Leptoquarks and Contact Interactions

Jolanta Sztuk-Dambietz
Hamburg University

for

H1 & ZEUS

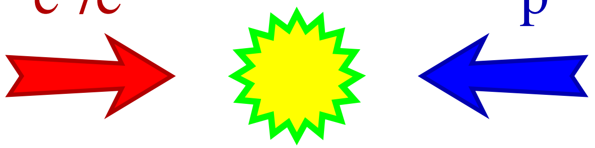
International Conference on High Energy Physics
Moscow, July 29^{th}, 2006

Outline:

- High-Q^2 DIS $\Rightarrow$ New Physics
- Leptoquarks
  - $\Rightarrow$ Leptoquark Model
  - $\Rightarrow$ Invariant Mass Spectra
  - $\Rightarrow$ LQ limits
- Contact Interaction
  - $\Rightarrow$ Compositeness models
  - $\Rightarrow$ Large Extra Dimensions
  - $\Rightarrow$ Quark form factor
  - $\Rightarrow$ Heavy Leptoquarks
- Summary

Introduction

HERA data

e^+/e^- →  ← p

27.5 GeV

820 GeV 1994-97
920 GeV 1998-05

Presented results

Year		$\langle P \rangle$	H1	ZEUS
HERA I				
1994-97	e^+p	-	37 pb^{-1}	48 pb^{-1}
1998-99	e^-p	-	15 pb^{-1}	16 pb^{-1}
1999-00	e^+p	-	65 pb^{-1}	64 pb^{-1}
HERA II				
2003-04	LH e^+p	-0.41	-	11.5 pb^{-1}
2003-04	RH e^+p	+0.32	-	12.3 pb^{-1}
2004-05	LH e^-p	-0.27	60 pb^{-1}	78.8 pb^{-1}
2004-05	RH e^-p	+0.33	32 pb^{-1}	42.7 pb^{-1}

where: P - is electron beam polarization

HERA II:

⇒ longitudinally polarized lepton beam

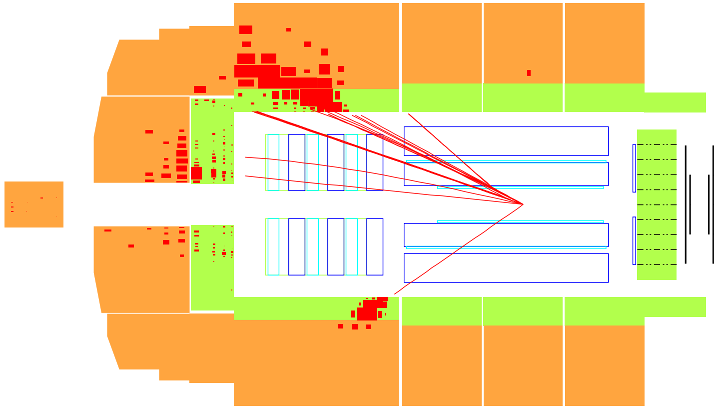
⇒ e^-p data sample much more than in HERA I

⇒ equal sharing between e^+p and e^-p

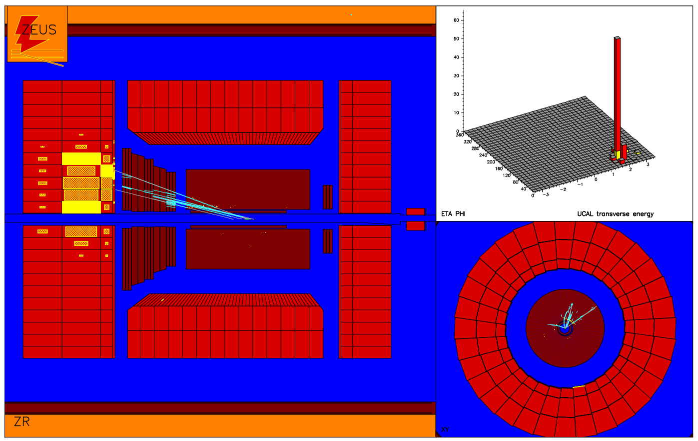
first results presented here!

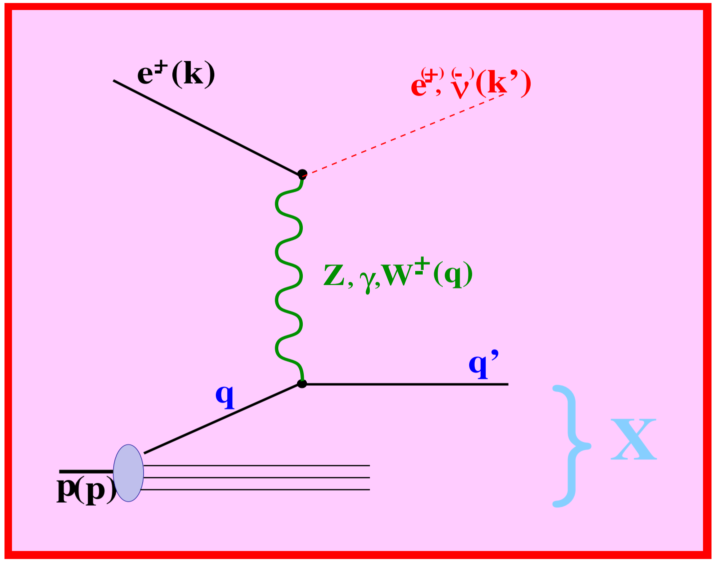
High-Q^2 DIS

NC DIS:



CC DIS:





- Q^2 = -(4-momentum of propagator)^2 - the virtuality of the exchanged boson.
- x - fractional momentum of proton carried by struck quark q
- y - fractional energy of the incoming lepton transfered to the proton in the proton's rest frame

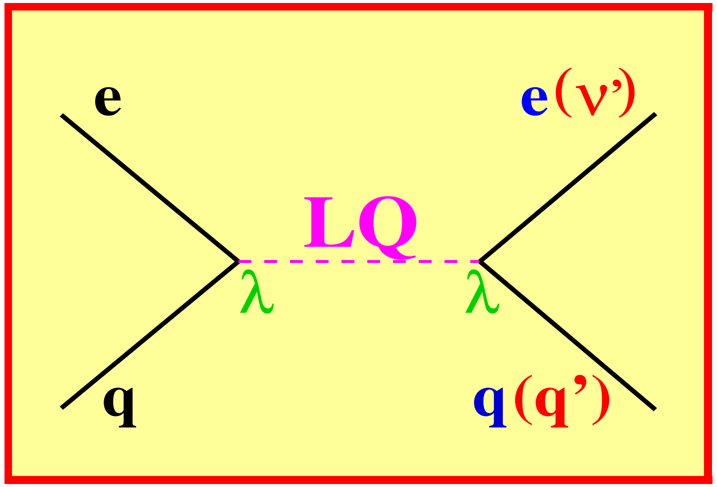
Introduction to the Leptoquark Model

LEPTOQUARKS:

Scalar or vector color triplet bosons carrying L and B numbers

$\Rightarrow$ **Fermion number** $F = 3B + L = 0, 2$

Resonant production in $e^{\pm}p$



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:

- All 14 LQ $\Rightarrow LQ \rightarrow eq'$
- 2 scalar and 2 vector LQ couple to both eq and νq

Introduction to the Leptoquark Model

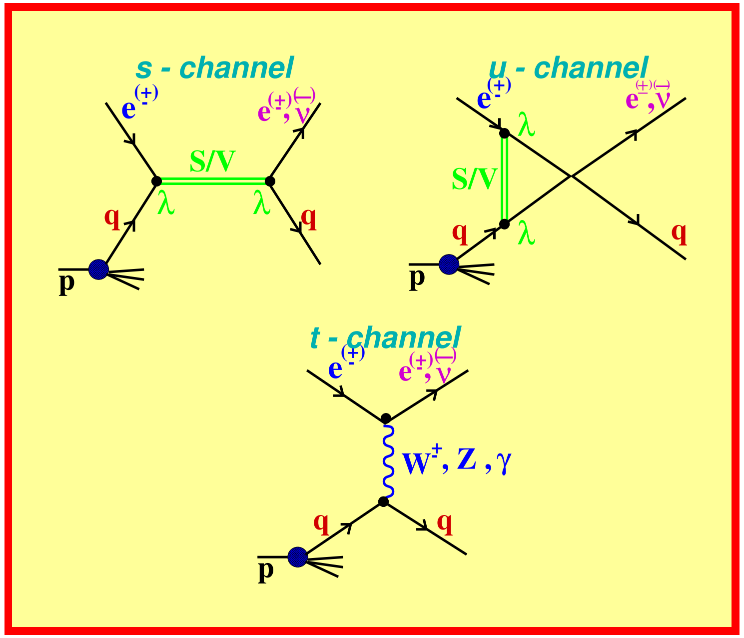
The total $e^{\pm}p \rightarrow \nu(e)X$ cross section:

$$\sigma(e^{\pm}p) = \sigma_{SM} + \sigma^{Int}_{u/SM} + \sigma^{Int}_{s/SM} + \sigma_u + \sigma_s$$

For small λ and $M_{LQ} \leq \sqrt{s}$: s-channel dominates

$\Downarrow$

LQ contribution to the SM $\Rightarrow$ resonance in M_{lj} distribution



In the general case (high masses, high couplings) all cross-section terms are important

$e^{-}p \Rightarrow$ F=2 LQ, $e^{+}p \Rightarrow$ F=0 LQ

(valence q $\gg$ sea q at high x)

