



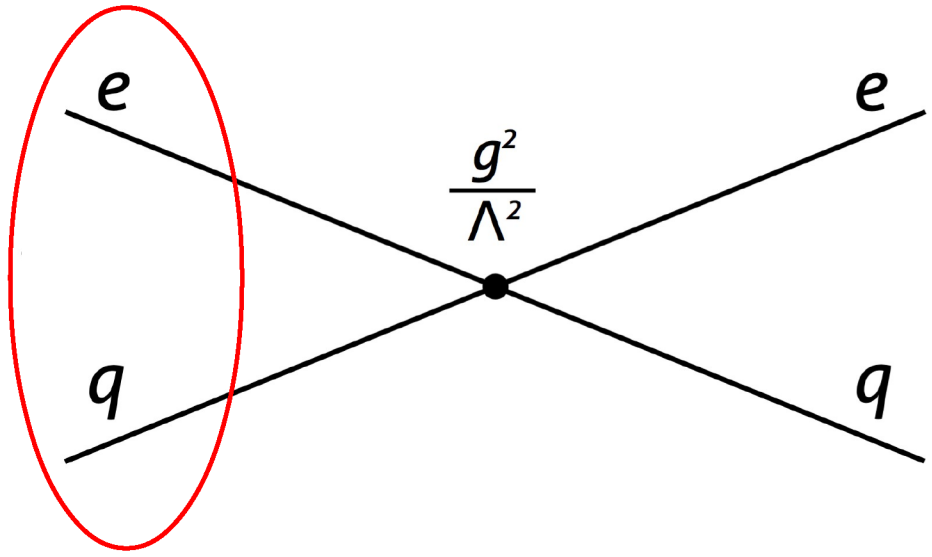
Contact Interactions
@ HERA

General Contact Interactions

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

$$\eta_{ij}^{eu} = \eta_{ij}^{ed} = \eta_{ij}^{es} = \eta_{ij}^{ec} = \eta_{ij}^{eb} = \eta_{ij}^{et}$$

$$\eta_{ij}^{eq} = \eta \epsilon_{ij} = \pm \frac{4\pi}{\Lambda^2} \epsilon_{ij}$$



... or heavy Leptoquarks

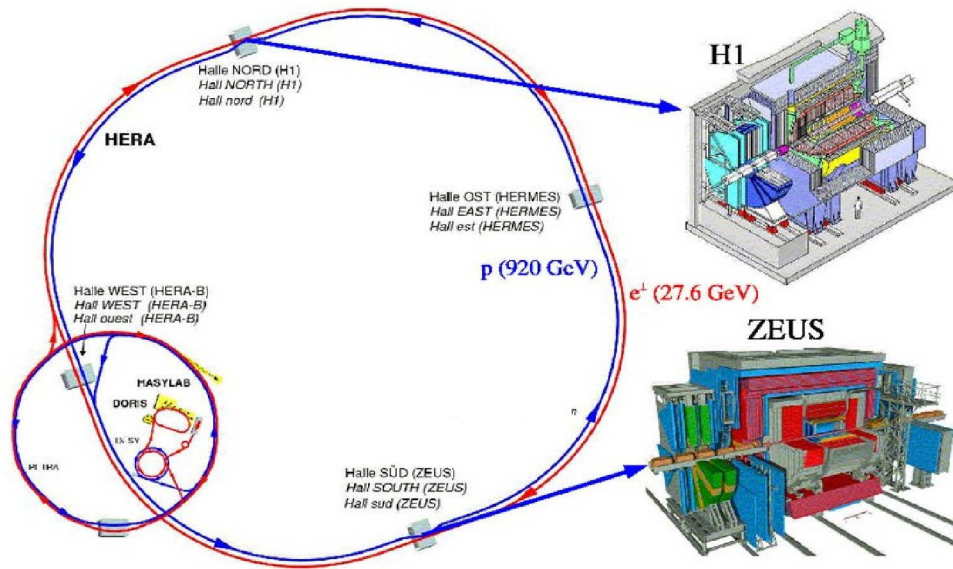
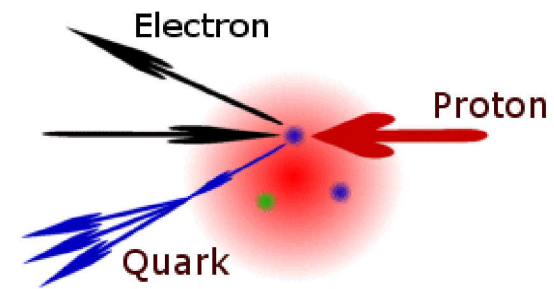
With effective LQ coupling: $\eta_{LQ} = \left(\frac{\lambda_{LQ}}{M_{LQ}} \right)^2$

With CI coupling:

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

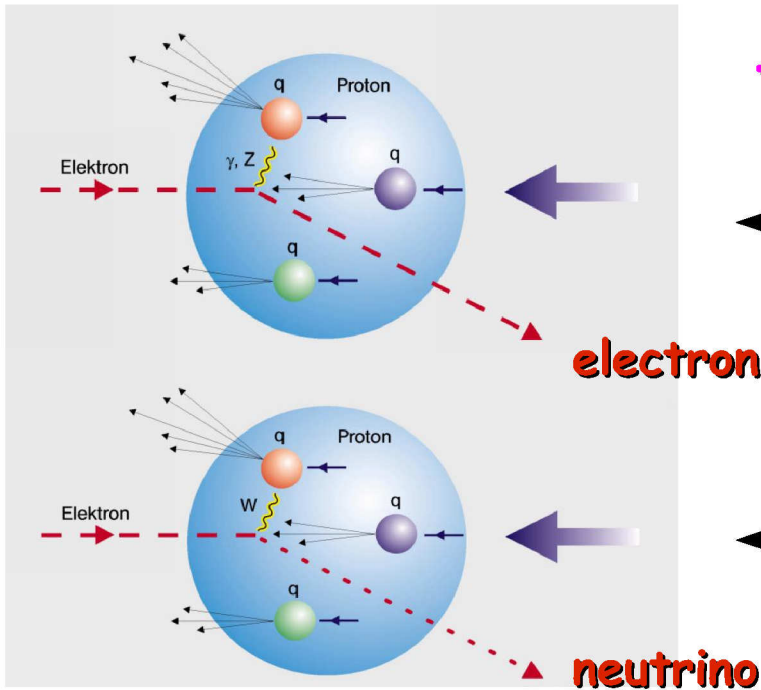
Where can we find abundant electrons and quarks to study this? ...

... at HERA, of course!



