

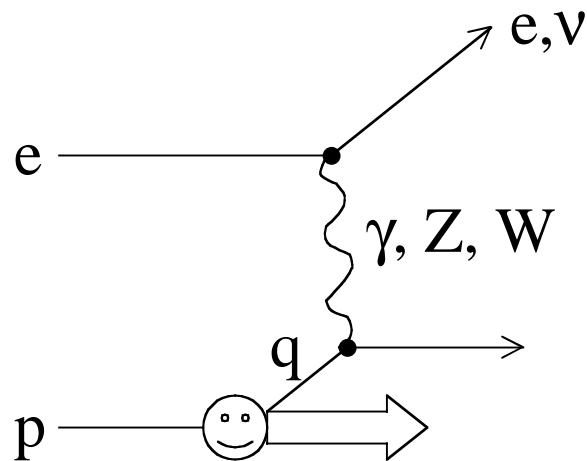
Search for New Physics at HERA

XV Rencontres de Physique de la Vallée d'Aoste
La Thuile, 7/Mar/2001

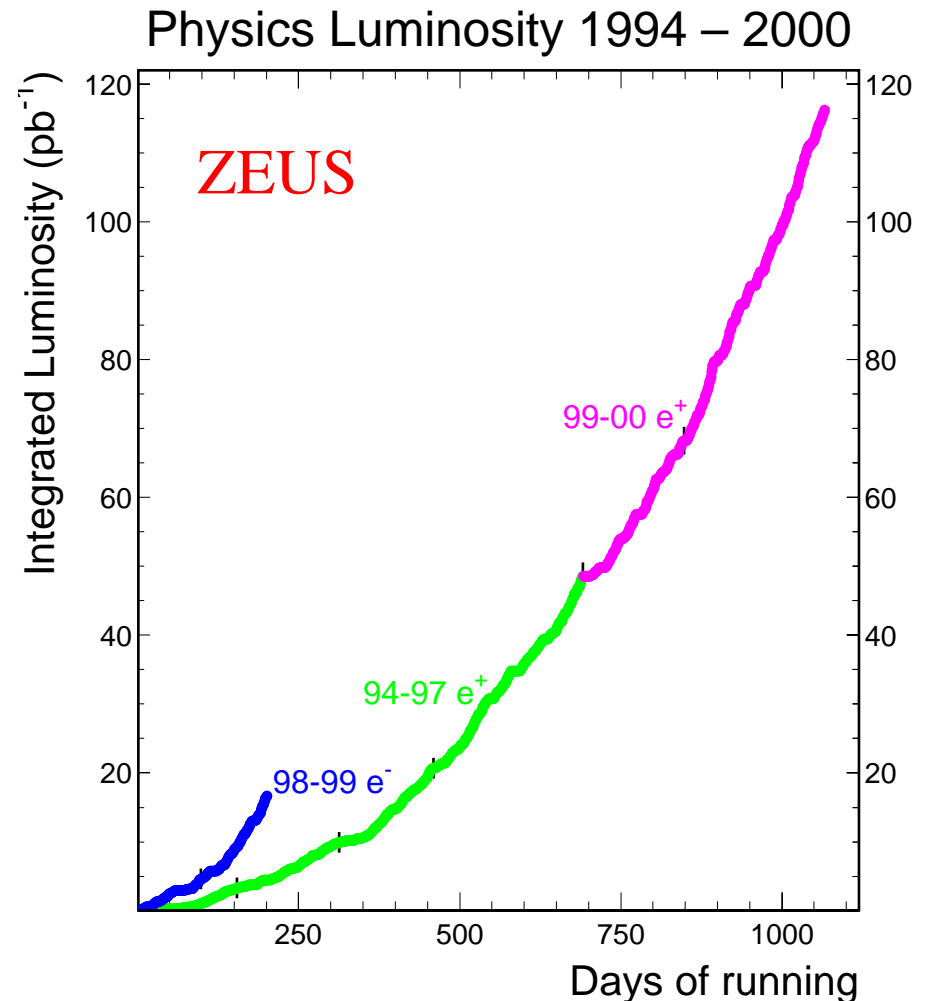
Masahiro Kuze (KEK-IPNS /ZEUS)
On behalf of H1 and ZEUS Collaborations

HERA *ep* collider @ DESY

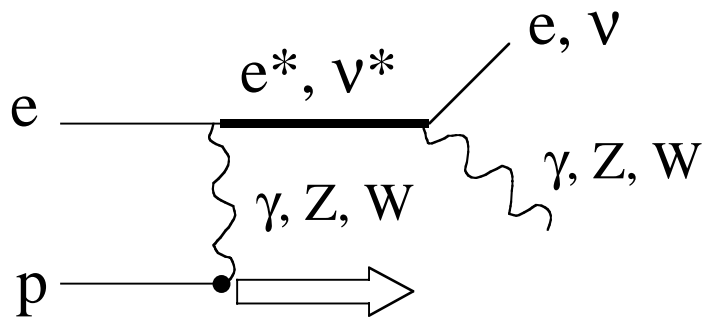
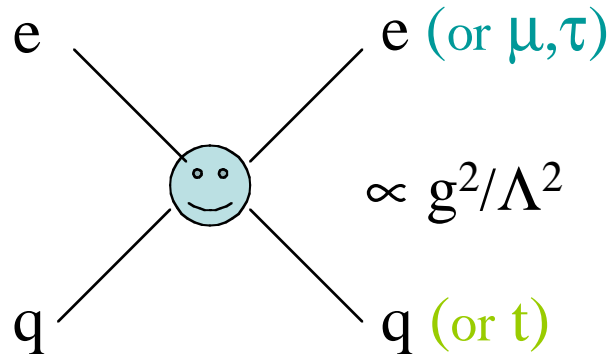
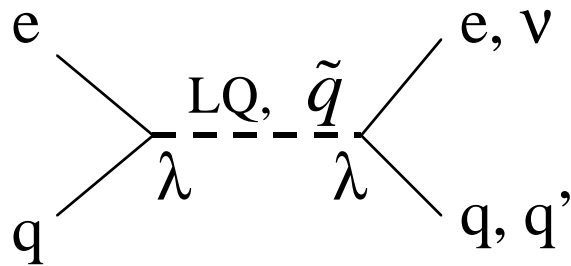
- $\sqrt{s} = 300 \text{ GeV}$ (– 1997), 318 GeV (1998 –)
- $\sim 110 \text{ pb}^{-1} e^+p$ and $\sim 15 \text{ pb}^{-1} e^-p$ data collected per exp't until 2000
- Kinematics of deep inelastic scattering:



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



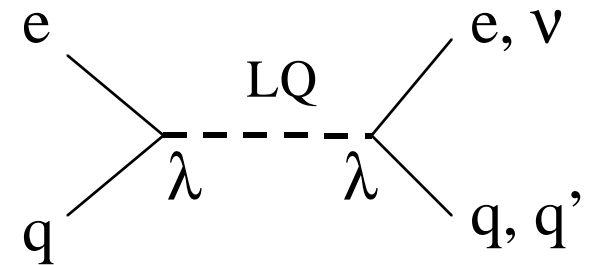
Signals of physics beyond SM at HERA



- **e-q resonances (Leptoquarks)**
 - Peak in $m=\sqrt{(sx)}$, decay to eq or $\nu q'$
- **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 ($e-\mu$, $e-\tau$) or **FCNC** transition ($u \rightarrow t$: single top)
- **Excitation of Fermions**
 - e^* , ν^* , q^* if fermions composite
 - Peak in $f-V$ invariant mass

