Contact Interactions at HERA

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for

H1 & ZEUS

Outline:

- Contact Interactions
- Analysis methods
- Results
  - ⇒ Compositeness models
  - ⇒ Large Extra Dimensions
  - ⇒ Quark form factor
  - ⇒ Leptoquarks and LFV
- Summary

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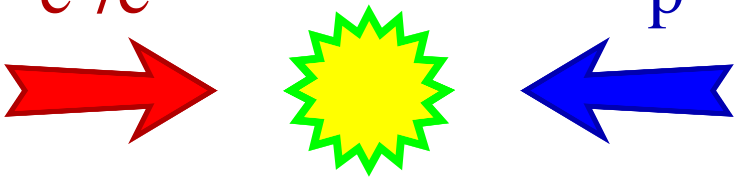
Bologna, 29 April 2001

Introduction

HERA data

e$^+$/e$^-$ p



27.5 GeV

820 GeV 1994-97

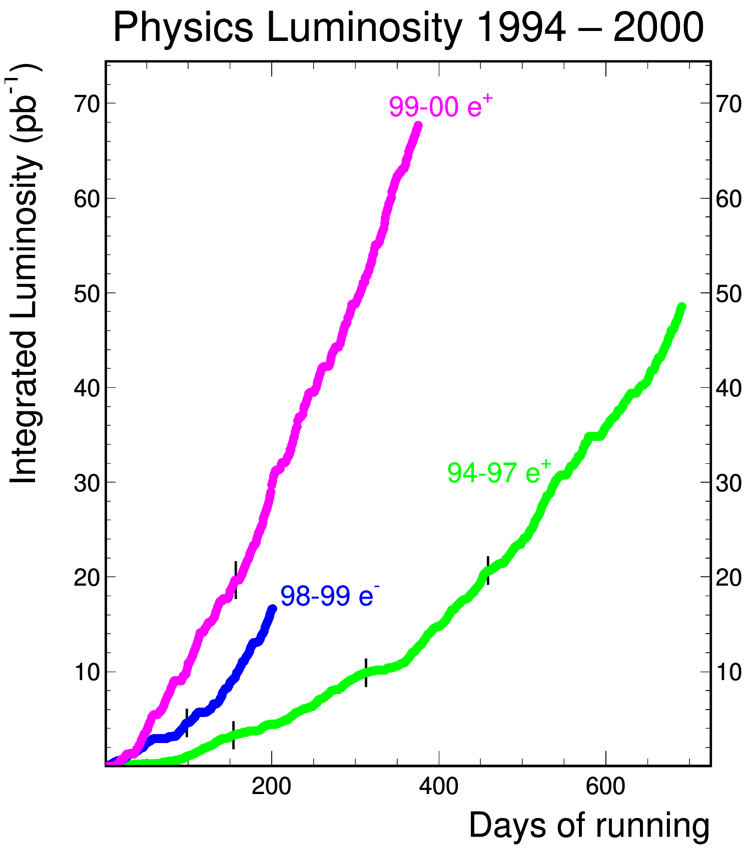
920 GeV 1998-00

Presented results

Year		$\sqrt{s}$	H1	ZEUS
1994-97	e^+p	300 GeV	36 pb^{-1}	48 pb^{-1}
1998-99	e^-p	318 GeV	15 pb^{-1}	16 pb^{-1}
1999-00	e^+p	318 GeV	46 pb^{-1}	64 pb^{-1}

Total of about $\sim$ 220 pb^{-1} of $e^{\pm}p$ data available.

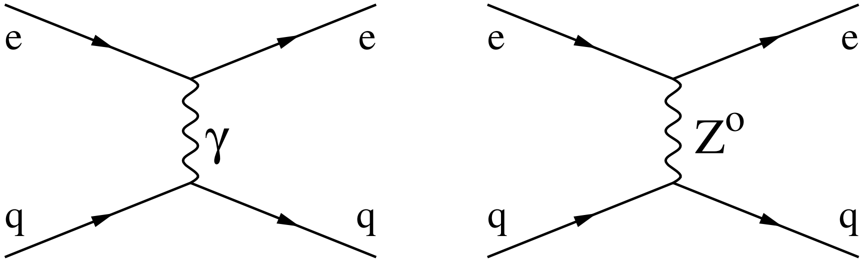
e^+p data sample more than doubled in 1999-2000:



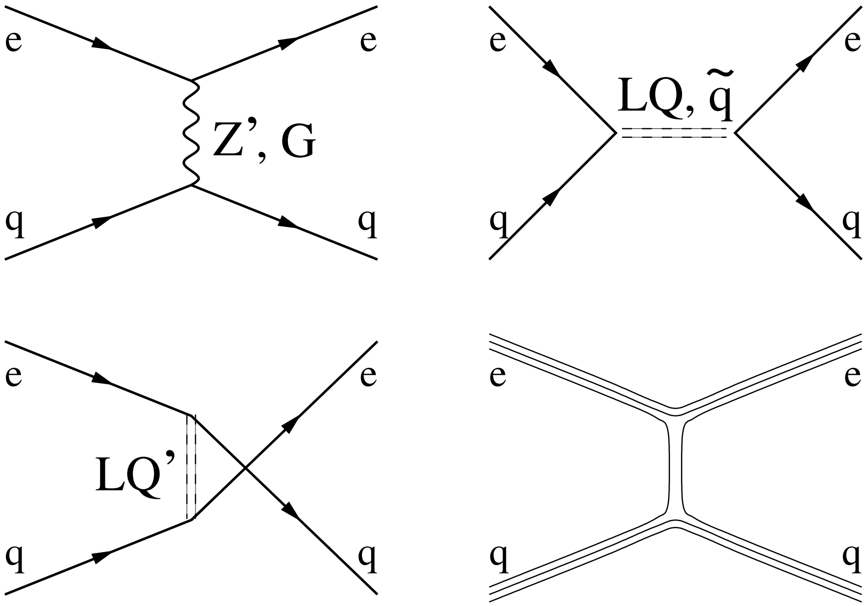
Contact Interactions

Neutral Current eq Scattering

Two processes contribute in SM:

