Search for Lepton Flavor Violation at HERA

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H1 Collaboration

Graduate students seminar

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Outline

- Introduction
- Model for LFV at HERA
- Former analyses
  - Strategy
  - Results
- Actual analysis
  - Motivation
  - Strategy
  - First plots

Lepton Flavor

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

In SM lepton flavor is individually conserved:

$$N_e = N(e^-) + N(\nu_e) - N(e^+) - N(\bar{\nu}_e)$$

$$N_\mu = N(\mu^-) + N(\nu_\mu) - N(\mu^+) - N(\bar{\nu}_\mu)$$

$$N_\tau = N(\tau^-) + N(\nu_\tau) - N(\tau^+) - N(\bar{\nu}_\tau)$$

But: We can consider lepton flavor as "book−keeping" quantum number, i.e. there is no underlying gauge symmetry preserving lepton flavor!

→ Many extensions of SM like GUT, technicolor, compositeness, SUSY give up lepton flavor conservation!

Lepton Flavor Violation

First evidence of LFV: Super−Kamiokande

neutrino oscillations: $\nu_\mu \leftrightarrow \nu_\tau$

Further searches for LFV: MEG, PSI $\mu \longrightarrow e\gamma$

E865, BNL $K^+ \longrightarrow \pi^+\mu^+e^-$

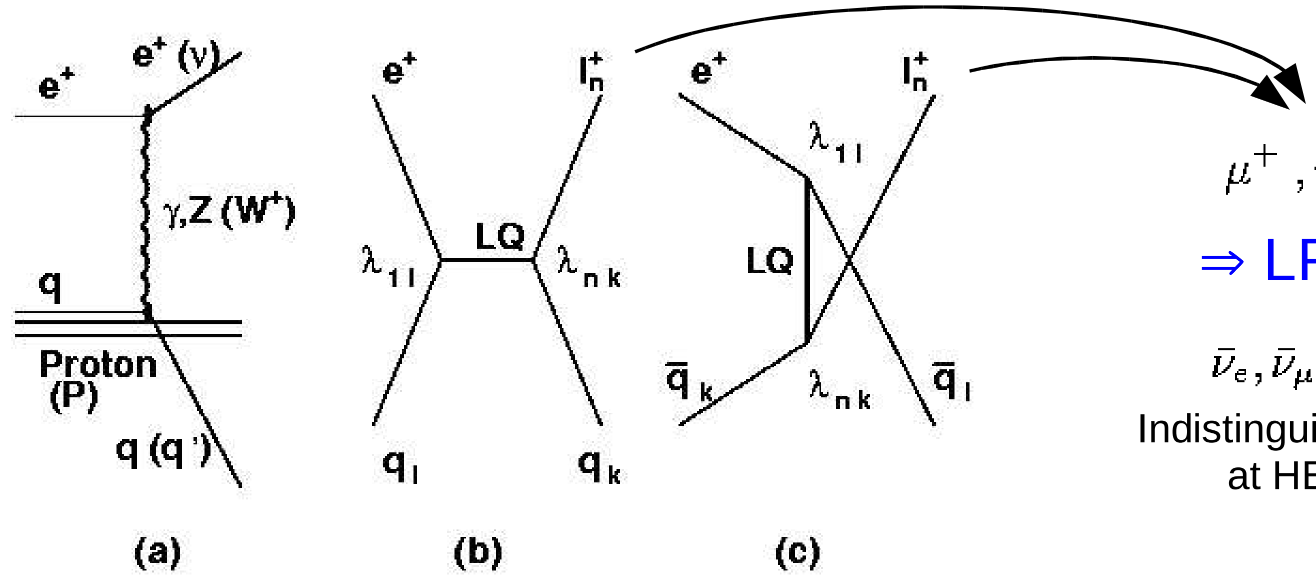
...

Are there concepts to look for LFV
in *ep* −collisions at HERA?

Yes, there are!

Leptoquarks

Leptoquarks couple to both quarks and leptons:



μ^+, τ^+

⇒ LFV!

$\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$

Indistinguishable at HERA

SM DIS s−channel u−channel

<u>Leptoquarks</u>

- color triplet bosons
- fractional charge
- Both lepton and baryon number $\neq 0$

<u>Parameters</u>

mass

coupling

quantum numbers

Leptoquarks (BRW−Model)

The most general LQ interactions with respect to SM symmetry yield

14 LQ−types according to their quantum numbers: ${}^{Q}S_{I}^{L,R}\ ,\ {}^{Q}V_{I}^{L,R}$

(Buchmüller, Rückl, Wyler, Phys. Lett. B191, 442, 1987)

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

$F=2$	Prod./Decay	BR	$F=0$	Prod./Decay	BR
Scalar Leptoquarks					
${}^{1/3}S_0$	$e_R^+\bar{u}_R \to l^+\bar{u}$	$1/2$	${}^{5/3}S_{1/2}$	$e_R^+u_R \to l^+u$	1
	$e_L^+\bar{u}_L \to l^+\bar{u}$	1		$e_L^+u_L \to l^+u$	1
${}^{4/3}\tilde{S}_0$	$e_L^+\bar{d}_L \to l^+\bar{d}$	1	${}^{2/3}S_{1/2}$	$e_L^+d_L \to l^+d$	1
${}^{4/3}S_1$	$e_R^+\bar{d}_R \to l^+\bar{d}$	1	${}^{2/3}\tilde{S}_{1/2}$	$e_R^+d_R \to l^+d$	1
${}^{1/3}S_1$	$e_R^+\bar{u}_R \to l^+\bar{u}$	$1/2$			
Vector Leptoquarks					
${}^{4/3}V_{1/2}$	$e_L^+\bar{d}_R \to l^+\bar{d}$	1	${}^{2/3}V_0$	$e_R^+d_L \to l^+d$	1
	$e_R^+\bar{d}_L \to l^+\bar{d}$	1		$e_L^+d_R \to l^+d$	$1/2$
${}^{1/3}V_{1/2}$	$e_L^+\bar{u}_R \to l^+\bar{u}$	1	${}^{5/3}\tilde{V}_0$	$e_L^+u_R \to l^+u$	1
${}^{1/3}\tilde{V}_{1/2}$	$e_R^+\bar{u}_L \to l^+\bar{u}$	1	${}^{5/3}V_1$	$e_R^+u_L \to l^+u$	1
			${}^{2/3}V_1$	$e_R^+d_L \to l^+d$	$1/2$

