Search for physics beyond Standard Model at HERA

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On behalf of H1 and ZEUS collaborations
HERA Ringberg workshop, 4 June 1999

- Introduction
- e-q resonances :
  Leptoquarks
  R-parity violating SUSY
- Excited fermions
- Contact Interactions
- Summary

Introduction

- ep collisions at HERA
  = non-zero L and B in initial state

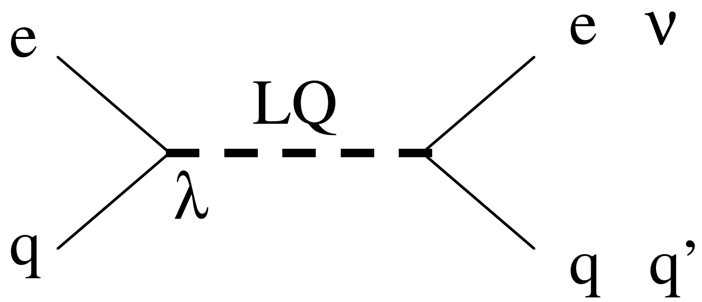
  ↓

  highest potential for producing:
- particles carrying both L and B
  (LQ, squark in Rp-violating SUSY)
- Excited states of leptons / quarks

Some numbers:

- E_{CM} = 300 GeV (from 1998: 318 GeV)
- Luminosity
  e^+p 94-97: 37pb^{-1} H1 + 47pb^{-1} ZEUS
  e^-p 98-99: 19pb^{-1} H1 + 16pb^{-1} ZEUS
  (up to end April: preliminary values)

Leptoquarks



- Buchmüller-Rückl-Wyler model:

  14 species under SU(3)xSU(2)xU(1) invariance
  (7 scalar and 7 vector, or 7 F=0 and 7 F=2; $F \equiv L+3B$)

- $F=0 \rightarrow$ best sensitivity with e^+q fusion
  $F=2 \rightarrow$ best sensitivity with e^-q fusion
  (IF couples to 1st-generation quark)

- LO production with s-channel diagram only (NWA) gives:
  $\sigma = (\pi/4s)\,\lambda^2\, q(x,M^2) * 1(\text{scalar}), 2(\text{vector})$ $(x = M^2/s)$
  $\Gamma = (1/16\pi)\,\lambda^2 M * 1(\text{scalar}), 2/3(\text{vector})$

  good approx. for valence quark, small λ, but
  u-channel, interference and finite width important for
  sea quark, large λ. (see e.g. hep-ph/9812481)

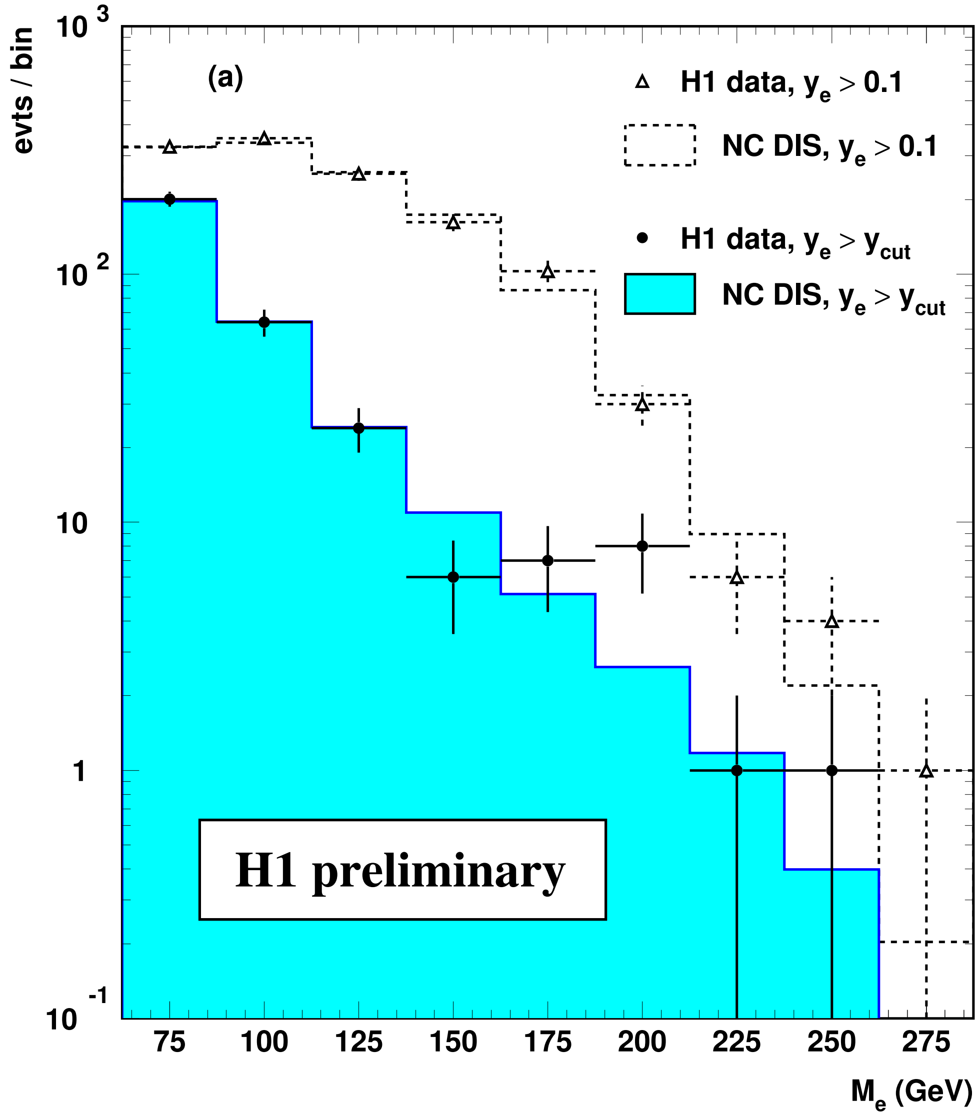
- $BR(LQ \rightarrow eq) = 1$ or $1/2$ (then $LQ \rightarrow \nu q$)

- decay angle: flat y distribution (scalar), $(1-y)^2$ (vector)
  $\longleftrightarrow$ $1/y^2$ for NC DIS background

LQ search: H1 data

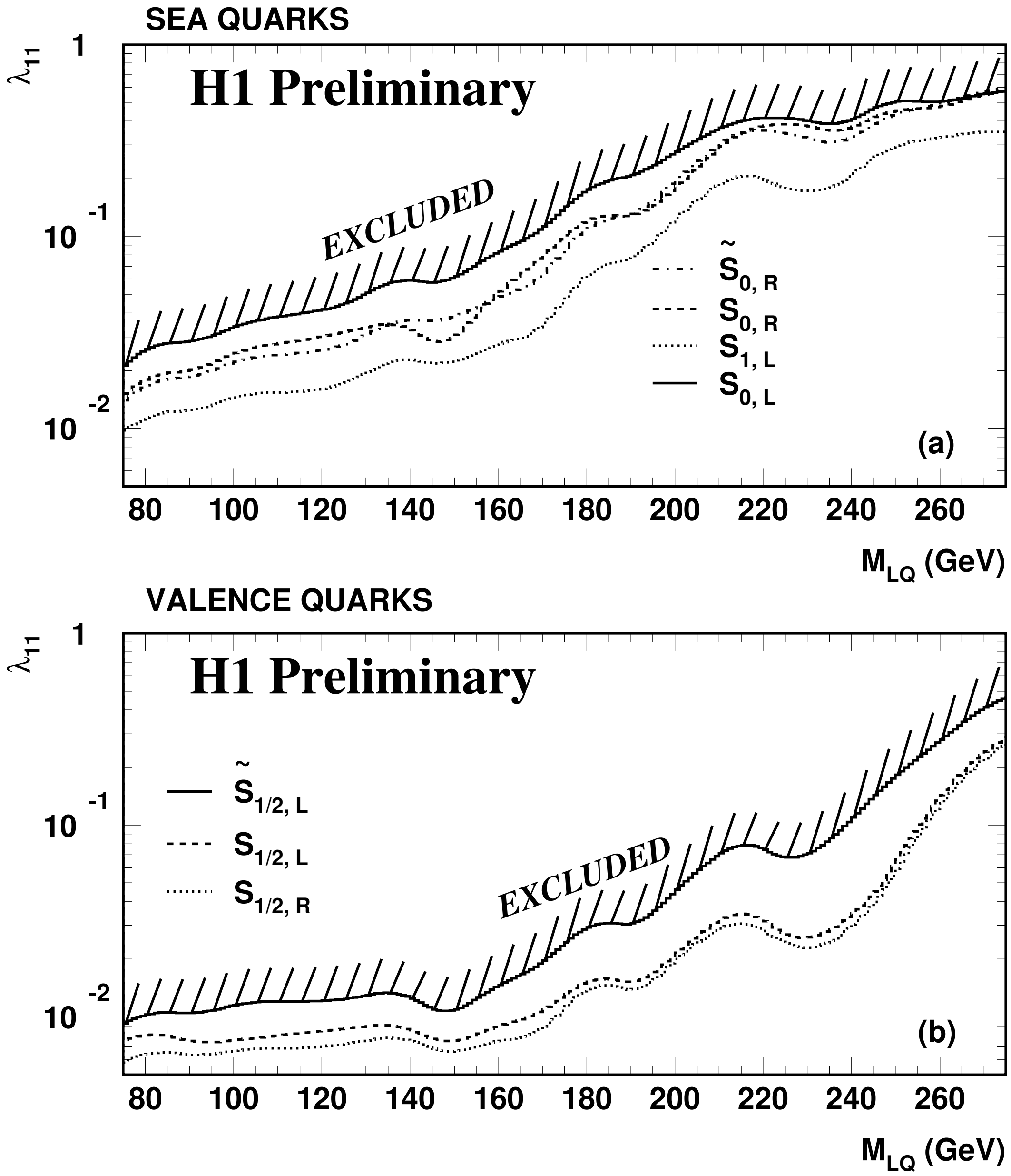
- NC DIS selection: $E_T(e)>15$ GeV, $40<E\text{-}Pz<70$ GeV
- Reconstruct M, y from electron energy/angle
- $y>y_{cut}(M)$ to optimize signal/background
- Also CC DIS events (νq) looked at (not shown)

(but not relevant for F=0 scalar LQs in BRW model)



Excess events at high y, M~200GeV still there (mainly from 94-96 data set)

H1: limits on LQ coupling



For λ=0.3 (EM strength), limits go as much as 275 GeV

cf. TeVatron (pair production $\rightarrow$ independent of λ)

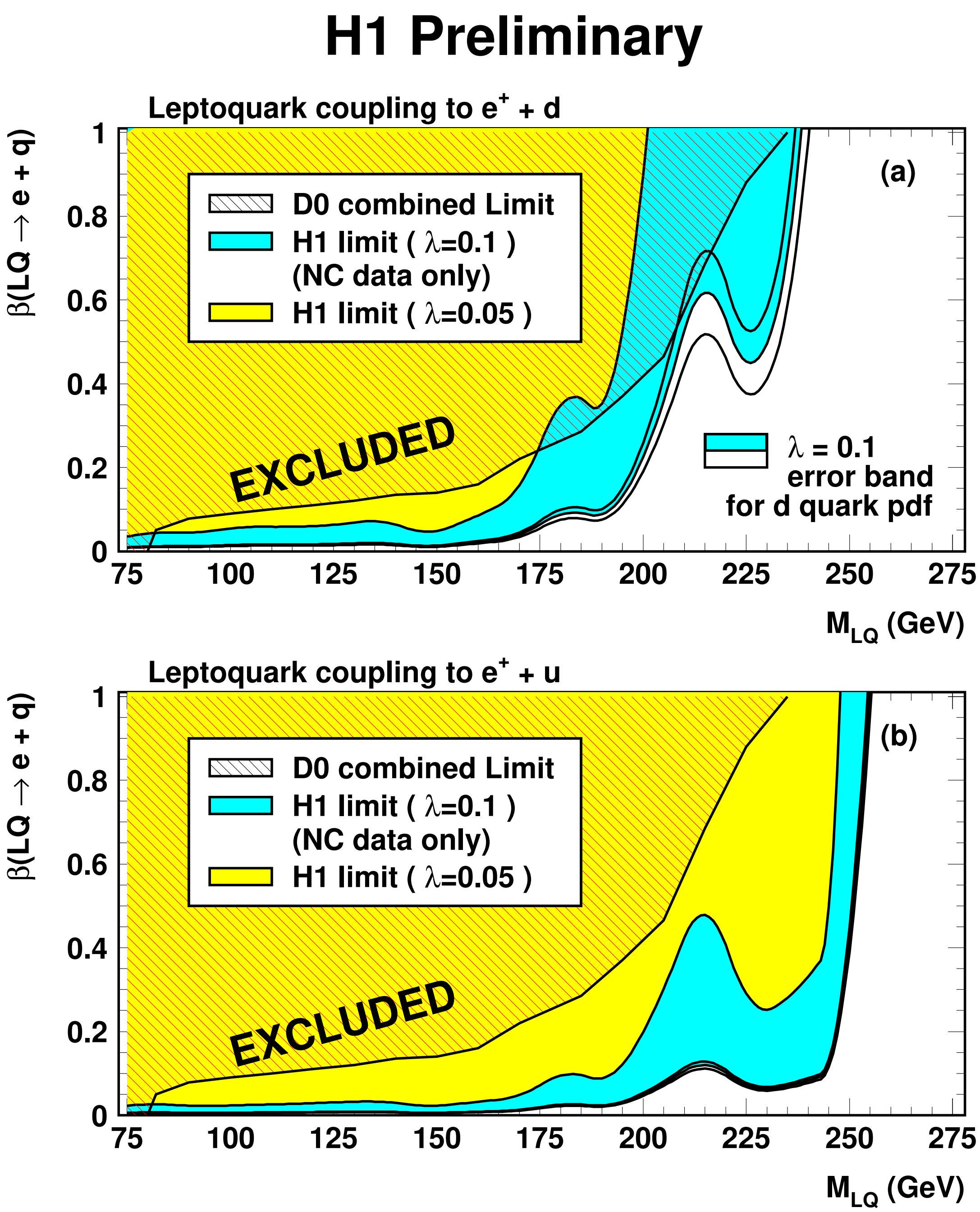
D0 limits 225 GeV (BR=1), 204 GeV (BR=0.5)

