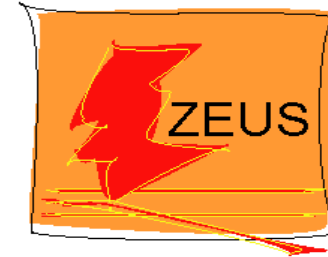


# Search for Leptoquarks and Contact Interactions at HERA



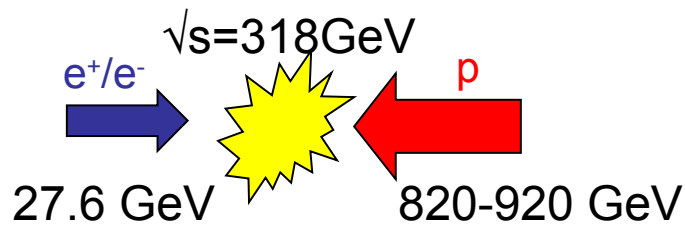
Ilias Panagoulias  
NTU Athens/DESY



**18th International Workshop On Deep Inelastic Scattering  
And Related Subjects (DIS 10)**

**19-23 Apr 2010 Florence, Italy**

# HERA Operation

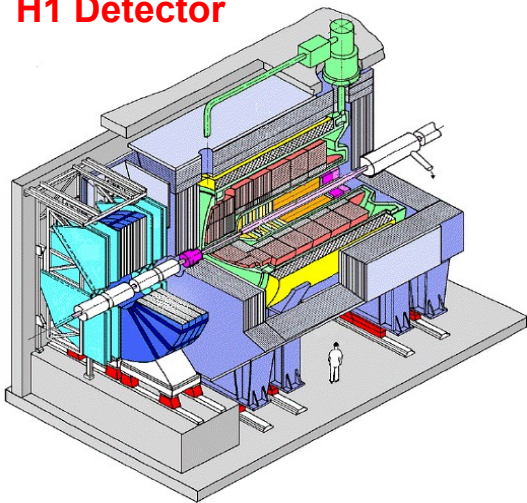


## HERA

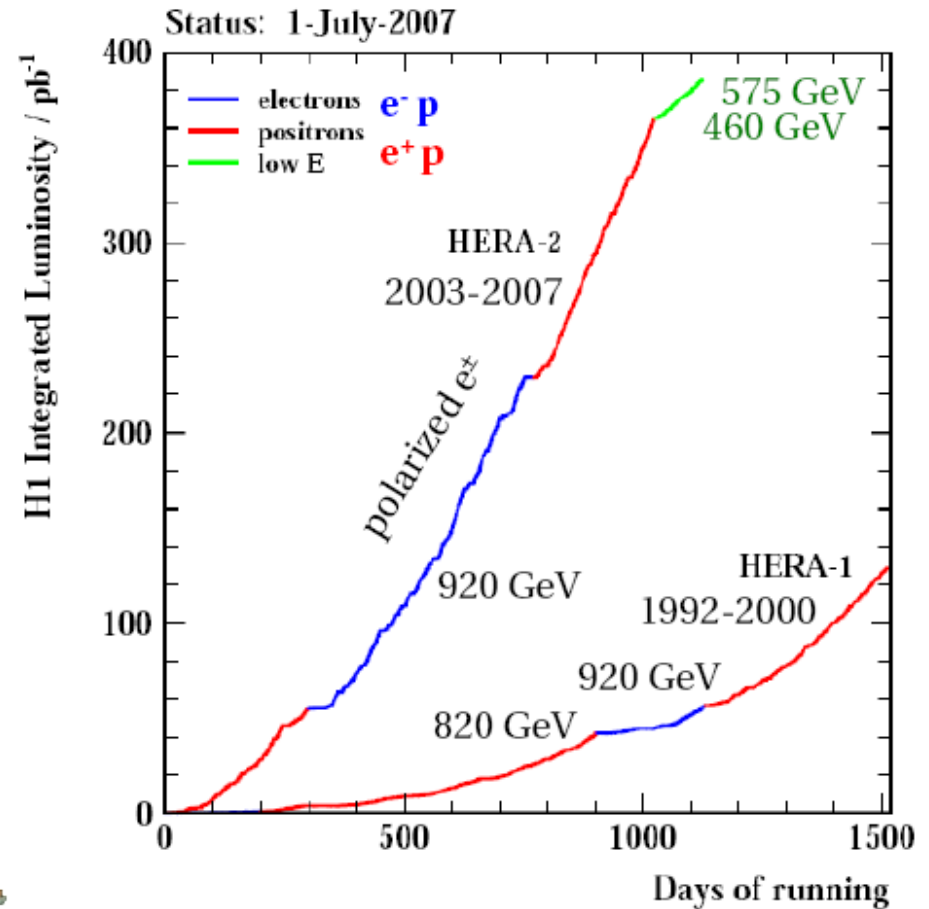
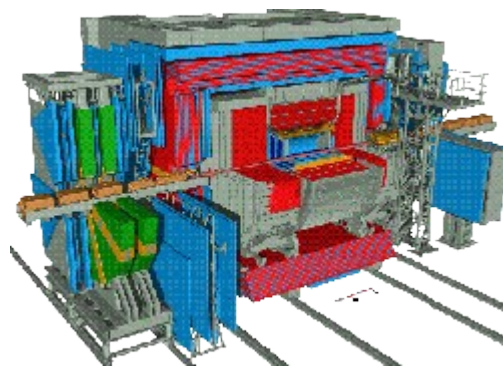
An unique  $e^+p$  collider (1992-2007)

Two large colliding general purpose detectors  
H1 and ZEUS with asymmetric design

H1 Detector



Zeus Detector

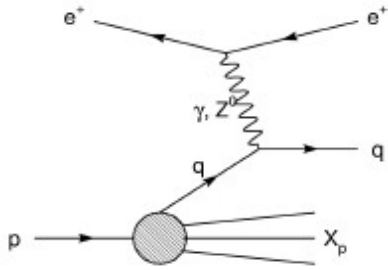


HERA I (1994-2000),  $L \sim 120 \text{ pb}^{-1}$

HERA II (2002-2007),  $L \sim 360 \text{ pb}^{-1}$   
Longitudinal polarisation of lepton beam ( $P=30-40\%$ )

