Search for New Physics at HERA

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on behalf of the H1 and ZEUS collaborations

Introduction to HERA

Leptoquarks, Lepton Flavour Violation

R_p **violating SUSY**

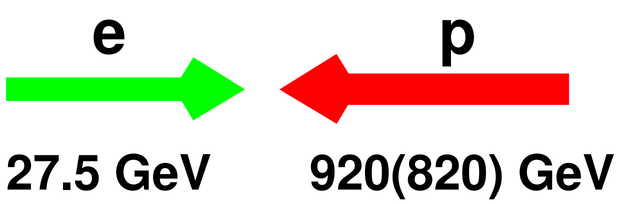
High P_T **Lepton Events**

Anomalous Top Production

Contact Interactions

Summary & Outlook

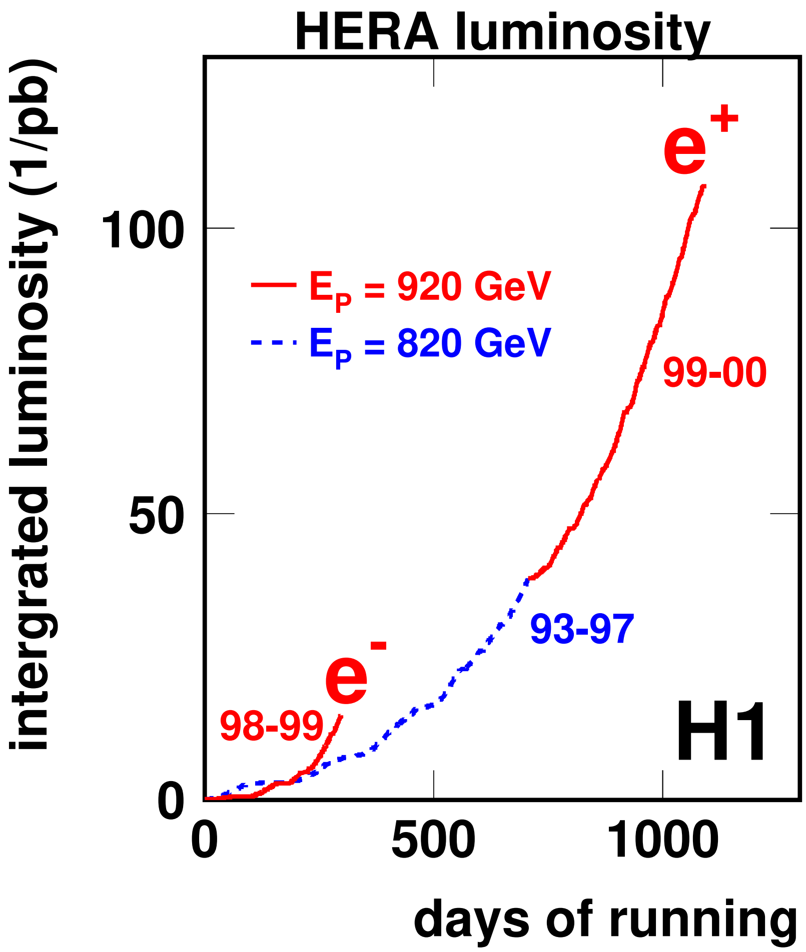
Introduction to HERA



$\sqrt{s} \approx 320(300)$ **GeV**

- HERA is unique in probing electron-quark interactions at high energies
  $\Rightarrow$ Ideal to look for **new particles** coupling to eq pairs

- Proton structure at distances of 10^{-16} cm for highest momentum transfers Q^2 can be probed



- Roughly $120\ \mathrm{pb}^{-1}$ per experiment in HERA I

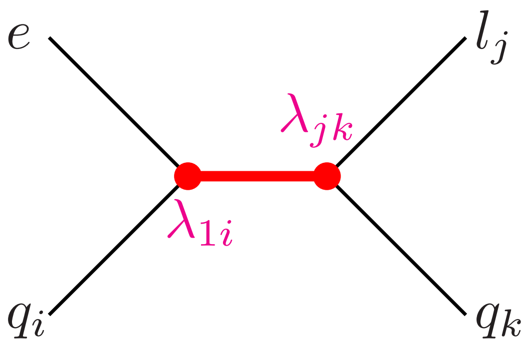
Leptoquarks

- Leptoquarks (LQ) predicted by many extensions of SM, e.g. GUT, SU(5) or SU(15)
  $\longrightarrow$ symmetry between lepton & quark sector

- Scalar or vector color triplet bosons with lepton and baryon numbers
  $\Rightarrow$ Fermion Number: $F = 3B + L = 0, 2$
  (e^+p mainly sensitive to LQ with $F = 0$, e^-p to $F = 2$ LQs)

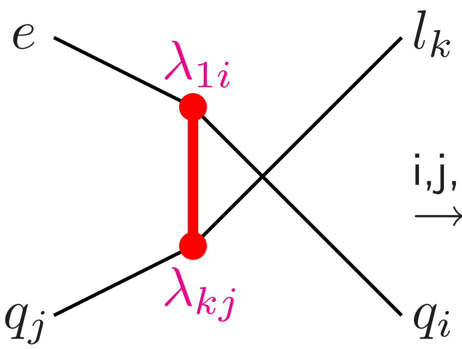
- Production at HERA via Yukawa coupling ($\propto \lambda^2$)

s channel



characterised by resonance peak (direct search)

t channel



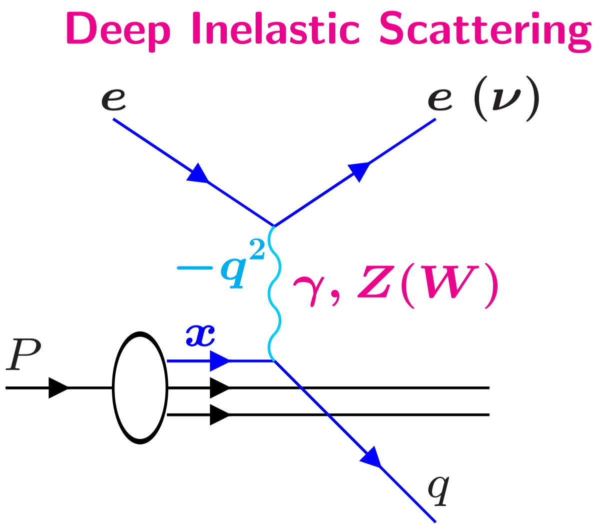
i,j,k flavour indices
$\longrightarrow$ Flavour Changing Currents

Leptoquarks

- Generic models:
  Branching Ratios $\beta_{eq} \equiv \beta(LQ \to eq)$, $\beta_{\nu q} \equiv \beta(LQ \to \nu q)$
  free parameters

- Buchmueller Rueckl Wyler (BRW) model:
  - $SU(3) \times SU(2) \times U(1)$ invariance
  - LQs only couple to chiral SM fermions
  - 14 species, 7 scalars and 7 vectors
  - BR fixed: $\beta_{eq} = 1, \frac{1}{2}$, $\beta_{\nu q} = 0, \frac{1}{2}$

- Dominant background from DIS processes



- Decay distributions:
  - flat in y for scalar LQ
  - $\propto (1-y)^2$ for vector LQ
  - $\propto 1/y^2$ for NC DIS

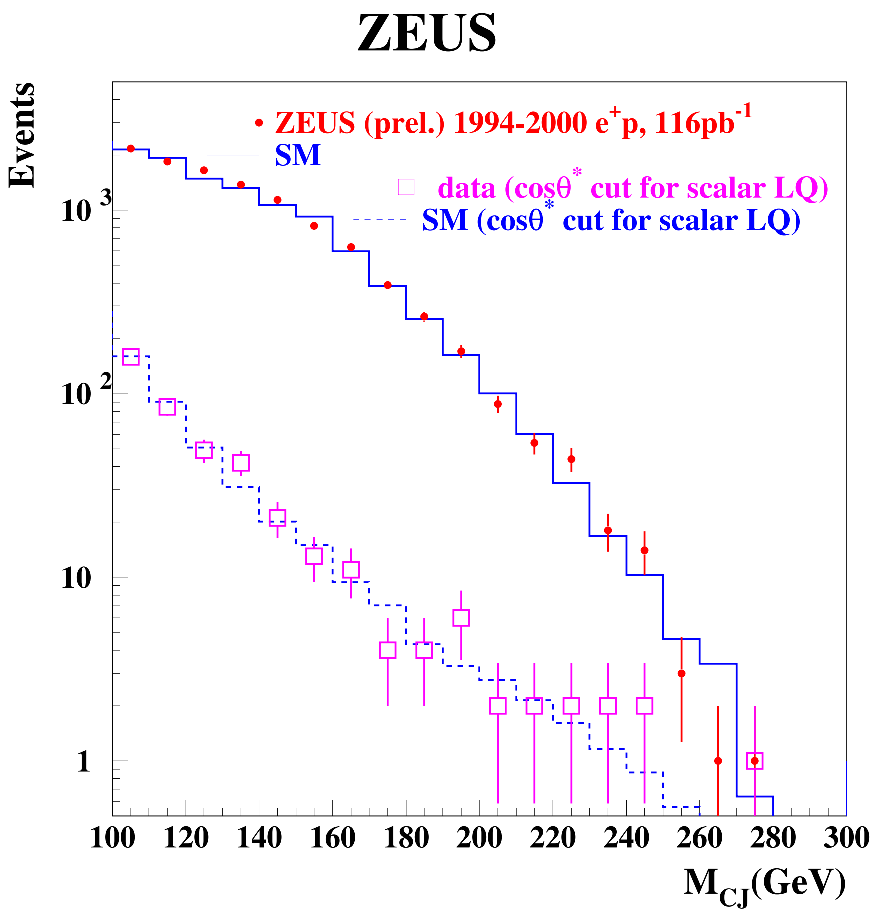
$\Rightarrow$ improved Signal/Background with optimised y cuts

