Limits on the effective quark radius and the contact-interaction mass scales from inclusive *ep* scattering at HERA.

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on behalf of the ZEUS collaboration

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Outline

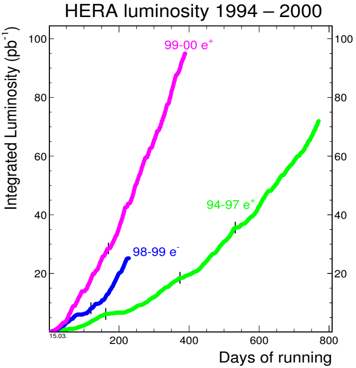
HERA

electron(positron)-proton collider at DESY

HERA I 1994-2000

about $100pb^{-1}$ collected per experiment

mainly e^+p data



Introduction

HERA

electron(positron)-proton collider at DESY

e+/e−   p

27.5 GeV   820 GeV 1994–1997
                  920 GeV 1998–2007

HERA I 1994-2000

about $100pb^{-1}$ collected per experiment

mainly e^+p data, unpolarised

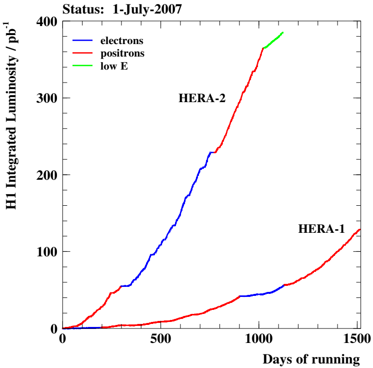
HERA II 2002-2007

about $400pb^{-1}$ per experiment

similar amount of e^-p and e^+p data

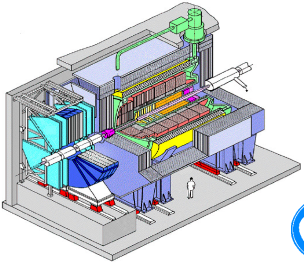
with longitudinal polarization of $e^{\pm}$ beams (30-40%)

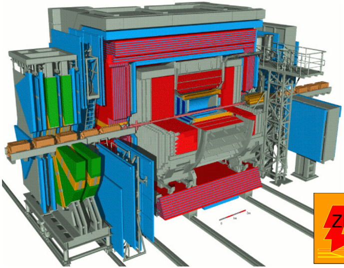
and small samples collected at reduced proton beam energy



Introduction

Two omni-purpose detectors





Both equipped with silicon tracking, drift chambers, hermetic calorimetry and muon detector system

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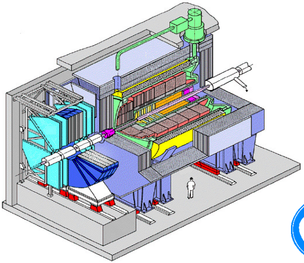
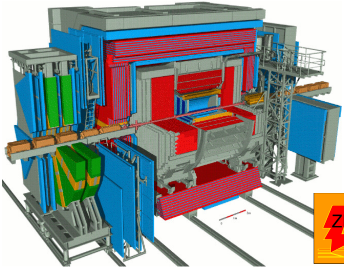




Both equipped with silicon tracking, drift chambers, hermetic calorimetry and muon detector system

Combining H1 and ZEUS measurements

Different detectors

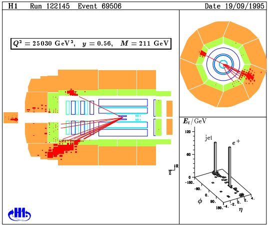
$\Rightarrow$ complementary event reconstruction methods

$\Rightarrow$ reduction of systematic uncertainties

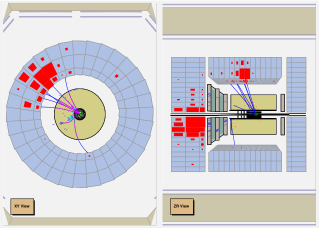
Deep Inelastic $e^{\pm}p$ Scattering

Main process studied at HERA

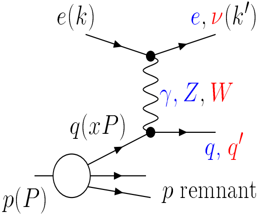
NC DIS



CC DIS



Kinematic variables:



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

$$x = \frac{Q^2}{2P \cdot (k - k')}$$

$$y = \frac{P \cdot (k - k')}{P \cdot k}$$

|virtuality| of the exchanged boson

- $\Rightarrow$ spatial resolution $\lambda \sim 1/Q$
- $\Rightarrow$ sensitivity to mass scales $\Lambda \sim Q$

Introduction

Deep Inelastic $e^{\pm}p$ Scattering

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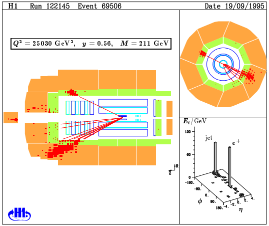

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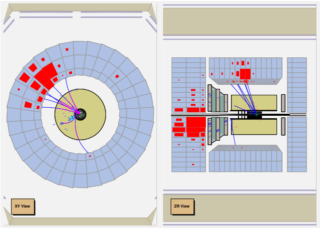

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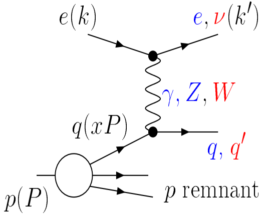


$$Q^2 = -(k - k')^2$$

|virtuality| of the exchanged boson

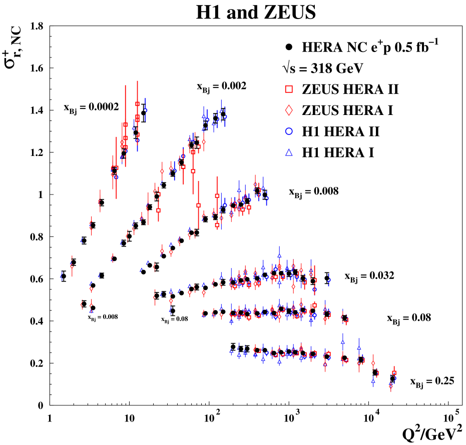
$$x = \frac{Q^2}{2P \cdot (k - k')}$$

fraction of proton momenta carried by stuck quark

$$y = \frac{P \cdot (k - k')}{P \cdot k}$$

fraction of lepton energy transfered in the proton rest frame

Combination of HERA measurements



All DIS data from H1 and ZEUS combined into one set of cross section measurements.
2927 data points ⇒ 1307

Good consistency between experiments and data sets

$$\chi^2/N_{df} \;=\; 1685/1620$$

Eur. Phys. J. C 75 (2015) 580, arXiv:1506.06042

QCD analysis

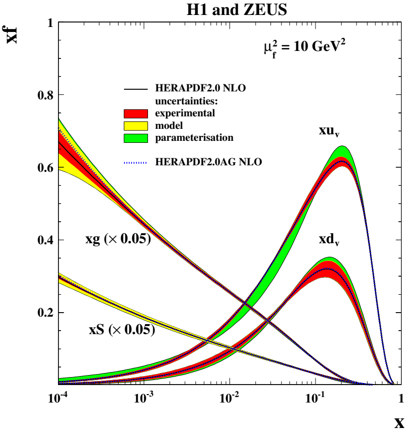
DIS cross sections can be described in terms of the parton distributions in the proton.

We parametrise Parton Density Functions (PDFs) at a starting scale of $Q^2 = 1.9$ GeV^2.

We then use QCD evolution equation to evolve them to arbitrary Q^2 scale.

Fit to combined H1+ZEUS data

$\Rightarrow$ **HERAPDF2.0**



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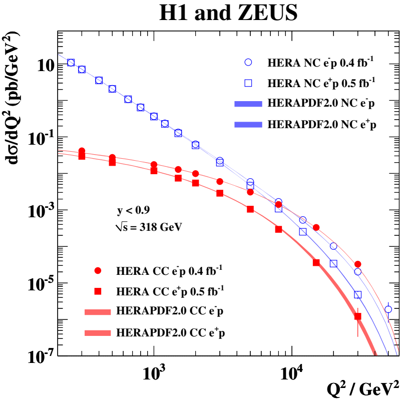
Resulting SM predictions



