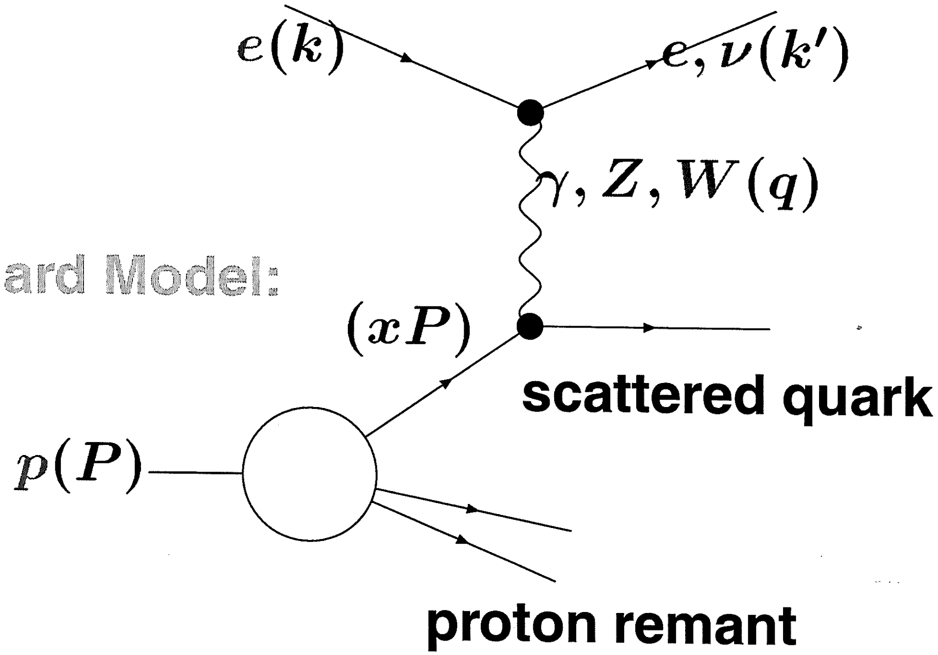
EPS Meeting (July 13th 2001)

Search for Leptoquarks and Contact Interactions at HERA

Xiang Liu, Columbia Univ. Representing ZEUS & H1.

Standard Model:



HERA: $e^{\pm}p$ Collision $\sqrt{S} \sim$ 320GeV

Neutral Current(NC): γ,Z

Charge Current(CC): W

ZEUS & H1 each collected

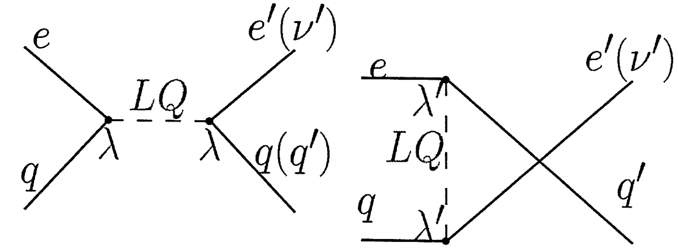
$\sim 110 pb^{-1}\ e^{+}p$ | $\sim 15 pb^{-1}\ e^{-}p$

Introduction to Leptoquark

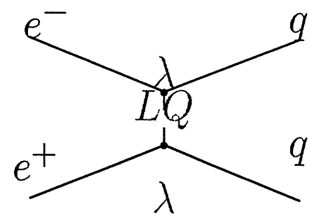
General LQ Model

- Color triplet carrying both B & L number. (F=3B+L,F=2 or 0). Decay to eq or νq .
- $e^- p \rightarrow$ F=2 LQ, $e^+ p \rightarrow$ F=0 LQ (valence q $>>$ sea q)
- $y = \frac{1}{2}(1 - \cos\theta^*)$
θ^*: e scattering angle in eq (νq) rest frame.
- Scalar LQ: flat in y
Vector LQ: $(1-y)^2$
NC DIS (Background) : $\sim 1/y^2$

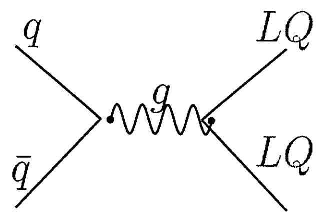
HERA



LEP



TEVATRON



Buchmüller-Rückl-Wyler (BRW) Model

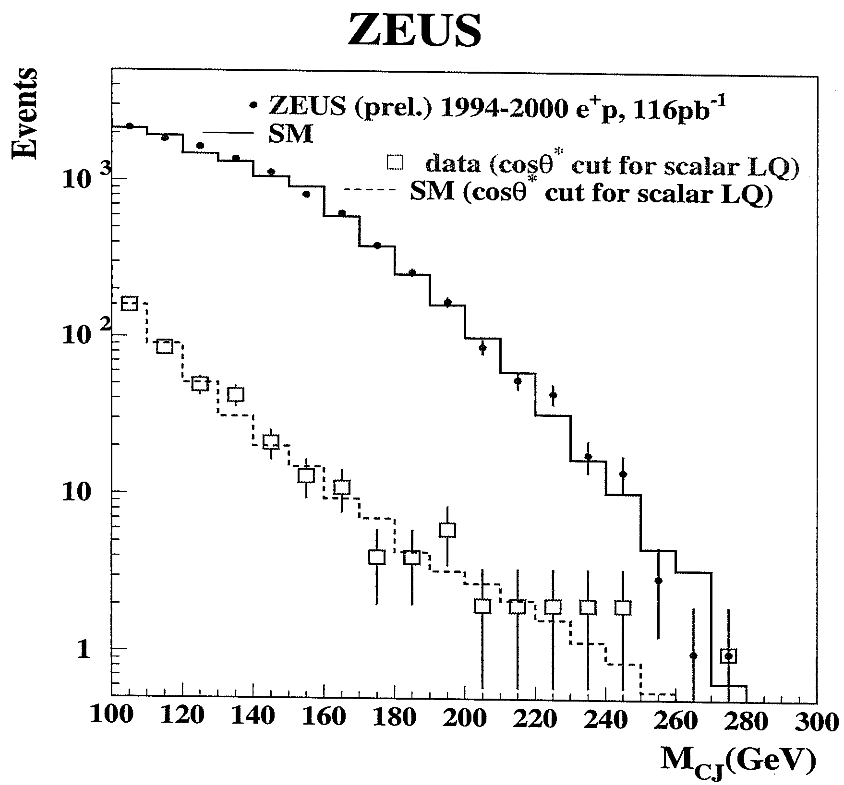
- SU(3)$\times$SU(2)$\times$U(1) Invariant
- 14 species, 7 scalars, 7 vectors.
- Decay: 100% to eq, or 50% to νq & eq, β fixed.

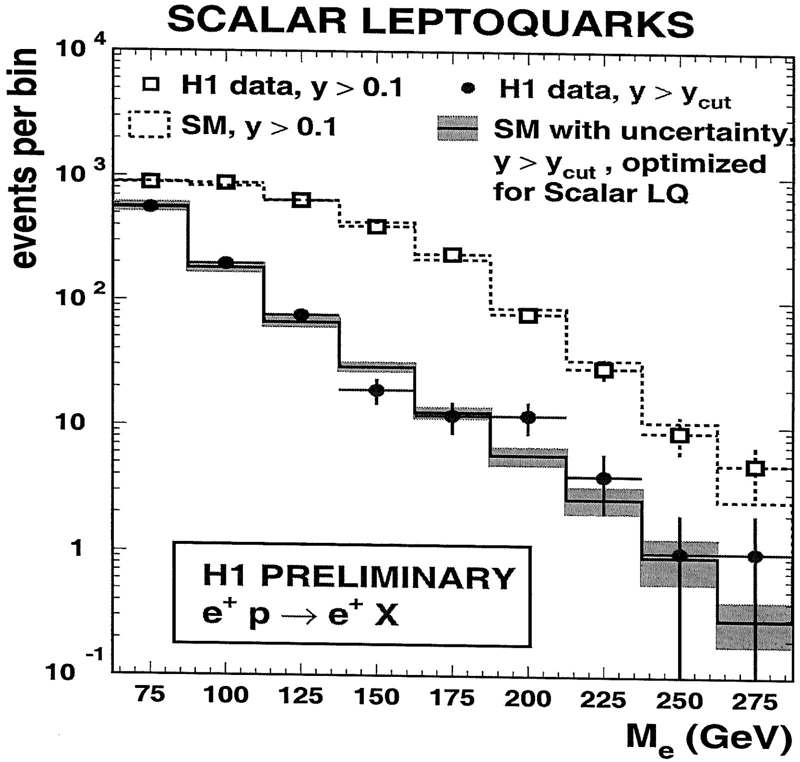
Narrow-Width-Approximation:

$$\sigma = \frac{\pi}{4S}\lambda^2 q(\frac{M_{LQ}^2}{S}) * (J+1) \quad (1)$$

q: quark density, J: spin, S: center of mass energy

eq Invariant Mass Spectrum from HERA e^+p

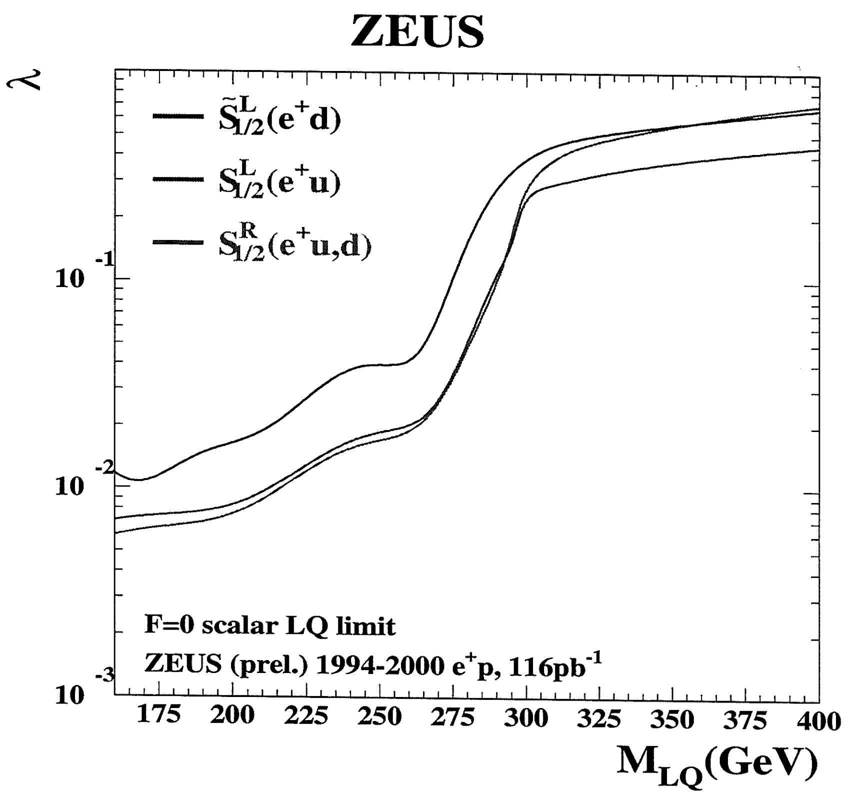


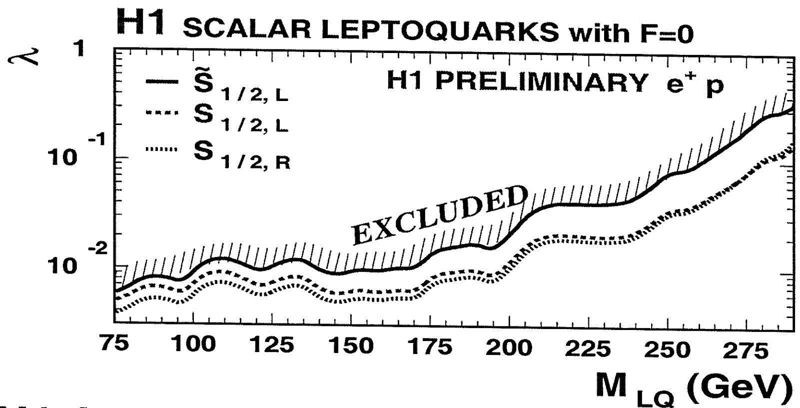


- y (or $\cos\theta^*$) cut $\rightarrow$ big reduction of NC DIS background.
- Final LQ efficiency $\sim$ 50%.

