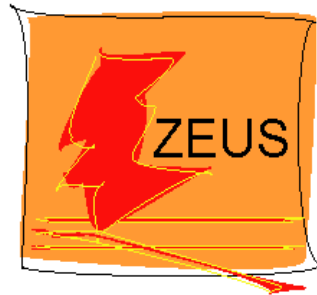


Searches for Physics beyond the Standard Model at ZEUS



Antje Hüttmann (DESY)
for the ZEUS collaboration



Hadron Structure and QCD
July ??, 2012

Outline

- The HERA collider
- Deep Inelastic Scattering (DIS)

- Search for leptoquarks

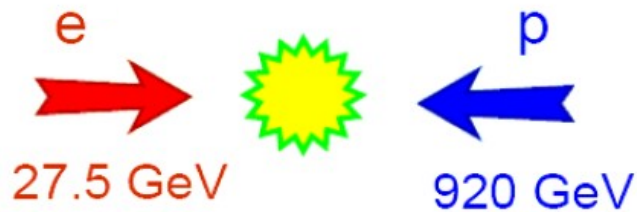
- Introduction
- Resonant searches
- Limits

- Search for single top production

- Introduction
- Event selection
- Limits

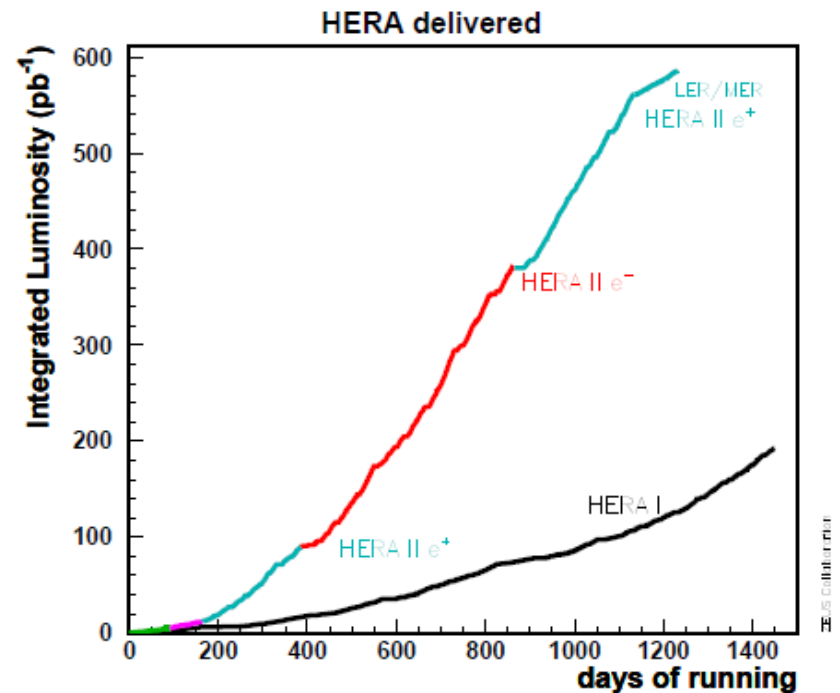
The HERA Collider

- World's only **ep collider**, located at DESY in Hamburg
- In operation from 1992-2007



Center of mass energy:
 $\sqrt{s} = 318 \text{ GeV}$

- Two running periods:
 - **HERA-I**: 1992-2000, $L=130 \text{ pb}^{-1}$
 - **HERA-II**: 2002-2007, $L=370 \text{ pb}^{-1}$
lepton beam longitudinally polarised (30-40%)
- Two **general purpose collider experiments**: ZEUS and H1



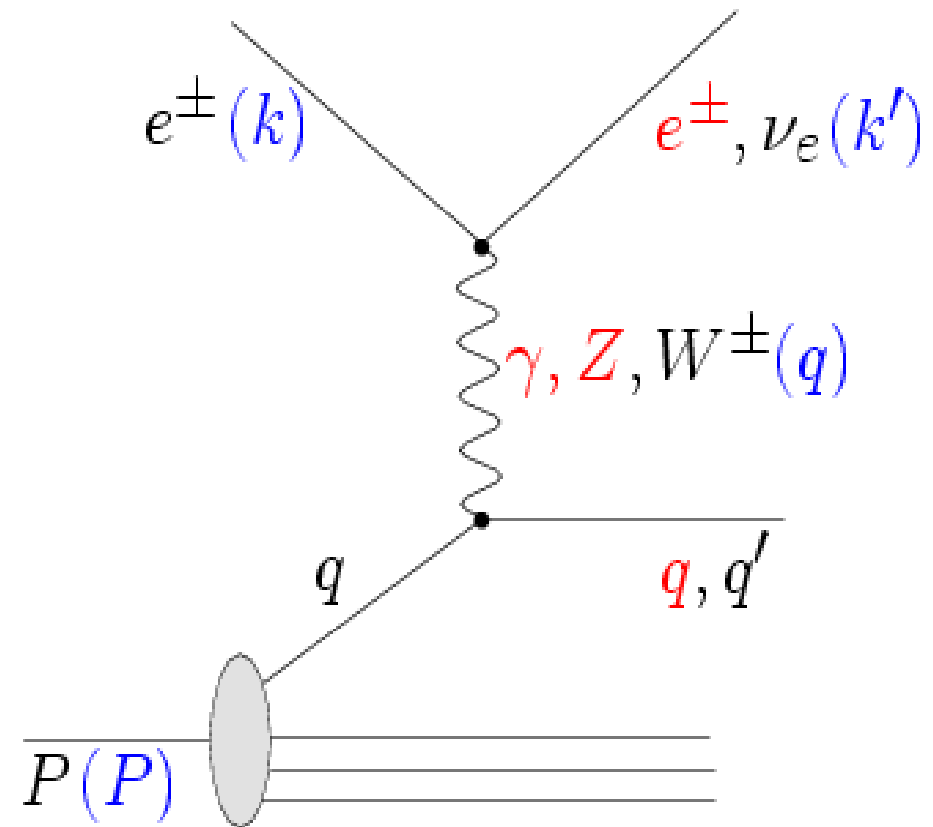
Deep Inelastic Scattering (DIS)

- **Neutral current (NC):** γ or Z exchanged, e^\pm in final state
- **Charged current (CC):** W^\pm exchanged, ν_e in final state
- Q^2 : boson virtuality

$$Q^2 = -q^2 = -(k - k')^2$$
- x : proton momentum fraction carried by struck quark q

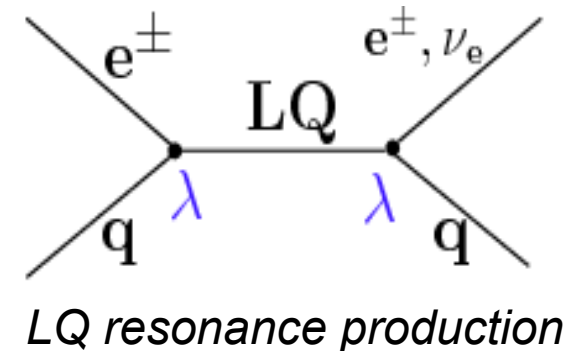
$$x = \frac{Q^2}{2P \cdot q}$$
- y : fractional energy loss of electron in rest frame of proton

$$y = \frac{P \cdot q}{P \cdot k}$$
- $Q^2 = xys$ (\sqrt{s} = center of mass energy)



