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PHYSICS AT HERA - PRESENT PROSPECTS FROM A THEORIST'S POINT OF VIEW +

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ABSTRACT

The physics at HERA is discussed in the framework set by present knowledge and speculations of particle theory. After a brief summary of the basic processes investigable in ep-collisions, I illustrate the potential of HERA in testing the standard model and probing new physics with the focus on particularly important and promising topics.

## 1. INTRODUCTION

HERA [1] is a high energy electron (positron)-proton collider under construction at DESY Hamburg. The designed maximum beam energies are 30 GeV for the $e^{\pm}$-beam and 820 GeV for the p-beam yielding the total center-of-mass energy $\sqrt{s}$ = 314 GeV. The projected average luminosity at this energy is $\mathcal{L} \simeq 10^{31}$ $cm^{-2}s^{-1}$. As a special and, as we will see later, important bonus, it seems possible to manufacture $e^{\pm}$-beams with a longitudinal polarization $P \simeq$ (60-80) %. According to the timetable,

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* Permanent address

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HERA experiments will start in 1990.

In this talk, I shall give a subjective and by no means complete overview of the physics at HERA [2-5] anticipated on the basis of present knowledge and perspectives of particle theory. Since I am speaking to a mixed audience of particle and nuclear physicists, it may be useful to first recall a few theoretical arguments and speculations in order to set the framework for the phenomenological considerations I want to present.

The standard $SU(3)_c \times SU(2)_L \times U(1)$ gauge theory of strong and electroweak interactions of leptons and quarks is commonly praised as a, by itself, perfectly consistent theory which has received impressive experimental support over the past decade [6,7]. On the other hand, some basic properties of leptons and quarks and their dynamics, although being nicely embedded in the standard model, lack any explanation, for example,

(i) the quantization of the electromagnetic charges of all known particles in multiples of e/3,

(ii) the mass spectrum and weak mixing of the fermions their replication in sequential families and their left-handedness in weak interactions,

(iii) the scale and dynamical origin of the electroweak symmetry breakdown.

If one is more ambitious, one can further criticize that the fundamental forces are not unified and that gravity is left aside altogether. Moreover, the Higgs sector, an indispensible part of the standard electroweak theory [8], is chosen rather ad hoc and one has not yet found any (at least any clear) experimental evidence for the existence of a Higgs particle. It is true that this failure does not pose an immediate problem. Whereas the vacuum expectation value of the Higgs field (one doublet in the minimal model) is fixed by hand such that the empirical Fermi scale

$$\Lambda_F = (\sqrt{2}\, G_F)^{-1/2} \simeq 250 \text{ GeV} \equiv \sqrt{2}\, \langle\phi\rangle \tag{1}$$

is reproduced, the mass of the physical Higgs scalar is essentially free. Some more involved considerations [9-12] suggest

$$m_H \simeq (10\text{-}1000) \text{ GeV} \tag{2}$$

as the probable mass range. For this reason and because of the very weak coupling to ordinary matter, it would not be in conflict with the standard model if the Higgs boson escaped detection even for quite some time in the future. Nevertheless, the Higgs sector does carry some information on the limitations of the standard model.

It has been argued [11,13] at tree level that for $m_H \gtrsim O(1\text{TeV})$ the <u>Higgs self-coupling becomes strong</u> and, as a result, new phenomena such as form factors and resonances in WW scattering may occur at very high energies. The breakdown of perturbation theory for $m_H \gtrsim O(1\text{TeV})$ is also indicated by <u>violation of partial wave unitarity.</u> [12,14] Furthermore, a 1-loop renormalization group analysis of the standard model shows that, at large energy scales and depending on the values of certain parameters, the effective Higgs self-coupling $\lambda$ eventually becomes stronger than any other coupling in the theory. Thus, one faces a <u>triviality problem</u> [15] similarly as in the case of a pure $\phi^4$-theory. Because of a pathological short-distance behavior, the latter is suspected to be consistent only in the free limit. This problem can be avoided if new physics exists which provides a physical cut-off $\Lambda$ to the standard model. The heavier the Higgs boson, the smaller $\Lambda$ must be. For $m_H \sim O(1\text{TeV})$ one must demand $\Lambda \lesssim O(1\text{TeV})$. Finally, a <u>naturalness problem</u> [16] arises for the standard model from the fact that the Higgs mass is not protected by a symmetry which appears when $m_H \to 0$. Thus, naturally one would expect [16]

$$m_H^2/\Lambda^2 \gtrsim O(\lambda) \gtrsim O(\alpha) \qquad (3)$$

where the mass scale $\Lambda$ is again associated with physics beyond the standard model [17), e.g. $\Lambda_{GUT} \simeq 10^{15}$ GeV in grand-unified theories and $\Lambda_{Planck} \simeq 10^{19}$ GeV if also gravity is considered. It would require unnatural fine tuning of parameters at the scale $\Lambda$ to an accuracy of $O(\Lambda_F/\Lambda)$ in order to assure an acceptable mass for the standard Higgs boson, i.e.

$$m_H^2 \simeq O(m_W^2), \qquad (4)$$

unless the effective physical cut-off $\Lambda \lesssim O(1\text{TeV})$. Related to the naturalness problem is the gauge hierarchy problem [17) that is the difficulty to understand the minute ratios $\Lambda_F/\Lambda_{GUT} \simeq 10^{-13}$ or $\Lambda_F/\Lambda_{Planck} \simeq 10^{-17}$. It is quite striking that from all of the above arguments the 1 TeV scale emerges as a magic number for the threshold to new physics.

To summarize, the success of the standard model, on the one side, and its shortcomings and theoretical difficulties, on the other side, suggest very strongly the existence of new physics at energies which will be shortly accessible. Whatever the more fundamental theory may look like, it should preserve the standard model as a low energy limit, but get ride of at least some of the deficiencies and problems mentioned above. In chapter 2, I will briefly introduce the most favoured approaches. Then, after a summary of basic processes investigable in ep-collisions in chapter 3 and some remarks on experimental conditions at HERA in chapter 4, I will discuss some examples of standard model as well as new physics particularly suited for investigation at HERA.

## 2. THEORETICAL PERSPECTIVES

Three popular ideas have been put forward how and where to go beyond the standard model: grand-unification [7], supersymmetry [17] and compositeness [18]. In fact, more sophisticated models often combine elements of the different schemes such as supersymmetric composite models and supersymmetric grand-unified theories or, nowadays, superstring theories. The ultimate theory will perhaps comprise all of these ideas. Since this fantasy-land of physics has been described in some detail by a previous speaker [19] at this Conference, it suffices here to recapitulate those features which are of more experimental interest.

Concerning grand-unification I will be very brief since there is little which can be tested at colliders. GUT is an attempt to derive the diverse forces observed at low energies from a common origin, usually a large nonabelian gauge symmetry such as SU(5), SO(10), $E_6$ and others. The requirement that the three independent effective gauge couplings of the standard model merge in a single gauge coupling at some scale $\Lambda_{GUT}$ puts this scale above $10^{14}$ to $10^{15}$ GeV. Left behind is a vast desert between the Fermi scale and the GUT scale. It is, therefore, very difficult to test [7] this idea directly. One either needs enormous energies which were only available in the very early universe and, thus, has to search for such an ancient relic as GUT monopoles, or one has to look for very rare events at low energies such as proton decay. Up to this day, all experimental efforts have been unsuccessful in this respect. On the other hand, GUTs explain the baryon asymmetry of the universe and the charge quantization, and correctly predict the value of $\sin^2\theta_W$ . It is not unlikely that the GUT idea will survive implemented in one form or the other in a more complete theory. The superstring models [19,20] provide a promising example. In some of these models [21] as well as in SO(10) and $E_6$ GUTs [7] one expects new neutral vector bosons associated with extra U(1) symmetries. Present neutral current phenomenology and CERN $p\bar{p}$ collider data put model-dependent lower bounds on the mass of the additional

Z' boson in the range [7,22]

$$m_{Z'} \gtrsim \begin{cases} (100 - 280)\ \text{GeV} & \text{NC} \\ (110 - 140)\ \text{GeV} & p\bar{p} \end{cases} \quad (5)$$

At HERA one can explore this mass range directly, in particular, above 150 GeV, and push the limits to somewhat higher values.

Next I will give a few thoughts to supersymmetry. SUSY relates bosonic and fermionic degrees of freedom and, hence, can solve the naturalness problem of the standard model very profoundly by protecting scalar Higgs masses similarly as fermion masses are protected by a chiral symmetry. It is a general feature of SUSY models that all ordinary particles have superpartners which differ by half a unit in spin from the former. Together, they form supermultiplets and, therefore, have equal masses and internal quantum numbers such as color, weak isospin and so on. As a consequence [17], in naive perturbation theory with a physical cut-off $\Lambda$ their quadratically divergent loop contributions to the Higgs mass, $\delta m_H^2 \sim \alpha \Lambda^2$ , cancel exactly. However, since no supersymmetric particles have been observed so far, SUSY must obviously be broken such that $\tilde{m} \gg m$ where m and $\tilde{m}$ stand for the masses of light ordinary particles and their superpartners, respectively. This disturbs the cancellations asserted above and one gets

$$\delta m_H^2 \sim \alpha \left| \tilde{m}^2 - m^2 \right| \ln \Lambda^2 . \quad (6)$$

The condition eq. (4) then implies

$$\left| \tilde{m}^2 - m^2 \right| \lesssim O(1\ \text{Tev}^2), \quad (7)$$

that is the existence of SUSY particles in a mass range reachable at the next generation of colliders. The precise particle content and the mass spectrum depend on the choice of the gauge group, the representations of the matter fields, the Higgs sector, the SUSY breaking mechanism and some free parameters. These details cannot be discussed here [17,19]. For later reference, the minimal particle content is stated in Table 1. In order to give masses to the fermions one now

Table 1: Particle content of the minimal N=1 SUSY extension of the standard model.

