Exotics and R-Parity Violating SUSY at HERA

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Abstract

Experimental searches for physics beyond the Standard Model at the HERA ep collider are presented. Constraints established at HERA$_I$ and prospects for HERA$_{II}$ are discussed for leptoquarks, for theories with extra compactified dimensions, contact interactions, forbidden lepton and quark flavour-changing processes, R-parity violating supersymmetry and doubly charged higgses.

1 Introduction

The search for physics beyond the Standard $SU(3) \times SU(2) \times U(1)$ Model of strong, electromagnetic and weak forces has been, and remains, a central duty for collider experiments. The HERA experiments have contributed in an original manner to this great quest and will continue to do so in the near future with upgraded detectors. In this contribution, the status and prospects of the search for new particles and interactions at HERA is presented and a comparison is made with results from experiments at LEP e^+e^- and Tevatron $p\bar{p}$ colliders.

But before entering the discussion on specific search results, it is worth reminding about the status of the HERA detectors and machine, as well as providing motivations for the new physics eventually accessible at colliders.

HERA experiments and the Standard Model

The H1 and ZEUS experiments have now completed a first generation of measurements at the ep collider HERA$_I$. Each experiment has collected in this first phase, from 1992 to 2000, an integrated luminosity of $\mathcal{O}(100 \text{ pb}^{-1})$ at centre-of-mass energies $\sqrt{s_{ep}}$ of 300 and 318 GeV. In roughly the same period, namely from 1989 to 2000, the ALEPH, DELPHI, L3 and OPAL experiments at the LEP e^+e^- collider have each collected $\sim 160 \text{ pb}^{-1}$ at $\sqrt{s_{ee}} \simeq M_Z$ (LEP$_I$) and $\sim 620 \text{ pb}^{-1}$ at $\sqrt{s_{ee}} \gtrsim 2 \times M_W$ (LEP$_{II}$). At the Tevatron$_I$ $p\bar{p}$ collider, the CDF and D0 experiments have each collected of $\mathcal{O}(100 \text{ pb}^{-1})$ at $\sqrt{s_{pp}} \simeq$ 1.8 TeV in two running periods from 1987 to 1996.

Yet, the measurements at HERA$_I$ have all been successfully embedded in the framework of the Standard Model (SM). In the strong sector, the experiments have contributed to a better understanding of the quark-gluon structure of the proton at short distances and its evolution via quantum chromodynamics (QCD). In the electroweak (EW) sector, they have performed tests of the space-like propagator contribution (virtual exchange of Z^0 and $W^{\pm}$ bosons) to deep inelastic scattering (DIS) processes. Needless to say, in this sector the SM has otherwise been remarkably confirmed by the precision results at LEP.

As we shall discuss next in this introduction, the SM, although remarkably confirmed at the phenomenological level, remains incomplete and unsatisfactory. This dissatisfaction is a strong incitement to pursue the search for new physics at both the upgraded HERA$_{II}$ and Tevatron$_{II}$ colliders where data taking resumes in 2002. Within about five to six years, the HERA experiments expect to each collect of $\mathcal{O}(1\ \text{fb}^{-1})$ at $\sqrt{s_{ep}} \simeq 320$ GeV with upgraded detectors and a modified machine design offering longitudinally polarized lepton beams. Measurement with polarized lepton beams of DIS at largest squared momentum transfer Q^2 should allow to determine vector and axial-vector couplings of light quarks to the Z^0 with precisions comparable to those obtained at LEP for heavy quarks. The combination of Neutral Current (NC) ($e^{\pm}p \rightarrow e^{\pm}X$) and Charged Current (CC) ($e^{\pm}p \rightarrow \nu X$) DIS event samples will help to further improve on the extraction of flavour-dependent quark momentum distribution functions in the proton. Whether or not the increase in luminosity at HERA could be sufficient to bring new physics within discovery reach is a central issue for the H1 and ZEUS experiments. Meanwhile, the CDF and D∅ experiments at Tevatron$_{II}$ expect each to collect $\mathcal{O}(2\ \text{fb}^{-1})$ at $\sqrt{s_{pp}} \simeq 2$ TeV.

