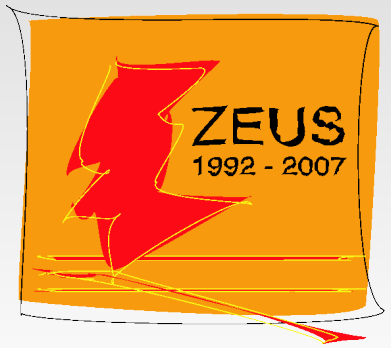


Search for Leptoquarks and Contact Interactions at HERA

Robert Ciesielski
on behalf of H1 and ZEUS Collaborations

EPS-HEP 2009, Krakow
18 July 2009

HERA operation

World's only *ep* collider, located at DESY Hamburg.
Ended in June 2007, after 15 years of successful running.
Two colliding experiments: H1 and ZEUS.

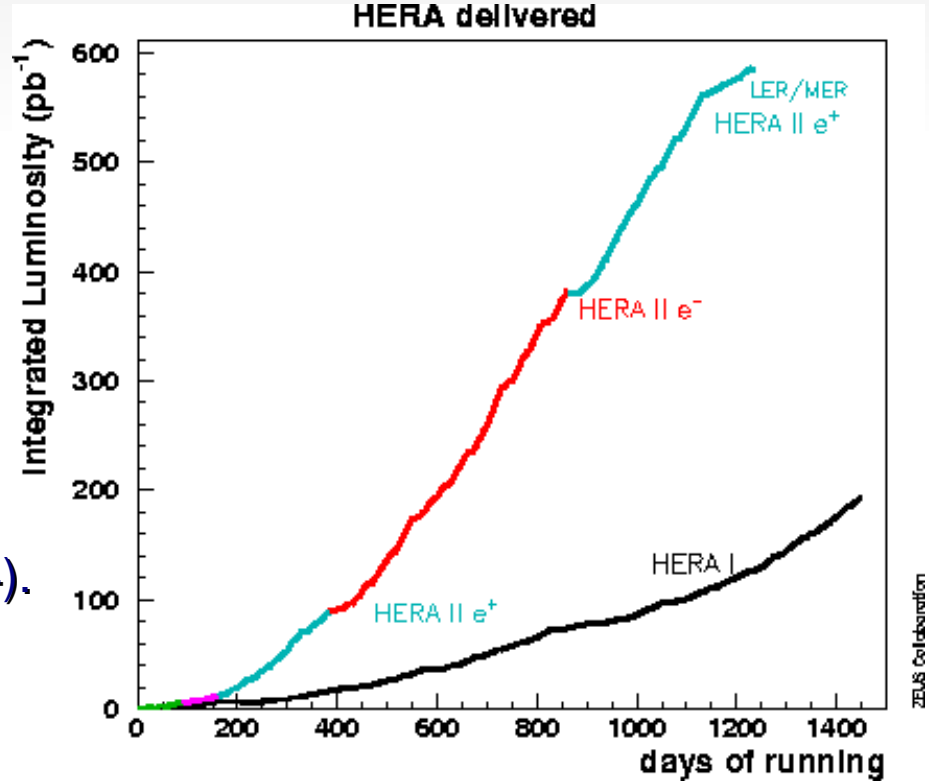
p (820/920 GeV) e (27.5 GeV)

$\sqrt{s}$ = 318 GeV

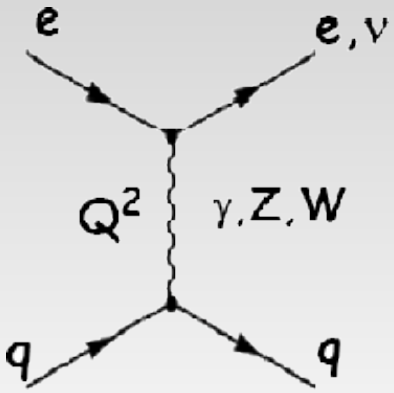
HERA I (1994-2000)
L=~120 pb^{-1} collected per experiment.
Mostly e$^+$p.

HERA II (2002-2007)
L=~360 pb^{-1} collected per experiment.
Similar amount of e$^+$p and e$^-$p.
Longitudinal polarisation of lepton beam (P=0.3-0.4).

Presented results are based on full datasets
(almost 0.5 fb^{-1} per experiment).



High-Q^2 NC and CC Cross Sections



Main processes studies at HERA:

Neutral Current (NC) DIS, ep→eX, mediated by γ or Z^0.

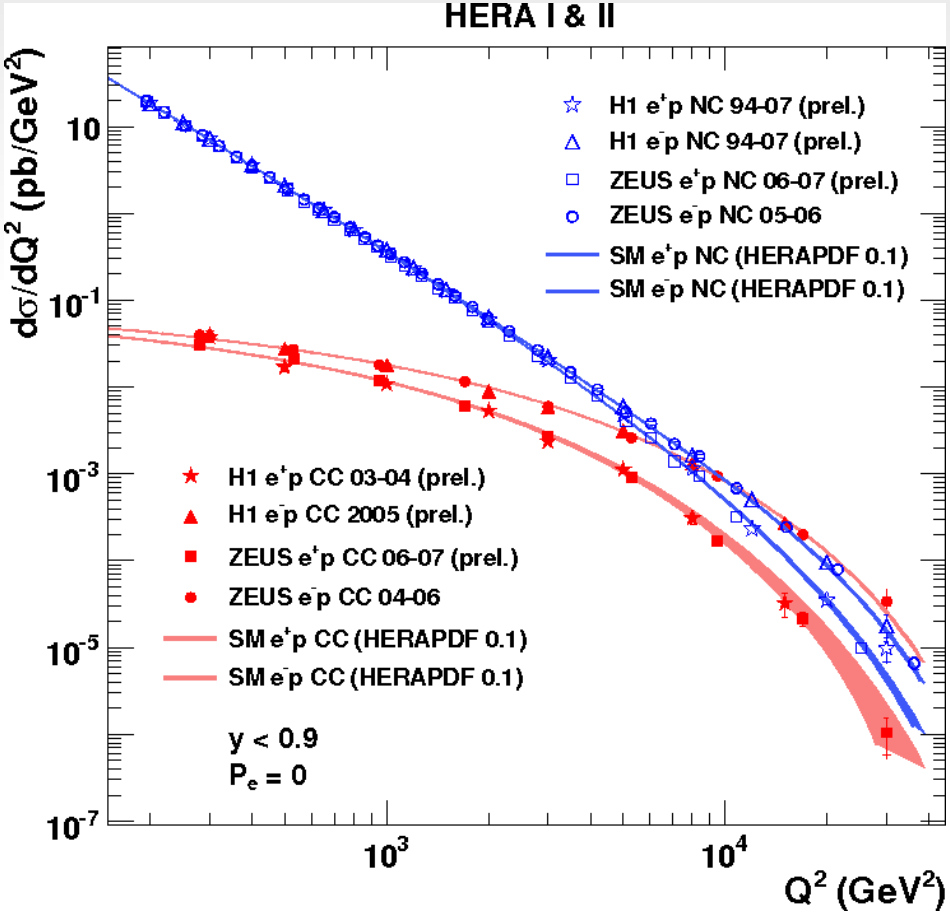
Charged Current (CC) DIS, ep→νX, mediated by $W^{\pm}$.

Excellent agreement between data and SM predictions over many orders of magnitude.
Precise tests of QCD and EW physics.

Q^2 (resolving power) up to 40000 GeV^2.
Spatial resolution ~ $1/Q \simeq 10^{-18}$ m = 10^{-3} fm.
1/1000 of proton radius.