The Leptoquark Model

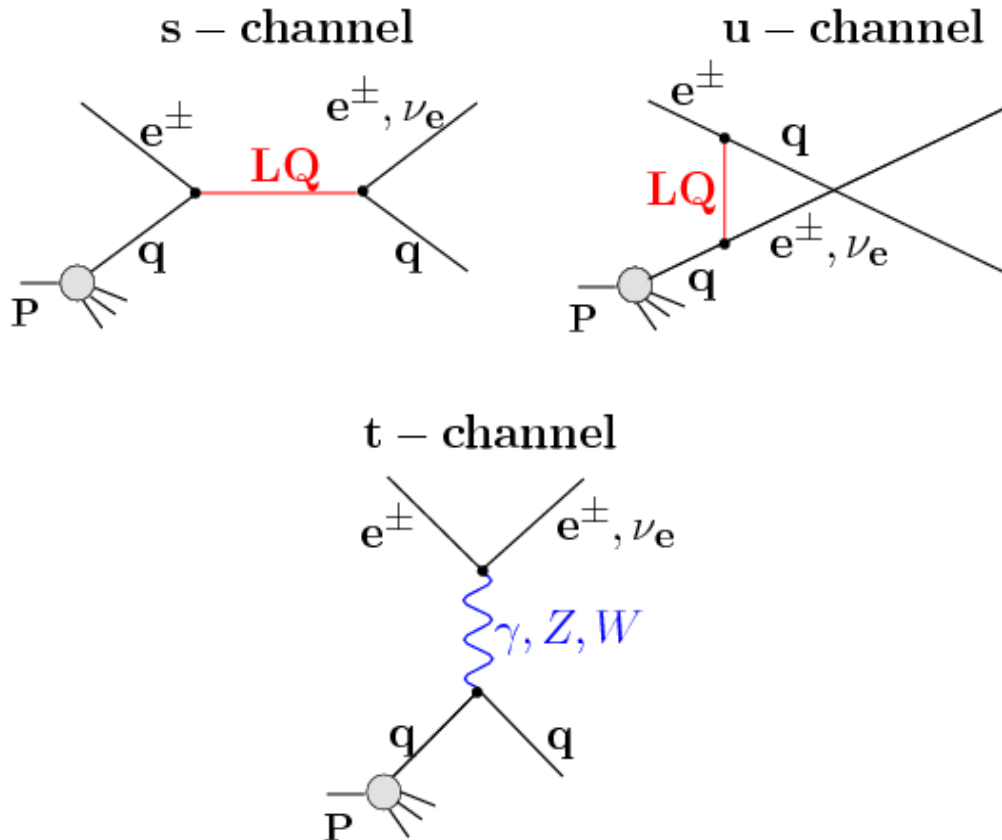
- Leptoquarks are scalar or vector colour triplet bosons, carry both lepton and baryon number → HERA is well suited for leptoquark searches
- Fermion number: $F=L+3B$, ($F=0,2$)
- The Buchmüller-Rückl-Wyler model:
 - Standard Model symmetry conserved
 - Lepton and baryon number conserved
 - LQs couple either to right-handed or to left-handed leptons
 - No flavour-violating couplings
 - → 7 scalar and 7 vector 1st generation leptoquarks
 - All 14 LQs couple to eq , 2 scalar and 2 vector LQs also to νq
- LQ processes at HERA have the same initial and final state as NC/CC DIS → interfere with the SM



The Leptoquark Cross Section

Total cross section:

$$\sigma(e^\pm p) = \sigma_{SM} + \sigma_{s/SM}^{Int} + \sigma_{u/SM}^{Int} + \sigma_s + \sigma_u$$



Angular dependence:

$$y = 0.5 (1 - \cos\theta^*)$$

(θ^* : lepton scattering angle in the lepton-quark c.m.s.)

- **scalar** leptoquarks:

$$\left. \frac{d\sigma}{dy} \right|_{scalar} : \text{independent of } y$$

- **vector** leptoquarks:

$$\left. \frac{d\sigma}{dy} \right|_{vector} \sim (1 - y)^2$$

s-channel

- **NC DIS background:**

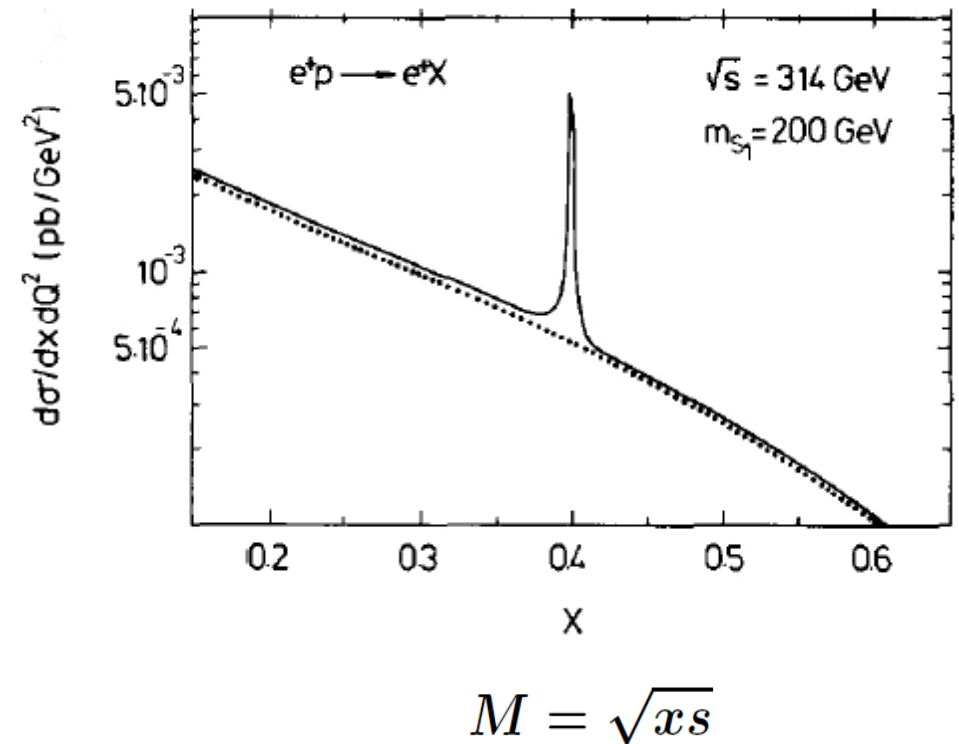
$$\left. \frac{d\sigma}{dy} \right|_{SM} \sim \frac{1}{y^2}$$

→ signal-to-background ratio can be improved by restricting the search to the **high- y region** (negative $\cos\theta^*$)

- For $M_{LQ} \leq \sqrt{s}$, the **s-channel dominates**

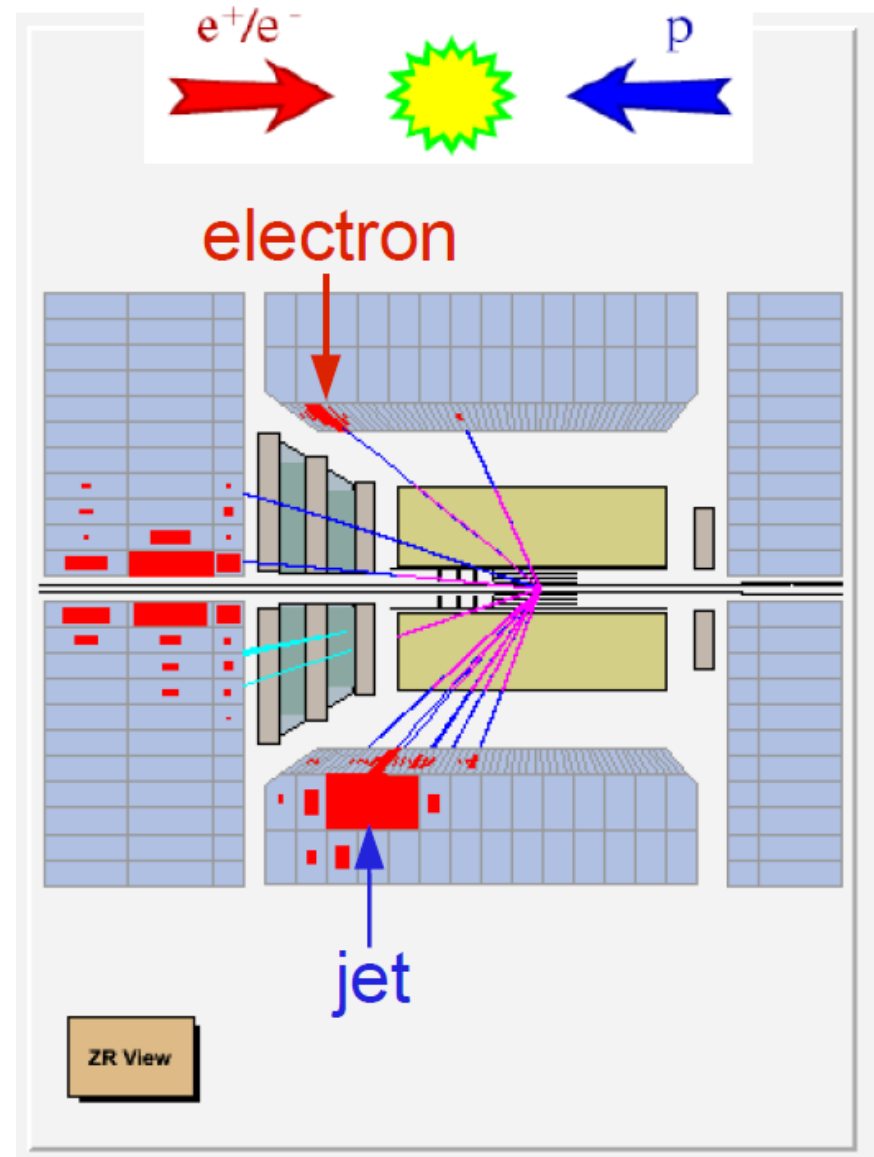
Search Strategy

- Leptoquark events have the **same signature as NC or CC events**
- LQ contribution in addition to SM would lead to **peak in invariant mass distribution** (for $M_{LQ} < \sqrt{s}$)
- LQ cross section has different **polarization dependence** than NC (or CC) cross section → data samples with different polarization examined separately