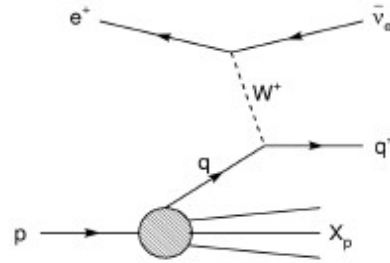
# High $Q^2$ NC and CC processes

## Main processes studied at HERA



### Neutral Current DIS

$$ep \rightarrow eX$$



### Charged Current DIS

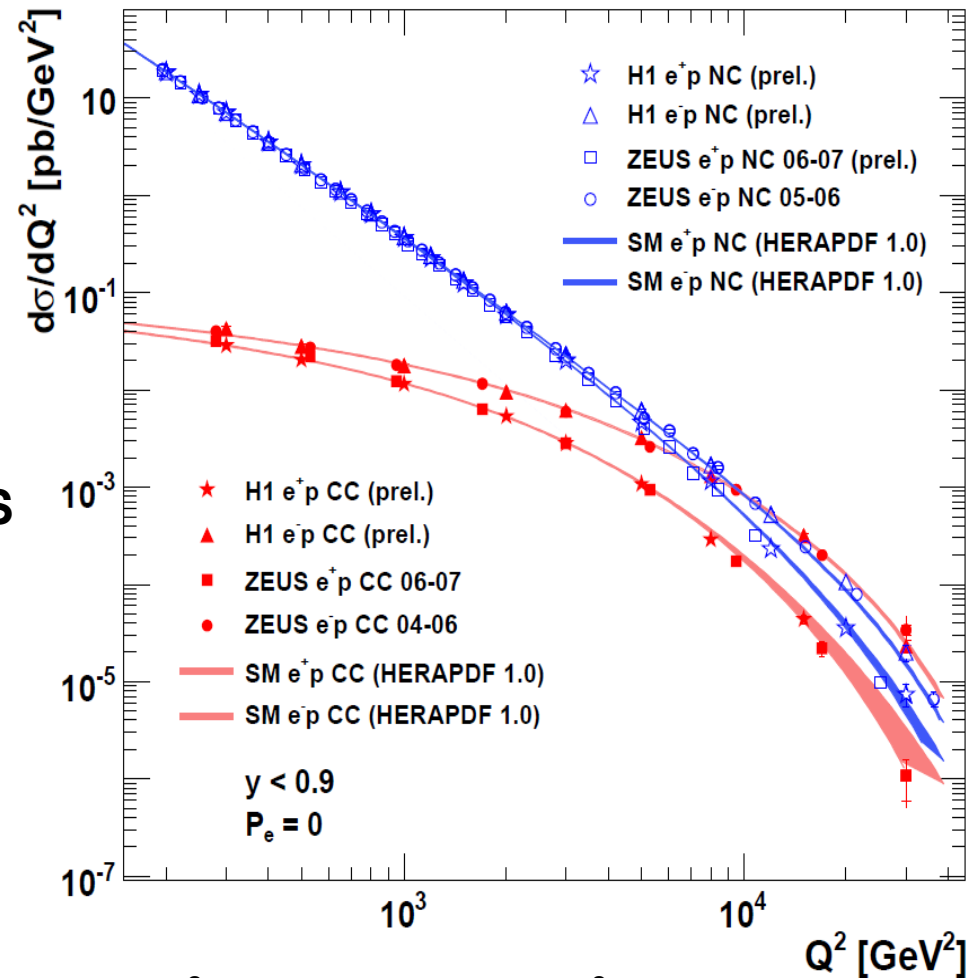
$$ep \rightarrow \nu X$$

Excellent agreement between data and SM  
Precise tests of QCD and EW Physics

Possible deviation at high  $Q^2$  should indicate  
Beyond SM physics

- Leptoquark production
- Contact Interactions

## HERA



$Q^2$  up to 40.000  $\text{GeV}^2$   
Spatial resolution  $\sim 1/Q = 10^{-3}$  fm  
Probe small distances

# Search for quark substructure

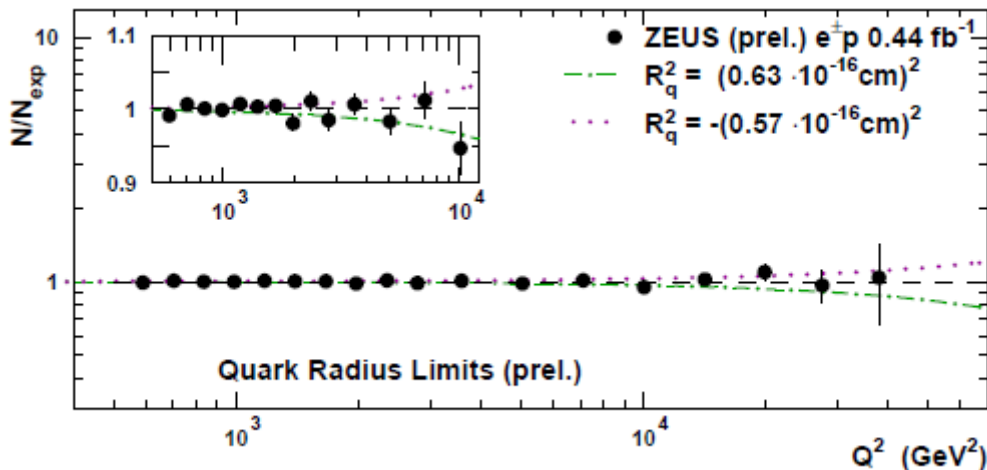
Form factor analysis to search for quark substructure.

If a quark has a finite size, the SM prediction for the cross sections are modified to

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

- Electron assumed to be point-like
- $R_q$  is a root mean square radius of the EW charge of the quark
- Cross section expected to decrease as higher  $Q^2$
- Same dependence for  $e^-p$ ,  $e^+p$

## ZEUS



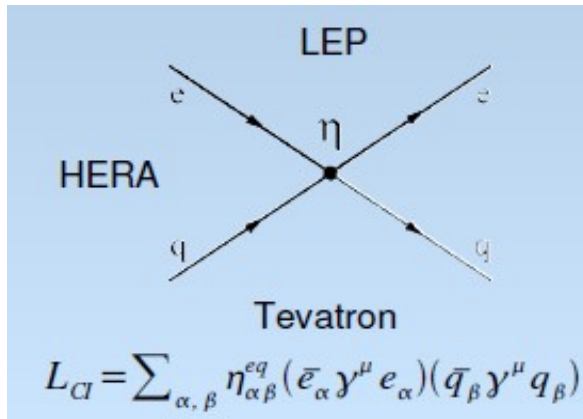
**ZEUS (94-07 data):  $R_q < 0.63 \times 10^{-3} \text{ fm}$**   
**H1 (94-07 data):  $R_q < 0.74 \times 10^{-3} \text{ fm}$**   
 (preliminary results)

Excellent agreement with SM up to highest  $Q^2$

Effect of quark radius limit in SM cross section

# Contact Interactions (CI)

New interactions at higher scale ( $\Lambda \gg \sqrt{s}$ ) can be effectively described at lower energies as 4-fermion  $eeqq$  Contact Interaction.



where  $\alpha, \beta$  are the electrons and quark helicities (L,R)

Coupling  $\eta$ , is related to the mass scale  $\Lambda$

$$\eta_{\alpha\beta}^{eq} = \frac{\epsilon g_{CI}^2}{\Lambda^2}$$

$$\epsilon = \pm 1$$

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

Models conserving parity:

Model	$\eta_{LL}^{ed}$	$\eta_{LR}^{ed}$	$\eta_{RL}^{ed}$	$\eta_{RR}^{ed}$	$\eta_{LL}^{eu}$	$\eta_{LR}^{eu}$	$\eta_{RL}^{eu}$	$\eta_{RR}^{eu}$
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				$+\eta$				$+\eta$

