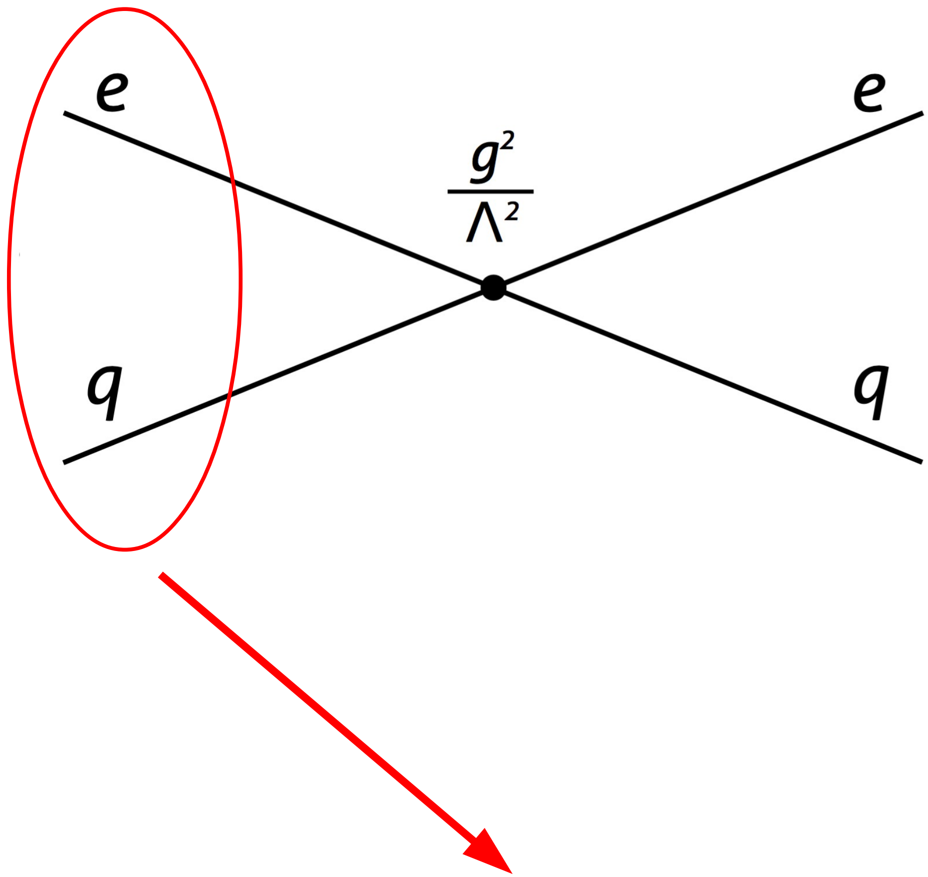

Contact Interactions
@ HERA

General Contact Interactions

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

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

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



... or heavy Leptoqurks

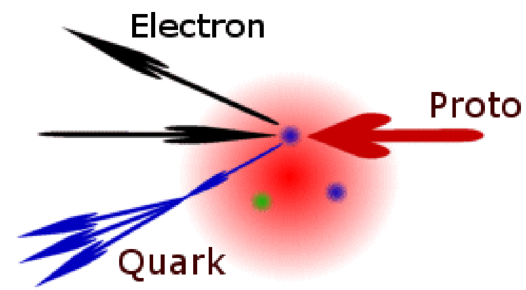
With effective LQ coupling: $\eta_{\mathrm{LQ}} = \left(\frac{\lambda_{\mathrm{LQ}}}{M_{\mathrm{LQ}}}\right)^2$

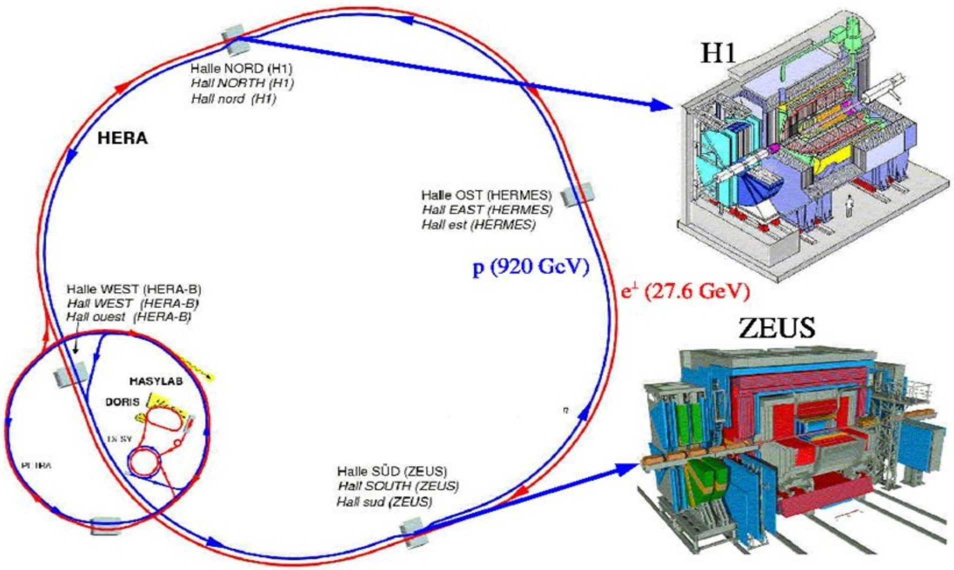
With CI coupling:

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

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

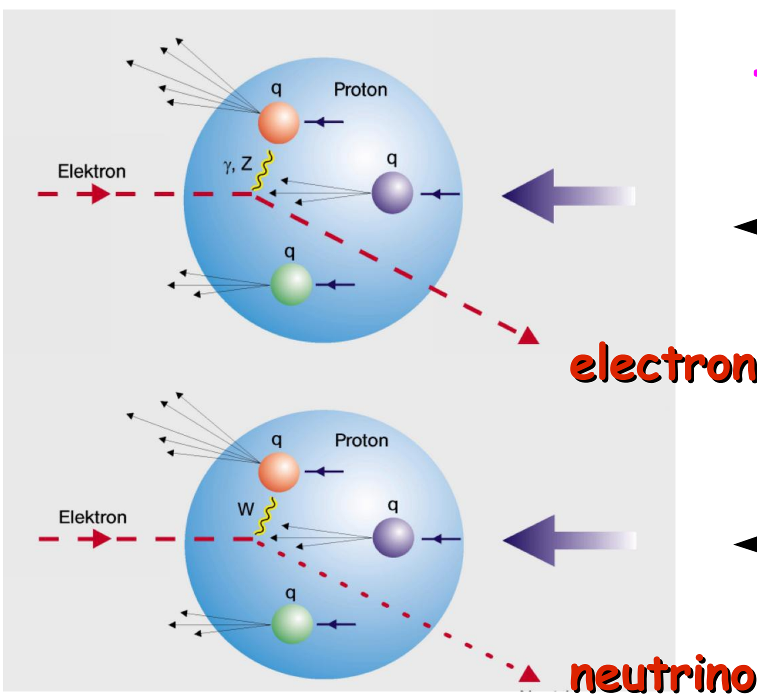
… at HERA, of course!