Search for Beyond SM physics performed by looking for possible deviations at highest Q^2:

- Contact Interactions (NC)
- Leptoquark production (NC,CC)

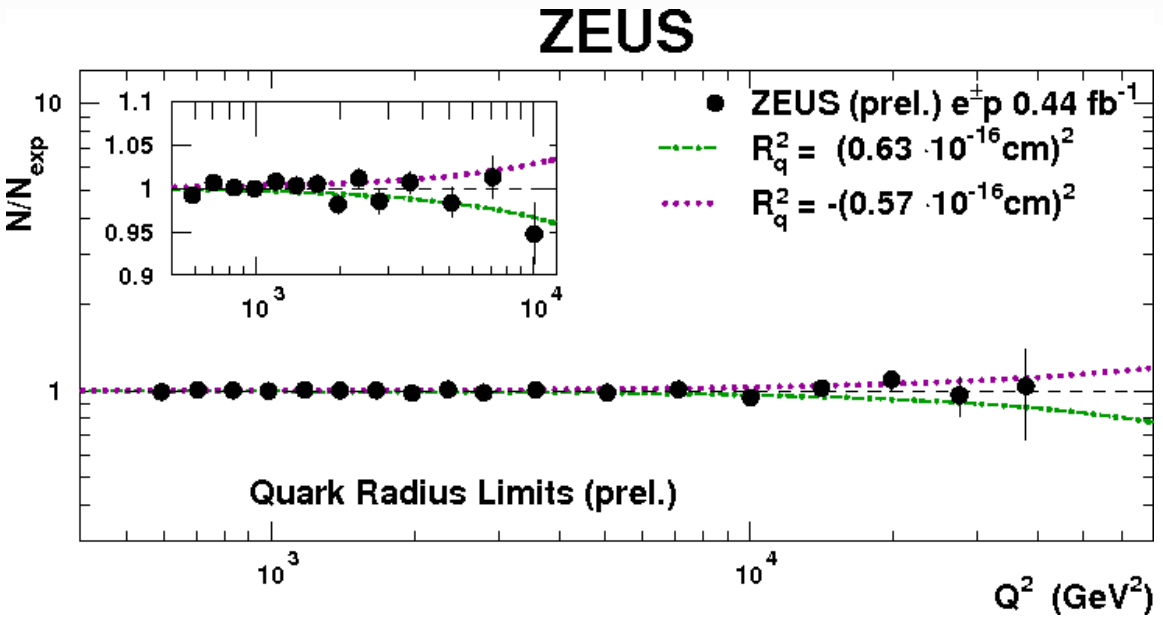


Quark Radius

Quark form-factor (electron assumed to be point-like).
If a quark has a finite size, the SM cross section is expected to decrease at higher Q^2:

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

R_q is a root-mean-square radius of the EW charge distribution in the quark.
The same dependence expected for e^-p and e^+p.



Excellent agreement with SM expectations up to highest Q^2.

ZEUS (94-07 data): $R_q < 0.63 \times 10^{-3}$ fm
H1 (94-07 data): $R_q < 0.74 \times 10^{-3}$ fm
@ 95% C.L.

Large Extra Dimensions

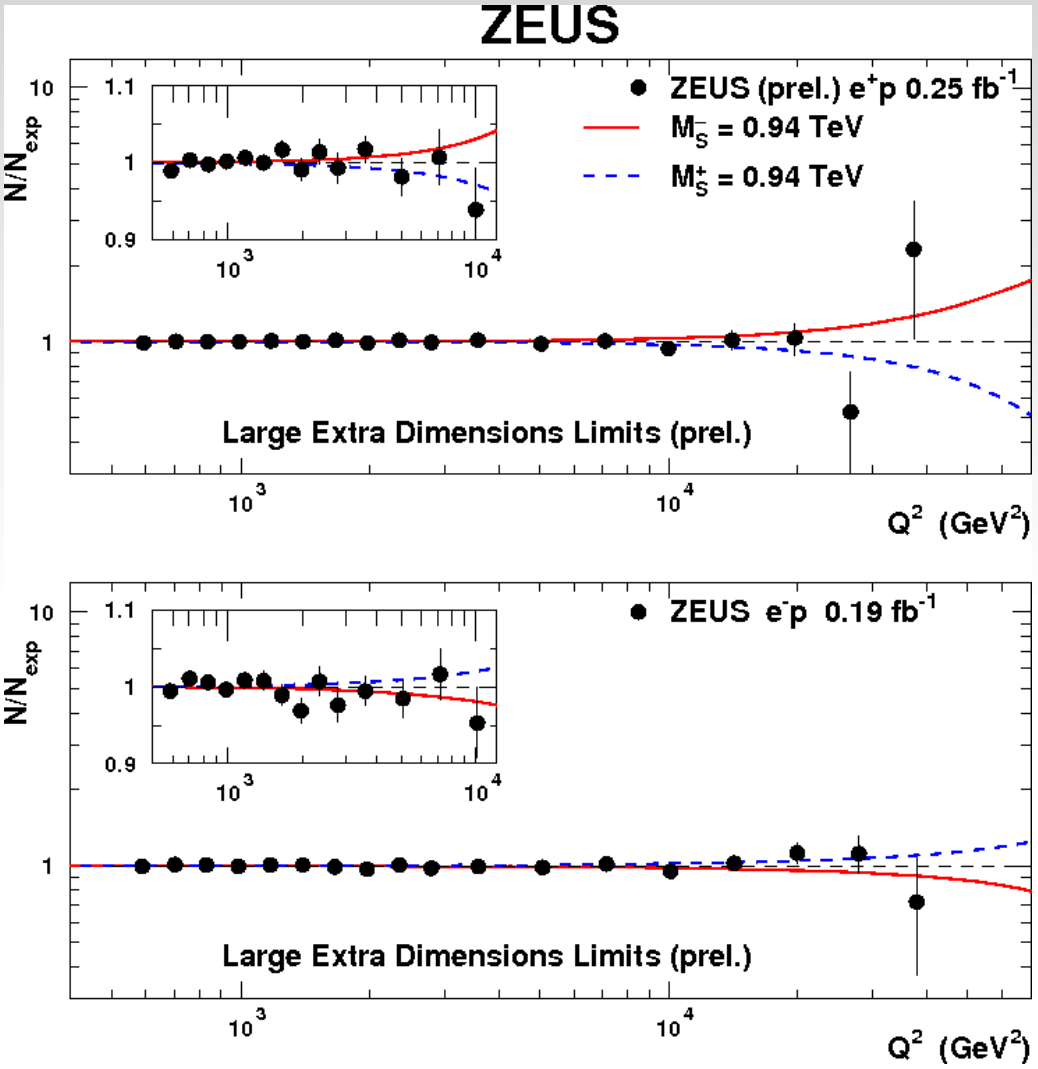
Arkani-Hamed-Dimopolous-Dvali Model

If gravity propagates in 4+δ dimensions, effective Plank scale M_S can be as low as 1 TeV. Gravity becomes comparable in strength to electroweak interactions.

Contribution of graviton exchange (Kaluza-Klein tower) to $e^{\pm}p$ NC DIS can be described by effective coupling:

$$\eta_G = \lambda \frac{\epsilon^2}{M_S^4}$$

where $\lambda = \pm 1$ is the coupling strengh and ϵ is related to the energy scale of hard interaction.

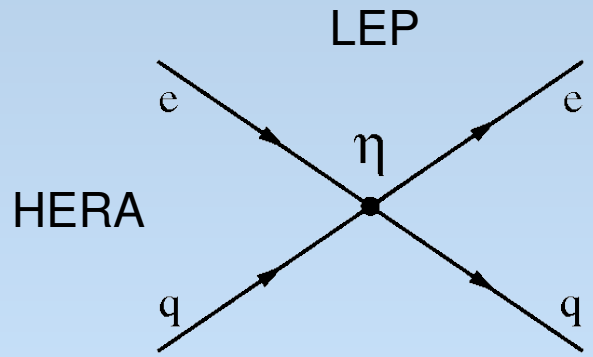


ZEUS (94-07 data): $M_S^+ > 0.94$ TeV, $M_S^- > 0.94$ TeV (95% C.L.)

