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Searches for New Physics at HERA

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Summary. — Recent results from searches for new physics at HERA are presented. HERA finished 16 years of successful data taking and both the H1 and ZEUS Collaborations are finalizing analyses based on the full HERA datasets. Possible new phenomena were probed, like quark substructure, new interactions between electrons and quarks and excited states of fermions. The data are also used to investigate rare final states like multi-lepton events at high transverse momentum and events with isolated leptons and missing transverse momentum. A model-independent search for deviations from the standard model in a multitude of event topologies is also presented.

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1. – Introduction

The world's only *ep* collider, HERA, collided an electron or positron beam of 27.5 GeV with a proton beam of 920 GeV (820 GeV until 1997) and yielded the center-of-mass energy of $\sqrt{s} = 318\,\text{GeV}$. The kinematic range of deep inelastic scattering (DIS) measurements was extended by two orders of magnitude in the negative four-momentum transfer squared, Q^2, and the *eq* interaction has been probed at very small distance of about one-thousandth proton size, *i.e.* $\sim 10^{-3}$ fm. Measurements in this domain allow searches for beyond standard model (BSM) phenomena at characteristic mass scales in the TeV range predominantly in the t-channel, which is complementary to s-channel LEP and TeVatron searches.

HERA operation started on summer 1992 and ceased in June 2007. In the 16 years of successful data taking, H1 and ZEUS Collaborations collected data samples with integrated luminosities of $\sim 0.5\,\text{fb}^{-1}$ for each experiment. In this paper, recent results of the BSM searches at HERA from H1 and ZEUS Collaborations utilizing full data sets are presented for model-dependent and -independent searches.

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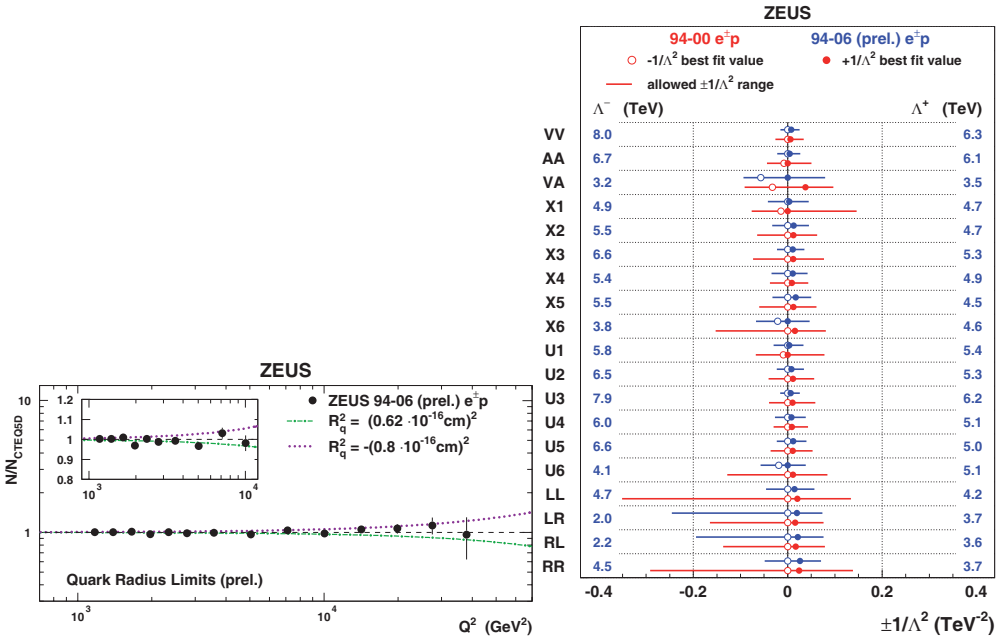

Fig. 1. – Left: measured cross-section as a function of Q^2 normalized to the SM predictions using ZEUS e^+p and e^-p combined data obtained in 1994-2006 running. The results are compared with 95% CL exclusion limits on R_q. The inset shows the comparison in the $Q^2 < 10^4\,\mathrm{GeV}^2$ region with linear scale. Right: confidence intervals of $\pm 1/\lambda^2$ at 95% CL for considered CI models. The numbers at the right (left) margin are the corresponding lower limits on the Λ for positive (negative) couplings and the filled (open) circles correspond to the best-fit values for positive (negative) couplings.

