Searches for Contact Interactions at HERA

A.F.Żarnecki

University of Warsaw

for

XVI International Workshop on Deep-Inelastic Scattering and Related Subjects
7-11 April 2008, University College London

Outline

- Introduction
  HERA running

Outline

- Introduction
  HERA running
- Neutral Current Deep Inelastic $e^{\pm}p$ Scattering
  Possible Contact Interaction contribution

Outline

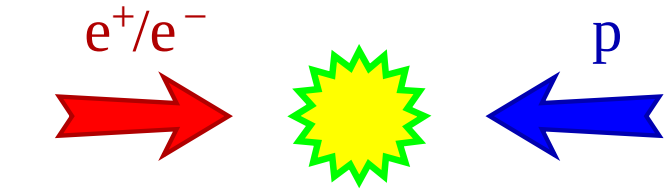
- Introduction
  - HERA running
- Neutral Current Deep Inelastic $e^{\pm}p$ Scattering
  - Possible Contact Interaction contribution
- Contact Interaction results
  - Compositeness models
  - Large Extra Dimensions
  - Heavy leptoquarks
  - Quark form factor

Outline

- Introduction
  - HERA running
- Neutral Current Deep Inelastic $e^{\pm}p$ Scattering
  - Possible Contact Interaction contribution
- Contact Interaction results
  - Compositeness models
  - Large Extra Dimensions
  - Heavy leptoquarks
  - Quark form factor
- Conclusions

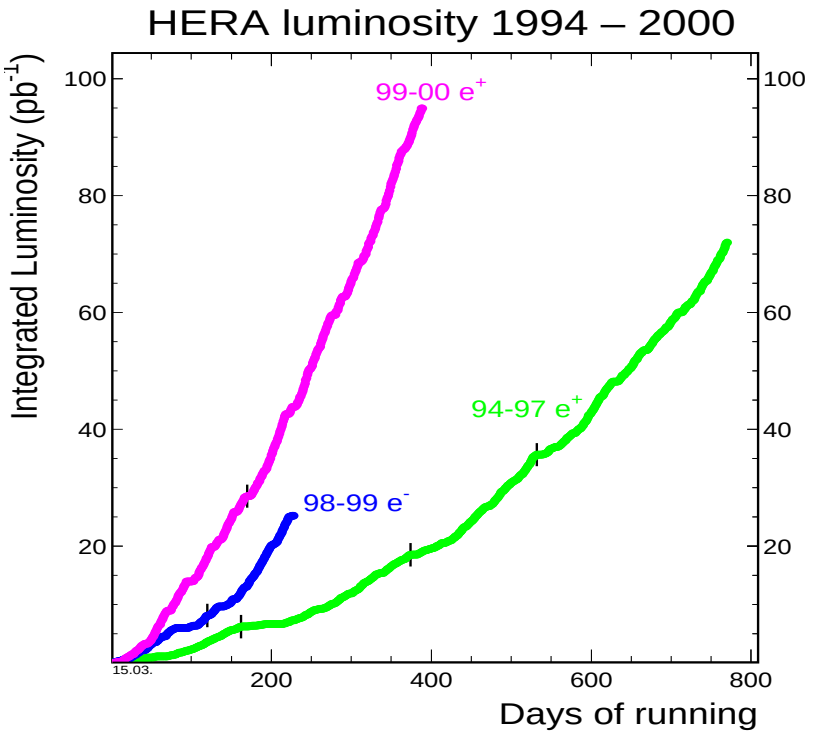
Introduction

HERA
electron(positron)-proton collider at DESY



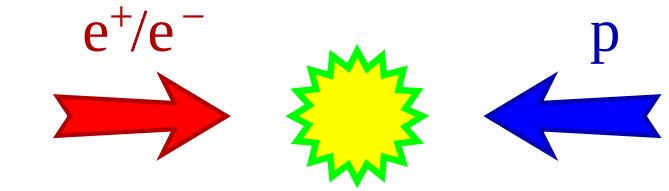
1994−1997
1998−2007

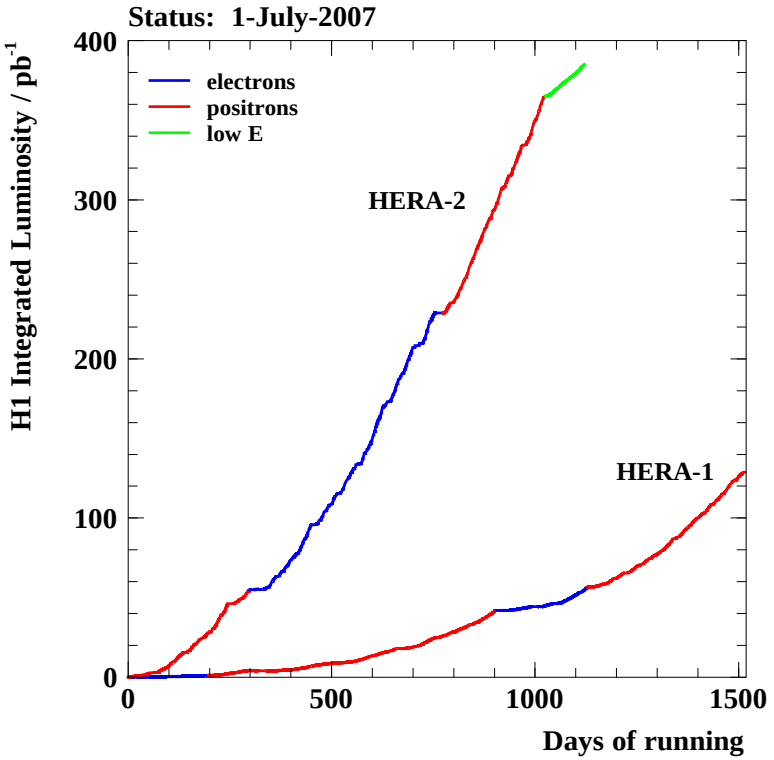
HERA I 1994-2000
over $100 pb^{-1}$ collected per experiment
mainly e^+p data



Introduction

HERA
electron(positron)-proton collider at DESY





HERA I 1994-2000
over 100pb^{-1} collected per experiment
mainly e^+p data

HERA II 2002-2007
about 400pb^{-1} per experiment
similar amount of e^-p and e^+p data

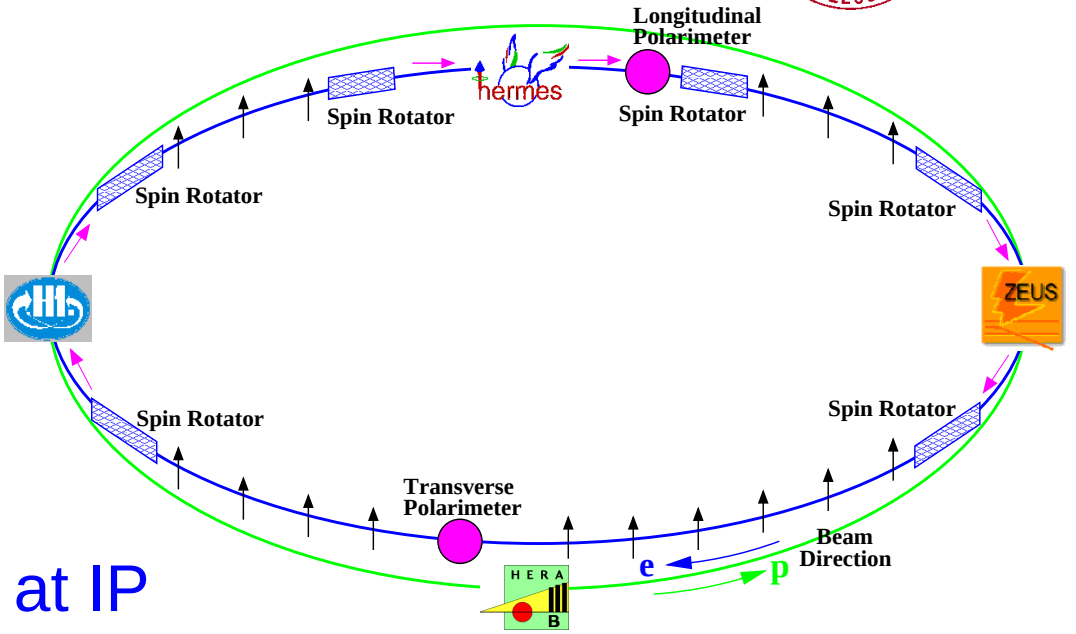
$\sim 20pb^{-1}$ of data from low and medium energy running: not considered here

