Leptoquarks and Contact Interactions

Jolanta Sztuk
Łodź University

for

&

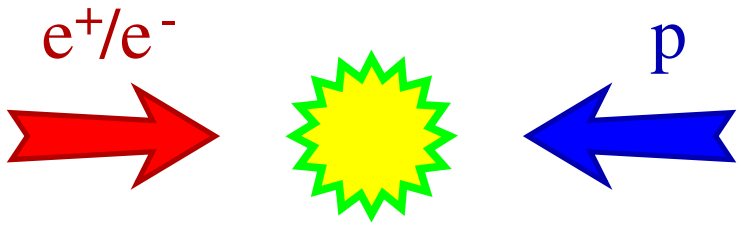
Outline:

- 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

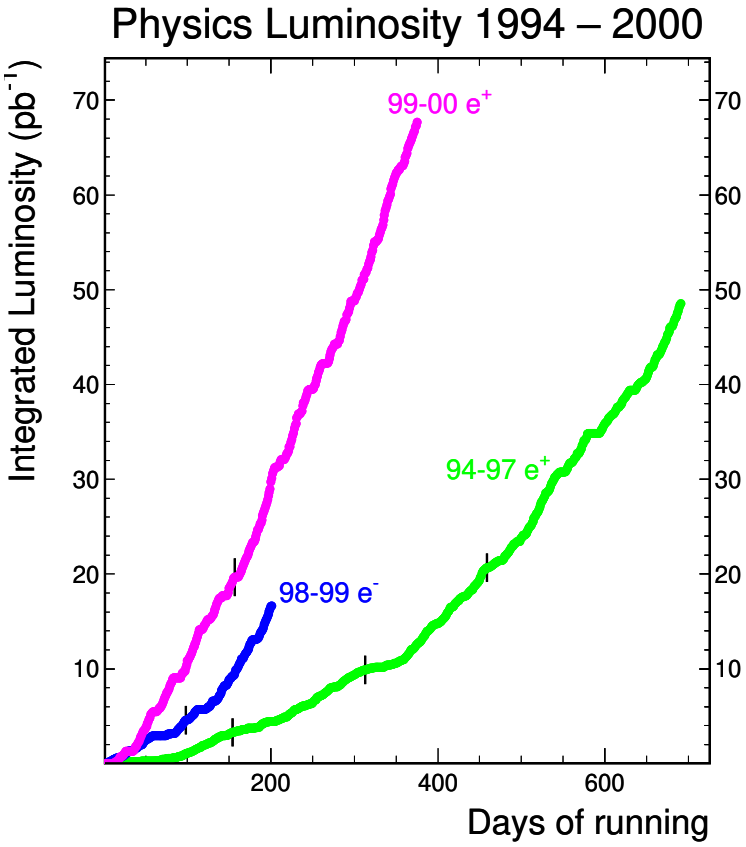
XII International Workshop on Deep Inelastic Scattering
Štrbské Pleso, April 15^{th}, 2004

Introduction

HERA data



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



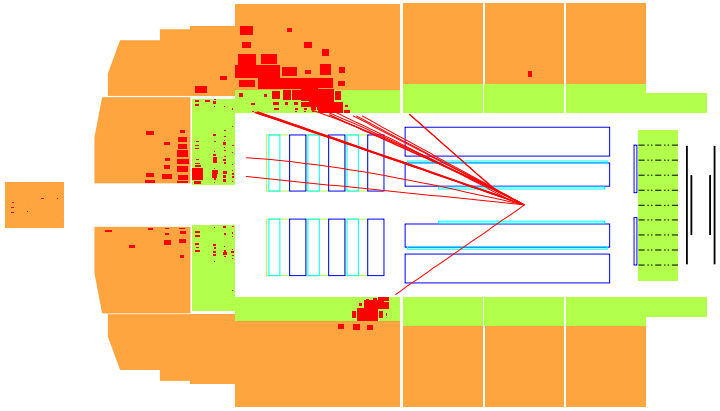
Presented results

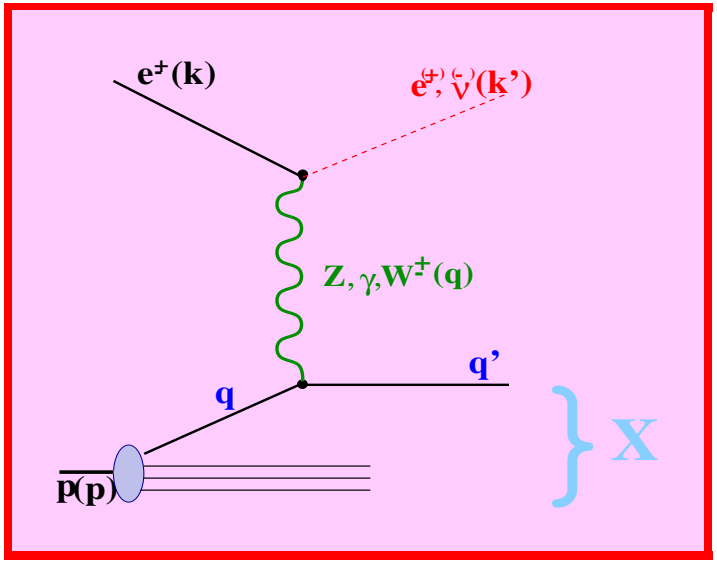
Year		$\sqrt{s}$	H1	ZEUS
1994-97	e^+p	300 GeV	37 pb^{-1}	48 pb^{-1}
1998-99	e^-p	318 GeV	15pb^{-1}	16 pb^{-1}
1999-00	e^+p	318 GeV	65 pb^{-1}	64 pb^{-1}

Total of about $\sim$ 240 pb^{-1} of $e^{\pm}p$ data.

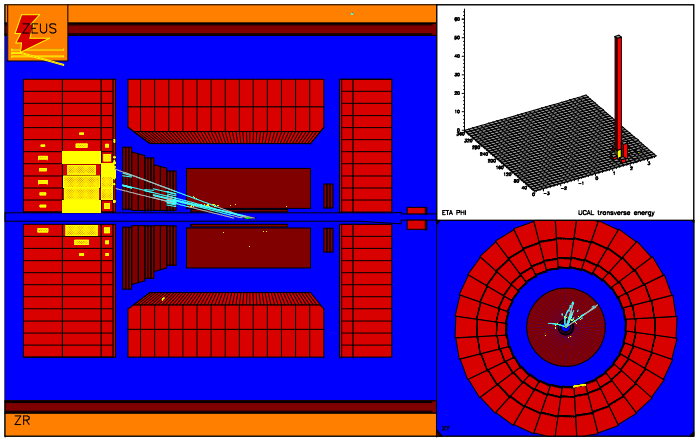
High-Q^2 DIS

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

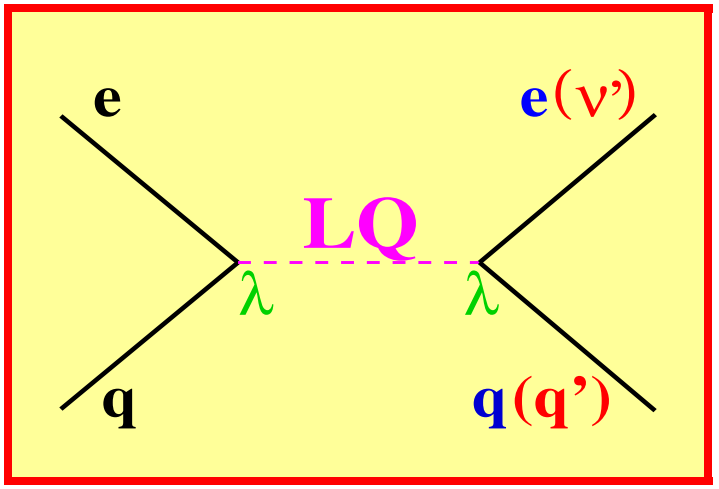
LEPTOQUARKS:

Scalar or vector color triplet bosons carrying L and B numbers

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

Buchmüller-Rückl-Wyler (BRW) model

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



- $SU(3)_C \times SU(2)_L \times U(1)_Y$ 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

Narrow Width Approximation:

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

- the s-channel dominates
- cross section

$$\sigma^{NWA} = (J+1)\frac{\pi}{4s}\lambda^2 q(x_0, M_{LQ}^2)$$

where:

$q(x_0, M_{LQ}^2)$ - quark density

J - spin of the leptoquark (J=0,1)