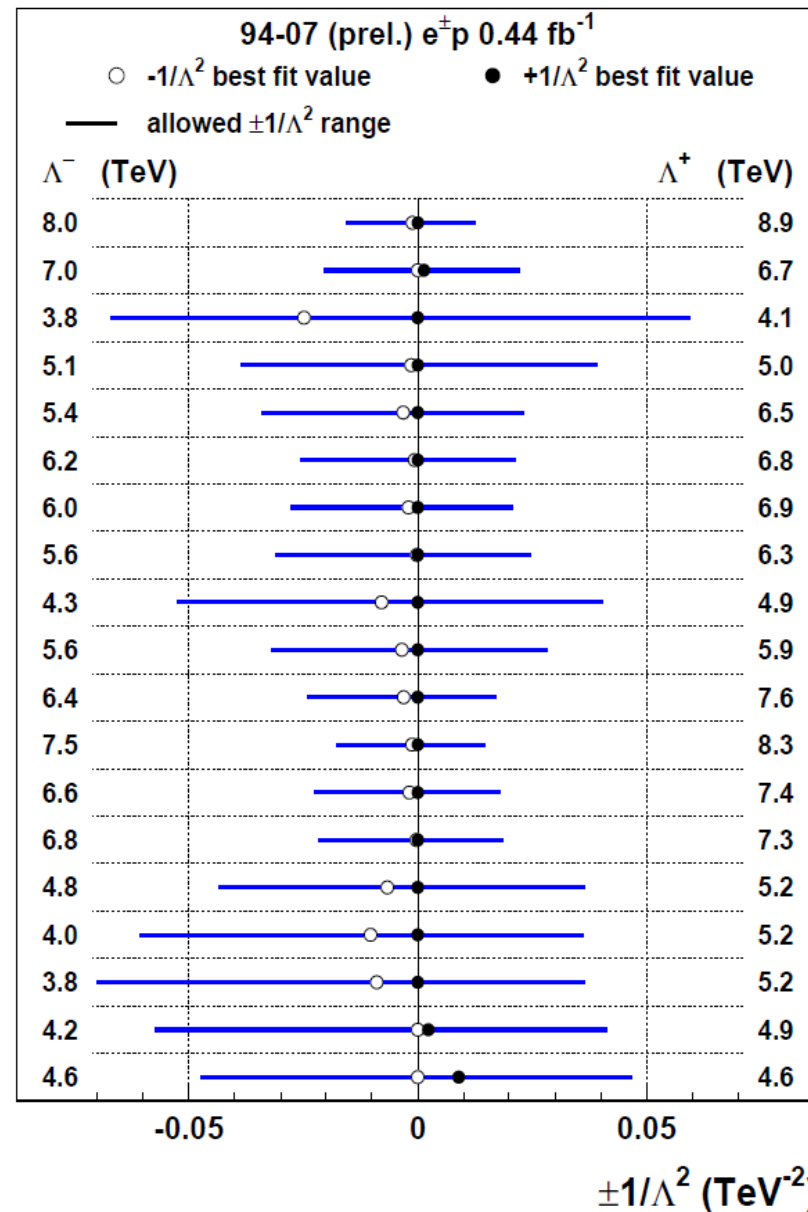
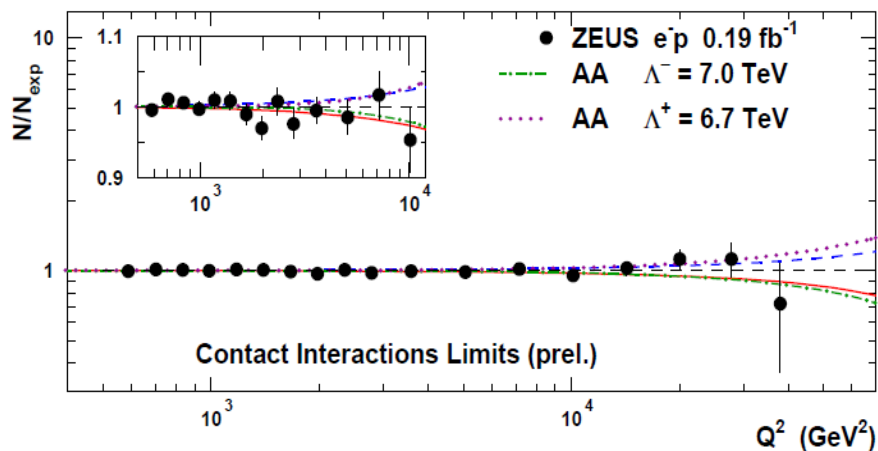
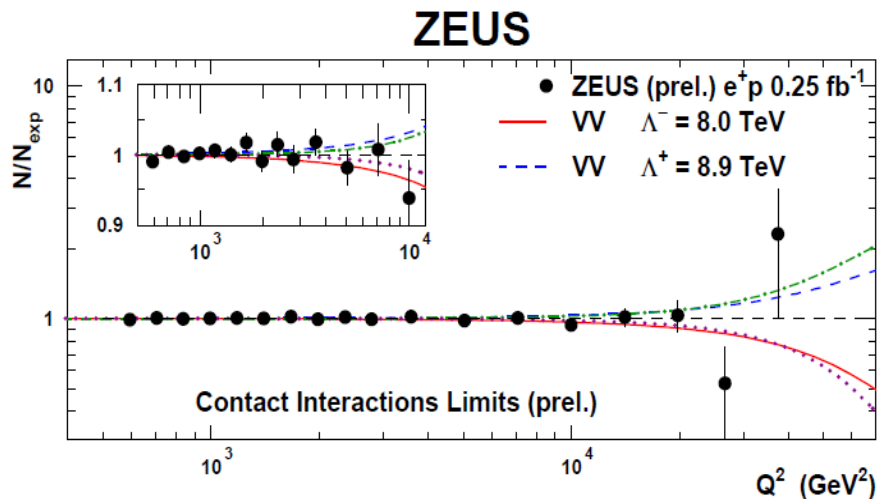
Different models assume different helicity structure of new interactions, given by set of couplings  $\eta_{\alpha\beta}^{eq}$



# Contact Interactions (CI)

ZEUS CI analysis based on full NC sample

ZEUS



ZEUS (94-07 data):  $\Lambda > 3.8\text{-}8.9 \text{ TeV}$ , 95% CL

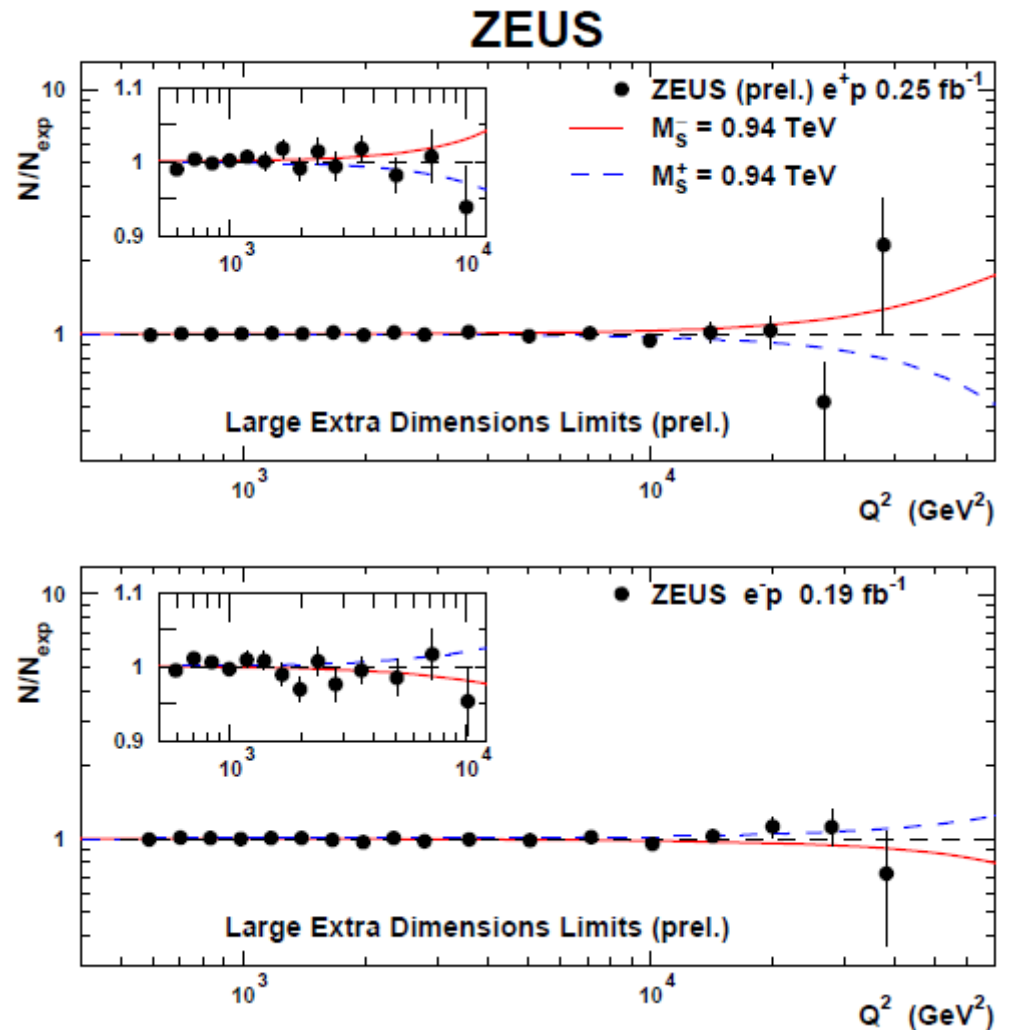
# Search for Large Extra Dimensions

Arkani-Hamed, Dimopoulos, Dvali model  
(proposed solution to the hierarchy problem)

- Gravity can propagate to  $4+n$  dimensions
- effective Plank scale  $M_D$  can be  $\sim 1\text{TeV}$
- At high energies, the strengths of gravitational and electroweak interactions can be comparable.