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

… in Deep Inelastic Scattering



Neutral Current (NC)

γ, Z^0 exchange

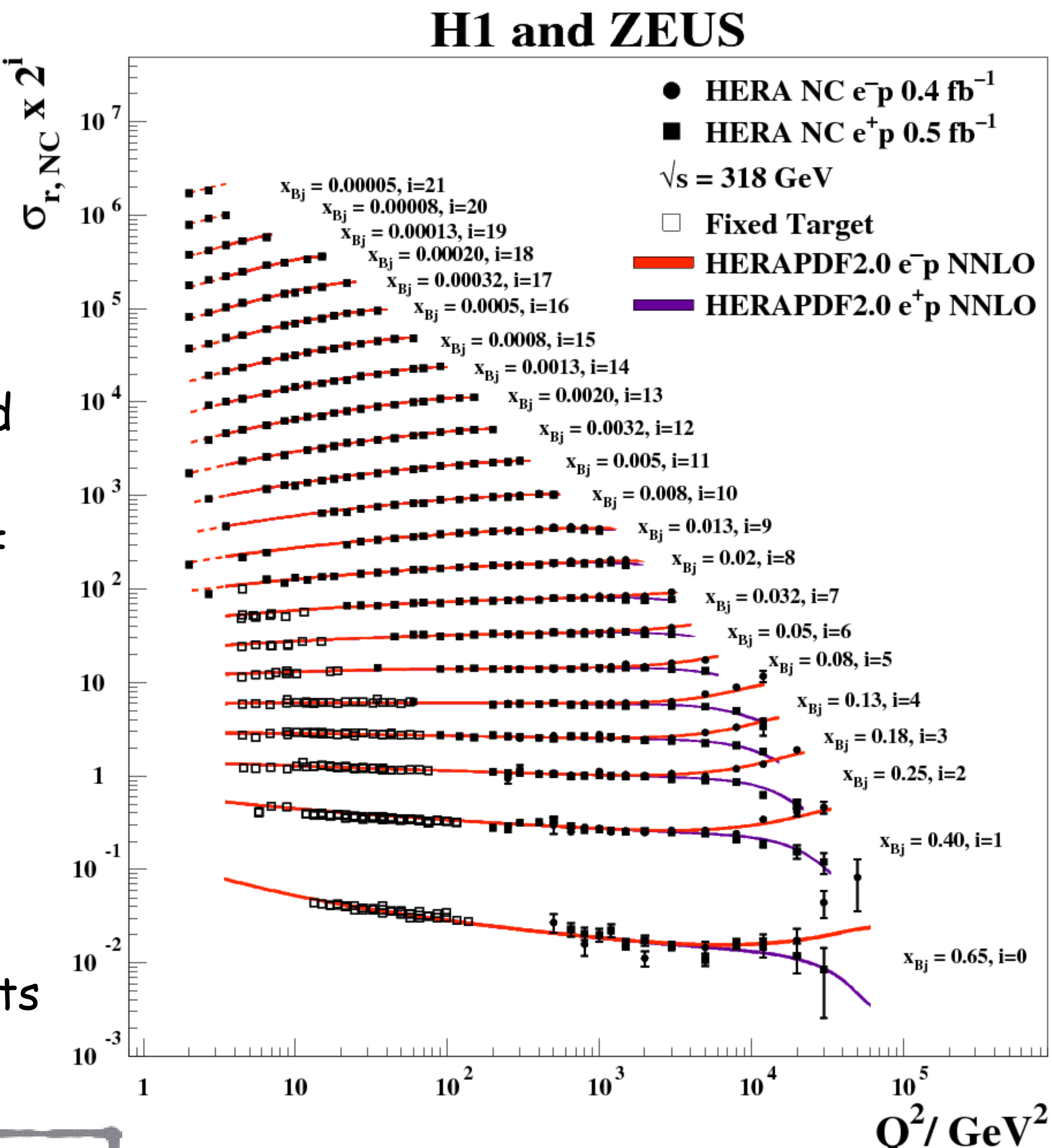
$$Q^2 = -q^2 = -(k - k')^2$$

Charged Current (CC)

$W^{\pm}$ exchange

HERA combined inclusive cross sections

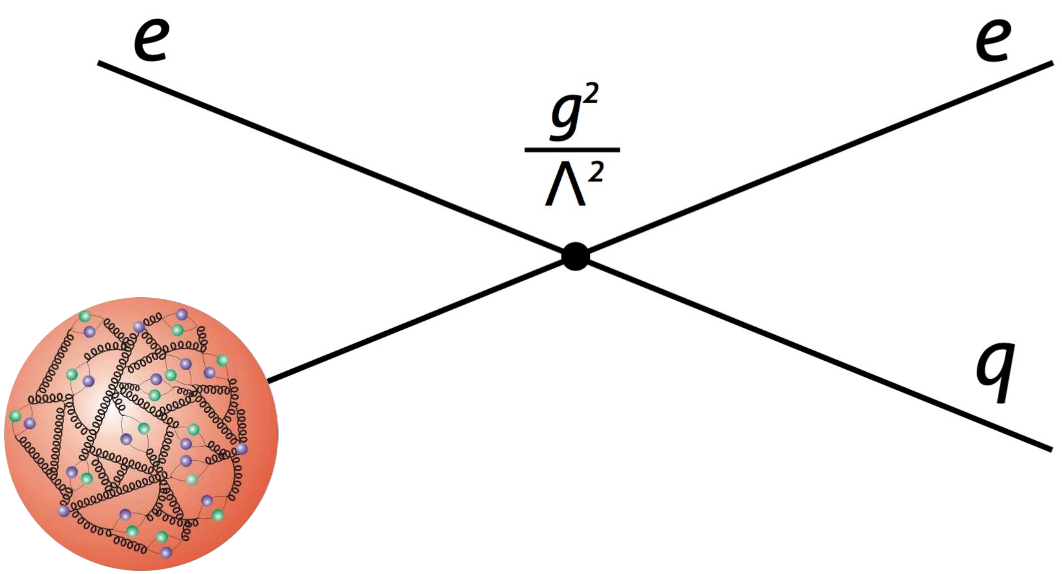
- HERA combined DIS data
- 2927 data points combined to 1307
- impressive improvement of precision due to:
  - increased statistics
  - better understanding of systematics
  - cross-calibration of the data from two experiments



