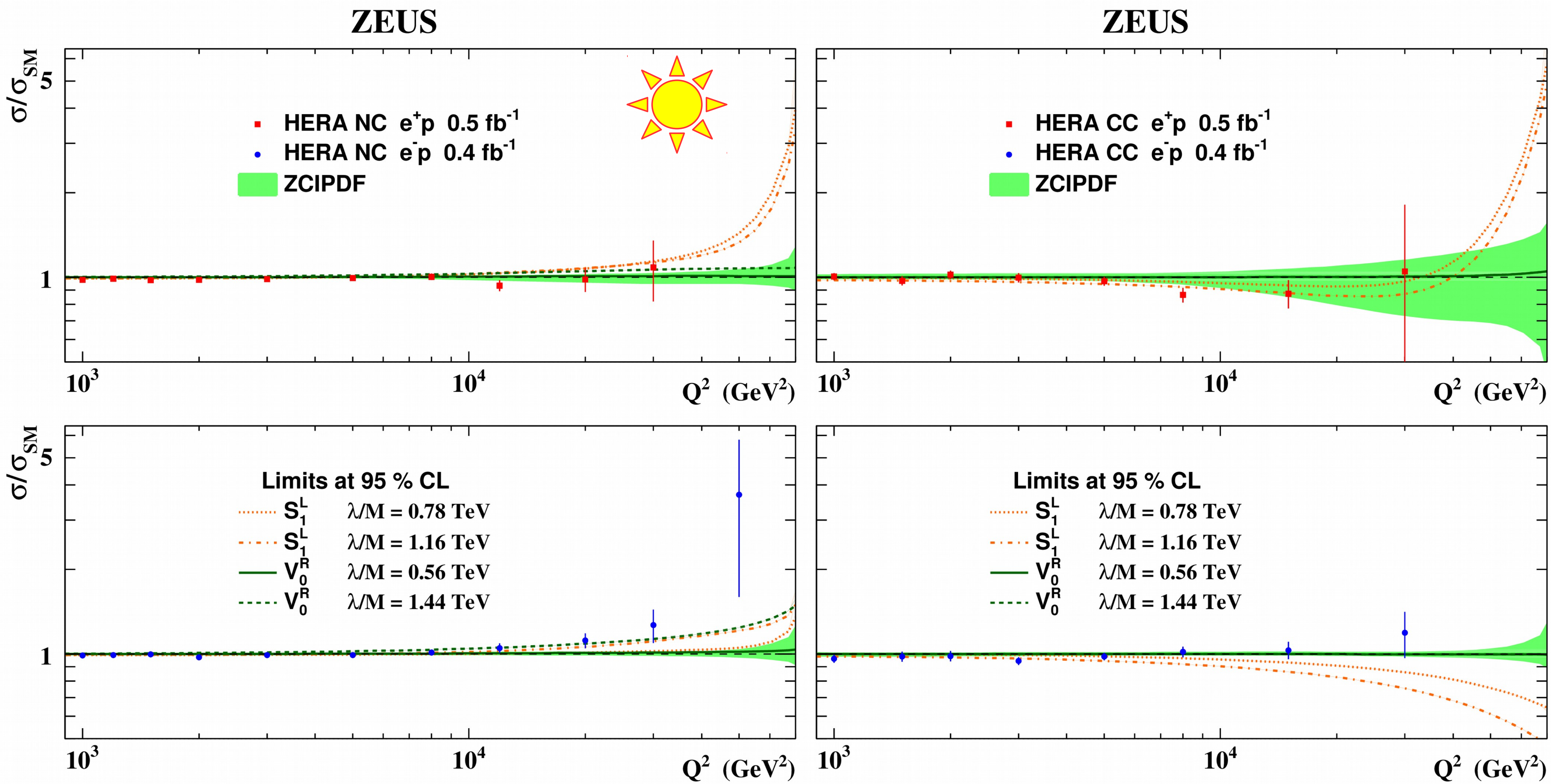
HERA $e^{\pm}p$ 1994-2007 data

Model	Coupling Structure	η_{LQ}^{Data} (TeV^{-2})	p_{SM} (%)	λ_{LQ}/M_{LQ} 95% C.L. limits (TeV^{-1}) Measured (exp)	Measured (exp+mod)	Expected
$S_\circ^L$	$a_{LL}^{eu} = +\frac{1}{2}$	-0.258	9.0	0.27	0.34	0.56
$S_\circ^R$	$a_{RR}^{eu} = +\frac{1}{2}$	0.533	5.5	1.02	1.06	0.72
$\tilde{S}_\circ^R$	$a_{RR}^{ed} = +\frac{1}{2}$	-2.561	1.8	-	-	1.71
$S_{1/2}^L$	$a_{LR}^{eu} = -\frac{1}{2}$	0.054	43	0.8	0.83	0.76
$S_{1/2}^R$	$a_{RL}^{ed} = a_{RL}^{eu} = -\frac{1}{2}$	0.112	39	0.99	1.02	0.92
$\tilde{S}_{1/2}^L$	$a_{LR}^{ed} = -\frac{1}{2}$	0.464	38	1.51	1.77	1.39
S_1^L	$a_{LL}^{ed} = +1,\ a_{LL}^{eu} = +\frac{1}{2}$	0.974	< 0.01	0.78-1.16	0.60-1.17	0.62
$V_\circ^L$	$a_{LL}^{ed} = -1$	-0.325	0.5	-	-	0.44
$V_\circ^R$	$a_{RR}^{ed} = -1$	1.280	1.8	0.56-1.44	0.45 - 1.50	0.99
$\tilde{V}_\circ^R$	$a_{RR}^{eu} = -1$	-0.267	5.5	0.16	0.21	0.53
$V_{1/2}^L$	$a_{LR}^{ed} = +1$	-0.232	38	1.11	1.11	1.29
$V_{1/2}^R$	$a_{RL}^{ed} = a_{RL}^{eu} = +1$	-0.056	39	0.53	0.69	0.57
$\tilde{V}_{1/2}^L$	$a_{LR}^{eu} = +1$	-0.027	43	0.47	0.61	0.49
V_1^L	$a_{LL}^{ed} = -1,\ a_{LL}^{eu} = -2$	0.029	32	0.27	0.42	0.25

Results

Comparison of heavy leptoquark M/λ confidence intervals with SM predictions

Plots to be updated for final (exp+mod) limits



Conclusions

- HERA combined data used to search for possible deviations from SM predictions within the *eeqq* Contact Interaction framework
- New procedure:
  simultaneous fit of PDF parameters and the CI coupling crucial for unbiased new physics searches
- Significant improvement in the description of HERA data observed for selected CI and LQ scenarios
- Confidence coupling intervals calculated using Monte Carlo replicas, taking into account data and modelling uncertainties
- Most significant discrepancy for S_1^L model is unlikely to be explained statistical fluctuations or any of the considered model and parameterisation variations.
- Theoretical predictions have to be reexamined carefully before the observation can be attributed to any scenario of “new physics”

Additional checks

- As mentioned at the beginning, the analysis is based on the HERAPDF2.0 framework and assumes validity of the HERAPDF2.0 parameterisation.
- Is the PDF form flexible enough?
- We tried to use bi-log parameterisation, also available in xFitter (completely different form, more parameters)
- Results of QCD+CI fits for X6 and S1L models are consistent within the modelling variations of the HERAPDF2.0 approach