Graviton exchange contribution to  $eq \rightarrow eq$  interactions can be described as a contact interaction with an effective coupling of

$$\eta \sim 1/M^4$$



**ZEUS (94-07 data):  $M_S > 0.94 \text{ TeV}$ , 95% CL**

# The Leptoquark Model

## LEPTOQUARKS

Hypothetical bosons which appear in many SM extensions to explain symmetry between leptons and quarks

LQs are coupled to both leptons and quarks and carry SU(3) colour, fractional electrical charge, baryon ( $B$ ) and lepton ( $L$ ) numbers

→ Fermion number  $F = 3B + L = 0, 2$

## Buchmuller-Ruckl-Wyler Model

SU(3)<sub>C</sub> × SU(2)<sub>L</sub> × U(1)<sub>Y</sub> invariance

Lepton and baryon number conservation

Chiral particles: either left- or right-handed couplings

7 scalar and 7 vector LQs

Resonance width

$$\Gamma \sim \lambda^2 \cdot M_{LQ}$$

Each LQ characterized by two free parameters:

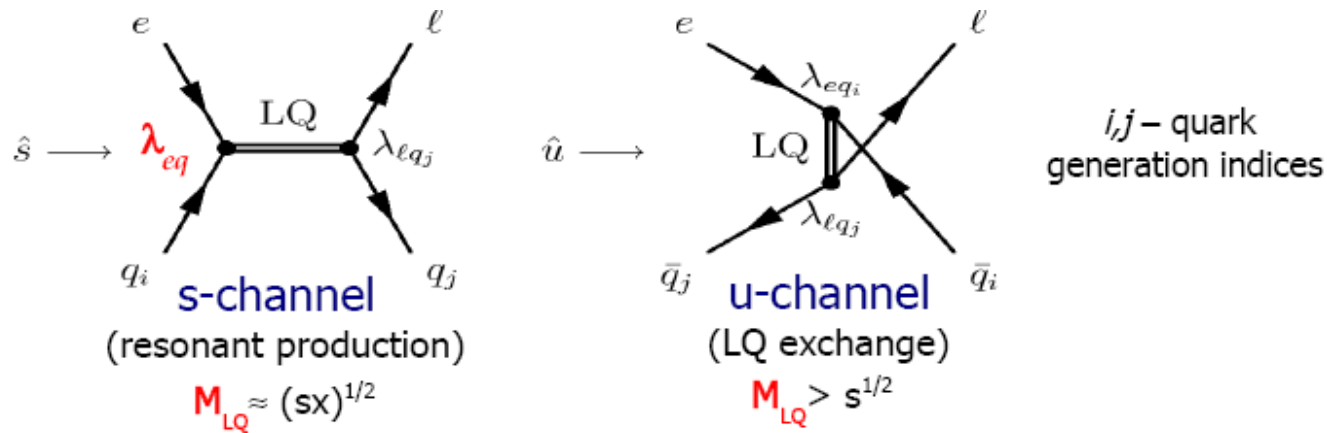
LQ mass,  $M_{LQ}$

LQ-l-q Yukawa coupling,  $\lambda$

$F = 2$	Prod./Decay	$\beta_e$	$F = 0$	Prod./Decay	$\beta_e$	
<b>e<sup>-</sup>p</b>		Scalar Leptoquarks				<b>e<sup>+</sup>p</b>
$S_{0,L}$	$e_L^- u_L \rightarrow e^- u$ $\rightarrow \nu d$	1/2 1/2	$S_{1/2,L}$	$e_R^+ u_R \rightarrow e^+ u$	1	
$S_{0,R}$	$e_R^- u_R \rightarrow e^- u$	1	$S_{1/2,R}$	$e_L^+ u_L \rightarrow e^+ u$	1	
$\tilde{S}_{0,R}$	$e_R^- d_R \rightarrow e^- d$	1		$e_L^+ d_L \rightarrow e^+ d$	1	
$S_{1,L}$	$e_L^- d_L \rightarrow e^- d$	1	$\tilde{S}_{1/2,L}$	$e_R^+ d_R \rightarrow e^+ d$	1	
	$e_L^- u_L \rightarrow e^- u$	1/2				
	$\rightarrow \nu d$	1/2				
Vector Leptoquarks						
$V_{1/2,R}$	$e_R^- d_L \rightarrow e^- d$	1	$V_{0,R}$	$e_L^+ d_R \rightarrow e^+ d$	1	
	$e_R^- u_L \rightarrow e^- u$	1	$V_{0,L}$	$e_R^+ d_L \rightarrow e^+ d$	1/2	
				$\rightarrow \bar{\nu} u$	1/2	
$V_{1/2,L}$	$e_L^- d_R \rightarrow e^- d$	1	$\tilde{V}_{0,R}$	$e_L^+ u_R \rightarrow e^+ u$	1	
$\tilde{V}_{1/2,L}$	$e_L^- u_R \rightarrow e^- u$	1	$V_{1,L}$	$e_R^+ u_L \rightarrow e^+ u$	1	
				$e_R^+ d_L \rightarrow e^+ d$	1/2	
				$\rightarrow \bar{\nu} u$	1/2	



# LQ production at HERA



If  $\text{LQ} \rightarrow e q$ , Lepton Flavor Conserving (LFC) decays, (1<sup>st</sup> generation LQ's)

If  $\text{LQ} \rightarrow \mu q / \tau q$ , Lepton Flavor Violating (LFV) decays, (2<sup>nd</sup>/3<sup>rd</sup> generation LQ's)

resonant production in s-channel

exchange in u-channel

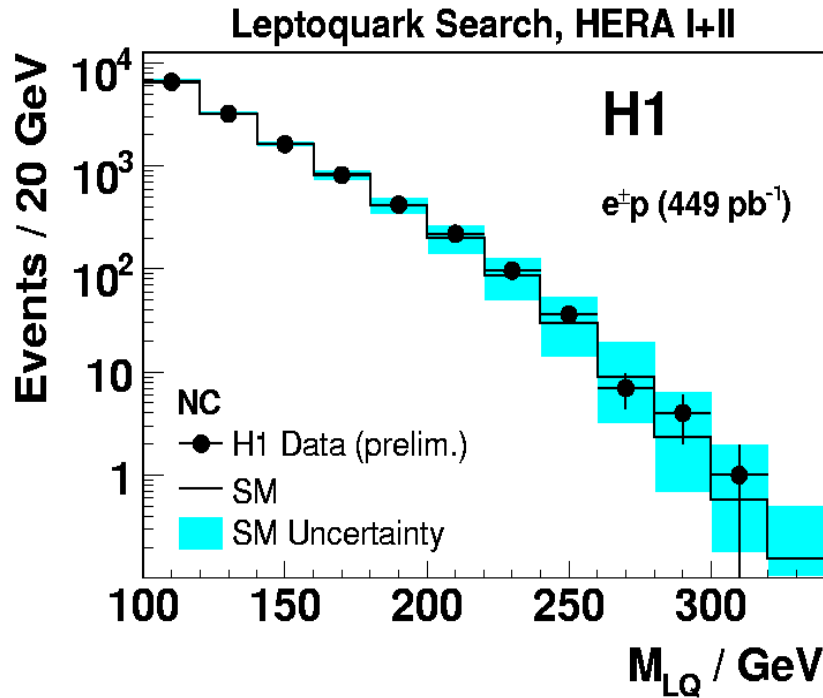
signature one jet & one l/v

final state indistinguishable from SM NC/CC DIS for 1<sup>st</sup> generation LQs

clear signal if we assume LFV

# Search for 1<sup>st</sup> generations Leptoquarks

Complete HERA e<sup>+</sup>p/e<sup>-</sup>p data analysed, L~0.45 fb<sup>-1</sup>