CDF+D0 combined limit 242 GeV

Another view of limits:

BR(eq) as a function of M, for fixed λ

(move away from BRW model)



For a reasonably large coupling and small BR(eq), still discovery potential for HERA even at ~200 GeV

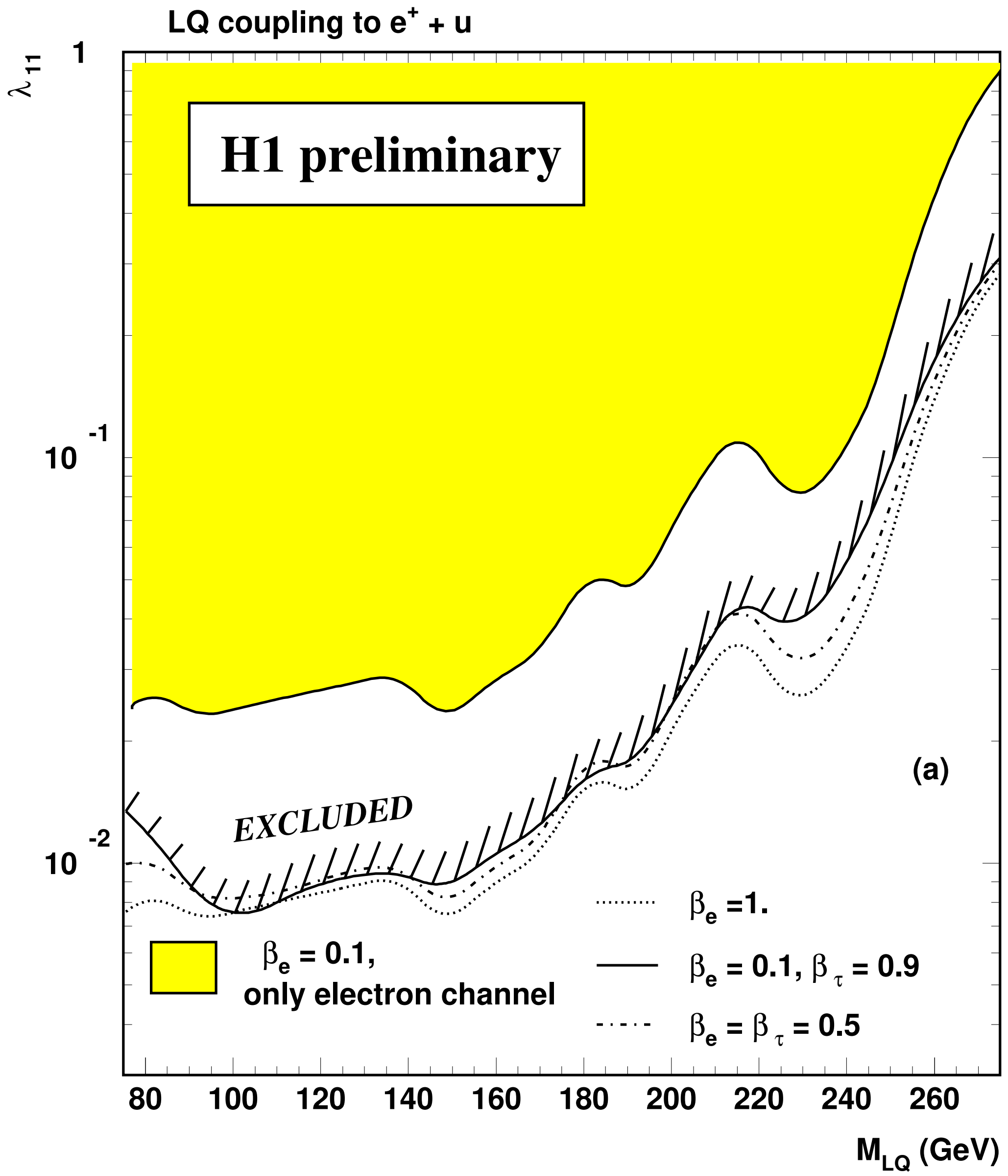
Lepton Flavor Changing LQ:

eq $\rightarrow$LQ $\rightarrow$ eq *or* τq

τq event selection

- pencil-like jet (hadronic decay of τ)
- missing Pt
- back-to-back with hadronic jet

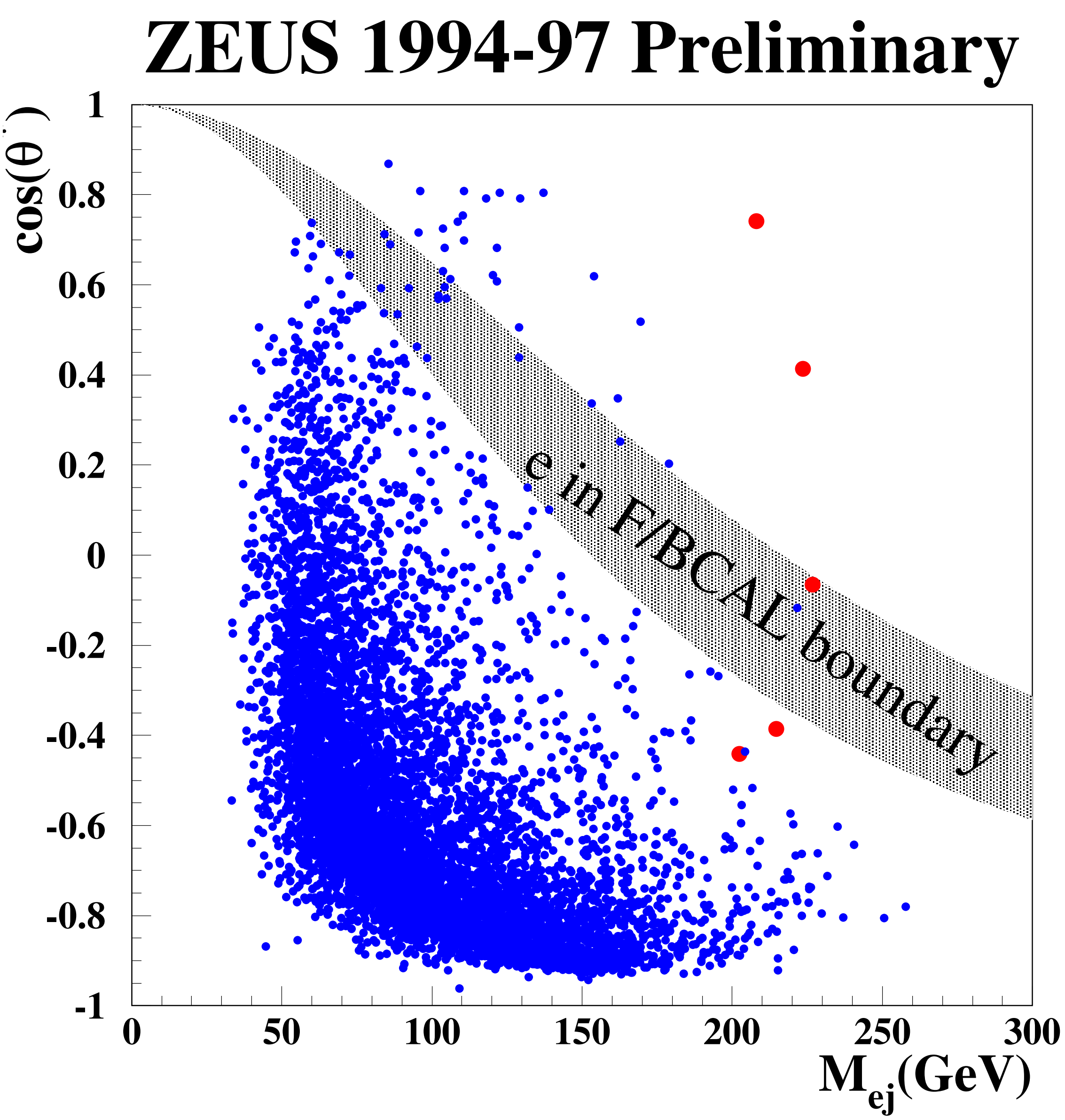
$\rightarrow$ 0 events left



Limits stable against varying branching ratios

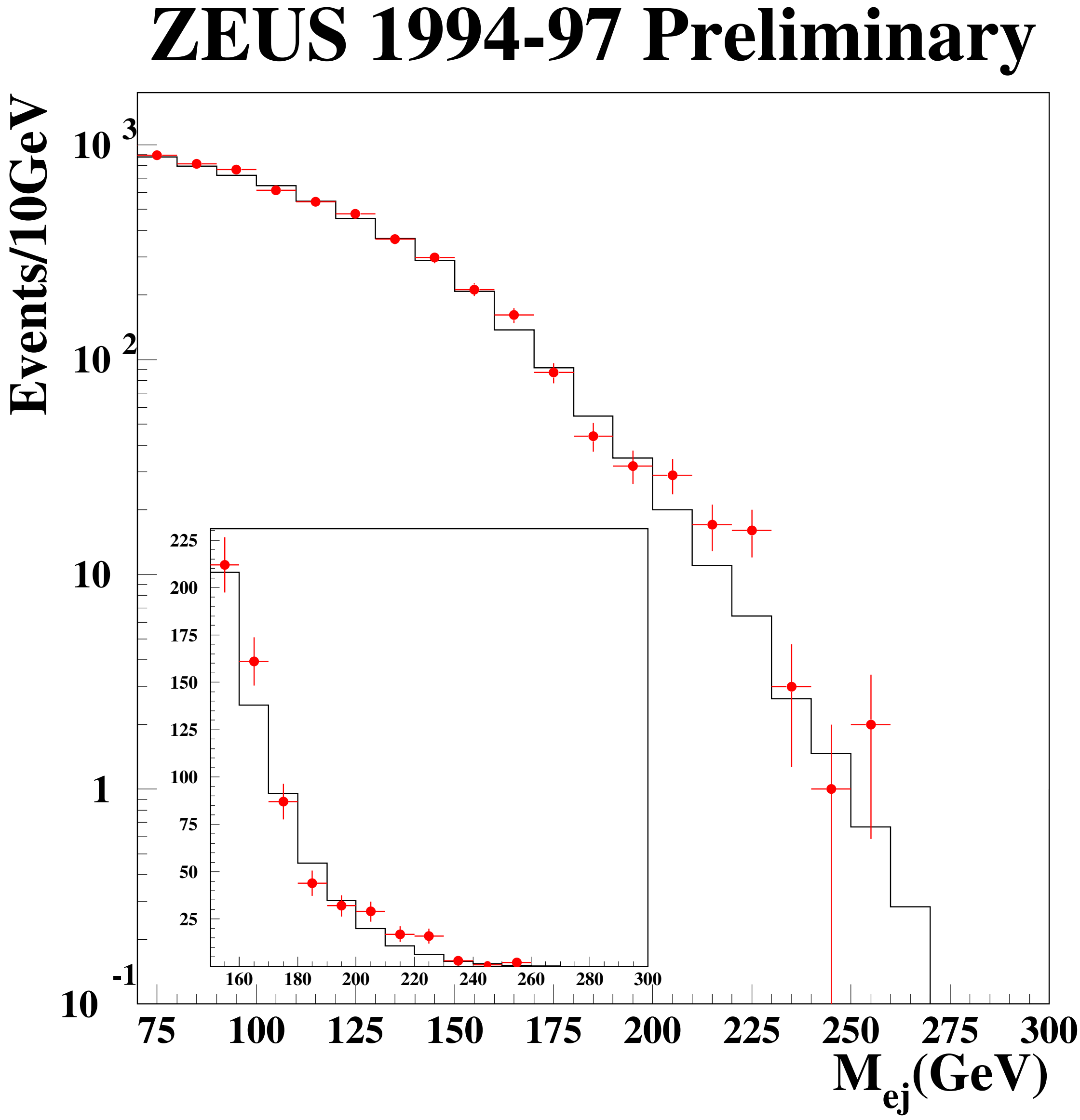
ZEUS approach for eq resonance

- Select events with
  E_T>60 GeV, E(e)>25 GeV, E_T (jet)>10 GeV
- Look at electron-jet invariant mass Mej
  (no use of kinematical constraints)
- $\cos\theta^* = 2y-1$ (decay angle in e-jet rest frame)



