A search for resonance decays to lepton+jet at HERA and limits on leptoquarks

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- HERA Accelerator & ZEUS Detector
- Search for leptoquarks at HERA
- Limits on leptoquarks
- Single top production: appetizer
HERA Accelerator

- HERA: ep collider, $\sqrt{s} = 320$ GeV
- From 2003 polarised lepton beam
- 2 colliding beams experiments: H1 & ZEUS
  - collected 0.5 pb$^{-1}$/exp of luminosity in 1992-2007

ZEUS: multi-purpose detector at HERA
Deep Inelastic Scattering

4-momentum transfer
\[ Q^2 = -q^2 = -(k - k')^2 \]
parton momentum fraction
\[ x = Q^2/(2p \cdot q) \]
inelasticity
\[ y = p \cdot q/(p \cdot k) \]
center of mass (c.m.s) energy \( \sqrt{s} \):
\[ s = (k + p)^2 \]
at fixed c.m.s energy: \( y = Q^2/xs \)

lepton vertex: pointlike particle, determined by electroweak Standard Model (SM)
proton vertex: object with structure
quark-parton-model (QPM):
elastic scattering on pointlike parton (quark);
quark momentum distribution \( xq(x) \) inside proton

neutral current (NC): \( \gamma, Z^0 \) exchange
charged current (CC): \( W^\pm \) exchange

NC: electron + jet

CC: missing \( p_T \) + jet
Leptoquarks @ HERA

- Leptoquarks - scalar or vector colour triplet bosons, carrying both lepton (L) and baryon (B) number
  - HERA is well suited for leptoquark searches
  - Fermion number: $F = L + 3B$, $F = 0, 2$
  - spin: 0, 1

(a) @ HERA leptoquarks can be produced in $s$-channel for $M_{LQ} < \sqrt{s}$
(b) ...or exchanged in $u$-channel

(c) LQs @ HERA have the same initial and final state as NC/CC DIS
  - $e$-jet or $\nu$-jet in the final state
  → interfere with the SM
Search Strategy @ HERA

- Leptoquark events: the same signature as NC or CC events
- LQ contribution in SM: 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
- Lepton scattering angle $\theta^*$ in the lepton-jets scattering frame can be used to reduce DIS background
  • leptoquarks have different distributions than NC DIS

Look for LQ-deviations from SM in NC & CC distributions
Leptoquarks in ZEUS Detector

Integrated luminosity of 366 pb\(^{-1}\) (2003-2007)

\[ M_{e\text{-jet}} \]

\( e^+\text{jet} \) final state

\[ M_{ejs} \, (\text{GeV}) \]

\[ M_{\nu\text{-jet}} \]

\( \nu^+\text{jet} \) final state

\[ M_{\nujs} \, (\text{GeV}) \]
NC Invariant Mass Distribution

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

Good agreement between data and MC $\rightarrow$ no evidence for LQs
CC Invariant Mass Distribution

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

Good agreement between data and MC $\rightarrow$ no evidence for LQs
Leptoquark Limits

• No evidence for LQs observed → limits set within BRW model
• The Buchmüller-Rückl-Wyler model:
  • Standard Model symmetry conserved
  • Lepton and baryon number conserved
  • LQ resonance production
  • 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
• Limits are set on Yukawa coupling $\lambda$ (e-q-LQ coupling) using Bayesian approach

Full HERA statistics of 0.5 fb$^{-1}$ used for limit setting
Limits for Leptoquarks with F=0

Scalar LQs:
- Lower limit on $M_{LQ}$ assuming $\lambda = 0.3$
  - $292 \text{ GeV} - 345 \text{ GeV}$

Vector LQs:
- Lower limit on $M_{LQ}$ assuming $\lambda = 0.3$
  - $292 \text{ GeV} - 699 \text{ GeV}$
Limits for Leptoquarks with F=2

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

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

- New results using full HERA luminosity of 0.5 fb$^{-1}$ on LQs: **DESY-12-077**
- No evidence of leptoquarks observed
  → Coupling limits set as function of LQ mass
- Limits for some LQs similar to results from other experiments
- ZEUS results competitive and complementary to other experiments