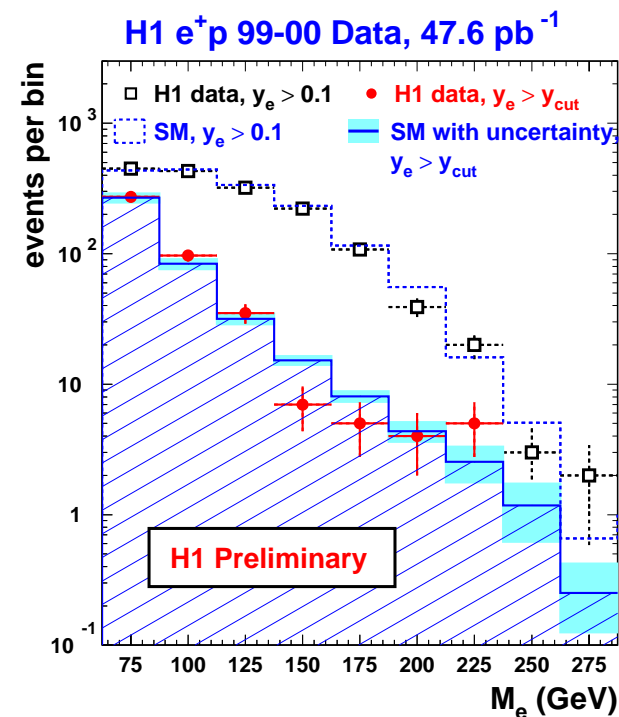
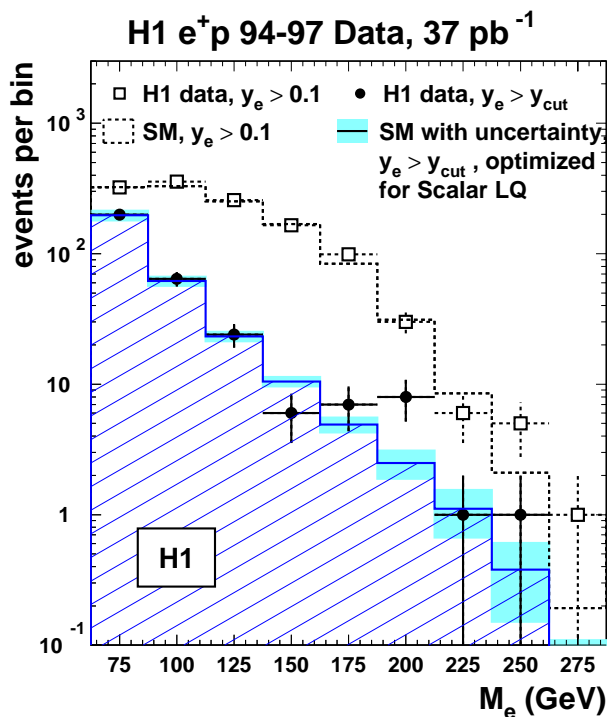
Leptoquarks

- Carry both L and B numbers
- **Buchmüller-Rückl-Wyler (BRW) model:**
 - $SU(3) \times SU(2) \times U(1)$ invariance
 - LQs only couple to chiral SM fermions
 - 14 species, 7 scalars and 7 vectors
 - Decays: 100% to $e q$, 100% to νq or 50% to each
- Production at HERA $\propto \lambda^2$ (Yukawa coupling)
 - $e^+ p$ and $e^- p$ sensitive to **different LQ** (valence \gg 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)

($x=0.55 \leftrightarrow m=220\text{GeV}$)



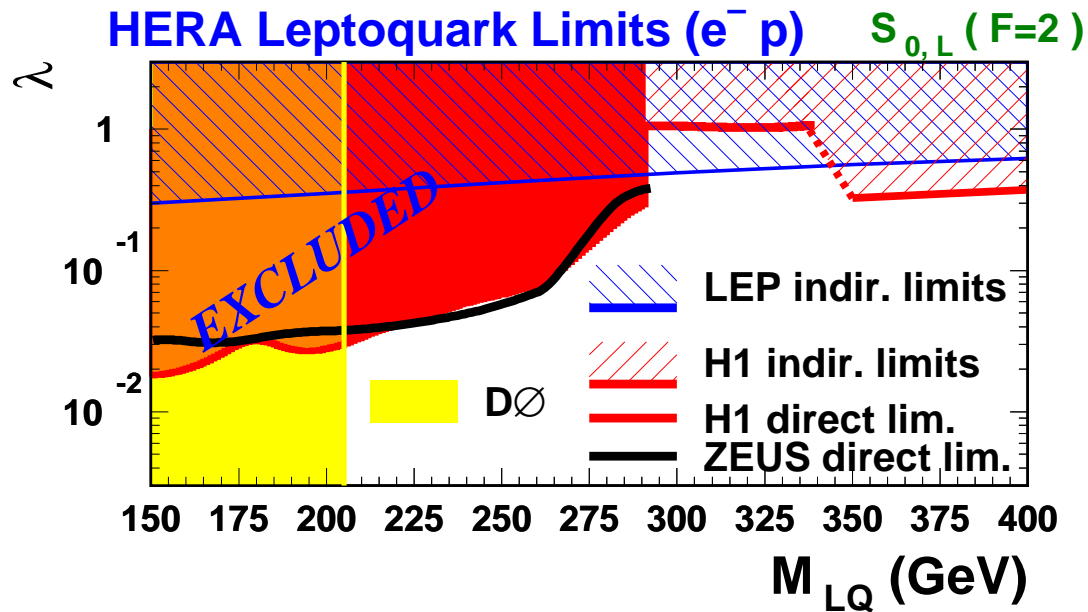
0 event

1.6 expected from SM

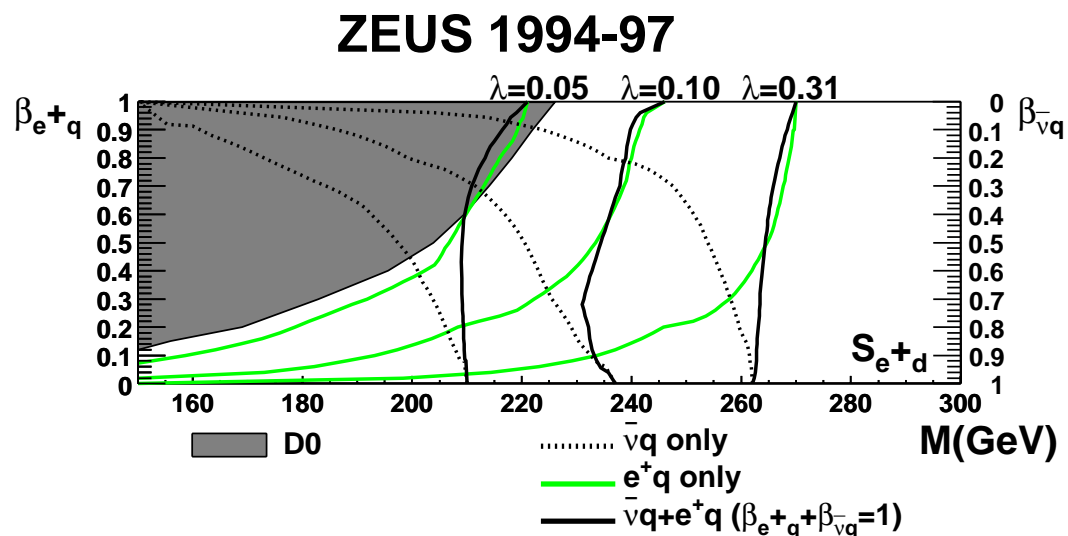
(39 pb⁻¹ 1999-00 April)