- $e^- p \Rightarrow$ 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

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

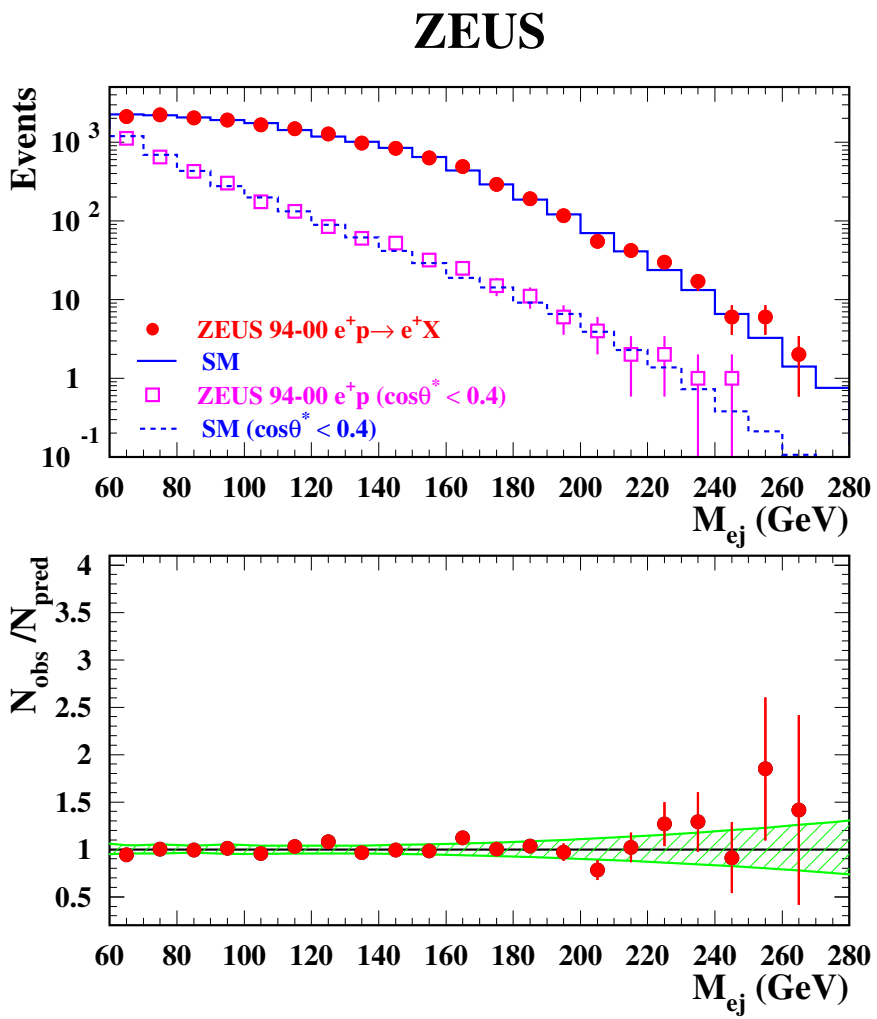
Vector Leptoquarks

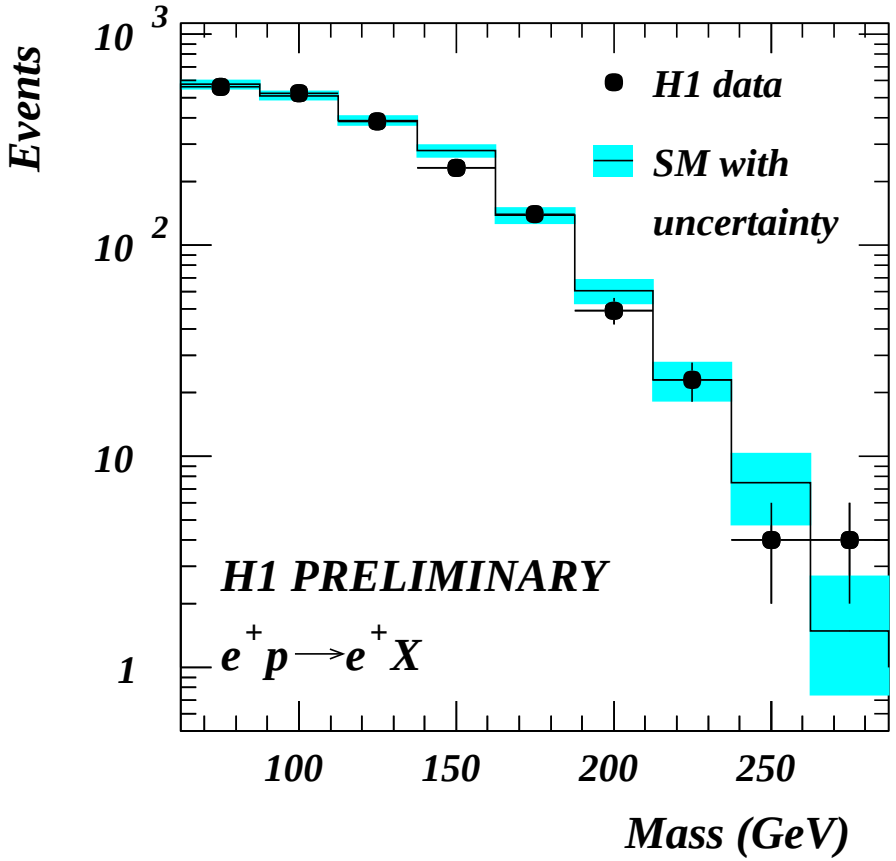
$$\left.\frac{d\sigma}{dy}\right|_{vector} \sim (1-y)^2$$

NC DIS (Background)

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

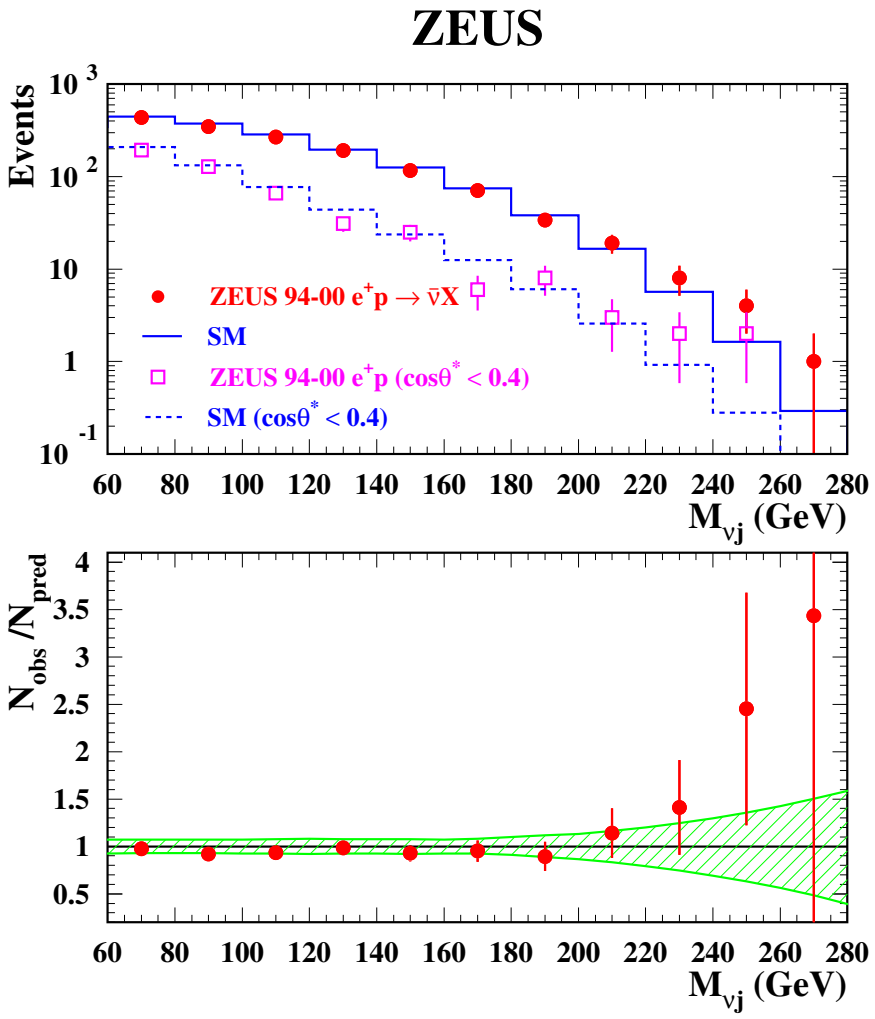
eq Invariant Mass Spectrum from HERA e^+p