Event Selection

- All HERA-II data (0.37 pb^{-1}) were analysed
- NC DIS:
 - $Q^2 > 2500 \text{ GeV}^2$
 - $x > 0.1$
 - isolated electron
 - ≥ 1 jet with $p_T > 15 \text{ GeV}$
 - 9369 events selected, 9465 ± 494 are expected
- CC DIS:
 - $Q^2 > 700 \text{ GeV}^2$
 - Missing transverse momentum $p_T > 22 \text{ GeV}$
 - ≥ 1 jet with $p_T > 10 \text{ GeV}$
 - 8990 events selected, 9068 ± 501 are expected
- The **invariant mass** is calculated from the lepton and all selected jets



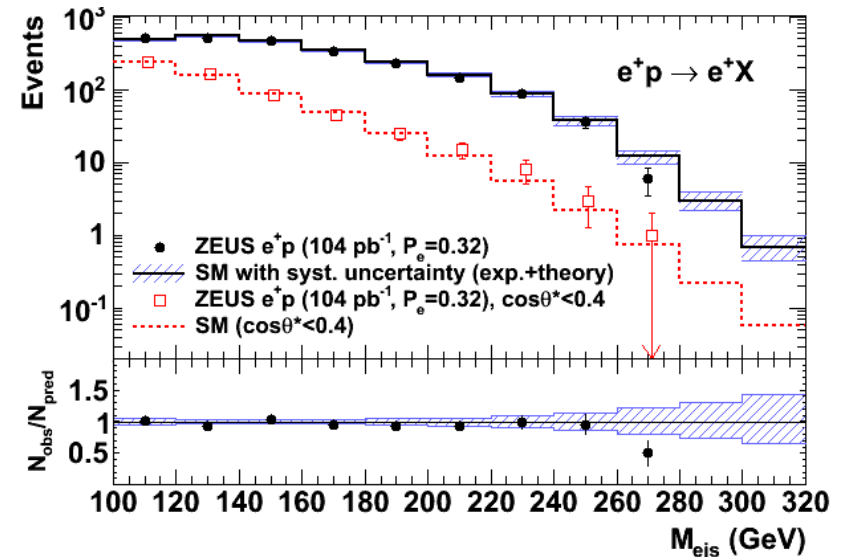
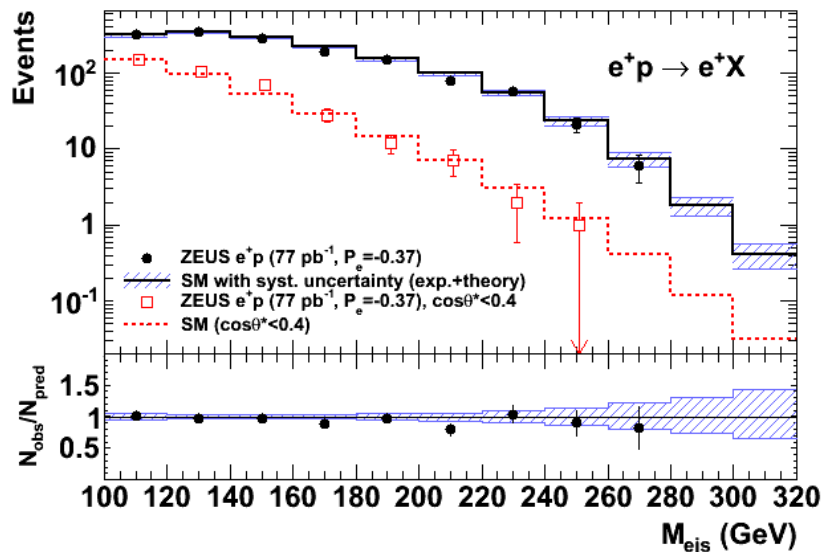
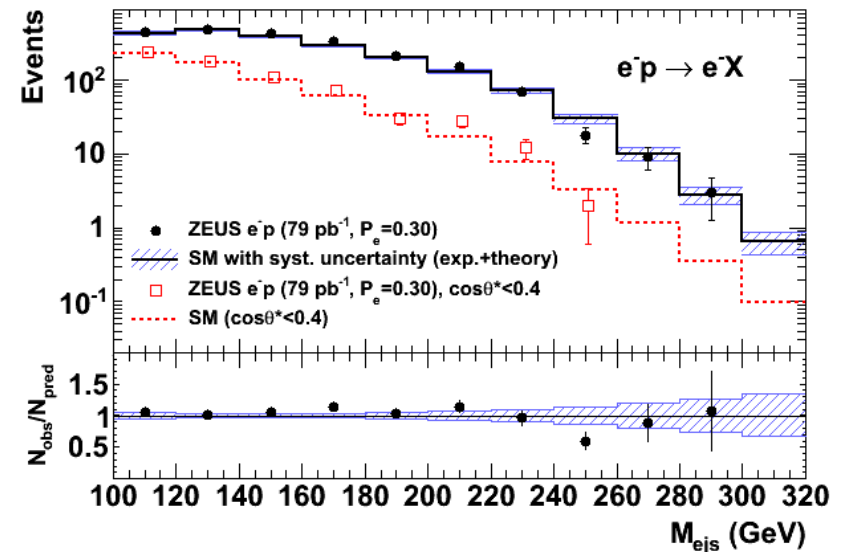
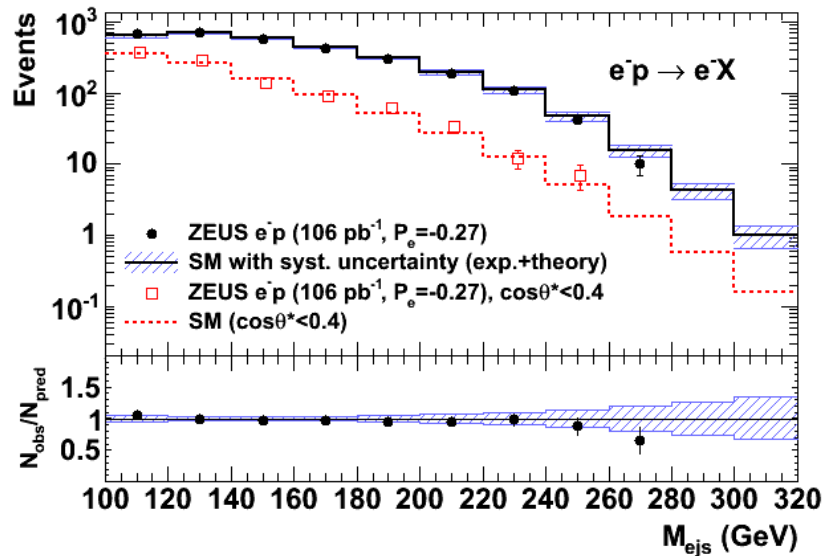
Neutral current DIS event