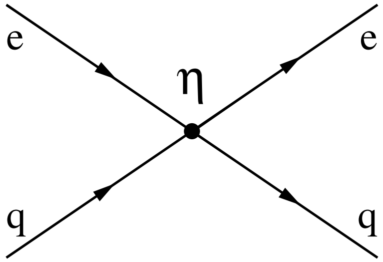


Possible "new physics" processes:



For $\sqrt{s}$ much smaller than process scale Λ

$\Rightarrow$ effective parameterization:



$eeqq$ contact interactions (CI)

Effective Lagrangian for vector $eeqq$ contact interactions:

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

Scalar and tensor CI constrained beyond HERA sensitivity.

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

Contact Interactions

Cross-section

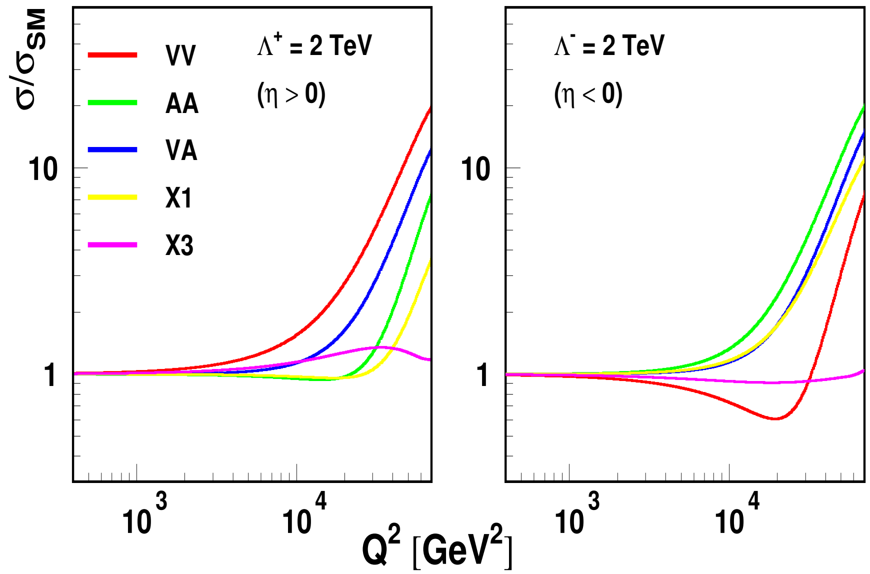
Contact Interactions modify tree level $eq \rightarrow eq$ scattering amplitudes $M^{eq}_{\alpha\beta}$:

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

Resulting contribution to the differential NC DIS cross-section:

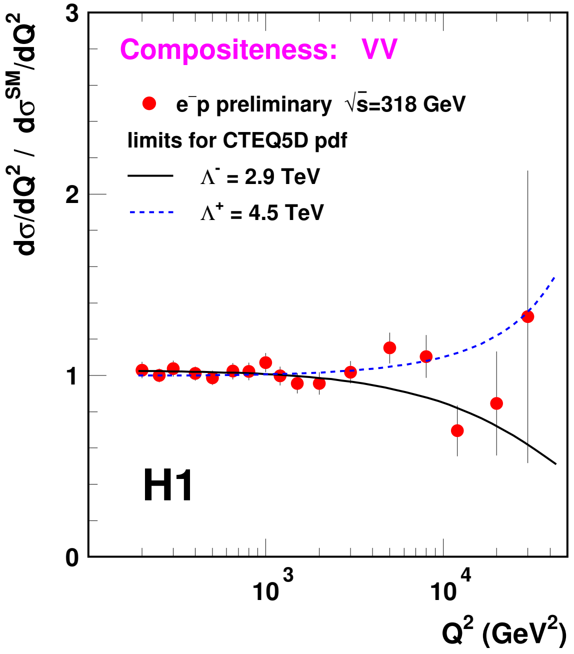
$$\frac{d\sigma}{dx\, dQ^2}(\eta) = \frac{d\sigma^{SM}}{dx\, dQ^2} \cdot \left[1 + A(x,Q^2)\,\eta + B(x,Q^2)\,\eta^2\right]$$

General formula for all CI type models



Analysis

H1 method



Measured NC DIS cross-section $\frac{d\sigma}{dQ^2}$ is compared with the predicted SM+CI cross-section.

Calculated χ^2 function includes both statistical and systematic uncertainties.

Correlated systematics:

- normalization
- $e^\pm$ energy scale
- $e^\pm$ scattering angle
- strong coupling α_s (in PDF)

95% CL limits on the model parameter:

$$\chi^2(\eta) - \chi^2_{SM} = 3.84$$

PDFs $\Rightarrow$ most conservative results quoted.

Analysis

ZEUS method

Measured event distribution is compared to the density of MC events for given CI model.

1994-97:

Unbinned 2-D Log-Likelihood in (x, y):

$$L(\eta) \quad = \quad - \sum_i \log p(x_i, y_i; \eta)$$

$p(x_i, y_i; \eta)$ - probability that an event i is observed at (x_i, y_i).

