The XVIth International Workshop
High Energy Physics and Quantum Field Theory
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Search for New Particles at HERA

On behalf of the
H1 and ZEUS
Collaborations

- Kinematics at HERA
- H1 and ZEUS Detectors
- Inclusive Searches:
  - Contact Interactions
  - Extra Dimensions
  - Leptoquarks
- Exclusive Searches:
  - Lepton Flavour violation
  - Squarks produced by $\not{R}_p$
  - Excited fermions
  - Observation of isolated lepton events
  - Single top production
- Conclusion and Prospects

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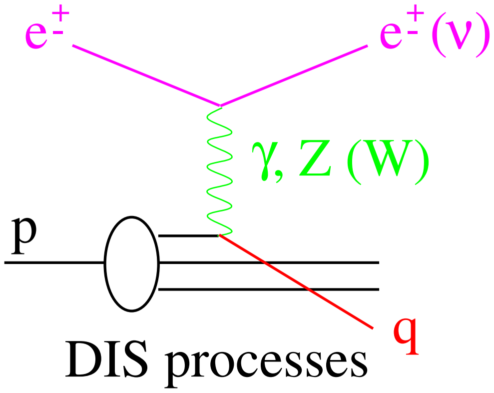
Kinematics at HERA



$$\begin{cases} E_e = 27.5 \text{ GeV} \\ E_p = 920(820) \text{ GeV} \end{cases}$$

$$\Rightarrow \sqrt{s} = 318(300) \text{ GeV}$$

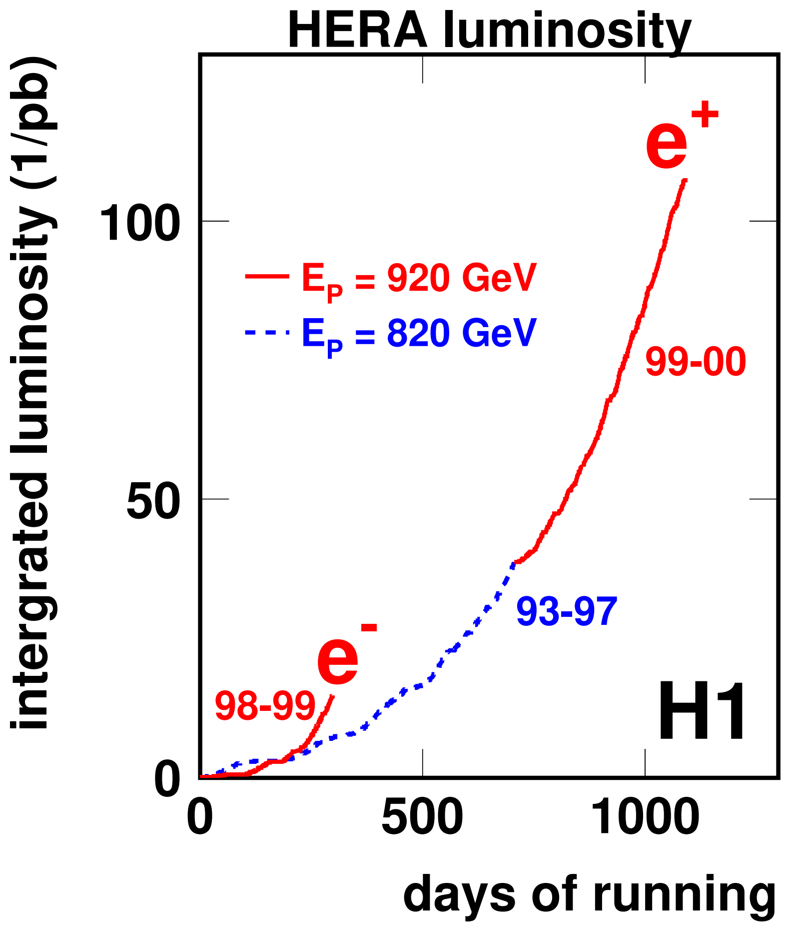
$\Rightarrow$ Ideal to look for NEW PARTICLES coupling to eq pairs.

- $\sqrt{s} = \sqrt{4E_eE_p}$: Centre-of-mass energy
- $Q^2 = -q^2 = xys$: Virtuality
- $x = \frac{Q^2}{2p.q}$:
  Fraction of the p carried by the struck q
- $y = \frac{p.q}{p.k} \propto (1 - \cos\theta^*)$:
  Retrodiffusion angle in eq system
- θ^*: Electron angle in the eq center-of-mass
- $M = \sqrt{xs}$: Quark-lepton invariant mass

HERA Luminosities

Year	Collision	$\sqrt{s}$(GeV)	H1	ZEUS
94-97	e^+p	300	~ 36 pb^{-1}	~ 48 pb^{-1}
98-99	e^-p	318	~ 14 pb^{-1}	~ 16 pb^{-1}
99-00	e^+p	318	~ 65 pb^{-1}	~ 64 pb^{-1}
Total			~ 115 pb^{-1}	~ 128 pb^{-1}

$\Rightarrow$ More than 100 pb^{-1} per experiment.

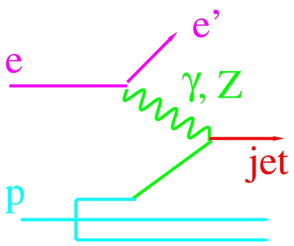


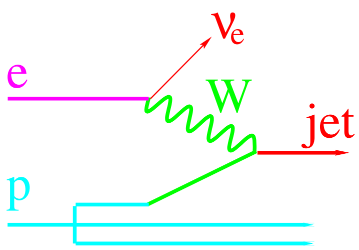
$\Rightarrow$ e^+p data have more than doubled in 1999-2000.

Processes at HERA

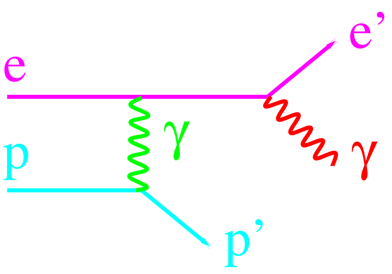
- High P_T SM processes at HERA:

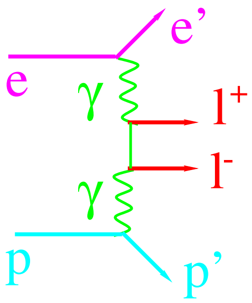
- Neutral Current (NC) $ep \to eqX$
- Charged Current (CC) $ep \to e\nu X$



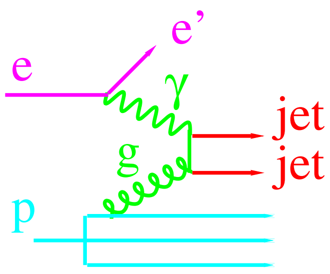


- QED Compton $ep \to ep\gamma$
- Lepton Pair Production $(\gamma\gamma)$ $ep \to l^+l^-$

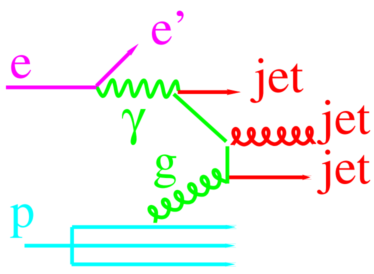




- Photoproduction (γp) $ep \to eqq(q)$

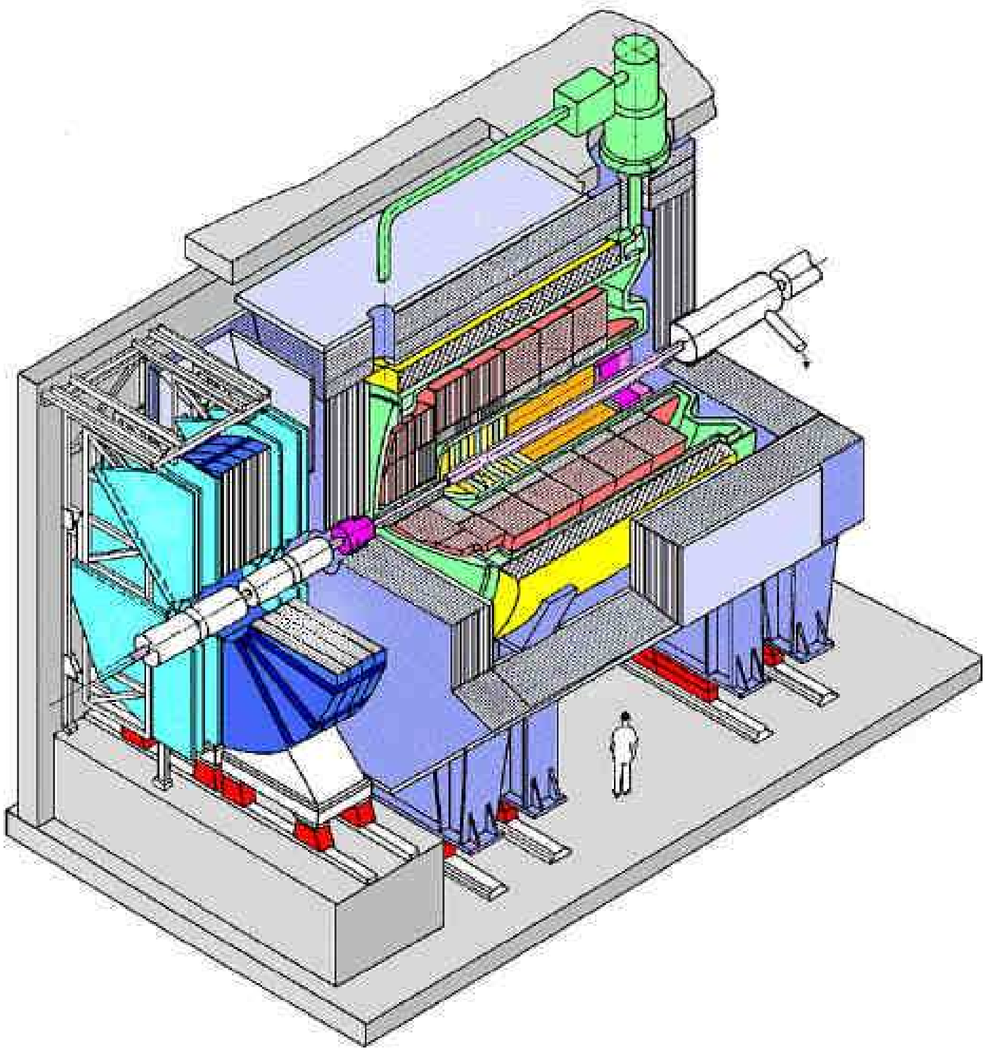


Direct



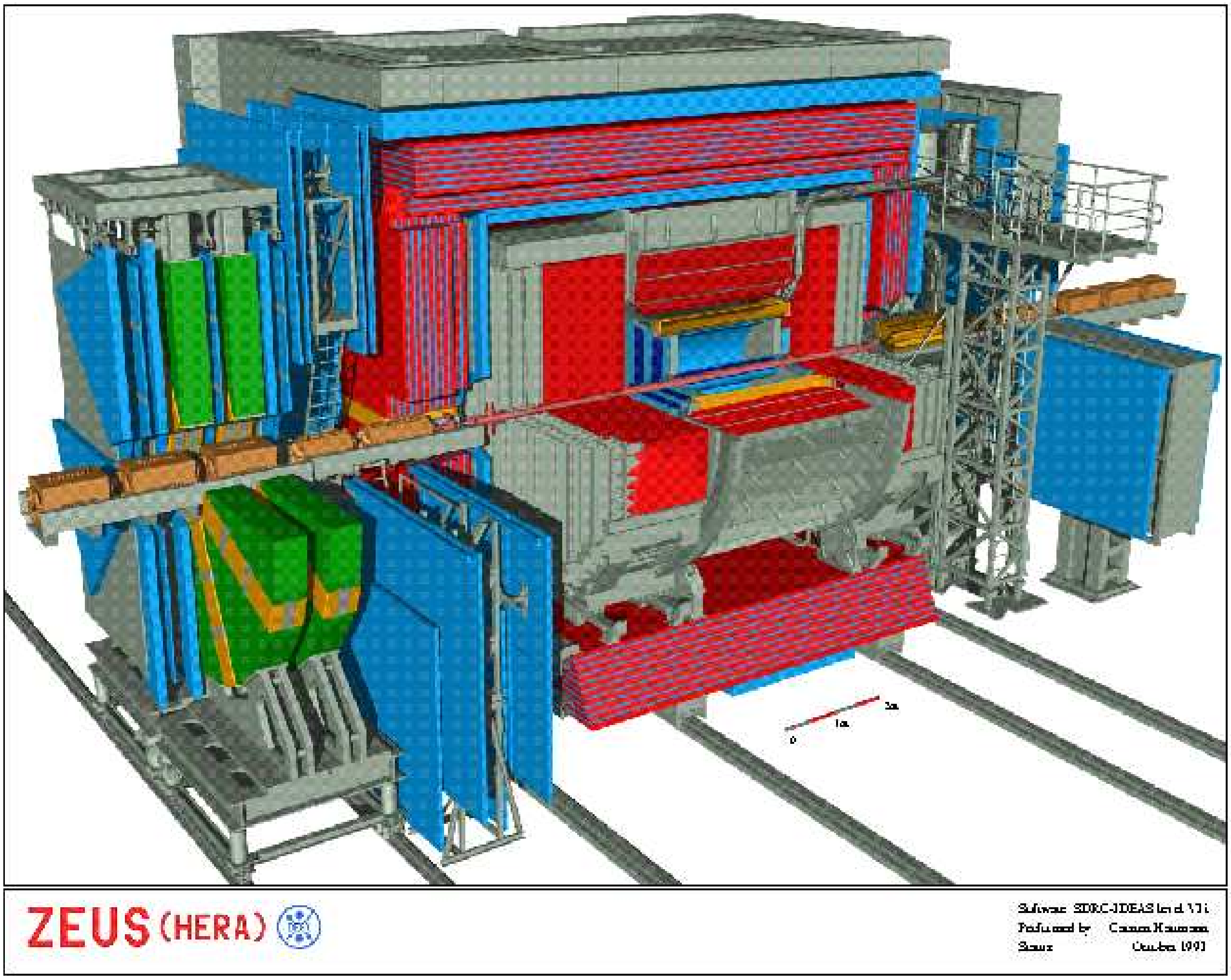
Resolved

H1 Detector



- Drift and Proportional Chambers
- Liquid Argon Calorimeter:
  - $\sigma(E)/E(EM) \approx 12\%/\sqrt{E/GeV} \oplus 1\%$
  - $\sigma(E)/E(had) \approx 50\%/\sqrt{E/GeV} \oplus 2\%$
- Muon System