Angular distribution:

$$y = 0.5(1 - cos\theta^{\star})$$

$\theta^{\star}$ - e scattering angle in eq (νq) rest frame

Scalar Leptoquarks

$$\left.\frac{d\sigma}{dy}\right|_{scalar} \rightarrow flat$$

Vector Leptoquarks

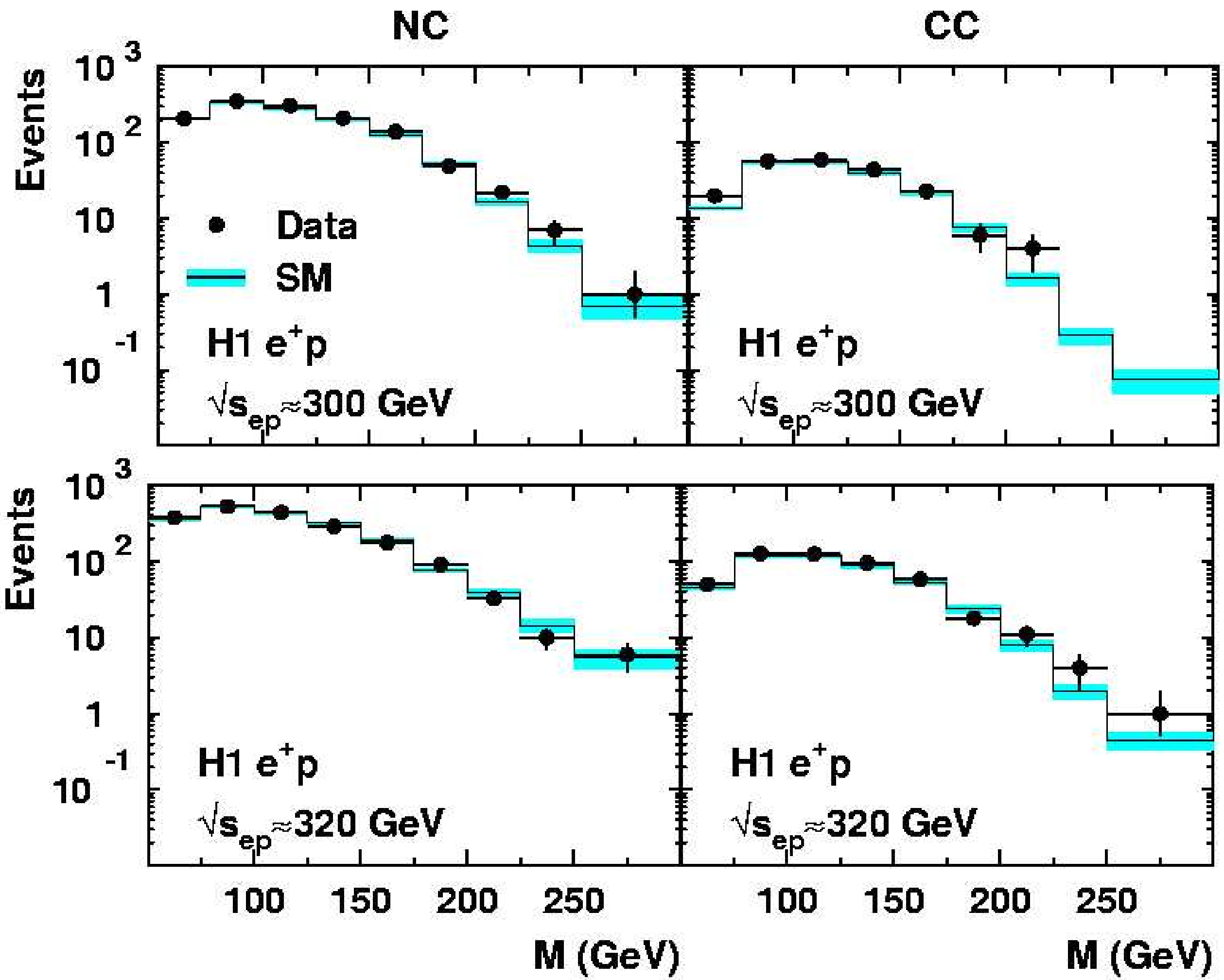
$$\left.\frac{d\sigma}{dy}\right|_{vector} \sim (1-y)^2$$

NC DIS (Background)

$$\frac{d\sigma^{e^{\pm}p}}{dy} \sim \frac{1}{y^2}$$

Invariant Mass Spectra from HERA I e^+p

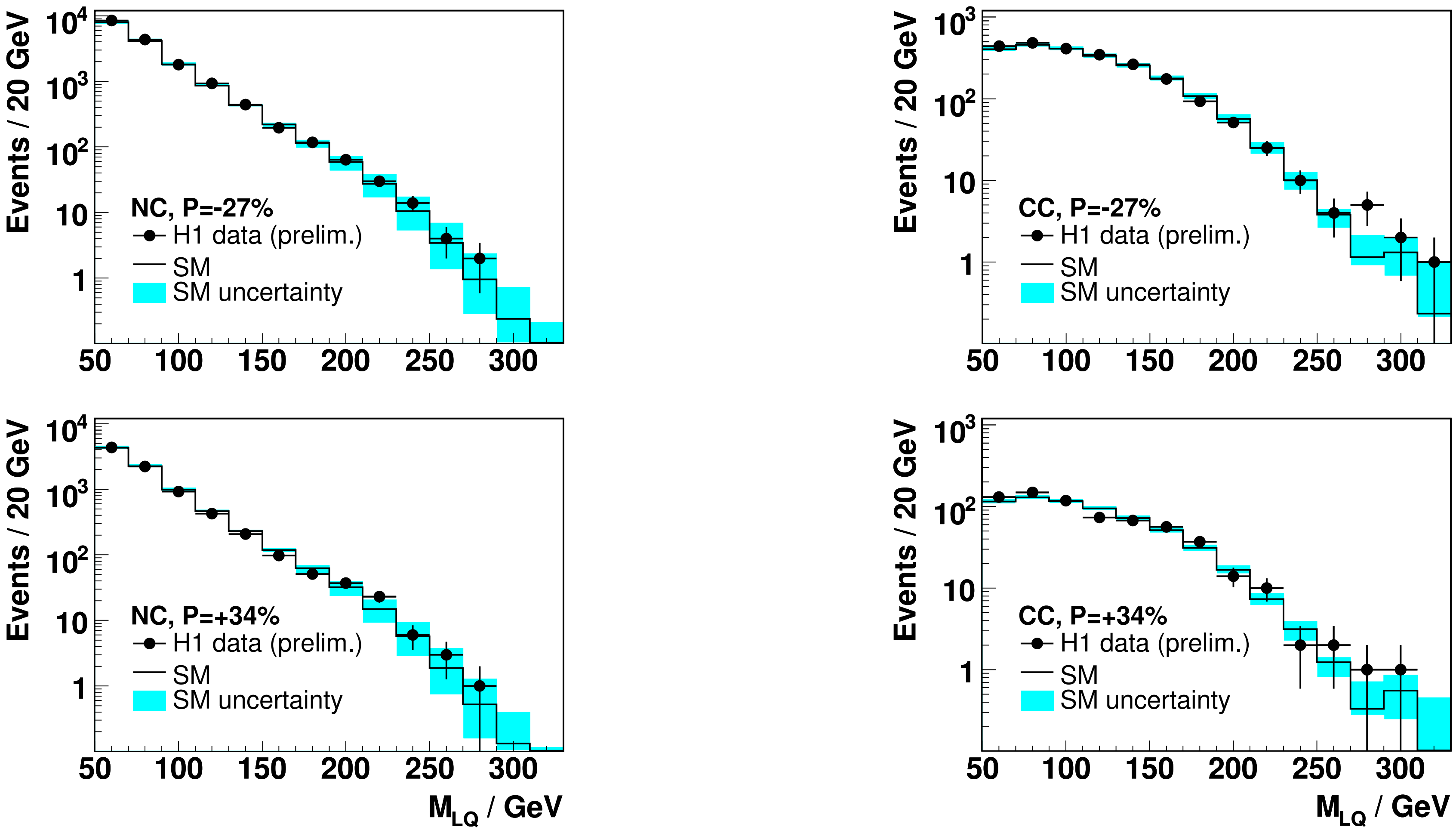
Physics Letters B629 (2005) 9-19



ZEUS has similar plots (Physical Review D 68 (2003) 052004)

Invariant Mass Spectra from HERA II $e^- p$

NC DIS: CC DIS:



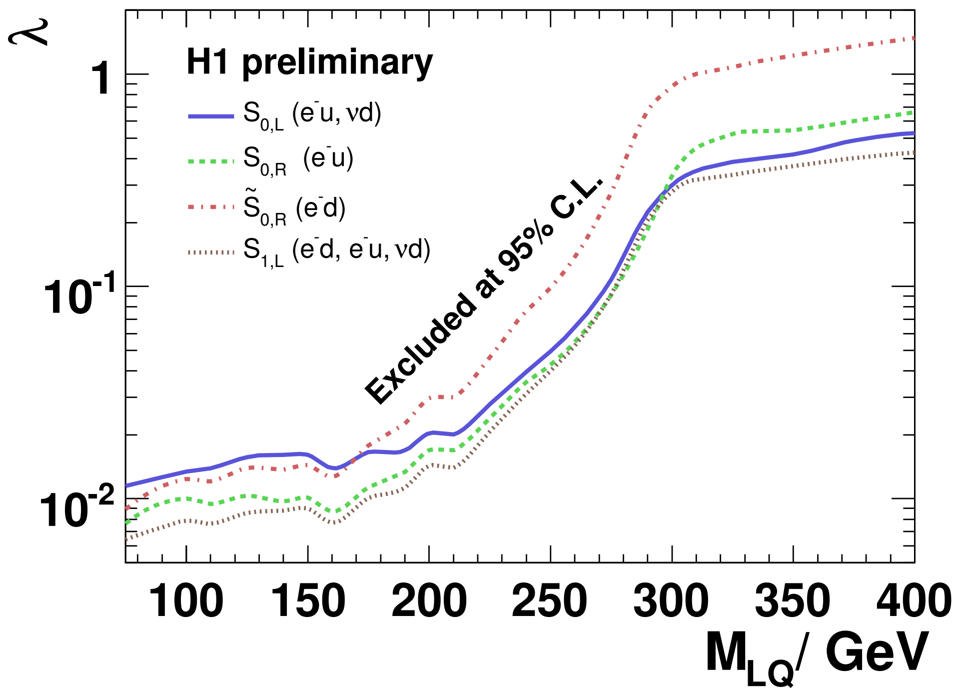
Good agreement between data and SM → no evidence of LQ

Scalar LQs with F=2 from H1 (HERA II)

No evidence for LQ production

$\Downarrow$

Limits on LQ Yukawa coupling λ as a function of M_{LQ}:



F=2 BRW LQ models

$\Rightarrow$ e^-p data more sensitive than e^+p

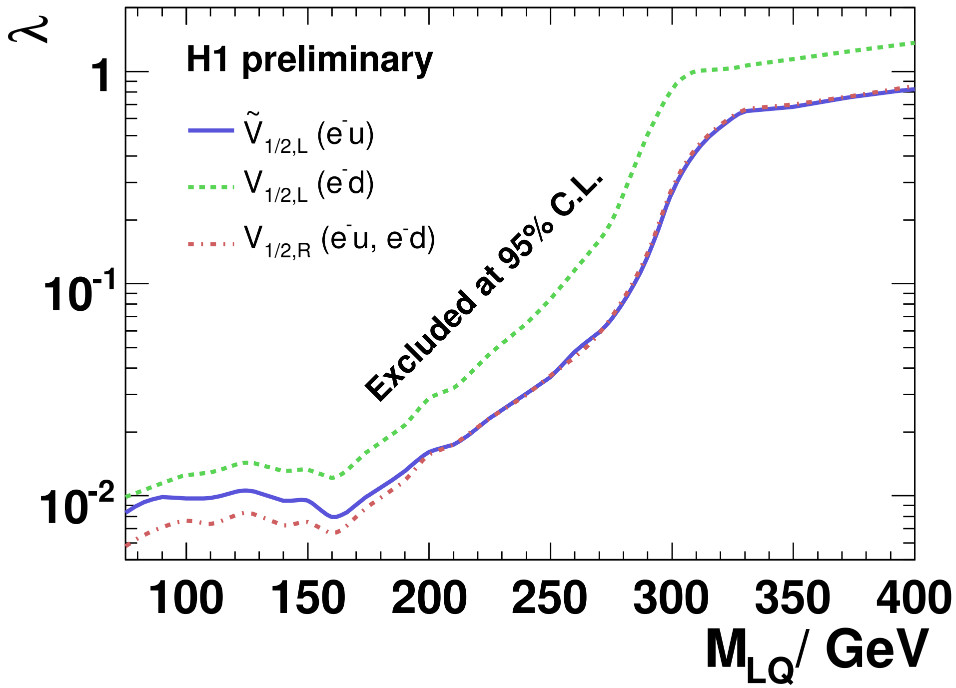
Combing NC $+$ CC data

for S_0^L and S_1^L LQ model

$\Rightarrow$ increases sensitivity

At $\lambda = \sqrt{4\pi\alpha} \approx 0.3$ lower limits on M_{LQ}: $>$ 276 - 304 GeV

Vector LQs with F=2 from H1 (HERA II)



F=2 BRW LQ models

$\Rightarrow$ e^-p data more sensitive than e^+p

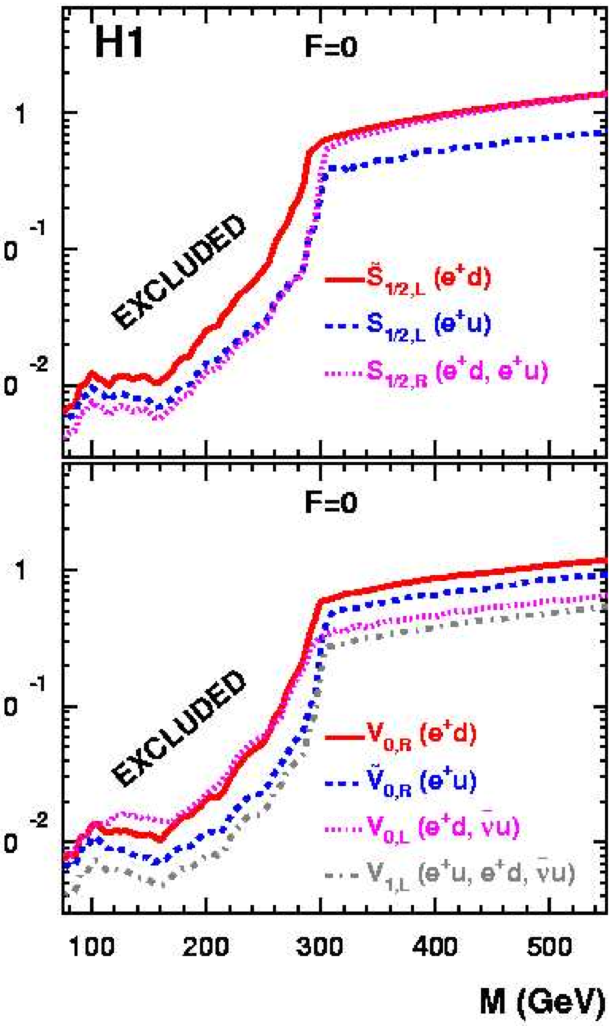
F=2 **vector** BRW LQ model

$\Rightarrow$ eq channel only

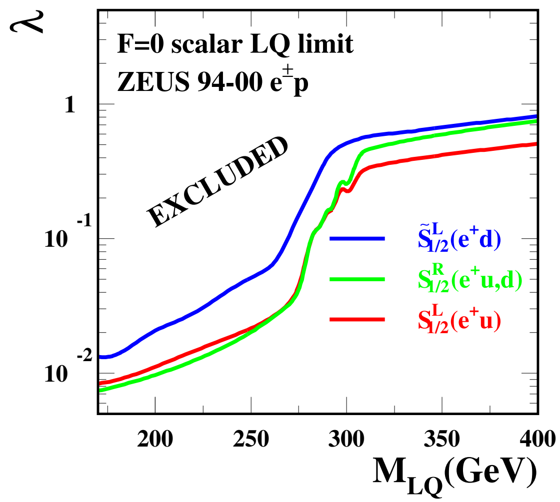
At $\lambda = \sqrt{4\pi\alpha} \approx 0.3$ lower limits on M_{LQ}: $>$ 280 - 303 GeV

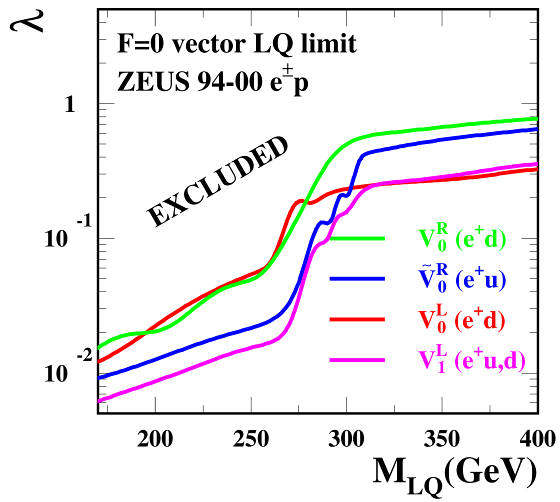
Limits on F=0 BRW LQ from HERA I

H1



ZEUS





F=0 **scalar** BRW LQ

⇒ couples to eq only

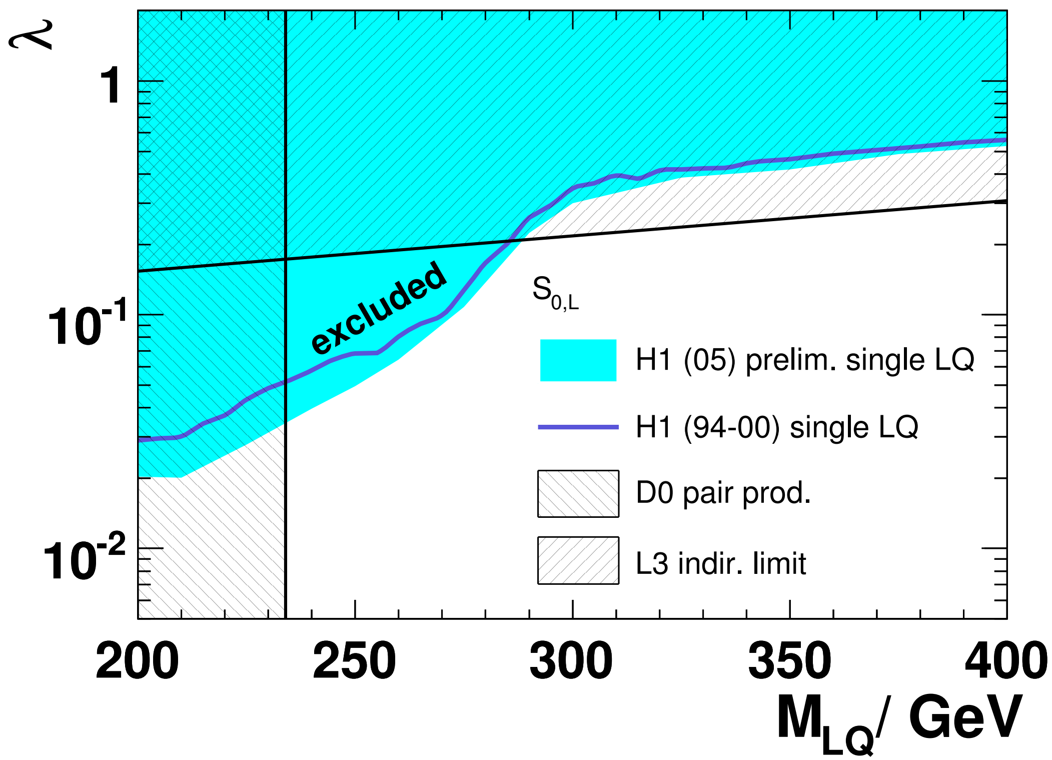
F=0 **vector** BRW LQ

⇒combine eq & νq channels

Both analyses give consistent results

Comparison with LEP, TEVATRON and HERA I

Scalar leptoquarks with F=2 S_0^L



TeVatron:

LQ pair production - λ independent

$$q\bar{q} \to l^+ l^- q\bar{q}$$

LEP:

indirect t/u-channel effect

in $q\bar{q}$-pair production

$$e^+ e^- \to q\bar{q}$$

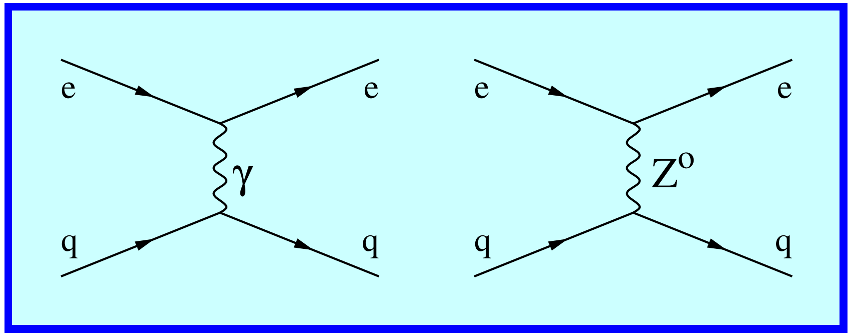
For couplings of em strength ($\lambda \sim 0.3$): mass exclusion $\sim$ 300 GeV

