# New physics from HERA?

*D. P. Roy*

*The H1 and ZEUS experiments at the HERA $e^{\pm}p$ collider at Hamburg have recently reported some anomalous hard-scattering events, which could be indicative of new physics beyond the standard model. I have tried to discuss in a nonspecialist language the significance of this result for particle physics along with its interpretation in terms of the currently popular extensions of the standard model.*

## Basic constituents of matter

OUR understanding of the basic constituents of matter has undergone two revolutionary changes during this century. The first was the Rutherford scattering experiment of 1911, which showed that the atom is made up of a compact nucleus (containing protons and neutrons), surrounded by tiny electrons. The second was the electron scattering experiment of 1968 at Stanford, performed at a thousand times higher energy, which showed that the proton and neutron are themselves made up of tiny constituents called quarks. Both proton and neutron are composed of two types of quarks called up and down. Thus these quarks along with the electrons constitute all the visible matter of the universe.

The electron along with its massless and neutral partner, neutrino, are called leptons. There are two heavier pairs of leptons as well as quarks. But they decay promptly into the light ones and hence do not occur freely in nature. All these quarks and leptons are fermions, since they carry spin 1/2 in natural units,

$$\hbar = c = 1, \tag{1}$$

where $\hbar$ and $c$ denote Plank's constant and the velocity of light.

## Basic interactions

Apart from gravity, whose influence in the subatomic world is negligible, there are 3 basic interactions – strong, electromagnetic and weak. They are all gauge interactions, mediated by spin 1 particles called gauge bosons. The quarks have strong interaction, mediated by gluons, which is responsible for binding them together inside proton and neutron. This is analogous to the electromagnetic interaction between the quarks and the electrons, mediated by the photon, which binds them together in the atom. All the quarks and leptons including the neutrinos experience weak interaction, which is responsible for nuclear decay. Unlike the strong and the electromagnetic interactions, which are mediated by massless gauge bosons, the weak interaction is mediated by massive gauge bosons called $W$ and $Z$. The theory of these basic constituents of matter along with their gauge interactions is known as the Standard Model (SM).

D. P. Roy is in the Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400 005, India.

## GeV to TeV energies

It follows from the Uncertainty Principle that the smaller the distance to be probed, the larger must be the beam energy. Thus to probe inside a proton of dimension about 1 fm ($10^{-13}$ cm), one needs an electron beam energy

$$E_e > \hbar c/1 \text{ fm i.e. } E_e > 1 \text{ GeV}, \tag{2}$$

where a GeV (Gega electron volt) is the energy acquired by the electron after passing through $10^9$ volts. It is customary to use the natural system of units[1], in which case the GeV becomes a convenient unit for mass, energy and momentum. The mass of the proton is about 1 GeV.

It is the multi-GeV electron beam energy that enabled the above-mentioned Stanford experiment of 1968 to probe the structure of the proton. Thanks to the colliding beam technology, we have seen a thousand fold increase of the invariant energy, from the GeV to the TeV scale, since then. The invariant energy corresponds to the energy measured in the centre of momentum (CM) frame, which is the effective energy available for particle creation. This has led to a string of discoveries over the past 25 years. The charm and bottom quarks, the tau lepton and the gluon were discovered during the seventies, thanks mainly to the electron–positron colliders at Stanford and Hamburg. This was followed by the discovery of the massive $W$, $Z$ bosons with masses

$$M_W \simeq 80 \text{ GeV}, M_Z \simeq 91 \text{ GeV}, \tag{3}$$

at the CERN proton–antiproton collider in 1983. Finally the last and the heaviest member of the quark family, the top quark with mass

$$M_t \simeq 175 \text{ GeV} \quad (4)$$

was discovered at the Tevatron proton–antiproton collider at Fermilab in 1995. Thus we have seen all the basic constituents of matter by now along with the carriers of the basic interactions. Moreover the large electron–positron (LEP) collider at CERN has made it possible to check the predictions of the standard model, including quantum corrections, to great accuracy. In particular the measured masses and widths of the $W$ and $Z$ bosons are in remarkable agreement with the predictions of the unified electroweak theory.

