Exotic searches at HERA

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for

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Outline:

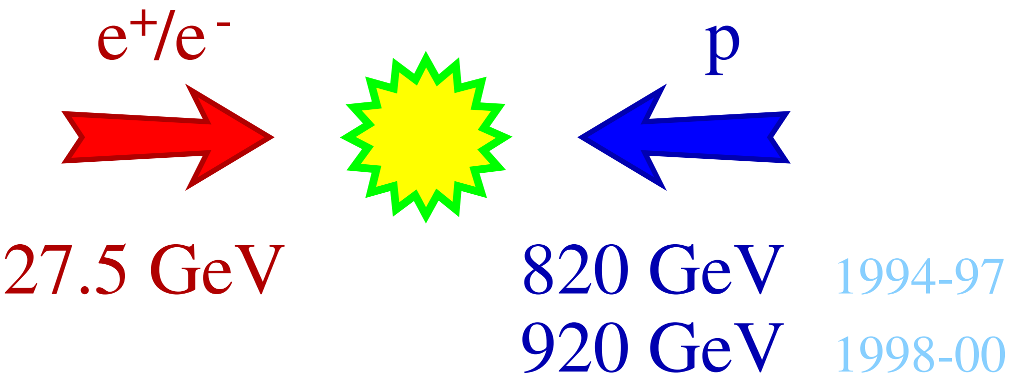
- Introduction
- High-Q^2 DIS
- Contact Interactions
- Leptoquarks
- Lepton Flavor Violation
- Excited Fermions
- Summary

Conference on Higgs and Supersymmetry
March 22, 2001

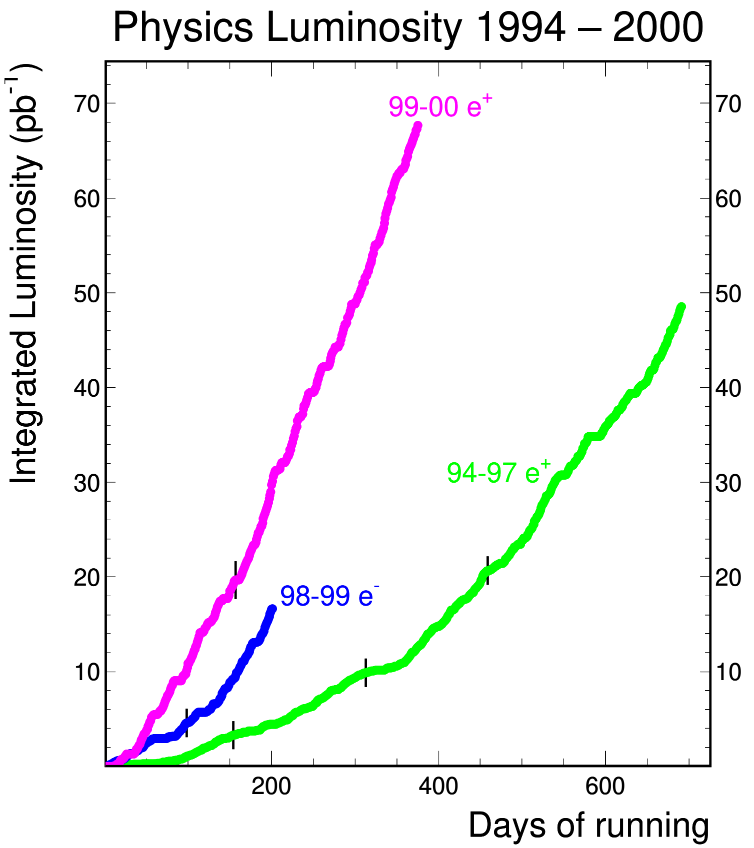
Introduction

HERA

electron(positron)-proton collider at DESY



Very successful HERA operation in 1999-2000:



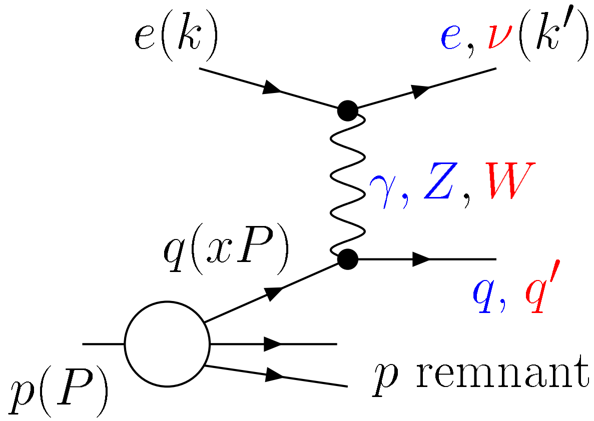
Presented results

Year		$\sqrt{s}$	H1	ZEUS
1994-97	e^+p	300 GeV	36 pb^{-1}	48 pb^{-1}
1998-99	e^-p	318 GeV	15 pb^{-1}	16 pb^{-1}
1999-00	e^+p	318 GeV	46 pb^{-1}	64 pb^{-1}

Total of about $\sim$ 220 pb^{-1} of $e^{\pm}p$ data available.

High-Q^2 DIS

Deep Inelastic Scattering

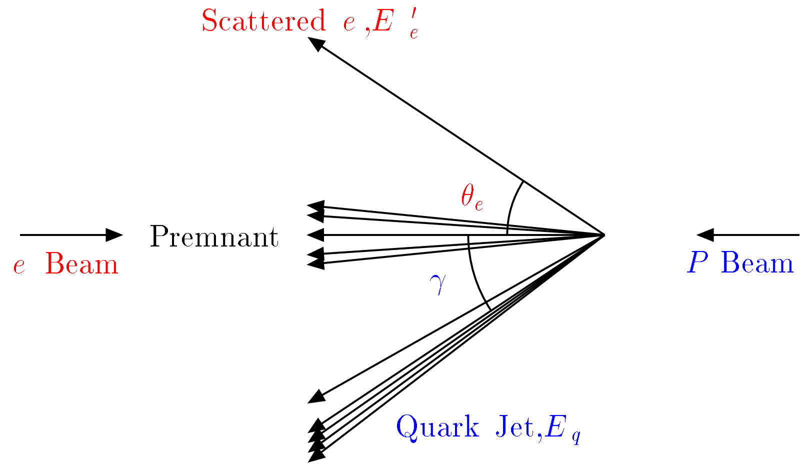


$$Q^2 = -(k - k')^2$$

$$x = \frac{Q^2}{2P \cdot (k - k')}$$

$$y = \frac{P \cdot (k - k')}{P \cdot k}$$

Kinematic Reconstruction



Virtuality Q^2

$\Rightarrow$ spatial resolution $\lambda \sim 1/Q$

$\Rightarrow$ sensitivity to new mass scales $\Lambda \sim Q$

eq invariant mass $M_{eq} = \sqrt{x \cdot s}$

$\Rightarrow$ search for resonances with $M < \sqrt{s}$

NC DIS events:

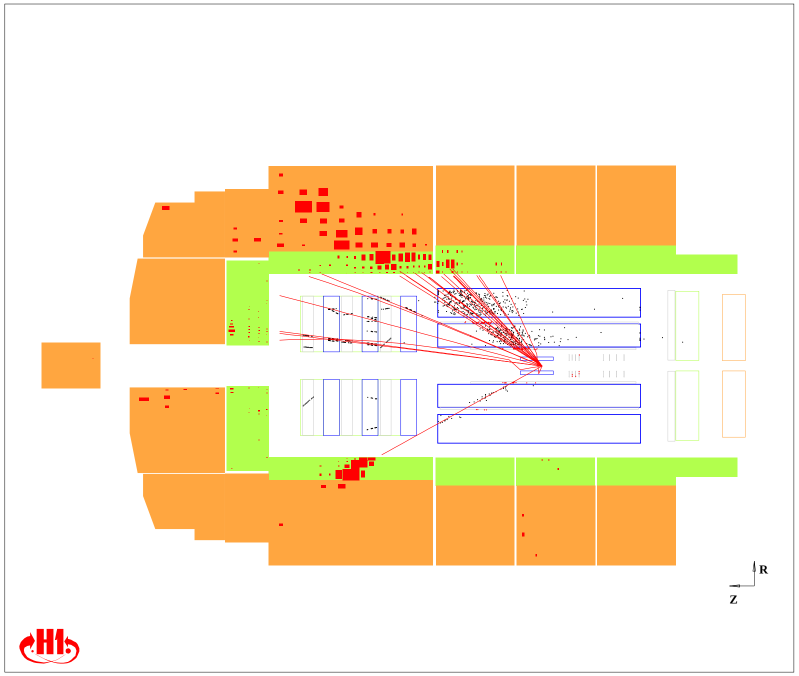
- electron: E_e, θ_e H1
- angles: θ_e, γ ZEUS

CC DIS events:

