New Physics of ep Colliders Beyond 2000

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Deep inelastic physics and the discovery reach beyond the Standard Model at existing and future ep colliders is discussed with an emphasis on the search for new bosons coupling to lepton-quark pairs.

1. INTRODUCTION: ep PHYSICS AT HERA$_I$

The basic Deep Inelastic (DIS) Standard Model (SM) process discussed throughout this paper is shown in Fig. 1. There has been considerable progress in the understanding of the physics of this reference process from data collected since 1992 at the ep collider HERA. An illustration of the essential SM frontiers already explored at HERA$_I$ is provided in Fig. 2.

The low x limit of perturbative QCD as been investigated down to $x \sim 10^{-5}$. At very low x the very high parton density could allow to penetrate a "transition" region (approaching effective confinement) where saturation effects would be observable. Towards highest x, up to $x \sim 0.65$, the u and d valence quark region has been tested both with pure electromagnetic and weak probes. While the low y domain $(0.005 \leftarrow y)$ has provided an overlap with fixed target experiments, the high y domain $(y \rightarrow 0.82)$ offered a sensitivity to the longitudinal structure function $F_L \equiv F_2 - 2xF_1$ which is driven to be non-vanishing due to QCD effects. The low Q^2 $(0.1 \leftarrow Q^2)$ domain made possible the connection from DIS to photoproduction (γp) physics in a single experiment.

At very high Q^2, $(Q^2 \rightarrow 30000\ \mathrm{GeV}^2)$, searches for physics beyond the SM have been carried. This concerned in particular new bosons coupling to lepton-quark pairs such as leptoquarks [1] or squarks [2] in R-parity violating ($\not{R}_p$) supersymmetry (SUSY). The energy available to create mass at the $e - quark$ interaction vertex which is simply given by $M = \sqrt{sx}$, reached a maximal value at $x \sim 1$ for HERA of about 300 GeV.

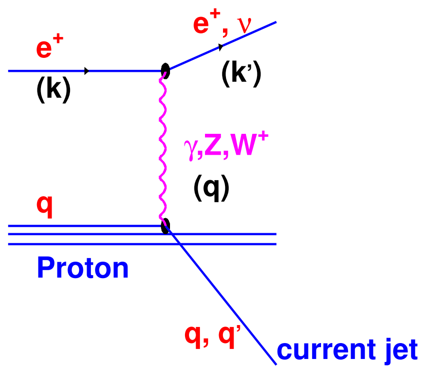

Figure 1. Standard DIS interaction in ep collisions through t-channel exchange of a virtual gauge boson. The process is characterized (at lowest order) by two Lorentz invariants chosen among the squared four-momentum tranfer $Q^2 = -(k-k')^2 = sxy$, the fractional proton momentum $x = Q^2/2(p.q)$ carried by the struck quark, and $y = p.q/p.k$ which is related to the polar angle θ^* of the final state lepton in the $e - quark$ centre of mass frame via $y = (1+\cos\theta_e^*)/2$.

Other exotic particles which can be singly formed as a resonance between the incoming lepton and gluons in the proton (leptogluons) or a gauge boson radiated off the proton (excited leptons) have been searched for [3]. While fermion substructure could possibly be revealed by relatively low mass excited states of known fermions, it could also be detected indirectly for much higher characteristic mass scales via effective four-fermion contact interactions (CI). CI searches generalized

Table 1
Existing and future ep colliders

		THE Existing Machine: Status			
HERA_I	$e^{\pm}p$	$\lesssim 100\ \mathrm{pb}^{-1}$	$\lesssim 320$ GeV	10^{-4}	≤ 2000
		THE Upgraded Machine: Prospects			
HERA_{II}	$e^{\pm}_{L,R}p$	$\lesssim \mathcal{O}(1\ \mathrm{fb}^{-1})$	~ 320 GeV	10^{-4}	$\gtrsim 2000$
				possible options	
	$e^{\pm}_{L,R}\vec{p}$ or $e^{\pm}_{L,R}A$	$\lesssim \mathcal{O}(1\ \mathrm{fb}^{-1})$	~ 320 GeV	10^{-4}	$\gtrsim 2005$
		The Possible Future Machines			
TESLA $\times$ HERA	$e^{-+}_{L,R}p$	$\sim 200\ \mathrm{pb}^{-1}$	$1 \rightarrow 1.3$ TeV	10^{-5}	$\gtrsim$ 201n
LEP $\times$ LHC	$e^{\pm}_{L,R}p$	$\simeq 2\ \mathrm{fb}^{-1}$	1.4 TeV	10^{-6}	$\gtrsim$ 201n
"LEP" $\times$ $\mathrm{VLHC}_{boost.}$	ep	$\mathcal{O}(1\ \mathrm{fb}^{-1})$	1 TeV	10^{-6}	$\gtrsim$ 201n

to probe various possible new heavy particles X at masses $M_X \gg \sqrt{s}$ have been carried [4] for the first time at HERA in DIS physics in a domain where electroweak-induced "scaling" violations dominate over QCD scaling violation. Finally, the unique quantum numbers provided at the hard lepton-quark (or lepton-gluon) vertices has opened in general new opportunities to look for outstanding event topologies with high transverse momentum leptons in the final state [5].

2. *ep* COLLIDERS BEYOND 2000

The "low luminosity" runs at HERA (henceforth called HERA_I runs) will be completed in spring 2000. The upgraded H1 and ZEUS detectors are expected to resume data taking in a high luminosity machine configuration (henceforth called HERA_{II}) in the year 2001, then collecting up to 250 pb^{-1} of integrated luminosity each with e^+, e^- and left- (L) or right- (R) handed polarization over a period of 4 to 5 years. In this post-LEP and pre-LHC era, the D0 and CDF experiments at the TeVatron $p\bar{p}$ at Fermilab (Chicago) are also expected to resume data taking, after 4 to 5 years of halt, in a high luminosity machine configuration (henceforth called $\mathrm{TeVatron}_{II}$) providing up to 1 fb^{-1} per year.

The possible ep collider options beyond HERA_{II} are summarized in table 1. The kinematics of the final state lepton and "current" jet for each of these collider options is illustrated by the iso-curves of Figs. 3, 4 and 5.