ZEUS Detector



- Drift and Proportional Chambers
- Uranium-Scintillator Calorimeter:
  - $\sigma(E)/E(EM) \approx 18\%/\sqrt{E/GeV} \oplus 1\%$
  - $\sigma(E)/E(had) \approx 35\%/\sqrt{E/GeV} \oplus 2\%$
- Muon System

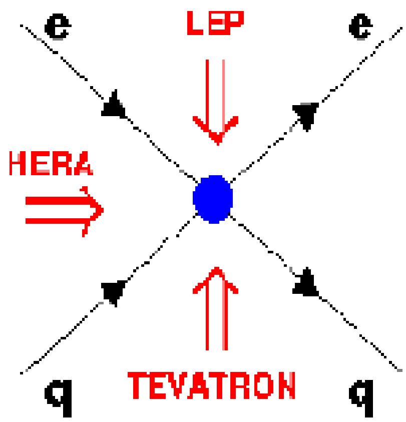
Contact Interactions (1)

- Introduction:

- Indirect Search for New Physics
- Describes effects of New Physics for an Effective Mass Scale $\Lambda \gg \sqrt{s}$
- Test models Beyond the SM:
  - Compositeness $\Rightarrow$ limits on mass scale $\Lambda^{\pm}$
  - Extra-Dimensions $\Rightarrow$ limits on scale M_s
  - High mass Leptoquarks $\Rightarrow$ limits on ratio M/λ
  - Quark Form Factor $\Rightarrow$ limits on radius R_q

- Phenomenology:

- Effective theory assuming the 4-fermions Formalism:



Contact Interactions (2)

- Represented by an additional Lagrangian:

$$\mathcal{L}_{CI} = \sum_{a,b=L,R} \eta^q_{ab} (\overline{e_a}\gamma_\mu e_a)(\overline{q_b}\gamma_\mu q_b)$$

with:

- $\eta^q_{ab} = \epsilon \frac{g^2}{(\Lambda^q_{ab})^2}$: Model-Dependant Coefts depending on Quark Flavour and Quark and Electron Chirality
- $\epsilon = \pm 1$: Sign of the interference w.r.t. SM
- g: Coupling Constant (convention: $g^2 = 4\pi$)
- Λ^q_{ab}: Effective Mass Scale

- Analysis Methods:

$\Rightarrow$ Look at deviations from SM in high P_T NC samples: $d\sigma/dQ^2$, Q^2, x and y distributions

- H1:

Distorsions are searched for using a χ^2 fit on the measured cross section

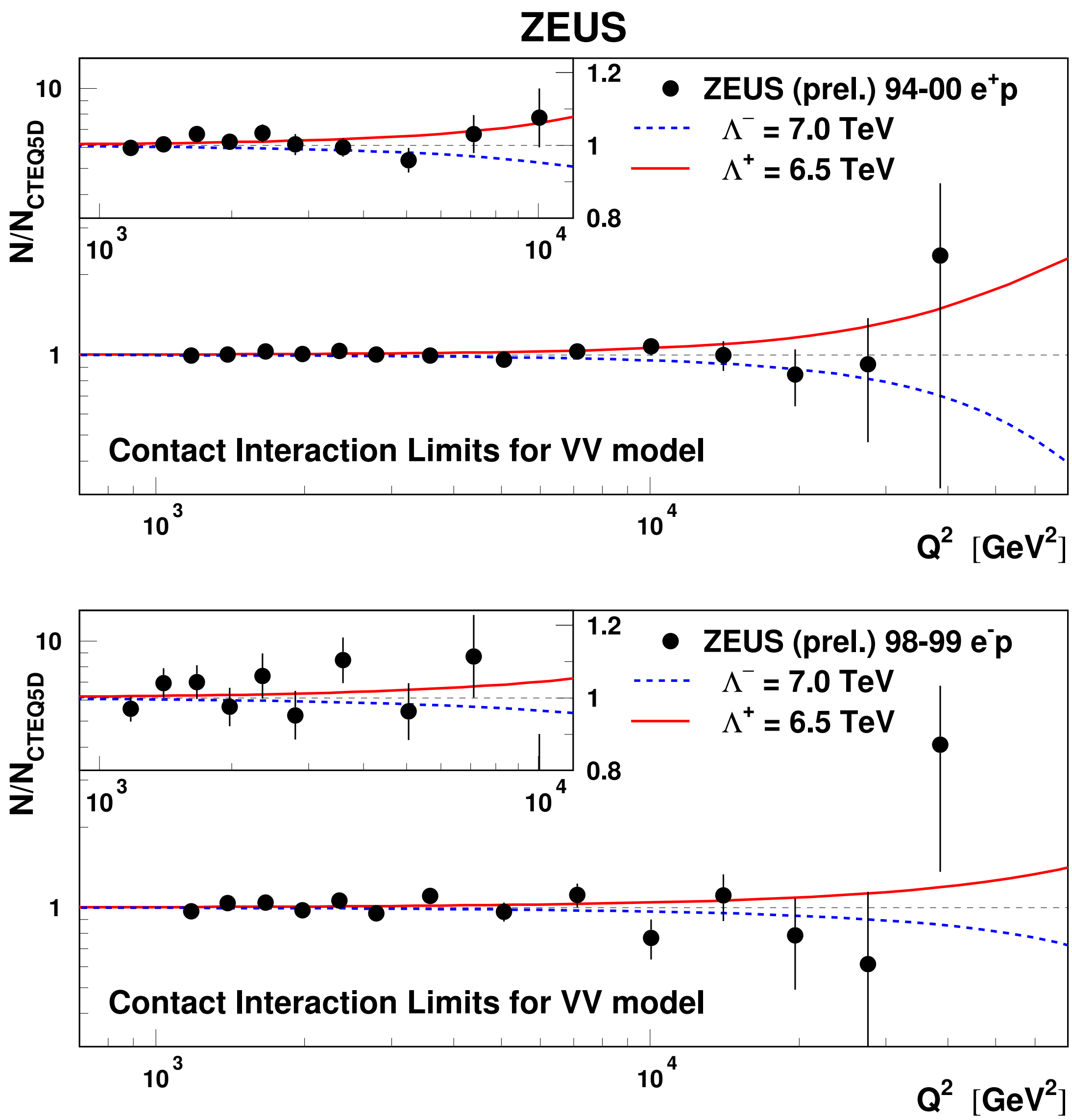
- ZEUS:

Fit the observed event distribution and use a “MC experiment” approach to derive limits.

$\Rightarrow$ Limits on the Mass Scale Λ can be deduced.

Contact Interactions (3)

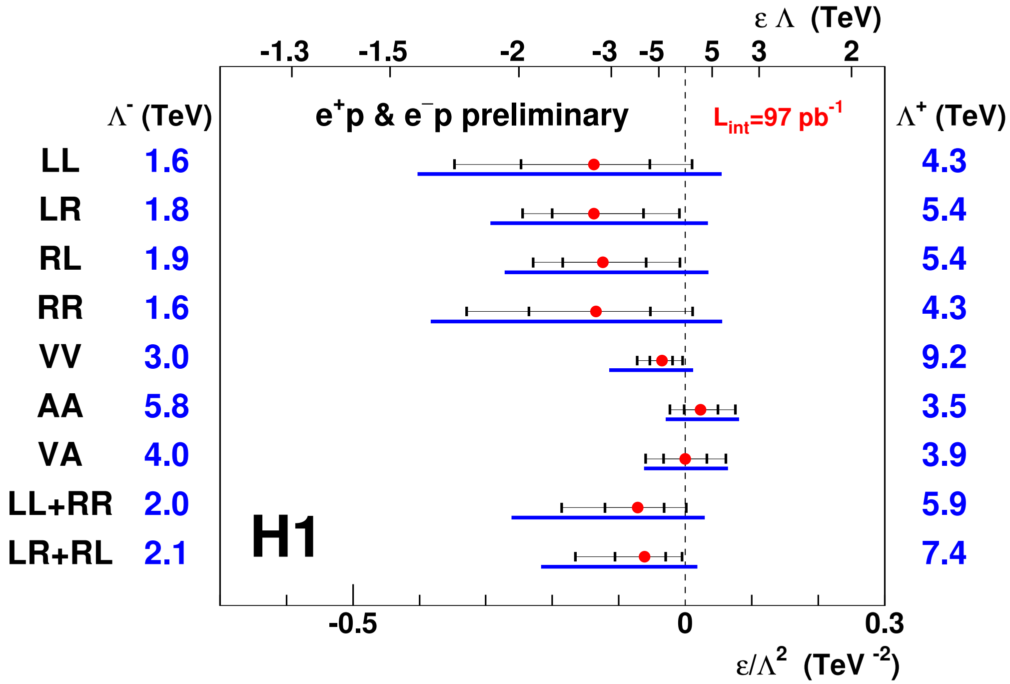
Example of fit in a NC Q^2 distribution:

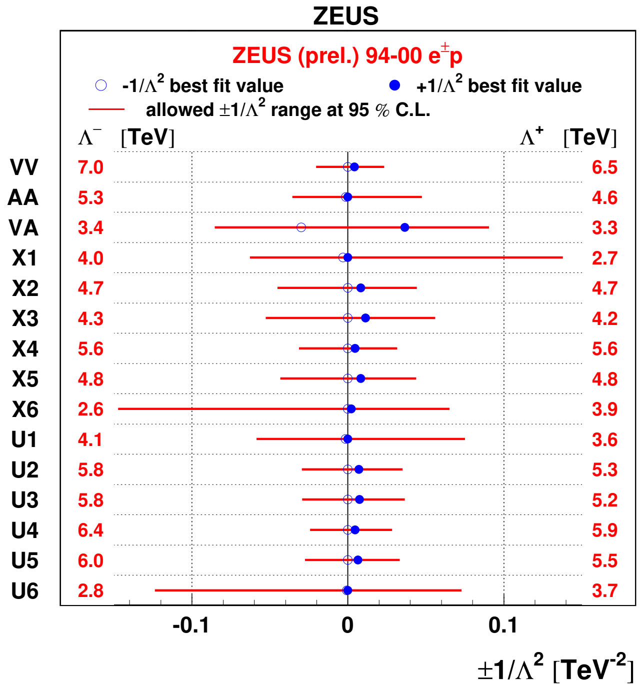


Any deviation at high Q^2 would be evidence of contact interactions.

Contact Interactions (4)

General Compositeness Models:





Data slightly undershoots SM at intermediate Q^2: Λ^- favoured.

Good agreement with SM.