2. – Model-dependent search

2˙1. *Limit on the quark radius.* – From ep collisions of incident e beam energy of $\sim 200\,\mathrm{MeV}$ on fixed proton in 1956, the proton was found to be not a point-like particle and its root-mean-square radii of charge and magnetic moment were measured. Since HERA serves as a giant electron-microscope, analogous search for quark substructure was performed.

If the quark charge is distributed over finite spatial size, R_q, the measured DIS cross-section deviates from the SM as

$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2} = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2}\right)_{\mathrm{SM}} \left(1 - \frac{R_q^2}{6}\right)^2, \tag{1}$$

where the electron is assumed to be point-like. As shown in fig. 1 (left), no deviation was found up to the highest Q^2 region, accessible at HERA. The H1 and ZEUS Collaborations set limits on R_q as

$$\text{ZEUS:} R_q < 0.62 \times 10^{-3}\,\mathrm{fm}, \tag{2}$$

$$\text{H1:} R_q < 0.74 \times 10^{-3}\,\mathrm{fm}. \tag{3}$$

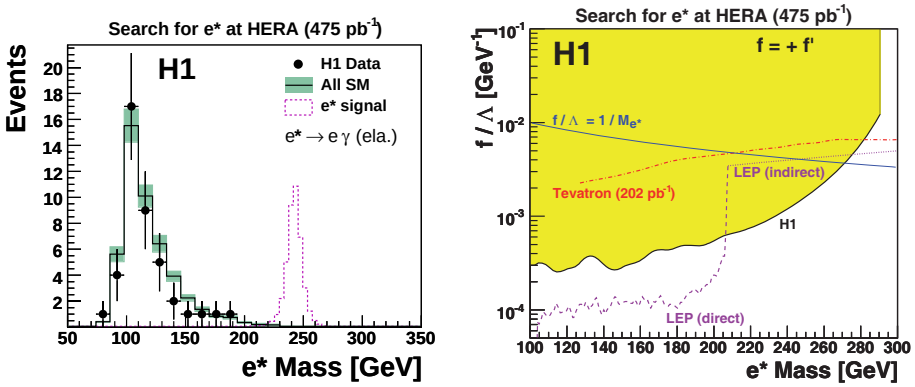

Fig. 2. – Left: invariant mass distribution of the $e^\star$ candidates in the elastic search channel. Data points are compared with the SM prediction drawn as histogram. The band of the SM shows the quadrature sum of model uncertainties and experimental systematic errors. The dashed line represents the reconstructed $e^\star$ distribution of $M_{e^\star} = 240\,\text{GeV}$ with an arbitrary normalisation. Right: mass-dependent exclusion limit on the coupling f/Λ at 95% CL with the assumption $f = +f'$. Limits obtained at LEP and TeVatron are overlaid for comparison. The curve $f/\Lambda = 1/M_{e^\star}$ is also indicated.

2˙2. *Search for the contact interactions*. – Searches of deviations from the SM at high Q^2 can be performed with a more general approach. New interactions between e and q at the energy scale higher than the center-of-mass energy may interfere with the SM processes and modify the cross-section as a function of Q^2. Such physics processes are modeled as an effective four-fermion contact interaction (CI) in their low-energy limit, in analyogy to Fermi's weak-interaction theory.

The amplitudes describing CI interactions are proportional to the ratio of a coupling strength (g) and an energy scale of new physics (Λ) as $\pm g^2/\Lambda^2$. The convention $g^2 = 4\pi$ is adopted here. Various models with different chiral structure of the CI were considered to take into account distinct interference effects with the SM processes.

Both H1 and ZEUS Collaborations used their DIS data at high Q^2 to search for the CI and found that the data agree well with the SM within statistical errors. Thus, limits were derived for each considered model as

(4) ZEUS 1994–2006 data: $\Lambda > 2.0$–$8.0\,\text{TeV}$,

(5) H1 1994–2000 data: $\Lambda > 1.6$–$5.5\,\text{TeV}$.

