Search for New Physics at HERA

XV Rencontres de Physique de la Vallee d'Aoste

La Thuile, 7/Mar/2001

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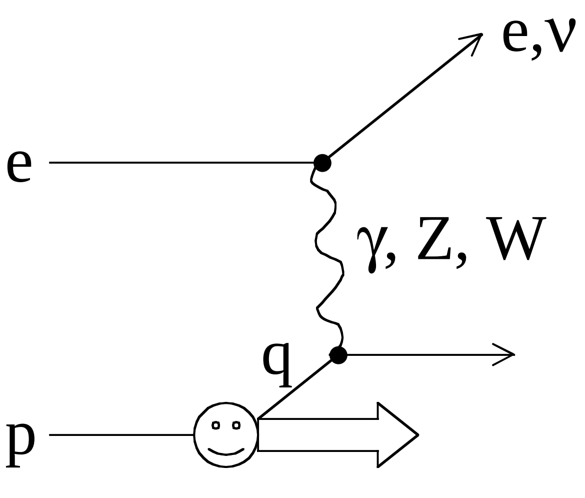
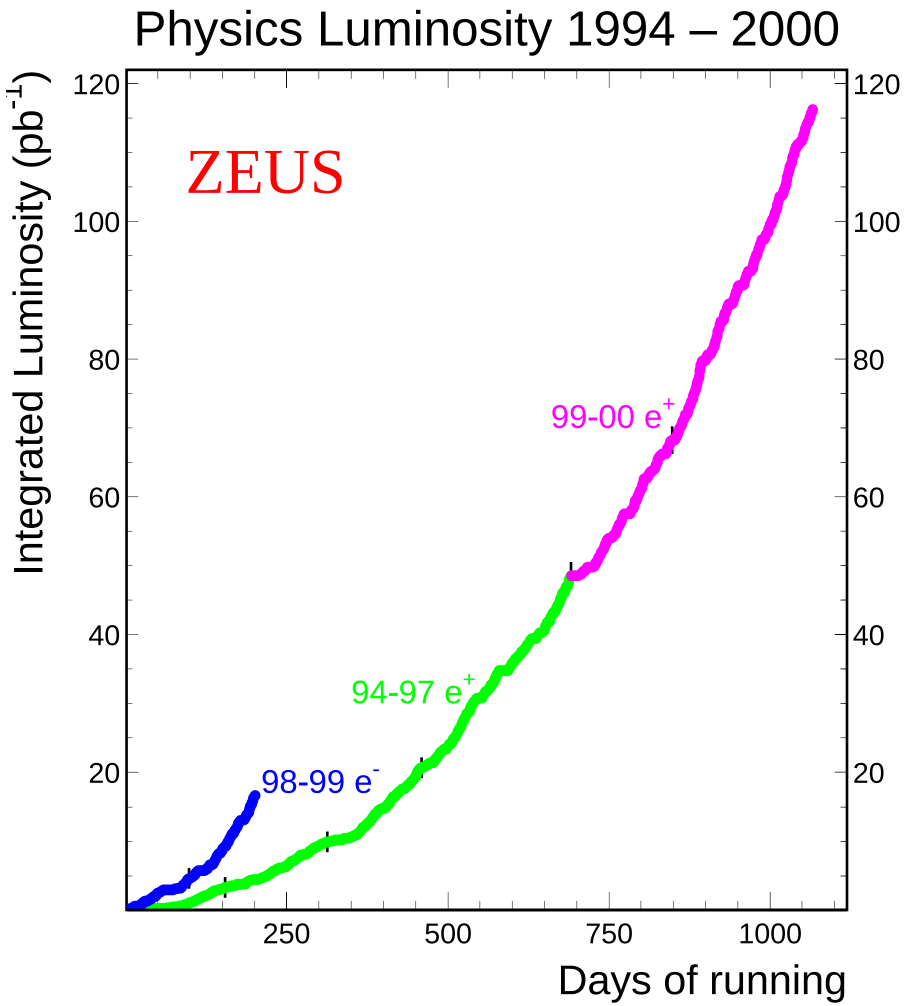
On behalf of H1 and ZEUS Collaborations

HERA *ep* collider @ DESY

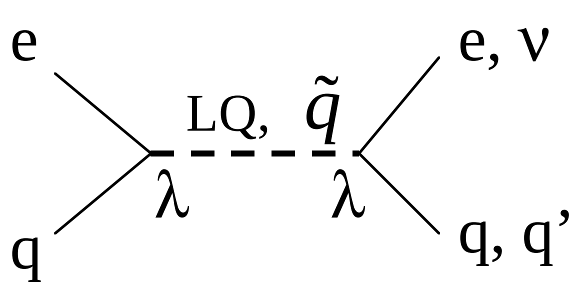
- $\sqrt{s}$ = 300 GeV (– 1997), 318 GeV (1998 –)
- ~110 pb^{-1} e^+p and ~15 pb^{-1} e^-p data collected per exp't until 2000
- Kinematics of deep inelatic scattering:



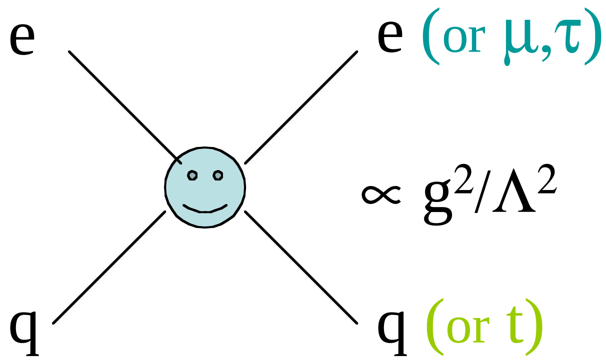


- Q^2 = –(4-momentum of propagator)^2
- x = fractional momentum of proton carried by struck quark
- $y = Q^2/sx = (1-\cos\theta^*)/2$
  θ^*: scattering angle in eq rest frame

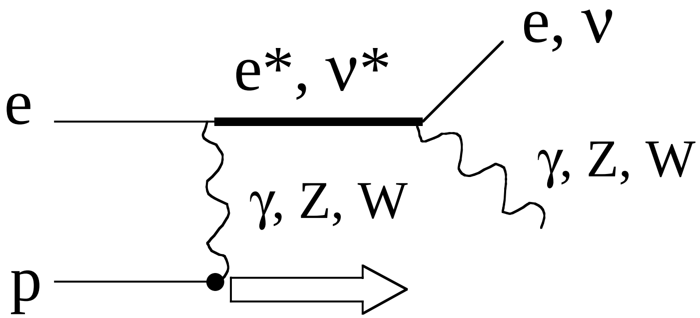
Signals of physics beyond SM at HERA



- e-q resonances (Leptoquarks)
  - Peak in $m=\sqrt{(sx)}$, decay to eq or νq'
- Squark in R-parity violating SUSY
  - Production similar to LQ but more decay modes (q+gaugino)

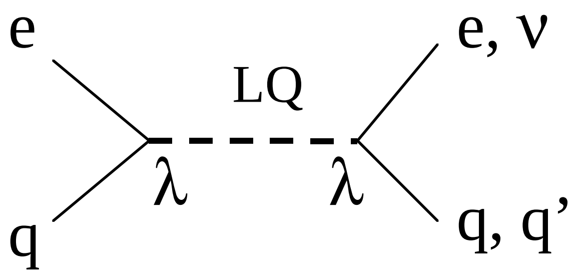


- Contact Interactions
  - Physics at higher scale ($\Lambda \gg \sqrt{s}$) 'felt' at highest Q^2 of HERA
  - Large Extra Dimensions, compositeness, …
  - Variant: LFV-mediating interactions (e–μ, e–τ) or FCNC transition (u→t : single top)



- Excitation of Fermions
  - e*, ν*, q* if fermions composite
  - Peak in *f*–*V* invariant mass