General Motivations for Physics Beyond the Standard Model

Although remarkably confirmed at the phenomenological level the SM remains incomplete and unsatisfactory. It is so because, first of all, it only offers a partial "unification" of the known forces. The carriers of the electromagnetic and weak force obey a common $SU(2)_L \times U(1)_Y$ symmetry but this is assumed to be spontaneously broken due to the non-zero field strength in the vacuum of a scalar boson field pervading the universe, the Higgs field. The electroweak interactions couple only to flavours and are indifferent to colours. The strong interaction of coloured quarks and gluons described in QCD by the $SU(3)$ gauge field theory remains separate. A "Grand Unification" of forces in a larger local gauge theory is simply postponed. The fact that these forces have couplings which are known to evolve towards large energies and nearly coincide at a scale of $\mathcal{O}(10^{15})$ GeV is left as a feature of the model. That this "unification scale" is in addition relatively close to the Planck scale of $\mathcal{O}(10^{19})$ GeV is left as a curiosity. No connection is made with an eventual quantum theory of gravity. The SM predictive power moreover suffers from a large number of arbitrary parameters. In the EW sector, the relative strength of the electromagnetic and weak forces is not predicted. After EW symmetry breaking, the elementary fermion masses originate from their Yukawa interactions of arbitrary strengths with the Higgs field. The mass of the Higgs boson itself also is not predicted but an upper bound must nevertheless be imposed to maintain the internal consistency of the model. The model offers no mechanism to preserve the Higgs boson mass from quadratically divergent renormalization corrections from physics at very high energy scales such as the Planck scale. The Higgs mechanism which gives masses to the $W^{\pm}$ and Z bosons and leaves the photon massless, remains unproven. The masses of protons and neutrons, which themselves contribute to more than 99% of the mass of ordinary cold matter, are understood to originate from the dynamics of colour confinement in QCD, but this remains to be formally proven. In the SM there are no direct couplings between quark and lepton families and the theory is consistent with a separate and exact conservation of lepton and baryon numbers in all processes. The viability of the SM rests on a somewhat empirical similarity between lepton and quark sectors. Disastrous anomalies that would prevent renormalizability of the theory are avoided by an exact cancellation between contributions of lepton and quark fields. No deeper understanding is provided for this exact cancellation, which happens thanks to the special arrangement of fermion multiplets in the model and the fact that quarks have the additional colour degree of freedom. Finally, the SM incorporates an apparent threefold "replica" of fermion generations which remain unexplained. The EW interaction Lagrangian is simply constructed separately for each of the lepton and quark generations, with anomalies cancelled within each generation. There are no direct couplings between different lepton families while, intriguingly, three quark families (at least) are needed if quark mixing is to be the cause of all observed electroweak CP violation.

Searches for Specific Exotics at Colliders

There are theoretical motivations for physics beyond the SM that could lie at energy scales below $\mathcal{O}(10)$ TeV, and thus be possibly accessible at existing HERA or Tevatron colliders or in the future at CERN Large Hadron Collider. A prominent case is made in supersymmetric models. Supersymmetry is a key ingredient of theories which might constitute the way of providence towards new physics [1], and which incorporates quantum gravity and the concept of Grand Unification of fundamental interactions in a universe with extra compactified spatial dimensions. Supersymmetric models offer a possibility to preserve masses in the Higgs sector from quadratically divergent renormalization corrections. But the mass of the new scalar partners of ordinary fermions must be close enough to the electroweak scale to avoid excessive "fine tuning". Another example case is provided by technicolour-like theories, in which new composite scalar fields are responsible for EW symmetry breaking, and in which a rich spectrum of new states must be introduced at EW scale. Observable effects at colliders are also expected in the case low-scale quantum gravity models from the propagation of fields in some "compactified" extra dimensions.

The HERA_{II} and $\mathrm{Tevatron}_{II}$ experiments will be able to further probe mass scales in some direct processes up to $\mathcal{O}(1\ \mathrm{TeV})$ and via virtual effects in some cases up to

$\mathcal{O}(10\,\text{TeV})$. It is not known for sure whether or not new physics will be within their discovery reach. At least, they will for sure be able to better constrain specific aspects of some leading theories beyond the SM where there exist a more-or-less strong prejudice for new physics "close to" EW scale. In the following, we review the motivations, status and prospects of the HERA searches for leptoquarks, lepton flavour violation, contact interactions, R-parity violating supersymmetry and large extra dimensions, in DIS processes. The searches for doubly charged Higgs bosons and for flavour changing neutral currents in the top sector are also briefly discussed as examples [2] of exclusive processes.