## What next?

The story, however, does not end here. A consistent theory of the massive gauge bosons, $W$ and $Z$, requires the presence of one or more scalar (spin 0) particles of comparable mass. These are called Higgs bosons. But the story does not end here either. In the absence of a protecting symmetry, the scalar masses are driven to infinity by the quantum corrections! Thus to control these scalar particle masses, one invokes supersymmetry (SUSY) – a symmetry between fermions and bosons. This implies the existence of scalar superpartners of quarks and leptons as well as fermionic partners of the gauge and Higgs bosons, again in the mass range of $W$ and Z bosons – i.e. around $10^2$ GeV (eq. (3)). Thus the Higgs and the SUSY particles represent minimal set of missing pieces, required for a consistent theory of fundamental particles. Besides, the lightest SUSY particle (LSP) is a promising candidate for the dark matter of the Universe. Thus the immediate goal of particle physics is largely focussed on these particles. On the other hand, the long term objectives are the unification of strong along with the electroweak interaction in the form of a Grand Unified Theory (GUT) and ultimately to rope in gravity as well. But it is fair to state here that there is as yet no experimental evidence for Higgs or SUSY particles, or for that matter any other form of new physics beyond the standard model.

## The HERA $e^{\pm}p$ collider

The latest colliding machine is HERA at Hamburg, operating since 1993, where a beam of electron $e^-$ (or positron $e^+$) collides head on against a beam of proton. Most of the data so far has been taken with the $e^+$ beam. The beam energies are 28 and 820 GeV for the $e^{\pm}$ and proton, compared to which the corresponding particle masses are negligible. Thus the CM energy is

$$\sqrt{s} = 2\sqrt{E_e E_p} = 2\sqrt{28 \times 820} \simeq 300 \text{ GeV}. \quad (5)$$

There are two detectors engaged in recording $e^+p$ collision events at HERA, named ZEUS and H1. HERA and ZEUS are named after the famous Greek deities (Hypertext Webster Gateway defines HERA as the sister and wife of ZEUS!), while H1 has evidently a more mundane origin.