Mass Distributions

ZEUS

Neutral Current

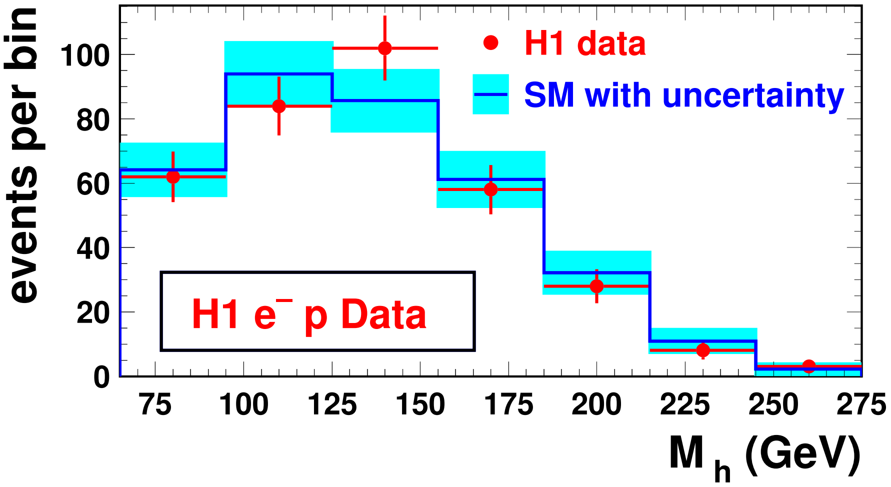
e^+p (94-00)



H1

Charged Current

e^-p (98-99)

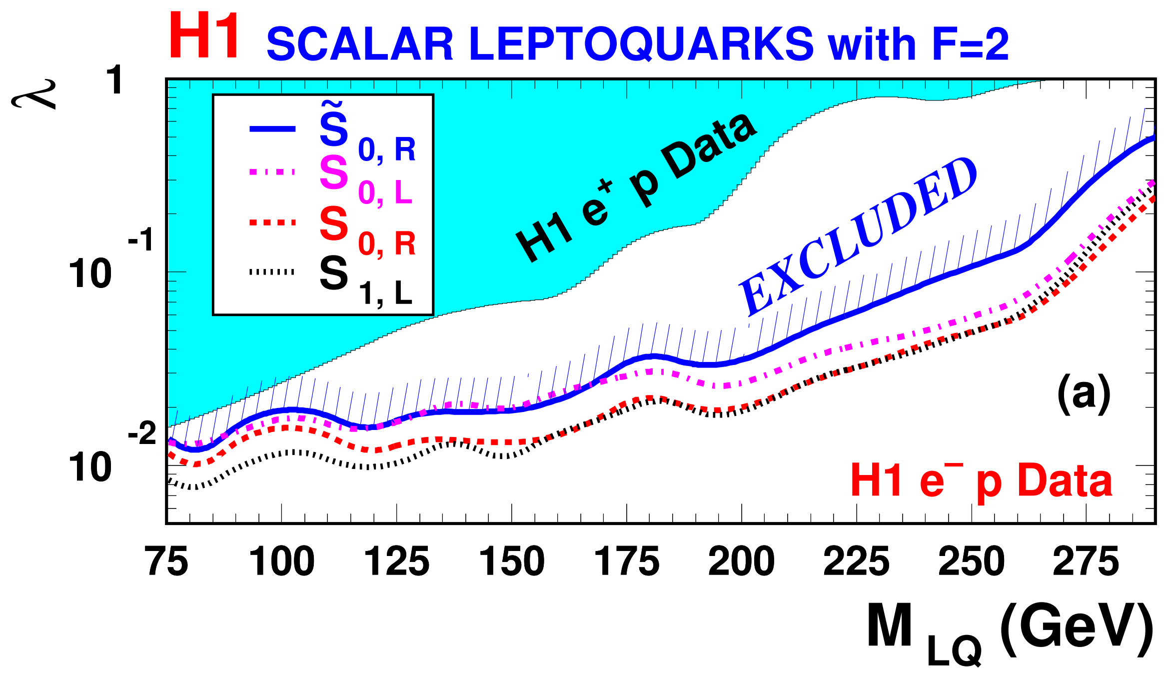


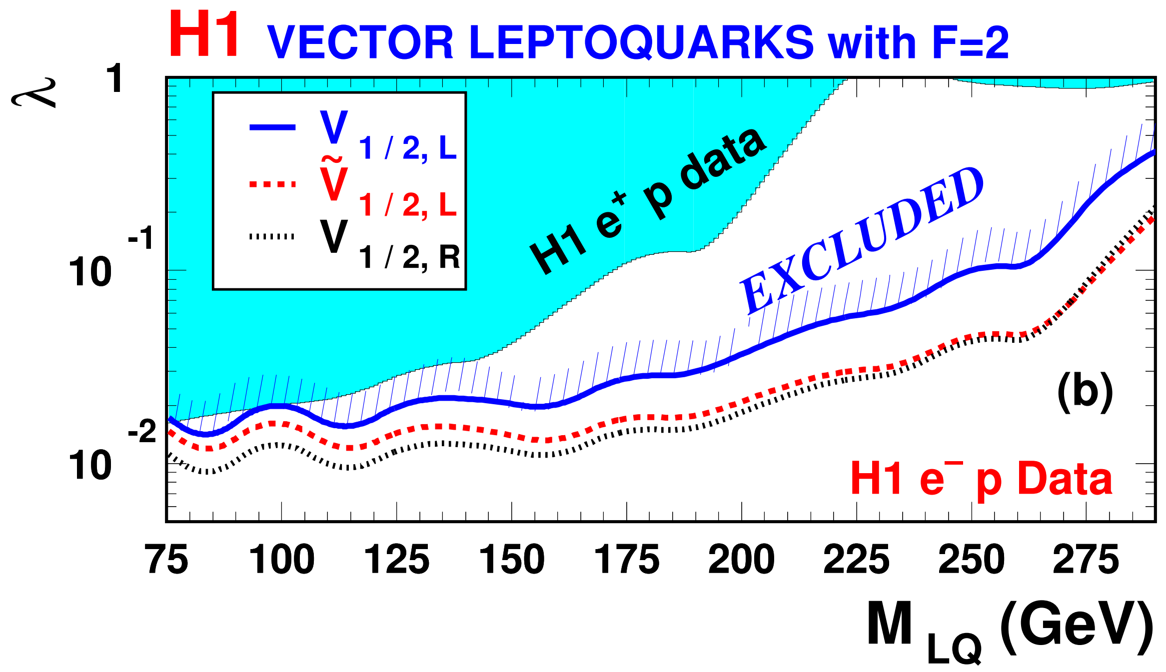
$\Rightarrow$ Good agreement with SM expectation for both experiments

$\Rightarrow$ Limits on couplings and branching ratios (BR) are derived

Limits on Coupling λ

Limits on λ for LQ from BRW model ($\rightarrow$ fixed β)



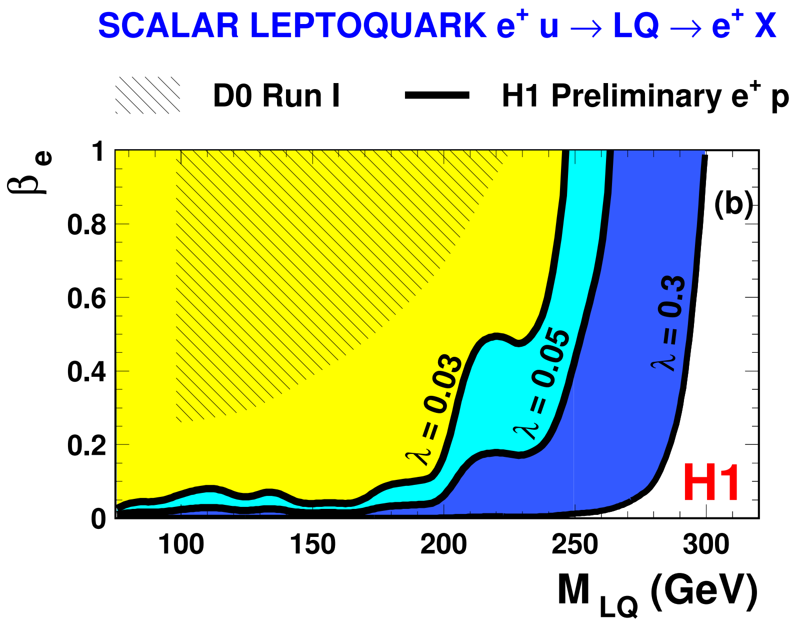


$\Rightarrow$ $e^{-}p$ data specifically sensitive for LQs with $F = 2$

$\Rightarrow$ for couplings $\lambda = \sqrt{4\pi\alpha_{\rm em}} \simeq 0.3$:
$M_{\rm LQ} < 275$ GeV excluded on 95% CL