| ordinary particles | spin | | SUSY particles |
|---|---|---|---|
| fermions $q_L q_R l_L l_R$ | $\frac{1}{2}$ | 0 | sfermions $\tilde{q}_L \tilde{q}_R \tilde{l}_L \tilde{l}_R$ |
| gauge bosons $g\ \gamma\ W^{\pm} Z^0$ | 1 | $\frac{1}{2}$ | gauginos $\tilde{g}\ \tilde{\gamma}\ \tilde{W}^{\pm} \tilde{Z}^0$ |
| Higgs bosons $H_1^0 H_2^0 H^{0'} H^{\pm}$ | 0 | $\frac{1}{2}$ | Higgsinos $\tilde{H}^0 \tilde{H}^{0'} \tilde{H}^{\pm}$ |

needs at least two Higgs doublets of which three neutral and two charged scalars remain in the physical particle spectrum. From Table 1, one can also easily verify the equality of the numbers of fermionic and bosonic degrees of freedom required by SUSY. Finally, I should not leave this subject without at least mentioning that SUSY may even explain the gauge hierarchy as such. Several schemes based on local supersymmetry, so-called supergravity models [17], have been proposed in which SUSY breaking (possibly induced in a hidden sector by gravitational interactions) triggers the breakdown ofthe e.w. symmetry. In case all of this proceeds by radiative mechanisms, one can obtain a realistic value of the Fermi scale starting from the only fundamental scale in the model, $\Lambda_{Planck} \simeq 10^{19}$ GeV, to wit

$$\Lambda_F \simeq \Lambda_{Planck}\, e^{-O\left(\frac{4\pi}{g^2_{\phi\bar{f}f}}\right)} \tag{8}$$

where $g_{\phi\bar{f}f}$ is a suitable Yukawa coupling. Other small mass scales are generated similarly. The important point for the present discussion is that this class of models typically predicts light SUSY particles with $\tilde{m} \sim O$ (100 GeV) and even less. Current bounds are summarized in

Table 2. At HERA one should be able to cover new regions in the parameter space of sfermion ($\tilde{e}$, $\tilde{\nu}_e$, $\tilde{q}$) and gaugino ($\tilde{\gamma}$, $\tilde{Z}$, $\tilde{W}$) masses.

Table 2: Bounds on SUSY particles in GeV derived (refs. 17,23) from $e^+e^-$ (PETRA/PEP) and $p\bar{p}$ (CERN collider) data under the assumptions stated in the brackets. The possibility of light gluinos, $m_{\tilde{g}} \sim O(10\text{ GeV})$, is controversial (ref. 17).

| $e^+e^-$ | $p\bar{p}$ |
|---|---|
| $m_{\tilde{e}} \gtrsim \begin{cases} 51 & (m_{\tilde{\gamma}} = 0) \\ 45 & (m_{\tilde{\gamma}} \lesssim 5) \\ 22 & (5 \lesssim m_{\tilde{\gamma}} \lesssim 20) \end{cases}$ | $m_{\tilde{e}_L} \gtrsim 26 \; (m_{\tilde{e}_L} \simeq m_{\tilde{\gamma}})$ |
| $m_{\tilde{W}^\pm} \gtrsim 22$ | $m_{\tilde{q}} \gtrsim \begin{cases} 50 - 60 & (m_{\tilde{g}} \gg m_{\tilde{q}}) \\ 60 - 70 & (m_{\tilde{g}} \simeq m_{\tilde{q}}) \end{cases}$ |
| $m_{\tilde{Z}} \gtrsim \begin{cases} 30 & (m_{\tilde{g}} < m_{\tilde{Z}}) \\ 40 & (m_{\tilde{g}} > m_{\tilde{Z}}) \end{cases}$ and $(m_{\tilde{\gamma}} \simeq 0,\; m_{\tilde{e}} < 50)$ | $m_{\tilde{g}} \gtrsim 45 - 50 \; (m_{\tilde{q}} \gg m_{\tilde{g}})$<br>$m_{\tilde{W}^\pm} \gtrsim 40 \; (m_{\tilde{l}^\pm} < m_{\tilde{W}^\pm} < \frac{m_Z}{2})$ |

Let us finally turn to the idea of compositeness. The main motivations of this approach are, firstly, to abandon the elementary Higgs sector of the standard theory and, thus, to get rid of the naturalness problem, secondly, to generate the weak boson and fermion masses dynamically and, thirdly, to solve the family puzzle. It is appropriate to distinguish between models [18] in which

(a) only the Higgs fields,

(b) the Higgs fields, leptons and quarks,

(c) the leptons and quarks and the weak bosons

are composite. In (a) and (b) one still proceeds from $SU(3)_c \times SU(2)_L \times U(1)$ as a fundamental gauge symmetry which is eventually broken dynamically to $SU(3)_c \times U(1)_{e.m.}$. This contrasts with (c) where only the $SU(3)_c \times U(1)_{e.m.}$ gauge interactions are considered fundamental while the weak interactions are described as effective interactions induced by some new dynamics at small distance scales (similarly as nuclear interactions are thought to be induced by QCD). I shall comment on the conjectures (a)-(c) in turn. A popular realization of (a) is provided by the technicolor models [24]. Suppose a new system of (techni-) fermions exists with (technicolor) gauge interactions which become strong at a scale $\Lambda_{TC} \gg \Lambda_{QCD}$. It is then arranged for the e.w. gauge symmetry as well as a chiral symmetry in the technicolor sector to be broken spontaneously by the condensation of technifermions in the vacuum, $\langle \bar{F}_L F_R \rangle \sim \Lambda^3_{TC}$ (similarly as quark condensation breaks the chiral symmetry of massless QCD). As a result, the weak bosons acquire a mass by absorbing three of the Goldstone bosons associated with the chiral symmetry breaking. The measured values of $m_{W,Z}$ require

$$\Lambda_{TC} \lesssim O(1\text{TeV}). \tag{9}$$

Hence, the $\bar{F}F$-composite fields which substitute the elementary Higgs fields of the standard model dissolve before any of the problems pointed out in the introduction become relevant. The next task is to generate masses also for the leptons and quarks. This can be accomplished by invoking again new interactions which couple the ordinary fermions to technifermions. One may assume that these interactions originate in a larger gauge symmetry (extended technicolor [24]) which breaks itself down to the TC-symmetry at a scale $\Lambda_{ETC} \gtrsim O(10\text{ TeV})$. However, not only is the dynamics of the ETC-symmetry breaking rather obscure, these models also tend to run into serious phenomenological problems with respect to flavor-changing neutral currents. This critical remark then takes us to the proposal (b). Suppose leptons and quarks are composite of more fundamental constituents (preons) bound together by a new confining force (hypercolor) with a typical confinement scale

$$\Lambda_{HC} \sim O(1\text{ TeV}). \tag{10}$$

In this case [25], the preons replace the technifermions in breaking the e.w. symmetry and making the weak gauge bosons massive, while the lepton and quark masses are likewise determined by the preon binding dynamics, at least in principle. Nevertheless, one can again raise an objection. Leptons and quarks being HC-singlet bound states possess a confinement radius $r_{HC} \sim O(\Lambda_{HC}^{-1})$. Together with eq. (10) and the known fermion masses, this implies

$$m_{l,q} \ll r_{HC}^{-1} \sim O(1\ \mathrm{TeV}), \qquad (11)$$

in striking contrast to what is the case for ordinary color bound states such as the nucleon. It has been pointed out [16] that massless leptons and quarks would be guaranteed by a chiral symmetry of the hypercolor theory if this symmetry remains unbroken at the bound state level and if certain consistency conditions having to do with anomalies can be met. Small fermion masses could then be generated radiatively by the usual $SU(3)_c \times SU(2)_L \times U(1)$ interactions. Unfortunately, the construction of realistic dynamical models [18,25] proves very difficult, in particular, if one wants the fermion families to emerge in a natural way. The above remarks also apply to composite models of type (c). These models investigate the possibility that the low-energy weak interactions do not result from a broken gauge symmetry, but are mediated by bosonic bound states of the same constituents of which leptons and quarks are built. Clearly, such a picture is only viable if it reproduces the usual charged and neutral current interactions to the accuracy required by the success of the standard model [7]. Borrowing the vector dominance principle from ordinary strong interaction theory, one has been able to demonstrate [25,26] that this is indeed possible given a global SU(2) symmetry, the dominance of the W-like ground states and large $W^3-\gamma$ mixing determined by $\sin\Theta_W \simeq 0.5 \gg O(\alpha)$. Conversely, the excitation energy of the composite weak bosons must be O(1 TeV). However, a severe problem is posed by the W,Z masses themselves, since

$$m_{W,Z} \ll O(1\ \mathrm{TeV}). \qquad (12)$$

One can consider two cases: either $\Lambda_{HC} \sim O(1\ \mathrm{TeV})$ and the ground state bosons are, for some unknown reason, unusually light, or $\Lambda_{HC} \sim O(m_{W,Z})$. In the first case one has to explain why $m_{W,Z} \ll \Lambda_{HC}$ on dynamical grounds, in the second case one must worry about the compatibility of such a "nearby compositeness" with experiment. So far no trace of any kind of substructure has been seen, despite the large variety of signals one would expect, which range from form factor effects and new interactions in the effective low-energy Lagrangian to a host of pseudo-Goldstone bosons and excited states of leptons, quarks and weak bosons. The already existing bounds which are summarized in Table 3 shed some light on the situation. Most importantly,

Table 3: Current bounds on the compositeness scale $\Lambda$ and on the masses of excited states and pseudo-Goldstone bosons.

| effects | bounds | processes | |
|---|---|---|---|
| $m_W^2/\Lambda^2$ terms in $\mathcal{L}^{weak}_{eff}$ | 2-5 TeV | universality<br>$\rho$-parameter | 28) |
| form factors $(1\pm q^2/\Lambda^2)$ | 150-350 GeV | $e^+e^- \to \bar{f}f$ | 29) |
| magn. transitions<br>$e\frac{m_l}{\Lambda^2}\bar{\psi}_L\sigma^{\mu\nu}\psi_R A_{\mu\nu}$ | 1.5 TeV<br>250 TeV | $(g-2)_\mu$<br>$\mu \to e\gamma$ | 28) |
| contact interactions<br>$\frac{4\pi}{\Lambda^2}\bar{\psi}_a\psi_b\bar{\psi}_c\psi_d$ | 1-4 TeV<br>370 GeV<br>O(10-1000) TeV | $e^+e^- \to e^+e^-, \mu^+\mu^-$<br>$p\bar{p}$<br>$K \to e\mu$, $\mu \to 3e$, ... | 29)<br>30)<br>28) |
| excited leptons<br>excited bosons<br>pseudo-Goldstone bosons | 20-70 GeV<br>O(100-1000) GeV<br>$\sim$20 GeV | $e^+e^-$<br>CC&NC<br>$e^+e^-$ | 29)<br>28,31)<br>29) |

one sees that flavor-nonconserving residual interactions must be suppressed to a very high degree or, else, compositeness at the TeV to a very high degree or else compositeness at the TeV scale is not viable. Whether or not this can be accomplished without giving up some of the original motivations for compositeness, is an open question. All other bounds appear to be compatible with a compositeness scale of O (1 or few TeV), in particular, when one considers their model- and process-dependence. Table 3 also clearly demonstrates the complimentary nature of low and high energy searches both of which ought to be conducted. HERA can make some unique contributions to these joint efforts as substantiated later.