- HERA: ep collider in Hamburg
- Operation: 1992-2007
- Colliding experiments: H1 and ZEUS

... in Deep Inelastic Scattering



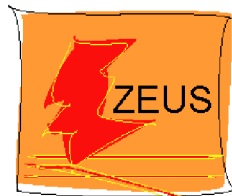
Neutral Current (NC)
 γ, Z^0 exchange

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

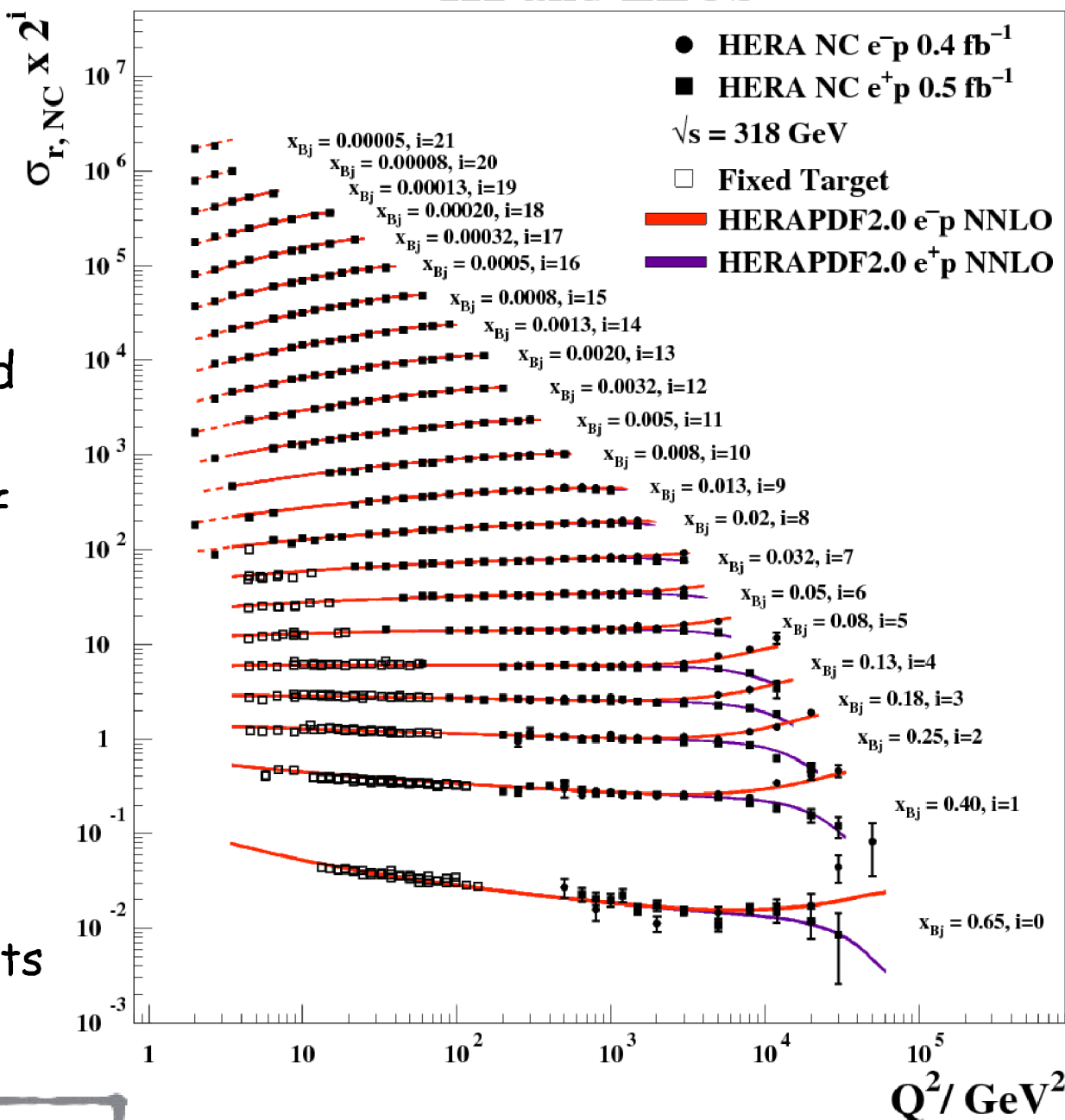
Charged Current (CC)
 W^\pm exchange

HERA combined inclusive cross sections

H1 and ZEUS

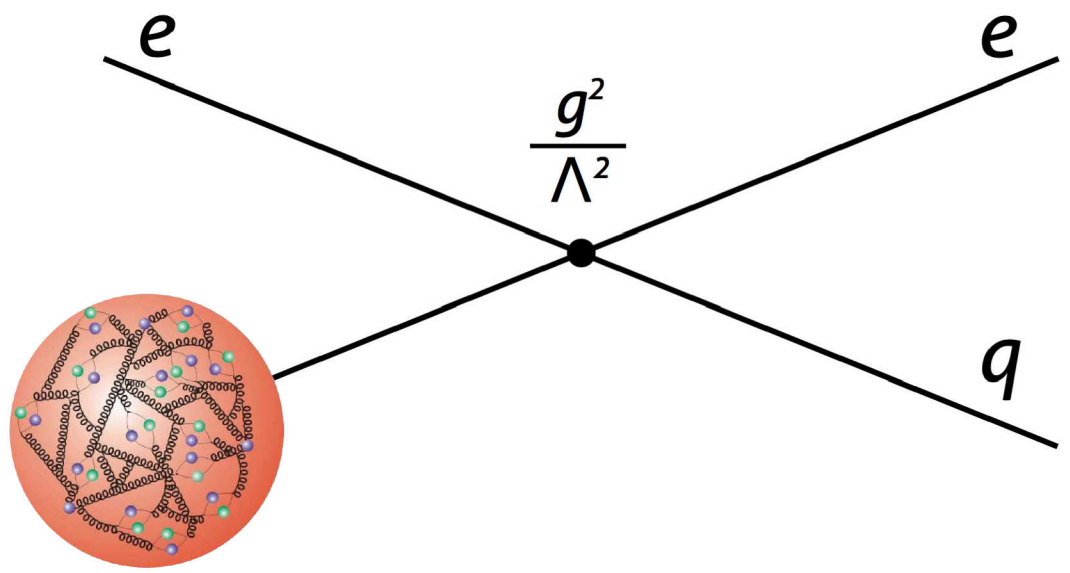
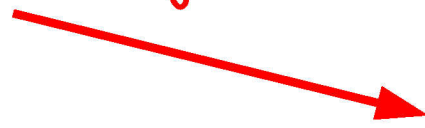


- HERA combined DIS data
- 2927 data points combined to 1307
- impressive improvement of precision due to:
 - increased statistics
 - better understanding of systematics
 - cross-calibration of the data from two experiments



HERA data are (almost) perfect but there is a caveat ...

