Lepton flavor violation and FCNC at HERA

SUSY01

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On behalf of the H1 and ZEUS collaborations

Overview

- **At the ep collider HERA @ DESY signs of physics beyond the Standard Model (SM) can be searched for in events with high Pt leptons and missing calorimeter energy ($\not{P}t$) :**

  - Search for Lepton Flavor Violation (LFV) in μ and τ channels

  - Search for high Pt leptons (e, μ) as possible signal of Flavor Changing Neutral Current (FCNC) single top production

→ **Such process would be clear signal of physics beyond SM**

HERA ep collider

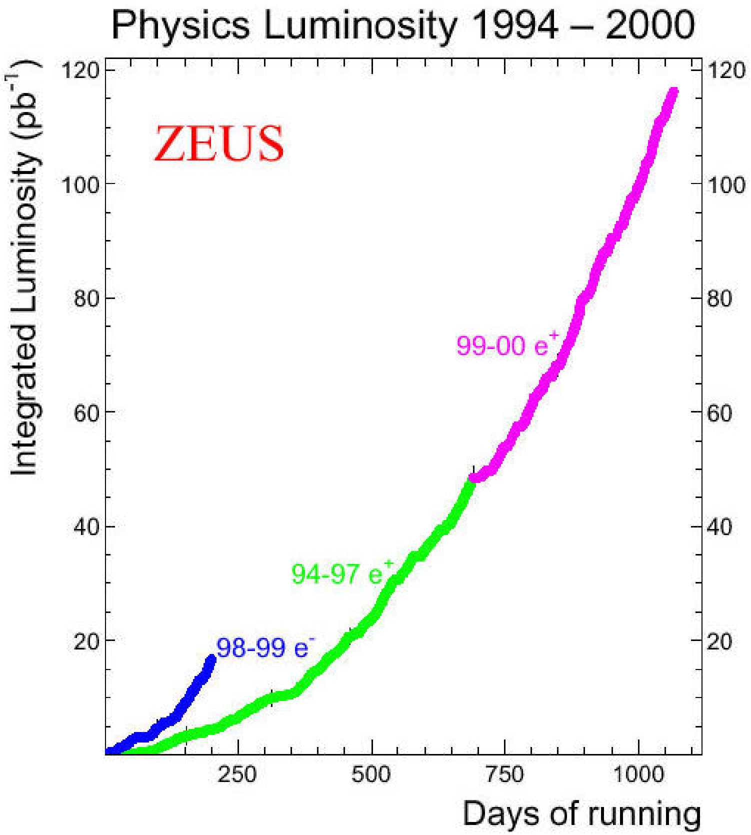
e → 27.5 GeV

p ← 920 GeV
820 GeV up to 1997

$\sqrt{s} \approx 320$ GeV
$\sqrt{s} \approx 300$ GeV

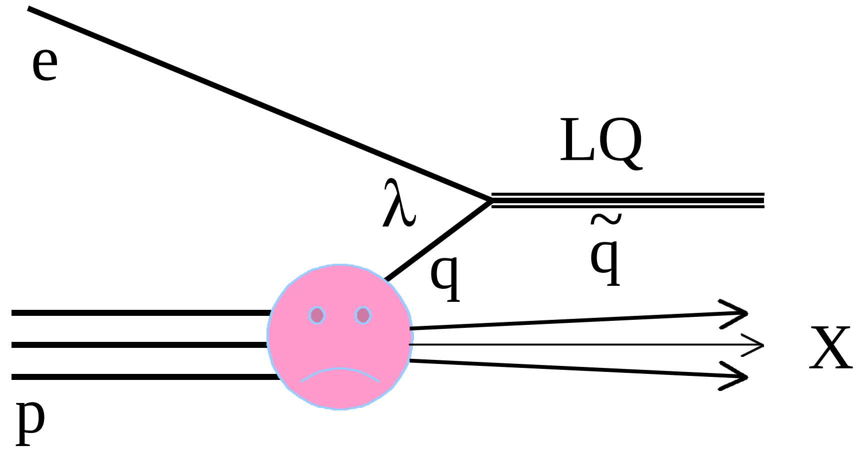
HERA performance strongly increased with time

Year	$\sqrt{s}$	beam	L(pb^{-1})
94-97	300	$e^+ p$	≈ 48
98-99	320	$e^- p$	≈ 17
99-00	320	$e^+ p$	≈ 70



Leptoquark phenomenology

- Since the initial state contains both lepton and baryon numbers, HERA is the ideal environment to study new particles which couple, with a Yukawa coupling λ, to eq .



Such state forseen by GUT theories (LQ) or by R̸p SUSY models (squarks)

Büchmuller-Rückl-Weyler (BRW) model:

- Most general LQ interactions which respect SM symmetry

14 LQ types **See next**

LQ classification

- 7 scalar + 7 vector states
- both lepton and baryon number

$F = L + 3B = 0,2$

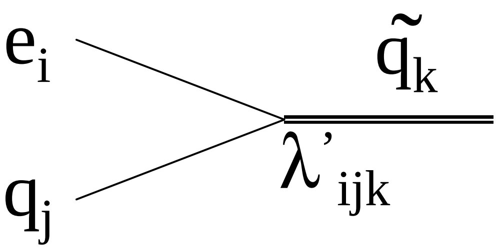
$e^+ q \rightarrow$ LQ (F=0)

$e^- q \rightarrow$ LQ (F=2)

- **$\not{R}p$ SUSY models**

$Rp \equiv (-1)^{F+2S}$ $\not{R}p$ $\rightarrow$ sparticles singly produced and LSP not stable