Leptoquarks

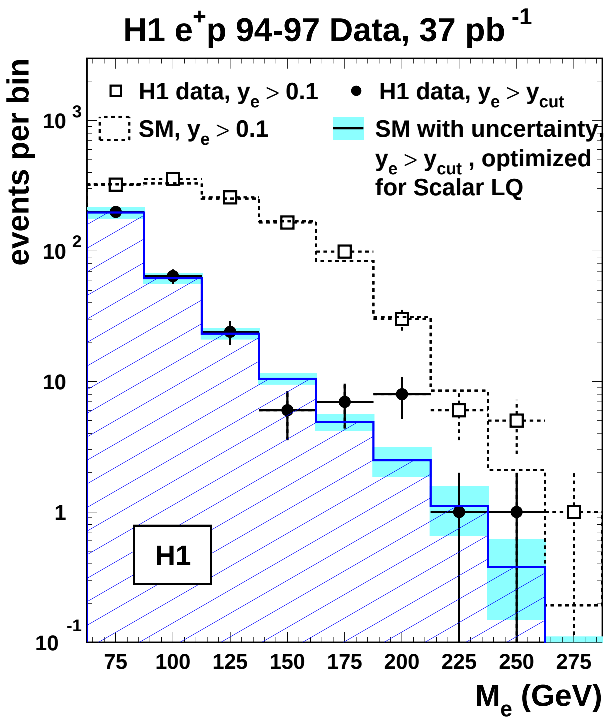


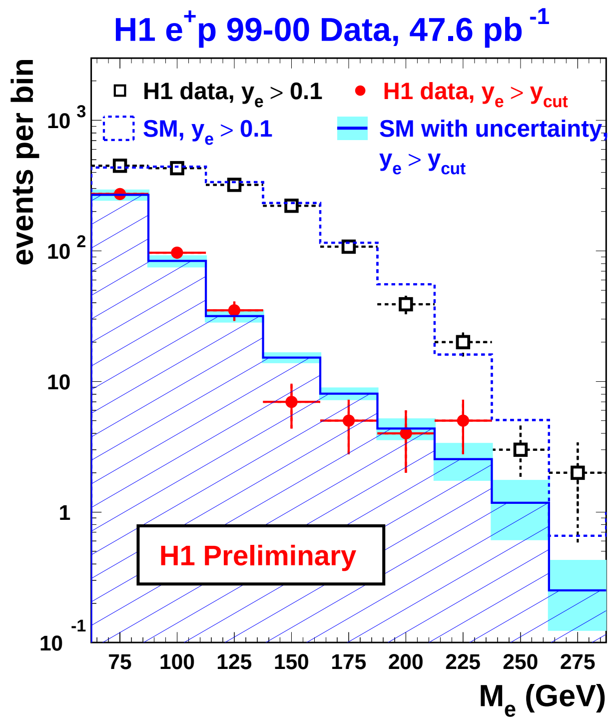
- Carry both L and B numbers
- Buchmüller-Rückl-Wyler (BRW) model:
  - SU(3)×SU(2) ×U(1) invariance
  - LQs only couple to chiral SM fermions
  - 14 species, 7 scalars and 7 vectors
  - Decays: 100% to eq, 100% to νq or 50% to each
- Production at HERA ∝ λ^2 (Yukawa coupling)
  - e^+p and e^-p sensitive to different LQ (valence >> sea quark density)
  - Decay distribution: flat in y (scalar) or $(1-y)^2$ (vector)
    → signal prominent at high y where NC DIS ($\propto 1/y^2$) suppressed

- Old H1 and ZEUS e^+p data (especially in 1994-96) showed excess of high-mass, high-y events.
  →Results from new e^+p data (at higher $\sqrt{s}$) taken in 1999+2000(partially) were shown last summer.

Resonance search: old and new data

- H1





- ZEUS

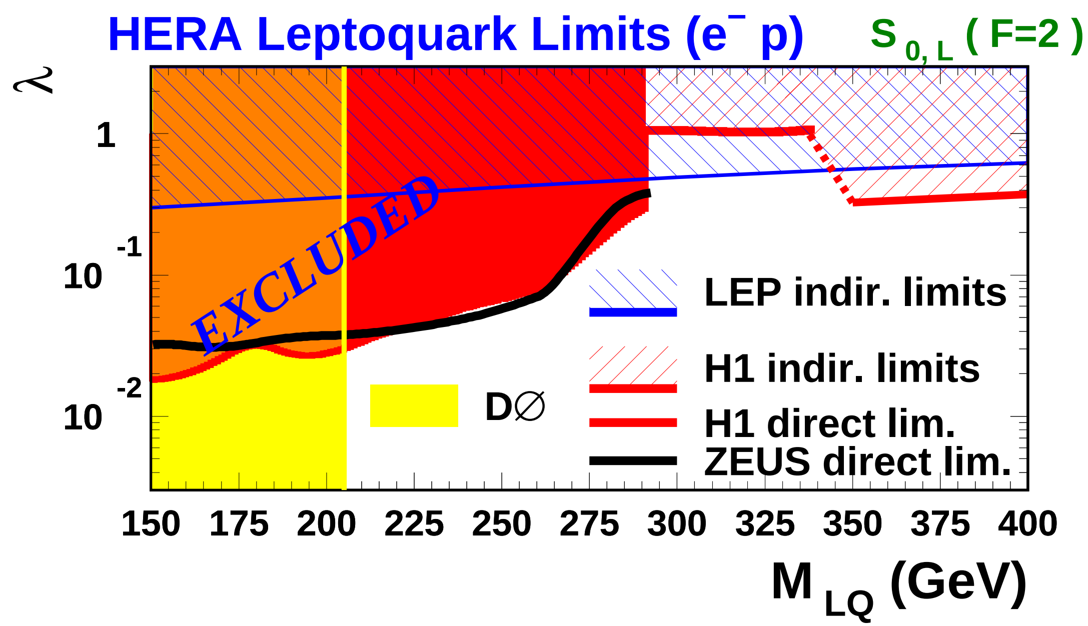
  4 events in (x>0.55, y>0.25)
  1.9 expected from SM
  (48 pb^{-1} 1994-97)

  0 event
  1.6 exected from SM
  (39 pb^{-1} 1999-00 April)

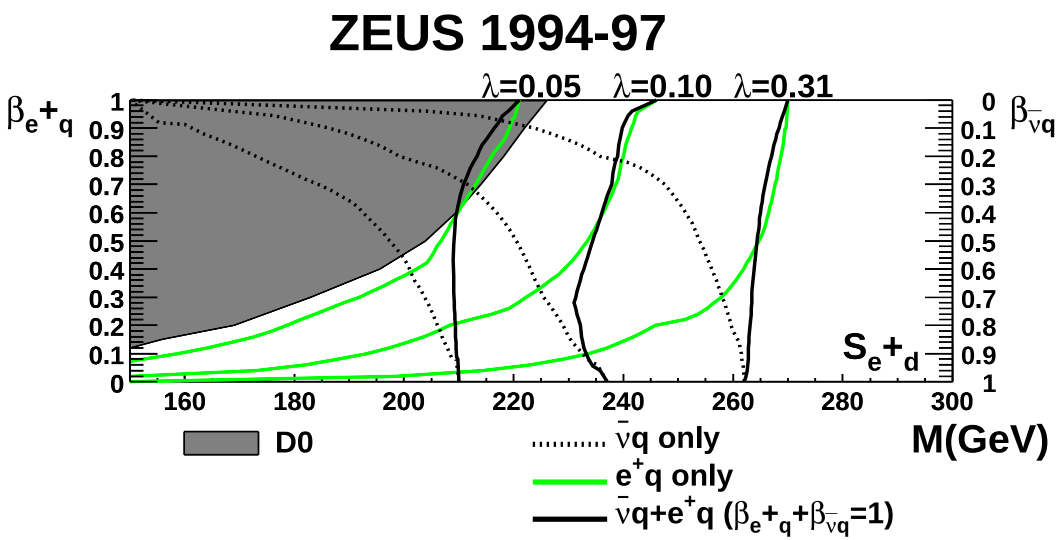
  (x=0.55↔m=220GeV)