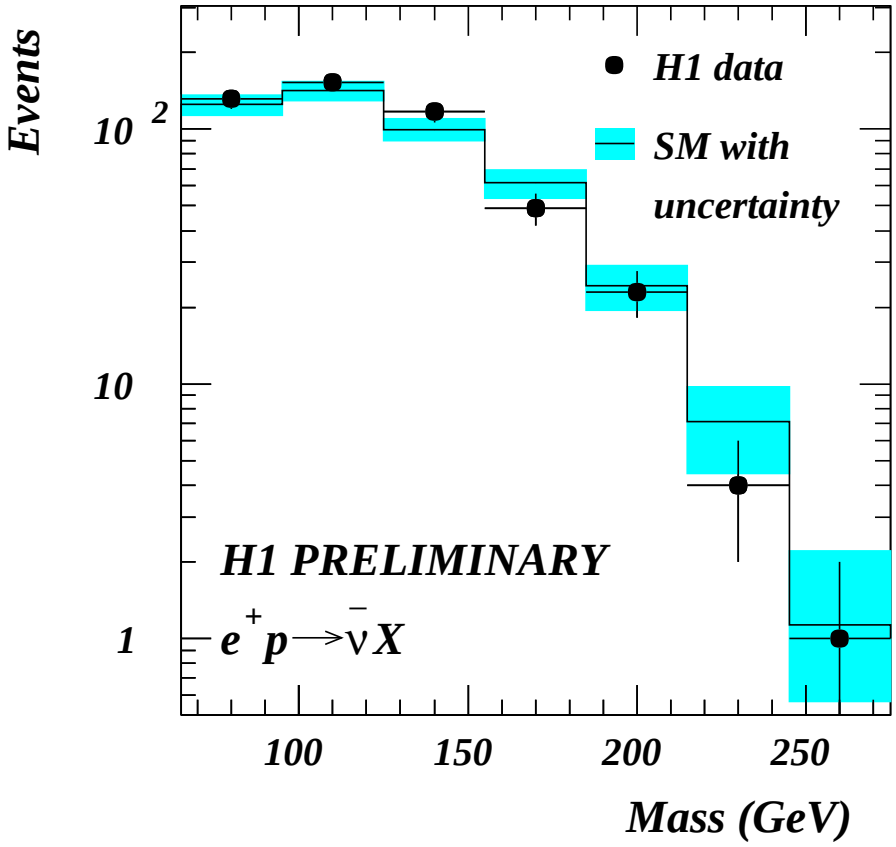




Good agreement between data and SM → no evidence of LQ

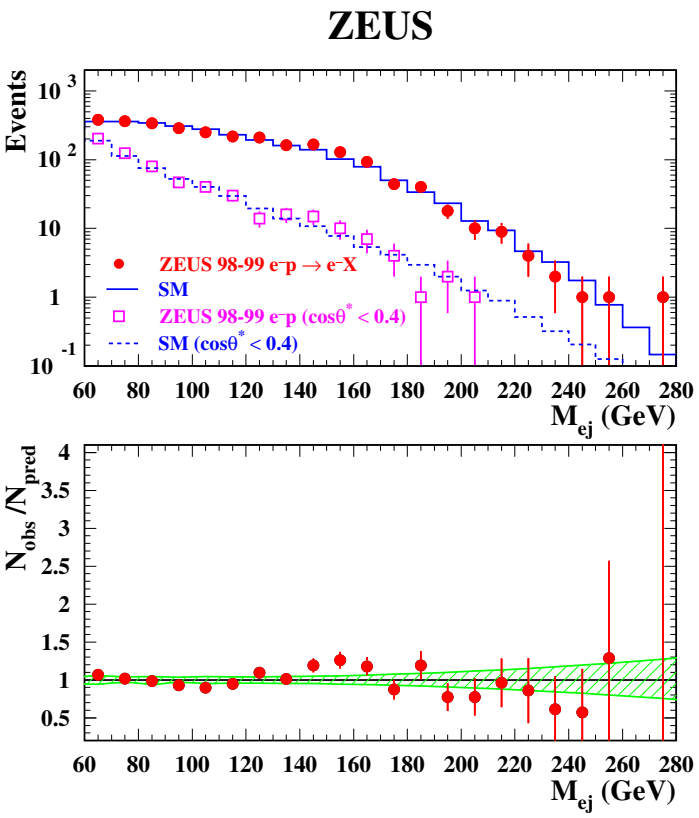
νq Invariant Mass Spectrum from HERA e^+p



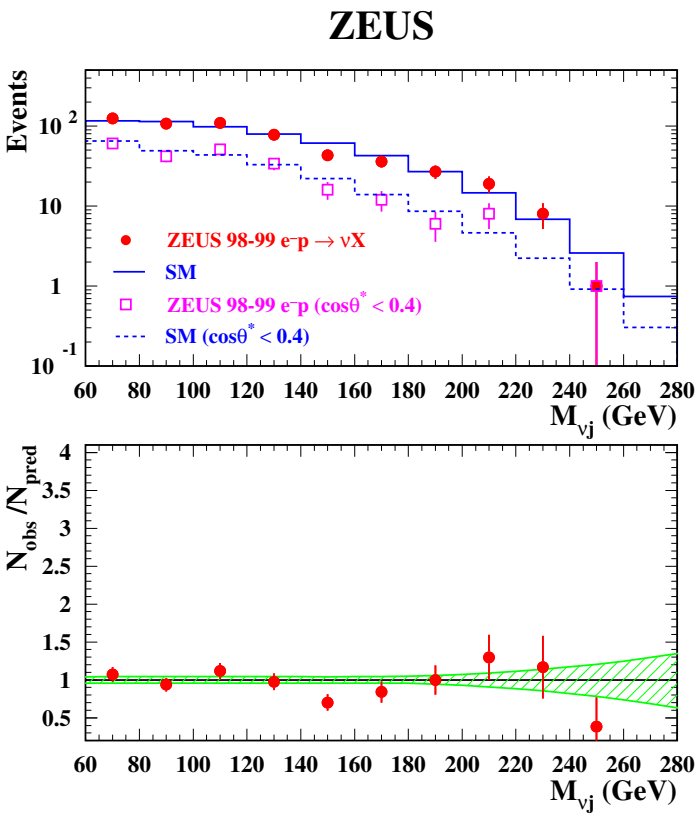


Invariant Mass Spectrum from HERA $e^- p$

NC DIS:



CC DIS:



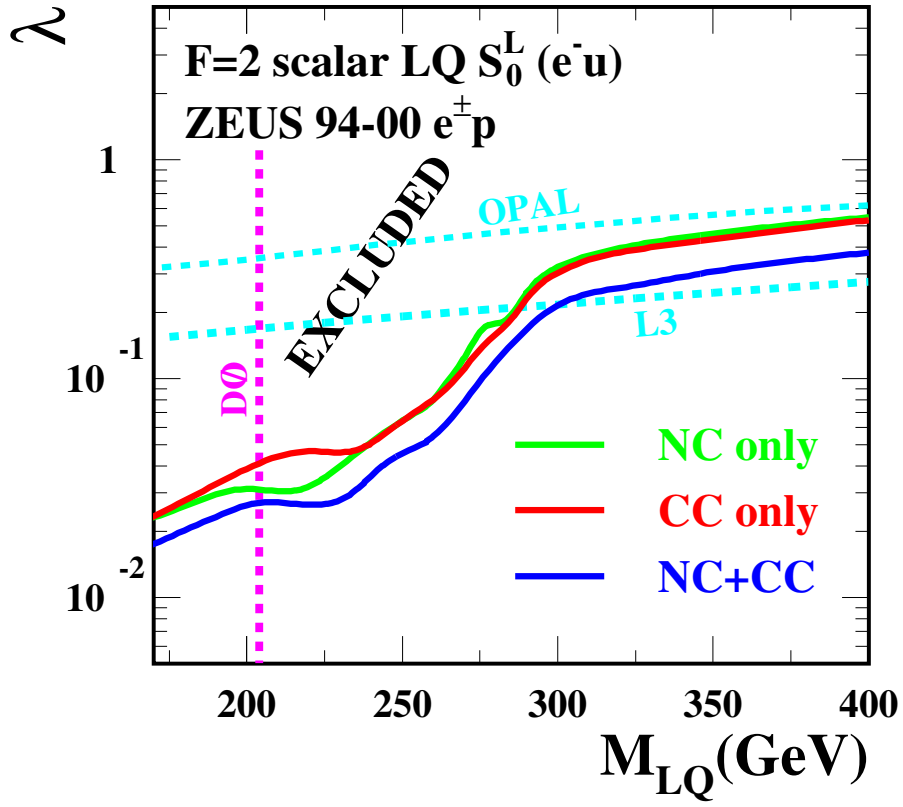
H1 has similar plots (Phys. Lett. B523 (2001) 234 ,07/01)

Scalar LQ with F=2

No evidence for LQ production

$\Downarrow$

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



F=2 S_0^L BRW LQ model

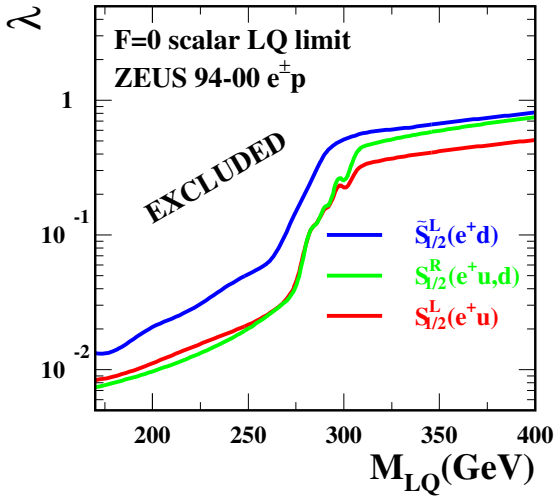
$\Rightarrow e^- p$ data more sensitive than $e^+ p$