$L_i Q_j \bar{D}_k$ coupling of interest at HERA



$\tilde{d}$ → S_0^L

$\tilde{u}$ → $\tilde{S}_{1/2}^L$

Aachen	F	J	I	I_3	Y	Q	q	c	B
S_0^L	2	0	0	0	1/3	−1/3	u	1	1/4
S_0^R	2	0	0	0	1/3	−1/3	u	1	1/2
$\tilde{S}_0^R$	2	0	0	0	4/3	−4/3	d	1	1/2
S_1^L	2	0	1	1	1/3	+2/3	−	2	0
				0		−1/3	u	1	1/4
				−1		−4/3	d	2	1/2
$V_{1/2}^L$	2	1	1/2	1/2	5/6	−1/3	−	1	0
				−1/2		−4/3	d	1	1/2
$V_{1/2}^R$	2	1	1/2	1/2	5/6	−1/3	u	1	1/2
				−1/2		−4/3	d	1	1/2
$\tilde{V}_{1/2}^L$	2	1	1/2	1/2	−1/6	+2/3	−	1	0
				−1/2		−1/3	u	1	1/2
V_0^L	0	1	0	0	2/3	−2/3	$\bar{d}$	1	1/4
V_0^R	0	1	0	0	2/3	−2/3	$\bar{d}$	1	1/2
$\tilde{V}_0^R$	0	1	0	0	5/3	−5/3	$\bar{u}$	1	1/2
V_1^L	0	1	1	1	2/3	+1/3	−	2	0
				0		−2/3	$\bar{d}$	1	1/4
				−1		−5/3	$\bar{u}$	2	1/2
$S_{1/2}^L$	0	0	1/2	1/2	7/6	−2/3	−	1	0
				−1/2		−5/3	$\bar{u}$	1	1/2
$S_{1/2}^R$	0	0	1/2	1/2	7/6	−2/3	$\bar{d}$	1	1/2
				−1/2		−5/3	$\bar{u}$	1	1/2
$\tilde{S}_{1/2}^L$	0	0	1/2	1/2	1/6	+1/3	−	1	0
				−1/2		−2/3	$\bar{d}$	1	1/2

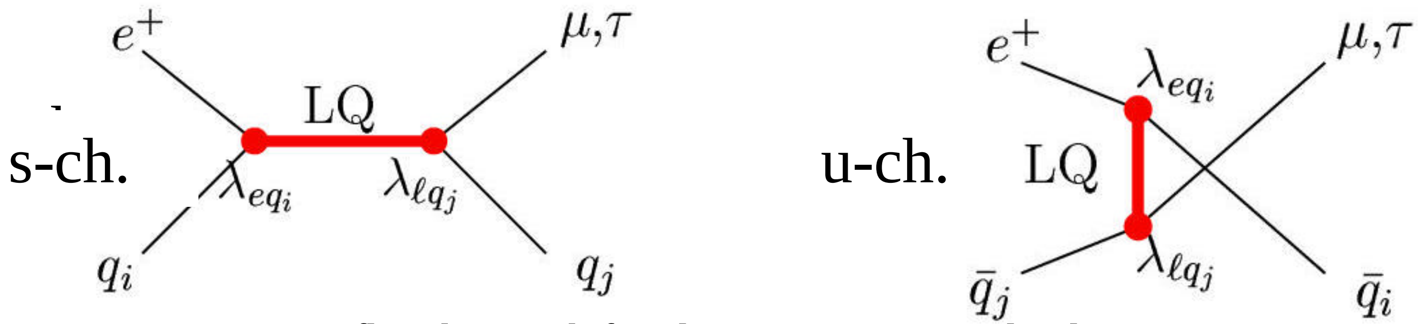
Lepton flavor violation

Motivation

- **There is no fundamental reason why lepton flavor should be conserved. Several SM extensions (GUT, technicolor, compositeness, SUSY), indeed, exploit the LFV possibility.**
- **Signal of LFV in charged lepton sector would be a clear signal of physics beyond the SM.**

Process

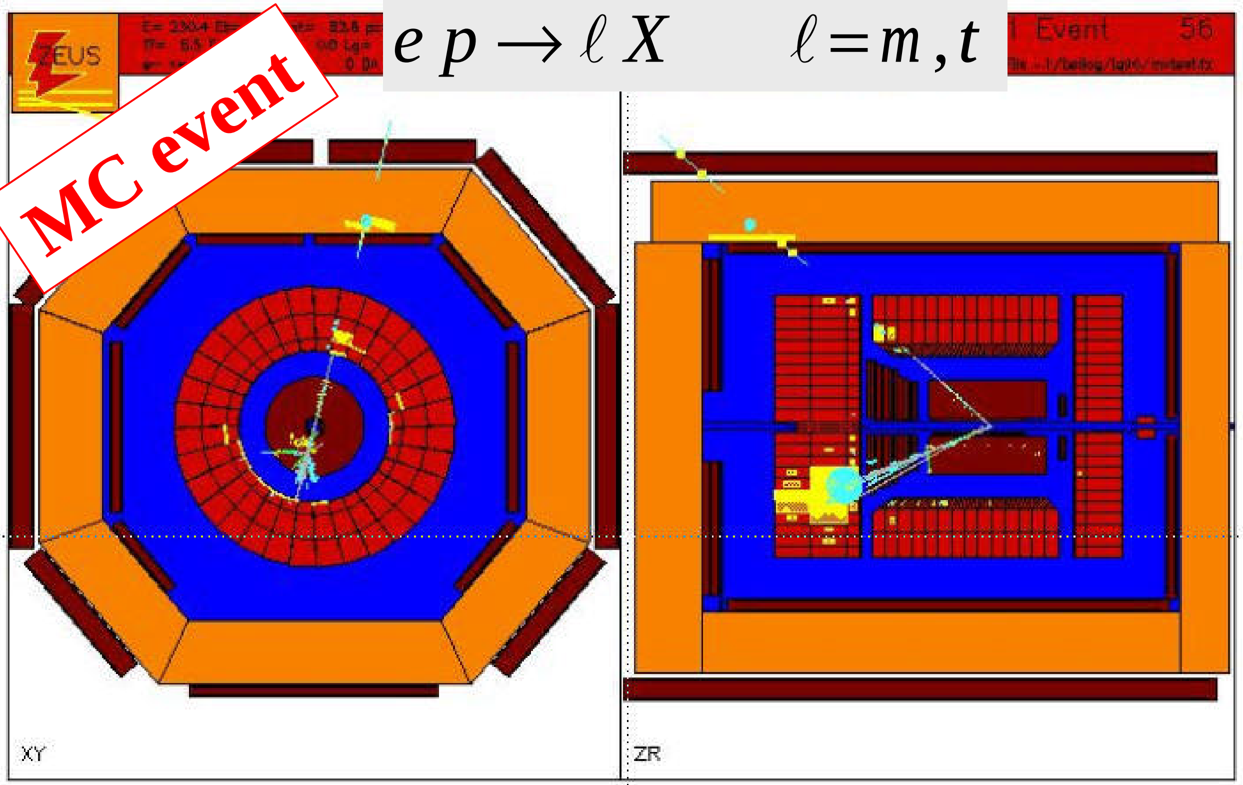
- **The process involve both s- and u-channels**
- **Two different couplings are involved at the eq and lq interaction vertices**



i,j flag the quark family generations involved

Event signature

$e\,p \rightarrow \ell\, X \qquad \ell = m, t$



Similar to a standard NC DIS with a μ or a τ replacing the scattered electron:

- **High Pt isolated μ or τ balanced by a jet in the transverse plane**
- **High missing calorimeter Pt ($\not{P}t$)**

Striking signature essentially background free

Event selection

94-97 e^+p data L = 37./47.7 pb-1 (H1/ZEUS)

ZEUS event selection (main cuts):

- Charged Current DIS like selection:
  - μ channel - $\not{P}t > 20$ GeV
  - τ channel - $\not{P}t > 12$ ($\tau \rightarrow$ had.), 15 ($\tau \rightarrow$ e), 20 ($\tau \rightarrow \mu$) GeV

- An identified μ or τ aligned in azimuth with $\not{P}t$
- for the τ channel at least one jet with Pt > 15 GeV

H1 made similar selection
(for the τ channel only $\tau \rightarrow$ had. was considered)

Both H1 and ZEUS found no candidates

→ **Limits on LQ ($\tilde{q}$) couplings and masses**

Limits

<u>Limits evaluated for</u> :

$M_{LQ} < \sqrt{s}$ (low mass) → F=0 using Narrow Width Appr. (NWA)

In this case s-channel dominates and F=0 LQs, coupling to a quark for an e^+ beam, have a much larger cross section and hence stronger constraints than F=2 LQs.

Efficiency selection: 40-60% for μ, 20-30% for τ (depending of LQ masses and types).

$M_{LQ} >> \sqrt{s}$ (high mass) → F=0, F=2 using Contact Interaction Appr.

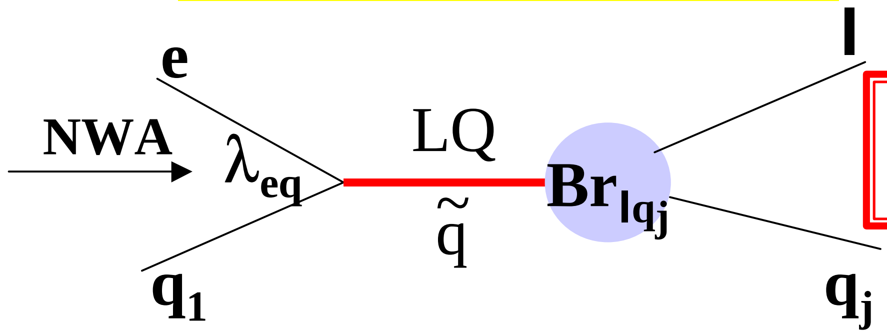
In this case both s- and u-channel contribute.

Limits evaluated for every combination of quark generation (i, j) i,j=1,2,3

Efficiency selection: 15-45% for μ, 5-20% for τ (mainly depending of the quark generation involved)

Low mass limits (1)

$M_{LQ} < \sqrt{s}$



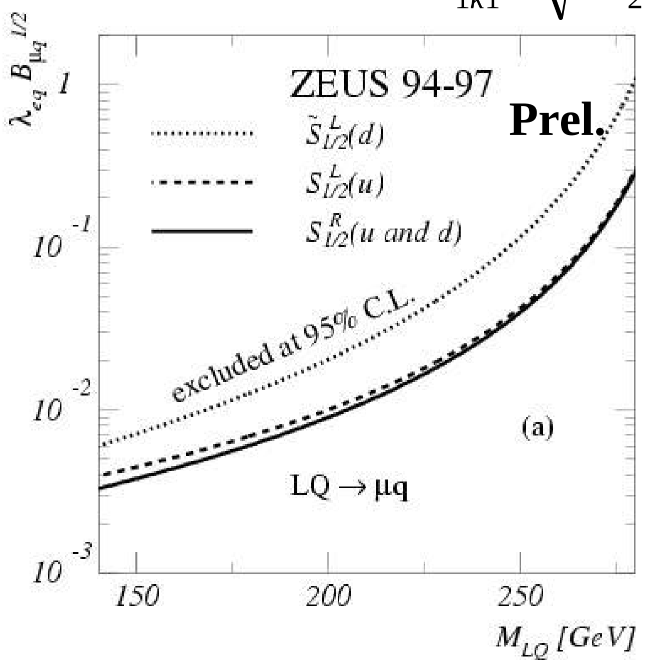
$\sigma_{NWA} \propto \lambda^2_{eq_1} \, Br_{\ell q_j}$

$LQ \rightarrow \lambda_{eq_1} \times \sqrt{Br_{\mu q_j}}$

$\tilde{u} \rightarrow \lambda'_{1k1} \times \sqrt{Br_{2kj}}$

$LQ \rightarrow \lambda_{eq_1}$

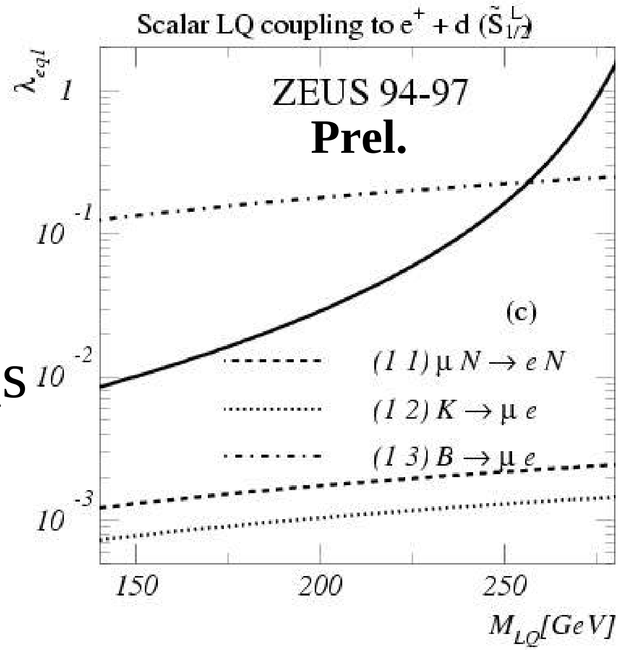
assuming $\lambda_{eq_1} = \lambda_{lq_j}$