2 Leptoquarks in Minimal Models

The known symmetry between the lepton and quark sectors could possibly be an indication that these are fundamentally connected through a new interaction. Leptoquarks (LQs) are colour-triplet scalar (S) or vector (V) bosons carrying lepton and baryon numbers, and a fractional electromagnetic charge, Q_{em}. They appear naturally in both "Georgi-Glashow" [3] and "Pati-Salam" [4] types of Grand Unification theories (GUT) as well as in superstring-"inspired" E_6 models [5]. They also appear as mediators between quark and lepton doublets in horizontal-symmetry schemes [6], in Technicolour theories addressing the issue of electroweak symmetry breaking, in strongly coupled weak-interaction models attempting to reconcile the conceptual differences between the weak and strong sectors [7], and in some matter-compositeness theories [8] attempting to provide an explanation for the three generations of fermions.

Actual searches at colliders have been mostly carried out in the context of effective models. The Buchmüller, Rückl and Wyler (BRW) model [9] describes leptoquark interactions in a most general effective Lagrangian under the assumptions that leptoquarks have renormalizable interactions invariant under SM gauge groups, and that they couple only to gauge bosons and to ordinary fermions. Futher restrictions are imposed in a minimal BRW model (mBRW) to cope with existing low-energy constraints [10, 11, 12, 13]. Unacceptable instability of the proton are avoided by assuming that leptoquarks conserve leptonic number and baryonic number separately. Possibly large tree-level flavour-changing neutral currents and flavour-universality violations are avoided by assuming a Yukawa coupling (λ) to a single lepton-quark generation. Forbidden contributions to chirally suppressed meson decays are avoided by assuming pure chiral couplings to ordinary fermions ($\lambda_L \times \lambda_R \simeq 0$). For each fermion generation, the mBRW model allows for the existence of different weak-isospin families for both scalar (S) and vector (V) leptoquarks. Assuming mass degeneracy within each isospin family, one distinguishes in total seven scalars and seven vectors with fermionic numbers $|F| = 0$ or 2 and coupling to either left- or right-handed leptons. Generally, only a subset of the allowed BRW-leptoquark states exist in a specific fundamental model [4, 5, 14, 15, 16].

First-generation leptoquarks can be resonantly produced at HERA by the fusion of

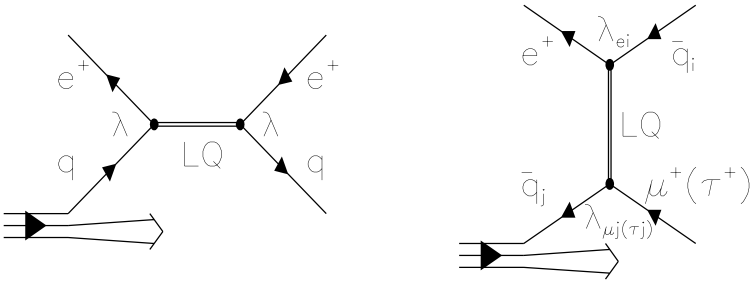

Figure 1: Typical diagrams for leptoquark production at HERA collider; a) resonnant s-channel production ; b) virtual u-channel exchange (here shown assuming additional lepton flavour violating couplings); c) contribution to effective four-fermion interactions. In (c) the tree-level exchanges through couplings g_X of the heavy X particle is shown “contracted” to an point-like effective four-fermion contact interaction with couplings $\eta \propto g_X^2/\Lambda^2$ where the scale Λ can be taken as $\Lambda \simeq M_{LQ}$.

an e beam particle with a q from the proton, or virtually exchanged in the u-channel (Fig. 1). These processes interfere with t-channel electroweak-boson exchange. Thus, LQ searches at HERA involve the analysis of event signatures indistinguishable from Standard Model DIS at high squared momentum transfer, Q^2. For real production, the experimental search is made by looking for a mass resonance which can be reconstructed either from the decay products (charged lepton+jet) in the final state or from the DIS-like kinematical relation $M \simeq \sqrt{x s_{ep}}$, where x is the standard Bjorken variable representing at lowest order the fraction of the initial proton momenta carried by the participating quark.