To investigate further the structure of the proton and of QCD in hadronic matter, two distinct avenues are being considered at DESY beyond HERA_{II}: **i)** the acceleration of nucleus in the HERA proton ring could allow through eA collisions the study of non-linear QCD dynamics and saturation effects in a small coupling regime, of colour transparency and in general of propagation of partons through nuclear medium, etc. (for recent reviews see [6]); **ii)** the quark and gluonic carriers of the proton spin could studied in a new kinematic regime through $\vec{e}\vec{p}$ collisions with polarized proton in the HERA proton ring (for recent reviews see [7]). Decisions on whether (and which) one of these avenues will be taken will realistically have to await for the convergence of the leading project for DESY, the future TESLA e^+e^- collider [8]. The installa-

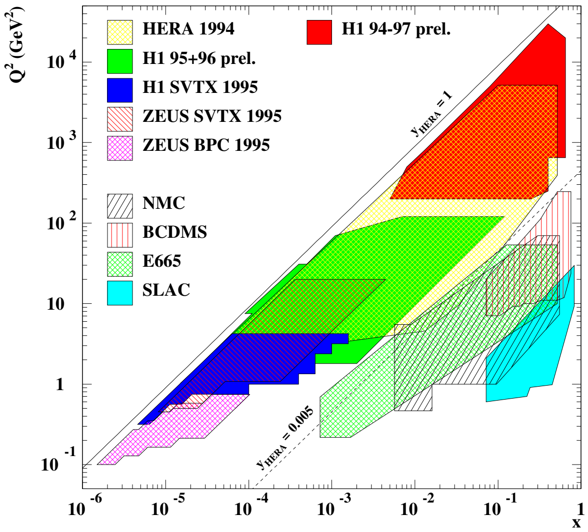

Figure 2. The $Q^2 - x$ kinematical plane explored at HERA$_I$.

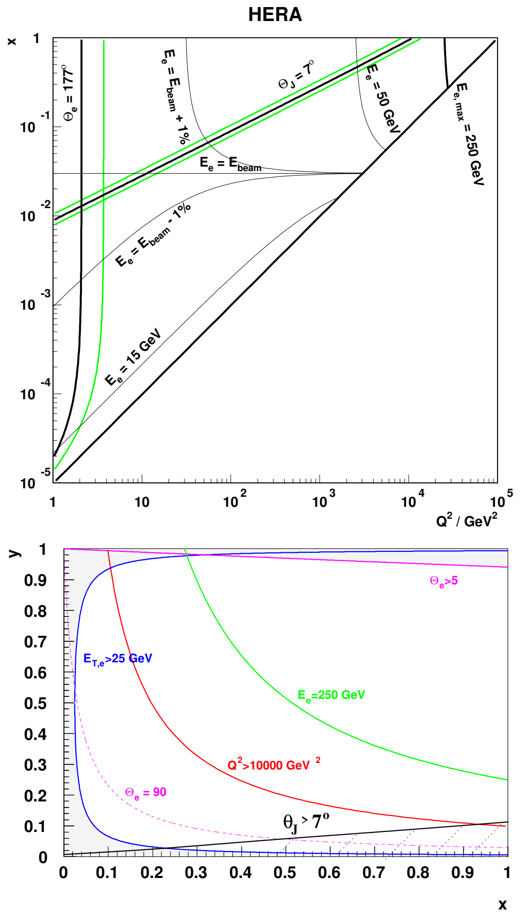

Figure 3. Kinematic plane at HERA$_{II}$ for *(top)* x versus Q^2 and *(bottom)* y versus x.

tion of a TESLA-like collider tangent to HERA would open a TESLA $\times$ HERA *ep* option. A possible machine configuration and corresponding performances were described in [10]. Whether or not a future e^+e^- collider like TESLA eventually obtains world-wide approval (e.g. being highly motivated by precision measurements in the Higgs sector) is here a critical aspect. The LEP $\times$ LHC option is in principle part of the approved "CERN Large Hadron Collider project" at CERN near Geneva and was described in [9]. Whether or not the capability to re-built the LEP collider can be realistically preserved for some years after its dismantling to allow for LHC installation is here a critical aspect. The futuristic "LEP" $\times$ VLHC$_{boost.}$ option would profit from the first stages of an eventual development for a Very Large Hadron Collider at Fermilab near Chicago [11].

3. STANDARD MODEL PHYSICS AND BEYOND FUTURE *ep* COLLIDERS

3.1. The Standard DIS Model

There are a number of excellent physics motivations within the SM for an ugraded (higher luminosities) HERA machine (HERA$_{II}$) beyond the year 2000. The gluon density in the proton $xg(x, Q^2)$ will be measured at higher Q^2 over a wide x range. The low x range (e.g. $10^{-3} - 10^{-2}$) will set constraints relevant for the Higgs luminosities at LHC where $gg \to H$ is the dominant production process. The high x range ($\gtrsim 10^{-1}$) is poorly known and a region where HERA can

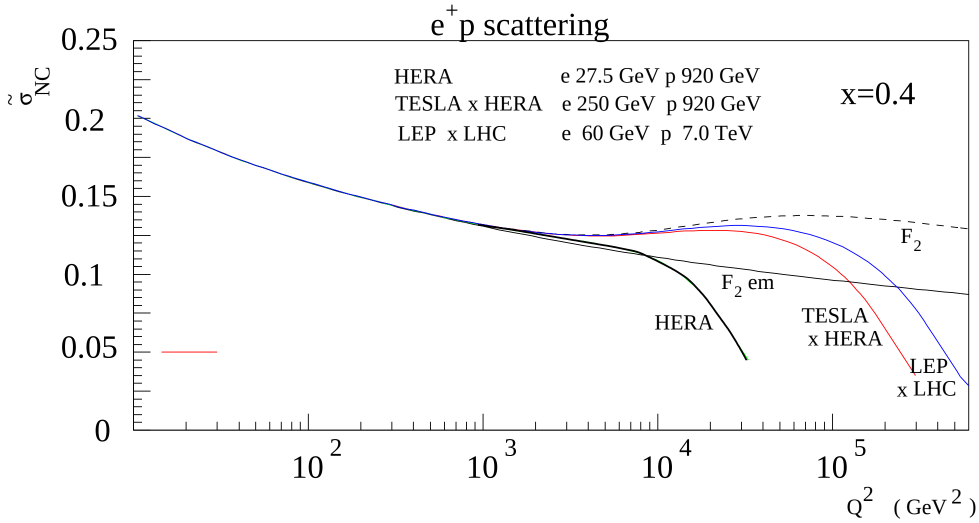

Figure 6. Comparison of NC DIS reduced cross-section in e^+p collisions for $x = 0.4$ at HERA, TESLA×HERA and LEP×LHC colliders.

provide direct measurements for example through di-jets. The u or d valence quark densities can be constrained at large x, using high Q^2 CC data, away from nuclear effects. Better constraints in particular on the d quark at largest x is essential to profit from the full discovery reach of ep colliders. The parity violating xF_3 at high Q^2 will be derived from a combination of e^-p and e^+p data. In the electroweak sector, precision measurement of the axial and vector couplings of light quarks will be performed. Finally, as will be discussed below, HERA$_{II}$ will provide unique opportunities for physics beyond the Standard Model, with a discovery potential in particular for new bosons with (chiral) couplings to $e-q$ pairs or new (contact) interaction at very large mass scales.