**HERA limits are the best to date at high masses**
High-$P_T$ Lepton and Missing $E_T$

- another example of similar topology:

\[
\begin{align*}
\text{single top production}
\end{align*}
\]

- no evidence of single top found

- limits set on anomalous single top production

Search for single top production in $ep$ collisions at HERA

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In $ep$ (with a electron or positron) collisions at HERA, the production of single top quark is possible due to the large centre-of-mass energy $|s| = 315$ GeV. The dominant production process of single top quark in the Standard Model (SM) is the charged current (CC) deep inelastic scattering (DIS) reaction $ep \rightarrow \ell^- X$, which has a cross section of less than 1 fb [2]. No noticeable production is hence expected in our data sample and any excess can be attributed to new physics. In several extensions of the SM, single top production can happen via a flavour changing neutral current (FCNC) process mediated by a heavy scalar or pseudoscalar boson (or $Z'$) [3]. The analysis has been performed with 0.37 fb$^{-1}$ and extends the previously published ZEUS results [4] corresponding to 0.15 fb$^{-1}$. Limits for single top production via FCNC were compared with the previous ZEUS one [4], for a total luminosity of 0.50 fb$^{-1}$. The cross section upper limit at 95% Credibility Level (C.L.) was 1.3 pb at a centre-of-mass energy of $s = 315$ GeV. The results of this analysis have been published in [5].

Event selection

The event selection was optimized for single-top production via photon exchange, looking for the dominant decay $t \rightarrow W b$ and subsequent $W$ decay to $\ell \nu$ and their respective antiparticles. The selection is based on imposing an isolated, high-$p_T$, leptonic, large missing transverse momentum and high invariant mass $m_{t\bar{t}}$.

Preselection plots

The FCNC couplings could induce single-top production in $ep$ collisions. In this process, the incoming lepton exchanges a $Z'$ or $Z$ with an up quark in the proton, yielding a top quark in the final state. Owing to the large $Z'$ mass, this process is more sensitive to a coupling of the type $y$. Furthermore, large values of $y$, the fraction of the proton momentum carried by the $Z'$, are needed to produce a top quark. Since the $Z'$-quark production distribution function (PDF) of the photon is dominant at large $y$, the production of single-top quarks is most sensitive to the $y$ coupling.

Systematic uncertainties

The main contribution to the systematic uncertainties on the predicted SM events is due to the following sources:

- the theoretical uncertainty on the $W$ background normalisation, $15%$
- the statistical uncertainty on the total SM prediction after the final selection, $13%$ and $9\%$ for the $e$- and $\mu$-channels, respectively.
- the uncertainty on the DIS background, $15\%$ for the preselection and $8\%$ for the final selection in the $e$- and $\mu$-channels.

Limits evaluation

Since no visible excess was found beyond the SM prediction, a limit, assuming a vanishing $y$, was evaluated on the signal cross section using a Bayesian approach, ensuring a constant prior on the cross section $\sigma$. The results are $\sigma < 0.24$ (95% C.L.) pb at $s = 315$ GeV. Such limit was converted into a limit on the coupling $\lambda_{y\ell} < 0.66$ (95% C.L.). The result of this analysis was combined with the previous ZEUS result [4]: $\lambda_{y\ell} < 0.43$ (95% C.L.). Constraints on the anomalous top branching ratios $e \rightarrow \ell \nu (\ell \nu)$ and $e \rightarrow \ell \gamma$ were also evaluated assuming a non-zero coupling $y$. Such limits were evaluated in the $(\ell \nu, \ell \gamma)$ plane following a Bayesian approach.

This figure shows the ZEUS boundary in the $(\ell \nu, \ell \gamma)$ plane compared to limits from other experiments. The $e$ and $\mu$ lepton cuts, contrary to HERA, have similar sensitivities to $y$ and $e$-quark; their limits are hence on both decays $e \rightarrow \ell \nu$ with $y$. The yellow area is excluded by ZEUS. The dark shaded region denotes the area uniquely excluded by ZEUS. The limits set by the ZEUS experiments in the region where $2 \gamma$ is less than $-4\%$ are the best to date.
Single-top Production: Appetizer

- Dark shaded area uniquely excluded by ZEUS

For details see ZEUS Single-top Poster