... quarks don't come for free, they are bound in proton which is a complicated object

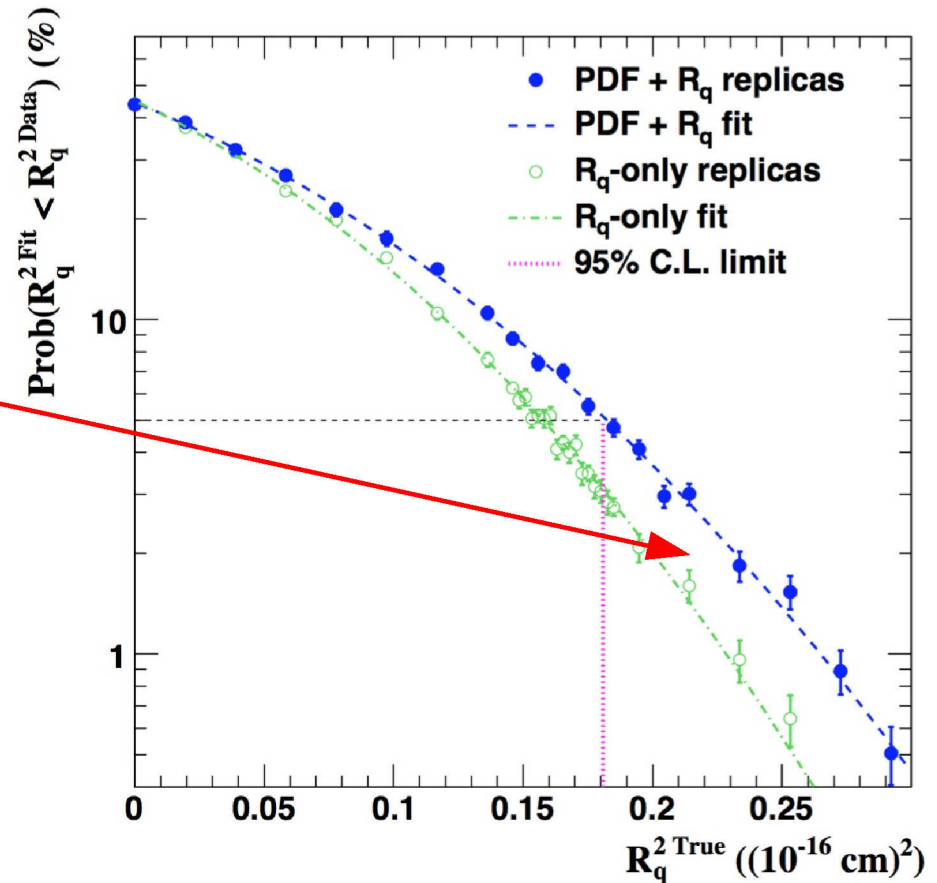


- To study any reactions with interacting proton, we need parton densities
- BSM signal in data could affect PDF fit and result in **biased PDFs**

HERA data are (almost) perfect but there is a caveat ...

ZEUS

- Use of biased PDFs in the BSM analysis results in overestimated limits
- showed in HERA quark radius analysis: Phys. Lett. B 757 (2016) 468



- All high-precision PDF fits include HERA DIS data → unavoidable problem

proper way →

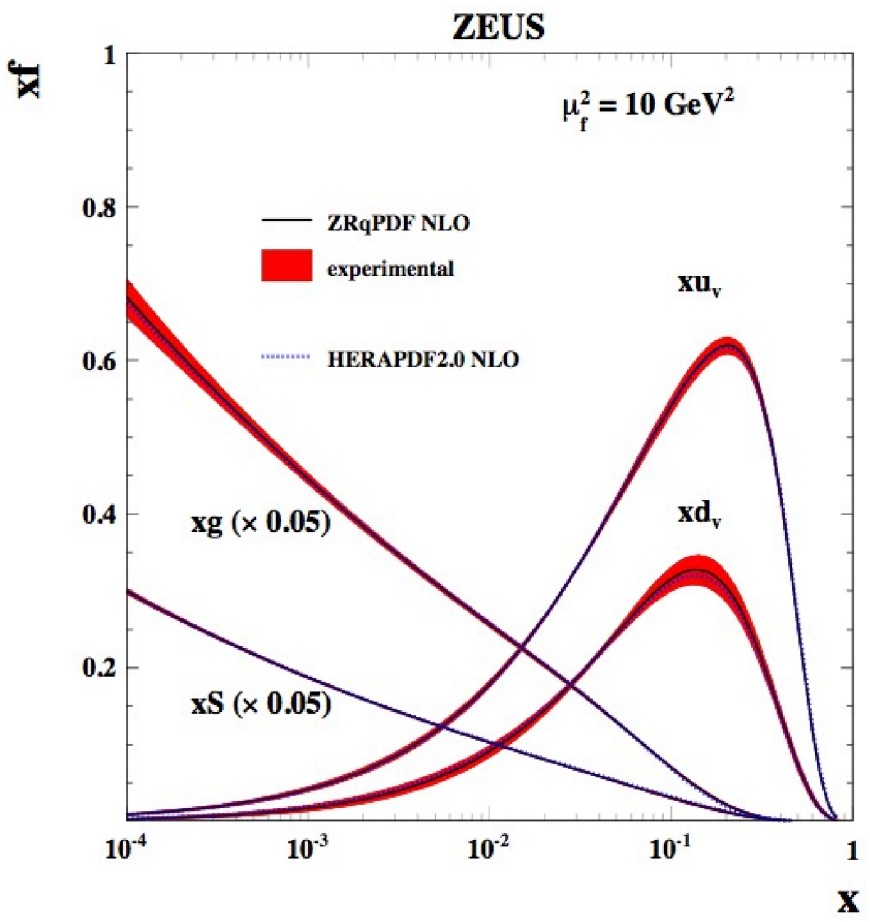
simultaneous global QCD fit of HERA data with possible BSM contribution

Simultaneous QCD + CI fit



- Fit together parton distribution functions and CI contributions
 - comparison of measured inclusive cross sections with NLO predictions
 - follows HERAPDF2.0 determination using xFitter
 - NLO QCD predictions at given x and Q^2 scaled

$$R_{CI} = \frac{\frac{d^2\sigma}{dx dQ^2}^{SM+CI}}{\frac{d^2\sigma}{dx dQ^2}^{SM}}$$