Figure 1 (right) shows the result from ZEUS at 95% CL for models with different chiral structure. By including high-statistics data taken after 2000, results are clearly improved.

2˙3. *Searches for excited fermions*. – An attractive explanation of three-family structure and mass hierarchy of fermions are provided by models assuming that quark and leptons are built from more fundamental particles. In such models, fermions can be excited to a higher-mass scale and decay into the stable state via the emission of gauge bosons such as γ, Z and W. Thus, the search strategy is to reconstruct the invariant mass of fermion and boson.

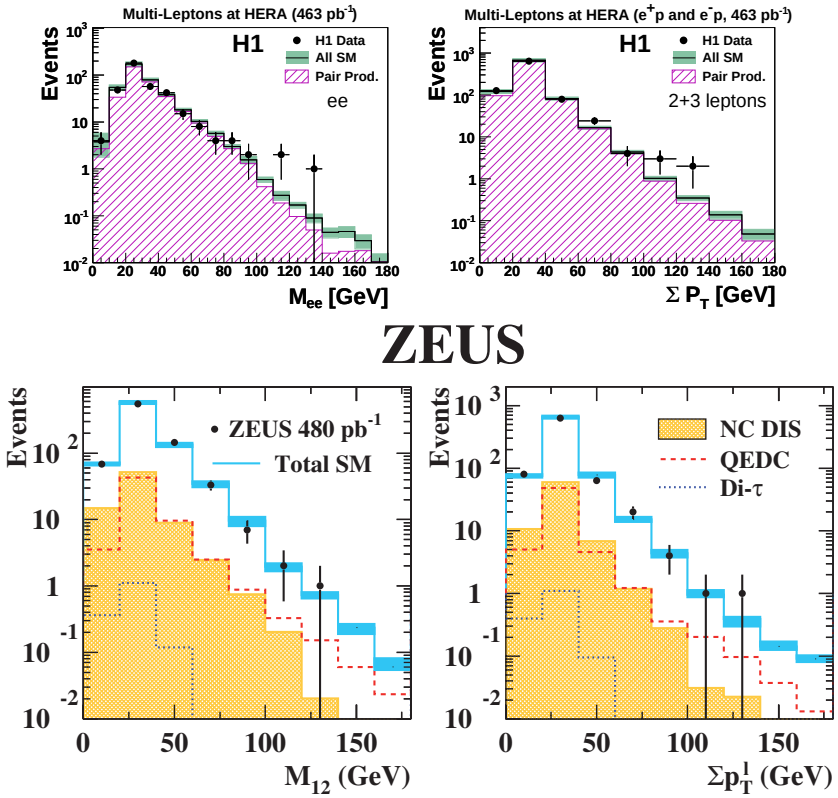

Fig. 3. – The results of multi-lepton search performed by the H1 (upper plots) and ZEUS (bottom plots) Collaborations. Left: invariant mass distribution of ee (combined e and μ) channel(s) from H1 (ZEUS) experiment. Right: scalar sum of the transverse momentum for combined e and μ channels. Data points are compared with the SM expectation shown as histograms.

H1 searched for excited fermions in the following decay channels: $q^\star \to q\gamma, qZ, q'W$; $e^\star \to e\gamma, eZ, \nu W$ using full data set of $\sim 0.5\,\mathrm{fb}^{-1}$; and $\nu^\star \to \nu\gamma, \nu Z, eW$ using electron data of $\sim 0.2\,\mathrm{fb}^{-1}$([1]); where subsequent hadronic or leptonic decays of W and Z are considered [1].

Figure 2 (left) shows, as an example, the invariant mass distribution of the $e^\star$ candidates in the elastic search channel. Including also other decay channels, observed distributions were in agreement with the SM expectation and no evidence for a resonance was found. Therefore, limits were set based on gauge mediated model in which the production cross sections depend on coupling constants, f, f' and f_s associated to the gauge groups $SU(2)$, $U(1)$ and $SU(3)$, respectively, and the compositeness scale, Λ. Once the relationships between the couplings are fixed, the decay branching ratios to different gauge bosons are determined and the cross-section depends only on the ratio f/Λ for given invariant mass of excited fermion.

