Searches Beyond the Standard Model at HERA

André Schöning

ETH Zürich, Switzerland

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Electroweak Interactions
and Unified Theories
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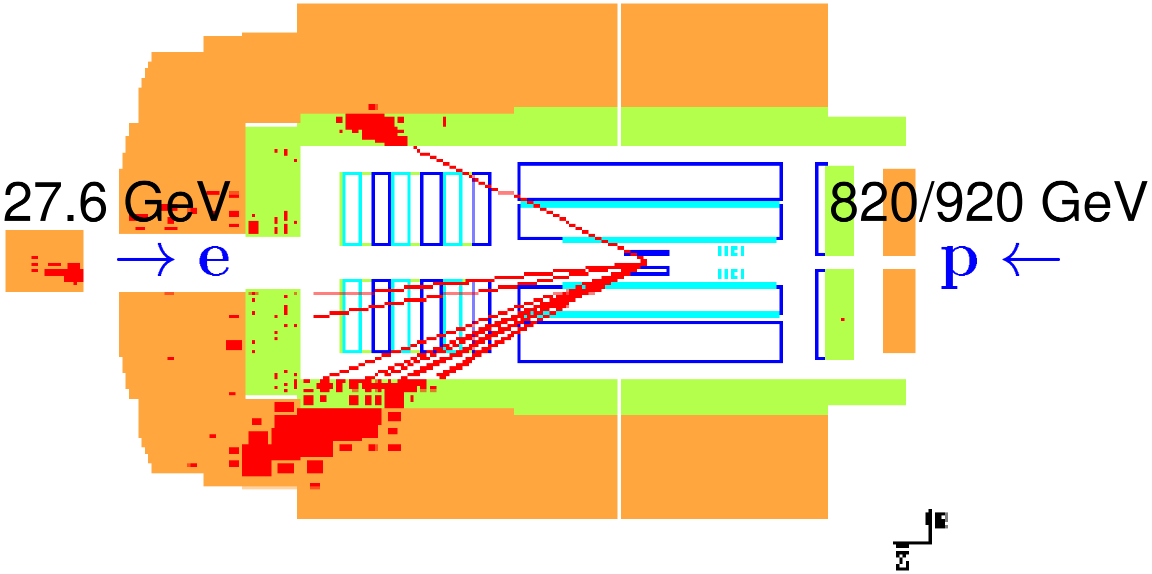
- HERA Kinematics
- DIS at high Q^2 $\Rightarrow$ contact interaction
- Leptoquarks, Lepton Flavour Violation
- R_pViolating SUSY
- Excited Fermions
- Isolated Leptons $\Rightarrow$ anomalous top production
- Conclusion / Outlook

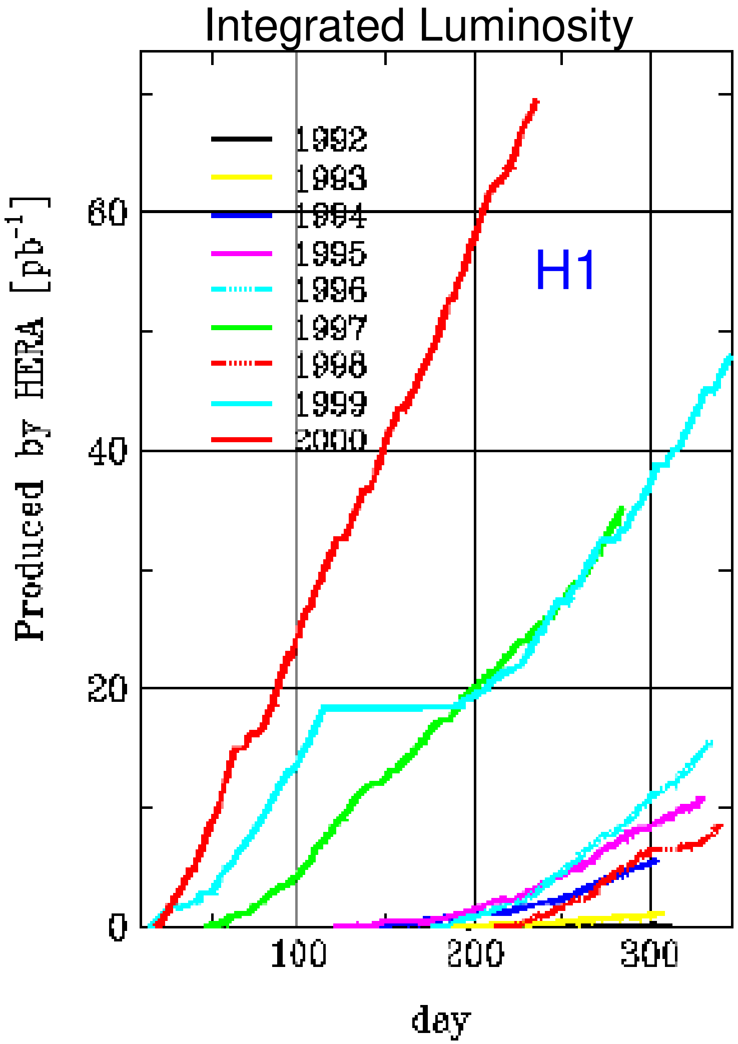
Introduction to HERA

HERA: ep collider at $\sqrt{s} \approx 300/320$ GeV



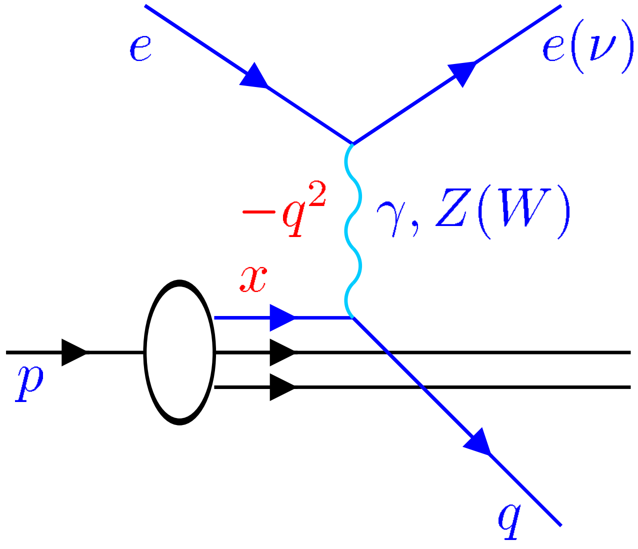
Neutral (Charged) Current: $\mathbf{ep} \rightarrow \mathbf{e}(\nu)\mathbf{X}$

Year	collision	$\sqrt{s}$ (GeV)	$\int$ Luminosity (pb^{-1})
94-97	$\mathbf{e^+p}$	300	≈ 40
98-99	$\mathbf{e^-p}$	320	≈ 15
99-00	$\mathbf{e^+p}$	320	≈ 80



HERA did a great job!

Deep Inelastic Scattering at high Q^2



HERA Kinematics

$$s = 4\, E_e\, E_p$$

$$Q^2 = -q^2 = xys$$

spatial resolution $\rightarrow r = 10^{-16}$ cm

$$x = \frac{Q^2}{2\, p \cdot q}$$

quark momentum fraction of the proton

$$y = \frac{p \cdot q}{p \cdot \ell}$$

“energy transfer” $\propto (1 - \cos\theta^*]$ related to the scattering angle $\Rightarrow$ coupling