NC Invariant Mass Distributions

ZEUS

in red: with cut on $\cos\theta^ < 0.4$*

ZEUS



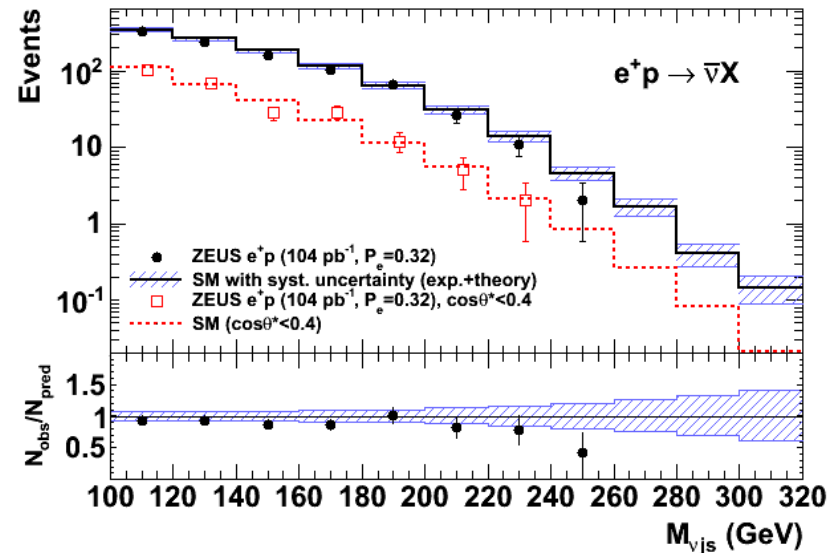
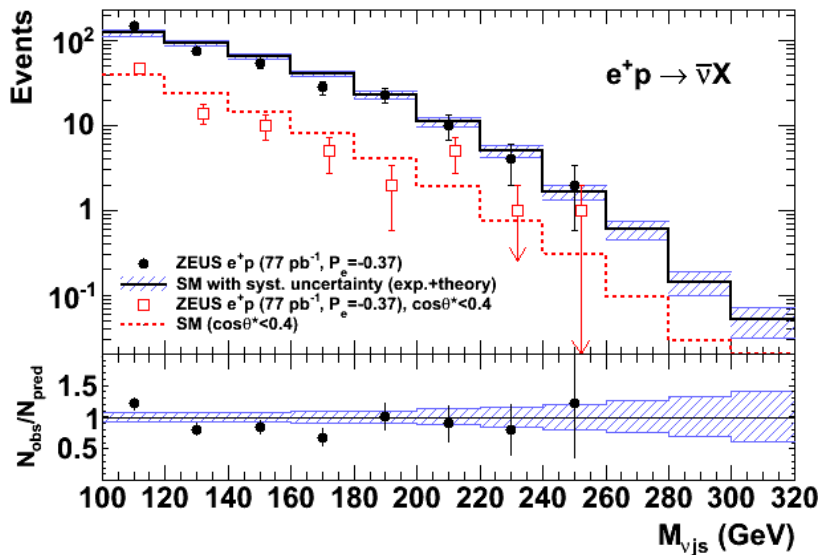
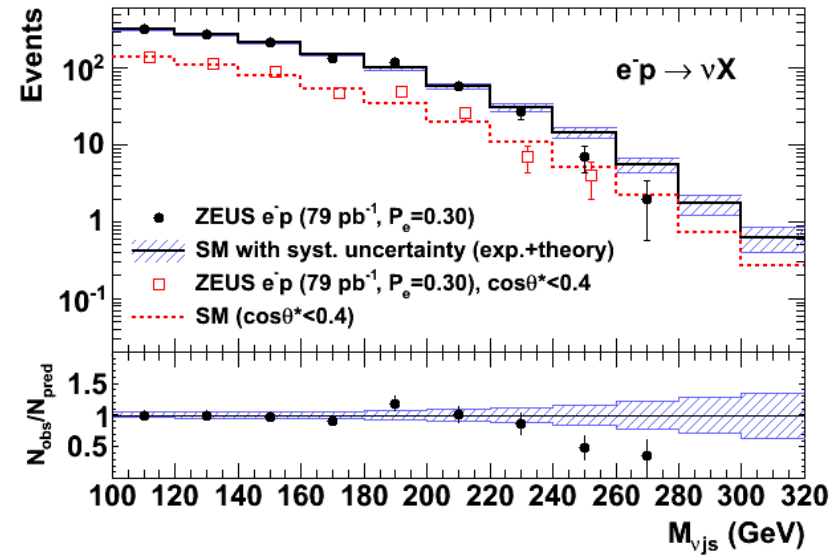
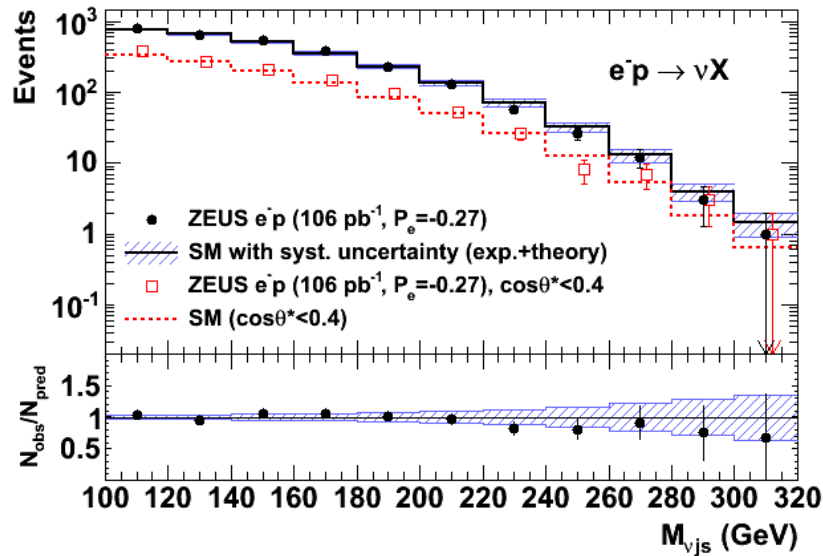
Good agreement between data and MC → no evidence for leptoquarks

CC Invariant Mass Distributions

ZEUS

in red: with cut on $\cos\theta^ < 0.4$*

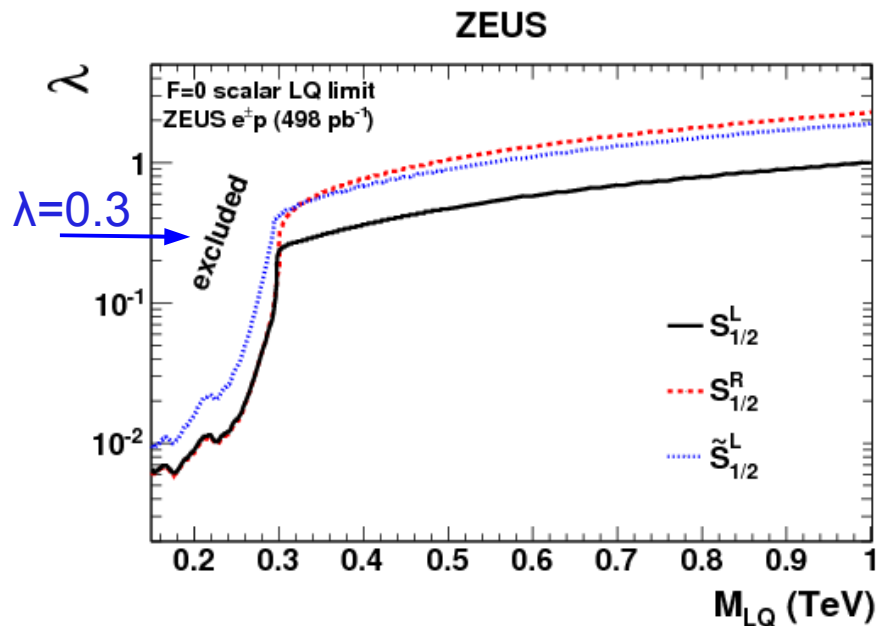
ZEUS



Good agreement between data and MC → no evidence for leptoquarks

Limits for Leptoquarks with $F=0$

- Limits are set on the **Yukawa coupling λ** (e-q-LQ coupling) using a Bayesian approach
- HERA-I data is included in the limit setting

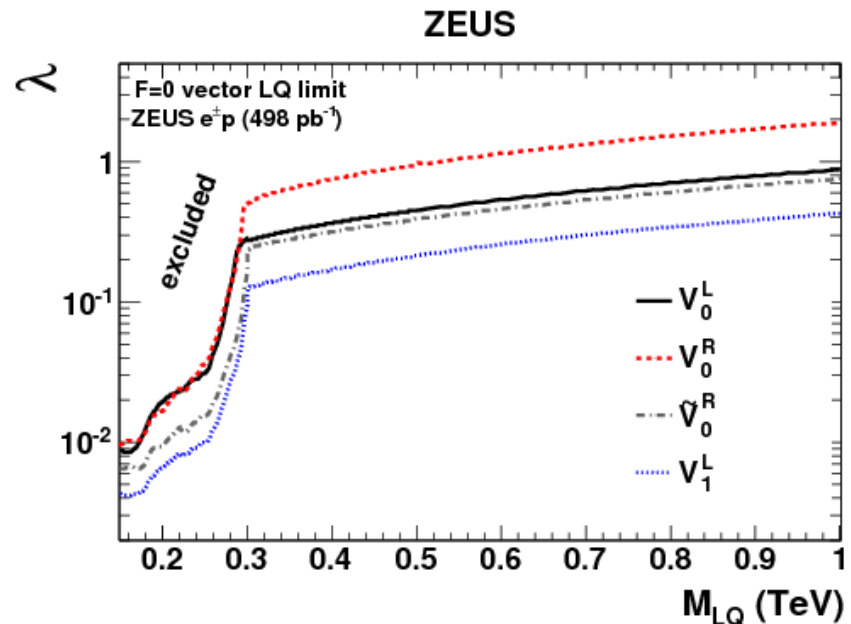


Scalar LQs:

Lower limit on M_{LQ}

assuming $\lambda = \sqrt{4\pi\alpha} = 0.3$:

292 GeV ($\tilde{S}_{1/2}^L$) - 345 GeV ($S_{1/2}^L$)



Vector LQs:

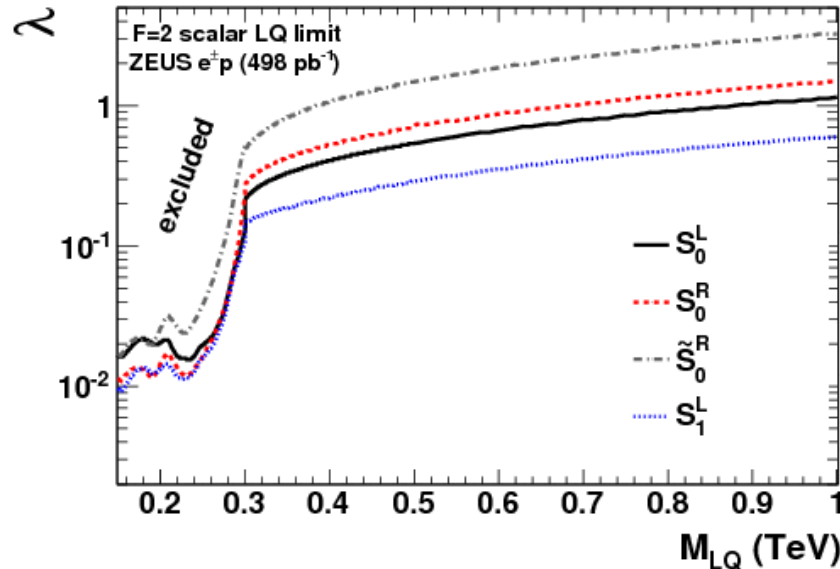
Lower limit on M_{LQ}

assuming $\lambda=0.3$:

292 - 699 GeV

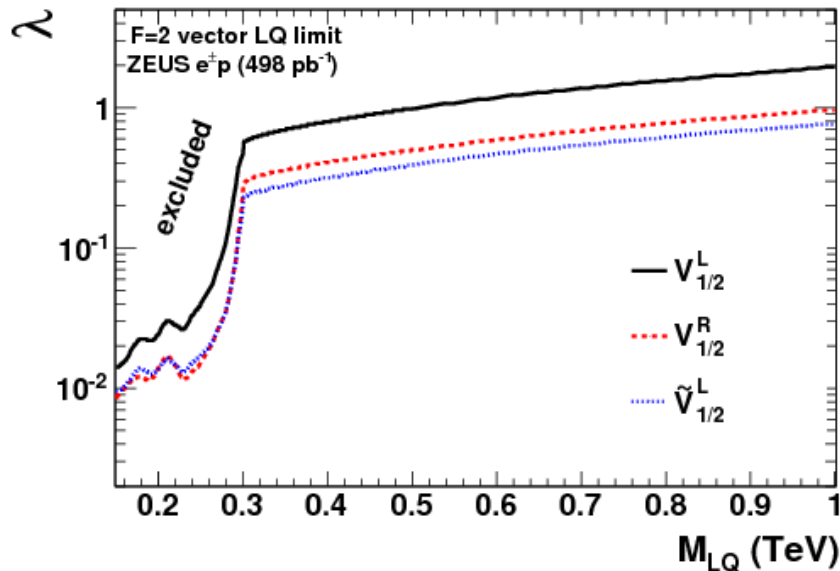
Limits for Leptoquarks with $F=2$

ZEUS



Scalar LQs:

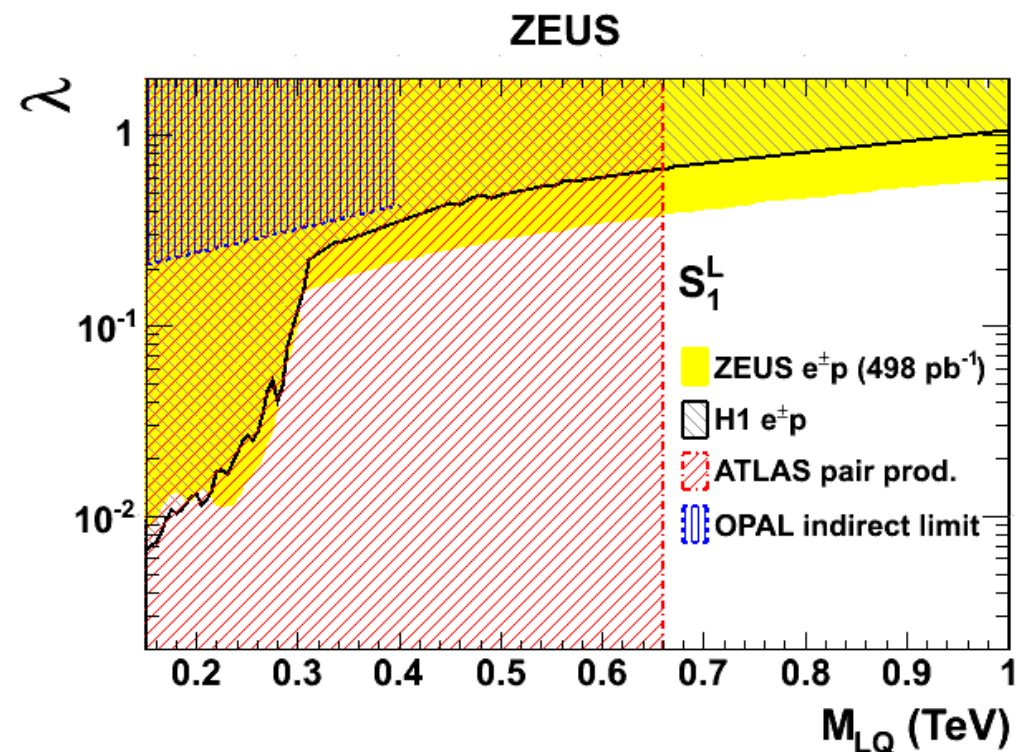
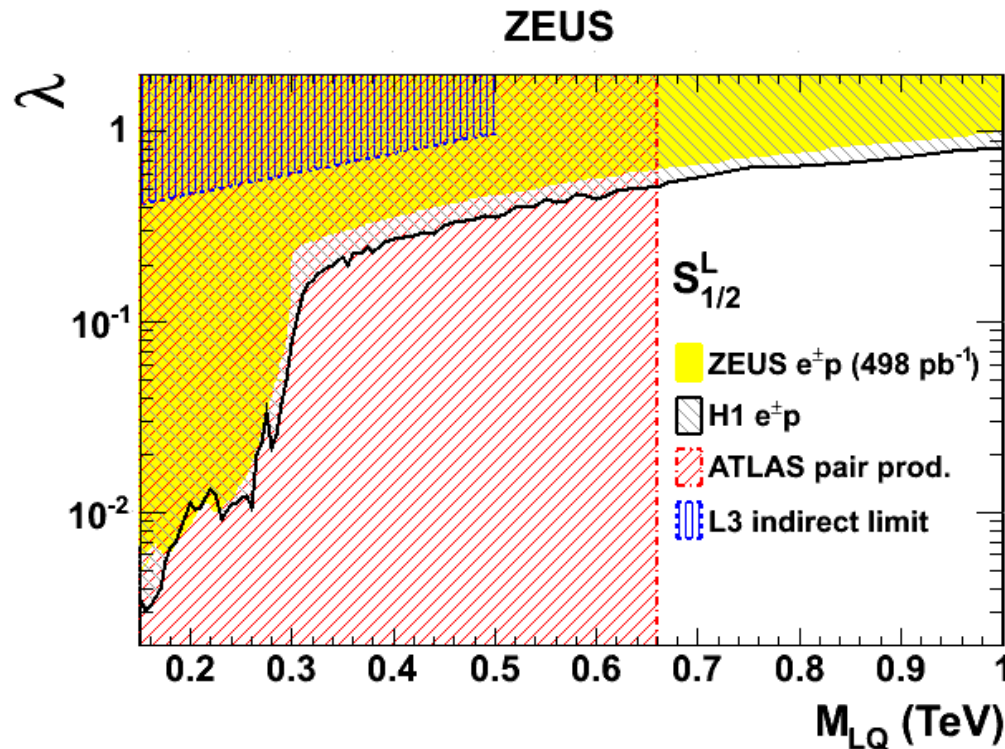
Lower limit on M_{LQ} assuming $\lambda=0.3$:
290 - 506 GeV



Vector LQs:

Lower limit on M_{LQ} assuming $\lambda=0.3$:
292 - 376 GeV

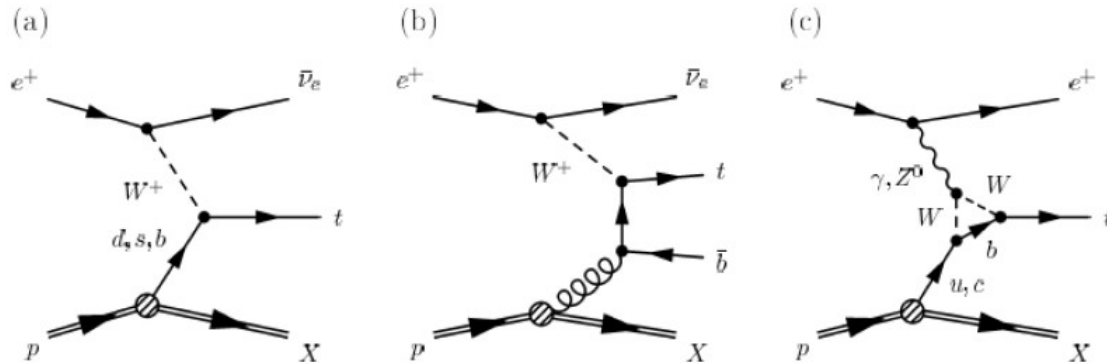
Comparison with Other Experiments



- **ATLAS:** leptoquark pair production \rightarrow mass limits independent of λ
- **L3/OPAL:** indirect t/u -channel effects in $e^+e^- \rightarrow q\bar{q} \rightarrow$ limits on λ as a function of the LQ mass
- **HERA** limits are the best to date at high masses