Contact Interactions (CI)

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

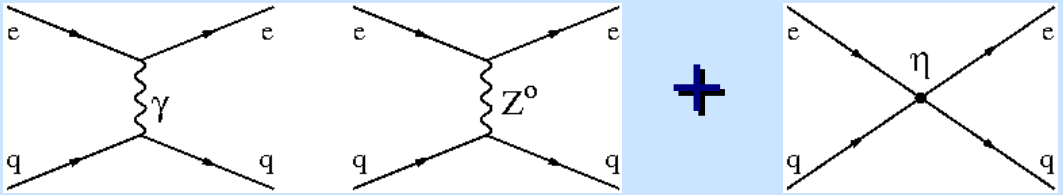
Reminder: before W and Z^0 were discovered, weak interactions ($\Lambda \approx M_W$) were described as 4-fermion CI with Fermi constant $G_F = g^2/M^2_W$.



$$L_{CI} = \sum_{\alpha,\beta} \eta^{eq}_{\alpha\beta} (\bar{e}_\alpha \gamma^\mu e_\alpha)(\bar{q}_\beta \gamma^\mu q_\beta)$$

where α and β are electron and quark helicities (L,R).

At HERA:



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

CI modify the tree level eq→eq scattering amplitudes.

e^-p sensitive to η^{eq}_{LL} and η^{eq}_{RR}
e^+p sensitive to η^{eq}_{LR} and η^{eq}_{RL}

CI, General Models

Also referred to as Compositeness Models.

Couplings $\eta^{eq}_{\alpha\beta}$ are related to the mass scale Λ at which new interactions accour:

$$\eta^{eq}_{\alpha\beta} = \frac{\epsilon\, g^2_{CI}}{\Lambda^2}$$

g_{CI} is a coupling strength of new interactions and $\varepsilon = \pm 1$.
By convention $g^2_{CI} = 4\pi$.

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

Parity conserving models fulfill the relation:

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

Family universality assumed.

Models conserving parity:

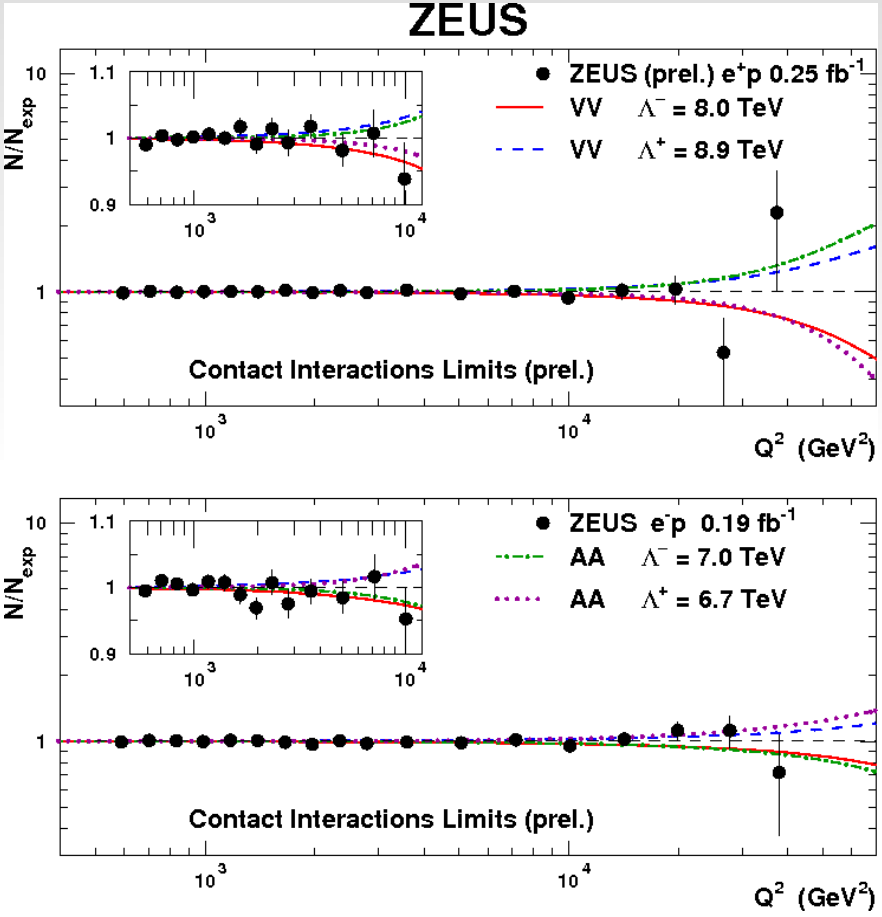
Model	η^{ed}_{LL}	η^{ed}_{LR}	η^{ed}_{RL}	η^{ed}_{RR}	η^{eu}_{LL}	η^{eu}_{LR}	η^{eu}_{RL}	η^{eu}_{RR}
VV	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$
AA	$+\eta$	$-\eta$	$-\eta$	$+\eta$	$+\eta$	$-\eta$	$-\eta$	$+\eta$
VA	$+\eta$	$-\eta$	$+\eta$	$-\eta$	$+\eta$	$-\eta$	$+\eta$	$-\eta$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

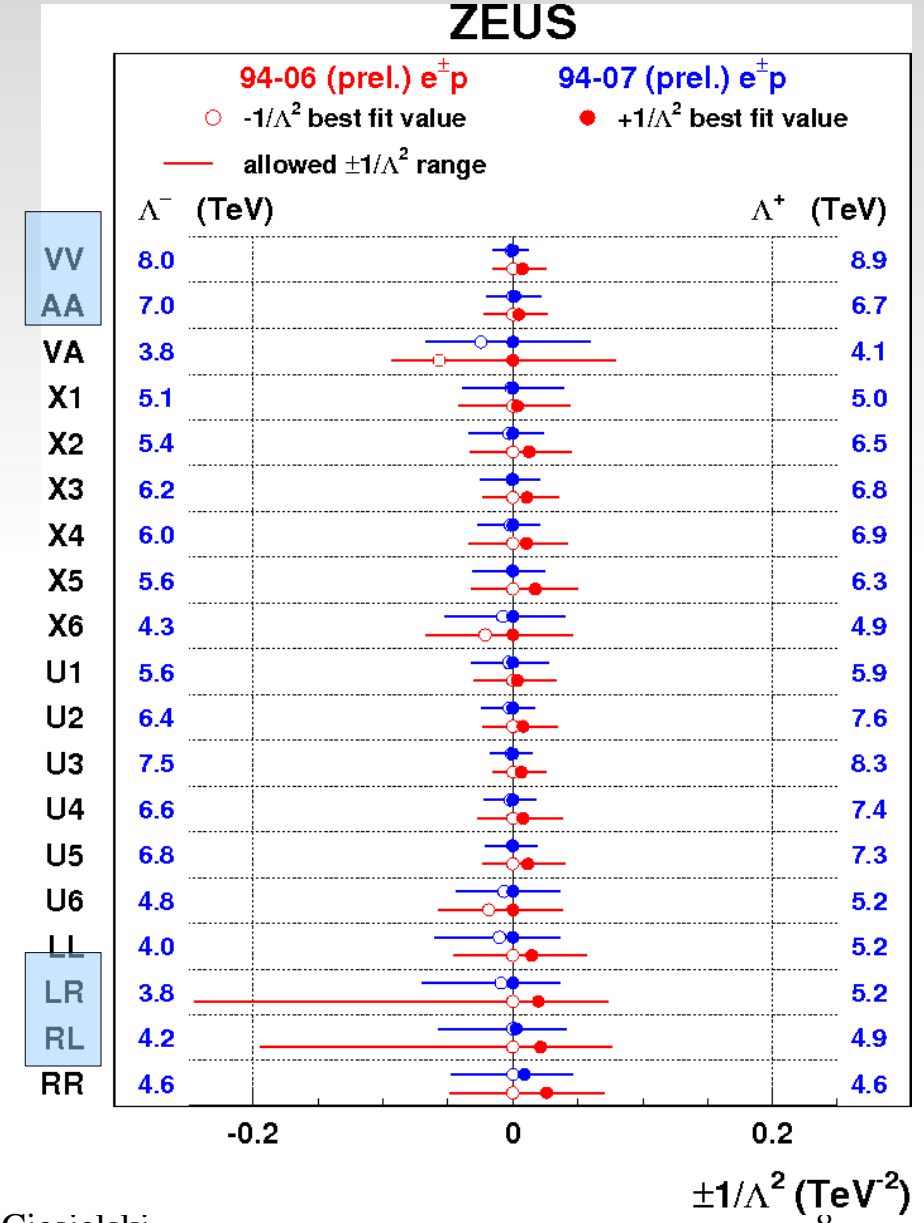
Models violating parity:

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

CI, General Models

ZEUS CI analysis based on full NC sample of L=0.44 fb^{-1} (with recently included NC e$^+$p data).