In summary, the current ideas on physics beyond the standard model suggest a number of distinct routes to a deeper understanding of the laws of Nature. Which one is believed to be the correct one is still a mere matter of taste. In this situation, every experimental hint is most important. Not to forget, our imagination is limited and biased by traditional theoretical principles. At the 1 TeV scale there may be nothing but the standard model, a possibility which calls for high precision tests, or something totally different from what is promised by the speculations sketched above.

## 3. BASIC PROCESSES IN ep COLLISIONS

Before entering into a more detailed discussion of selected topics of ep physics at HERA I will briefly introduce the basic processes which can take place in ep collisions. One may classify these processes according to the "on-shell" particles in the initial state.

(1) Electron-quark scattering. Deep-inelastic scattering played a decisive role in the discovery of the quark structure of matter and in systematic tests of QCD. The quark-parton model description is illustrated in Fig. 1. Up to now, this process has been studied in fixed-target experiments at momentum transfers $Q \lesssim 15$ GeV $\ll m_{W,Z}$. HERA will reach one order of magnitude farther in Q. This should allow to map the internal structure of the proton in fine details, to put the scaling violations predicted by QCD to a stringent test

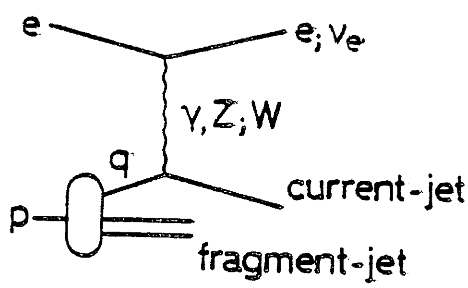



Fig. 1. Deep-inelastic electron-quark scattering.

and to study the properties of hadronic jets. Moreover, there is a good chance for having $e^{\pm}_{L,R}$ beams at one's disposal. Since these states behave differently in weak processes one can investigate the violation of parity and charge conjugation in several independent ways. A further advantage is the possibility of probing the charged (CC) and neutral (NC) current structure and the W and Z propagators simultaneously. Polarization also helps to track new effective interactions such as contact interactions (Fig. 2) expected for composite leptons and quarks. Finally, the diagrams shown in Fig. 3 typify processes involving new

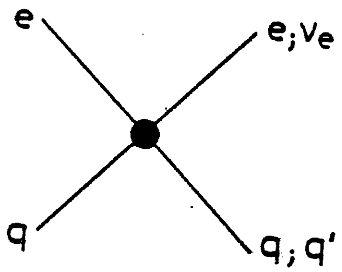



Fig. 2. Residual contact interactions.

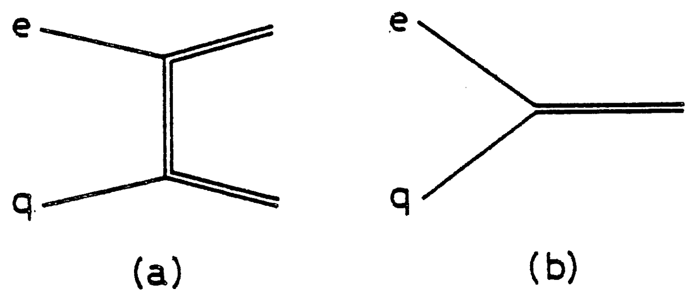



Fig. 3. Production and exchange of new particles.

weak currents and bosons (a), the associated production of sleptons and squarks (a), the resonance production of leptoquarks (b) and other examples of new physics.

(2) Photon-quark (electron) scattering. The standard model processes which belong to this class are depicted in Fig. 4. In fixed-target experiments at relatively low energies QED/QCD Compton scattering (Fig. 4a) has proven remarkably efficient in testing QCD, in particular, higher order effects [32]. This should also be so or even better at HERA. Single W and Z production, on the other hand, requires very high energies.

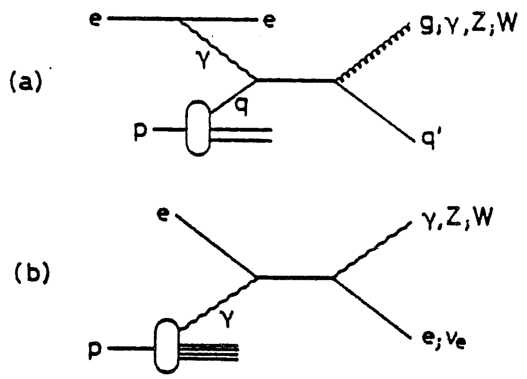



Fig. 4. QCD and electroweak Compton scattering.

The number of W's and Z's which will be produced at HERA is still quite low. For example, from the process shown in Fig. 4b one expects[33] about 8 Z and 3 W bosons per 200 $pb^{-1}$. Of course, in this channel one can also produce exotic particles such as $\tilde{e}_{L,R}$ and $\tilde{q}$ associated with gauginos (Fig. 5a) and, most notably, excited electrons and quarks (Fig. 5b).

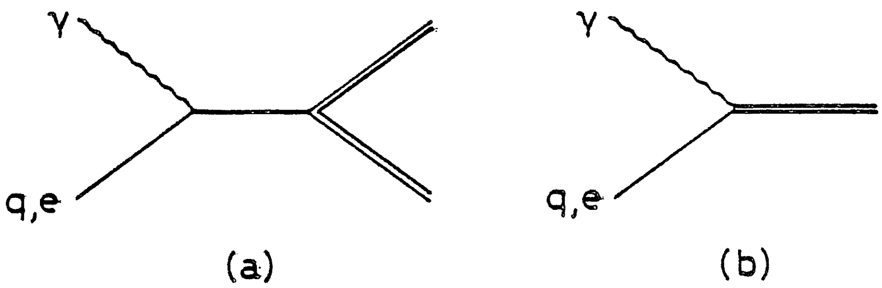



Fig. 5. Associated and resonance production of exotic particles.

(3) Gluon-electron scattering. Obviously, this process exists within the standard model only in higher orders. In composite models, on the other hand, it constitutes the best way to produce such exotic species of the particle ZOO as leptoquarks (Fig. 6a) and color-octet electrons (Fig. 6b). More generally, any particle which couples to electron and gluons can be produced in this channel.

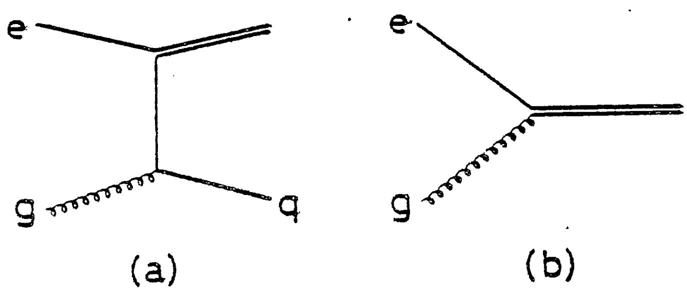



Fig. 6. Production of colored states with electron-number.

(4) Photon-gluon fusion. The standard model version of this process (Fig. 7) represents the third mechanism well-known from fixed-target experiments, in particular, for its efficiency as a charm factory. Furthermore, photon-gluon fusion plays an important role as

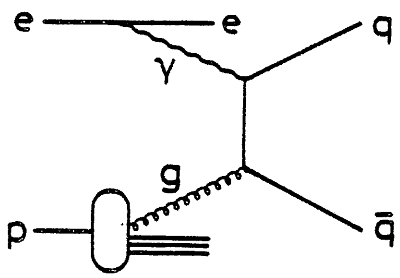



Fig. 7. Photon-gluon fusion.

a direct probe of the gluon density inside nucleons and a source of three-jet final states. Concerning the production of new particles (Fig. 8) I would like to point out both an advantage and a disadvantage: on the one hand, every particle with color and e.m. interactions can be produced in this channel, on the other hand, the usable energy is considerable smaller than the total ep c.m. energy. Interesting cases include pair-production of squarks and leptoquarks and resonance-production of color-octet bosons.

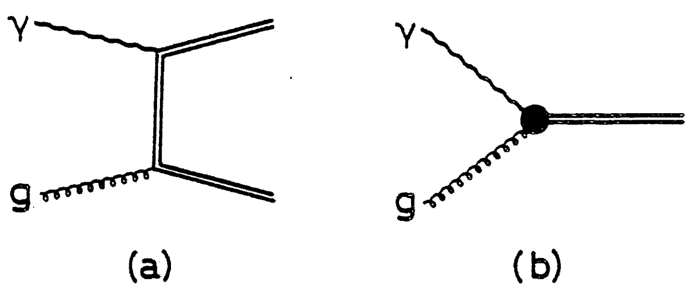



Fig. 8. Production of new particles via $\gamma$-g fusion.