F= 0: particle −antiparticle

F= 2: (anti)particle −(anti)particle

LL, RR: scalar LQ

LR, RL: vector LQ

s−channel production:

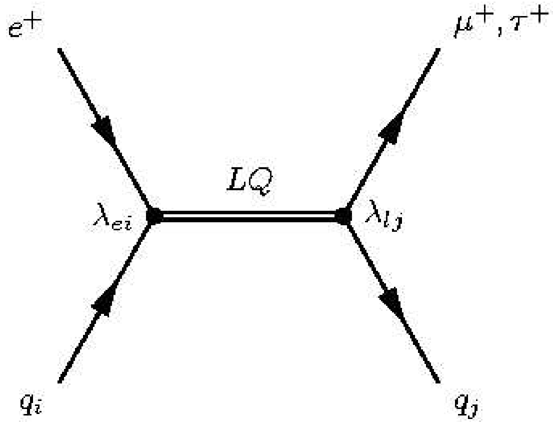
$$e^+p \longrightarrow LQ\ with\ F = 0$$

$$e^-p \longrightarrow LQ\ with\ F = 2$$

Search for LQ

low mass:

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

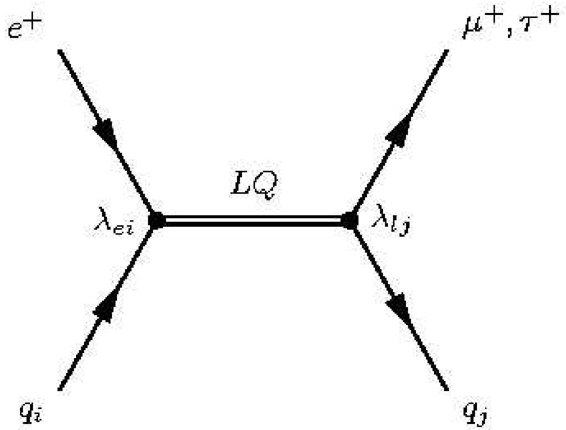


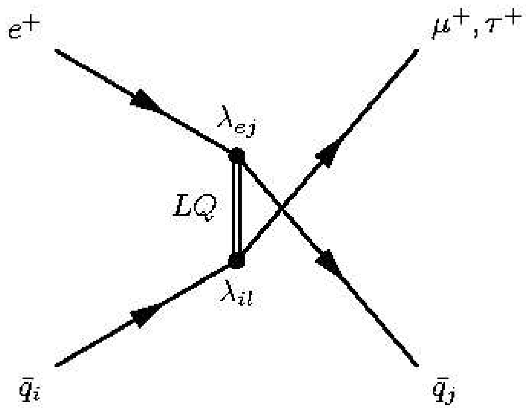
$$\sigma \propto (\lambda_{ei} \times \sqrt{BR})^2 q(x_0)$$

narrow resonance
in *x* at: $x_0 = \frac{M_{LQ}^2}{s}$

high mass:

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



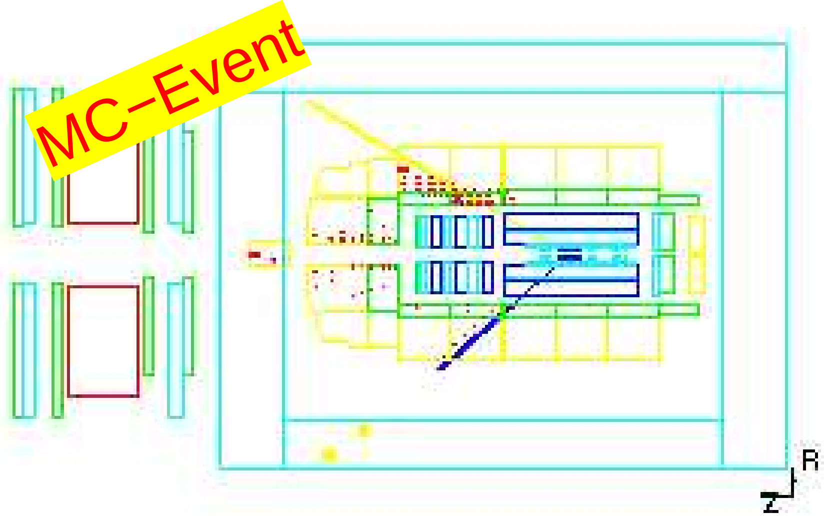


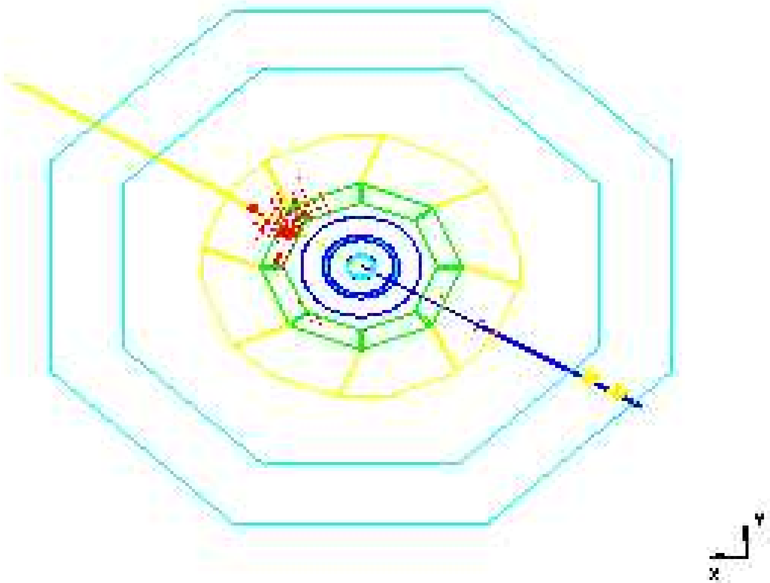
$$\sigma \propto \left[\frac{\lambda_{ei}\lambda_{lj}}{M_{LQ}^2}\right]^2$$

Four fermions −Fermi coupling
⇒ consider F=0 and F=2 LQ

$ep \rightarrow \mu X$

Signature: high p_T muon instead of electron $\rightarrow$ high p_T^{miss}(calo.)





Strategy:

- No e with $p_T >$ 5 GeV
- At least one high−p_T jet
- One isolated high−p_T muon
- CC sample (Q^2 > 1000 GeV^2, p_T^{miss} (calo.) > 25 GeV

$ep \rightarrow \tau X$

Signature: high p_T tau instead of electron, but...

tau almost decays at vertex ($c_\tau \sim 88\ \mu m$)

decay modes:

τ^+	$\longrightarrow$	$e^+\nu_e\bar{\nu}_\tau$	17.9%
τ^+	$\longrightarrow$	$\mu^+\nu_\mu\bar{\nu}_\tau$	17.6%
τ^+	$\longrightarrow$	$h^+\bar{\nu}_\tau + 0$ neutrals	50.3%
τ^+	$\longrightarrow$	$2h^+h^-\bar{\nu}_\tau + 0$ neutrals	14.0%
τ^+	$\longrightarrow$	$\geq 5h^\pm\bar{\nu}_\tau + 0$ neutrals	0.1%

characteristic for hadronic decay:

- "pencil- like" jet with low charged multiplicity
- narrow cluster
- 1- 3 tracks to narrow cluster

Strategy:

- high- p_T electron in direction of p_T^{miss}
- high- p_T muon in direction of p_T^{miss} (calo.)
- narrow high- p_T jet in direction of p_T^{miss}

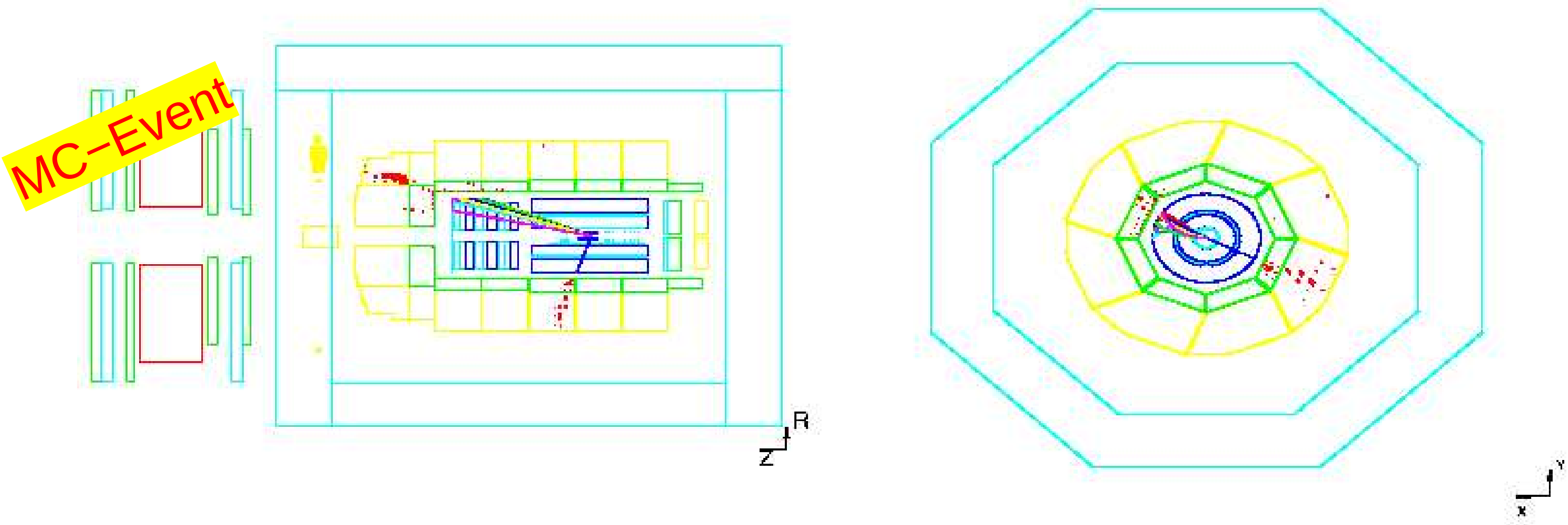
$\tau \rightarrow$ *hadrons*

Event selection in previous searches for LFV at H1 and ZEUS:

high−p_T preselection (CC−trigger, high Q^2−NC−trigger), no electron with E_T > 5 GeV found