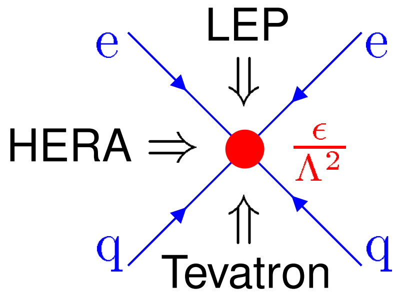
$$M = \sqrt{xs}$$

quark-lepton invariant mass $\rightarrow$ leptoquark resonances

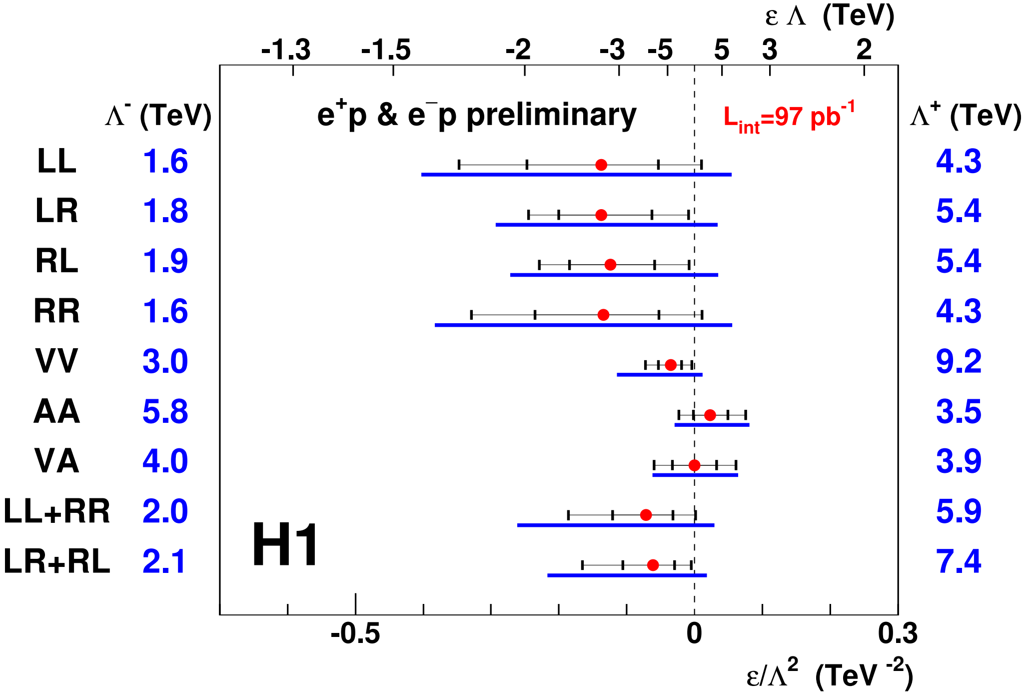
HERA is unique in probing directly electron-quark interactions at high energies

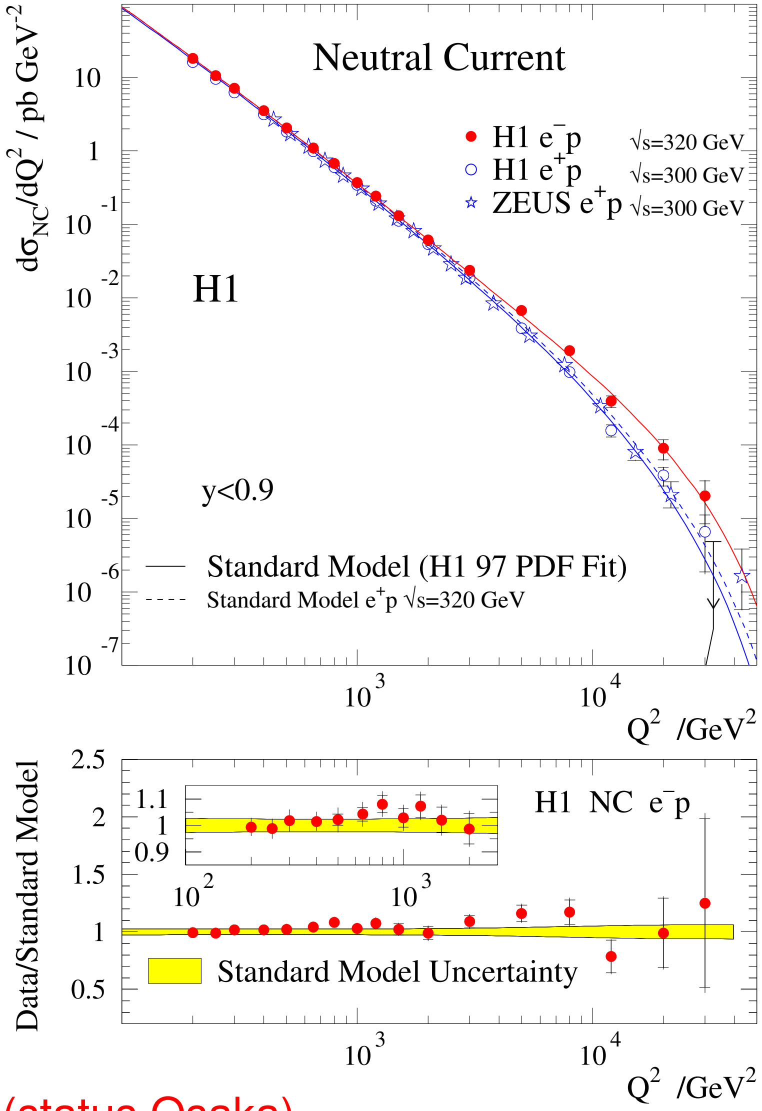
Search for new Physics at high Q^2

Contact Interactions:



- Composite Fermions
- new Heavy Particles
- quantum gravity effects





⇒ Depending on chirality of coupling limits up to 9 TeV (status Osaka)

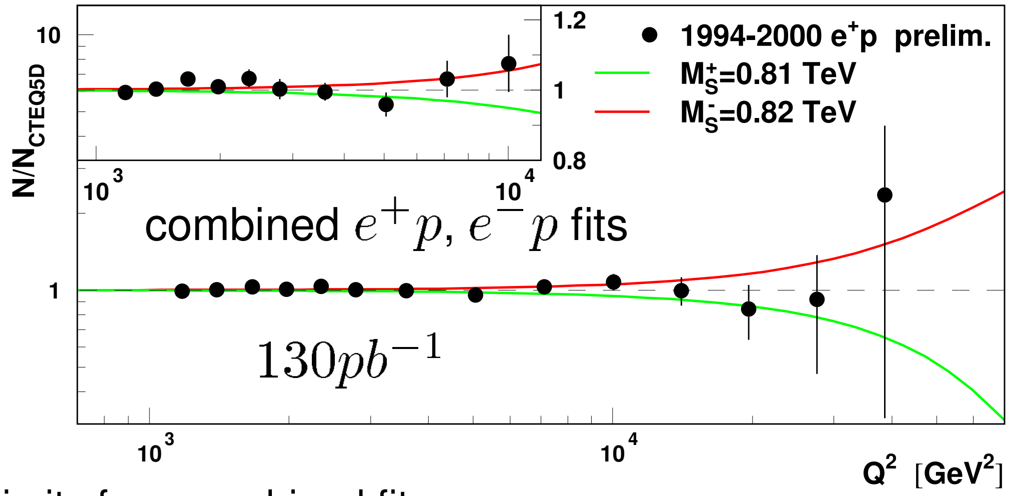
Search for Effects of Large Extra Dimensions

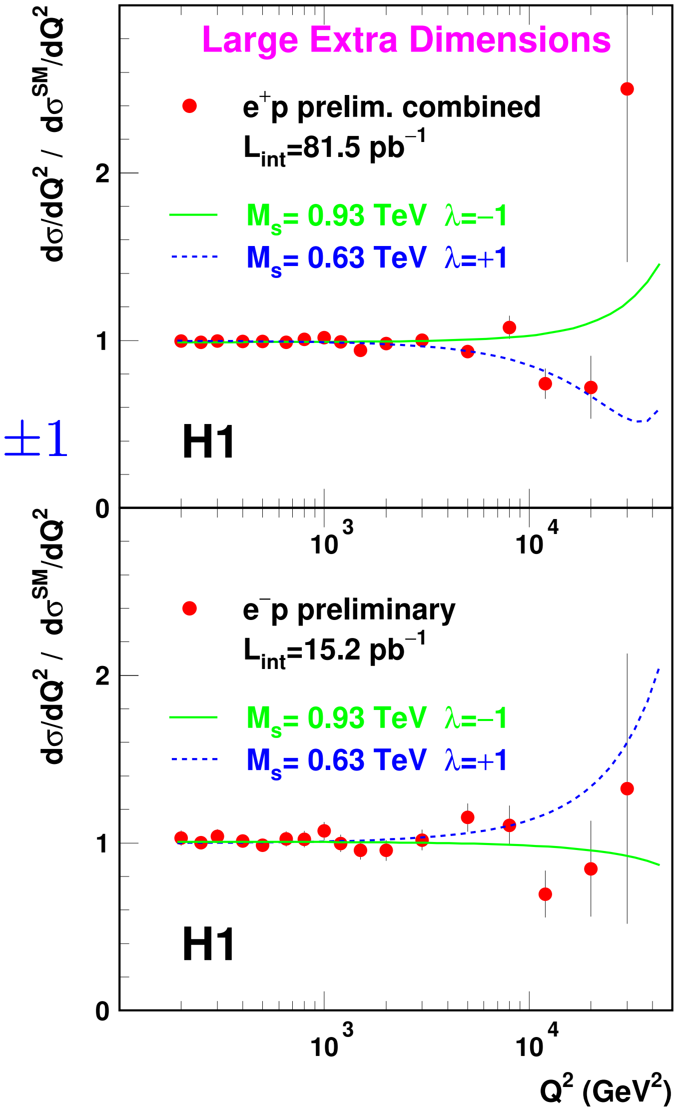
- Large Extra Dimensions:
  - Kaluza-Klein graviton exchange in
    $\mathbf{(4) + n}$ extra dimensions of radius $\mathbf{R}$

$$M_s^{2+n} \sim \frac{M_{Pl}^2}{R^n} \sim \mathcal{O}(\mathrm{TeV})$$

  - Limits depend on interference with SM $\propto \frac{\lambda}{M_s^4}$ with $\lambda = \pm 1$