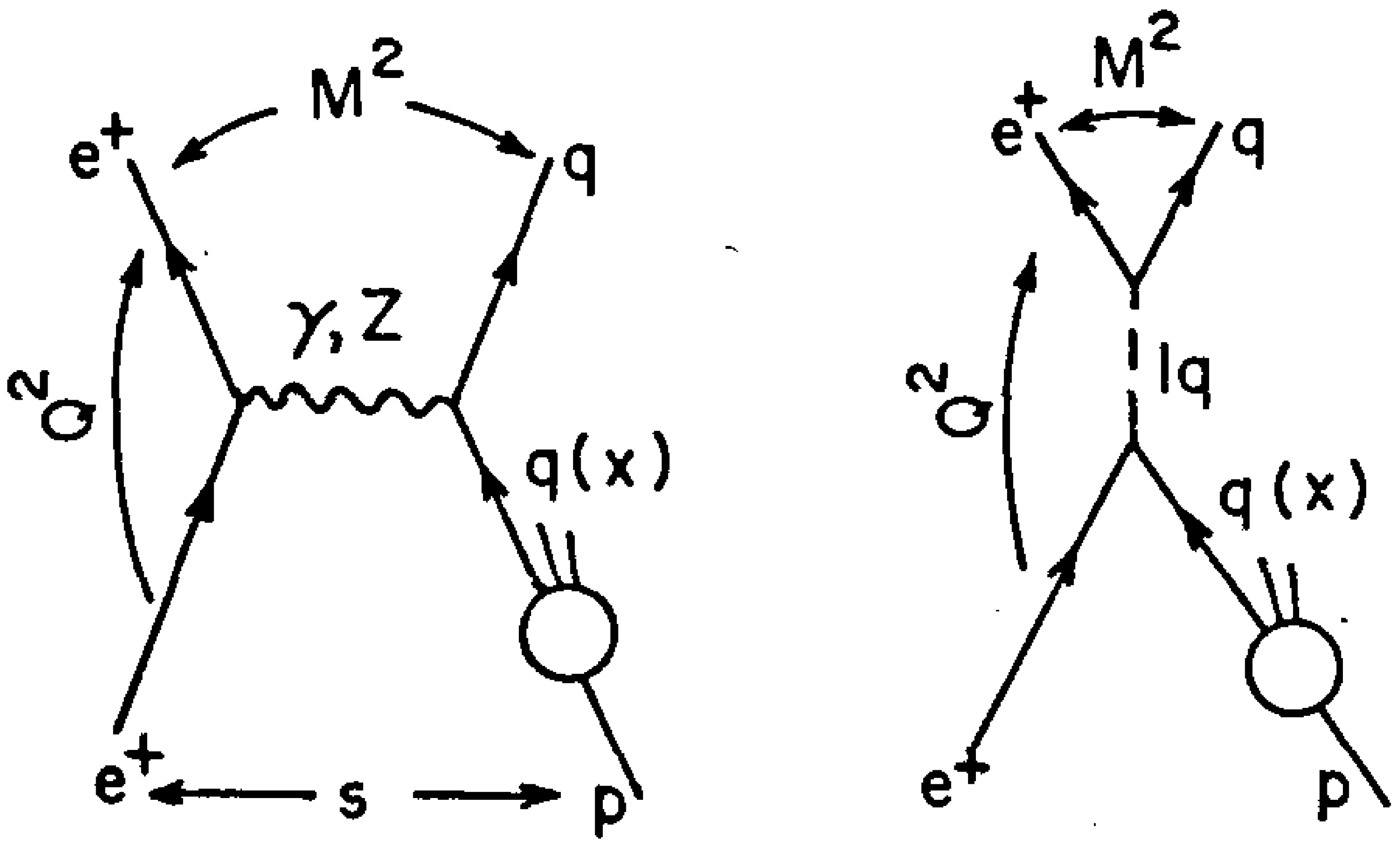
The higher machine energy has made it possible to probe the quark and gluon distributions inside the proton much more precisely at HERA than in earlier experiments. But more importantly, a recent analysis of the data collected by these two experiments during 1994–96 has shown about 10 anomalous events, which could be suggestive of New Physics beyond the SM. The results were presented in a joint seminar by the two groups at Hamburg followed by a press report last February, which have recently been published[1,2]. While the event sample is still very small, it has generated a good deal of excitement around the world along with a flurry of e-prints, of which only a partial list is given in refs 3–8. In order to discuss the significance of these events and their theoretical interpretation, it will help to briefly summarize the kinematics of $ep$ scattering at HERA.

Figure 1 shows a space–time picture of $ep$ scattering, with time axis running vertically upwards. The positron interacts with a quark carrying a 4-momentum fraction $x$ of the proton. Thus the invariant energy of the $eq$ pair is

$$M = \sqrt{s \cdot x}. \quad (6)$$

Over the hard scattering region of interest the measured quark momentum distribution inside the proton roughly corresponds to

$$\langle x \rangle \simeq 0.1, \langle M \rangle \simeq 100 \text{ GeV}. \quad (7)$$




(*a*) (*b*)

**Figure 1.** Space–time picture of $e^+p$ scattering (*a*), via photon and Z boson exchanges (SM), and (*b*), via a leptoquark state.

