Perspectives on New Phenomena

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Abstract A compilation of searches for new phenomena at HERA is presented. Reviewed are direct searches of new fermions and leptoquarks and indirect signatures of compositeness, leptoquarks and new heavy neutral vector bosons mediated through contact interactions.

1 Introduction

This article reviews the perspectives to discover new phenomena beyond the Standard Model at the future upgraded HERA $e\,p$ collider. Direct formation of new particles, *e.g.* heavy fermions or leptoquarks, typically occur as s-channel resonance and would lead to a spectacular mass peak at $M_X = \sqrt{x\,s} \lesssim 300$ GeV. A considerably larger mass range can be explored through the study of effects from new *virtual* particle exchange or contact interactions. All details and formulae on the underlying model assumptions can be found in the Proceedings *Physics at HERA* of the previous 1991 workshop [1].

The present status of searches for heavy fermions, leptoquarks and contact interactions at HERA is reviewed, labeled as HERA '95, *i.e.* including 1995 data with typical luminosities of $\mathcal{L} = 5 \div 10$ pb^{-1} (H1 and ZEUS publications or contributions to ICHEP 96, Warsaw). Comparing the achieved results with the projections of ref. [1], it turns out that these Monte Carlo analyses are quite realistic. It is therefore appropriate to extrapolate the expected sensitivity on masses and couplings with increasing luminosity by simple scaling laws. Only in few cases new Monte Carlo studies were necessary. Direct searches are assumed to scale as $\propto \mathcal{L}^{1/2}$, while the sensitivity of indirect searches increases like $\propto \mathcal{L}^{1/4}$. Expectations for $\mathcal{L} = 250$ pb^{-1} are labeled HERA 250, those for $\mathcal{L} = 1000$ pb^{-1} as HERA 1000.

Results from other colliders or experiments are included, taking the values compiled by the Particle Data Group [2]. No attempt is made to give a complete list of references.

2 New Fermions

2.1 Exotic Leptons

Searches for exotic leptons $L = E,\ N$ have so far not being carried out at HERA [1] due to the limited luminosity. Mixing angles to ordinary leptons are expected to be smaller than $\mathcal{O}(10^{-1})$.

[1] Recently ZEUS [3] searched for right-handed electron neutrinos decaying into a relatively light right-handed W boson, $N_R \to e\,W_R$

The coupling parameters $\zeta = \zeta_L$ or ζ_R (left or right handed leptons) should be close to the values of the mixing angles. The neutral and charged current Lagrangians are

$$\mathcal{L}^{NC} = \frac{e}{4\,\sin\theta_W\,\cos\theta_W}\left[\zeta_L^E\,\bar{e}\,\gamma_\mu\,(1-\gamma_5)\,E + \zeta_R^E\,\bar{e}\,\gamma_\mu\,(1+\gamma_5)\,E\right]\,Z^\mu + h.c.\,, \qquad (1)$$

$$\mathcal{L}^{CC} = \frac{e}{2\,\sqrt{2}\,\sin\theta_W}\left[\zeta_L^N\,\bar{e}\,\gamma_\mu\,(1-\gamma_5)\,N + \zeta_R^N\,\bar{e}\,\gamma_\mu\,(1+\gamma_5)\,N\right]\,W^\mu + h.c.\,, \qquad (2)$$

$$\Gamma_{L\to Z\,l} \simeq \frac{G_F}{16\,\sqrt{2}\,\pi}\,\zeta^2\,M_L^3\,, \qquad \Gamma_{L\to W\,l} \simeq \frac{G_F}{8\,\sqrt{2}\,\pi}\,\zeta^2\,M_L^3\,. \qquad (3)$$

The cross section for heavy lepton production at HERA can be parametrized as

$$\sigma(e\,p\to L\,X) \simeq c\,\zeta^2\left(\frac{M_L}{100\ \mathrm{GeV}}\right)^{-b}\ \mathrm{pb}\,, \qquad (4)$$

with the coefficients

$c(N_L) = 15\,,\quad c(N_R) = 10\,,\quad b(N_L \text{ or } N_R) = 4.5\,,$
$c(E_L) = 2.5\,,\quad c(E_R) = 1.5\,,\quad b(E_L \text{ or } E_R) = 3.5\,.$

heavy lepton	HERA 250 M_L [GeV]	HERA 1000 M_L [GeV]
N_L	130	170
N_R	115	160
E_L	60	110
E_R	50	90

Table 1: Accessible heavy lepton masses ($N_{evt}^{obs} \geq 20$) for couplings $\zeta^2 = 0.02$ and a detection efficiency $\epsilon = 0.5$

Experiments at e^+e^- colliders can exclude heavy lepton masses up to $M_L \lesssim \sqrt{s}/2$.