Single Top Production at HERA

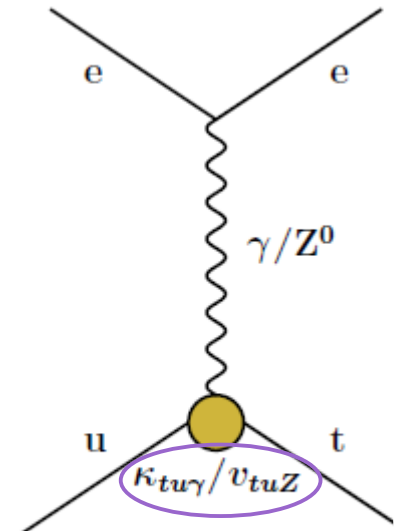
- Top quarks at HERA can only be singly produced
- Production in the SM:



- **Strongly suppressed** by the GIM mechanism, $\sigma < 1$ fb
- Single top production at HERA **via FCNC** predicted by **several BSM theories** → **observation would be clear indication of new physics**
- FCNC transition induced by **coupling tuV** parametrised as:

$$\Delta\mathcal{L}_{\text{eff}} = e e_t \bar{t} \frac{i\sigma_{\mu\nu} p^\nu}{\Lambda} (\kappa_\gamma) u A^\mu + \frac{g}{2 \cos \theta_W} \bar{t} \gamma_\mu (v_Z) u Z^\mu + \text{h.c.}$$

- At HERA, **most sensitive to coupling $\kappa_{tu\gamma}$**



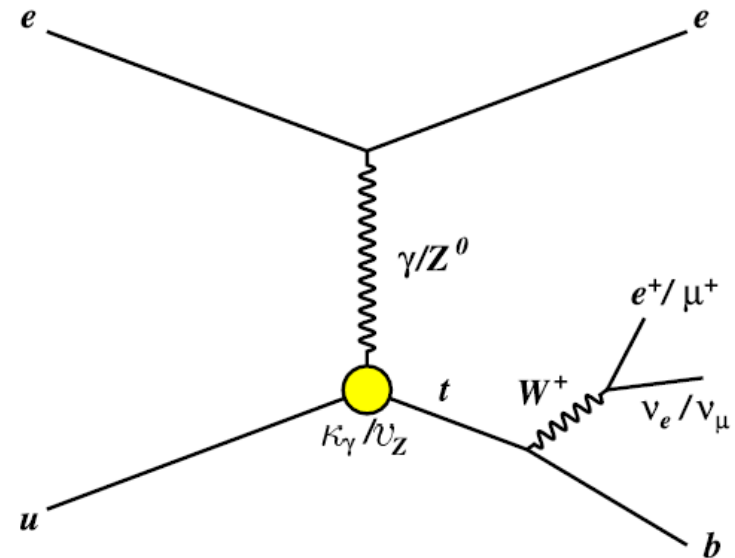
Event Topology

- Single top production was searched for in two channels:

- muon channel: $t \rightarrow b\mu\nu_\mu$
- electron channel: $t \rightarrow be\nu_e$

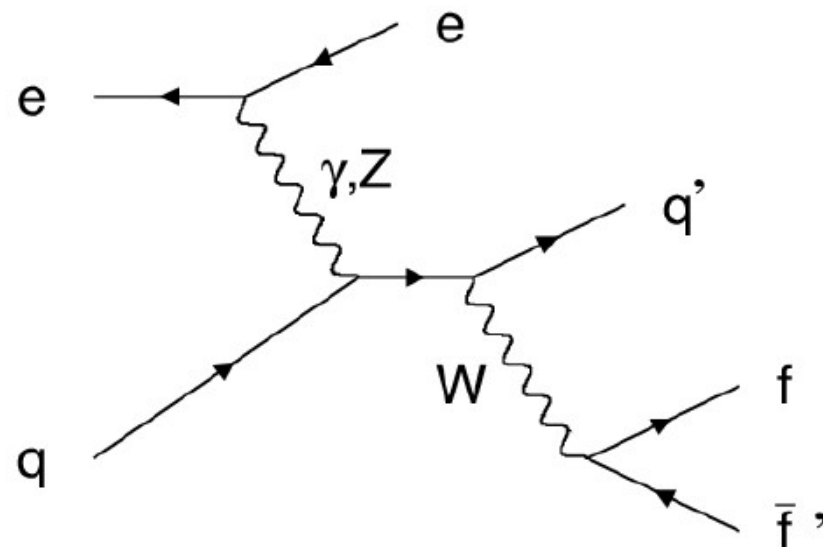
- Event topology:

- 1 isolated lepton with high p_T
- Large missing p_T
- High hadronic transverse momentum $p_{T,had}$



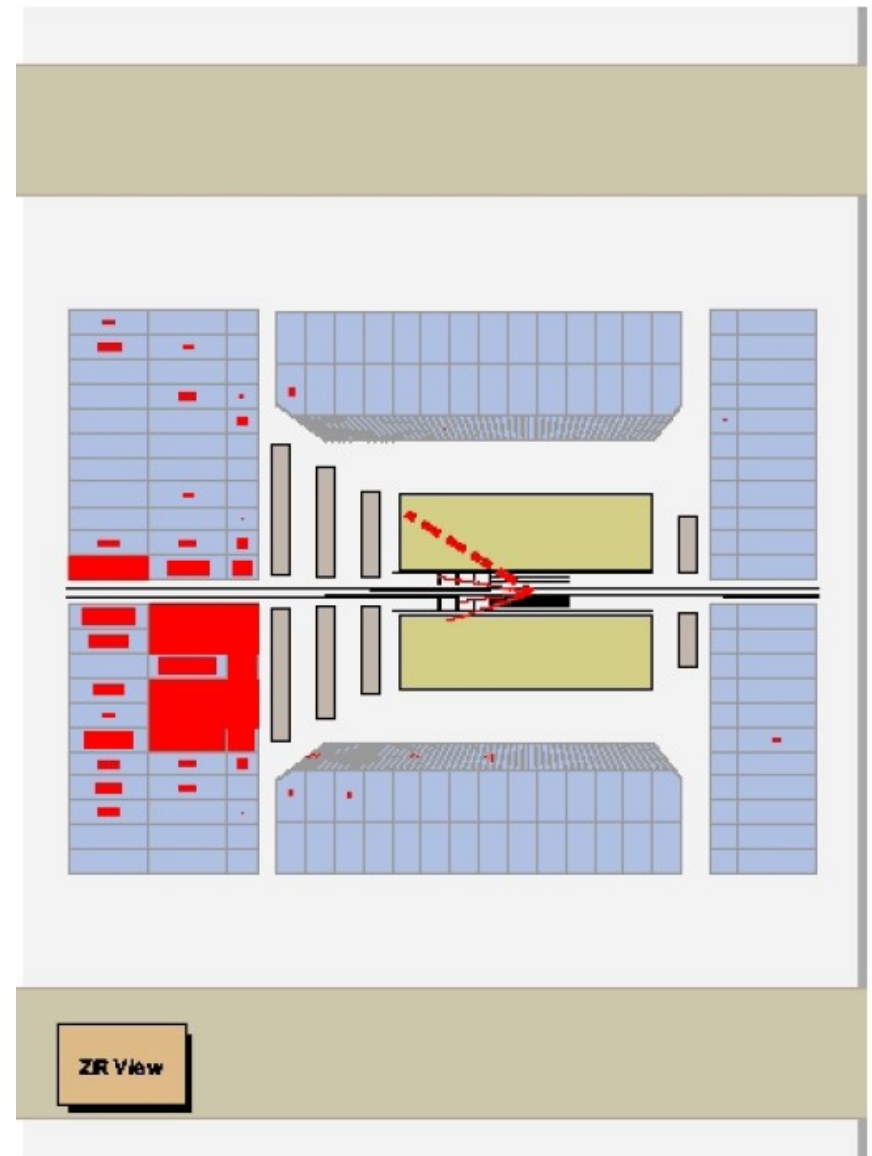
High- p_T isolated lepton events

- In the SM, events with **high- p_T isolated leptons and large missing p_T** are mainly due to **single W production** ($\sigma \sim 1$ pb)
- In contrast to single top production, this process has low $p_{T,had} \rightarrow$ **$p_{T,had}$ can be used to discriminate the two processes**
- Sources of **background**:
 - Dimuon production (muon channel)
 - NC DIS (electron channel)
 - CC DIS
 - Photoproduction
 - Cosmic background (muon channel)