Eur. Phys. J. **C75** (2015), 12, 580

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

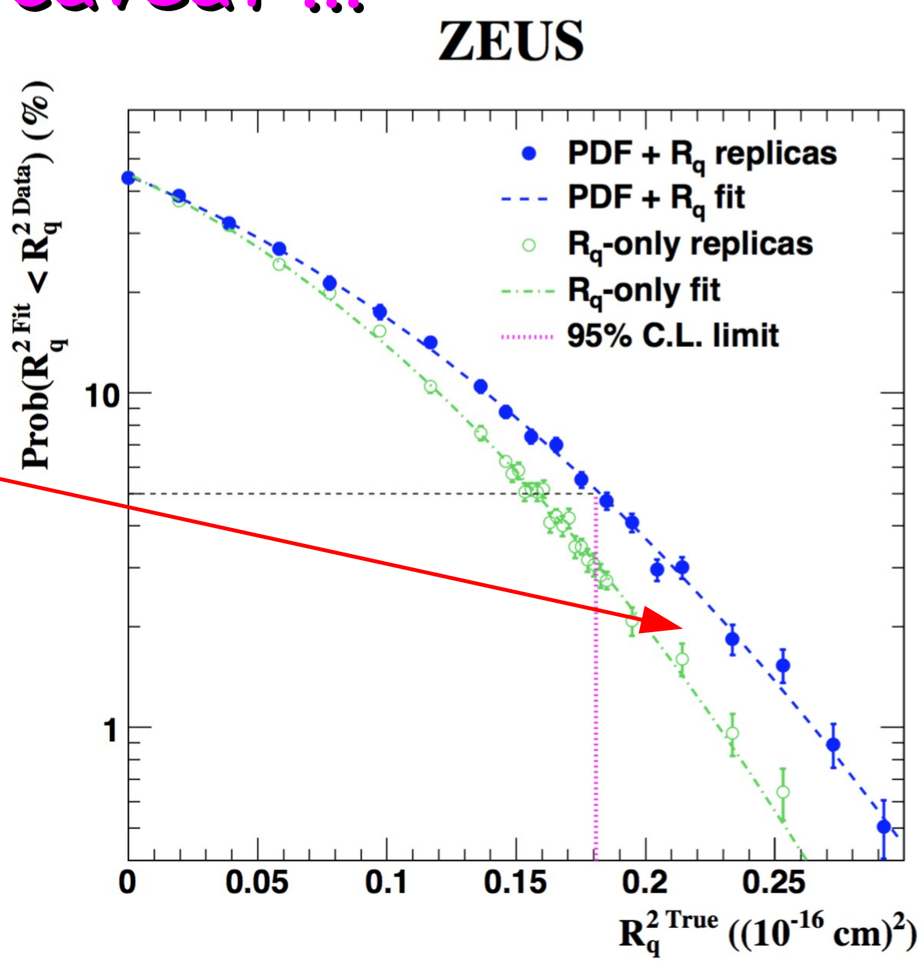


- To study any reactions with interacting proton, we need parton densities
- BSM signal in data could affect PDF fit and result in **biased PDFs**