([1]) Since electron data have a much higher sensitivity than positron data for the $\nu^\star$ search.

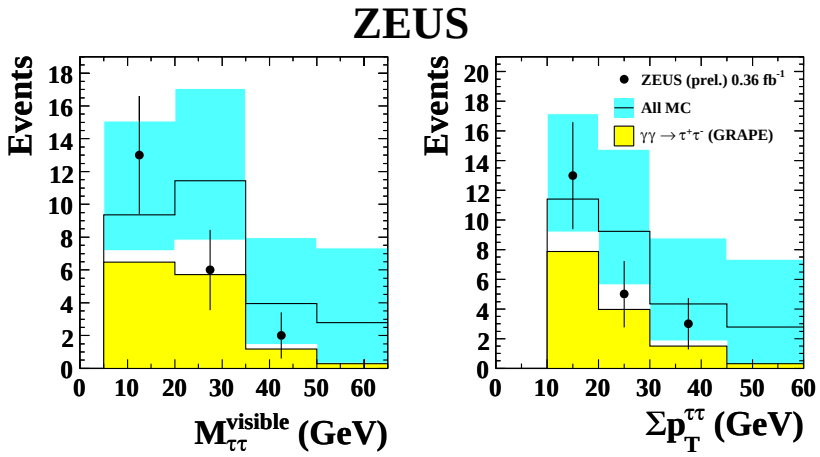

Fig. 4. – Distributions of the visible invariant mass and the scalar sum of the transverse momentum of di-τ from ZEUS experiment. Data points are compared with the SM expectation as given by the histogram in which uncertainty is represented as error bands.

Figure 2 (right) shows, as an example, the upper limit on the f/Λ as a function of the excited fermion mass for $e^\star$. The HERA limits show unique sensitivity in the high-mass region beyond the LEP center-of-mass energy. With the conventional assumption $f/\Lambda = 1/M_{f^\star}$, masses of excited fermions are excluded below 252 GeV for $q^\star$, 272 GeV for $e^\star$ and 213 GeV for $\nu^\star$ at 95% CL. For the $q^\star$ search, the limits on f/Λ are derived under the assumptions of $f = f'$ and $f_s = 0$ where the latter condition yields results complementary to searches at the TeVatron using $f_s \neq 0$.

3. – Model-independent search

Signature based searches for any deviations from the SM were performed in various topologies. This approach does not rely on any *a priori* definition of new physics and thus provides another way to find possible BSM phenomena complementary to searches presented above.

3˙1. *Multi-lepton events.* – Multi-lepton events at HERA are produced mainly in the Bethe-Heitler reaction $\gamma\gamma \to l^+l^-$ where the photons are radiated from the initial q and e. Such events are sensitive to the BSM phenomena, because the SM cross-section is low at high transverse momenta, where new physics is expected to show up.

Both the H1 and ZEUS Collaborations have finished the search for e and μ channels using their full data set of $\sim 0.5\,\text{fb}^{-1}$ [2]. Two-lepton and three-lepton topologies: ee, $e\mu$, $\mu\mu$, eee and $e\mu\mu$, were considered. The three-lepton events included the scattered electron detected in the central detector. Figure 3 (left) shows the invariant mass distribution for ee channel from H1 (upper plot) and combined e and μ channels from ZEUS (bottom plot). Figure 3 (right) shows the scalar sum of the transverse momentum for the combined e and μ channels from H1 (upper plot) and ZEUS (bottom plot). Agreement with the SM was found up to the high-mass region $M > 100\,\text{GeV}$. A combination of H1 and ZEUS results is ongoing.