red points = high-x, high-Q^2 events in 94-96 paper

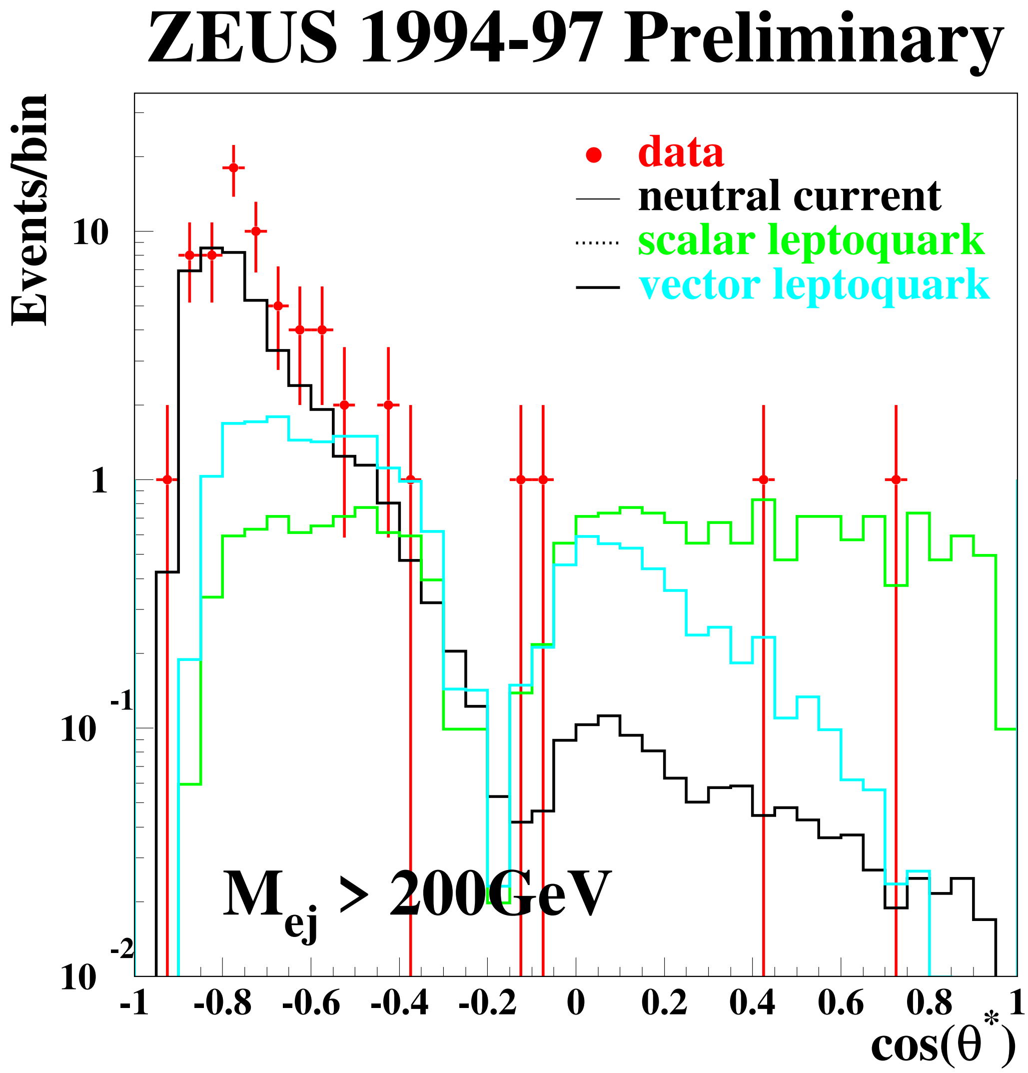
ZEUS M_{ej} spectrum



68 events observed at M > 200 GeV

43^{+14}_{-12} events expected from NC MC

Angular distribution of high-mass events

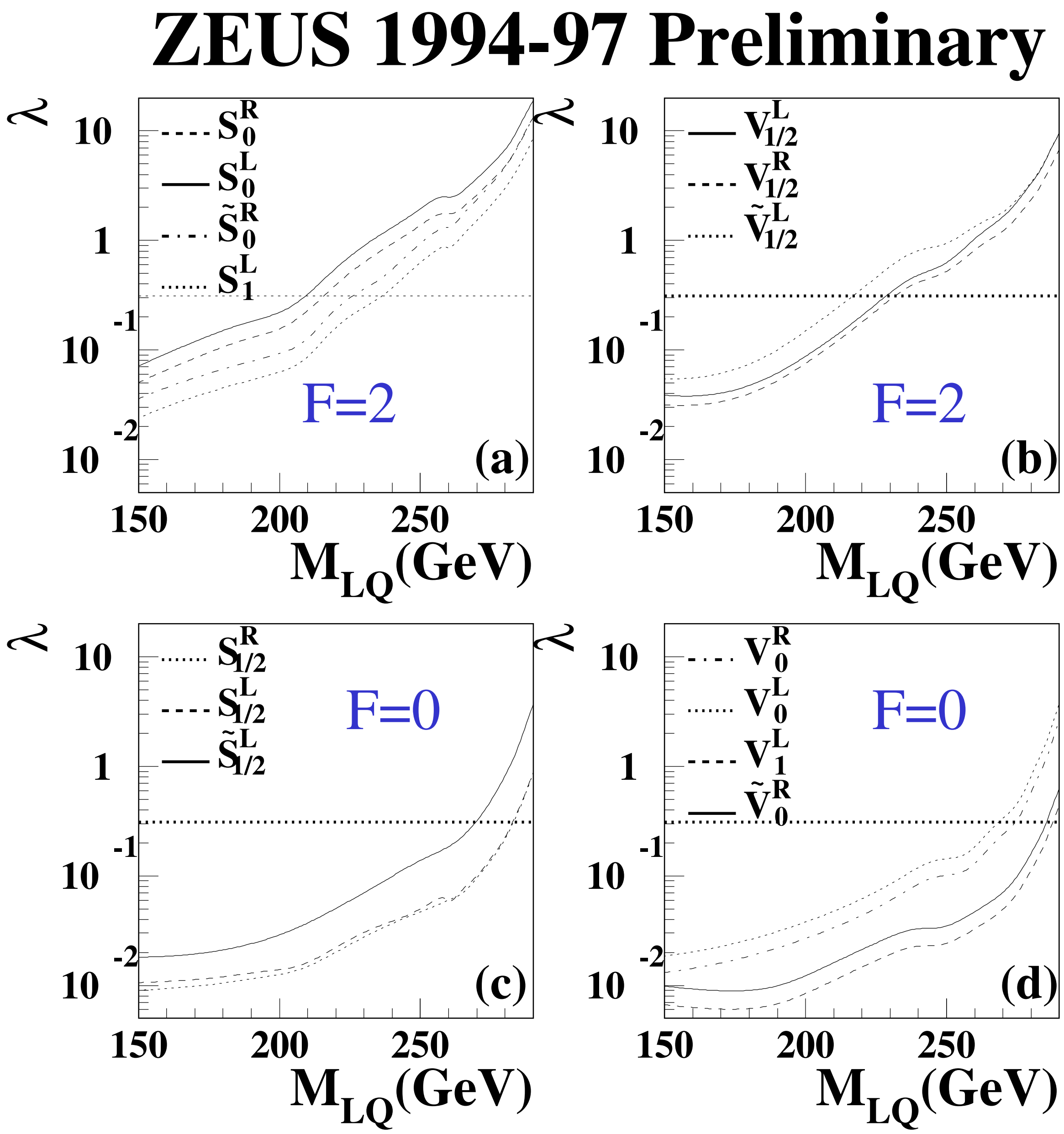


- Similar to NC DIS distribution, excess events peak at small $\cos(\theta^*)$ (low y) - not LQ-like.
- Need to investigate systematic effects carefully (e.g. jet with low polar angle), which is ongoing,
- but, is there a model which predicts such excess?

Excess not LQ resonance-like

- introduce θ^* cut to optimize LQ limits

(equivalent to y cut of H1)

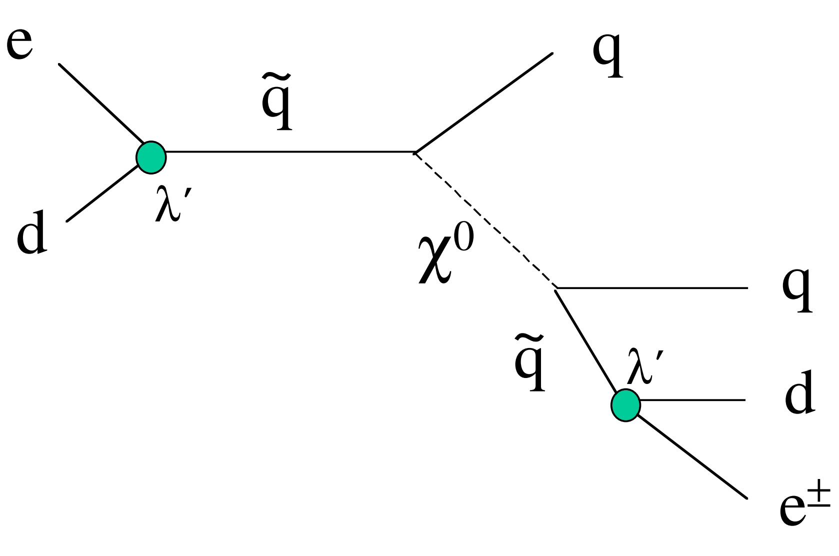


Note - ZEUS uses here NWA cross section (weaker limits than H1 for F=2 at large mass)

Limits up to above 280 GeV for EM coupling.

Another eq resonance - R-parity violating squark

- $R_P \equiv (-1)^{F+2S} = (-1)^{L+3B+2S}$
- $\lambda'_{ijk} L_i Q_j D_k$ term interesting for HERA: $e^+d \rightarrow \tilde{u}, \tilde{c}, \tilde{t}$ possible (single production)
- LQ decay $(\tilde{q} \rightarrow eq)$ and gauge decay $(\tilde{q} \rightarrow q\chi^0, q\chi^+)$ compete, B.R. depends on λ'
- LSP can decay to normal particles via λ'

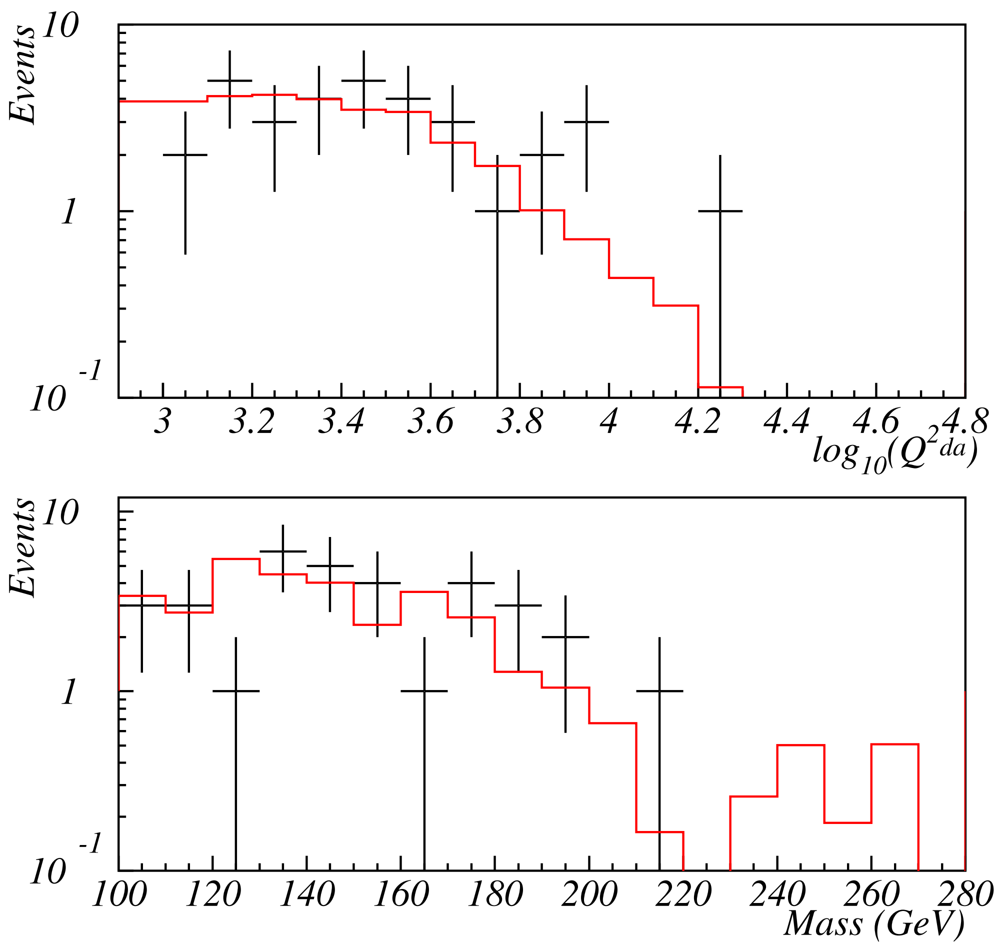


- e + multijet final state (also ν + multijet)
- $e^\pm \rightarrow$ wrong sign lepton possible (b.g. free)

ZEUS analysis

eq decay channel (S1): essentially same as LQ
eqqq channels: 2 (or more) jets, E_T > 40, 20 GeV
looser electron isolation than NC DIS selection
P_T / E_T (had) < 0.75, 0.4 < y_{DA} < 0.95
then require wrong charge (S4) or not (S3)

S3: Q^2 and e^+ + jets invariant mass



S3: 33 events observed, 33.6 expected from MC
(background mainly NC DIS and some photoprod.)
S4: 0 event observed, 0.06 events expected