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

Leptoquark limits



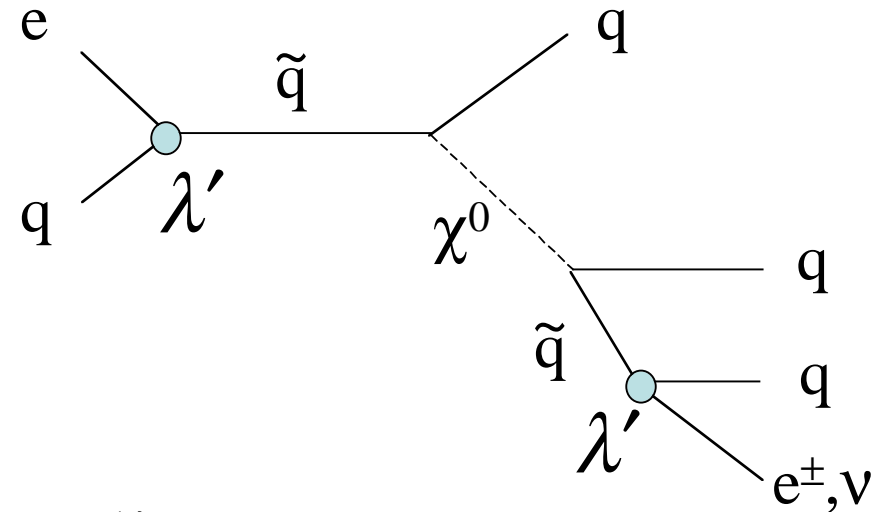
- BRW framework:
 - λ vs. mass
 - TeVatron: pair production, independent of λ
 - LEP: virtual effects in $e^+e^- \rightarrow \text{hadrons}$



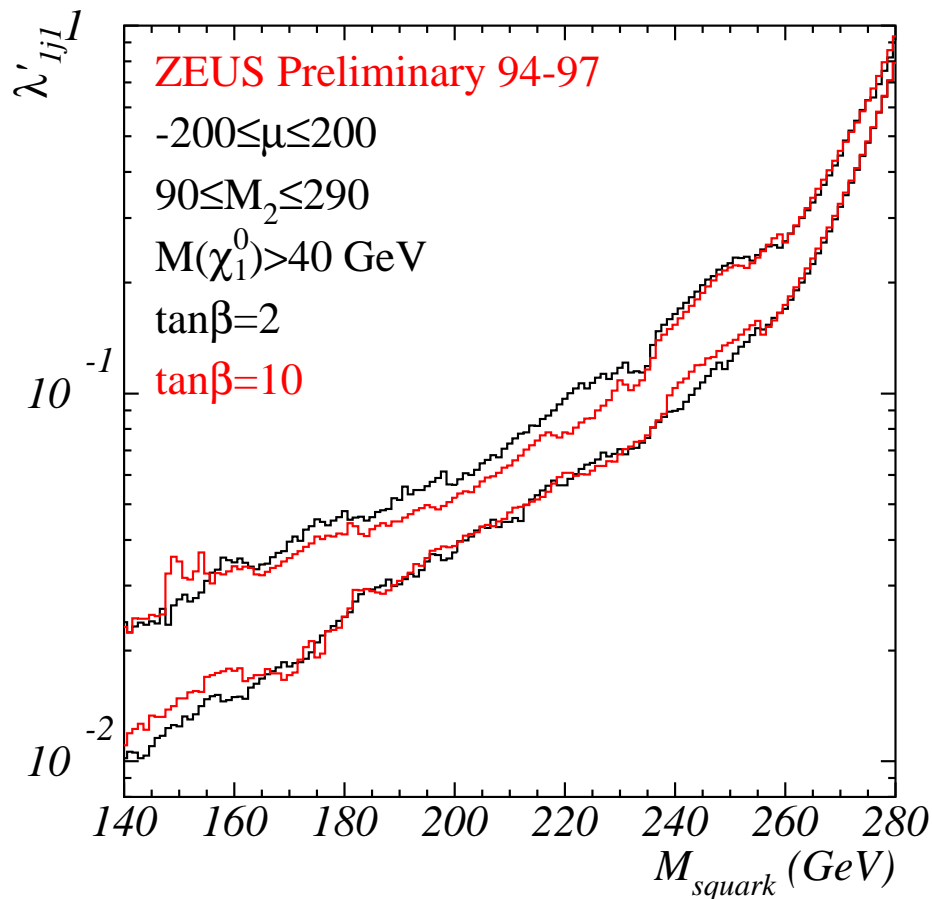
- General case: stay away from BRW model
 - Treat $\beta(LQ \rightarrow eq)$ as free
 - If $\beta(eq) + \beta(vq) = 1$:
Combining NC and CC events, limits almost independent on β
 - TeVatron limits degrade at low β

R-parity violating SUSY

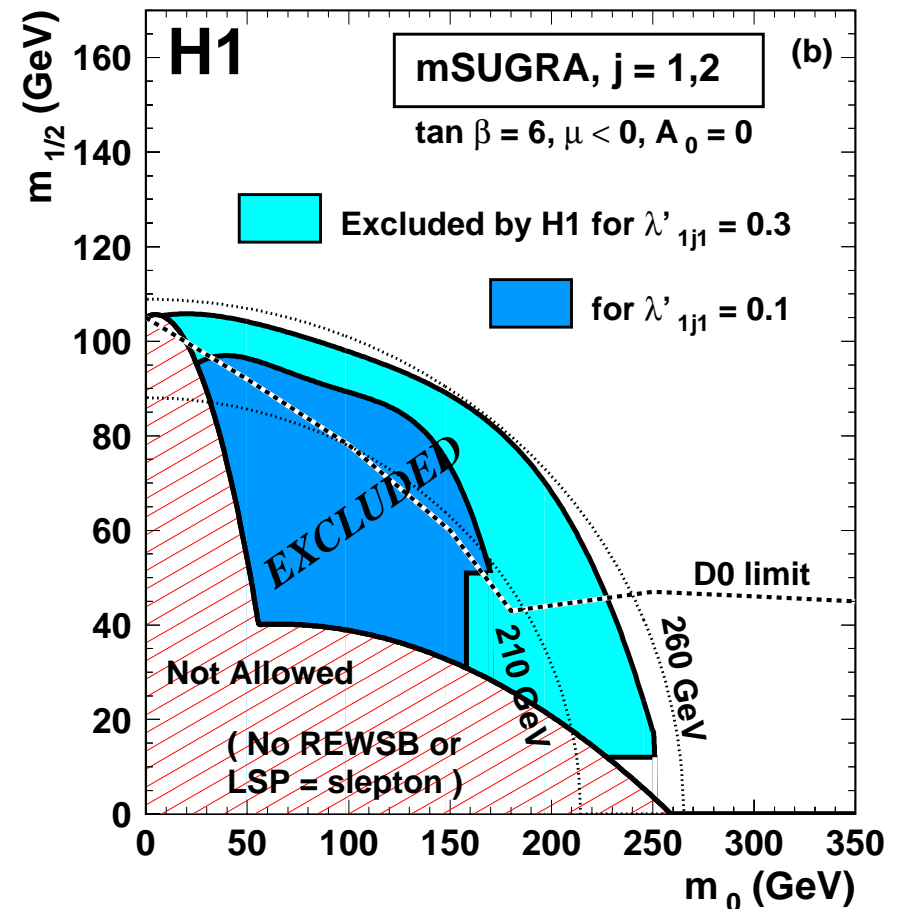
- $R_P \equiv (-1)^{F+2S} = (-1)^{L+3B+2S}$
 R_P violation \rightarrow sparticles singly produced and LSP not stable.
- $L_i Q_j \bar{D}_k$ coupling interesting for HERA:
 $e q \rightarrow$ squark (like LQ)
- Final states more complicated than LQ:
 χ^0 decays with the same coupling to $e^\pm q q$ or $\nu q q$
 (“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