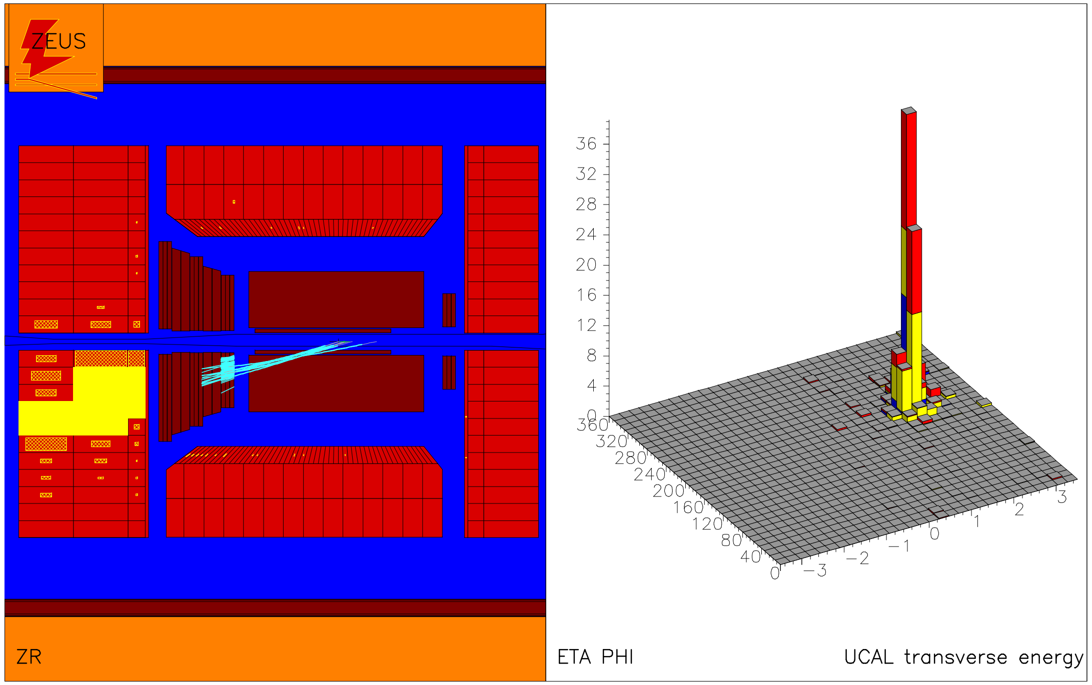
- quark jet: E_q, γ

High-Q^2 DIS

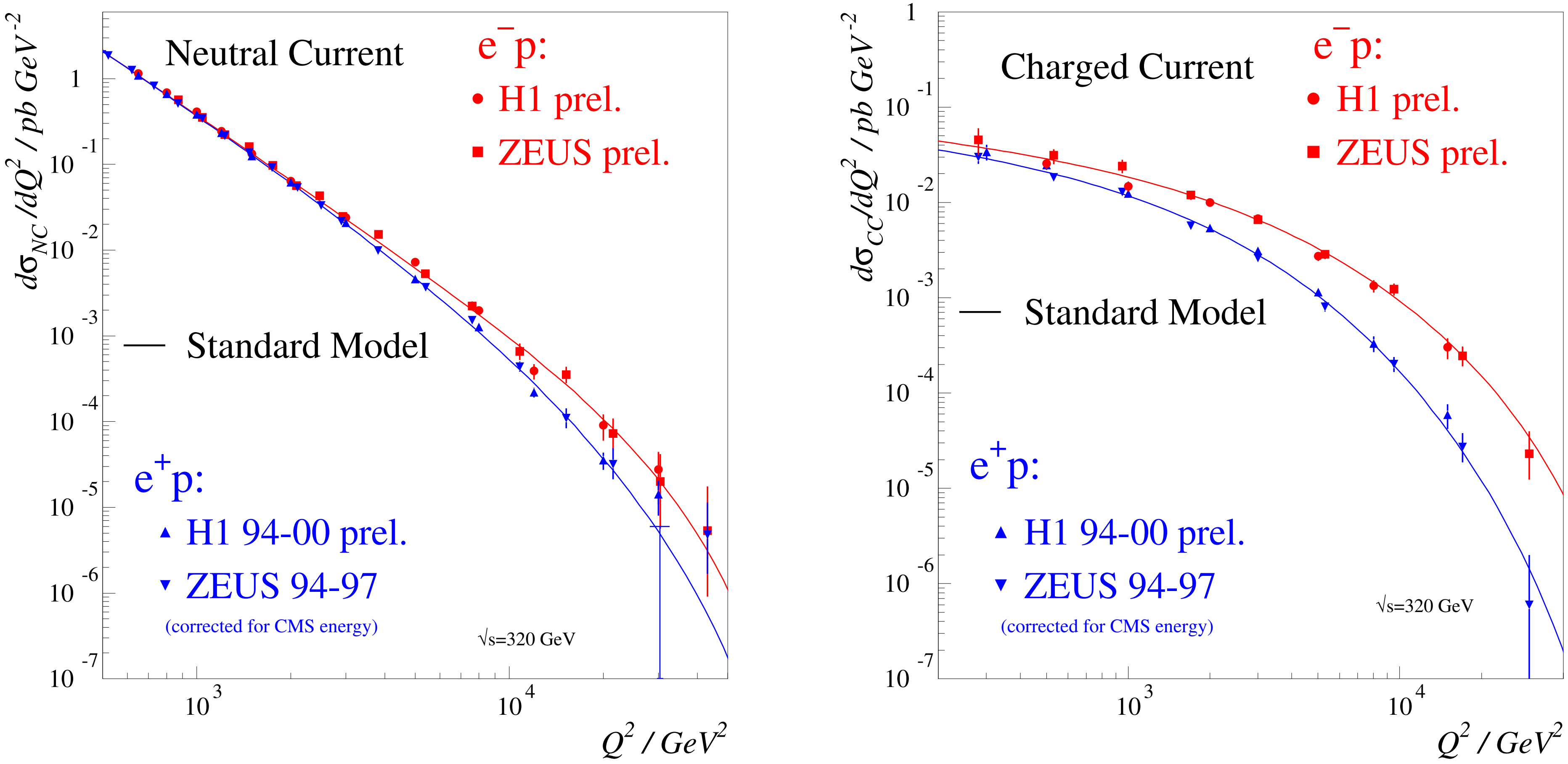
NC DIS



CC DIS



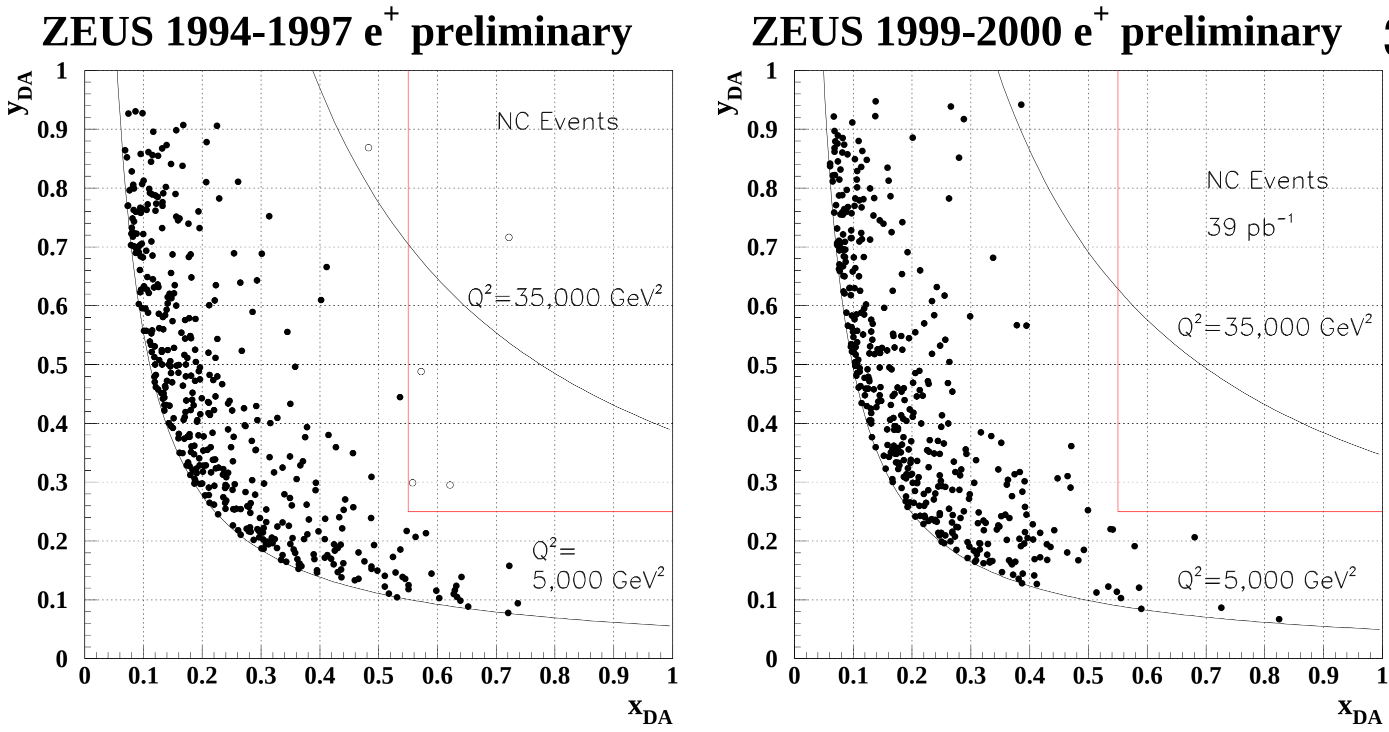
High-Q^2 DIS



⇒ Good agreement with the Standard Model over ∼6 orders of magnitude.

High-Q^2 DIS

High-Q^2 / high-x excess ?



39 pb^{-1}

Excess observed in old data not confirmed

ZEUS

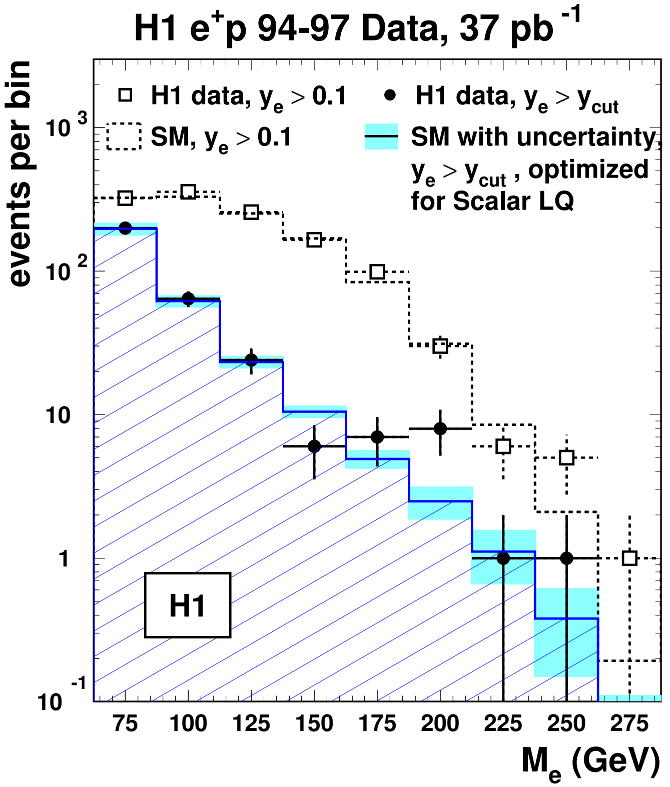
N_{obs} (N_{exp})	1994-97	1998-99	1999-00(part)
$Q^2 > 35\,000$ GeV^2	2 (0.34)	2 (1.02)	1 (0.53)
$x >$0.55 & $y > 0.25$	4 (1.9)	1 (1.3)	0 (1.6)

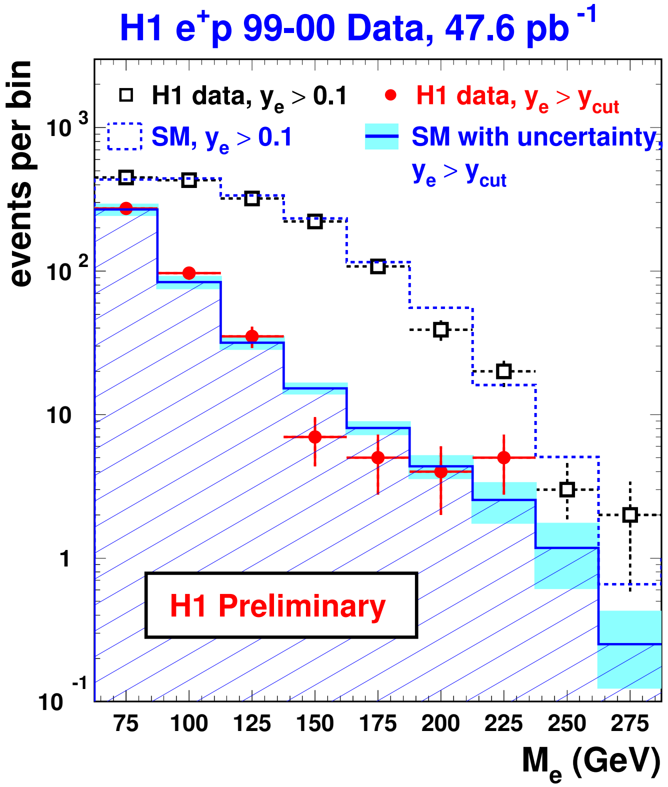
1994-96
2 (0.15)
4 (0.91)

High-Q^2 DIS

High mass excess ?

Old H1 e^+p data (especially in 1994-96) showed excess at M$\sim$ 200 GeV





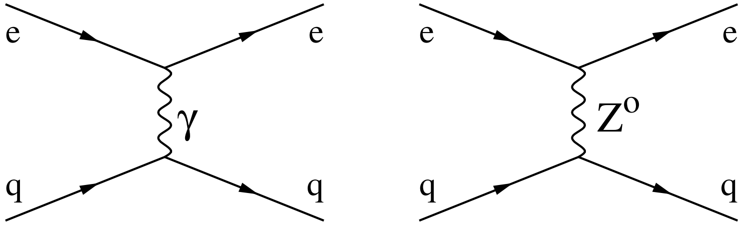
excess at high y
consistent with leptoquark production

$\Rightarrow$ not confirmed by new data...