Parameterised at starting scale

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

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

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

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

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

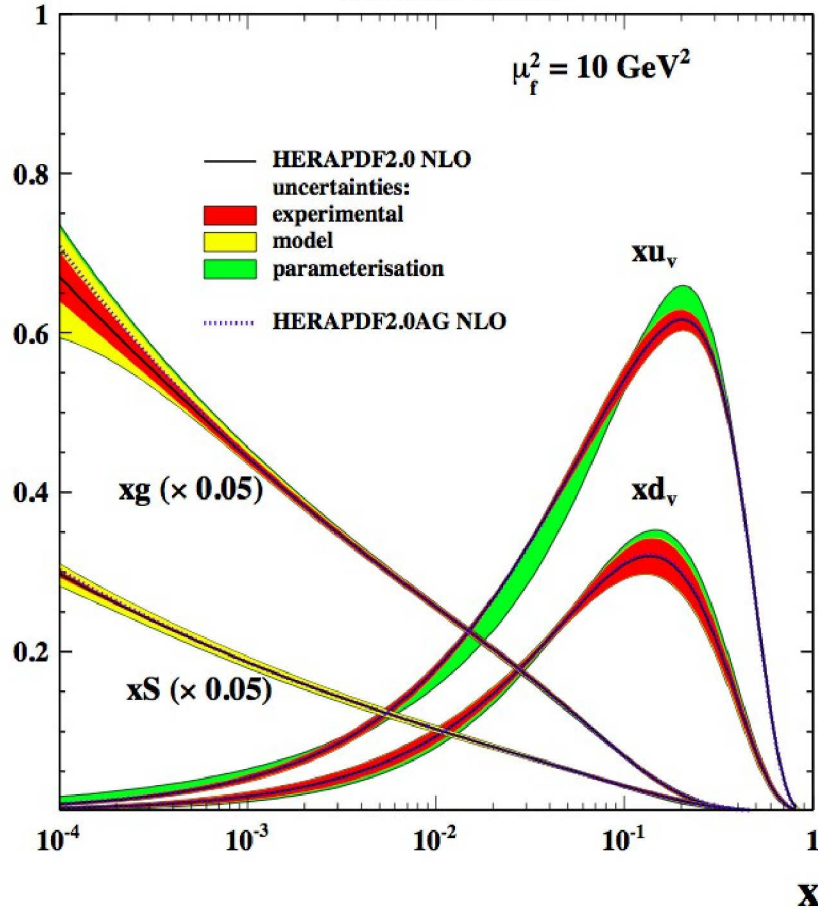
- fixed or calculated by the sum-rules
- set equal

- Evolve with DGLAP at NLO
- Obtained PDF: **ZCIPDF**
 - have good agreement with HERAPDF2.0

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

PDF uncertainties

H1 and ZEUS



- For ZCIPDF experimental and model uncertainties estimated

Experimental uncertainties:

- Hessian method
- Conventional $\Delta\chi^2 = 1 \Rightarrow 68\% \text{ CL}$

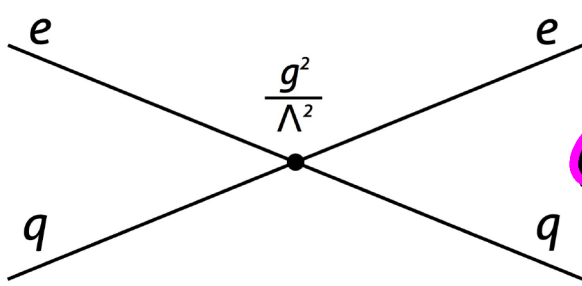
Variation	Standard Value	Lower Limit	Upper Limit
Q_{\min}^2 [GeV ²]	3.5	2.5	5.0
Q_{\min}^2 [GeV ²] HiQ2	10.0	7.5	12.5
M_c (NLO) [GeV]	1.47	1.41	1.53
M_c (NNLO) [GeV]	1.43	1.37	1.49
M_b [GeV]	4.5	4.25	4.75
f_s	0.4	0.3	0.5
μ_{f_0} [GeV]	1.9	1.6	2.2

Adding D and E parameters to each PDF

Parametrisation uncertainties
- largest deviation

Model uncertainties
- variations added in quadrature

CI models studied in this analysis



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

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... or heavy Leptoquarks

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

With CI coupling:

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

Free parameter in PDF fit

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



Results of simultaneous QCD + CI fit



- For some model improvement in data description after adding CI terms
 - Modeling uncertainties can play important role