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

- 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

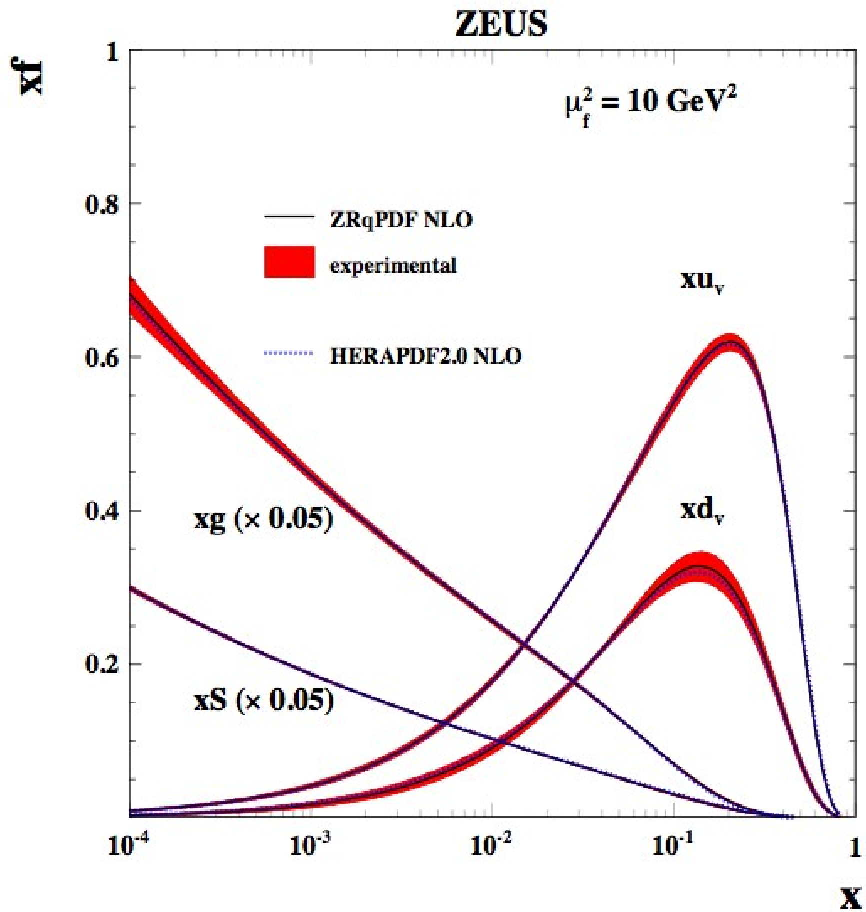
proper way →

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

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



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

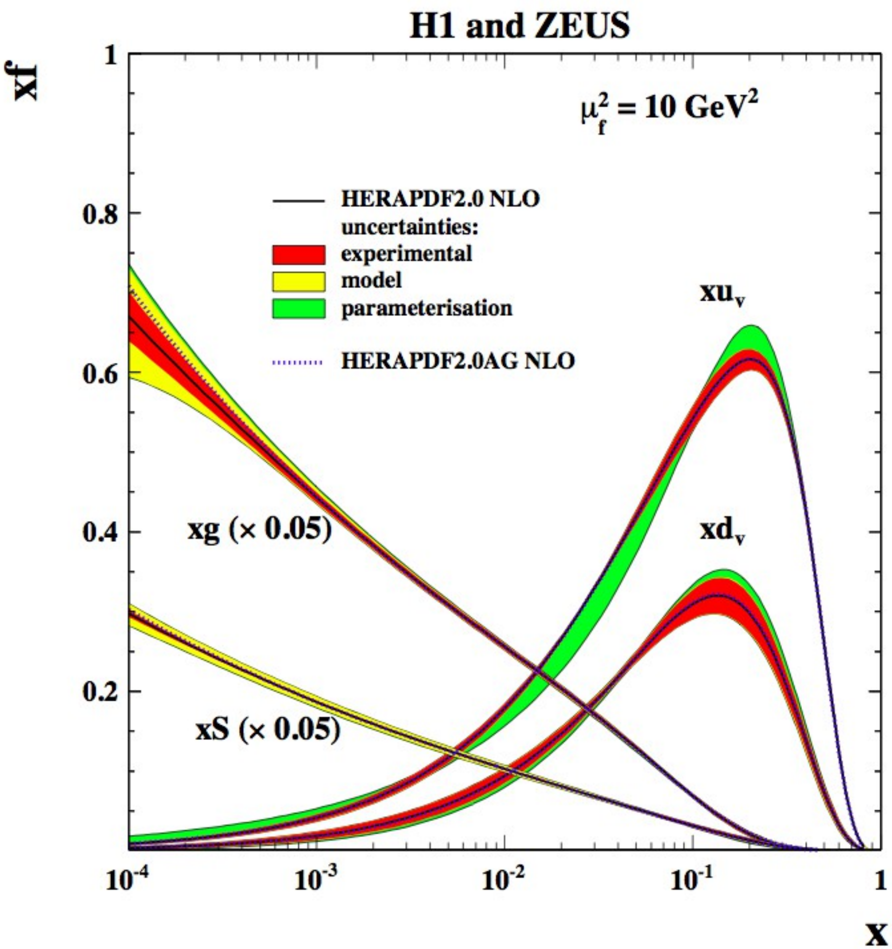
Parameterised at starting scale

$$xg(x) = A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g}$$
$$xu_v(x) = A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+E_{u_v}x^2\right)$$
$$xd_v(x) = A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}$$
$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}\left(1+D_{\bar{U}}x\right)$$
$$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}$$

(grey) fixed or calculated by the sum-rules
(pink) set equal

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

PDF uncertainties



- For ZCIPDF experimental and model uncertainties estimated

Experimental uncertainties:

- Hessian method
- Conventional $\Delta\chi^2 = 1$ => 68% CL

Variation	Standard Value	Lower Limit	Upper Limit
Q^2_{min} [GeV^2]	3.5	2.5	5.0
Q^2_{min} [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

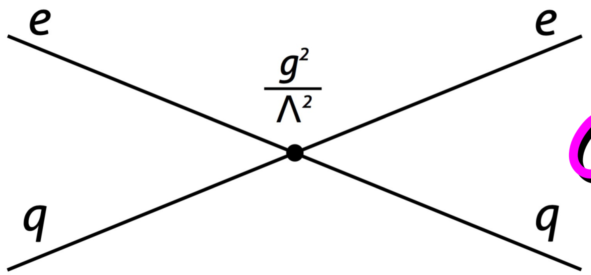
Parametrisation uncertainties

- largest deviation

Model uncertainties

- ariations added in quadrature

arXiv:1902.03048, accepted by PRD



CI models studied in this analysis

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

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

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

… or heavy Leptoqurks

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

With CI coupling:

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

Free parameter in PDF fit

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

Model	Coupling structure $[\epsilon_{LL}, \epsilon_{LR}, \epsilon_{RL}, \epsilon_{RR}]$	Coupling fit results (TeV^{-2}) 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