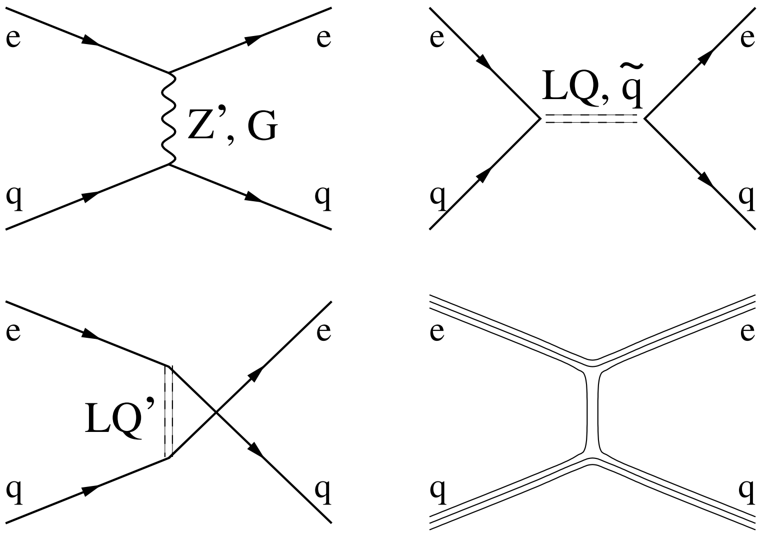
Contact Interactions

Neutral Current eq Scattering

Two processes contribute in SM:

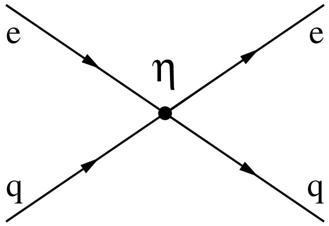


Possible "new physics" processes:



For $\sqrt{s}$ much smaller than process scale Λ

⇒ effective parameterization:



$eeqq$ contact interactions (CI)

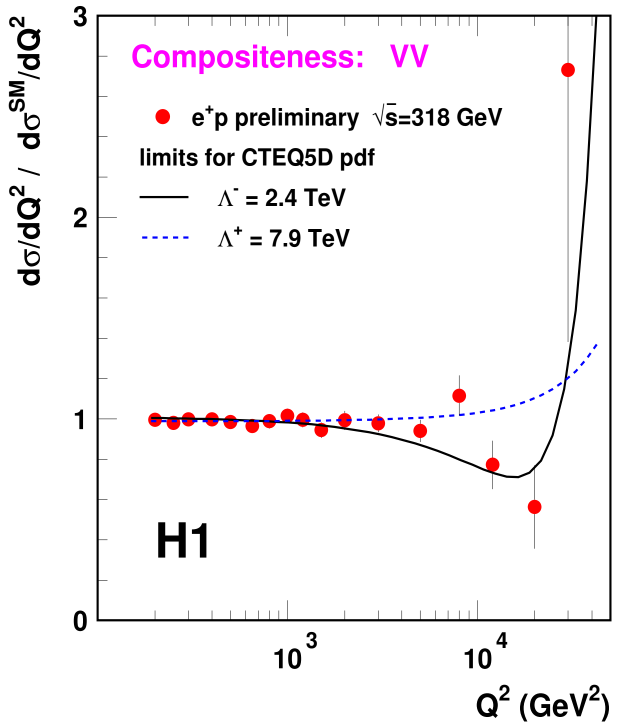
Contribution to the differential NC cross-section:

$$\frac{d\sigma}{dx\,dQ^2}(\eta) \;=\; \frac{d\sigma^{SM}}{dx\,dQ^2} \cdot \left[1 + A(x,Q^2)\,\eta + B(x,Q^2)\,\eta^2\right]$$

Contact Interactions

Analysis method

H1



- look for deviations in $\frac{d\sigma}{dQ^2}$
- 95% CL limits: $\chi^2(\Lambda) - \chi^2_{SM} = 3.84$

ZEUS

- 95% CL limits from MC experiments
  (∼ LEP method for higgs limits)

1994-97

- look for deviations in $\frac{d\sigma}{dx\,dy}$

1994-2000 (preliminary)