Limits comparable to those obtained at LEP and Tevatron

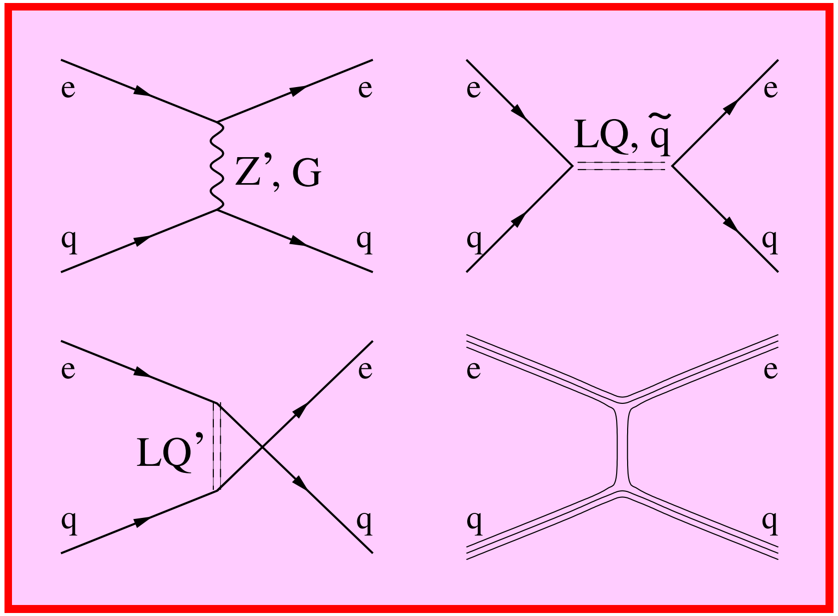
Contact Interactions

Neutral Current eq Scattering

Standard Model processes:

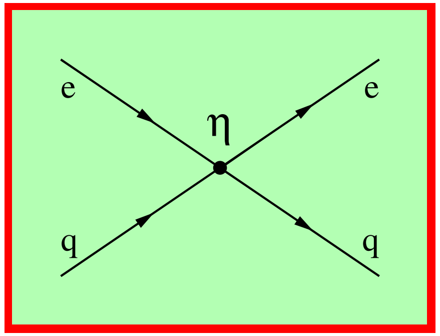


Possible "new physics" processes:



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 formula

For NC e^-p DIS with unpolarized beam

$$\frac{d^2\sigma^{e^-p}}{dxdy} =$$

$$\frac{sx}{16\pi}\sum_q \quad q(x)\left\{ \quad |M^{eq}_{LL}|^2 + \quad |M^{eq}_{RR}|^2 + (1-y)^2\left[\quad |M^{eq}_{LR}|^2 + \quad |M^{eq}_{RL}|^2\right]\right\}$$

$$+ \quad \bar{q}(x)\left\{ \quad |M^{eq}_{LR}|^2 + \quad |M^{eq}_{RL}|^2 + (1-y)^2\left[\quad |M^{eq}_{LL}|^2 + \quad |M^{eq}_{RR}|^2\right]\right\}$$

$\Rightarrow$ most sensitive to η^{eq}_{LL} and η^{eq}_{RR} (q=u,d)

Contact Interactions

Cross-section formula

For NC e^-p DIS with polarized beam

$$\frac{d^2\sigma^{e^-p}}{dxdy} =$$

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

$$+ \quad \bar{q}(x)\left\{\mathcal{P}_-|M^{eq}_{LR}|^2 + \mathcal{P}_+|M^{eq}_{RL}|^2 + (1-y)^2\left[\mathcal{P}_-|M^{eq}_{LL}|^2 + \mathcal{P}_+|M^{eq}_{RR}|^2\right]\right\}$$

$\Rightarrow$ most sensitive to η^{eq}_{LL} and η^{eq}_{RR} (q=u,d)

where: $\mathcal{P}_\pm = (1 \pm P)$

P is electron beam polarization

Contact Interactions

Cross-section formula

For NC e^+p DIS with polarized beam

$$\frac{d^2\sigma^{e^+p}}{dxdy} =$$

$$\frac{sx}{16\pi}\sum_q \quad q(x)\left\{\mathcal{P}_+|M_{LR}^{eq}|^2 + \mathcal{P}_-|M_{RL}^{eq}|^2 + (1-y)^2\left[\mathcal{P}_+|M_{LL}^{eq}|^2 + \mathcal{P}_-|M_{RR}^{eq}|^2\right]\right\}$$

$$+ \quad \bar{q}(x)\left\{\mathcal{P}_+|M_{LL}^{eq}|^2 + \mathcal{P}_-|M_{RR}^{eq}|^2 + (1-y)^2\left[\mathcal{P}_+|M_{LR}^{eq}|^2 + \mathcal{P}_-|M_{RL}^{eq}|^2\right]\right\}$$

$\Rightarrow$ most sensitive to η_{LR}^{eq} and η_{RL}^{eq} (q=u,d)

$\Rightarrow$ Combining e^+p and e^-p can significantly improve limits

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 $\varepsilon = \pm 1$.

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

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

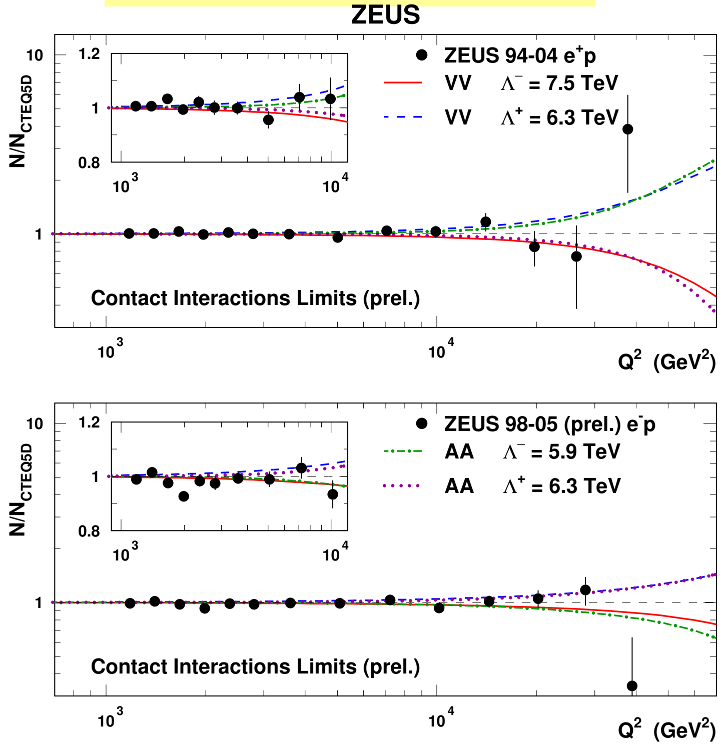
Also referred to as compositeness models

(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							$+\eta$	$-\eta$

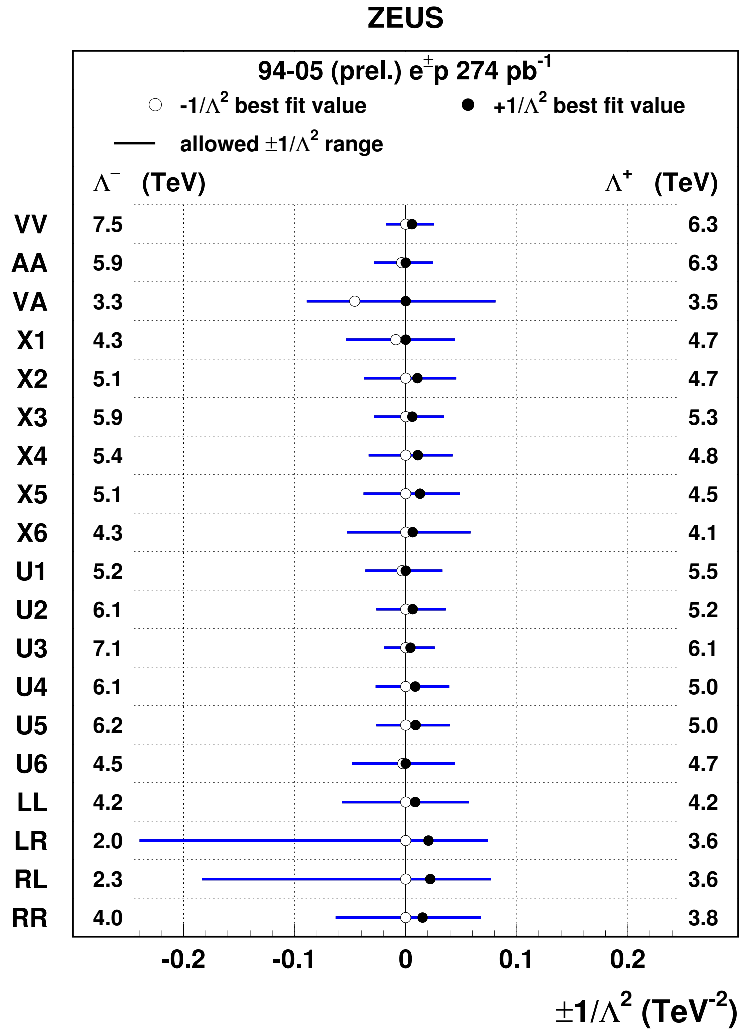
General Models - Results

ZEUS 1994-05 analysis



95% CL limits: $\Lambda > 2.0 - 7.5$ TeV

Significant improvement of limits for
models sensitive to LL and RR couplings
(constrained mainly by e^-p data)



Limits comparable to those obtained at LEP and Tevatron

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.