HERA $e^\pm p$ 1994–2007 data

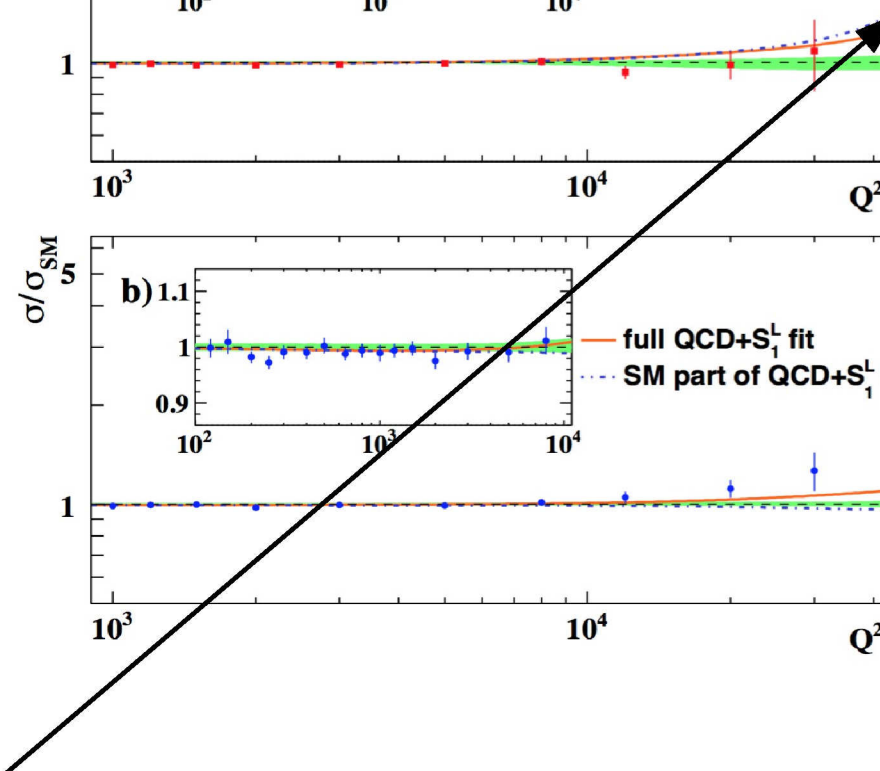
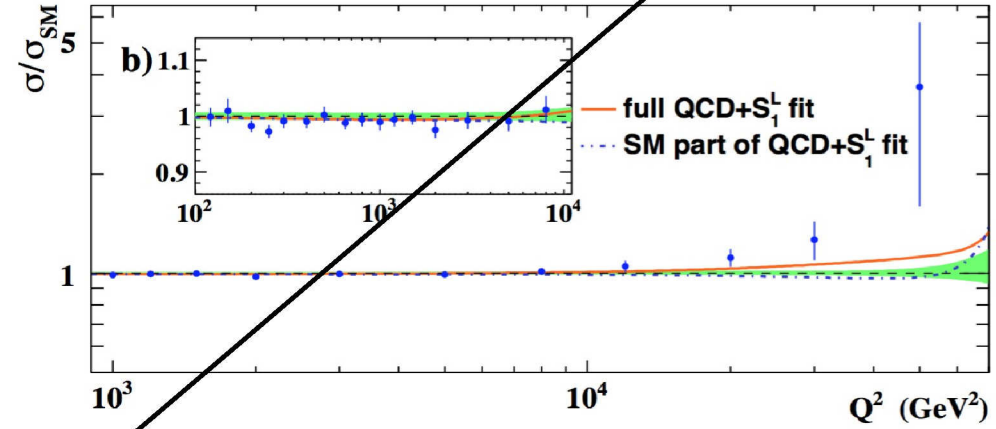
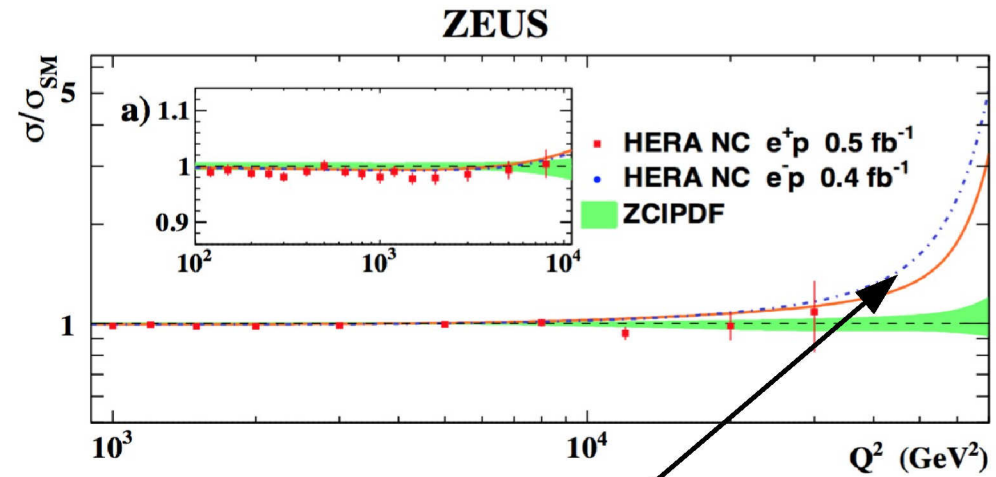
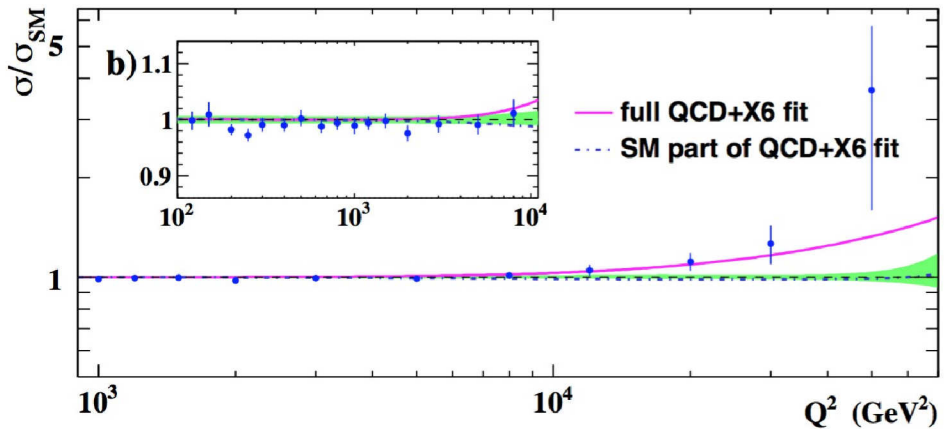
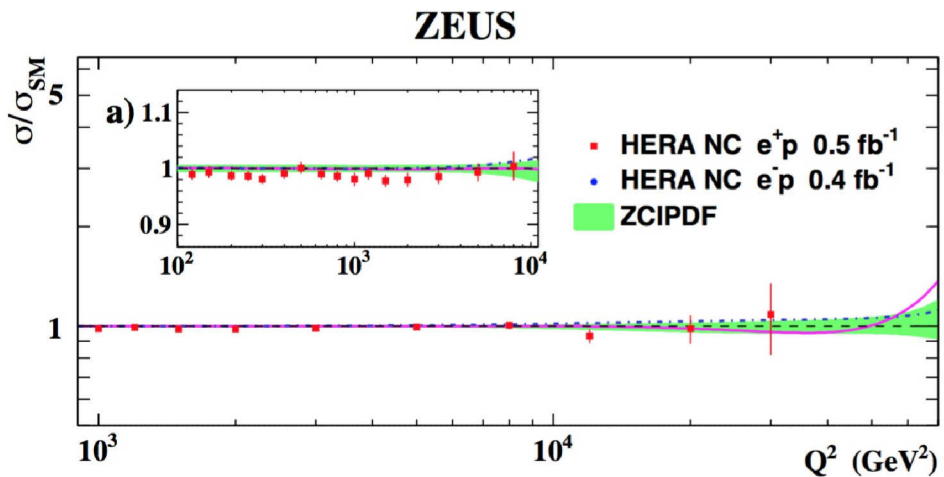
Coupling structure		Coupling fit results (TeV ⁻²)				$\Delta\chi^2$
Model	$[\epsilon_{LL}, \epsilon_{LR}, \epsilon_{RL}, \epsilon_{RR}]$	η^{Data}	δ_{exp}	δ_{mod}	δ_{tot}	
LL	[+1, 0, 0, 0]	0.305	0.206	+0.017 -0.037	+0.207 -0.209	-2.06
RR	[0, 0, 0, +1]	0.338	0.210	+0.019 -0.038	+0.210 -0.213	-2.30
LR	[0, +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