- Excess in old data not confirmed by new data by both experiments

Leptoquark limits

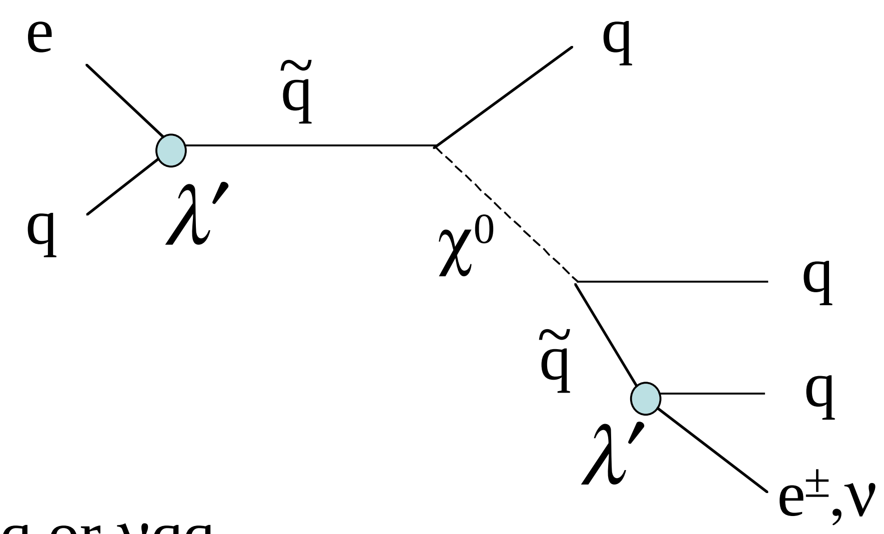


- BRW framework:
  λ vs. mass
  - TeVatron: pair production, independent of λ
  - LEP: virtual effects in $e^+e^- \to$ hadrons



- General case: stay away from BRW model
  - Treat β(LQ→eq) as free
  - If β(eq)+ β(νq)=1:
    Combining NC and CC events, limis almost independent on β
  - TeVatron limits degrade at low β

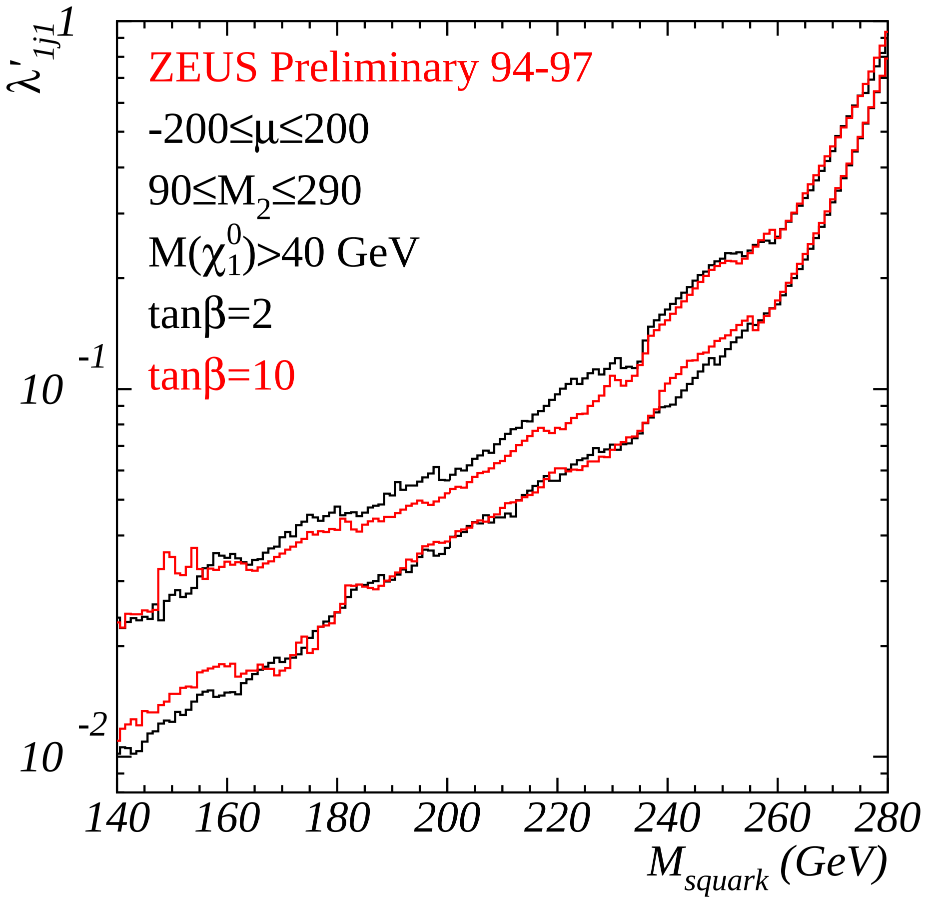
R-parity violating SUSY

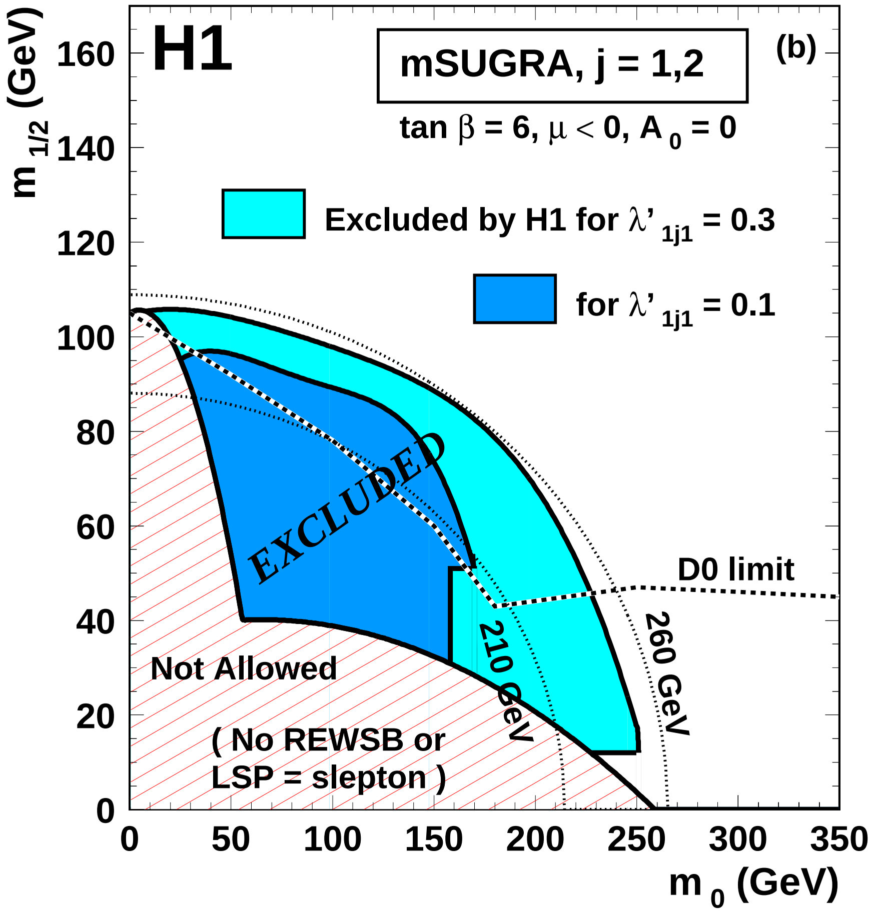


- $R_P \equiv (-1)^{F+2S} = (-1)^{L+3B+2S}$
  R_P violation $\rightarrow$ sparticles singly produced and LSP not stable.
- $L_i Q_j \overline{D}_k$ coupling interesting for HERA:
  eq $\rightarrow$ squark (like LQ)
- Final states more complicated than LQ:
  χ^0 decays with the same coupling to $e^{\pm}qq$ or νqq
  ("wrong sign" lepton gives b.g. free channel)
- Also cascade decays $\chi_2 \rightarrow \chi_1$ etc.
  multi-jet / multi-lepton final states

- No evidence found in 94-97 e^+p data$\rightarrow$ limits set in unconstrained MSSM (squark mass independent of μ, M_2, $\tan\beta$) or in mSUGRA