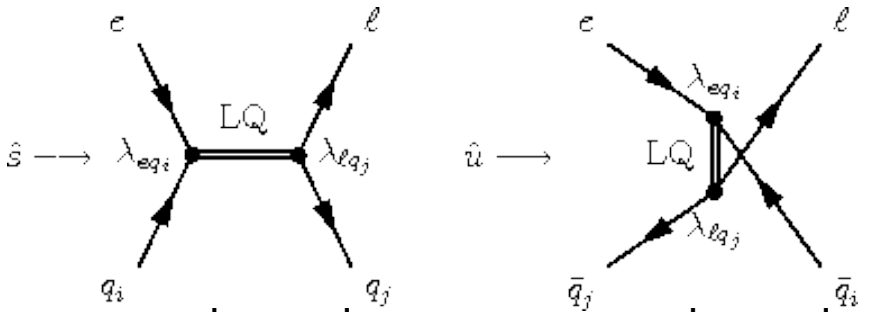
ZEUS (94-07 data): Λ > 3.8 - 8.9 TeV (95% C.L.)

Leptoquarks Production

The Buchmueller-Rueckl-Wyler Model

Leptoquarks (LQ) - hypothetical boson connecting lepton and quark sectors. Carry SU(3) colour, fractional electric charge, lepton (L),barion (B) and fermion number F=3B+L=0,2. Conserve SM symmetries. Chiral objects ie. either left- or right-handed coupling to lepton, but not both.
7 scalar and 7 vector LQs coupling to *eq*.
4 LQs couple also to νq.

At HERA LQs can be resonantly produced in s-channel ($M_{LQ} < \sqrt{s}$, with $\Gamma = \lambda^2 M_{LQ}$)
or exchanged in u-channel.

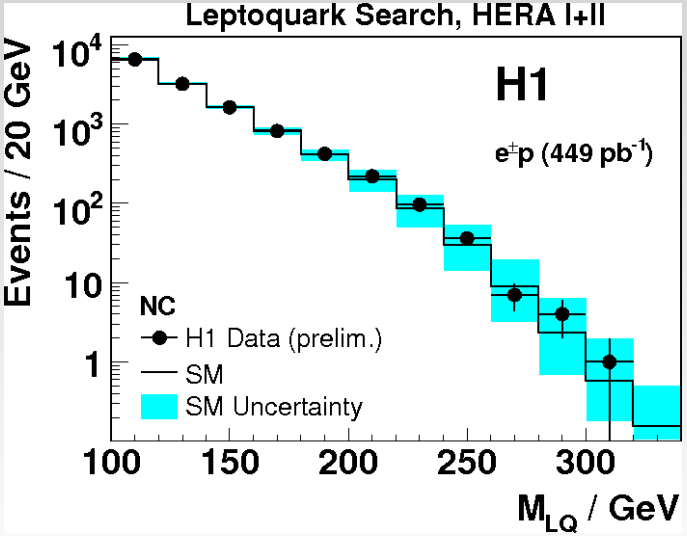


s-channel u-channel

λ is the Yukawa LQ-*e*-*q* couplling.
Limit setting on M_{LQ}/λ.

$F=2$	Prod./Decay	β_e	$F=0$	Prod./Decay	β_e
	e^-p Scalar Leptoquarks			**e^+p**	
$S_{0,L}$	$e_L^- u_L \to e^- u$	1/2	$S_{1/2,L}$	$e_R^+ u_R \to e^+ u$	1
	$\to \nu d$	1/2			
$S_{0,R}$	$e_R^- u_R \to e^- u$	1	$S_{1/2,R}$	$e_L^+ u_L \to e^+ u$	1
$\tilde{S}_{0,R}$	$e_R^- d_R \to e^- d$	1		$e_L^+ d_L \to e^+ d$	1
$S_{1,L}$	$e_L^- d_L \to e^- d$	1	$\tilde{S}_{1/2,L}$	$e_R^+ d_R \to e^+ d$	1
	$e_L^- u_L \to e^- u$	1/2			
	$\to \nu d$	1/2			
	Vector Leptoquarks				
$V_{1/2,R}$	$e_R^- d_L \to e^- d$	1	$V_{0,R}$	$e_L^+ d_R \to e^+ d$	1
	$e_R^- u_L \to e^- u$	1	$V_{0,L}$	$e_R^+ d_L \to e^+ d$	1/2
				$\to \overline{\nu} u$	1/2
$V_{1/2,L}$	$e_L^- d_R \to e^- d$	1	$\tilde{V}_{0,R}$	$e_L^+ u_R \to e^+ u$	1
$\tilde{V}_{1/2,L}$	$e_L^- u_R \to e^- u$	1	$V_{1,L}$	$e_R^+ u_L \to e^+ u$	1
				$e_R^+ d_L \to e^+ d$	1/2
				$\to \overline{\nu} u$	1/2

1st Generation Leptoquarks



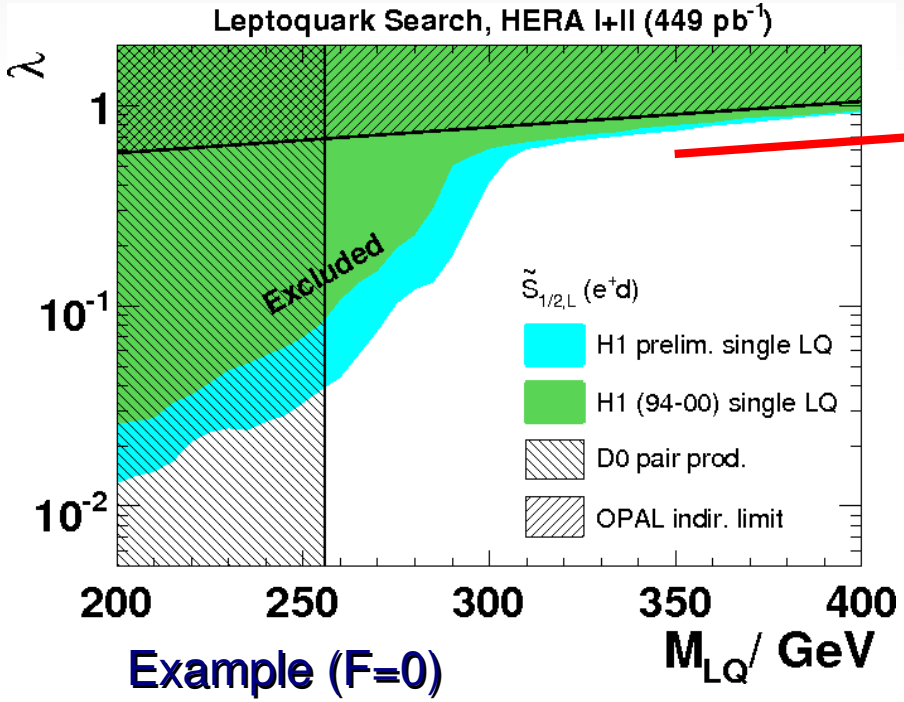
H1 analysis based on full NC and CC samples of L=0.45 fb^{-1}

LQ → eq

Large SM background from NC and CC processes.
Good description of data by SM prediction (also for CC, for e^-p and e^+p separately and for polarized samples). No LQ signal observed.

Limits set for all 14 LQs.

H1 (94-07 data): For $\lambda=\sqrt{4\pi\alpha}=0.3$
M_{LQ}<291-330 GeV are excluded at 95%C.L.



