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ABSTRACT

A brief summary is presented of the physics opportunities provided by *ep* colliders with proton beam energies in the 1 - 10 TeV range. HERA and a hypothetical LEP/LHC combination are taken as examples.

1 Electron-Proton Colliders

Fixed target lepton-nucleon experiments have played an essential role in the development of the standard model of elementary particle physics. With the electron-proton ring accelerator HERA under construction at DESY one will begin a new chapter in the study of lepton-nucleon interactions. HERA will, for the first time, provide collisions of electrons and protons. The parameters of the machine [1],

- beam energies: $E_e = 30$ GeV, $E_p = 820$ GeV
- c.m. energy: $\sqrt{s} = 314$ GeV
- luminosity: $\mathcal{L} = (1\text{–}2) \times 10^{31}$ cm^{-2}s^{-1}
- longitudinal e beam polarization: $P \leq 80\,\%$, $T \leq 30$ min

promise exciting opportunities. For example, one will be able to reach one to two orders of magnitude beyond the regions in c.m. energy, momentum transfer and the Bjorken-x variable accessible in present-day experiments. As a matter of fact, it would require a 50 TeV lepton beam on a fixed target in order to obtain the same c.m. energy, a figure which underlines the enormous increase in exploratory power achievable with HERA. Furthermore, although the c.m. energy of elementary electron-quark collisions is degraded by the square root of the fraction of the proton momentum carried by quarks, one quite frequently expects energies in the 100–200 GeV range. This is comparable with the e^+e^- c.m. energies at SLC and LEP, and also with the collision energies of quarks and gluons at the TEVATRON.

Possibilities to provide *ep* collisions at still higher energies are being investigated in connection with the design studies for hadron supercolliders. The proposition is to let such colliders operate in two modes: proton on proton and, together with a relatively low energy electron ring, electron on proton. Options which appear feasible at CERN by using an electron beam of LEP and a proton beam of LHC, a hadron collider in the LEP tunnel, are characterized below [2]:

- beam energies: $E_e = 50\text{–}100$ GeV, $E_p = 8$ TeV
- c.m. energy: $\sqrt{s} = 1.3\text{–}1.8$ TeV
- luminosity: $\mathcal{L} = 10^{32} - 10^{31}$ cm^{-2}s^{-1}
- longitudinal e beam polarization: *likely-unlikely*

With a 20 TeV proton beam of the American Superconducting Supercollider SSC and a 50–100 GeV electron beam [3] one would even reach c.m. energies of 2–3 TeV. Finally, with respect to the theme of the present Workshop, it should be mentioned that by intersecting a 100 TeV proton ring with a 100 GeV electron ring one could gain another factor of two in *ep* energy. Thus, if the LHC is called a 10% ELOISATRON, the LEP/LHC ep option may be considered the 25% version of an *ep* collider involving the ELOISATRON [4]. Clearly, electron-proton physics in the TeV energy range would be an extremely interesting addition to the physics program at a supercollider which may be built in the future.

Before describing the physics potential I want to recall some peculiarities of the final states expected at *ep* colliders such as HERA and LEP/LHC. The special features are due to the compositeness of the proton as compared to the (more) elementary nature of the electron

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[1] Summary of talk delivered at the *7th* ELOISATRON Workshop, Centro di Cultura Scientifica "Ettore Majorana", Erice-Trapani, Sicily, Italy, June 10-27, 1988

and due to the fact that the proton beam is much more energetic than the electron beam. In most processes, possibly with the exception of some rare, exotic events, the lepton side being relatively clean and quiet can be clearly distinguished from the hadron side which contains the fragmentation products of the spectator and interacting quarks and gluons, and the decay products of heavy hadrons created in the collision. Most of the particles are emitted along the proton beam direction in a cone which is the narrower, the more asymmetric the e and p beam energies are. Thus, on the one hand, final states produced in ep collisions tend to be less complex than the majority of final states one has to deal with in $\bar{p}p$ and pp collisions. On the other hand, the strong forward boost leads to difficulties in the reconstruction and analysis of events and puts additional requirements on the detector design and performance. The two HERA detectors, H1 and ZEUS, represent solutions based on existing technology [5].

In the following, I shall present a brief résumé of the physics opportunities provided by ep colliders with p beam energies of 1–10 TeV. More complete and detailed discussions can be found in the literature [6].

2 Standard Model Physics

One of the primary task of future accelerators is the completion and test of the standard model. As a characteristic feature, ep collisions involve strong and electroweak physics in a way which leads to multiple correlations. These have to be carefully taken into account in the studies of standard model issues. A fairly detailed but not complete list of topics includes

- proton structure and quark/gluon distributions
- QCD scaling violations and running coupling constant
- longitudinal structure function, sum rules
- behavior at very small ('wee') Bjorken-x
- jets and energy flow
- heavy quark physics
- structure of neutral and charged weak currents
- electroweak parameters and relations
- radiative effects
- W, Z production
- Higgs boson production

One can roughly estimate the power available to attack these questions by considering the relevant elementary processes and the rates at which they occur in ep collisions. The subsequent examples apply to HERA and a hypothetical LEP/LHC option. Event rates are quoted for integrated luminosities obtainable in one to two years' running, that is 200 pb^{-1} at HERA and 1 fb^{-1} at LEP/LHC.