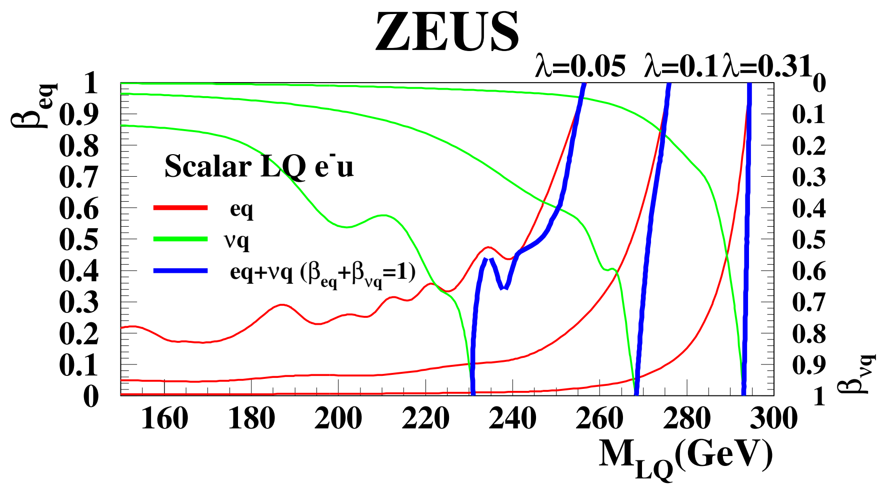
Leptoquark Limits on Branching Ratio β

general limit on β_e



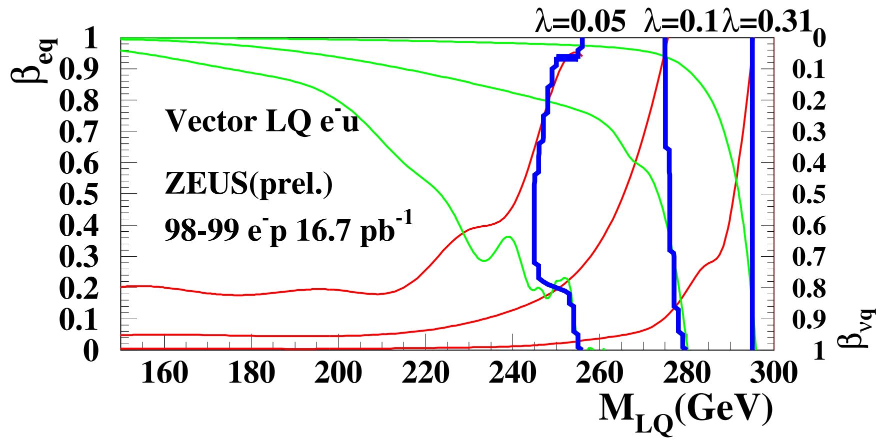
$\Rightarrow$ HERA extends limits to small branching ratios β_e

$\Rightarrow$ HERA limits more stringent than TeVatron limits for large values of λ (TeVatron limits independent on λ)



$\longleftarrow$ SCALAR LQ

combined limit assuming $\beta_e + \beta_\nu = 1$ almost independent of β

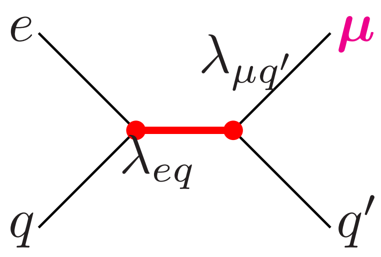


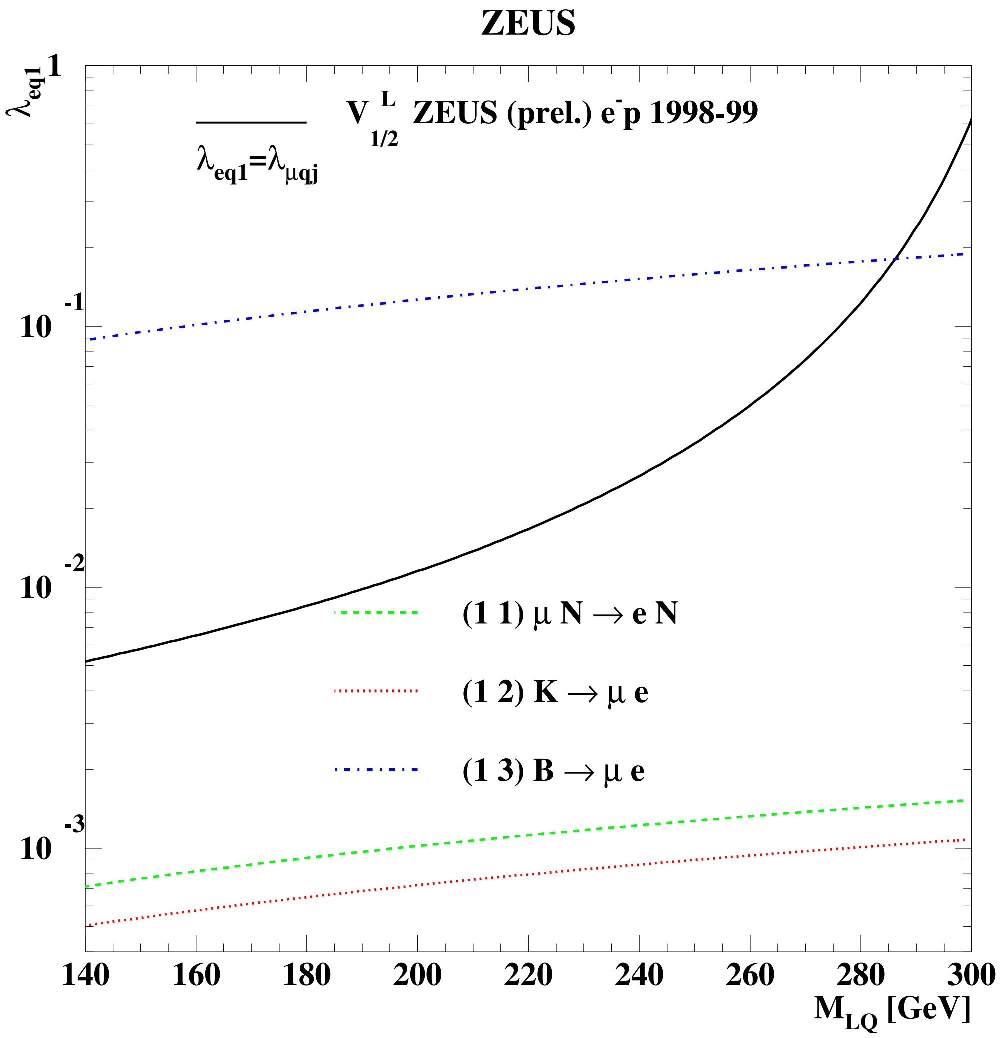
$\longleftarrow$ VECTOR LQ

Lepton Flavour Violation

- Search for processes $eq \rightarrow \mu q'$ or $eq \rightarrow \tau q'$ (LFV)
  $\Rightarrow$ Mediation via LQs possible

two coupling constants involved: $\boldsymbol{\lambda_{eq}}$ and $\boldsymbol{\lambda_{\mu q'}}$





$\boldsymbol{V^{L}_{1/2}}$:
$(\beta_{\mu q} = 0.5)$

assuming
$\lambda_{eq_1} = \lambda_{\mu q_j}$

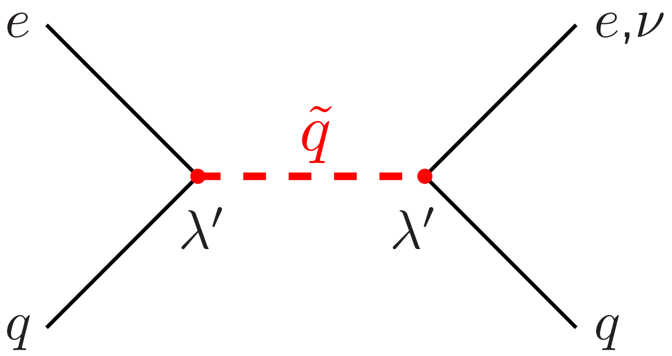
- Sensitivity on heavy quarks (b):
  More stringent limit on λ compared to low energy experiments

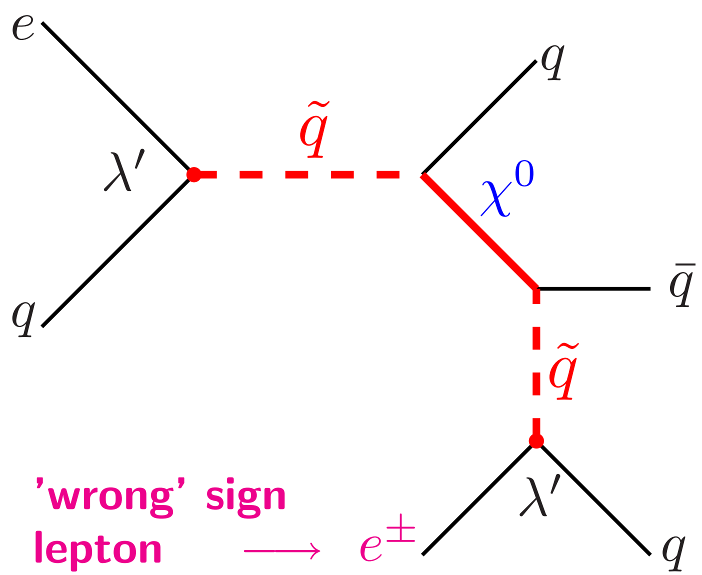
R-Parity Violating Supersymmetry

- $R_p = (-1)^{L+3B+2S}$ broken
  $\Rightarrow$ SUSY particles ($R_p = -1$) singly produced and LSP not stable

- At HERA $\lambda'_{1jk}\mathrm{LQ\bar{D}}$ Yukawa couplings can be tested $\longrightarrow$ Lepton Number Violation (especially sensitiv to $eq \to \tilde{t}$)

- look for resonant particle production decays:





No signal observed in 94-97 data

$\Downarrow$

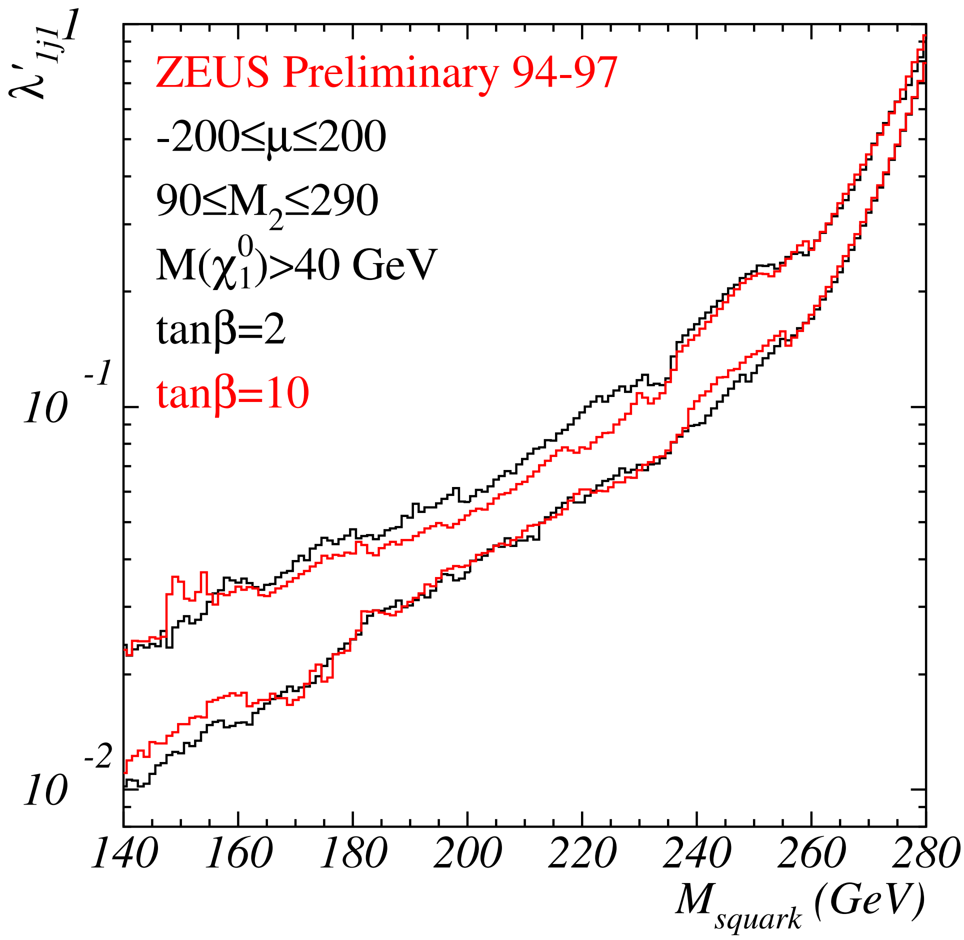
SUSY parameter scan for exclusion limits

R-Parity Violating Supersymmetry

Unconstrained (phenomenological) MSSM:

Assume that sfermions and gaugino sector not related
$\Rightarrow$ sfermion masses $M_{\tilde{q}}$, $M_{\tilde{l}}$ free parameters

Limits variation in parameter scan:

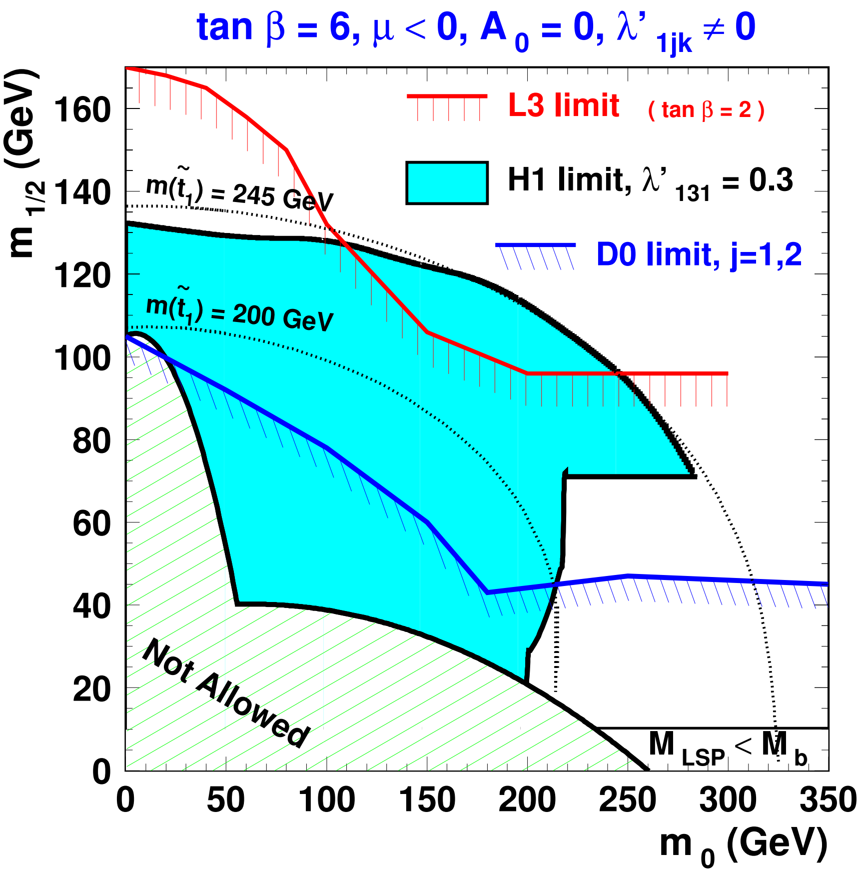


- Limits are widely model independent
- $\lambda'_{1j1} = 0.3$ (elem. strength):
  $M_{\tilde{q}} < 260$ GeV are excluded at 95% CL

R-Parity Violating Supersymmetry

- **Constrained models:**
  - Sfermion and gaugino sector related by RGE
  - $m_0 =$ common fermion mass at GUT scale
  - $m_{1/2} =$ common gaugino mass at GUT scale

- **particular case of minimal Supergravity (mSUGRA):**
  - additional assumption: electroweak symmetry breaking driven by radiative corrections
    $\Rightarrow$ only 5 parameters: m_0, $m_{1/2}$, sign(μ), tan β, A_0



Bounds from LEP and TeVatron independent on λ'

HERA probes domain not ruled out by D0

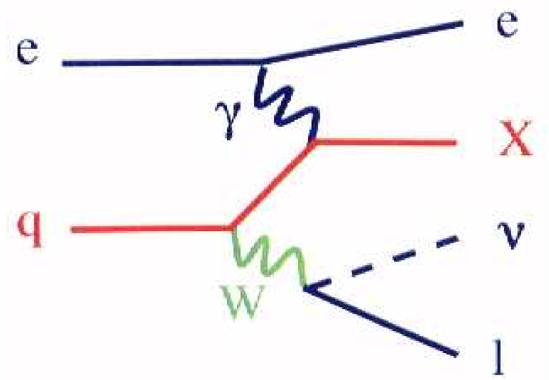
High P_T Lepton Events

- Excess of High P_T isolated lepton events with large missing transverse momentum observed by H1

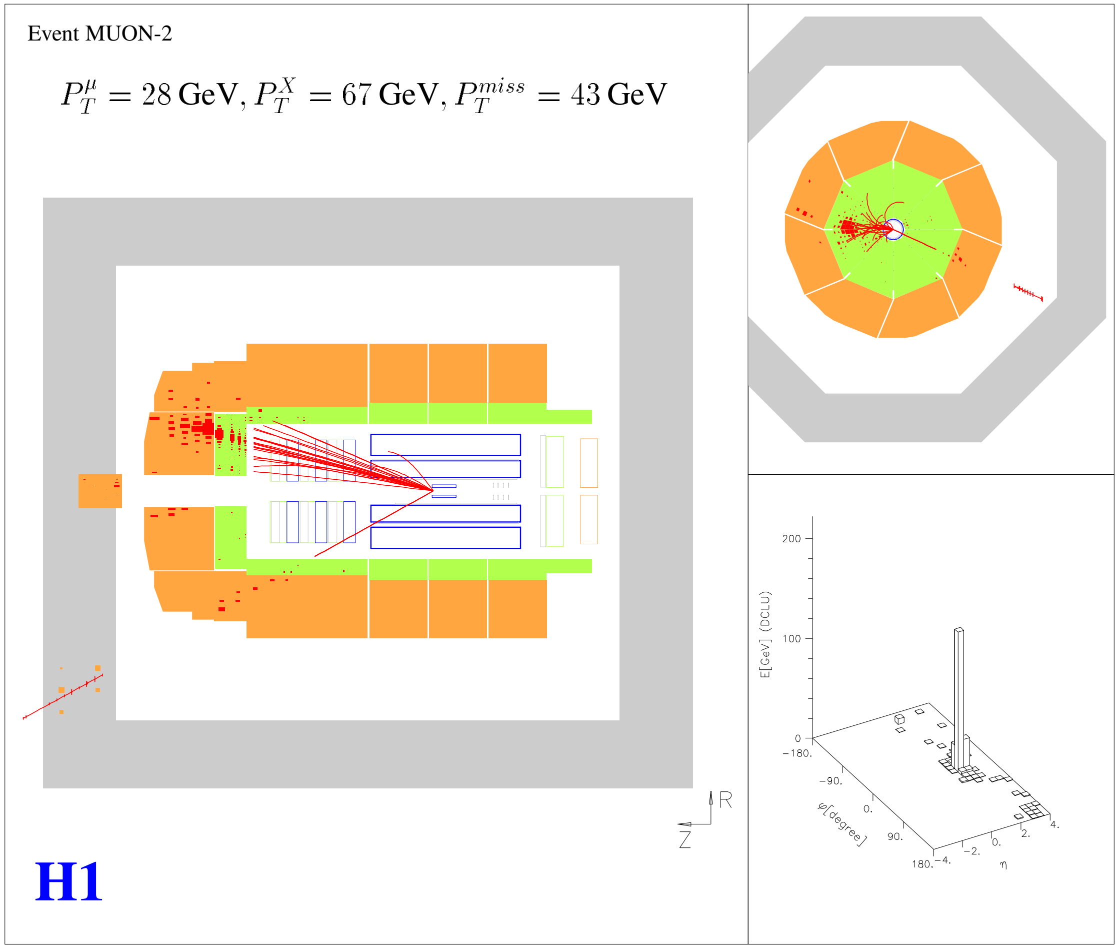
  (H1 Coll. Eur.Phys.J. C5(1998)575)