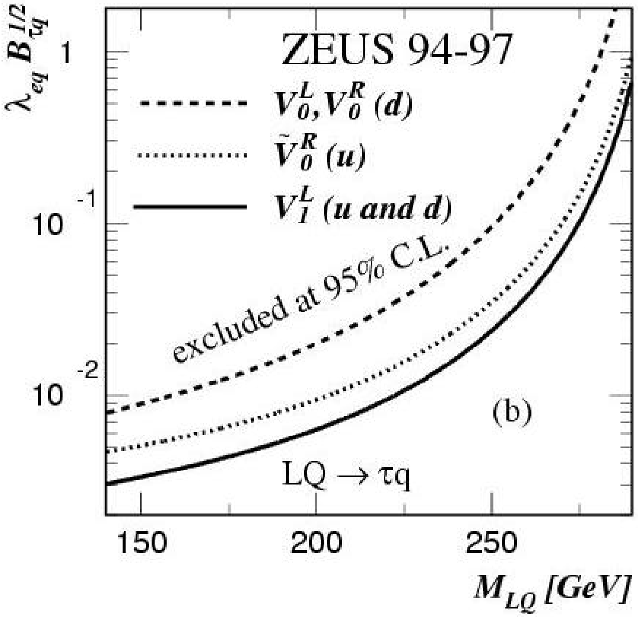
$e \rightarrow \mu$

95% CL limits

Scalar F = 0 LQs



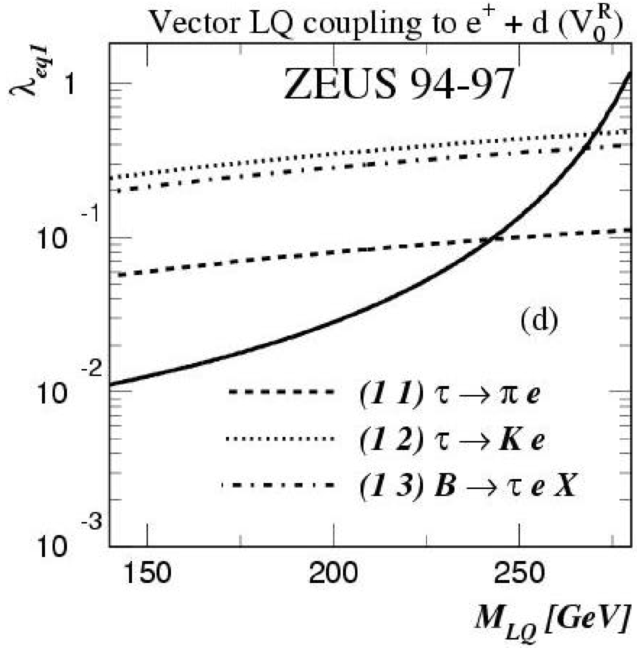
Low mass limits (2)



$e \to t$

95% CL limits

Vector F = 0 LQs



95 % CL upper limit on LQ mass assuming $\lambda_{eq1} = \lambda_{lqj} = 0.3$

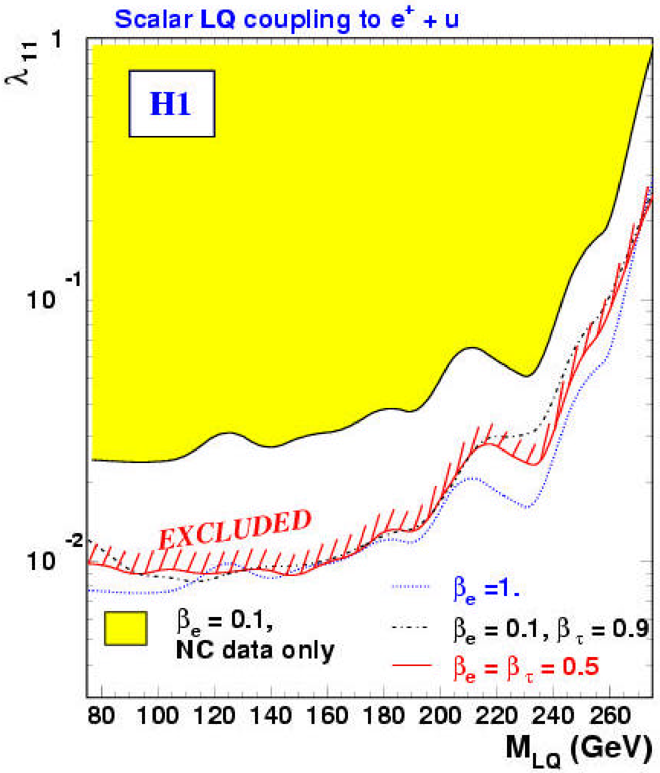
$e \to m$

LQ type	$\tilde{S}_{1/2}^L$	$S_{1/2}^L$	$S_{1/2}^R$	V_0^L	V_0^R	$\tilde{V}_0^R$	V_1^L
Mass limit [GeV]	262	277	278	264	269	282	285

$e \to t$

LQ type	$\tilde{S}_{1/2}^L$	$S_{1/2}^L$	$S_{1/2}^R$	V_0^L	V_0^R	$\tilde{V}_0^R$	V_1^L
Mass limit [GeV]	259	276	277	260	265	279	283

Combining e and τ channel



95% CL mass dependent limits on λ_{11} when fixing β_e and β_τ.