At possible future ep colliders the Standard Model physics of DIS scattering will differ from that at HERA in a fundamental way as illustrated in Fig. 6. The TESLA×HERA and LEP×LHC colliders will offer a very much restricted region of validity of the approximation $F_2^{em} \equiv \sum_f e_f^2(xq_f + x\bar{q}_f) \approx \tilde{\sigma}_{NC}(e^+)$. The consequences of this was analysed in detail in the LEP×LHC context at the 1990 LHC Workshop [12]. Over a wide $x - Q^2$ range, the proton structure will be probed with weak currents.

Stringent and nicely simple search for right-handed weak currents can be performed at HERA$_{II}$ with $\gtrsim$60% lepton beam polarization and later at TESLA×HERA with $\gtrsim$80% lepton beam polarization as shown in Fig. 7.

3.2. Beyond the Standard Model

As mentioned in the introduction, ep colliders are particularly suited to search for new bosons coupling to lepton-quark pairs.

Prominent among such bosons are leptoquarks. Leptoquarks are colour triplet bosons (scalars S or vectors V) carrying lepton L and baryon B quantum numbers and fractional electric charge. They appear naturally in GUT-like theories to "explain" symmetry between the leptonic and quarkonic sectors [13], as well as in Superstring-inspired E_6 models [14], Technicolor theories [15] and in Compositeness models [16].

In the minimal model of Buchmüller-Rückl-Wyler (BRW) [17], leptoquarks must: **i)** have couplings invariant under SM gauge interactions; **ii)** have renormalizable interactions; **iii)** each couple to a single lepton-quark generation; **iv)** have pure chiral couplings to SM fermions; **v)** conserve L and B separately; **vi)** couple only to SM fermions and gauge bosons. This allows for the existence of 7 scalars from 5 isospin families with fermionic number $F = 2$ ($S_{0,R}$, $S_{0,L}$, $\tilde{S}_{0,R}$,

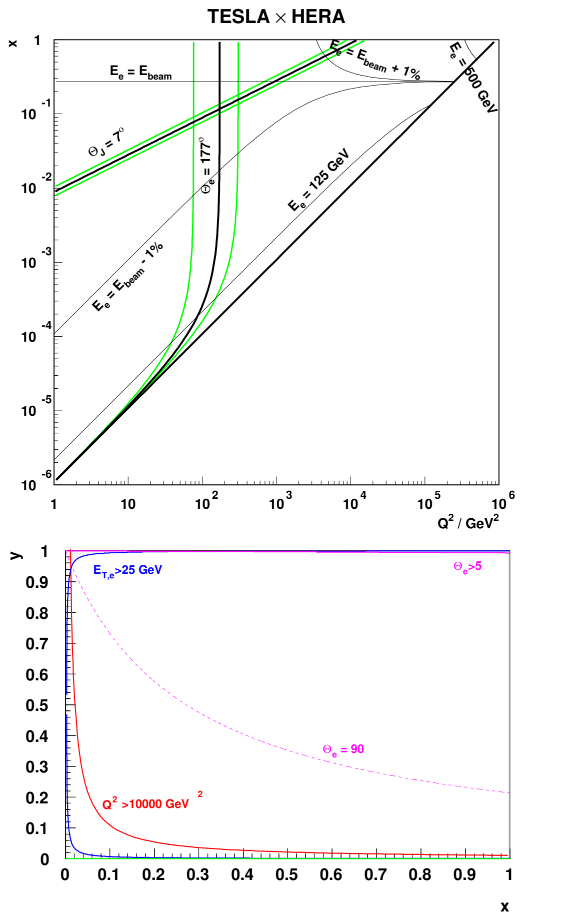

Figure 4. Kinematic plane at TESLA $\times$ HERA for *(top)* x versus Q^2 and *(bottom)* y versus x.

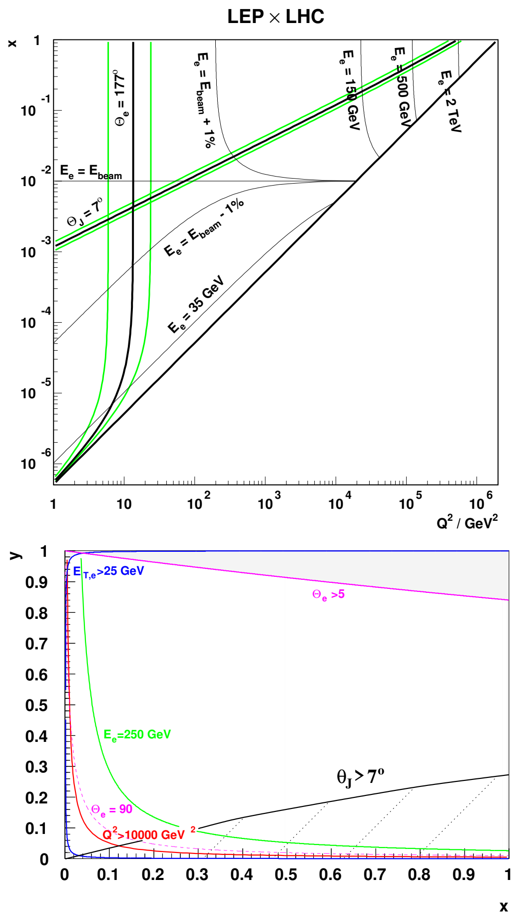

Figure 5. Kinematic plane at LEP $\times$ LHC for *(top)* x versus Q^2 and *(bottom)* y versus x.

$S_{1,L}$) or $F = 0$ ($S_{1/2,L}$, $\tilde{S}_{1/2,L}$, $\tilde{S}_{1/2,R}$), and for 7 vectors also from 5 isospin families with with fermionic number $F = 2$ ($V_{1/2,R}$, $V_{1/2,L}$,$\tilde{V}_{1/2,L}$) or $F = 0$ ($V_{0,L}$,$\tilde{V}_{0,R}$,$V_{1,L}$). In such a minimal model, leptoquarks have fixed decay branching ratio into $e + q$ pairs.