ZEUS Large Extra Dimensions Limits



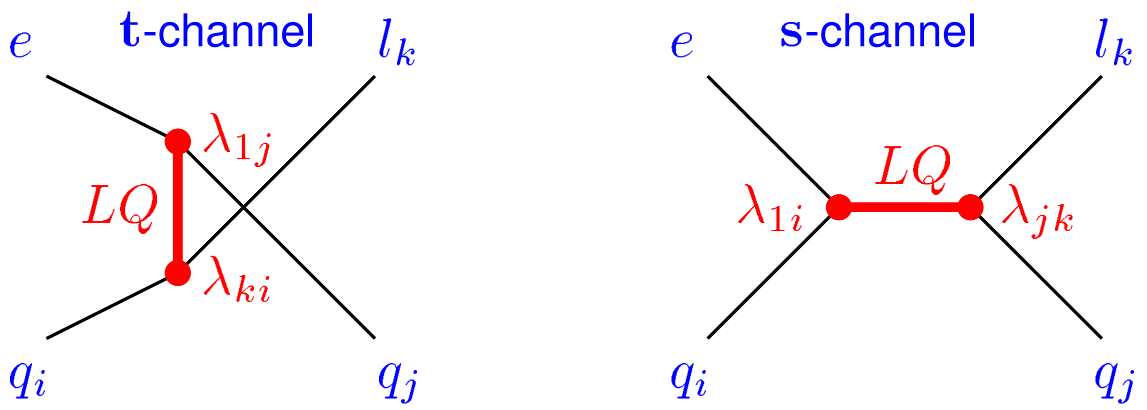


Limits from combined fits:

$\Rightarrow$ **ZEUS:** $M_s^+ > 0.81\ \mathrm{TeV},\ M_s^- > 0.82\ \mathrm{TeV}$ $\Rightarrow$ **H1:** $M_s^+ > 0.63\ \mathrm{TeV},\ M_s^- > 0.93\ \mathrm{TeV}$

Search for Leptoquarks

Leptoquarks considered as extension of SM carry $B, L \neq 0$ and couple to leptons and quarks:



i, j, k flavour indices

$\Rightarrow$ flavour changing NC/CC

$\rightarrow$ characterised by resonance peak $\Rightarrow$ direct search

- Buchmüller-Rückl-Wyler (BRW) model:

  Scalar and Vector Leptoquarks with fermion number $F = 0, 2$ couple to chiral SM fermions

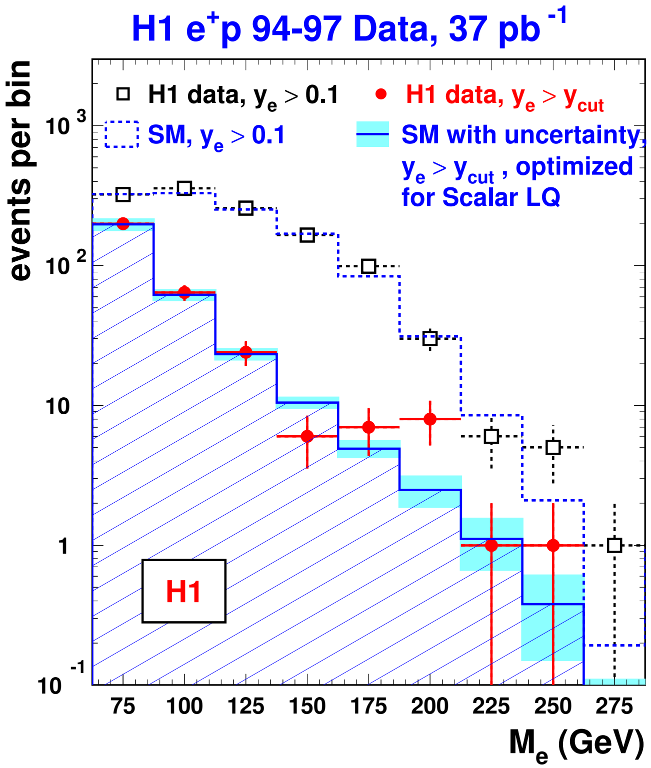
  decays: fixed branching $100, 50, 0\%$ into eq and/or νq

- Production at HERA via Yukawa coupling ($\propto \lambda^2$)

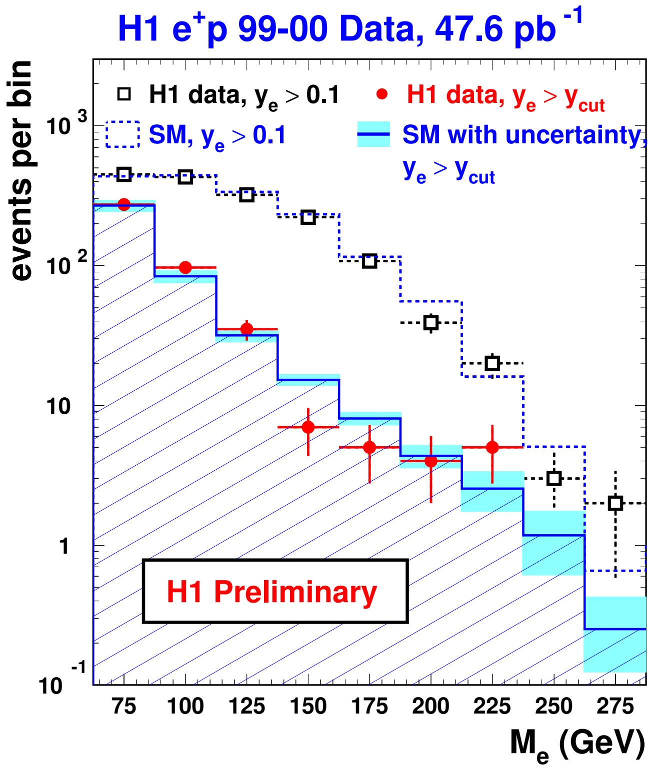
  distinct decays: $\propto y$ (Scalar) and $\propto (1-y)^2$ (Vector) $\neq 1/y^2$ (NC DIS)

