Results on Searches Beyond the Standard Model at HERA

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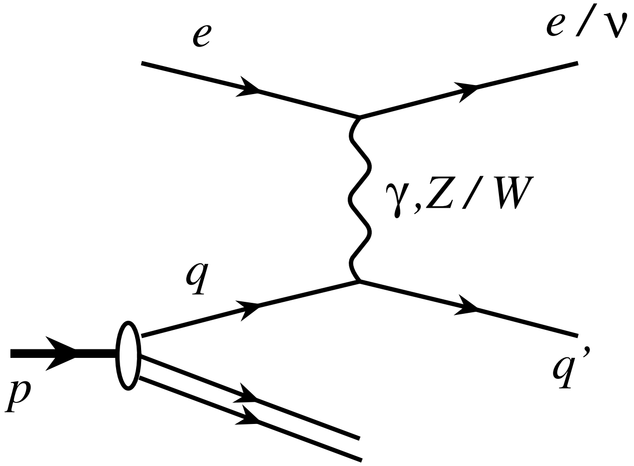
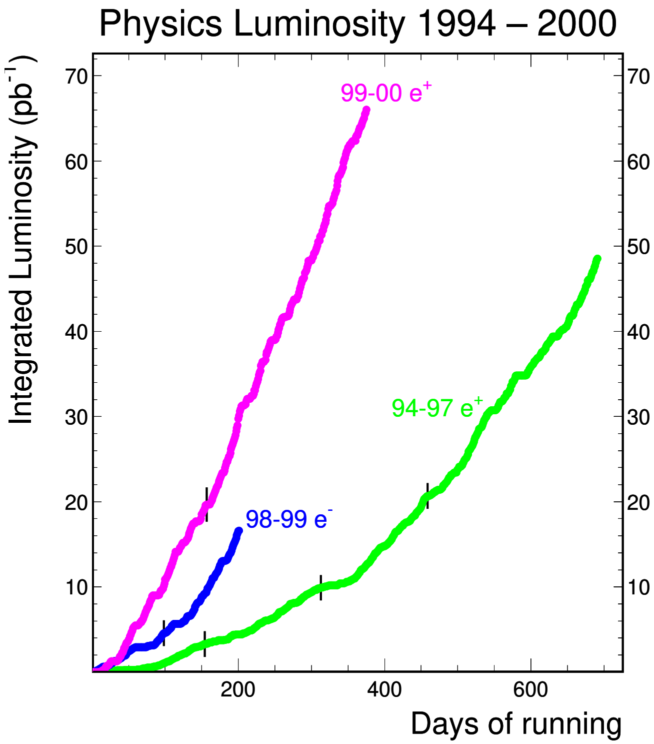
- HERA kinematics
- Results on searches for:
  - Contact Interactions
  - Leptoquarks
  - Rp-violating SUSY
  - Excited Fermions
  - High-p_t Lepton Events
  - Single Top Production in FCNC
- Summary

HERA kinematics and luminosity

$e^{\pm}$ → 27.5 GeV ← p 820-920 GeV

$$\sqrt{s} = \text{centre-of-mass energy}$$
$$Q^2 = \text{-(propagator 4-momentum)}^2$$
$$x = \text{fraction of proton momentum carried by struck quark}$$





HERA I summary

year	mode	$\sqrt{s}$ (GeV)	$\int \mathcal{L}$ (pb^{-1})
1994-1997	e^+p	300	$\sim$40
1998-1999	e^-p	318	$\sim$15
1999-2000	e^+p	318	$\sim$70

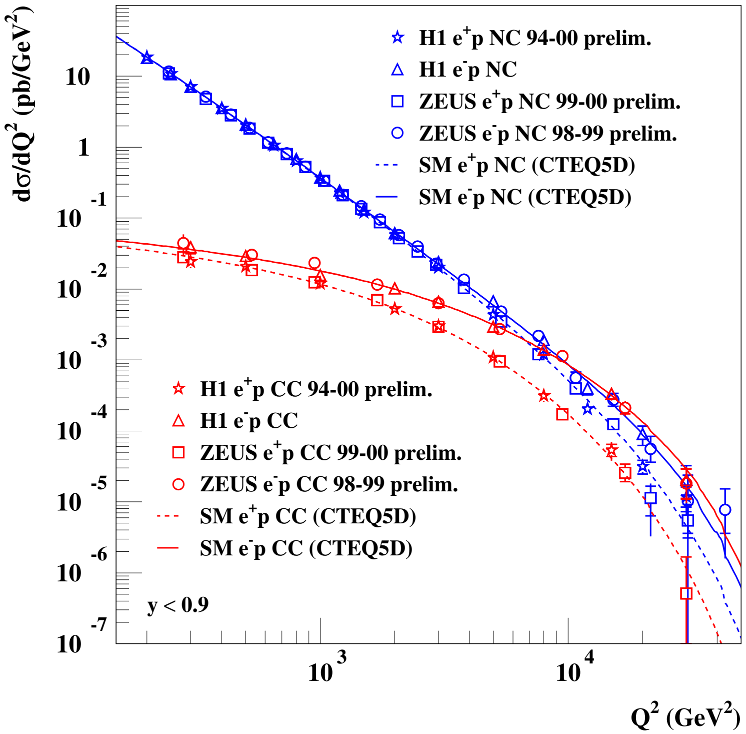
Search for signals of new physics at HERA

- Direct search for new states with definite lepton and/or baryon number:
  - eq resonances
  - excited states e^*, ν^*, q^*
  - Flavor Changing Neutral Currents ($eu \to et$)

- Search for deviations, at high Q^2, of the measured ep cross section from the SM predictions:
  - contact interaction approach

NC: $ep \to eX$

CC: $ep \to \nu X$



Large Q^2 range covered by HERA measurements, up to $Q^2 \sim 40000$ GeV^2
$\to$ probed distance $= 1/Q \sim 10^{-16}$cm

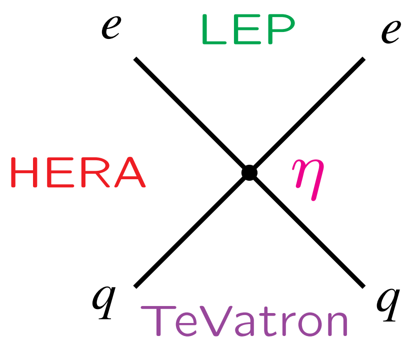
Comparison data/SM in very good agreement for both experiments

Contact interactions

Effects at low energy from new physics at much higher energy scale (Λ)
(examples: compositeness, new heavy bosons, heavy leptoquarks, ...)
$\Longrightarrow$ deviations in cross section at high Q^2

Describe process by effective theory modeled as 4-fermion contact interaction
For general $eeqq$ CI, additional terms in SM lagrangian (only vector terms considered):

$$L_{CI} = \sum_{\alpha,\beta=L,R}^{q=u,d} \eta^q_{\alpha\beta} (\bar{e}_\alpha \gamma^\mu e_\alpha)(\bar{q}_\beta \gamma_\mu q_\beta)$$