Good description of the data also at the highest Q^2 values

$$Q^2 \sim M_Z^2, \ M_W^2$$

NC and CC DIS cross sections comparable

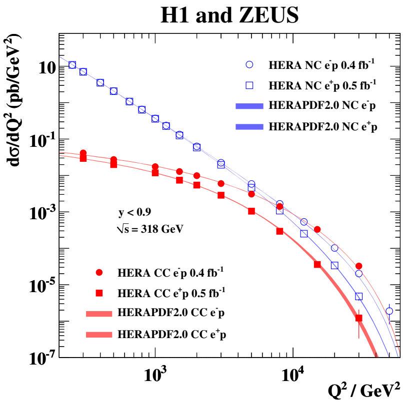
Sizable contribution also from $\gamma - Z^\circ$ interference

Combined QCD+EW analysis shows good agreement with SM predictions

⇒ see presentation by Amanda Cooper-Sarkar (ID: 314)

Phys. Rev. D 93 (2016) 092002, arXiv:1603.09628

Resulting SM predictions



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NC and CC DIS cross sections comparable

Sizable contribution also from $\gamma - Z^\circ$ interference

High precision data could be used to look for possible BSM effects...

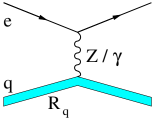
However, PDF fit may have been biased by BSM contributions!

$\Rightarrow$ new approach needed

Quark form factor

"classical" method to look for possible fermion (sub)structure.

If a quark has finite size, the standard model cross-section is expected to decrease at high momentum transfer:



$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2} \cdot \left[1 - \frac{R_q^2}{6} Q^2\right]^2 \cdot \left[1 - \frac{R_e^2}{6} Q^2\right]^2$$

where R_q is the root mean-square radius of the electroweak charge distribution in the quark.

We do not consider the possibility of finite electron size...

same dependence expected for e^+p and e^-p !

QCD+BSM fit

Approach used for HERAPDF2.0 determination extended to take into account the possible BSM contribution

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

$\boldsymbol{p}$ and $\boldsymbol{s}$ are vectors of PDF parameters p_k and systematic shifts s_j, η is the parameter describing BSM contribution (eg. $\eta = R_q^2$)

$\Rightarrow$ we fit them simultaneously to the combined HERA data

$$R_q^{2\ \mathrm{Data}} = -0.2 \cdot 10^{-33}\ \mathrm{cm}^2$$

μ^i_0 and $m^i(\boldsymbol{p}, \eta)$ are measured and predicted (SM+BSM) cross sections, γ^i_j, $\delta_{i,\mathrm{stat}}$ and $\delta_{i,\mathrm{uncor}}$ are the relative correlated systematic, relative statistical and relative uncorrelated systematic uncertainties of the input data point i

Limit setting

Limits derived using the technique of MC replicas (frequentist approach).

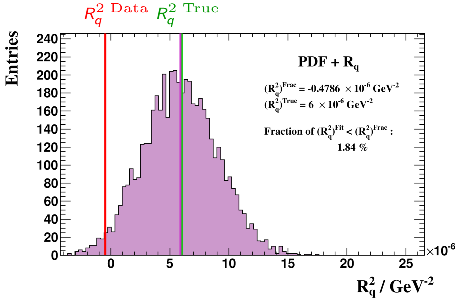
Replicas are generated sets of cross-section values that are calculated for given $R_q^{2\ \mathrm{True}}$ and varied randomly according to the statistical and systematic uncertainties (including correlations) of the input data.

Each replica is then used as an input to QCD+BSM fit

$\Rightarrow R_q^{2\ \mathrm{Fit}}$

Number of replicas for each considered $R_q^{2\ \mathrm{True}}$ value

$\Rightarrow$ distribution of $R_q^{2\ \mathrm{Fit}}$



$R_q^{2\ \mathrm{True}}$ is tested by comparing $R_q^{2\ \mathrm{Fit}}$ distribution with the value of $R_q^{2\ \mathrm{Data}}$