$\Rightarrow \Lambda > 1.6 - 9.2$ TeV

$\Rightarrow \Lambda > 2.6 - 7.0$ TeV

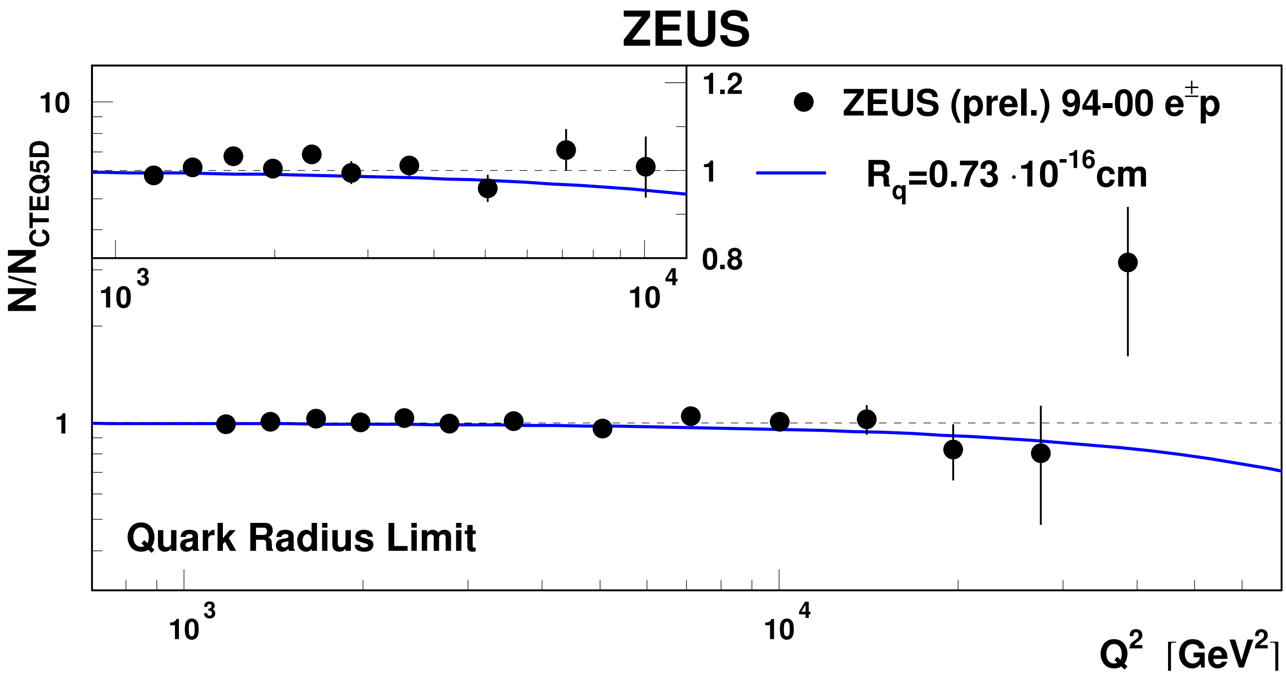
Other Interpretation

Quark Form Factor:

- Measurement of the spatial charge distribution of the quark
- Classic form factor approximation
  $\Rightarrow$ Cross section deviations from SM:

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

R_e, R_q: root of the mean square radius of the electroweak charge of the electron and quark
(electron assumed to be point-like: $R_e = 0$)



$\Longrightarrow$ Quark radius: $R_q < 0.73 \cdot 10^{-18}$ m

Extra-Dimensions (1)

- Phenomenology:

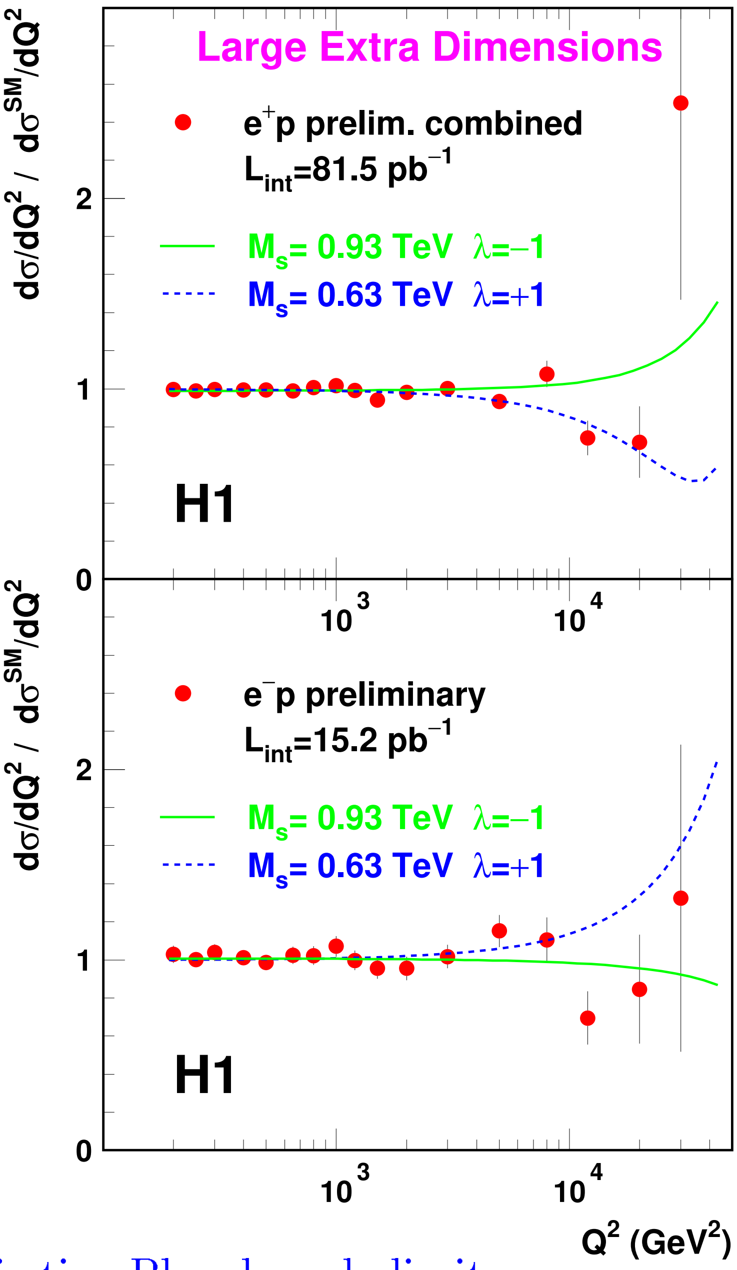
  - Arkani-Hamed, Dimopoulos and Dvali Model
  - Space-time with $(4+n)$ dimensions:
    - SM particles including strong and electroweak bosons are confined in a 4D world
    - Gravitons could propagate in n extra-dimensions
  - Coupling strength between graviton and SM particles: $1/M_s$ (M_s: effective Planck scale)
  - If extra-dimensions are large enough:
    $\Rightarrow$ M_s may be of the order of TeV
  - Contribution of graviton exchange to the $eq \to eq$ scattering can be described by an effective contact interaction

- Analysis Method:

  - Model tested using NC samples
  - Cross section fitted to a formula including graviton exchange with M_s as free parameter

Extra-Dimensions (2)

Results:



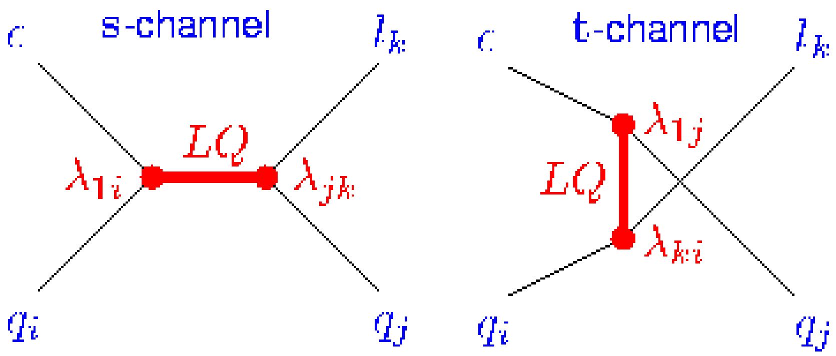
$\Rightarrow$ Effective Planck scale limits:

	H1	ZEUS
- Negative Coupling:	$M_s^- > 0.93$ TeV	$M_s^- > 0.82$ TeV
- Positive Coupling:	$M_s^+ > 0.63$ TeV	$M_s^+ > 0.81$ TeV

Lepto-Quarks (1)

- Phenomenology:

- Predicted by the Grand Unification Theory
- Triplet of coloured bosons produced by an eq fusion at HERA:



- Characterized by:
  - Weak Isospin: $T = 0,\ 1/2,\ 1$
  - Fermionic number: $F = 0,\ 2\ (F = L + 3B)$
  - Spin: $J = 0, 1$ (0: Scalar, 1: Vector)
  - Chirality: (L: left, R: right)
  - Hypercharge

Lepto-Quarks (2)

- Buchmüller, Rückl and Wyler Model:
  - 14 LQs predicted
    - 7 LQs with $F = 0$:
      $\Rightarrow$ Searched for in e^+p collisions
    - 7 LQs with $|F| = 2$:
      $\Rightarrow$ Searched for in e^-p collisions
  - Fixed Branching Ratios
- Other models where BR are not fixed may be considered.
- Analysis Method:
  - LQs interfere with DIS processes:
    - $LQ \rightarrow eq$: searched for in NC data
    - $LQ \rightarrow \nu q$: searched for in CC data
  - Presence of LQs would manifest itself by an excess at large decay angle.

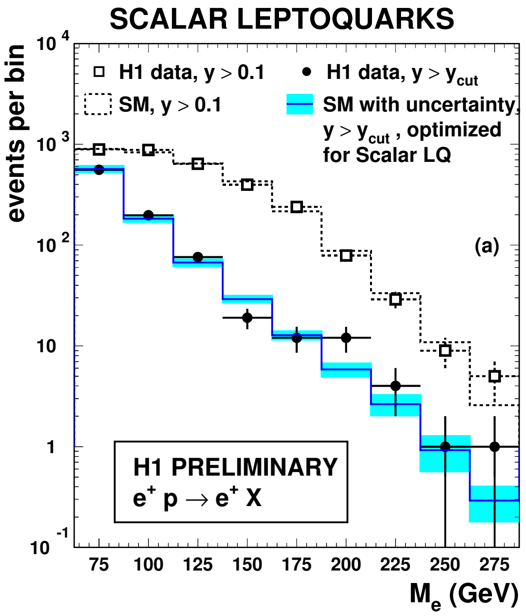
    $\Rightarrow$ An angular cut varying with LQ mass is used to optimize the LQs search.

Lepto-Quarks (3)

Mass distributions in NC channel:

- H1:

e^+p (94-00)

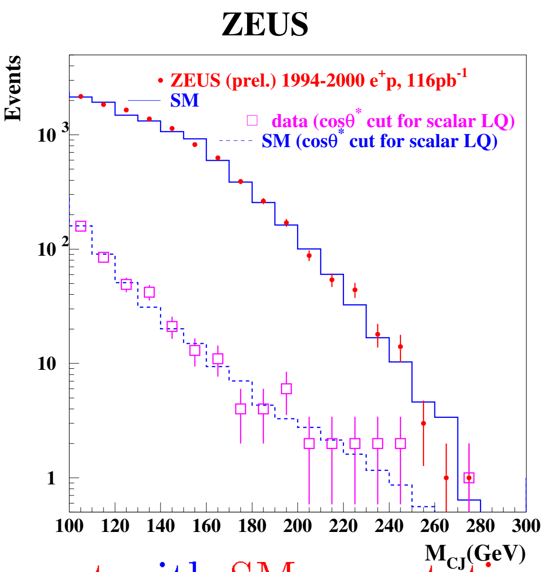


$\Rightarrow$ Previous excess at $M \approx 200$ GeV (1994-97 data) not confirmed.

$\Rightarrow$ Compatible with SM prediction.

- ZEUS:

e^+p (94-00)



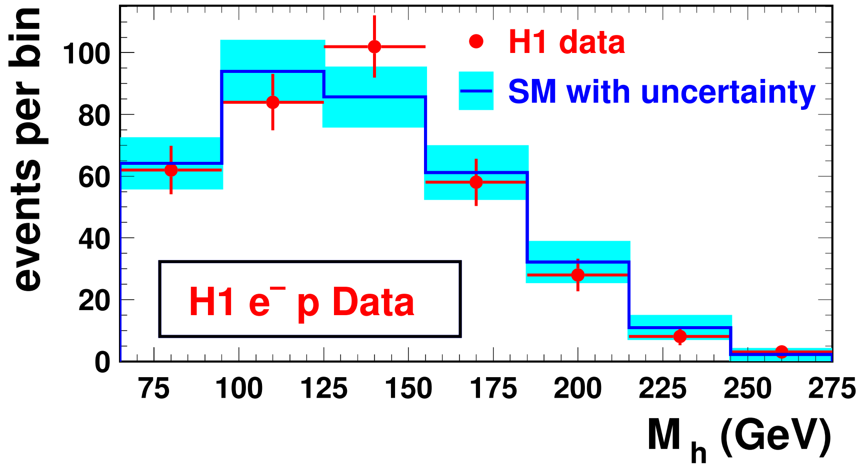
$\Rightarrow$ Good agreement with SM expectation.