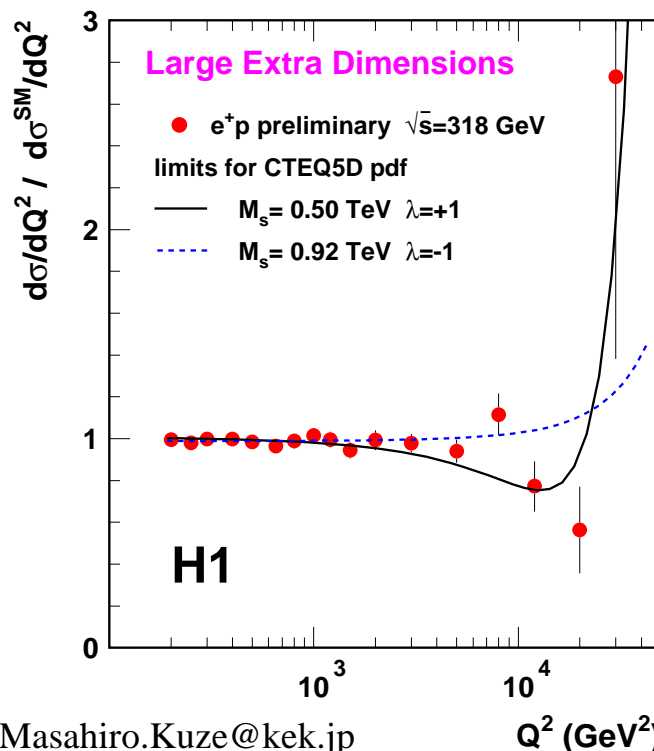
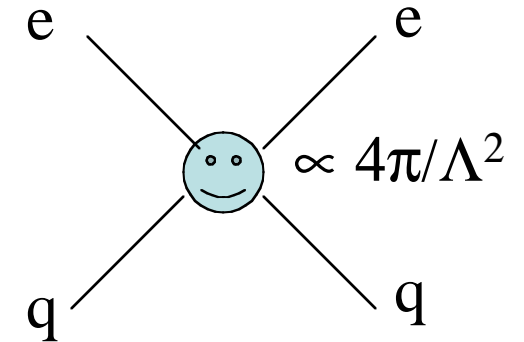


- mSUGRA:
For reasonably large λ' values,
HERA exclusion exceeds TeVatron
limits

DESY 01-021

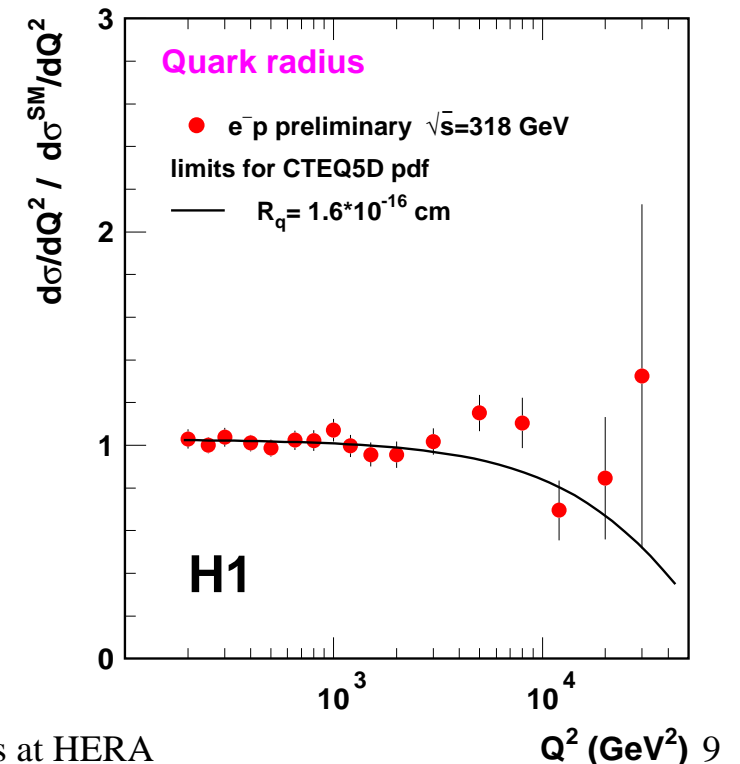
Contact Interactions

- Look for deviation at highest Q^2
Probed distance $=1/Q \sim 0.001$ fm for $Q^2 \sim 10^4$ GeV²
- General $eeqq$ CI: limits depend on chirality combination (LL, LR, VV, AA....), up to **9 TeV**
- Comparable to LEP ($e^+e^- \rightarrow$ 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:
 $F = (1 - R^2 Q^2 / 6)$
 R: quark “radius”



Lepton Flavor Violation

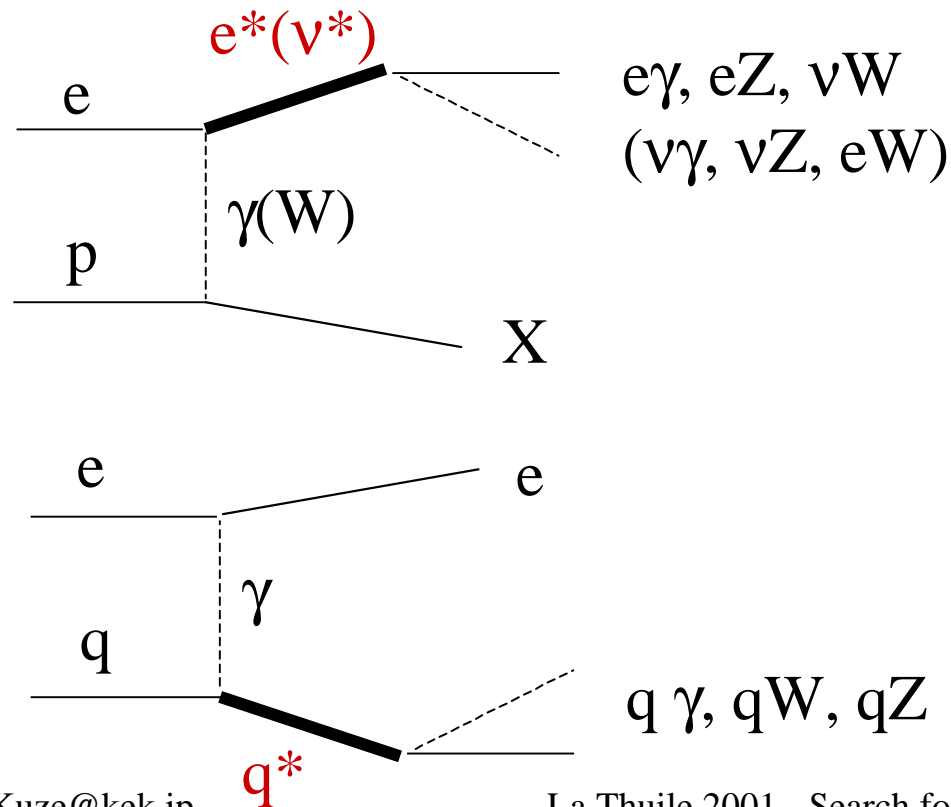
$e \leftrightarrow \tau$				$F = 0$			
$q_i q_j$	$S_{1/2}^L$ $e^+ u$	$S_{1/2}^R$ $e^+ (u + d)$	$\tilde{S}_{1/2}^L$ $e^+ d$	V_0^L $e^+ d$	V_0^R $e^+ d$	\tilde{V}_0^R $e^+ u$	V_1^L $e^+ (\sqrt{2}u + d)$
1 1	$\tau \rightarrow \pi e$ 0.0032 0.030	$\tau \rightarrow \pi e$ 0.0016 0.025	$\tau \rightarrow \pi e$ 0.0032 0.046	G_F 0.002 0.033	$\tau \rightarrow \pi e$ 0.0016 0.033	$\tau \rightarrow \pi e$ 0.0016 0.024	G_F 0.002 0.012
1 2	$H1: 0.047$ 0.030	$\tau \rightarrow K e$ 0.05 0.025	$\tau \rightarrow K e$ 0.05 0.046	$\tau \rightarrow K e$ 0.03 0.036	$\tau \rightarrow K e$ 0.03 0.036	$H1: 0.045$ 0.026	$K \rightarrow \pi \nu \bar{\nu}$ $2.5 \cdot 10^{-6}$ 0.012
1 3	*	$B \rightarrow \tau e X$ 0.08 0.049	$B \rightarrow \tau e X$ 0.08 0.049	$B \rightarrow l \nu X$ 0.02 0.044	$B \rightarrow \tau e X$ 0.04 0.044	*	$B \rightarrow l \nu X$ 0.02 0.044
2 1	$H1: 0.15$ 0.15	$\tau \rightarrow K e$ 0.05 0.092	$\tau \rightarrow K e$ 0.05 0.11	$\tau \rightarrow K e$ 0.03 0.049	$\tau \rightarrow K e$ 0.03 0.049	$H1: 0.073$ 0.061	$K \rightarrow \pi \nu \bar{\nu}$ $2.5 \cdot 10^{-6}$ 0.026
2 2	$\tau \rightarrow e \gamma$ 0.03 0.19	$\tau \rightarrow e \gamma$ 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	*	$B \rightarrow \tau e X$ 0.08 0.15	$B \rightarrow \tau e X$ 0.08 0.15	$B \rightarrow l \nu X$ 0.02 0.10	$B \rightarrow \tau e X$ 0.04 0.10	*	$B \rightarrow l \nu X$ 0.02 0.10
3 1	*	$B \rightarrow \tau e X$ 0.08 0.16	$B \rightarrow \tau e X$ 0.08 0.16	V_{ub} 0.002 0.052	$B \rightarrow \tau e X$ 0.04 0.052	*	V_{ub} 0.002 0.052
3 2	*	$B \rightarrow \tau e X$ 0.08 0.20	$B \rightarrow \tau e X$ 0.08 0.20	$B \rightarrow l \nu X$ 0.02 0.073	$B \rightarrow \tau e X$ 0.04 0.073	*	$B \rightarrow l \nu X$ 0.02 0.073
3 3	*	$H1: 0.23$ 0.28	$H1: 0.23$ 0.28	$\tau \rightarrow e \gamma$ 0.51 0.14	$\tau \rightarrow e \gamma$ 0.51 0.14	*	$H1: 0.14$ 0.14