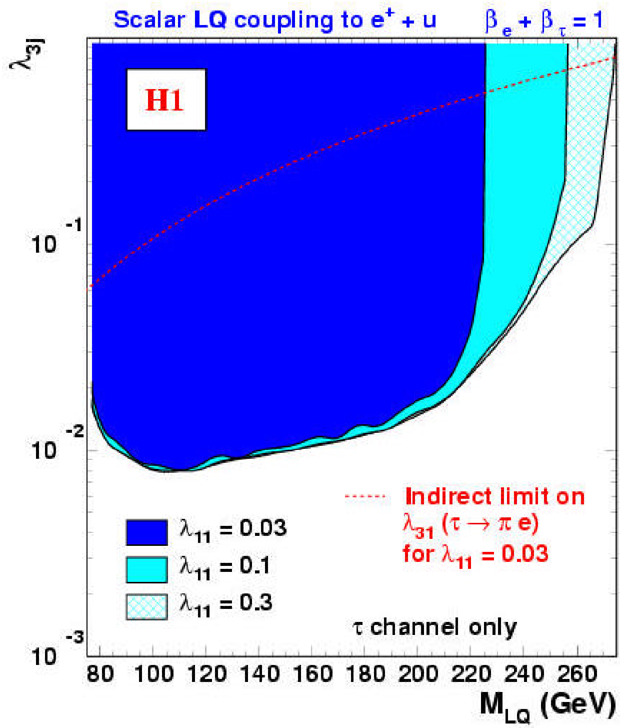
For λ_{11} = 0.3 and $\beta_e + \beta_\tau \sim 1$:

M_{LQ} < 275 GeV excluded

95% CL mass dependent limits on λ_{3j} for different fixed values of λ_{11}.

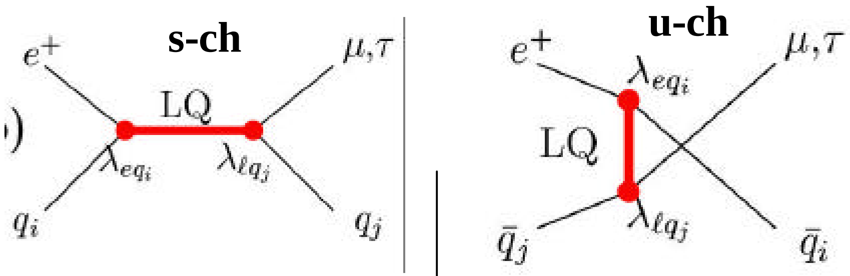
For $\lambda_{11} = \lambda_{3j}$ = 0.3:

M_{LQ} < 270 GeV excluded

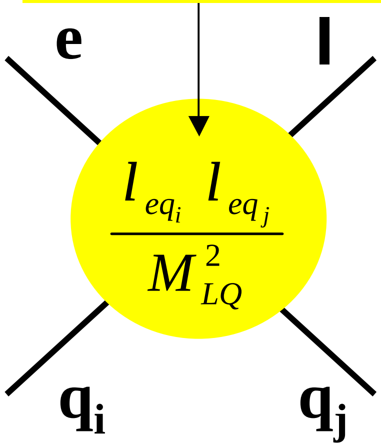


(H1, EPJC 11(1999) 447)

High mass limits



$$M_{LQ} >> \sqrt{s}$$



ZEUS 1994-1997 Preliminary

$e \rightarrow \tau$ F=0

(also H1, EPJC 11(1999) 447)

$e \leftrightarrow \tau$				$F=0$			
q_iq_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	$\tau\rightarrow\pi e$ 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 $\boxed{\mathbf{0.030}}$	$\tau\rightarrow$K e 0.05 $\boxed{\mathbf{0.025}}$	$\tau\rightarrow$K e 0.05 $\boxed{\mathbf{0.046}}$	$\tau\rightarrow$K e 0.03 $\boxed{\mathbf{0.036}}$	$\tau\rightarrow$K e 0.03 $\boxed{\mathbf{0.036}}$	*H1:* 0.045 $\boxed{\mathbf{0.026}}$	K $\rightarrow\pi\nu\bar{\nu}$ $2.5\cdot10^{-6}$ **0.012**
1 3	*	B$\rightarrow\tau$e X 0.08 $\boxed{\mathbf{0.049}}$	B$\rightarrow\tau$e X 0.08 $\boxed{\mathbf{0.049}}$	B$\rightarrow l\nu$X 0.02 **0.044**	B$\rightarrow\tau$e X 0.04 $\boxed{\mathbf{0.044}}$	*	B$\rightarrow l\nu$X 0.02 **0.044**
2 1	*H1:* 0.15 $\boxed{\mathbf{0.15}}$	$\tau\rightarrow$K e 0.05 $\boxed{\mathbf{0.092}}$	$\tau\rightarrow$K e 0.05 **0.11**	$\tau\rightarrow$K e 0.03 $\boxed{\mathbf{0.049}}$	$\tau\rightarrow$K e 0.03 $\boxed{\mathbf{0.049}}$	*H1:* 0.073 $\boxed{\mathbf{0.061}}$	K $\rightarrow\pi\nu\bar{\nu}$ $2.5\cdot10^{-6}$ **0.026**
2 2	$\tau\rightarrow e\gamma$ 0.03 **0.19**	$\tau\rightarrow e\gamma$ 0.02 **0.10**	*H1:* 0.13 $\boxed{\mathbf{0.12}}$	*H1:* 0.076 $\boxed{\mathbf{0.061}}$	*H1:* 0.076 $\boxed{\mathbf{0.061}}$	*H1:* 0.107 $\boxed{\mathbf{0.10}}$	*H1:* 0.044 $\boxed{\mathbf{0.041}}$
2 3	*	B$\rightarrow\tau$e X 0.08 $\boxed{\mathbf{0.15}}$	B$\rightarrow\tau$e X 0.08 $\boxed{\mathbf{0.15}}$	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 $\boxed{\mathbf{0.052}}$	*	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 $\boxed{\mathbf{0.073}}$	*	B$\rightarrow l\nu$X 0.02 **0.073**
3 3	*	*H1:* 0.23 $\boxed{\mathbf{0.28}}$	*H1:* 0.23 $\boxed{\mathbf{0.28}}$	$\tau\rightarrow e\gamma$ 0.51 **0.14**	$\tau\rightarrow e\gamma$ 0.51 **0.14**	*	*H1:* 0.14 $\boxed{\mathbf{0.14}}$

$$95\%\ CL\ \text{Limits on}\ \frac{l_{eq_i}\, l_{\ell q_j}}{M^2_{LQ}}\left[GeV^{-2}\right]$$

LFV future perspectives

HERA limits improves in most cases when heavy quarks are involved constraints from low-energy experiment, especially for the τ channel.