Lepto-Quarks (4)

Mass distributions in CC channel:

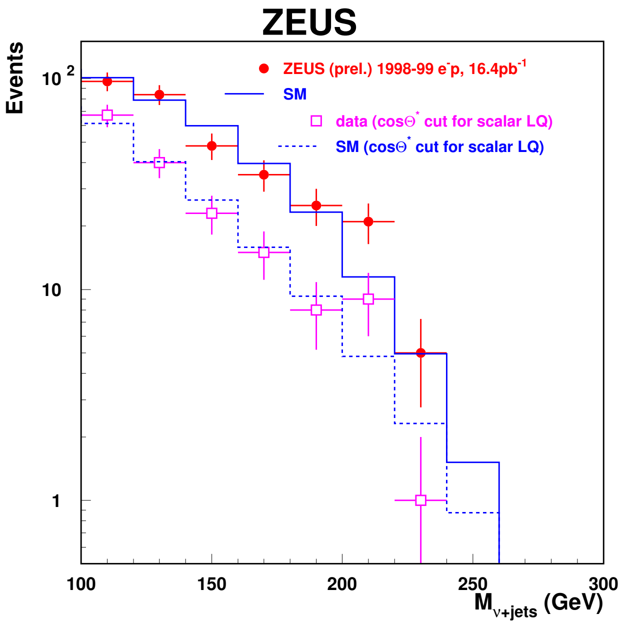
- H1:

$e^- p$ (98-99)



- ZEUS:

$e^- p$ (98-99)

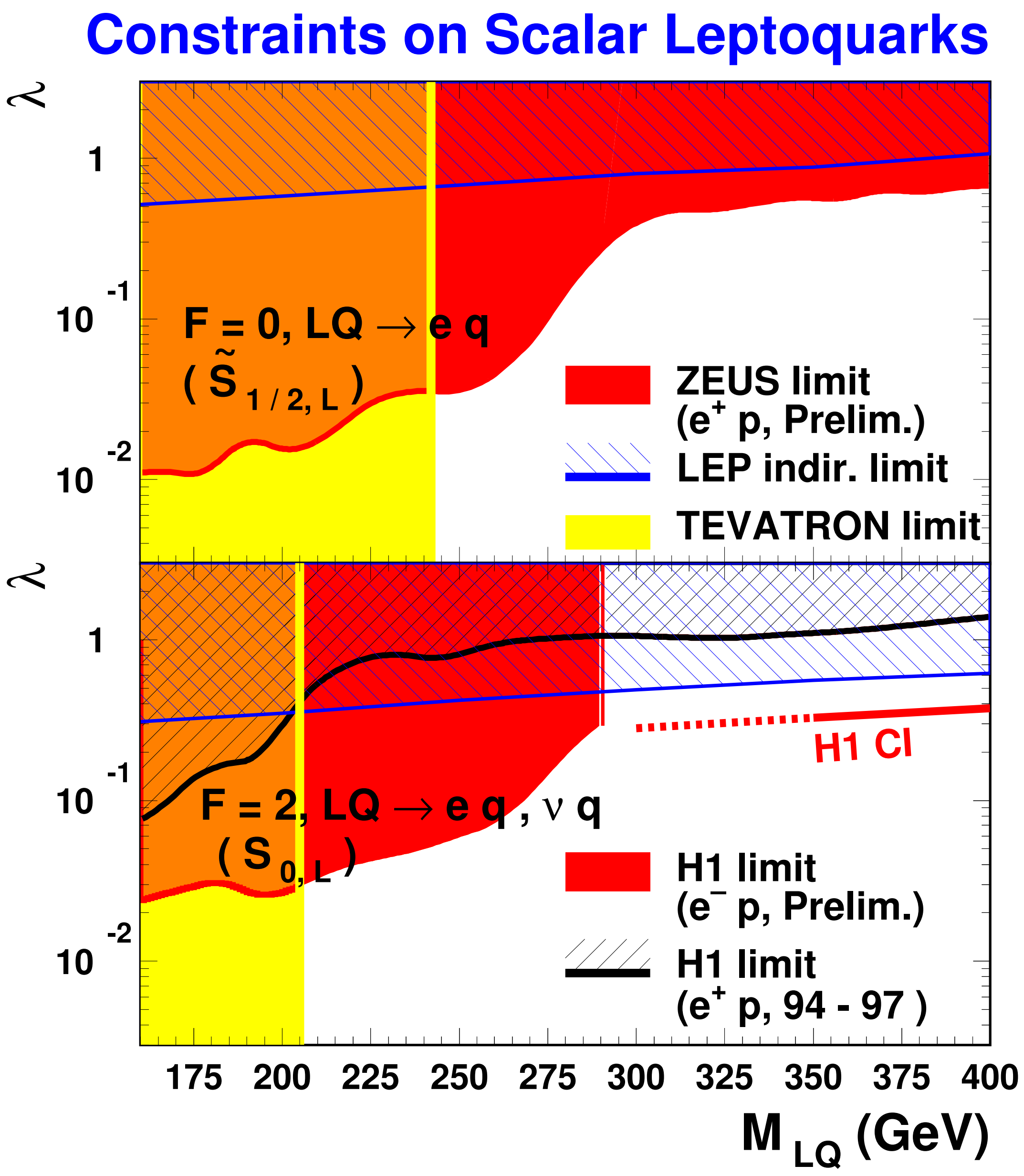


$\Rightarrow$ Good agreement with SM expectation for both experiments.

$\Rightarrow$ Limits are derived.

Lepto-Quarks (5)

Limits on λ for β fixed (BRW Model):



⇒ HERA limits are competitive with other experiments.

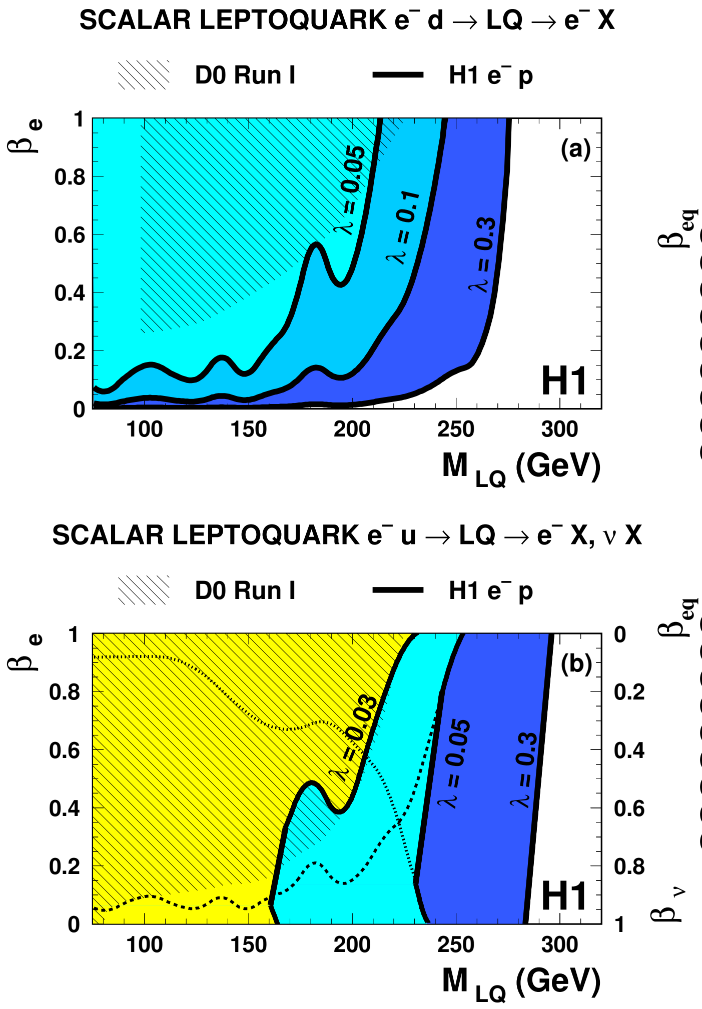
⇒ HERA extends the exclusion region at high M_{LQ}.

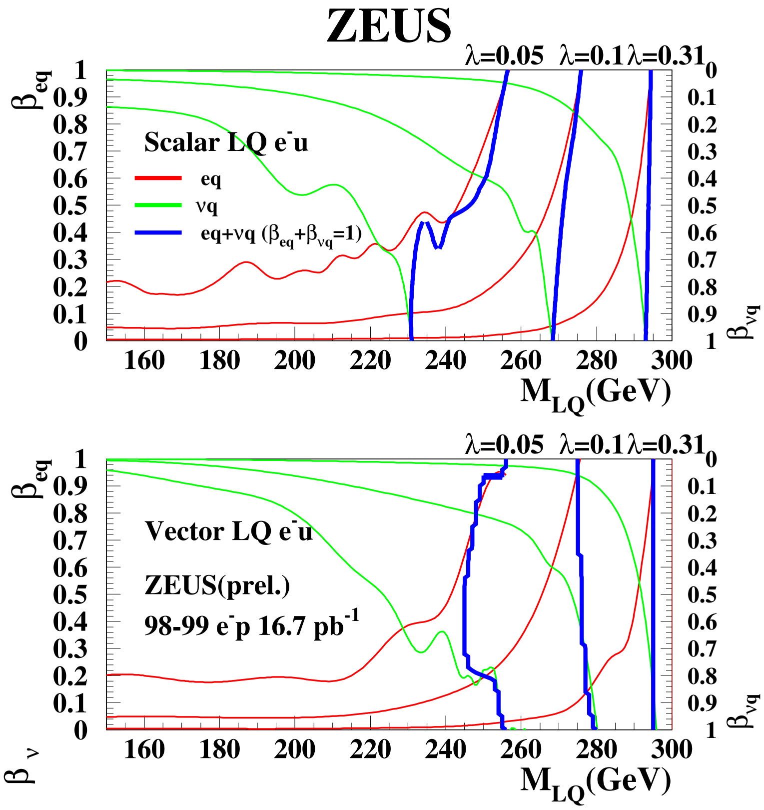
Lepto-Quarks (6)

Limits on β_e:

$\Rightarrow$ General case

$\Rightarrow$ Assuming $\beta_{eq} + \beta_{\nu q} = 1$





$\Rightarrow$ HERA limits are comparable with TeVatron for low λ and superior at large λ.

$\Rightarrow$ HERA extends limits to small β_e.

Lepton Flavour Violation (1)

- Introduction:

- Neutrino Oscillations
  $\Rightarrow$ Lepton Number probably violated
- Search for $eq \to \mu q'$ or $eq \to \tau q'$ processes

- Phenomenology:

- Processes involving 2 coupling constants:
  λ_{eq} and $\lambda_{\mu q}$
- Low-mass LQ:
  Upper limits on $\lambda_{eq} \times \sqrt{BR_{LQ \to \mu q}}$ versus the LQ mass can be deduced.
- High-mass LQ:
  Cross section is proportional to $\left(\frac{\lambda_{eq}\lambda_{\mu q}}{M^2}\right)^2$ where M is the mass of the exchanged particle (e.g. LQs).

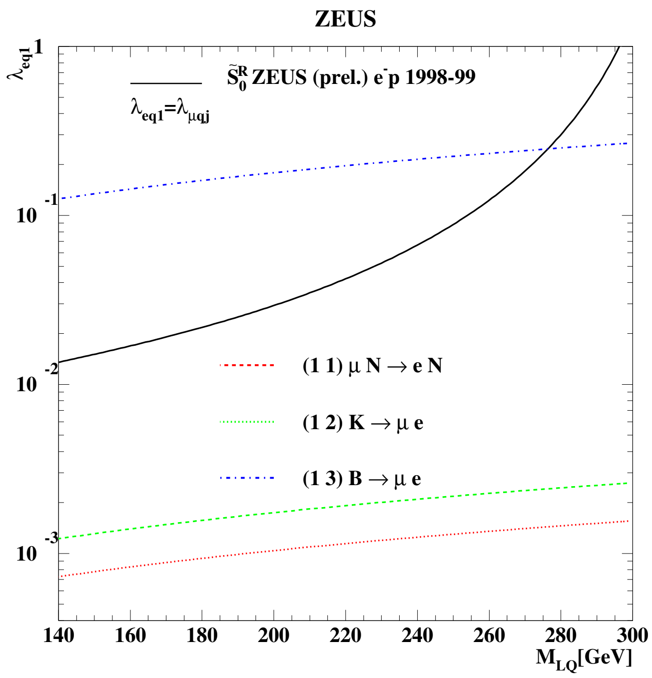
Lepton Flavour Violation (2)

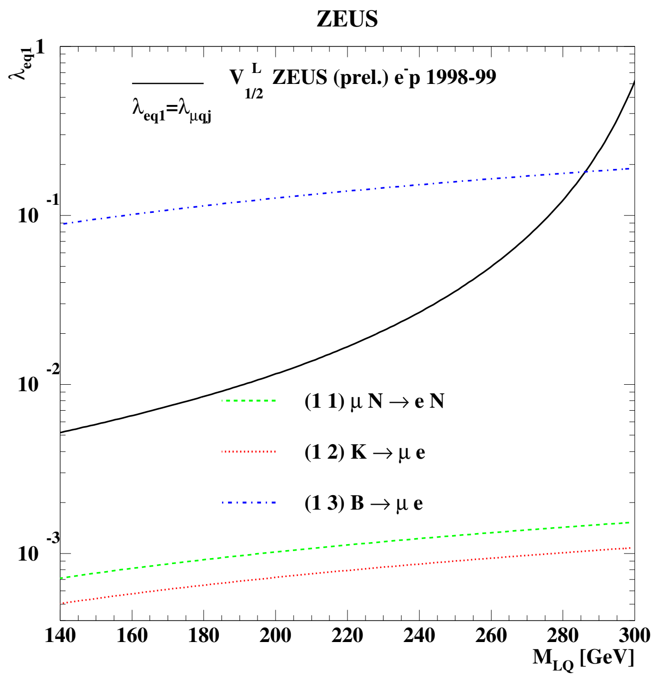
Limits on λ_{eq}:

No signal has been found $\Rightarrow$ Limits are set.

Assume $\lambda_{eq} = \lambda_{\mu q}$

$\Rightarrow BR_{\mu q}$ fixed to 0.5 and limit on λ_{eq} can be deduced.