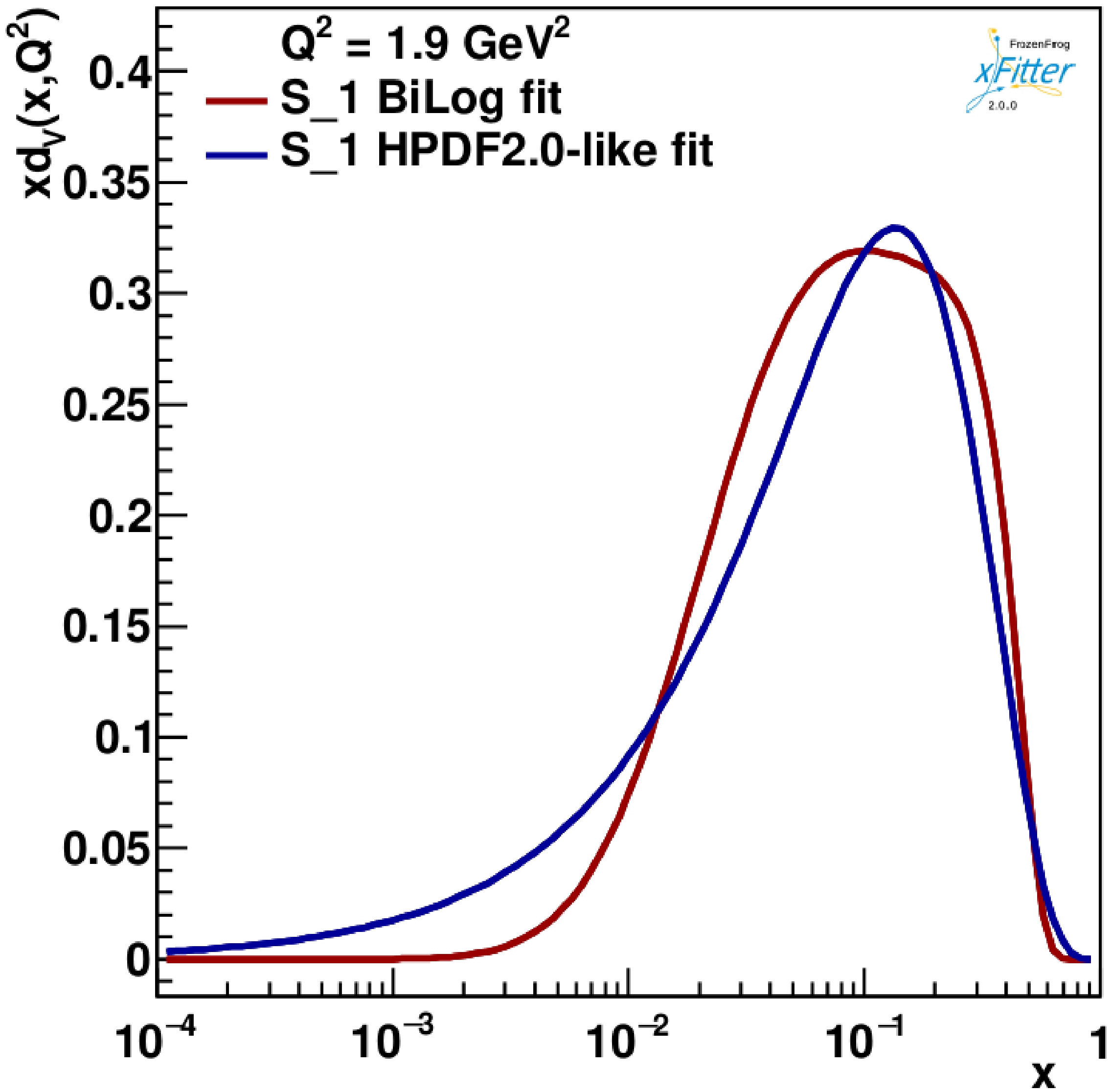
Additional checks

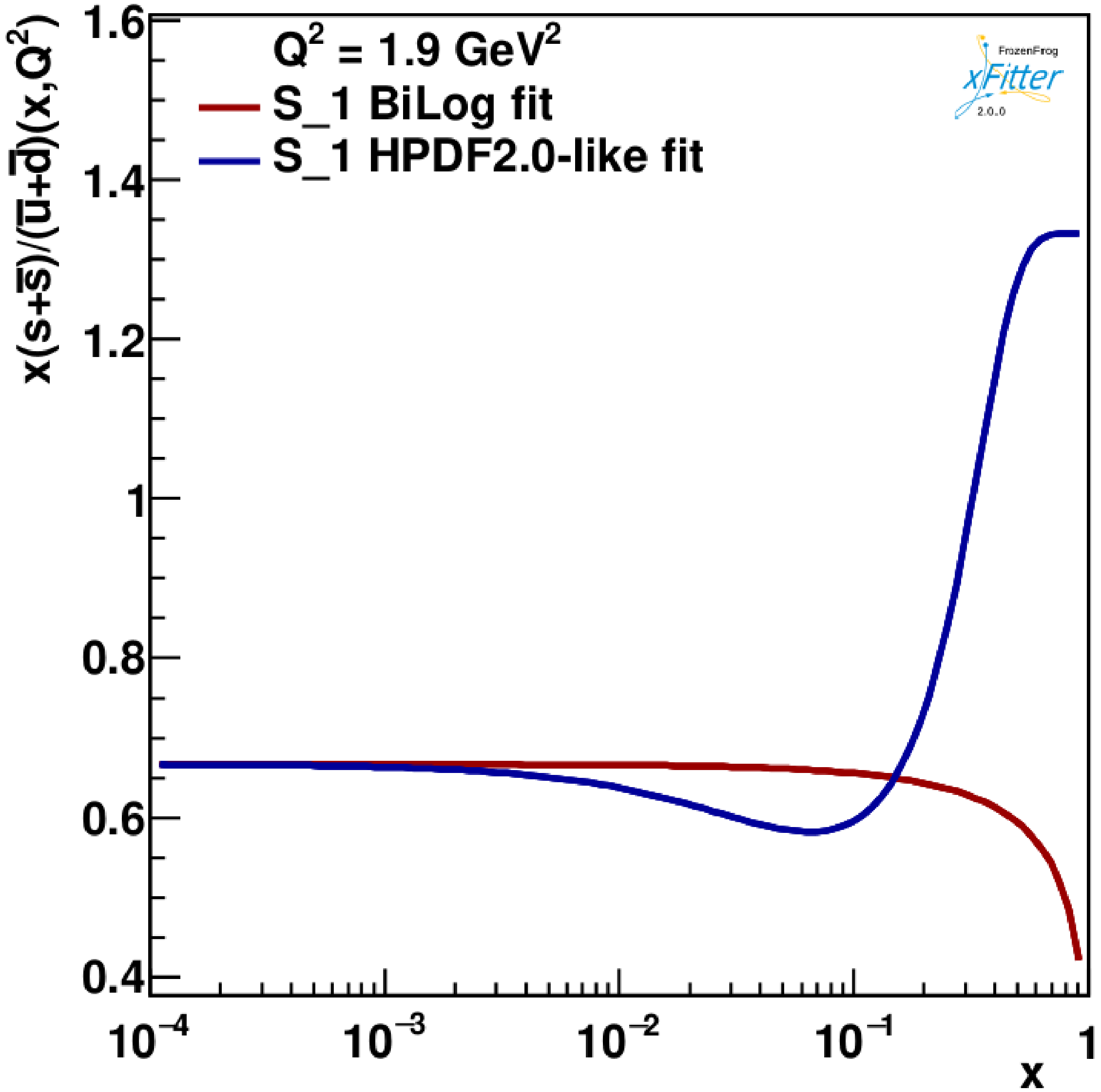
Very different parametrisation form and fit results at the starting scale Q^2_0

Consistent fit results for S_1^L model coupling

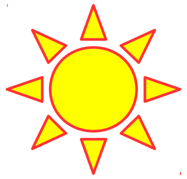
HERAPDF2.0 variations: η^{Data} = +0.759 TeV^{-2} to +1.016 TeV^{-2}

Bi-log fit: η^{Data} = +0.737 TeV^{-2} $\Delta\chi^2 \approx -9$





Public results

Indicated by 

Tables

- Fit results for CI and LQ models (tables 1 & 2, see slides 11 & 12)
- p_{SM} values and coupling intervals/limits for CI and LQ models (tables 3 & 4, slides 22 & 24)

Figures

- Fit result for X6 and S1L models compared with NC DIS data (figures 1 and 2, slides 9 & 10)
- Confidence intervals for general CI models (figure 3, slide 21)
- Comparison of limits with HERA NC DIS data (figures 4 and 5, slides 23 & 25)

- Additional plots available for confidence interval definition (slide 16)