HERA $e^\pm p$ 1994–2007 data

Model	Coupling Structure	Coupling fit results (TeV ⁻²)				$\Delta\chi^2$
		$\eta_{\text{LQ}}^{\text{Data}}$	δ_{exp}	δ_{mod}	δ_{tot}	
S_0^L	$a_{LL}^{eu} = +\frac{1}{2}$	-0.258	0.196	+0.034 -0.036	+0.199 -0.199	-1.56
S_0^R	$a_{RR}^{eu} = +\frac{1}{2}$	0.533	0.331	+0.034 -0.061	+0.332 -0.336	-2.53
\tilde{S}_0^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_0^L	$a_{LL}^{ed} = -1$	-0.325	0.116	+0.030 -0.101	+0.120 -0.154	-6.17
V_0^R	$a_{RR}^{ed} = -1$	1.280	0.558	+0.111 -0.163	+0.568 -0.581	-3.98
\tilde{V}_0^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

S_1^L improvement persists after taking into account model uncertainties

Predictions for X_6 and S_1^L models

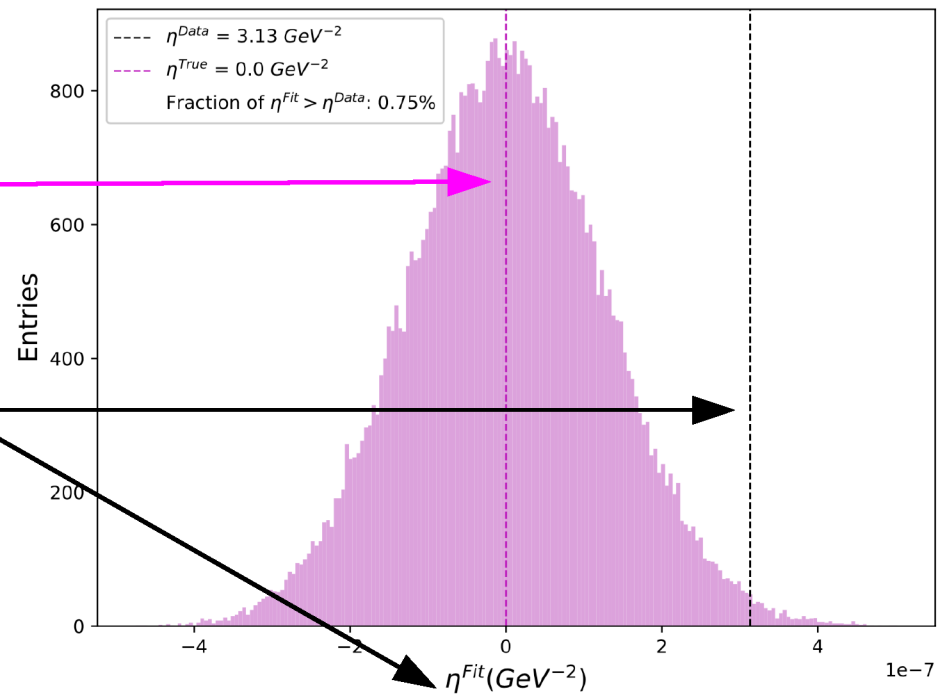


- For S_1^L description of the proton PDFs significantly affected when heavy-LQ contribution added

Setting limits using MC replicas

- Limits derived in frequentis approach using Monte Carlo replicas technique

- MC replicas of cross sections for some η^{True} calculated
- each MC replica fitted for η^{Fit} parameter **simultaneously** with PDFs
- fraction of η^{Fit} values less than η^{Data} obtained from fit of data evaluated
 → used further as $\text{Prob}(\eta^{\text{Fit}} < \eta^{\text{Data}})$

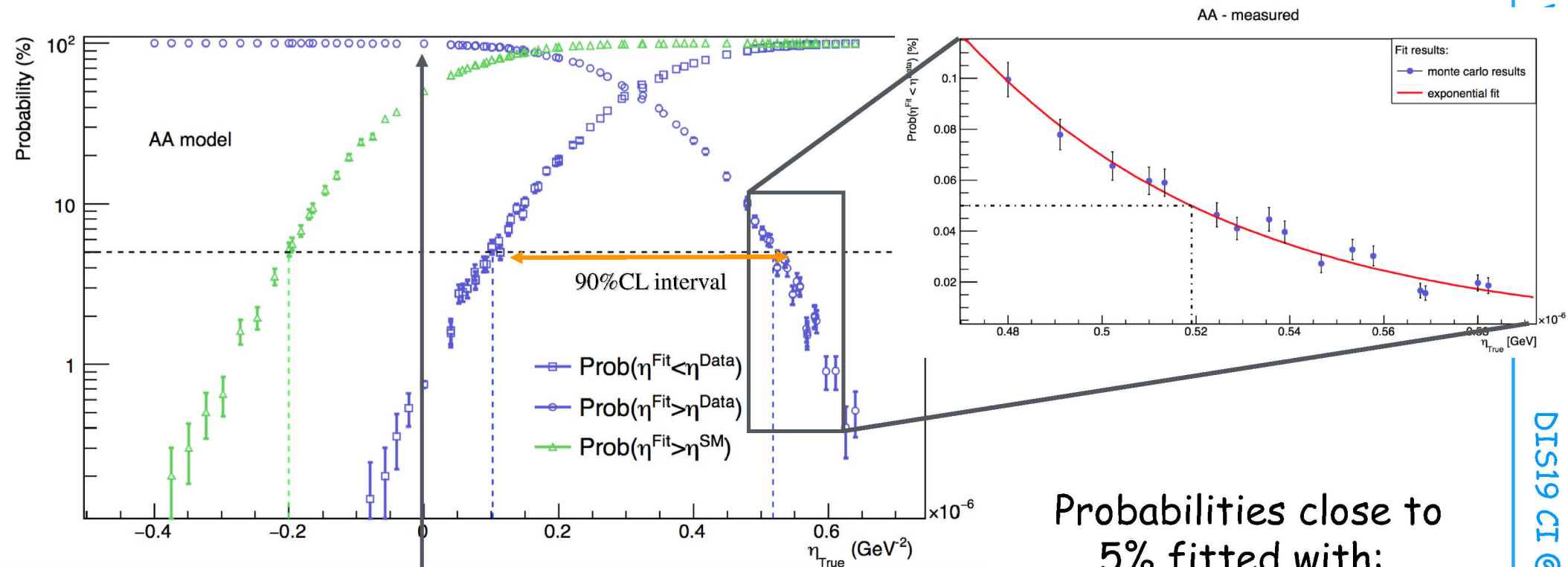


Cross-section prediction from ZRqPDF modified with η^{True} Measured cross sections Correlated systematic uncertainties