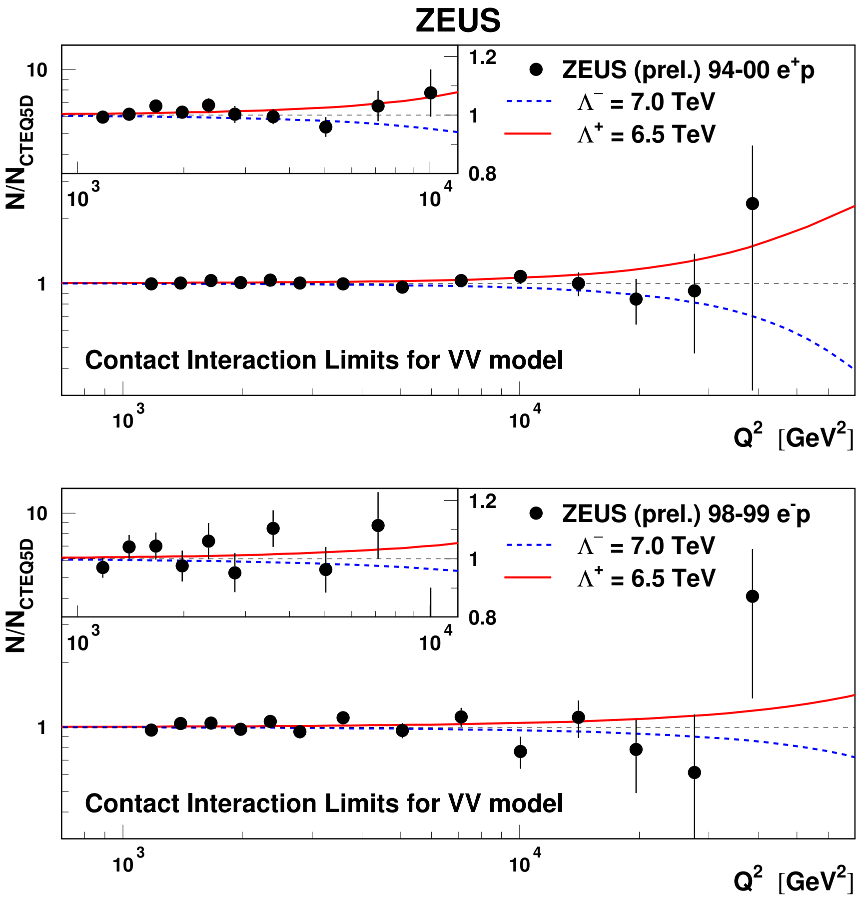
with $\eta = \epsilon g^2/\Lambda^2$
$\epsilon = \pm 1$, $g^2 = 4\pi$

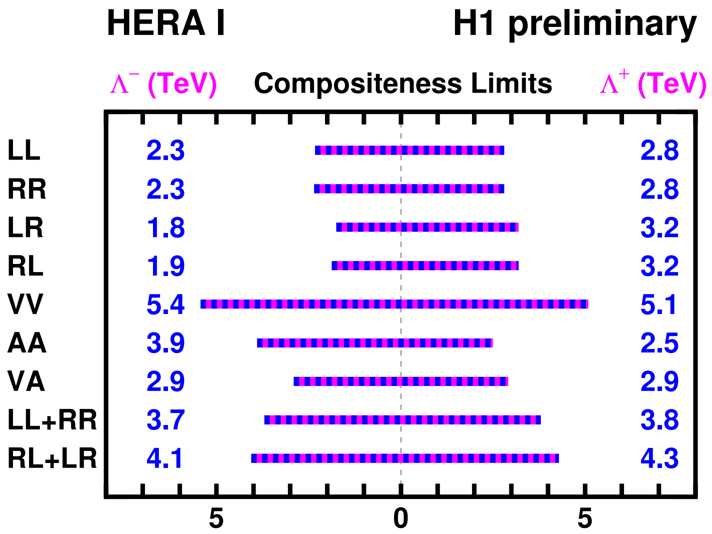
Several CI scenarios depending on fermion chirality combinations, e.g.:

$VV : \eta_{LL} = +\eta_{LR} = +\eta_{RL} = \eta_{RR}$
$AA : \eta_{LL} = -\eta_{LR} = -\eta_{RL} = \eta_{RR}$

Q^2 fits and Λ limits

Measure Q^2 distribution of events or $d\sigma/dQ^2$
$\longrightarrow$ use statistical analysis method to evaluate modifications w.r.t. SM expectations due to CI-SM inteference or pure CI contribution





Curves are 95% C.L. exclusion limits for positive (Λ^+) or negative (Λ^-) interference terms

Limit range on effective mass scale Λ_{eeqq}: ZEUS 2.0-7.0 TeV
H1 1.8-5.4 TeV

Similar ranges obtained at LEP and TeVatron

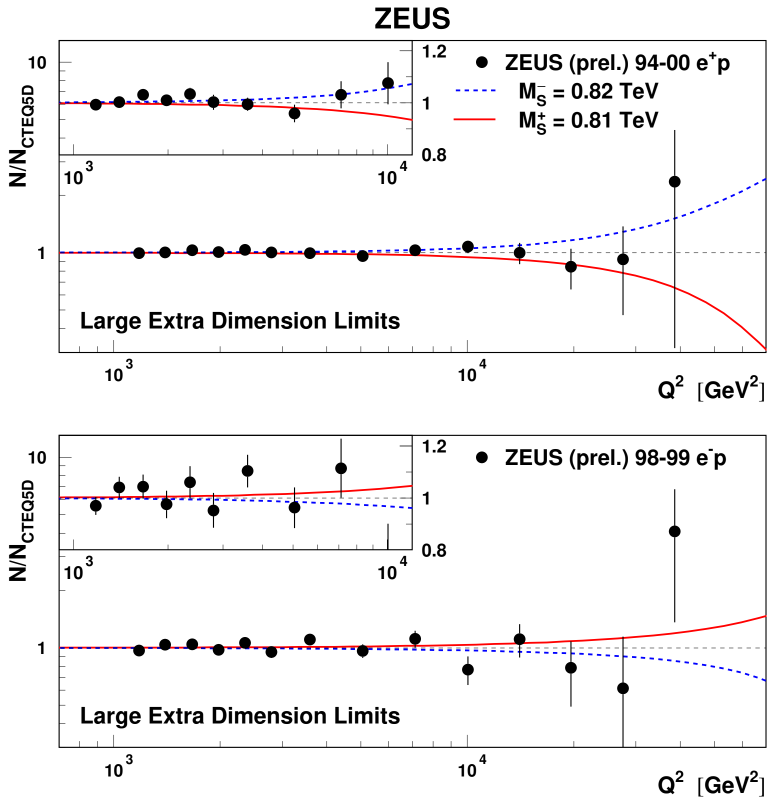
Large Extra Dimensions

Model proposed by Arkani-Hamed, Dimopoulos and Dvali:
space-time has $4 + n$ dimensions

Extra dimensions compactified on scale R$\lesssim$1mm accessible to gravitation only
Depending on $R \rightarrow$ effective Planck scale $M_S \sim$ 1TeV (with $M_S^{2+n} = M_P^2 R^n$)

Graviton exchange modifies DIS cross-section at high energy by coupling to SM particles with effective strength $\sim \lambda / M_S^4$ (Giudice, Rattazzi and Wells):

Assuming $\lambda = \pm 1 \Rightarrow$, use CI formalism to set limits on M_S



Limits on M_S (TeV)

	H1	ZEUS
$\lambda = -1$	>0.79	>0.82
$\lambda = +1$	>0.83	>0.81

LEP and TeVatron limits $\sim$1 TeV

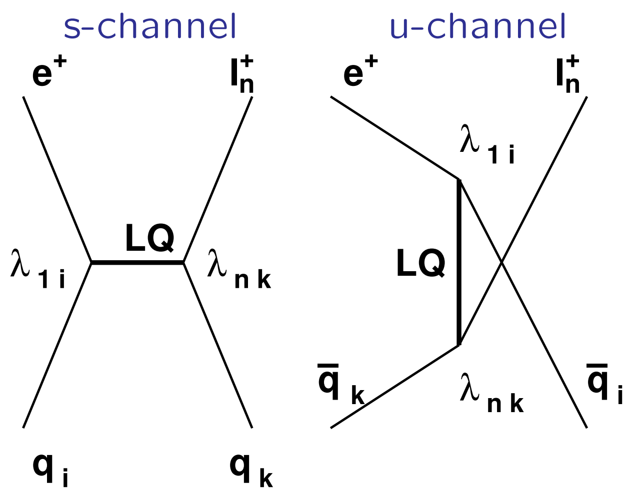
Leptoquarks

Colored bosons with L and B number predicted by several theories beyond SM (GUT,Technicolor,...)