(5) <u>2-vector boson process.</u> This reaction plays a somewhat academic role although it is a favourable channel for Higgs boson production (Fig. 9). The rates are simply too small. For example, the standard model with one Higgs doublet predicts [34] the tiny cross section $\sigma(ep \to eH^0X) \simeq 5\cdot10^{-3}$ pb for $m_H$ = 40 GeV and HERA energy. In the case of a non-minimal Higgs sector the rates may increase to about $10^{-1}$ pb. Thus, one should keep an eye on this possibility.

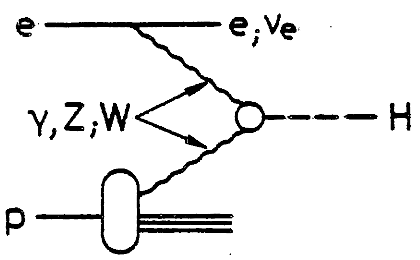



Fig. 9. Higgs boson production via vector boson fusion.

To summarize, ep collisions provide access to a wide variety of basic scattering and production processes. The complimentarity with the physics of $e^+e^-$ and $\overset{(-)}{p}p$ collisions is an obvious consequence of having both an energetic lepton <u>and</u> quark in the initial state. Advantages are the great versatility in comparison to $e^+e^-$ collisions and the better knowledge of the quark flavors involved in a given reaction in comparison to $\overset{(-)}{p}p$ collisions. Longitudinal polarization of the electron beam provides additional handles to study certain physics questions. Exploiting all these virtues one can expect a rich harvest.

## 4. EXPERIMENTAL CONDITIONS AT HERA

Some important lessons can already be learned from a superficial consideration of the experimental conditions one will encounter at HERA. A peculiarity resulting from the very different energies of the electron and proton beam is the extreme forward-kinematics with respect to the proton direction. This has far-reaching consequences. The physics of deep-inelastic scattering processes illustrated in Fig. 1 is usually described in terms of the momentum fraction x of the proton carried by a given quark flavor and the (negative) invariant mass squared $Q^2$ of the virtual vector boson. In principle, these variables can be completely determined either by measuring the scattering angle and energy of the final electron or by reconstructing the corresponding quantities of the current quark jet. Experimentally, however, this procedure is not practicable everywhere in the phase space as can be seen from Fig. 10. Roughly speaking, the problematic regions are at large lepton and quark scattering angles and at very forward quark-jet angles. In order to determine x and $Q^2$ accurately in a range as wide as possible, both e and q-jet measurements must be combined. In this respect, CC studies will be inferior to NC studies since the neutrino escapes undetected. Furthermore, an excellent forward-detector is needed. If the experimental apparatus meets the admittedly high requirements [35], one can also expect a good separation of current-jets from proton fragments [35] and, last but not least, an appreciable reduction of the conventional background to exotic processes [4] by exploiting the e-q correlations characteristic for the NC-current interactions in Fig. 1.

Apart from the excellence of experimentalists, it is the event rates predestined by physics which determines the potential of a

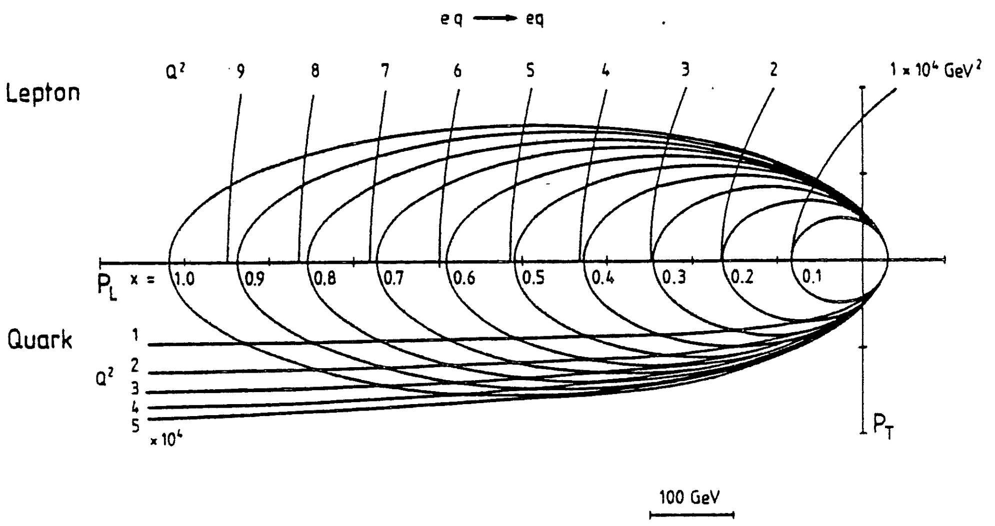



Fig. 10. The phase space of deep-inelastic ep scattering for massless leptons and quarks. The proton beam comes from the right side. The curves correspond to fixed x and $Q^2$, respectively. The scattering angles and energies of the final lepton (q-jet) can be read off by joining a given $(x,Q^2)$-point of the lepton (quark) side with the origin of the diagram (from ref. 4).

facility. In ep collisions, one is particularly interested in reaching large values of $Q^2$, for example, in order to perform high quality QCD and e.w. tests. In Fig. 11, the average $Q^2$ is plotted versus the c.m. energy for CC ep scattering. At HERA, $\langle Q^2 \rangle_{CC} \simeq 3000\ GeV^2$ that is two orders of magnitude higher than in past and present fixed-target experiments and still one order of magnitude higher than in a hypothetical future experiment with a 1 TeV $\nu$-beam. From Fig. 11 one can also see the depletion of $\langle Q^2 \rangle$ beyond HERA energies due to the W-propagator and scaling violations. The maximum $Q^2$ values accessible at HERA can be assessed from the following event rates [3] per 100 $pb^{-1}$:

$$\#\ \text{events} \sim \begin{cases} 400 \text{ for } Q^2 > 10^4\ GeV^2 \\ 60 \text{ for } Q^2 > 2\cdot 10^4\ GeV^2. \end{cases} \qquad (13)$$

These numbers approximately apply to both CC and NC processes. Hence, the rates should allow to reach $Q^2$ values in the range $(2\text{-}3)\cdot 10^4\ GeV^2$, again a two orders of magnitude gain in comparison to previous experi-

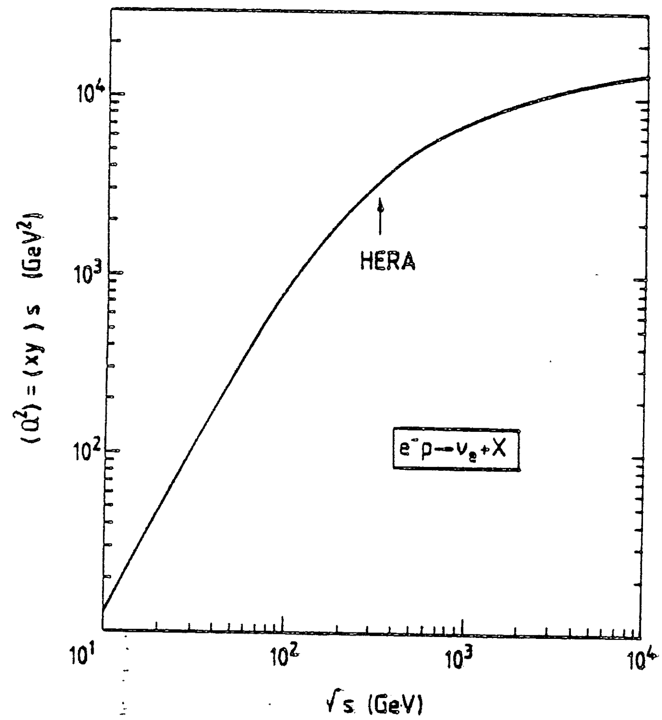



Fig. 11. Average momentum transfer squared versus c.m. energy (from ref. 3).

periments.

At extremely low values of $Q^2$ ($< O(1\ \mathrm{GeV}^2)$), on the other hand, one basically has $\gamma p$ collisions where the almost real photons are radiated off by the electrons. I must leave the discussion of the requirements of small angle e-tagging and other experimental issues to the experts [36]. However, I should remark that photoproduction rates are generally big. For example, in the case of QCD Compton scattering (Fig. 4a) one predicts [36]

$$\sigma(\gamma p \to gqX) \simeq 400\ \mathrm{nb} \qquad (14)$$

for a photon energy $E_\gamma = 15$ GeV and a transverse momentum of the gluon-jet $p_T^g > 2$ GeV. Furthermore, heavy quark flavors are produced via photon-gluon fusion (Fig. 7) with a cross section [37]

$$\sigma(ep \to eQ\bar{Q}X) \simeq 0.1\ \mathrm{pb} \qquad (15)$$

for $m_Q \simeq 50$ GeV and $e_Q = \frac{2}{3}$. In this context, I want to define a minimum measurable cross section for later reference. Given a luminosity $\mathcal{L} \simeq 10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, one can collect $O(100\ \mathrm{pb}^{-1})$ per year. Given also a reasonably good signature, one should be able to detect a certain signal if one has at least 10 events/100 $\mathrm{pb}^{-1}$ of this type. This corresponds to a minimum cross section $\sigma \simeq 0.1$ pb.

In summary, the peculiar kinematics at HERA puts non-trivial requirements on detectors which, however, can be met. From the point of view of the event rates, it will be possible to explore ep and $\gamma$ p physics in a new range of momentum transfers, $Q^2 \sim O(10^4\ \mathrm{GeV}^2)$, and collision energies. Here, the colliding mode of HERA pays really off: the equivalent lepton and photon beam energies in fixed-target experiments would be $E_e \simeq 50$ TeV and $E_\gamma \simeq$ 10-30 TeV.

## 5. ILLUSTRATIVE EXAMPLES OF PHYSICS AT HERA

Having described theoretical and experimental prospects of physics at HERA from a more general point of view, I will now discuss a number of illustrative examples in some detail.