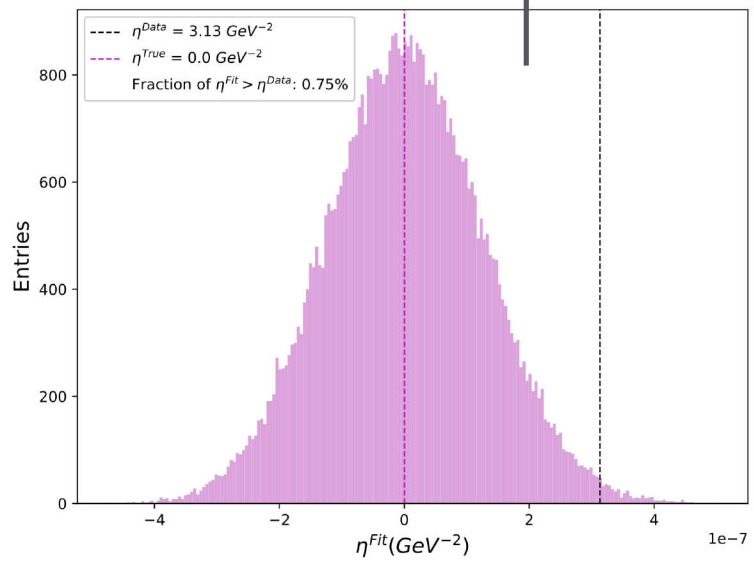
$$\mu^i = \left[m_0^i + \sqrt{\delta_{i,stat}^2 + \delta_{i,uncor}^2} \cdot \mu_0^i \cdot r_i \right] \cdot \left(1 + \sum_j \gamma_j^i \cdot r_j \right)$$

Relative stat. and uncorrelated syst. uncertainties Random numbers from normal distribution

Analysis strategy



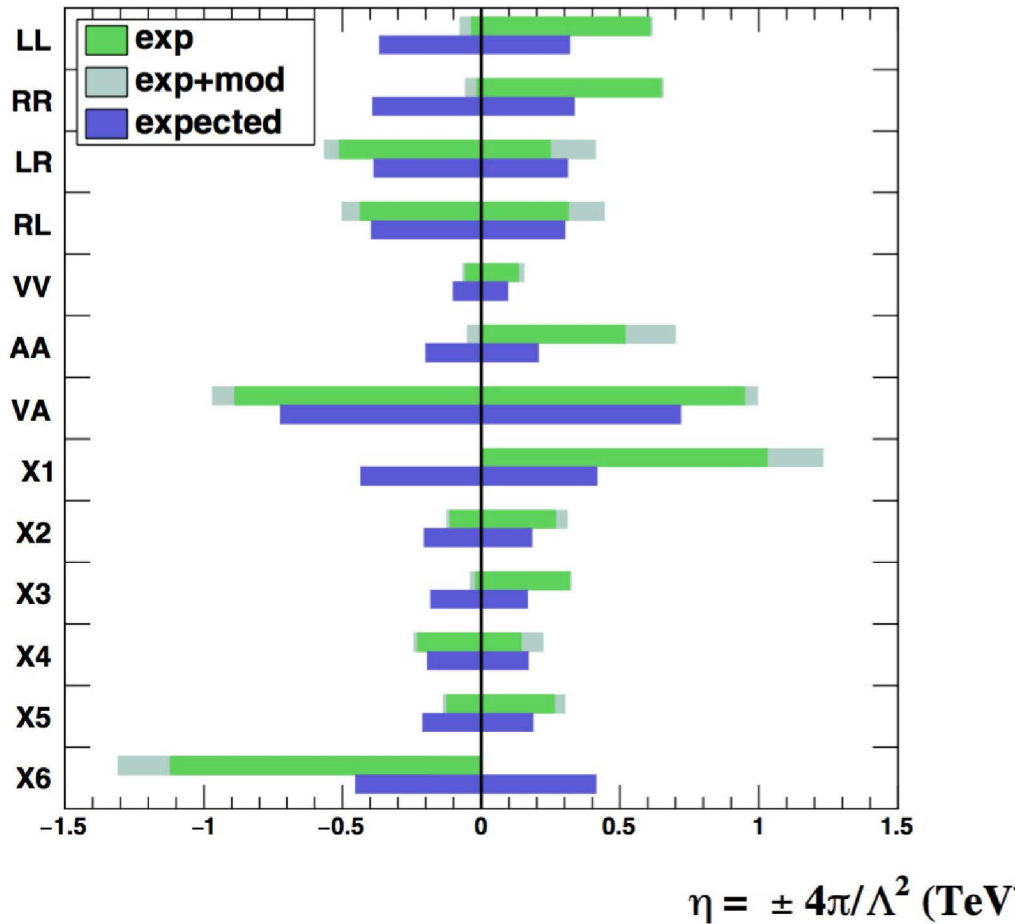
Probabilities close to 5% fitted with:

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


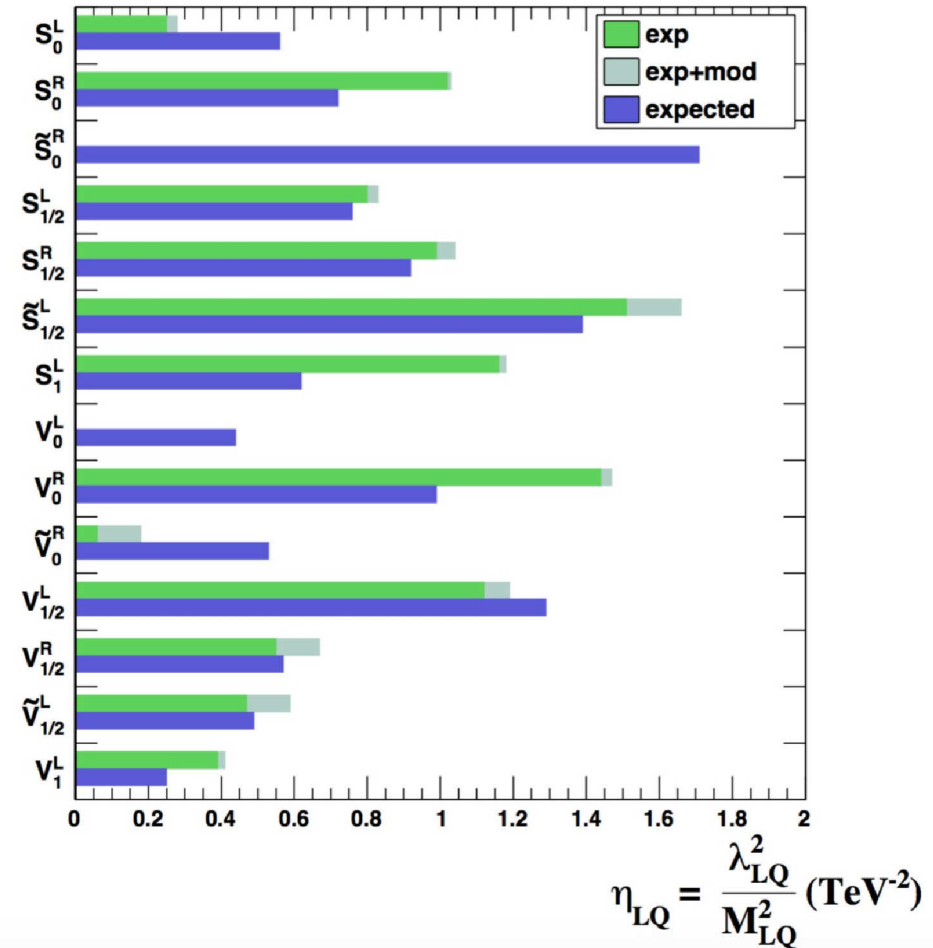
- Procedure is repeated for different η_{True}
- central 90% CL coupling interval evaluated