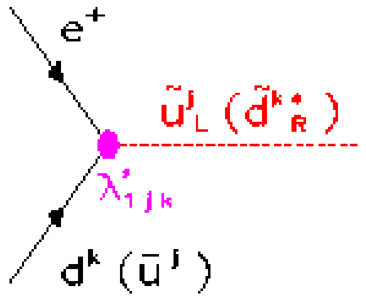
Limits are better than low-energy experiments for $ed \to \mu b$ transitions for $M_{LQ} < 280\ GeV$.

Squarks produced by $\not{R}_p$ (1)

- Minimal Supersymmetric Standard Model:

- R-parity: $R_p = (-1)^{3B+L+2S}$
  - SM Particles: $R_p = 1$
  - Supersymmetric Partners: $R_p = -1$

- Superparticles would be singly produced at HERA by eq fusion: $ep \to \tilde{q}X$
  $\Rightarrow$ R-parity Violating Yukawa Couplings



- R_P-Violating Term: $\lambda'_{ijk}\ L_i Q_j \overline{D}_k$ (i, j, k: families)
  λ': R_p-Violating Coupling

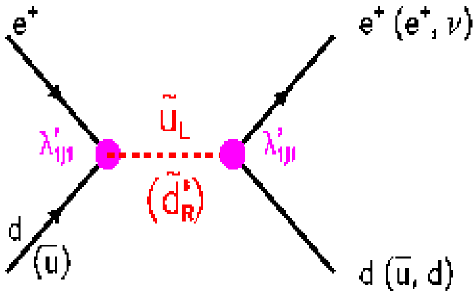
e^+ beam $\Rightarrow$ Mainly λ'_{1j1} will be probed ($e^+ + d \to \tilde{u}_L$).

- MSSM Parameters:
  - $M_{\tilde{q}}$: squark mass
  - M_2: soft SUSY breaking mass term
  - μ: mixing mass term for Higgs doublets
  - $\tan\beta$: ratio of the vev's of the 2 neutral Higgses

Squarks produced by $\not{R}_p$ (2)

- Decay Modes:

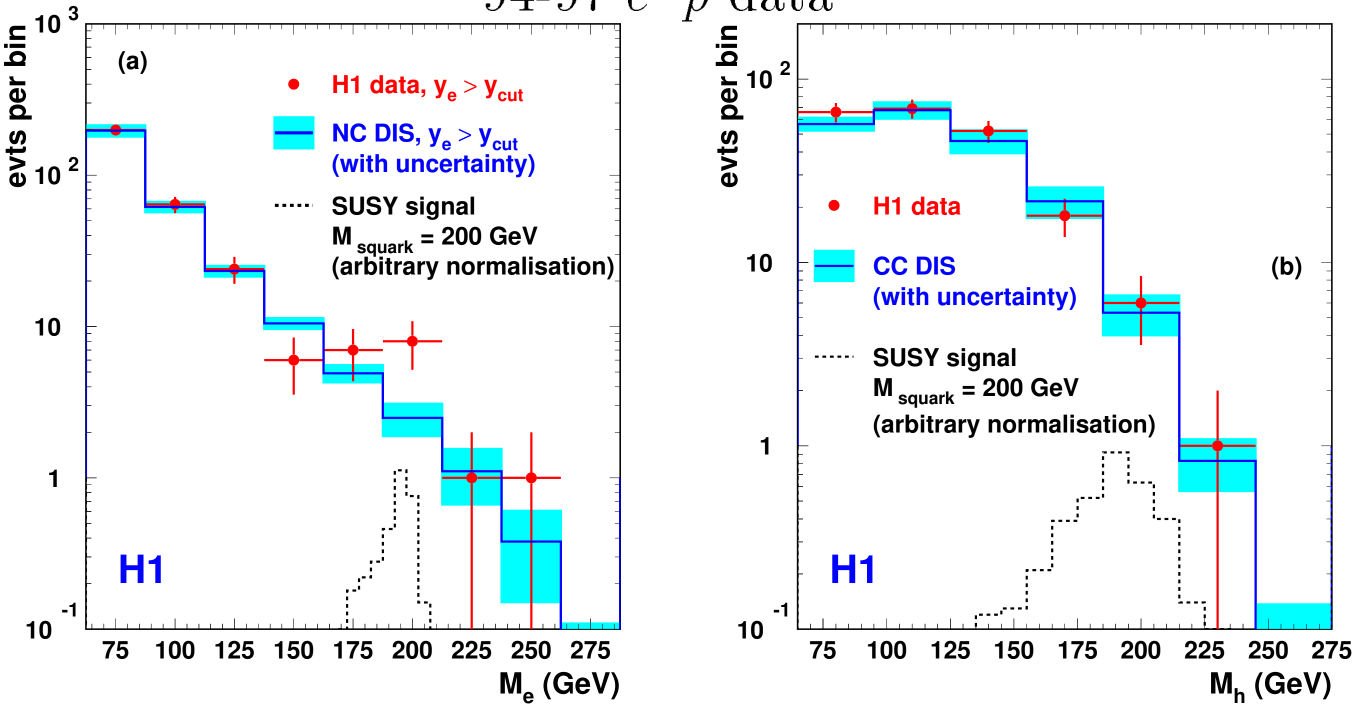
  - $\not{R}_p$ decays:



Signature	Main Bkg
e+jet	NC
ν+jet	CC

$\Downarrow$

94-97 $e^{+}p$ data

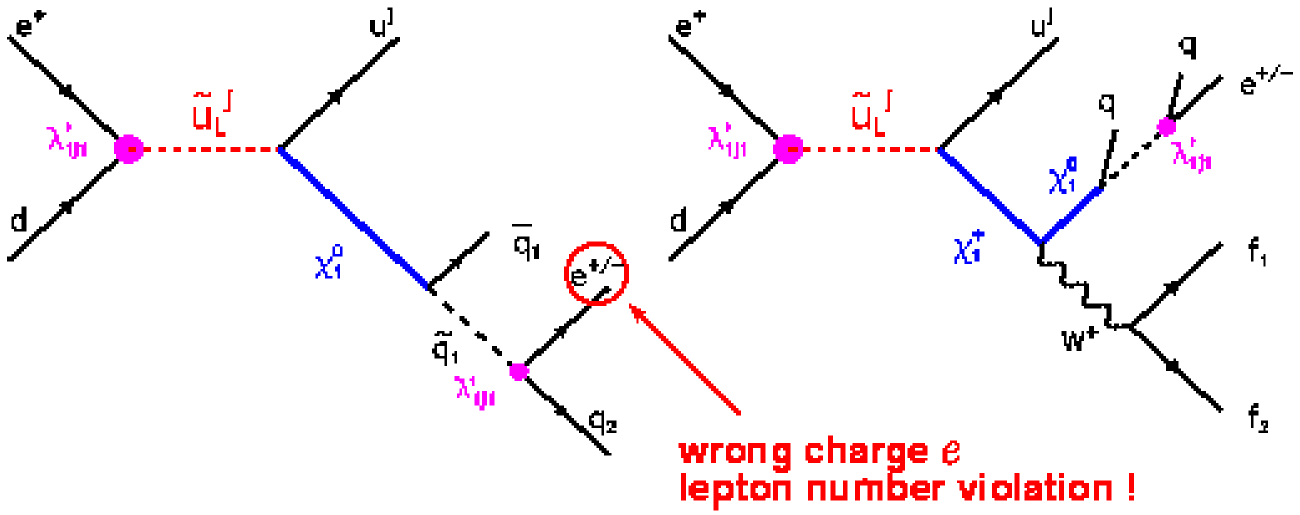


$\Rightarrow$ Slight excess around 200 GeV.

$\Rightarrow$ Good agreement with SM expectation.

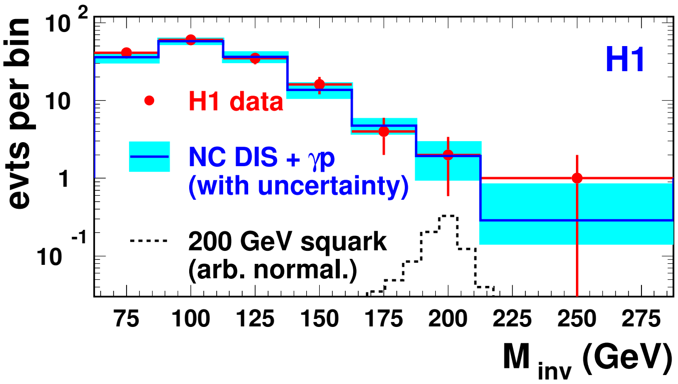
Squarks produced by $\not R_p$ (3)

- Gauge decays:



Signature	Main Bkg
e^++multi-jets	NC
e^-+multi-jets	$\sim$ Bkg Free
ν+multi-jets	CC
$e+l$+multi-jets	Small SM Bkg

94-97 e^+p data (e^++multi-jets)



$\Rightarrow$ No deviation from SM prediction.

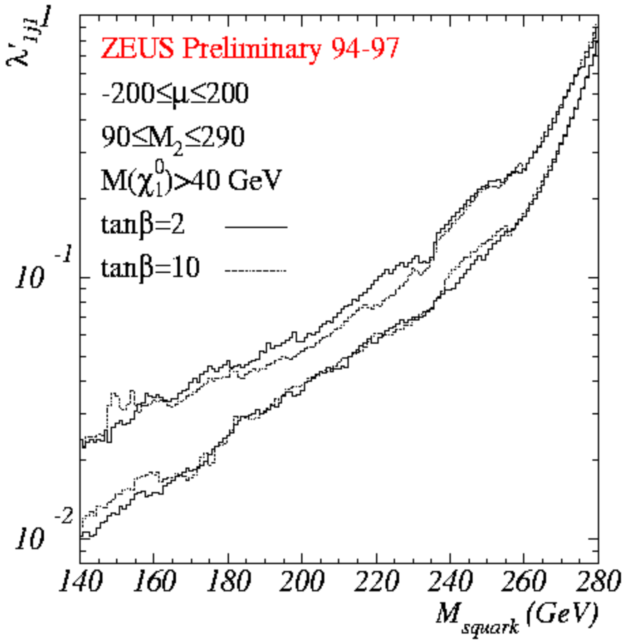
$\Rightarrow$ Limits on λ' are derived.

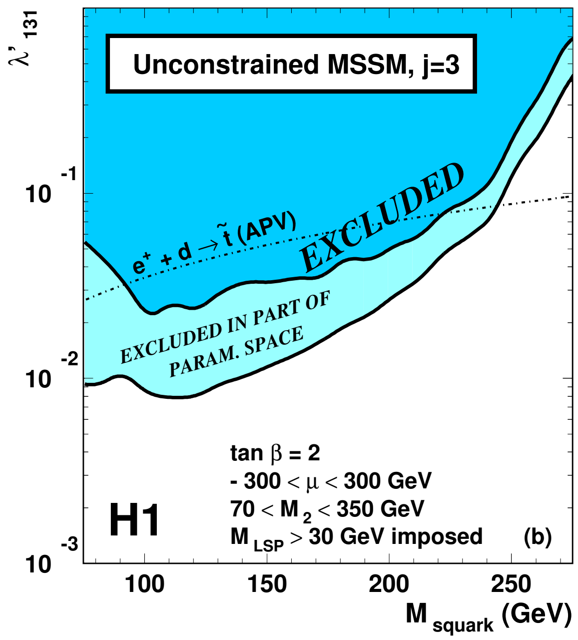
Squarks produced by $\not R_p$ (4)

Unconstrained MSSM:

⇒ Sfermion Masses are Free Parameters.

⇒ Scan in SUSY parameter space $(M_2, \mu, \tan\beta)$.





⇒ Limits are Model Independant.

⇒ For $\lambda'_{1j1} = 0.3$: $M_{\tilde{q}} > 260$ GeV.

⇒ Limits are more restrictive than indirect bounds from Atomic Parity Violation for j=3.

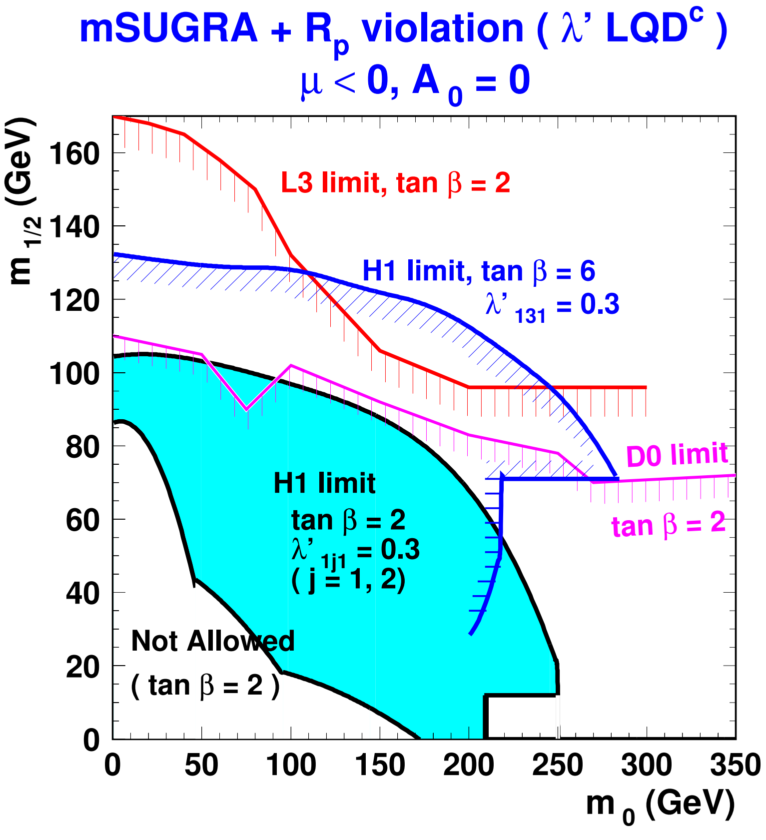
Squarks produced by $\not{R}_p$ (5)

mSUGRA Model:

$\Rightarrow$ A universal mass m_0 for all sfermions is introduced.