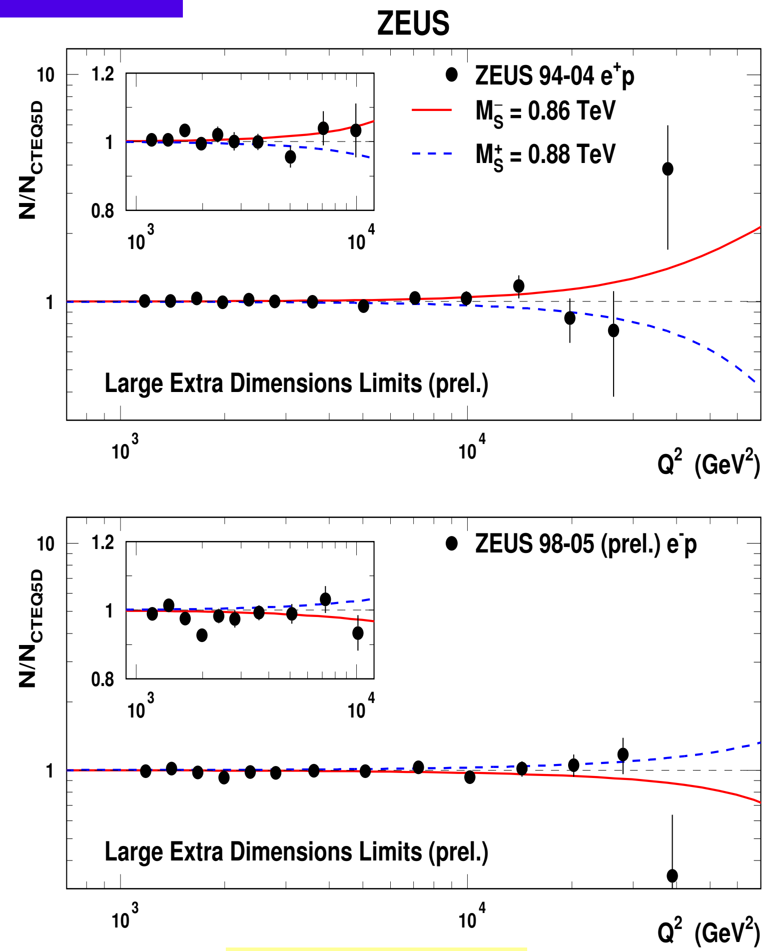
$\Rightarrow$ Gravitational interactions become comparable in strength to electroweak interactions.

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. $(\sqrt{s}, Q^2)$

CI results from H1 (HERA I) $\Rightarrow$ Phys Lett B568 (2003) 35-47



ZEUS results

$M_S^- > 0.86$ TeV
$M_S^+ > 0.88$ TeV

Quark Form Factor

Model

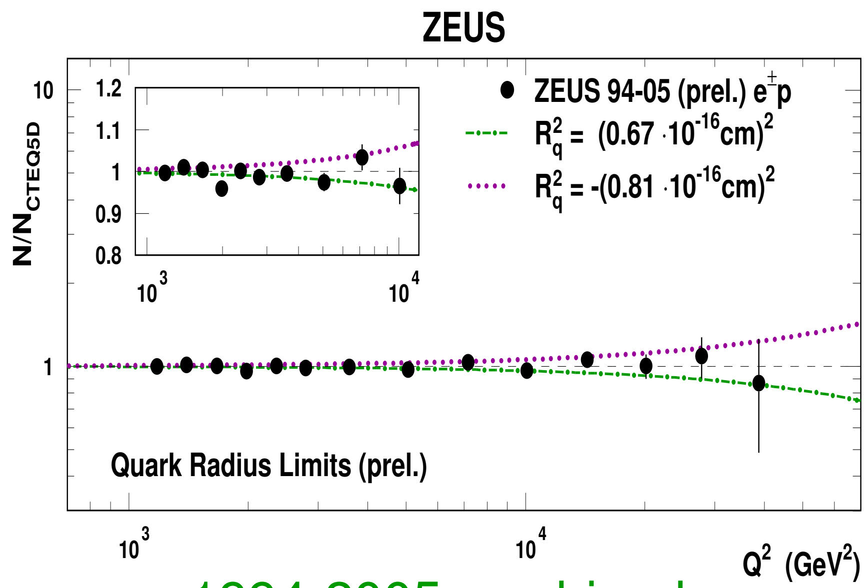
"classical" method to look for possible fermion (sub)structure.

If a quark has finite size $\Rightarrow$ SM cross-section **decreases** 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.

Results



1994-2005 combined ZEUS

$R_q < 0.67 \cdot 10^{-16}$cm

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

High Mass Leptoquarks

For high mass leptoquarks

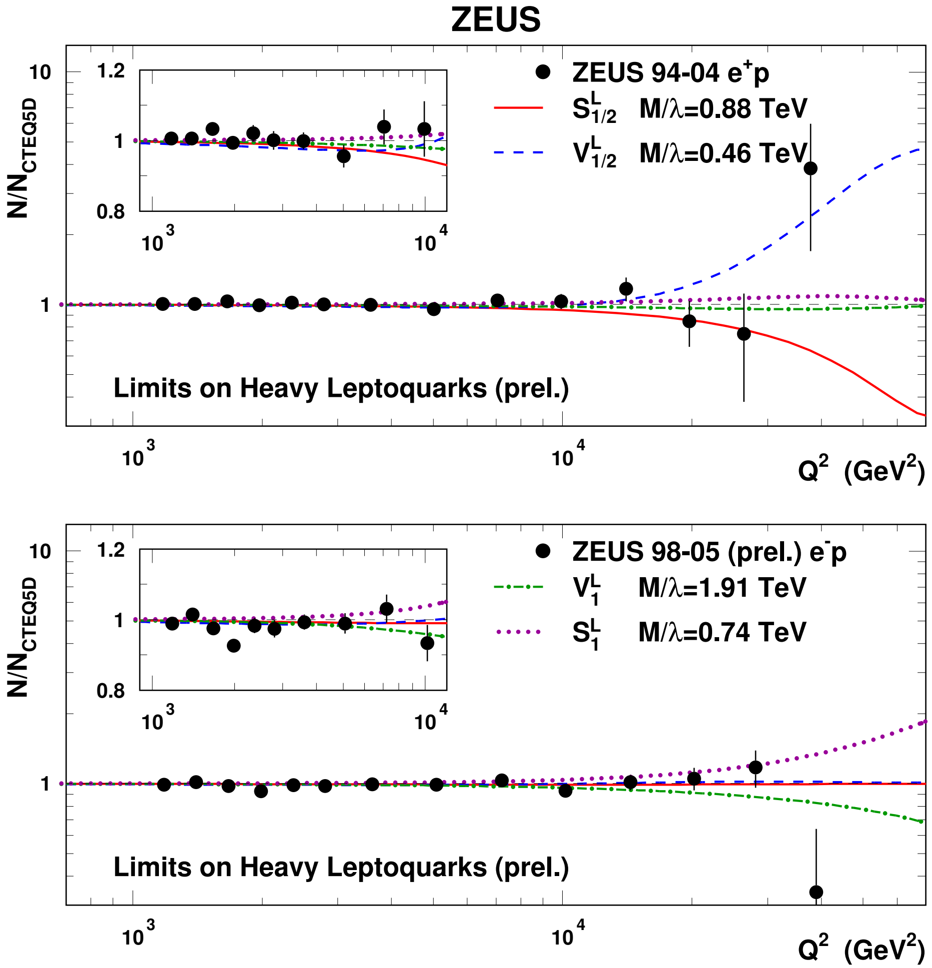
$$M_{LQ} \gg \sqrt{s}$$

both s- and u-channel important

$$\Downarrow$$

Virtual LQ production/exchange results in an effective coupling:

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



95% CL lower limits on M_{LQ} to the Yukawa coupling ratio from ZEUS:

M_{LQ}/λ_{LQ}: 0.32 - 1.91 TeV

Limits at HERA complementary/competitive to LEP

Summary and Outlook

- Both experiments published the LQ and CI searches on all HERA I data

- First results based on HERA II data were presented

- No evidence for New Physics:
  $\Rightarrow$ LQ limits from H1 using HERA II e^-p data: M$_{LQ}$ $>$ 276-304 GeV for $\lambda = 0.3$
  $\Rightarrow$ CI limits from ZEUS using all HERA I+II data:

  - Compositeness scale: $\Lambda >$ 2-7.5 TeV
  - Heavy LQ: M$_{LQ}/\lambda >$ 0.32-1.9 TeV
  - Quark radius: R$_q$ $<$0.67$\cdot$10^{-16} cm
  - LED: M$_S^+$ $>$0.88 TeV

- Limits for LQ with F=2 improved by using HERA II data

- CI analysis including HERA I+II data $\Rightarrow$ significant improvement of limits

- More data HERA I+II and possible H1 + ZEUS data combination ($\sim$ 700 pb^{-1})
  $\Rightarrow$ Improvements are expected!