Introduction

HERA II

Through the emission of synchrotron radiation electron beam at HERA becomes transversely polarized

Spin Rotators installed
to obtain longitudinal polarization at IP

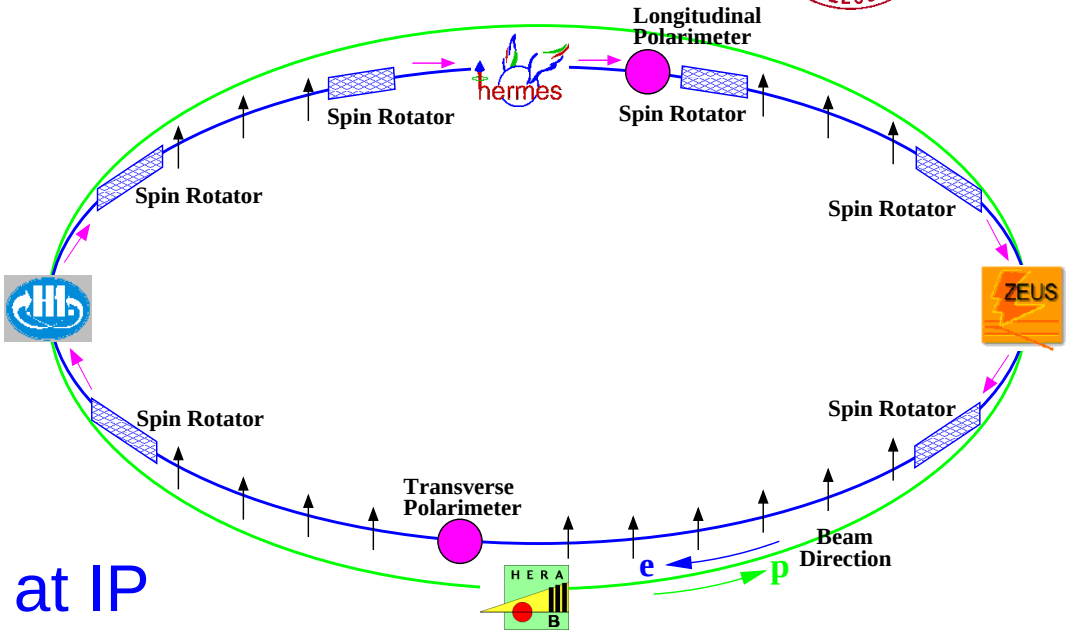


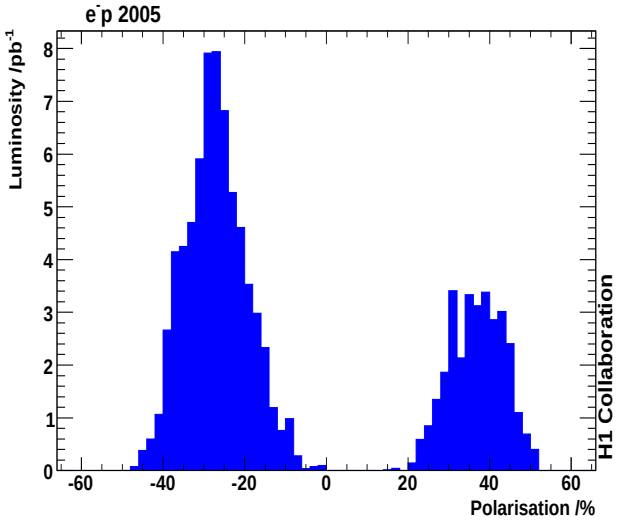
Introduction

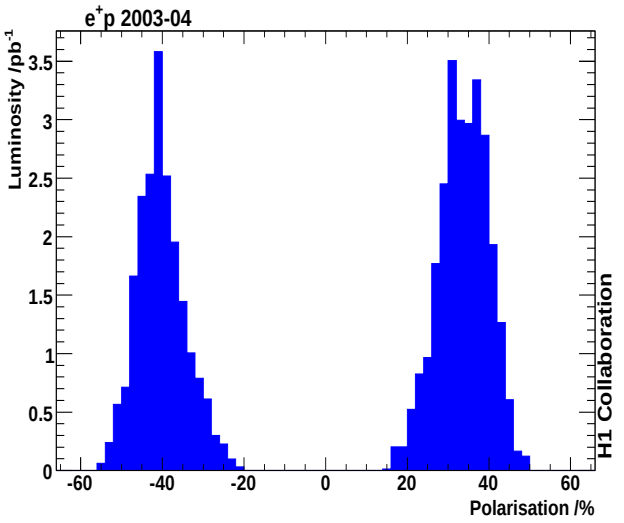
HERA II

Through the emission of synchrotron radiation electron beam at HERA becomes transversely polarized

Spin Rotators installed
to obtain longitudinal polarization at IP







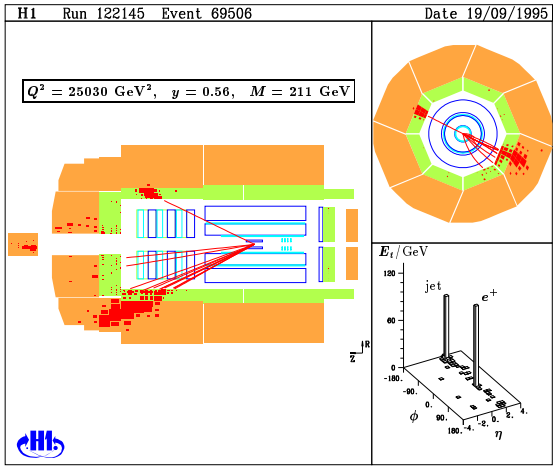
Polarization measured in dedicated polarimeters