The squared 4-momentum transfer between the incident and outgoing positron (or quark) is denoted by $Q^2$. This is related to the CM scattering angle $\theta^*$ of the $e$–$q$ pair via

$$Q^2 = yM^2, \quad y = (1 - \cos\theta^*)/2, \tag{8}$$

i.e.

$$0 < Q^2 < M^2. \tag{9}$$

The SM interaction between the $e^{\pm}$ and the quark is the electroweak interaction mediated by the photon ($\gamma$) and the massive $Z$ boson exchanges as shown in Figure 1 *a*. The $Q^2$ dependence resulting from the $\gamma$ and $Z$ propagators is

$$\frac{d\sigma_\gamma(M)}{dQ^2} \propto \frac{1}{Q^4}, \quad \frac{d\sigma_Z(M)}{dQ^2} \propto \frac{1}{(Q^2 + M_Z^2)^2}. \tag{10}$$

The corresponding $M$-integrated scattering cross-sections will fall even faster with increasing $Q^2$ because of the kinematic constraint (eq. (9)).

In contrast, the presence of a heavy leptoquark state (a hypothetical particle coupling to lepton and quark), illustrated in Figure 1 *b*, would signal events which are clustered around a high invariant mass of the $e$–$q$ pair

$$M \simeq M_{lq}, \; x \simeq M_{lq}^2 / s. \tag{11}$$

Moreover they would have a flat $Q^2$ distribution as the sense of the original direction is lost after the formation of the leptoquark. In particular, a scalar leptoquark would have an isotropic decay and hence a flat $Q^2$ distribution via eq. (8).

Each of the two HERA experiments shows an excess of high $Q^2$ events over the SM prediction, indicating an anomalous hard component in $e^+p$ scattering.