Limits in SUSY parameter space



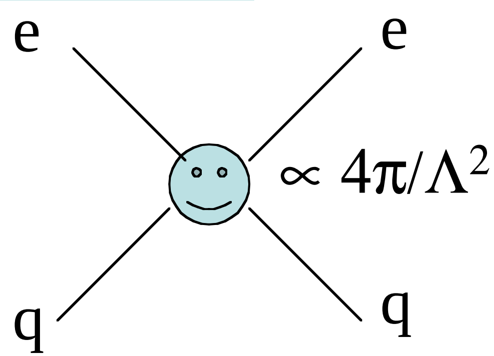


- Unconstrained MSSM:
  limits variation in parameter scan

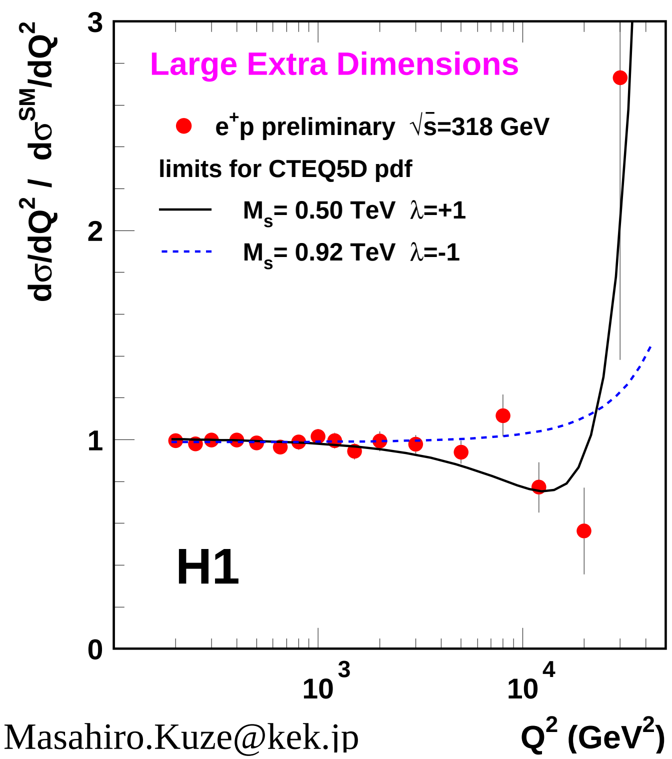
- mSUGRA:
  For reasonably large λ' values,
  HERA exclusion exceeds TeVatron limits

DESY 01-021

Contact Interactions

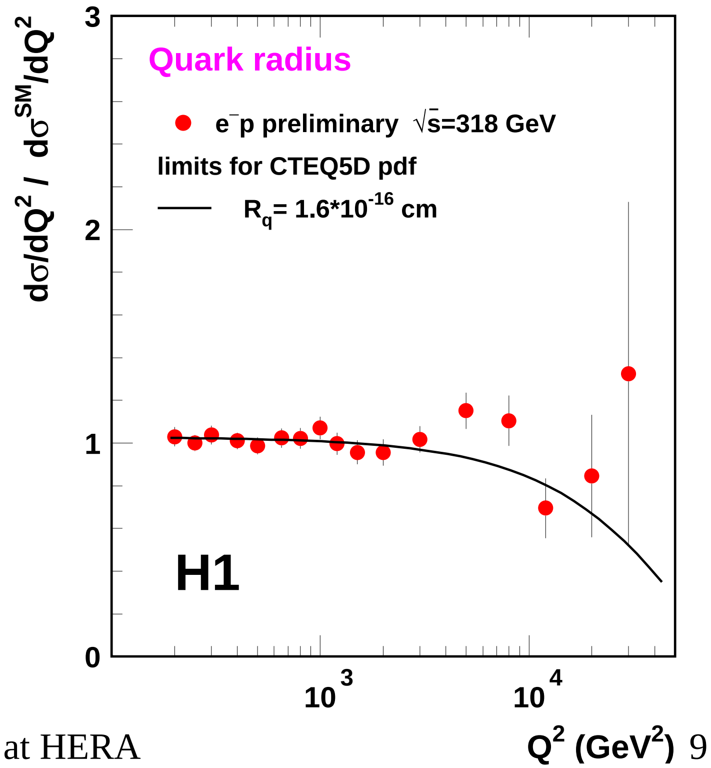


- Look for deviation at highest Q^2
  Probed distance =1/Q ~0.001 fm for Q^2~10^4 GeV^2
- General *eeqq* CI: limits depend on chirality combination (LL, LR, VV, AA….), up to 9 TeV
- Comparable to LEP ($e^+e^- \to$ hadrons), TeVatron (Drell-Yan)
- Limits also set on some specific models:



← Kaluza-Klein graviton exchange in Large Extra Dimension models

Interpretation in quark form factor: →
$F=(1-R^2Q^2/6)$
R: quark "radius"



Lepton Flavor Violation

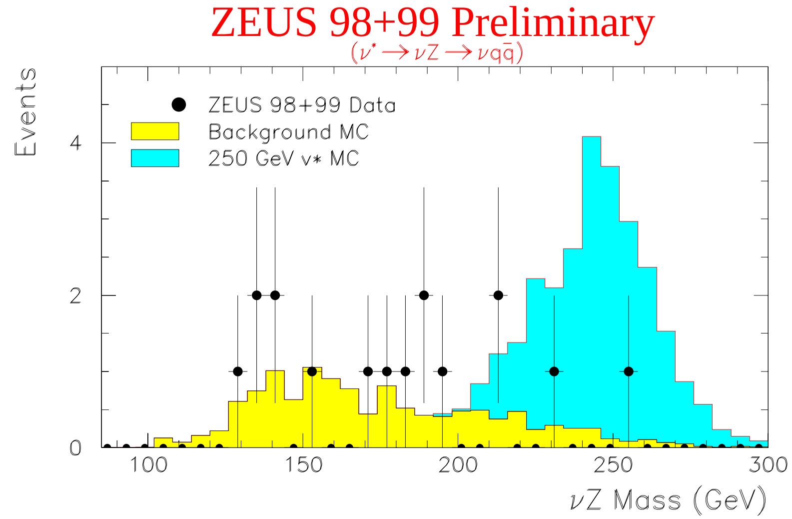
$e \leftrightarrow \tau$				$F=0$			
$q_i q_j$	$S^L_{1/2}$ e^+u	$S^R_{1/2}$ $e^+(u+d)$	$\tilde{S}^L_{1/2}$ e^+d	V^L_0 e^+d	V^R_0 e^+d	$\tilde{V}^R_0$ e^+u	V^L_1 $e^+(\sqrt{2}u+d)$
1 1	$\tau \to \pi e$ 0.0032 **0.030**	$\tau \to \pi e$ 0.0016 **0.025**	$\tau \to \pi e$ 0.0032 **0.046**	G_F 0.002 **0.033**	$\tau \to \pi e$ 0.0016 **0.033**	$\tau \to \pi e$ 0.0016 **0.024**	G_F 0.002 **0.012**
1 2	*H1:* 0.047 **0.030**	$\tau \to$K e 0.05 **0.025**	$\tau \to$K e 0.05 **0.046**	$\tau \to$K e 0.03 **0.036**	$\tau \to$K e 0.03 **0.036**	*H1:* 0.045 **0.026**	K $\to \pi\nu\bar{\nu}$ $2.5 \cdot 10^{-6}$ **0.012**
1 3	*	B$\to \tau$e X 0.08 **0.049**	B$\to \tau$e X 0.08 **0.049**	B$\to l\nu$X 0.02 **0.044**	B$\to \tau$e X 0.04 **0.044**	*	B$\to l\nu$X 0.02 **0.044**
2 1	*H1:* 0.15 **0.15**	$\tau \to$K e 0.05 **0.092**	$\tau \to$K e 0.05 **0.11**	$\tau \to$K e 0.03 **0.049**	$\tau \to$K e 0.03 **0.049**	*H1:* 0.073 **0.061**	K $\to \pi\nu\bar{\nu}$ $2.5 \cdot 10^{-6}$ **0.026**
2 2	$\tau \to e\gamma$ 0.03 **0.19**	$\tau \to e\gamma$ 0.02 **0.10**	*H1:* 0.13 **0.12**	*H1:* 0.076 **0.061**	*H1:* 0.076 **0.061**	*H1:* 0.107 **0.10**	*H1:* 0.044 **0.041**
2 3	*	B$\to \tau$e X 0.08 **0.15**	B$\to \tau$e X 0.08 **0.15**	B$\to l\nu$X 0.02 **0.10**	B$\to \tau$e X 0.04 **0.10**	*	B$\to l\nu$X 0.02 **0.10**
3 1	*	B$\to \tau$e X 0.08 **0.16**	B$\to \tau$e X 0.08 **0.16**	V_{ub} 0.002 **0.052**	B$\to \tau$e X 0.04 **0.052**	*	V_{ub} 0.002 **0.052**
3 2	*	B$\to \tau$e X 0.08 **0.20**	B$\to \tau$e X 0.08 **0.20**	B$\to l\nu$X 0.02 **0.073**	B$\to \tau$e X 0.04 **0.073**	*	B$\to l\nu$X 0.02 **0.073**
3 3	*	*H1:* 0.23 **0.28**	*H1:* 0.23 **0.28**	$\tau \to e\gamma$ 0.51 **0.14**	$\tau \to e\gamma$ 0.51 **0.14**	*	*H1:* 0.14 **0.14**