Irrespective of a specific theoretical motivation, the leptoquark search can be extended to "generic" models by (e.g.) dropping some of the above constraints. It might for instance be reasonable to assume, contrary to assumption (vi), that leptoquarks could also couple to other (unspecified) new fields and thus acquire non-standard decay branching ratio into into $e + q$ pairs. Alternatively, relaxing the assumptions (iii) or (v) in the lepton sector could allow for Lepton Flavour Violating (LFV) leptoquark processes.

In ep collisions, leptoquarks can be singly produced by the s-channel fusion of a lepton and a quark or exchanged in the u-channel where a lepton (quark) is converted into a (quark) lepton a illustrated in the diagrams of Fig. 8. When involving first generation fermions in the final state, both types of leptoquark diagrams will interfere with the SM gauge boson exchange of Fig. 1. Different kinds of leptoquarks are produced dominantly depending on the charge of the initial lep-

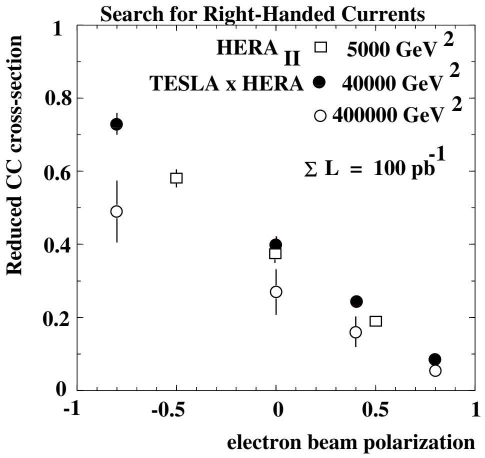

Figure 7. Search for new right-handed weak currents in e^-p collisions at HERA_{II} and TESLA×HERA (*courtesy of M. Klein*).

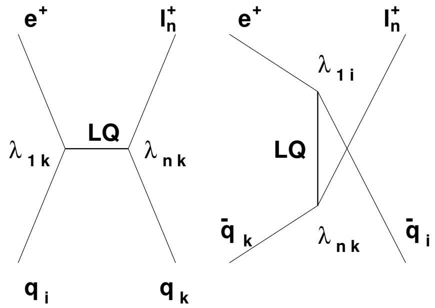

Figure 8. Single leptoquark s- and u-channel production diagrams in e^+p collisions. The indices i and j of the couplings λ_{ij} at the LQ−lepton−quark vertices refer to the lepton i^{th} and quark j^{th} generation respectively.

ton; e.g. for scalars, e^-p favours S_0,$\tilde{S}_0$ and S_1 while e^+p favours (anti-) $S_{1/2}$ and $\tilde{S}_{1/2}$.

Three mass regimes can be distinguished for ep colliders. For simplicity these are discussed here for $F = 0$ leptoquarks.

For leptoquark nominal masses $\boldsymbol{M_{LQ} \ll \sqrt{s_{ep}x}}$, the resonant production cross section can be calculated in the narrow-width approximation (NWA) and for the s-channel process $eq_i \rightarrow l_n q_k$ scales as $\sigma_{\mathrm{NWA}} \propto \lambda^2 \beta_n q(x)$ where $q(x)$ is the density of the struck parton in the incoming proton and β_n is the decay branching ratio into a $l_n q_k$ pair. The u-channel contribution is highly suppressed by less favorable parton densities as it proceeds via an exchange involving an *antiquark* from the proton. The decay width of a scalar (S) or vector (V) leptoquark into a lepton is calculated as $\Gamma_S = (3/2)\Gamma_V = \lambda_{ij}^2 M_{LQ}/16\pi$ and is expected to be small. As an example at HERA for $M_{LQ} = 200$ GeV, one would expect $\Gamma_S \simeq 360$ MeV for $\lambda_{ij} = \sqrt{4\pi\alpha} = 0.3$ [1]. Scalar and vector leptoquarks will lead to distinct angular spectra (i.e. y spectrum) of the final state lepton. Scalar LQs produced in the s-channel decay isotropically in their rest frame leading to a flat $\mathrm{d}\sigma\,/\,\mathrm{d}y$ spectrum. In contrast, events resulting from the production and decay of vector LQs would be distributed according to $\mathrm{d}\sigma\,/\,\mathrm{d}y \propto (1-y)^2$. These y spectra are markedly different from the $\mathrm{d}\sigma\,/\,\mathrm{d}y \propto y^{-2}$ distribution expected at fixed x for the dominant t-channel photon exchange in neutral current DIS events [2].

For $\boldsymbol{M_{LQ} >> \sqrt{s_{ep}}}$, the propagator entering the leptoquark amplitudes can be contracted to a four-fermion interaction. One is left with a contact interaction mostly affecting the measured inclusive DIS Q^2 spectrum through interference effects which scale with λ^2. Constraints on such four-fermion couplings can be translated into limits on M_{LQ}/λ.

For $\boldsymbol{M_{LQ} \sim \sqrt{s_{ep}}}$, the search is hampered by several complications. In approaching $\sqrt{s_{ep}}$ from below, the interference of the LQ s-channel production and u-channel exchange with SM bosons exchange can in general no longer be ne-

[1] In practice, the leptoquark mass resolution will be dominated either by detector effects or by kinematic migrations mainly coming from initial state QED bremsstrahlung and QCD final state parton showers. The former case applies to a reconstruction of M_{LQ} via the LQ decay products. The latter case applies to a reconstruction of M_{LQ} via the final state lepton in the DIS parton approximation.

[2] At TESLA×HERA or LEP×LHC, the significant Z^0 exchange contribution to DIS physics (over a large fraction of the accessible Q^2 range) will lead to less pronounced differences in the y spectra between LQ signal and DIS background.