Average polarization
30-40%

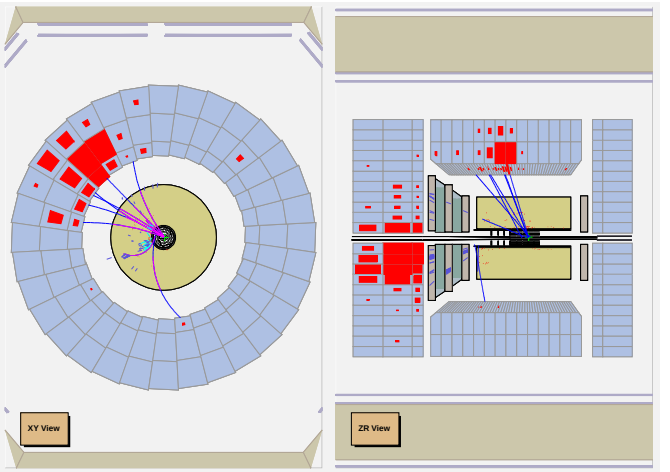
Deep Inelastic $e^{\pm}p$ Scattering

Main process studied at H1 and ZEUS

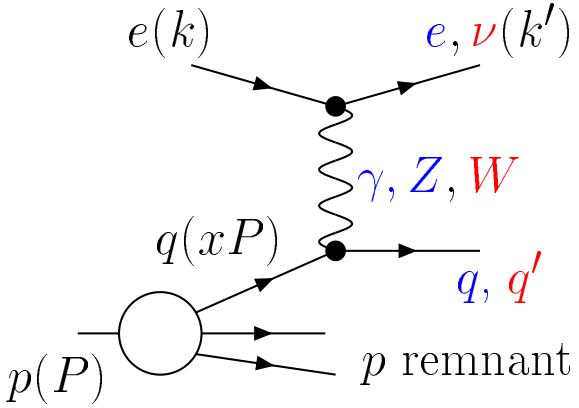
NC DIS



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

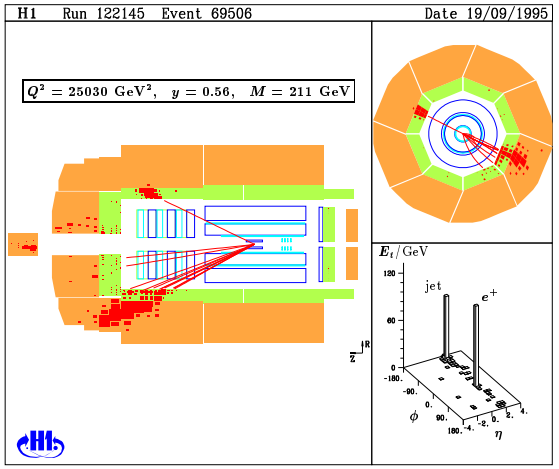
$\Rightarrow$ spatial resolution $\lambda \sim 1/Q$

$\Rightarrow$ sensitivity to mass scales $\Lambda \sim Q$

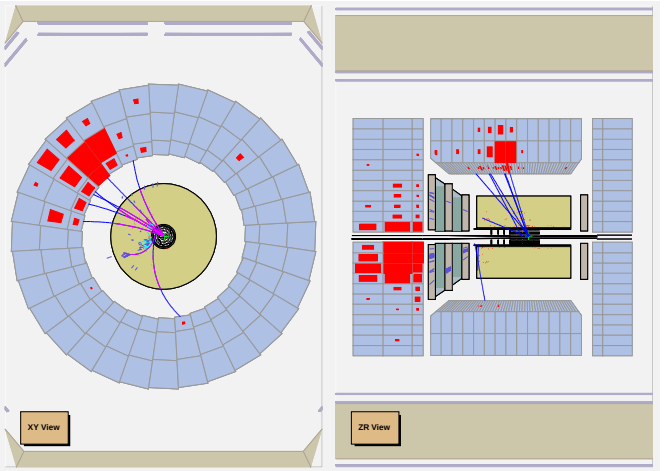
Deep Inelastic $e^{\pm}p$ Scattering

Main process studied at H1 and ZEUS

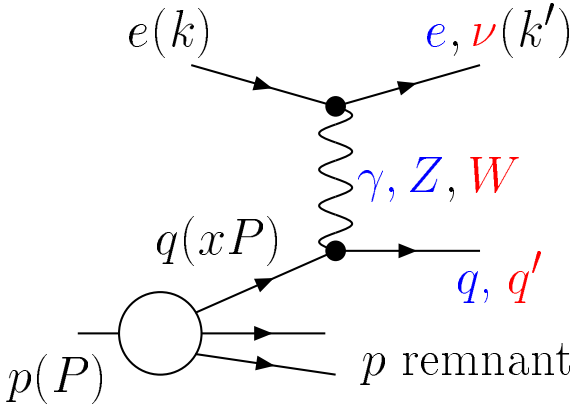
NC DIS



CC DIS



Kinematic variables:



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

|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

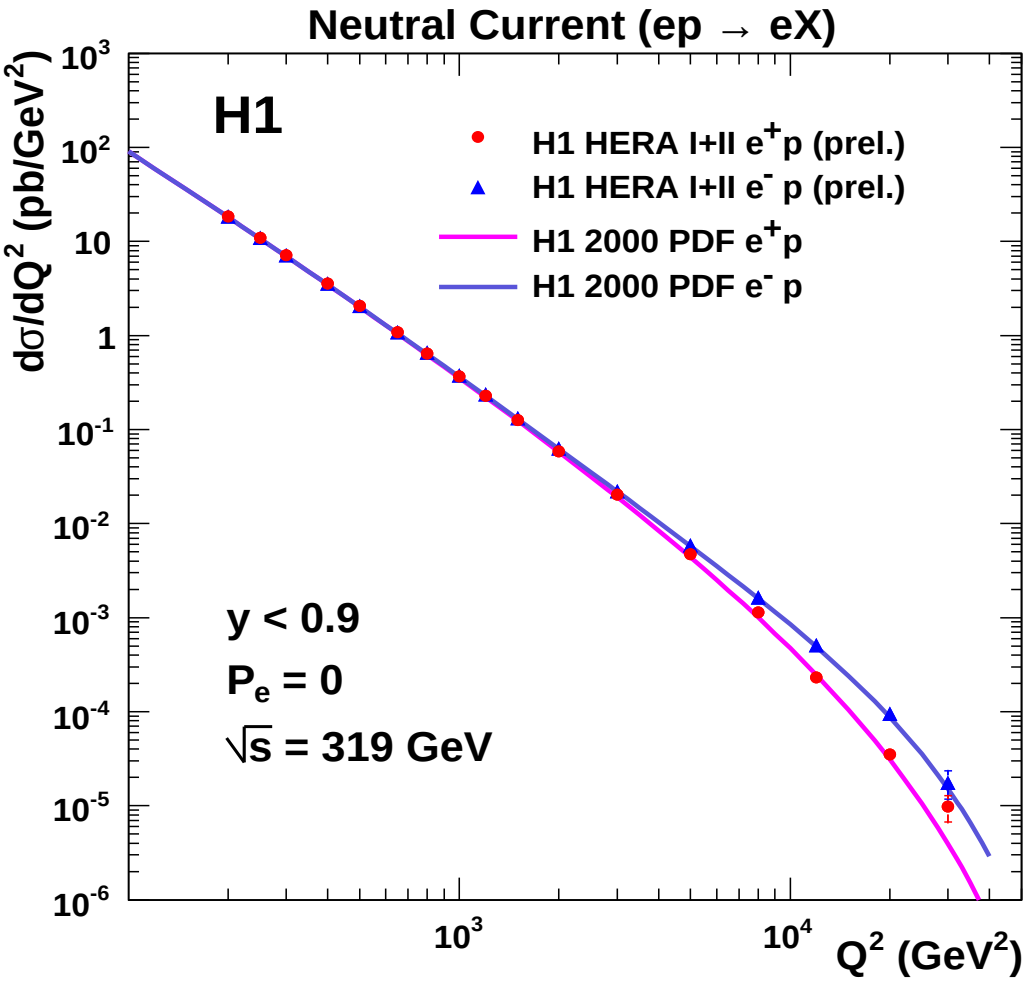
Deep Inelastic $e^{\pm}p$ Scattering

Neutral Current DIS at highest Q^2
Z° contribution significant

Excellent agreement of precise data with Standard Model over many orders of magnitude
$\Rightarrow$ test ground for SM and QCD