Example (F=0)

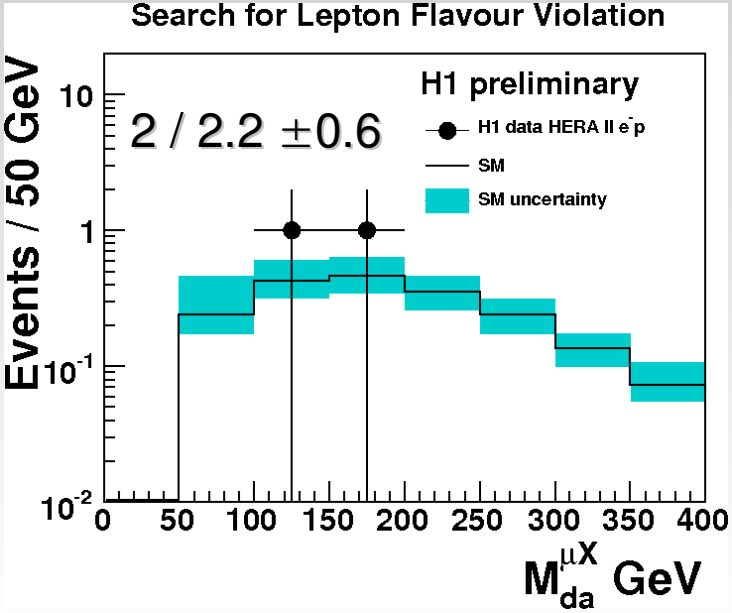
ZEUS CI (94-07 data):

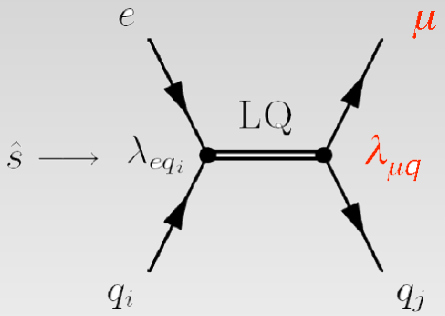
$$\eta^{eq}_{\alpha\beta} \propto \left(\frac{\lambda}{M_{LQ}}\right)^2$$

M_{LQ}/λ > 0.41-1.88 TeV @95% C.L.

LEP (OPAL, L3): indirect constraints from ee→qq.
Tevatron (D0): LQ+LQ pair production from qq anihilation or gg fusion (λ independent).

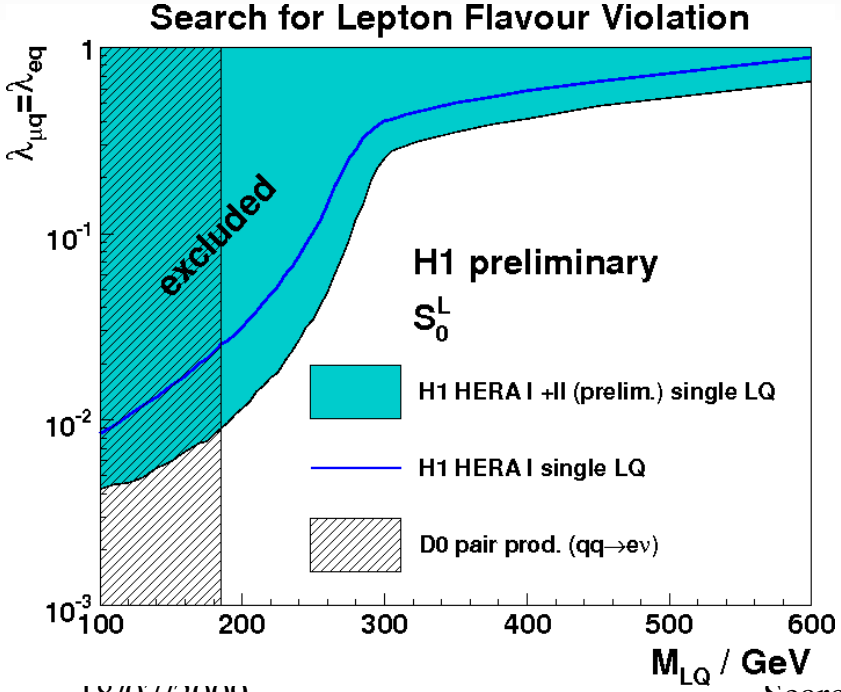
2nd Generation Leptoquarks





$e^-p \to LQ \to \mu X$ with e^-p data.

Search for Lepton Flavour Violation mediated by LQ.
Experimentaly clear process. Background dominated by lepton pair production.
No evidence for signal.



Limits set for 7 LQs (F=2), under assumption:
$\lambda_{\mu q}=\lambda_{eq}$, $\lambda_{\tau q}=0$.

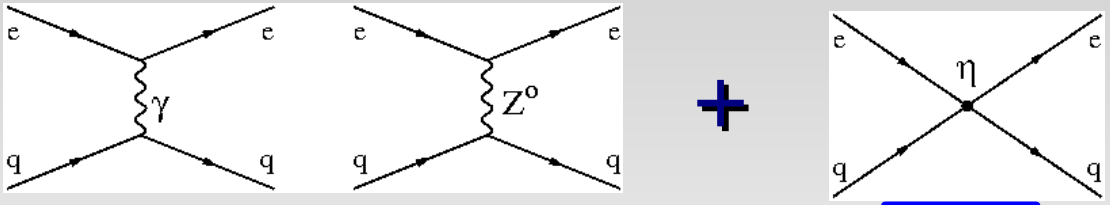
For $\lambda=\sqrt{4\pi\alpha}=0.3$
M_{LQ}<291-433 GeV are excluded at 95%C.L.

Summary

- Search for deviations from SM in High-Q^2 e^+p and e^-p DIS data has been performed by ZEUS and H1 based on full datasets of ~0.45 fb^{-1} (per experiment).
- No deviations have been found.
- ZEUS (NC DIS): 95% C.L. limits have been set for different CI models.
- H1 (NC, CC DIS): 95% C.L. limits have been set for resonant and non-resonant LQ production.
- HERA limits complementary to Tevatron and LEP limits.

Contact Interactions

4-fermion CI at HERA:



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

α, β - electron and quark helicities (L,R).

NC e^-p scattering:

$$\frac{d^2\sigma(e^- p)}{dxdy} = \frac{sx}{16\pi}\sum q(x)\left\{P_- M^2_{LL} + P_+ M^2_{RR} + (1-y)^2\left(P_- M^2_{LR} + P_+ M^2_{RL}\right)\right\}$$
$$+\bar{q}(x)\left\{P_- M^2_{LR} + P_+ M^2_{RL} + (1-y)^2\left(P_- M^2_{RR} + P_+ M^2_{LL}\right)\right\}$$

NC e^+p scattering:

$$\frac{d^2\sigma(e^+ p)}{dxdy} = \frac{sx}{16\pi}\sum q(x)\left\{P_+ M^2_{LR} + P_- M^2_{RL} + (1-y)^2\left(P_+ M^2_{LL} + P_- M^2_{RR}\right)\right\}$$
$$+\bar{q}(x)\left\{P_+ M^2_{LL} + P_- M^2_{RR} + (1-y)^2\left(P_+ M^2_{LR} + P_- M^2_{RL}\right)\right\}$$

At high Q^2 and high x quark distribution dominate (valence quarks).
Some contributions are suppresed by helicity factor $(1-y)^2$.
NC e^-p sensitive to LL and RR, NC e^+p sensitive to LR and RL configurations.