1994-2000 (preliminary):

Log-Likelihood calculated from the binned event distribution in Q^2.

Limit setting based on “MC experiments”

(∼ LEP method for higgs limits)

Model which results in worse agreement with the SM than observed in the data, in more than 95% of MC experiments, is excluded on 95% CL.

New 1994-2000 results:

- normalization uncertainty
  $\Rightarrow$ included in $\log L$ function.
- other systematic uncertainties
  - $e^{\pm}$ energy scale
  - hadronic energy scale
  - strong coupling α_s (in PDF)

  $\Rightarrow$ varied in MC event simulation

General models

Coupling structure

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 $g^2_{CI} \;=\; 4\pi$.

Different models assume different helicity structure of new interactions $\Longrightarrow$

Also referred to as compositeness models

(Λ - compositeness scale)

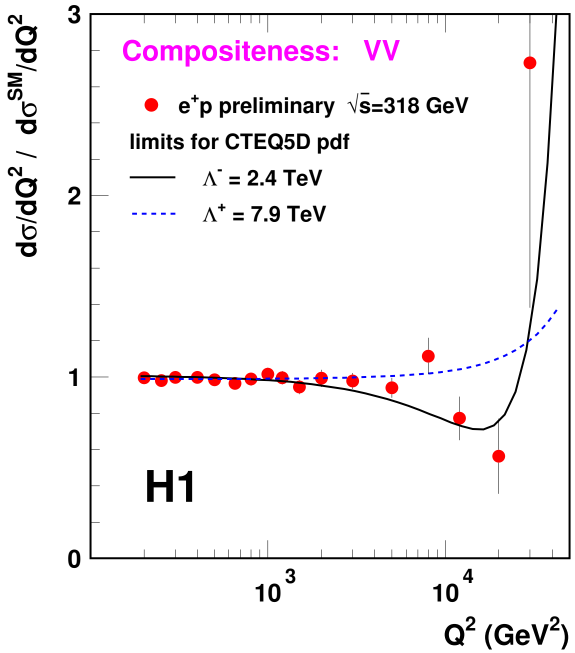
Model	η^{ed}_{LL}	η^{ed}_{LR}	η^{ed}_{RL}	η^{ed}_{RR}	η^{eu}_{LL}	η^{eu}_{LR}	η^{eu}_{RL}	η^{eu}_{RR}
LL	$+\eta$				$+\eta$			
LR		$+\eta$				$+\eta$		
RL			$+\eta$				$+\eta$	
RR				$+\eta$				$+\eta$
VV	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$
AA	$+\eta$	$-\eta$	$-\eta$	$+\eta$	$+\eta$	$-\eta$	$-\eta$	$+\eta$
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							$+\eta$	$-\eta$