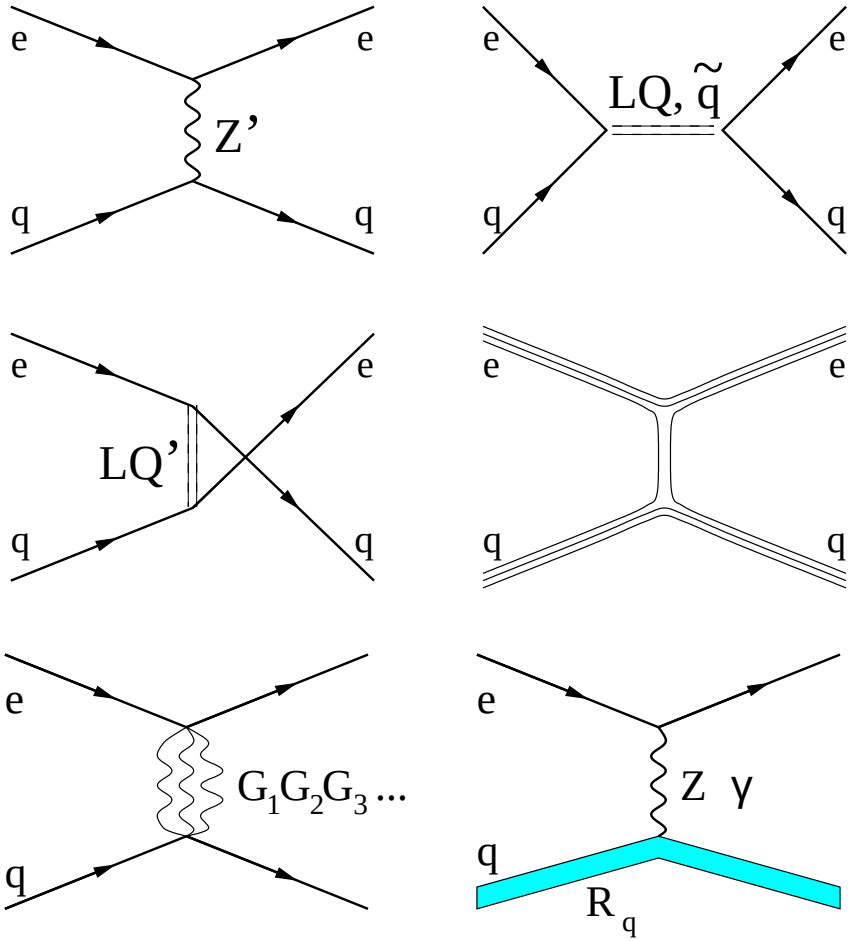
Contact Interactions analysis: search for possible deviations at highest Q^2

Considered data samples:
ZEUS: $Q^2 > 1000$ GeV^2
H1: $Q^2 > 200$ GeV^2

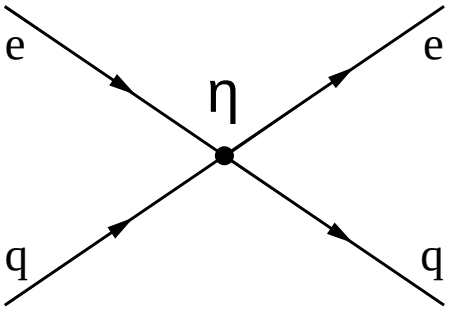


Deep Inelastic $e^{\pm}p$ Scattering

Possible "new physics" in NC DIS:



For $\sqrt{s}$ much smaller than process scale Λ
$\Rightarrow$ effective parametrization:



$eeqq$ contact interactions (CI)

Effective Lagrangian for vector $eeqq$ contact interactions:

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

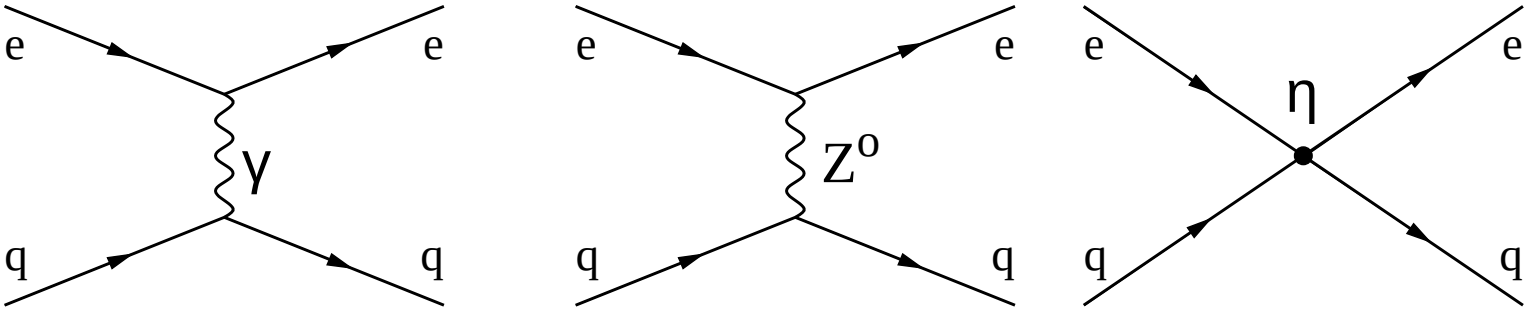
$\eta^{eq}_{\alpha\beta}$ - 4 possible couplings for every flavor q

Scalar and tensor CI constrained beyond HERA sensitivity.

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

Contact Interactions

Contact Interactions modify tree level $eq \to eq$ scattering amplitudes $M^{eq}_{\alpha\beta}$:



$$M^{eq}_{\alpha\beta}(Q^2) = \frac{e^2 e_q}{Q^2} - \frac{e^2}{sin^2\theta_W \cdot cos^2\theta_W} \cdot \frac{g^e_\alpha g^q_\beta}{Q^2 + m_Z^2} + \eta^{eq}_{\alpha\beta}$$

$\alpha, \beta = L, R$ $\quad$ γ $\quad$ Z° $\quad$?