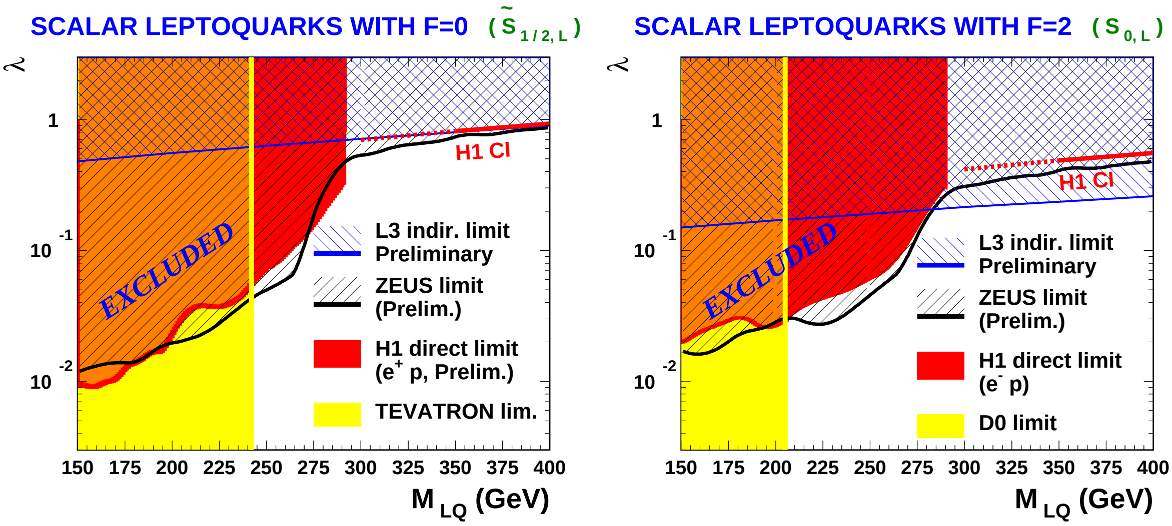

Figure 2: Constraints from HERA experiments in the framework of the BRW model for a leptoquark (a) with fermion number $F = 0$ and (b) with $|F| = 2$.

A resonance search is thus possible at HERA both in neutral current and charged current DIS-like processes. At large masses, e^+p collisions provide a better sensitivity to the coupling of $F = 0$ leptoquarks while e^-p collisions better probe $|F| = 2$ leptoquarks. The leptoquark signal is enhanced with respect to the DIS background towards large values of $y = (1 - \cos\theta^*)/2$ where θ^* is the lepton decay angle in the leptoquark rest frame. In terms of DIS-like observables, y is reconstructed as $y \equiv Q^2/xs_{ep}$. Recent H1 and ZEUS results combining most or all available $e^{\pm}p$ data taken at HERA_I have been recently discussed in Refs. [17, 18, 19, 20]. In absence of significant deviations from standard DIS expectation in the reconstructed mass spectra, exclusion limits have been derived.

HERA results for first-generation leptoquarks of the mBRW model are shown in Fig. 2 and compared to results from LEP and Tevatron colliders [2]. The exclusion limits in Fig. 2a are obtained for a typical scalar with $F = 0$; namely the $\tilde{S}_{1/2,L}$ for which $\beta_{eq} \equiv \beta(LQ \rightarrow eq) = 1.0$. The limits in Fig. 2b are for a typical scalar with $F = 2$; namely the $S_{0,L}$ for which $\beta_{eq} = 0.5$. For a scalar carrying the quantum numbers of the $\tilde{S}_{1/2,L}$, the $\mathrm{Tevatron}_I$ experiments exclude leptoquark masses up to 242 GeV (independently of λ) by searching for leptoquark pair production via gauge couplings in $q\bar{q}$ annihilation and gg fusion processes. For a $S_{0,L}$ ($\beta = 0.5$), the $\mathrm{Tevatron}_I$ exclusion limit decreases to 204 GeV. For $\lambda \ll 1$, in the mass range beyond the reach of $\mathrm{Tevatron}_I$ and below ~ 300 GeV, a discovery domain remains open for HERA_{II}. In this domain, and for masses not too close to the kinematical limit, the partial width of the leptoquark state is expected to be very narrow and the production cross-section scales with λ^2. There the observation is limited only by the experimental mass resolution. The observation is more difficult at HERA when approaching the kinematical limit, where large λ values are necessary to compensate the suppression from low parton densities in the proton, and where effects from virtual exchange can no longer be neglected. For an interaction stronger than the electromagnetic interaction (i.e. $\lambda^2/4\pi\alpha > 1$), virtual LQ exchange at HERA_I and LEP_{II} are seen in Fig. 2 to provide comparable exclusion limits.