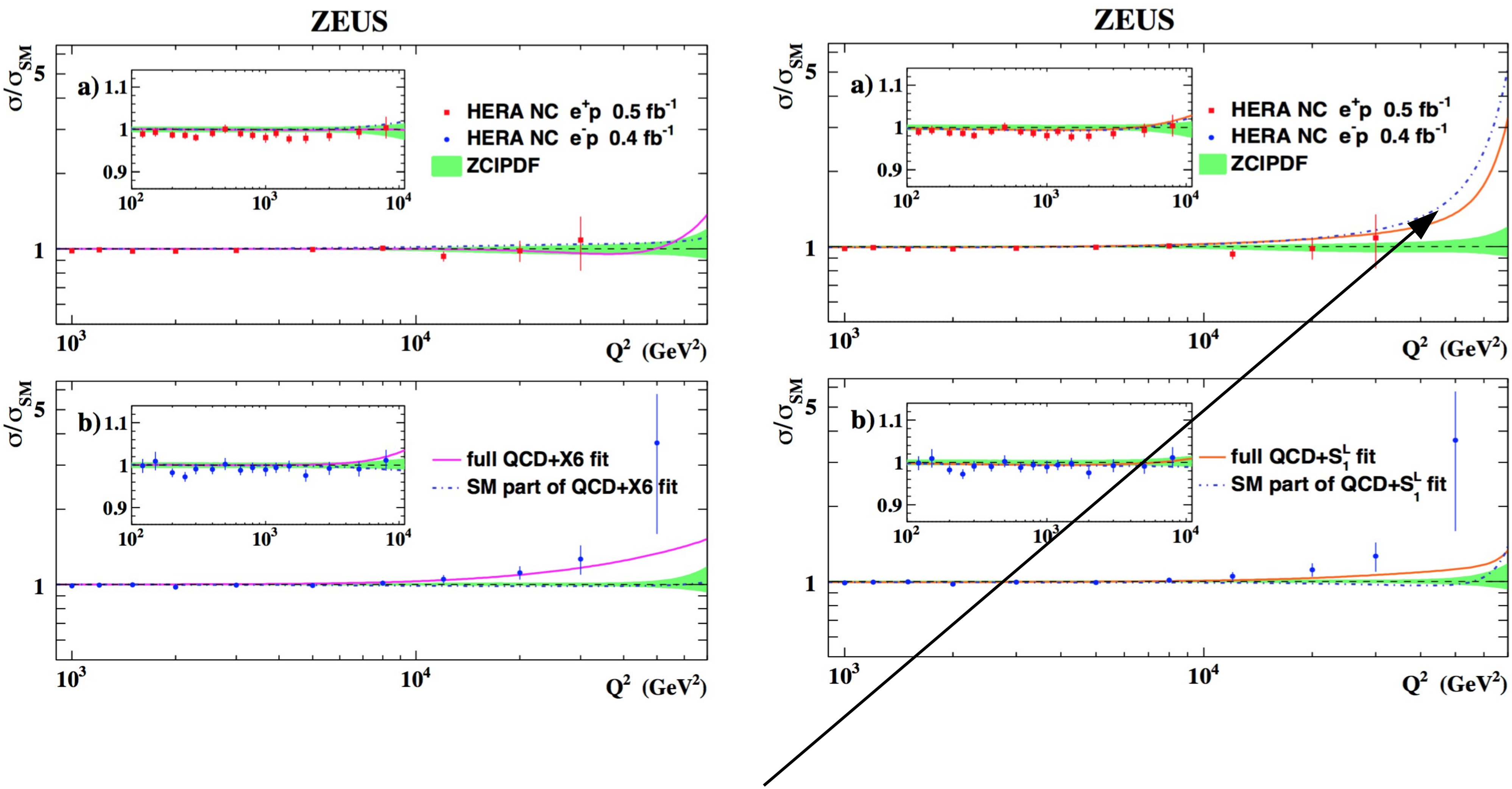
HERA $e^{\pm}p$ 1994–2007 data

Model	Coupling Structure	Coupling fit results (TeV^{-2}) $\eta^{\mathrm{Data}}_{\mathrm{LQ}}$	δ_{exp}	δ_{mod}	δ_{tot}	$\Delta\chi^2$
S_0^L	$a^{eu}_{LL} = +\frac{1}{2}$	−0.258	0.196	$^{+0.034}_{-0.036}$	$^{+0.199}_{-0.199}$	−1.56
S_0^R	$a^{eu}_{RR} = +\frac{1}{2}$	0.533	0.331	$^{+0.034}_{-0.061}$	$^{+0.332}_{-0.336}$	−2.53
$\tilde{S}_0^R$	$a^{ed}_{RR} = +\frac{1}{2}$	−2.561	1.115	$^{+0.323}_{-0.221}$	$^{+1.161}_{-1.137}$	−3.98
$S_{1/2}^L$	$a^{eu}_{LR} = -\frac{1}{2}$	0.054	0.341	$^{+0.075}_{-0.280}$	$^{+0.349}_{-0.441}$	−0.02
$S_{1/2}^R$	$a^{ed}_{RL} = a^{eu}_{RL} = -\frac{1}{2}$	0.112	0.491	$^{+0.118}_{-0.412}$	$^{+0.505}_{-0.641}$	−0.05
$\tilde{S}_{1/2}^L$	$a^{ed}_{LR} = -\frac{1}{2}$	0.464	1.371	$^{+0.925}_{-0.264}$	$^{+1.654}_{-1.396}$	−0.10
S_1^L	$a^{ed}_{LL} = +1,\ a^{eu}_{LL} = +\frac{1}{2}$	0.974	0.203	$^{+0.043}_{-0.337}$	$^{+0.207}_{-0.393}$	−11.10
V_0^L	$a^{ed}_{LL} = -1$	−0.325	0.116	$^{+0.030}_{-0.101}$	$^{+0.120}_{-0.154}$	−6.17
V_0^R	$a^{ed}_{RR} = -1$	1.280	0.558	$^{+0.111}_{-0.163}$	$^{+0.568}_{-0.581}$	−3.98
$\tilde{V}_0^R$	$a^{eu}_{RR} = -1$	−0.267	0.165	$^{+0.030}_{-0.017}$	$^{+0.168}_{-0.166}$	−2.53
$V_{1/2}^L$	$a^{ed}_{LR} = +1$	−0.232	0.685	$^{+0.132}_{-0.460}$	$^{+0.698}_{-0.825}$	−0.10
$V_{1/2}^R$	$a^{ed}_{RL} = a^{eu}_{RL} = +1$	−0.056	0.246	$^{+0.206}_{-0.059}$	$^{+0.320}_{-0.253}$	−0.05
$\tilde{V}_{1/2}^L$	$a^{eu}_{LR} = +1$	−0.027	0.171	$^{+0.139}_{-0.038}$	$^{+0.220}_{-0.175}$	−0.02
V_1^L	$a^{ed}_{LL} = -1,\ a^{eu}_{LL} = -2$	0.029	0.077	$^{+0.015}_{-0.013}$	$^{+0.079}_{-0.079}$	−0.14

S^L_1 improvement persists after taking into account model uncertainties

K. Wichmann

Predictions for X6 and S^L_1 models



- For S^L_1 description of the proton PDFs significantly affected when heavy-LQ contribution added