### 5.1 Proton Structure and QCD

HERA can directly reveal structures inside the proton at distance scales

$$d \simeq \frac{2\cdot 10^{-14}}{Q(\mathrm{GeV})} \gtrsim 10^{-16}\ \mathrm{cm}. \qquad (16)$$

Writing the NC & CC cross sections in the form

$$\frac{d\sigma(e^{\mp})}{dx\,dQ^2} = \frac{2\pi\alpha^2}{x\,Q^4}\left[2xF_1\left(1+(1-y)^2\right) + F_2\,2(1-y) \pm xF_3\left(1-(1-y)^2\right)\right] \qquad (17)$$

where $y = Q^2/xs$, the deep-inelastic structure functions $F_i(x,Q^2)$, i=1,2,3 carry the whole information on the proton constituents and their dynamics. For example, in the quark-parton model (Fig. 1),

$$\begin{aligned} F_2 = 2xF_1 &= \sum_f A_f^{(2)}(Q^2)\, x\left(q_f(x) + \bar{q}_f(x)\right) \\ xF_3 &= \sum_f A_f^{(3)}(Q^2)\, x\left(q_f(x) - \bar{q}_f(x)\right) \end{aligned} \qquad (18)$$

where $(\bar{q}_f(x))q_f(x)$ is the (anti)-quark density for a given flavor f inside the proton and $A_f^{(2,3)}$ are coefficients which depend on the e.w. charges and the W,Z propagators. It is summed over all active flavors. To be more specific, in the CC case one simply has

$$A_f^{(2)} = A_f^{(3)} = \left[4 \sin^2\theta_W \left(1 + m_W^2/Q^2\right)\right]^{-2}, \tag{19}$$

while f runs over all positively ($e^-p \to \nu_e X$) or negatively ($e^+p \to \bar{\nu}_e X$) charged quarks and antiquarks. Apart from the trivial $Q^2$-dependence due to the weak boson propagators, the structure functions eq. (18) depend only on the parton momentum fractions x. This is the scaling limit [38]. As everybody knows, the color interactions of quarks and gluons induce logarithmic violations of scaling. A particularly transparent representation of this fact is provided by the Altarelli-Parisi equations [40] for the quark and gluon densities. Schematically,

$$\begin{aligned} \frac{\partial q(x,Q^2)}{\partial \ln Q^2} &= \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 \frac{dz}{z} \left[ q(z,Q^2)\, P_{qq}\left(\frac{x}{z}\right) + G(z,Q^2)\, P_{gq}\left(\frac{x}{z}\right)\right] \\ \frac{\partial G(x,Q^2)}{\partial \ln Q^2} &= \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 \frac{dz}{z} \left[ \sum_q q(z,Q^2)\, P_{qg}\left(\frac{x}{z}\right) + G(z,Q^2)\, P_{gg}\left(\frac{x}{z}\right)\right] \end{aligned} \tag{20}$$

where $\alpha_s(Q^2)$ is the effective coupling constant of QCD. The socalled splitting functions $P_{ab}(z)$ describe the momentum distribution of a "parton b inside a parton a" and can be derived from the fundamental vertices of QCD. In short, the scaling violations are determined by

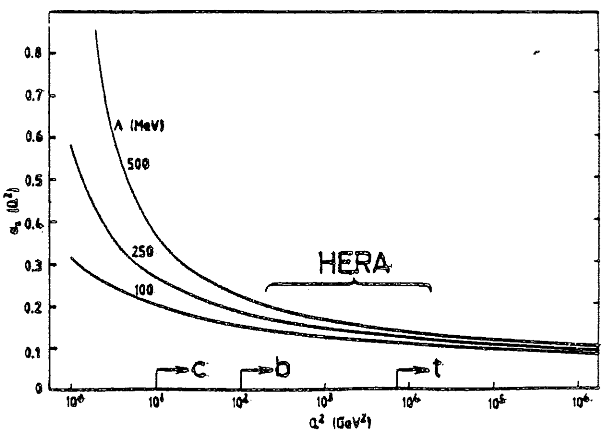
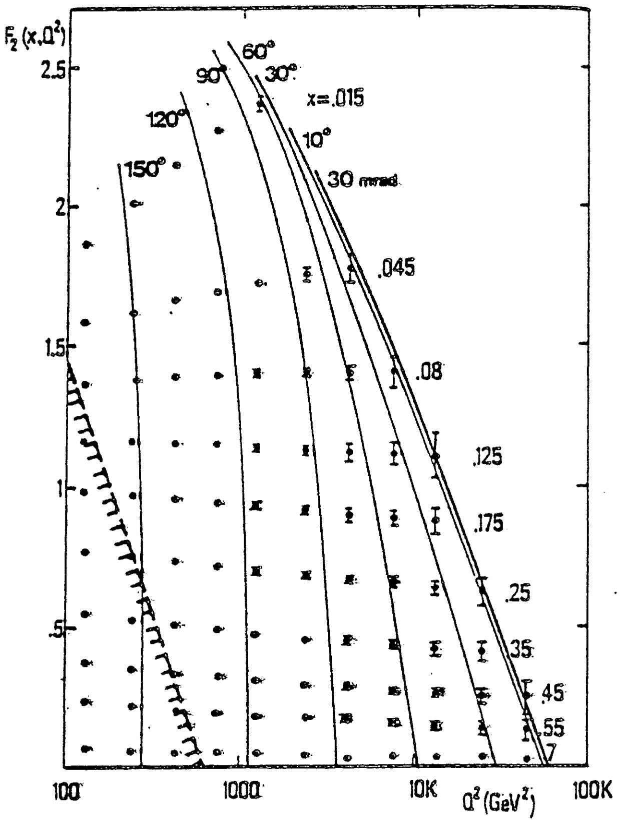



Fig. 12. The running coupling constant of QCD in two-loop approximation for various values of the QCD scale $\Lambda$ including heavy quark thresholds (from ref. 3)

the running of $\alpha_s$ with $Q^2$ and by anomalous dimensions related to moments of the splitting functions. The running of $\alpha_s(Q^2)$ is demonstrated in Fig. 12. One observes that, irrespectively of uncertainties in $\Lambda$ which at present scales are due to non-perturbative effects [41], $\alpha_s(Q^2)$ is predicted rather precisely in the $Q^2$ range of HERA. Consequently, it will not be possible at HERA to fix $\Lambda$ accurately, however, one can undoubtedly check the correct running of $\alpha_s(Q^2)$ starting from the values measured at low scales.

Similarly, quantitative tests of the QCD scaling violations at present energies [41] are affected by uncertainties concerning higher twist operators, target mass and charm threshold effects, and other non-perturbative contributions. This background is expected to fall off like a power in $Q^2$ and, hence, should disappear much faster than the genuine QCD signal as $Q^2$ increases. Therefore, by establishing contact with the structure functions measured at present energies and following their evolution up to the highest possible values of $Q^2$ at HERA, one can be confident to provide one of the most relevant QCD tests. This assertion assumes that electroweak effects (charges, propagators, radiation) as well as heavy flavor thresholds (b-quark) are carefully taken into account. Some manipulations [35,42] are required in order to bridge the formal differences of today's (isoscalar target) and HERA's (proton target) structure functions. The statistics itself is not a problem as illustrated in Fig. 13. Finally, although the usable low $Q^2$ range at HERA is limited by large errors in x and $Q^2$ measurements in this region of phase space (Fig. 10), overlap in $Q^2$ with existing data can be accomplished by running at lower c.m. energies.

Another obvious task at HERA is the determination of quark and gluon densities, in particular, at large $Q^2$. This not only provides information on the structure of matter at $10^{-16}$ cm, but also solidifies the basis for analyses and predictions of physics at present and future hadron colliders. Whereas quark densities can be extracted from NC & CC structure functions [42], preferably measured at various c.m.




energies, the gluon density must be determined indirectly from the observed pattern of scaling violations. How successful one is in this respect at present energies, is nicely described in another talk [41] at this Conference. Just to indicate what one can optimistically expect from HERA, the quality of the constraints on $F_2 \sim x(q+\bar{q})$ and gluon density G at fixed $Q^2$ (resulting from QCD fits to NC-structure functions) is depicted in Fig. 14.

Fig. 13. QCD evolution exemplified by the structure function $F_2(x, Q^2 = 3\ \mathrm{GeV}^2) \sim x(1-x)^3$.. Also shown are statistical errors for a NC-run of 250 $\mathrm{pb}^{-1}$ at HERA. Continuous lines represent fixed final e angle. The low $Q^2$ region not accessible at the maximum HERA energy is indicated (from ref. 35).

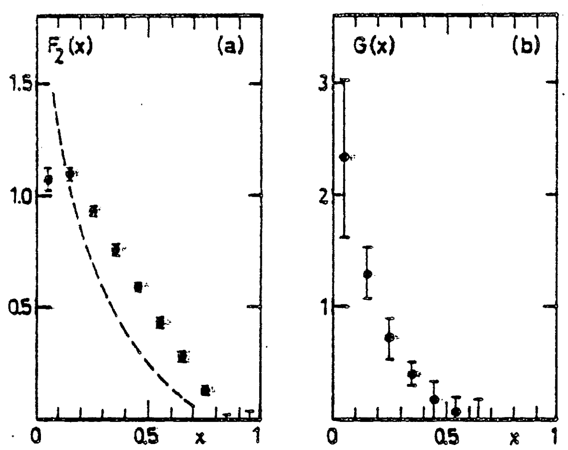



Fig. 14. Constraints on input x-distributions at $Q^2 = 3\ \mathrm{GeV}^2$ from QCD fits to scaling violations for a very good detector. $F_2$ is as in previous figure and $G \sim (1-x)^5$. The dashed curve indicates $F_2$ evolved to $Q^2 \simeq 10^3\ \mathrm{GeV}^2$ (from ref. 35).

Unfortunately, I have no time to discuss other topics of conventional physics [2,5] at HERA. It is however clear that systematic QCD studies must and will also include longitudinal structure functions [35,41] ($F_L = F_2 - 2xF_1$), jets, [35,43] energy flow, [2,44], and last but certainly not least (gluon distribution!) photoproduction [32,36]. Needless to say, thorough consideration ought to be given to e.w. physics both as a "background" in QCD tests and as an own subject of great theoretical interest.