- Topology of the events:
  - High Energy Lepton
  - Lepton is **isolated**: large distance to tracks & jets
  - Missing P_T
  - High P_T Jet (P_T^X)

- Most likely SM interpretation is W production



$$e^+p \to \mu^+X$$



High P_T Lepton Events

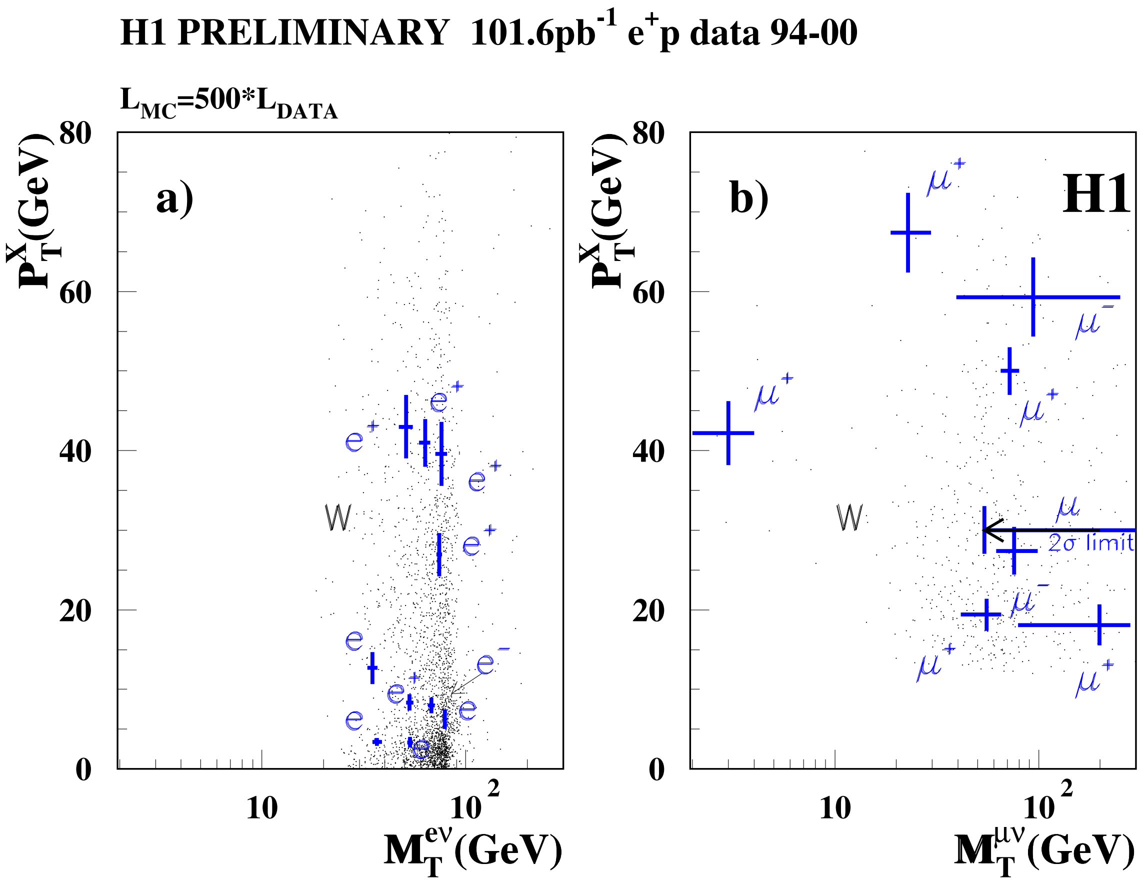
H1 preliminary 94-00 e^+p ($101.6\,\mathrm{pb}^{-1}$)	**Electron** Obs./expected (W)	**Muon** Obs./expected (W)	**combined** Obs./exp.
$p_T^X > 25$ GeV	$4/1.29 \pm 0.33$ (1.05)	$6/1.54 \pm 0.41$ (1.29)	$10/2.8 \pm 0.7$
$p_T^X > 40$ GeV	$2/0.41 \pm 0.12$ (0.40)	$4/0.58 \pm 0.16$ (0.53)	$6/1.0 \pm 0.3$

$\Rightarrow$ more events than expected from SM processes at high P_T^X in H1 for e^+p data
$\Rightarrow$ in e^-p data (14 pb^{-1}) no deviations seen ($0/1.8 \pm 0.4$)

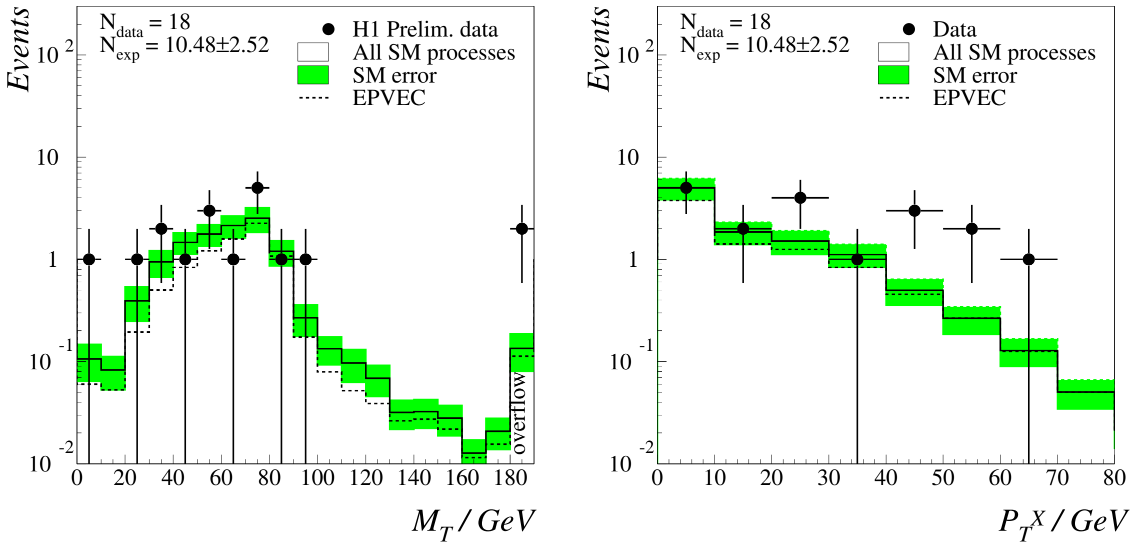
ZEUS preliminary 94-00 $e^{\pm}p$ ($130\,\mathrm{pb}^{-1}$)	**Electron** Obs./expected (W)	**Muon** Obs./expected (W)	**combined** Obs./exp.
$p_T^X > 25$ GeV	$1/1.14 \pm 0.06$ (1.10)	$1/1.29 \pm 0.16$ (0.95)	$1/2.4 \pm 0.22$
$p_T^X > 40$ GeV	$0/0.46 \pm 0.03$ (0.46)	$0/0.50 \pm 0.08$ (0.41)	$0/0.96 \pm 0.1$

$\Rightarrow$ Good agreement with SM expectation for ZEUS

Kinematics of High P_T Lepton Events



- Isolated leptons at hight P_T^X have all positive charge except one μ-event



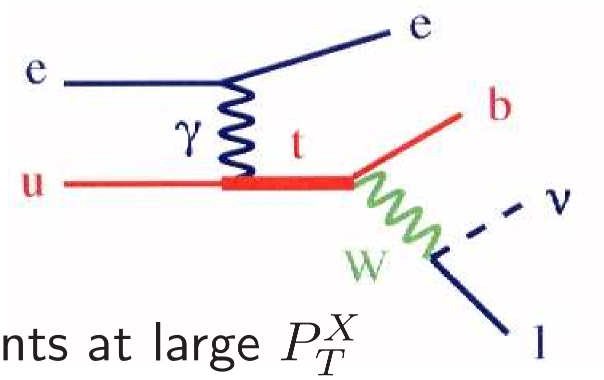
Result in agreement with W interpretation

However, excess at high P_T^X

Anomalous Single Top Production

- Single Top production in SM is negligible
  ⇒ top signal would indicate New Physics