Setting limits using MC replicas

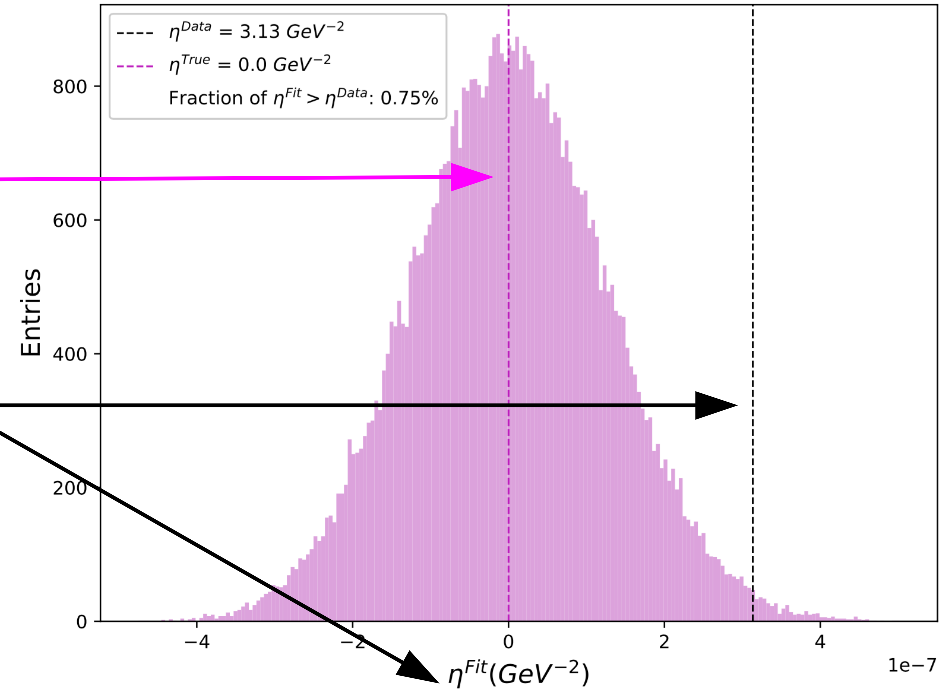
- Limits derived in frequentis approach using Monte Carlo replicas technique

(1) MC replicas of cross sections for some η^{True} calculated

(2) each MC replica fitted for η^{Fit} parameter **simultaneously** with PDFs

(3) fraction of η^{Fit} values less than η^{Data} obtained from fit of data evaluated

→ used further as Prob($\eta^{Fit} < \eta^{Data}$)



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

Measured cross sections

Correlated systematic uncertainties

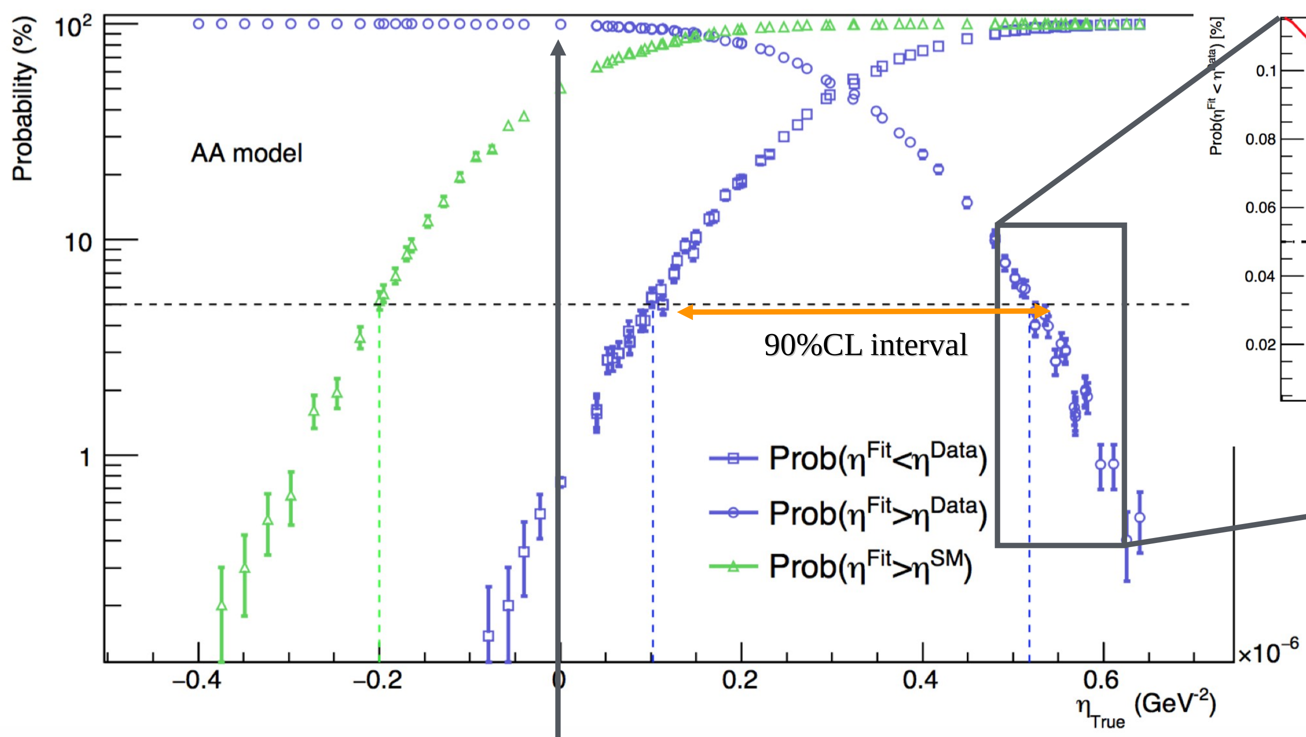
$$\mu^i = \left[m_0^i + \sqrt{\delta_{i,stat}^2 + \delta_{i,uncor}^2} \cdot \mu_0^i \cdot r_i\right] \cdot \left(1 + \sum_j \gamma_j^i \cdot r_j\right)$$

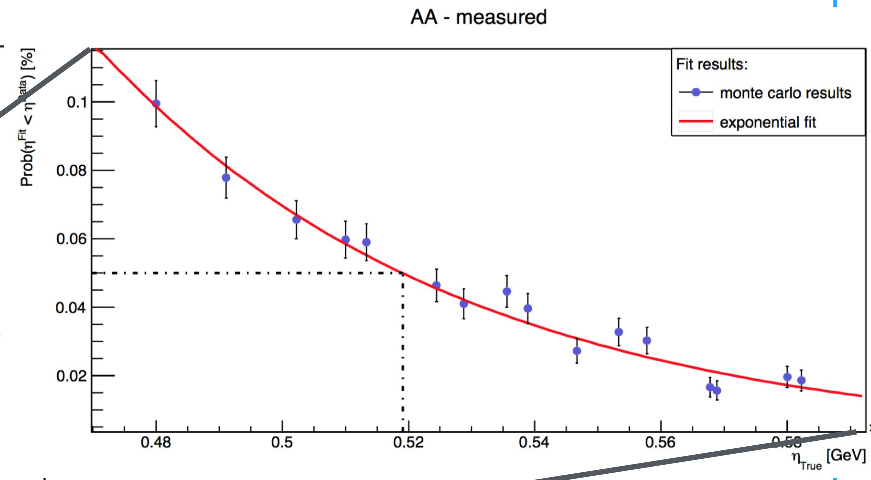
Relative stat. and uncorrelated syst. uncertainties