$\rightarrow$ Set λ limit for F=0 BRW LQ.

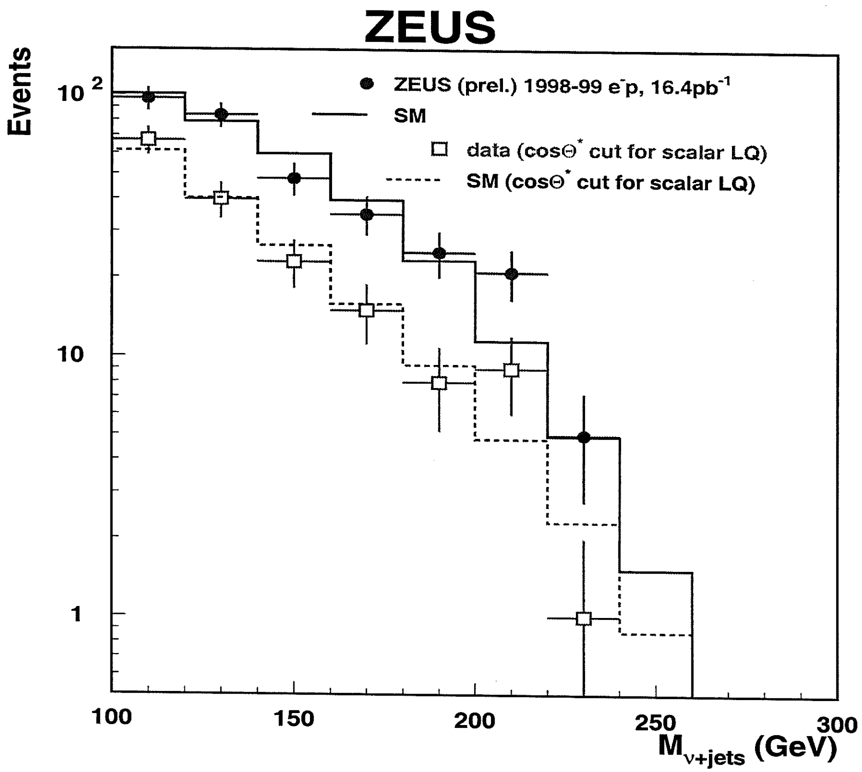
F=0 BRW LQ limit from HERA e^+p

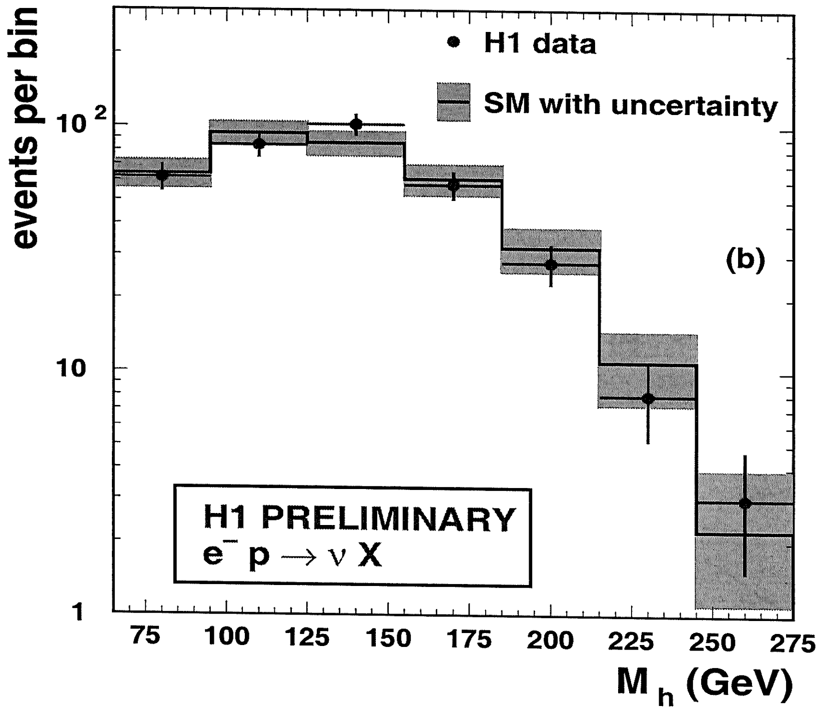




- H1 has LQ limit to 400GeV with 94-97 e^+p data. (Eur. Phys. J. C11 (1999) 447-471, 07/99)
- H1 & ZEUS has limit on F=0 vector BRW LQ.
- At $M_{LQ} > \sqrt{S}$, LQ-SM-interference dominant.

νq Invariant Mass Spectrum from HERA $e^{-}p$

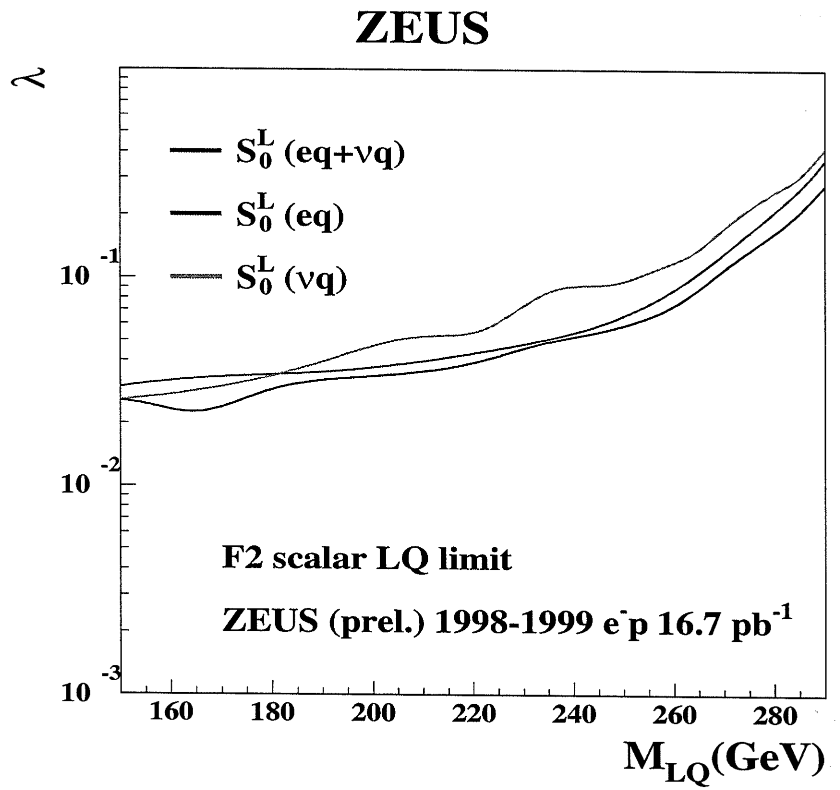


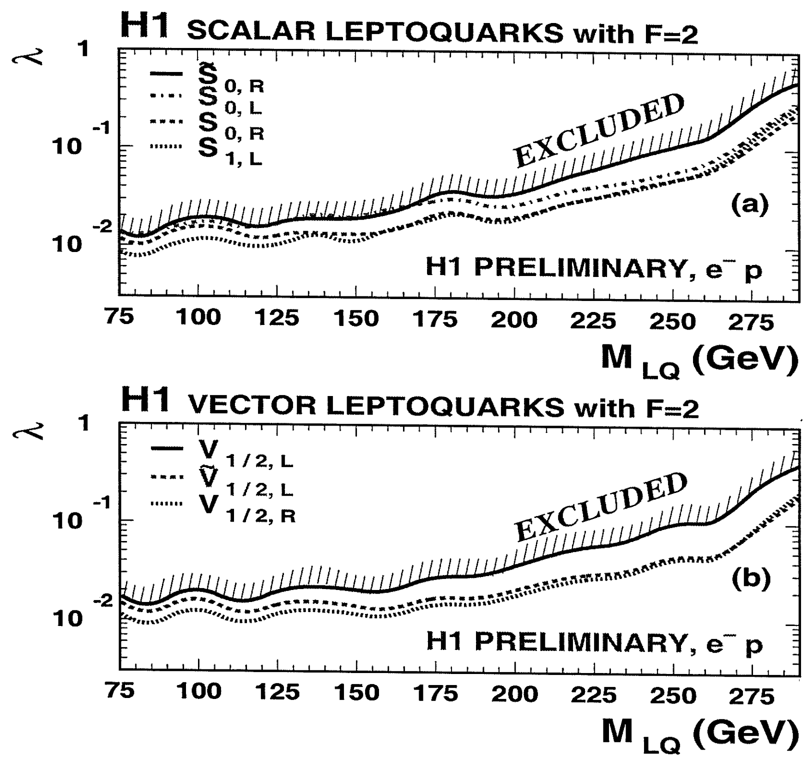


- M_{e-q} **Spectra shown in previous conferences, both H1 & ZEUS no evidence of LQ.**

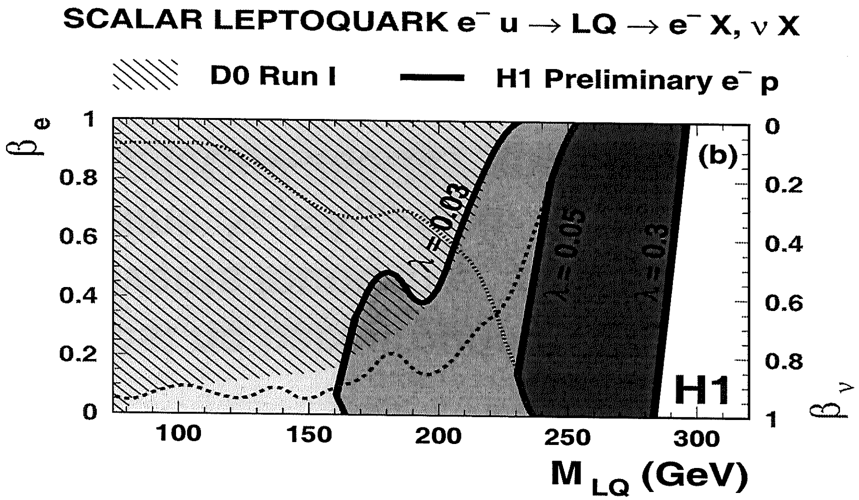
Limit on F=2 BRW LQ with eq+νq from HERA $e^{-}p$

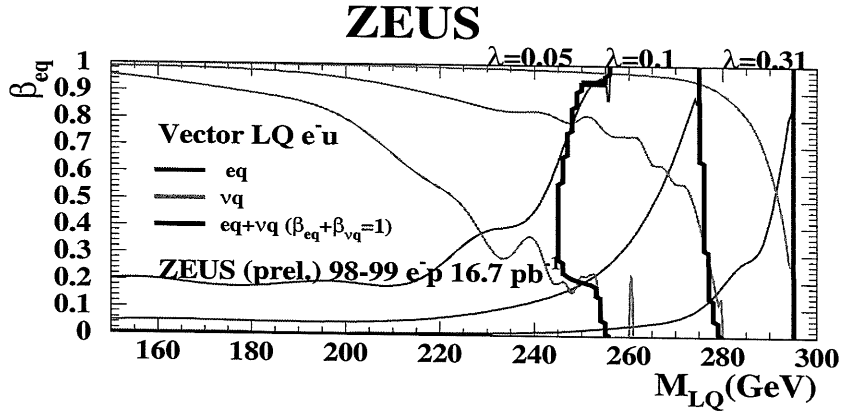
Combine eq & νq channel (β_{eq},$\beta_{\nu q}$ fixed) $\rightarrow$ limit on F=2 BRW LQ.