$\Rightarrow$ Number of free parameters is reduced to $m_0, , m_{1/2}$, sign of μ, $\tan\beta$

$\Rightarrow$ EW Symmetry Breaking driven by Radiative Corrections.

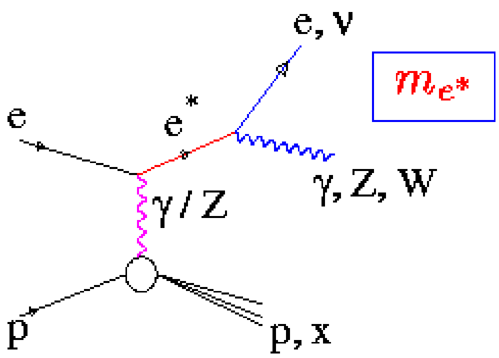


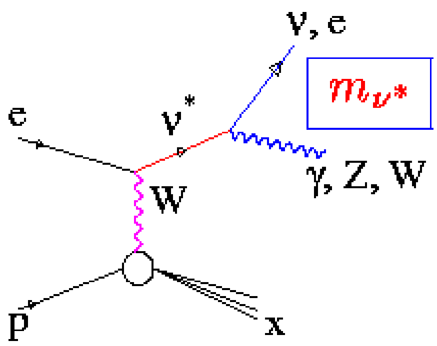
$\Rightarrow$ HERA is competitive with TeVatron for $\tan\beta = 2$ and also with LEP for large $\tan\beta$.

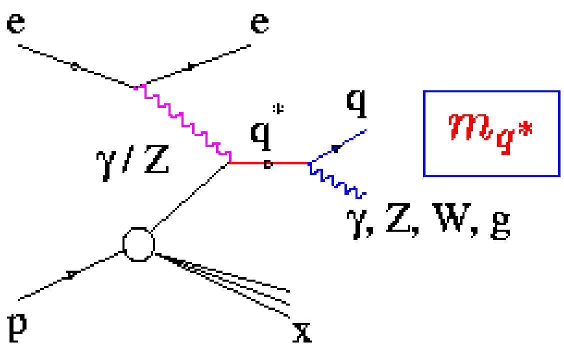
Excited Fermions (1)

- Introduction:

- Hagiwara, Komamiya and Zeppenfeld Model
- If fermions have a substructure:
  ⇒ They can be observed in excited states
  ⇒ Search for excited electrons, neutrinos and quarks: e^*, ν^*, q^*
- Fermion desexcitation by emission of electroweak bosons γ, Z, W







⇒ Different final states topologies are searched for.

Excited Fermions (2)

- Phenomenology:

- BR of excited fermions depend on the form factor f', f and f_s describing the coupling between the fermion and the bosons associated respectively to the gauge groups U(1), SU(2) and SU(3)

- Effective Lagrangian:

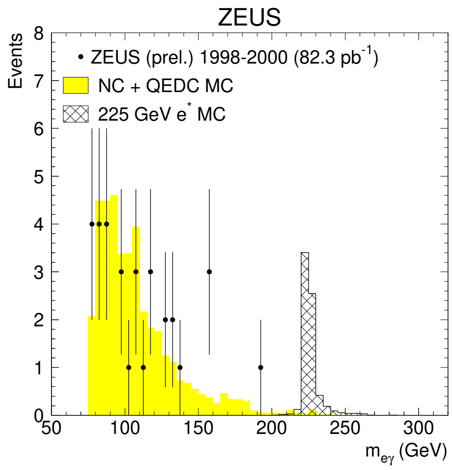
$$\mathcal{L}_{int} = \frac{1}{2\Lambda}\overline{F}^{*}_{R}\sigma^{\mu\nu}\left[\underbrace{g f \frac{\tau^a}{2} W^a_{\mu\nu}}_{\Downarrow\ SU(2)} + \underbrace{g' f' \frac{Y}{2} B_{\mu\nu}}_{\Downarrow\ U(1)} + \underbrace{g_s f_s \frac{\lambda^a}{2} G^a_{\mu\nu}}_{\Downarrow\ SU(3)}\right] F_L$$

  – g, g', g_s: SM couplings
  – f, f', f_s: Gauge group weights
  – Λ: Compositeness Scale

- Assuming relations between f, f' and f_s:
  $\Rightarrow$ BR are fixed and limits on f/Λ versus excited fermion mass can be deduced.

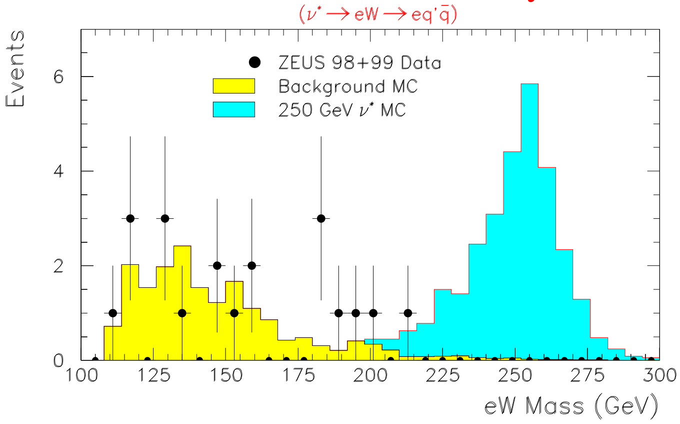
Excited Fermions (3)

Results:



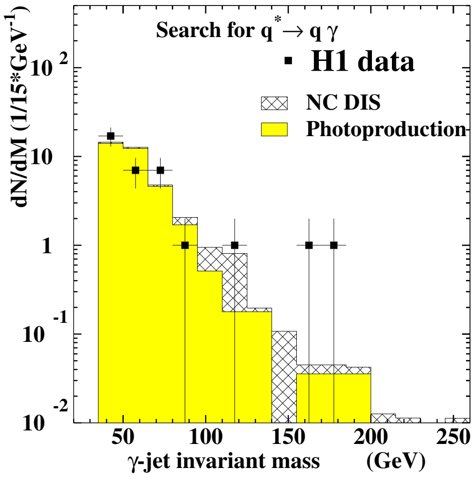
e^*

$e^{\pm}p$ (98-00)



ν^*

e^-p (98-99)



q^*

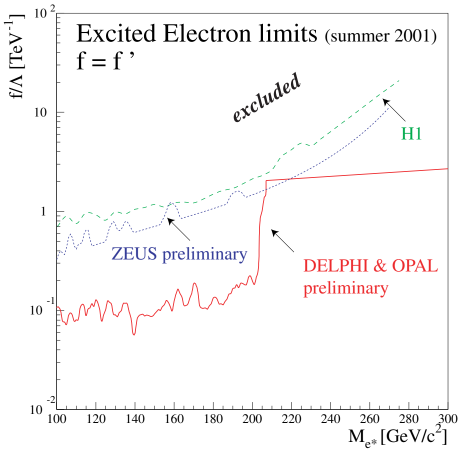
e^+p (94-97)

$\Rightarrow$ No evidence for excited fermions.

$\Rightarrow$ Limits are established.

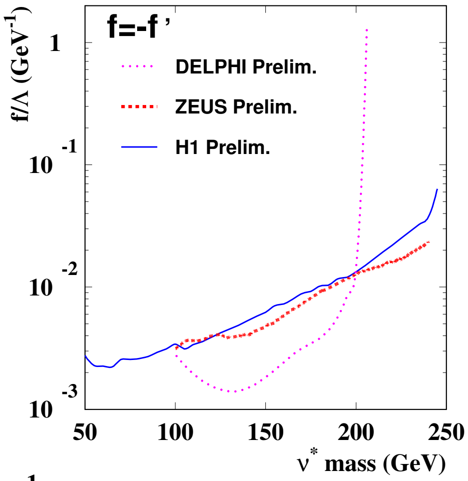
Excited Fermions (4)

Limits obtained on f ($f = \pm f'$):



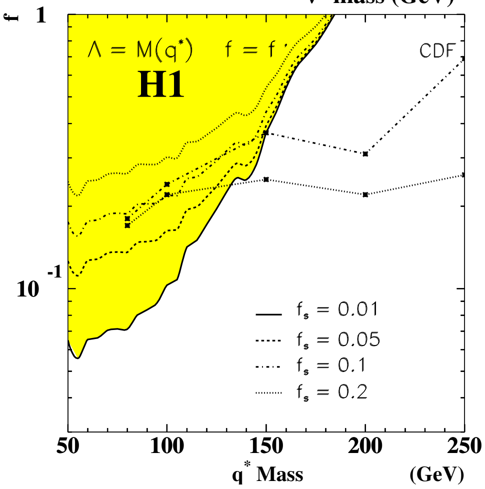
$\boxed{e^*}$ $e^{\pm}p$ (98-00)

$\Rightarrow$ Limits are competitive with LEP at high m_e^*



$\boxed{\nu^*}$ e^-p (98-99)

$\Rightarrow$ Unique sensitivity at high m_{ν^*}



$\boxed{q^*}$ e^+p (94-97)

$\Rightarrow$ More sensitive than TeVatron at small f_s

$\Rightarrow$ Competitive with LEP for e^* and ν^*.

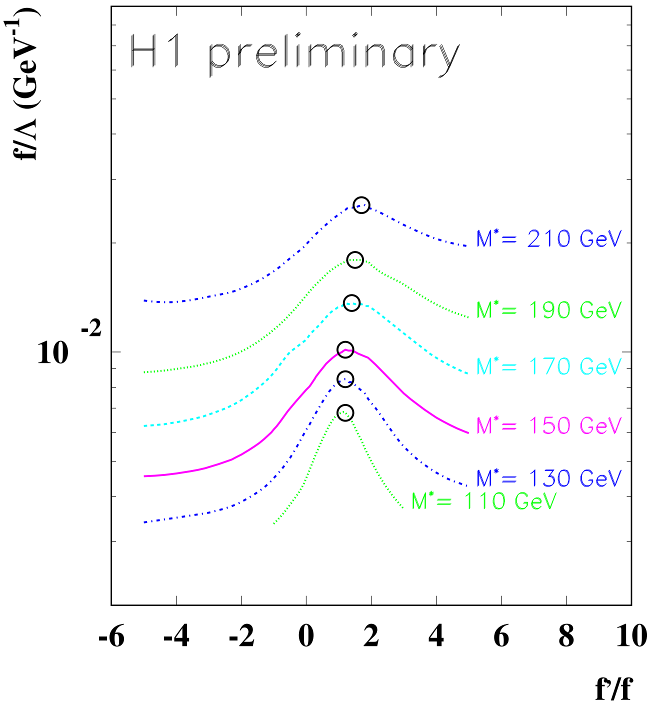
$\Rightarrow$ Complementary to TeVatron for q^*.

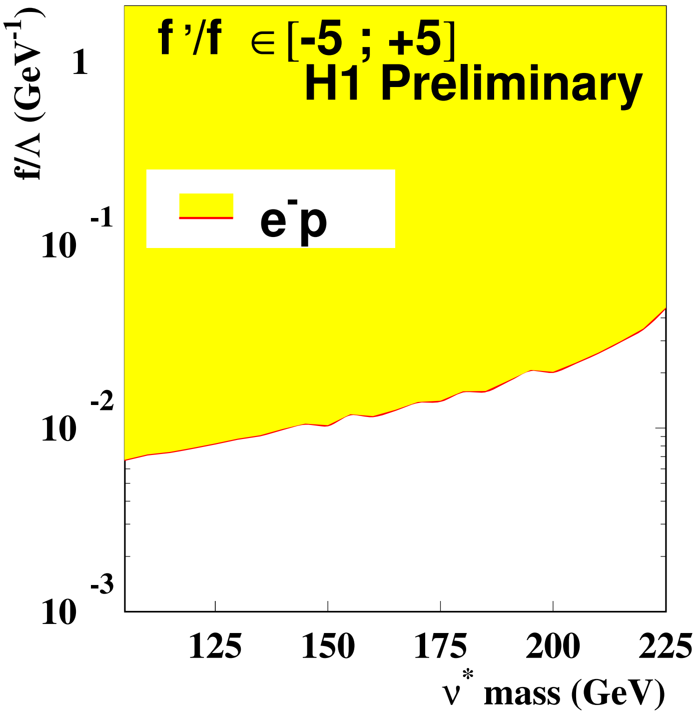
Excited Fermions (5)

Less Model dependent limits for f/Λ:

$\Rightarrow$ The arbitrary ratio f'/f is considered.