ZEUS preliminary

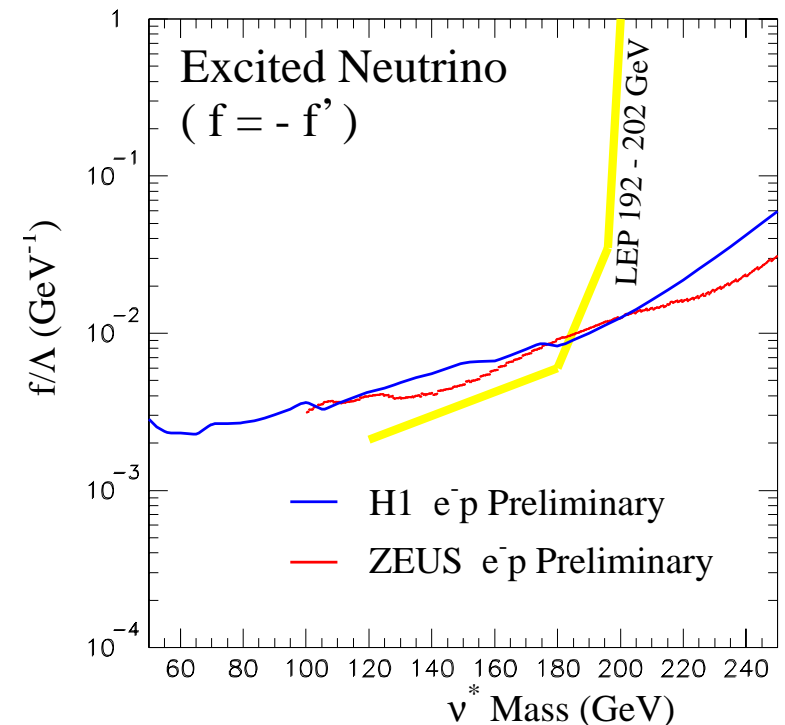
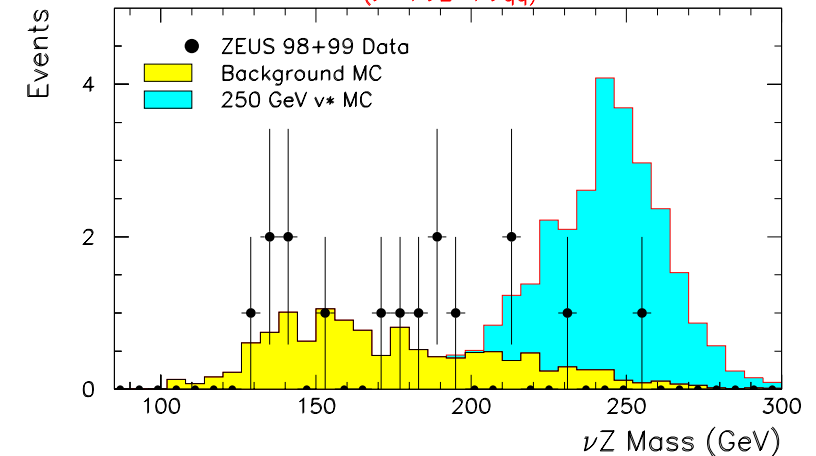
- Variant of CI: $eq \rightarrow lq$ ($l=\mu, \tau$) mediated by LFV Leptoquarks
- Spectacular signal; no event found in H1/ZEUS 94-97 data
- Limits expressed in $\lambda_{eq} \lambda_{lq} / M^2$ (10^{-4}GeV^{-2}) for 3×3 (q, q') generation combinations
- For light-quark only cases, limits from low-energy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