## 5.2 Quark Form Factors and New Interactions

Of course, experimentation at HERA would be even more exciting, if some effect signaling new physics were discovered. Suppose quarks are composite with a typical radius $r \sim 1/\Lambda$ while leptons are considerably more pointlike. In this case, [3] photons with $Q^2 < \Lambda^2$ would see quarks, i.e. $F_2 \sim \langle Q_q^2 \rangle \times Q(x)$, whereas photons with $Q^2 > \Lambda^2$ would resolve the preon substructure, i.e. $F_2 \sim \langle Q_p^2 \rangle \times P(x)$. Making, furthermore, the rather conservative assumptions that the preon structure of quarks is very similar to the quark structure of nucleons, $xQ \simeq 2(1-x)^3$, and that the quark-preon transition is described by a dipol form factor, $f(Q^2/\Lambda^2) = (1+Q^2/\Lambda^2)^{-2}$, one has the situation illustrated in Figs. 15 and 16. Considering the dramatic <u>collapse of the parton densities</u> towards small x (Fig. 15), it is at first sight a little surprising that there would be almost no effect in the structure functions at HERA (Fig. 16). The last statement can be turned into a maximum observable form factor scale, to wit $\Lambda \sim \sqrt{s} \sim 300$ GeV.

However, the situation can be quite different if quarks <u>and</u> leptons are composite at approximately the same scale $\Lambda_H$. In this case, one expects [45] <u>residual 4-fermion interactions</u> (Fig. 2) arising, for example, from the interchange of preons. The corresponding operators in $\mathcal{L}_{eff}$ have dimension 6 and, consequently, dimensionful effective couplings $\sim g^2/\Lambda_H^2$. Since the preon binding force is most likely strong, one may plausibly assume $g^2/4\pi = O(1)$. This then implies large signals in NC and CC cross sections and asymmetries [46] already at $Q^2 \ll \Lambda_H^2$ as exemplified by Figs. 17 and 18 for contact interactions of the form $\frac{g^2}{\Lambda_H^2} (\bar{e}e)_{LorR}(\bar{q}q)_{LorR}$. Here, $(\bar{\Psi}\Psi)_{L,R}$ denote usual left(right)-handed

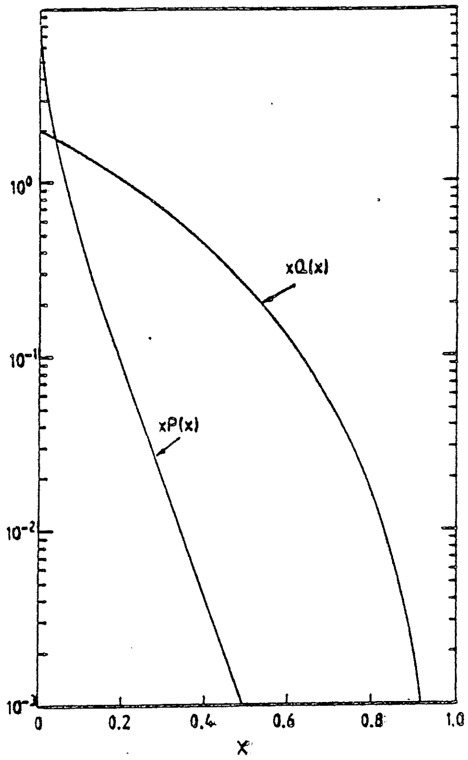



Fig. 15. Momentum distributions of quarks (xQ) and preons (xP) inside nucleons under the assumptions described in the text (from ref. 3)

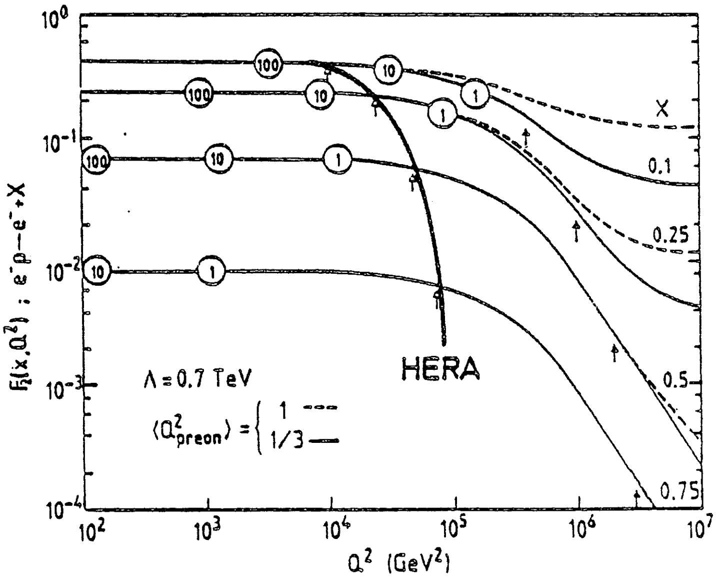



Fig. 16. Transition of the proton structure function $F_2$ from the quark to the preon scaling region for a compositeness scale $\Lambda$ = 0.7TeV and a dipol form factor. The numbers in the circles are events per day assuming scaling, $\sqrt{s} = \infty$ and $\mathcal{L} = 10^{32}$ $cm^{-2}s^{-1}$. The actual phase space boundary of HERA is indicated (from ref. 3).

currents. One can see that HERA will probe compositeness of electrons and light quarks up to scales $\Lambda_H \sim$ (3-5) TeV. Remarkable [46] is also the sensitivity of asymmetries to the detailed Lorentz structure of contact interactions.

## 5.3 New Weak Currents and Bosons

Effective contact interactions may also arise from the exchange of new very heavy bosons. In particular, models for composite W and Z predict a whole spectrum of excited states with masses $M \sim O(\Lambda_H)$. However, these states are expected [31] to couple weakly, i.e. $g^2/4\pi \sim O(g_W^2/4\pi \simeq 10^{-2})$, in contrast to what was assumed in 5.2. Correspondingly, the above limit $\Lambda_H \lesssim$ (3-5) TeV has to be rescaled to $M \lesssim$ (300-500) GeV. This rough estimate is confirmed by more detailled

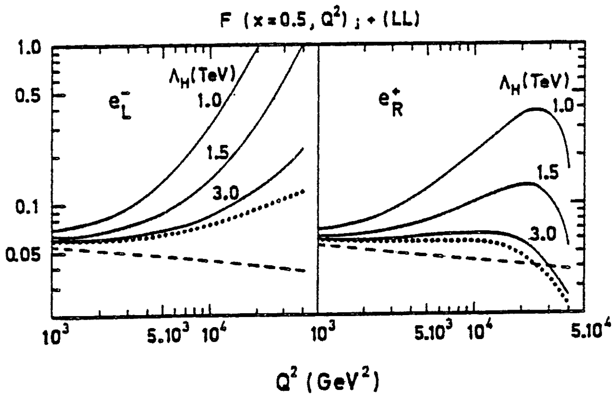



Fig. 17. The reduced cross section $F = \frac{d\sigma}{dx\,dy} \Big/ \frac{2\pi\alpha^2 s}{Q^4}\left(1+(1-y)^2\right)$ for polarized NC processes at HERA. The dashed curves expose the contributions from $\gamma$-exchange; the dotted curves display the full standard model predictions; the full curves include L•L contact terms for various values of $\Lambda_H$ (from ref. 46).

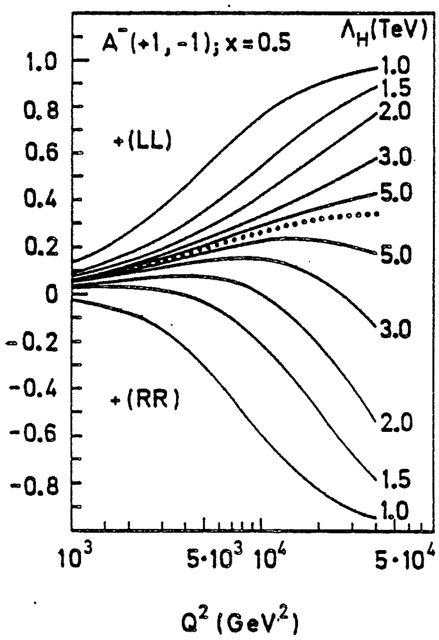



Fig. 18. Polarization asymmetry $A^-(+1,-1) = \frac{d\sigma_L - d\sigma_R}{d\sigma_L + d\sigma_R}$ for $e^-_{L,R}$ NC-scattering at HERA. The dotted curve is the standard model prediction, the full curves include L•L and R•R contact terms, respectively (from ref. 46).

model studies [3,4].

As a rather simple example, one can study new weak bosons W' and Z' which couple to ordinary leptons and quarks similarly as the known intermediate vector bosons do. If one requires a minimum effect of (20-30) % on cross sections or asymmetries at $Q^2 \gtrsim 10^4$ GeV in order to detect the signal, one can generally reach $M_{W',Z'} \sim 400$ GeV. It is also conceivable that the new bosons connect old (light) and new (heavy) fermions as indicated in Fig. 3a. Assuming the existence of heavy partners with degenerate masses for all flavors, one estimates a cross section [3] $\sigma(ep \to L^0 QX) \simeq 0.1$ pb for $M_{W'} \simeq 400$ (200) GeV and $m_{L^0} \simeq m_Q \simeq 50(100)$ GeV. The decays of the heavy fermions produce multi-lepton/jet final states which constitute a good signature [4].