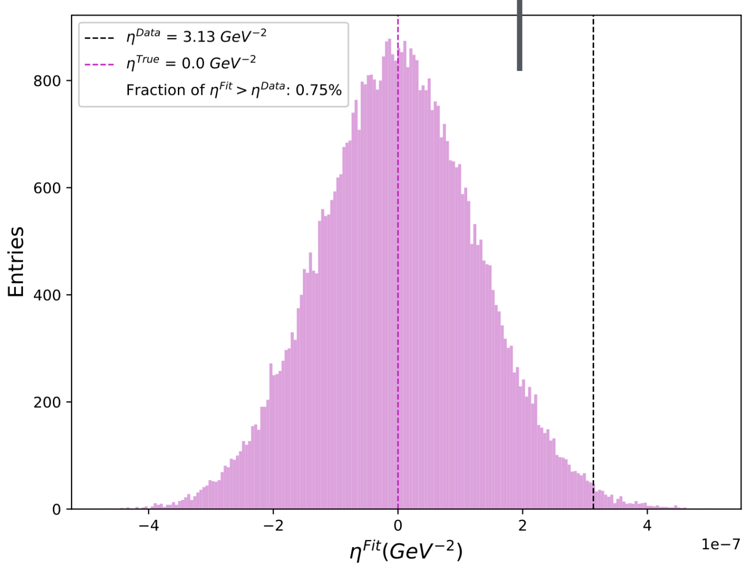
Random numbers from normal distribution

K. Wichmann

Analysis strategy







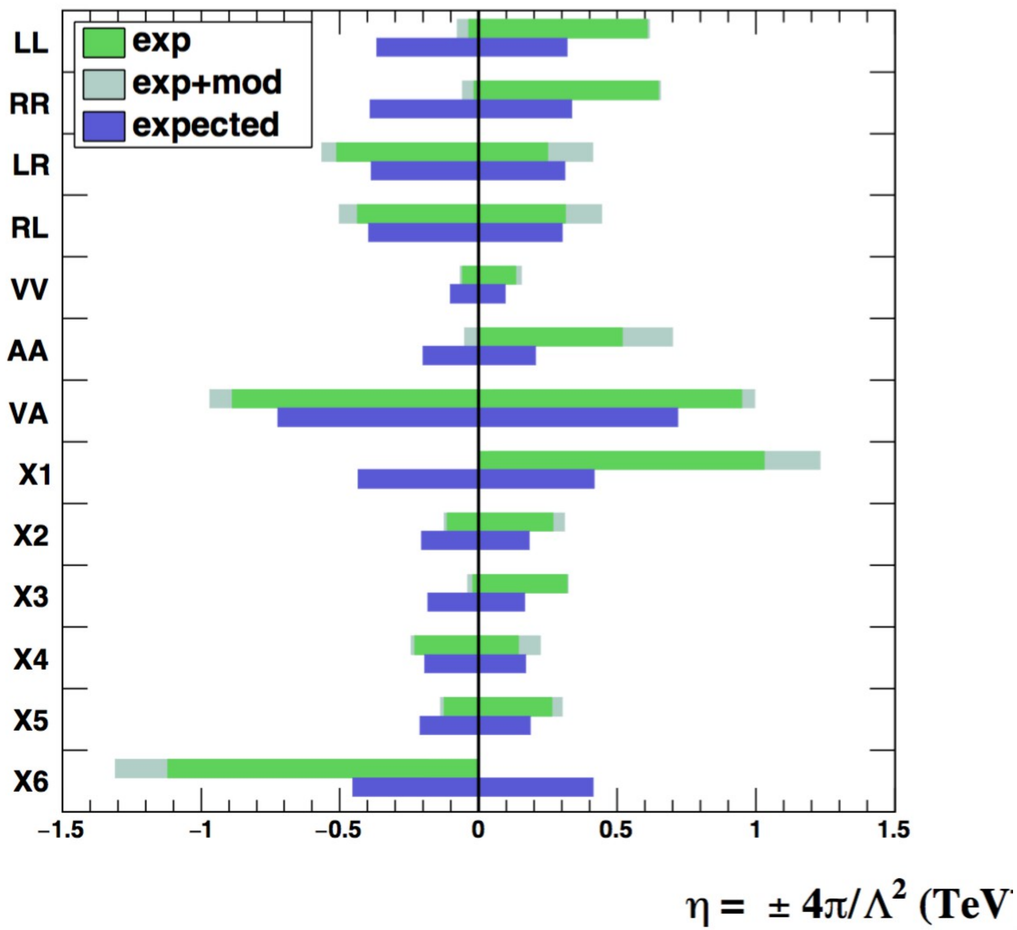
Probabilities close to 5% fitted with:

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

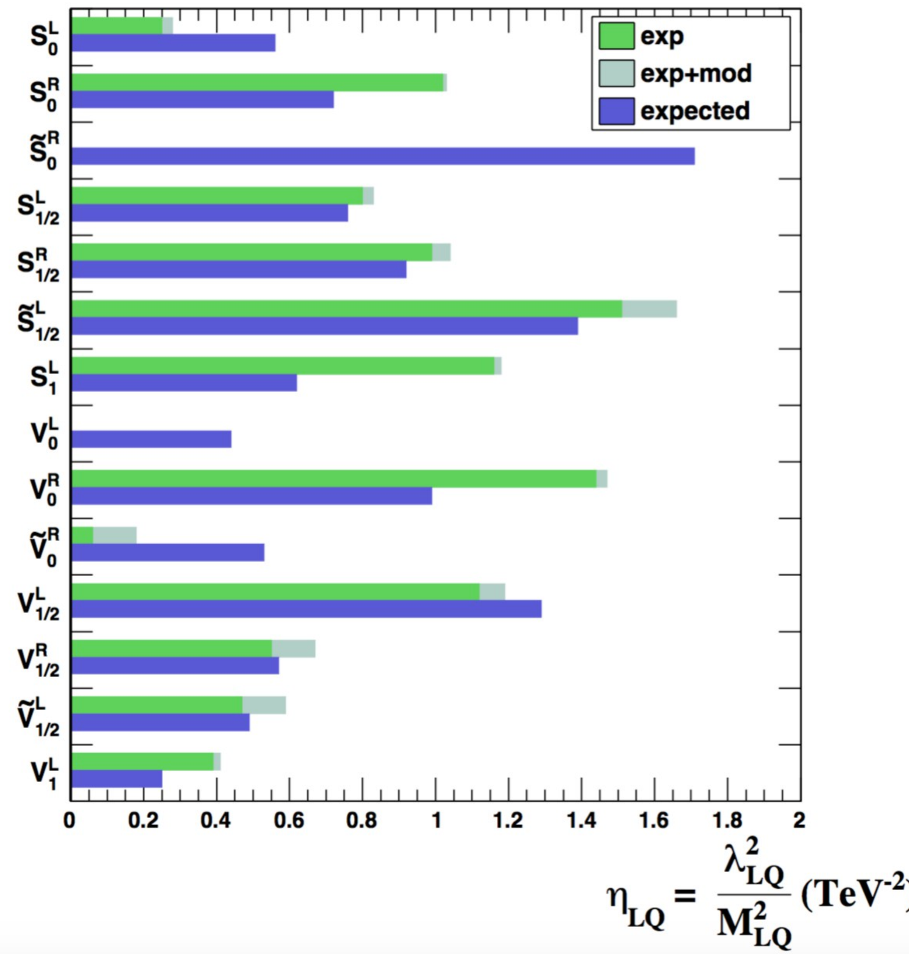
- Procedure is repeated for different η^{True}
- central 90% CL coupling interval evaluated

Results

general CI



heavy LQs



- For Yukawa coupling λ_{LQ} = 1 corresponding lower limits on LQ mass vary between 0.66 TeV for the $\tilde{S}^L_{1/2}$ and 16 TeV for $\tilde{V}^R_0$
- 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

$\rightarrow$ 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

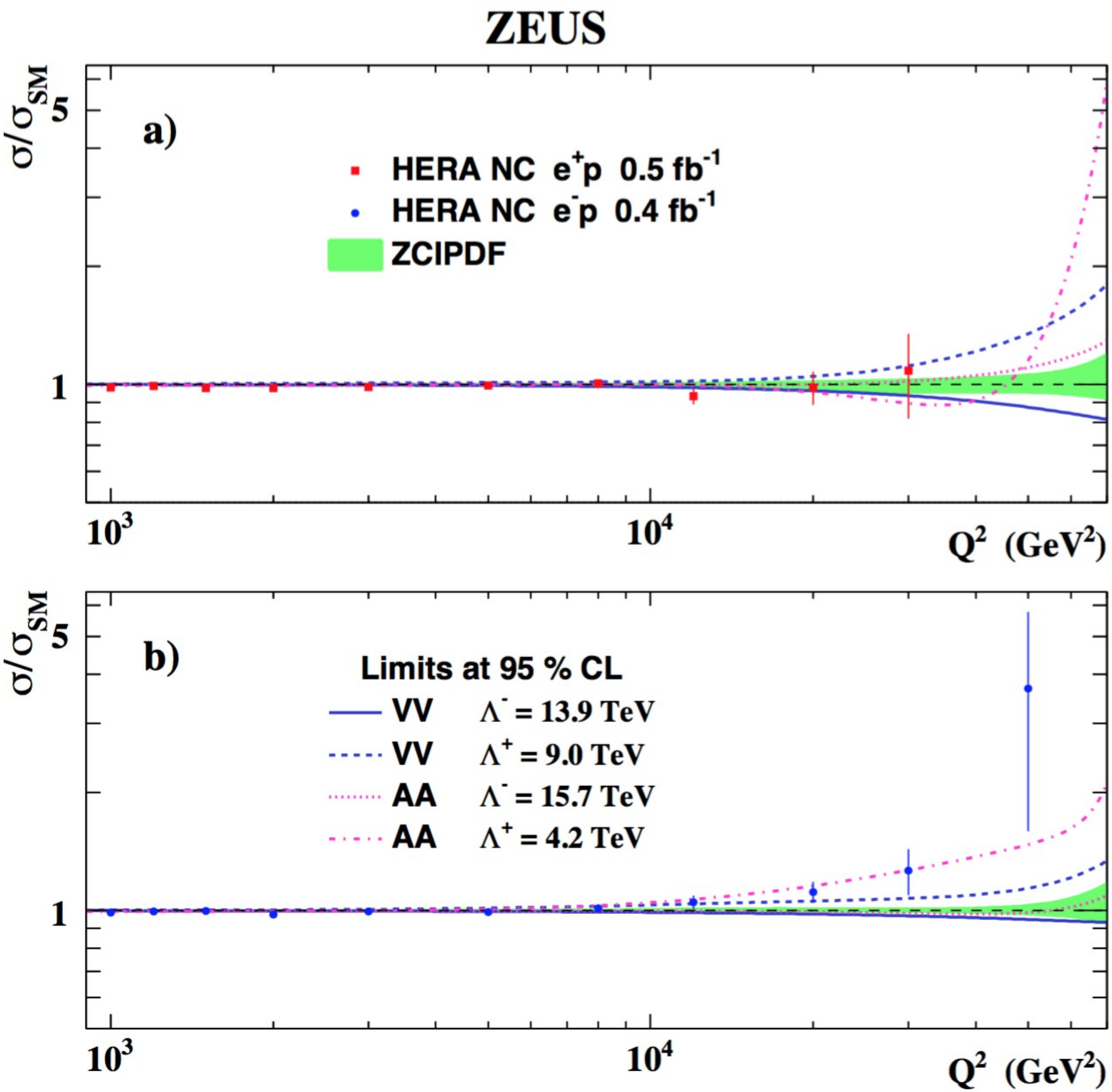
→ Differences from SM up to ~2.7 σ

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

→ Difference from SM ~ 4σ

Back up slides

Data description: general CI



Data description: heavy LQs