Conclusion HERA is an excellent place to search for exotic leptons E and N.

2.2 Excited Leptons

The cross section for excited lepton l^* production in narrow width approximation is

$$\sigma(e\,p\to l^*\,X) = \frac{4\,\pi^2}{s}\,(2\,J+1)\,\frac{\Gamma_{l^*}}{M_{l^*}}\,\mathcal{B}\ f_{\gamma/p}(M_{l^*}^2/s)\,, \qquad (5)$$

$$\Gamma_{l^*} \simeq \alpha\,M_{l^*}^3\,\frac{c_{V\,l^*\,l}^2}{\Lambda^2}\,. \qquad (6)$$

The decay into an ordinary lepton l and vector boson V, branching ratio $\mathcal{B}(l^*\to l\,V)$, occurs via magnetic coupling $-i\,\frac{e}{\Lambda}\,\sigma_{\mu\nu}\,q^\nu\,(1-\gamma_5)\,c_{V\,l^*\,l}$. $f_{\gamma/p}(x)$ is the photon density in the proton.

LEP experiments can exclude excited leptons up to masses $M_{l^*} \lesssim \sqrt{s}/2$ for pair production and $M_{l^*} \lesssim \sqrt{s}$ for single production, assuming $\mathcal{B}(l^*\to l\,\gamma) = 1$ and electroweak couplings to the photon (λ_γ) or Z (λ_Z) exchange. The relation between the couplings is $\lambda/M_{l^*} = \sqrt{2}\,c_{V\,l^*\,l}/\Lambda$.

	HERA '95	
$e^* \to e\,\gamma$	$\sigma \lesssim 0.8\ (2)$ pb	$M \gtrsim 100\ (50)$ GeV
$e^* \to \nu\,W,\ e\,Z$	$\sigma \lesssim 2$ pb	$M \gtrsim 110$ GeV
$\nu^* \to \nu\,\gamma$	$\sigma \lesssim 1$ pb	$M \gtrsim 50$ GeV
$\nu^* \to e\,W,\ \nu\,Z$	$\sigma \lesssim 2.5$ pb	$M \gtrsim 125$ GeV

Table 2: Upper limits (95% cl) on the cross section for excited lepton production

M_{l^*} [GeV]	HERA '95 $c\,\mathcal{B}^{1/2}/\Lambda$ [GeV]$^{-1}$	HERA 250 $c\,\mathcal{B}^{1/2}/\Lambda$ [GeV]$^{-1}$	HERA 1000 $c\,\mathcal{B}^{1/2}/\Lambda$ [GeV]$^{-1}$
$e^* \to e\,\gamma$			
100	$1 \cdot 10^{-3}$	$2 \cdot 10^{-4}$	$1 \cdot 10^{-4}$
150	$1.2 \cdot 10^{-3}$	$2 \cdot 10^{-4}$	$1 \cdot 10^{-4}$
200	$2.5 \cdot 10^{-3}$	$5 \cdot 10^{-4}$	$2.5 \cdot 10^{-4}$
250	$1 \cdot 10^{-2}$	$2 \cdot 10^{-3}$	$1 \cdot 10^{-3}$
$\nu^* \to \nu\,\gamma$			
100	$8 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$	$8 \cdot 10^{-4}$
150	$1 \cdot 10^{-2}$	$2 \cdot 10^{-3}$	$1 \cdot 10^{-3}$
200	$2.5 \cdot 10^{-2}$	$5 \cdot 10^{-3}$	$2.5 \cdot 10^{-3}$

Table 3: Upper limits (95% cl) on couplings $c\,\mathcal{B}^{1/2}/\Lambda$ as a function of the excited lepton mass

Conclusion HERA is an excellent place to search for excited electrons and neutrinos. The sensitivity to couplings $c\,\mathcal{B}^{1/2}/\Lambda$ can be increased by an order of magnitude.