Backup slides

Simplified fit procedure

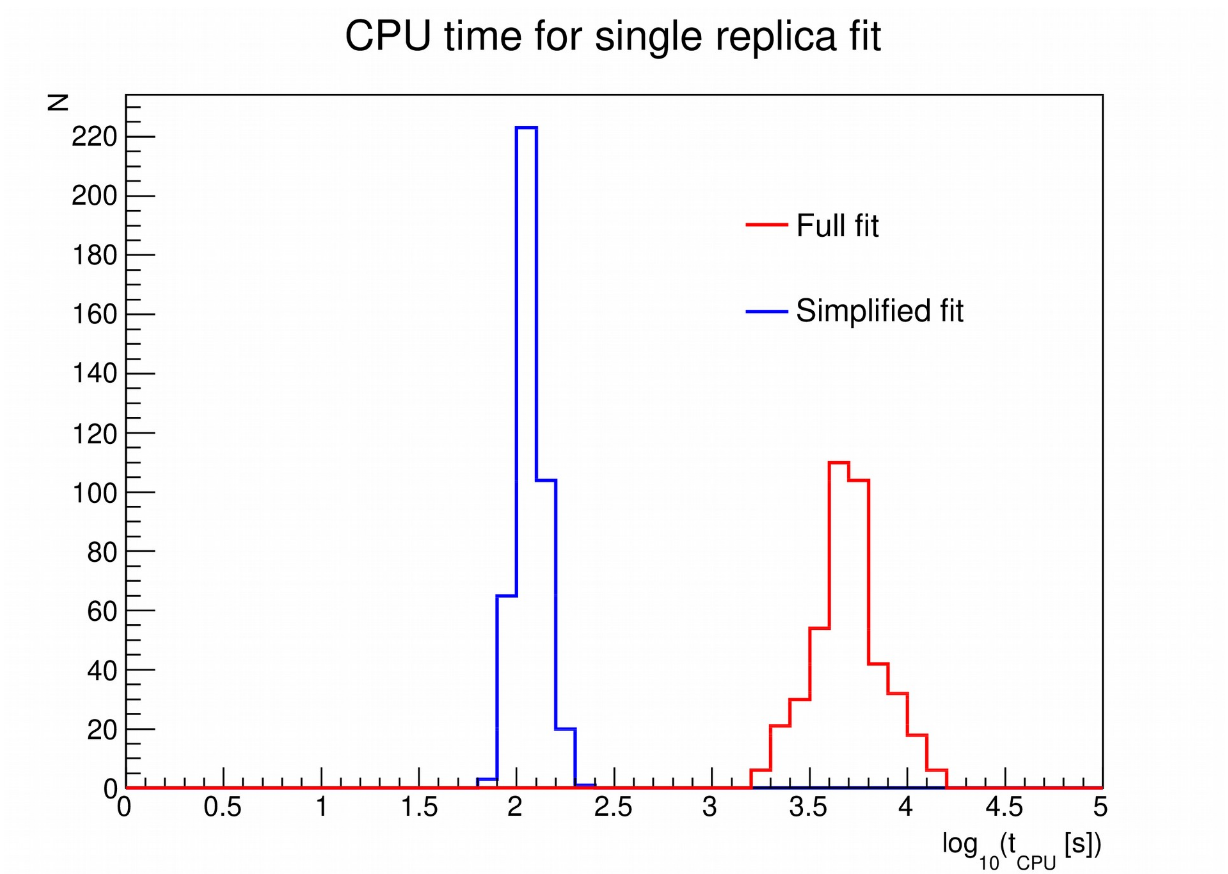
About 3000-5000 Monte Carlo replicas have to be generated and fitted for each value of η^{True} and for each considered CI scenario. With a single QCD fit to the full HERA data set taking on average about 1.5 hour of CPU time, processing time was a limiting factor for including more models in the analysis (single model analysis required about 30 years of CPU time).

We developed a simplied fit method, based on the Taylor expansion of the cross section predictions in terms of PDF parameters, which allowed us to reduce the limit calculation time by almost two orders of magnitude.

A note describing our simplified fit:

ZEUS-Note 2016-001

arXiv:1606.06670



Simplified fit procedure

The simplified procedure was first tested for the R_q model, perfectly reproducing results of the full QCD+BSM fit.

Replica fit results for $R_q^{2,True}$ corresponding to the limit set in the analysis