Unique sensitivity at HERA because of L and B number initial state

Buchmüller-Rückl-Wyler (BRW) phenomenological model:

- SU(3) $\times$ SU(2) $\times$ U(1) invariance
- 7 scalar and 7 vector LQ species
- fermion number: $F = 3B + L$ — $F = 0$: $e^-\bar{q}$ or e^+q, best sensitivity in e^+p; $F = 2$: e^-q or $e^+\bar{q}$, best sensitivity in e^-p
- couple only to chiral SM fermions
- branching ratio to $eq/\nu q$: 1, 1/2, 0



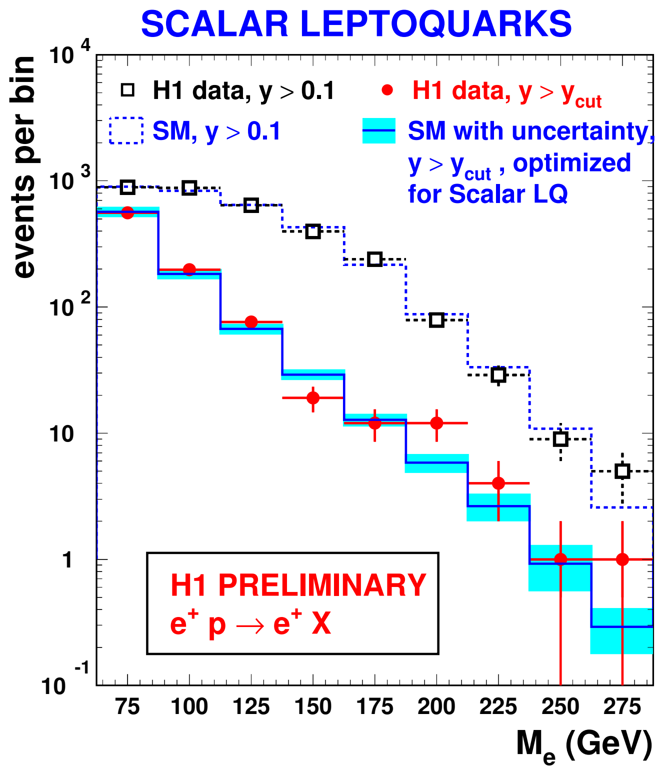
- $M_{LQ} < \sqrt{s}$: direct production, s-channel dominated
- $M_{LQ} \gg \sqrt{s}$: CI analysis ($g/\Lambda \rightarrow \lambda/M_{LQ}$), both s- and u-channel contribute

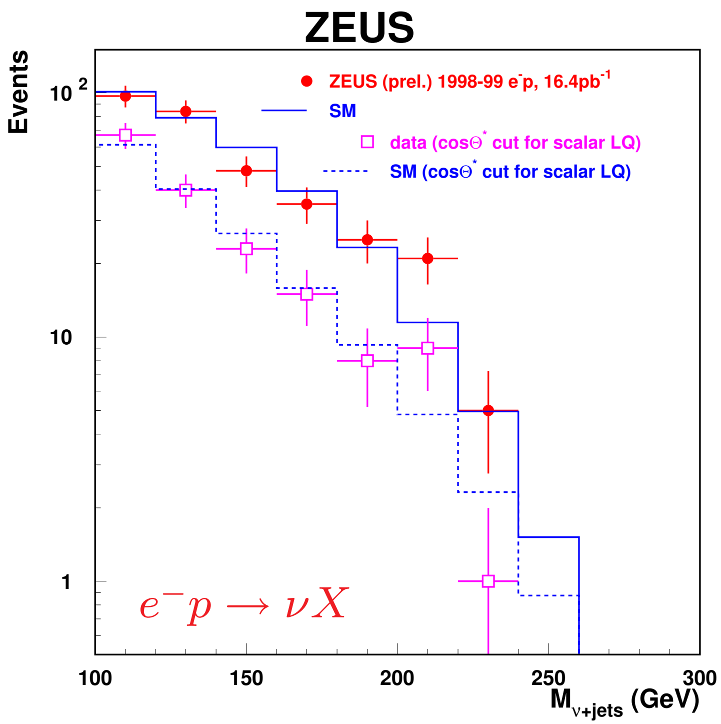
  limit on $M_{LQ}/\lambda >$ 0.31-1.42 TeV ZEUS; 0.29-1.69 TeV H1 — depending on the LQ type

Search for direct LQ production

Signature: LQ $\rightarrow eq$ or νq
search for a peak in the lepton-jet invariant mass