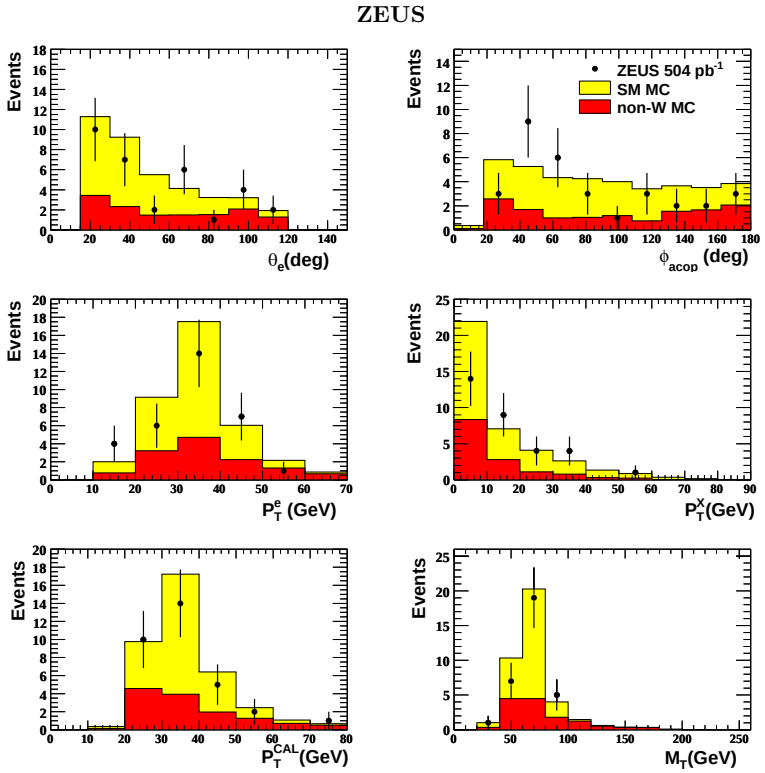

Fig. 5. – Distributions of the isolated e events from ZEUS. Shown are the polar angle of e (θ_e), the acoplanarity angle between e and hadronic particles ($\phi_{\rm acop}$), the p_T of e (p_T^e), the p_T of hadronic particles (p_T^X), the missing transverse momentum measured by the calorimeter ($p_T^{\rm CAL}$), and the transverse mass for W bosons (M_T). The data points are compared with the SM expectation represented as histograms in which all SM processes and non-W production processes are shown separately.

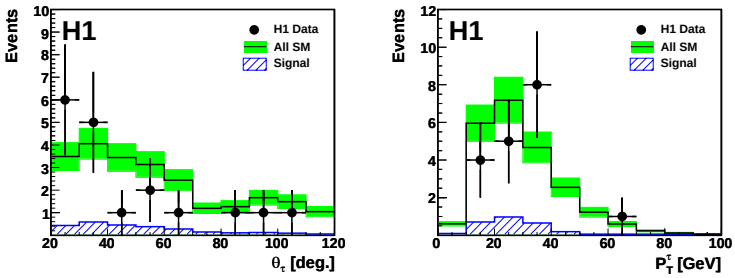

Fig. 6. – Distributions of the isolated τ events from H1. Shown are the polar angle and the p_T of the τ-jet candidates. The data points are compared with the SM expectation represented as histograms with total uncertainty shown as the shaded band.