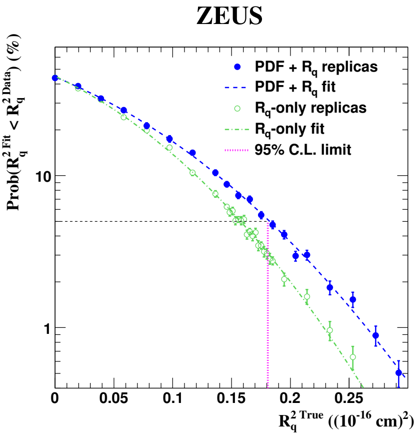
Limit setting

The probability of obtaining a $R_q^{2\ \mathrm{Fit}}$ value smaller than that obtained for the actual data

$$\mathrm{Prob}(R_q^{2\ \mathrm{Fit}} < R_q^{2\ \mathrm{Data}})$$

is studied as a function of $R_q^{2\ \mathrm{True}}$

$R_q^{2\ \mathrm{True}}$ values corresponding to the probability smaller than 5% are excluded at the 95% C.L.

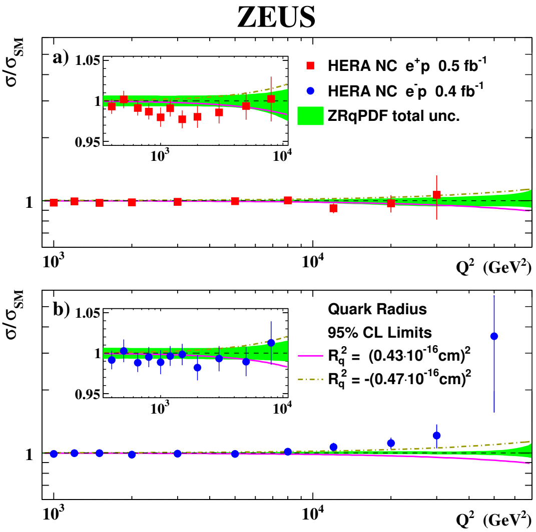


$$R_q < 0.43 \cdot 10^{-16}\mathrm{cm}$$

limits obtained for fixed PDF parameters are too strong by about 10%

Phys. Lett. B757 (2016) 468, arXiv:1604.01280

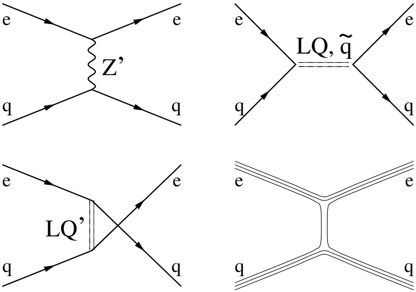
Results



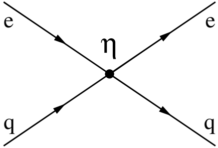
$$-(0.47 \cdot 10^{-16}\mathrm{cm})^2 < R_q^2 < (0.43 \cdot 10^{-16}\mathrm{cm})^2$$

Contact Interactions

For many scenarios of "new physics" at much larger energy scale, BSM interactions can be approximated as *eeqq* Contact Interactions (CI)



$\Rightarrow$



eeqq contact interactions (CI)

Contact Interactions

For many scenarios of "new physics" at much larger energy scale, BSM interactions can be approximated as *eeqq* Contact Interactions (CI)

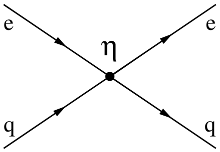
Effective Lagrangian for vector *eeqq* contact interactions:

$$\mathcal{L}_{CI} = \sum_{\substack{\alpha,\beta=L,R \\ q}} \eta^{eq}_{\alpha\beta} \cdot (\bar{e}_\alpha \gamma^\mu e_\alpha)(\bar{q}_\beta \gamma_\mu q_\beta)$$

$\eta^{eq}_{\alpha\beta}$ - 4 possible couplings per flavor q related to the coupling strength η or the "new physics" mass scale Λ by:

$$\eta_{\alpha\beta} = \varepsilon_{\alpha\beta} \cdot \eta = \varepsilon_{\alpha\beta} \cdot \frac{4\pi}{\Lambda^2}$$

where $\varepsilon_{\alpha\beta} = \pm 1$



eeqq contact interactions (CI)

Different CI scenarios assume different helicity structure of new interactions, given by set of $\varepsilon_{\alpha\beta}$

General models

Also referred to as compositeness models
(Λ - compositeness scale)

Family universality assumed:

$$\eta^{eu}_{\alpha\beta} = \eta^{ed}_{\alpha\beta} = \eta^{es}_{\alpha\beta} = \eta^{ec}_{\alpha\beta} = \eta^{eb}_{\alpha\beta}$$