- **A new run is starting after the luminosity upgrade**

L ≈1 fb^{-1} in 5 years → improvement in limits ≈ 4.5 (∝ √L)

R.Kerger DIS2000

- [red] **H1 & ZEUS (~40 pb^{-1}) > indir. limits**
- [orange] **HERA (1 fb^{-1}) > indir. limits**
- [yellow] **HERA (1 fb^{-1}) will compete with Limits from rare B decays**

e → τ F=0

$q_i q_j$	$S^L_{1/2}$	$S^R_{1/2}$	$\tilde{S}^L_{1/2}$	V^R_0	V^L_0	$\tilde{V}^R_0$	V^L_1
1 1							
1 2	[red]	[red]	[red]	[orange]	[orange]	[red]	
1 3	-	[yellow]	[yellow]	[yellow]	[yellow]	-	[yellow]
2 1	[red]	[red]	[red]	[orange]	[orange]	[red]	
2 2		[orange]	[red]	[red]	[red]	[red]	[red]
2 3	-	[yellow]	[yellow]	[yellow]	[yellow]	-	[yellow]
3 1	-	[yellow]	[yellow]	[yellow]	[yellow]	-	[yellow]
3 2	-	[yellow]	[yellow]	[yellow]	[yellow]	-	[yellow]
3 3	-	[red]	[red]	[red]	[red]	-	[red]

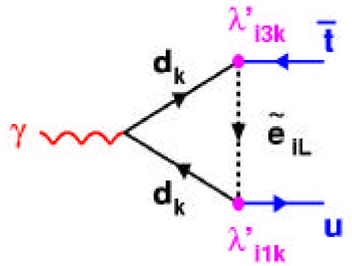
- **The detector upgrade can offer new tools for the analysis when heavy quarks are involved. Both H1 and ZEUS have installed a μvertex which, in case of candidate events, can give further insight with a secondary vertex tag.**

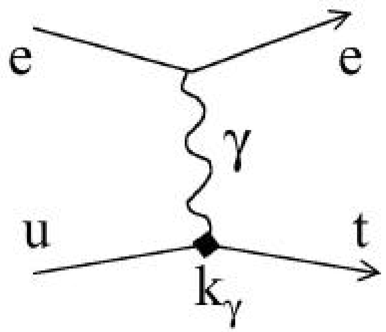
High pt leptons and top production by FCNC

In the Standard Model FCNC are forbidden at the tree level.
top $\to$ u transition can only proceed via loops ➡ no sizeable rate expected

But anomalous top coupling often arise in models which extend SM

E.g. SUSY with two R̸p couplings:



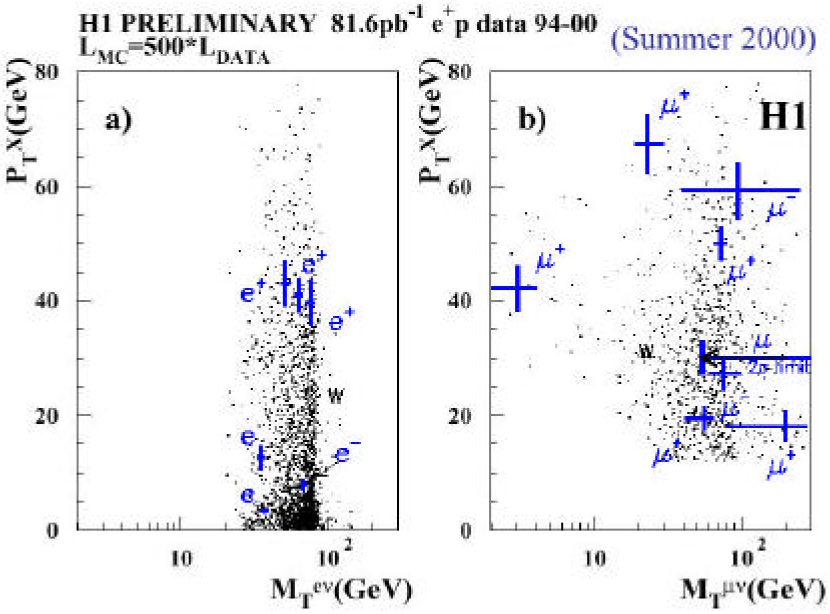


- **High Pt isolated leptons and missing calorimeter Pt**

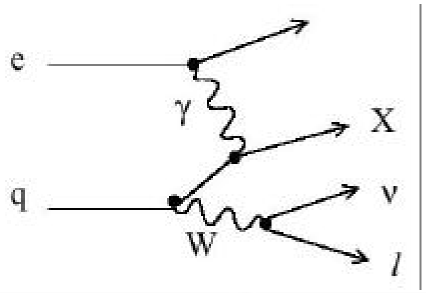
$$t \to bW \to b\,\ell n \qquad \ell = e, m$$

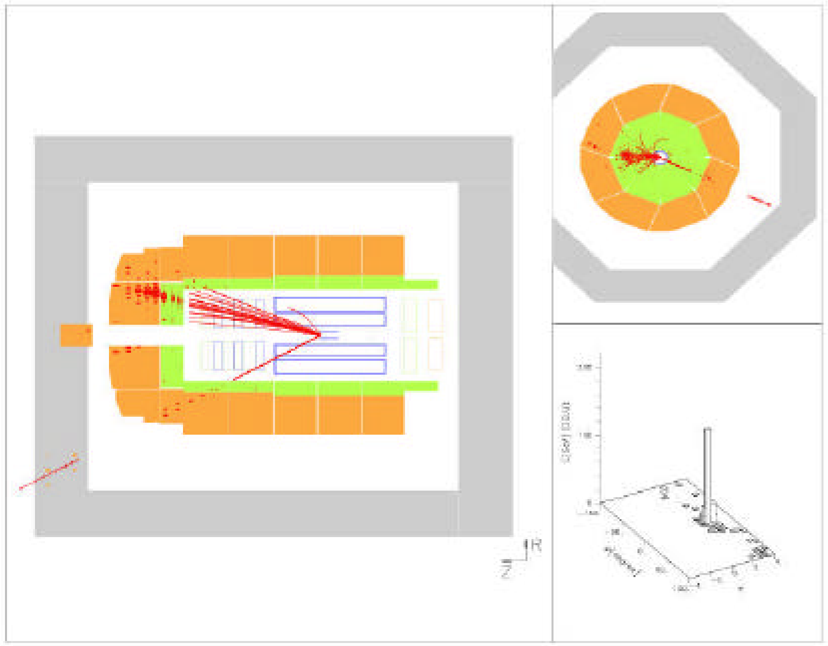
Interest in this process triggered by H1 excess