ν^* analysis, e^-p (98-99):



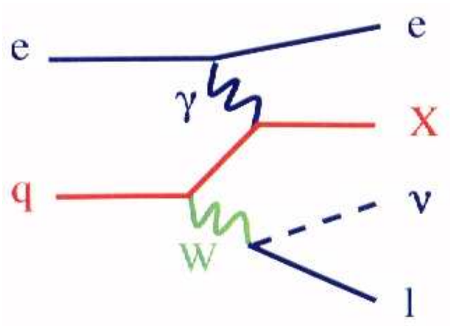


$\Rightarrow$ NEW LIMITS are obtained which do not depend on a specific ratio of f'/f.

Isolated Lepton Events (1)

- Introduction:

- High P_T isolated lepton events was observed in 94-97 H1-data
  (H1 Collab. *Eur. Phys. J.* C5 (1998) 575)
- Analysis extended to the Full HERA-1 data
- The most likely SM interpretation of is W production:

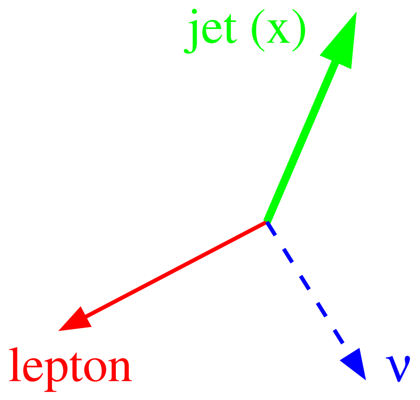


- Theory:
  - LO cross section available: $\sigma^{W}_{tot} = 1.3$ pb
  - NLO cross section calculation under way

Isolated Lepton Events (2)

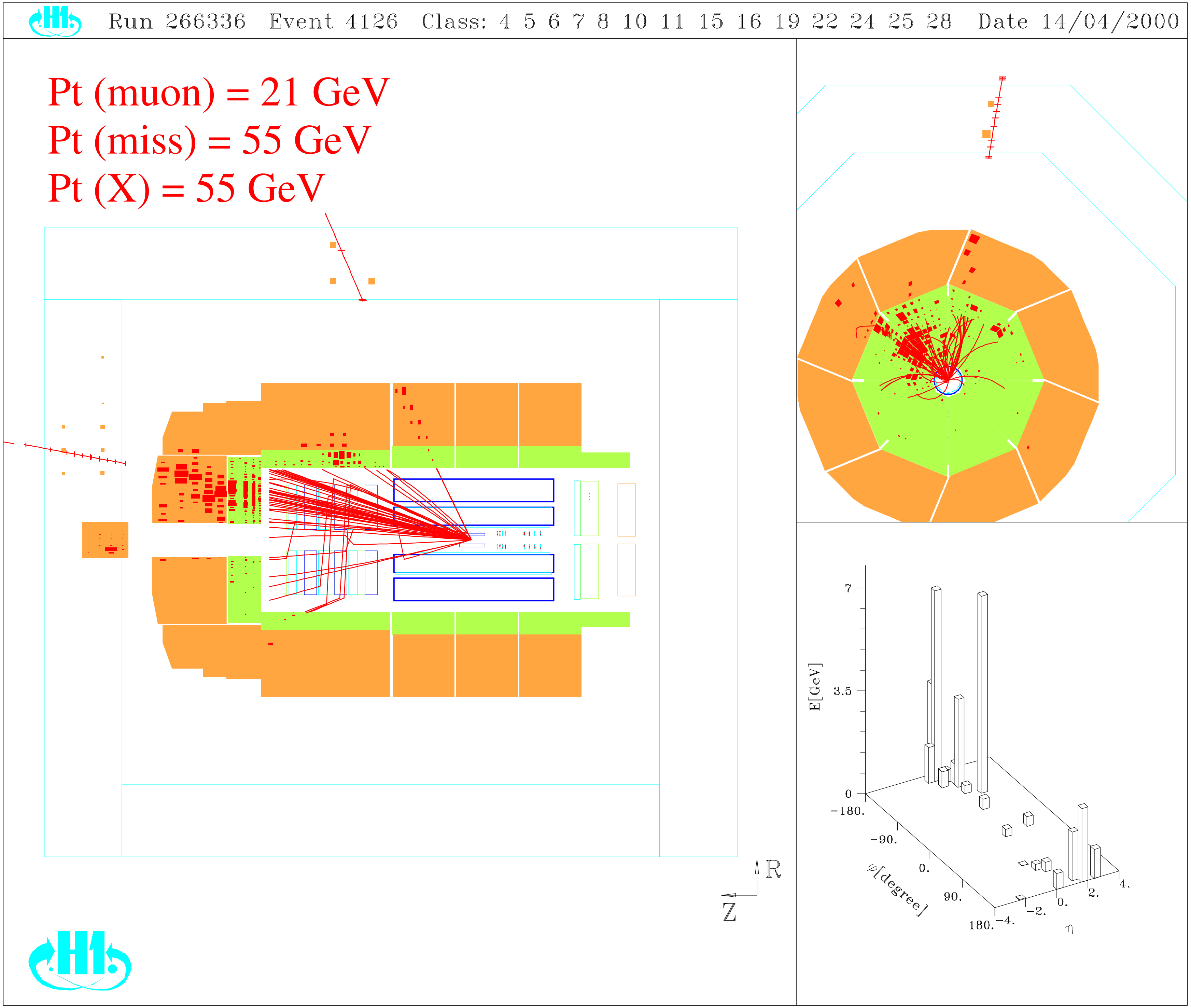
- Analysis:

- Topology of the events:



  - Missing P_T
  - High energy lepton
  - Possibly a jet

- Two channels are explored:
  - Electron and Muon decay channels
    ($W \rightarrow e\nu$ and $W \rightarrow \mu\nu$)
  - Tau decay channel not explicitely searched for


Run 266336 Event 4126 Class: 4 5 6 7 8 10 11 15 16 19 22 24 25 28 Date 14/04/2000
Pt (muon) = 21 GeV
Pt (miss) = 55 GeV
Pt (X) = 55 GeV
R
Z
E[GeV]
7
3.5
0
φ[degree]
−180.
−90.
0.
90.
180.
η
−4.
−2.
0.
2.
4.

Isolated Lepton Events (3)

Latest Results, e and μ channels:

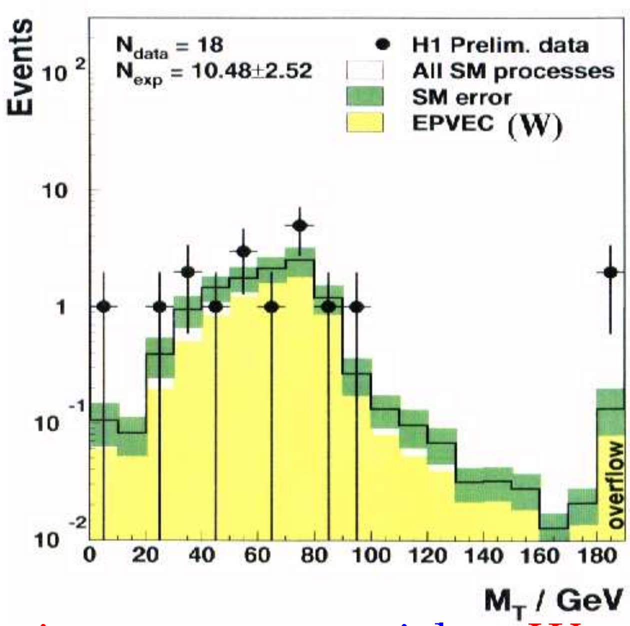
Data/SM	H1 Prelim. (e^+p, 102 pb^{-1})	ZEUS Prelim. ($e^\pm p$, 130 pb^{-1})
$P_T^X > 0\ GeV$	$18/10.5 \pm 2.5$	–
$P_T^X > 25\ GeV$	$10/2.8 \pm 0.7$	$2/2.4 \pm 0.2$
$P_T^X > 40\ GeV$	$6/1.0 \pm 0.3$	$0/1.0 \pm 0.1$
	(e^-p, 14 pb^{-1}) $0/1.8 \pm 0.4$	

$\Rightarrow$ Good Agreement with SM at low P_T^X

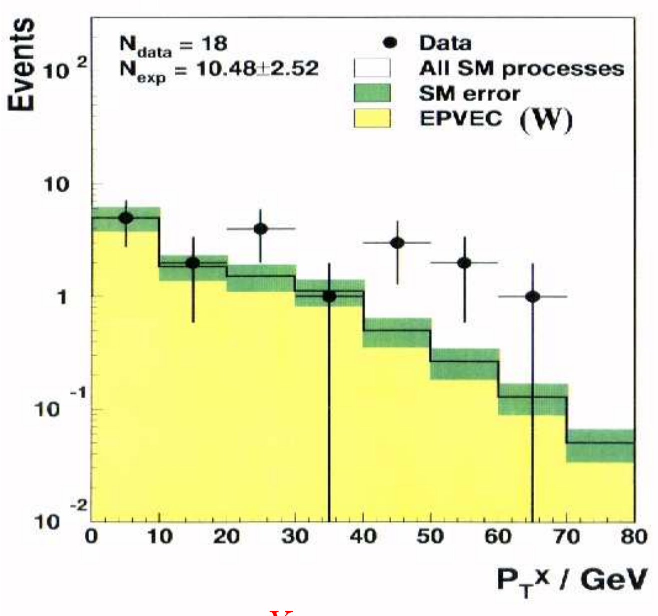
$\Rightarrow$ More Events than expected at high P_T^X in H1 data.

Isolated Lepton Events (4)

Kinematics of the events:



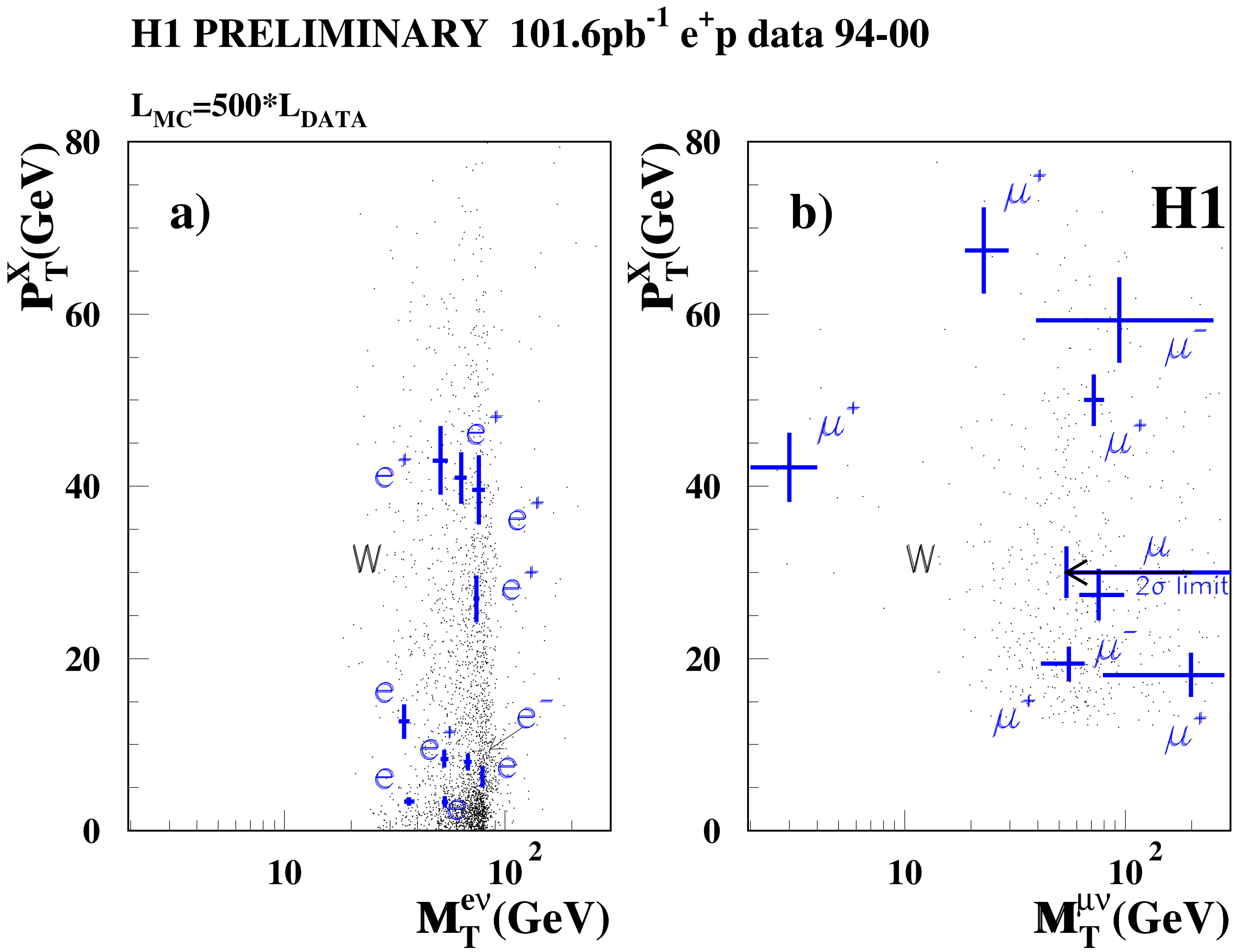
⇒ Results in agreement with a W interpretation.