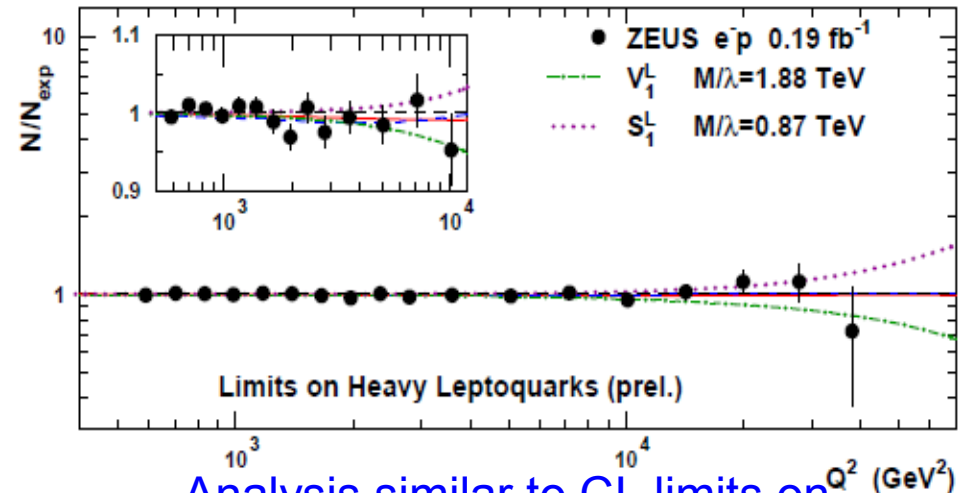
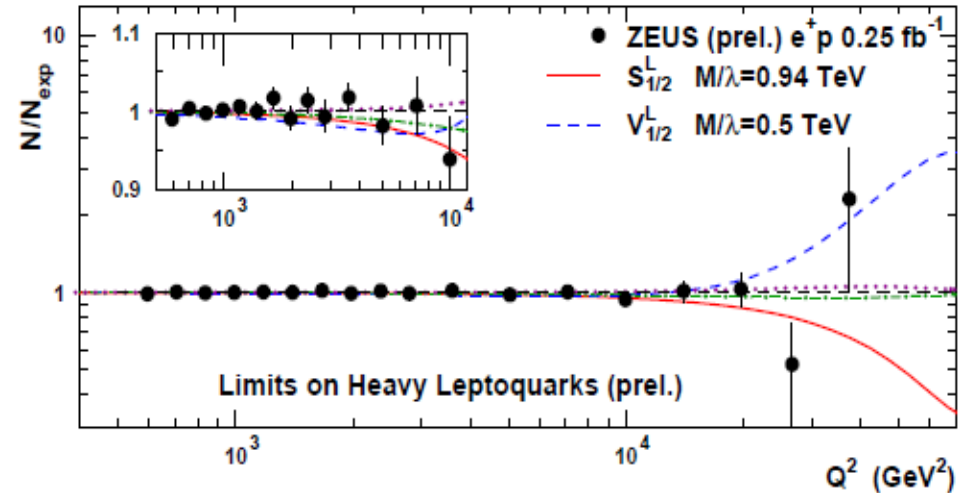


Good description of data by SM prediction in both NC and CC processes

Data analysed taking into account the different polarization periods

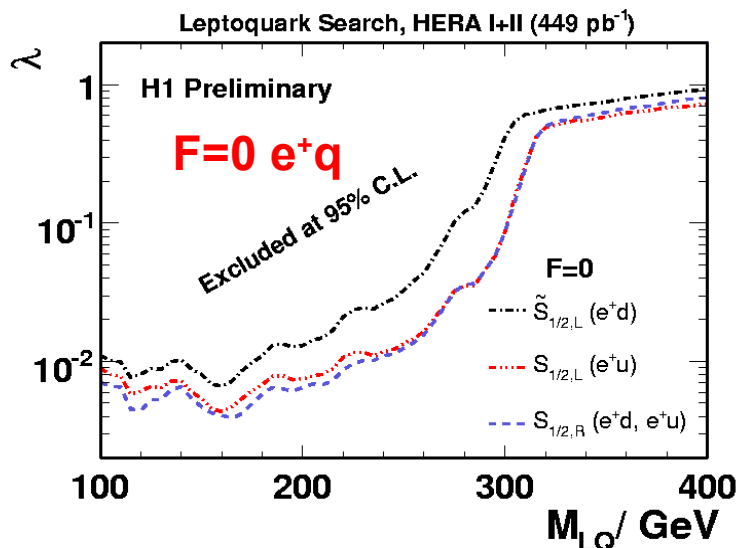
No evidence for signal → interpretation in terms of exclusion limits

## ZEUS



Analysis similar to CI, limits on heavy LQ's

# Search for 1<sup>st</sup> generation Leptoquarks



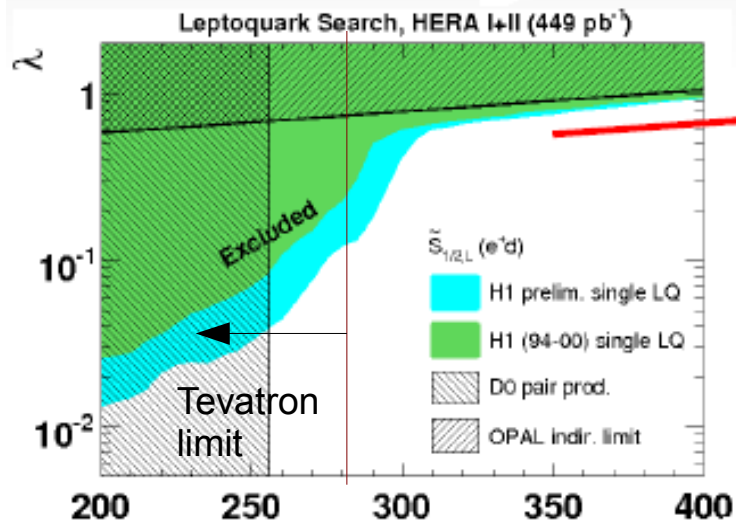
For electromagnetic strength  $\lambda=0.3$

$M_{LQ} < 291-330$  GeV can be ruled out

ZEUS Preliminary 1994-2007 $e^\pm p$		95% C.L. (TeV)
Model	Coupling Structure	$M_{LQ}/\lambda_{LQ}$
$S_0^L$	$a_{LL}^{eu} = +\frac{1}{2}$	1.24
$S_0^R$	$a_{RR}^{eu} = +\frac{1}{2}$	1.02
$\tilde{S}_0^R$	$a_{RR}^{ed} = +\frac{1}{2}$	0.41
$S_{1/2}^L$	$a_{LR}^{eu} = -\frac{1}{2}$	0.94
$S_{1/2}^R$	$a_{RL}^{ed} = a_{RL}^{eu} = -\frac{1}{2}$	0.81
$\tilde{S}_{1/2}^L$	$a_{LR}^{ed} = -\frac{1}{2}$	0.60
$S_1^L$	$a_{LL}^{ed} = +1, a_{LL}^{eu} = +\frac{1}{2}$	0.87
$V_0^L$	$a_{LL}^{ed} = -1$	1.05
$V_0^R$	$a_{RR}^{ed} = -1$	0.77
$\tilde{V}_0^R$	$a_{RR}^{eu} = -1$	1.50
$V_{1/2}^L$	$a_{LR}^{ed} = +1$	0.50
$V_{1/2}^R$	$a_{RL}^{ed} = a_{RL}^{eu} = +1$	1.36
$\tilde{V}_{1/2}^L$	$a_{LR}^{eu} = +1$	1.60
$V_1^L$	$a_{LL}^{ed} = -1, a_{LL}^{eu} = -2$	1.88