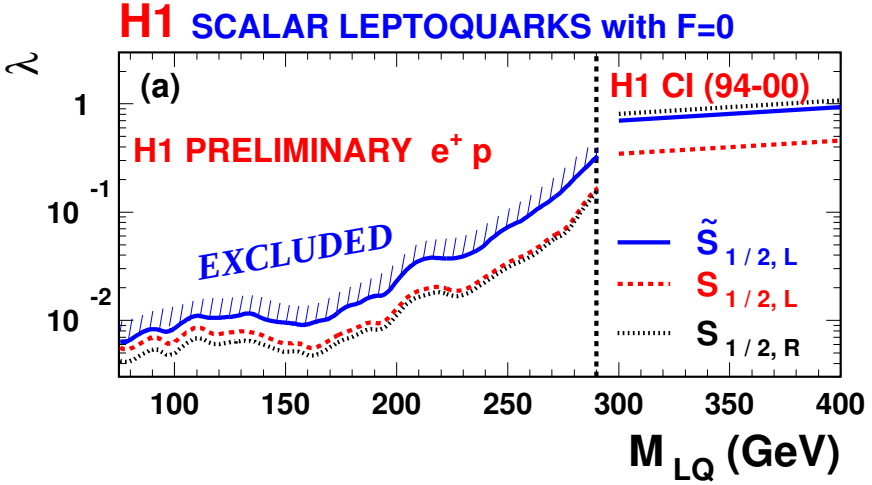
Combing NC + CC data

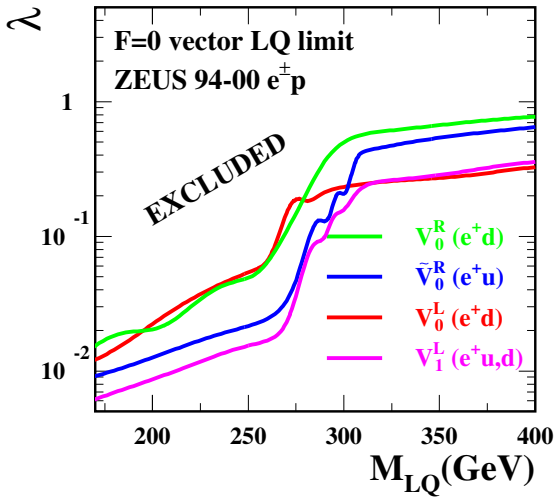
$\Rightarrow$ increases sensitivity

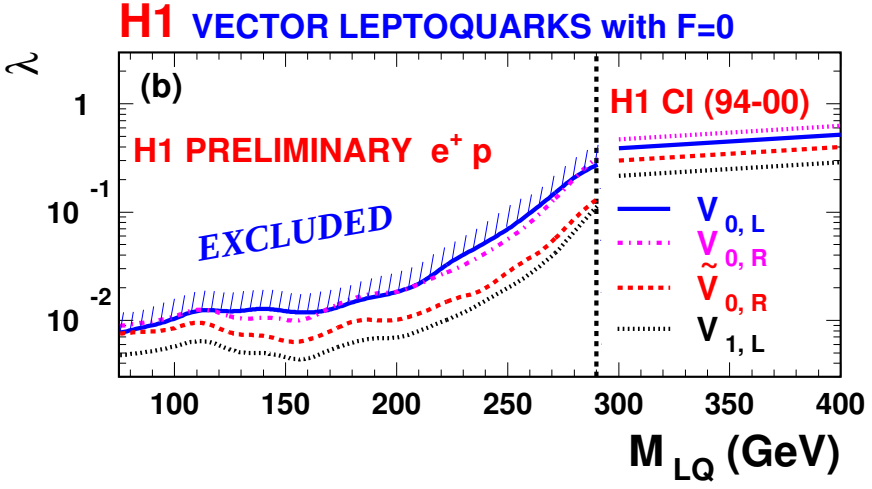
Limits on F=0 BRW LQ

ZEUS









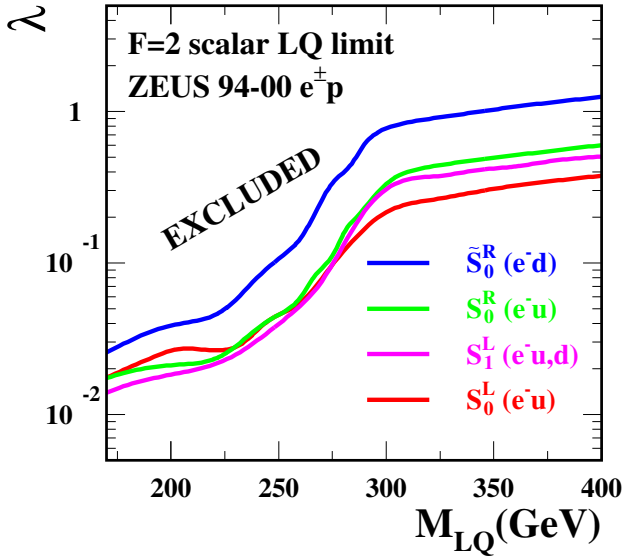
F=0 **scalar** BRW LQ

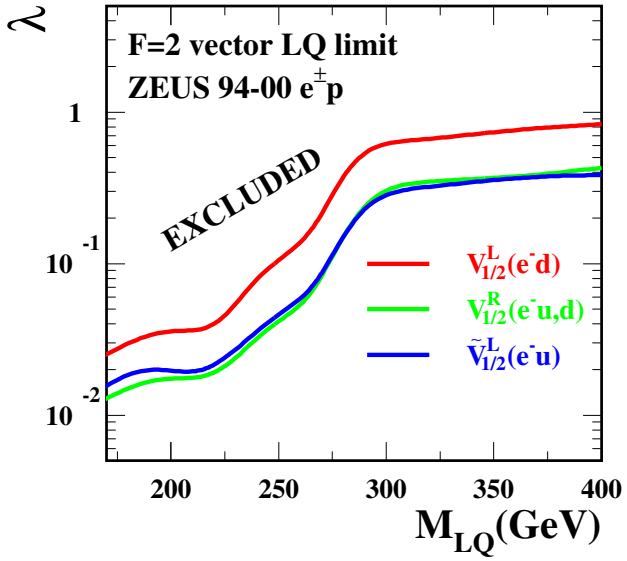
$\Rightarrow$ couples to eq only

F=2 **vector** BRW LQ

$\Rightarrow$combine eq & νq channels

Limits on F=2 BRW LQ with eq + νq from ZEUS





F=2 **scalar** BRW LQ model

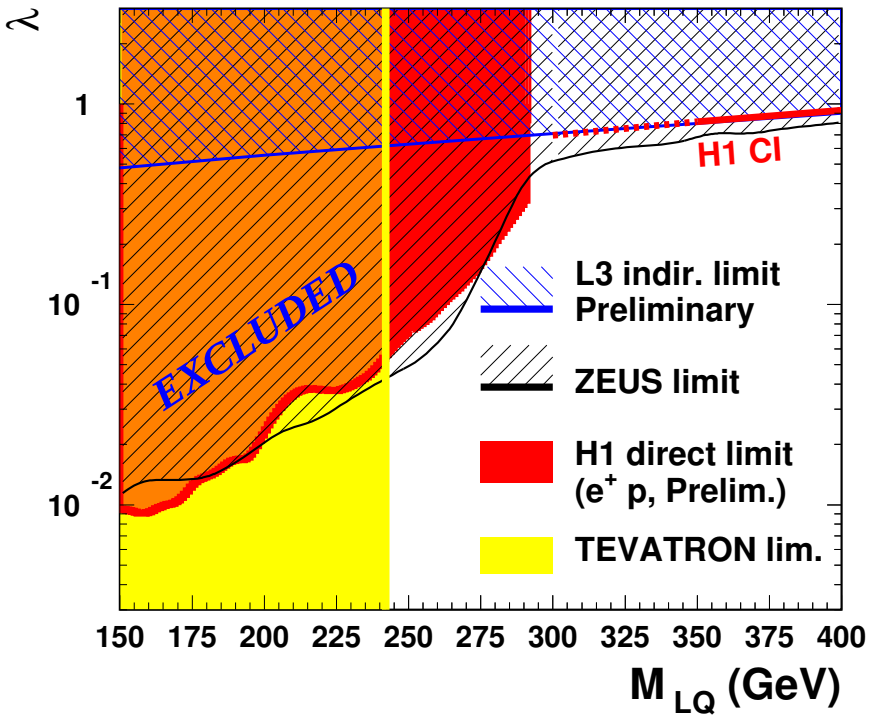
$\Rightarrow$Combine eq & νq channels

F=2 **vector** BRW LQ model

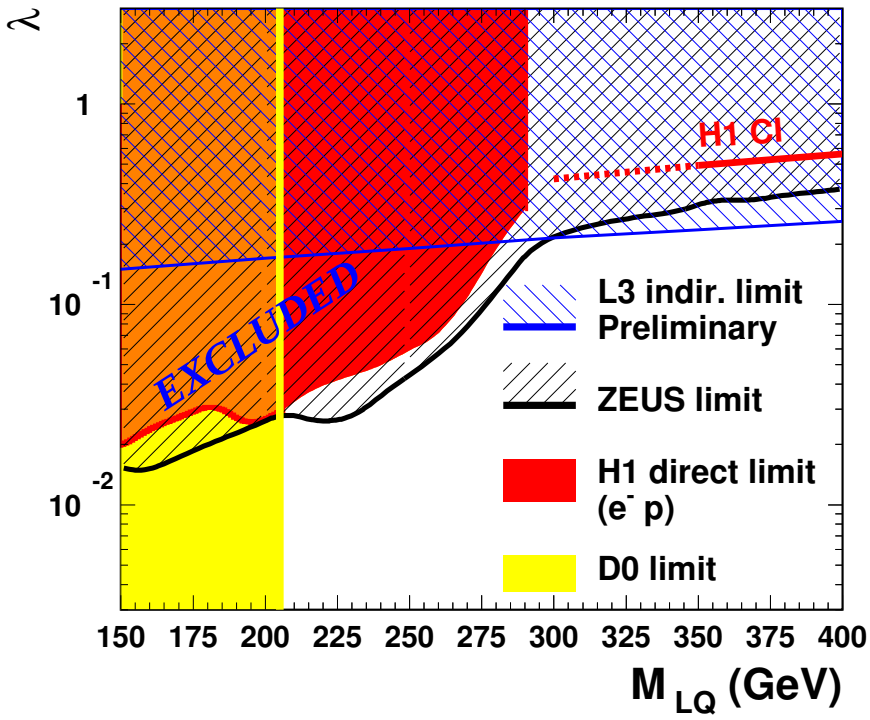
$\Rightarrow$ eq channel only

Comparison with LEP and TEVATRON

SCALAR LEPTOQUARKS WITH F=0 ($\tilde{S}_{1/2,L}$)