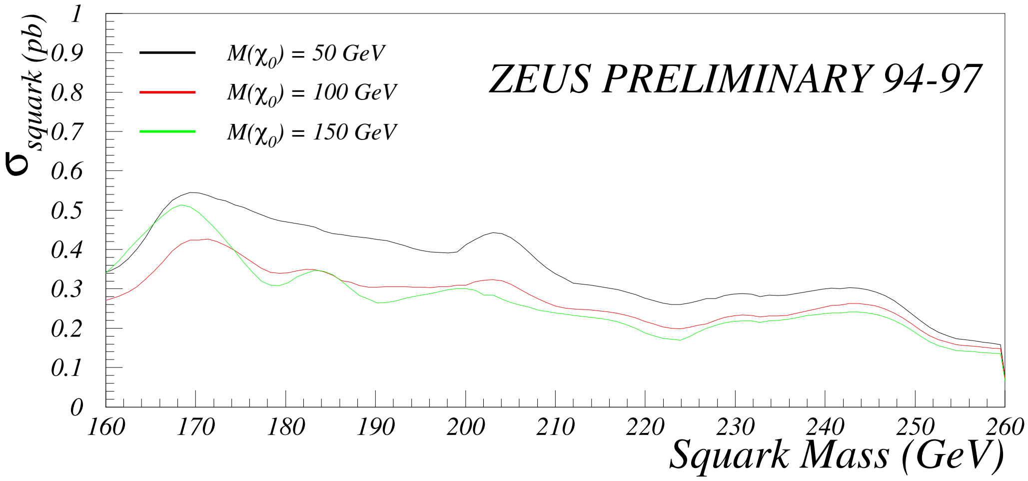
Cross section limits

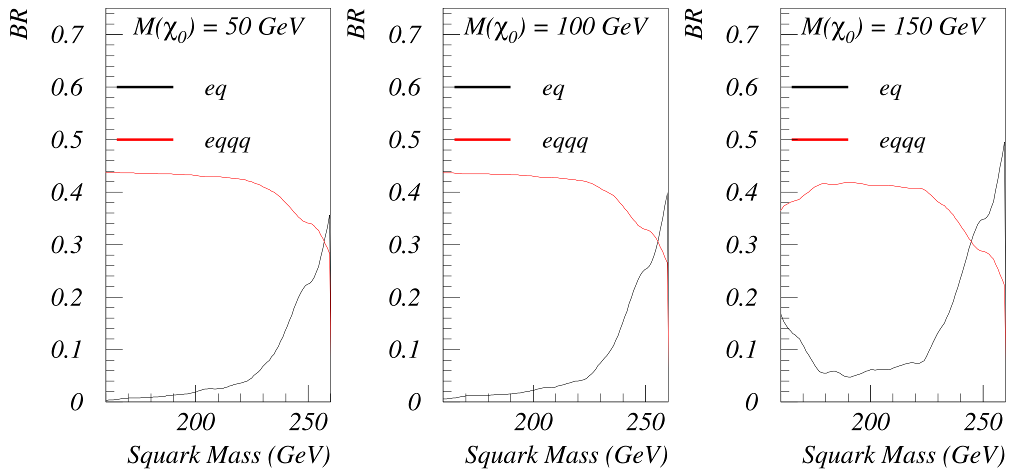
Assumptions

- Neutralino is a pure photino BR($\chi^0 \to$eqq) = 88%
- Heavier neutralinos and charginos assumed to be heavier than squark: cascade decays not considered

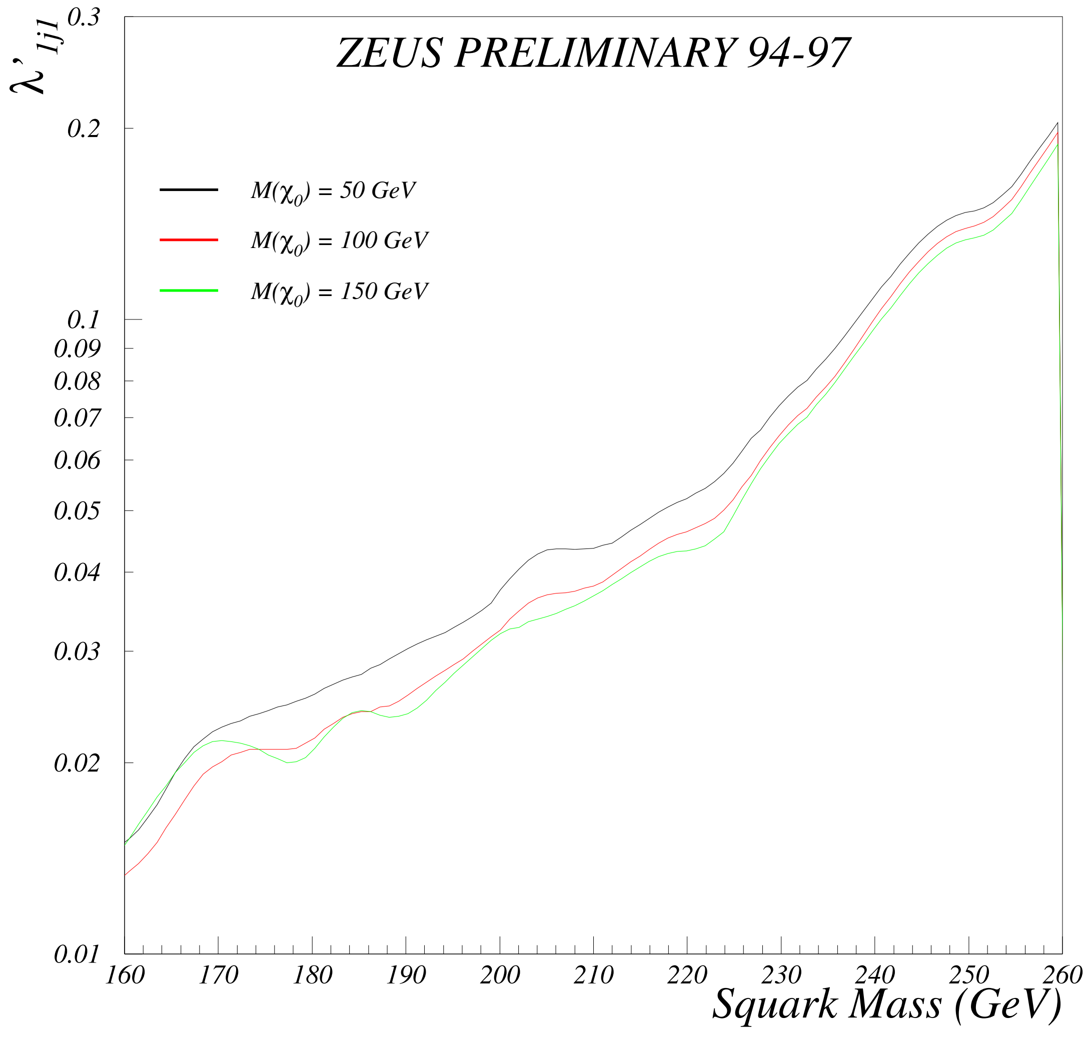
$$\tilde{q} \to \chi_2^0 q, \chi_2^0 \to \chi_1^0 q\bar{q}, \ldots$$

$$\tilde{q} \to \chi_1^+ q', \chi_1^+ \to \chi_1^0 q\bar{q}', \ldots$$



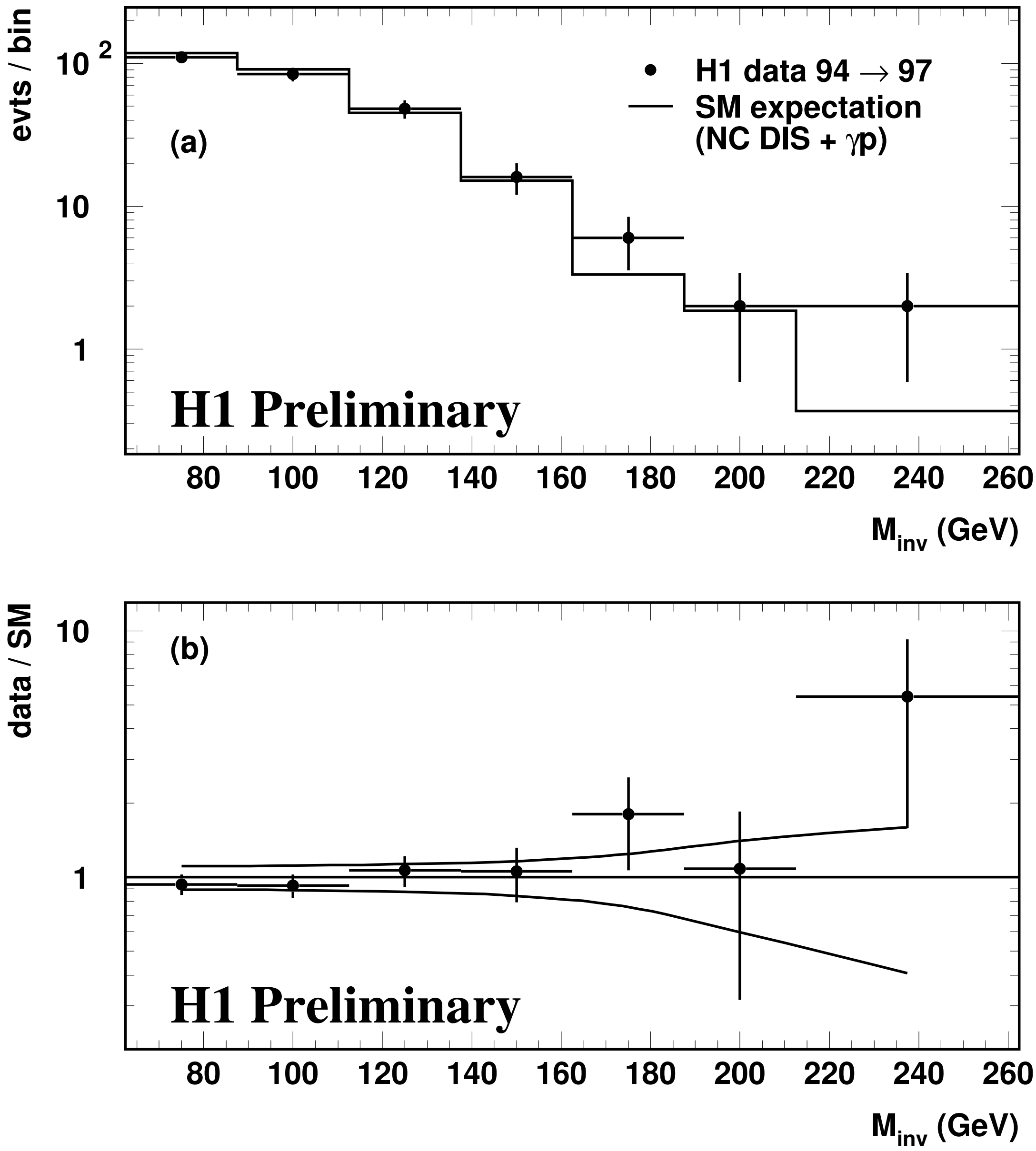


Limits on R_P-violating coupling as a function of squark mass



H1: invariant mass in S3

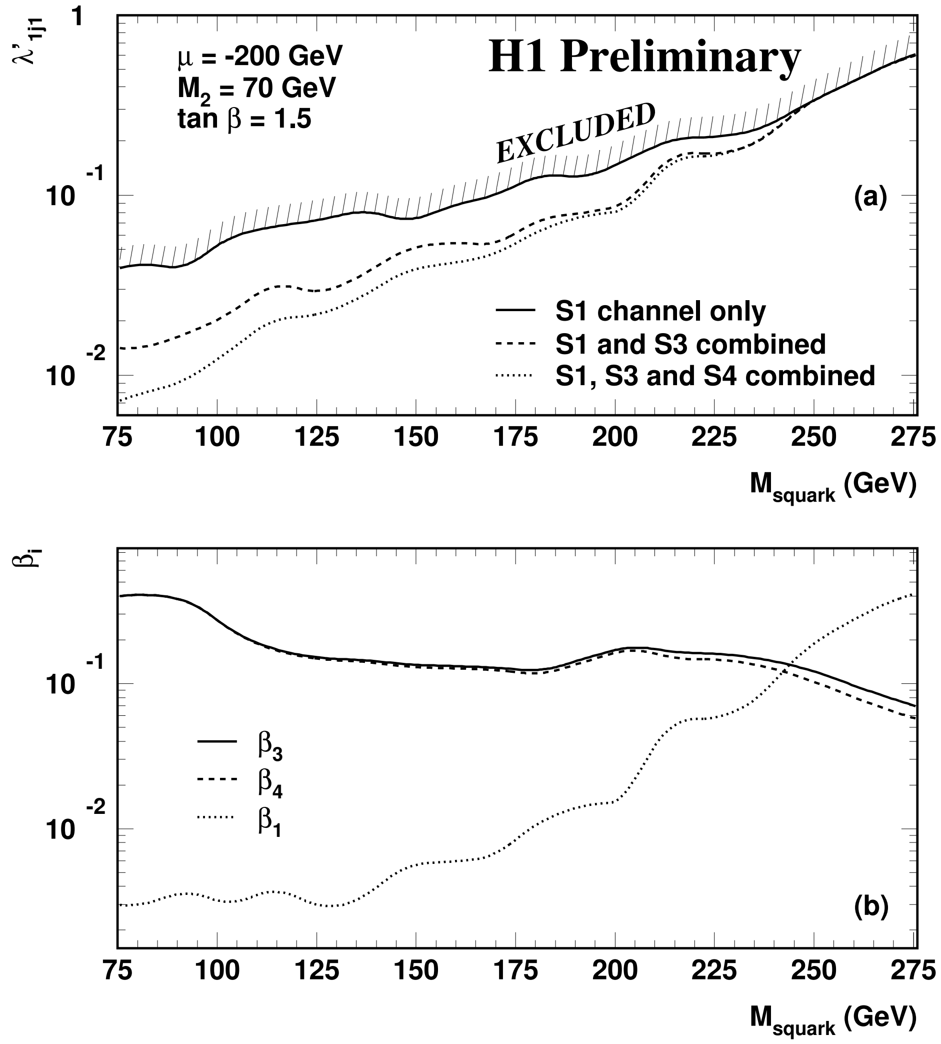
$E_T(e) > 5$ GeV
E_T (jets) $> 15, 7$ GeV