Event Selection

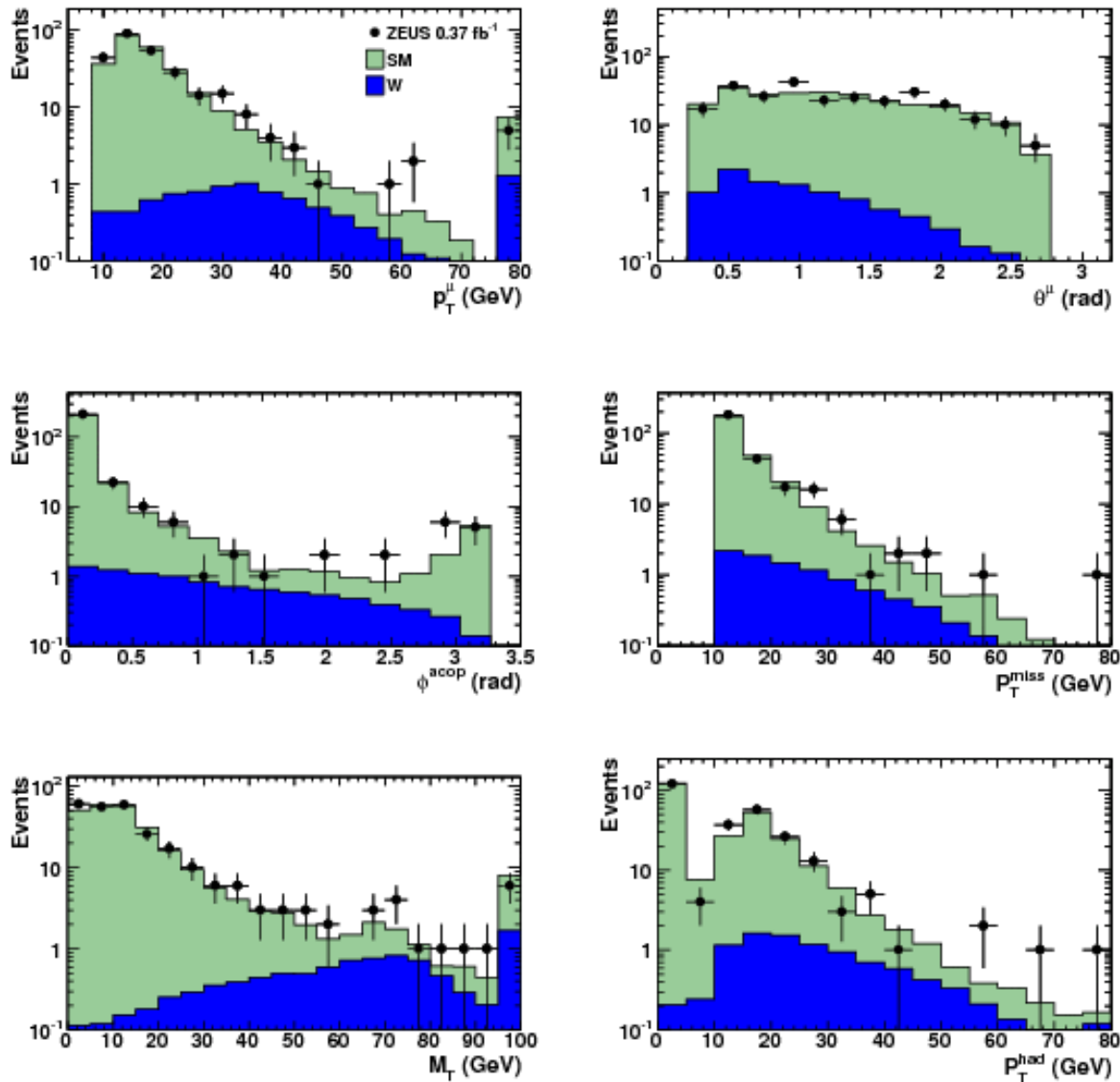
- All HERA-II data (0.37 pb^{-1}) were analysed
- Muon channel:
 - $|Z_{\text{vtx}}| < 30 \text{ cm}$
 - $E-P_z > 10 \text{ GeV}$
 - $P_{T,\text{miss}} > 10 \text{ GeV}$
 - ≥ 1 muon candidate with an isolated track coming from the primary vertex, $p_T > 8 \text{ GeV}$
- Electron channel:
 - $|Z_{\text{vtx}}| < 30 \text{ cm}$
 - $5 < E-P_z < 50 \text{ GeV}$
 - $P_{T,\text{miss}} > 12 \text{ GeV}$
 - ≥ 1 electron candidate with an isolated track coming from the primary vertex, $p_T > 10 \text{ GeV}$
 - $0.1 < \text{acoplanarity} < (\pi - 0.1) \text{ rad}$



Selected event in the muon channel

Muon Channel

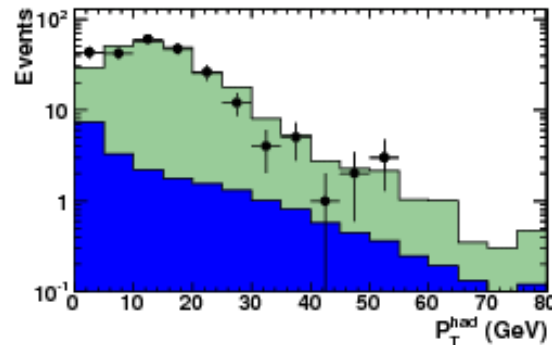
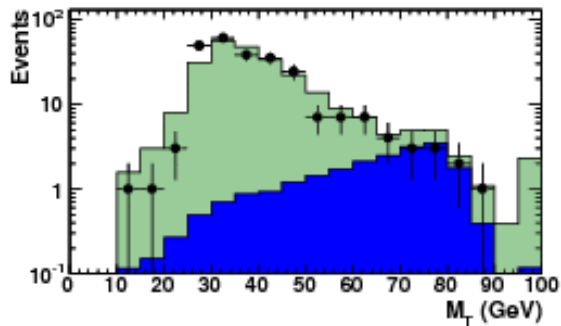
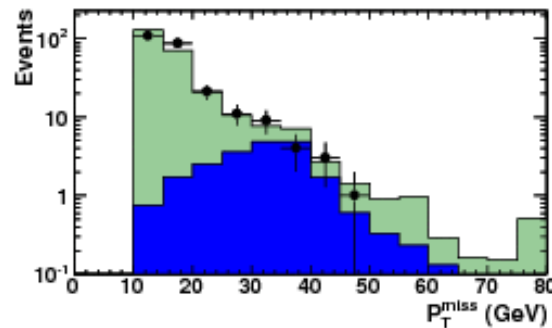
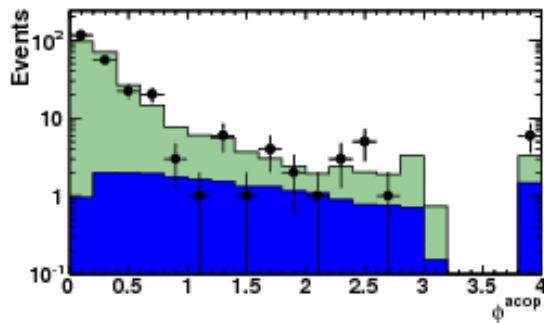
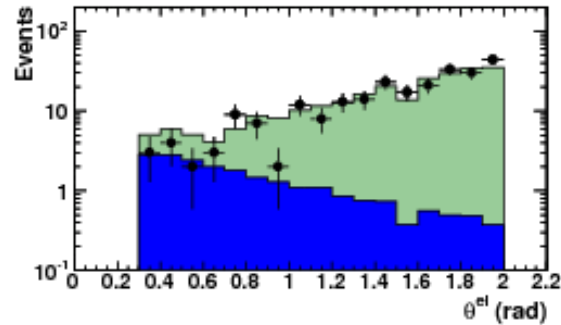
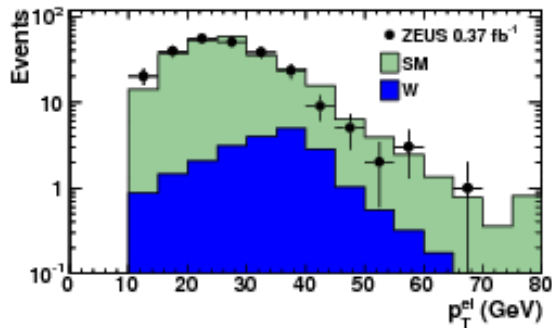
ZEUS



- Good agreement between data and MC
- 269 events selected, 260 ± 3 are expected
- Dominated by dimuon production