- look at $\frac{d\sigma}{dQ^2}$

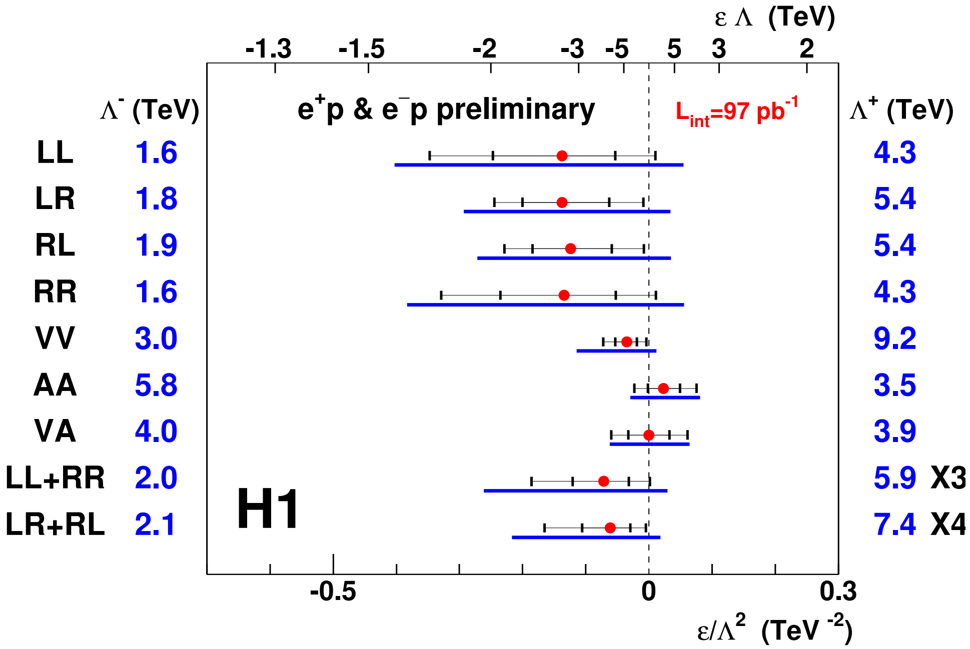
Contact Interactions

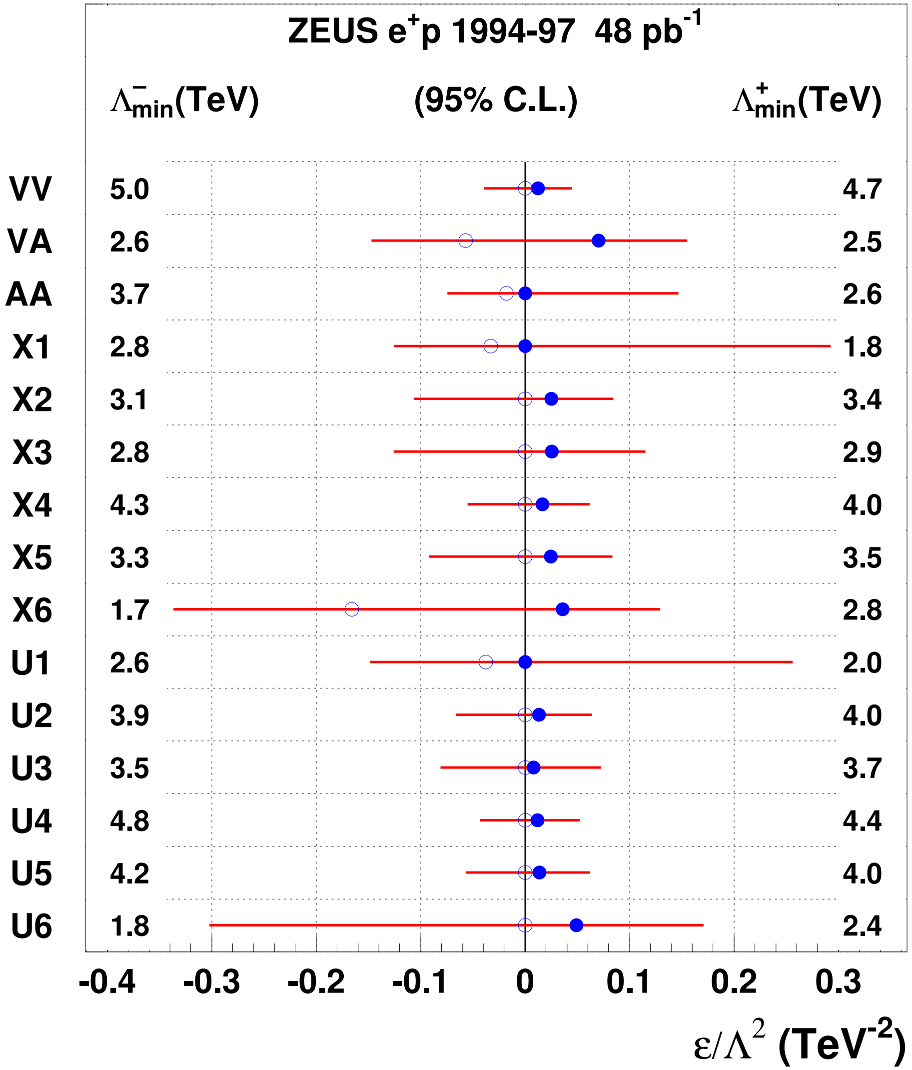
Compositeness models

Contact interaction coupling

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

Λ - compositeness scale $>$ 1.6 - 9.2 TeV





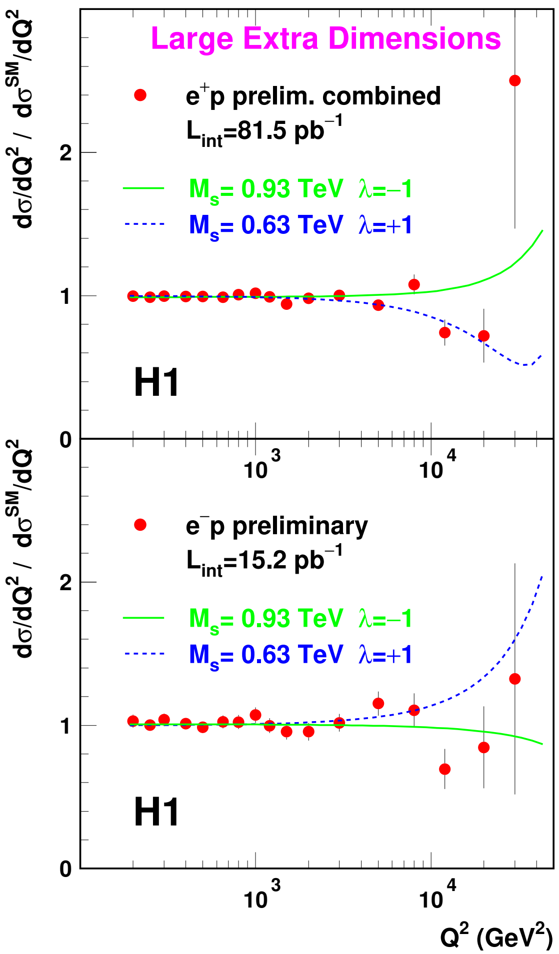
$\sim 2\sigma$ deviation in most models

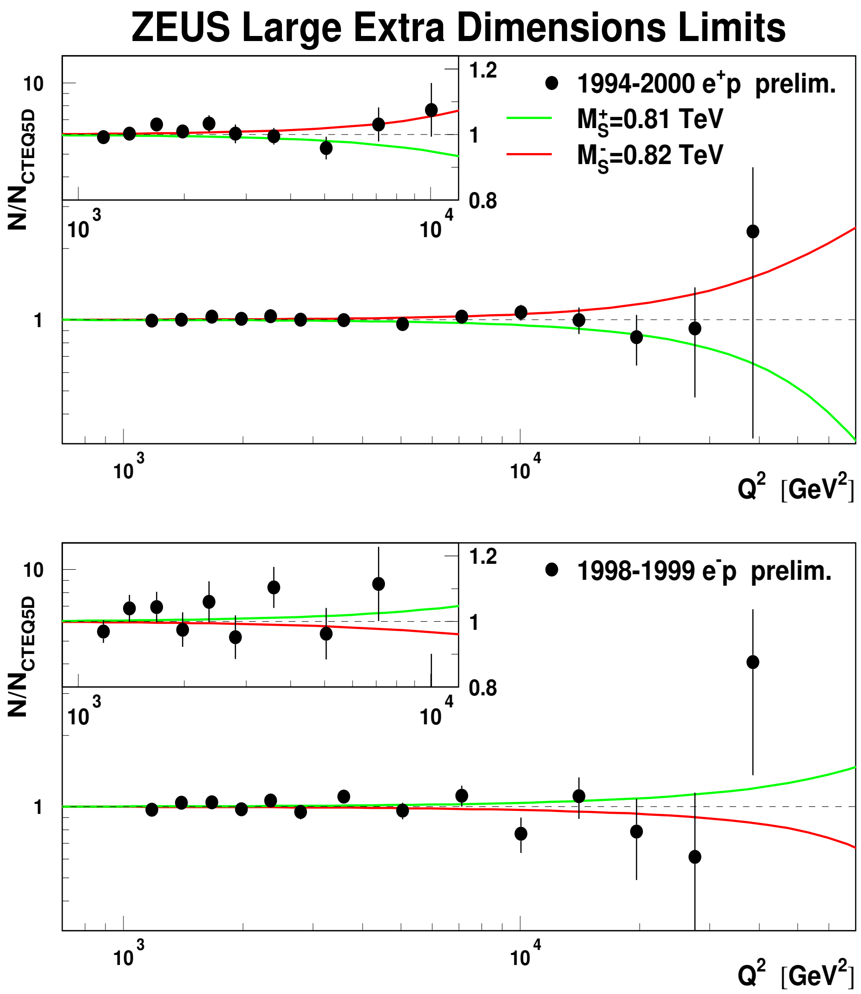
data undershoots SM slightly at high Q2

Good agreement with the Standard Model

Contact Interactions

Kaluza-Klein graviton exchange in $4 + n$ dimensions $\Rightarrow$ effective scale $M_S \sim \mathcal{O}(TeV)$





Preliminary 95% CL

1994-2000 combined:

$M_S^- > 0.93$ TeV
$M_S^+ > 0.63$ TeV

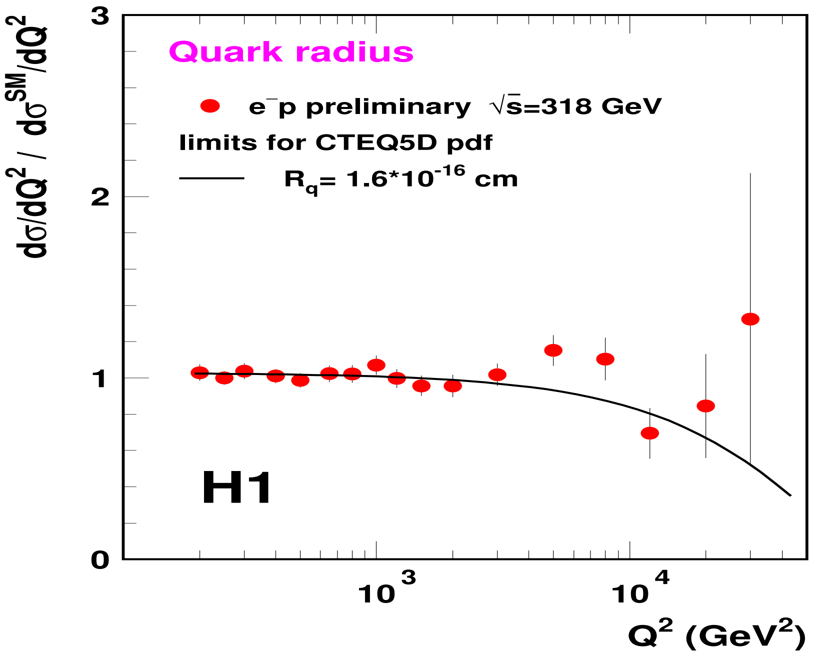
H1

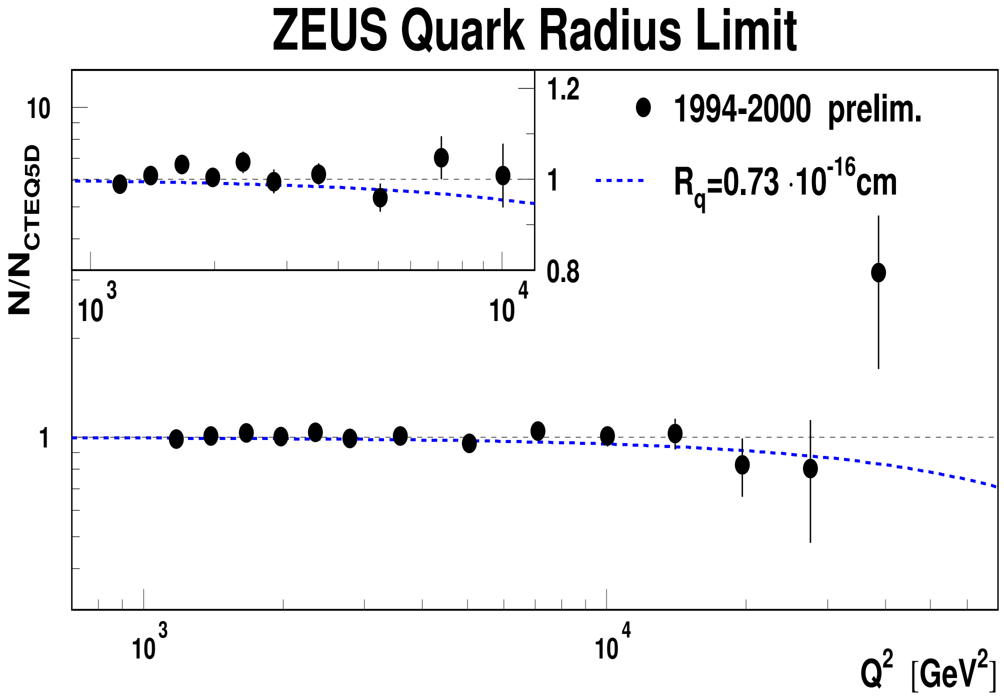
$M_S^- > 0.82$ TeV
$M_S^+ > 0.81$ TeV

ZEUS

Contact Interactions

Quark form factor: $$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2} \cdot \left[1 - \frac{R_q^2}{6} Q^2\right]^2$$ R_q - quark "radius"





Preliminary 95% CL

$$R_q < 1.6 \cdot 10^{-16}\text{cm}$$

H1

$$R_q < 0.73 \cdot 10^{-16}\text{cm}$$

ZEUS

Contact Interactions / Leptoquarks

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

  $\Rightarrow$ fermion number F=0,2

  $\Rightarrow$ branching ratio to eq: $\beta = 0, \frac{1}{2}, 1$

    $\Rightarrow$ resonant production in e^+p (F=0) and e^-p (F=2)

    $\Rightarrow$ production cross-section $\sim \lambda^2$

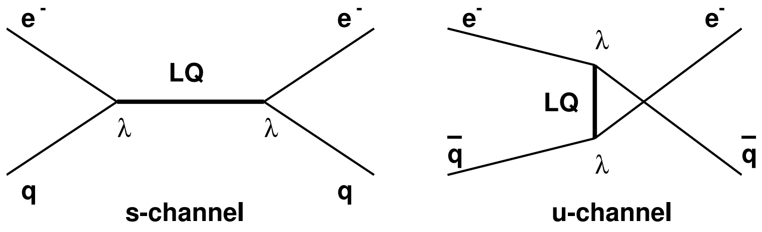
    $\Rightarrow$ decay distribution flat in y (scalar) or $\sim (1-y)^2$ (vector)

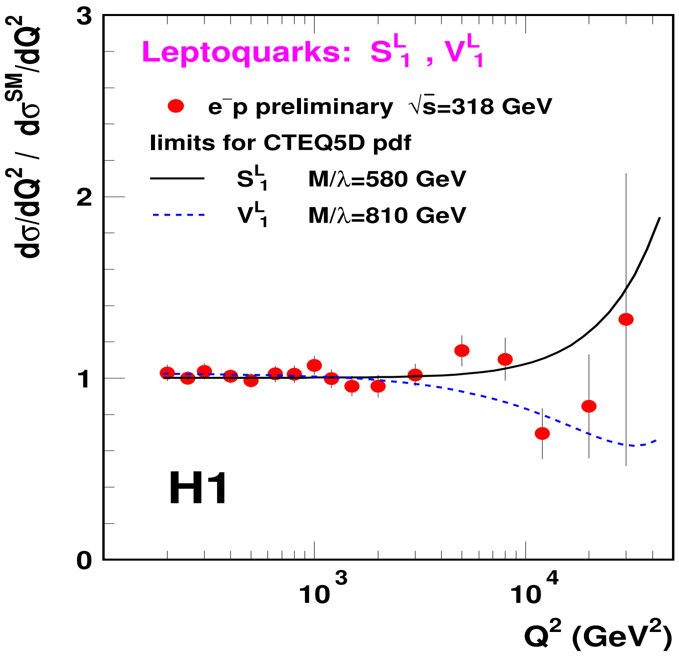
    $\Rightarrow$ virtual production/exchange: $\eta_{CI} \sim (\lambda/M)^2$