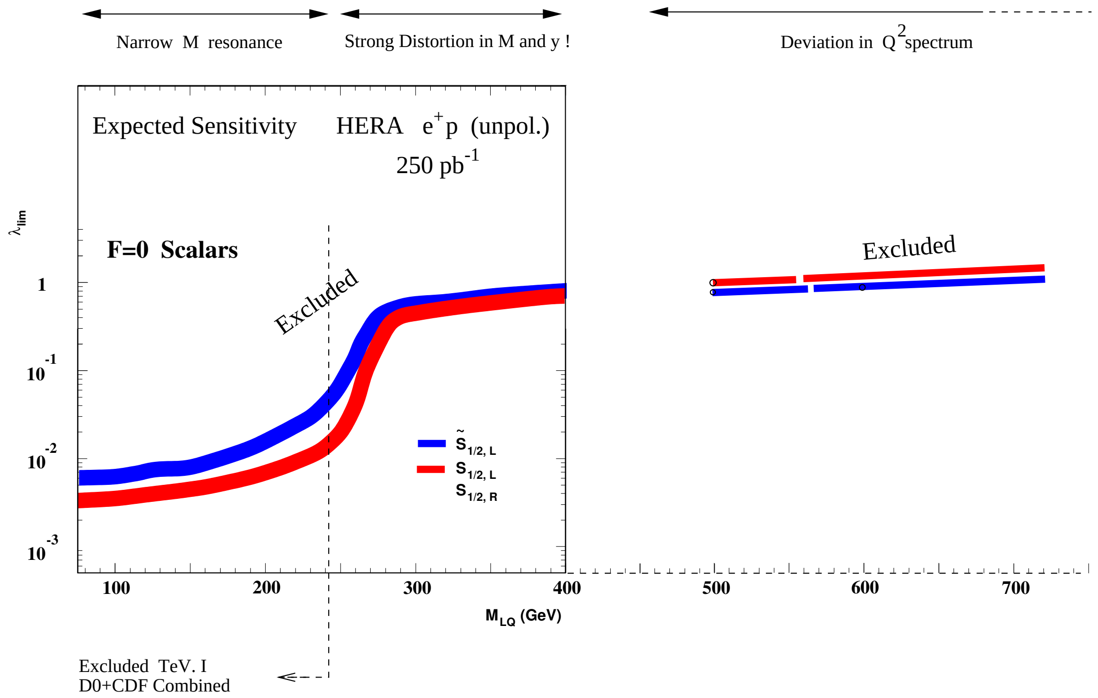

Figure 9. Expected constraints on leptoquarks from HERA$_{II}$ for an integrated luminosity of 250 pb^{-1}. The rejection limit curves are obtained by extrapolating recent HERA direct searches and Contact Interaction results.

glected. This interference can be constructive or destructive[3]. Concomitantly, the values of $q(x)$ become exceedingly small when approaching $x \sim 1$ such that to obtain observable cross-sections, large coupling values (stronger interactions) are required. Thus the NWA becomes in any case invalidated. Moreover, the convolution of the steeply falling $q(x)$ with the Breit-Wigner distribution of finite width characterizing the resonance leads to a strong distortion (large tails towards low values) of the leptoquark mass peak. Even for M_{LQ} above $\sqrt{s_{ep}}$, a sizeable s-channel contribution (e.g. for $F = 0$ leptoquarks) might originate from this convolution provided that the coupling λ is not too small (since such contributions scales with λ^4).

[3]The correct signs of the interference terms between SM gauge boson and $F = 0$ LQ contributions can be found in an erratum [18]

The figure 9 shows what can be expected from an exploitation of 250 pb^{-1} of e^+p data from HERA$_{II}$ for the three $F = 0$ scalars in the BRW model. Also shown is the actual constraints from TeVatron experiments where leptoquarks are mostly produced in pair via the strong interaction independently of the Yukawa coupling values. With the substantial increase of luminosity expected at future TeVatron runs at TeVatron$_{II}$, most of the easy domain where a narrow resonance could be discovered at HERA$_{II}$ will be covered by TeVatron searches ... unless the branching ratio $\beta_{eq} \equiv \beta(LQ \to eq) \ll 1$. In case of a discovery, only HERA$_{II}$ could resolve completely the quantum numbers of the leptoquark by the combination $e^{\pm}_{L,R}$ beams [19].

That a discovery domain remains for HERA$_{II}$ for $\beta_{eq} \ll 1$ is shown in Fig. 10 which compares actual HERA$_I$ and TeVatron$_I$ results. Similar ex-

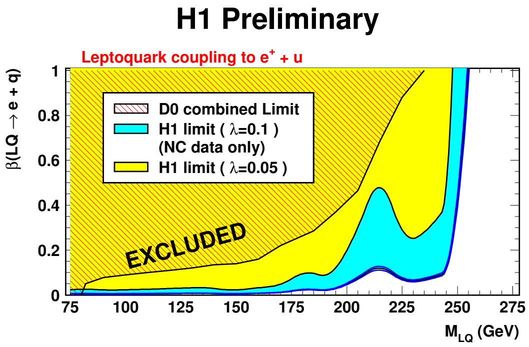

Figure 10. Constraints on leptoquarks in generic models; branching ratio β_{eq} upper limits ($95\% CL$) versus M_{LQ} obtained at HERA$_I$ compared to actual TeVatron constraints.

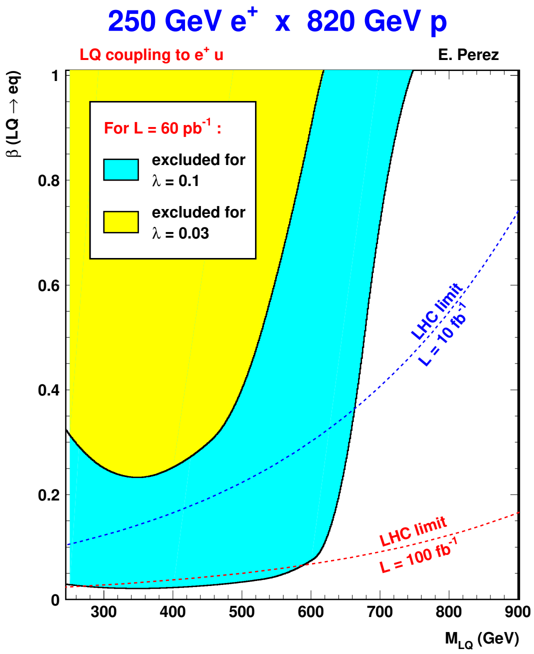

Figure 11. Constraints on leptoquarks in generic models; branching ratio β_{eq} upper limits ($95\% CL$) versus M_{LQ} expected from TESLA $\times$ HERA compared to expected LHC constraints.

clusion limits are shown in Fig. 11 as a figure of merit of the TESLA $\times$ HERA configuration after $\lesssim 1$ year of operation, in comparison to $\mathcal{O}(1)$ year of operation of the LHC at low and high luminosity. It can be seen that the search for new bosons coupling to lepton-quark pairs of the first generation at TESLA $\times$ HERA could be competitive only during the initial LHC startup phase or alternatively for very small β_{eq}. In one year, TESLA $\times$ HERA could be sensitive to masses M_{LQ} up to $\simeq 600$ GeV for $\beta_{eq} \lesssim 20\%$.