Resonance Search: old and new data

- H1



$\Longrightarrow$

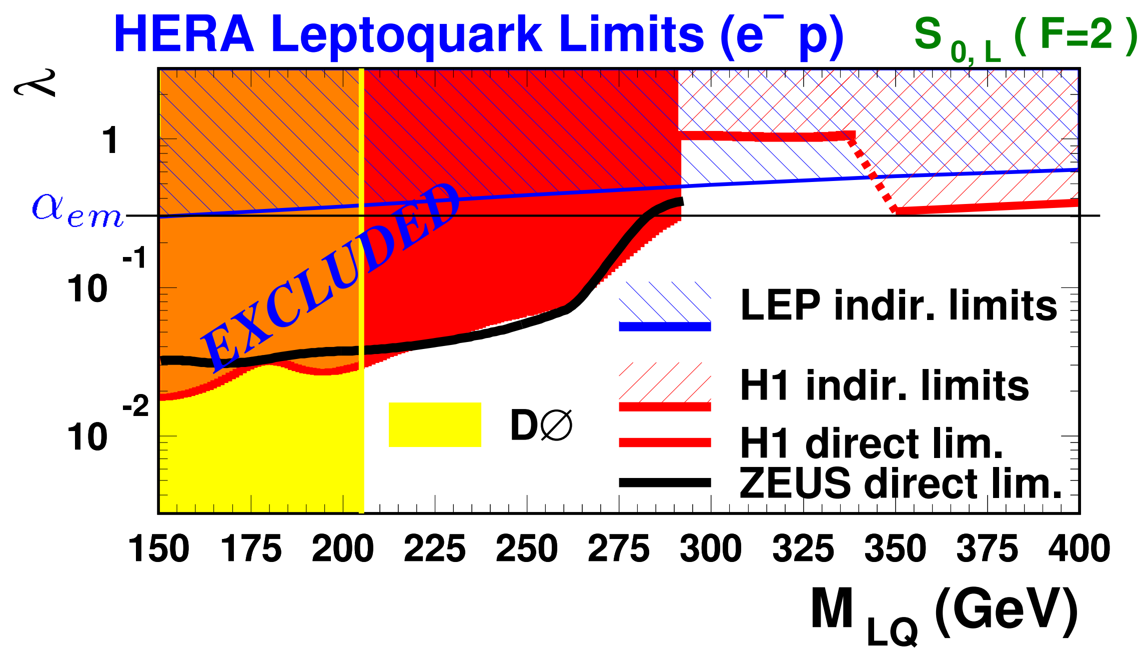


- ZEUS: $x > 0.55$ ($M > 220$ GeV) and $y > 0.25$

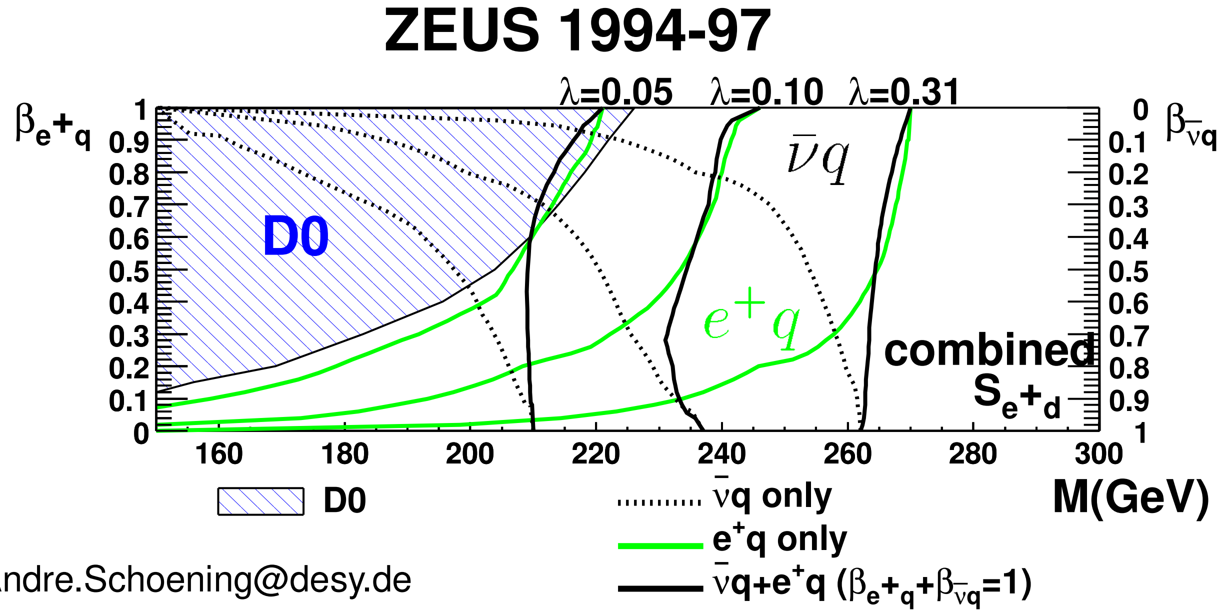
94-97		99-00
4 events	$\Longrightarrow$	0 events
1.9 expected from SM		1.6 expected from SM
(48 pb^{-1} 94-97)		(39 pb^{-1} 99-00 April)

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

Leptoquark Limits



- BRW model (β fixed):
  - **Tevatron** pair production independent of λ
  - **LEP**: t-channel contribution to $e^+e^- \to \text{hadrons}$



- General case: any BR
  - Combined limit (NC and CC) assuming $\beta(eq) + \beta(\nu q) = 1$ almost independent of β

$$F = 0 \quad e \leftrightarrow \tau$$

q_iq_j	$S^L_{1/2}$	$S^R_{1/2}$	$\tilde{S}^L_{1/2}$	V^L_0	V^R_0	$\tilde{V}^R_0$	V^L_1
1 1	$\tau\to\pi e$ 0.0032 0.030 0.046	$\tau\to\pi e$ 0.0016 0.025 0.037	$\tau\to\pi e$ 0.0032 0.046 0.062	G_F 0.002 0.033 0.049	$\tau\to\pi e$ 0.0016 0.033 0.049	$\tau\to\pi e$ 0.0016 0.024 0.041	G_F 0.002 0.012 0.019
1 2	$\boxed{0.030}$ 0.047	$\tau\to$K e 0.05 $\boxed{0.025}$ 0.038	$\tau\to$K e 0.05 $\boxed{0.046}$ 0.063	$\tau\to$K e 0.03 0.036 0.053	$\tau\to$K e 0.03 0.036 0.053	$\boxed{0.026}$ 0.045	K $\to\pi\nu\bar{\nu}$ $2.5\cdot10^{-6}$ 0.012 0.021
1 3	—	B$\to\tau e$ X 0.08 $\boxed{0.049}$ 0.065	B$\to\tau e$ X 0.08 $\boxed{0.049}$ 0.065	B$\to l\nu$X 0.02 0.044 0.062	B$\to\tau e$ X 0.04 0.044 0.062	—	B$\to l\nu$X 0.02 0.044 0.062
2 1	0.153 $\boxed{0.15}$	$\tau\to$K e 0.05 0.092 0.095	$\tau\to$K e 0.05 0.105 0.12	$\tau\to$K e 0.03 0.049 0.064	$\tau\to$K e 0.03 0.049 0.064	$\boxed{0.061}$ 0.073	K $\to\pi\nu\bar{\nu}$ $2.5\cdot10^{-6}$ 0.026 0.032
2 2	$\tau\to e\gamma$ 0.03 0.187 0.18	$\tau\to e\gamma$ 0.02 0.101 0.10	$\boxed{0.120}$ 0.13	$\boxed{0.061}$ 0.076	$\boxed{0.061}$ 0.076	$\boxed{0.102}$ 0.107	$\boxed{0.041}$ 0.044
2 3	—	B$\to\tau e$ X 0.08 0.153 0.14	B$\to\tau e$ X 0.08 0.153 0.14	B$\to l\nu$X 0.02 0.102 0.112	B$\to\tau e$ X 0.04 0.102 0.112	—	B$\to l\nu$X 0.02 0.102 0.112
3 1	—	B$\to\tau e$ X 0.08 0.162 0.16	B$\to\tau e$ X 0.08 0.162 0.16	V_{ub} 0.002 0.052 0.068	B$\to\tau e$ X 0.04 0.052 0.068	—	V_{ub} 0.002 0.052 0.068
3 2	—	B$\to\tau e$ X 0.08 0.202 0.19	B$\to\tau e$ X 0.08 0.202 0.19	B$\to l\nu$X 0.02 0.073 0.083	B$\to\tau e$ X 0.04 0.073 0.083	—	B$\to l\nu$X 0.02 0.073 0.083
3 3	—	0.275 $\boxed{0.23}$	0.275 $\boxed{0.23}$	$\tau\to e\gamma$ 0.51 0.144 $\boxed{0.14}$	$\tau\to e\gamma$ 0.51 0.144 $\boxed{0.14}$	—	0.144 $\boxed{0.14}$

94-97 data

Lepton Flavour Violation

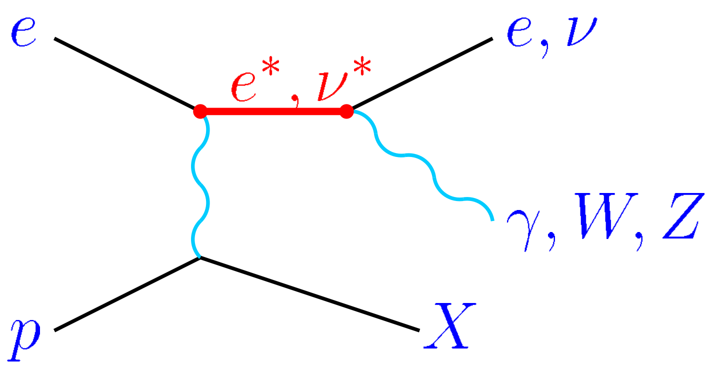
- Flavour Changing Contact I.
  $eq \to \mu q,\ \tau q$
  mediated by Leptoquarks
- No signal found by H1/ZEUS
  in data from 94-97
  $\Rightarrow$ limits derived on $\dfrac{\lambda_{eq_i}\lambda_{\tau q_j}}{M^2_{\mathrm{LQ}}}$