Excited Fermions

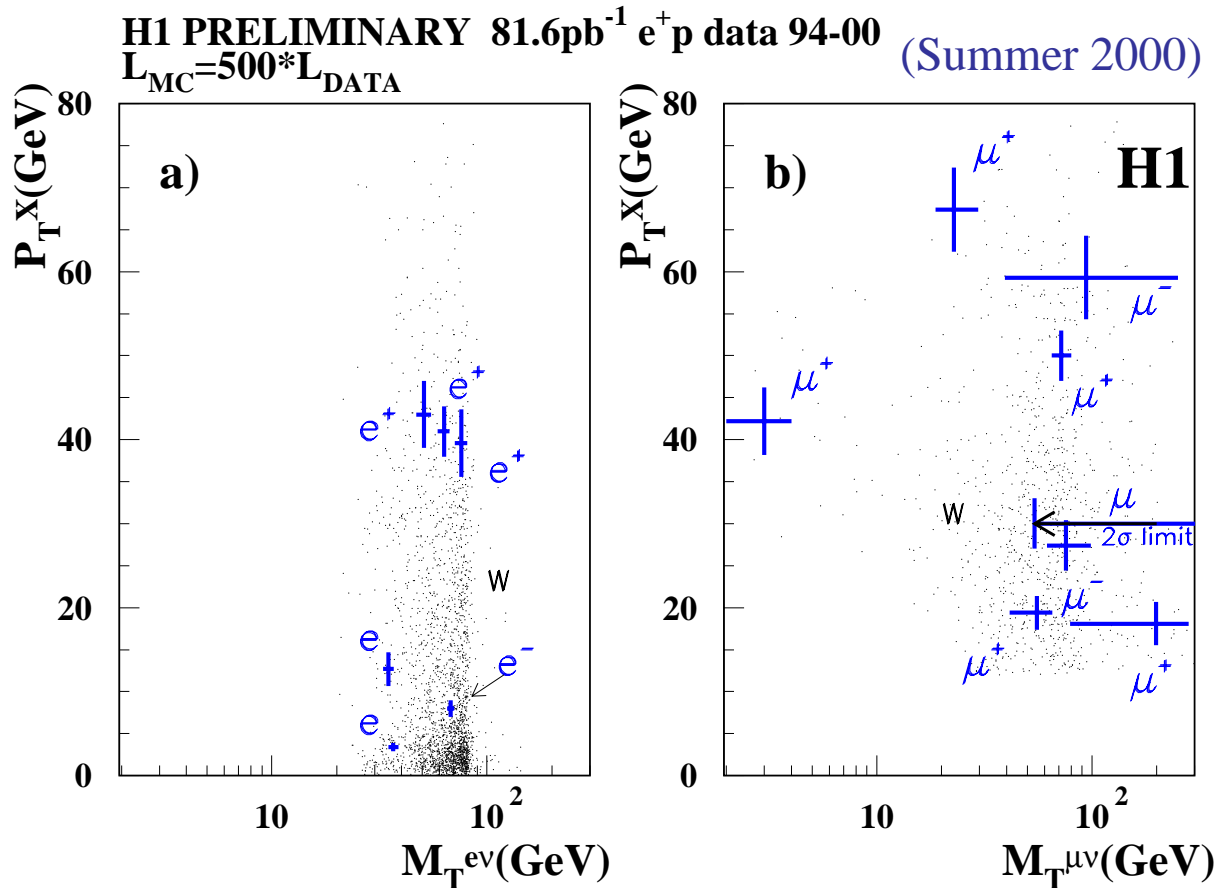
- Composite fermions \rightarrow excited states
- Hagiwara-Komamiya-Zeppenfeld
 $L_{ff^*} \propto [f \cdot \text{SU}(2) + f' \cdot \text{U}(1) + f_s \cdot \text{SU}(3)] / \Lambda$
- ν^* example \rightarrow
 Sensitivity extends above LEP2 energy



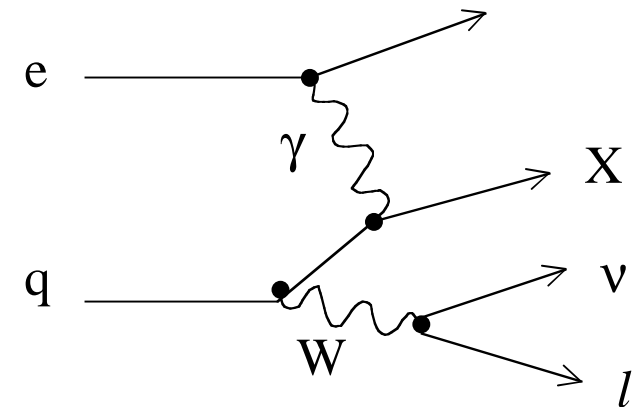
ZEUS 98+99 Preliminary
 $(\nu^* \rightarrow \nu Z \rightarrow \nu q \bar{q})$



Something unexpected: high-Pt leptons



- Events with high-Pt **isolated lepton** and missing calorimeter Pt
- At large P_T^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)
$P_T^X > 25 \text{ GeV}$	3 / 1.05±0.27 (0.83)	6 / 1.21±0.32 (1.01)
$P_T^X > 40 \text{ GeV}$	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

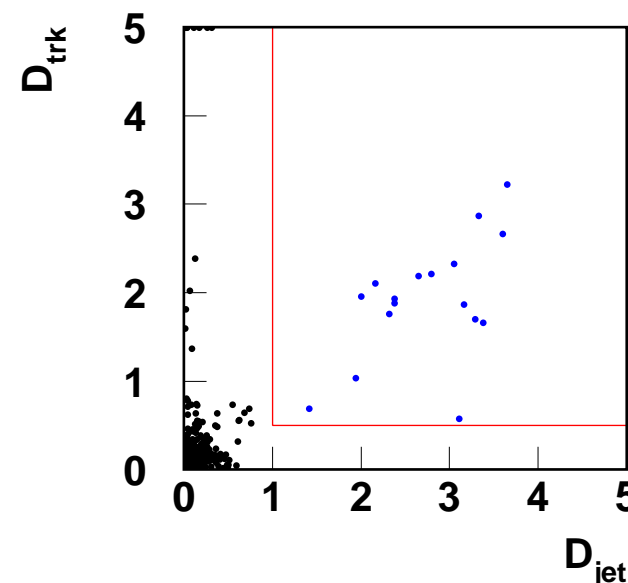
- Main cuts:

- $Pt(CAL) > 20 \text{ GeV}$, $Pt(track) > 10 \text{ GeV}$
- $D_{trk} > 0.5$ (in $\eta-\phi$) from other tracks
- $D_{jet} > 1.0$ 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)

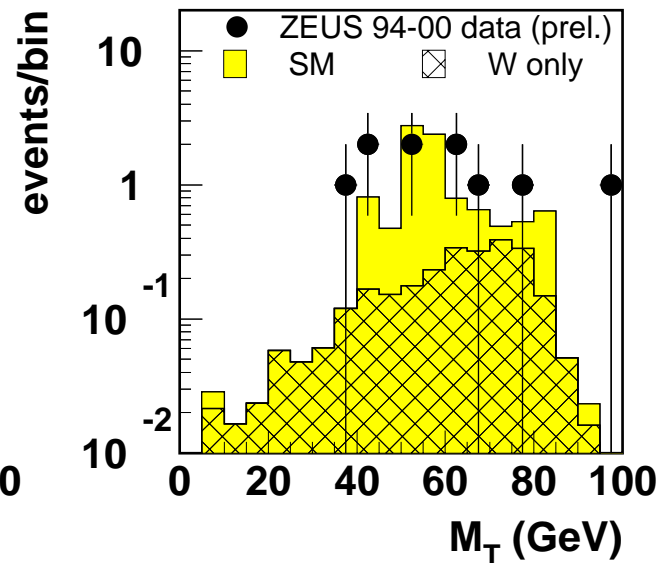
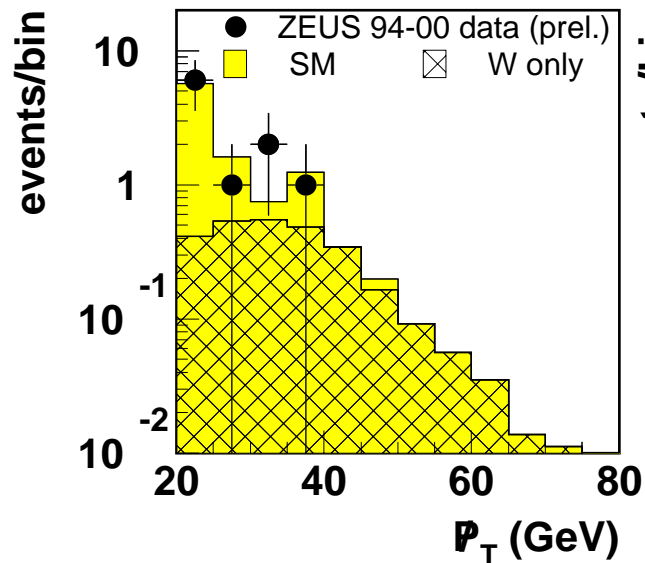
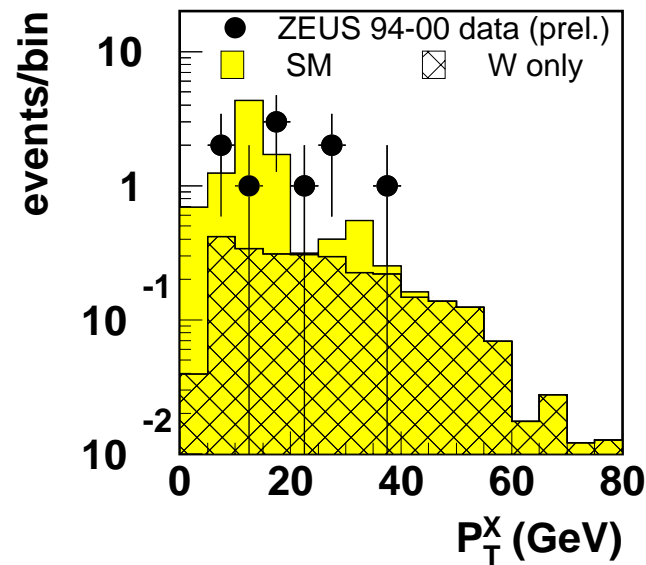
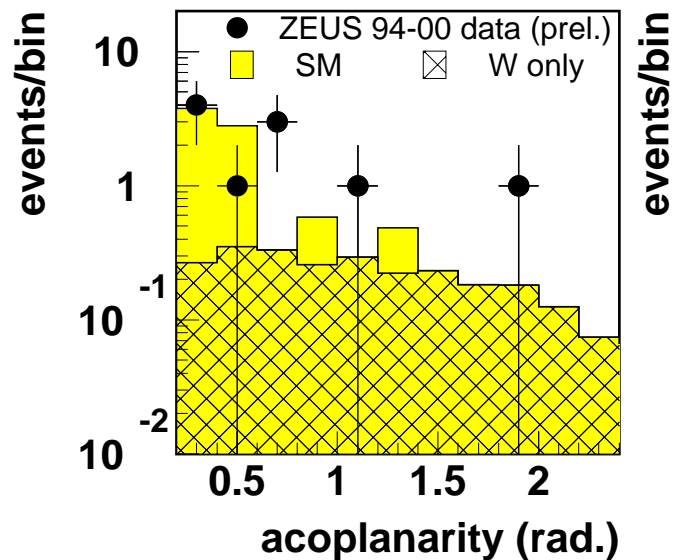
ZEUS 1994–2000 preliminary