- Production via Flavour Changing Neutral Currents due to anomalous coupling κ_γ

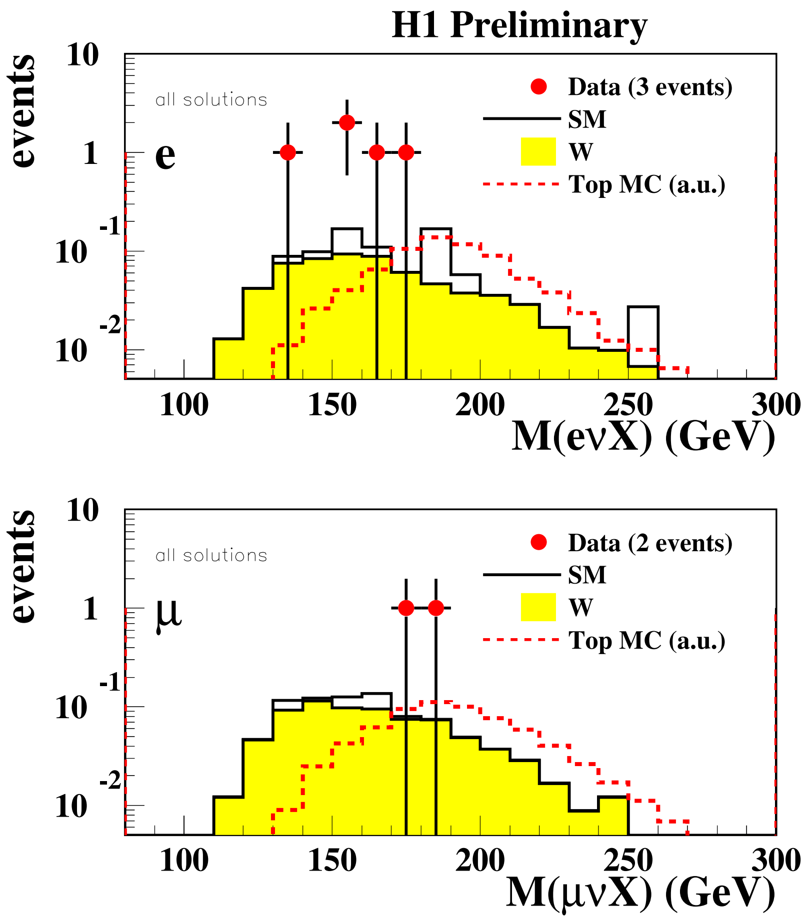


- H1 excess of high P_T lepton events at large P_T^X
  ⇒ Search for Anomalous Single Top:

$W \to l\nu$

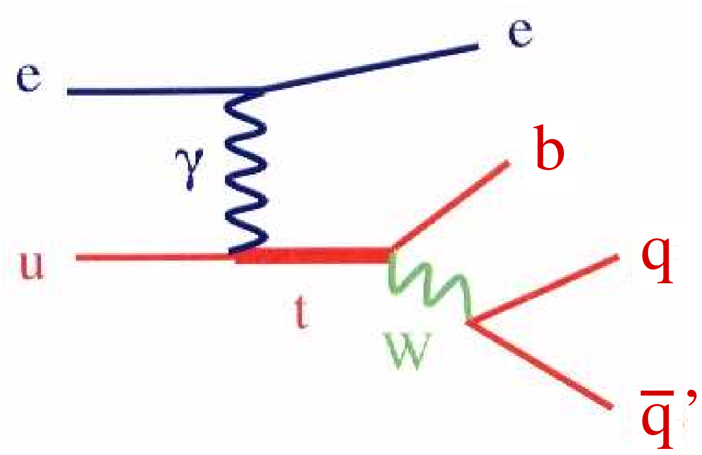
prelim.	Data/SM
H1	$5/1.8 \pm 0.5$
ZEUS	$0/1.0$

Several H1 events are compatible with top hypothesis



Anomalous Single Top Production

- **Hadronic W decay:** 3 jets in final state

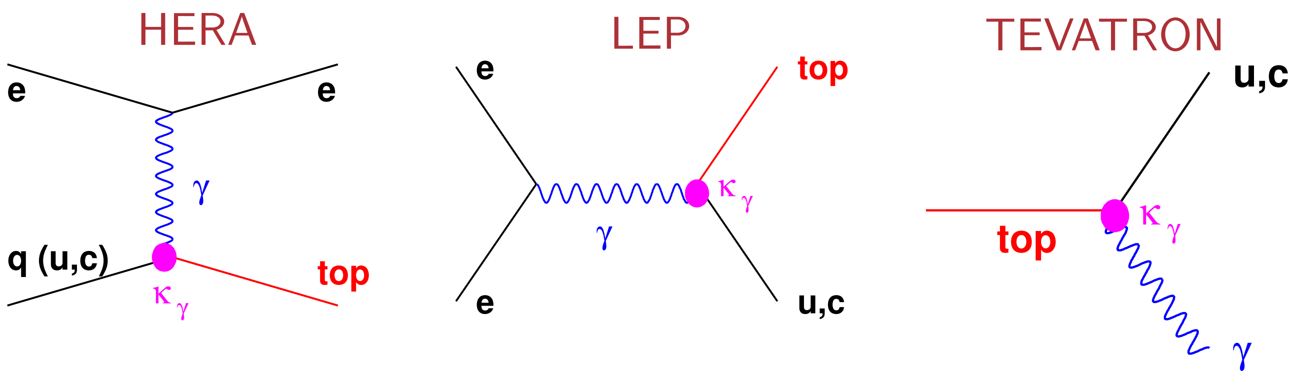


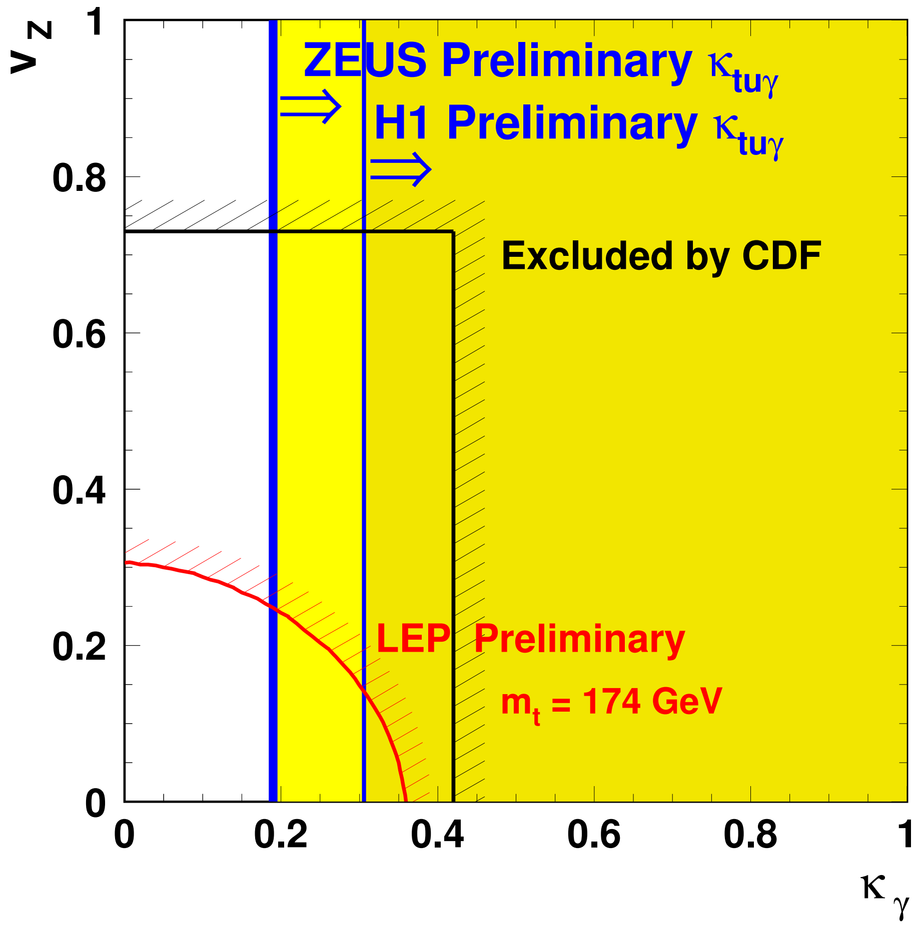
	Data/SM
H1 prel.	$10/8.3^{+4.2}_{-1.9} \pm 4.2$
ZEUS prel.	$19/20.0$

$\Rightarrow$ No visible excess compared to SM

$\Rightarrow$ Limits on Anomalous Top Couplings are derived

Limits on Anomalous Top Couplings





v_Z:
anomalous tqZ (vector) coupling

κ_γ:
anomalous $tq\gamma$ (magnetic) coupl.

H1 95% CL limit: $\kappa_{tu\gamma} < 0.305$
ZEUS 95% CL limit: $\kappa_{tu\gamma} < 0.19$

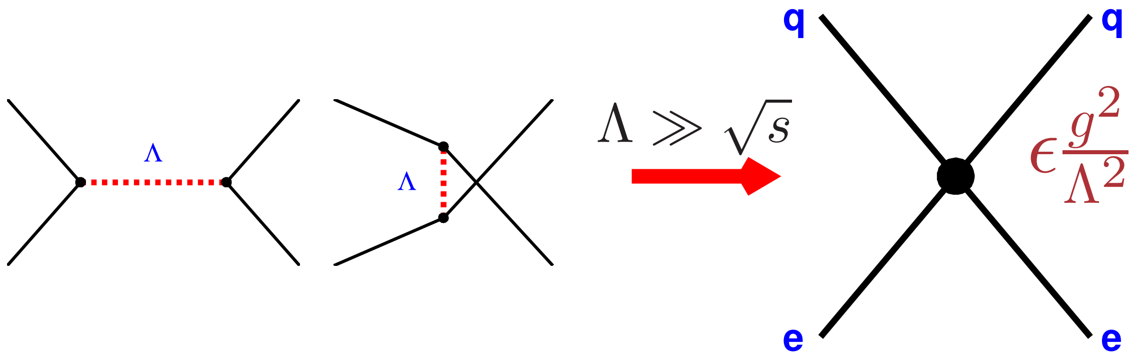
$\Rightarrow$ HERA limits are competetive with LEP and TeVatron

Contact Interactions

- Contact Interaction formalism allows for **indirect searches** of physics beyond SM

- At large scales $\Lambda \gg \sqrt{s}$:
  New physics possibly observable as deviations from SM prediction due to virtual exchange of new particles
  $\longrightarrow$ e.g. distorsion of Q^2-spectrum at high Q^2

- Parametrisation as effective low energy approximation



propagators contract to pointlike four fermion CI with effective coupling g^2/Λ^2