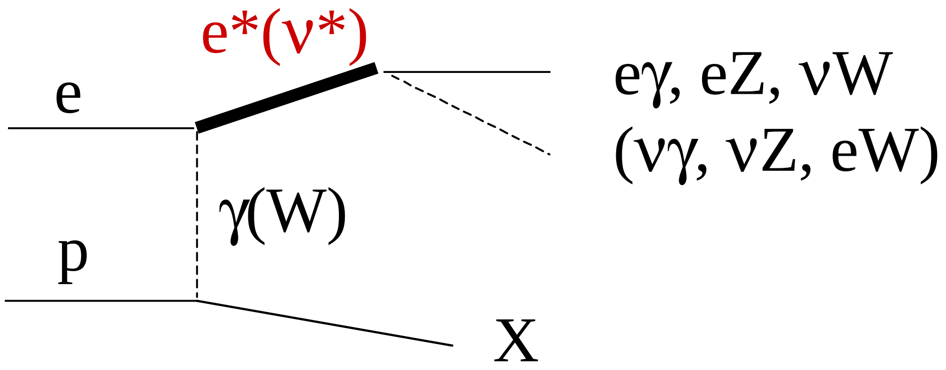
ZEUS preliminary

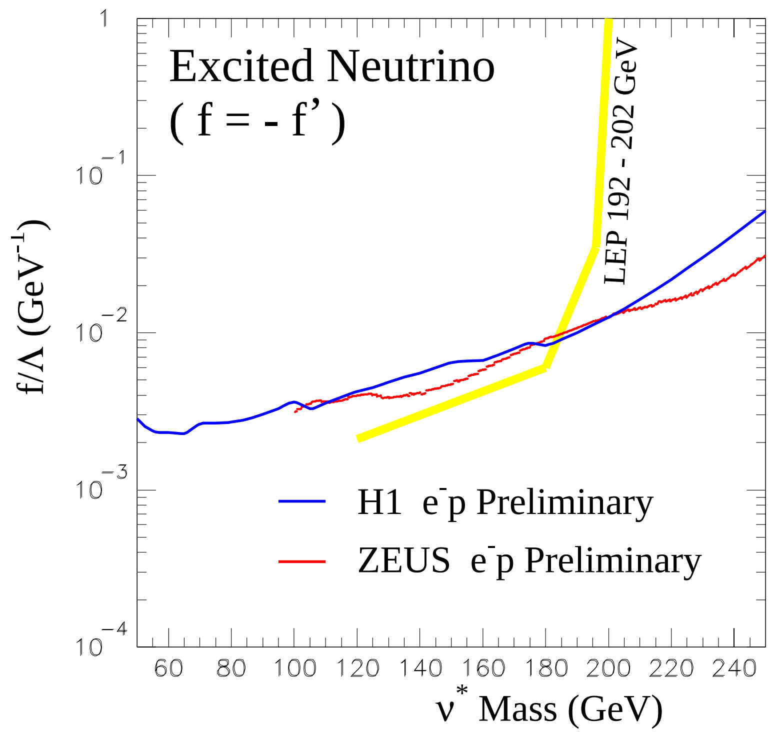
- Variant of CI: $eq \to lq$ ($l=\mu,\tau$) mediated by LFV Leptoquarks
- Spectacular signal; no event found in H1/ZEUS 94-97 data
- Limits expressed in $\lambda_{eq}\lambda_{lq'}/M^2$ (10^{-4}GeV^{-2}) for 3×3 (q,q') generation combinations
- For light-quark only cases, limits from low-energy exp'ts superior, but HERA has good (or unique) sensitivity when heavy quarks involved.

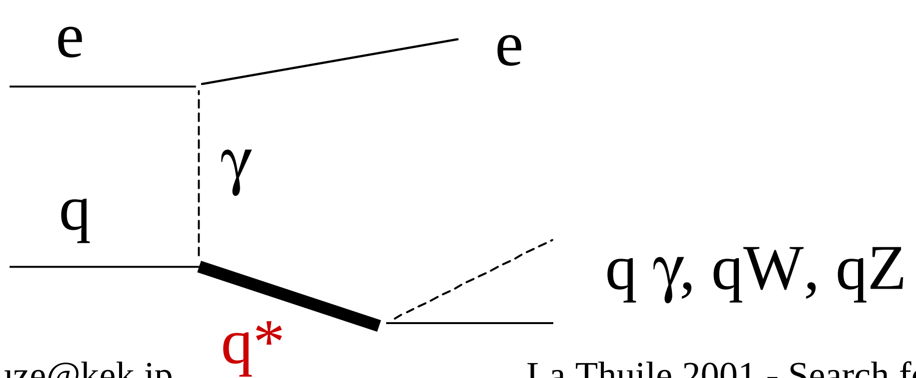
Excited Fermions

- Composite fermions →excited states
- Hagiwara-Komamiya-Zeppenfeld
  $L_{ff*} \propto [f \bullet SU(2) + f' \bullet U(1) + f_s \bullet SU(3)]/\Lambda$
- ν* example →
  Sensitivity extends above LEP2 energy