Photoproduction.

The scattering of (almost) real photons on protons has by far largest cross section of all ep processes. The hadronic nature of the photon as described by the vector dominance model should emerge at low transverse momenta. On the other hand, the pointlike coupling of photons and quarks gives rise to production of high p_T jets via the hard scattering processes $\gamma q \rightarrow gq$ and $\gamma g \rightarrow q\bar{q}$. The rates are substantial, as can be seen from the following predictions for 2-jet events with $p_{Tj} \geq p_{T min}$.

$p_{T min}$	HERA (0.3 TeV)
10 GeV	10^6
30 GeV	10^4
60 GeV	10^2

Higher order subprocesses produce in addition multijet events. Here, the short-distance quark/gluon structure of the photon predicted by QCD plays a significant role. It leads to qq, qg, and gg scattering processes which contribute to jet production in the low and medium p_T region. Furthermore, Compton scattering $\gamma q \rightarrow \gamma q$ can provide complementary and, because of the relative simplicity of the process, very reliable tests. Finally, photoproduction of heavy quarks is considered to constitute one of the highlights of ep physics as emphasized in more detail later. In summary, photon-proton processes allow for a great variety of studies ranging from soft hadronic physics to QCD perturbation theory, jet fragmentation and parton distributions.

Deep inelastic scattering.

Virtual γ, Z and W exchange gives rise to the neutral and charged current scattering processes, $eq \rightarrow eq$ and $eq \rightarrow \nu q'$, respectively. Unprecedented and therefore particularly interesting is the access to very large values of momentum transfer Q and to very small values of Bjorken-x. The following table of inclusive rates for CC events $e^-p \rightarrow \nu_e X$ exemplifies the reach in Q^2.

Q^2_{min}	HERA (0.3 TeV)	LEP/LHC (1.4 TeV)
10^3 GeV^2	10^4	2×10^5
10^4 GeV^2	10^3	5×10^4
10^5 GeV^2	—	2×10^3

While at $Q^2 \geq m^2_{W,Z}$ the CC and NC rates are similar in magnitude, reflecting the roughly equal strength of electromagnetic and weak interactions at such high energy scales, at $Q^2 \leq 10^3\, GeV^2$ the NC rates are considerably larger than the CC rates due to the dominance of photon-exchange. The latter is also responsible for the large cross sections expected as x approaches zero. The table below shows event rates in the 'wee'-x region for $Q^2 \geq 5$ GeV^2 and $y = Q^2/(xs) \geq 0.01$, predicted by extrapolating a conventional parametrization of quark distributions. One can put forward theoretical arguments which suggest quite a different behavior of structure functions at small x resulting in even higher cross sections [6].

x-region	HERA (0.3 TeV)	LEP/LHC (1.4 TeV)
$10^{-4} - 10^{-3}$	4×10^6	3×10^7
$10^{-3} - 10^{-2}$	7×10^6	8×10^6

With such large rates it should be possible to determine quark distributions of the proton with sufficient accuracy to resolve structures as small as 10^{-3} fm, to study scaling violations and test QCD at 'asymptotic' values of Q^2, and to explore the limit $x \to 0$. Small-x physics is not only theoretically very intriguing [7], it also plays an essential role in phenomenology, in particular at supercolliders. Therefore, one cannot overemphasize the importance of direct measurements to clarify the issue. Finally, the simultaneous occurrence of NC *and* CC processes, the access to large momentum transfer $Q \geq m_{W,Z}$, and longitudinal e-beam polarization make ep colliders also powerful tools for electroweak studies.

Heavy quark production.

Charm, bottom and top quarks are dominantly produced via photon-gluon fusion $\gamma g \to Q\overline{Q}$, except a heavy top with $m_t \geq 50$ GeV which is more efficiently created in the W boson-gluon fusion process $Wg \to t\bar{b}$. Assuming a conventional gluon distribution one predicts the following integrated inclusive yields.

flavor	HERA (0.3 TeV)	LEP/LHC (1.4 TeV)
c	10^8	10^9
b	10^6	5×10^7
$t(m_t = 50\,\mathrm{GeV})$	200	10^5
$t(m_t = 100\,\mathrm{GeV})$	4	10^4

The numbers speak for themselves. Particularly remarkable is the potential of ep colliders in b-physics and the interesting window for top search which exists at HERA. Heavy flavor production is also known as one of the processes which are best suited for application of perturbative QCD. Moreover, it can be used as a sensitive probe of the gluon density. The production of quarkonium resonances such as J/ψ and Υ has turned out to be a rich source of additional information.