Limits on heavy LQ's

**ZEUS (94-07 data):**  
 $M_{LQ}/\lambda > 0.41-1,88$  TeV,  
**95% CL**



LEP (OPAL, L3) : indirect constraints from  $e^+e^- \rightarrow qq$

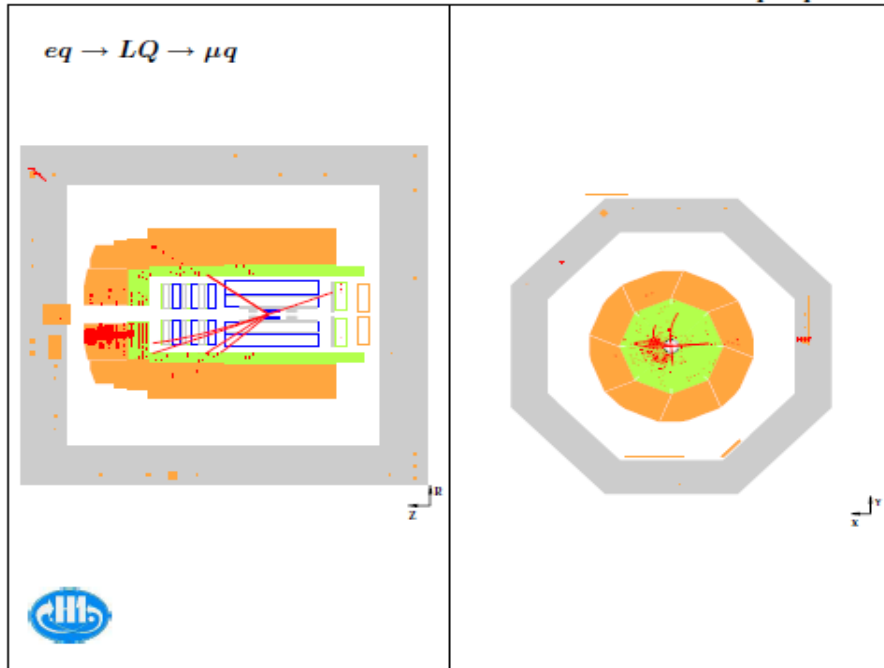
TEVATRON (D0) :  $qq$  annihilation or  $gg$  fusion (pair production), limit independent of  $\lambda$

HERA extends the excluded domain

# Search for 2<sup>nd</sup> generation Leptoquarks

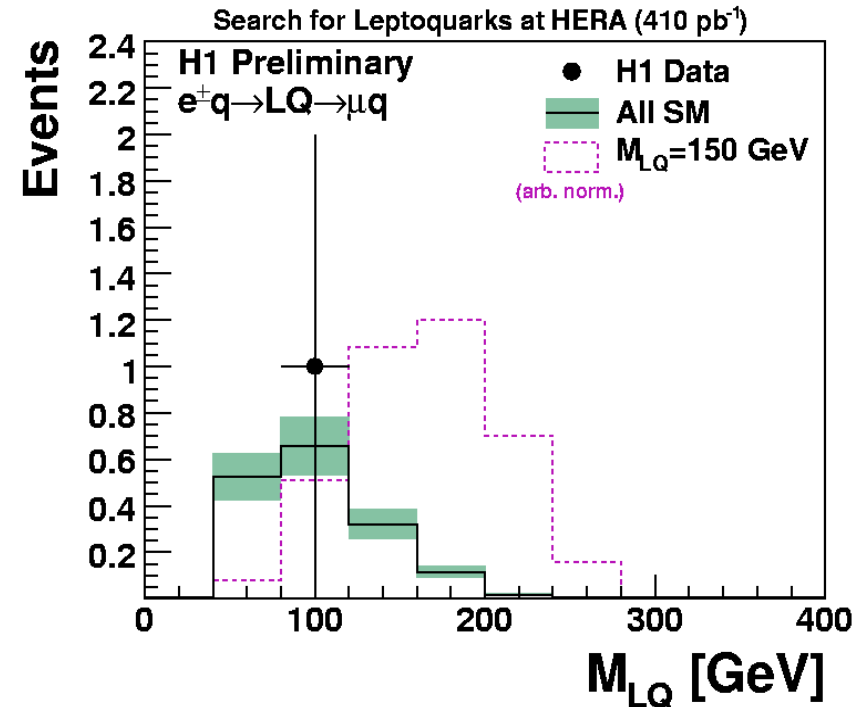
LQ could decay to a muon

H1 Candidate Event in the Search for Second Generation Leptoquarks



No evidence for signal  
Limits set for all 14 LQ types, under assumption

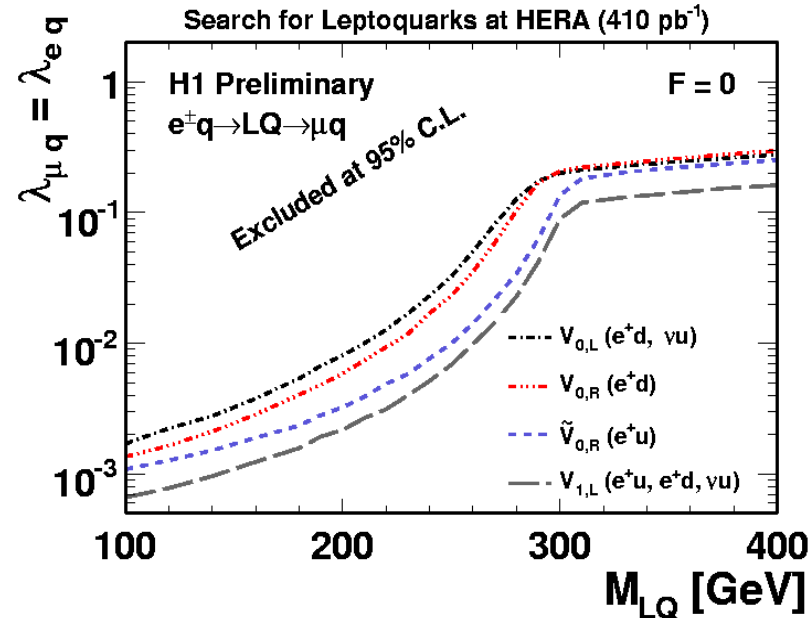
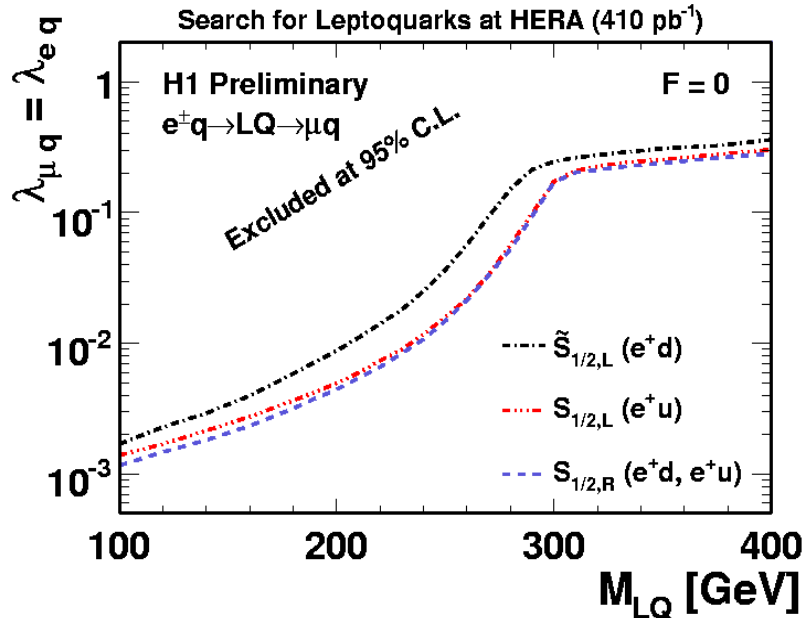
$$\lambda_{\mu q} = \lambda_{eq}, \lambda_{\tau q} = 0$$