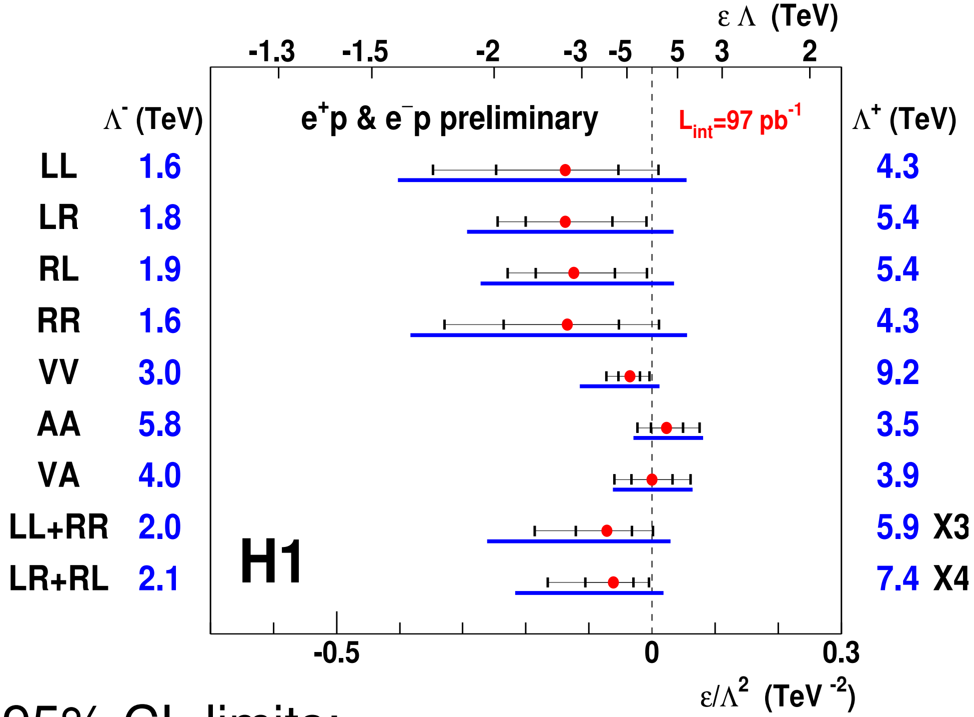
General models

Results

H1 1994-2000 analysis

data undershoots SM slightly at high Q^2





$\Rightarrow \sim 2\sigma$ deviation in most models

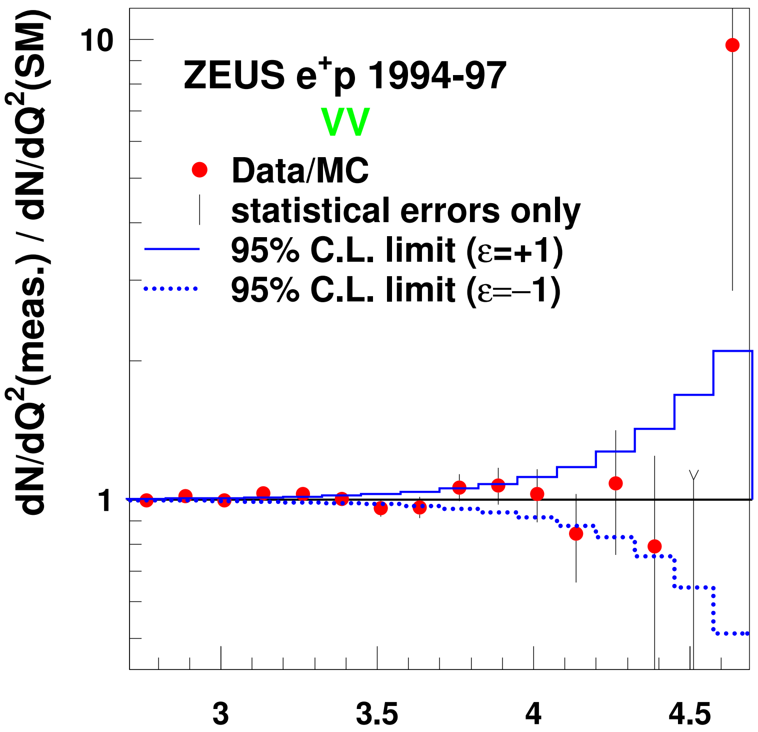
95% CL limits:

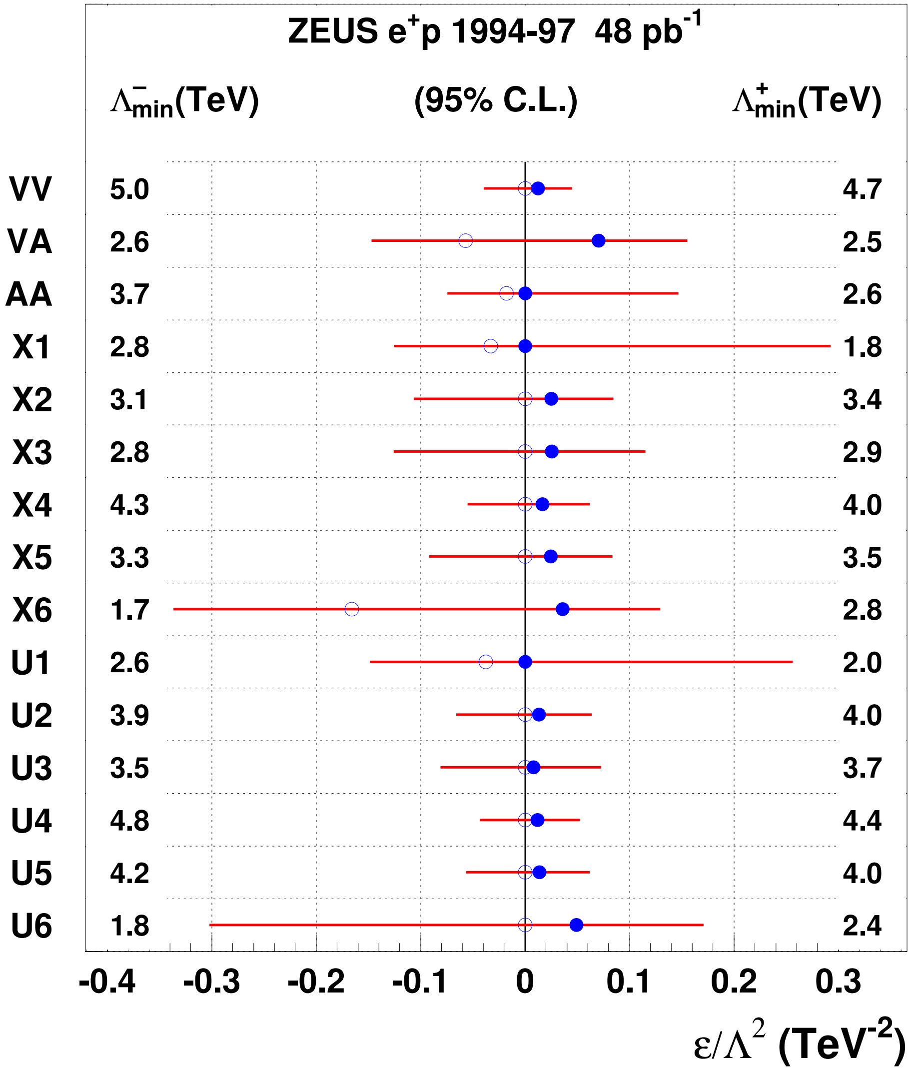
$\Lambda \; > \; 1.6 - 9.2$ TeV

General models

Results

ZEUS 1994-97 analysis





Good agreement with the Standard Model

95% CL limits:

$$\Lambda > 1.7 - 5.0 \text{ TeV}$$

Large Extra Dimensions

Arkani-Hamed–Dimopoulos–Dvali Model

If gravity propagates in the $4+\delta$ dimensions, the effective mass scale M_S can be as low as 1 TeV.