High Pt isolated leptons – H1



SM background at high Pt^X (hadronic Pt) dominated by W production

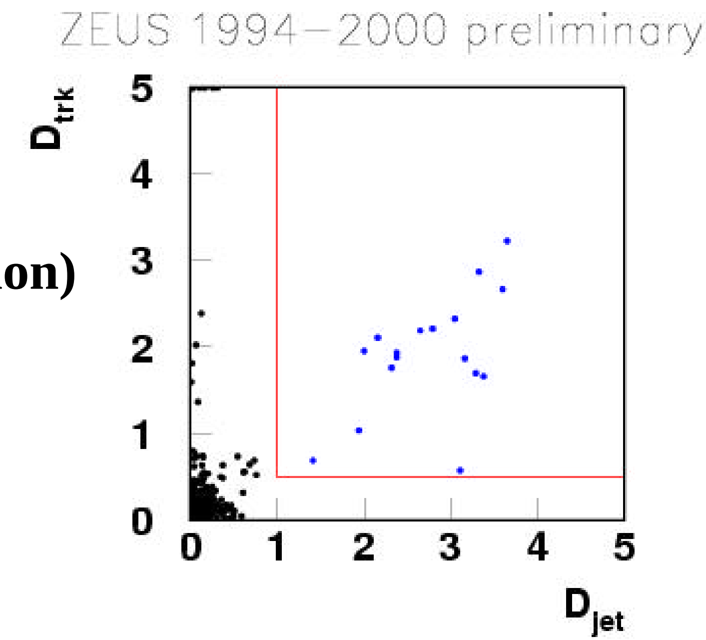




H1 excess!

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)

High Pt leptons – ZEUS (1)



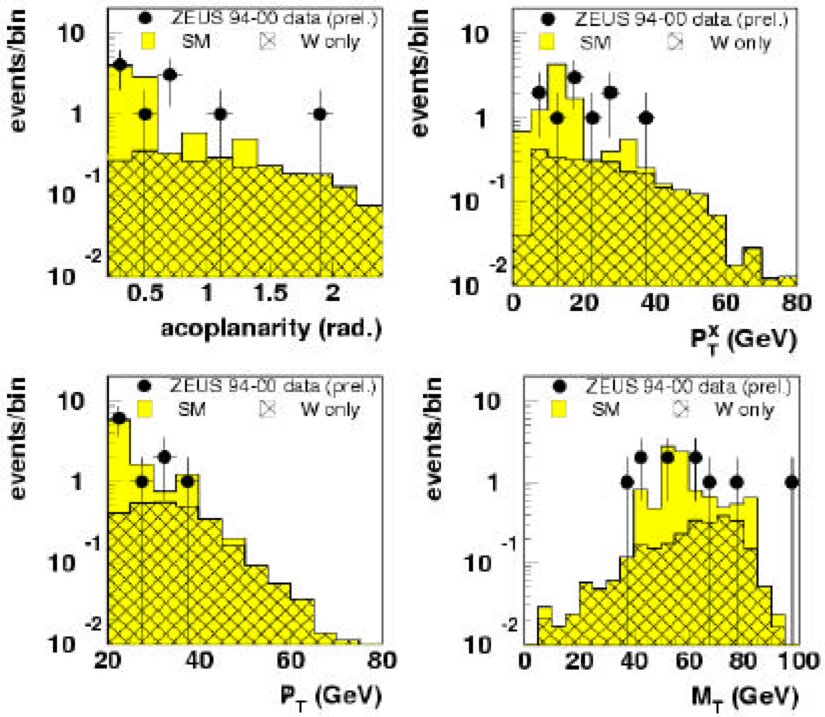
Selection:
- **Pt(cal) > 20 GeV, Pt(track) > 10 GeV**
- **Dtrk > 0.5 (in η-ϕ) from other tracks (isolation)**
- **Djet > 1.0 from other hadronic jets**

NB: Selection cuts looser than H1
No Pt^X cut, SM not dominated by W

ZEUS results consistent with SM expectations

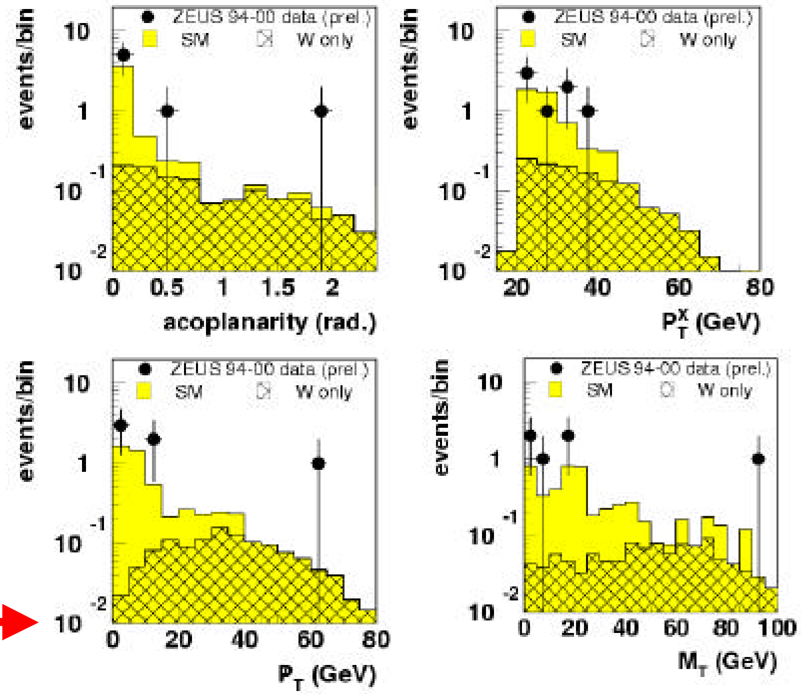
ZEUS preliminary 1994-2000	Electrons Observed/expected (W)	Muons Observed/expected (W)
e^+p 114 pb^{-1}	7 / 9.9±1.6 (2.4)	7 / 4.6±0.6 (1.1)
e^-p 16 pb^{-1}	3 / 1.1±0.4 (0.3)	0 / 0.8±0.1 (0.2)
Total 130 pb^{-1}	10 / 11.0±1.6 (2.7)	7 / 5.4±0.7 (1.3)