S3: 289 events observed, 285.7±28.0 MC exp.
S4: 1 event observed, 0.49±0.2 MC expectation

λ limit and branching ratio

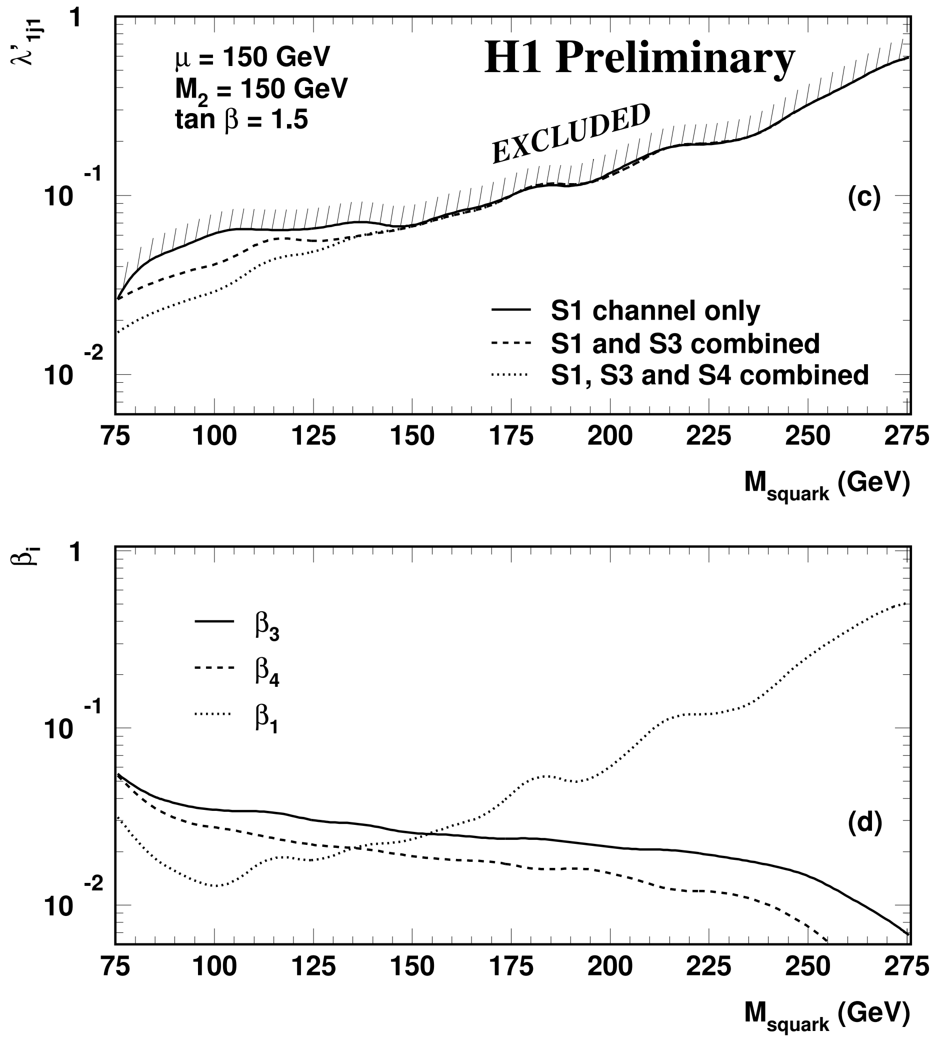
40 GeV χ^0, photino-dominated
(H1 takes neutralino mixing and cascade decays into account)



For low squark mass, contribution from S3 and S4 quite substantial

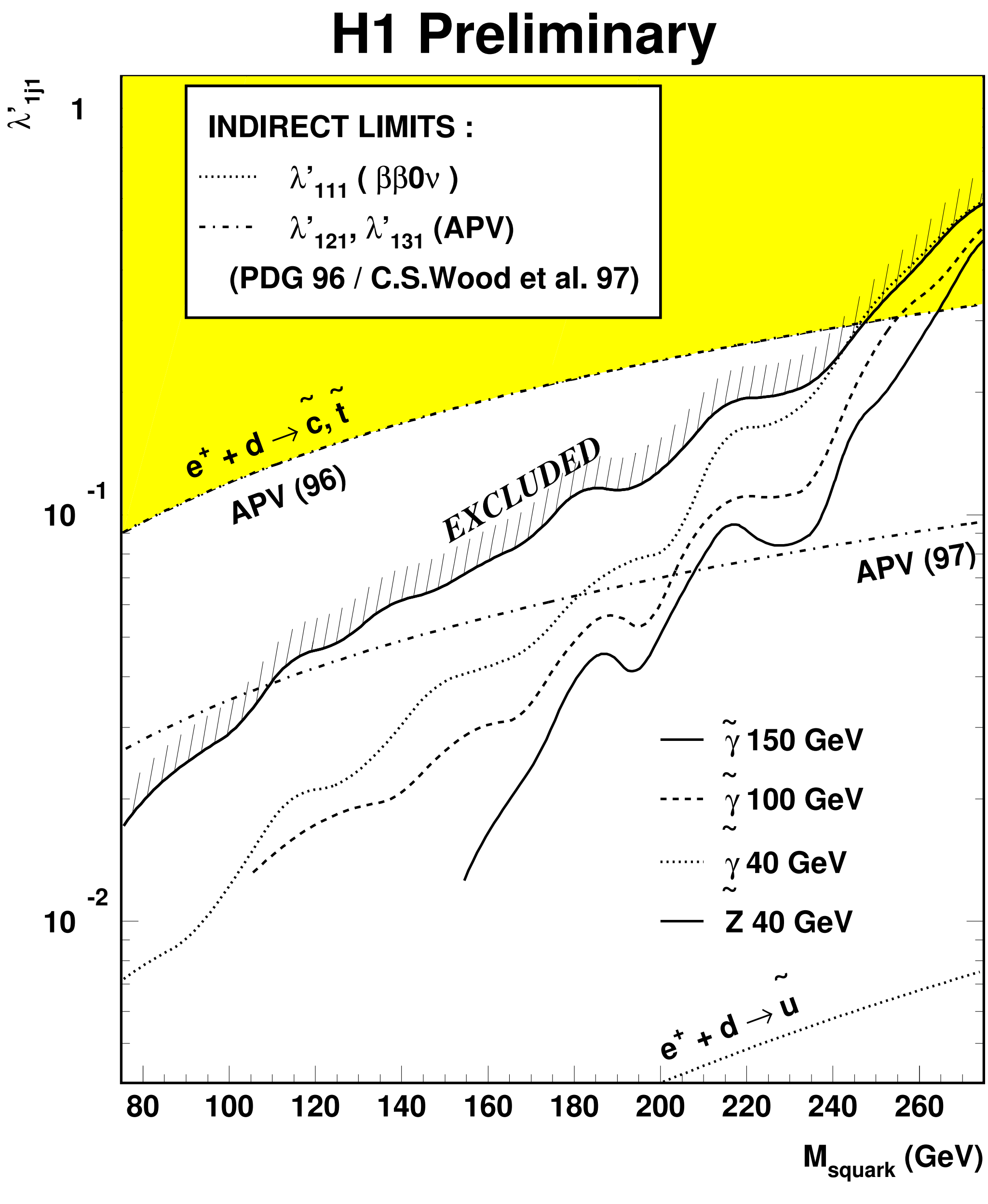
Another SUSY parameter set

40 GeV χ^0, but dominated by zino component



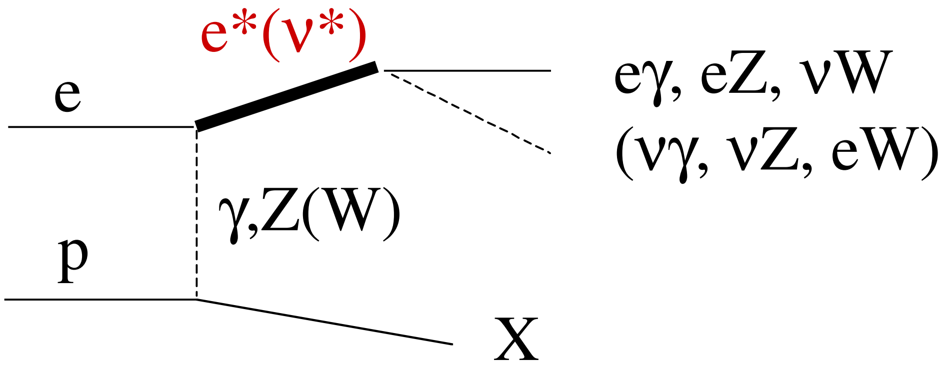
In this case $\chi^0 \rightarrow \nu qq$ decay B.R. high,
multi-jet CC topology important
(not yet looked at here)

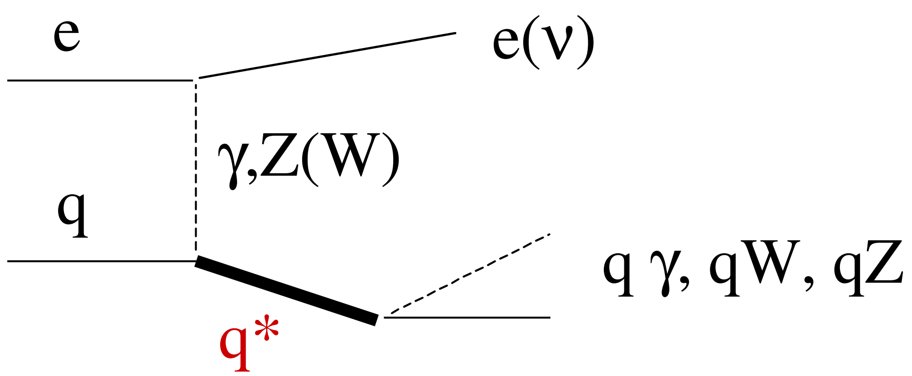
Results compared to other limits



For λ_{111}, double-beta decay limits quite stringent
For λ_{121} and λ_{131}, comparable/better than APV limits

Excited Fermions





- Composite model of fermions →excited state

- Decays to fermion + gauge boson
  B.R. depends on couplings f, f' , f_s
corresponding
  to gauge groups SU(2), U(1), SU(3)
  (formulation: Hagiwara-Komamiya-Zeppenfeld)

- Decay modes of Z,W →variety of final state

- e*: elastic production possible (X=p)

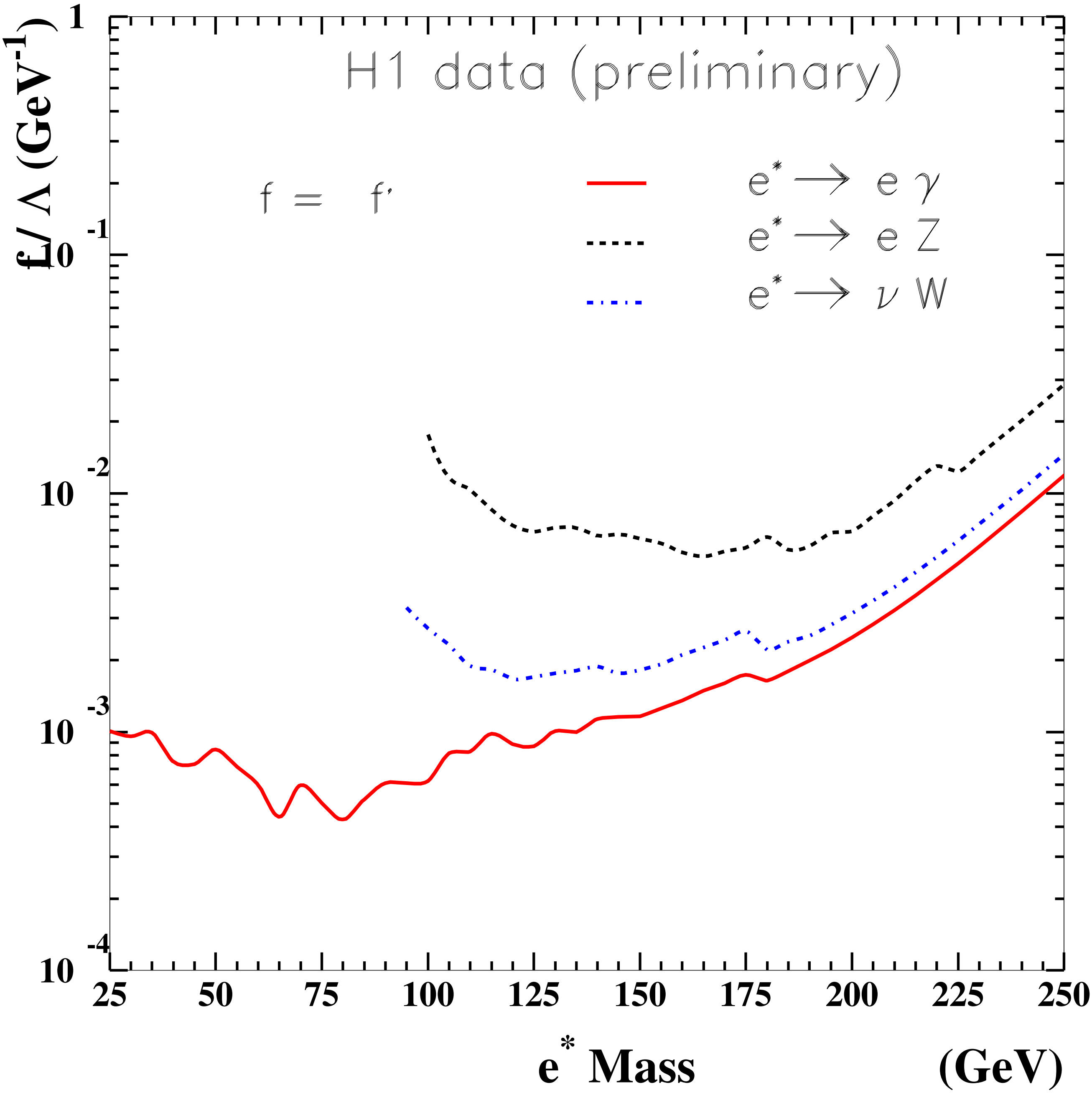
- q*: TeVatron limits can be evaded if $f_s = 0$
  Note: q* →qW → qμν μ+jet+missing P_T