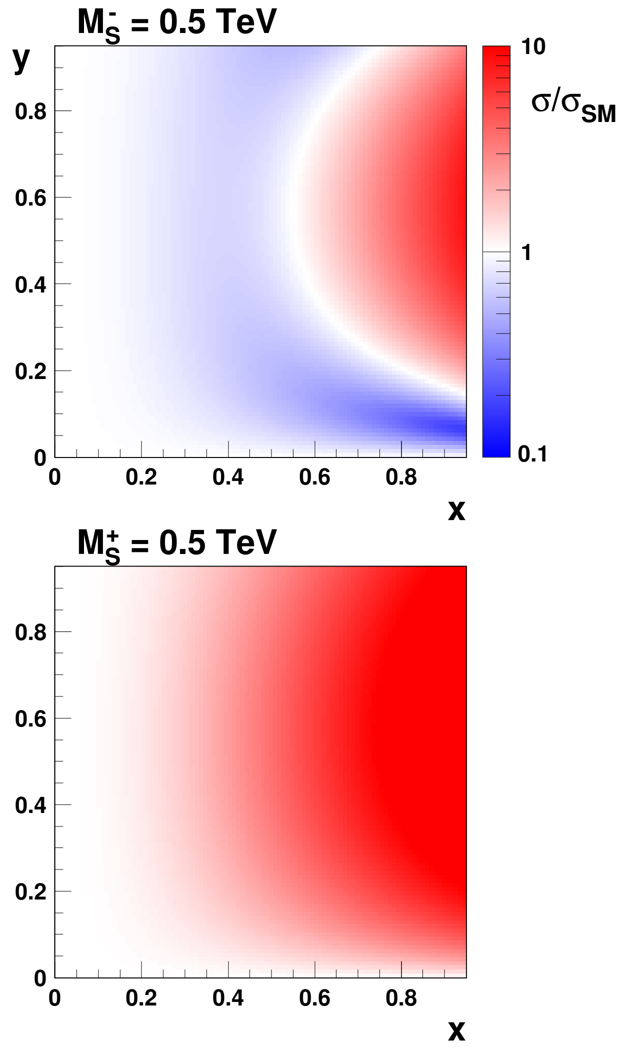
$\Rightarrow$ Gravitational interactions become comparable in strength to electroweak interactions.

The contribution of graviton (Kaluza-Klein tower) exchange to the $e^{\pm}p$ NC DIS cross section can be described by an effective contact interaction type coupling:

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

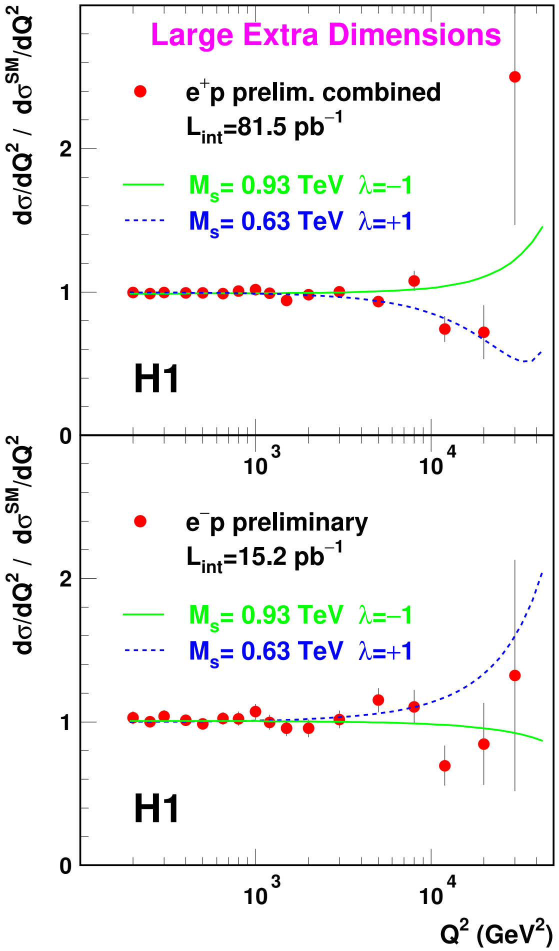
where λ is the coupling strength and $\mathcal{E}$ is related to the energy scales of hard interaction. $(\sqrt{s},\, Q^2)$

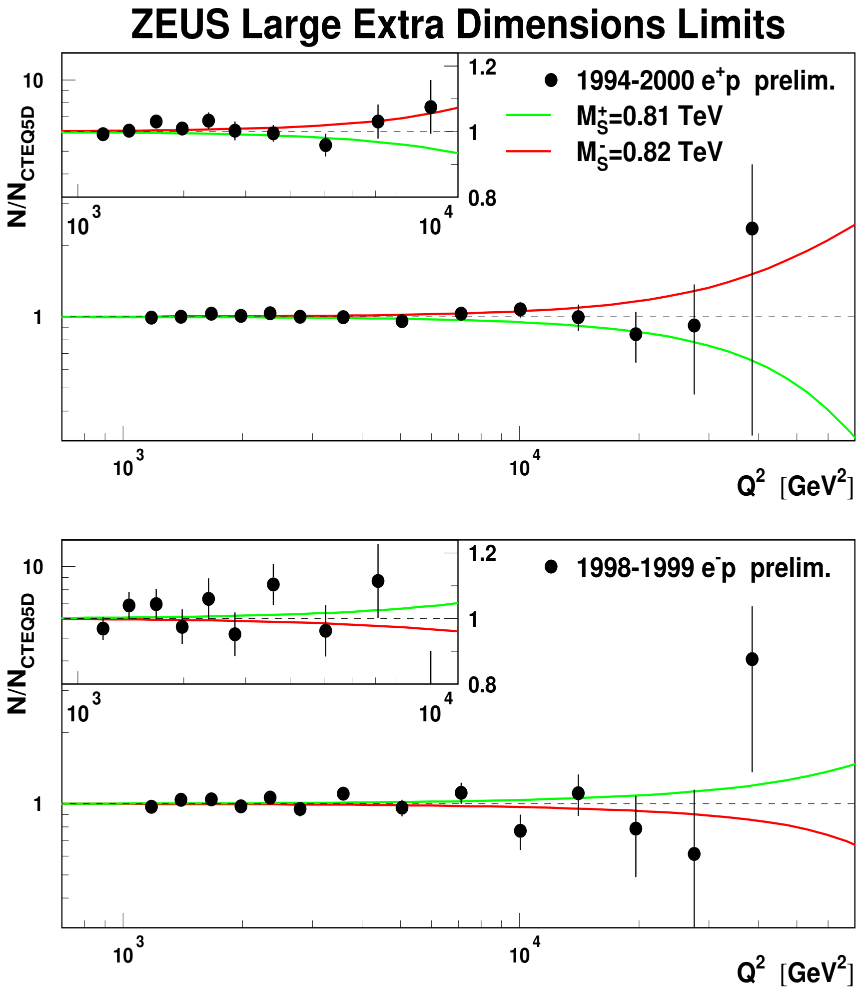
Cross-section deviations for e^-p:



Large Extra Dimensions

Results





Preliminary 95% CL

1994-2000 combined:

$M_S^- > 0.93$ TeV
$M_S^+ > 0.63$ TeV

H1

$M_S^- > 0.82$ TeV
$M_S^+ > 0.81$ TeV

ZEUS

Mass scale definition as proposed by G.F.Giudice et al.

Quark form factor

Model

“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:

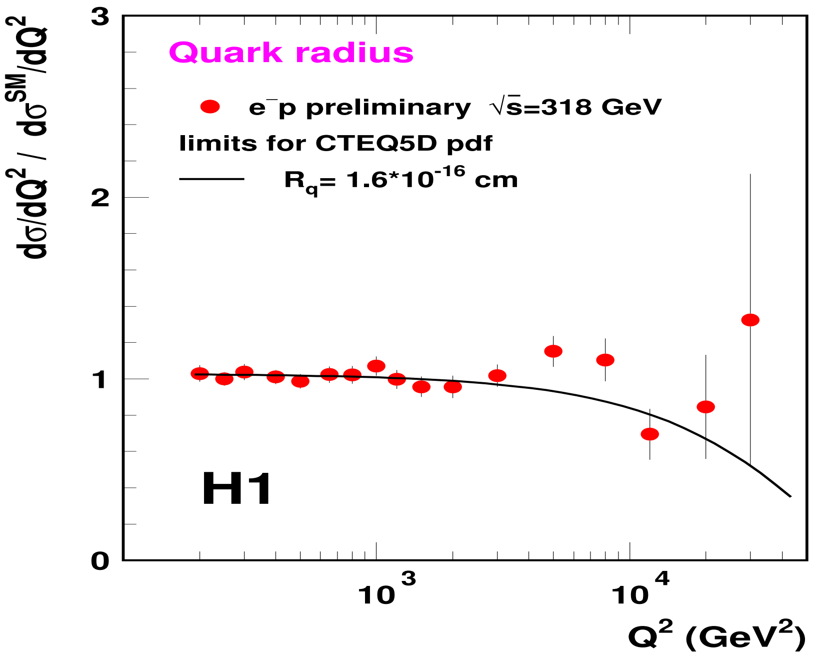
$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2} \cdot \left[1 - \frac{R_q^2}{6} Q^2\right]^2$$

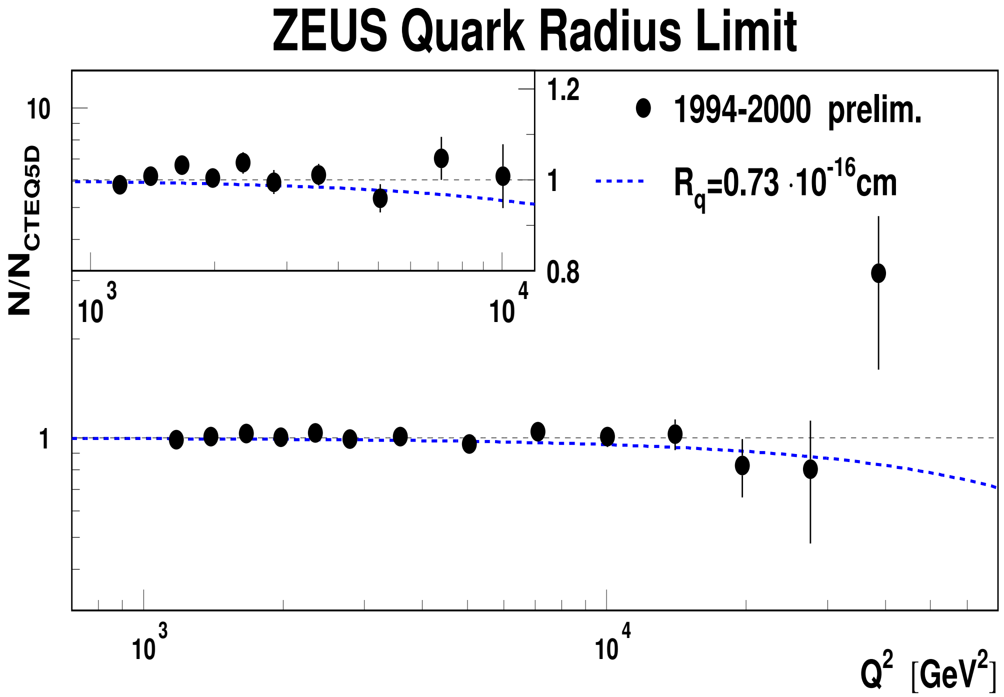
where R_q is the root mean-square radius of the electroweak charge distribution in the quark.