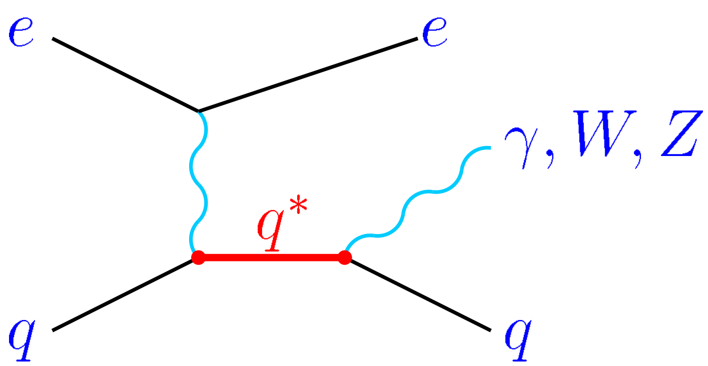
- blue = low energy experiments
- red = ZEUS preliminary
- green = H1

- Competitive or even better
  than low energy experiments
  if heavy quarks involved

Excited Fermions

- Compositeness of fermions would manifest in excited states f^*
- Only single production of e^*, ν^*, q^* considered at HERA





- (De-)excitation described by effective Lagrangian (Hagiwara et al.):

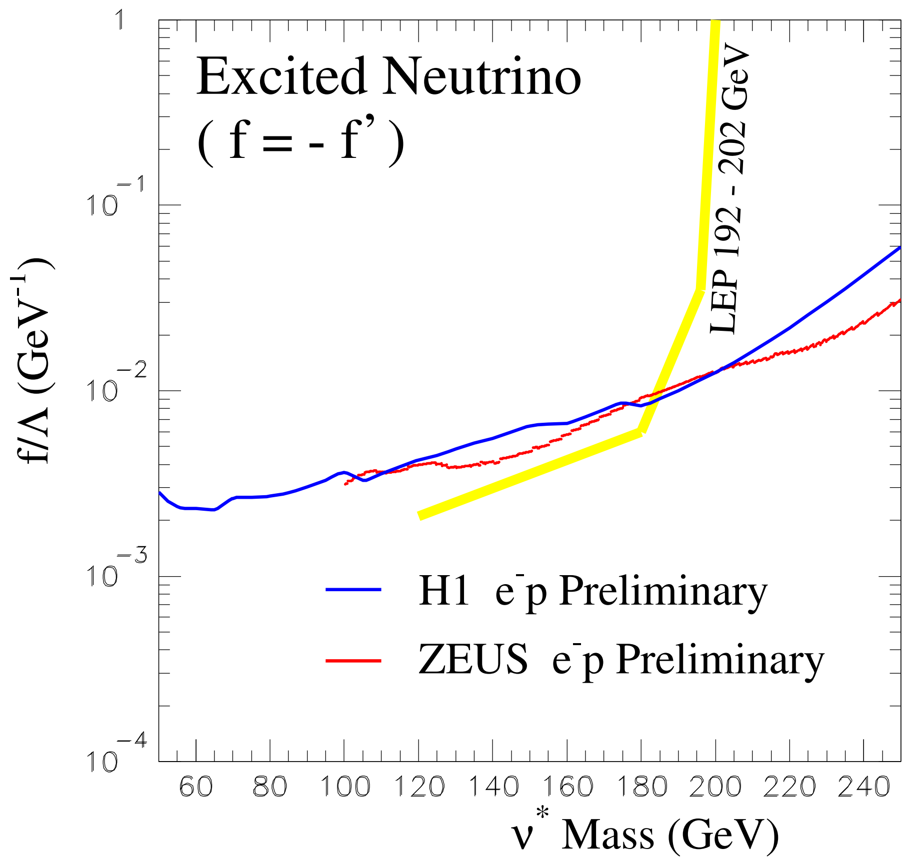
$$\mathcal{L} \;=\; \frac{1}{\Lambda} \cdot F_R^* \left[f\, SU(2)_W + f' U(1)_Y + f_s SU(3)_C \right] F_L$$

Λ: Compositeness scale

f, f', f_s: gauge group weights

Limits on Excited Fermions

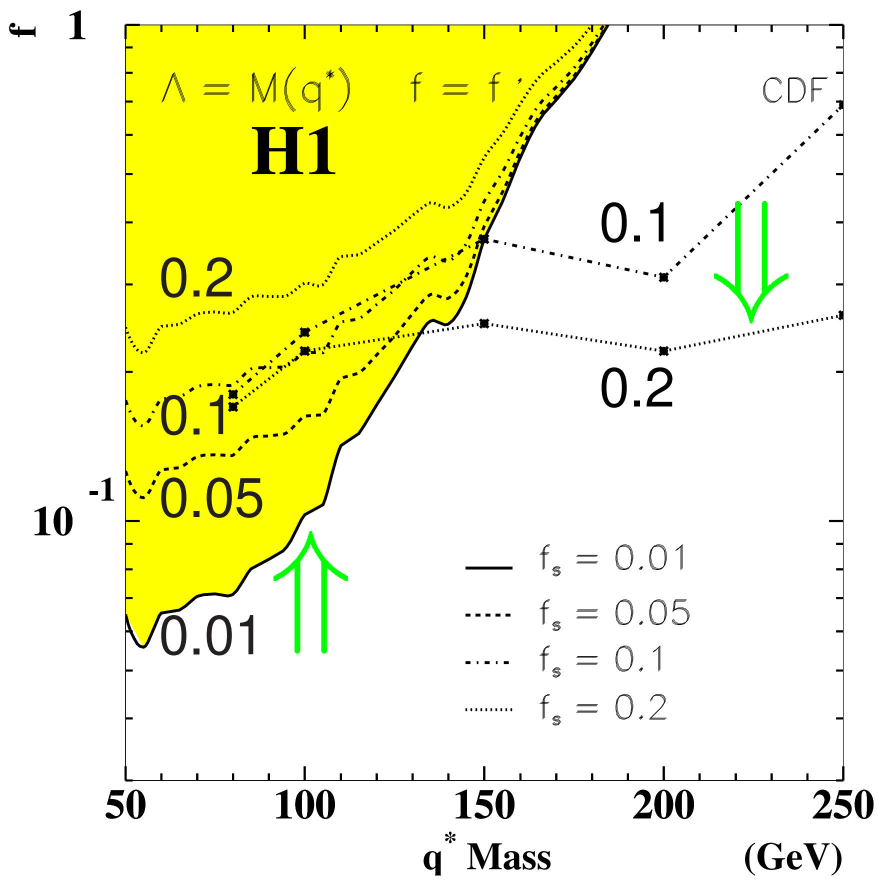
e.g. Excited Neutrinos



HERA extends LEP limits

beyond $M > 200$ GeV

Excited Quarks



Limit on f for $\Lambda = M(q^*)$

$\Rightarrow$ HERA more sensitive for small f_s

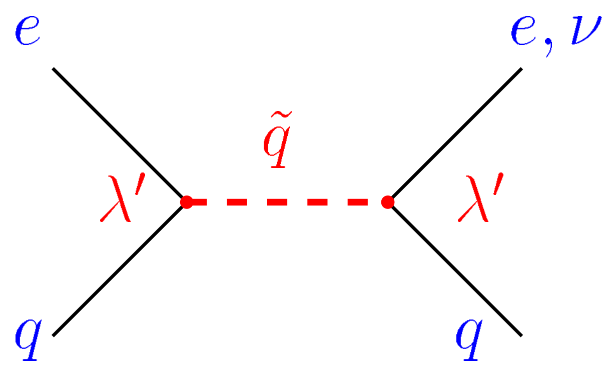
R-Parity Violating Supersymmetry

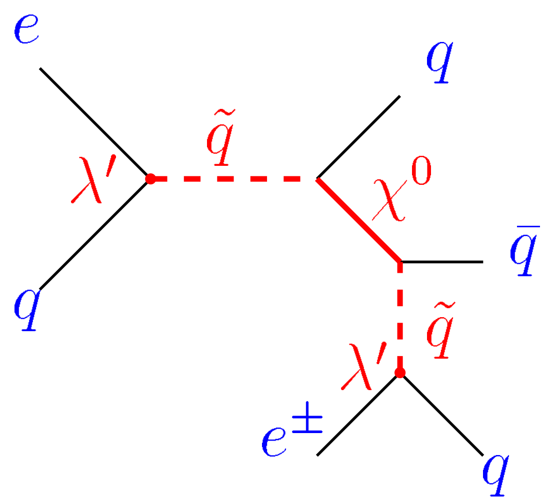
- $R_p = (-1)^{L+3B+2S}$ broken

  $\Rightarrow$ SUSY particles singly produced and LSP not stable

- HERA is an ideal machine for testing $\lambda'_{\rm 1jk}\rm LQ\bar{D}$ Yukawa couplings ($\rightarrow \not{L}$)
  (especially $eq \rightarrow \tilde{t}$)