Perhaps more interesting is the conjecture [7] of the existence of new gauge bosons associated with a $SU(2)_R$ symmetry. Replacing the standard e.w. gauge group $SU(2)_L \times U(1)$ by $SU(2)_L \times SU(2)_R \times U(1)$ one can attempt to generate the observed P and C violations in weak interactions by spontaneous symmetry breaking. The usual $SU(2)_L$ fermion doublets become singlets under $SU(2)_R$, while the right-handed fermion components which are singlets under $SU(2)_L$ now become doublets under $SU(2)_R$. In particular, right-handed neutrinos $\nu_R$ appear as partners of the right-handed charged leptons. A discrete L-R symmetry enforces $g_L = g_R$ upon the $SU(2)_{L,R}$ couplings. After symmetry breaking, the $SU(2)_{L,R}$ bosons $W^{\pm}_{L,R}$ mix and form the mass eigenstates $W^{\pm}_{1,2}$. In order to agree with weak interaction phenomenology, one has to require $W^{\pm}_1 = W^{\pm}(83\text{ GeV}) \simeq W^{\pm}_L$ and $W^{\pm}_2 \simeq W^{\pm}_R$ with $M_{W_R} \gg m_W$. Similar constraints hold for the neutral partners $Z^0_{1,2}$. The present lower bounds [7] on $m_{W_R}, Z_R$ range from few hundred GeV to few TeV in the case of $W_R$. However, the more stringent bounds are also theoretically more uncertain. Thus, being cautious one cannot yet firmly rule out $M_{W_R}, Z_R \simeq O(300\text{ GeV})$. This limit cannot be pushed very much farther at HERA. In the theoreretically preferred case, that is for a heavy Majorana neutrino with $m_{\nu_R} \simeq M_{W_R}$, one is limited by phase space. On the other hand, one would have a spectacular signature: $\nu_R \to e^-X$ and $e^+X$ with 50 % branching ratio for each channel. Unfortunately, the cross section is rather discouraging, $\sigma(ep \to \nu_R X) \simeq 0.1$ pb for $m_{\nu_R} \simeq M_{W_R} \simeq 180$ GeV. In the other extreme, for $m_{\nu_R} \lesssim O(\text{few GeV})$ one can expect considerably larger rates as illustrated in Fig. 19. However, now the $\nu_R$ is most likely a Dirac fermion and one looses the nice signature. One way out is to show that $\sigma^{cc}(e^-_R p \text{ or } e^+_L p) \neq 0$ in contrast to the standard model expectation. This makes polarization mandatory. Unfortunately, with $P \simeq (60\text{-}80)$ % the background from ordinary left-handed weak interactions is big which decreases the sensitivity. [35] Nevertheless, the signal should be detectable if $M_{W_R} \lesssim 400$ Gev. A similar conclusion can be drawn from Fig. 20 which shows the effect of the $Z_R$ boson on a NC-asymmetry.

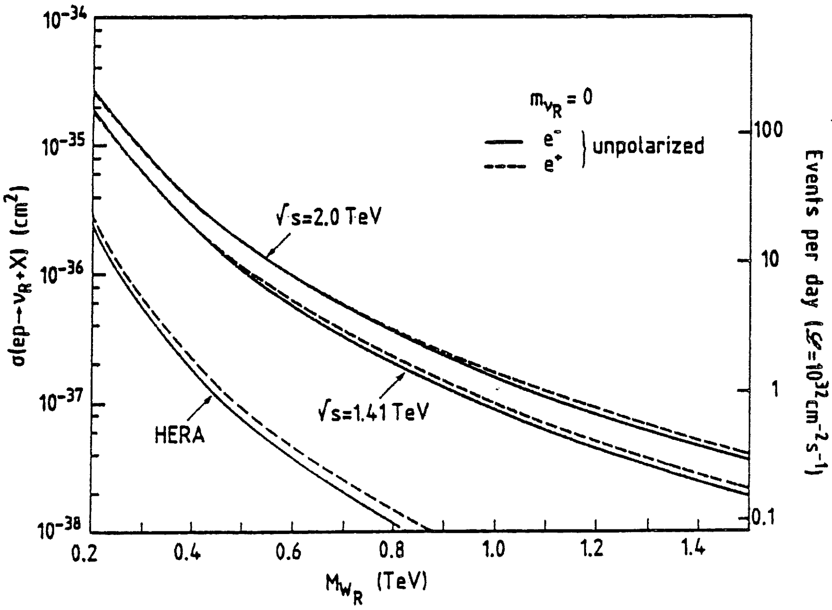



Fig. 19. Right-handed CC cross sections for the case of a very light right-handed neutrino (from ref. 3).

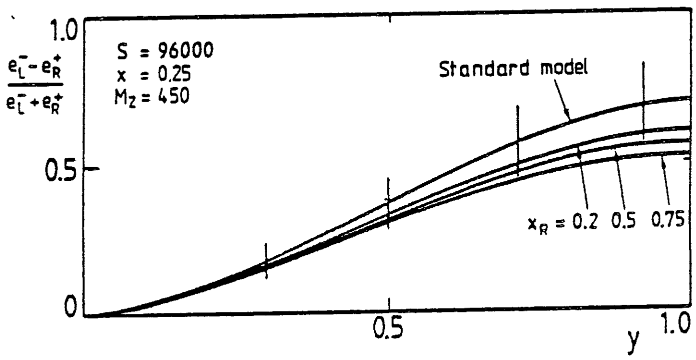



Fig. 20. Signal of a $Z_R$ boson for $M_{Z_R}$ = 450 GeV $(x_R = \sin^2\theta_R\,,\ y = Q^2/xs)$. The experimental error corresponds to a run of 100 $pb^{-1}$ for each polarization (from ref. 4).

## 5.4 Production of New Particles

As pointed out in 2., technicolor models [24] and composite models [25] of leptons and quarks typically predict massless Goldstone bosons associated with the spontaneous breaking of a global symmetry. Some of these become pseudo-Goldstone bosons by acquiring a radiative mass of $O(\alpha\Lambda)$ or $O(\alpha_s\Lambda)$ from standard $SU(3)_c \times SU(2)_L \times U(1)$ interactions. Particularly interesting species of this kind are the leptoquarks P, bosons which carry both lepton and quark internal quantum numbers. Technicolor models suggest [24] $m_p \simeq (100\text{-}200)$ GeV. The couplings to l's and q's are proportional to the fermion masses, $S_{lq} \frac{m_q - m_l}{\Lambda_{Tc}} (\bar{q}\, l)\, P$ and involve unknown flavor mixing parameters $S_{lq}$. The latter make predictions on production rates rather uncertain. Nevertheless, one may expect the processes drawn in Figs. 3b and 6a to constitute the most efficient sources of leptoquarks in ep collisions [47,48]. In both processes, the dominant contribution presumably comes from the coupling to the top flavor. Cross sections estimated from the diagram in Fig. 6a are shown in Fig. 21. The decay $P \to \tau \bar{t}$ followed by heavy flavor decays leads to final states with multilepton/jet and missing energy signatures. These signals can hardly be missed [4]. Thus, unless the production is very much suppressed by a small mixing parameter $S_{et}$, one should clearly be able to observe leptoquarks in the predicted mass range around 150 GeV if they exist. Note that production via $\gamma$g-fusion (Fig. 8a) is not affected by flavor mixing, however, the cross section is moderate, to wit $\sigma(ep \to PPX) \simeq 0.1$ pb for $m_p \simeq 60$ GeV.

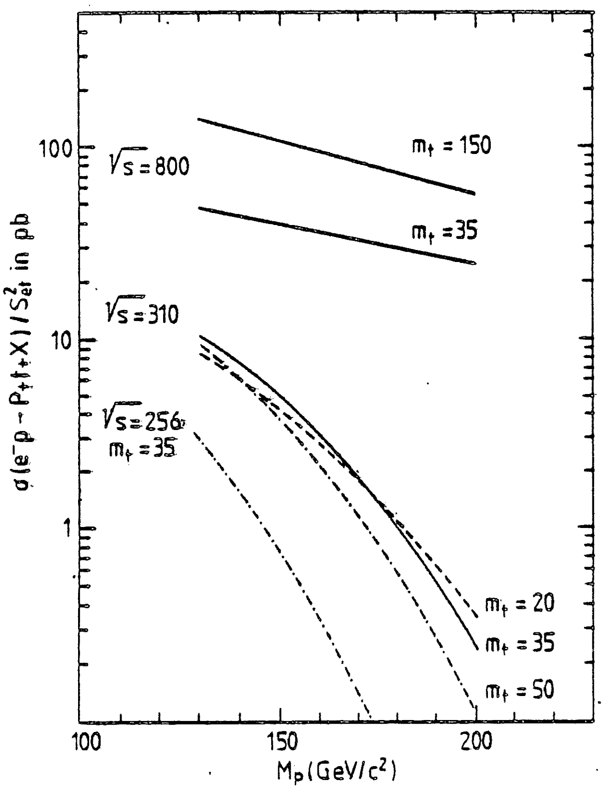



Fig. 21. Leptoquark production via diagram in Fig. 6a (from ref. 48).

Composite models of leptons and quarks also predict many excited fermions with conventional and exotic quantum numbers. Naively, one expects $m^* \sim O(\Lambda_H)$ which would preclude searches at HERA in case $\Lambda_H \gtrsim O(1\text{TeV})$ as suggested by Table 3. However, it is possible that the same mechanism which keeps the ground state fermions light, also leads to some relatively light excited states. If this is true, excited leptons and quarks can be produced at HERA with rather comfortable rates via the processes depicted in Figs. 5b and 6b. The most conventional case of a heavy electron with the same quantum numbers as the ordinary electron is illustrated first. Gauge invariance requires a magnetic-type $e^*e\gamma$-coupling, while problems with (g-2) constraints can be avoided if this coupling is restricted to one helicity component of the electron:

$$\frac{e(f+f')}{2\Lambda} \cdot \bar{e}^* \sigma^{\mu\nu} e_L F_{\mu\nu} .$$

The results of a calculation[49] which also includes W and Z couplings are shown in Fig. 22. The cross section for e* production turns out to be rather favorable. Moreover, the decay $e^* \to e\gamma$ provides a very clean signature [4]. Similar rates as for the e* are obtained for excited quark production, $ep \to eq^*X$, if the results given in ref. 50 are rescaled in order to conciliate the different assumptions on the effective $f^*f\gamma$-coupling strength in refs. 49 and 50. Another interesting possibility is the production of color-octet electrons according to Fig. 6b. Again, one finds [51,2] big cross sections, for example, $\sigma(ep \to e_8 X) \simeq O(10\text{-}10^3)$ pb for $m_{e_8} \simeq$ 100 GeV where the range reflects the theoretical uncertainty in the effective $e_8eg$-coupling. In this case, the most obvious signature is a peak in the invariant e+jet mass distribution due to the decay $e_8 \to eg$. In conclusion, the prospects of excited fermion searches at HERA are very good.