"pencil−like" jet with 1−3 tracks to jet: narrow and hadronical

LQ specific: high p_t^{miss}, at least one high−p_T−jet & "τ−jet" aligned with p_t^{miss}



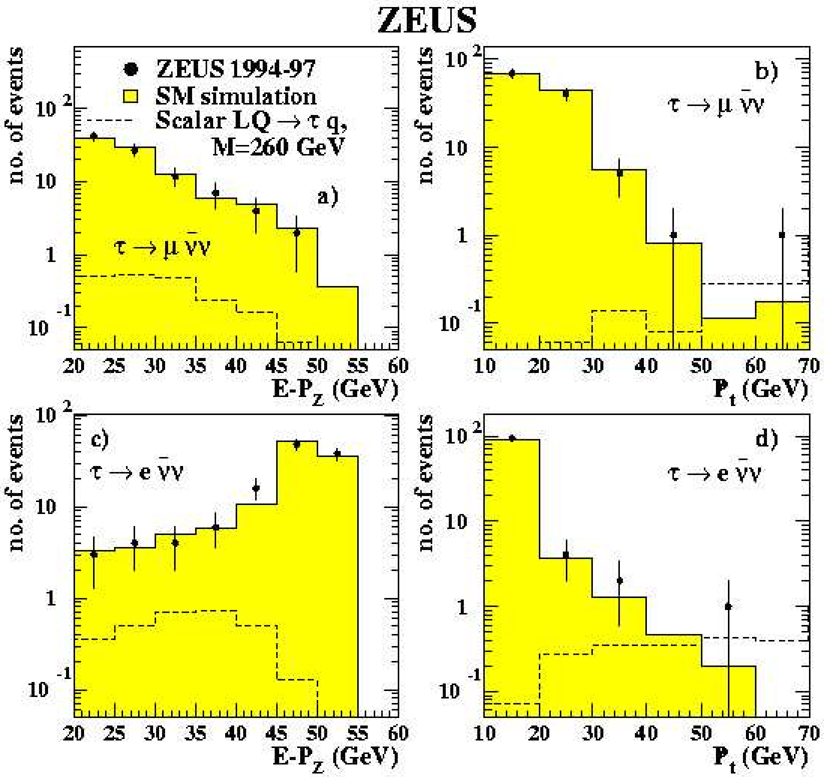
$\tau \to \mu\nu\nu, \ e\nu\nu$

The $\mu\nu\nu$-channel should be covered implicitely by the LQ $\to$ μq search with additional p_T^{miss} in the direction of the muon $\to$ cross check

H1: hadronic decays only

ZEUS:

- **CC sample (p_T^{miss} > 15 GeV for $e\nu\nu$, p_T^{miss} > 20 GeV for $\mu\nu\nu$)**
- **high−p_T electron or muon**
- **at least one high−p_T jet (p_T > 15 GeV)**
- **lepton aligned in azimuth with p_T^{miss}**



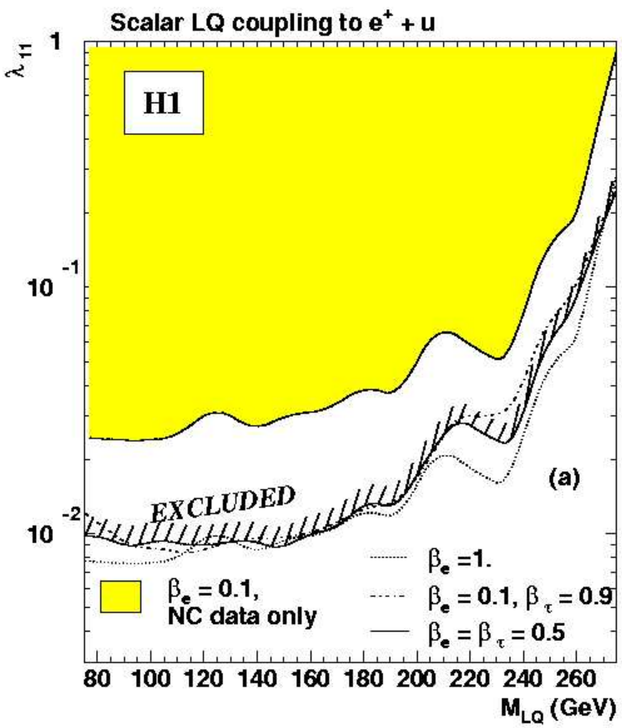
⇒ Overall τ−selection efficiency ~25%−~31%for M_{LQ}< 320 GeV

ep →τX: Limits on low−mass LQ's

H1 data 94−97: combined result for eX− and τX−channel

for e.m. Coupling and $\beta_e + \beta_\tau \sim 1$:

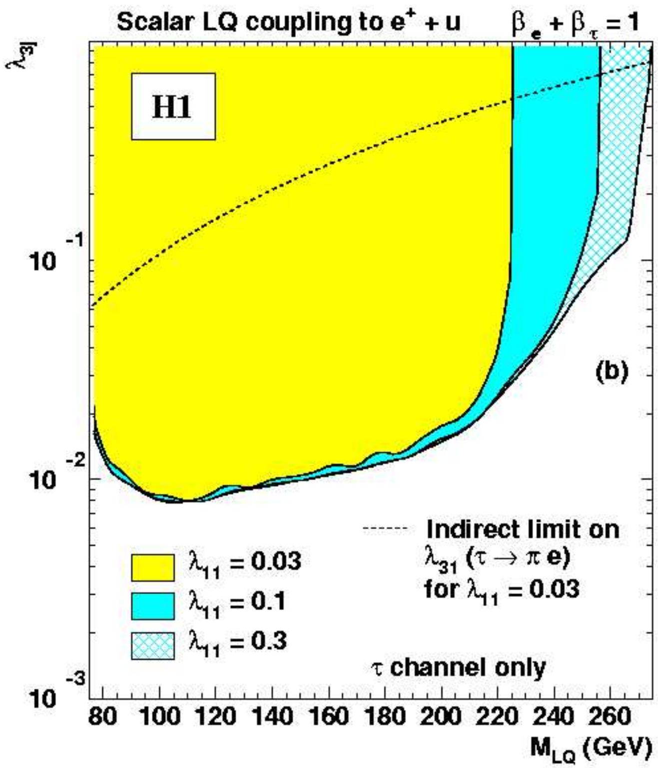
M_{LQ}> 275 GeV excluded



$$if\ \lambda_{11} = \lambda_{3j} = \sqrt{4\pi\alpha}$$

M_{LQ}< 270 GeV excluded

95%C.L. mass dep. limits on λ_{3j} for fixed values of λ_{11}



ep $\to \tau X$: Limits on high–mass LQ's

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

BEST EXCLUSION UPPER LIMITS ON $\frac{\lambda_{1i}\,\lambda_{3j}}{M^2_{LQ}}$ (in 10^{-4} GeV^{-2})

FOR LEPTON FLAVOUR VIOLATING LEPTOQUARKS

$q_i\,q_j$	$S_{1/2,L}$	$S_{1/2,R}$	$\tilde{S}_{1/2,L}$	$V_{0,L}$	$V_{0,R}$	$\tilde{V}_{0,R}$	$V_{1,L}$
1 1	$\tau \to \pi e$ 0.0032 H1: 0.046	$\tau \to \pi e$ 0.0016 H1: 0.037	$\tau \to \pi e$ 0.0032 H1: 0.062	G_F 0.002 H1: 0.015	$\tau \to \pi e$ 0.0016 H1: 0.015	$\tau \to \pi e$ 0.0016 H1: 0.013	G_F 0.002 H1: 0.0060
1 2	ZEUS 0.12 H1: 0.047	$\tau \to K e$ 0.05 H1: 0.038	$\tau \to K e$ 0.05 H1: 0.063	$\tau \to K e$ 0.03 H1: 0.017	$\tau \to K e$ 0.03 H1: 0.017	ZEUS 0.10 H1: 0.014	$K \to \pi \nu \bar{\nu}$ 2.5×10^{-6} H1: 0.0065
1 3	*	$B \to \tau \bar{e} X$ 0.08 H1: 0.065	$B \to \tau \bar{e} X$ 0.08 H1: 0.065	$B \to l \nu X$ 0.02 H1: 0.020	$B \to \tau \bar{e} X$ 0.04 H1: 0.020	*	$B \to l \nu X$ 0.02 H1: 0.020
2 1	ZEUS 0.14 H1: 0.15	$\tau \to K e$ 0.05 H1: 0.095	$\tau \to K e$ 0.05 H1: 0.12	$\tau \to K e$ 0.03 H1: 0.020	$\tau \to K e$ 0.03 H1: 0.020	ZEUS 0.10 H1: 0.023	$K \to \pi \nu \bar{\nu}$ 2.5×10^{-6} H1: 0.010
2 2	$\tau \to e\gamma$ 0.03 H1: 0.18	$\tau \to e\gamma$ 0.02 H1: 0.10	ZEUS 0.48 H1: 0.13	ZEUS 0.15 H1: 0.024	ZEUS 0.15 H1: 0.024	ZEUS 0.11 H1: 0.034	ZEUS 0.11 H1: 0.014
2 3	*	$B \to \tau \bar{e} X$ 0.08 H1: 0.14	$B \to \tau \bar{e} X$ 0.08 H1: 0.14	$B \to l \nu X$ 0.02 H1: 0.035	$B \to \tau \bar{e} X$ 0.04 H1: 0.035	*	$B \to l \nu X$ 0.02 H1: 0.035
3 1	*	$B \to \tau \bar{e} X$ 0.08 H1: 0.16	$B \to \tau \bar{e} X$ 0.08 H1: 0.16	V_{ub} 0.002 H1: 0.022	$B \to \tau \bar{e} X$ 0.04 H1: 0.022	*	V_{ub} 0.002 H1: 0.022
3 2	*	$B \to \tau \bar{e} X$ 0.08 H1: 0.19	$B \to \tau \bar{e} X$ 0.08 H1: 0.19	$B \to l \nu X$ 0.02 H1: 0.026	$B \to \tau \bar{e} X$ 0.04 H1: 0.026	*	$B \to l \nu X$ 0.02 H1: 0.026
3 3	*	ZEUS 0.72 H1: 0.23	ZEUS 0.72 H1: 0.23	$\tau \to e\gamma$ 0.51 = H1: 0.045	$\tau \to e\gamma$ 0.51 = H1: 0.045	*	ZEUS 0.18 H1: 0.045

$e \leftrightarrow \tau$ **F = 2**

BEST EXCLUSION UPPER LIMITS ON $\frac{\lambda_{1i}\,\lambda_{3j}}{M^2_{LQ}}$ (in 10^{-4} GeV^{-2})