Different models assume different helicity structure of new interactions, given by set of couplings $\eta^{eq}_{\alpha\beta}$ (4 for every flavor q)

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

Cross-section formula

Leading Order

For NC $e^{\pm}p$ DIS with unpolarized beam

$$\frac{d^2\sigma^{e^-p}}{dxdy} = \frac{sx}{16\pi}\sum_q q(x)\{\ |M^{eq}_{LL}|^2 + |M^{eq}_{RR}|^2 + (1-y)^2[\ |M^{eq}_{LR}|^2 + |M^{eq}_{RL}|^2]\} + \bar{q}(x)\{\ |M^{eq}_{LR}|^2 + |M^{eq}_{RL}|^2 + (1-y)^2[\ |M^{eq}_{LL}|^2 + |M^{eq}_{RR}|^2]\}$$

$$\frac{d^2\sigma^{e^+p}}{dxdy} = \frac{sx}{16\pi}\sum_q q(x)\{\ |M^{eq}_{LR}|^2 + |M^{eq}_{RL}|^2 + (1-y)^2[\ |M^{eq}_{LL}|^2 + |M^{eq}_{RR}|^2]\} + \bar{q}(x)\{\ |M^{eq}_{LL}|^2 + |M^{eq}_{RR}|^2 + (1-y)^2[\ |M^{eq}_{LR}|^2 + |M^{eq}_{RL}|^2]\}$$

e^-p most sensitive to η^{eq}_{LL} and η^{eq}_{RR}

e^+p most sensitive to η^{eq}_{LR} and η^{eq}_{RL} (q=u,d)

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

Cross-section formula Leading Order

For NC $e^{\pm}p$ DIS with polarized beam

$$\frac{d^2\sigma^{e^-p}}{dxdy} = \frac{sx}{16\pi}\sum_q q(x)\left\{\mathcal{P}_-|M^{eq}_{LL}|^2 + \mathcal{P}_+|M^{eq}_{RR}|^2 + (1-y)^2\left[\mathcal{P}_-|M^{eq}_{LR}|^2 + \mathcal{P}_+|M^{eq}_{RL}|^2\right]\right\}$$
$$+\bar{q}(x)\left\{\mathcal{P}_-|M^{eq}_{LR}|^2 + \mathcal{P}_+|M^{eq}_{RL}|^2 + (1-y)^2\left[\mathcal{P}_-|M^{eq}_{LL}|^2 + \mathcal{P}_+|M^{eq}_{RR}|^2\right]\right\}$$

$$\frac{d^2\sigma^{e^+p}}{dxdy} = \frac{sx}{16\pi}\sum_q q(x)\left\{\mathcal{P}_+|M^{eq}_{LR}|^2 + \mathcal{P}_-|M^{eq}_{RL}|^2 + (1-y)^2\left[\mathcal{P}_+|M^{eq}_{LL}|^2 + \mathcal{P}_-|M^{eq}_{RR}|^2\right]\right\}$$
$$+\bar{q}(x)\left\{\mathcal{P}_+|M^{eq}_{LL}|^2 + \mathcal{P}_-|M^{eq}_{RR}|^2 + (1-y)^2\left[\mathcal{P}_+|M^{eq}_{LR}|^2 + \mathcal{P}_-|M^{eq}_{RL}|^2\right]\right\}$$

e^-p most sensitive to η^{eq}_{LL} and η^{eq}_{RR}

e^+p most sensitive to η^{eq}_{LR} and η^{eq}_{RL} (q=u,d)

where: $\mathcal{P}_{\pm} = (1 \pm P)$ P is lepton beam polarization

Combining polarized e^+p and e^-p data we can set better constrains on $M^{eq}_{\alpha\beta}$

Contact Interaction results

General models

Also referred to as compositeness models

Couplings $\eta^{eq}_{\alpha\beta}$ are related to the "new physics" mass scale Λ by the formula:

$$\eta \;=\; \frac{\varepsilon \cdot g^2_{CI}}{\Lambda^2}$$

where g_{CI} is the coupling strength of new interactions and $\varepsilon = \pm 1$.

By convention we set $g^2_{CI} \;=\; 4\pi$.

Models conserving parity:

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

Family universality assumed !

Models conserving parity:

Model	η^{ed}_{LL}	η^{ed}_{LR}	η^{ed}_{RL}	η^{ed}_{RR}	η^{eu}_{LL}	η^{eu}_{LR}	η^{eu}_{RL}	η^{eu}_{RR}
VV	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$
AA	$+\eta$	$-\eta$	$-\eta$	$+\eta$	$+\eta$	$-\eta$	$-\eta$	$+\eta$
VA	$+\eta$	$-\eta$	$+\eta$	$-\eta$	$+\eta$	$-\eta$	$+\eta$	$-\eta$
X1	$+\eta$	$-\eta$			$+\eta$	$-\eta$		
X2	$+\eta$		$+\eta$		$+\eta$		$+\eta$	
X3	$+\eta$			$+\eta$	$+\eta$			$+\eta$
X4		$+\eta$	$+\eta$			$+\eta$	$+\eta$	
X5		$+\eta$		$+\eta$		$+\eta$		$+\eta$
X6			$+\eta$	$-\eta$			$+\eta$	$-\eta$
U1					$+\eta$	$-\eta$		
U2					$+\eta$		$+\eta$	
U3					$+\eta$			$+\eta$
U4						$+\eta$	$+\eta$	
U5						$+\eta$		$+\eta$
U6							$+\eta$	$-\eta$

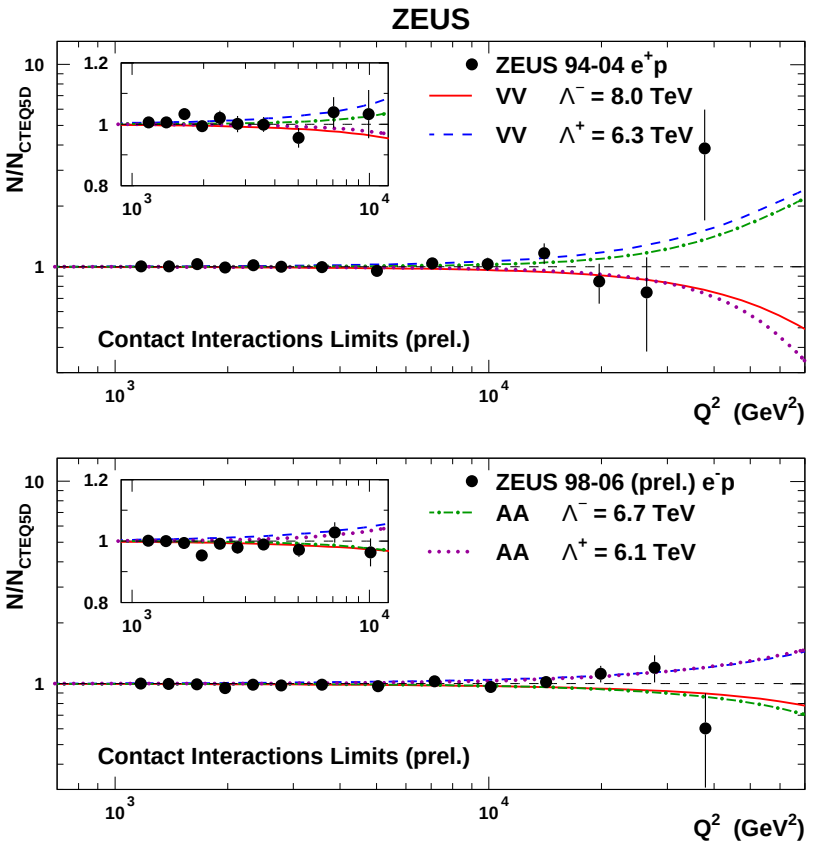
Models violating parity:

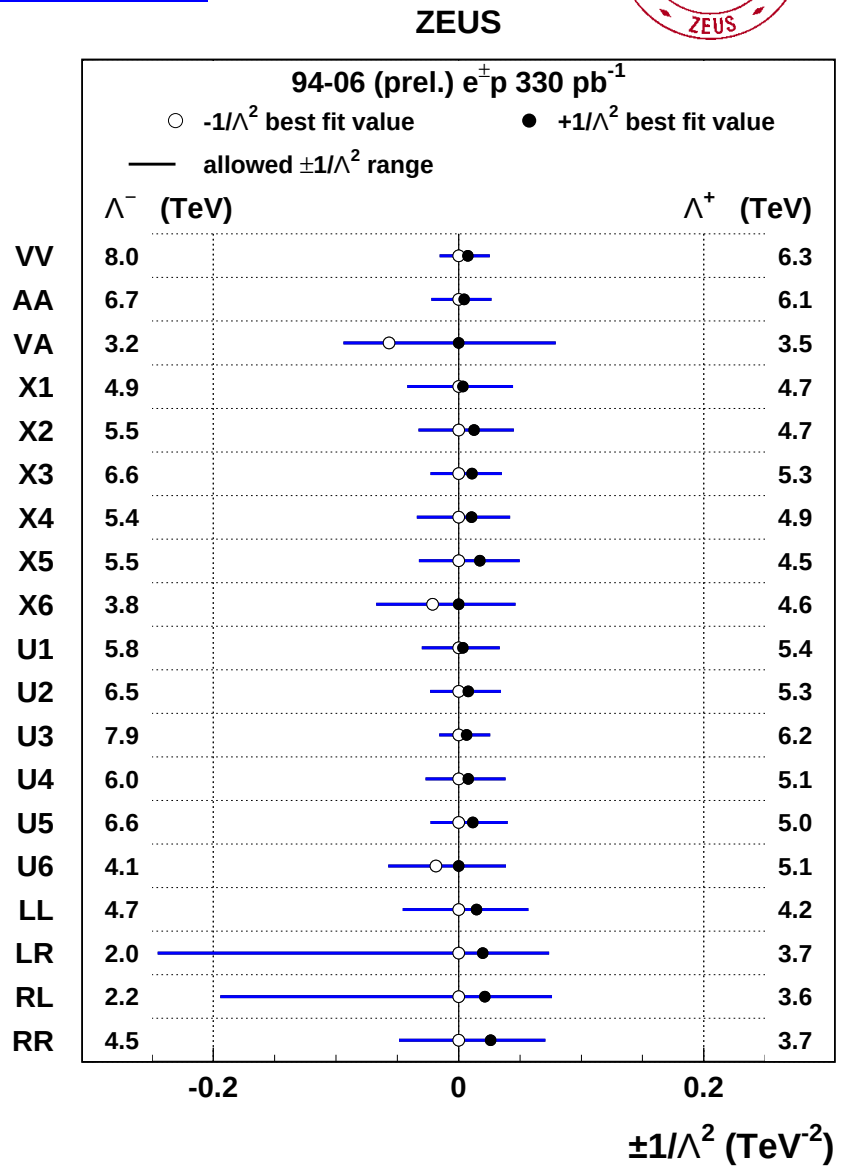
LL	$+\eta$				$+\eta$			
LR		$+\eta$				$+\eta$		
RL			$+\eta$				$+\eta$	
RR				$+\eta$				$+\eta$

Contact Interaction results

General models

ZEUS data 1994-2006 compared with SM:





ZEUS 95% CL limits: $\Lambda > 2.0 - 8.0$ TeV

H1 95% CL limits: $\Lambda > 1.6 - 5.5$ TeV (HERA I; Phys Lett B568 (2003) 35-47)

Contact Interaction results

Large Extra Dimensions

Arkani-Hamed–Dimopoulos–Dvali Model

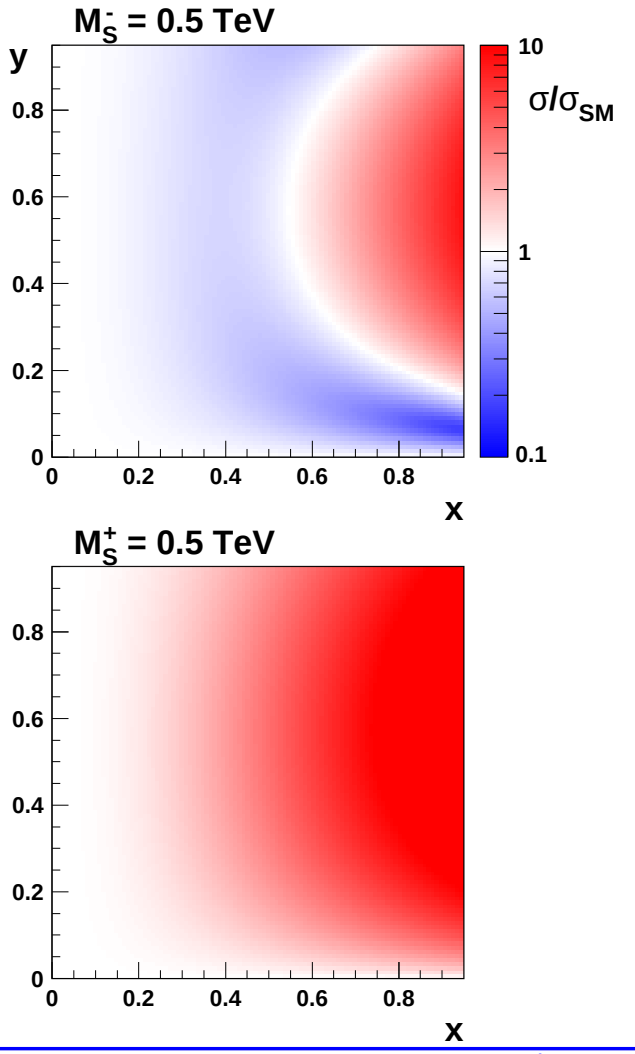
If gravity propagates in $4+\delta$ D, effective mass scale M_S can be as low as 1 TeV.
$\Rightarrow$ gravity becomes comparable in strength to electroweak interactions.

Contribution of graviton (Kaluza-Klein tower) exchange to the $e^{\pm}p$ NC DIS:
effective contact interaction type coupling

$$\eta_G = \pm\lambda \cdot \frac{\mathcal{E}^2}{M_S^4}$$

where λ is the coupling strength and $\mathcal{E}$ is related to the energy scales of hard interaction. $(\sqrt{s}, Q^2)$

Cross-section deviations for e^-p:



Contact Interaction results

Large Extra Dimensions

Arkani-Hamed–Dimopoulos–Dvali Model

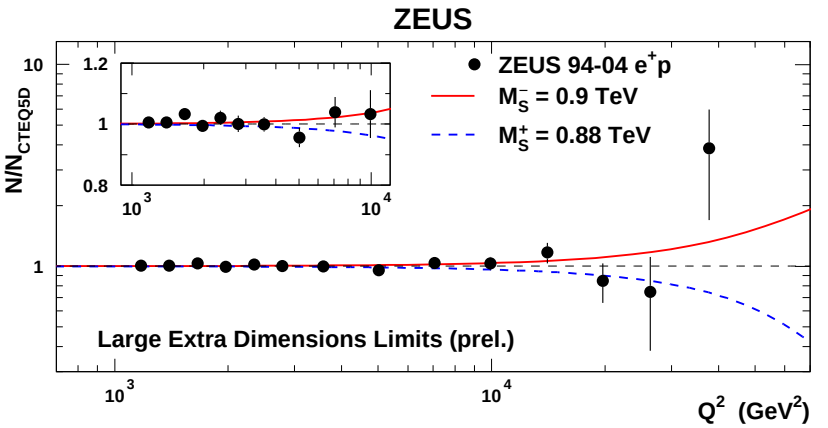
If gravity propagates in $4+\delta$ D, effective mass scale M_S can be as low as 1 TeV.
$\Rightarrow$ gravity becomes comparable in strength to electroweak interactions.