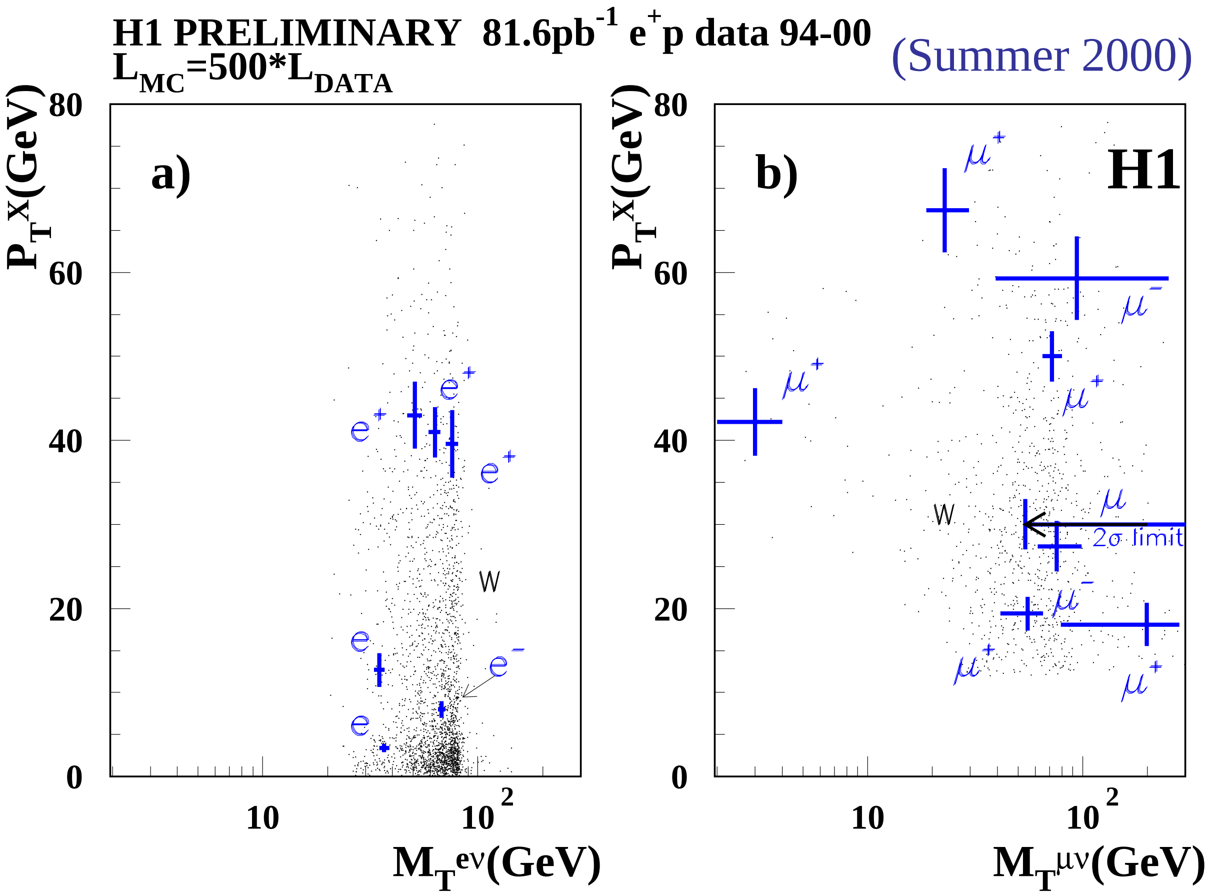




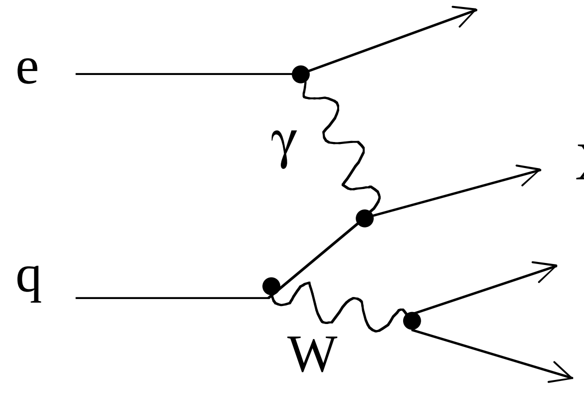




Something unexpected: high-Pt leptons



- Events with high-Pt isolated lepton and missing calorimeter Pt
- At large Pt^X (hadronic Pt), SM prediction dominated by W production

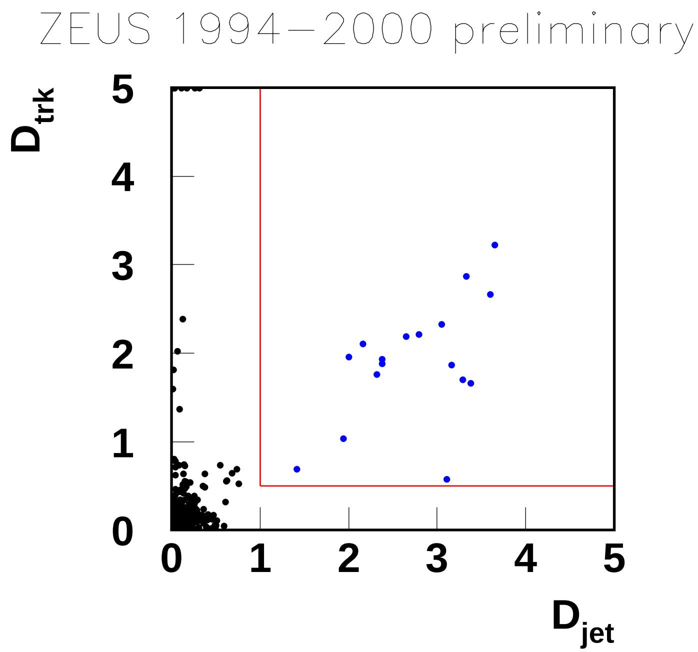


H1 preliminary 1994-2000 e^+p 82 pb^{-1}	Electrons Observed/expected (W)	Muons Observed/expected (W)
P_T^X > 25 GeV	3 / 1.05±0.27 (0.83)	6 / 1.21±0.32 (1.01)
P_T^X > 40 GeV	2 / 0.33±0.10 (0.31)	4 / 0.46±0.13 (0.43)

- H1 observes excess of events at large P_T^X

New ZEUS results with 2000 data

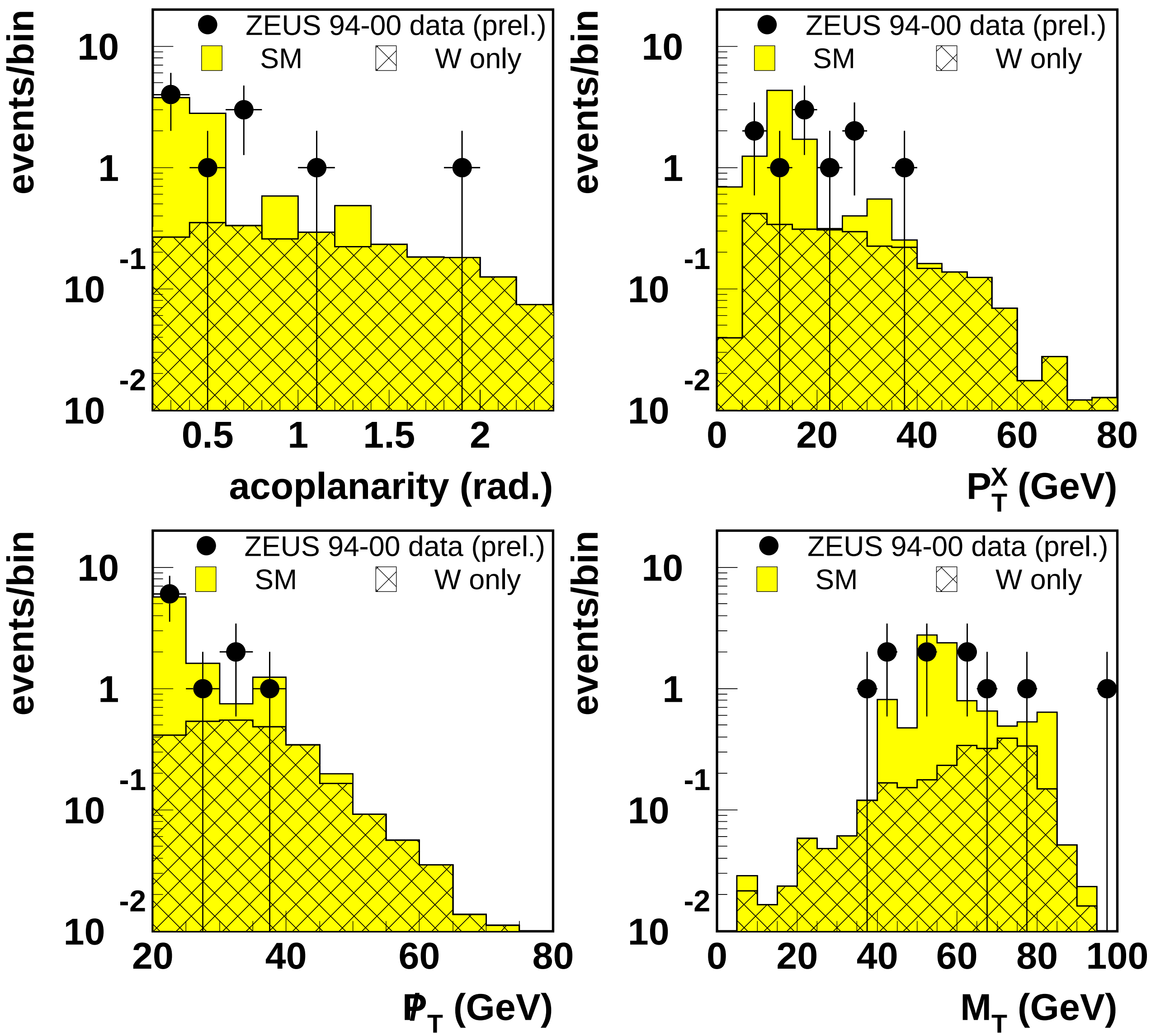
- ZEUS saw no such excess from 1994–1999; update with 2000 data shown for the 1st time
- Main cuts:
  - Pt(CAL) > 20 GeV, Pt(track) > 10 GeV
  - Dtrk > 0.5 (in η–φ) from other tracks
  - Djet > 1.0 from hadronic jets
- 10 e & 7 μ events from 1994–2000 (2 e & 3 μ from 2000 data)
  Note: cuts at this stage looser than H1
  (No Pt^X cut; SM not dominated by W)