Parity conservation require:

$$\eta^{eq}_{LL} + \eta^{eq}_{LR} - \eta^{eq}_{RL} - \eta^{eq}_{RR} = 0$$

Models violating parity:

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

Models conserving parity:

VV	$+1$	$+1$	$+1$	$+1$
AA	$+1$	-1	-1	$+1$
VA	$+1$	-1	$+1$	-1
X1	$+1$	-1		
X2	$+1$		$+1$	
X4		$+1$	$+1$	

Simplified fit procedure

Limit setting in the replica method is very time consuming.
Full fit of HERA data: QCD evolution of PDFs repeated at each iteration.

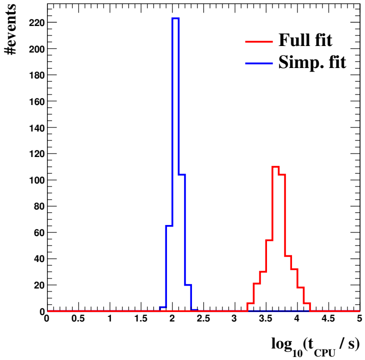
R_q analysis: 3000–5000 Monte Carlo replicas for each value of $R_q^{2\ \mathrm{True}}$
$\Rightarrow$ over 200'000 fits to set final limits

Processing time was a limiting factor for including more models

Simplified fit method, based on the Taylor expansion of the cross section predictions in terms of PDF parameters

$\Rightarrow$ reduce the limit calculation time by almost two orders of magnitude.

For details see arXiv:1606.06670



Results

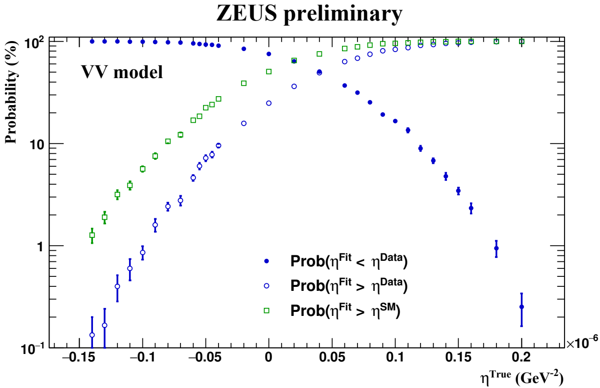
Same limit setting procedure applied to contact interaction models.

Use replicas to calculate:

$$\mathrm{Prob}(\eta^{\mathrm{Fit}} < \eta^{\mathrm{Data}}) \quad \text{for} \quad \eta > \eta^{\mathrm{Data}}$$

$$\mathrm{Prob}(\eta^{\mathrm{Fit}} > \eta^{\mathrm{Data}}) \quad \text{for} \quad \eta < \eta^{\mathrm{Data}}$$

for different η^{True}



Contact Interaction limits

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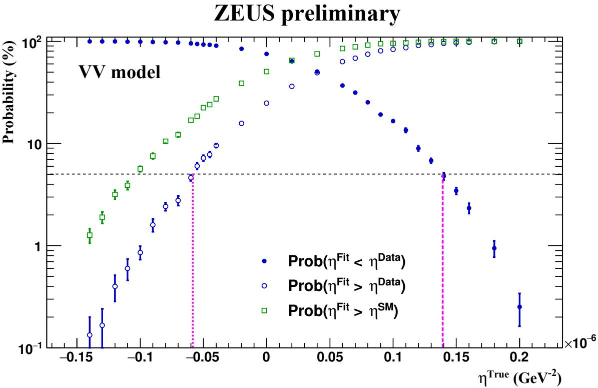
Excluded on 95% C.L. are η^{True} resulting in probability below 5%.