Production of weak gauge bosons.

In contrast to e^+e^- and hadronic collisions where weak gauge bosons can be resonance-produced, in ep collisions the dominant source of W and Z bosons is photoproduction at the hadronic vertex, $\gamma q \to (W,Z)q'$. Production at the leptonic vertex, $e\gamma \to (W,Z)l$, is less efficient. Since these are higher order electroweak processes, the rates are relatively small as indicated below for inelastic production $ep \to l(W,Z)X$.

	HERA (0.3 TeV)	LEP/LHC (1.5 TeV)
W	160	2×10^4
Z	40	2×10^3

Nevertheless, these processes are interesting, for example, as electroweak versions of Compton scattering, probes of the anomalous magnetic moment of the W, and sources of events with missing energy and momentum. The latter arise from the decays $W \to l\bar{\nu}_l$ ($Br \approx 8\,\%$) and $Z \to \nu\bar{\nu}$ ($Br \approx 18\,\%$), and might produce an important background to missing energy signals from new physics such as production and decay of supersymmetric particles.

Higgs boson production.

The only relevant production mechanism for the standard Higgs boson in ep collisions is W-W fusion in the process $eq \to lq'H$. It is therefore not surprising that Higgs boson production at HERA energies is very strongly suppressed. However, ep colliders in the TeV energy range maybe useful for Higgs searches as indicated by the production rates listed below.

mass	HERA (0.3 TeV)	LEP/LHC (1.5 TeV)
50 GeV	2	300
100 GeV	—	180
200 GeV	—	60
300 GeV	—	25

The possibility of complementary searches is particularly important in the intermediate mass range $m_W \leq m_H \leq 200$ GeV which is difficult to explore at LEP and hadron supercolliders.

3 Physics Beyond the Standard Model

Another primary task of future accelerators is the search for physics beyond the standard model. Although the standard model can so far accommodate all confirmed experimental results, one has put forward plausible, and by now well-known, theoretical arguments which strongly suggest the existence of some kind of new phenomena at or not too far above the Fermi scale. Suppositions about the nature of the new physics are based on attempts to construct more fundamental theories involving larger gauge groups, deeper levels of substructure, supersymmetry and ultimately even gravity. Concrete models are designed such as to reproduce the standard theory at low energies. In addition, they predict a whole variety of new particles and interactions, some of which may be light or, respectively, strong enough to induce observable effects in the TeV energy range. Candidates are

- new weak bosons and currents
- residual strong interactions
- pseudo-Goldstone bosons
- exotic fermions
- excited leptons and quarks
- leptoquarks, leptogluons
- scalar leptons and quarks, gauge fermions, Higgs fermions

and others. However, experimental contraints derived from existing data do not leave too much room for such speculations in the energy range of TEVATRON, SLC/LEP and HERA. In other words, considering the present bounds, it appears more likely that one will observe some slight deviations from standard model expectations or rare exotic events rather than striking and unambiguous signals. In that case, the possibility of complementary tests in e^+e^-, $\bar{p}p$ and ep collisions may turn out extremely important in order to establish clear evidence for new physics and discriminate possible interpretations.

The following examples are supposed to illustrate the discovery potential of *ep* colliders. I shall again focus on HERA and LEP/LHC assuming the same integrated luminosities as before that is 200 pb^{-1} and 1 fb^{-1}, respectively. For brevity, I have selected only a few typical study cases. The theoretical motivation and prejudices cannot be discussed here. Furthermore, the sensitivity limits which I shall quote involve many assumptions and should therefore be taken only as rough indications.

W' and Z' bosons.

Additional weak gauge bosons can be produced in γq and $e\gamma$ subprocesses similarly as the ordinary W and Z bosons. However, at least at HERA, the mass window for direct W' and Z' searches is rather small as can be seen from the moderate production rates predicted for W and Z. Moreover, new bosons in the 100–300 GeV range are already more or less excluded by experiment. In order to reach heavier masses one has to search for indirect effects on inclusive NC and CC scattering processes $ep \to lX$. More definitely, virtual Z' and W' exchange and Z–Z' and W–W' mixing lead to small deviations in cross sections and asymmetries from the standard model predictions. The magnitude and pattern of these effects, and hence also the sensitivity depend strongly on the Z' and W' properties and on the observables considered. The most sensitive tests are generally provided by accurate measurements of distributions in Q^2, preferentially with polarized e beams. In the case of E_6-type and left-right symmetric models with only one extra Z' boson at low energies and negligible Z–Z' mixing, one can expect to reach the Z' masses indicated below.

model	HERA (0.3 TeV)	LEP/LHC (1.4 TeV)
E_6-type	up to 300 GeV	up to 500 GeV
L-R	500 GeV	800 GeV

Contact interactions.