- Event rate consistent with SM prediction

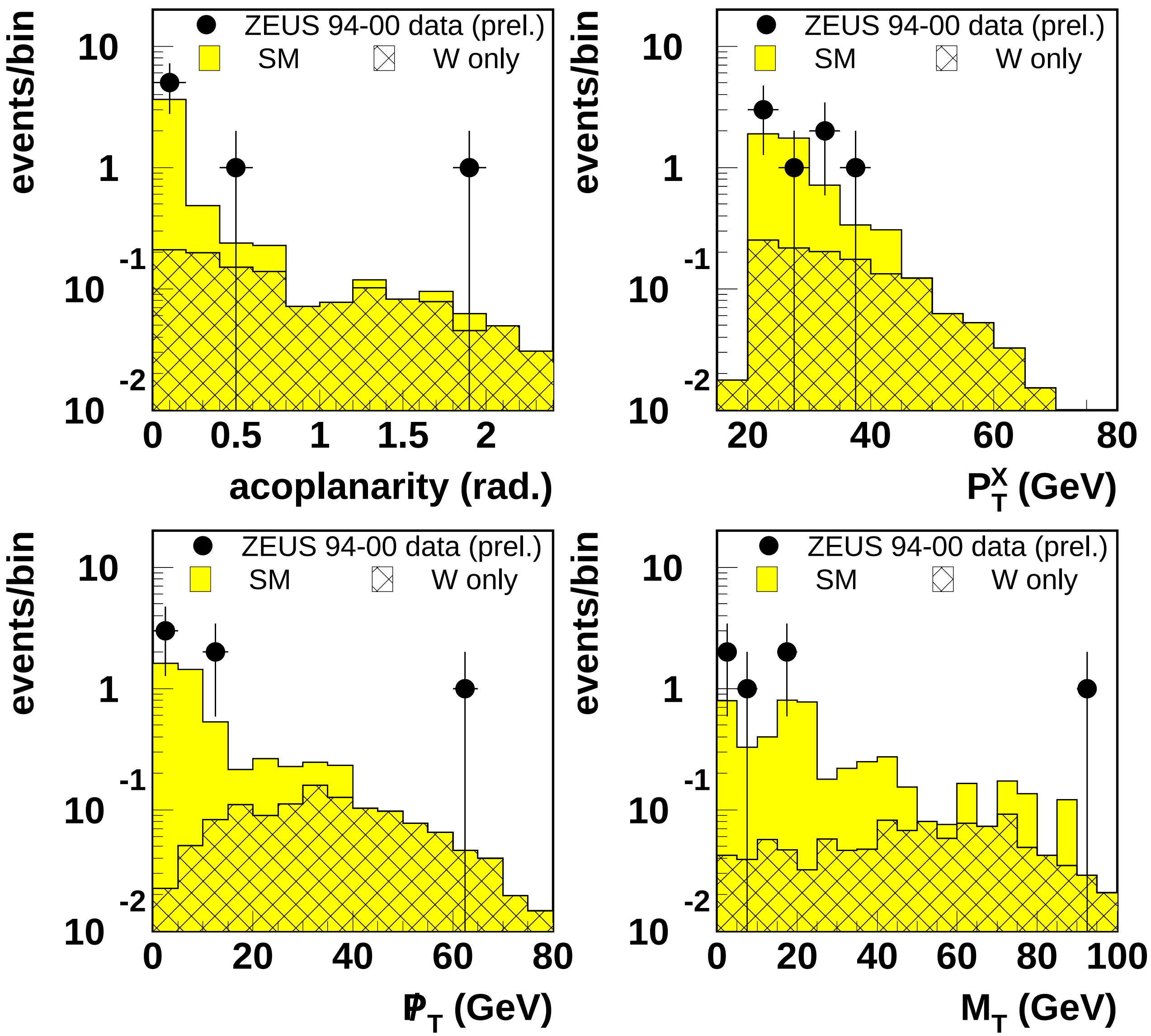
ZEUS preliminary 1994-2000	Electrons Observed/expected (W)	Muons Observed/expected (W)
e^+p 114 pb^{-1}	7 / 9.9±1.6 (2.4)	7 / 4.6±0.6 (1.1)
e^-p 16 pb^{-1}	3 / 1.1±0.4 (0.3)	0 / 0.8±0.1 (0.2)
Total 130 pb^{-1}	10 / 11.0±1.6 (2.7)	7 / 5.4±0.7 (1.3)

Electron events: kinematical distribution



- Overall distribution consistent with SM (dominated by NC DIS)
- Small acoplanarity and small missing Pt

Muon events: kinematical distribution



- Overall distribution consistent with SM (dominated by $\gamma\gamma\to\mu\mu$)
- Most events have μ & jet back-to-back, balancing net missing Pt
- One exceptional event with large acoplanarity and large transverse mass (see next)

Comparison of events at large Pt^X

- Apply further cuts to suppress non-W SM processes
  - Reject if 2nd μ found. Require net missing Pt > 12 GeV for μ events (suppress γγ)
  - Require E-Pz < 45 GeV for e events (suppress NC DIS)
- ZEUS events at large Pt^X:

ZEUS preliminary **1994-2000 $e^{\pm}p$ 130 pb^{-1}**	Electrons Observed/expected (W)	Muons Observed/expected (W)
P_T^X > 25 GeV	1 / 1.14±0.06 (1.10)	1 / 1.29±0.16 (0.95)
P_T^X > 40 GeV	0 / 0.46±0.03 (0.46)	0 / 0.50±0.08 (0.41)

1 new μ event at Pt^X > 25 GeV, but consistent with total expectation

- For comparison: limit H1 track polar-angle to ZEUS range (0.3–2.0rad)