- Event rate consistent with SM prediction

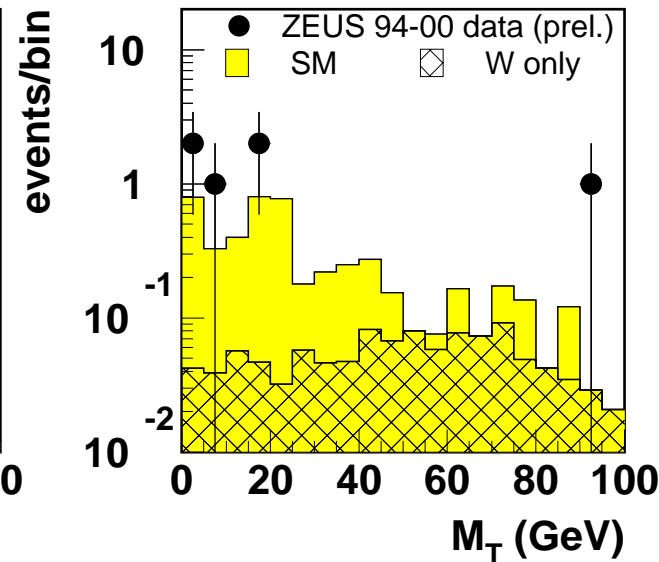
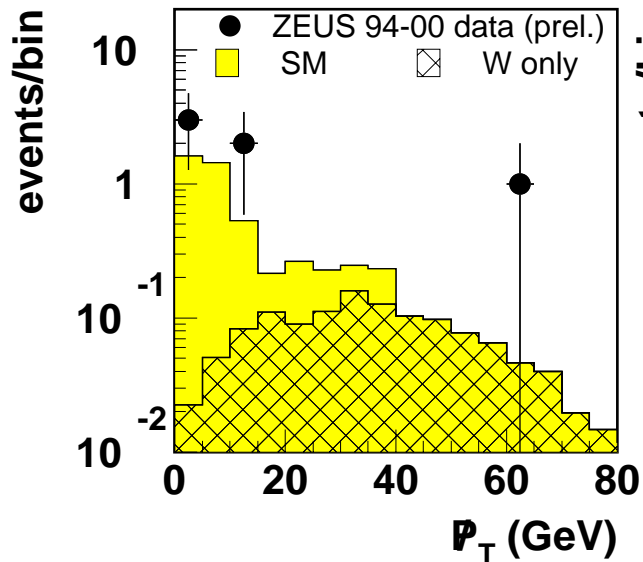
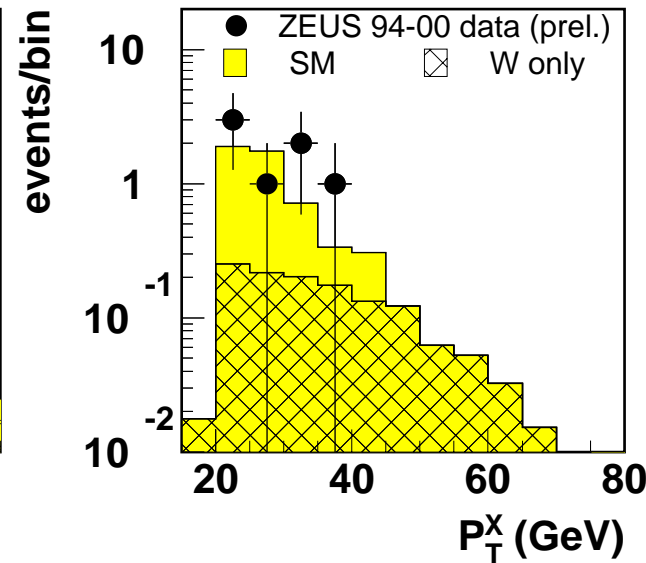
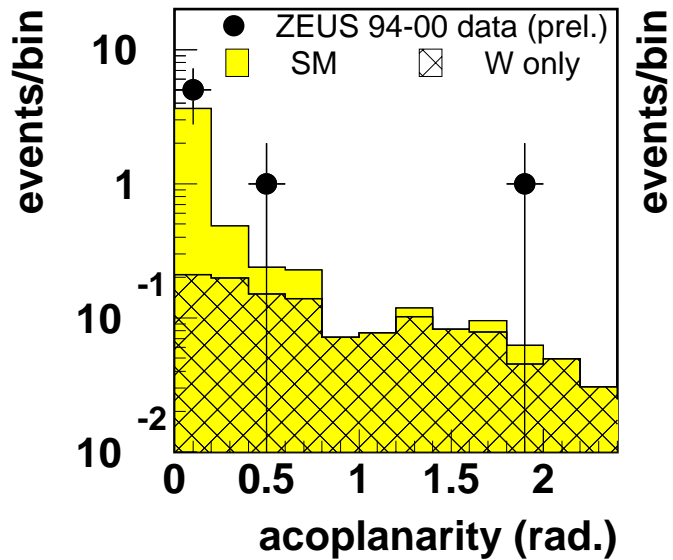
ZEUS preliminary 1994-2000	Electrons Observed/expected (W)	Muons Observed/expected (W)
e^+p 114 pb^{-1}	7 / 9.9 ± 1.6 (2.4)	7 / 4.6 ± 0.6 (1.1)
e^-p 16 pb^{-1}	3 / 1.1 ± 0.4 (0.3)	0 / 0.8 ± 0.1 (0.2)
Total 130 pb^{-1}	10 / 11.0 ± 1.6 (2.7)	7 / 5.4 ± 0.7 (1.3)

Electron events: kinematical distribution



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

Muon events: kinematical distribution



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

Comparison of events at large P_t^X

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

ZEUS preliminary 1994-2000 e^+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 $P_t^X > 25$ GeV, but consistent with total expectation