H1 search results summary

Channels	N_{DATA}	N_{EXP}
$e^* \to e\gamma$	223	239±7
$\nu^* \to \nu\gamma$	0	1.3±0.7
$q^* \to q\gamma$	35	34.3±5.7
$e^* \to eZ \to eqq$ $\nu^* \to eW \to eqq$	38	48±3
$e^* \to \nu W \to \nu qq$ $\nu^* \to \nu Z \to \nu qq$	3	3.8±0.5
$e^* \to eZ \to e\nu\nu$ $e^* \to \nu W \to \nu e\nu$	1	3.6±0.7
$\nu^* \to \nu Z \to \nu ee$ $\nu^* \to eW \to ee\nu$	0	0.38±0.16
$e^* \to eZ \to eee$	3	1.4±0.3
$q^* \to qW \to qe\nu$	1	1.4±0.3

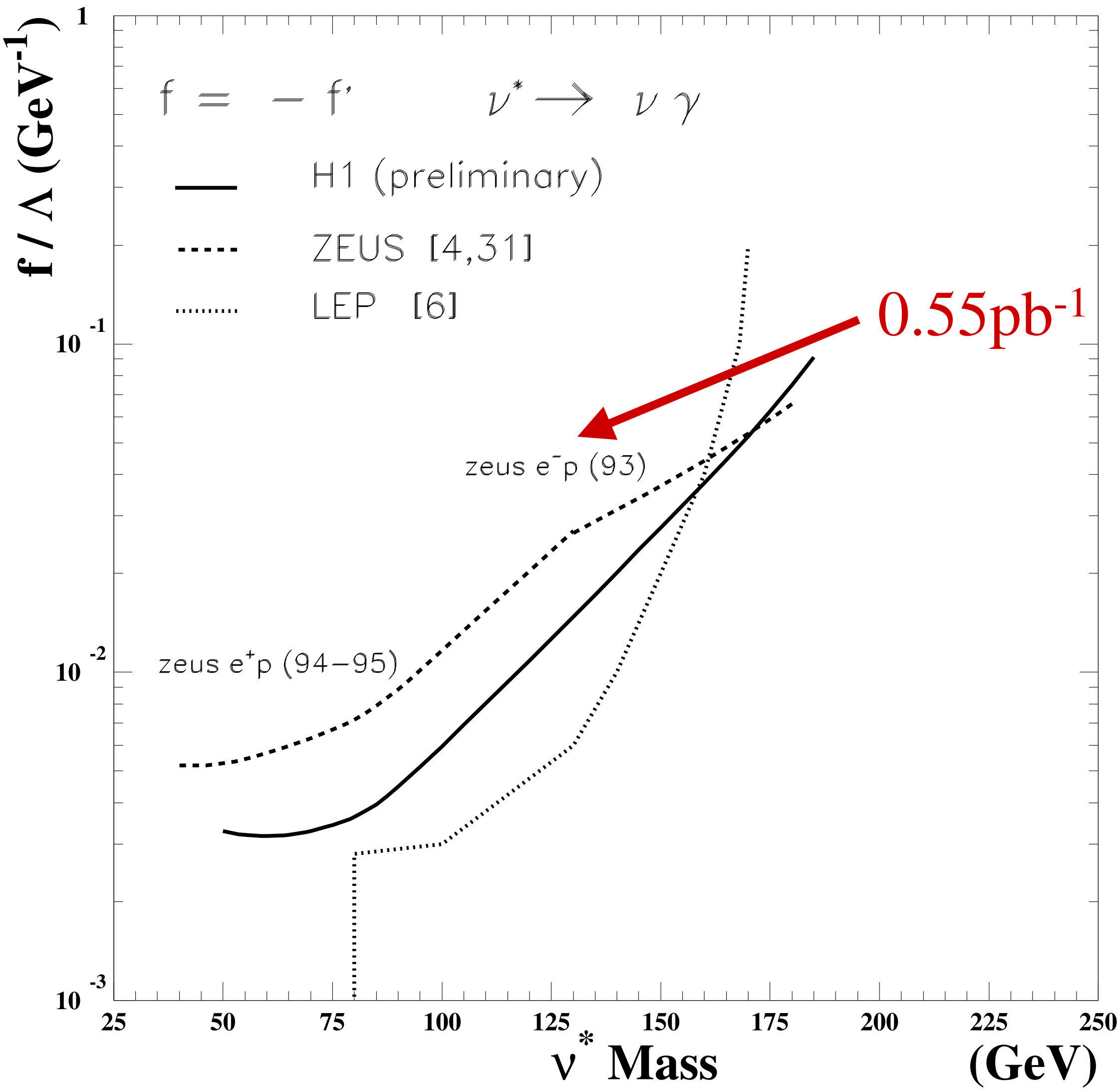
No excess observed: derive limits on coupling

e* coupling limits vs. mass



Λ = compositeness scale

ν* coupling limits vs. mass

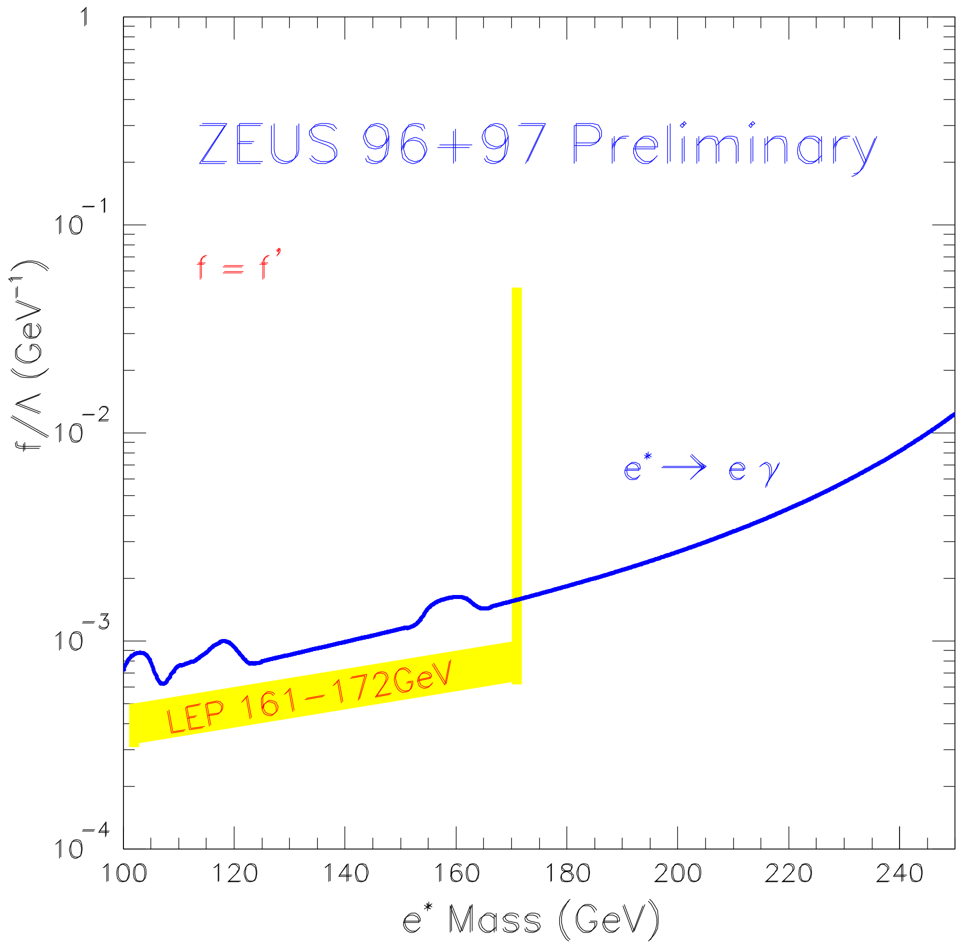


e⁻p data quite powerful for ν* limits

→ good prospects for 98/99 data

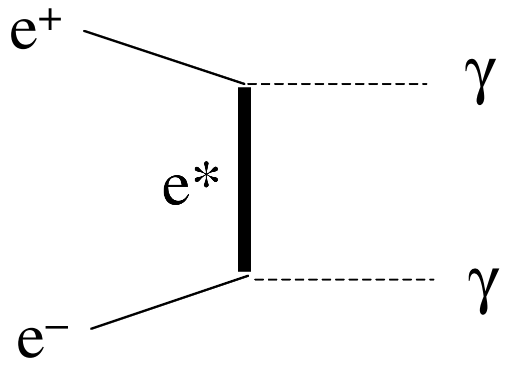
ZEUS: e*→eγ channel

(96/97 data, 37pb^{-1})

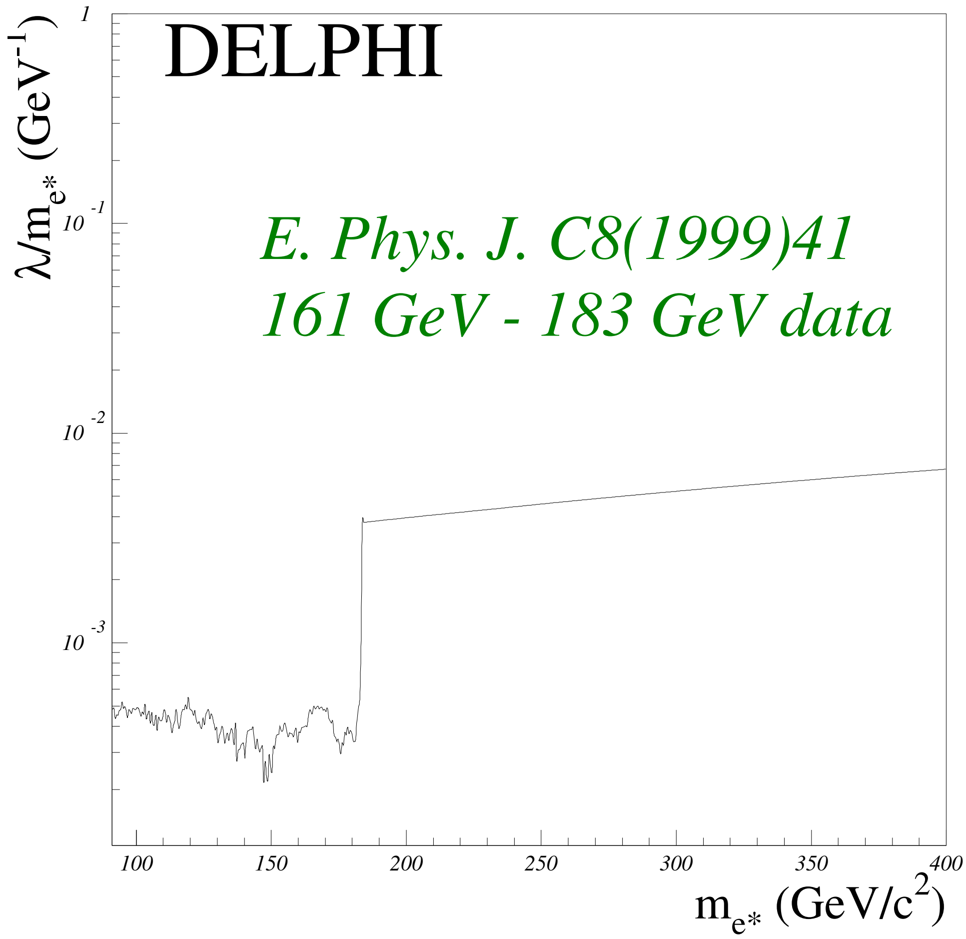


Above CM energy of LEP2, HERA has the best potential of discovery, but...