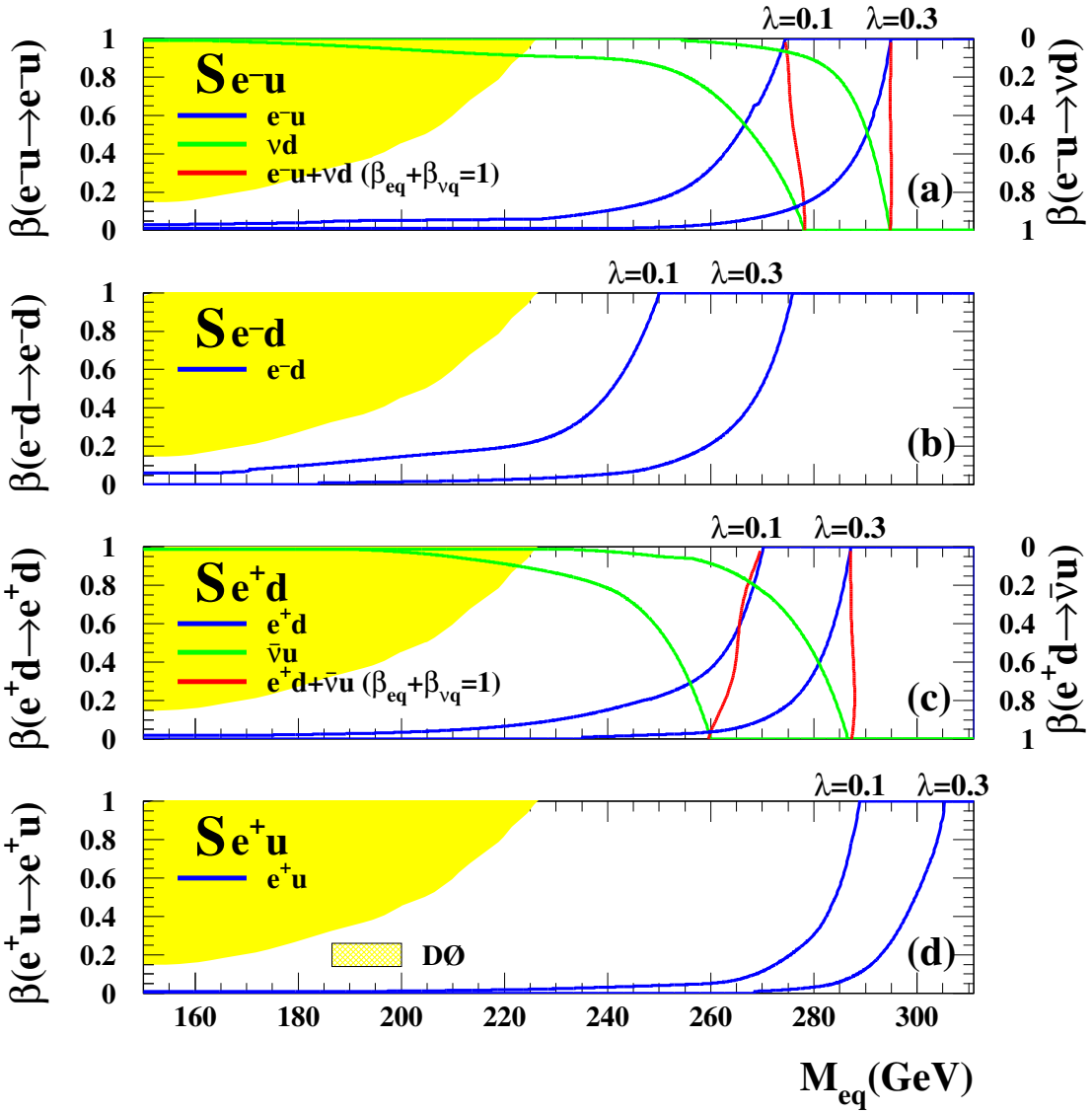
SCALAR LEPTOQUARKS WITH F=2 ($S_{0,L}$)



- TeVatron:
  LQ pair production - λ independent

- LEP:
  indirect t/u-channel effect in quark-pair production
  $e^+e^- \to q\bar{q}$

General LQ limits from ZEUS



General LQ Model

⇓

No $\beta(eq)$ constraint

Combined limit (NC & CC) assuming

$\beta(eq) + \beta(\nu q) = 1$

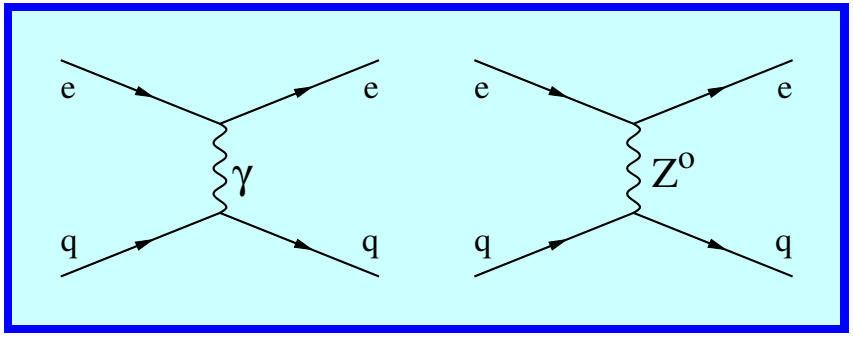
At $\lambda = 0.3$, M_{LQ} up to 300 GeV excluded, independent of β

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

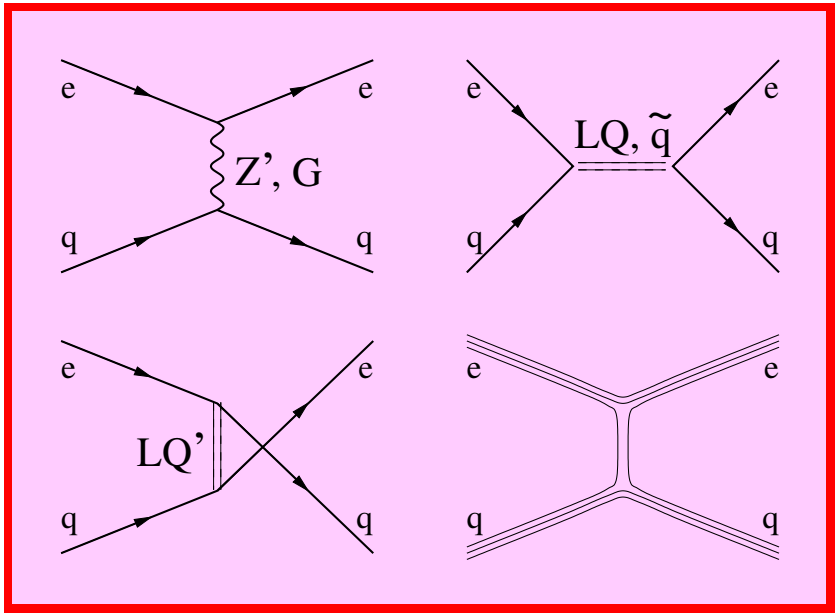
Contact Interactions

Neutral Current eq Scattering

Standard Model processes:

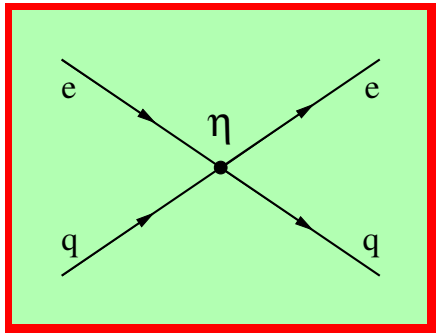


Possible "new physics" processes:



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

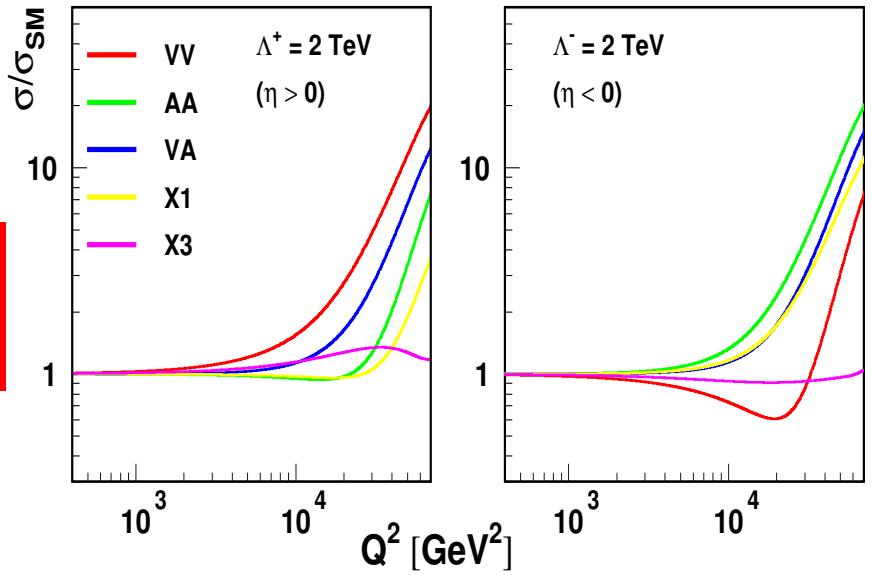
Contact Interactions modify tree level $eq \to eq$ scattering amplitudes $M^{eq}_{\alpha\beta}$:

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

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



General models

Coupling structure

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

$$\eta = \frac{\varepsilon \cdot g_{CI}^2}{\Lambda^2}$$

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

$$g_{CI}^2 = 4\pi$$

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

Also referred to as compositeness models

(Λ - compositeness scale)

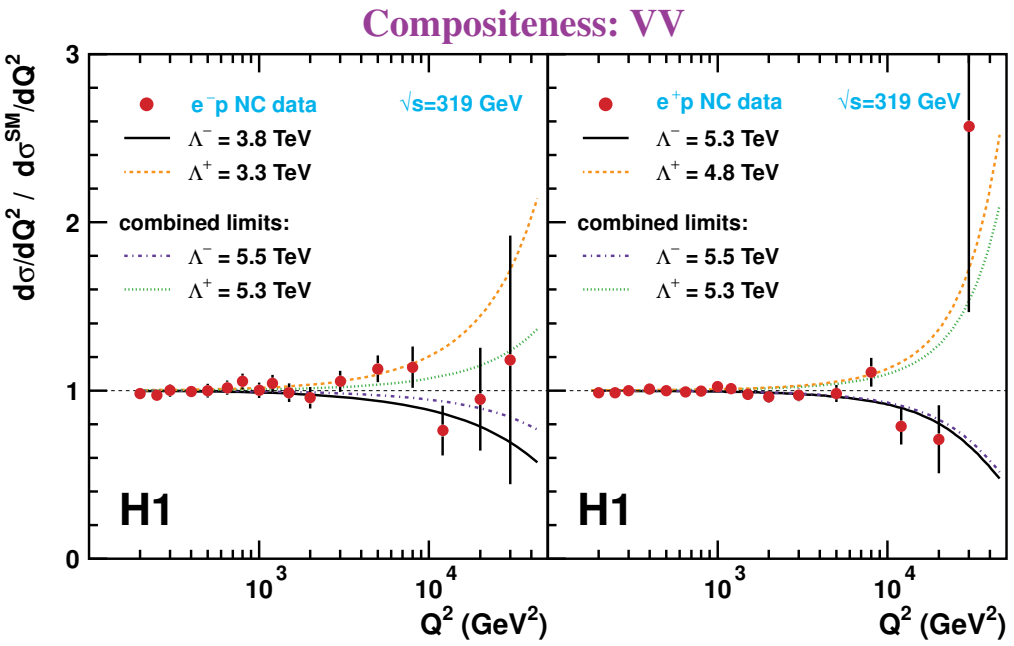
Model	η^{ed}_{LL}	η^{ed}_{LR}	η^{ed}_{RL}	η^{ed}_{RR}	η^{eu}_{LL}	η^{eu}_{LR}	η^{eu}_{RL}	η^{eu}_{RR}
LL	$+\eta$				$+\eta$			
LR		$+\eta$				$+\eta$		
RL			$+\eta$				$+\eta$	
RR				$+\eta$				$+\eta$
VV	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$
AA	$+\eta$	$-\eta$	$-\eta$	$+\eta$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

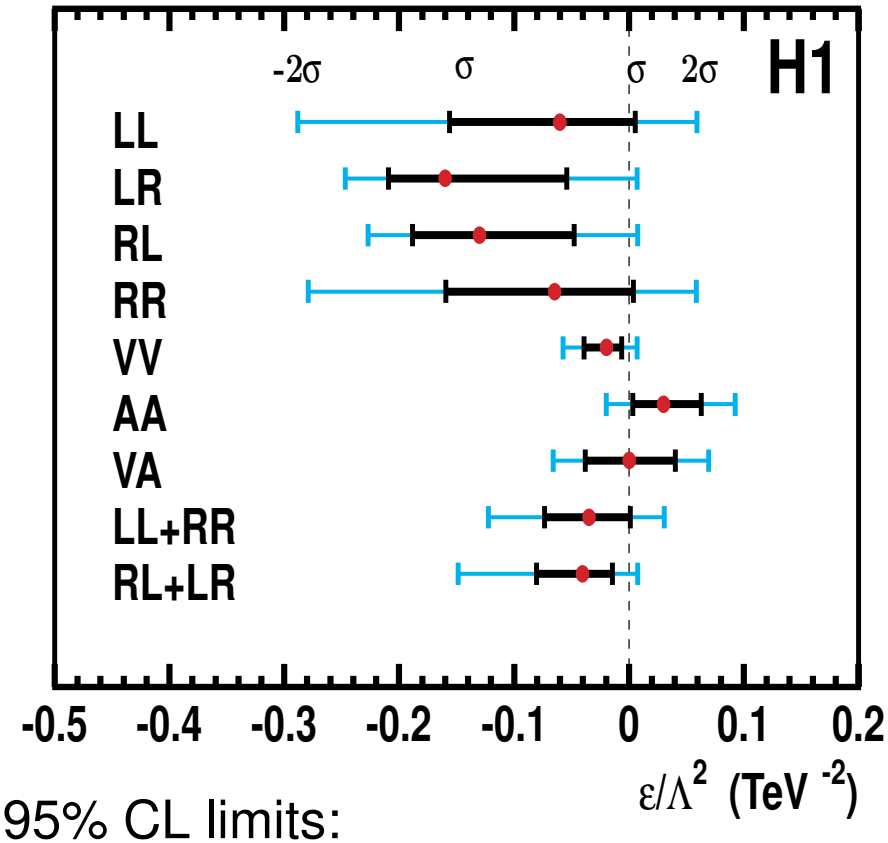
General models

Results

H1 1994-2000 analysis

data undershoots SM slightly at high Q^2





95% CL limits:

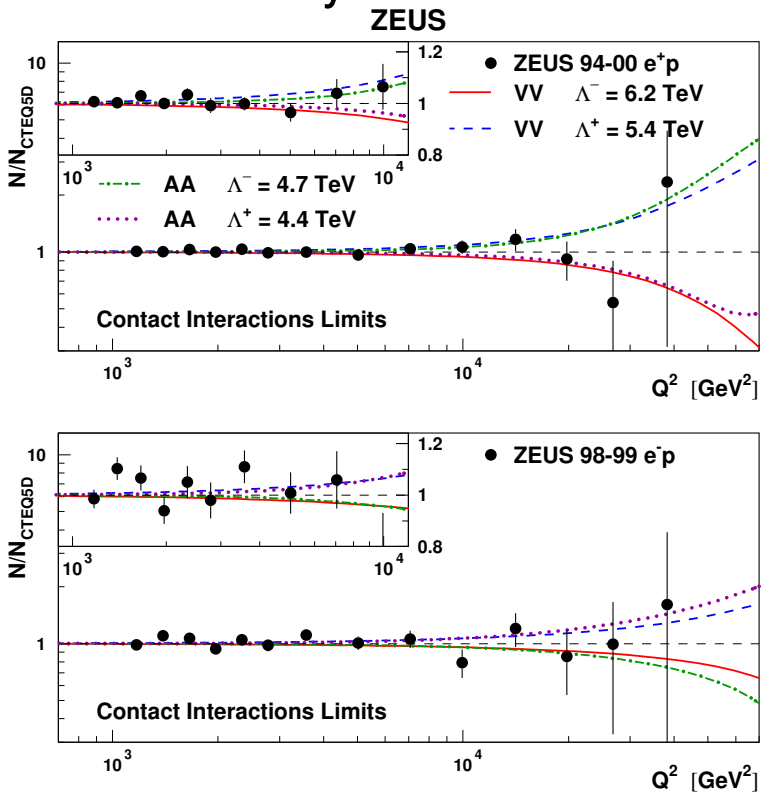
$\Lambda > 1.6 - 5.5$ TeV

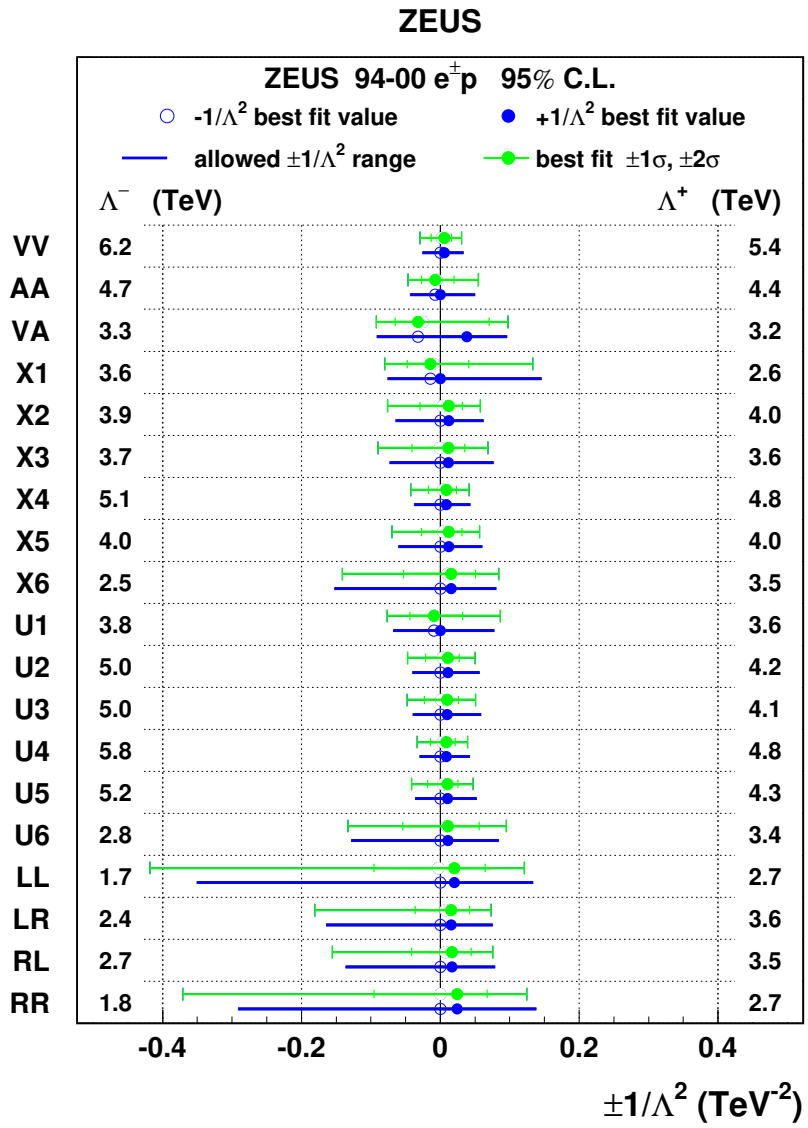
$\Rightarrow \sim 2\sigma$ deviation in most models

General models

Results

ZEUS 1994-00 analysis





Good agreement with the Standard Model

95% CL limits:

$\Lambda > 1.7 - 6.2$ TeV

General Model - comparison with LEP and TeVatron

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

	ZEUS		H1		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	1.6	2.8	4.2	3.3	3.7	2.5	6.2	5.4	2.8	4.2	3.1	5.5
LR	2.4	3.6	1.9	3.3	3.6	3.4	3.3	2.8	3.3	3.0	3.5	3.3	4.4	3.8
RL	2.7	3.5	2.0	3.3	3.7	3.3	3.2	2.9	4.0	2.4	4.6	2.5	6.4	2.7
RR	1.8	2.7	2.2	2.8	4.0	3.3	3.6	2.6	4.4	3.9	3.8	3.1	4.9	3.5
VV	6.2	5.4	5.5	5.3	6.1	4.9	5.2	3.5	7.1	6.4	5.5	4.2	7.2	4.7
AA	4.7	4.4	4.1	2.5	5.5	4.7	4.8	3.8	7.9	7.2	3.8	6.1	4.2	8.1
VA	3.3	3.2	3.0	2.9										
X1	3.6	2.6			4.5	3.9								
X2	3.9	4.0												
X3	3.7	3.6	3.9	3.7	5.1	4.2			7.4	6.7	3.7	4.4	4.4	5.4
X4	5.1	4.8	4.4	4.4	4.4	3.9			4.5	2.9	5.2	3.1	7.1	3.4
X5	4.0	4.0												
X6	2.5	3.5			4.3	4.0								
U1	3.8	3.6												
U2	5.0	4.2												
U3	5.0	4.1									5.2	9.2		
U4	5.8	4.8									3.2	2.3		
U5	5.2	4.3												
U6	2.8	3.4												

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.

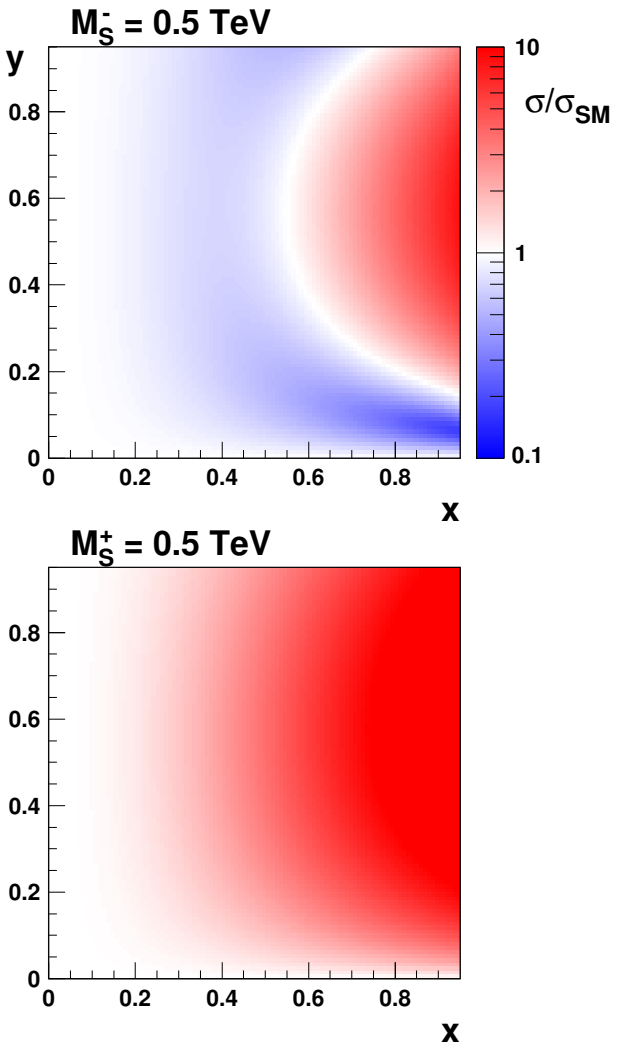
$\Rightarrow$ Gravitational interactions become comparable in strength to electroweak interactions.

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:

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

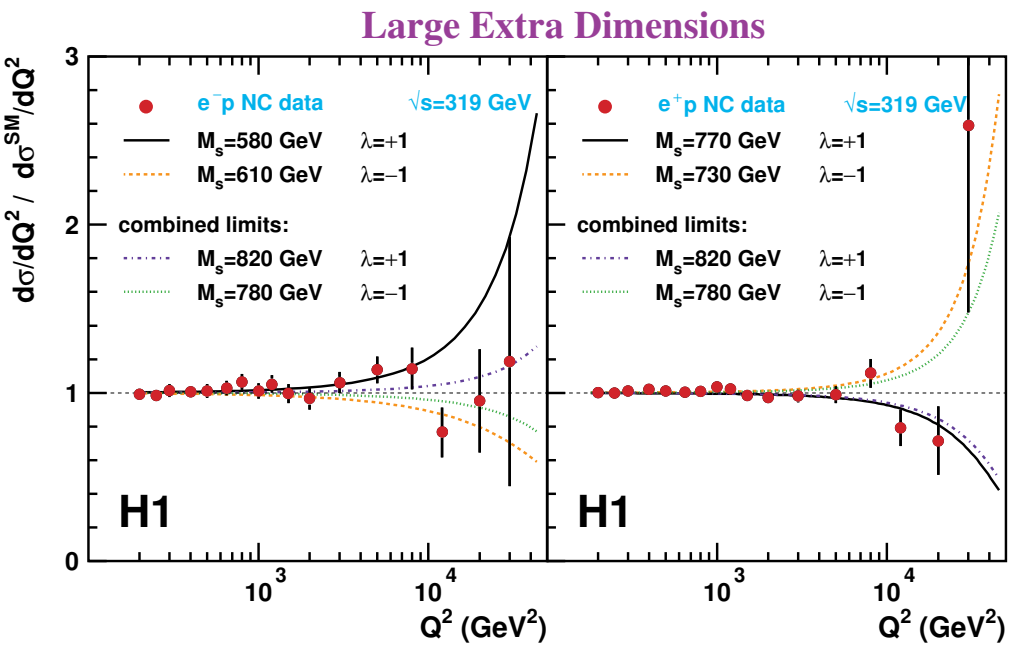
where λ is the coupling strength and $\mathcal{E}$ is related to the energy scales of hard interaction. $(\sqrt{s}, Q^2)$

Cross-section deviations for e^-p:



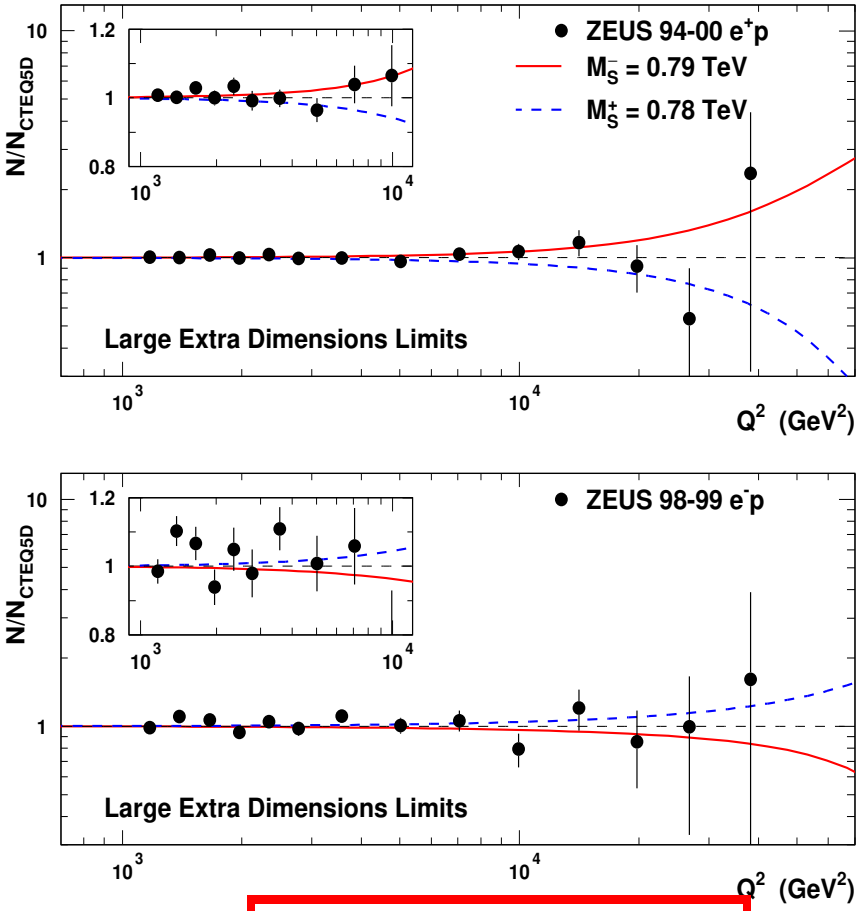
Large Extra Dimensions

H1 results



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

ZEUS results



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

Quark form factor

Model

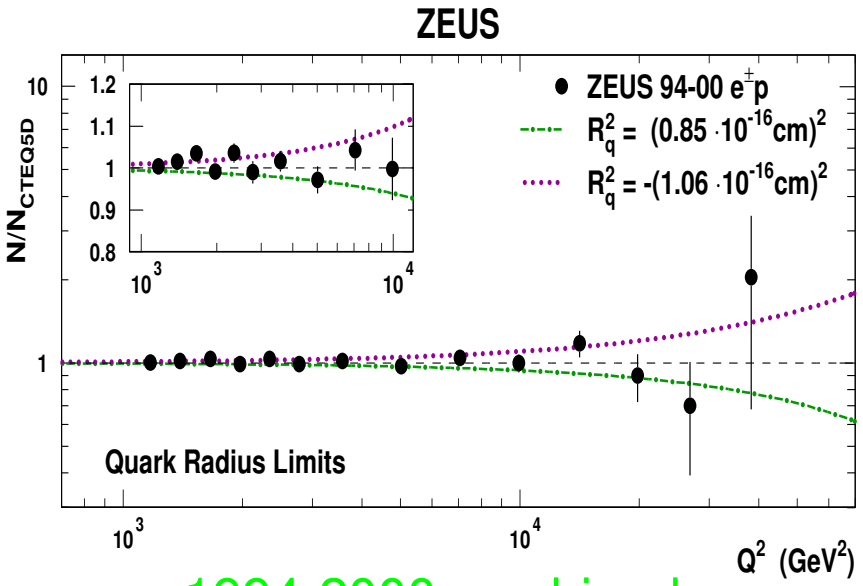
"classical" method to look for possible fermion (sub)structure.

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



1994-2000 combined

H1

$R_q < 1.0 \cdot 10^{-16}$cm

ZEUS

$R_q < 0.85 \cdot 10^{-16}$cm

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

High mass leptoquarks

For high mass leptoquarks

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

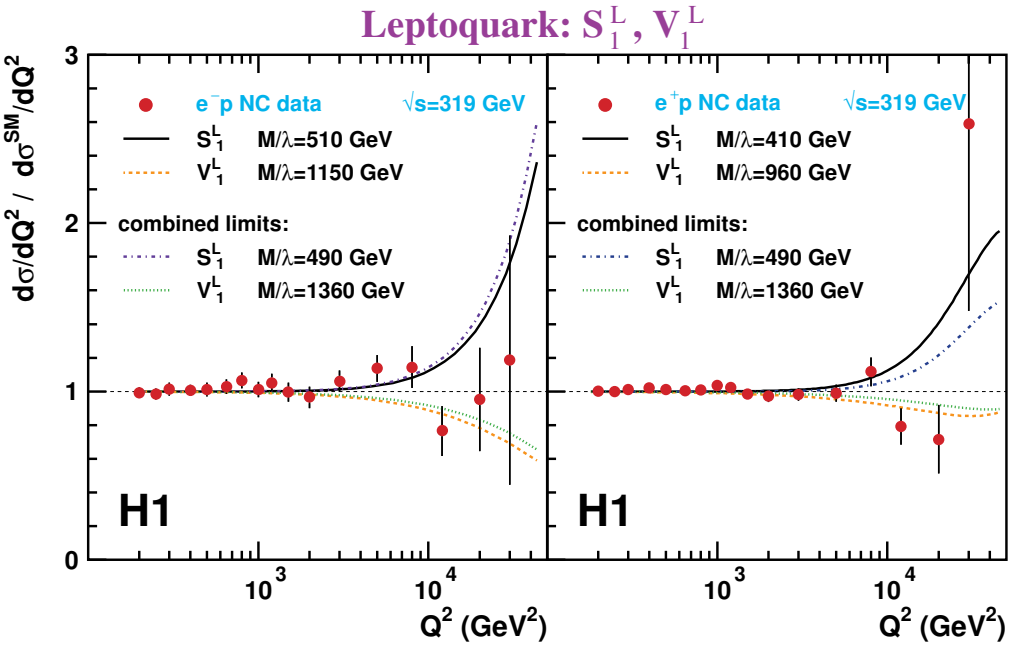
both s- and u-channel important

$\Downarrow$

Virtual LQ production/exchange results in an effective coupling:

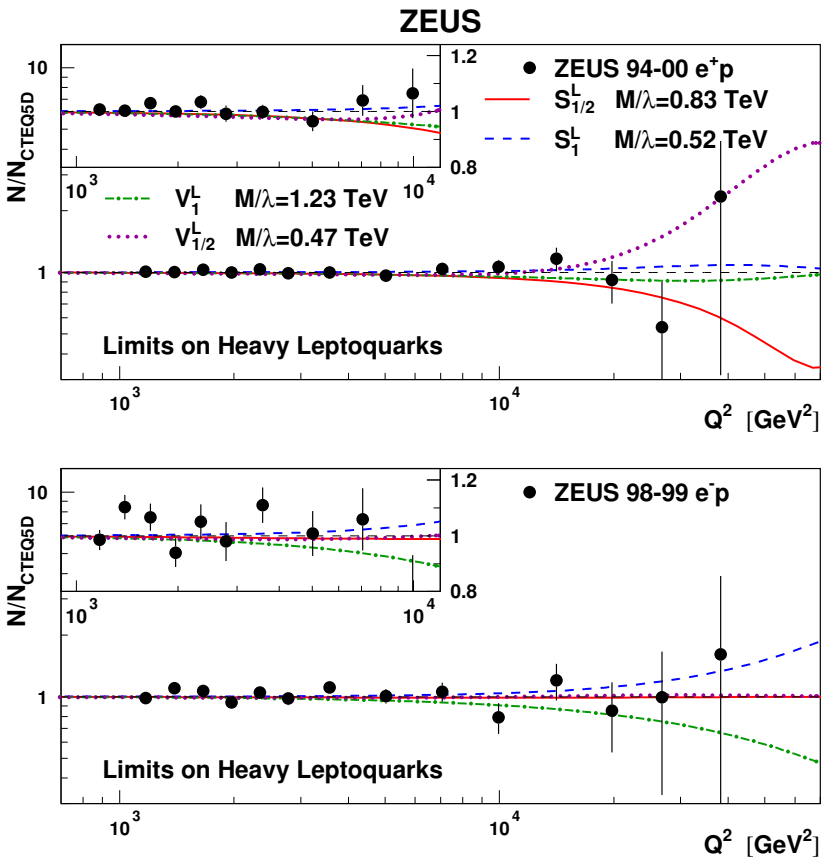
$$\eta_{CI} \sim (\frac{\lambda}{M})^2$$

H1 Results



High mass leptoquarks

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		

Summary

- Both experiments published or are publishing the LQ and CI searches on all HERA I data
- Over $\sim$ 240 pb^{-1} of $e^{\pm}p$ data collected by H1 and ZEUS
- No evidence for New Physics
- Limits at HERA complementary to Tevatron (limit depends strongly on β) and LEP
- HERA2: Luminosity upgrade, $\sim 1 fb^{-1}$ in 5 years, with ZEUS & H1 detectors upgrade

Exciting future with HERA upgrade

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	$e_L \bar{d}$		$\overline{\tilde{u}_L}$
		$+1/3$	0		$\nu \bar{d}$	$\overline{\tilde{d}_L}$
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		$\nu \bar{d}$	