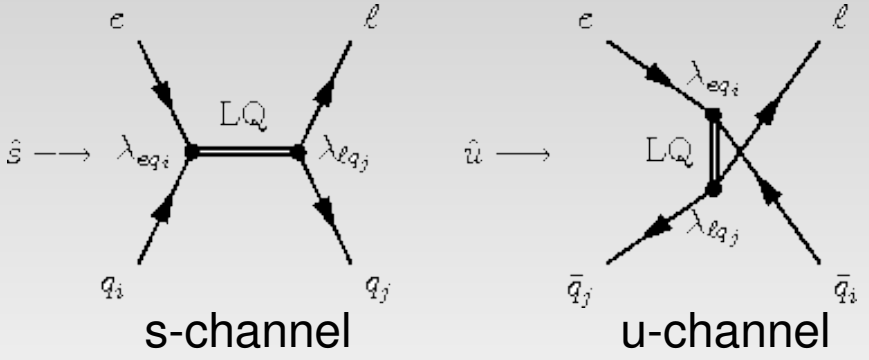
$$P_\pm = 1 \pm P$$

SM MEs modyfied by quark form-factor: $M^{eq}_{\alpha\beta}(Q^2) = M^{eq}_{\alpha\beta}(Q^2)^{SM}(1 - R_q^2 Q^2/6)$

CI, Heavy Leptoquarks

The Buchmueller-Rueckl-Wyler Model

At HERA can be resonantly produced in s-channel ($M_{LQ} < \sqrt{s}$) or exchanged in u-channel.



s-channel u-channel

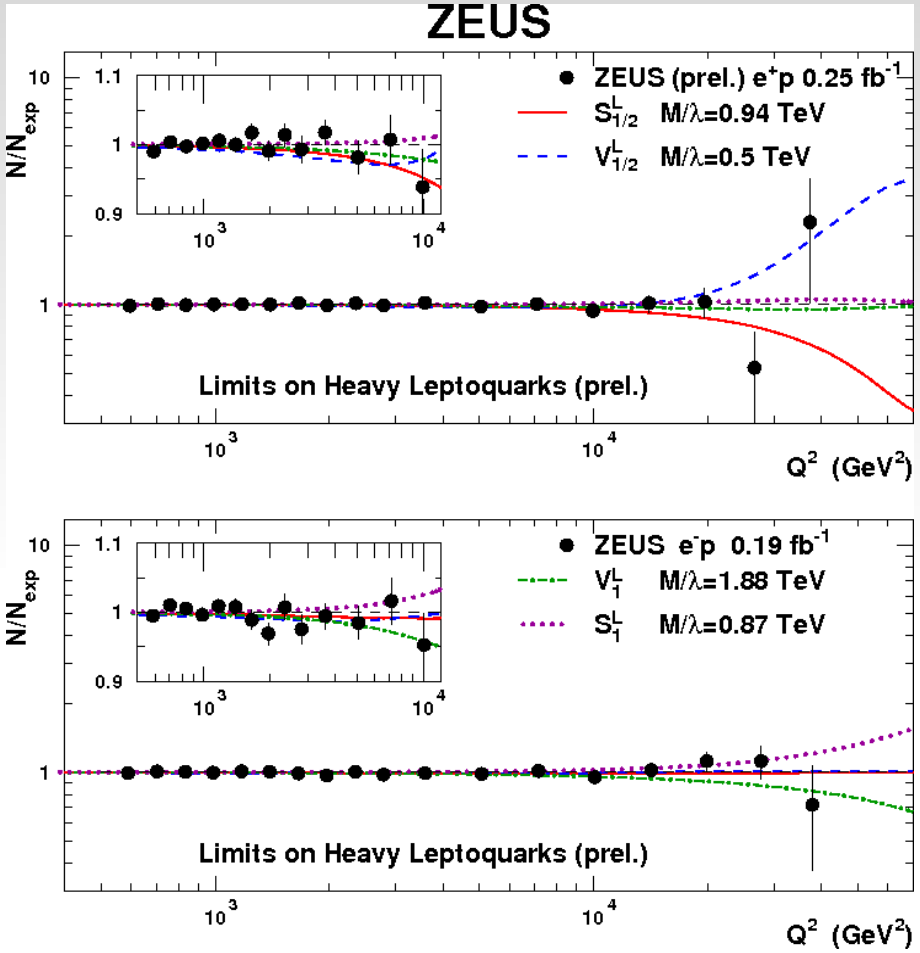
For high mass LQs ($M_{LQ} \gg \sqrt{s}$) virtual production/exchange results in the effective CI coupling:

$$\eta^{eq}_{\alpha\beta} = a^{eq}_{\alpha\beta}\left(\frac{\lambda}{M_{LQ}}\right)^2$$

where $a^{eq}_{\alpha\beta}$ is a coefficient and λ is the Yukawa LQ-*e*-*q* couplling.
Limit setting on M_{LQ}/λ.

Model	a^{ed}_{LL}	a^{ed}_{LR}	a^{ed}_{RL}	a^{ed}_{RR}	a^{eu}_{LL}	a^{eu}_{LR}	a^{eu}_{RL}	a^{eu}_{RR}
$S^L_\circ$					$+\frac{1}{2}$			
$S^R_\circ$								$+\frac{1}{2}$
$\tilde{S}_\circ$				$+\frac{1}{2}$				
$S^L_{1/2}$						$-\frac{1}{2}$		
$S^R_{1/2}$			$-\frac{1}{2}$				$-\frac{1}{2}$	
$\tilde{S}_{1/2}$		$-\frac{1}{2}$						
S_1	$+1$				$+\frac{1}{2}$			
$V^L_\circ$	-1							
$V^R_\circ$				-1				
$\tilde{V}_\circ$								-1
$V^L_{1/2}$		$+1$						
$V^R_{1/2}$			$+1$				$+1$	
$\tilde{V}_{1/2}$						$+1$		
V_1	-1				-2			

CI, Heavy Leptoquarks



ZEUS Preliminary 1994-2007 $e^{\pm}p$		95% C.L. (TeV)
Model	Coupling Structure	M_{LQ}/λ_{LQ}
$S_{\circ}^{L}$	$a_{LL}^{eu} = +\frac{1}{2}$	1.24
$S_{\circ}^{R}$	$a_{RR}^{eu} = +\frac{1}{2}$	1.02
$\tilde{S}_{\circ}^{R}$	$a_{RR}^{ed} = +\frac{1}{2}$	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
$V_{\circ}^{L}$	$a_{LL}^{ed} = -1$	1.05
$V_{\circ}^{R}$	$a_{RR}^{ed} = -1$	0.77
$\tilde{V}_{\circ}^{R}$	$a_{RR}^{eu} = -1$	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

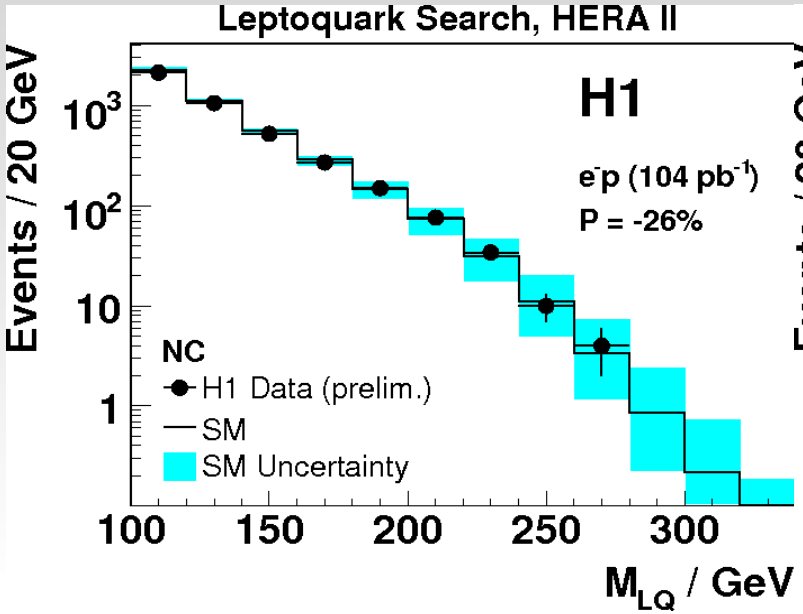
Only sensitive to M_{LQ}/λ.