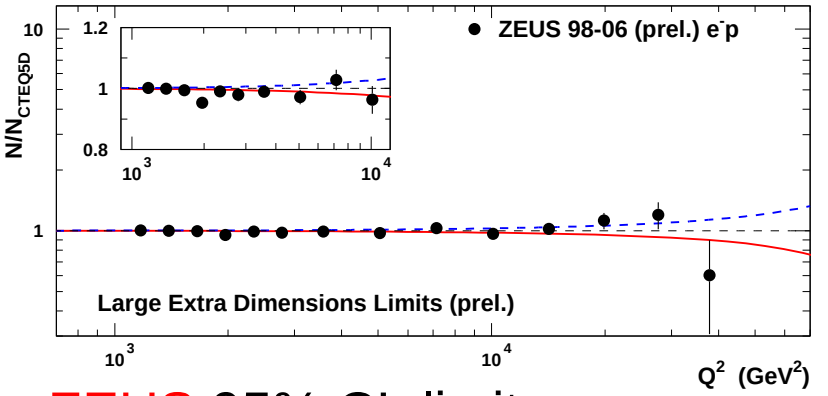
Contribution of graviton (Kaluza-Klein tower) exchange to the $e^{\pm}p$ NC DIS:
effective contact interaction type coupling

$$\eta_G = \pm\lambda \cdot \frac{\mathcal{E}^2}{M_S^4}$$

where λ is the coupling strength and $\mathcal{E}$ is related to the energy scales of hard interaction. $(\sqrt{s}, Q^2)$

ZEUS data 1994-2006:





ZEUS 95% CL limits:

$M_S^- > 0.90$ TeV, $M_S^+ > 0.88$ TeV

H1 (HERA I): $M_S^- > 0.78$ TeV, $M_S^+ > 0.82$ TeV

Contact Interaction results

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.

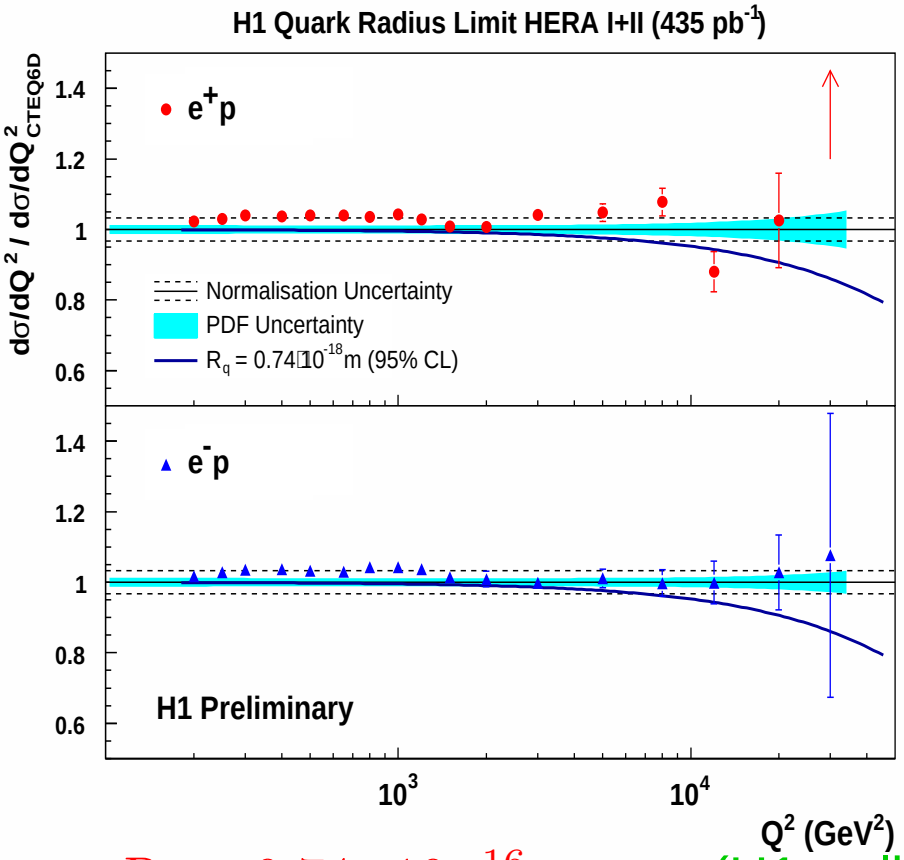
We do not consider the possibility of finite electron size...

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

Contact Interaction results

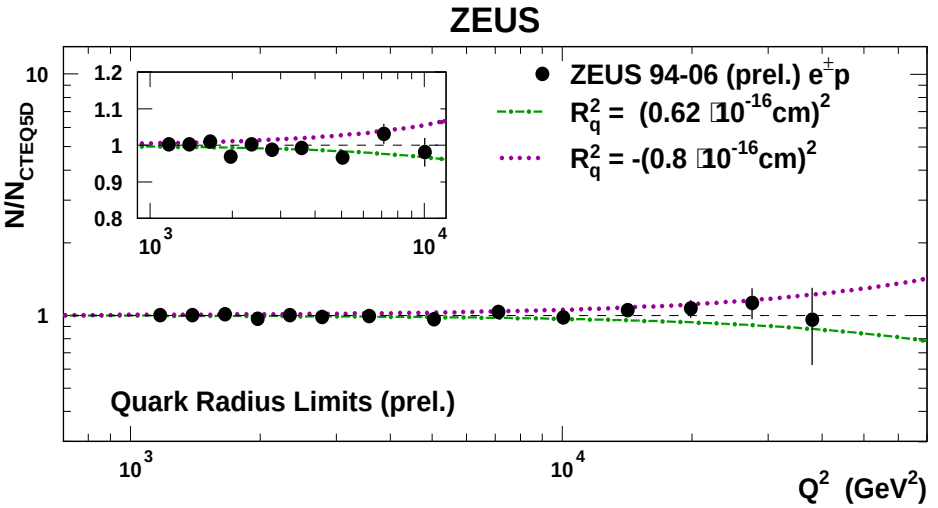
Quark form factor

H1 1994-2007:



$R_q < 0.74 \cdot 10^{-16}$ cm

ZEUS 1994-2006:



$R_q < 0.62 \cdot 10^{-16}$ cm

(H1prelim-07-141 for LP'2007)