If leptons and quarks are composite at a scale Λ, the new binding force is expected to give rise to residual interactions which may be observable already at energies much smaller than Λ. For example, four-fermion interactions involving products of left- and right-handed lepton and quark currents with effective couplings g^2/Λ^2 are practically unavoidable. Such contact interactions would affect NC and CC scattering similarly as heavy Z' and W' bosons and can, therefore, be tested by the same inclusive measurements as the latter. Estimates have shown that, depending on the chiral structure of the contact interactions, one should be able to probe lepton and quark compositeness up to the following values of Λ.

coupling	HERA (0.3 TeV)	LEP/LHC (1.4 TeV)
$\frac{g^2}{4\pi} = 1$	(4–7) TeV	(7–14) TeV

Furthermore, asymmetry measurements with polarized electrons are very powerful in determining the helicity structure of contact interactions.

Scalar leptons and quarks.

In supersymmetric extensions of the standard model, the supersymmetric partners are usually distinguished from the conventional particles by a conserved parity-like quantum number.

Correspondingly, supersymmetric partners can only be produced in pairs and the lightest of them (LSP) is stable. This has far-reaching phenomenological consequences. In *ep* collisions, the most important SUSY process is pair-production of sleptons and squarks, $eq \to \tilde{e}\tilde{q}$ and $eq \to \tilde{\nu}\tilde{q}'$, via neutralino and chargino exchange, respectively. The observable final states resulting from slepton and squark decays carry missing energy and momentum signatures. Particularly clear signals would be provided by the decays $\tilde{l} \to l\tilde{\gamma}$ and $\tilde{q} \to q\tilde{\gamma}$ where the photino $\tilde{\gamma}$ is the LSP and escapes undetected. In this case, the visible particles are the same as in ordinary NC and CC events, $eq \to lq$, but the l and q momenta are uncorrelated in contrast to the completely correlated l and q momenta of the background. It is thereforenot too difficult to suppress this background. Under such favorable conditions one can explore the existence of scalar leptons and quarks with masses within the following values for the sum $m_{\tilde{l}} + m_{\tilde{q}}$.

process	HERA (0.3 TeV)	LEP/LHC (1.4 TeV)
$eq \to \tilde{e}\tilde{q} \to (e\tilde{\gamma})(q\tilde{\gamma})$	180 GeV	750 GeV

Excited leptons.

An interesting example for new particles which can be singly produced is provided by a heavy replica e^* of the ordinary electron. The subprocess $eq \to e^*q$ is dominated by the photon pole with the strength of the magnetic transition $e\gamma \to e^*$ being inversely proportional to a heavy mass scale such as the compositeness scale Λ or the mass m_{e^*}. Obviously, the signature provided by the decay $e^* \to e\gamma$ is simple and clear. Hence, *ep* colliders are well suited for e^* searches as can be seen from the following detection limits.

process	HERA (0.3 TeV)	LEP/LHC (1.4 TeV)
$eq \to e^*q \to (e\gamma)q$	250 GeV	1 TeV

Leptoquarks.

Among the most exotic particles are species carrying lepton and quark quantum numbers, generically called leptoquarks. They typically appear in unified models. In *ep* collisions, leptoquarks can be resonance-produced in the channel $eq \to LQ$, provided the coupling is not suppressed by the electron and light quark masses. Not only is the resonance cross section comparatively large, also the signatures from the decays $LQ \to eq$ and $LQ \to \nu q'$ are rather striking, e.g. flat y-distributions in contrast to the steep fall-off in y typical for ordinary NC and CC events and, even more spectacular, narrow resonance peaks in x-distributions at $x = m_{LQ}^2/s$. Consequently, for couplings of the order of the electromagnetic coupling, leptoquarks can be detected up to masses near the phase space limit as indicated below.

process	HERA (0.3 TeV)	LEP/LHC (1.4 TeV)
$eq \to LQ \to (eq)$ and $(\nu q')$	250 GeV	1.2 TeV

4 Conclusions

Electron-proton collisions provide an excellent testing-ground for the standard model and numerous interesting channels to trace new physics. As compared to e^+e^- and hadron machines, *ep* colliders are unique tools to investigate the substructure of hadronic matter down to extremely small distances, to test QCD free of non-asymptotic background, and to explore the existence of new particles carrying the e-number such as excited electrons, scalar electrons and electroquarks. In addition, *ep* colliders provide valuable complementary means of studying heavy quark physics and electroweak interactions. In conclusion, electron-proton physics with 1–10 TeV proton beams is rich and in many respects complementary to the physics opportunities at e^+e^- and hadron colliders. Thus, the possibility for future supercolliders to operate in a *ep* mode is of great interest.

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