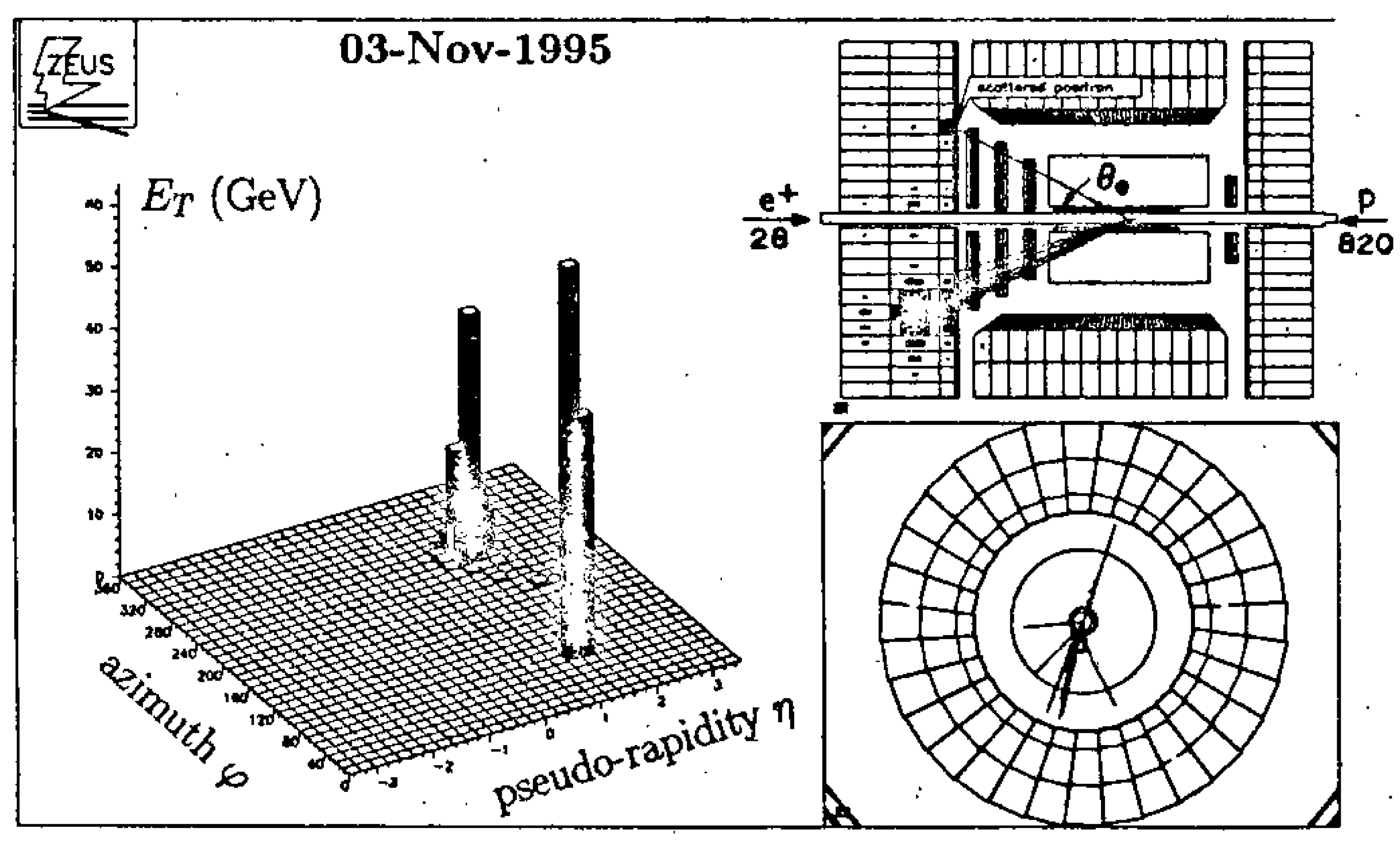



**Figure 2.** One of the anomalous high $Q^2$ events from the ZEUS experiment. The top (bottom) inset shows the scattered positron and quark-jet in the scattering (transverse) plane. The lego plot shows the transverse energy distribution in azimuthal angle and rapidity ($\eta = -\ln \tan\theta/2$).