H1 HERA (98-07) sample

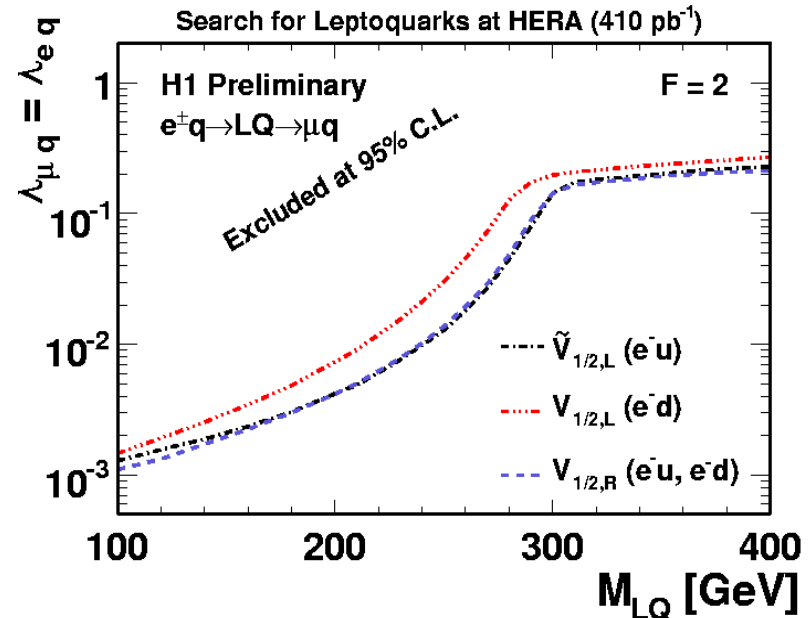
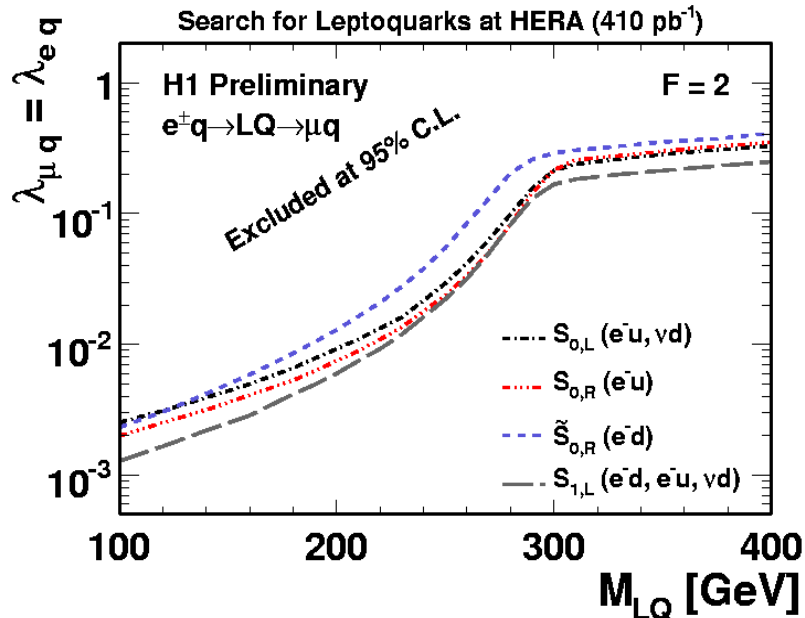
1 event seen/ $1.6 \pm 0.5$  expected

# Search for 2<sup>st</sup> generation Leptoquarks



For  
electromagnetic  
strength  $\lambda=0.3$

$M_{LQ} < 304-530$  GeV  
can be ruled out



For scalar LQ,  
 $\beta=0.5$   
Tevatron limit  
 $M_{LQ} > 259$  GeV



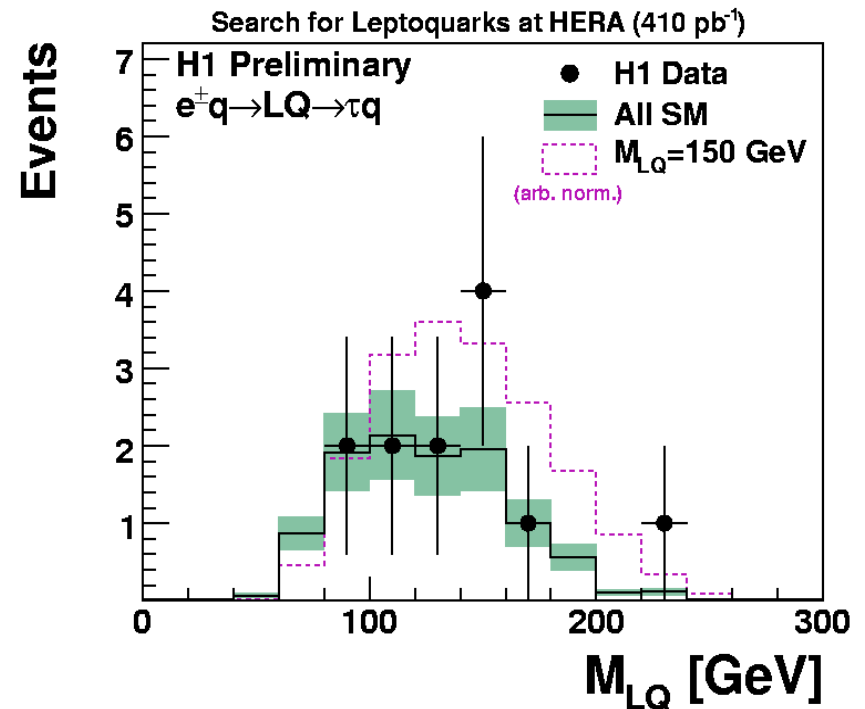
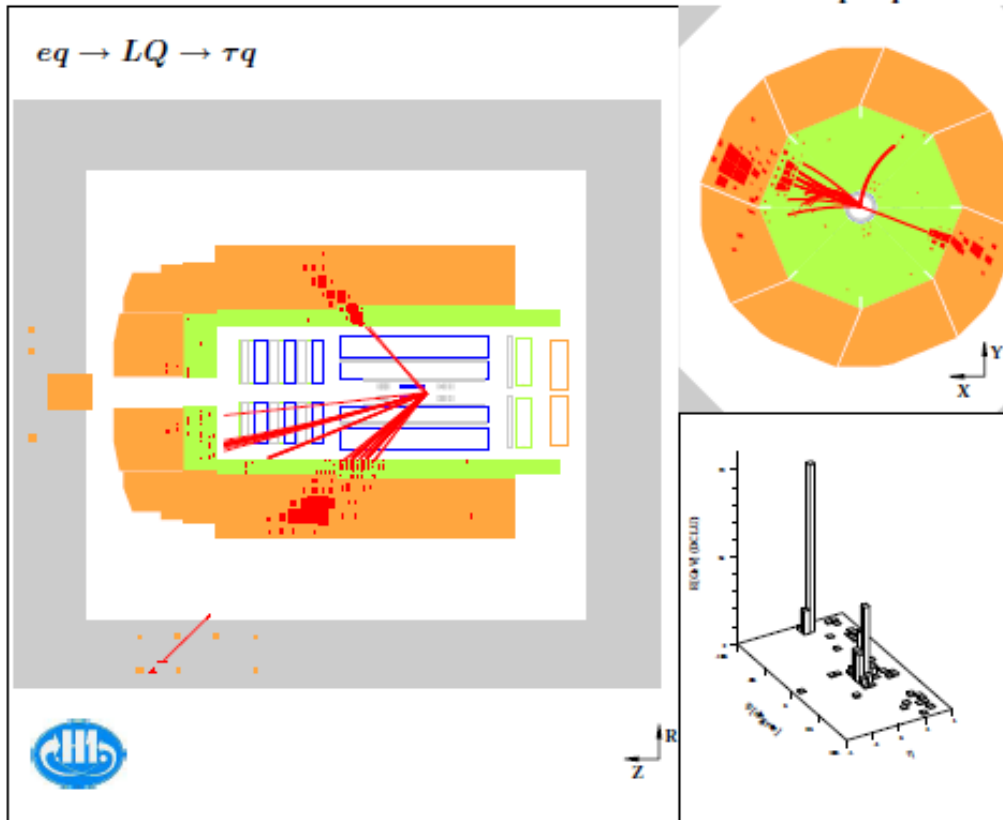
# Search for 3<sup>rd</sup> generation Leptoquarks