FOR LEPTON FLAVOUR VIOLATING LEPTOQUARKS

$q_i\,q_j$	$S_{0,L}$	$S_{0,R}$	$\tilde{S}_{0,R}$	$S_{1,L}$	$V_{1/2,L}$	$V_{1/2,R}$	$\tilde{V}_{1/2,L}$
1 1	G_F 0.003 H1: 0.026	$\tau \to \pi e$ 0.0032 H1: 0.026	$\tau \to \pi e$ 0.0032 H1: 0.031	G_F 0.003 H1: 0.013	$\tau \to \pi e$ 0.0016 H1: 0.030	$\tau \to \pi e$ 8×10^{-4} H1: 0.018	$\tau \to \pi e$ 0.0016 H1: 0.023
1 2	$K \to \pi \nu \bar{\nu}$ 10^{-5} H1: 0.046	ZEUS 0.20 H1: 0.046	$\tau \to K e$ 0.05 H1: 0.041	$K \to \pi \nu \bar{\nu}$ 10^{-5} H1: 0.019	$K \to \pi \nu \bar{\nu}$ 5×10^{-6} H1: 0.060	$\tau \to K e$ 0.03 H1: 0.048	ZEUS 0.16 H1: 0.078
1 3	V_{ub} 0.004	*	$B \to \tau \bar{e} X$ 0.08 H1: 0.044	V_{ub} 0.004 H1: 0.022	$B \to \tau \bar{e} X$ 0.04 H1: 0.084	$B \to \tau \bar{e} X$ 0.04 H1: 0.084	*
2 1	$K \to \pi \nu \bar{\nu}$ 10^{-5} H1: 0.028	ZEUS 0.22 H1: 0.028	$\tau \to K e$ 0.05 H1: 0.034	$K \to \pi \nu \bar{\nu}$ 10^{-5} H1: 0.014	$K \to \pi \nu \bar{\nu}$ 5×10^{-6} H1: 0.031	$\tau \to K e$ 0.03 H1: 0.018	ZEUS 0.06 H1: 0.023
2 2	$\tau \to e\gamma$ 0.075 H1: 0.067	$\tau \to e\gamma$ 0.075 H1: 0.067	$\tau \to e\gamma$ 0.045 H1: 0.048	$\tau \to e\gamma$ 0.015 H1: 0.023	ZEUS 0.15 H1: 0.064	ZEUS 0.19 H1: 0.053	ZEUS 0.11 H1: 0.091
2 3	$B \to l \nu X$ 0.04	*	$B \to \tau \bar{e} X$ 0.08 H1: 0.053	$B \to l \nu X$ 0.04 H1: 0.026	$B \to \tau \bar{e} X$ 0.04 H1: 0.095	$B \to \tau \bar{e} X$ 0.04 H1: 0.095	*
3 1	$B \to l \nu X$ 0.04	*	$B \to \tau \bar{e} X$ 0.08 H1: 0.039	$B \to l \nu X$ 0.04 H1: 0.019	$B \to \tau \bar{e} X$ 0.04 H1: 0.031	$B \to \tau \bar{e} X$ 0.04 H1: 0.032	*
3 2	$B \to l \nu X$ 0.04	*	$B \to \tau \bar{e} X$ 0.08 H1: 0.069	$B \to l \nu X$ 0.04 H1: 0.034	$B \to \tau \bar{e} X$ 0.04 H1: 0.071	$B \to \tau \bar{e} X$ 0.04 H1: 0.071	*
3 3		*	$\tau \to e\gamma$ 0.045 H1: 0.086	$\tau \to e\gamma$ 0.015 H1: 0.043	ZEUS 0.18 H1: 0.120	ZEUS 0.18 H1: 0.12	*

Motivation for actual search

- 1998−1999: e^-p data gives sensitivity to F=2 LQ's
- 1999−2000: e^+p data gives better limits on F=0 LQ's
- 2003−2006: increased luminosity after upgrade will rigorously improve current limits

  polarisation of electrons allows for various exclusive analysis methods

Especially for $e \leftrightarrow \tau$, we expect HERA to set most stringent limits on high−mass LQ's couplings:

$$\frac{\lambda_{ei}\lambda_{\tau j}}{M_{LQ}^2}$$

Strategy

Analysis of H1 data that covers not only the $\tau \rightarrow$ hadrons channel, but also the $\tau \rightarrow e\upsilon\upsilon$ and $\tau \rightarrow \mu\upsilon\upsilon$ channel:

99/00 e^+p data, limits on F=0 LQ's

↓

98/99 e^-p data, limits on F=2 LQ's

↓

03/06 HERAII data, see how far we can get...

On top of introduced analysis techniques use existing tau−finders and/ or develop new tau−finder to increase selection efficiency!

Recent efforts of finding τ's at H1 promising...

Use the object−oriented framework!

Kinematics

There is **no** scattered electron!

So, how do we reconstruct the kinematics?

From hadronic final state only (Jaques−Blondel−Method) ?

depends strongly on HFS energy calibration...

There is a better way!