Contact Interactions / Leptoquarks

High mass leptoquarks $M_{LQ} \gg \sqrt{s}$

Both s- and u-channel important



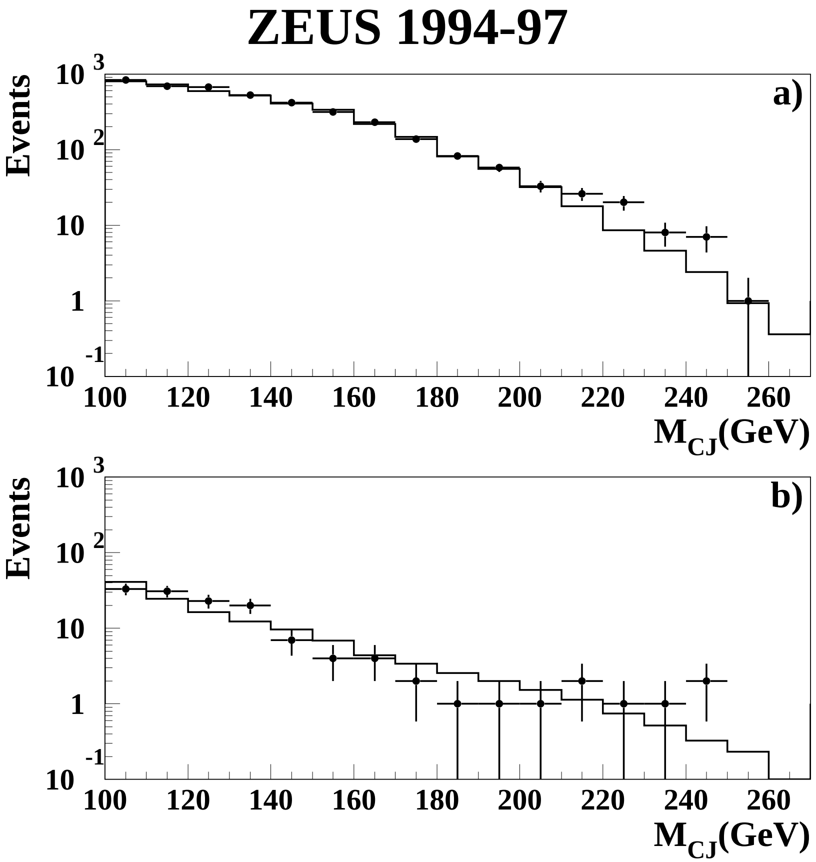


H1 1994-00 preliminary, 95% CL limits

LQ	η^u $(\lambda/M_{LQ})^2$	η^d $(\lambda/M_{LQ})^2$	F	M_{LQ}/λ [GeV]
S^L_0	$+\frac{1}{2}$		2	1070
S^R_0	$+\frac{1}{2}$		2	960
$\tilde{S}^R_0$		$+\frac{1}{2}$	2	290
$S^L_{1/2}$	$-\frac{1}{2}$		0	380
$S^R_{1/2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	0	380
$\tilde{S}^L_{1/2}$		$-\frac{1}{2}$	0	650
S^L_1	$+\frac{1}{2}$	$+1$	2	690
V^L_0		-1	0	1030
V^R_0		-1	0	810
$\tilde{V}^R_0$	-1		0	530
$V^L_{1/2}$		$+1$	2	480
$V^R_{1/2}$	$+1$	$+1$	2	1510
$\tilde{V}^L_{1/2}$	$+1$		2	1690
V^L_1	-2	-1	0	680

Leptoquarks

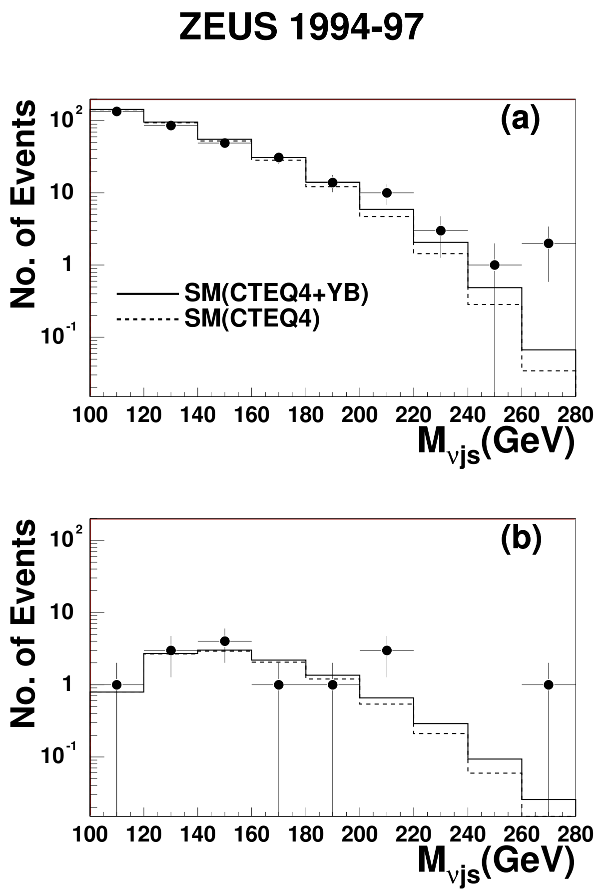
LQ$\rightarrow e^{\pm} + jet$



all selected events

after cut on y (cos $\theta^{\star}$)

LQ$\rightarrow \nu + jet$

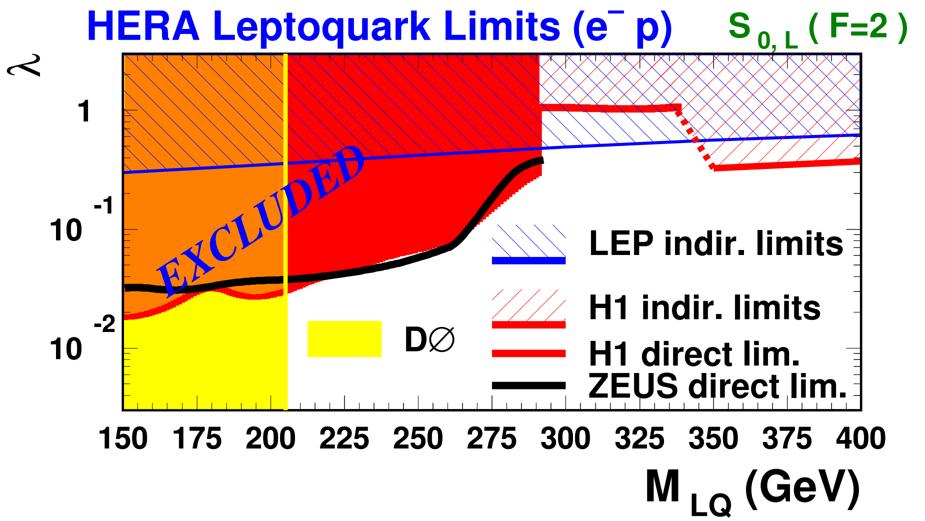


excess for M>210 GeV at low y only
not consistent with scalar or vector resonance

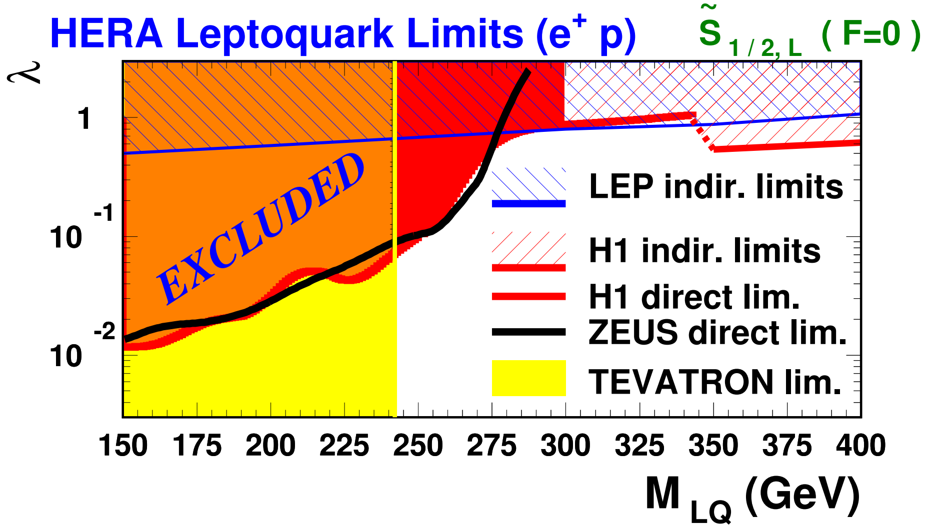
Leptoquarks

BRW model

LQ branching fractions fixed



$S_0^L\ (\tilde{d}_R)$ $\beta = \frac{1}{2}$



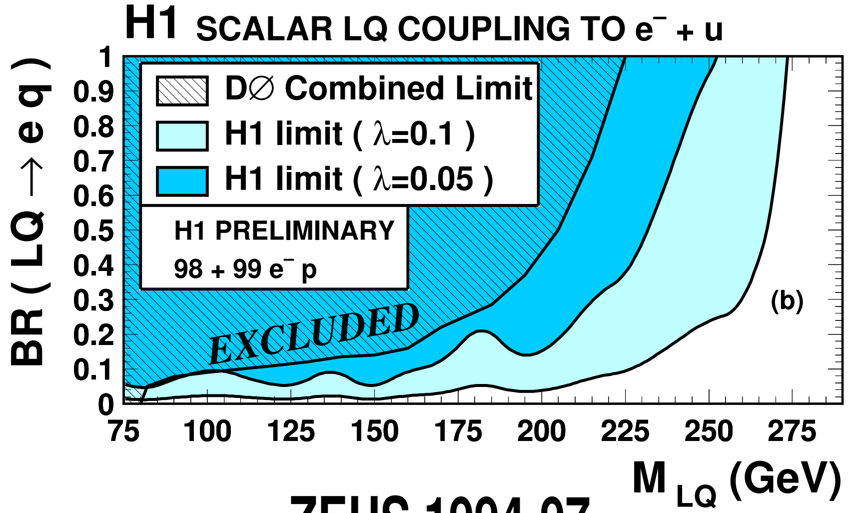
$S_{1/2}^L\ (\overline{\tilde{u}_L})$ $\beta = 1$

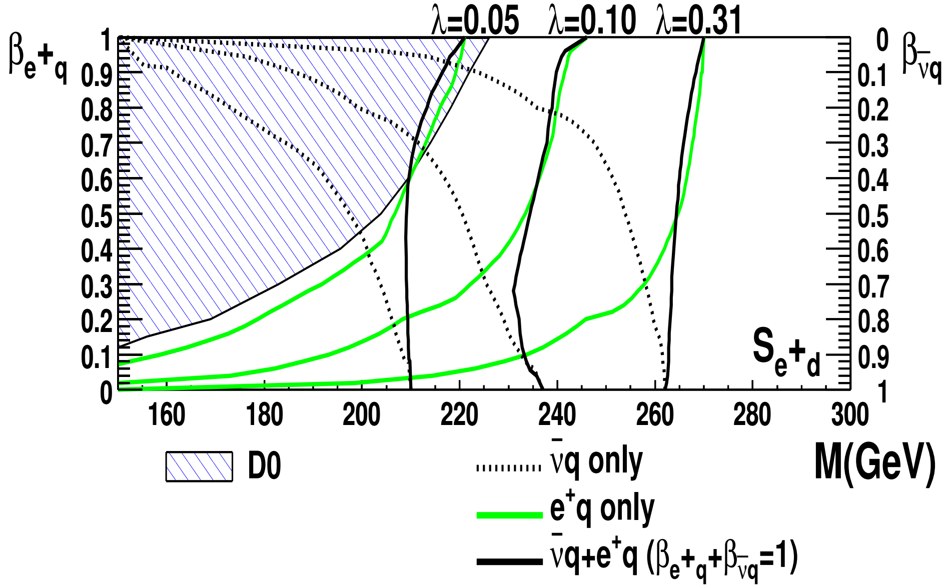
Leptoquarks

General LQ model

β free

$\Rightarrow$ study β vs M_{LQ} for fixed λ





NC and CC combined

$\Rightarrow$ limits on M_{LQ} independent on β

$\beta_{eq} + \beta_{\nu q} \equiv 1$

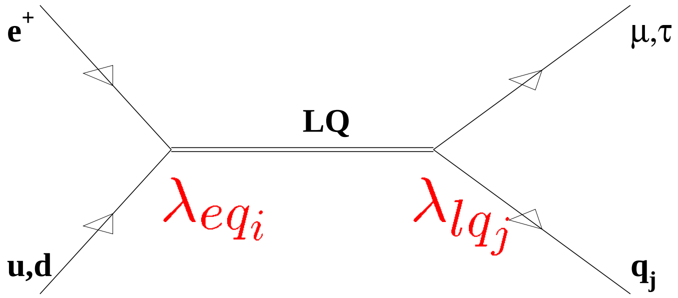
Lepton Flavor Violation

Model

LQ coupling to different generations

e.g. $LQ \rightarrow e q_i$ and $LQ \rightarrow \tau q_j$

$\Rightarrow$ Lepton Flavor Violation



No signal found by H1/ZEUS 1994-97

For $M_{LQ} \gg \sqrt{s}$ $\Rightarrow$ LFV contact interactions

H1 and ZEUS 95% CL limits on $\dfrac{\lambda_{eq_i}\,\lambda_{\tau q_j}}{M^2}$ $\Rightarrow$