Backup Slide

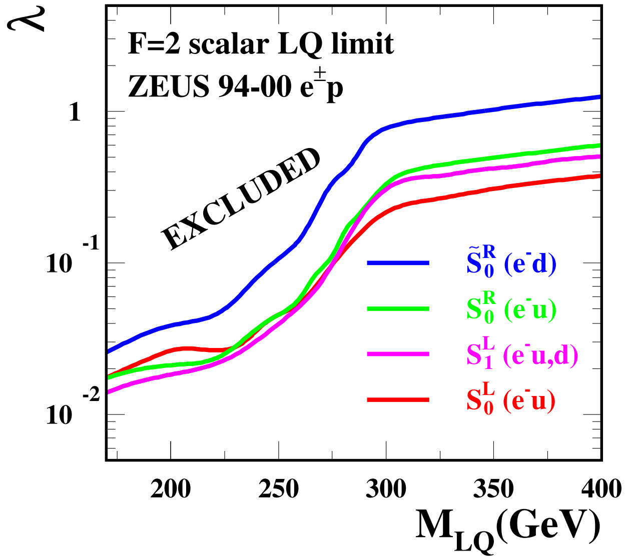
Models

Leptoquarks

Aachen notation

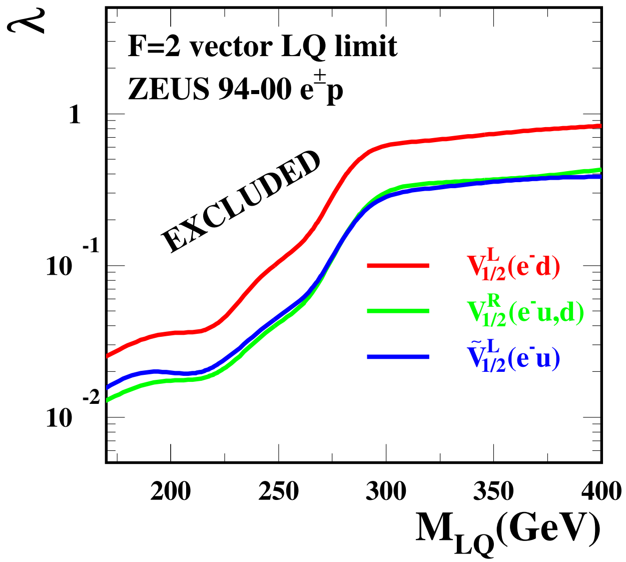
Model	Fermion number F	Charge Q	$BR(LQ \to e^{\pm}q)$ β	Coupling		Squark type
$S_{\circ}^{L}$	2	$-1/3$	1/2	$e_L u$	νd	$\tilde{d}_R$
$S_{\circ}^{R}$	2	$-1/3$	1	$e_R u$		
$\tilde{S}_{\circ}$	2	$-4/3$	1	$e_R d$		
$S_{1/2}^{L}$	0	$-5/3$	1	$e_L \bar{u}$		
		$-2/3$	0		$\nu \bar{u}$	
$S_{1/2}^{R}$	0	$-5/3$	1	$e_R \bar{u}$		
		$-2/3$	1	$e_R \bar{d}$		
$\tilde{S}_{1/2}$	0	$-2/3$	1	$e_L \bar{d}$		$\bar{\tilde{u}}_L$
		$+1/3$	0		$\nu \bar{d}$	$\bar{\tilde{d}}_L$
S_1	2	$-4/3$	1	$e_L d$		
		$-1/3$	1/2	$e_L u$	νd	
		$+2/3$	0		νu	
$V_{\circ}^{L}$	0	$-2/3$	1/2	$e_L \bar{d}$	$\nu \bar{u}$	
$V_{\circ}^{R}$	0	$-2/3$	1	$e_R \bar{d}$		
$\tilde{V}_{\circ}$	0	$-5/3$	1	$e_R \bar{u}$		
$V_{1/2}^{L}$	2	$-4/3$	1	$e_L d$		
		$-1/3$	0		νd	
$V_{1/2}^{R}$	2	$-4/3$	1	$e_R d$		
		$-1/3$	1	$e_R u$		
$\tilde{V}_{1/2}$	2	$-1/3$	1	$e_L u$		
		$+2/3$	0		νu	
V_1	0	$-5/3$	1	$e_L \bar{u}$		
		$-2/3$	1/2	$e_L \bar{d}$	$\nu \bar{u}$	
		$+1/3$	0		$\nu \bar{d}$	

Limits on F=2 BRW LQ from ZEUS (HERA I)



F=2 **scalar** BRW LQ model

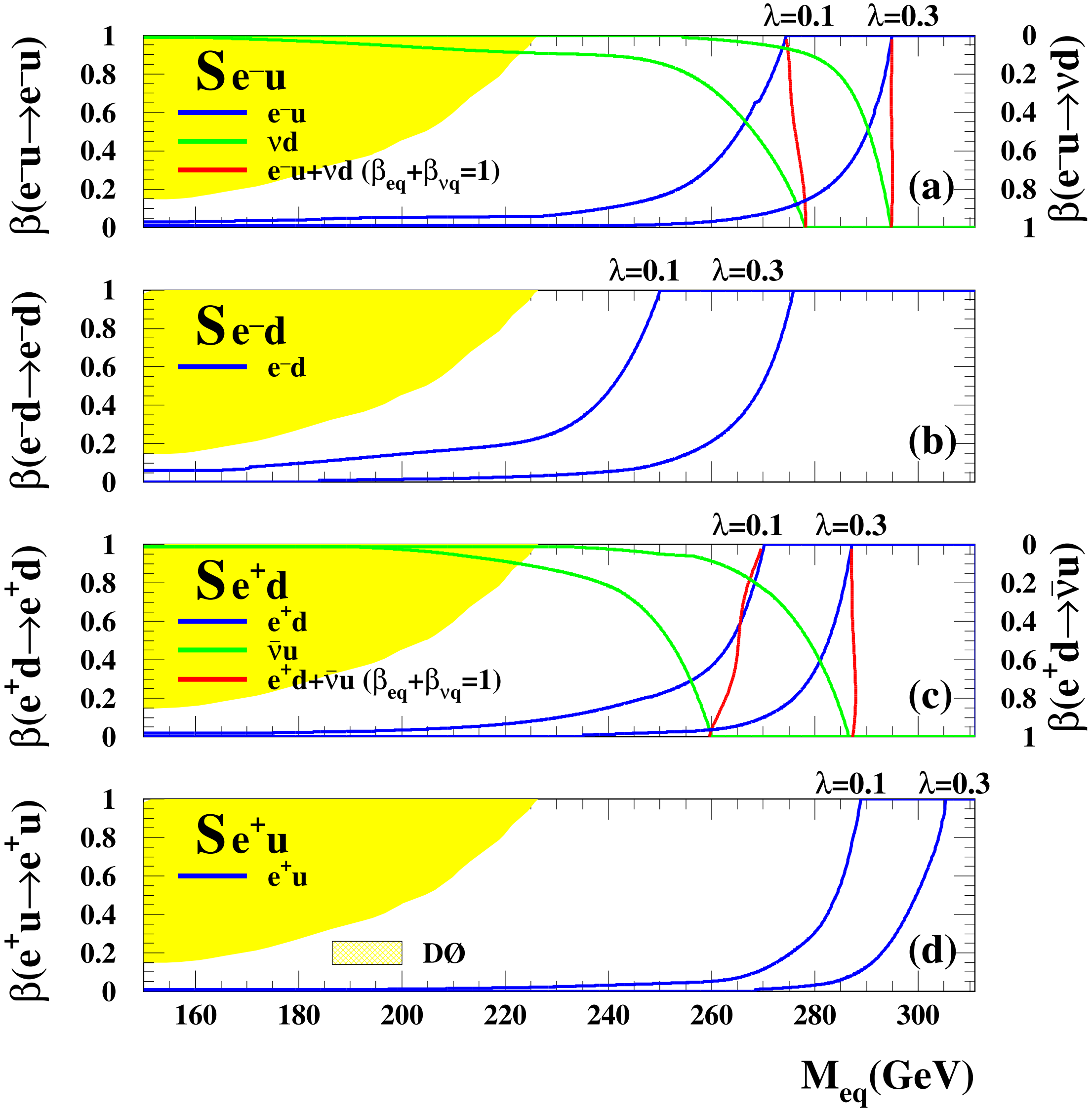
⇒Combine eq & νq channels



F=2 **vector** BRW LQ model

⇒ eq channel only

General LQ limits from ZEUS



General LQ Model

⇓

No $\beta(eq)$ constraint

Combined limit (NC & CC) assuming
$\beta(eq) + \beta(\nu q) = 1$

At $\lambda = 0.3$, M_{LQ} up to 300 GeV excluded, independent of β

Tevatron limits independent of λ, but less sensitive to $\nu q \Rightarrow$ degrade at low β

Contact Interactions

Cross-section

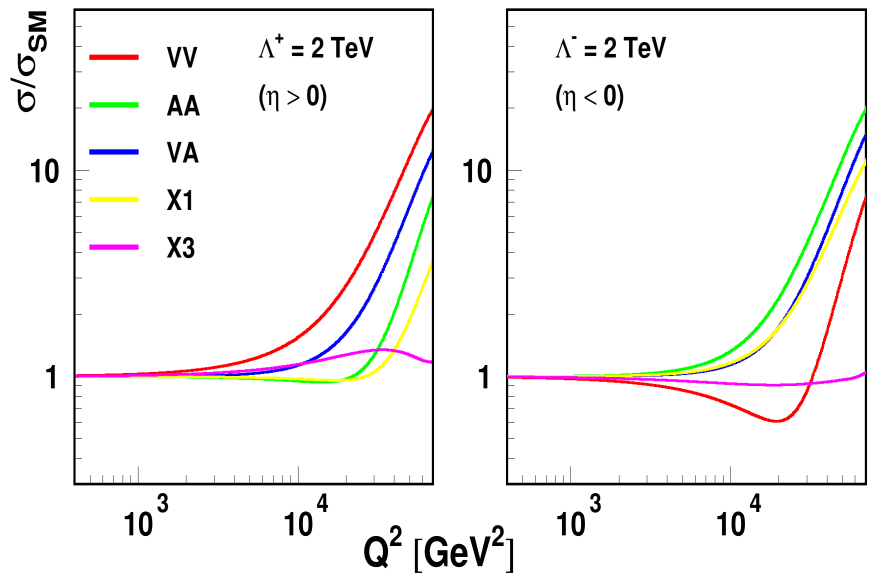
Contact Interactions modify tree level $eq \rightarrow eq$ scattering amplitudes $M^{eq}_{\alpha\beta}$:

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

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

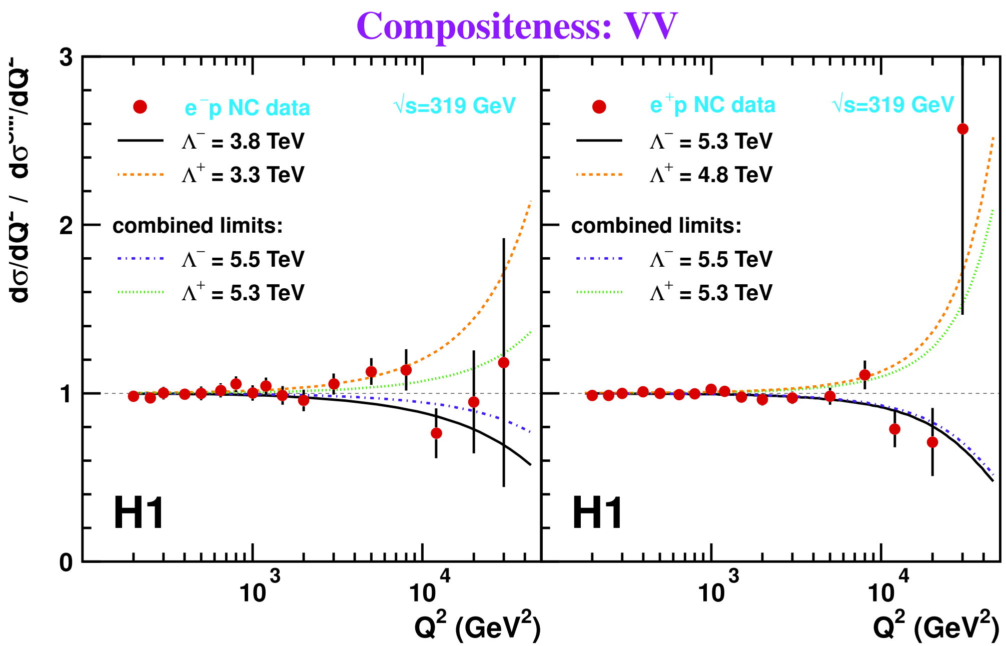


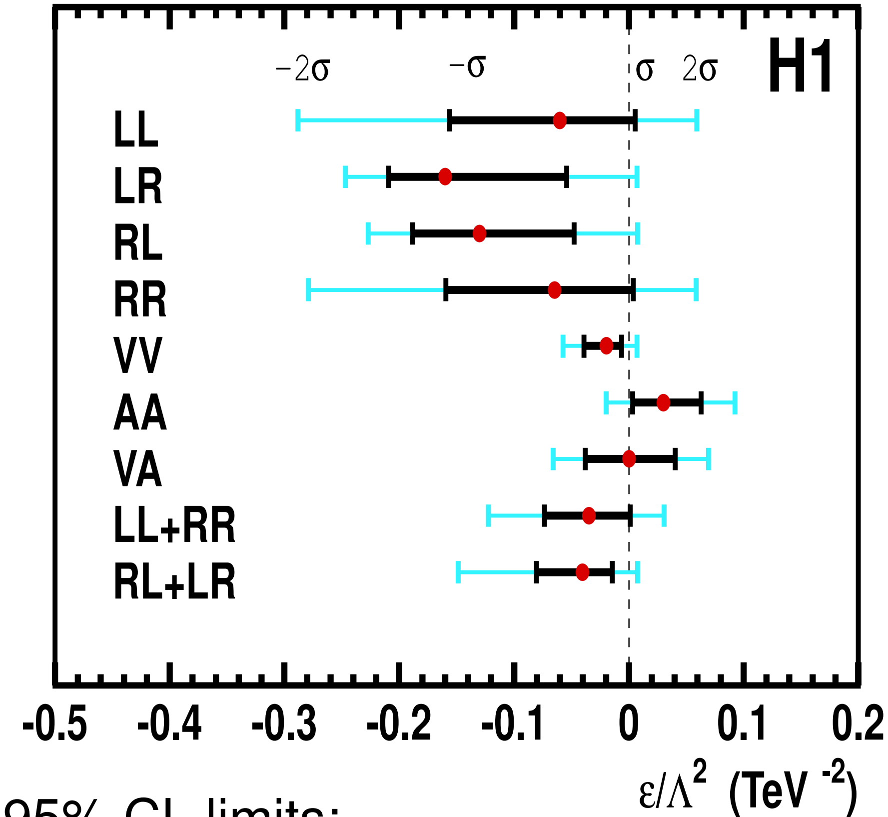
General models from H1 (HERAI)

Results

H1 1994-2000 analysis

data undershoots SM slightly at high Q^2





95% CL limits:

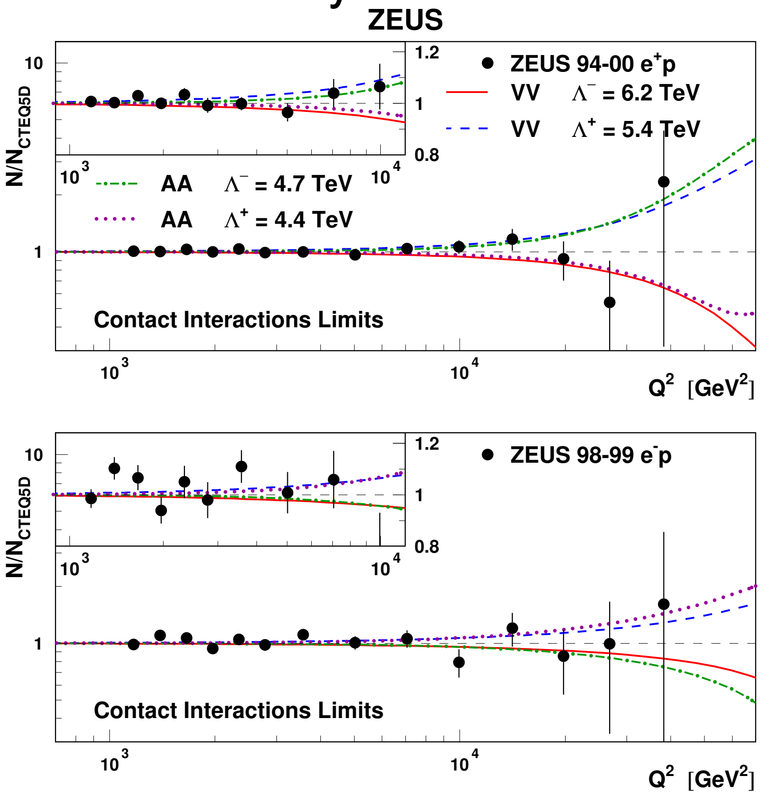
$\Lambda > 1.6 - 5.5$ TeV

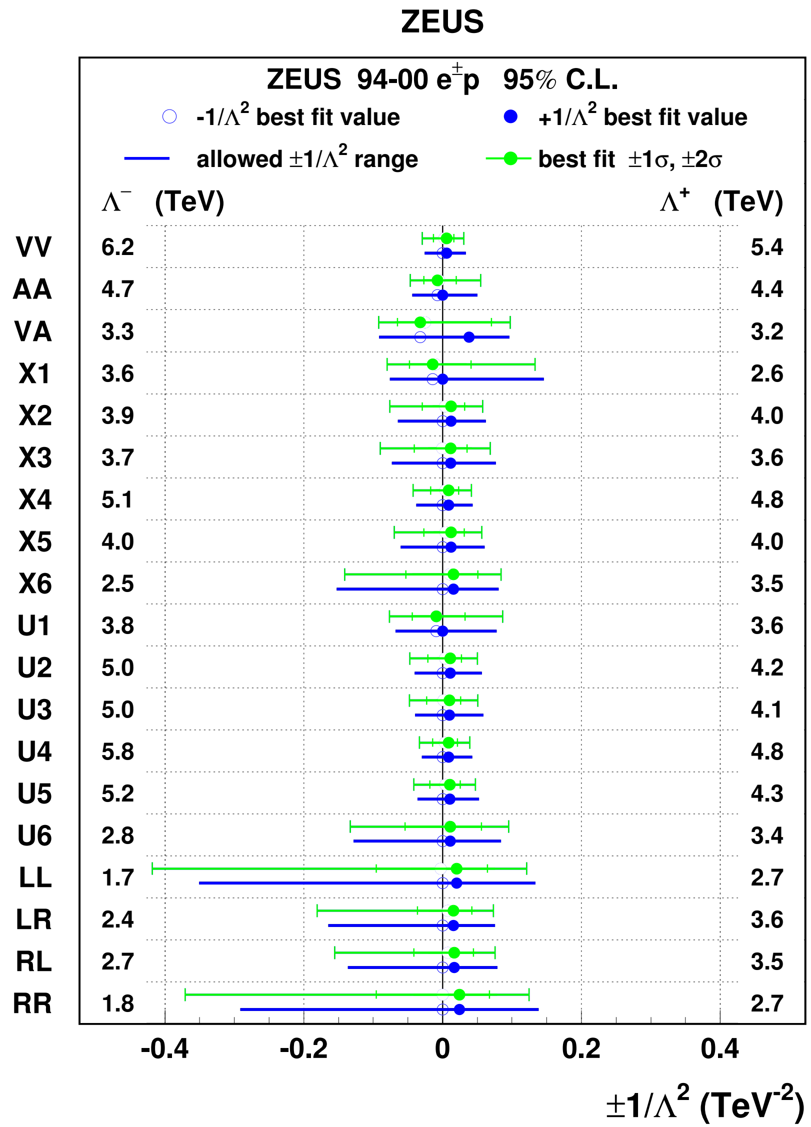
$\Rightarrow \sim 2\sigma$ deviation in most models

General models from ZEUS (HERA I)

Results

ZEUS 1994-00 analysis





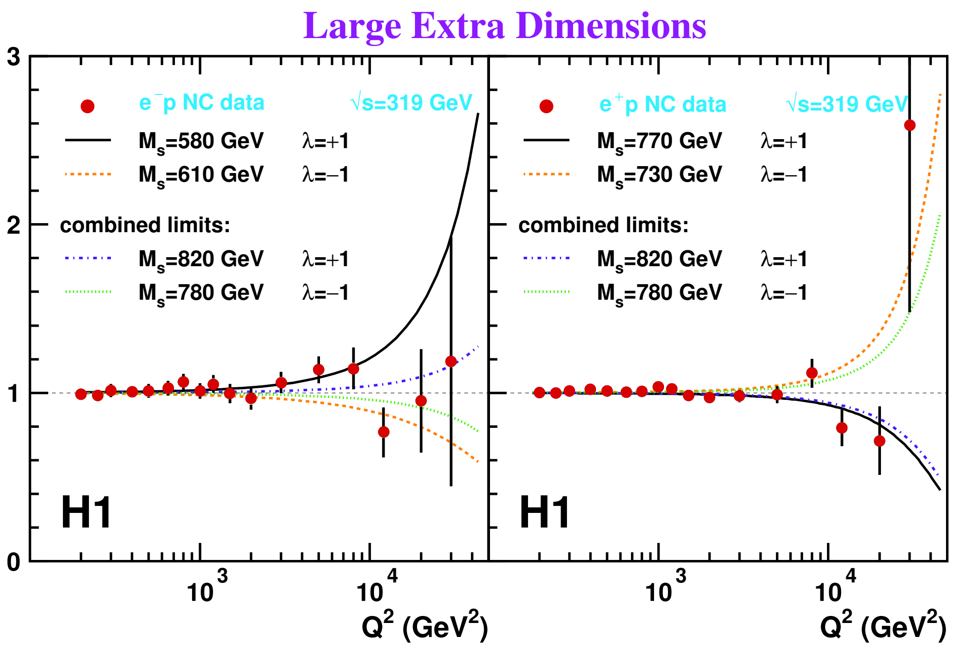
Good agreement with the Standard Model

95% CL limits:

$\Lambda > 1.7 - 6.2$ TeV

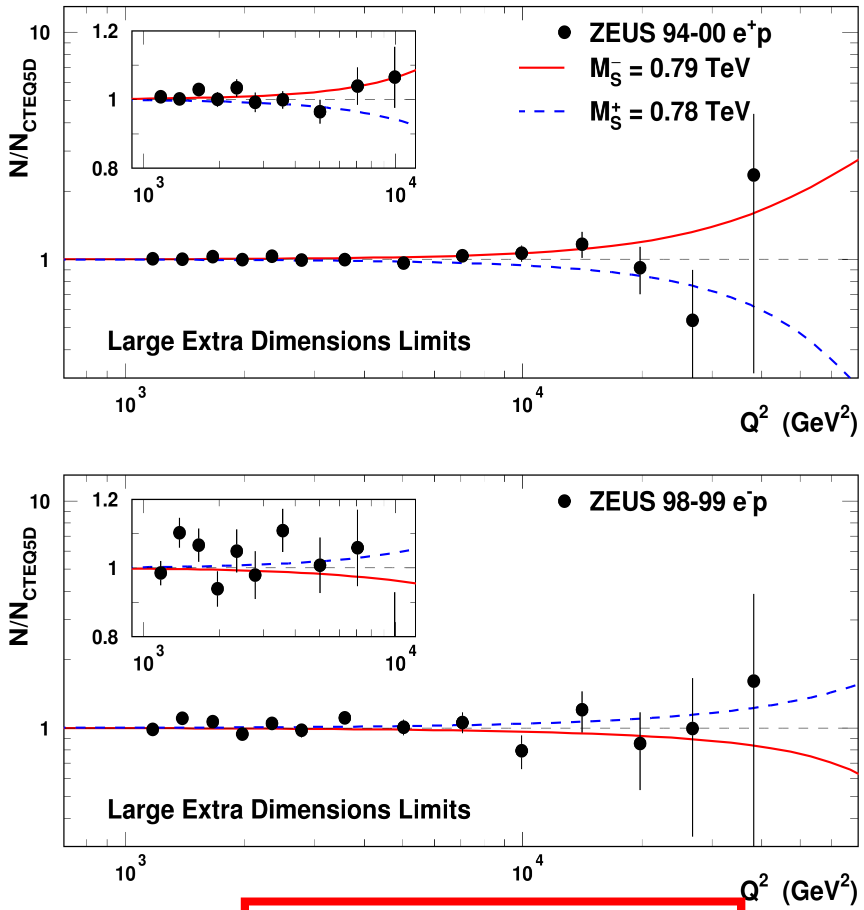
Large Extra Dimensions from HERA I

H1 results



$M_S^- > 0.78$ TeV
$M_S^+ > 0.82$ TeV

ZEUS results



$M_S^- > 0.79$ TeV
$M_S^+ > 0.78$ TeV

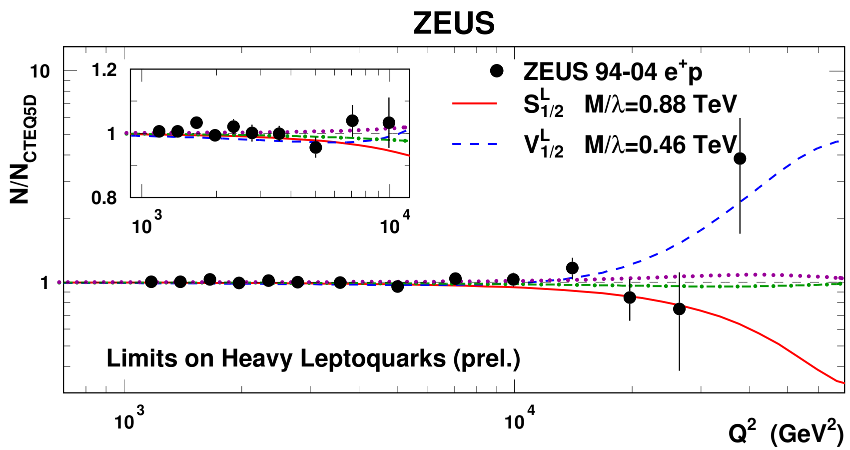
General Model - comparison with LEP and TeVatron

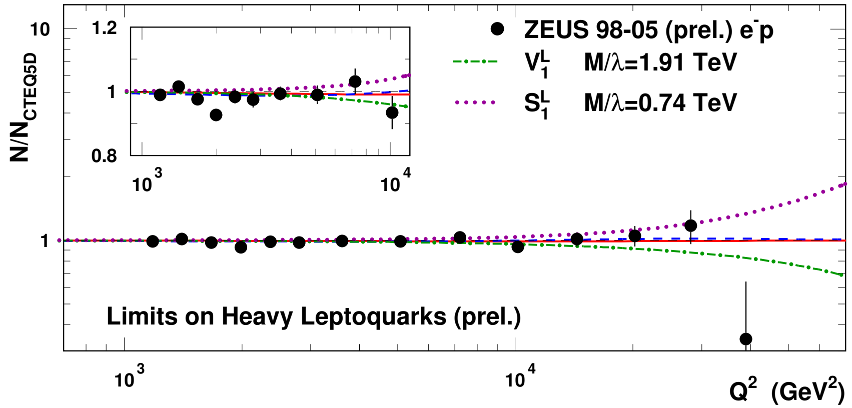
95 % CL limits on the compositeness scale, Λ (TeV):

	ZEUS pub.		ZEUS HERAI+II		DO		CDF		ALEPH		L3		OPAL	
Model	Λ^-	Λ^+	Λ^-	Λ^+	Λ^-	Λ^+	Λ^-	Λ^+	Λ^-	Λ^+	Λ^-	Λ^+	Λ^-	Λ^+
LL	1.7	2.7	4.2	4.2	6.2	3.6	5.9	3.7	6.2	5.4	2.8	4.2	3.1	5.5
LR	2.4	3.6	2.0	3.6	4.8	4.5	5.5	4.7	3.3	3.0	3.5	3.3	4.4	3.8
RL	2.7	3.5	2.3	3.6	5.0	4.3	5.8	4.5	4.0	2.4	4.6	2.5	6.4	2.7
RR	1.8	2.7	4.0	3.8	5.8	3.8	5.6	3.9	4.4	3.9	3.8	3.1	4.9	3.5
VV	6.2	5.4	7.5	6.3	9.1	4.9	8.7	7.8	7.1	6.4	5.5	4.2	7.2	4.7
AA	4.7	4.4	5.9	6.3	7.8	5.7	7.8	7.8	7.9	7.2	3.8	6.1	4.2	8.1
VA	3.3	3.2	3.3	3.5										
X1	3.6	2.6	4.3	4.7	6.4	4.8								
X2	3.9	4.0	5.1	4.7										
X3	3.7	3.6	5.9	5.3	7.9	4.1			7.4	6.7	3.7	4.4	4.4	5.4
X4	5.1	4.8	5.4	4.8	6.0	5.0			4.5	2.9	5.2	3.1	7.1	3.4
X5	4.0	4.0	5.1	4.5										
X6	2.5	3.5	4.3	4.1	4.7	6.8								
U1	3.8	3.6	5.2	5.5										
U2	5.0	4.2	6.1	5.2										
U3	5.0	4.1	7.1	6.1							5.2	9.2		
U4	5.8	4.8	6.1	5.0							3.2	2.3		
U5	5.2	4.3	6.2	5.0										
U6	2.8	3.4	4.5	4.7										

High mass leptoquarks from HERA I

ZEUS Results





Results - Comparison to LEP

95% CL lower limits on M_{LQ} to the Yukawa coupling ratio M_{LQ}/λ_{LQ} (TeV):

Model	ZEUS	H1	L3	OPAL
$S_\circ^L$	0.61	0.71	1.40	0.98
$S_\circ^R$	0.56	0.64	0.30	0.30
$\tilde{S}_\circ^R$	0.27	0.33	0.58	0.80
$S_{1/2}^L$	0.83	0.85	0.54	0.74
$S_{1/2}^R$	0.53	0.37		0.86
$\tilde{S}_{1/2}^L$	0.43	0.43	0.42	0.48
S_1^L	0.52	0.49		
$V_\circ^L$	0.55	0.73	1.83	1.27
$V_\circ^R$	0.47	0.58	0.51	0.54
$\tilde{V}_\circ^R$	0.87	0.99	1.02	1.44
$V_{1/2}^L$	0.47	0.42	0.71	0.90
$V_{1/2}^R$	0.99	0.95		0.71
$\tilde{V}_{1/2}^L$	1.06	1.02	0.54	0.59
V_1^L	1.23	1.36		

High mass leptoquarks

Results - Comparison to LEP

95% CL lower limits on M_{LQ} to the Yukawa coupling ratio M_{LQ}/λ_{LQ} (TeV):

Model	ZEUS pub	ZEUS HERAI+II	L3	OPAL
$S_\circ^L$	0.61	0.96	1.40	0.98
$S_\circ^R$	0.56	0.82	0.30	0.30
$\tilde{S}_\circ^R$	0.27	0.32	0.58	0.80
$S_{1/2}^L$	0.83	0.88	0.54	0.74
$S_{1/2}^R$	0.53	0.46		0.86
$\tilde{S}_{1/2}^L$	0.43	0.44	0.42	0.48
S_1^L	0.52	0.74		
$V_\circ^L$	0.55	0.80	1.83	1.27
$V_\circ^R$	0.47	0.62	0.51	0.54
$\tilde{V}_\circ^R$	0.87	1.33	1.02	1.44
$V_{1/2}^L$	0.47	0.46	0.71	0.90
$V_{1/2}^R$	0.99	1.00		0.71
$\tilde{V}_{1/2}^L$	1.06	1.10	0.54	0.59
V_1^L	1.23	1.91		