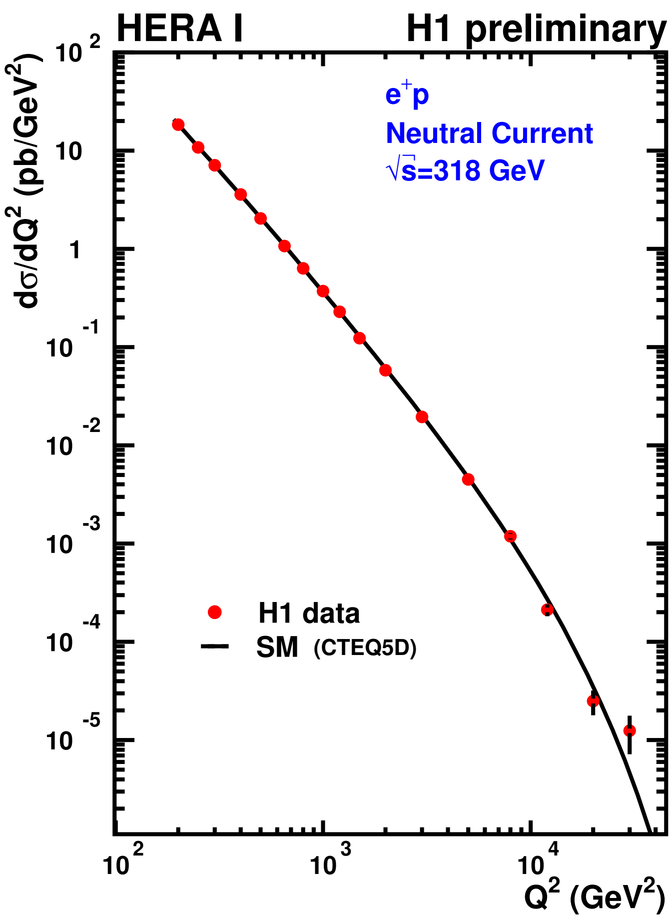
- Effective Lagrangian: (vector terms only)

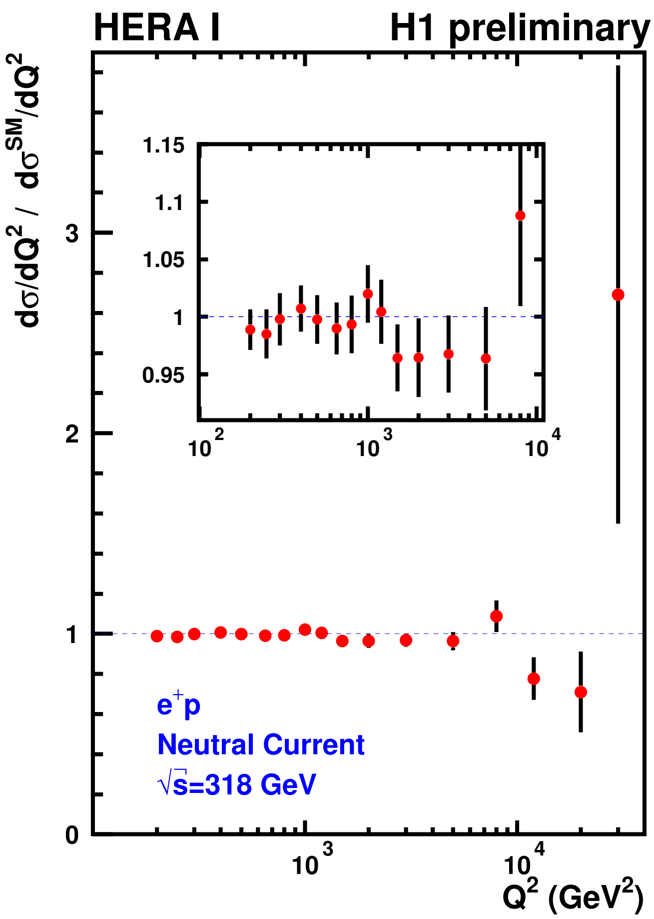
$$\mathcal{L}_{CI} = \sum_{q=u,d} \sum_{a,b=L,\,R} \eta^q_{ab} (\bar{e}_a \gamma_\mu e_a)(\bar{q}_b \gamma^\mu q_b)$$

8 couplings:
$\eta^q_{ab} \equiv \pm(g/\Lambda^q_{ab})^2$

- Different chiral structures are considered

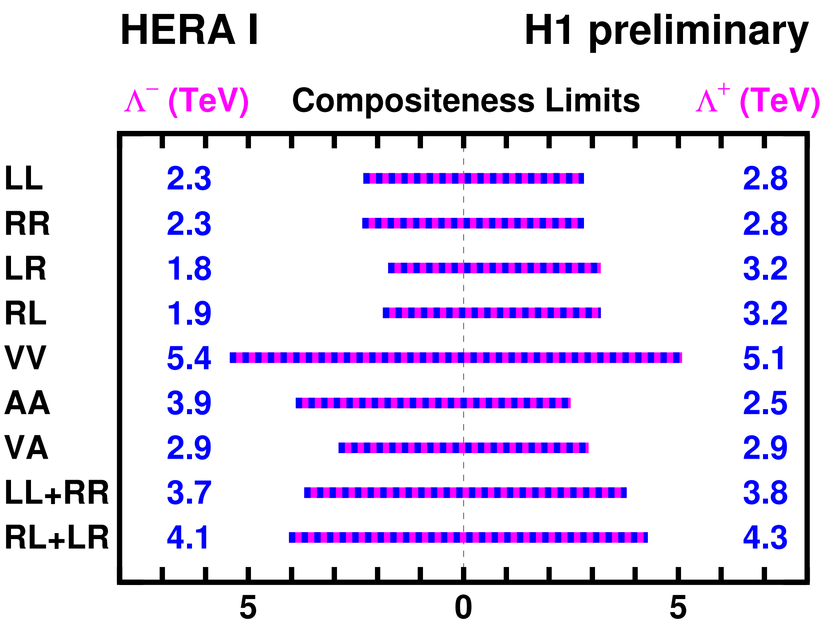
Contact Interactions





No significant deviations from SM prediction seen

$\Rightarrow$ Limits on Λ for different CI scenarios



95% CL limits derived with frequentist approach for pos./neg. interference

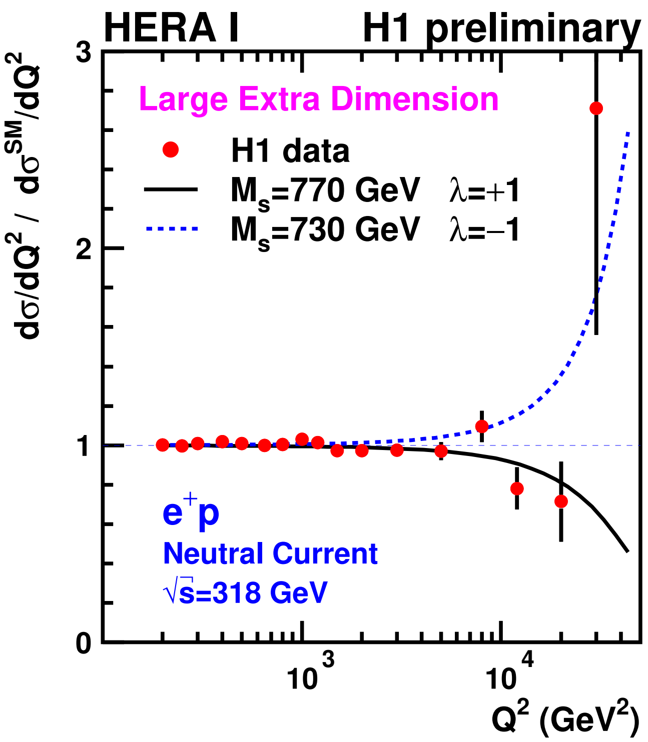
H1 limits between 1.8 GeV and 5.4 GeV (similar to ZEUS)

Comparable to LEP and TeVatron

Large Extra Dimensions

- Space time with (4+n) dimensions (Arkani-Hamed et al.):
  - SM particles are confined in 4D world
  - Gravitions propagate also in n extra dimensions which are compactified to radius R
  - R could be large (!): $R \sim 1/M_s$ with $M_s \sim \mathcal{O}(1\,TeV)$
- Contribution of graviton exchange to $eq \to eq$ scattering can be described by an effective CI with couplings $\eta_s = \lambda/M_s^4$
- Limits are derived on scale M_s for $\lambda = \pm 1$

Cross Section Ratios



HERA I data

95% CL limits on M_s	$\lambda=+1$ (TeV)	$\lambda=-1$ (TeV)
H1 prel.	0.83	0.79
ZEUS prel.	0.81	0.82

$\Rightarrow$ ZEUS and H1 give very similar limits

Summary

- HERA unique collider to study eq interactions at high energies
  $\Rightarrow$ ideal to look for new particles coupling to eq pairs

- **No** evidence for Physics beyond SM at HERA I
  $\Rightarrow$ constraints on new physics were presented**:**

  - Leptoquarks
    ($F = 2$ **:** $M_{\mathrm{LQ}} < 275$ GeV excl. for $\lambda = 0.3$)
  - Lepton Flavour Violation
  - R_p violating SUSY
    (unconstrained MSSM**:** $M_{\tilde{q}} < 260$ GeV for $\lambda'_{1j1} = 0.3$)
  - Contact Interactions
  - Large Extra Dimensions
    ($M_S < 0.79$-0.83 TeV excluded)
  - Anomalous Top Production
    ($\kappa_{tu\gamma} < 0.19$ excluded)

- Search for Isolated Lepton Events still puzzling...