compared to low energy experiments

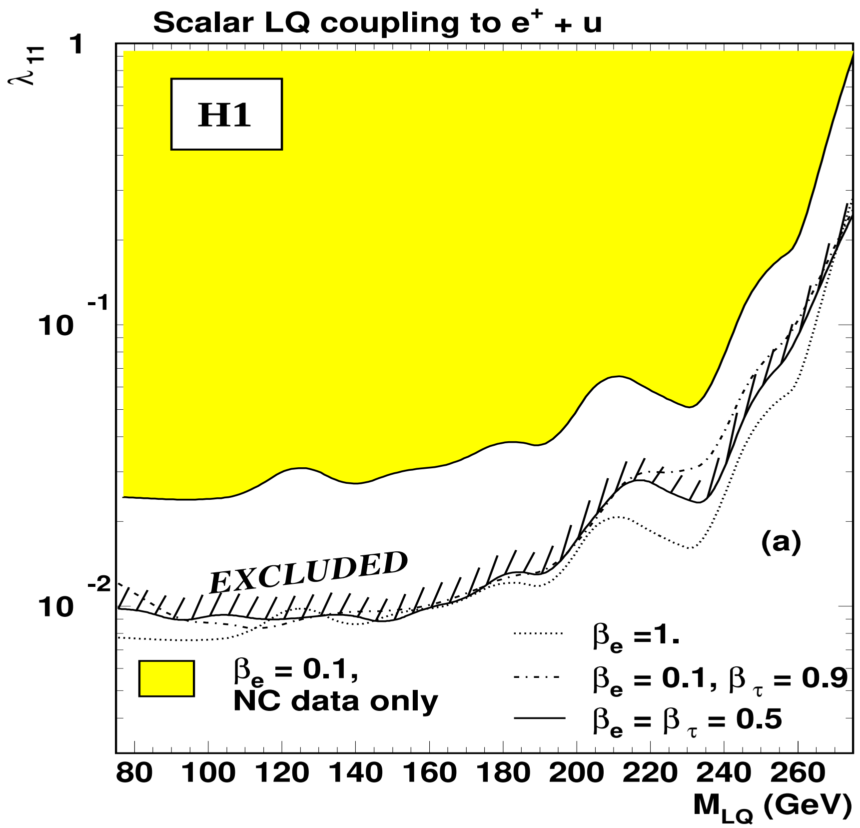
$[10^{-4}\ \mathrm{GeV}^{-2}]$

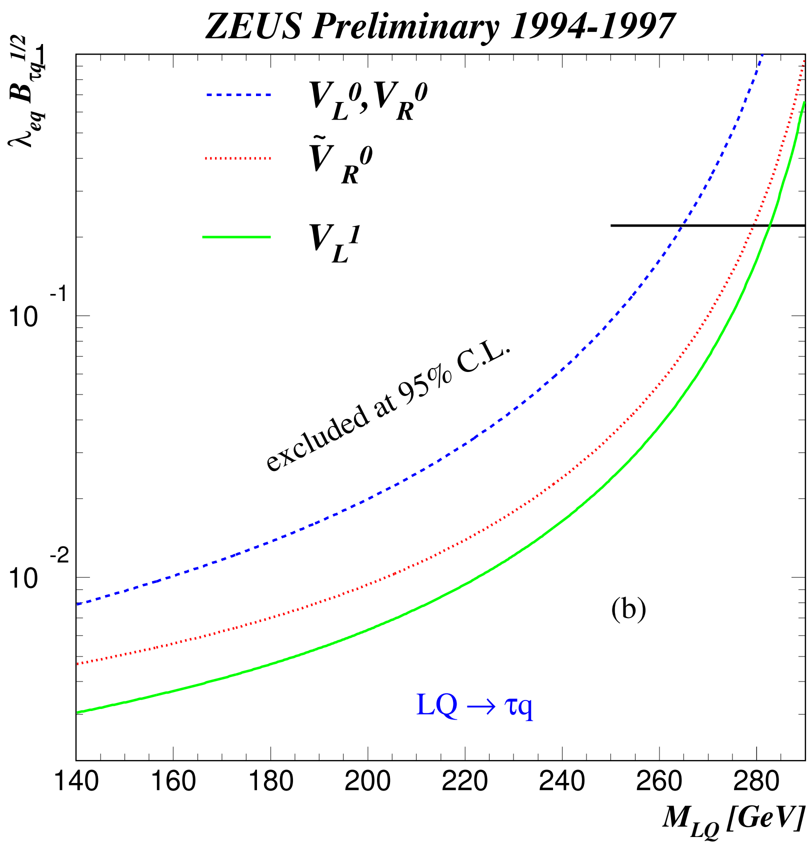
$q_i q_j$	$S^L_{1/2}$	$S^R_{1/2}$	$\tilde{S}^L_{1/2}$	V^L_0	V^R_0	$\tilde{V}^R_0$	V^L_1
1 1	$\tau \rightarrow \pi e$ 0.0032 0.030 0.046	$\tau \rightarrow \pi e$ 0.0016 0.025 0.037	$\tau \rightarrow \pi e$ 0.0032 0.046 0.062	G_F 0.002 0.033 0.049	$\tau \rightarrow \pi e$ 0.0016 0.033 0.049	$\tau \rightarrow \pi e$ 0.0016 0.024 0.041	G_F 0.002 0.012 0.019
1 2	$\boxed{0.030}$ 0.047	$\tau \rightarrow$K e 0.05 $\boxed{0.025}$ 0.038	$\tau \rightarrow$K e 0.05 $\boxed{0.046}$ 0.063	$\tau \rightarrow$K e 0.03 0.036 0.053	$\tau \rightarrow$K e 0.03 0.036 0.053	$\boxed{0.026}$ 0.045	K $\rightarrow \pi\nu\bar{\nu}$ $2.5 \cdot 10^{-6}$ 0.012 0.021
1 3	——	B$\rightarrow \tau e$ X 0.08 $\boxed{0.049}$ 0.065	B$\rightarrow \tau e$ X 0.08 $\boxed{0.049}$ 0.065	B$\rightarrow l\nu$X 0.02 0.044 0.062	B$\rightarrow \tau e$ X 0.04 0.044 0.062	——	B$\rightarrow l\nu$X 0.02 0.044 0.062
2 1	0.153 $\boxed{0.15}$	$\tau \rightarrow$K e 0.05 0.092 0.095	$\tau \rightarrow$K e 0.05 0.105 0.12	$\tau \rightarrow$K e 0.03 0.049 0.064	$\tau \rightarrow$K e 0.03 0.049 0.064	$\boxed{0.061}$ 0.073	K $\rightarrow \pi\nu\bar{\nu}$ $2.5 \cdot 10^{-6}$ 0.026 0.032
2 2	$\tau \rightarrow e\gamma$ 0.03 0.187 0.18	$\tau \rightarrow e\gamma$ 0.02 0.101 0.10	$\boxed{0.120}$ 0.13	$\boxed{0.061}$ 0.076	$\boxed{0.061}$ 0.076	$\boxed{0.102}$ 0.107	$\boxed{0.041}$ 0.044
2 3	——	B$\rightarrow \tau e$ X 0.08 0.153 0.14	B$\rightarrow \tau e$ X 0.08 0.153 0.14	B$\rightarrow l\nu$X 0.02 0.102 0.112	B$\rightarrow \tau e$ X 0.04 0.102 0.112	——	B$\rightarrow l\nu$X 0.02 0.102 0.112
3 1	——	B$\rightarrow \tau e$ X 0.08 0.162 0.16	B$\rightarrow \tau e$ X 0.08 0.162 0.16	V_{ub} 0.002 0.052 0.068	B$\rightarrow \tau e$ X 0.04 0.052 0.068	——	V_{ub} 0.002 0.052 0.068
3 2	——	B$\rightarrow \tau e$ X 0.08 0.202 0.19	B$\rightarrow \tau e$ X 0.08 0.202 0.19	B$\rightarrow l\nu$X 0.02 0.073 0.083	B$\rightarrow \tau e$ X 0.04 0.073 0.083	——	B$\rightarrow l\nu$X 0.02 0.073 0.083
3 3	——	0.275 $\boxed{0.23}$	0.275 $\boxed{0.23}$	$\tau \rightarrow e\gamma$ 0.51 0.144 $\boxed{0.14}$	$\tau \rightarrow e\gamma$ 0.51 0.144 $\boxed{0.14}$	——	0.144 $\boxed{0.14}$

Lepton Flavor Violation

Resonance search

Limit curves for $M_{LQ} < \sqrt{s}$ $(eq \to \tau q')$





$\lambda_{eq} = \lambda_{\tau q'} = \sqrt{4\pi\alpha_{em}}$:

$M_{LQ} >$ 270 GeV (e^+u)

$M_{LQ} >$ 259 - 283 GeV
(depending on model)

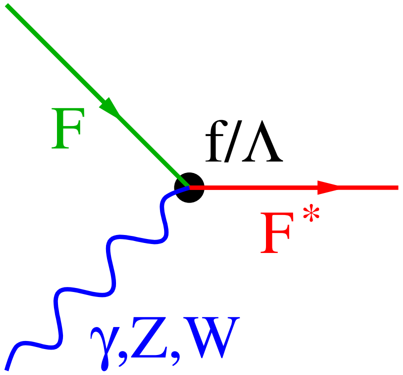
Excited Fermions

Model

Compositeness $\Rightarrow$ excited fermion states

Single excitation of electrons, neutrinos and quarks possible at HERA.