We do not know why lepton flavour should be exactly exactly conserved in nature, and there are indications from the Superkamiokande underground neutrino experiment that this might actually not be the case [22] at least in the neutrino sector. Yet, lepton flavour violation (LFV) has not been observed in a few decades of extensive and dedicated searches based for instance on μ nuclear capture, rare or forbidden μ and τ decays, rare or forbidden K or B and D-mesons decays. Lepton flavour is conserved in all interactions of the SM and the observation lepton flavour violation (LFV) processes could be a guide beyond our actual essential paradigm.

The ep colliders offer possible striking signal for LFV through s-, t- or u-channel exchange of new bosons such as leptoquarks possessing both a coupling λ_{11} to first generation lepton-quark pairs as well as a coupling λ_{3j} with leptons of the third generation. The Fig. 12 show the exclusion domain that could be covered at HERA$_{II}$ for such a LFV leptoquark. It emphasizes the specific sensitivity to the coupling λ_{31} which is provided in ep collisions by the quasi-background free analysis of τ + jet final states. Here a scalar LQ formed via e^+u fusion (i.e. carrying the quantum numbers of the $S_{1/2,L}$ in the BRW model) has been considered. Only couplings λ_{3j} with $j = 1, 2$ are relevant and the simplifying assumption that $\beta_e + \beta_\tau = 1$ is made. For $\lambda_{11} = \lambda_{3j} = 0.03$ (i.e. an interaction strength a hundred times weaker than the electromagnetic strength) leptoquarks lighter than $\simeq 250$ GeV could be excluded 95% CL. Also shown in Fig. 12 is the best indirect constraints on λ_{31} (shown for $\lambda_{11} = 0.3$ or 0.03) which can be de-

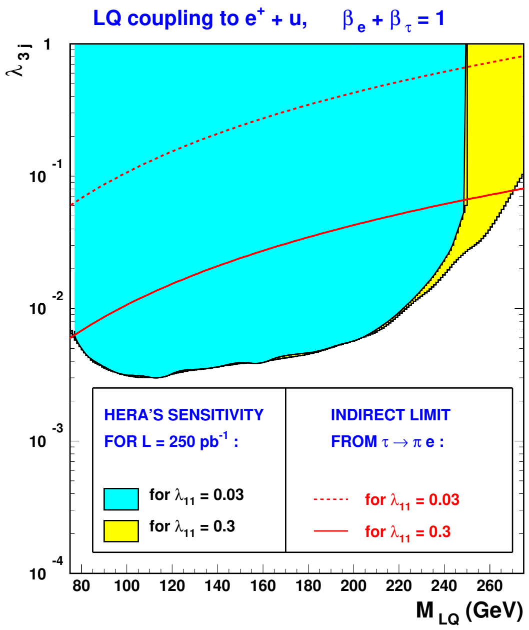

Figure 12. Constraints on Lepton Flavour Violating leptoquarks from HERA$_{II}$ for an integrated luminosity of 250 pb^{-1}.

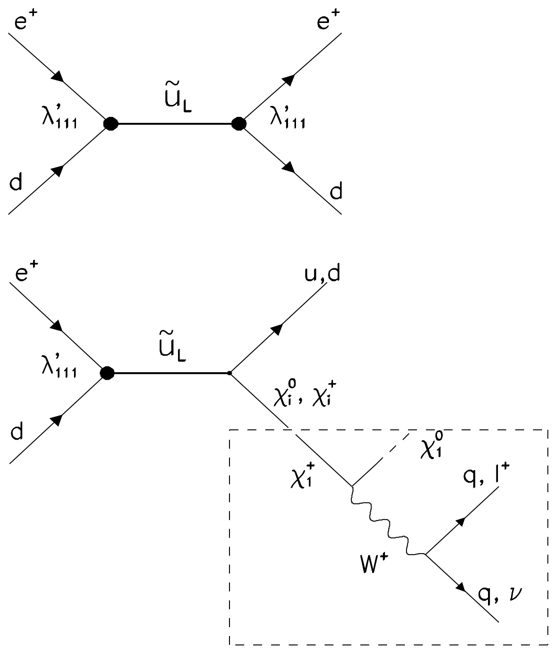

Figure 13. Typical diagrams for the production and decay of $\tilde{u}_L$-like squarks in ep collisions; (a) example of $\not{R}_p$-decay of the $\tilde{u}_L$; (b) example of gauge decay of the $\tilde{u}_L$.

rived [20] from the upper limit on the branching ratio $\beta(\tau \to \pi^0 e)$. This process could be affected by the chain $\tau^+ \to \bar{u} + LQ$ followed by the $e^+ + u$ decay of the virtual leptoquark. Here the most recent upper limit [21] on $\beta(\tau \to \pi^0 e)$ has been used to update the bound derived in [20]. No low energy process constrains the coupling products involving λ_{32}.

Lepton flavour or lepton number violation is naturally incorporated in SUSY theories. In addition to the standard terms corresponding to the Minimal Supersymmetric Standard Model (MSSM), the general superpotential contains the terms $W_{\not{R}_p} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}k$ which violates the conservation of the R-Parity (R_p) defined as $R_p = (-1)^{3B+L+2S}$ ($+1$ for particles; -1 for sparticles). The ijk are generation indices and L, Q (E, D, U) are doublet (singlet) superfields. The exact conservation of R_P (i.e. strictly vanishing λ_{ijk}, λ'_{ijk} and λ''_{ijk}) is an *ad hoc* assumption in the MSSM which leads to the absolute stability of the lighest SUSY particle (LSP). Postulating $\lambda'' = 0$ (baryon number conservation) is actually sufficient to ensure proton stability and there could exist non-vanishing λ or λ' lepton number violating couplings. The 21 λ' couplings are of particular interest for *ep* colliders. Nine of these could allow for resonant production of squarks through $e - q$ fusion. Example of basic production and decay diagrams are shown for a $\tilde{u}_L$ squark in Fig. 13. Different kinds of $\tilde{q}$ would be produced dominantly for e^+ or e^- beams; $e^- p$ collisions are mostly sensitive to λ'_{11k} couplings and $\tilde{d}_R$-like squarks; $e^+ p$ collisions are mostly sensitive to λ'_{1j1} couplings and $\tilde{u}_L$-like