LEP2 explores even above CM energy

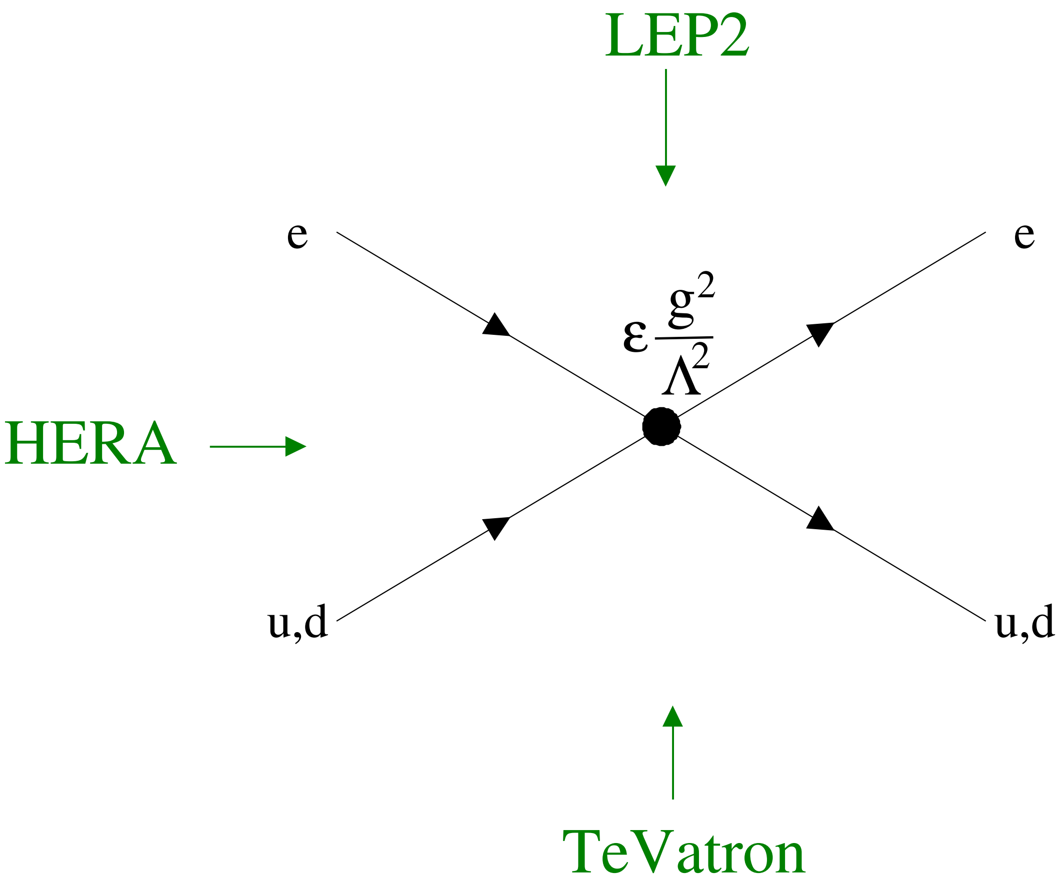


Virtual effect; no mass resonance



$f/\Lambda = \sqrt{2}\ \lambda/m_{e^*}$

Contact Interactions



- Effect of physics at much higher scale > $\sqrt{s}$ (e.g. heavy LQ, new gauge boson, compositeness.). →manifest itself as effective 4-fermion CI
- eeqq: playground for all 3 colliders!
- Convention: $\varepsilon=\pm1,0$ and $g^2=4\pi$
- Only vector CI considered
- Effect on cross section:

  pure CI term Q^4/Λ^4 - always increase

  SM-CI interference Q^2/Λ^2 - increase or decrease

Various CI models tested

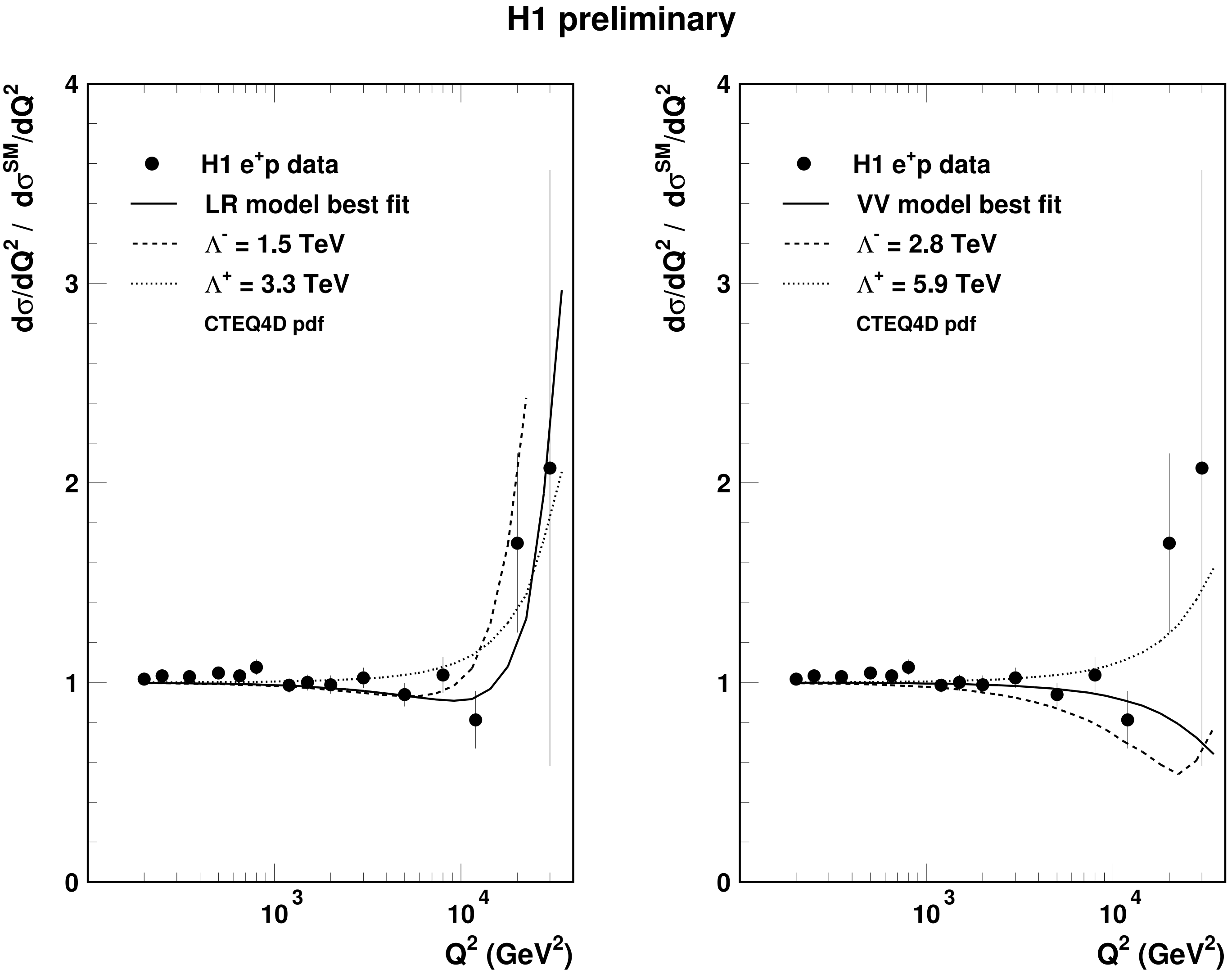
CI	ϵ^u_{LL}	ϵ^u_{LR}	ϵ^u_{RL}	ϵ^u_{RR}	ϵ^d_{LL}	ϵ^d_{LR}	ϵ^d_{RL}	ϵ^d_{RR}
VV	+	+	+	+	+	+	+	+
AA	+	−	−	+	+	−	−	+
VA	+	−	+	−	+	−	+	−
X1	+	−	0	0	+	−	0	0
X2	+	0	+	0	+	0	+	0
X3	+	0	0	+	+	0	0	+
X4	0	+	+	0	0	+	+	0
X5	0	+	0	+	0	+	0	+
X6	0	0	+	−	0	0	+	−
U1	+	−	0	0	0	0	0	0
U2	+	0	+	0	0	0	0	0
U3	+	0	0	+	0	0	0	0
U4	0	+	+	0	0	0	0	0
U5	0	+	0	+	0	0	0	0
U6	0	0	+	−	0	0	0	0

Limits from atomic parity violation can be evaded
if $\varepsilon_{LL} + \varepsilon_{LR} - \varepsilon_{RL} - \varepsilon_{RR} = 0$
$\varepsilon^u_{RL} = \varepsilon^d_{RL}$ obeys $SU(2)_L \times U(1)_Y$ symmetry (not U2,4,6)

H1 analysis

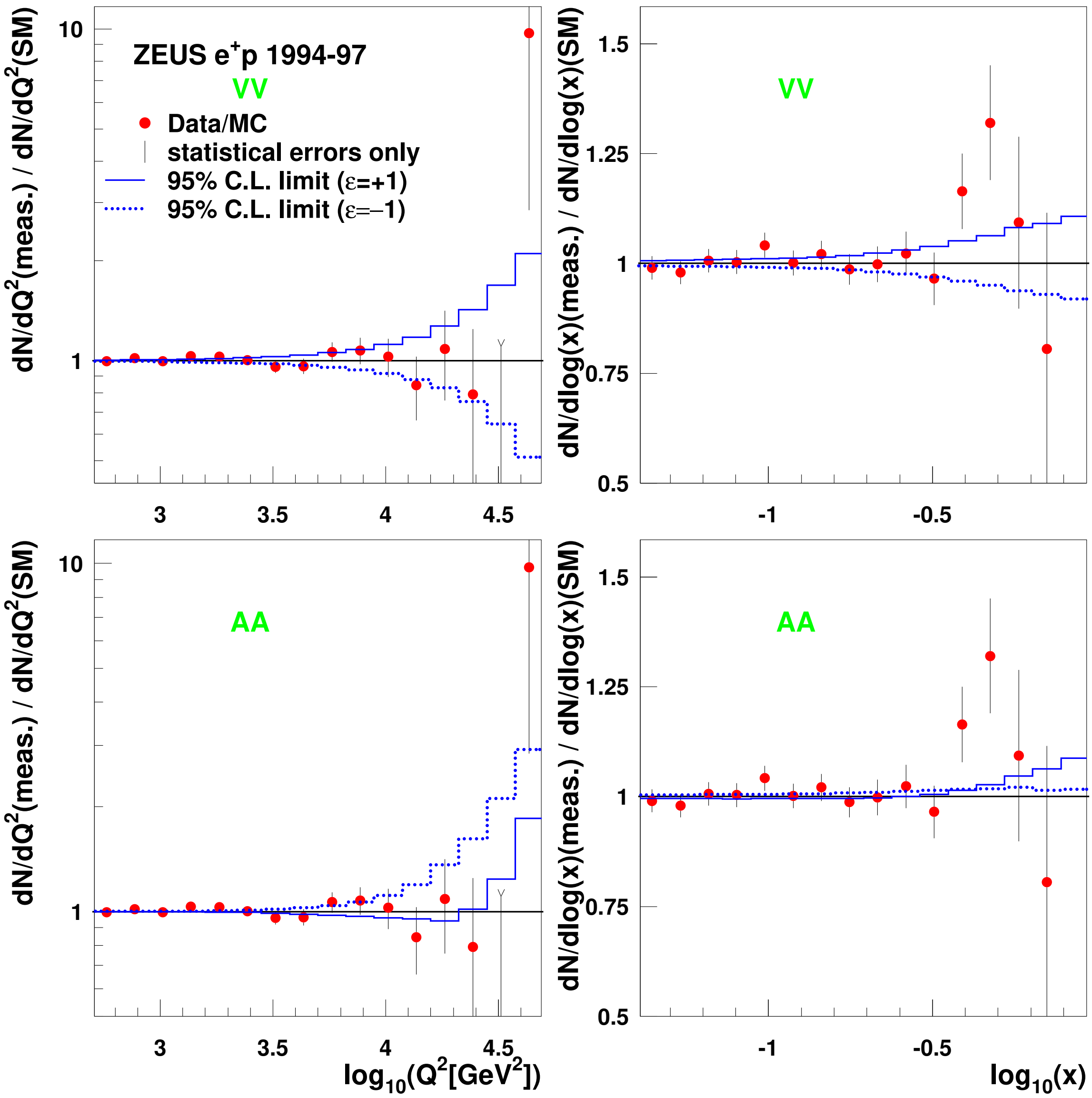
χ^2 fit to NC $d\sigma/dQ^2$ cross section with CI scenario

Note: H1 gives results also on purely chiral CI (LL,LR,RL,RR)