Effective Lagrangian (Hagiwara et al.):



$$\mathcal{L}_{FF^\star} \;=\; \frac{1}{\Lambda} F_R^\star \left[f\, SU(2)_W + f'\, U(1)_Y + f_s\, SU(3)_C \right] F_L$$

Λ - compositeness scale

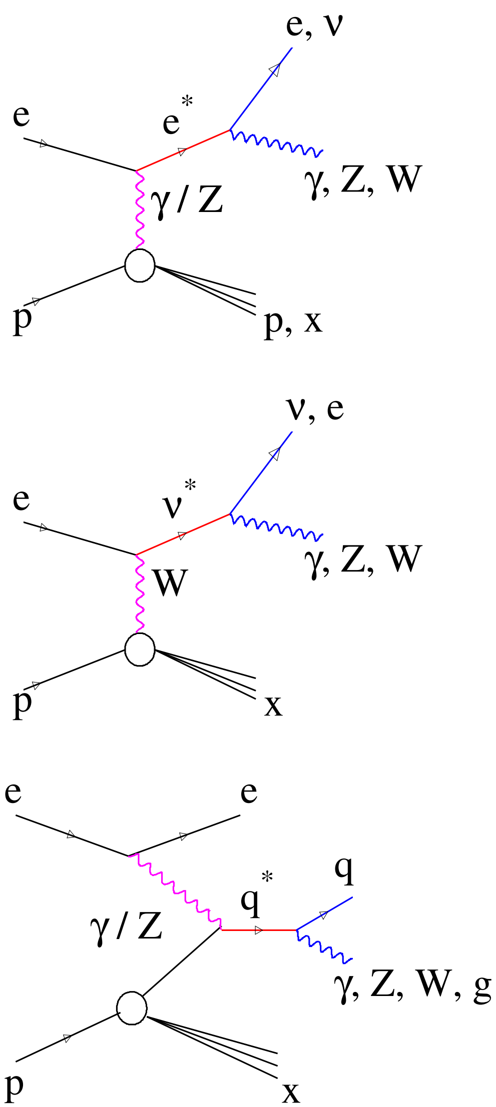
Production at HERA

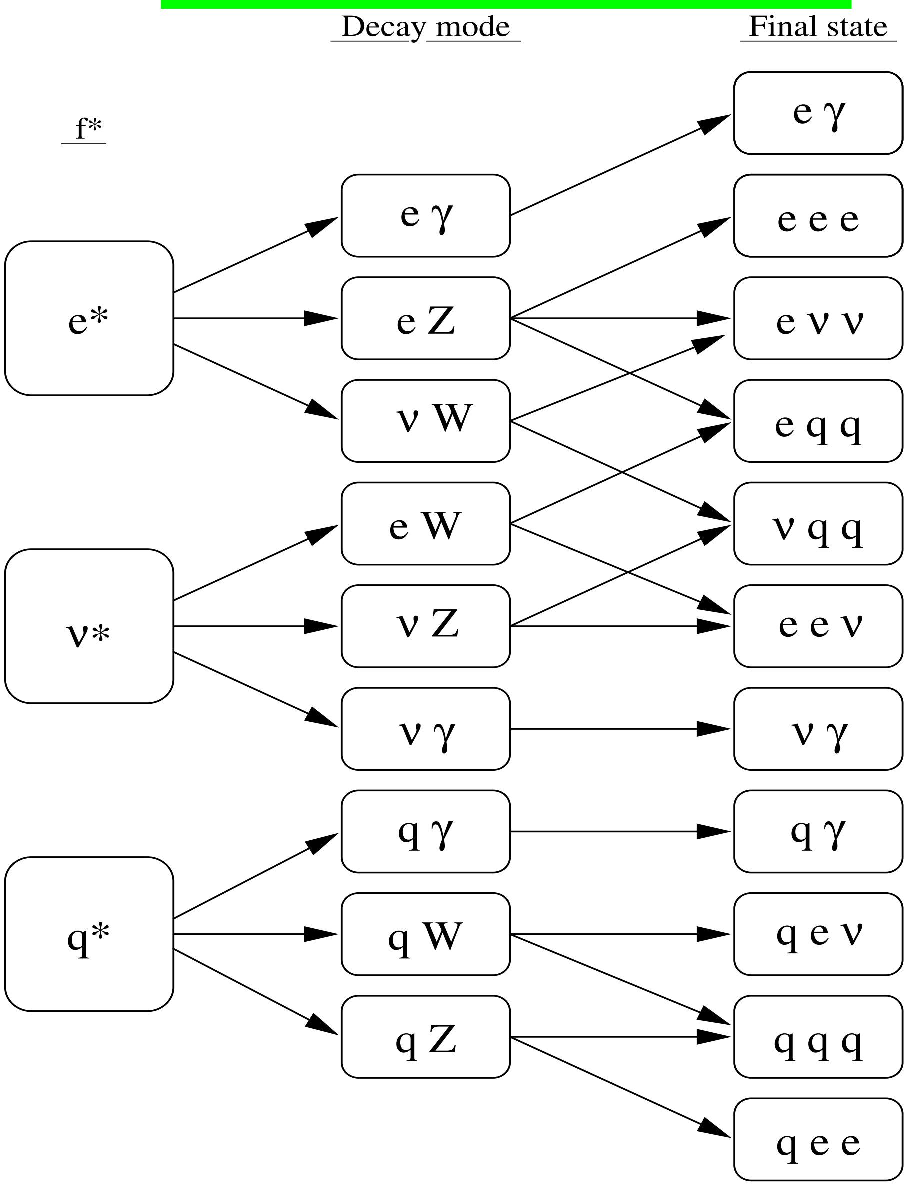
$$\sigma(ep \rightarrow F^\star X) \;\sim\; \left(\frac{f_i}{\Lambda}\right)^2$$

$$f_i = f, f', f_s$$

Excited Fermions

Search channels





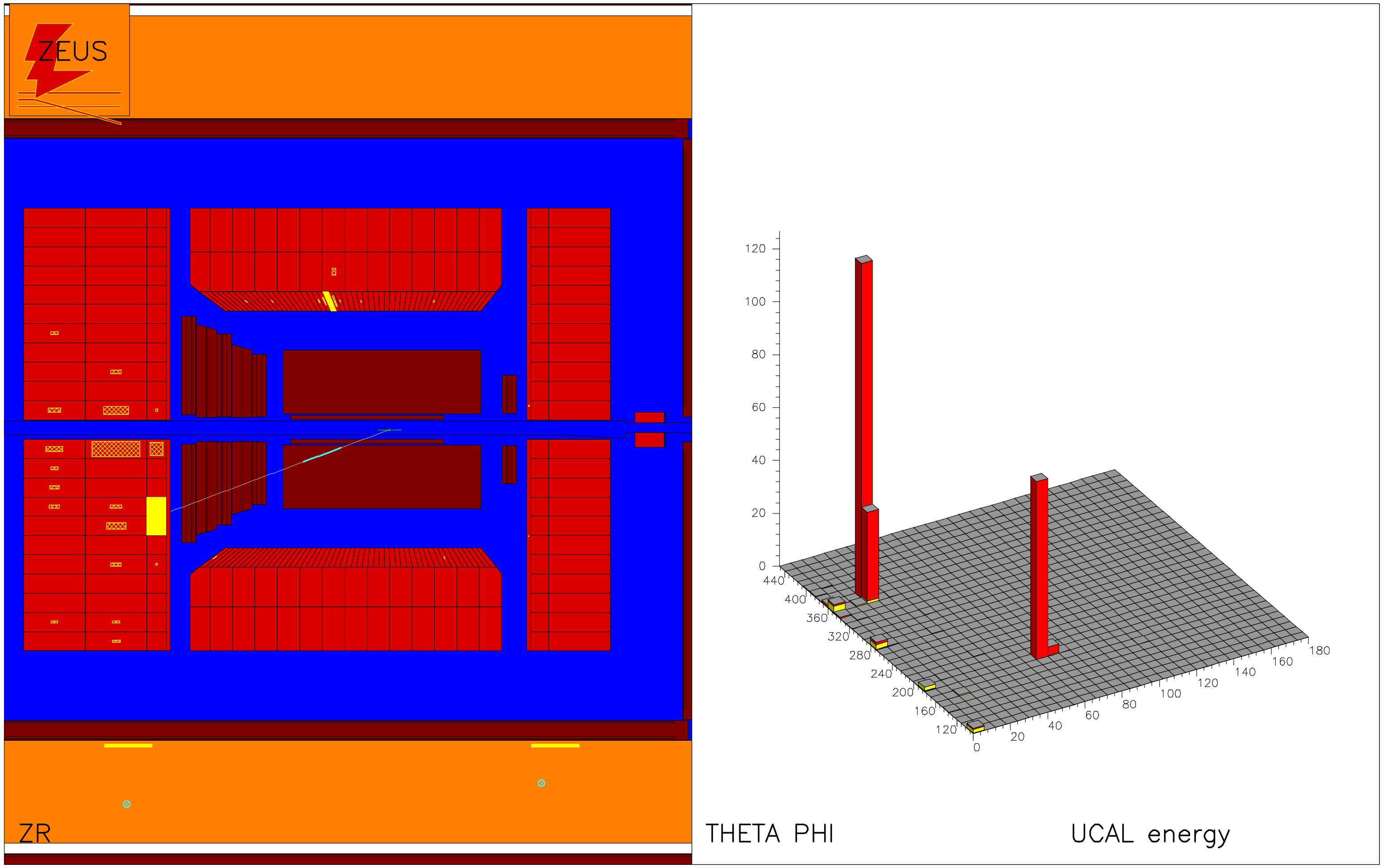
Final state	Experiment	Signature
e γ	H1 ZEUS	2 EM clusters
e e e	H1	3 EM clusters
e ν ν	H1	EM cluster (+track), $\not{p}_t$
e q q	H1 ZEUS	EM cluster, large $E_{t,\,had}$ M_{had}
ν q q	H1 ZEUS	$\not{p}_t$, large $E_{t,\,had}$ M_{had}
e e ν		2 EM clusters, $\not{p}_t$
ν γ	H1 ZEUS	EM cluster (no track), $\not{p}_t$
q γ	H1 ZEUS	EM cluster (no track), large $E_{t,\,had}$
q e ν	H1 ZEUS	$\not{p}_t$, EM cluster, large $E_{t,\,had}$
q q q	H1	3 high E_t jets
q e e	H1	2 EM clusters and high E_t jet