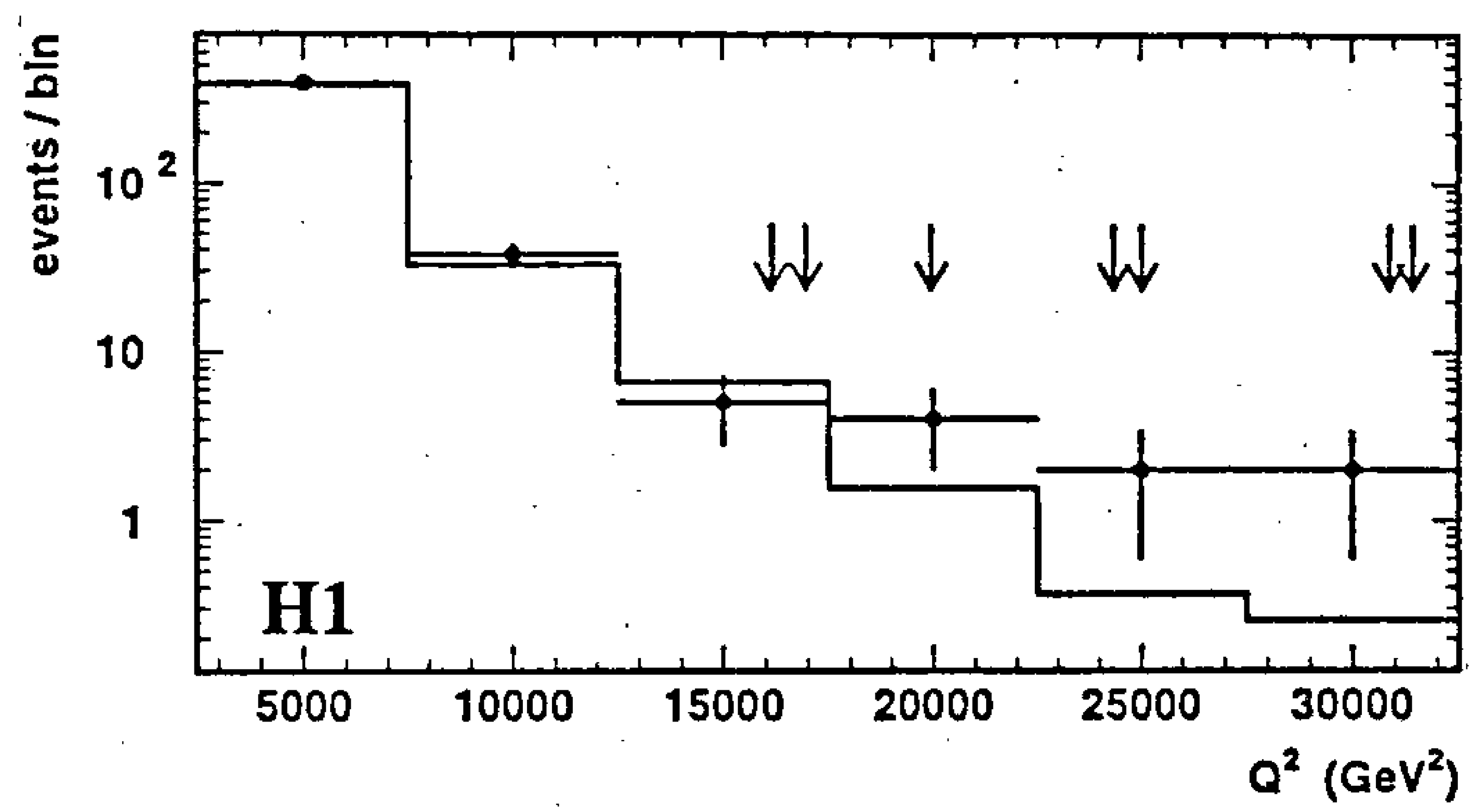



**Figure 3.** The $Q^2$ distribution of the H1 events showing an excess of 7 events over the SM prediction of 5 for $Q^2 > 15000$ GeV$^2$. The arrows indicate the 7 events having common $M = 200 \pm 20$ GeV.

## High $Q^2$ events

The ZEUS experiment shows 5 events against the SM prediction of 2 for $Q^2 > 20000$ GeV$^2$. Moreover, the excess of 3 events are consistent with a common $e^+q$ invariant mass $M \simeq 200$ GeV. One of these events is shown in Figure 2. The inset on top clearly shows the scattered positron and quark-jet in the scattering plane, while the remaining proton fragments escape in the beam pipe. The bottom inset shows their back-to-back configuration in the transverse plane, as required for transverse momentum balance. The magnitude of their transverse momenta is shown in the lego plot as $E_T$, i.e.

$$E_T^e \simeq E_T^q \simeq 100 \text{ GeV}. \tag{12}$$

In fact from this figure one can easily reconstruct the rough magnitudes of $M$ and $Q^2$. It has evidently an unlikely kinematic configuration for SM scattering as it corresponds to a very hard quark ($x \simeq 0.5$) and a backward $e^+q$ scattering in the CM frame ($\theta^* > 90°$).

The H1 experiment shows 12 events against a SM prediction of 5 for $Q^2 > 15000$ GeV$^2$, as shown in Figure 3. Moreover the excess of 7 events is consistent with a common invariant mass $M = 200 \pm 20$ GeV, as indicated by arrows in this figure. Indeed the common mass and the flat distribution over a very wide range of $Q^2$ are suggestive of isotropic decay of a leptoquark state as discussed above.