Table 2
Existing and future ep colliders

	HERA$_{II}$ sensitivity	**Indirect Limits**	
	$\tilde{\gamma}$-like χ_1^0	Value	Process
λ'_{111}	0.008	0.003	$\beta\beta 0\nu$ decay
λ'_{112}	0.020	0.05	CC-universality
λ'_{113}	0.026	0.05	CC-universality
λ'_{121}	0.008	0.5	$D^+ \rightarrow K$ decays
λ'_{122}	0.027	0.04	ν_e-mass
λ'_{123}	0.043	0.5	$D^+ \rightarrow K$ decays
λ'_{131}	0.007	0.77	R_e^{exp}
λ'_{132}	0.027	0.091	R_e^{exp}
λ'_{133}	0.068	0.0015	ν_e-mass

squarks. The λ'_{131} is of particular interest as it allows for resonant production of $\tilde{t}$ squarks. The $\tilde{t}$ is by far the least constrained squark at TeVatron and it's lightest mass eigenstates $\tilde{t}_1$ could be the lightest colored sparticle.

Exclusion upper limits (95% CL) on λ'_{ijk} expected at HERA$_{II}$ for an integrated luminosity of $\mathcal{L} = 500$ pb^{-1} of e^+p data are given in table 2. The limits have been evaluated here for $M_{\tilde{q}} = 150$ GeV and a neutralino LSP of $M_{\chi_1^0} = 40$ GeV taking into account realistic detection efficiencies and proper relative branching ratios for $\not{R}_p$ and gauge decays. Except for λ'_{111} and λ'_{133}, HERA$_{II}$ could provide a sensitivity comparable or better than the best indirect experiments.

While SUSY could be discovered through the $\not{R}_p$ Yukawa sector at HERA$_{II}$ (e.g. via resonant $\tilde{t}$ production), it is unlikely that such a discovery potential for SUSY will remain beyond LHC given the stringent constraints to be set there on the Higgs sector and on sparticle searches.

The ep colliders can be sensitive to physics beyond SM at mass scales $M_X \gg \sqrt{s}$ through the interference the new heavy particle (boson) X with SM fields due to virtual exchange. In such cases the s-, t- or u- channel propagators contract to a pointlike four-fermion CI with an effective coupling g_X^2/M_X^2 $[mass^{-2}]$. Such a pointlike interaction as probed in complementary manners at ep, e^+e^- and $p\bar{p}$ colliders is illustrated in 14. The new heavy particle could be for instance a Z', a leptoquark or a squark, or the interaction could be driven by the exchange of preons between composite leptons and quarks.

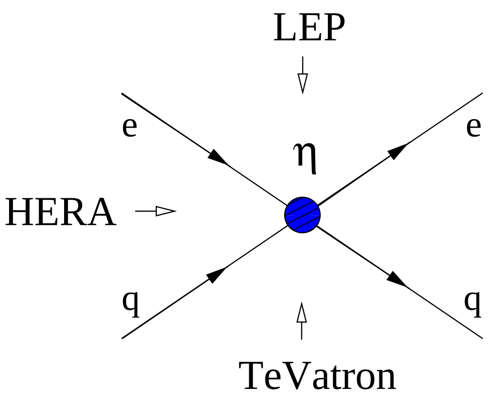

Figure 14. Contact interactions as probed in complementary manners at HERA, LEP and TeVatron.

The general effective Lagrangian for vector $eeqq$ interactions [4] can be written as $\mathcal{L}_{CI} = \sum_{\alpha,\beta=L,R;q=u,d} \eta^q_{\alpha\beta} (\bar{e}_\alpha \gamma_\mu e_\alpha)(\bar{q}_\beta \gamma^\mu q_\beta)$ where $\eta_{\alpha\beta} \equiv \pm g^2/\Lambda^2_{\alpha\beta}$. The coupling strength g is conventionally chosen as $g^2 = 4\pi$ and the scale parameter $\Lambda_{\alpha\beta}$ is set to $\Lambda_{\alpha\beta} = M_X$. Assuming quark flavour symmetry, the Lagrangian thus contains 8 vector current terms with $\oplus$ or $\ominus$ interference with SM currents.

The 4 pure chiral couplings (for u or d-like

[4] Scalar and tensor terms are constrained beyond HERA$_{II}$ sensitivity.

Table 3
Contact interaction constraints at 95% CL from HERA, LEP and the TeVatron (see text).

	$\Lambda^{\pm}_{lim}$ (TeV)						
CI Model	ZEUS	HERA	ALEPH	L3	OPAL	CDF	D0
VV+	4.7	5.0	6.4	3.8	4.1	3.5	4.9
VV−	5.0	1.9	7.1	5.0	5.7	5.2	6.1
AA+	2.6	2.0	7.2	5.6	6.3	3.8	4.7
AA−	3.7	3.4	7.9	3.5	3.8	4.8	5.5
U3+	3.7	3.1	-	6.1	4.1	-	-
U3−	3.5	1.3	-	4.9	5.8	-	-
U4+	4.4	4.1	-	2.1	2.3	-	-
U4−	4.8	1.8	-	2.9	3.2	-	-

quark flavours) η^{eq}_{LL},η^{eq}_{LR},η^{eq}_{RL} and η^{eq}_{RR} can be combined vector or axial-vector combinations (e.g.)

VV ($\eta^{eq}_{LL} = \eta^{eq}_{LR} = \eta^{eq}_{RL} = \eta^{eq}_{RR}$);
AA ($\eta^{eq}_{LL} = -\eta^{eq}_{LR} = -\eta^{eq}_{RL} = \eta^{eq}_{RR}$);
U3 ($\eta^{eu}_{LL} = \eta^{eu}_{RR}$; all others $= 0$);
U4 ($\eta^{eu}_{LR} = \eta^{eu}_{RL}$; all others $= 0$);

each preserving parity to avoid Atomic Parity Violation contraints, $\eta^{eq}_{LL} + \eta^{eq}_{LR} - \eta^{eq}_{RL} - \eta^{eq}_{RR} = 0$.

The sensitivity to CI interactions at existing colliders is illustrated in table 3 for **VV** and **AA** chiral structures imposing $\eta^{eu}_{RL} = \eta^{ed}_{RL}$ as required by $SU(2)_L$ invariance and for **U3** and **U4** chiral structures which violate this relation.