Electron Channel

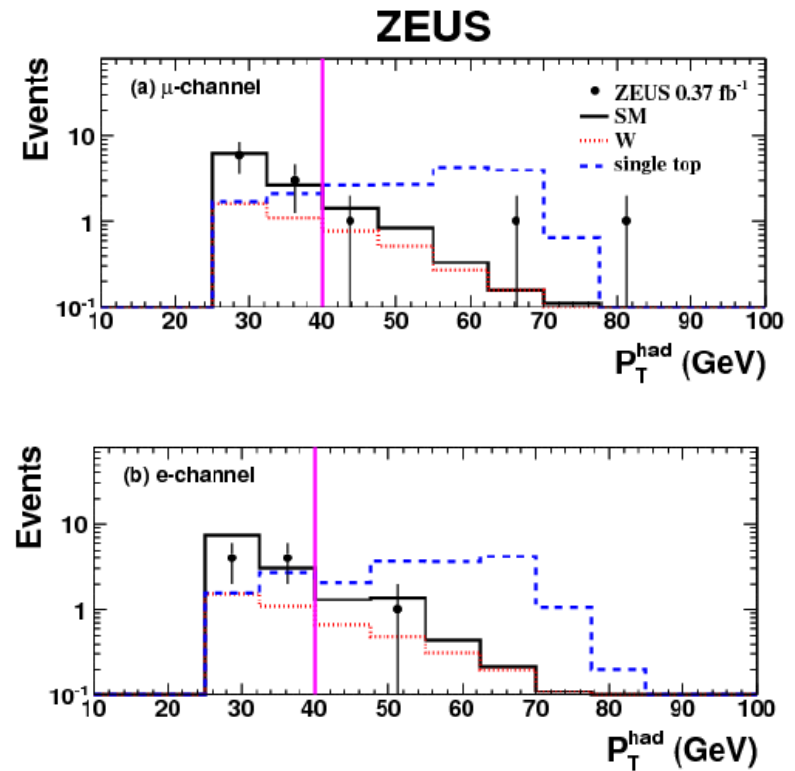
ZEUS



- Good agreement between data and MC
- 245 events selected, 253 ± 6 are expected
- Dominated by NC DIS

Selection of Single Top Candidates

- No excess above the SM is seen → further selection is made to maximise the sensitivity to a possible FCNC top signal:
- $p_{T,had} > 40$ GeV for both channels
- Muon channel:
 - Acoplanarity > 0.05 rad
 - Events with more than one isolated muon are rejected
- Electron channel:
 - Acoplanarity > 0.15 rad
 - $p_{T,miss} > 15$ GeV
- Good agreement between data and MC
- No discrepancy at high $p_{T,had}$



Limit Setting (I)

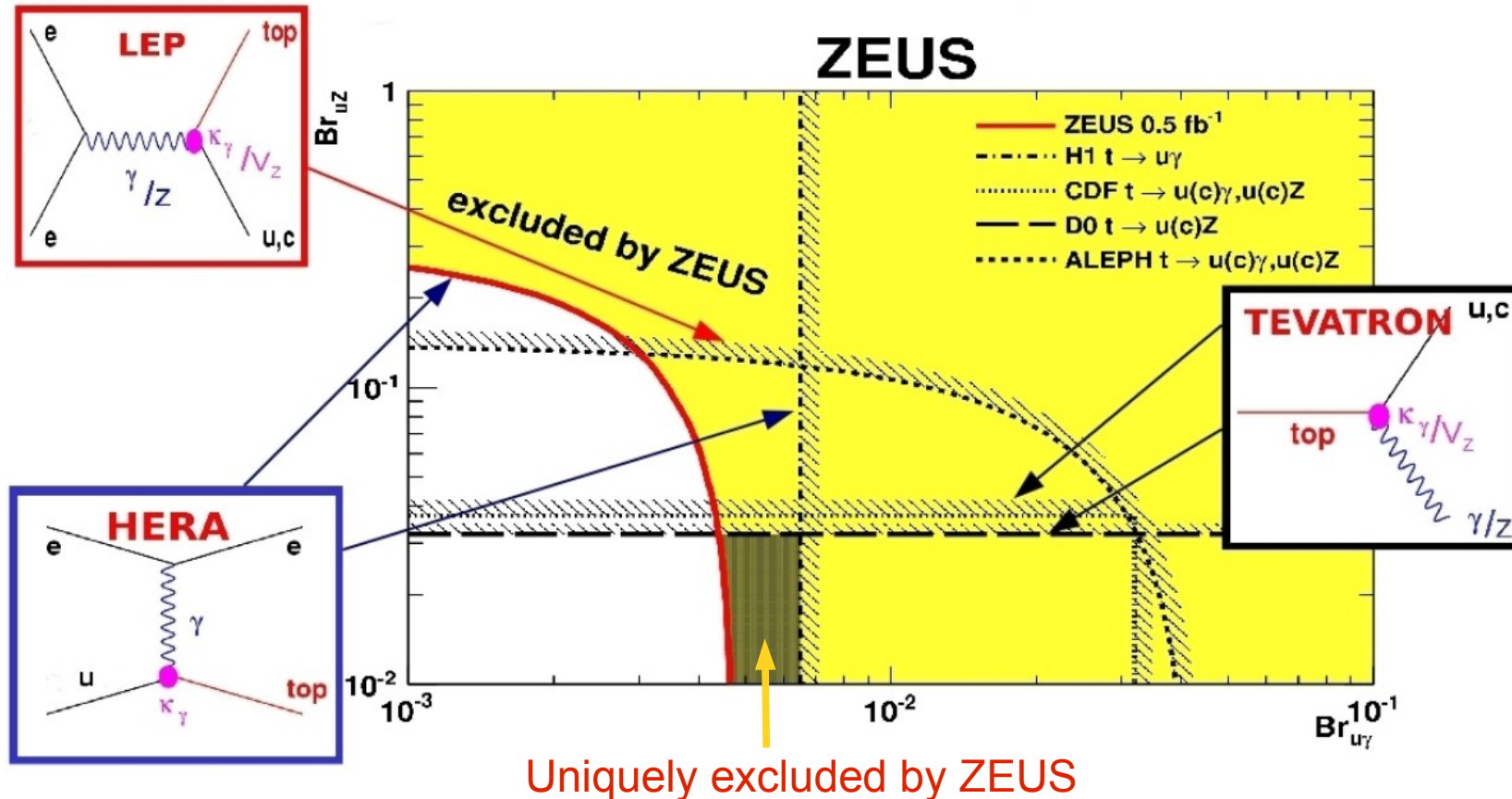
- Single top selection:

	N^{obs}	N^{pred}	$W[\%]$
electron channel e^+p	0	1.7 ± 0.4	53 ± 11
muon channel e^+p	1	1.5 ± 0.2	64 ± 9
electron channel e^-p	1	1.9 ± 0.4	51 ± 11
muon channel e^-p	2	1.5 ± 0.3	63 ± 9
electron channel ep	1	3.6 ± 0.6	52 ± 9
muon channel ep	3	3.0 ± 0.4	64 ± 7

- No excess above SM \rightarrow set **limits on the tuV couplings**
- **HERA-I data is included** in the limit setting
- First step: **limit** set on **signal cross section and κ_γ assuming $v_Z=0$**
- **Bayesian approach** used assuming constant prior on σ
 $\rightarrow \sigma < 0.13 \text{ pb (95\% CL) at } \sqrt{s}=315 \text{ GeV}$
- Converts to limit on coupling: $\kappa_\gamma < 0.12 \text{ (95\% CL)}$

Limit Setting (II)

- Second step: assume $v_Z \neq 0$ and set limits in $(BR(t \rightarrow u\gamma), BR(t \rightarrow uZ))$ plane
- Same coupling was probed by LEP, Tevatron and H1



- In the region where $BR(t \rightarrow uZ) < 4\%$, the ZEUS limits are the best to date

Summary

- Recent searches for new physics at ZEUS have been presented
- No signs of new physics were observed
- Limits set on 1st generation leptoquarks and anomalous single top production
- ZEUS results are competitive and complementary to other experiments

Backup

Leptoquarks in Aachen Notation

Model	Fermion number F	Charge Q	$BR(LQ \rightarrow e^\pm q)$ β	Coupling	Squark type
S_\circ^L	2	-1/3	1/2	$e_L u \quad \nu d$	\tilde{d}_R
S_\circ^R	2	-1/3	1	$e_R u$	
\tilde{S}_\circ	2	-4/3	1	$e_R d$	
$S_{1/2}^L$	0	-5/3 -2/3	1 0	$e_L \bar{u}$ $\nu \bar{u}$	
$S_{1/2}^R$	0	-5/3 -2/3	1 1	$e_R \bar{u}$ $e_R \bar{d}$	
$\tilde{S}_{1/2}$	0	-2/3 +1/3	1 0	$e_L \bar{d}$ $\nu \bar{d}$	$\overline{\tilde{u}_L}$ $\overline{\tilde{d}_L}$
S_1	2	-4/3 -1/3 +2/3	1 1/2 0	$e_L d$ $e_L u \quad \nu d$ νu	
V_\circ^L	0	-2/3	1/2	$e_L \bar{d} \quad \nu \bar{u}$	
V_\circ^R	0	-2/3	1	$e_R \bar{d}$	
\tilde{V}_\circ	0	-5/3	1	$e_R \bar{u}$	
$V_{1/2}^L$	2	-4/3 -1/3	1 0	$e_L d$ νd	
$V_{1/2}^R$	2	-4/3 -1/3	1 1	$e_R d$ $e_R u$	
$\tilde{V}_{1/2}$	2	-1/3 +2/3	1 0	$e_L u$ νu	
V_1	0	-5/3 -2/3 +1/3	1 1/2 0	$e_L \bar{u}$ $e_L \bar{d} \quad \nu \bar{u}$ $\nu \bar{d}$	