Background: standard DIS, but different angular distribution of scattered lepton



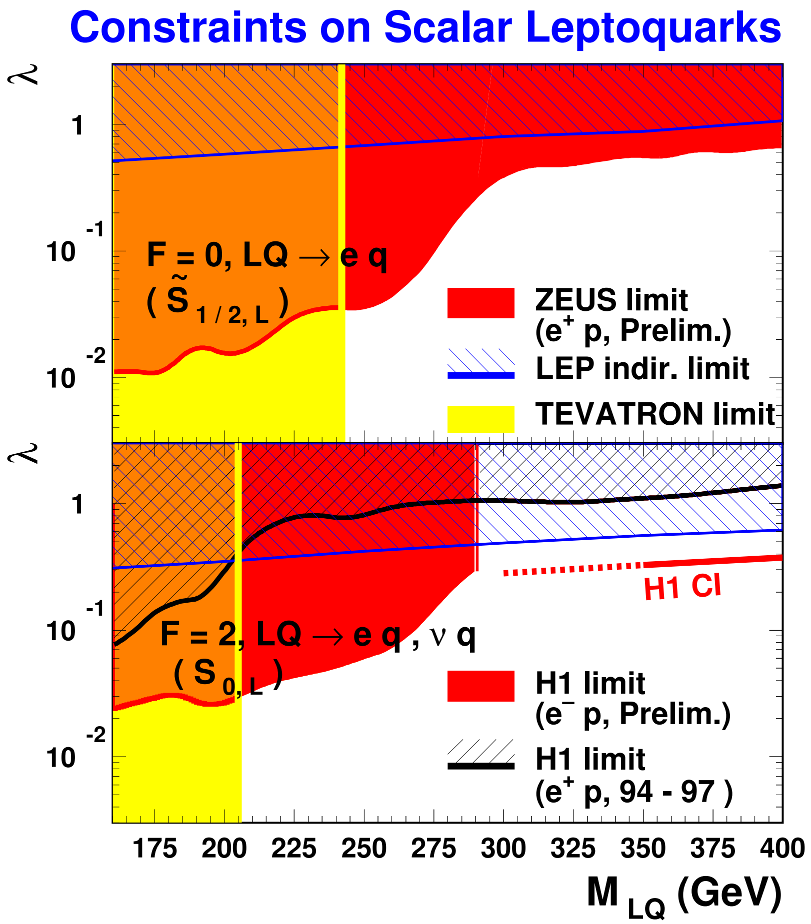


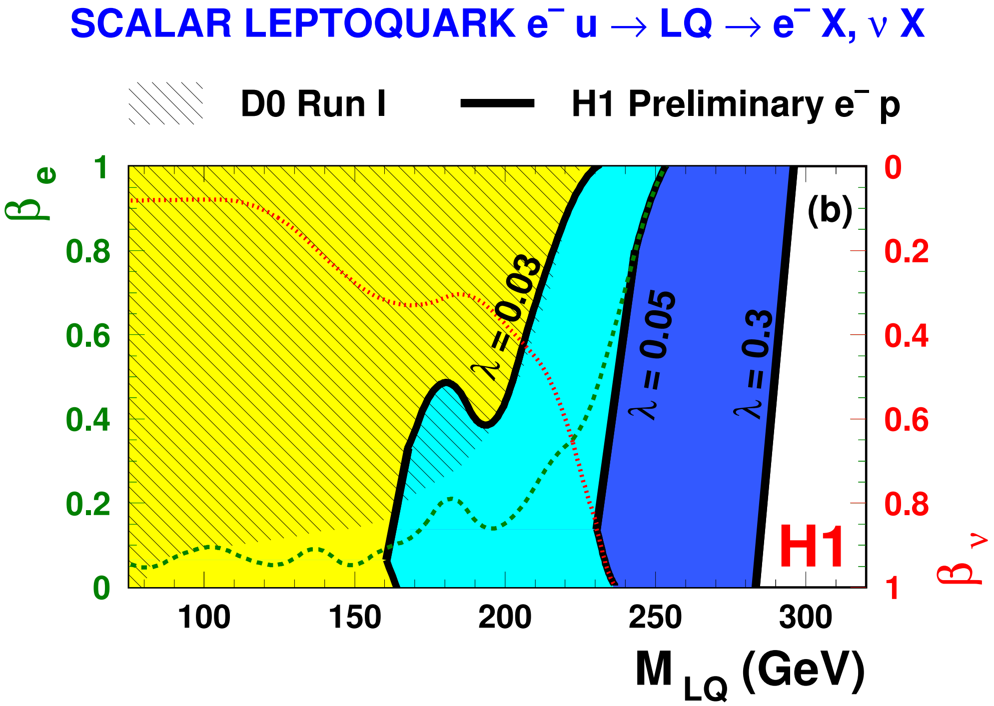
Good agreement with the SM found

- eq channel searched in the full data sample (94-00)
- νq channel searched in 94-97 e^+ and 98-99 e^-

Limits on scalar LQ

Limit on the coupling λ as a function of M_{LQ}





Assuming $\lambda = \sqrt{4\pi\alpha} = 0.31 \rightarrow M_{LQ} > 280$ GeV

General LQ models: $\beta(LQ \rightarrow eq)$ free
If $\beta(eq) + \beta(\nu q) = 1$ → limits almost independent from branching ratios
Good sensitivity at $\beta(eq) \ll 1$ (Tevatron limits independent of λ)

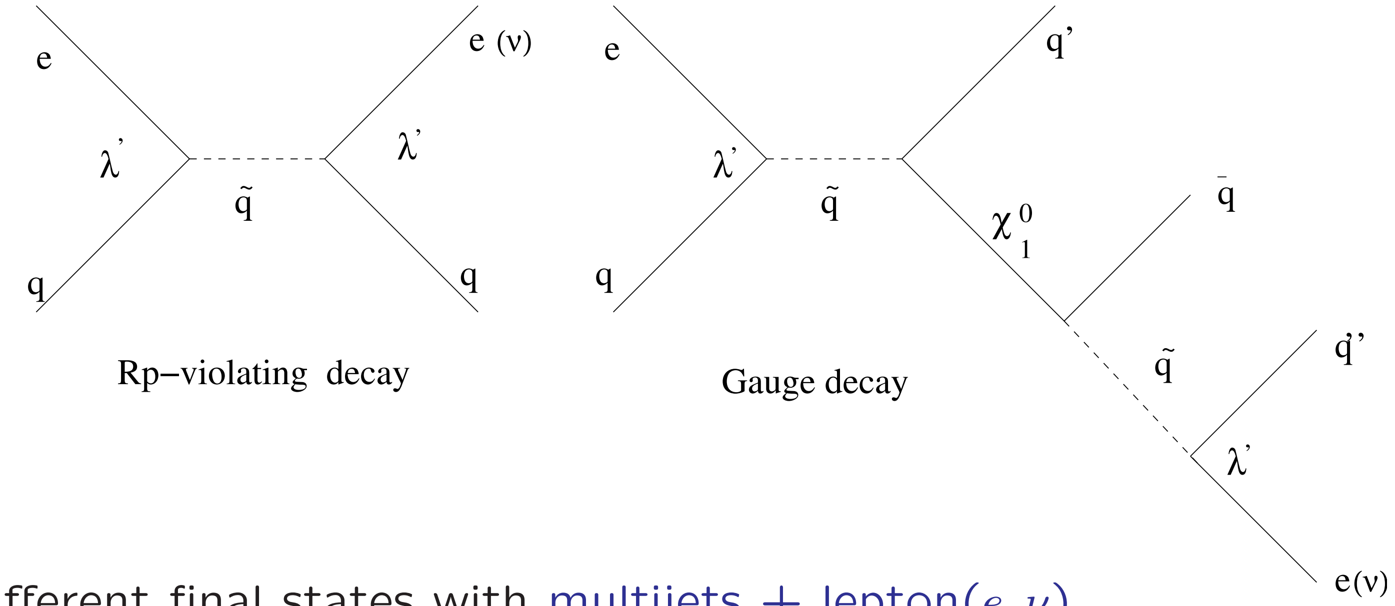
R-parity violating SUSY

$R_p = (-1)^{L+3B+2S}$ $\rightarrow$ distinguishes between standard particles ($R_p = 1$) and SUSY partners ($R_p = -1$)

If $\not{R}_p$ $\rightarrow$ single sparticle production and LSP not stable

At HERA direct test of Yukawa coupling of squark to lepton-quark pair: $eq \rightarrow \tilde{q}$