General F=2 LQ limit from HERA $e^- p$





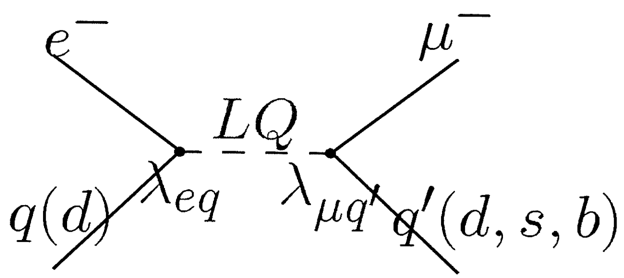
General LQ Model (No $\beta_{LQ\to eq}$ constraint)

- **Assume $\beta_{eq} + \beta_{\nu q} = 1$ for combination.**
- **At λ 0.31, M_{LQ} up to 295GeVexcluded, independent of β.**
- **HERA sensitive to both eq & νq .**
- **Tevatron result independent of λ, but less sensitive to νq**

$\rightarrow$ degrade when $\beta_{LQ\to eq}$ small.

F=2 BRW LQ limit from LFV with HERA e^-p

Search LQ through Lepton-Flavor-Violation



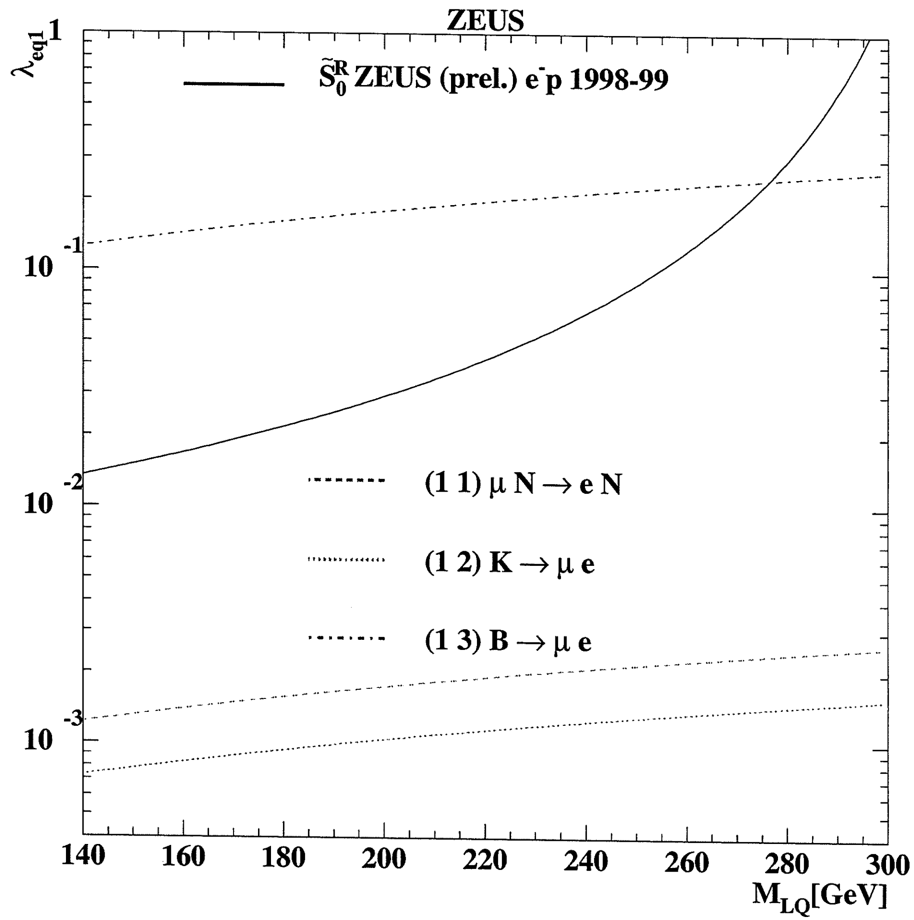
- Almost no background.
- No events found in e^-p.
- Assume λ_{eq}=$\lambda_{\mu q'}$=0.3,

M_{LQ} 260GeV-280GeV and above excluded.

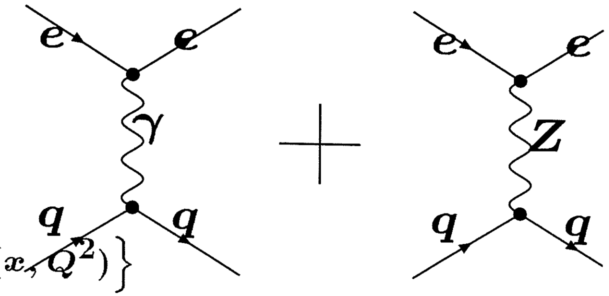
- $q' = d, s$

$\rightarrow$ strict limit from low energy experiment.

- $q' = b \rightarrow$ HERA superior to rare B decay.



Contact Interactions at HERA



Standard Model

$$\frac{d^2\sigma(e^{\pm}p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left\{(1+(1-y)^2)F_2(x,Q^2) \mp (1-(1-y)^2)xF_3(x,Q^2)\right\}$$

$$F_2(x,Q^2) = \frac{1}{2}\sum_f xq_f^{+}(x,Q^2)\left\{(V_f^L)^2+(V_f^R)^2+(A_f^L)^2+(A_f^R)^2\right\}$$

$$xF_3(x,Q^2) = \sum_f xq_f^{-}(x,Q^2)\left\{V_f^L A_f^R - V_f^R A_f^L\right\}$$

$Q^2 : -(4\ P\ of\ porpagator)^2$

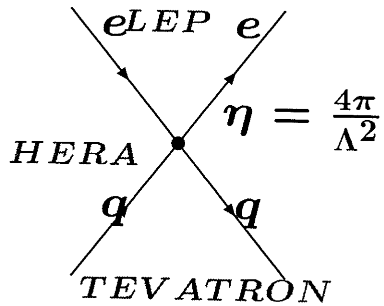
Contact Interaction

$$V_f^L = e_f \quad -(v_e+a_e)v_f P_Z(Q^2) + \frac{Q^2}{8\pi\alpha}(\eta_{LL}+\eta_{LR})$$

$$V_f^R = e_f \quad -(v_e-a_e)v_f P_Z(Q^2) + \frac{Q^2}{8\pi\alpha}(\eta_{RL}+\eta_{RR})$$

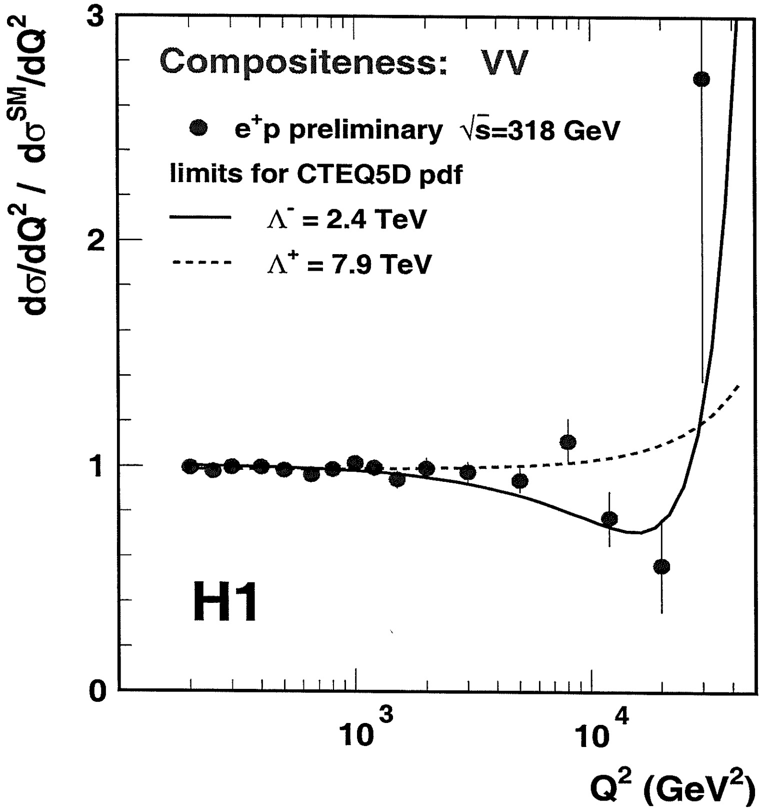
$$A_f^L = \quad -(v_e+a_e)a_f P_Z(Q^2) + \frac{Q^2}{8\pi\alpha}(\eta_{LL}-\eta_{LR})$$

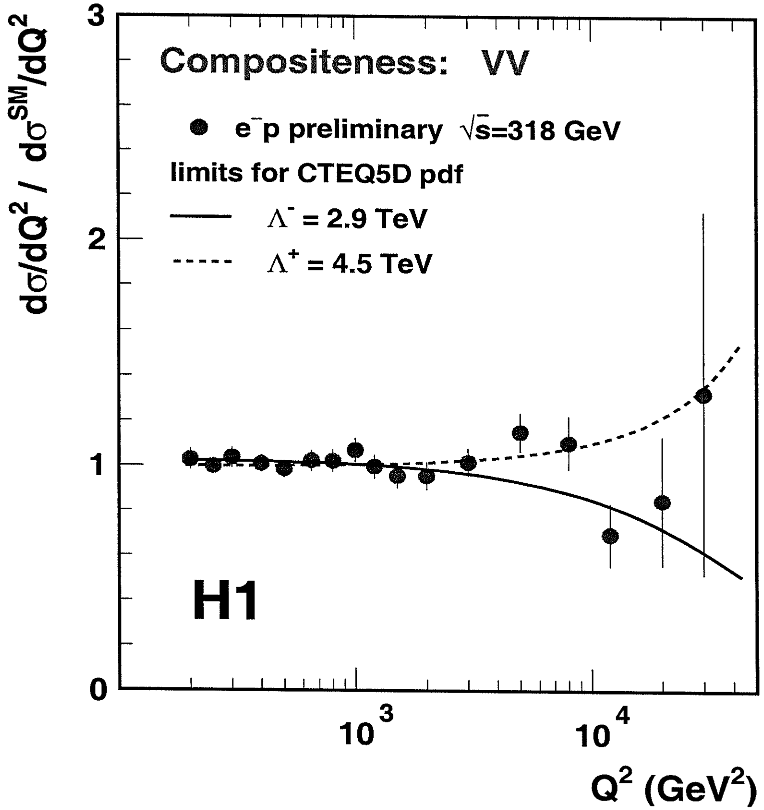
$$A_f^R = \quad -(v_e-a_e)a_f P_Z(Q^2) + \frac{Q^2}{8\pi\alpha}(\eta_{RL}-\eta_{RR})$$



Contact Interaction: physics with scale $\Lambda >> \sqrt{S}$
SM $\sim 1/Q^4$; CI: some terms independent of Q^2
$\rightarrow$ Effect at HERA Highest Q^2 Region

Limit on CI VV Model





- With all HERA data, search deviation at highest Q^2 region.
- Probing distance $\sim$ 1/Q $\sim$ 0.001 fm, with $Q^2 \sim 10^4 GeV^2$.
- 95%CL Limit: ZEUS(H1) Λ^-=7.0(9.2)TeV Λ^+=6.5(3.0)TeV

General Contact Interaction

Model	η_{LL}^{ed}	η_{LR}^{ed}	η_{RL}^{ed}	η_{RR}^{ed}	η_{LL}^{eu}	η_{LR}^{eu}	η_{RL}^{eu}	η_{RR}^{eu}	95% CL [TeV] ZEUS(H1) Λ^-	Λ^+
	Coupling structure									
VV	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	7.0 (9.2)	6.5 (3.0)
AA	$+\eta$	$-\eta$	$-\eta$	$+\eta$	$+\eta$	$-\eta$	$-\eta$	$+\eta$	5.3 (3.5)	4.6 (5.8)
VA	$+\eta$	$-\eta$	$+\eta$	$-\eta$	$+\eta$	$-\eta$	$+\eta$	$-\eta$	3.4 (3.9)	3.3 (4.0)
X1	$+\eta$	$-\eta$			$+\eta$	$-\eta$			4.0	2.7
X2	$+\eta$		$+\eta$		$+\eta$		$+\eta$		4.7	4.7
X3	$+\eta$			$+\eta$	$+\eta$			$+\eta$	4.3 (5.9)	4.2 (2.0)
X4		$+\eta$	$+\eta$			$+\eta$	$+\eta$		5.6 (7.4)	5.6 (2.1)
X5		$+\eta$		$+\eta$		$+\eta$		$+\eta$	4.8	4.8
X6			$+\eta$	$-\eta$			$+\eta$	$-\eta$	2.6	3.9
U1					$+\eta$	$-\eta$			4.1	3.6
U2					$+\eta$		$+\eta$		5.8	5.3
U3					$+\eta$			$+\eta$	5.8	5.2
U4						$+\eta$	$+\eta$		6.4	5.9
U5						$+\eta$		$+\eta$	6.0	5.5
U6							$+\eta$	$-\eta$	2.8	3.7

$$\eta_{mn} = \pm\frac{4\pi}{\Lambda_{mn}^2}, m, n = L, R$$

ZEUS H1 achieve similar results.