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

Quark form factor

Results





Preliminary 95% CL: 1994-2000 combined

$$R_q < 1.6 \cdot 10^{-16}\text{cm}$$

H1

$$R_q < 0.73 \cdot 10^{-16}\text{cm}$$

ZEUS

High mass leptoquarks

Buchmüller-Rückl-Wyler (BRW) model

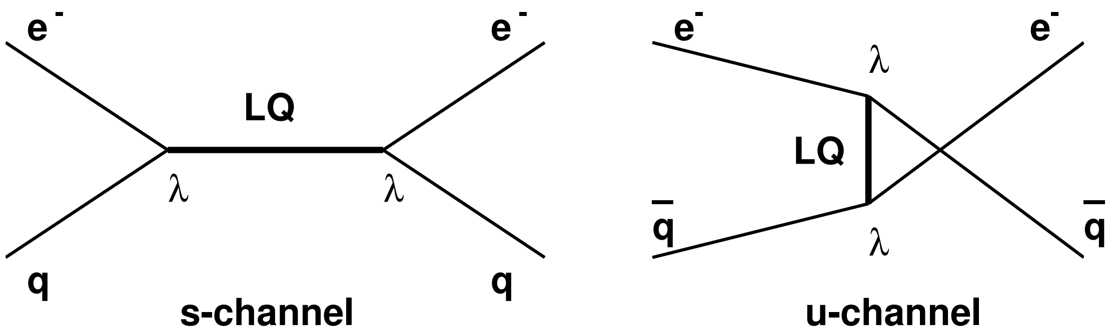
- $SU(3)_C \times SU(2)_L \times U(1)_Y$ invariance
- lepton and baryon number conservation
- strong bounds from rare decays $\Rightarrow$ either left- or right-handed couplings
- family diagonal if not $\Rightarrow$ LFV

$\Rightarrow$ 7 scalar and 7 vector leptoquarks

For high mass leptoquarks

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

both s- and u-channel important $\Rightarrow$

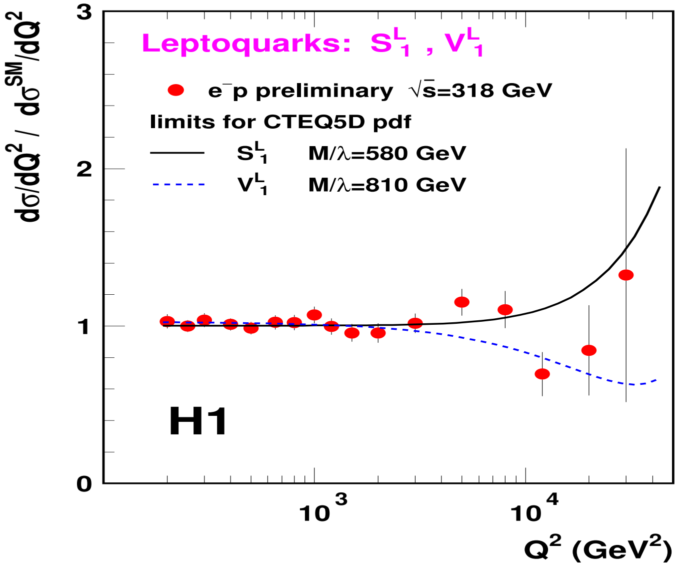


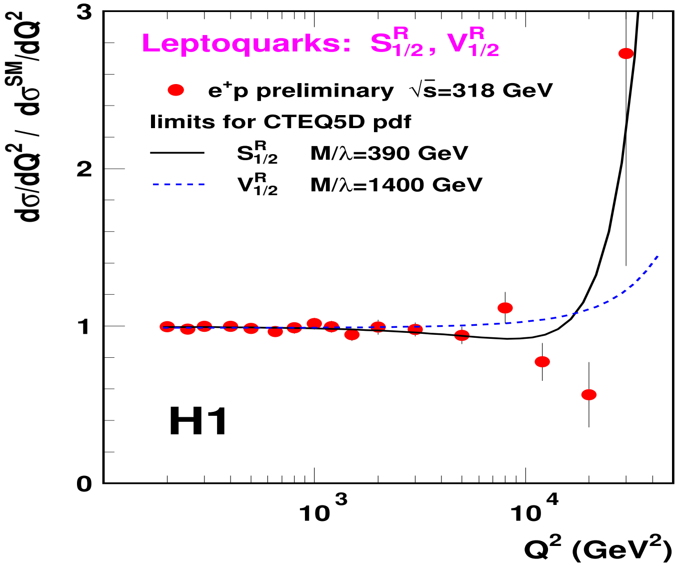
Virtual LQ production/exchange results in an effective coupling:

$$\eta_{CI} \sim (\lambda/M)^2$$

High mass leptoquarks

Results





H1 1994-00 preliminary, 95% CL limits

LQ	η^u $(\lambda/M_{LQ})^2$	η^d $(\lambda/M_{LQ})^2$	F	M_{LQ}/λ [GeV]
S_0^L	$+\frac{1}{2}$		2	1070
S_0^R	$+\frac{1}{2}$		2	960
$\tilde{S}_0^R$		$+\frac{1}{2}$	2	290
$S_{1/2}^L$	$-\frac{1}{2}$		0	380
$S_{1/2}^R$	$-\frac{1}{2}$	$-\frac{1}{2}$	0	380
$\tilde{S}_{1/2}^L$		$-\frac{1}{2}$	0	650
S_1^L	$+\frac{1}{2}$	$+1$	2	690
V_0^L		-1	0	1030
V_0^R		-1	0	810
$\tilde{V}_0^R$	-1		0	530
$V_{1/2}^L$		$+1$	2	480
$V_{1/2}^R$	$+1$	$+1$	2	1510
$\tilde{V}_{1/2}^L$	$+1$		2	1690
V_1^L	-2	-1	0	680