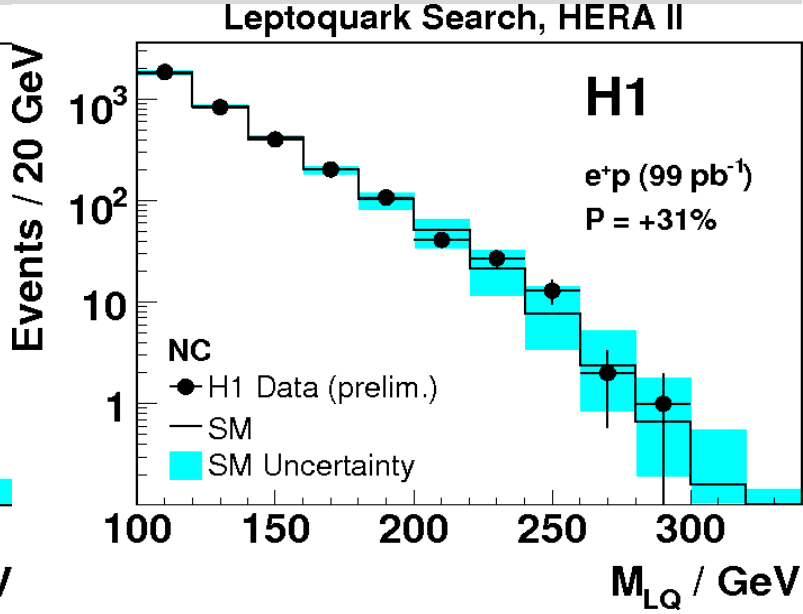
ZEUS (94-07 data): M_{LQ}/λ > 0.41 - 1.88 TeV (95% C.L.)

1st Generation Leptoquarks

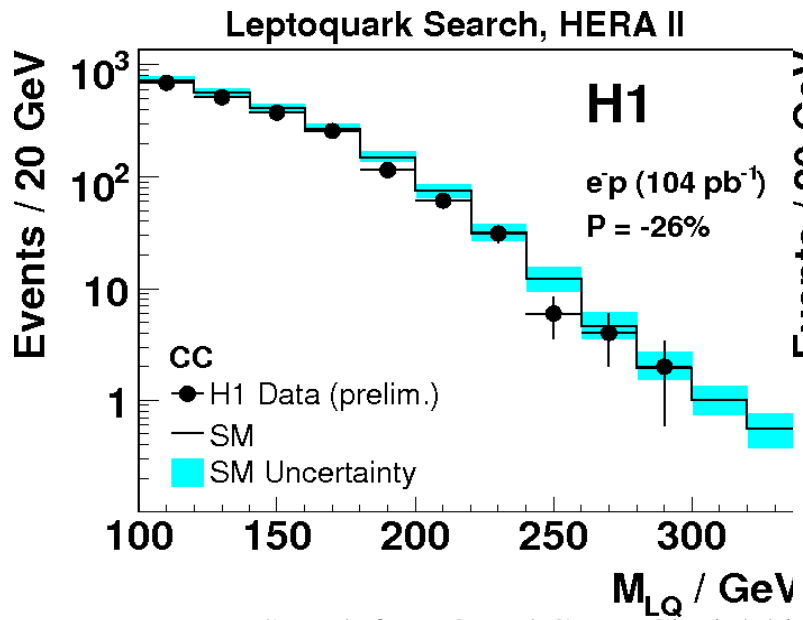
LH e^-p RH e^+p

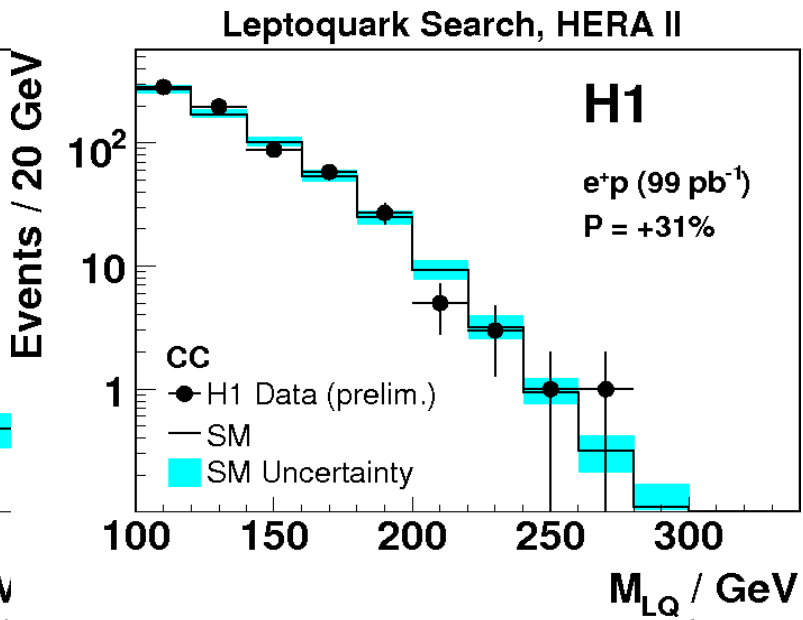
NC:





CC:





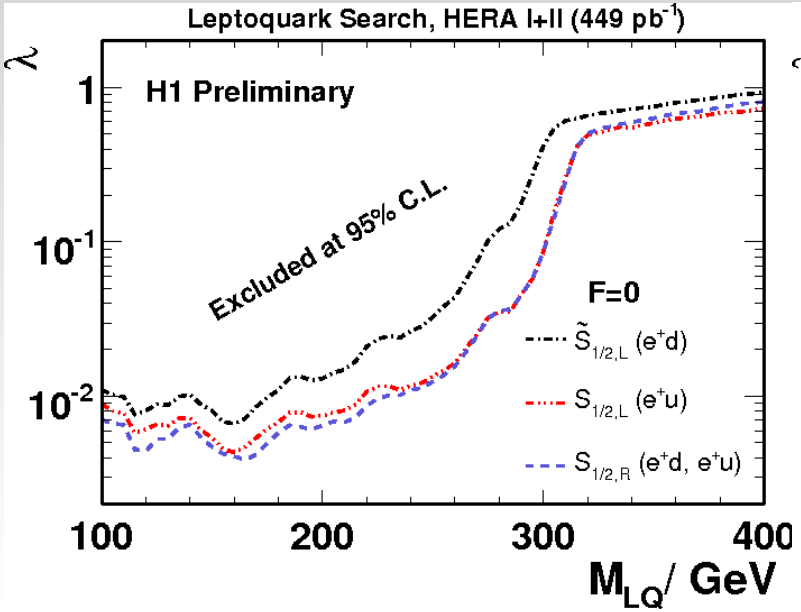
1st Generation Leptoquarks

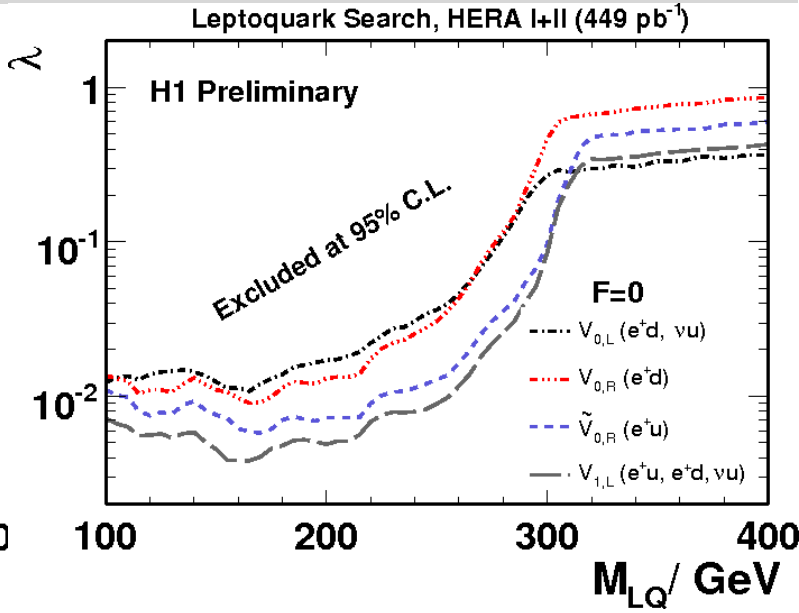
Limits for all 14 LQs.