References HERA data: H1 Collaboration [4], ZEUS Collaboration [5]

2.3 Leptogluons

The cross section for leptogluon LG production in narrow width approximation is

$$\sigma(e\,p \to LG\,X) = \frac{2\,\pi^2\,\alpha_s}{s} \left(\frac{M_{LG}}{\Lambda}\right)^2 g(M_{LG}^2/s)\ , \tag{7}$$

$$\Gamma_{LG} = \frac{\alpha_s}{4}\,\frac{M_{LQ}^3}{\Lambda^2}\ , \tag{8}$$

where $g(x)$ is the gluon density in the proton.

Conclusion HERA has a rich potential to search for leptogluons. Scale parameters Λ of more than one order of magnitude larger can be probed.

References HERA data: H1 Collaboration [6]

M_{LG} [GeV]	HERA '95 Λ [TeV]	HERA 250 Λ [TeV]	HERA 1000 Λ [TeV]
50	5	125	250
100	3	65	125
150	1.2	30	65
200	0.5	25	50
250	0.2	6	15
280	0.1	1.5	3

Table 4: Lower limits (95% *cl*) on the scale parameter Λ as a function of the leptogluon mass

2.4 Excited Quarks

At HERA excited quark q^* production proceeds via electroweak couplings $\gamma\, q \to q^*$. The cross section for excited quark production can be written analogous to the excited fermion case including a convolution of the photon densities in the electron $f_{\gamma/e}$

$$\sigma(e\,p \to q^*\,X) \;=\; \frac{4\,\pi^2}{s}\,(2\,J+1)\,\frac{\Gamma_{q^*}}{M_{q^*}}\,\mathcal{B}\;f_{\gamma/e}\;f_{q/p}(M_{q^*}^2/s)\;, \tag{9}$$

$$\Gamma_{q^*} \;\simeq\; \alpha\,M_{q^*}^3\,\frac{c_{V\,q^*\,l}^2}{\Lambda^2}\;. \tag{10}$$

The actual upper limit on the cross section for q^* production (HERA '95 data at 95% *cl*) is

$$\sigma(e\,p \to q^*\,X)\cdot\mathcal{B}(q^* \to q\,\gamma) \;\lesssim\; 2 \text{ pb} \qquad \text{for} \quad M_{q^*} \gtrsim 100 \text{ GeV}\;.$$

M_{q^*} [GeV]	HERA '95 $c\,\mathcal{B}^{1/2}/\Lambda$ [GeV]$^{-1}$	HERA 250 $c\,\mathcal{B}^{1/2}/\Lambda$ [GeV]$^{-1}$	HERA 1000 $c\,\mathcal{B}^{1/2}/\Lambda$ [GeV]$^{-1}$
100	$1\cdot 10^{-3}$	$2\cdot 10^{-4}$	$1\cdot 10^{-4}$
150	$1.2\cdot 10^{-3}$	$2.5\cdot 10^{-4}$	$1.2\cdot 10^{-4}$
200	$3\cdot 10^{-3}$	$6\cdot 10^{-4}$	$3\cdot 10^{-4}$
250	$2\cdot 10^{-2}$	$4\cdot 10^{-3}$	$2\cdot 10^{-3}$

Table 5: Upper limits (95% *cl*) on couplings $c\,\mathcal{B}^{1/2}/\Lambda$ as a function of the excited quark mass

LEP experiments can exclude excited quarks up to masses $M_{q^*} \lesssim \sqrt{s}/2$ for pair production and $M_{q^*} \lesssim \sqrt{s}$ for single production. At the TEVATRON excited quark production proceeds via QCD couplings $g\,q \to q^*$, yielding $M_{q^*} > 540$ GeV.

Conclusion HERA is superior to LEP in the search for excited quarks q^*. The mass limit from $\bar{p}\,p$ experiments, giving complementary information on the $g\,q$ coupling, cannot be reached.

References HERA data: H1 Collaboration [4], ZEUS Collaboration [5]

3 Leptoquarks

Leptoquarks LQ are colour triplet bosons of spin 0 (7 scalars S) or 1 (7 vectors V), carrying lepton and baryon number and fractional electric charge.