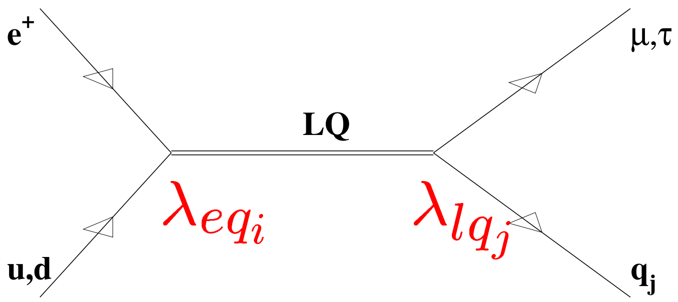
Lepton Flavor Violation

High mass limit

LQ coupling to different generations

e.g. $LQ \rightarrow e q_i$ and $LQ \rightarrow \tau q_j$

$\Rightarrow$ Lepton Flavor Violation



No signal found by H1/ZEUS 1994-97

For $M_{LQ} \gg \sqrt{s}$ $\Rightarrow$ LFV contact interactions

H1 and ZEUS 95% CL limits on $\frac{\lambda_{eq_i}\lambda_{\tau q_j}}{M^2}$ $\Rightarrow$

compared to low energy experiments

$q_i q_j$	$S^L_{1/2}$	$S^R_{1/2}$	$\tilde{S}^L_{1/2}$	V^L_0	V^R_0	$\tilde{V}^R_0$	V^L_1
1 1	$\tau \to \pi e$ 0.0032 0.030 0.046	$\tau \to \pi e$ 0.0016 0.025 0.037	$\tau \to \pi e$ 0.0032 0.046 0.062	G_F 0.002 0.033 0.049	$\tau \to \pi e$ 0.0016 0.033 0.049	$\tau \to \pi e$ 0.0016 0.024 0.041	G_F 0.002 0.012 0.019
1 2	$\boxed{0.030}$ 0.047	$\tau \to$K e 0.05 $\boxed{0.025}$ 0.038	$\tau \to$K e 0.05 $\boxed{0.046}$ 0.063	$\tau \to$K e 0.03 0.036 0.053	$\tau \to$K e 0.03 0.036 0.053	$\boxed{0.026}$ 0.045	K $\to \pi\nu\bar{\nu}$ $2.5 \cdot 10^{-6}$ 0.012 0.021
1 3	—	B$\to \tau e$ X 0.08 $\boxed{0.049}$ 0.065	B$\to \tau e$ X 0.08 $\boxed{0.049}$ 0.065	B$\to l\nu$X 0.02 0.044 0.062	B$\to \tau e$ X 0.04 0.044 0.062	—	B$\to l\nu$X 0.02 0.044 0.062
2 1	0.153 $\boxed{0.15}$	$\tau \to$K e 0.05 0.092 0.095	$\tau \to$K e 0.05 0.105 0.12	$\tau \to$K e 0.03 0.049 0.064	$\tau \to$K e 0.03 0.049 0.064	$\boxed{0.061}$ 0.073	K $\to \pi\nu\bar{\nu}$ $2.5 \cdot 10^{-6}$ 0.026 0.032
2 2	$\tau \to e\gamma$ 0.03 0.187 0.18	$\tau \to e\gamma$ 0.02 0.101 0.10	$\boxed{0.120}$ 0.13	$\boxed{0.061}$ 0.076	$\boxed{0.061}$ 0.076	$\boxed{0.102}$ 0.107	$\boxed{0.041}$ 0.044
2 3	—	B$\to \tau e$ X 0.08 0.153 0.14	B$\to \tau e$ X 0.08 0.153 0.14	B$\to l\nu$X 0.02 0.102 0.112	B$\to \tau e$ X 0.04 0.102 0.112	—	B$\to l\nu$X 0.02 0.102 0.112
3 1	—	B$\to \tau e$ X 0.08 0.162 0.16	B$\to \tau e$ X 0.08 0.162 0.16	V_{ub} 0.002 0.052 0.068	B$\to \tau e$ X 0.04 0.052 0.068	—	V_{ub} 0.002 0.052 0.068
3 2	—	B$\to \tau e$ X 0.08 0.202 0.19	B$\to \tau e$ X 0.08 0.202 0.19	B$\to l\nu$X 0.02 0.073 0.083	B$\to \tau e$ X 0.04 0.073 0.083	—	B$\to l\nu$X 0.02 0.073 0.083
3 3	—	0.275 $\boxed{0.23}$	0.275 $\boxed{0.23}$	$\tau \to e\gamma$ 0.51 0.144 $\boxed{0.14}$	$\tau \to e\gamma$ 0.51 0.144 $\boxed{0.14}$	—	0.144 $\boxed{0.14}$

Summary

- Over 200 pb^{-1} of $e^{\pm}p$ data collected by H1 and ZEUS
- Contact Interaction approximation used to search for:
  - ⇒ Compositeness
  - ⇒ Large Extra Dimensions
  - ⇒ Quark radius
  - ⇒ High mass leptoquarks
  - ⇒ Lepton Flavor Violation
- No evidence for new physics so far...
- Limits comparable/complementary to LEP/Tevatron
- Exciting future after HERA upgrade...