H1: also final states with μ

Excited Fermions

$e^\star \to e\gamma$

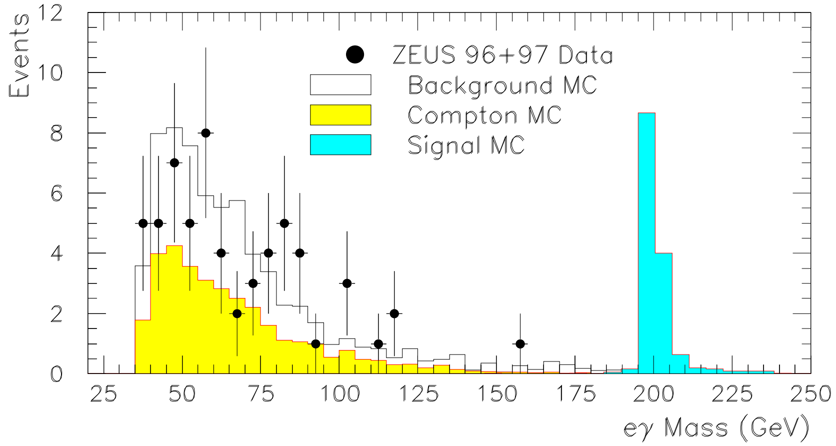
candidate event



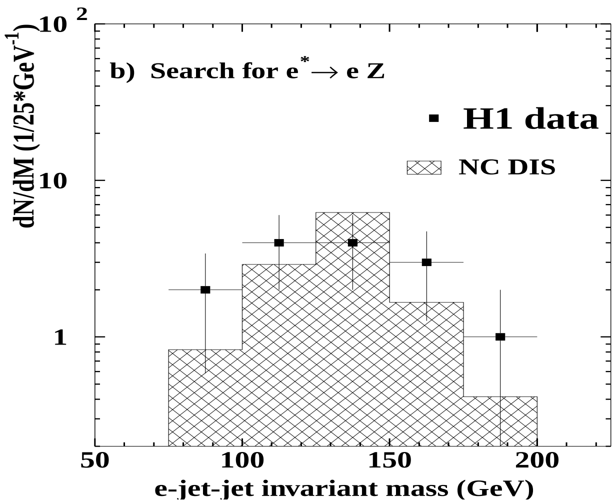
Excited Fermions

$e^\star \to e\gamma$

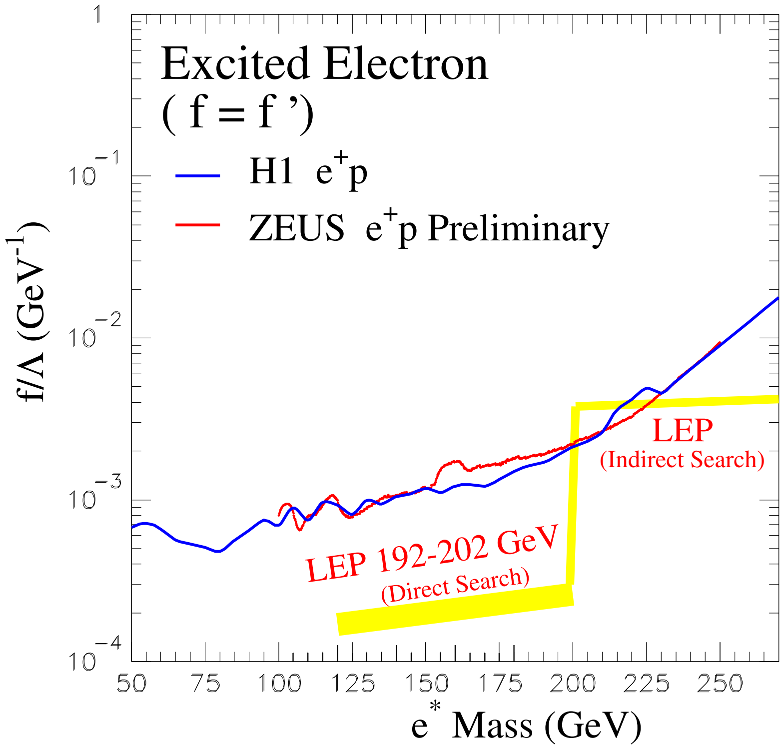
ZEUS 96+97 Preliminary



$e^\star \to eZ$



95% CL limits on f/Λ:



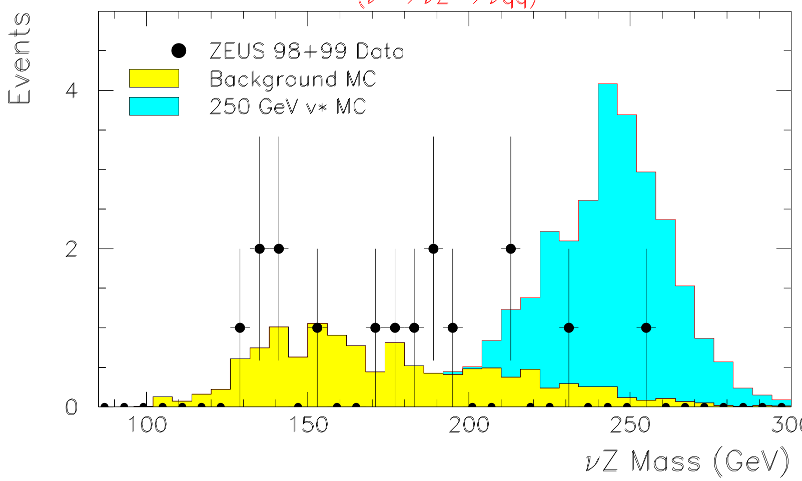
Assuming $f/\Lambda = 1/M_{e^\star}$:

$M_{e^\star} >$ 223 GeV (H1) $>$ 229 GeV (ZEUS)

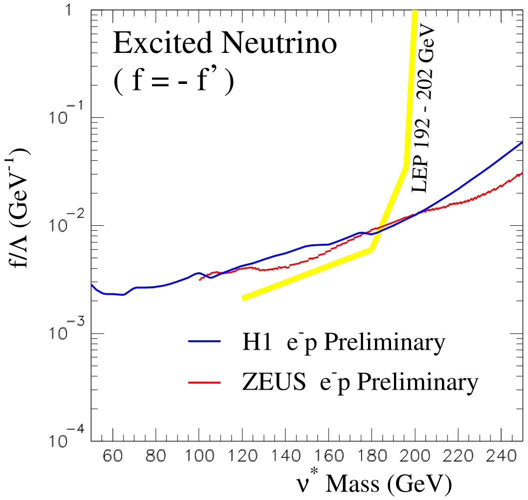
Excited Fermions

$\nu^\star \to \nu Z$

ZEUS 98+99 Preliminary



95% CL limits

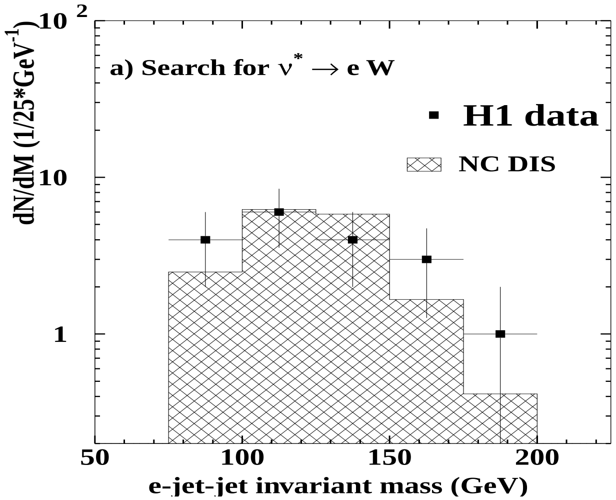


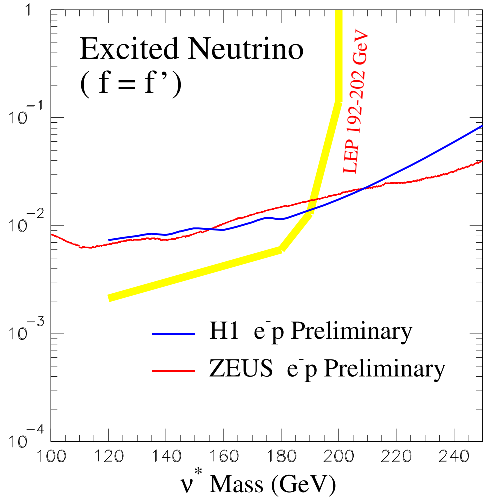
$f/\Lambda = 1/M_{\nu^\star}$:

$M_{\nu^\star} >$ 150 GeV (H1)

$M_{\nu^\star} >$ 163 GeV (ZEUS)

$\nu^\star \to eW$





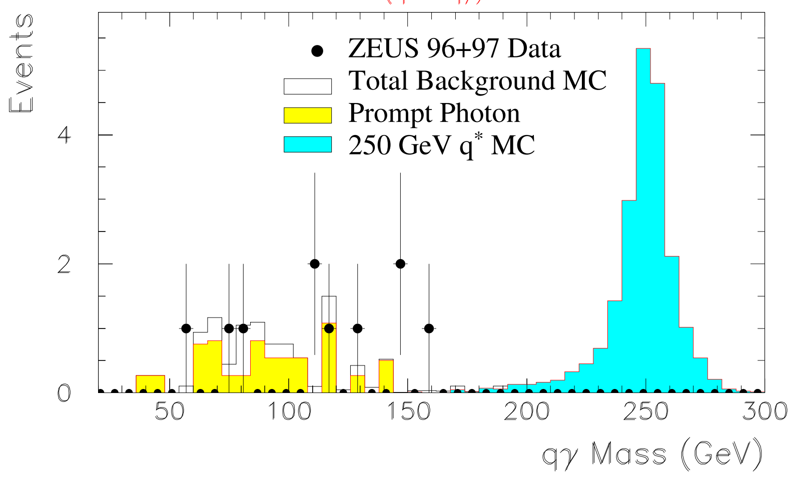
$M_{\nu^\star} >$ 134 GeV (H1)

$M_{\nu^\star} >$ 133 GeV (ZEUS)

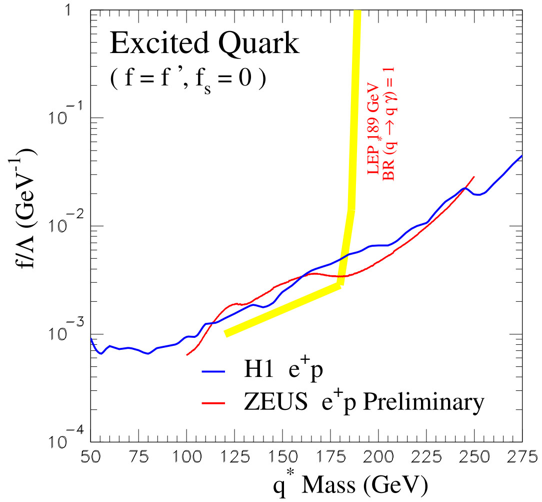
Excited Fermions

$q^\star \to q\gamma$

ZEUS 96+97 Preliminary



95% CL limits

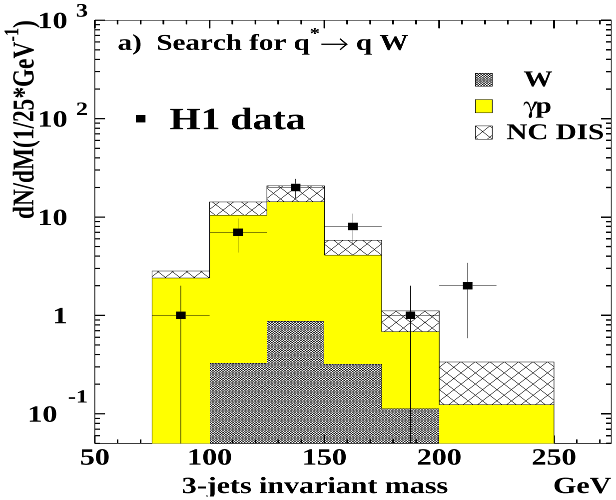


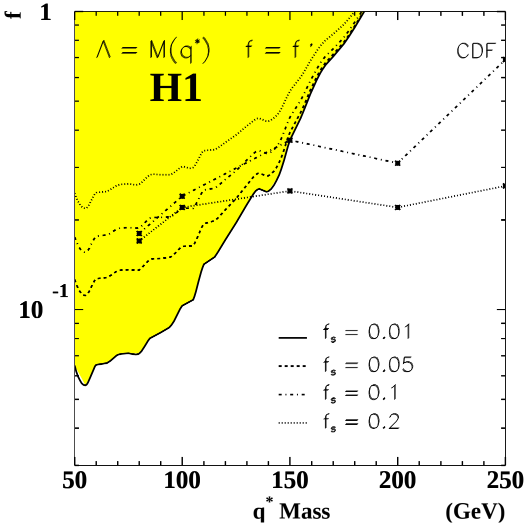
$f/\Lambda = 1/M_{q^\star}$:

$M_{q^\star} >$ 188 GeV (H1)

$M_{q^\star} >$ 203 GeV (ZEUS)

$q^\star \to qW$





Complementary to Tevatron

Summary

- Over 200 pb^{-1} of $e^{\pm}p$ data collected at HERA
- H1 and ZEUS has performed searches for

⇒ Contact Interactions

- ∗ Compositeness
- ∗ Large Extra Dimensions
- ∗ Quark Form Factor

⇒ Leptoquarks

⇒ Lepton Flavor Violation

⇒ Excited Fermions

- No evidence for new physics so far...
- Limits comparable/complementary to LEP/Tevatron
- Exciting future after HERA upgrade...

most current limits statistics limited