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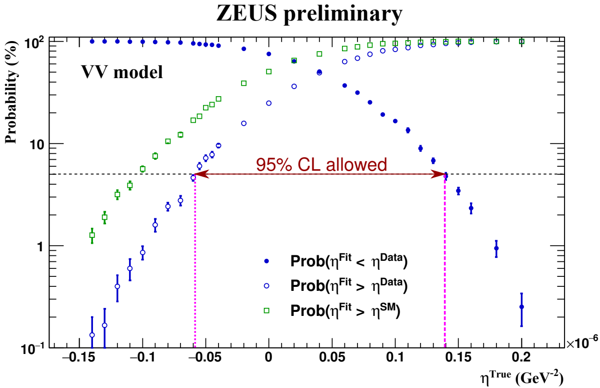


$\Lambda^- > 14.7$ TeV $\quad$ $\Lambda^+ > 9.5$ TeV

Results

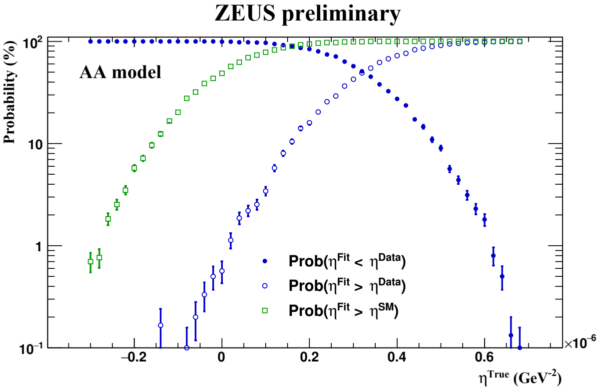
For AA scenario, QCD+CI fit gives improved description of the data

Fitted coupling

$$\eta^{Data} = 0.32\ \mathrm{TeV}^{-2}$$

corresponding to

$$\Lambda^{Data} = 6.2\ \mathrm{TeV}$$



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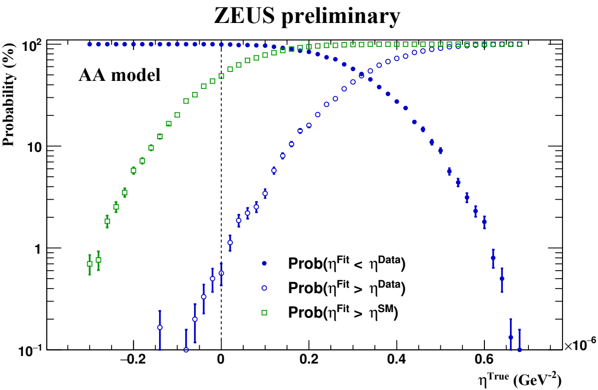
The probability of obtaining larger best-fit coupling for $\eta^{\mathrm{True}} = 0$

$p_{SM} = 0.7\%$ $(2.5\ \sigma)$



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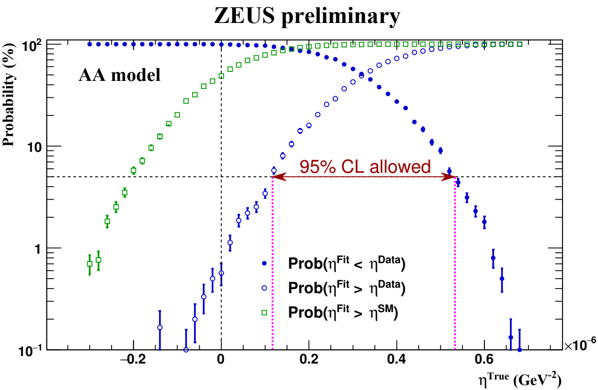

$$4.9\ \mathrm{TeV} < \Lambda^{+} < 10.4\ \mathrm{TeV}$$

Results

Improved description of the HERA data also for VA and X1 models
(models with opposite coupling sign for left- and right-handed quarks)
probability that the SM reproduces the data is $p_{SM} = 2.1\%$ and 0.3% respectively

The fits suggest a positive deviation in NC $e^{-}p$ DIS at highest Q^2, while a negative deviation is preferred for $e^{+}p$.