Large Extra Dimension & Quark Radius

Same technic (searching high Q^2 deviation) apply to LED & R_q.

· Large Extra Dimension

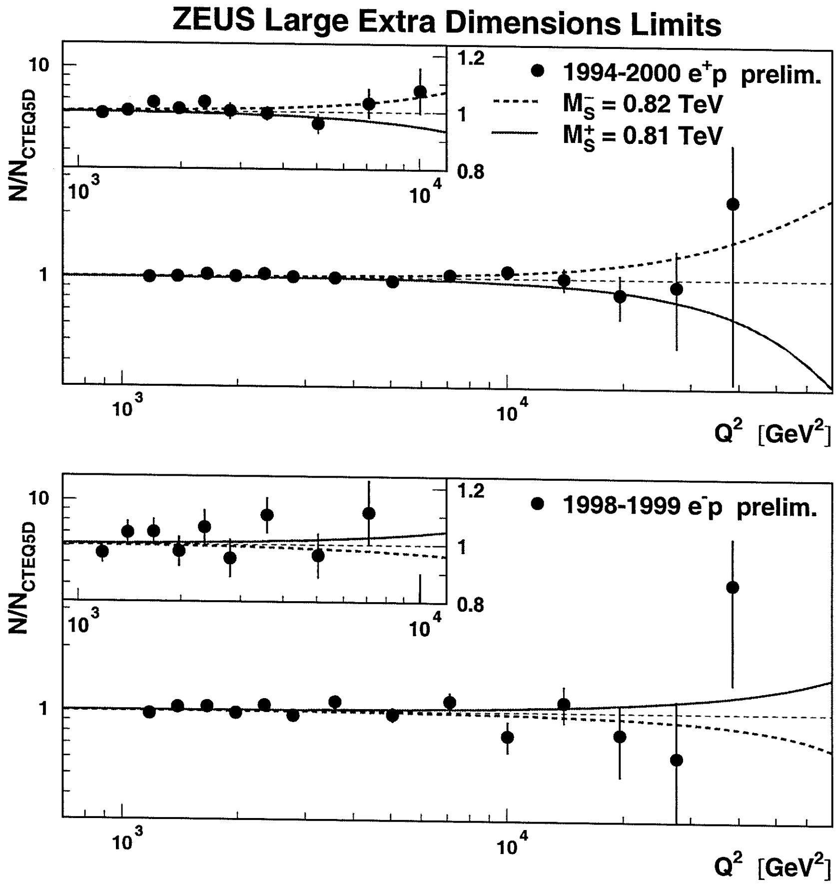
$$\eta = \frac{\pm\lambda}{M_S^4}, M_S : \ Planck\ Scale.$$

ZEUS 95% CL:
$M_S^- = 0.82 TeV, M_S^+ = 0.81 TeV$
H1 95% CL:
$M_S^- = 0.93 TeV, M_S^+ = 0.63 TeV$

· R_q: **Form factor due to finite charge distribution.**

$$f(Q^2) = 1 - \frac{R^2}{6}Q^2, R^2 = \int r^2 \rho(r)\ 4\pi r^2 dr$$

ZEUS 95% CL: $R_q < 0.73 \cdot 10^{-16}$**cm**
H1 95% CL: $R_q < 1.6 \cdot 10^{-16}$**cm**



Limit on BRW LQ M_{LQ}/λ_{LQ}

High mass LQ $M_{LQ} >> \sqrt{S} \rightarrow$ CI

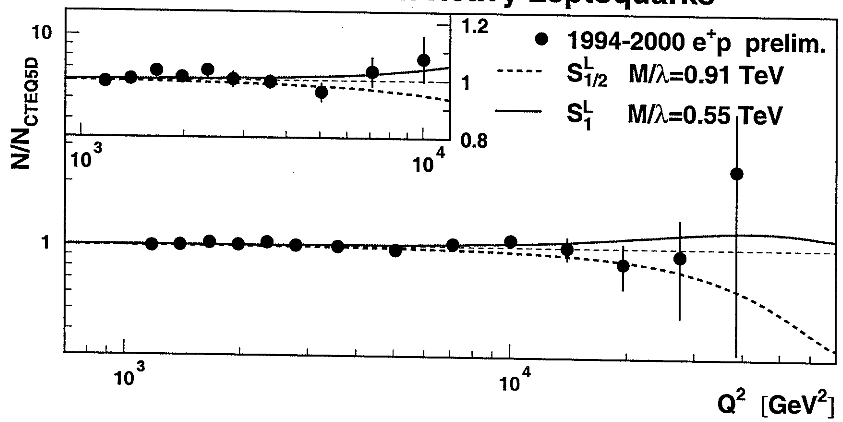
$$\eta^{eq}_{mn} = a^{eq}_{mn} \cdot \left(\frac{\lambda_{LQ}}{M_{LQ}}\right)^2 \quad m, n = L, R$$

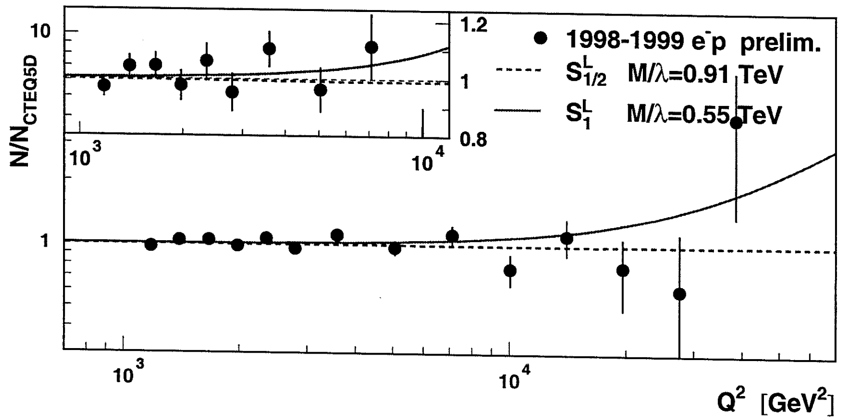
$$a = \pm\frac{1}{2}, \ or \ \pm 1$$

Limit on $\frac{M_{LQ}}{\lambda_{LQ}}$(TeV):

LQ Type	H1 (ZEUS)	LQ Type	H1 (ZEUS)
S_0^L	1.07(0.75)	V_0^L	1.03(0.69)
S_0^R	0.96(0.69)	V_0^R	0.81(0.58)
$\tilde{S}_0^R$	0.29(0.31)	$\tilde{V}_0^R$	0.53(1.03)
S_1^L	0.50(0.55)	$V_{1/2}^L$	0.48(0.49)
$S_{1/2}^L$	0.38(0.91)	$V_{1/2}^R$	1.51(1.15)
$S_{1/2}^R$	0.38(0.69)	V_1^L	0.68(1.42)
$\tilde{S}_{1/2}^L$	0.65(0.50)	$\tilde{V}_1^L$	0.68(1.42)

ZEUS Limits on Heavy Leptoquarks





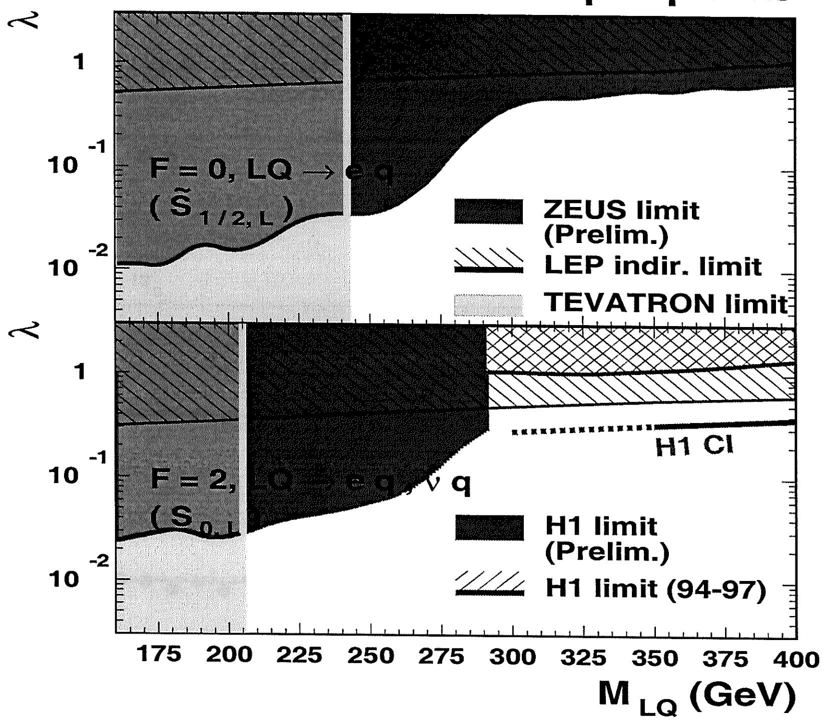
Leptoquark & Contact Interaction Summary

- HERA 1: $\sim$ 110 pb^{-1} e^+p, $\sim$ 15 pb^{-1} e^-p data per experiment. No evidence found for LQ or CI.
- In general HERA has better LQ limit than LEP.
- TEVATRON limit depends strongly on β_{eq}, insensitive to $LQ \rightarrow \nu q$.
- HERA 2: Luminosity upgrade, $\sim$ 1 fb^{-1} in $\sim$ 5 years, with ZEUS & H1 detectors upgrade.
- HERA 2 vs. TEVATRON II:

If λ large enough, HERA 2 will have 10 times more signal,(TEVATRON independent of λ.)
If β_{eq} small, TEVATRON less sensitive.
Evenif β_{eq}=100%, HERA still sensitive to LFV etc.

$\rightarrow$ HERA will compete with TEVATRON for new physics!