Decay channels available: R_p-violating decay
gauge decay



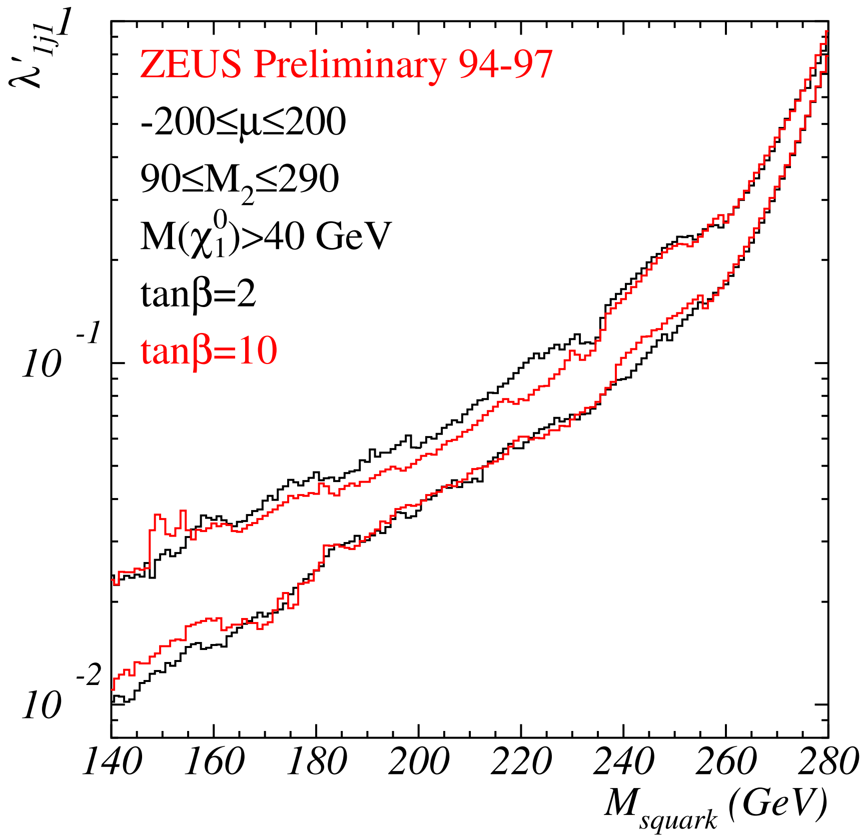
Many different final states with multijets + lepton(e, ν)
Background sources: NC or CC DIS

No deviation from SM found $\rightarrow$ limits on unconstrained MSSM

Limits on R_p-violating squarks

ZEUS (and H1, not shown) results based on 94-97 e^+p data

Unconstrained MSSM

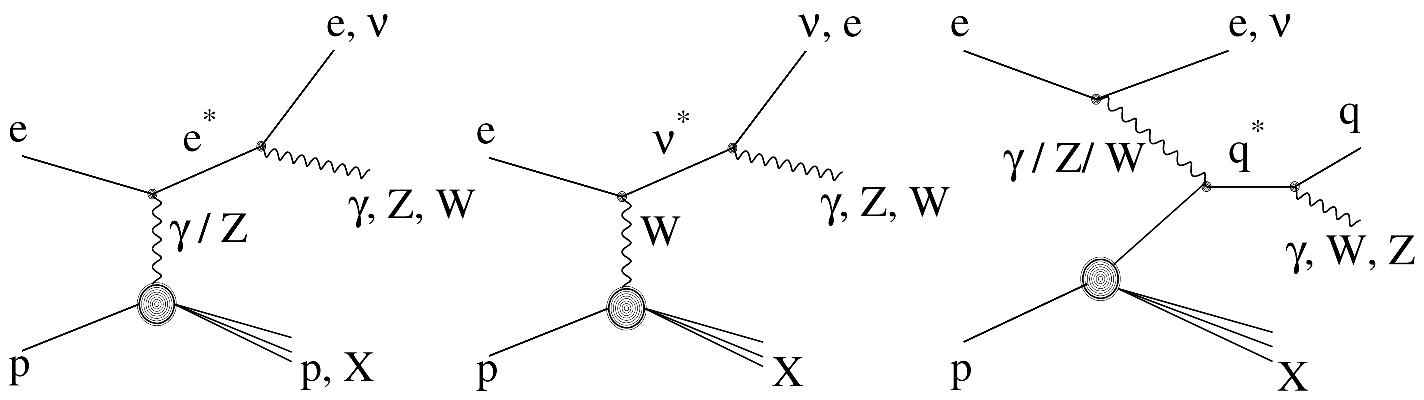


For $M_{\tilde{q}} = 200$ GeV: $\lambda'_{1j1} < 0.05$ at HERA
$\lambda'_{1j1} < 0.07$ in *atomic parity violation*

Excited fermions

Compositeness models of fermions $\Rightarrow$ excited states f^*

Single production mechanisms at HERA:



$f - f^*$ interaction described by effective lagrangian (Hagiwara-Komamiya-Zeppenfeld):

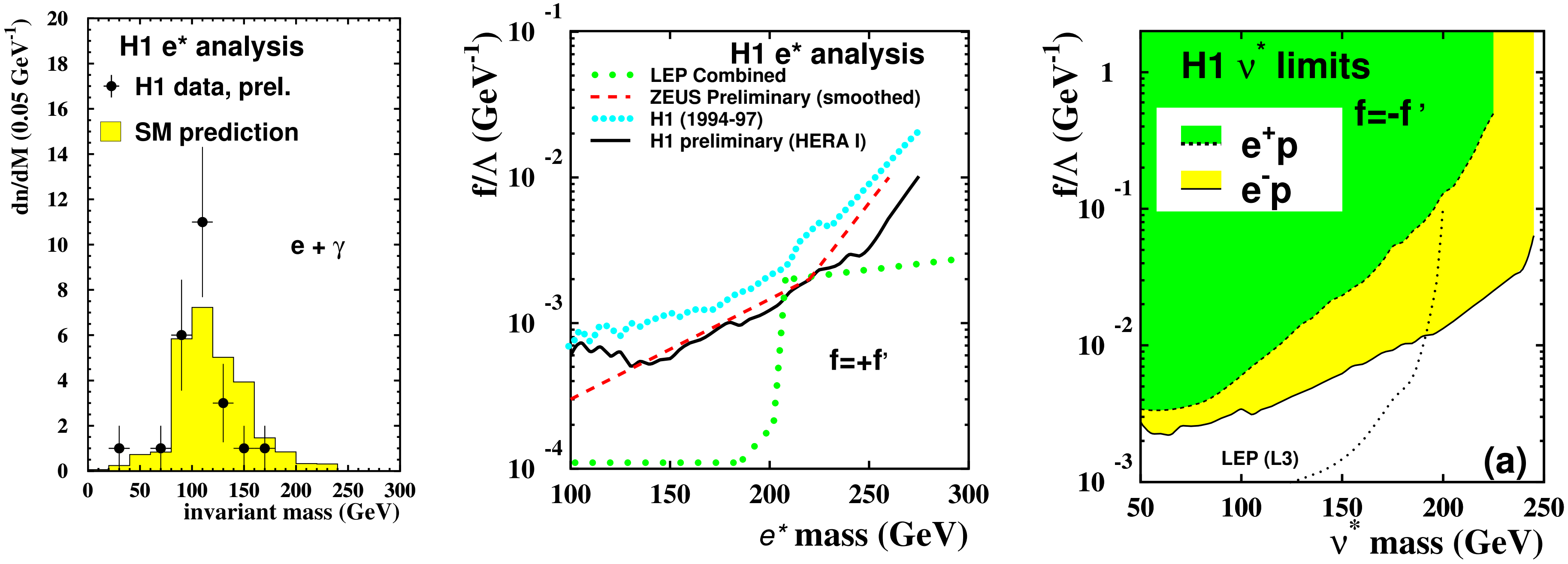
$$L_{eff} \propto \frac{1}{\Lambda}\left[f SU(2)_W + f' U(1)_Y + f_s SU(3)_C\right]$$

Λ = compositeness scale
f, f', f_s = weight factors for gauge groups

Assuming relation between $f, f', f_s \rightarrow$ cross section depends only on f/Λ