- look for resonant particle production including more complex (cascade) decays:



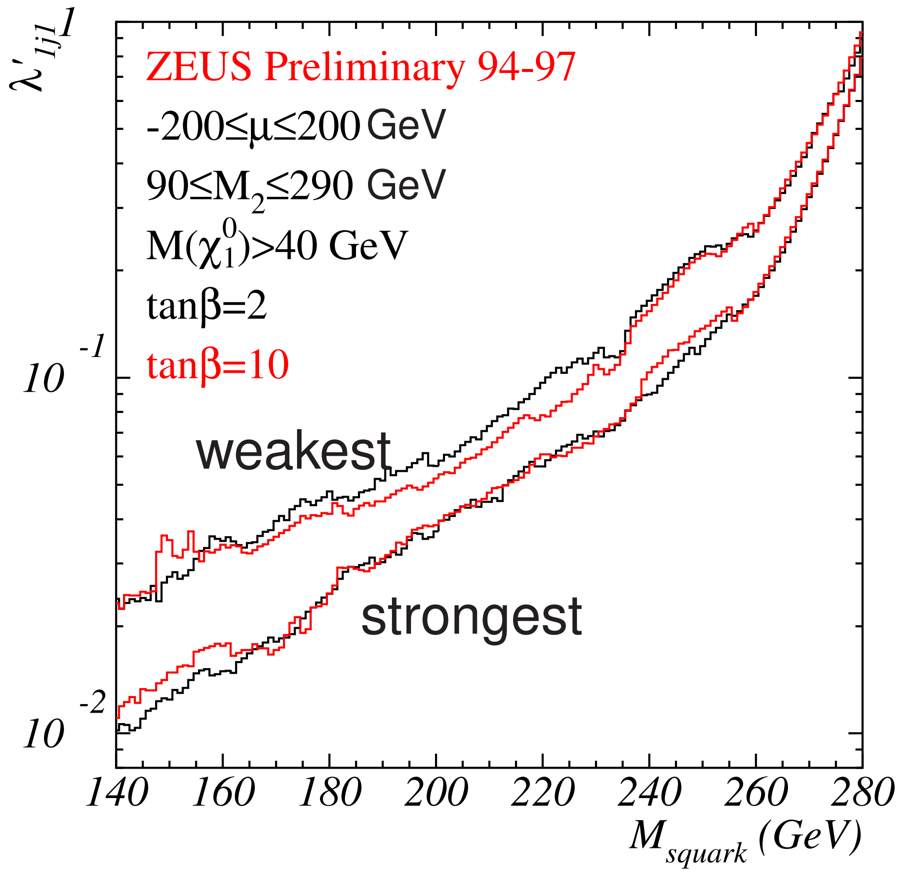


"Wrong" sign lepton

No signal observed
in 94-97 data
$\Rightarrow$ SUSY parameter scan
for exclusion limits

Limits on R_p Violating Supersymmetry

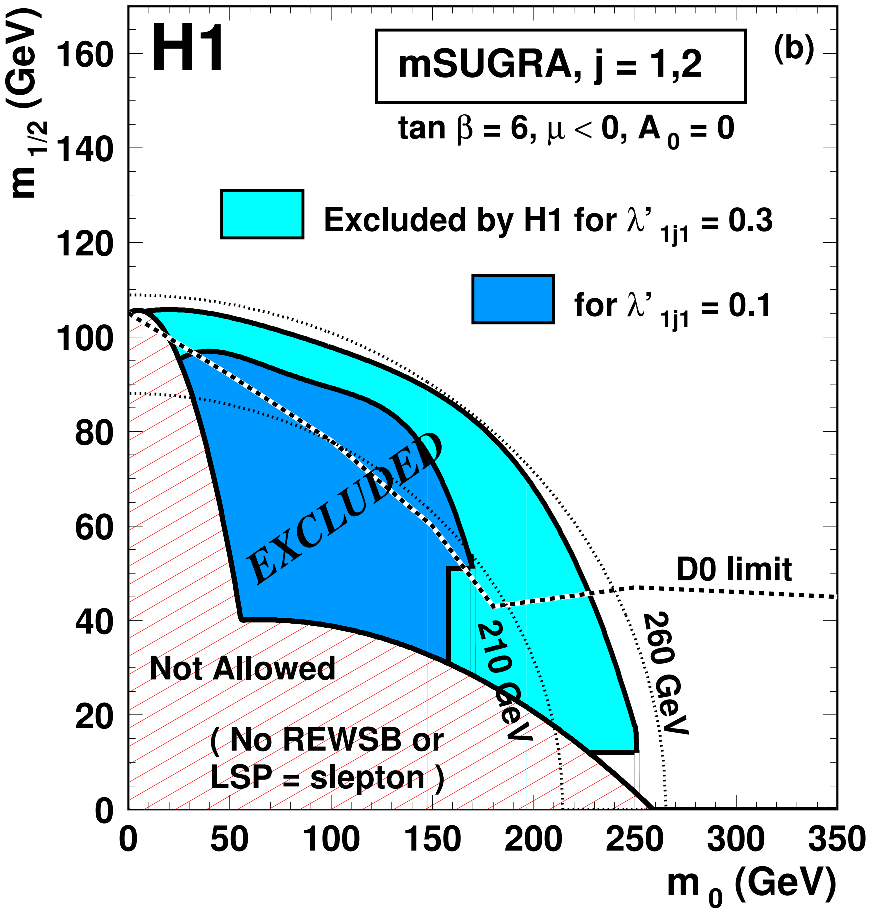
Unconstrained MSSM



M_{squark} free parameter

mSUGRA

hep-ex/0102050
Eur. Phys. J. C , 02/01



HERA improves TEVATRON limits
for Yukawa couplings $\lambda_{1j1} \sim \alpha_{em}$

The "Mystery" of H1's Isolated Leptons

- H1 observed an excess of high p_t isolated lepton events with large missing transverse momentum $\not{p}_t$ (H1 Coll. Eur.Phys.J. C5(1998) 575)

- Main selection cuts:

$p_t^\ell > 10$ GeV, ≥ 1 track

$\not{p}_t > 12$ GeV, $5° < \Theta_\ell < 145°$

$p_t^{\mathrm{calo}} > 12$ GeV, $D_{\mathrm{jet}} > 1$

- Main background:
  - W production
  - misidentified $\gamma\gamma \to \mu\mu$

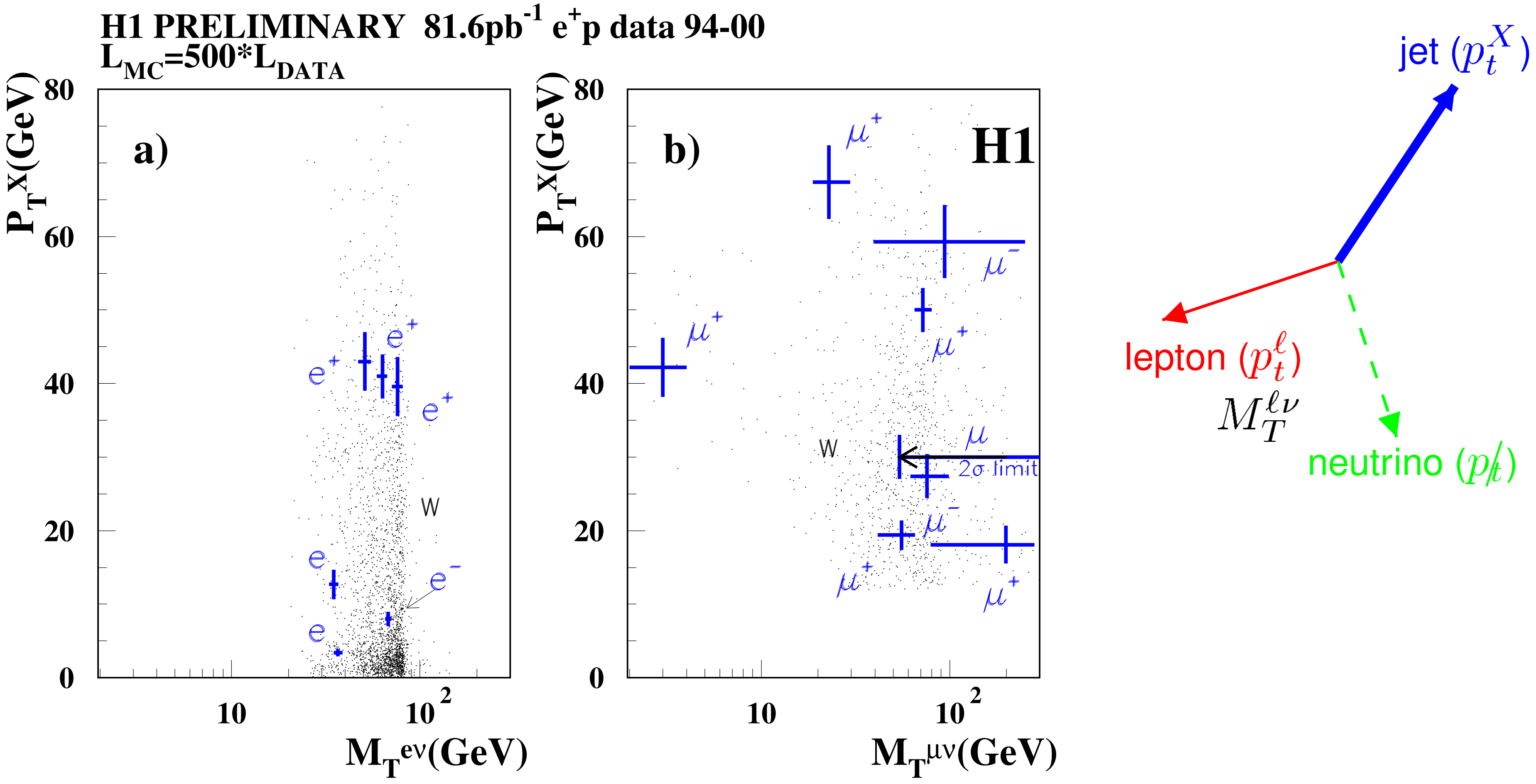
H1 preliminary 1994-2000 $\mathrm{e}^+\mathrm{p}$ (82 pb^{-1})	Electrons Obs./expected (W)	Muons Obs./expected (W)
$p_t^X > 25$ GeV	$3/1.05 \pm 0.27$ (0.83)	$6/1.21 \pm 0.32$ (1.01)
$p_t^X > 40$ GeV	$2/0.33 \pm 0.10$ (0.31)	$4/0.46 \pm 0.13$ (0.43)

p_t^X = hadronic (jet) transverse momentum

- Excess found in both 94-97 e^+p data and 99-00 (Osaka) e^+p data

H1's Isolated Lepton Events

- Distribution of events in the $M_T^{\ell\nu}$ versus p_t^X (jet p_t) plane:



- Isolated leptons at high p_t^X have all positive charge except one event

ZEUS Isolated Lepton Events with 2000 data

- Full $e^{+}p$ data 94-00 analysed (130 pb^{-1})
- Main ZEUS Cuts:

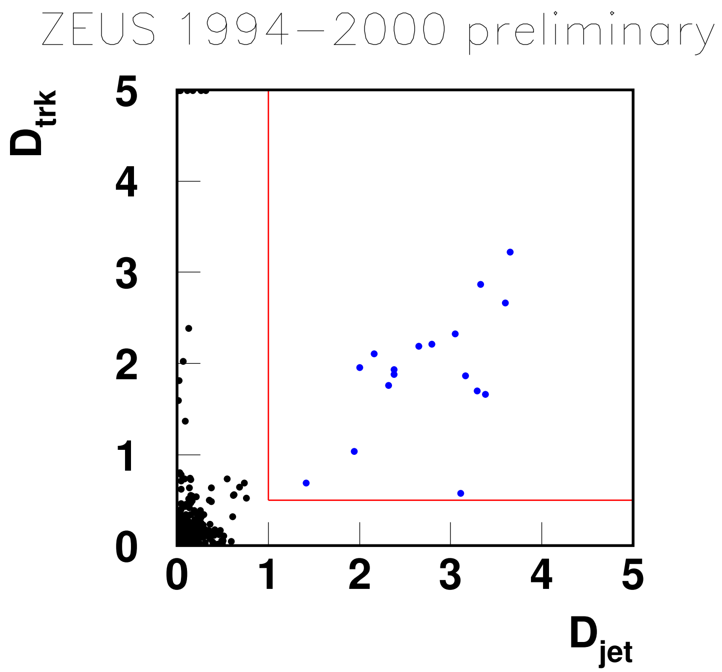
  $p_t^{\ell} > 10$ GeV, $\quad D_{\mathrm{jet}} > 1$

  $p_t^{\mathrm{calo}} > 20$ GeV, $\quad D_{\mathrm{track}} > 0.5$

- $10e$ and 7μ events in 94-00

  ($2e$ and 3μ in 00)