Neutrinos from high−p_T−τ−decay are boosted in direction of e, μ or jet

⇒ e, μ or jet carries less energy than the "scattered" τ,

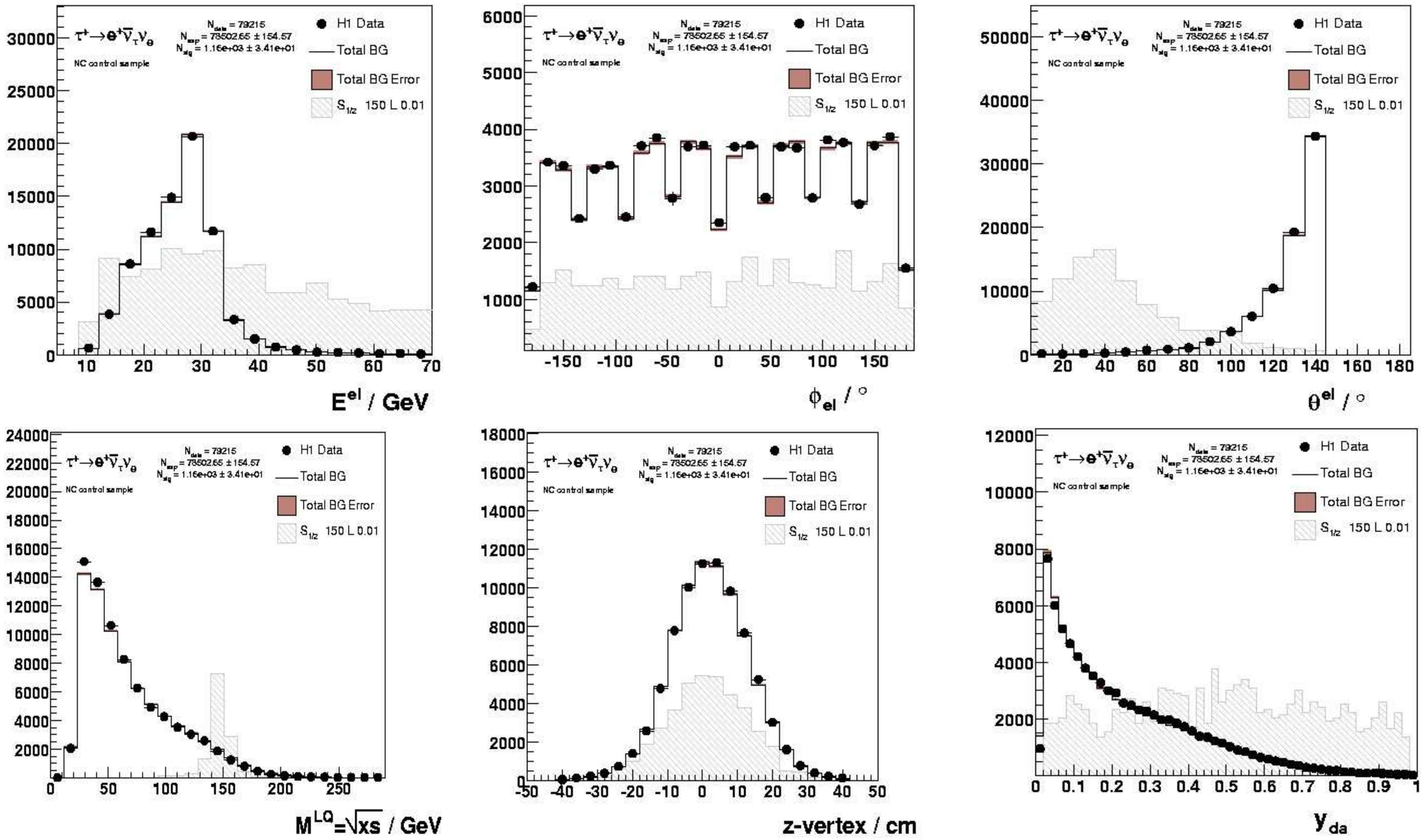
but it's direction can be used!