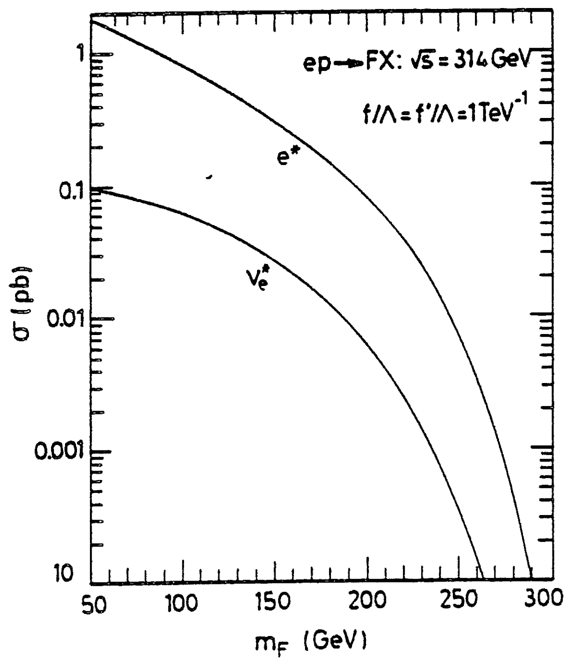



Fig. 22. Excited lepton production at HERA (from ref. 49)

The final example I want to consider is the production of SUSY particles (Table 1). Here, all couplings [52] are fixed by supersymmetry and gauge invariance. Unknown are only the masses of the SUSY particles and the mixing [52] of the weak eigenstates $(\tilde{W}^{\pm}, \tilde{H}^{\pm})$ and

$(\tilde{B}, \tilde{W}^3, \tilde{H}^o_{1,2})$ in the mass eigenstates $\tilde{\chi}^{\pm}_{1,2}$ and $(\tilde{\gamma}, \tilde{H}^o, \tilde{Z}^o_{1,2})$, respectively. The latter are called charginos and neutralinos, respectively. In the usual models [52], there is a discrete symmetry, called R-parity, which distinguishes ordinary particles (R = +1) from their superpartners (R = -1) and which is conserved multiplicatively. This has two important phenomenological consequences: firstly, SUSY particles can only be produced in pairs and, secondly, the lightest SUSY particle (in most models the $\tilde{\gamma}$ or $\tilde{H}^o$) is stable. Thus, SUSY events will always show missing energy and imbalance of transverse momentum. The most promising channels [53] to look for SUSY particles at HERA are $eq \rightarrow \tilde{e}\tilde{q}$ via neutralino exchange and $eq \rightarrow \tilde{\nu}\tilde{q}'$ via chargino exchange (see Fig. 3a). Fig. 23 summarizes the cross sections for $\tilde{e}\tilde{q}$ production as a function of $m_{\tilde{e}}$ and $m_{\tilde{q}}$. The uncertainty [54] due to neutralino mixing amounts to a factor 2 in both directions. One sees that $\sigma(eq \rightarrow \tilde{e}\tilde{q}) \simeq 0.1$ pb for $m_{\tilde{e}} + m_{\tilde{q}} \simeq 170$ GeV. It is relatively easy to detect this process if the photino is the lightest SUSY particle and $m_{\tilde{g}} > m_{\tilde{q}}$. In this case [4], the two-body decays $\tilde{e} \rightarrow e\tilde{\gamma}$ and $\tilde{q} \rightarrow q\tilde{\gamma}$ give rise to final states with a clear $p_T$-imbalance, and eq-correlations which are very different from the correlations in the standard NC process (Fig. 1). However, it is also quite possible [52] that the dominant decay modes are more complicated leading to multiparticle final states and, therefore, less striking missing energy signatures. For example, for $m_{\tilde{g}} < m_{\tilde{q}}$ one expects $\tilde{q} \rightarrow q\tilde{g}$, $\tilde{g} \rightarrow q\bar{q}\tilde{\gamma}$ to be the main decay chain. Thus, it should also be searched for multilepton/jet signatures. This is particularly advisable [4] in the case of $\tilde{\nu}\tilde{q}'$ pro-

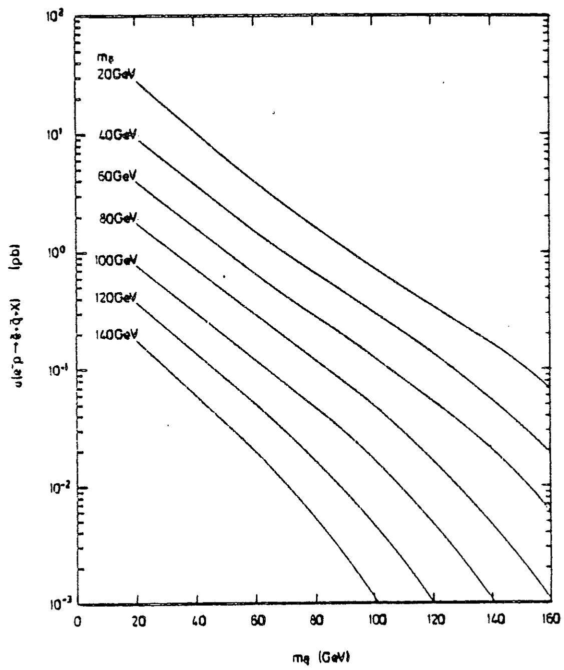



Fig. 23. Associated production of selectrons and squarks at HERA via $\tilde{\gamma}$ ($m_{\tilde{\gamma}}$ =0) and $\tilde{Z}^o$ ($m_{\tilde{Z}}$ = 95 GeV) exchange (from ref. 4).

duction since $\tilde{\nu} \to \nu\tilde{\gamma}$ may have a small branching ratio. Moreover, the decay products are invisible and, hence, it is more difficult to suppress the background from standard CC interactions (Fig. 1). The cross sections for $\tilde{\nu}\tilde{q}'$ production are of similar size as the ones shown in Fig. 23. However, the uncertainty [54] from chargino mixing is O(10). All other ways to produce SUSY particles at HERA are considerably less efficient. This applies to (i) squark production via $\gamma g \to \tilde{q}\bar{\tilde{q}}$ (Fig. 8a), (ii) squark-gluino production [55] via $\gamma q \to \tilde{q}\tilde{g}$ (Fig. 5a), and in particular to (iii) slepton-gaugino production [56], for example, via $e\gamma \to \tilde{e}\tilde{\gamma}$ (Fig. 5a). The largest accessible masses corresponding to a minimum cross section of 0.1 pb are as follows: (i) $m_{\tilde{q}} \simeq 60$ GeV, (ii) $m_{\tilde{q}} + m_{\tilde{g}} \simeq 80$ GeV and (iii) $m_{\tilde{e}} \simeq 30$ GeV if ($m_{\tilde{\gamma}} \simeq 0$). Finally, indirect traces of supersymmetry [55,57] in the running of $\alpha_s(Q^2)$, the evolution of the structure functions, the longitudinal structure functions and other effects of this kind, are very difficult to detect, unless squarks or gluinos are very light, $\tilde{m} \lesssim O$(few GeV). Note that the CERN $\bar{p}p$ collider data almost exclude such a possibility as can be seen from Table 2.

## 6. SUMMARY AND CONCLUSIONS

In this talk, I have discussed present prospects of physics at HERA from a theoretical point of view. The suggestions I presented are based on facts and on a belief. The facts are that the standard model successfully describes physics at present energies, but fails in a number of fundamental questions and that, because of these deficiencies, new physics must exist somewhere between the Fermi scale and the Planck mass. The belief (supported by good arguments) is that the energy scale of the new physics is so near that signals should be discovered at the next generation of accelerators.

I have briefly introduced the most popular ideas of how to supersede or complete the standard model: grand unification, supersymmetry and compositeness. Because of the total lack of experimental hints, one does really not know which one, if anyone, of these suggestions has some truth in it. However, the existing models can serve as a guidance how to find out.

Quite generally, all these models predict small deviations from the standard theory at energies far below the new scale and rather clear signals if one comes sufficiently close. Since the new scale is unknown, future experiments have two complementary tasks: tests of the standard model to the highest possible accuracy and dedicated searches for "exotic" events.

HERA offers many ways to put the standard model to test in a new energy domain, most notably, by

- probing the proton structure at high $Q^2$,
- checking the correct running of $\alpha_s$ and the pattern of scaling violations over a large range in $Q^2$,
- investigating hard QCD scattering processes,
- studying electroweak properties, simultaneously in NC & CC processes and with polarized $e^{\pm}$-beams.

One can be confident of very stringent results if data from HERA, the new $e^+e^-$ colliders, Tevatron and existing data are combined.

HERA can also probe the existence of new physics directly by searching for

| | | |
|---|---|---|
| quark form factors | : | $\Lambda \lesssim$ 300 GeV |
| residual interactions | : | $\Lambda \lesssim$ 3-5 TeV |
| new weak bosons | : | $m \lesssim$ 400 GeV |
| leptoquarks | : | $m \lesssim$ 200 GeV |
| excited fermions | : | $m \lesssim$ 200 GeV |
| SUSY particles | : | $m_{\tilde{e}}+m_{\tilde{q}} \lesssim$ 200 GeV |

The numbers given above indicate the maximum accessible scales and masses guessed from the model studies I have presented. Most of the estimates involve considerable theoretical uncertainties: I have tried to be realistic but not pessimistic. Comparison with the present bounds summarized in Table 2 and 3 shows that HERA can push some limits farther up, or find a signal. Of course, new bounds (or discoveries) can be expected from Tevatron, SLC and LEP I before HERA starts running. However, the physics at these colliders is complementary in some respects [58]. Concerning new particle search, ep collisions are optimal for discovering particles which carry the electron lepton number.

As a final remark, HERA is the only ep collider, at least in the foreseeable future, and therefore also technologically a unique adventure.

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