3 Contact Interactions

For masses M_{LQ} well above the kinematical limit, the effect of the new physics can be described by adding four-fermion vector-vector bilinear terms [21, 22, 23] to the SM interaction Lagrangian. The propagators in the s- or u-channel LQ exchange diagram “contract” to an effective point-like four-fermion contact interaction (CI). This is illustrated in Fig. 1c. At HERA, such a $eqeq$ CI would modify the NC DIS cross-sections at high Q^2. Figure 3 shows preliminary e^-p and e^+p cross-sections measured by H1 as a ratio to the SM prediction [24]. No significant deviations are observed and fits corresponding to leptoquark exclusion limits are also plotted for comparison.

The constraints obtained by H1 and ZEUS [24, 25] for various scalar models are listed in Table 1 and compared [2] to $eeqq$ results from LEP experiments, and to low energy

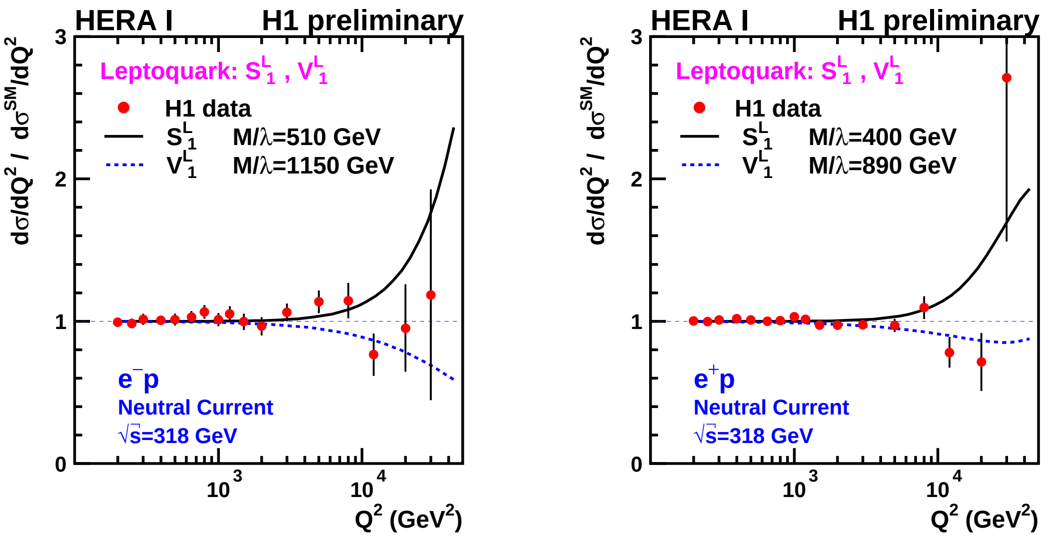

Figure 3: Contact Interactions constraints on leptoquark models.

95% CL limit M_{LQ}/λ_{LQ} [GeV]								
Model	Coupling Structure	H1	ZEUS	ALEPH	L3	OPAL	Indirect	SM Fits
$S_\circ^L$	$\epsilon_{LL}^u = +\frac{1}{2}$	720	750	640	1240	640	3500	3700
$S_\circ^R$	$\epsilon_{RR}^u = +\frac{1}{2}$	670	690		960		2800	3900
$\tilde{S}_\circ^R$	$\epsilon_{LL}^d = +\frac{1}{2}$	330	310	220	260	590	3000	3600
$S_{1/2}^L$	$\epsilon_{LR}^u = -\frac{1}{2}$	870	910	-	180	460	2800	3500
$S_{1/2}^R$	$\epsilon_{RL}^d = \epsilon_{RL}^u = -\frac{1}{2}$	370	690		350	630	2100	2100
$\tilde{S}_{1/2}^L$	$\epsilon_{LR}^d = -\frac{1}{2}$	430	500			370	3000	3800
S_1^L	$\epsilon_{LL}^d = 2 \cdot \epsilon_{LL}^u = +1$	480	550	770	640	930	2500	2400