Constraints on Scalar Leptoquarks



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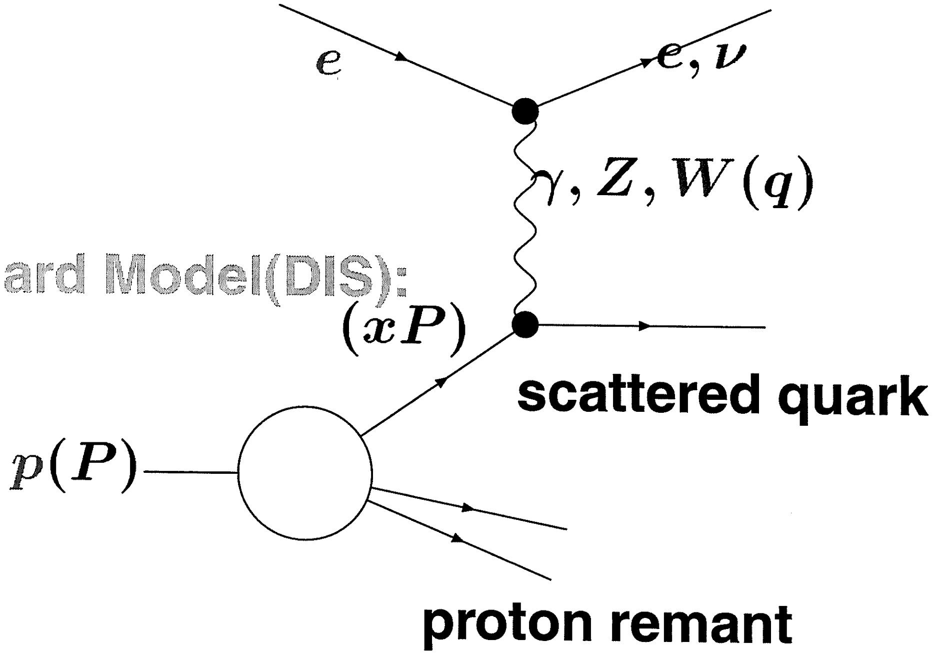
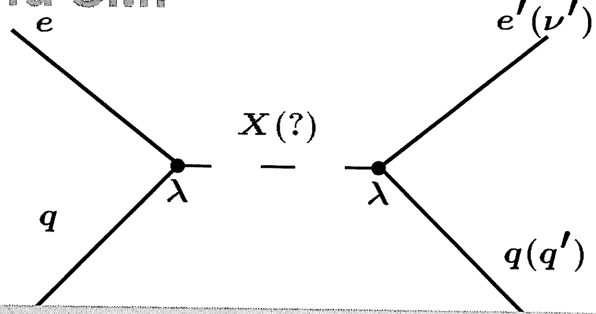


Beyond SM:



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ZEUS & H1 each collected

$\sim 110pb^{-1}\ e^{+}p$ $\sim 15pb^{-1}\ e^{-}p$

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· Scalar or Vector LQ.

Buchmüller-Rückl-Wyler (BRW) Model

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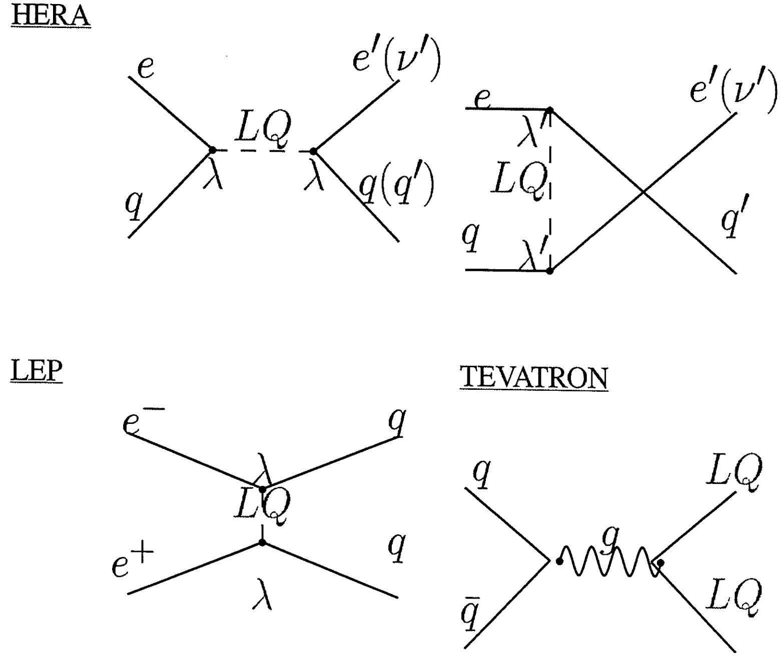
· Decay: 100% to eq, or 50% to νq & eq, β fixed.



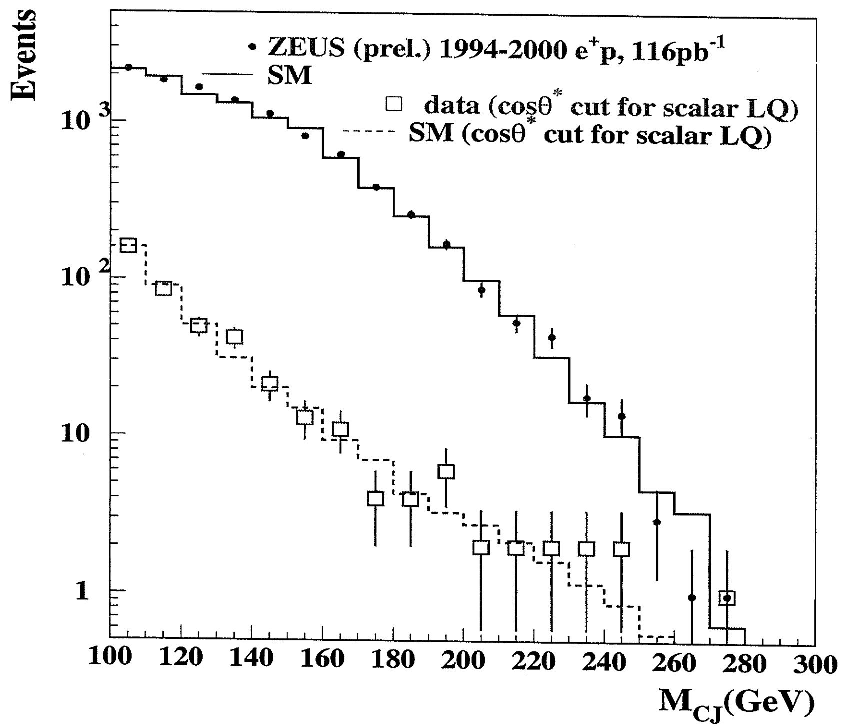
Narrow-Width-Approximation:

$$\sigma = \frac{\pi}{4S}\lambda^2 q\left(\frac{M_{LQ}^2}{S}\right) * (J+1) \qquad (1)$$

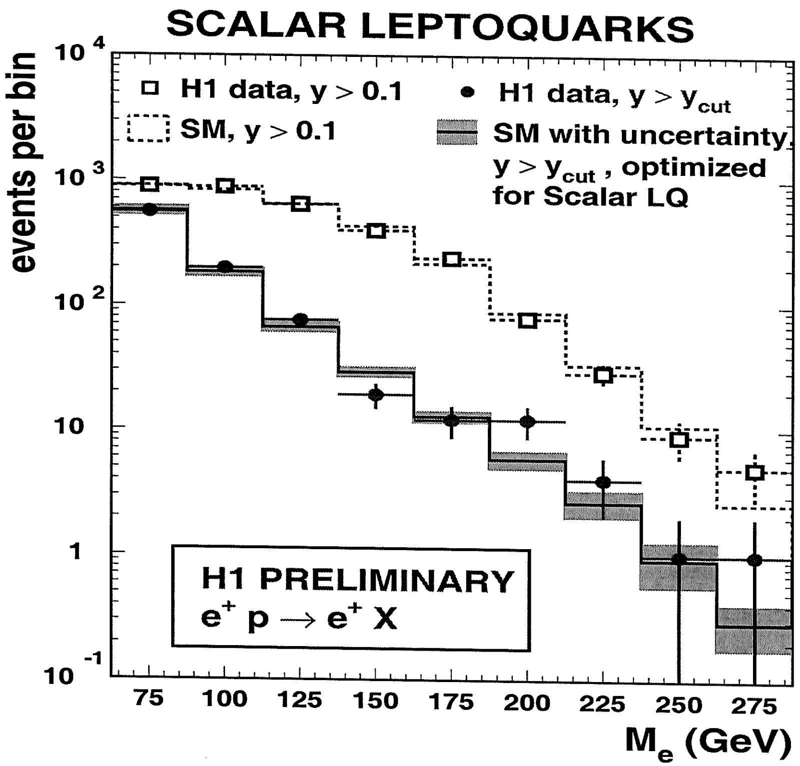
q: quark density, J: spin, S: center of mass energy

eq Invariant Mass Spectrum from HERA e^+p

ZEUS

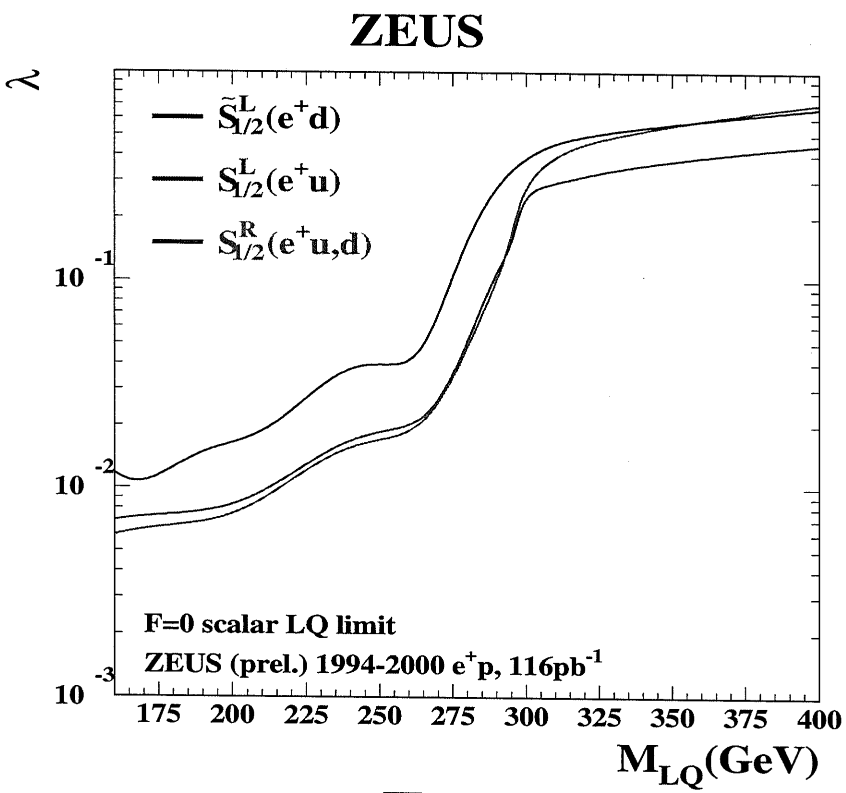


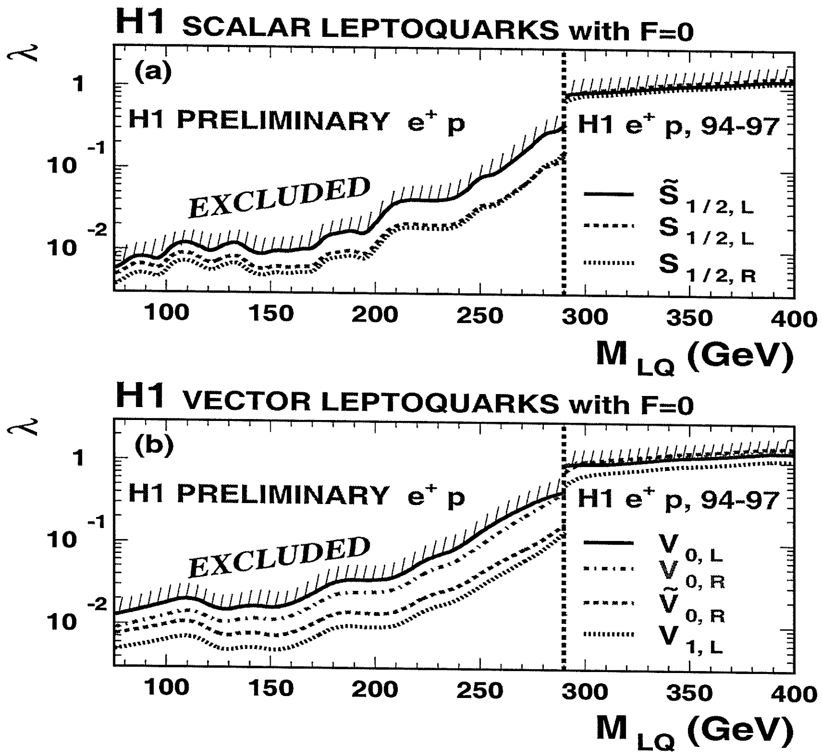
H1



- $y = \frac{1}{2}(1 - \cos\theta^*)$, θ^*: e angle from LQ decay in CM frame.
- Scalar LQ: flat in y ;Vector LQ: $(1-y)^2$; (Background : $\sim\ 1/y^2$ (Neutral Current DIS))
- Cut on angular (y or $\cos\theta^*$) $\rightarrow$ big reduction of NC DIS background.
- Final LQ efficiency $\sim$ 50%.