- Limits are competetive or complementary to LEP and TeVatron

Outlook

- **Luminosity Upgrade and Detector Upgrades completed**
  - Improved Detectors
    $\Rightarrow$ Increased Sensitivity
  - New focussing Magnets
    $\Rightarrow$ Increased Luminosity

- HERA II will give $\mathbf{1}\ \mathrm{fb}^{-1}$ in ~ 5 years
  (Factor 10 increase)

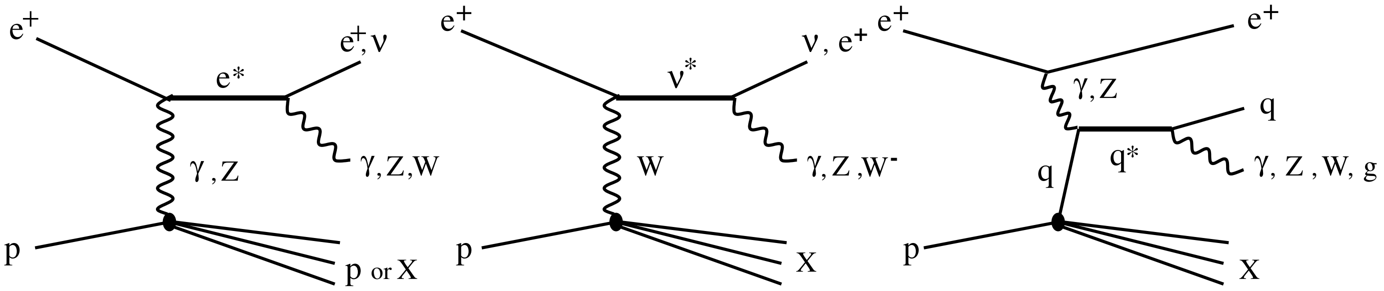
- polarised $e^{\pm}$ beams will give additional informations
  e.g. increased squark production cross section

Searches have an exciting future at HERA !

Excited Fermions

- Excited fermions f^* $\Leftrightarrow$ evidence for compositeness

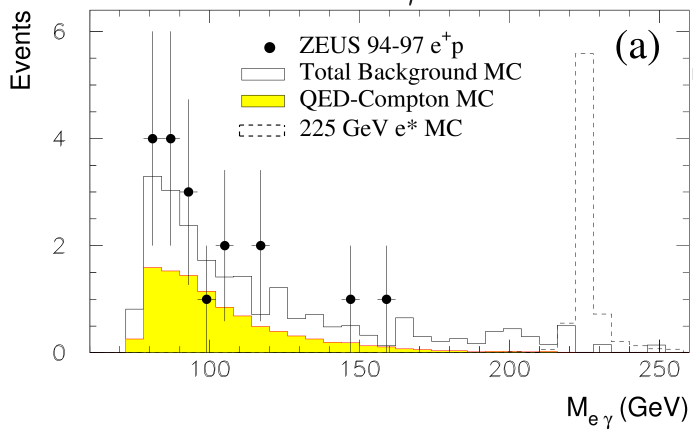
- Single Production of e^*, ν^*, q^* at HERA considered:



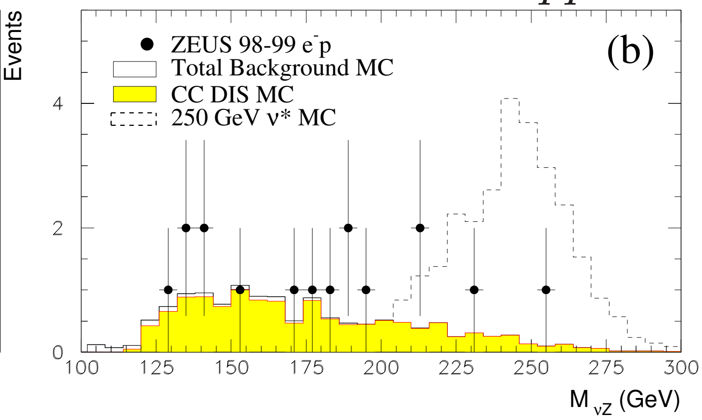
- Search for different final state topologies

Mass distributions

ZEUS: $e^* \rightarrow e\gamma$



ZEUS: $\nu^* \rightarrow \nu Z \rightarrow \nu q\bar{q}$



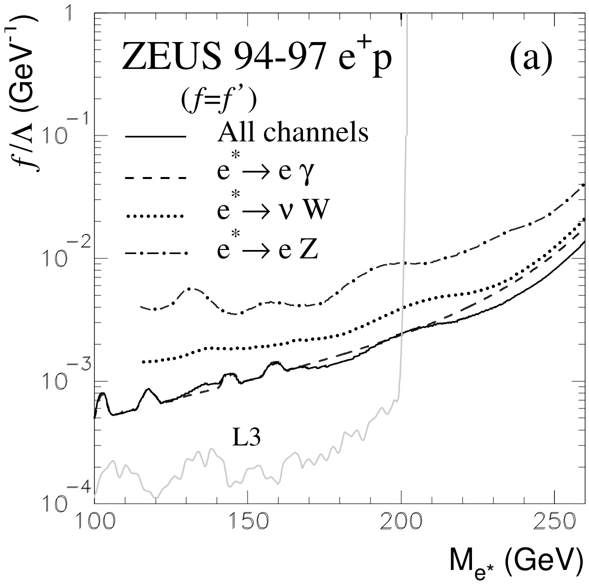
- (De-)excitation described by effective Lagrangian (Hagiwara et al.)

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

Λ: Compositeness scale
f, f', f_s: gauge group weights $\leftrightarrow$ coupling strengths

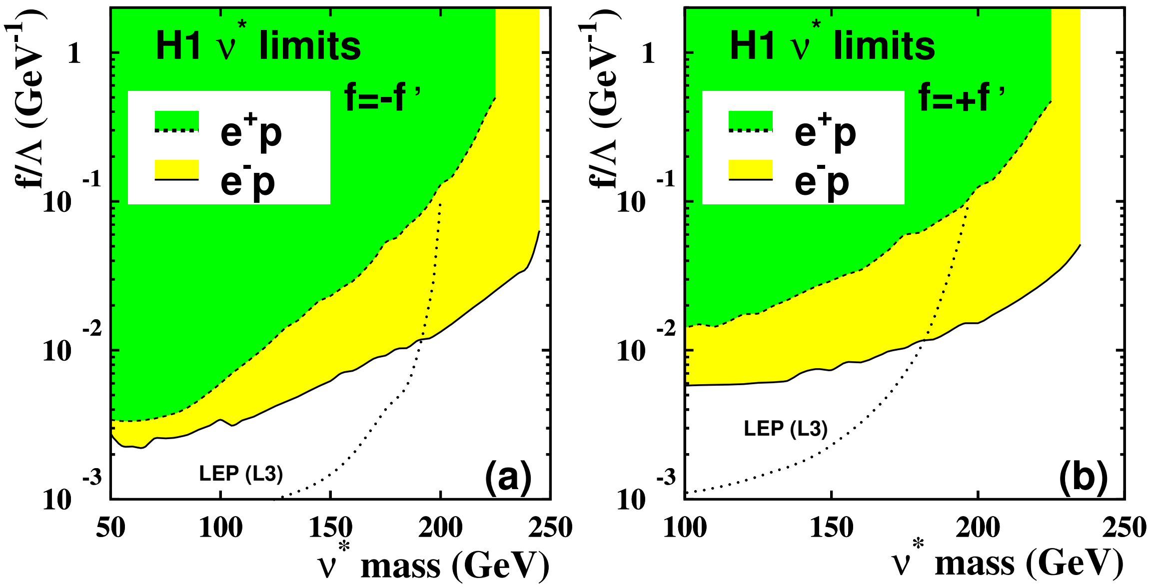
Excited Fermions

- 95% CL limits on f/Λ for e^* under assumption $f = f'$



$$e^* \longrightarrow e\gamma$$
$$e^* \longrightarrow \nu W$$
$$e^* \longrightarrow eZ$$

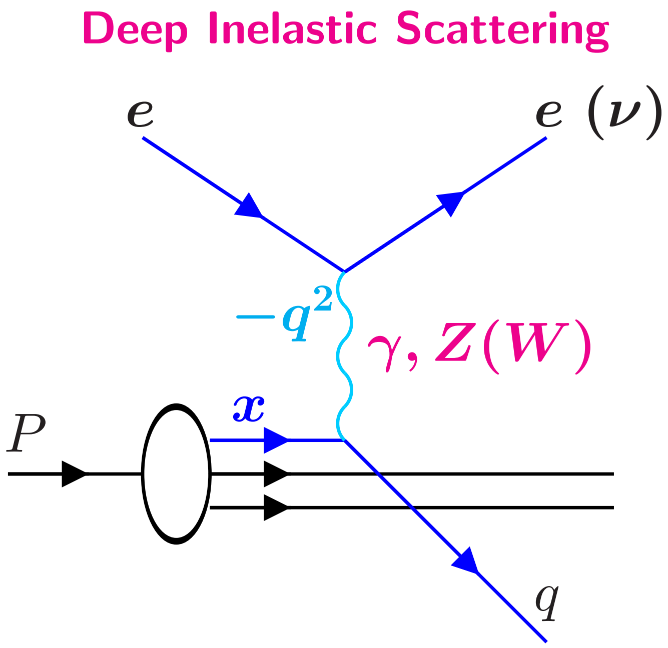
- 95% CL limits on f/Λ for ν^* under assumption $f = \pm f'$



- Much larger cross section for possible ν^* production in e^-p compared to e^+p (higher sensitivity)

- HERA limits more stringent at high masses beyond the kinematic reach of LEP II

HERA Kinematics



- $Q^2 = -q^2 = xys$
  Four momentum transfer (virtuality)

- $x = \frac{Q^2}{2p \cdot q}$
  Quark momentum fraction carried by the struck q

- $y = \frac{p \cdot q}{p \cdot l} = \frac{1}{2}(1 + \cos\theta^*)$
  Inelasticity
  θ^*: polar angle of lepton in the eq cms frame

- $M = \sqrt{xs}$
  quark-lepton invariant mass