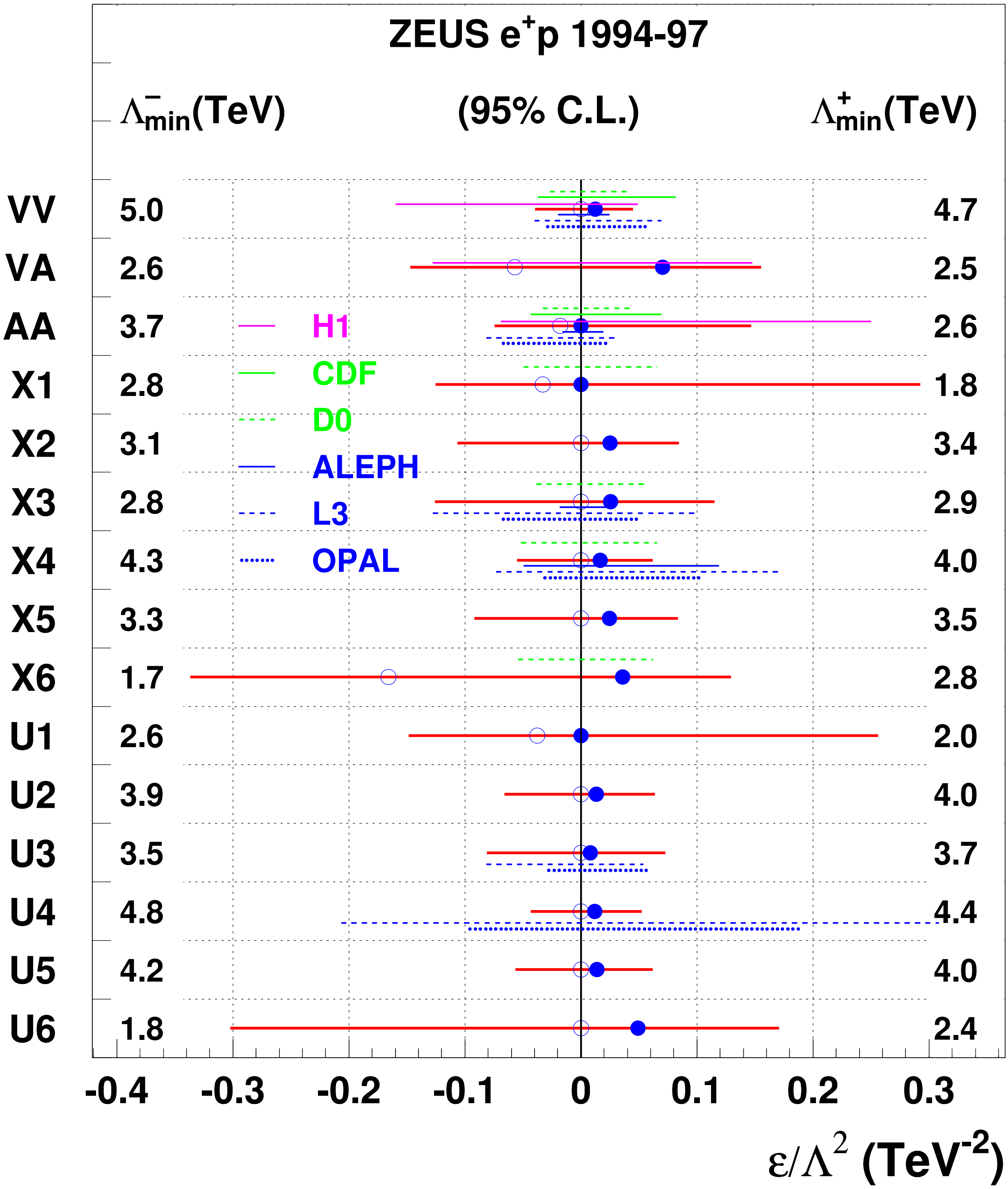
ZEUS analysis

Unbinned log-likelihood fit in (x,y)
- sensitive to also x dependence



Result: no significant evidence in either experiment

Limits on Λ



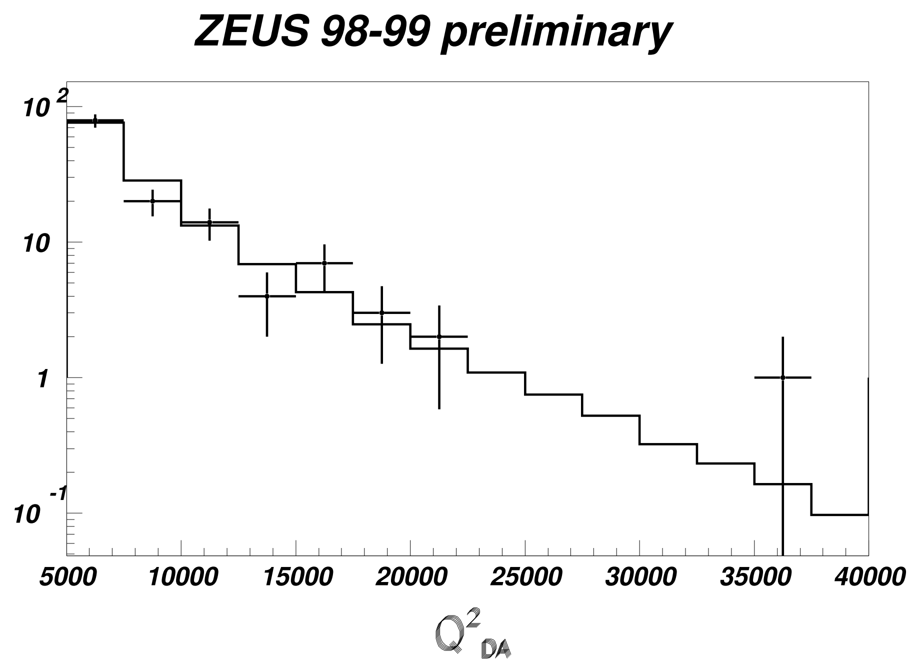
Nice competition with LEP2/TeVatron achieved

- Comparable, or sometimes best/only limits depending on the scenarios

Flash from 98/99 e⁻p data

8.6 pb^{-1} ZEUS status of high-Q^2 NC events

Q^2_{DA} (GeV^2) >	data	MC
5000	130	136.8
10,000	31	32.0
20,000	3	5.1
30,000	1	1.1

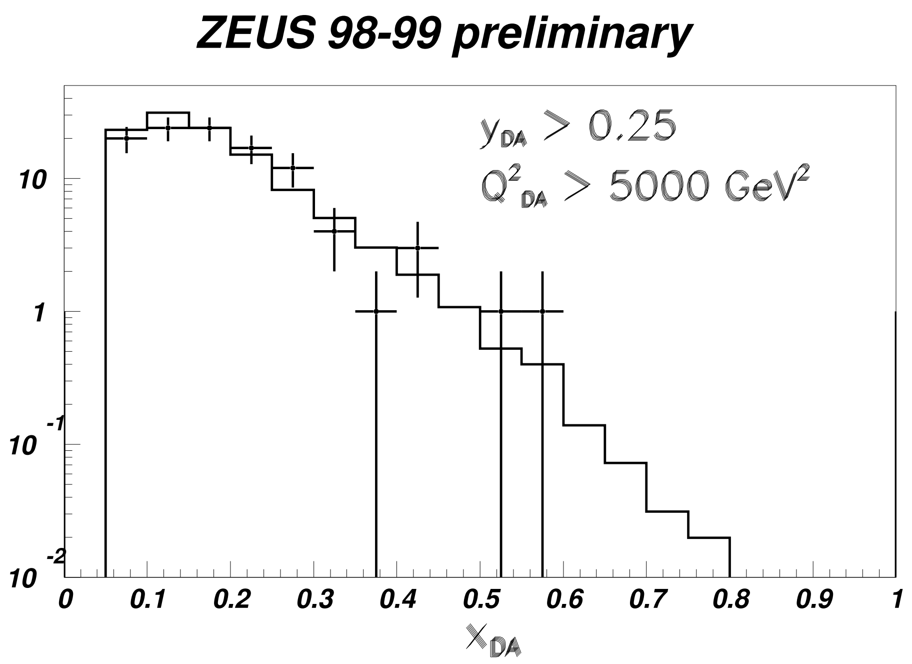


Already Q^2>30000 GeV^2 event observed,
but consistent with MC: σ(e⁻p) > σ(e⁺p)

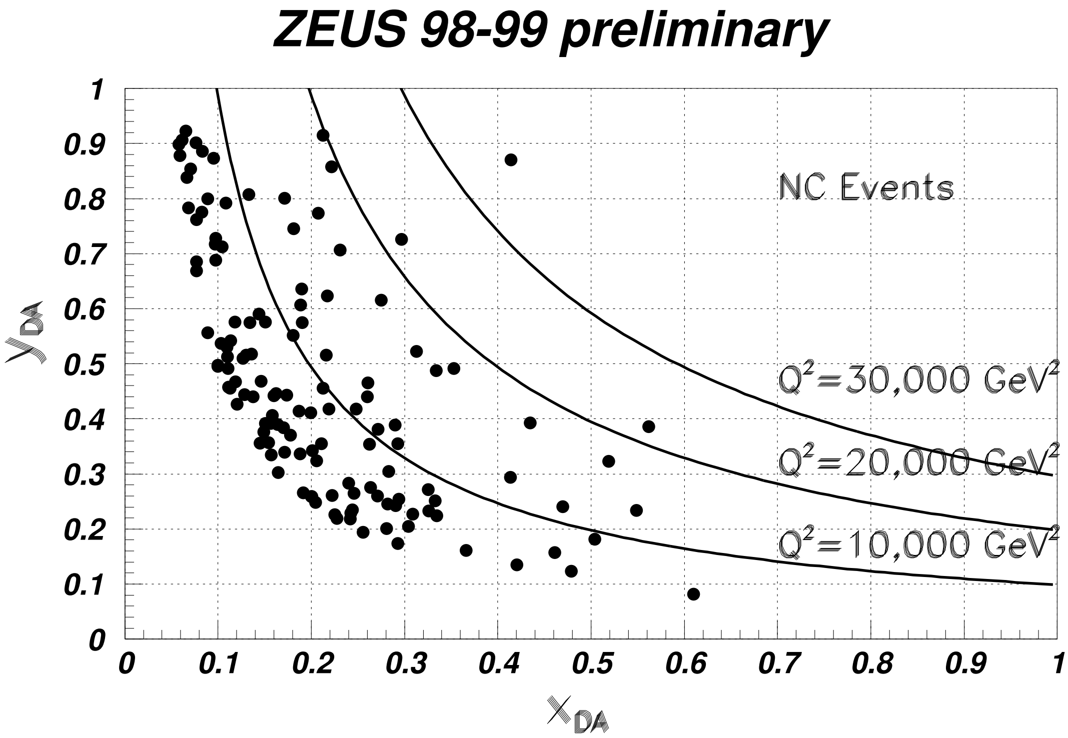
High-x, high-y events?

$y_{DA} > 0.25$:

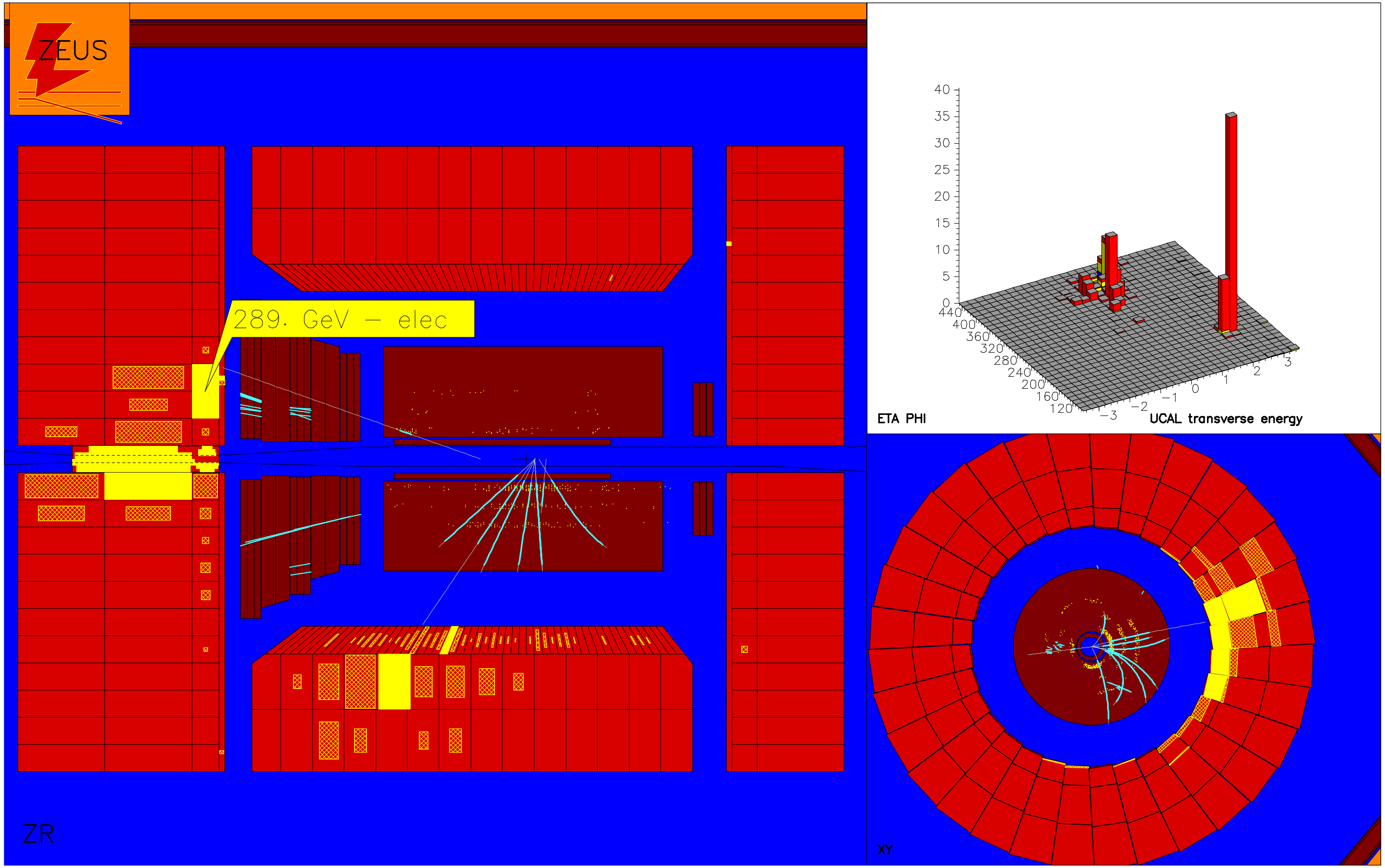
$x_{DA} >$	Data	MC
0.1	87	90.8
0.2	39	35.6
0.3	10	12.3
0.4	5	4.2
0.5	2	1.2



No need to panic, so far...



ZEUS 98-99 preliminary
NC Events
Q^2=30,000 GeV^2
Q^2=20,000 GeV^2
Q^2=10,000 GeV^2
y_{DA}
x_{DA}
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1



Highest Q^2 event: Q^2=36500 x=0.41 y=0.87

Summary and Conclusion

- HERA has a lot of discovery potentials for beyond-SM physics:
- LQ - limit close to kin. limit for EM coupling, explore small λ above CDF/D0 exclusion, or explore small BR(eq) even below it
- R_P violating squarks - in addition to LQ decay, variety of decay modes need to be looked at
- $e \leftrightarrow \mu$, $e \leftrightarrow \tau$ Lepton Flavor Violation (not presented here in detail) - can explore better than rare decay etc. if τ or heavy quark involved
- Exited fermions - e^*, ν^* above LEP2 $\sqrt{s}$, or q^* when it has only electroweak coupling
- eeqq Contact Interaction - good competition with LEP2 and TeVatron continuing
- $\rightarrow$ more suggestions highly welcome!

- 98/99 run - big amount of e^-p collision data complementary species of LQ, R_P squarks, much higher sensitivity for ν^*
- 00/01 luminosity upgrade - order of 1000pb^{-1} data till ~2005, with polarized e^+/e^- beams $\rightarrow$ look forward to excitements!