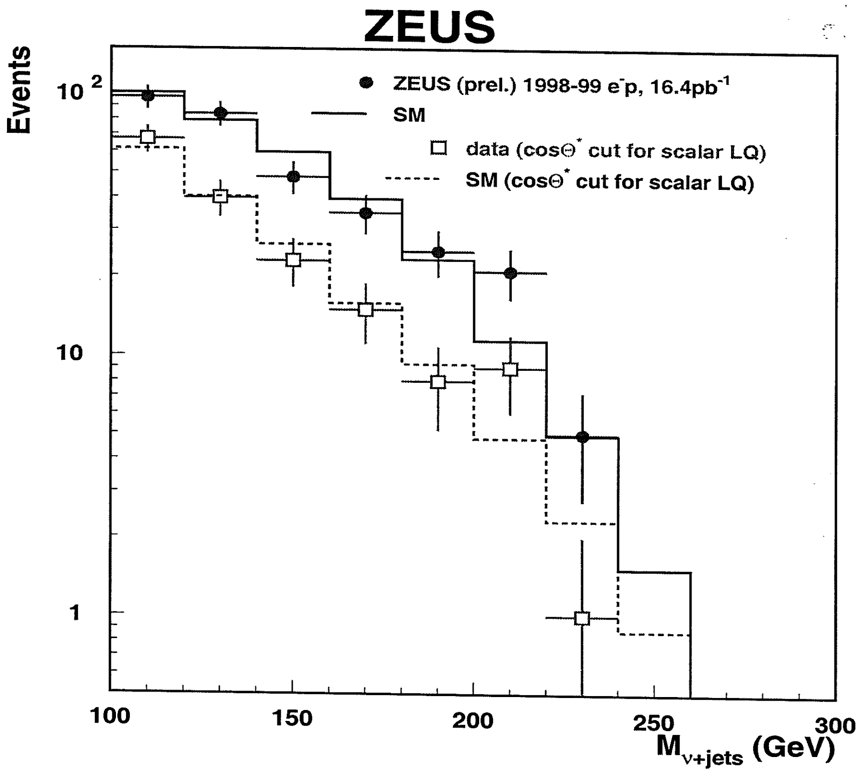
F=0 BRW LQ limit from HERA e^+p

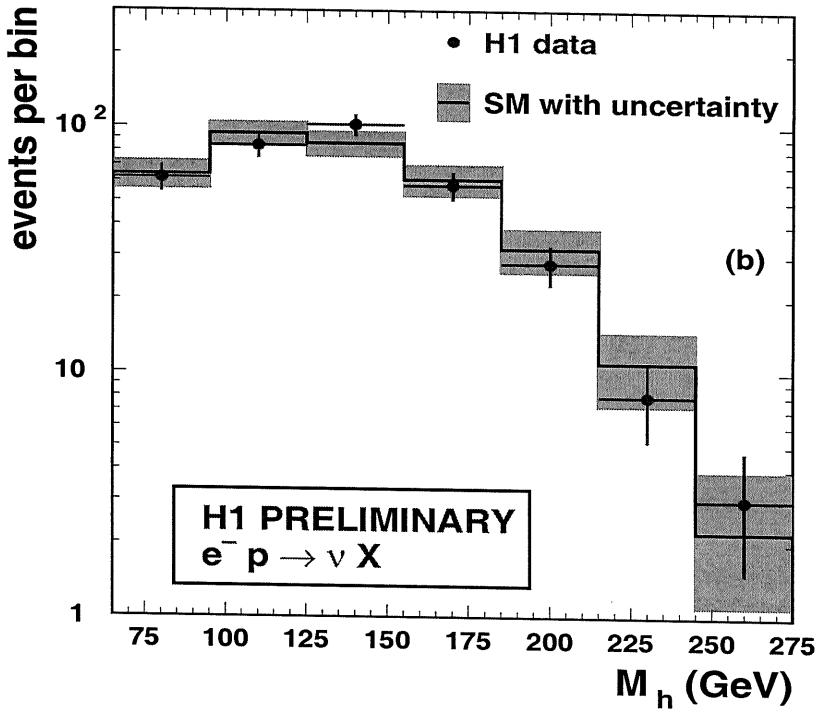




- Extension to $> \sqrt{S}$ via virtual exchange in s- or u-channel.
- At $M_{LQ} > \sqrt{S}$, interference of LQ with Neutral Current dominant.
- At EW coupling strength 0.31, LQ with mass up to 290GeV excluded.

νq Invariant Mass Spectrum from HERA $e^- p$

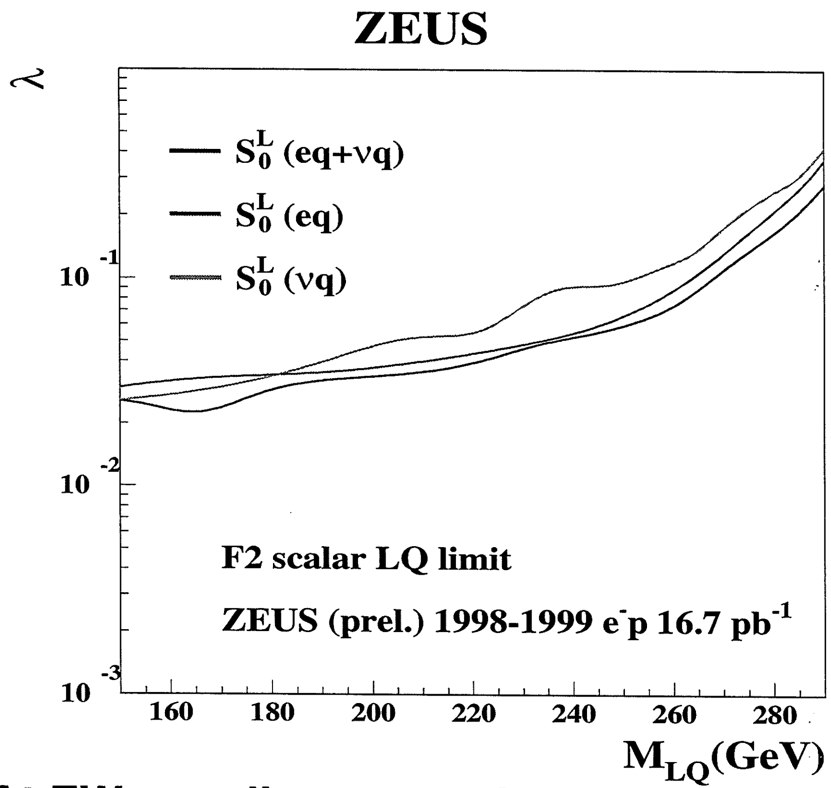


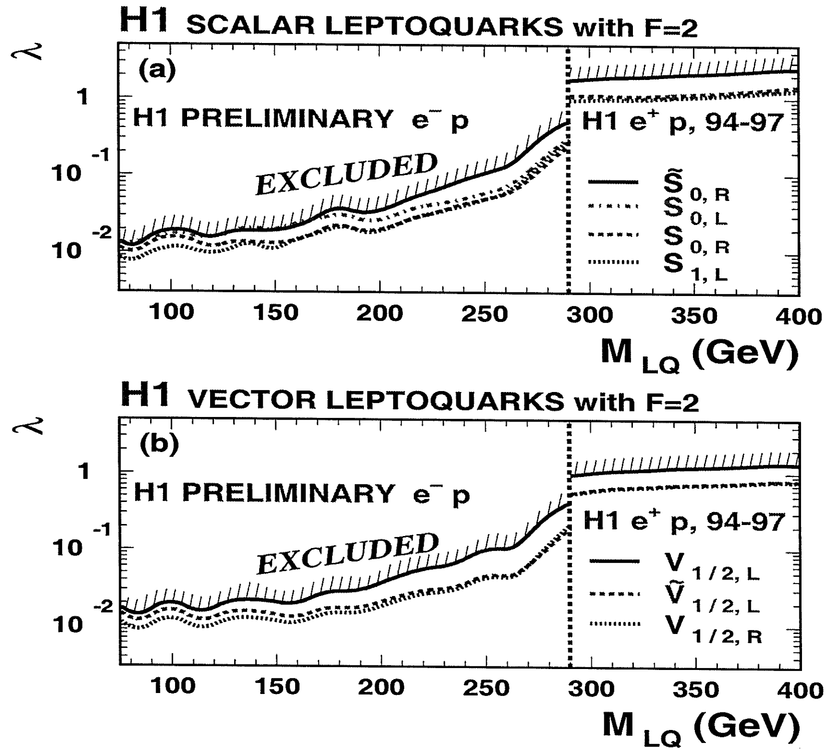


- M_{e-q} Spectra shown in previous conferences, both H1 & ZEUS no evidence of LQ.

Limit on F=2 BRW LQ with eq+νq from HERA e^-p

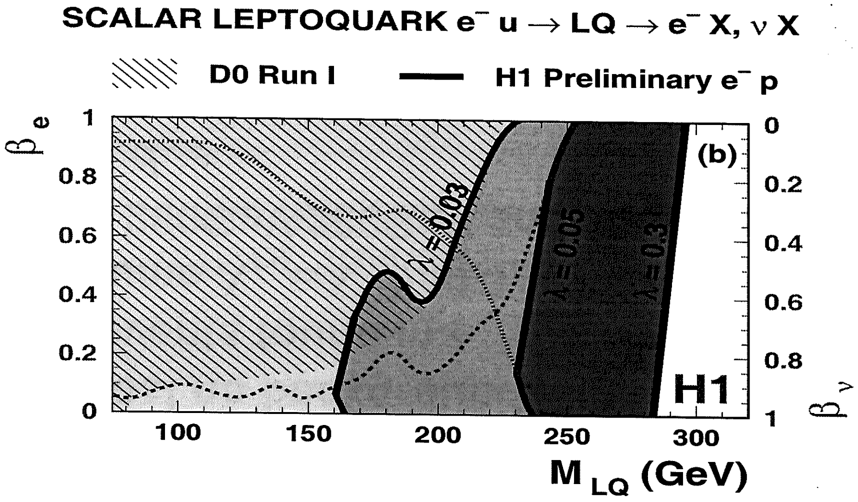
Combine eq & νq channel (β_{eq},$\beta_{\nu q}$ fixed) $\rightarrow$ limit on F=2 BRW LQ.