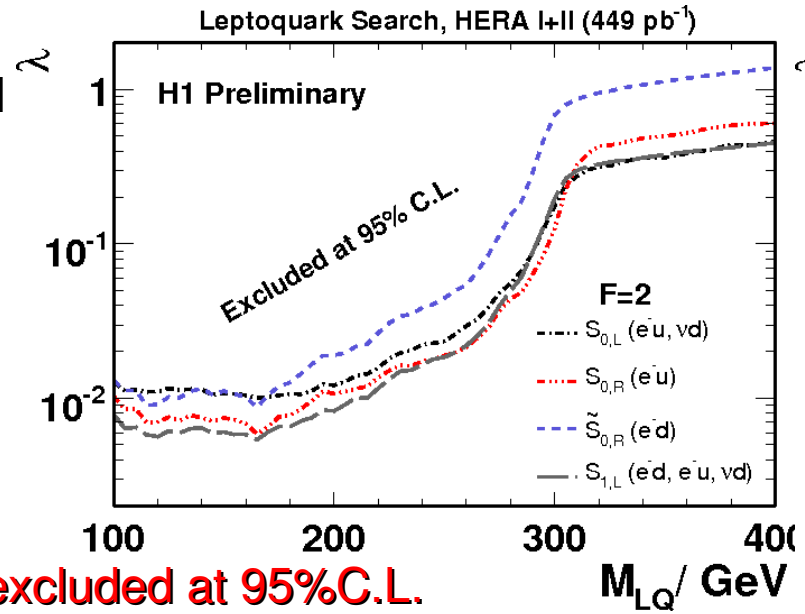
$M_{LQ} < \sqrt{s} = 300$ GeV resonant production stronger limits.

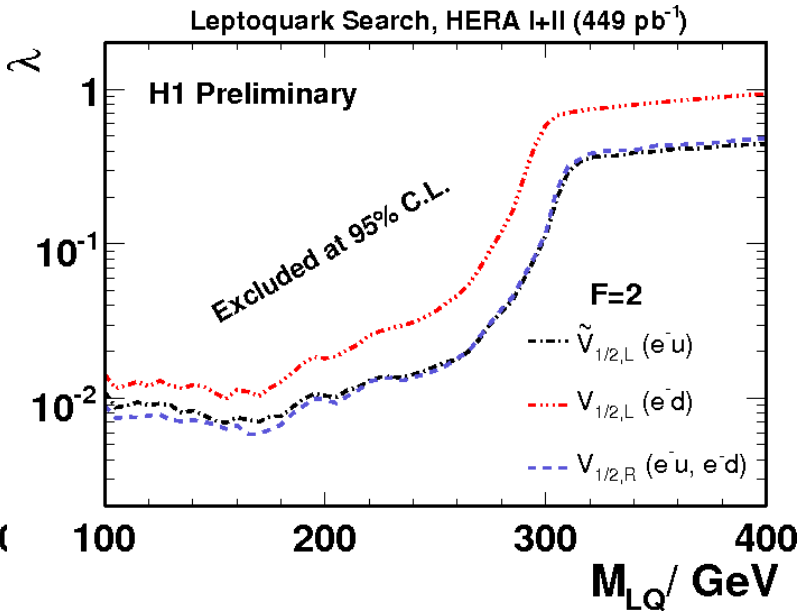
$M_{LQ} > \sqrt{s}$, only u-channel exchange, CI region.

For $\lambda = \sqrt{4\pi\alpha} = 0.3$
M_{LQ}<291-330 GeV are excluded at 95%C.L.







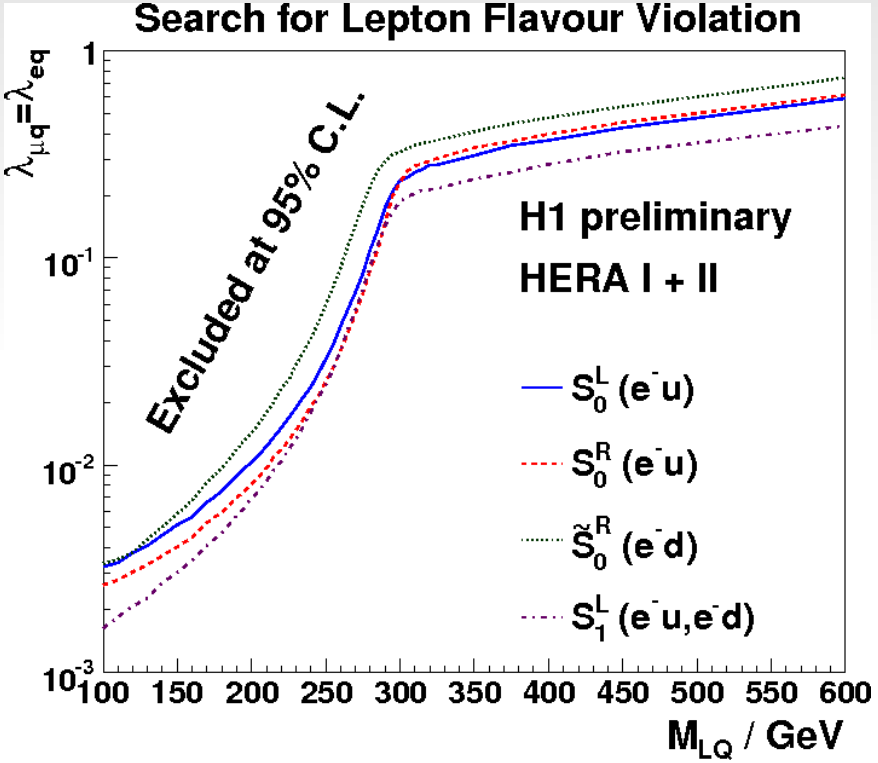


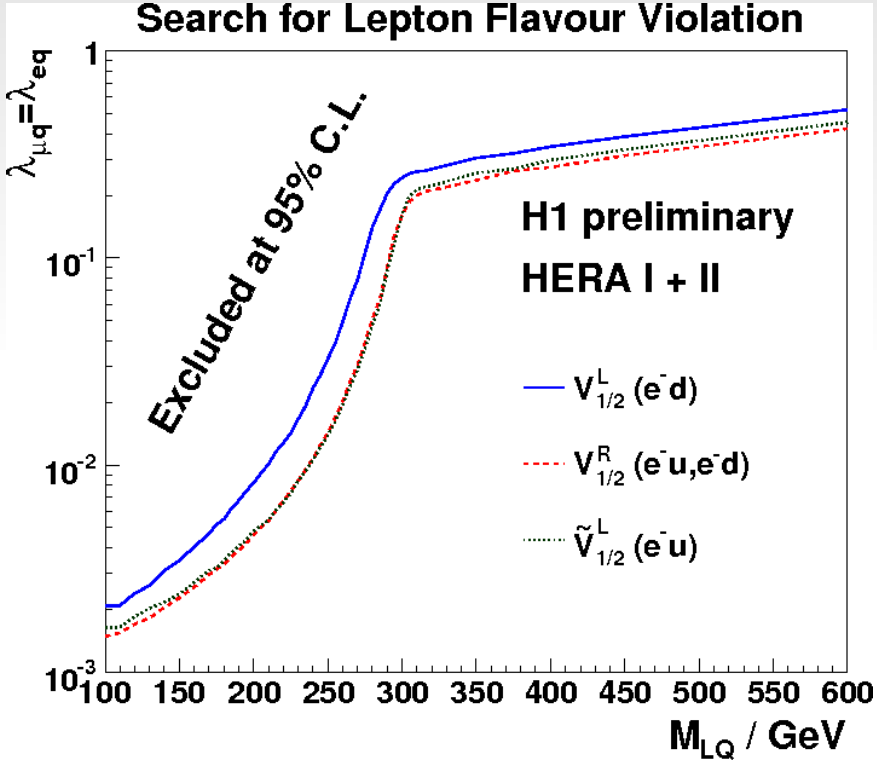
2nd Generation Leptoquarks

$e^-p \to LQ \to \mu X$ with e^-p data.

Search for Lepton Flavour Violation mediated by LQ.

Limits set for 7 LQs (F=2), under assumption $\lambda_{\mu q}=\lambda_{eq}$, $\lambda_{\tau q}=0$.





For $\lambda=\sqrt{4\pi\alpha}=0.3$

M_{LQ}<291-433 GeV are excluded at 95%C.L.

3rd Generation Leptoquarks

H1 analysis based on HERA-I data.
(DESY 07-009)

Limits set for 14 LQs,
under assumption $\lambda_{\tau q} = \lambda_{eq}$