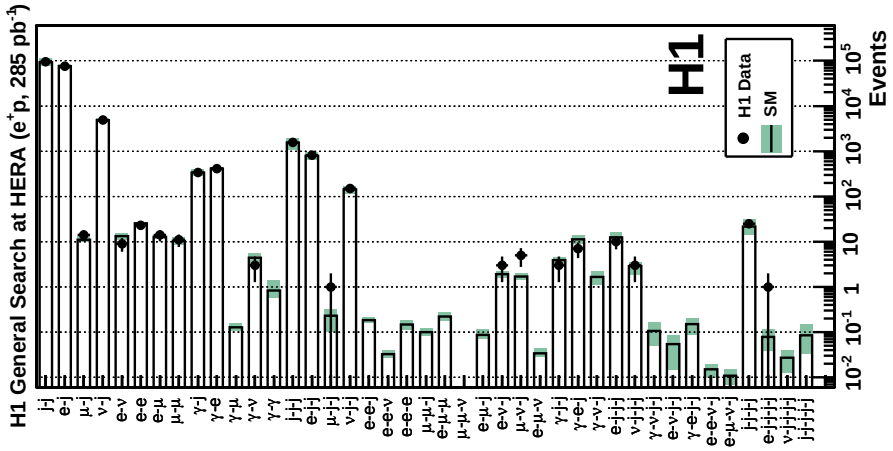

Fig. 7. – Event yield comparison between observed data events and the SM expectation for each considered event topologies for e^+p collisions. The error bands on the SM predictions represent quadrature sum of model uncertainties and experimental systematic errors.

ZEUS also performed a search for events containing two high transverse momentum τ using $0.36\,\mathrm{fb}^{-1}$. Since the branching fraction of τ leptons to hadronic particles is greater than 60%, the hadronic decay channel was used to reconstruct the τ lepton. It is a challenging analysis to discriminate hadron jets produced by τ from huge backgrounds of other QCD induced jets. Properties of hadron τ jets, *i.e.* low mass, low multiplicity and pencil-like jet, were utilized. Figure 4 shows the visible invariant mass distribution and the scalar p_T sum of di-τ for selected events. A total of 21 data events were selected with a 48% purity while $27.3^{+5.8}_{-5.2}$ SM events were expected. Thus, consistent results with the SM were obtained.

3˙2. *Events with isolated lepton and missing transverse momentum.* – Events with isolated e or μ and missing p_T are studied by H1 and ZEUS experiments using their full $e^{\pm}p$ data sets [3]. Within the SM, such types of events are very rare and mainly originate from the single W boson production.

Figure 5 shows several distributions for e channel from ZEUS. The data were well described by the SM predictions. The same agreement was observed for the μ channel. Results obtained by H1 also show agreement with the SM.

Since no significant deviation from the SM was found, the total single W production cross section has been measured by each ZEUS and H1 experiment as

$$\text{ZEUS:}\quad 0.89^{+0.25}_{-0.22}(\text{stat.}) \pm 0.10(\text{sys.})\text{pb}, \tag{6}$$

$$\text{H1:}\quad 1.14 \pm 0.25(\text{stat.}) \pm 0.14(\text{sys.})\text{pb}, \tag{7}$$

in agreement with the SM prediction of $1.3 \pm 0.2\,\mathrm{pb}$.

In addition, H1 also performed the τ channel which complements the analysis of the e and μ channels to test lepton universality as predicted by the SM. The τ lepton was identified in the hadronic decay mode. Figure 6 shows the distributions of the τ-jet candidates for the polar angle and the p_T. 18 data events were observed in agreement with the SM expectation of 23.2 ± 3.8.

3˙3. *General search.* – A general search for events containing high-p_T objects such as: e, μ, j (jet), γ or ν, in the final state, was performed by H1 using full $e^{\pm}p$ data sets [4]. Events with at least two objects with $p_T > 20\,\text{GeV}$ were selected. According to the number and types of objects, the selected events were classified into mutually exclusive channels.

Data events were observed in 27 different final states and events containing up to 5 high-p_T objects were found. Event yields were compared between data and the SM expectation for each topology, as shown in fig. 7 for e^+p collisions. To search for regions with deviations from the SM, kinematical distributions of the invariant mass and the scalar sum of p_T were systematically investigated. In addition, angular distributions and energy sharing among reconstructed object were studied. A good agreement with the SM was found for all topologies under study. Therefore, the measurement demonstrated a good understanding of high-p_T SM phenomena observed at HERA.

4. – Conclusions and prospects

HERA finished 16 years of successful data taking and about $1\,\text{fb}^{-1}$ of data were taken by H1 and ZEUS Collaborations. These data provides a unique and complementary sensitivity to new physics compared to other collider experiments. In this paper, recent results from searches for new physics at HERA were presented for model-dependent and -independent analyses. A good agreement with the SM has been confirmed.

Searches at HERA are being finalized for each H1 and ZEUS experiment using full data sets, and to gain higher sensitivity, the combination of results by two experiments is also ongoing.

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