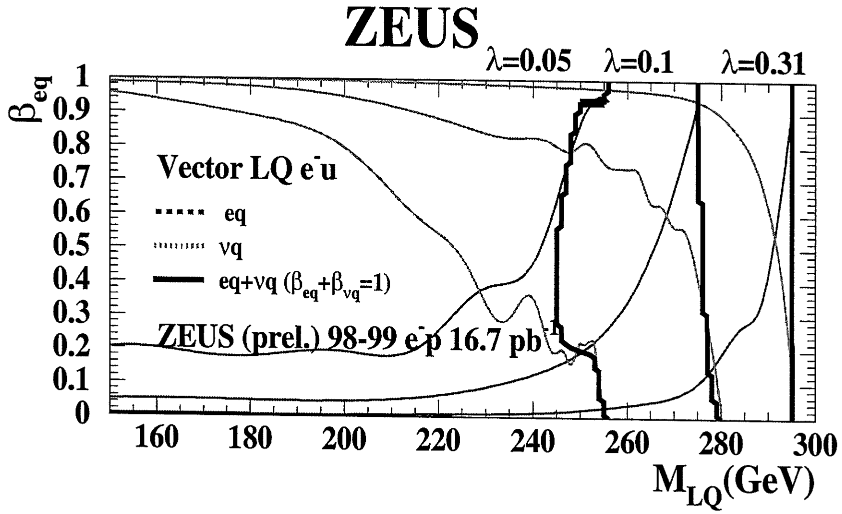




- **At EW coupling strength 0.31, LQ with mass up to 275GeV excluded.**

General F=2 LQ limit from HERA $e^- p$





General LQ Model (No $\beta_{LQ\to eq}$ constraint)

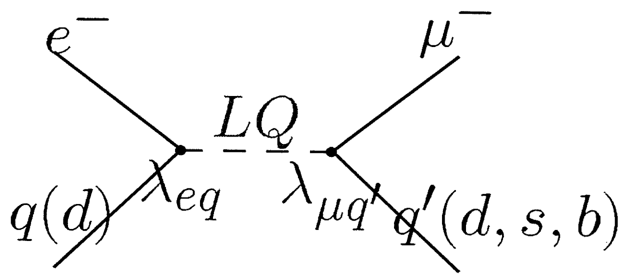
- **Assume $\beta_{eq} + \beta_{\nu q} = 1$ for combination.**
- **At λ 0.31, M_{LQ} up to 295GeVexcluded, independent of β.**
- **HERA sensitive to both eq & νq .**
- **Tevatron result independent of λ, but less sensitive to νq**

$\to$ degrade when $\beta_{LQ\to eq}$ small.

- **Limits in general models also derived from $e^+ p$ for F=0 LQs (H1)**

F=2 BRW LQ limit from LFV with HERA e^-p

Search LQ through Lepton-Flavor-Violation



- Almost no background.
- No events found in e^-p.
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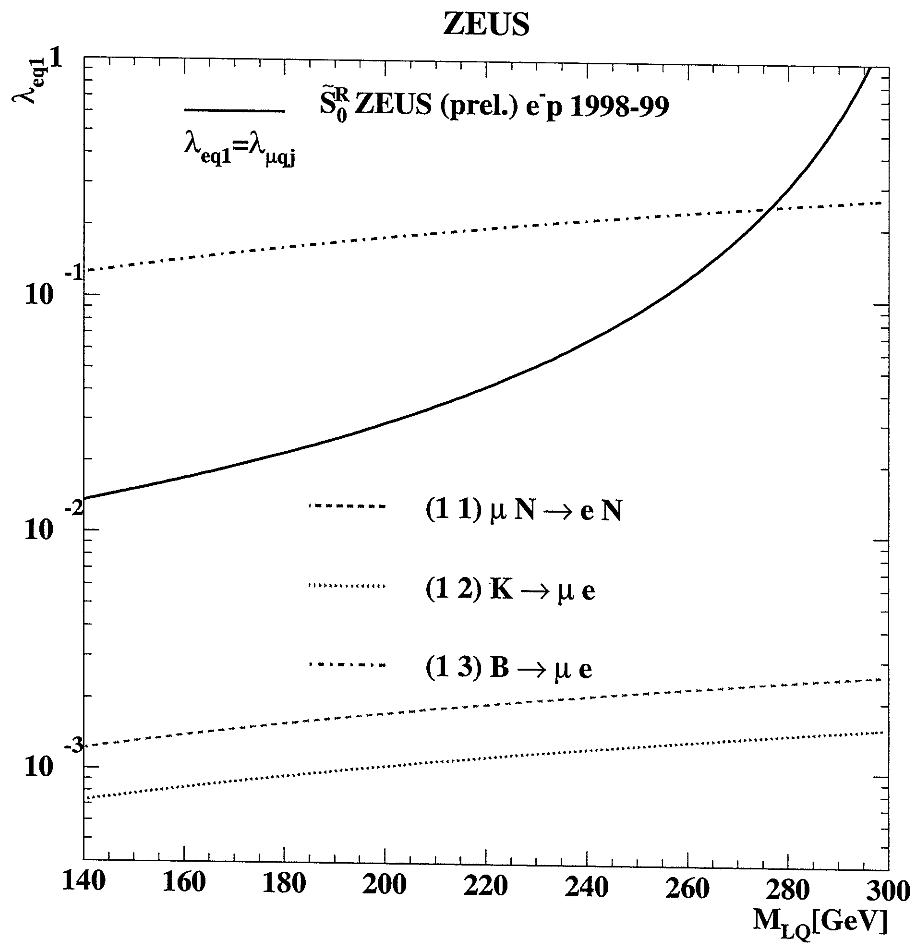
M_{LQ} 260GeV-280GeV and above excluded.

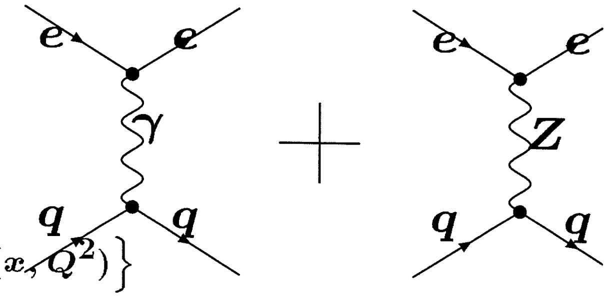
- $q' = d, s$

$\longrightarrow$ strict limit from low energy experiment.

- $q' = b \longrightarrow$ HERA superior to rare B decay.



Contact Interactions at HERA



Standard Model

$$\frac{d^2\sigma(e^{\pm}p)}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \left\{(1+(1-y)^2)F_2(x,Q^2) \mp (1-(1-y)^2)xF_3(x,Q^2)\right\}$$

$$F_2(x,Q^2) = \frac{1}{2} \sum_f x q_f^+(x,Q^2)\left\{(V_f^L)^2 + (V_f^R)^2 + (A_f^L)^2 + (A_f^R)^2\right\}$$

$$xF_3(x,Q^2) = \sum_f x q_f^-(x,Q^2)\left\{V_f^L A_f^R - V_f^R A_f^L\right\}$$

$Q^2 : -(4\ P\ of\ porpagator)^2$

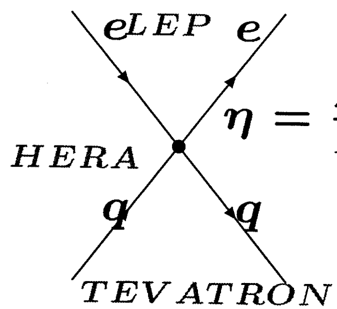
Contact Interaction

$$V_f^L = e_f \quad -(v_e + a_e)v_f P_Z(Q^2) + \frac{Q^2}{8\pi\alpha}(\eta_{LL} + \eta_{LR})$$

$$V_f^R = e_f \quad -(v_e - a_e)v_f P_Z(Q^2) + \frac{Q^2}{8\pi\alpha}(\eta_{RL} + \eta_{RR})$$

$$A_f^L = \quad -(v_e + a_e)a_f P_Z(Q^2) + \frac{Q^2}{8\pi\alpha}(\eta_{LL} - \eta_{LR})$$

$$A_f^R = \quad -(v_e - a_e)a_f P_Z(Q^2) + \frac{Q^2}{8\pi\alpha}(\eta_{RL} - \eta_{RR})$$



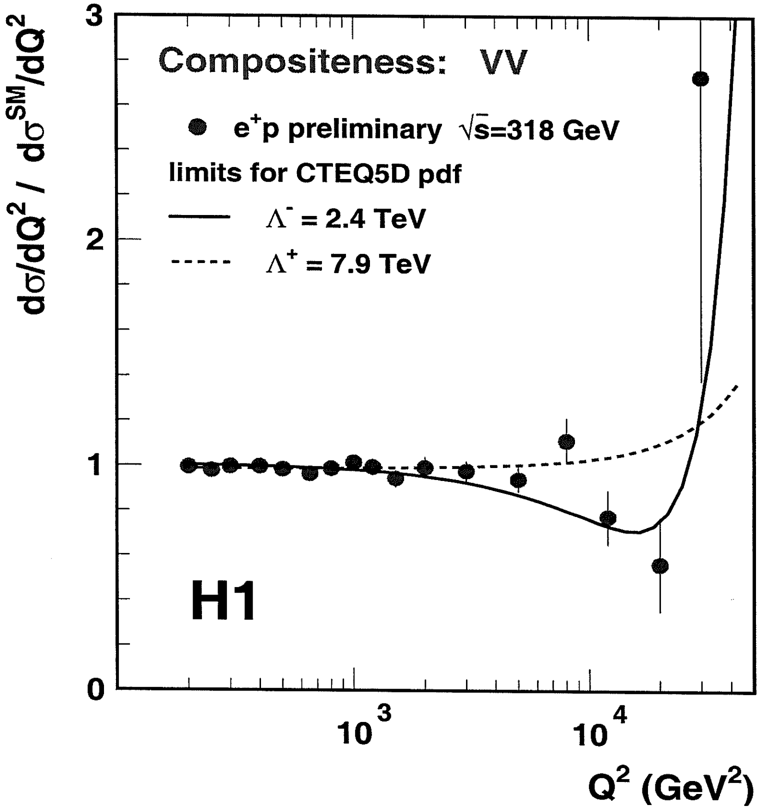
$\eta = \frac{4\pi}{\Lambda^2}$

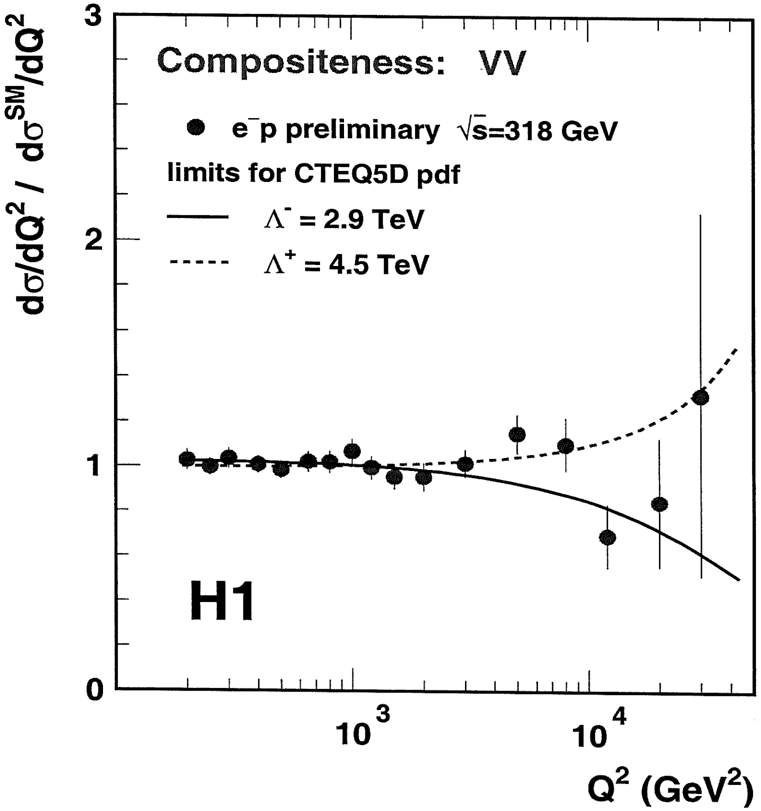
Contact Interaction: physics with scale $\Lambda >> \sqrt{S}$

SM $\sim 1/Q^4$; CI: some terms independent of Q^2

$\rightarrow$ Effect at HERA Highest Q^2 Region

Limit on CI VV Model





- With all HERA data, search deviation at highest Q^2 region.
- Probing distance $\sim$ 1/Q $\sim$ 0.001 fm, with $Q^2 \sim 10^4 GeV^2$.
- 95%CL Limit: ZEUS(H1) Λ^-=7.0(3.0)TeV Λ^+=6.5(9.2)TeV