The cross section for leptoquark production in narrow width approximation is

$$\sigma(e\,p \to LQ\,X) \quad = \quad \frac{\pi}{4\,s}\,\lambda^2\,(J+1)\,q(M_{LQ}^2/s)\ , \tag{11}$$

$$\Gamma_S \;=\; \frac{\lambda^2}{16\,\pi}\,M_{LQ}\ , \qquad \Gamma_V \;=\; \frac{\lambda^2}{24\,\pi}\,M_{LQ}\ , \tag{12}$$

where $q(x)$ denotes the quark densities in the proton.

There may exist 252 additional flavour changing leptoquarks (2 lepton flavours l, 3×3 initial and final quark generations i, j, couplings $\lambda^2 = \lambda_{ei}\,\lambda_{lj}$) with a production cross section

$$\sigma(e\,p \to LQ\,X) \quad = \quad \frac{s}{16\,\pi}\left(\frac{\lambda_{ei}\,\lambda_{lj}}{M_{LQ}^2}\right)^2 \int dx\,dy\,x\,q_i(x) \begin{cases} \frac{1}{2} & s\text{−channel } S \\ \frac{1}{2}\,(1-y)^2 & u\text{−channel } S \\ 2\,(1-y)^2 & s\text{−channel } V \\ 2 & u\text{−channel } V \end{cases} \tag{13}$$

Leptoquarks of the first generation with masses ranging from 215 GeV to 275 GeV are already excluded by present HERA data for couplings larger than the electromagnetic scale $\lambda > \sqrt{4\,\pi\,\alpha} = 0.3$. Masses of up to 250 GeV are excluded for couplings with leptons of the second and third generation larger than $\lambda > 0.3$.

Complementary information can be obtained from electron and positron beams. For the extrapolation to high luminosities an equal share of $e^\pm$ beams is assumed.

M_{LQ} [GeV]	HERA '95	HERA 250	HERA 1000
scalars			
100	$1.5\cdot10^{-2}$	$2\cdot10^{-3}$	$1\cdot10^{-3}$
150	$2.5\cdot10^{-2}$	$4\cdot10^{-3}$	$2\cdot10^{-3}$
200	$7\cdot10^{-2}$	$1\cdot10^{-2}$	$5\cdot10^{-3}$
250	$2.5\cdot10^{-1}$	$4\cdot10^{-2}$	$2\cdot10^{-2}$
vectors			
100	$1.5\cdot10^{-2}$	$2\cdot10^{-3}$	$1\cdot10^{-3}$
150	$2.5\cdot10^{-2}$	$4\cdot10^{-3}$	$2\cdot10^{-3}$
200	$5\cdot10^{-2}$	$8\cdot10^{-3}$	$4\cdot10^{-3}$
250	$2\cdot10^{-1}$	$3\cdot10^{-2}$	$1.5\cdot10^{-2}$

Table 6: Upper limits (95% *cl*) on first generation leptoquark couplings λ_{11}. Values of individual leptoquarks may differ by a factor of 2

In $\bar{p}\,p$ collisions leptoquarks are produced in pairs, thus their production does not depend on the coupling λ. However, the derived mass limits depend on the assumed decay branching ratio $\mathcal{B}(LQ \to l + jet)$.

M_{LQ} [GeV]	HERA '95	HERA 250	HERA 1000
scalar $S^L_{1/2}$			
100	$5 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$	$8 \cdot 10^{-4}$
150	$1 \cdot 10^{-2}$	$3 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$
200	$2.5 \cdot 10^{-2}$	$8 \cdot 10^{-3}$	$4 \cdot 10^{-3}$
225	$5 \cdot 10^{-2}$	$1.5 \cdot 10^{-2}$	$8 \cdot 10^{-3}$
vector $\tilde{V}^R_0$			
100	$3 \cdot 10^{-3}$	$1 \cdot 10^{-3}$	$5 \cdot 10^{-4}$
150	$7 \cdot 10^{-2}$	$2.5 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$
200	$1.5 \cdot 10^{-2}$	$5 \cdot 10^{-3}$	$2.5 \cdot 10^{-3}$
225	$3 \cdot 10^{-2}$	$1 \cdot 10^{-2}$	$5 \cdot 10^{-3}$

Table 7: Upper limits (95% *cl*) on second generation leptoquark couplings λ_{22}. Values for other leptoquarks may be up to a factor of 4 worse

	$\mathcal{B} = 1.0$ M_{LQ} [GeV]	$\mathcal{B} = 0.5$ M_{LQ} [GeV]
first generation		
scalars (CDF)	113	80
scalars (D0)	129	116
second generation		
scalars (CDF)	131	96
scalars (D0)	119	97
third generation		
scalars (CDF [9])	94	—

Table 8: Lower mass limits (95% *cl*) on first, second and third (preliminary) generation scalar leptoquarks from $\bar{p}\,p$ experiments, decay branching ratio $\mathcal{B}(LQ \rightarrow l + jet)$.