## Contact interaction

Apart from leptoquark production, there is another mechanism suggesting a flatter $Q^2$ dependence than the SM. This corresponds to the exchange of a very massive particle between the positron and quark in Figure 1 *a* – e.g. a heavy gauge boson $Z'$ occurring in many extensions of the SM. This is called contact interaction, since the exchange of a heavy particle is restricted to a tiny range ($\hbar/M_Z c$) via the Uncertainty Principle. Clearly the resulting cross-section of eq. (10) will be flat in $Q^2$ for $M_{\tilde{Z}}^2 \gg Q^2$. However, this interpretation is disfavoured on three counts: (i) The size of the effect required to explain the HERA events seems to be larger than the upper limit placed on this quantity from LEP and Tevatron collider data; (ii) It favours the standard $M$ distribution, as suggested by the measured quark distribution inside the proton (eq. (7)), instead of a clustering of events at a high value of $M$; (iii) For the above reason, the $M$ integrated cross-section falls significantly with increasing $Q^2$. Consequently this interpretation of the anomalous HERA events is strongly disfavoured[4,7], although it may not be completely ruled out[8].

## Leptoquarks

The kinematic distribution of the anomalous HERA events clearly favours the formation and decay of a bound state in the $e^+q$ system – i.e. a generic leptoquark[3–6]. So it is natural to ask whether the various extensions of the SM discussed above can naturally accommodate such a leptoquark. The leptons and quarks are unified in GUT, which naturally predict leptoquark states both as gauge bosons and Higgs scalars. However the exchange of these objects in the GUT generally leads to lepton and baryon number (or equivalently the quark number) violating interactions, and in particular to proton decay. Thus the stability of proton implies these objects to be very heavy ($M_{lq} > 15^{15}$ GeV), which puts them far beyond the reach of present or foreseeable future experiments.

A more plausible scenario for such generic leptoquarks is the scalar superpartner of quark (squark) in the so-called $R$-parity violating SUSY model[3–6]. As mentioned earlier, these particles are expected to occur in the right mass range of a few hundred GeV. In general they can have both lepton and baryon number violating Yukawa couplings and mediate proton decay. Usually these couplings are set to be zero by assuming $R$-parity conservation. Unlike the gauge couplings, however, these Yukawa couplings are not connected to any symmetry consideration. Therefore one can assume a finite value for the lepton number violating coupling while setting the baryon number violating one to zero. The former ensures squark coupling to the $e^+q$ channel, while the latter prevents proton decay. Thus in the $R$-parity violating SUSY model the squark can masquerade as a leptoquark and account for the anomalous HERA events. The price one has to pay is that in this case the lightest SUSY particle (LSP) will no longer be stable and hence is not a candidate for the dark matter. It is equally possible, of course, that these generic leptoquarks could have an origin outside the currently popular extensions of the SM.

## Concluding remarks

The most plausible explanation of the anomalous HERA events within the SM is the statistical fluctuation of a small number of events into an unlikely configuration. Using the standard statistical methods, the probability of this fluctuation can be estimated to be less than 1% for each experiment[1,2]. This corresponds to nearly a 3 sigma deviation, which is by no means a definitive signal for new physics. What gives credence to this result is, of course, its simultaneous observation in two experiments. Nonetheless one should bear in mind the risks of statistical fluctuation while dealing with so few signal events. The ongoing experiment at HERA is expected to double the data sample by the end of next year. Moreover, most of the new mechanisms for these events will imply visible effects in the dilepton channel in the present and forthcoming Tevatron collider data. Thus one expects a clear picture to emerge in a year or two.


1. H1 Collaboration, *Z. Phys.*, 1977, **C74**, 191.
2. ZEUS Collaboration, *Z. Phys.*, 1997, **C74**, 207.
3. Choudhury, D. and Raychaudhuri, S., hel-ph/9702392.
4. Altarelli, G., Ellis, J., Lola, S., Giudice, G. and Mangano, M. L., hel-ph/9703276.
5. Dreiner, H. and Morawitz, P., hep-ph/9703279.
6. Kalinowski, J., Ruckel, R., Spiesberger, H. and Zerwas, P. M., hep-ph/9703288.
7. Babu, K. S. Kolda, L., Russel, J. M. and Wlikzek, F., hep-ph/9703299.
8. Barger, V., Cheung, K., Hagikara, K. and Zeepenfeld, D., hel-ph/9703311.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