⇒ Excess at high P_T^X.

Isolated Lepton Events (5)

Kinematics of the events:



Some data events are found in regions where
SM expectation is low.

- Interpretation of these events?

$\Rightarrow$ Attempt with Single Top Production.

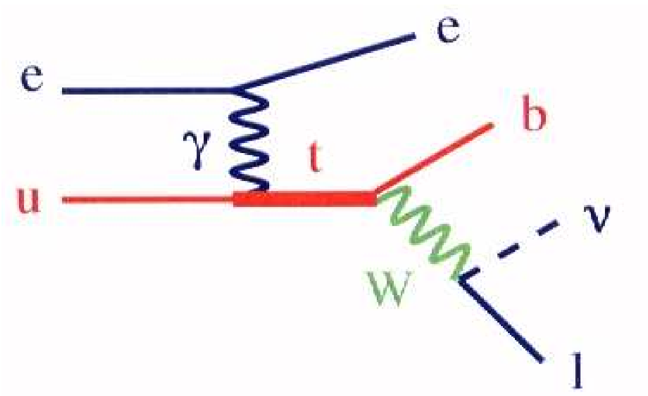
Single Top Production (1)

- Introduction:

- SM top quark is expected not to be produced at HERA

- If any top signal is found:
  $\Rightarrow$ Signature of New Physics

- Production by Flavour Changing Neutral Current in Lepton Channel:

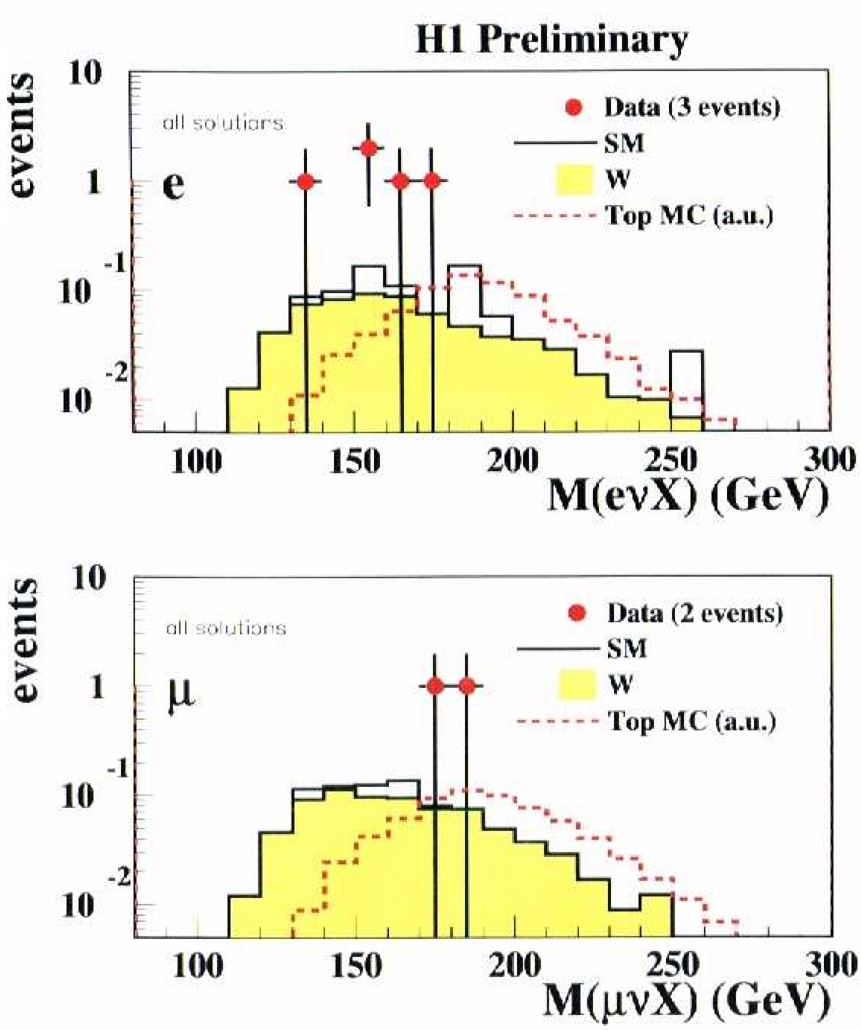


$\Rightarrow$ Tighter Selection
$\Rightarrow$ TOP Candidates

Single Top Production (2)

Results in Lepton Channel:

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

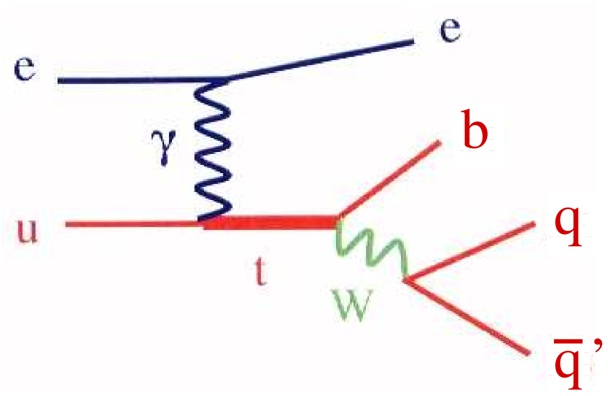


⇒ Several lepton events are consistent with the top mass.

Single Top Production (3)

- Hadronic Channel:

- A top search in Hadronic Channel has also been performed
- Topology of hadronic decay:



- Analysis:

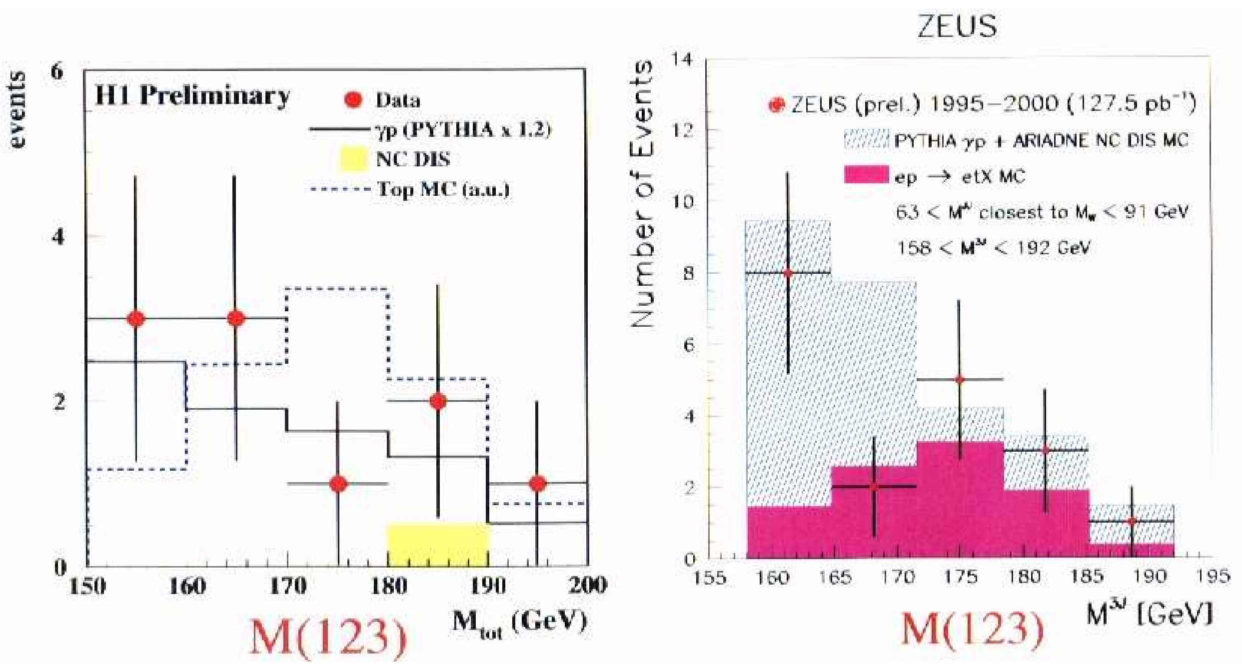
- Data analysed:
  - H1: 37 pb^{-1}
  - ZEUS: 128 pb^{-1}
- Use Mass Windows to enhance S/N ratio:

$$\begin{cases} M_{ij} = M_W \\ M_{123} = M_{top} \end{cases}$$

Single Top Production (4)

Results in Hadronic Channel:

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

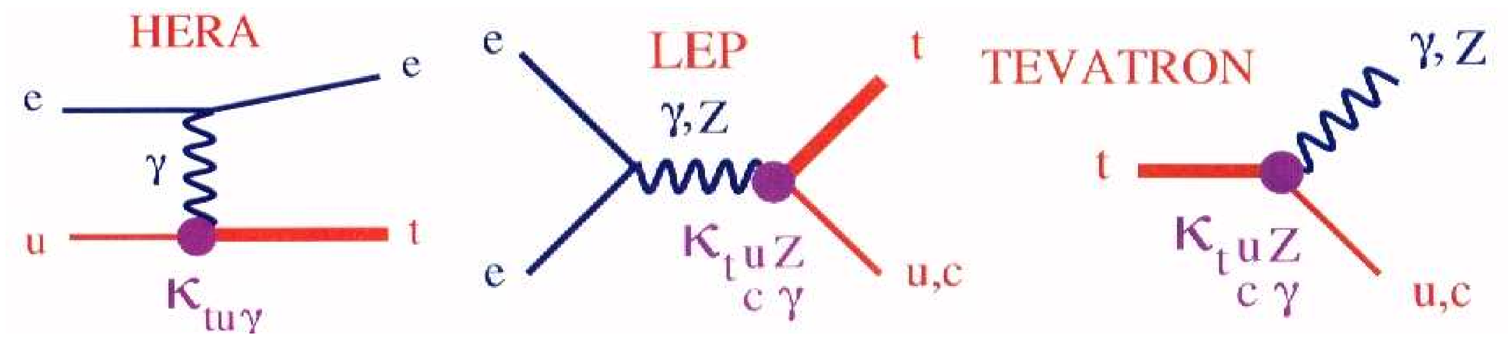


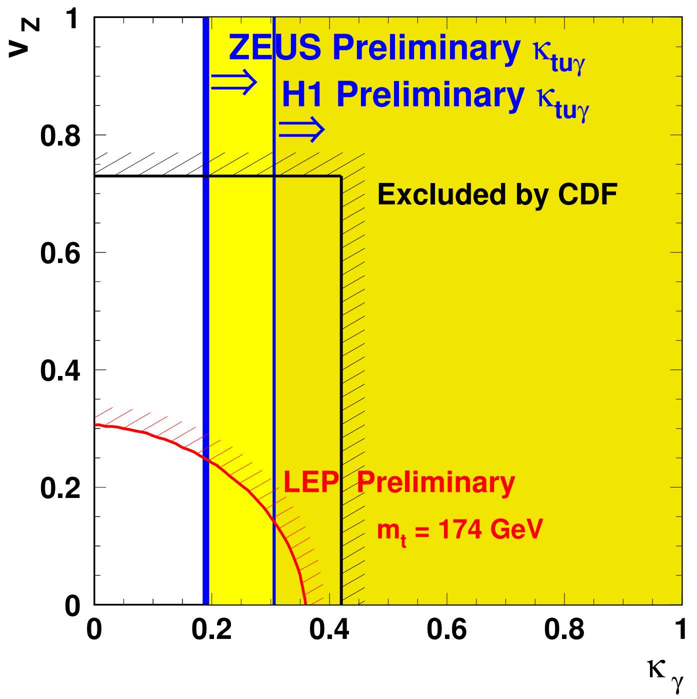
⇒ No visible excess compared to SM.

⇒ Limits on Anomalous Top Couplings are obtained.

Single Top Production (5)

Limits on Anomalous Top Couplings:





⇒ HERA limits on $\kappa_{tu\gamma}$ are:

- H1: $\kappa_{tu\gamma} < 0.305$
- ZEUS: $\kappa_{tu\gamma} < 0.19$

⇒ HERA limits are competitive with LEP and TeVatron.

Conclusion and Prospects (1)

- HERA: unique collider to test direct eq interactions
- HERA 1: $e^+p \sim 110$ pb^{-1}, $e^-p \sim 15$ pb^{-1} per experiment
  - No evidence for New Physics
    $\Rightarrow$ New constraints on:
    * Contact Interactions
    * Large Extra Dimensions
    * Leptoquarks
    * Lepton Flavour Violation
    * R_P-Violating SUSY
    * Excited Fermions
  - Search for Isolated Lepton Events still very puzzling...
- Limits are competitive and complementary to LEP and TeVatron searches.

Conclusion and Prospects (2)

- Shutdown since fall 2000
  $\Rightarrow$ Luminosity and Detector Upgrade
  - New Focussing Magnets
    $\Rightarrow$ Increased Luminosity
  - Detectors Improvements
    $\Rightarrow$ Increased Sensitivity
- First Luminosity runs: November 2001
  HERA-2 will give 1 fb^{-1} in $\sim$ 5 years
  $\Rightarrow$ Factor 10 increase expected in integrated luminosity

$\Rightarrow$ An Outstanding Discovery Potential For HERA...