Conclusion HERA remains competitive in the search for leptoquarks, in particular for leptoquarks with lepton flavour violating couplings, although the mass limits from $\bar{p}\,p$ experiments may increase in the future. The limits on coupling strengths λ can be improved by an order of magnitude.

References HERA data: H1 Collaboration [7], ZEUS Collaboration [8]

4 Contact Interactions $(\bar{e}e)\,(\bar{q}q)$

New currents or bosons may produce indirect effects through *interference* of a *virtual* particle exchange with the γ and Z fields of the Standard Model. For a sufficiently heavy particle X with mass $M_X \gg \sqrt{s}$ and coupling strength $g_{X\to i,\,f}$ $(i,\ f = L,\ R$ fermion helicities) new contact terms arise from contracting the particle propagators to an effective four-fermion pointlike interaction. The effective couplings η_{if} carry dimension [mass^{-2}]. The expected signatures are deviations from the Standard Model predictions at high Q^2, being either positive or negative.

The neutral current Lagrangian for deep inelastic scattering $e\,p \to e$ *hadrons* gets an additional term

$$\begin{aligned} \mathcal{L}^{NC}_{\rm contact} &= \sum_{q=u,\,d} \{\eta^q_{LL}\,(\bar{e}_L\gamma_\mu e_L)(\bar{q}_L\gamma^\mu q_L) + \eta^q_{LR}\,(\bar{e}_L\gamma_\mu e_L)(\bar{q}_R\gamma^\mu q_R) \\ &\qquad + \eta^q_{RL}\,(\bar{e}_R\gamma_\mu e_R)(\bar{q}_L\gamma^\mu q_L) + \eta^q_{RR}\,(\bar{e}_R\gamma_\mu e_R)(\bar{q}_R\gamma^\mu q_R)\}\ , \qquad (14) \\ \eta^q_{if} &\equiv \frac{g_{X\to i}\; g_{X\to f}}{M_X^2}\ . \qquad (15) \end{aligned}$$

Only vectorial Lorentz structures need to be considered. Scalar and tensor terms, involving helicity flip amplitudes proportional to a small fermion mass, are strongly suppressed at HERA.

Specific models, *e.g.* compositeness, leptoquarks or new gauge bosons Z', can be uniquely described in terms of the completely general *eight* coupling coefficients η^q_{ij}. This concept can be extended to charged current phenomena, but contact interactions in charged currents have not been considered in this workshop.

Note that contact interactions depend only on the ratio g_X/M_X and the sensitivity rises with the center of mass energy and luminosity as $\propto (s\cdot\mathcal{L})^{1/4}$.

Contrary to the opinion of several authors polarized leptons do not help in discovering new contact interaction phenomena. Polarization might only be useful, once a discrepancy with the Standard Model has been observed.

4.1 Compositeness Scales

In the Standard Model the fundamental particles – leptons, quarks and gauge bosons – are assumed to be pointlike. In extended models it is conceivable that leptons and quarks have a substructure. If they have common constituents a possible $e\,q$ compositeness can be characterized by a compositeness scale parameter Λ and a coupling strength g

$$\eta^q_{if} \equiv \pm\frac{g^2}{\Lambda^{\pm\,2}_{if}}\ ,$$

where $i,\ j$ are helicity indices $L,\ R$ and the signs indicate positive and negative interference with the Standard Model currents. The coupling strength is conventionally chosen as $g^2/4\,\pi = 1$.

Conclusion HERA is and will continue to be competitive with experiments at other colliders in the search for $e\,q$ compositeness. Compositeness scales Λ up to 8 TeV can be reached depending on the chiral structure and sign of interference.