General Contact Interaction

Model	η_{LL}^{ed}	η_{LR}^{ed}	η_{RL}^{ed}	η_{RR}^{ed}	η_{LL}^{eu}	η_{LR}^{eu}	η_{RL}^{eu}	η_{RR}^{eu}	95% CL [TeV] ZEUS(H1) Λ^-	Λ^+
	Coupling structure									
VV	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	7.0 (3.0)	6.5 (9.2)
AA	$+\eta$	$-\eta$	$-\eta$	$+\eta$	$+\eta$	$-\eta$	$-\eta$	$+\eta$	5.3 (5.8)	4.6 (3.5)
VA	$+\eta$	$-\eta$	$+\eta$	$-\eta$	$+\eta$	$-\eta$	$+\eta$	$-\eta$	3.4 (4.0)	3.3 (3.9)
X1	$+\eta$	$-\eta$			$+\eta$	$-\eta$			4.0	2.7
X2	$+\eta$		$+\eta$		$+\eta$		$+\eta$		4.7	4.7
X3	$+\eta$			$+\eta$	$+\eta$			$+\eta$	4.3 (2.0)	4.2 (5.9)
X4		$+\eta$	$+\eta$			$+\eta$	$+\eta$		5.6 (2.1)	5.6 (7.4)
X5		$+\eta$		$+\eta$		$+\eta$		$+\eta$	4.8	4.8
X6			$+\eta$	$-\eta$			$+\eta$	$-\eta$	2.6	3.9
U1					$+\eta$	$-\eta$			4.1	3.6
U2					$+\eta$		$+\eta$		5.8	5.3
U3					$+\eta$			$+\eta$	5.8	5.2
U4						$+\eta$	$+\eta$		6.4	5.9
U5						$+\eta$		$+\eta$	6.0	5.5
U6							$+\eta$	$-\eta$	2.8	3.7

$$\eta_{mn} = \pm\frac{4\pi}{\Lambda_{mn}^2}, m, n = L, R$$

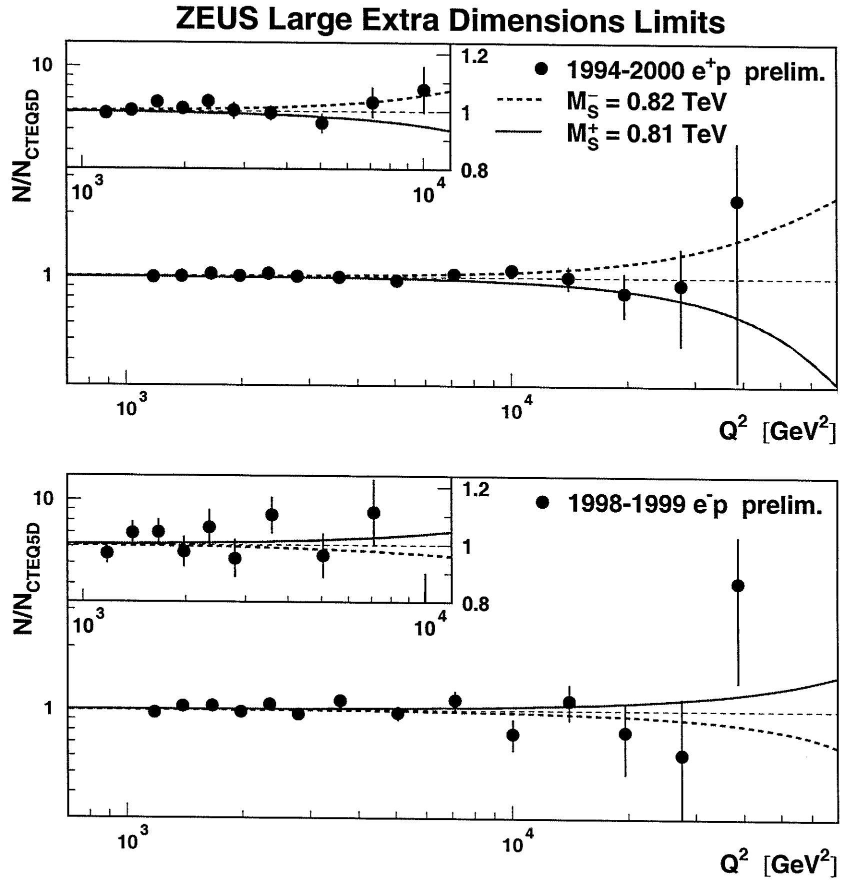
- **Some models constrained by HERA only**
- **HERA bounds do not rely on the flavor symmetry in the quark sector.**

Large Extra Dimension & Quark Radius

Same technic (searching high Q^2 deviation) apply to LED & R_q.

- Large Extra Dimension

$$\eta = \frac{\pm\lambda}{M_S^4}, \quad M_S : \; Planck\ Scale.$$



ZEUS 95% CL:

$M_S^- = 0.82TeV, M_S^+ = 0.81TeV$

H1 95% CL:

$M_S^- = 0.93TeV, M_S^+ = 0.63TeV$

- R_q: Form factor due to finite charge distribution.

$$f(Q^2) = 1 - \frac{R^2}{6}Q^2, R^2 = \int r^2\rho(r)\, 4\pi r^2 dr$$

ZEUS 95% CL: $R_q < 0.73 \cdot 10^{-16}$cm

H1 95% CL: $R_q < 1.6 \cdot 10^{-16}$cm

Limit on BRW LQ M_{LQ}/λ_{LQ}

High mass LQ $M_{LQ} >> \sqrt{S} \rightarrow$ CI

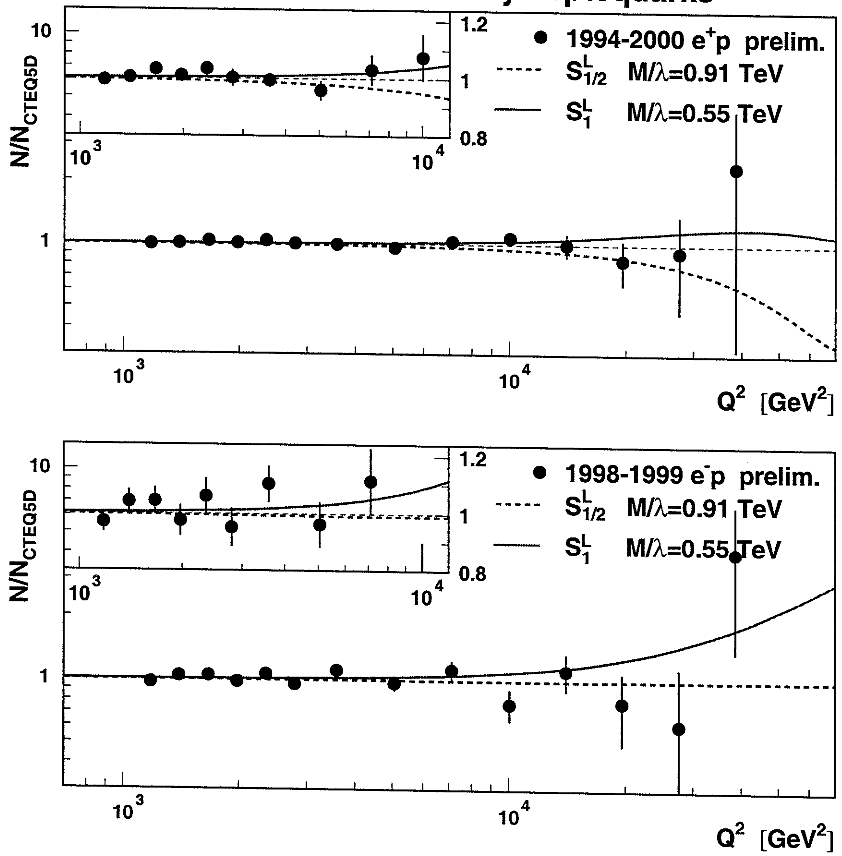
$$\eta^{eq}_{mn} = a^{eq}_{mn} \cdot \left(\frac{\lambda_{LQ}}{M_{LQ}}\right)^2 \quad m, n = L, R$$

$$a = \pm\frac{1}{2}, \ or \ \pm 1$$

Limit on $\frac{M_{LQ}}{\lambda_{LQ}}$(TeV):

LQ Type	H1 (ZEUS)	LQ Type	H1 (ZEUS)
S_0^L	1.07(0.75)	V_0^L	1.03(0.69)
S_0^R	0.96(0.69)	V_0^R	0.81(0.58)
$\tilde{S}_0^R$	0.29(0.31)	$\tilde{V}_0^R$	0.53(1.03)
S_1^L	0.69(0.55)	$V_{1/2}^L$	0.48(0.49)
$S_{1/2}^L$	0.38(0.91)	$V_{1/2}^R$	1.51(1.15)
$S_{1/2}^R$	0.38(0.69)	V_1^L	0.68(1.42)
$\tilde{S}_{1/2}^L$	0.65(0.50)	$\tilde{V}_{1/2}^L$	1.69(1.42)

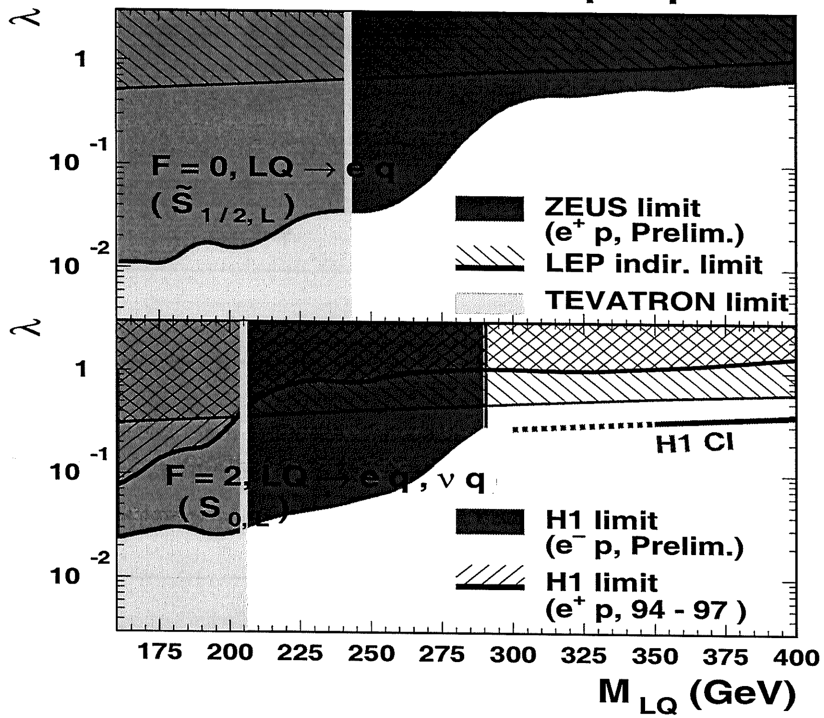
ZEUS Limits on Heavy Leptoquarks



Leptoquark & Contact Interaction Summary

- HERA 1: $\sim$ 110 pb^{-1} e^+p, $\sim$ 15 pb^{-1} e^-p data per experiment. No evidence found for LQ or CI.
- In general HERA has better LQ limit than LEP.
- TEVATRON LQ limit depends strongly on β_{eq}, insensitive to $LQ \rightarrow \nu q$.
- HERA excluded CI below scale 2-7TeV .
- HERA 95% CL Limit on Large Extra Dimensions $M_S \sim$ 0.8 TerV.
- HERA 95% CL Limit on quark radius: $< \frac{1}{1000}$ $R_p \rightarrow$ quark really small!

Constraints on Scalar Leptoquarks



Outlook: HERA 2 vs. TEVATRON II

- HERA 2: Luminosity upgrade, $\sim 1\ fb^{-1}$ in $\sim$ 5 years, with ZEUS & H1 detector upgrades.
- HERA 2 vs. TEVATRON II:

If λ large enough, HERA 2 will have 10 times more signal,(TEVATRON independent of λ.)

If β_{eq} small, TEVATRON less sensitive.

If $\beta_{e\nu}$ $\beta_{e\mu}$ small, HERA still sensitive to LFV.

$\longrightarrow$ **HERA will compete with TEVATRON for new physics**

Future Sensitivity on Scalar Leptoquarks