Signature: peak in fermion-boson invariant mass
Background: mainly QEDC

Excited fermion limits



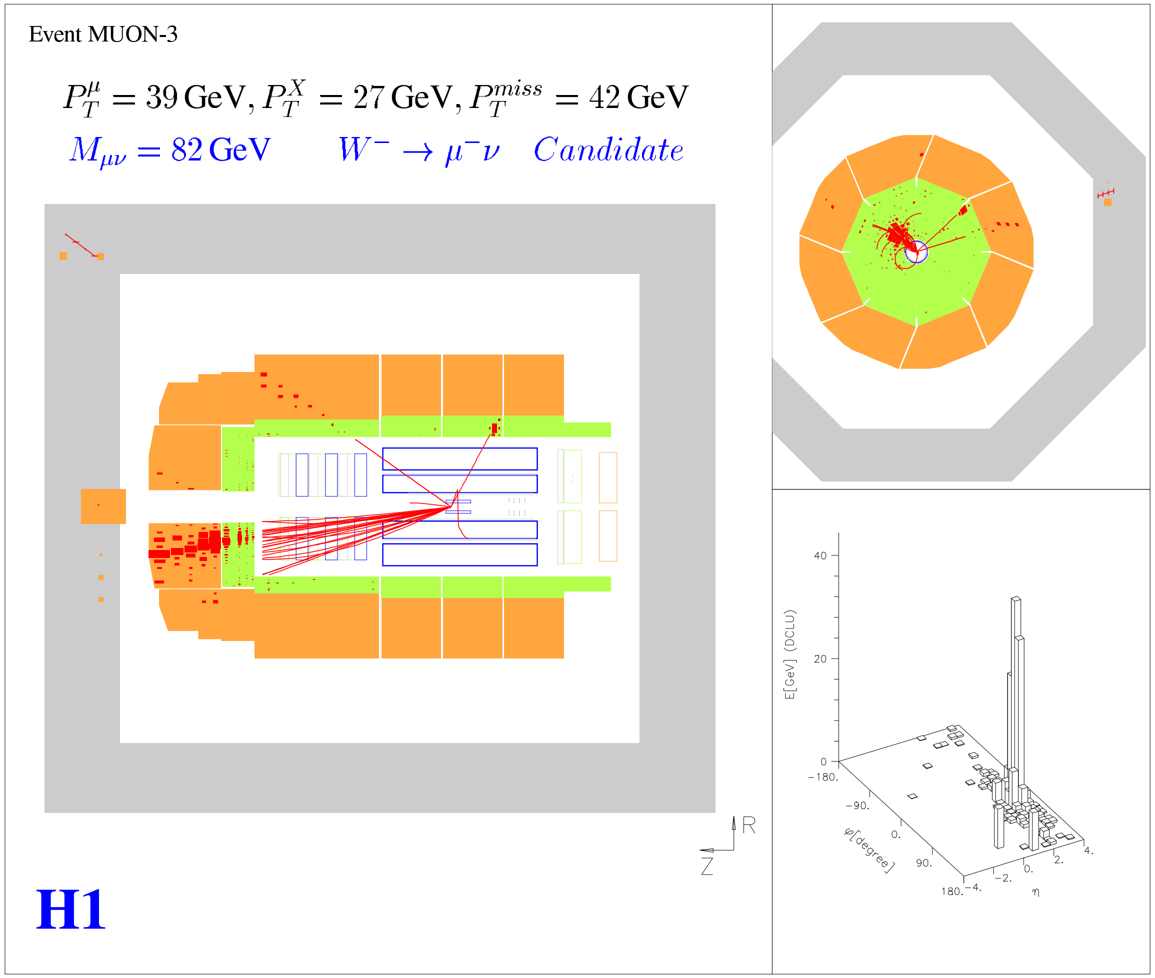
e^*: no deviation from SM in full 94-00 data set
H1 and ZEUS limits at the edge of LEP combined results
improvement with HERA II

ν^*: no deviation from SM in combined 94-97 e^+p and 98-99 e^-p data
direct limits extended above 200 GeV

Search for events with isolated high-p_t leptons

Excess of events with high-p_t isolated lepton and missing transverse momentum observed by H1 in 94-97 e^+p data (H1 Coll. **Eur.Phys.J. C5 (1998)** 575-584)

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



Event topology:
- high-p_t isolated μ or e
- large hadronic P_T (P_T^X)
- missing p_t

Background:
- mainly W production

$\Rightarrow$ full 94-00 data set analyzed by both experiments

Result on high-p_t lepton searches

ZEUS prel. 94-00 $e^{\pm}$p 130 pb^{-1}	Electrons Observed/Expected (W)	Muons Observed/Expected (W)
$P_T^X > 25$	$1/1.14 \pm 0.06$ (1.10)	$1/1.29 \pm 0.16$ (0.95)
$P_T^X > 40$	$0/0.46 \pm 0.03$ (0.46)	$0/0.50 \pm 0.08$ (0.41)

ZEUS is consistent with SM

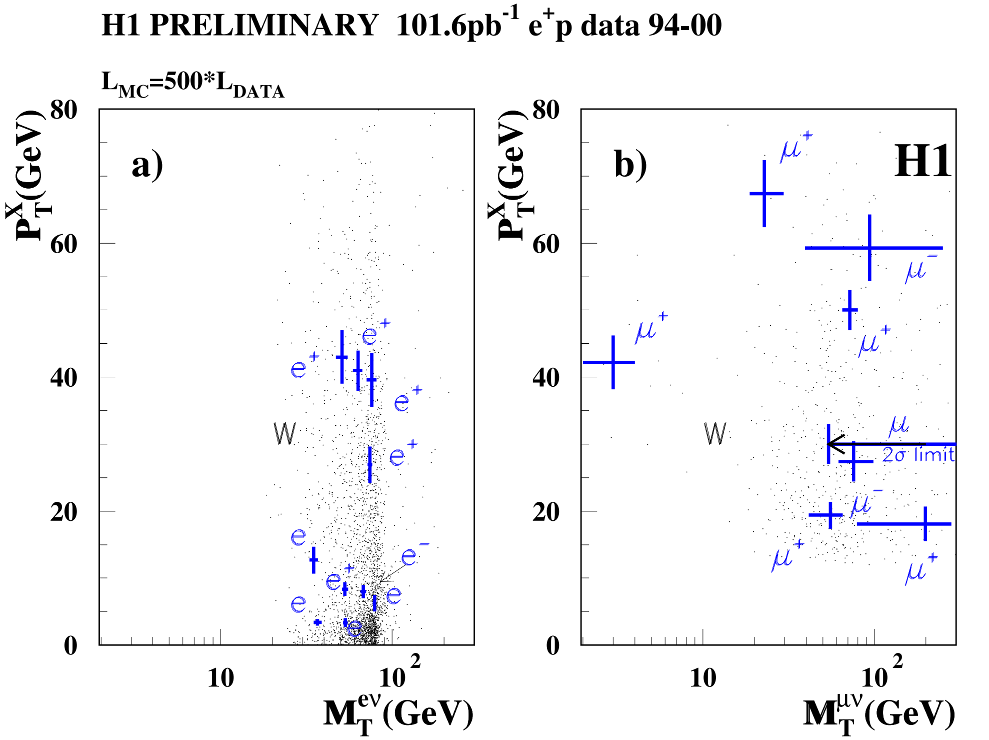
H1 prel. 94-00 e^{+}p 102 pb^{-1}	Electrons Observed/Expected (W)	Muons Observed/Expected (W)
$P_T^X > 25$	$4/1.29 \pm 0.33$ (1.05)	$6/1.54 \pm 0.41$ (1.29)
$P_T^X > 40$	$2/0.41 \pm 0.12$ (0.40)	$4/0.58 \pm 0.16$ (0.53)