References HERA data: H1 Collaboration [10], ZEUS Collaboration [11]

			HERA '95	HERA 250	HERA 1000	CDF		OPAL [12]	
Λ^+_{LL}	Λ^+_{RR}	[TeV]	$1.7 \div 2.3$	5.1	8.0	1.7	—	2.4	1.9
Λ^-_{LL}	Λ^-_{RR}	[TeV]	1.0	3.5	4.1	2.2	—	1.7	2.2
Λ^+_{LR}	Λ^+_{RL}	[TeV]	$2.1 \div 2.5$	5.1	6.3			2.0	1.6
Λ^-_{LR}	Λ^-_{RL}	[TeV]	$1.2 \div 1.4$	2.1	4.5			2.0	2.5

Table 9: Lower limits (95% *cl*) on $e\,q$ compositeness scale parameters $\Lambda^\pm$ for chiralities *LL, LR, RL* and *RR*, assuming $g^2/4\,\pi\;=\;1$. $\bar{p}\,p$ experiments use Drell-Yan production, in e^+e^- annihilation 5 quark flavours contribute

4.2 Form Factors and Quark Radii

An alternative method to study fermion substructures is to assign a finite size of radius R to the leptons and/or quarks. A convenient parametrisation is to introduce 'classical' form factors $f(Q^2)$ at the gauge boson–fermion vertices [13]. A finite extension of a lepton or quark is expected to diminish the Standard Model cross section at high Q^2

$$\frac{d\sigma}{dQ^2} \;=\; \frac{d\sigma^{SM}}{dQ^2}\, f_e^2(Q^2)\, f_q^2(Q^2)\;, \tag{16}$$

$$f(Q^2) \;=\; 1-\frac{1}{6}\,R^2\,Q^2\;. \tag{17}$$

Note that this concept does not imply interference effects as discussed in the previous section.

The HERA data are analyzed in terms of a single form factor for the light u and d quarks, since the pointlike nature of the electron is already established down to much smaller distances in e^+e^- and $(g-2)_e$ experiments.

	HERA '95	HERA 250	HERA 1000	$Z \to q\,\bar{q}$	$Z \to f\,\bar{f}$
R_q [cm]	$1.4 \div 2.6 \cdot 10^{-16}$	$0.6 \cdot 10^{-16}$	$0.4 \cdot 10^{-16}$	$1.2 \cdot 10^{-16}$	$0.2 \cdot 10^{-16}$

Table 10: Upper limits at 95% *confidence level* on quark radii. Z decays are for 5 quark flavours, the last column assumes lepton quark universality

Conclusion HERA is and will continue to be competitive with other colliders in the search for quark form factors or quark radii R_q down to distance of a few 10^{-17} cm.

References HERA data: H1 collaboration [10], ZEUS collaboration [11]

4.3 Leptoquarks

The direct search for leptoquarks can be complemented by contact interaction analyses, extending the accessible mass range beyond the HERA center of mass energy. Each leptoquark is specified by a set of coupling coefficients

$$\eta^q_{if} = c^q_{if}\left(\frac{\lambda}{M_{LQ}}\right)^2 ,$$

where the constants c^q_{if} are given by the model. *Note* that such a contact term analysis is only sensitive to the ratio coupling over mass and the resulting coupling limits may only be extrapolated to lower leptoquark masses $M_{LQ} \gtrsim \sqrt{s}$.

Contact interaction analyses at HERA have been carried out for the first, second and third leptoquark generation. In general one obtains more stringent bounds for vectors than for scalars. The access to various leptoquark types cannot be simply guessed on the basis of the quark densities in the proton. This naive expectation is spoiled by interference effects and by the fact that not all coefficients η^q_{if} contribute with the same weight and in addition to the s channel amplitudes of direct production the contact interaction ansatz implicitly contains the crossed t and u channel diagrams. The extrapolation to high luminosities assumes an equal share of $e^{\pm}$ beams.

Other indirect limits on leptoquarks come primarily from low energy data, using information from meson decays and atomic parity violation experiments. The bounds on M_{LQ}/λ derived by different authors differ by factors up to ~ 1.5 in either direction [14], reflecting the model dependent assumptions.

Conclusion Contact interactions provide a powerful tool to search for high mass leptoquark signals, thus complementing direct searches. With a substantial increase in luminosity HERA will be competitive with the results on M_{LQ}/λ of low energy experiments.