  Note! somewhat looser cuts than H1

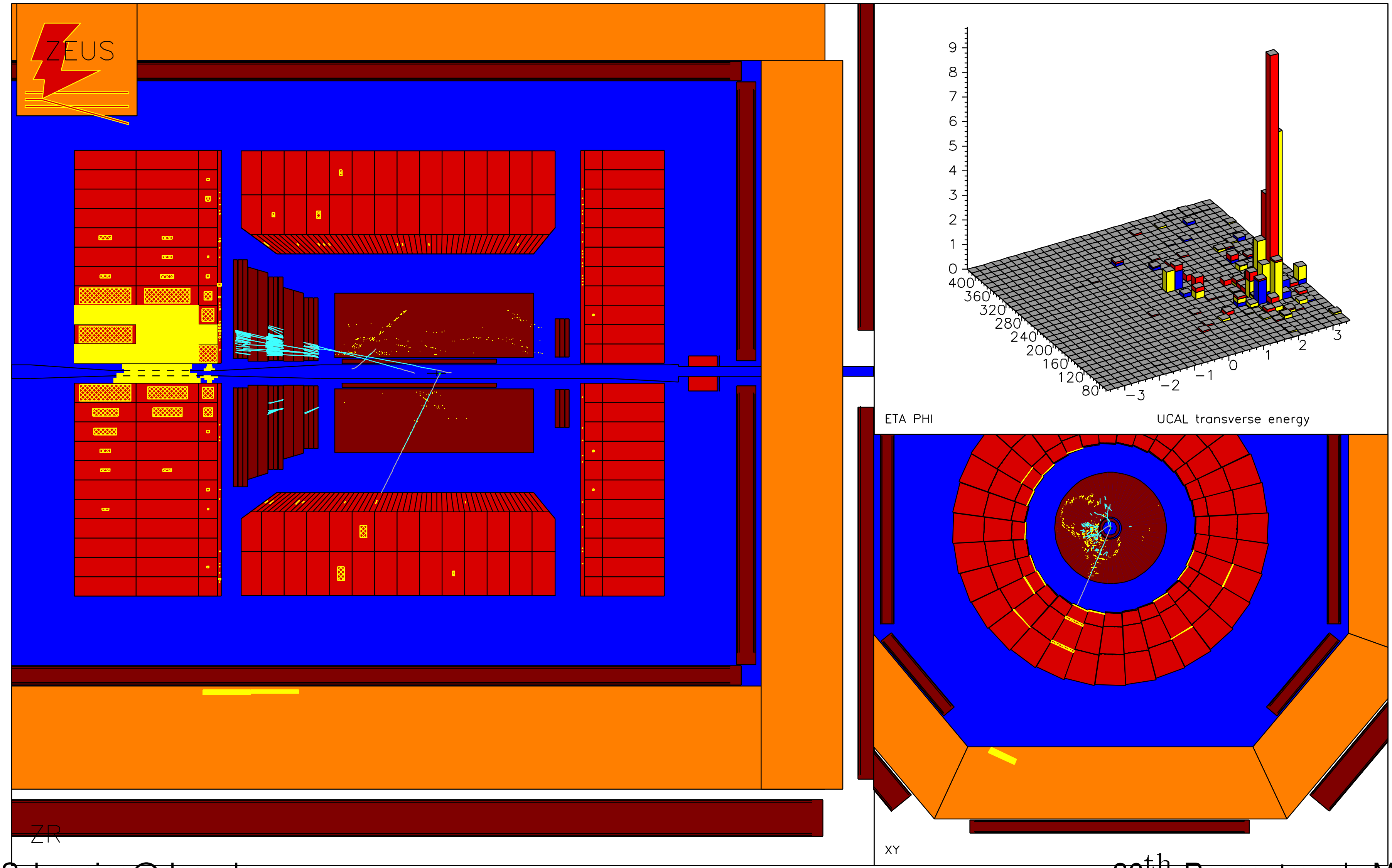


- Event rate consistent with SM prediction

ZEUS preliminary 1994-2000	**Electrons** Obs./expected (W)		**Muons** Obs./expected (W)	
$\mathbf{e^{+}p}$ (114 pb^{-1})	$7/9.9 \pm 1.6$	(2.4)	$7/4.6 \pm 0.6$	(1.1)
$\mathbf{e^{-}p}$ (16 pb^{-1})	$3/1.1 \pm 0.4$	(0.3)	$0/0.8 \pm 0.1$	(0.2)
Total (130 pb^{-1})	$10/11. \pm 1.6$	(2.7)	$7/5.4 \pm 0.7$	(1.3)

Isolated Muon Event at ZEUS

$P_T(\mu^+)$=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



Comparison H1 - ZEUS of Isolated Leptons Events

- After applying further cuts (ZEUS) to suppress non-W SM processes:

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

- H1 analysis (status Osaka):

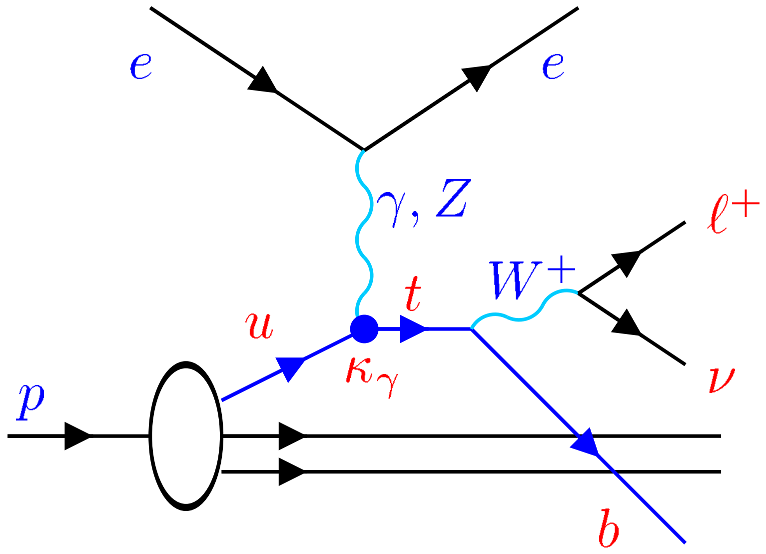
H1 preliminary 1994-2000 $\mathrm{e}^{+}\mathrm{p}$ (82 pb^{-1})	**Electrons** Obs./expected (W)	**Muons** Obs./expected (W)
$p_t^X > 25$ GeV	$3/1.05 \pm 0.27 \quad (0.83)$	$6/1.21 \pm 0.32 \quad (1.01)$
$p_t^X > 40$ GeV	$2/0.33 \pm 0.10 \quad (0.31)$	$4/0.46 \pm 0.13 \quad (0.43)$

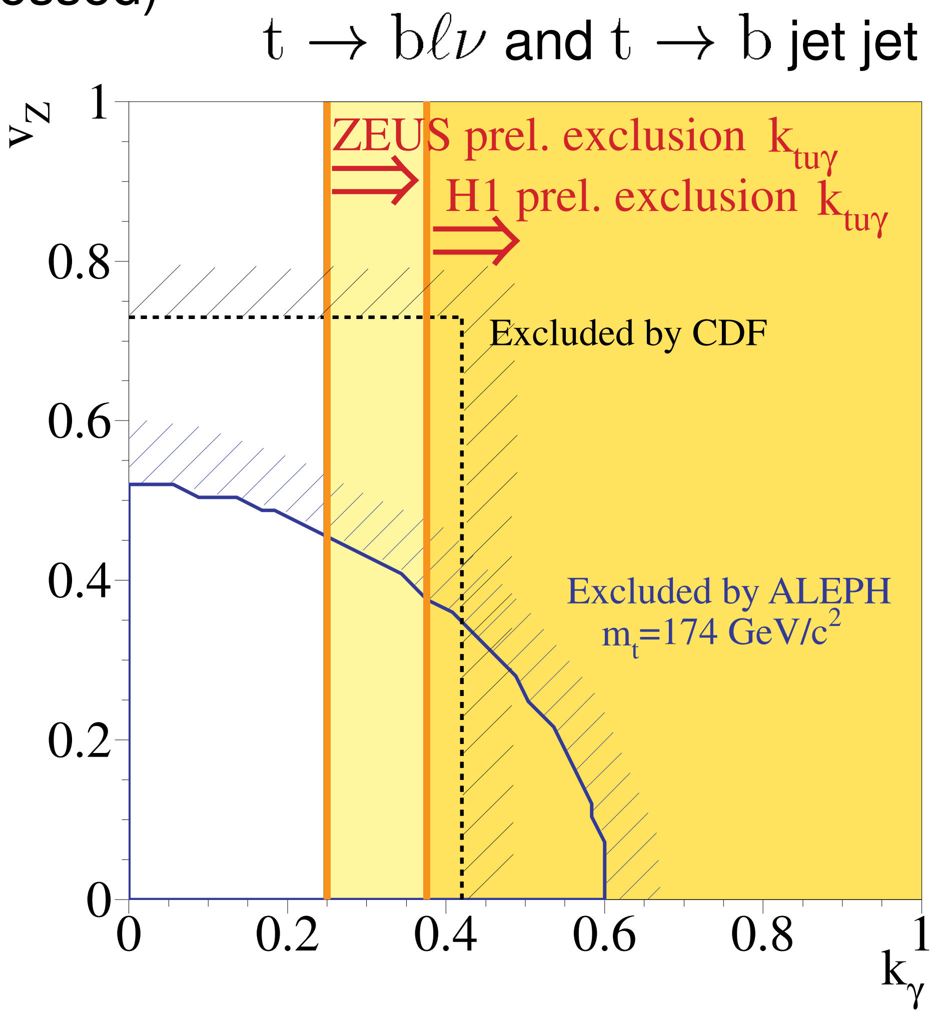
$\Rightarrow$ Background consistent but with increasing integrated luminosity observed event yields were becoming more and more inconsistent in the last years

Anomalous production of top quarks

- Process: $\mathrm{e\ u} \to \mathrm{t\ e}$ with $\mathrm{t} \to \mathrm{b}\ \ell^+\nu$

  ($e\ \bar{u} \to \bar{t}\ e$ with $t \to b\ \ell^-\bar{\nu}$ suppressed)





- Signature: Lepton + Jet + missing p_t

- SM top quark production ≈ 0

  $\Rightarrow$ HERA very sensitive

Conclusion

- **HERA I** era over, most recent data analysed now $\Rightarrow$ more to come in summer
- **HERA** is unique for testing directly electron-quark interactions
- No significant deviation from SM expectation found
- Limits on *New Physics* processes have been derived for:

  $\rightarrow$ Contact Interactions

  $\rightarrow$ Large Extra Dimensions

  $\rightarrow$ Leptoquarks

  $\rightarrow$ Lepton Flavour Violation

  $\rightarrow$ R_p Violating SUSY

  $\rightarrow$ Excited Fermions

  $\Rightarrow$ HERA has a large discovery reach

- Search for Isolated Lepton Events still puzzling and very exciting!

Outlook

- HERA start-up September
- Five times higher luminosity!
  after comissioning
- Polarized $e^{\pm}$ beams!

- more exciting HERA results
  to come...

HERA Upgrade (live picture from H1)