Contact Interaction results

High mass leptoquarks

For high mass leptoquarks

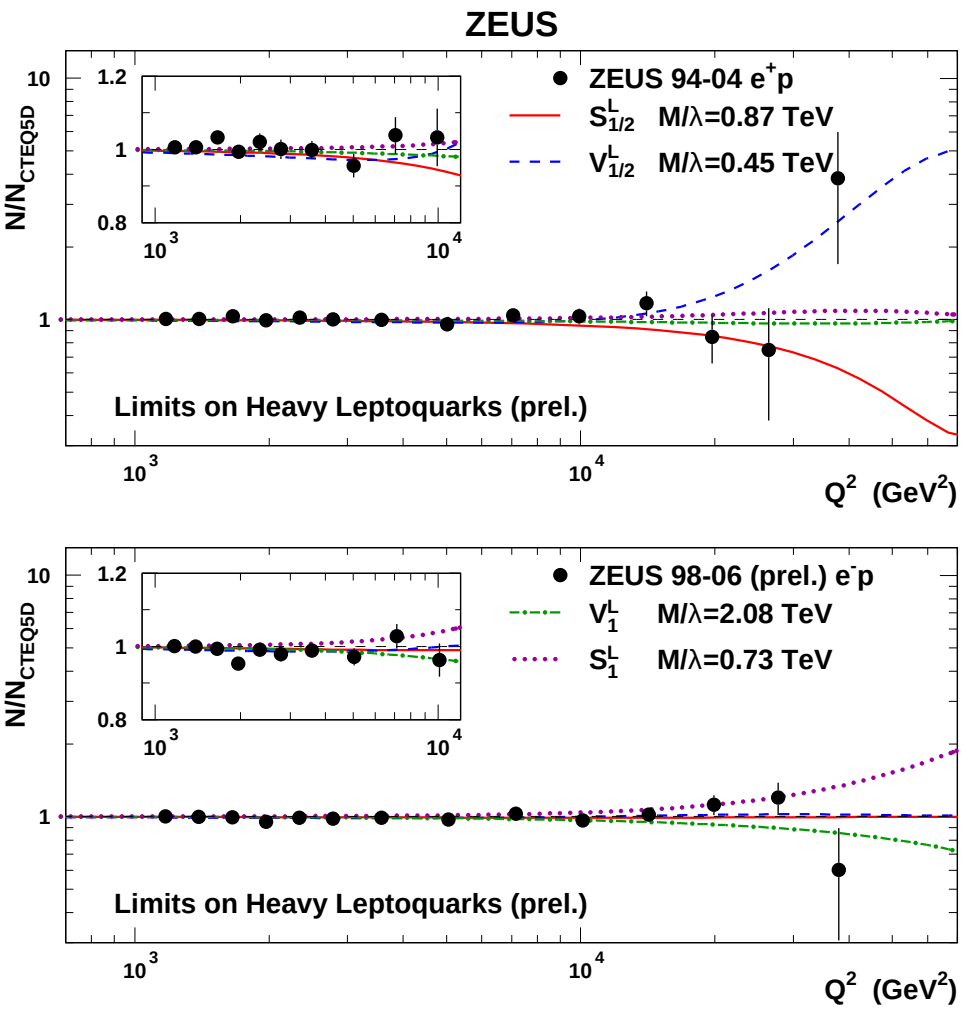
$$M_{LQ} \gg \sqrt{s}$$

virtual LQ production/exchange results in an effective CI coupling:

$$\eta_{CI} \sim \left(\frac{\lambda}{M}\right)^2$$

both s- and u-channel exchange important!
λ - leptoquark Yukawa coupling

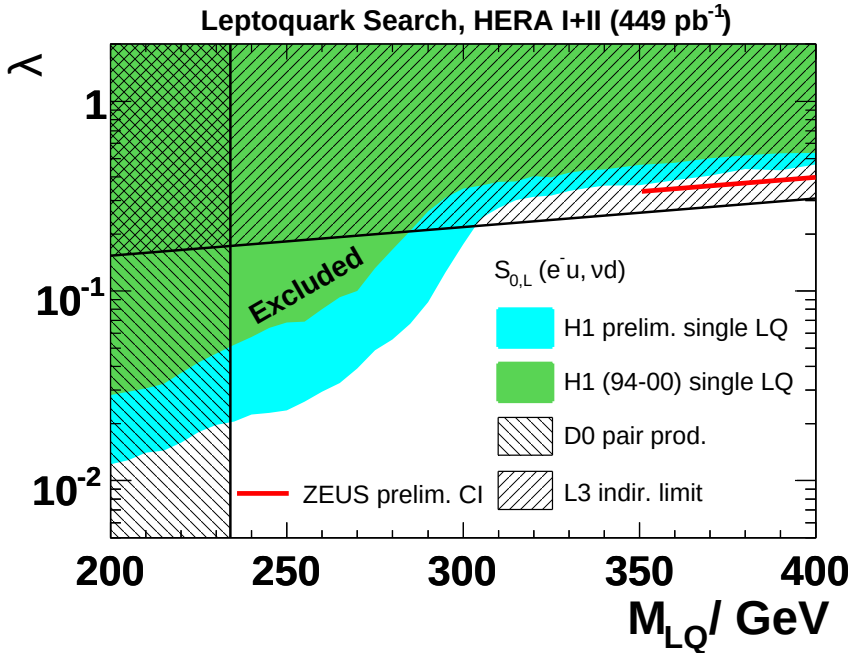
ZEUS 95% CL limits (1994-2006):
M_{LQ}/λ_{LQ} > 0.29 - 2.08 TeV

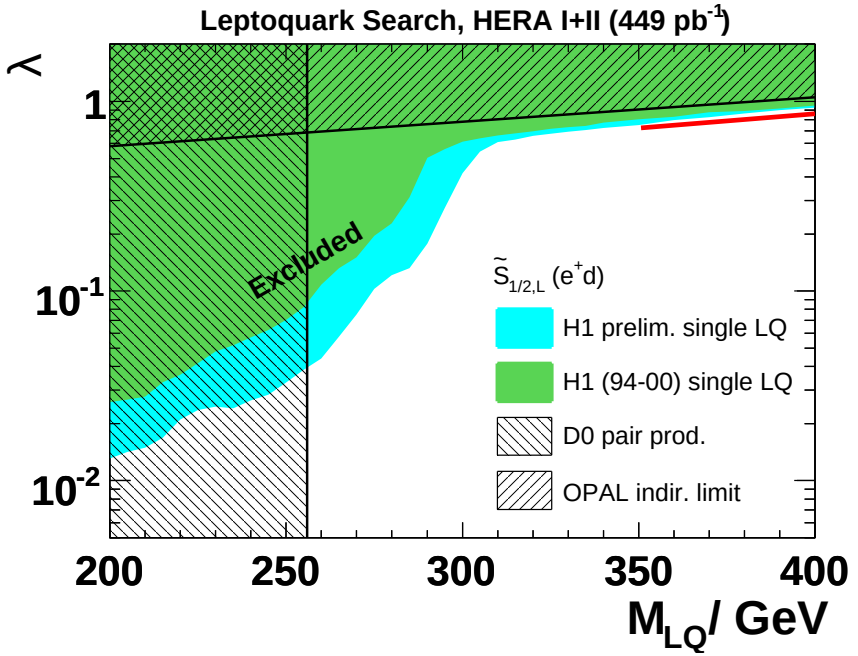


Contact Interaction results

High mass leptoquarks

Comparison of ZEUS limits from CI analysis with limits from LQ analysis of H1 and limits from other experiments:





HERA limits competitive to LEP and Tevatron limits.

H1 1994-2000: A. Aktas et al., Phys. Lett. B629 (2005) 9-19
H1 prel.: result submitted to LP'2007 (H1prelim-07-164)

Conclusions

HERA II

High luminosity + polarization $\Rightarrow$ new window for precise EW studies.

Conclusions

HERA II

High luminosity + polarization $\Rightarrow$ new window for precise EW studies.

NC DIS at high Q^2 in very good agreement with SM
limits on deviations from SM set in different models

- General Contact Interaction models,
- Large Extra Dimensions,
- Quark radius,
- High mass leptoquarks

Conclusions

HERA II

High luminosity + polarization $\Rightarrow$ new window for precise EW studies.

NC DIS at high Q^2 in very good agreement with SM
limits on deviations from SM set in different models

- General Contact Interaction models,
- Large Extra Dimensions,
- Quark radius,
- High mass leptoquarks

HERA running finished, but large samples of data collected with polarized lepton beams still being analyzed.
Many more interesting results expected.