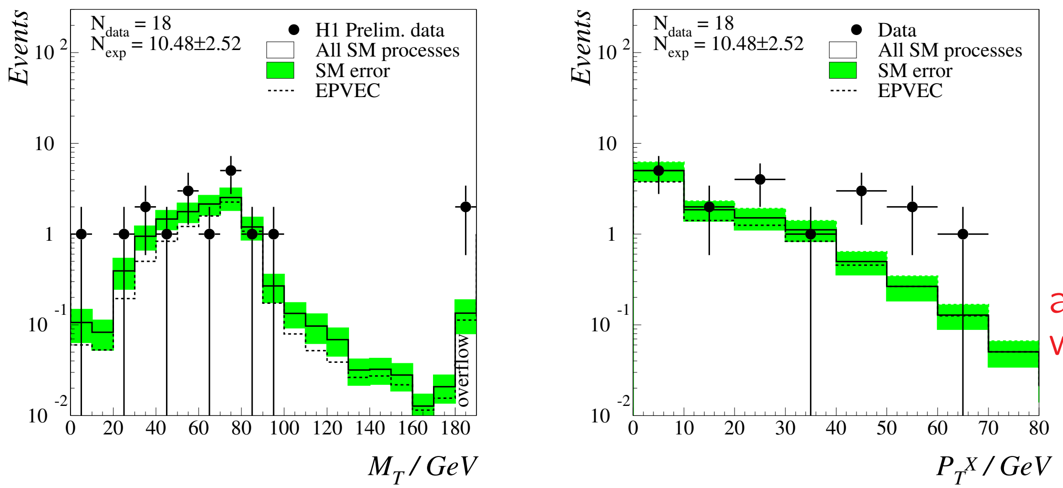
Excess of events observed at high P_T^X in H1

in 98-99 e^-p data (14 pb^{-1}) no excess observed (0/1.8$\pm$ 0.4)

Kinematics of H1 events with isolated lepton and missing P_t

before P_T^X cut →





Transverse mass distribution consistent with W

Excess of events at large hadronic P_T w.r.t. W production

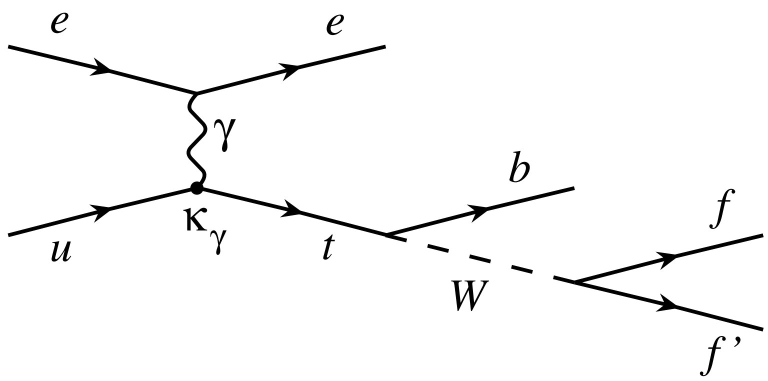
Possible explanation with single top production?

Search for single top production in FCNC

Cross section from SM processes very low

$$\sigma(ep \to etX) \sim 1\text{fb at } \sqrt{s} = 300 \text{ GeV}$$

SM extensions (SUSY) predict top with large FCNC interactions:
$\Rightarrow$ sizeable single top production at HERA



Dominant production mechanism: $tu\gamma$ coupling
propagator mass $\longrightarrow$ γ-exchange
heavy top mass $\longrightarrow$ large x quark involved

Search performed in leptonic and hadronic W decay channels

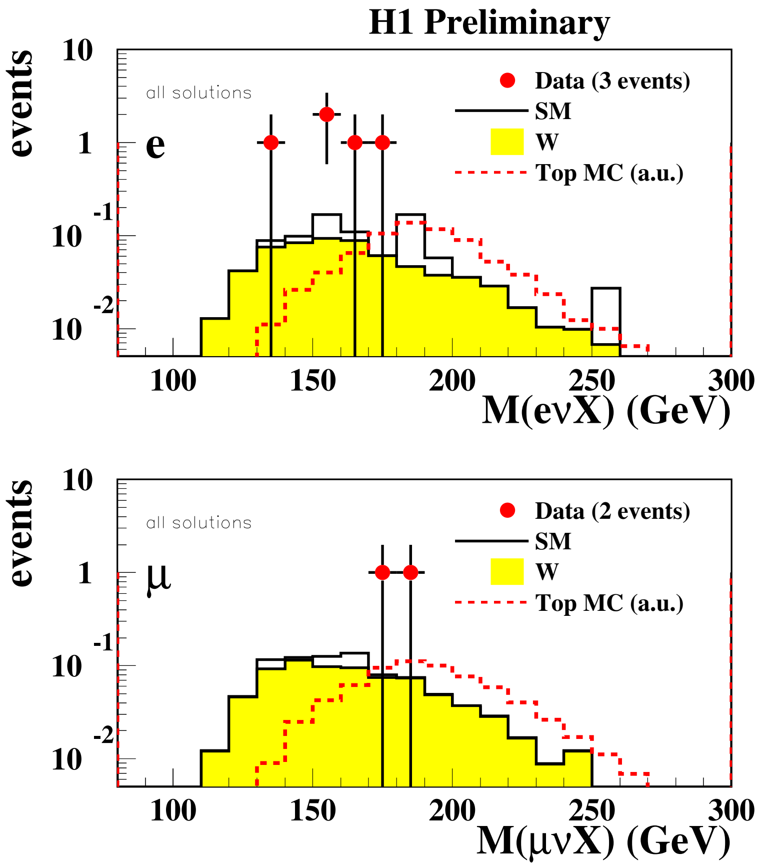
Single top search: leptonic mode

Search for process:

$$eu \to et \to ebW \to ebl\nu$$

Signature:
high p_t lepton (e or μ), missing P_t and large hadronic P_t (P_T^X)

Background:
dominated by W production (~1pb at HERA)