⇒Double−Angle−Method with high−p_T−τ−decay product

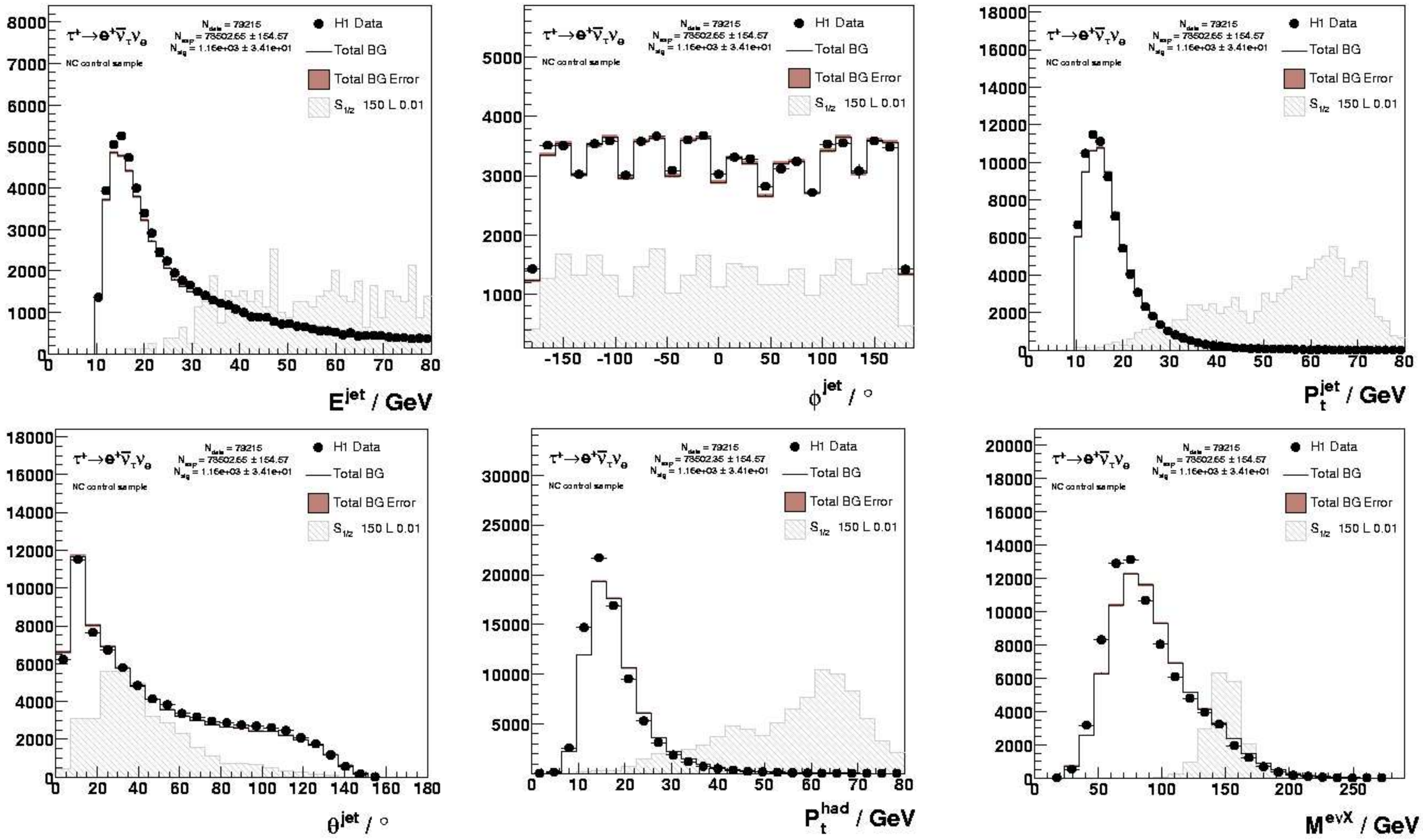
First high−p_T selection

- At least one jet with $p_T > 10$ GeV
- At least one electron, muon or jet with $p_T > 10$ GeV
- Electron, muon or jet in LAr, i.e. $5^o < \theta < 145^o$
- Electron 1^o away from phi−crack
- Non−ep background rejection

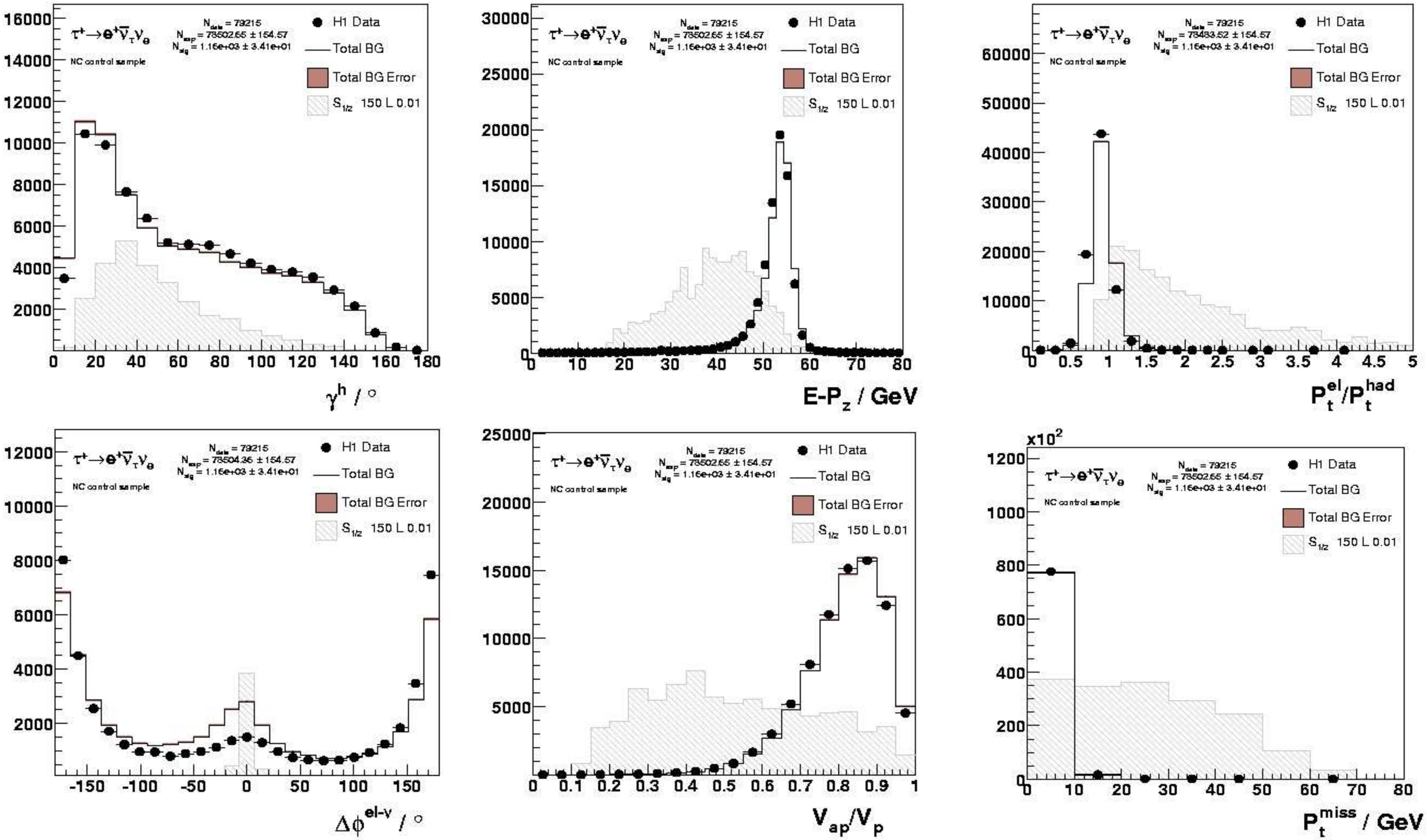
NC control sample



NC control sample



NC control sample



Summary

- HERA is ideally suited to search for LQ's possesing couplings to mixed fermion states, i.e LFV
- Published results of H1 and ZEUS were competetitive with indirect limits and will be even more so in the future
- The actual analysis is built up and shows progress
- Outlook:
  - More stringent selection criteria in all channels
  - Signal selection efficiencies
  - M_{LQ}−binning
  - Limits