High Pt leptons – ZEUS (2)



electrons

Consistent with the SM (dominated by NC DIS).
Small acoplanarity and small $\not{P}$t



Consistent with the SM (dominated by γγ→μμ).
Most events with μ and jet back to back balancing Pt

muons

High Pt leptons: H1-ZEUS comparison

Further cuts to compare results with H1:

- **μ events:** reject if 2nd μ found, require net $\not{P}t > 12$ GeV (suppress $\gamma\gamma \to \mu\mu$)
- **e events:** E-Pz < 45 GeV (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)

Limit H1 track polar-angle to ZEUS range (0.3 –2.0 rad.)

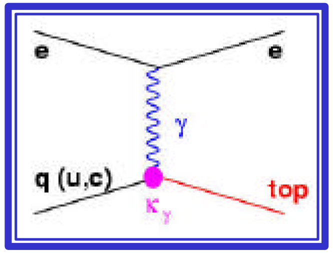
H1 preliminary **1994-2000 $e^{+}p$ 82 pb^{-1}**	Electrons Observed/expected (W)	Muons Observed/expected (W)
$P_T^X > 25$ GeV	3 / 0.84±0.22 (0.67)	6 / 0.94±0.26 (0.78)
$P_T^X > 40$ GeV	2 / 0.27±0.08 (0.26)	4 / 0.35±0.10 (0.33)

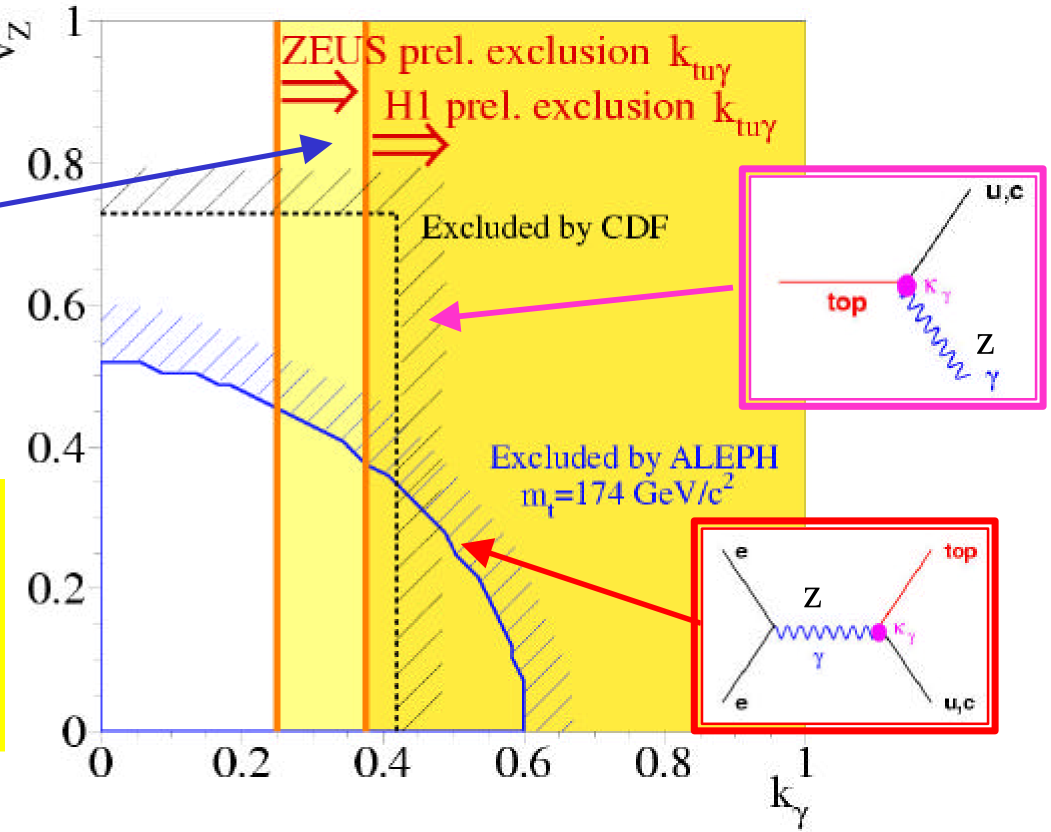
All H1 events remain ➡ more luminosity needed to understand discrepancy

Limits on top coupling

<u>top anomalous coupling could lead to:</u>

- Single top production at HERA and LEP
- $t \rightarrow q\,\gamma$ at Tevatron





95% exclusion limit on $k_{u\gamma t}$ by HERA experiments improves result from LEP and Tevatron

Conclusions

Events with high Pt leptons and $\not{P}t$ offer a very clean environment to study signal of physics beyond the Standard Model.

HERA1 collected 110 pb^{-1} e^+p and 15 pb^{-1} e^-p

- **LFV LQ and $\not{R}p$ SUSY $\tilde{q}$**
  - **new constraints which improves previous one especially for τ and when heavy quarks are involved.**
  - **in progress analysis of 98-99 e-p data which will improve low mass F=2 LQ ($\tilde{q}$) constraints**
- **Single top production via FCNC**
  - **HERA result improves limit from LEP and Tevatron**

Limits are in general comparable/complementary to LEP/Tevatron

HERA2 restart soon and will give 1 fb^{-1} in 5 years

- **Luminosity and detector upgrade will allow to substantially increase present constraints.**
- **What about intriguing H1 isolated leptons puzzle?**

An exciting post LEP – pre LHC era is starting !