References HERA data: H1 Collaboration [10], ZEUS Collaboration [8]

4.4 New Neutral Vector Bosons

New heavy neutral vector bosons Z' appear as extensions of the electroweak $SU(2)_L \times U(1)_Y$ Standard Model. The mass eigenstates Z^0_1, Z^0_2 mix to give the physical masses of Z and Z'

$$Z = \cos\theta\, Z^0_1 + \sin\theta\, Z^0_2 , \tag{18}$$

$$Z' = -\sin\theta\, Z^0_1 + \cos\theta\, Z^0_2 . \tag{19}$$

Popular models include:

- Standard Model couplings Z'_{SM}
  used as a reference for comparing different accelerators
- Left-right symmetric extension of the Standard Model Z_{LR}
  $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ $(g_L = g_R = g)$
- Gauge models of string inspired grand unifying E_6 theories Z_β
  $SU(2)_L \times U(1)_Y \times U(1)$

$$Z^0_2 \equiv Z_\beta = \cos\beta\, Z_\chi + \sin\beta\, Z_\psi , \tag{20}$$

$$Z_\eta = \frac{1}{4} Z_\chi + \frac{\sqrt{15}}{4} Z_\psi .$$

Table 11: Accessible lower bounds (95% *cl*) on M_{LQ}/λ [TeV] for first generation leptoquarks from contact interactions

leptoquark	F	coupling to u quark	coupling to d quark	HERA '95 M_{LQ}/λ	HERA 250 M_{LQ}/λ	HERA 1000 M_{LQ}/λ
S_0^L	2	$\eta_{LL}^u = -\frac{1}{2}\,(\lambda/M_{LQ})^2$			0.93	1.03
S_0^R	2	$\eta_{RR}^u = -\frac{1}{2}\,(\lambda/M_{LQ})^2$			0.85	0.92
$\tilde{S}_0^R$	2		$\eta_{RR}^d = -\frac{1}{2}\,(\lambda/M_{LQ})^2$	0.35	0.71	1.19
$S_{1/2}^L$	0	$\eta_{LR}^u = -\frac{1}{2}\,(\lambda/M_{LQ})^2$			0.62	1.05
$S_{1/2}^R$	0	$\eta_{RL}^u = -\frac{1}{2}\,(\lambda/M_{LQ})^2$	$\eta_{RL}^d = -\frac{1}{2}\,(\lambda/M_{LQ})^2$		0.48	0.87
$\tilde{S}_{1/2}^L$	0		$\eta_{LR}^d = -\frac{1}{2}\,(\lambda/M_{LQ})^2$	0.36	0.73	1.07
S_1^L	2	$\eta_{LL}^u = -\frac{1}{2}\,(\lambda/M_{LQ})^2$	$\eta_{LL}^d = -1\,(\lambda/M_{LQ})^2$	0.34	0.48	0.60
V_0^L	0		$\eta_{LL}^d = +1\,(\lambda/M_{LQ})^2$		0.78	0.83
V_0^R	0		$\eta_{RR}^d = +1\,(\lambda/M_{LQ})^2$		0.55	0.58
$\tilde{V}_0^R$	0	$\eta_{RR}^u = +1\,(\lambda/M_{LQ})^2$		0.76	1.70	2.78
$V_{1/2}^L$	2		$\eta_{LR}^d = +1\,(\lambda/M_{LQ})^2$	0.30	0.41	0.47
$V_{1/2}^R$	2	$\eta_{RL}^u = +1\,(\lambda/M_{LQ})^2$	$\eta_{RL}^d = +1\,(\lambda/M_{LQ})^2$	0.71	1.43	1.83
$\tilde{V}_{1/2}^L$	2	$\eta_{LR}^u = +1\,(\lambda/M_{LQ})^2$		0.80	1.71	2.27
V_1^L	0	$\eta_{LL}^u = +2\,(\lambda/M_{LQ})^2$	$\eta_{LL}^d = +1\,(\lambda/M_{LQ})^2$	1.02	2.34	3.74

model	HERA 250 M [GeV]	HERA 1000 M [GeV]	$p\,\bar{p}$ search M [GeV]	electroweak fit M [GeV]
Z'_{SM} (e^-)	460	650	505	779
Z_{LR} (e^-)	260	370	445	389
Z_χ (e^+)	235	340	425	321
Z_ψ $(e^\pm)$	95	135	415	160
Z_η (e^-)	145	200	440	182

Table 12: Lower mass limits (95% *cl*) on additional Z' bosons, indicated is the most sensitive lepton polarity at HERA

Conclusion HERA cannot compete with the direct Z' searches from $\bar{p}\,p$ collisions.

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