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

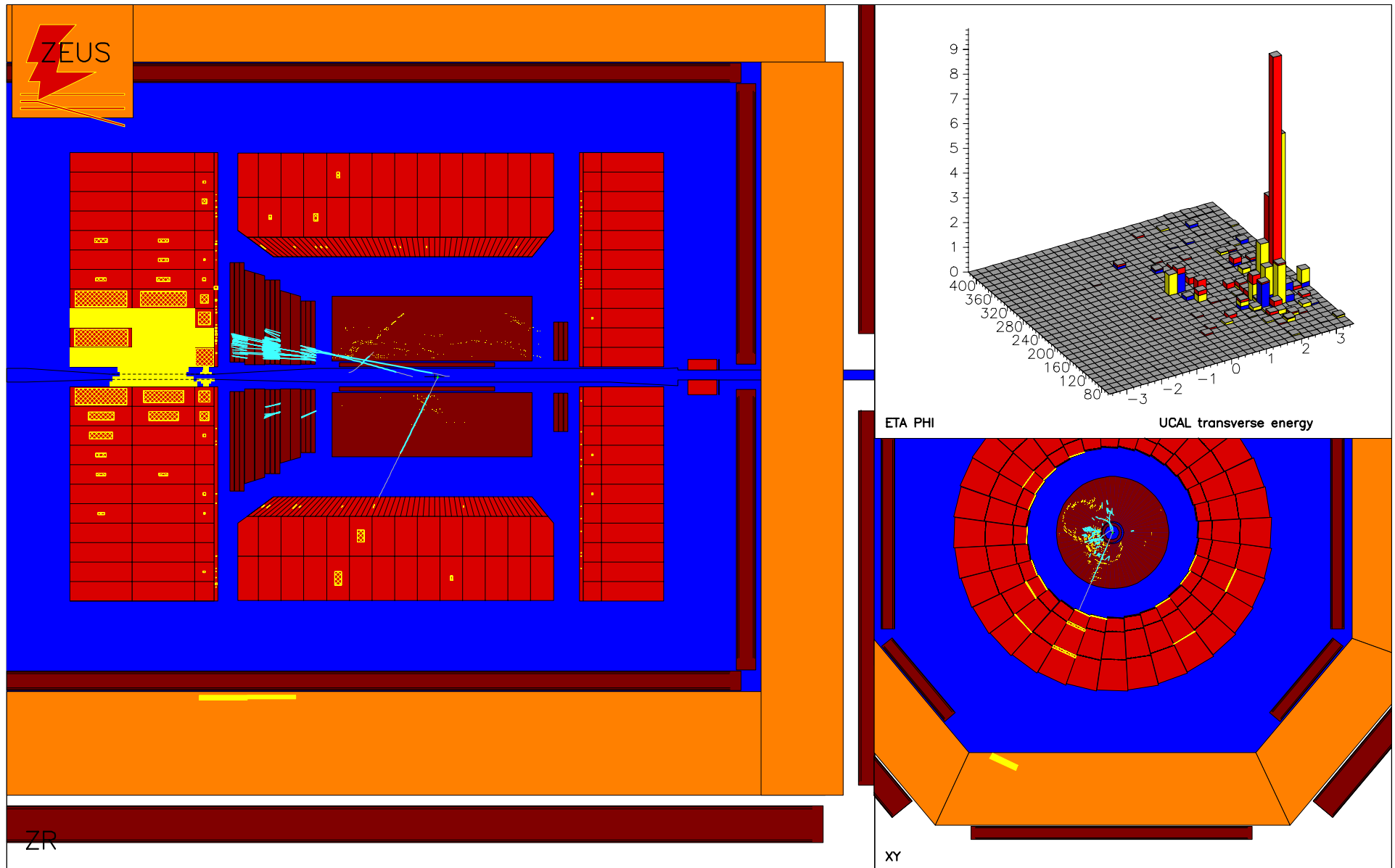
H1 preliminary 1994-2000 e^+p 82 pb^{-1}	Electrons Observed/expected (W)	Muons Observed/expected (W)
$P_t^X > 25$ GeV	3 / 0.84 ± 0.22 (0.67)	6 / 0.94 ± 0.26 (0.78)
$P_t^X > 40$ GeV	2 / 0.27 ± 0.08 (0.26)	4 / 0.35 ± 0.10 (0.33)

Errors include systematics

All events from nominal result remain: excess of events

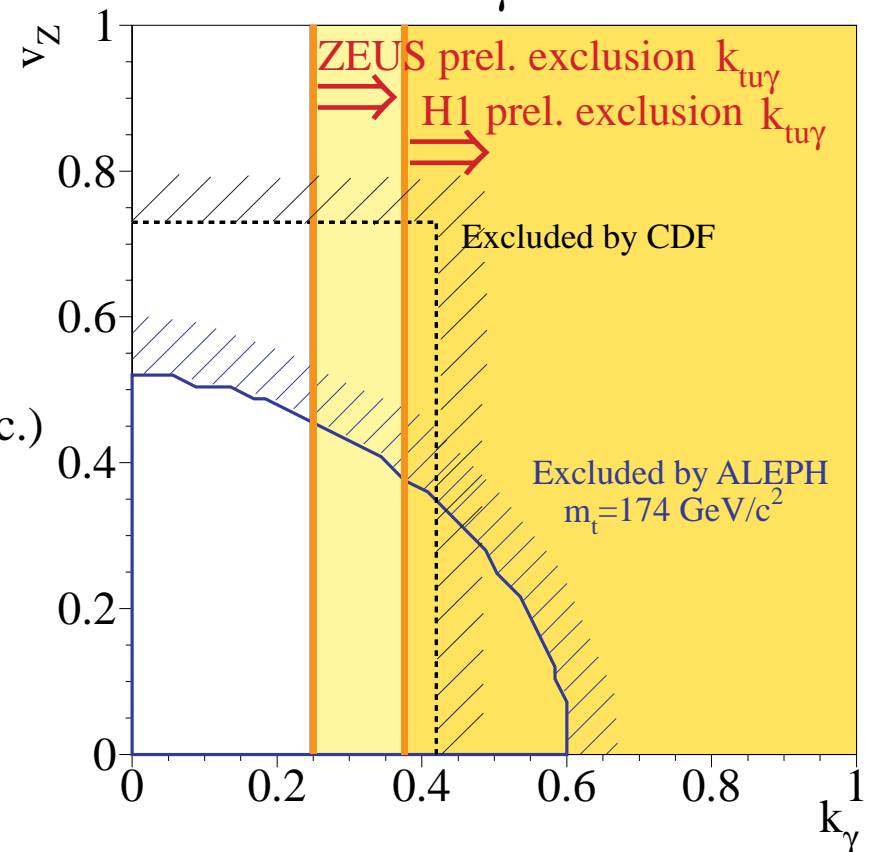
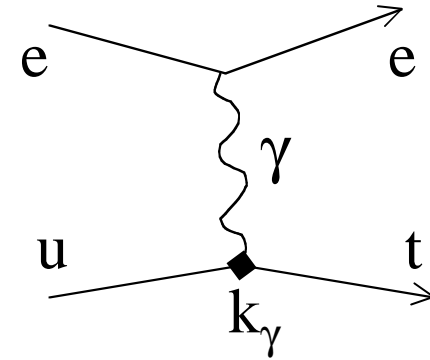
ZEUS μ event with large P_t^X

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



Single top production with FCNC

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



ALEPH: CERN-EP-2000-102

Summary and Future Prospects

- “HERA 1” : $\sim 110 \text{ pb}^{-1} e^+p$ and $\sim 15 \text{ pb}^{-1} e^-p$ 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 $\sim 1 \text{ fb}^{-1}$ 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

Future Sensitivity on Scalar Leptoquarks