	observed	SM expected
H1	$3e + 2\mu$	1.8
ZEUS	0	0.96

Five H1 events compatible with top production

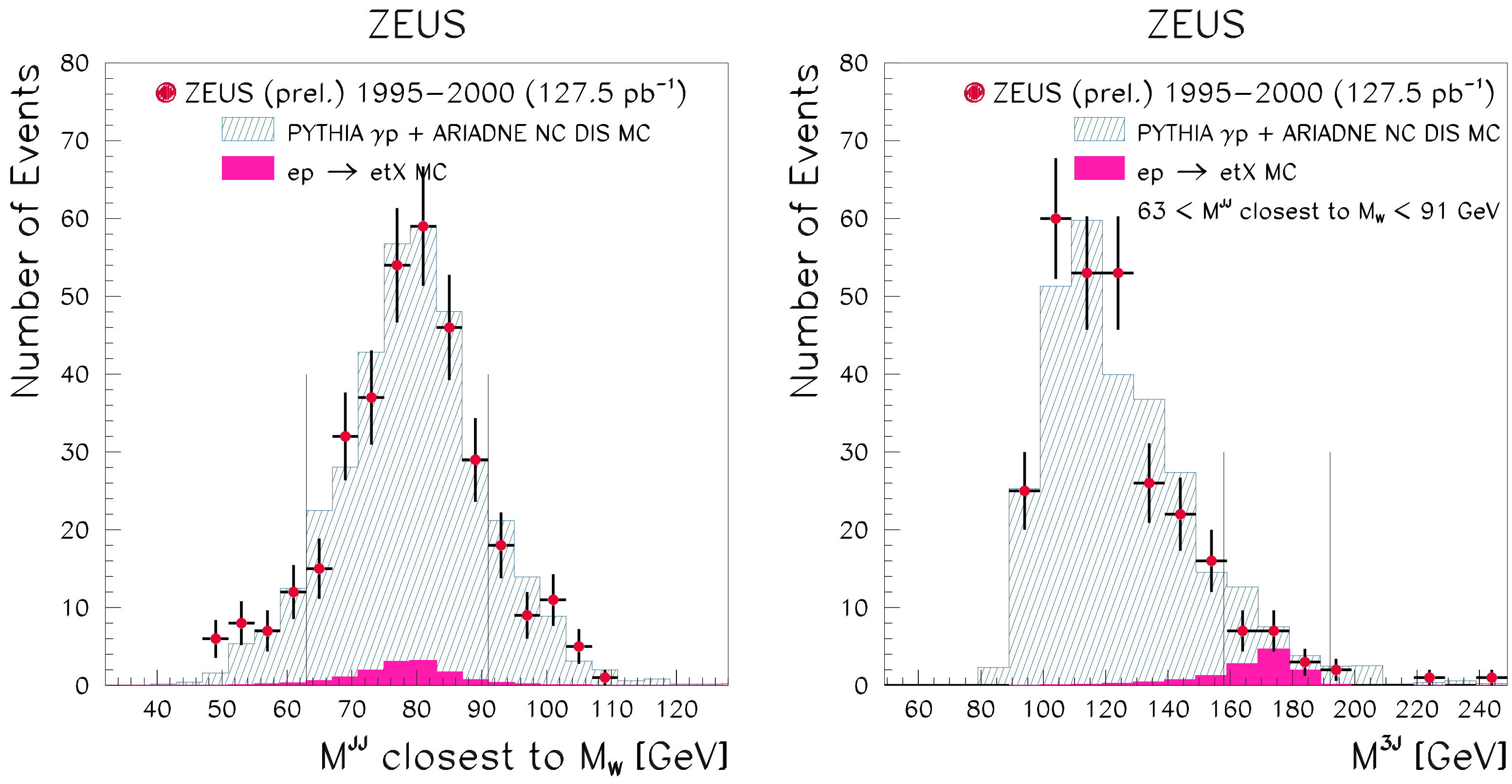
Single top search: hadronic mode

Search for process:

$$eu \to et \to ebW \to ebq\bar{q}$$

Signature: 3-jet events with $M^{jj} \simeq M_W$ and $M^{jjj} \simeq M_t$

Background: 3-jet photoproduction

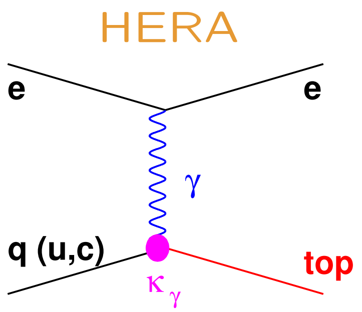


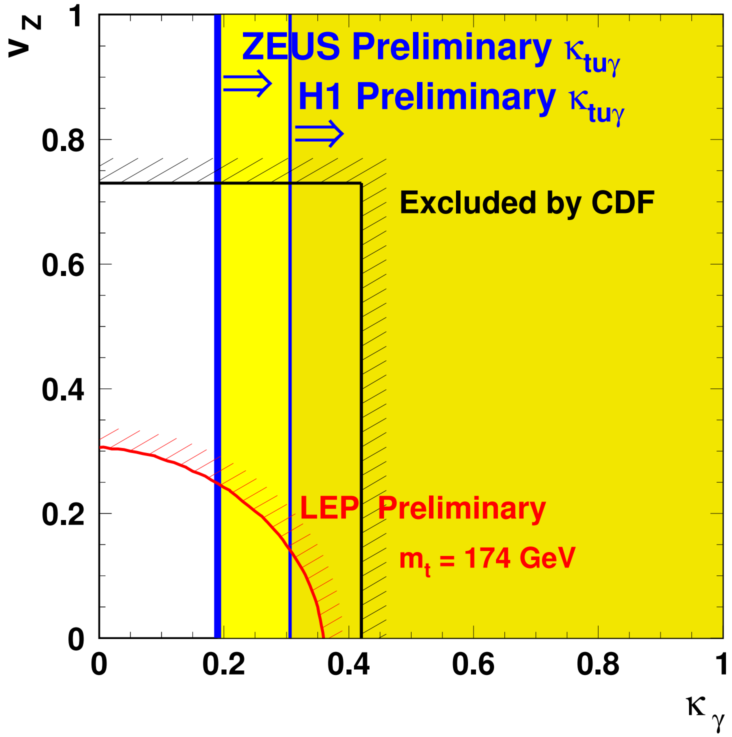
⇒ No excess observed in ZEUS (94-00 prel.) and H1 (94-97 prel.) data

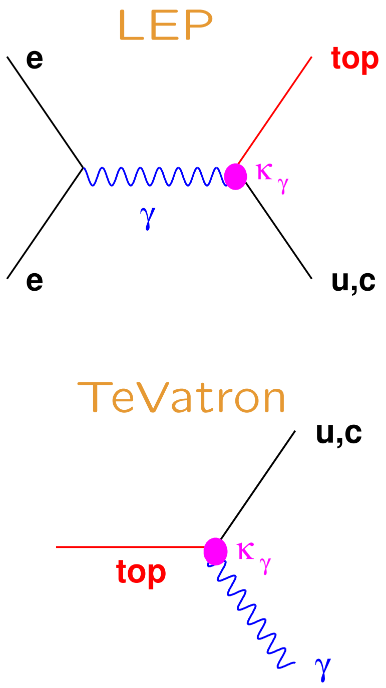
Lower sensitivity with respect to leptonic channel

Limits on anomalous $tu\gamma$ coupling

Combining leptonic + hadronic results:







κ_γ = magnetic coupling to photon
V_Z = vector coupling to Z

HERA results at world level (ZEUS more stringent because H1 finds candidates)

Summary from HERA I

H1 and ZEUS found no evidence of new processes at HERA

Competitive limits set on new physics, and namely:

- Contact Interactions, Extra Dim.: $\Lambda_{eeqq} \gtrsim 5\text{TeV}$
- Leptoquarks: $M_{LQ} >280$ GeV ($\lambda = 0.3$)
- R_p-violating SUSY: $M_{\tilde{t}} >245$ GeV ($\lambda = 0.3$)
- Excited Fermions: $f/\Lambda < 0.01$ at M_{ν^*} or $M_{e^*} = 200$ GeV
- Flavor Changing Neutral Currents: $\kappa_{tu\gamma} < 0.2$

H1 high-p_t lepton events still outstanding, but ZEUS is supporting SM!
Issue clarified by HERA II?

Outlook into HERA II

Promising years to come: the HERA II programme is starting now!

- Integrated luminosity per experiment: now $\sim 100\mathrm{pb}^{-1} \longrightarrow$ end-2006 $\sim 1\mathrm{fb}^{-1}$
  $\longrightarrow$ improve CI limits
  $\longrightarrow$ improve LQ limits
  $\longrightarrow$ improve f^* limits

- Polarized $e^{\pm}$ beam:
  $\longrightarrow$ enhance/disantangle signals coupling to chiral leptons
  $\longrightarrow$ control background processes

- Upgraded detectors: both equipped for heavy-quark tagging, improved forward tracking
  $\longrightarrow$ sensitivity to flavor specific processes