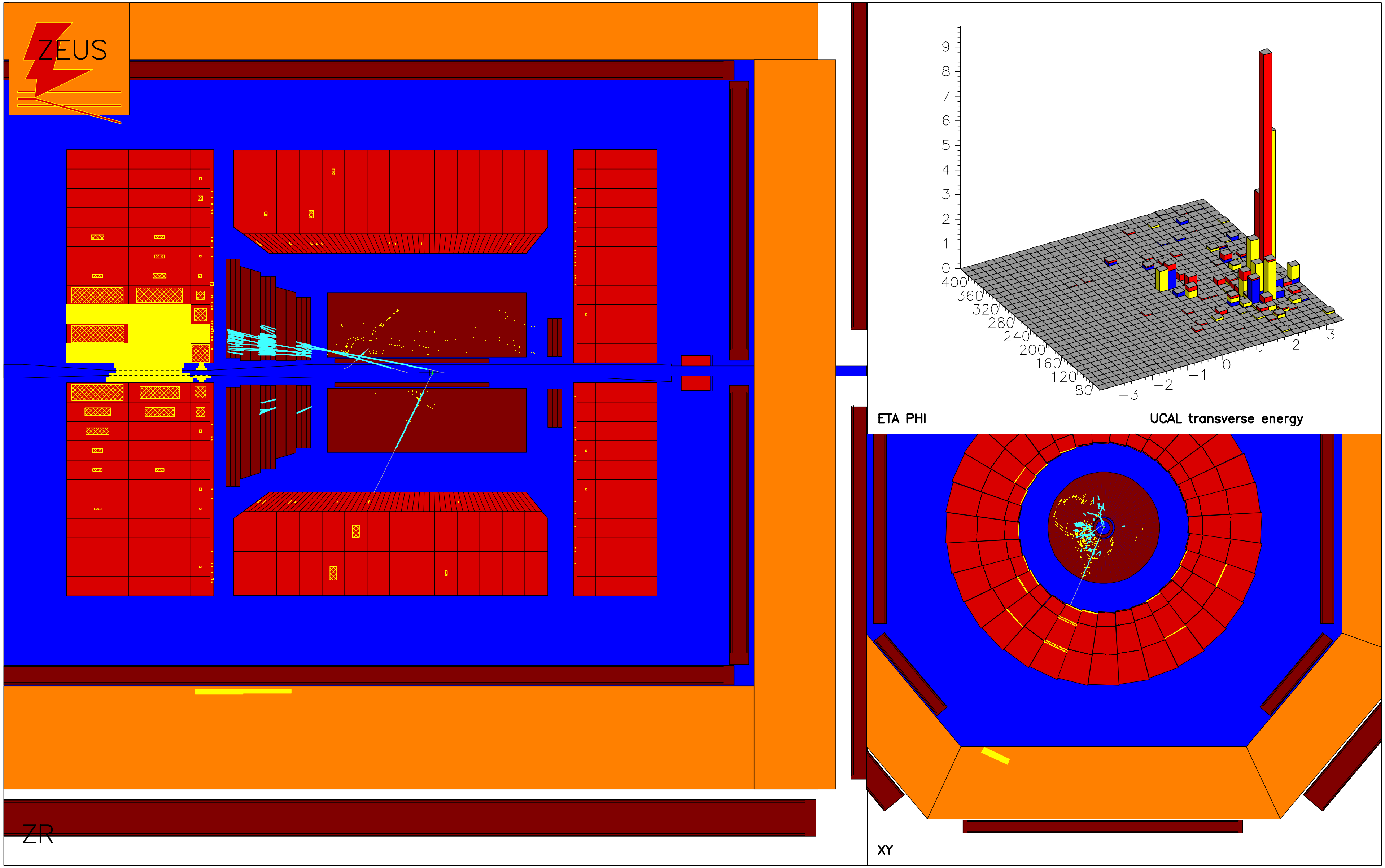
H1 preliminary **1994-2000 $e^{+}p$ 82 pb^{-1}**	Electrons Observed/expected (W)	Muons Observed/expected (W)
P_T^X > 25 GeV	3 / 0.84±0.22 (0.67)	6 / 0.94±0.26 (0.78)
P_T^X > 40 GeV	2 / 0.27±0.08 (0.26)	4 / 0.35±0.10 (0.33)

Errors include systematics

All events from nominal result remain: excess of events

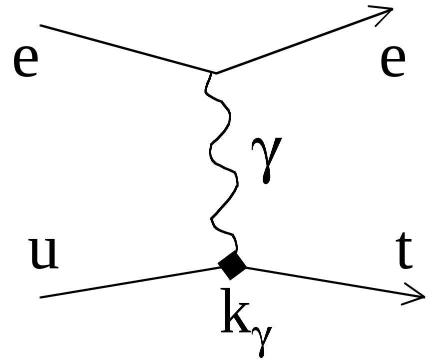
ZEUS μ event with large Pt^X

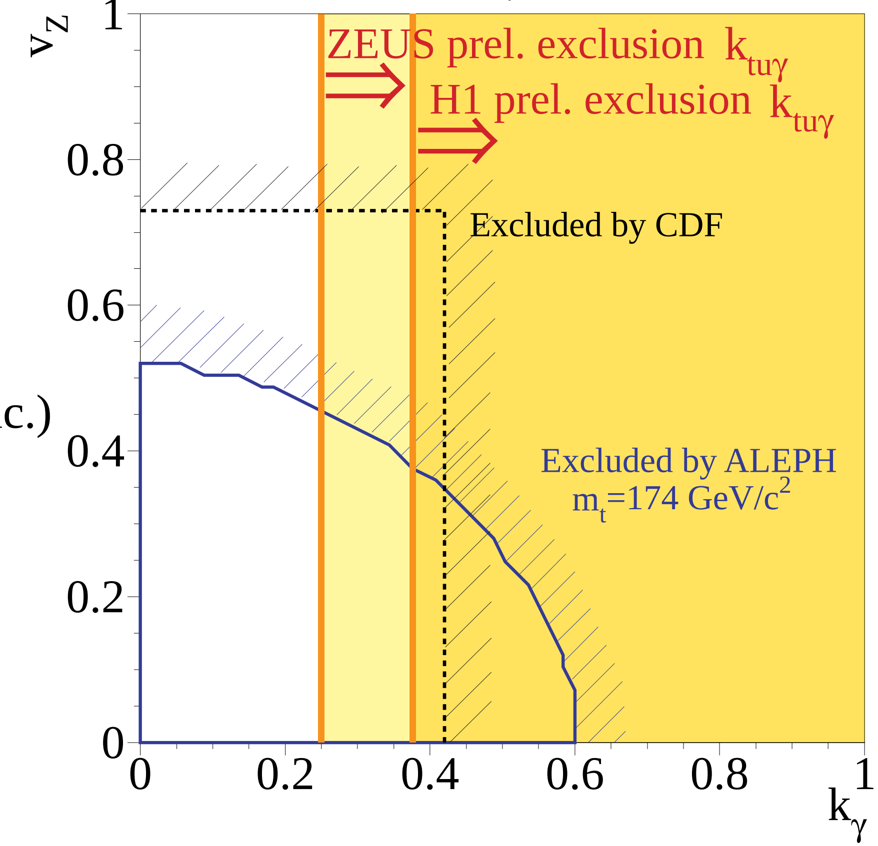
$P_T(\mu^+)$=38^{+20}_{-10} GeV, P_T^X=36 GeV, $Acoplanarity$=1.9, $\not{P}_T$=61^{+17}_{-8} GeV, M_T=91^{+39}_{-19} GeV



Single top production with FCNC

- Lepton + missingPt + high-Et jet : signature of t →bW →blν
- Single-top from SM negligible (FCNC); observation would imply beyond SM
- Dtrk>0.5, Djet>1.0, then Pt^X > 40 GeV → 0 event remained where 1.1 expected
- $L = (ee_q/\Lambda) t\, \sigma_{\mu\nu} q_\nu k_\gamma u A^\mu$ ($\Lambda = m_{top}$) →limit on $k_{tu\gamma}$ from cross-section limits (see Belyaev+Kidonakis hep-ph/0102072 for recent calc.)
- m_{top} dependence: ±5GeV →±20% on σ
- LEP: $e^+e^- \to (\gamma,Z) \to$ tc (tu)
- TeVatron: rare top decays t→ γq, Zq
- HERA results give strongest constraint on t-u-γ FCNC coupling





ALEPH: CERN-EP-2000-102

Summary and Future Prospects

- "HERA 1" : ~110 pb^{-1} e^+p and ~15 pb^{-1} e^-p data per experiment. So far no evidence for new physics; yielded new constraints on
  - Leptoquarks
  - Squarks in R-parity violating SUSY
  - eeqq Contact Interactions, Large Extra Dimensions, Quark form factor
  - Lepton-Flavor Violation
  - Excited electrons, neutrinos, quarks
- Limits comparable/complementary to LEP/TeVatron searches.
- H1 isolated leptons intriguing, though whole ZEUS data consistent with SM. Limits on single-top production gives strong constraint on FCNC coupling.

- Shutdown since fall 2000: luminosity upgrade = focusing magnets inside detector. Major modifications in the machine and detectors (+ new detector components, e.g. ZEUS will also have micro-vtx).
- Restart this summer: "HERA 2" will give ~1 fb^{-1} data in ~5 years.

Competition with TeVatron RUN II

- Example: LQ or Squarks in RpV SUSY
  If Yukawa coupling λ large enough favorably for HERA, it will detect new physics with 10 times more data to come.
- Otherwise, for some models RUN II will close its discovery window.
  e.g. BRW LQs which decay 100% to eq will be probed beyond HERA CM energy after 1-2 fb^{-1} of TeVatron data.
- There are however also cases where TeV. potential does not reach HERA; e.g. when LQ has low decay B.R. to eq. →
- Also some models not probed at TeV. extensively: e.g. LFV, e*, ν*
- Stay tuned for excitement for the next "post-LEP, pre-LHC" era !

hep-ph/0007282