Results

general CI



heavy LQs



- For Yukawa coupling $\lambda_{LQ} = 1$ corresponding lower limits on LQ mass vary between 0.66 TeV for the $\tilde{S}_{1/2}^L$ and 16 TeV for \tilde{V}_0^R
- With modeling uncertainties are included: 0.60 TeV - 5.6 TeV

Comparison to LHC limits

ZEUS

Coupling structure		95% C.L. limits (TeV)					
		HERA		ATLAS		CMS	
Model	$[\epsilon_{LL}, \epsilon_{LR}, \epsilon_{RL}, \epsilon_{RR}]$	Λ^-	Λ^+	Λ^-	Λ^+	Λ^-	Λ^+
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		

- Only four CI models considered at LHC data
- For these models, the statistical sensitivity of the LHC much higher
 - systematic uncertainties from proton PDFs can be underestimated, as possible bias in parameterisation not taken into account

Conclusions

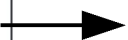
- General CI and heavy LQs studied using frequentist approach and MC replicas in simultaneous QCD+CI global fit of PDFs
- In some models deviations from SM found on level of 2-4 σ
- These deviations are unlikely to result from statistical fluctuations alone
 → might be explicable by combination of modeling uncertainties in fitting procedure and statistical fluctuations

Model	η^{Data} (TeV^{-2})	p_{SM} (%)
AA	0.326	0.6
X1	0.682	0.4
X6	-0.786	0.3



Differences from SM up to $\sim 2.7 \sigma$

Model	Coupling Structure	$\eta_{\text{LQ}}^{\text{Data}}$ (TeV^{-2})	p_{SM} (%)
S_1^L	$a_{LL}^{ed} = +1, a_{LL}^{eu} = +\frac{1}{2}$	0.974	< 0.01

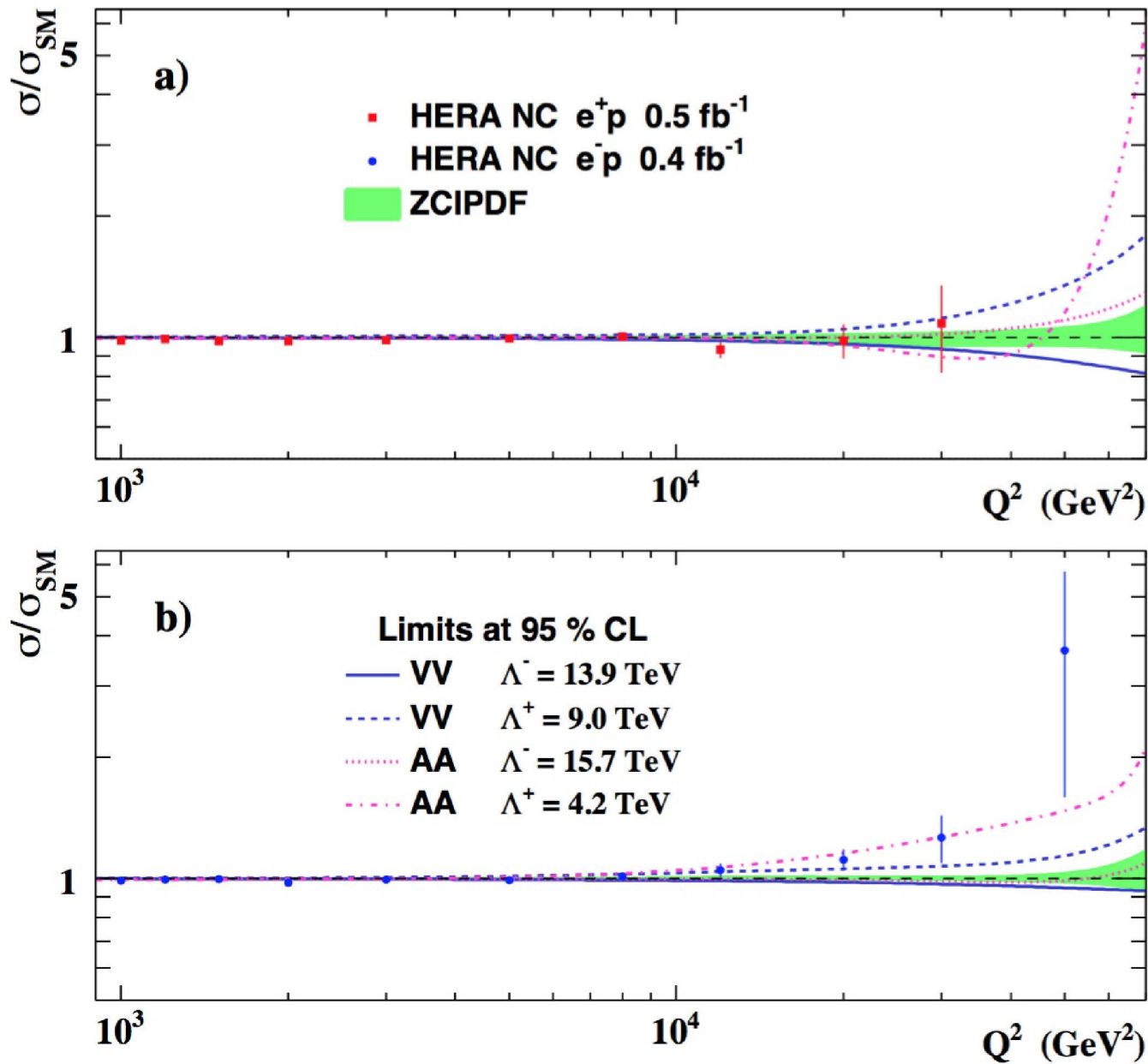


Difference from SM $\sim 4\sigma$

Back up slides

Data description: general CI

ZEUS



Data description: heavy LQs

ZEUS