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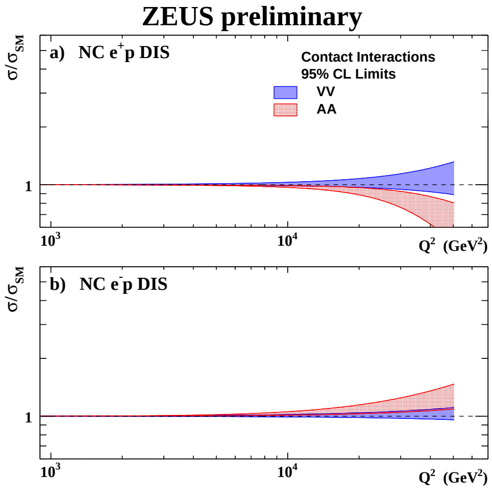
Possible explanations, before we attribute it to "new physics"

- missing higher-order EW corrections
- limitations of the assumed PDF parametrisation/evolution scheme

Results

Cross section deviations corresponding to the allowed coupling range for VV and AA models

No PDF variation included!



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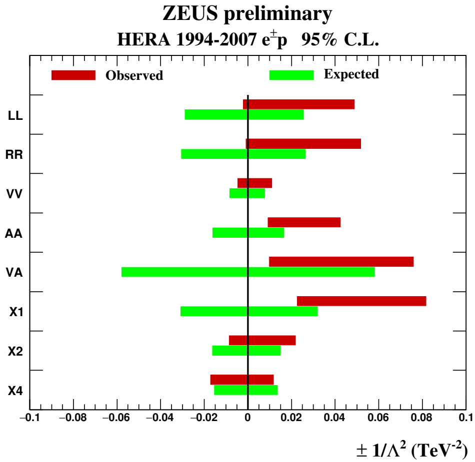
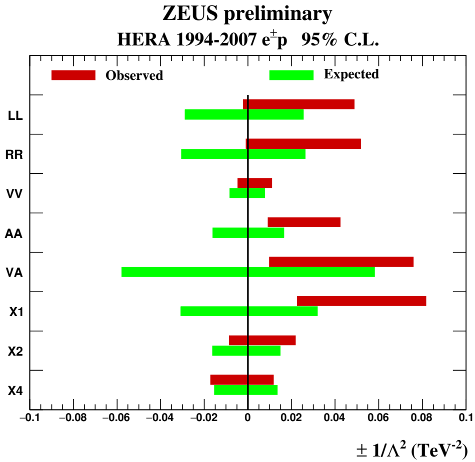


ZEUS preliminary

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

Model	95%C.L. limits (TeV)				p_{SM} (%)
	Observed		Expected		
	Λ^-	Λ^+	Λ^-	Λ^+	
LL	22.0	4.5	5.9	6.2	6.5
RR	32.9	4.4	5.7	6.1	5.6
VV	14.7	9.5	11.0	11.4	24.8
AA	-	4.8 - 10.4	7.9	7.8	0.7
VA	-	3.6 - 10.1	4.1	4.1	2.1
X1	-	3.5 - 6.6	5.7	5.6	0.3
X2	10.8	6.8	7.8	8.2	23.1
X4	7.6	9.2	8.0	8.6	60.3

Results



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X1	-	3.5 - 6.6	5.7	5.6	0.3
X2	10.8	6.8	7.8	8.2	23.1
X4	7.6	9.2	8.0	8.6	60.3

ATLAS limits from 13 TeV data:
arXiv:1607.03669

LL	25.2	17.8
RR	24.6	18.2

Conclusions

High-precision HERA inclusive data allow searches for "new physics" effects up to TeV scales.

New method developed for BSM analysis of HERA data: simultaneous fit of PDF parameters and BSM contribution.

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Limits from the CI analysis in the 10 TeV range

CI models with opposite coupling sign for left- and right-handed quarks give improved description of the data

$\Rightarrow$ theoretical predictions need to be reexamined carefully before any conclusions can be drawn

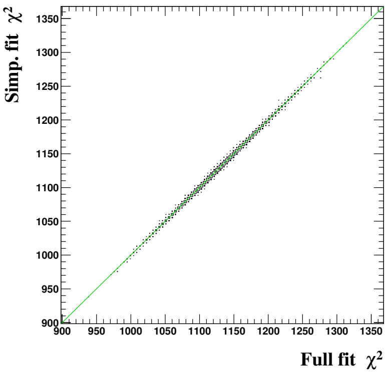
Thank you!

Simplified fit procedure

New procedure was validated by repeating R_q^2 limit setting procedure.

Comparison of results for replicas generated with $R_q^{2\ \mathrm{True}} = (R_q^{\mathrm{Limit}})^2$.

χ^2 of the fit



Fitted value of R_q^2