LQ could decay to a tau lepton

**Signature**  $ep \rightarrow \tau X$

( $\tau$  decays to 1 prong hadrons)

H1 Candidate Event in the Search for Third Generation Leptoquarks



H1 HERA (98-07) sample

12 events seen/10.6 expected

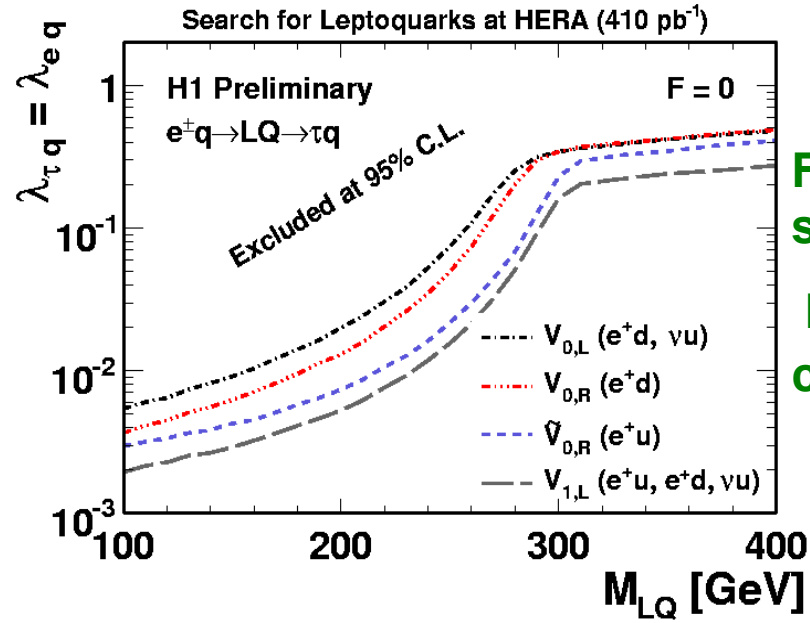
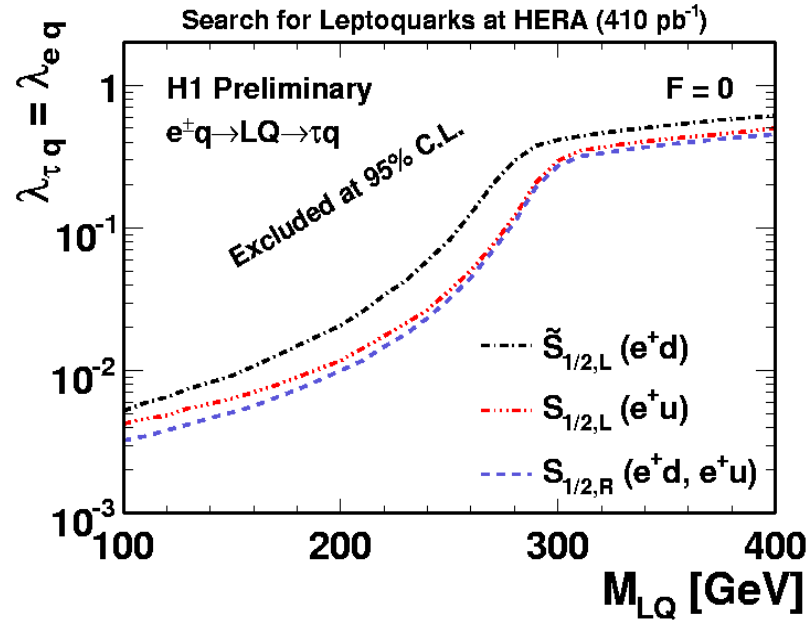
No evidence for signal

Limits set for all 14 LQ types

(for hadronic and muonic tau decays)

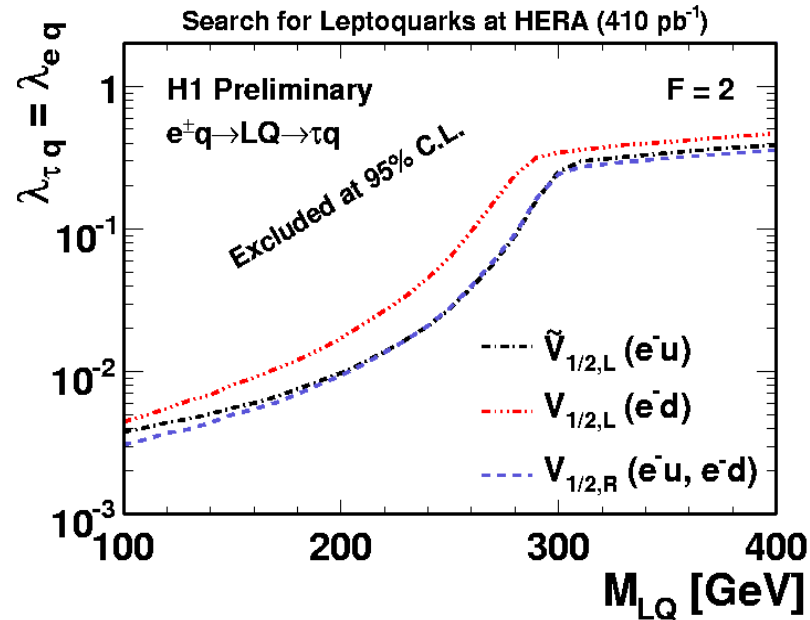
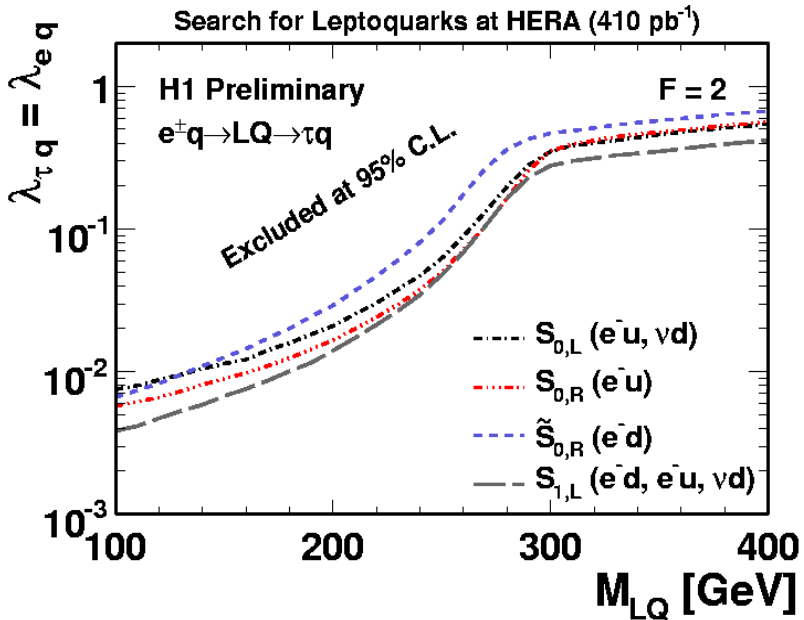
$$\lambda_{\tau q} = \lambda_{eq}, \quad \lambda_{\mu q} = 0$$

# Search for 3<sup>rd</sup> generation Leptoquarks



For electromagnetic strength  $\lambda=0.3$

$M_{LQ} < 272-450 \text{ GeV}$   
can be ruled out



For scalar LQ,  
 $\beta=0.5$   
Tevatron limit  
 $M_{LQ} > 207 \text{ GeV}$

# Conclusions

- Searches for deviations from SM in high  $Q^2$   $e^+p$  and  $e^-p$  DIS data has been performed by H1 and ZEUS based on full HERA datasets ( $\sim 0.45 \text{ fb}^{-1}$  per experiment)
- No data excess or deviations from SM cross sections have been found.
- ZEUS (NC DIS): 95% CL limits have been set for different CI models
- H1 (NC, CC DIS): 95% CL limits have been set for resonant and non-resonant 1<sup>st</sup> generation LQ production
- New limits from H1 on LFV LQ's with the complete HERA dataset
- HERA limits complementary to Tevatron and LEP limits