The table is extracted from a recent ZEUS [4] publication and completed with recent H1 preliminary results presented at this conference. It shows that despite the modest luminosity accumulated at HERA$_I$ with unpolarized lepton beams, a sensitivity comparable (and in the most favorable cases better) than that of experiments at other colliders is obtained. A recent global analysis by [23] presented at this conference as shown that a sensitivity to physics beyond SM remains for HERA$_{II}$ is slightly enhanced with polarized lepton beams. On the long term, the extension of the discovery window appears more favorable for Drell-Yan lepton pair production at TeVatron$_{II}$.

4. CONCLUSIONS

Essential SM measurements ($xg(x,Q^2)$, u_v/d_v, light quark couplings to the Z^0, etc ...) remain to be done at HERA$_{II}$. HERA$_{II}$ offers a rich discovery potential (Leptoquark bosons, $\tilde{t}$ in $\not{R}_p$-SUSY, Contact Interactions, etc. ...) beyond or complementary to TeVatron$_{II}$ and LEP$_{II}$ Future *ep* colliders offer exciting DIS Physics and beyond; with TESLA×HERA better suited for high Q^2 and LEP×LHC particularly attracting for very low x physics. It appears essential to preserve a viable LEP for a future *ep* option while contributing to the physics case for a future e^+e^- linear collider tangential to a proton accelerating ring such as HERA.

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REFERENCES

1. H1 Collab., S. Aid et al., Phys. Lett. **B369** (1996) 173; *ibid*, Z. Phys. **C64** (1994) 545; *ibid*, Nucl. Phys. **B396** (1993) 3; ZEUS Collab., M. Derrick et al., Phys. Lett. **B306** (1993) 173. *For recent H1 results see also* H1

Collab., "A Search for Leptoquark Bosons in DIS at High Q^2 at HERA", contrib. paper #579 at ICHEP98, Vancouver. *For recent ZEUS results see also* ZEUS Collab., "Resonance Search in ep Scattering at High x and Q^2 ..." contrib. paper #754 at ICHEP98.
2. H1 Collab., S. Aid et al., Z. Phys. **C71** (1996) 211. *For recent H1 results see also* H1 Collab., "A Search for Squarks of R-Parity Violating SUSY at HERA", contrib. paper #580 at ICHEP98. *For recent ZEUS results see also* B. Straub, for the ZEUS Collab., "Search for R-Parity Violating Squarks in ep collisions", Talk at the Higgs and Supersymmetry conf., Gainesville, USA (8 March 1999).
3. H1 Collab., I. Abt et al., Nucl. Phys. **B396** (1993) 3; *ibid*, Phys. Lett. **B340** (1994) 205; *ibid*, Nucl. Phys. **B483** (1997) 44. *For recent H1 results see also* H1 Collab., "A Search for Excited Fermions at HERA", contrib. paper #581 at ICHEP98. *For recent ZEUS results see also* ZEUS Collab., "Search for Excited Electrons in e^+p Collisions at HERA", contrib. paper #758 at ICHEP98.
4. H1 Collab., S. Aid et al., Phys. Lett. **B353** (1995) 578; ZEUS Collab., "Search for Contact Interactions in Deep Inelastic $e^+p \to e^+X$ Scattering at HERA", DESY preprint 99-058 (hep-ex/9905039). *For recent H1 results see also* H1 Collab., "A Search for Contact Interactions in Neutral Current Scattering at HERA", contrib. paper #584 at ICHEP98.
5. H1 Collab., C. Adloff et al., Eur. Phys. J. **C5** (1998) 575. *See also* C. Diaconu et al., "High Pt Leptons and W Production", 3rd UK Phenomenology Workshop on HERA Physics, Durham, England (20-25 September 1998).
6. Workshop "Physics with HERA as eA collider", DESY, Hambourg (25-26 May 1999) (G. Ingelman, M. Strikman and A. Wagner, Organizers).
7. Proceedings of the Workshop "Polarized Protons at High Energies (Accelerator Challenges and Physics Opportunities)", DESY, Hambourg (17-20 May 1999) *to be published*; See also Proceedings of the Workshop "Future Physics with Polarized Protons at HERA", DESY-Hamburg and DESY-Zeuthen, (March-September 1997), (A. De Roeck and T. Gehrmann, Editors).
8. E. Accomando et al., "Conceptual Design of a 500 GeV e^+e^- Linear Collider with Integrated X-ray Laser Facility", (R. Brinkmann et al., Editors) DESY reports 1997-048 (May 1997).
9. E. Keil, LHC PR 93, CERN, 1997.
10. R. Brinkmann, DESY M-97-05, Ankara Workshop, 1997.
11. J. Norem, ANL-HEP-CP-98-33, 1998.
12. G. Ingelman, LHC Workshop, Aachen 1990.
13. J.C. Pati and A. Salam, Phys. Rev. **D10** (1974) 275; P. Langacker, Phys. Rep. **72** (1981) 185; H. Georgi and S.L. Glashow, Phys. Rev. Lett. **32** (1974) 438.
14. A. Dobado, M.J. Herrero and C. Muñoz, Phys. Lett. **B191** (1987) 449; J.F. Gunion, E. Ma, Phys. Lett. **B195** (1987) 257; R.W. Robinett, Phys. Rev. **D37** (1988) 1321; J.A. Grifols and S. Peris, Phys. Lett. **B201** (1988) 287.
15. S. Dimopoulos and L. Susskind, Nucl. Phys. **B155** (1979) 237; S. Dimopoulos, Nucl. Phys. **B168** (1980) 69; E. Farhi, L. Susskind, Phys. Rev. **D20** (1979) 3404; *idem* Phys. Rep. **74** (1981) 277.
16. B. Schrempp and F. Schrempp, Phys. Lett **B153** (1985) 101, *and references therein*; J. Wudka, Phys. Lett. **B167** (1986) 337.
17. W. Buchmüller, R. Rückl and D. Wyler, Phys. Lett. **B191** (1987) 442.
18. W. Buchmüller, R. Rückl and D. Wyler, Phys. Lett. **B448** (1999) 320.
19. P. Schleper, Proceedings of the Workshop "Physics at HERA", DESY, Hamburg (October 1991) Vol. 2 p 1043.
20. S. Davidson, D. Bailey and B. Campbell, Z. Phys. **C61** (1994) 613.
21. Review of Particle Physics, European Phys. Journal **C3** Nr. 1-4 (1998).
22. SuperKamiokande Collab., Y. Fukuda et al., Phys. Rev. Lett. **82** (1999) 2644.
23. A. F. Zarnecki, hep-ph/9905565.