Table 1: Lower limits obtained for $M_{LQ} \gg \sqrt{s}$, on the ratio M_{LQ}/λ_{LQ} of the leptoquark mass M_{LQ} to the Yukawa coupling λ_{LQ} for various contact-interaction models corresponding to scalar leptoquarks of different types. The HERA bounds are compared to LEP and to low energy constraints (see text).

constraints derived from precision measurements of Atomic Parity Violation (APV) and lepton universality tests [10, 11, 12, 13]. Also given are constraints deduced via “global fits” [26, 27] to existing EW data. These stringent low energy bounds appear utterly unavoidable in the framework of the mBRW model. Thus, leptoquarks in the domain $M_{LQ} \gg \sqrt{s_{ep}}$ would most likely remain beyond the reach [28] of HERA$_{II}$ even when considering integrated luminosities $\mathcal{L}$ approaching 1 fb $^{-1}$ in a single experiment (the mass reach only improves in powers of $\mathcal{L}^{1/4}$). In the 200 to 300 GeV range, leptoquarks must have interactions with lepton-quark pairs much weaker than the electromagnetic

95% CL limit [TeV]		H1		ZEUS		CDF		DØ	
	Coupling structure								
Model	$[\epsilon_{LL},\epsilon_{LR},\epsilon_{RL},\epsilon_{RR}]$	Λ^-	Λ^+	Λ^-	Λ^+	Λ^-	Λ^+	Λ^-	Λ^+
VV	$[+1,+1,+1,+1]$	5.4	5.1	7.0	6.5	5.2	3.5	6.1	4.9
AA	$[+1,-1,-1,+1]$	3.9	2.5	5.3	4.6	4.8	3.8	5.5	4.7
VA	$[+1,-1,+1,-1]$	2.9	2.9	3.4	3.3				

Table 2: Lower limits (95% CL) on compositeness models.

interaction (i.e. $\lambda \ll 0.3$) to avoid the low energy constraints.

The CI concept finds a natural application in the search for a compositeness of ordinary leptons and quarks. The chirality structure of the compositeness model can be adjusted to avoid the severe indirect constraints coming in particular from atomic-parity violation [29, 30]. At HERA, a pure CI contribution would increase the cross-section at the highest Q^2, while the SM-CI interference could act either constructively (Λ^+) or destructively (Λ^-) down to an intermediate Q^2 range. Exclusion limits are given in Table 2 and compared [2] to Tevatron$_I$ bounds from $qqee$ (Drell-Yan) processes. HERA and the Tevatron are seen to offer comparable sensitivities.

4 Leptoquarks in Generic Models

Enriched phenomenology appears in leptoquark models that depart from the assumptions of the BRW model [12]. Searches at colliders can be performed in a "generic" model in which $\beta(LQ \rightarrow lq)$ is simply left as a free parameter. Exclusion limits [18] for such a case are shown in Fig. 4. HERA offers a better sensitivity than Tevatron experiments for small $\beta_{eq} = \beta(LQ \rightarrow eq)$ (e.g. assuming $\beta_{eq} + \beta_{\nu q} = 1$) since the $\nu\nu jetjet$ channel from pair production at the Tevatron suffers from harsh QCD background. The HERA and Tevatron constraints on first-generation scalar leptoquarks are summarized in Table 3. Tevatron$_{II}$ will offer a better mass reach for $\beta_{eq} \simeq 1$. HERA$_{II}$ will provide a better sensitivity for $\beta_{eq} \lesssim 0.5$ for Yukawa interaction strengths down to about two orders of magnitude weaker than the electromagnetic strength.

A recent review of constraints for second- and third-generation leptoquarks can be found in Ref. [2].

5 Lepton Flavour Violation

Small β_{eq} may by envisaged by simply relaxing the diagonality requirement of the mBRW model to allow for lepton-flavour violating (LFV) decays, and possibly also connect different quark generations. Yet, LFV processes involving charged-leptons have never been

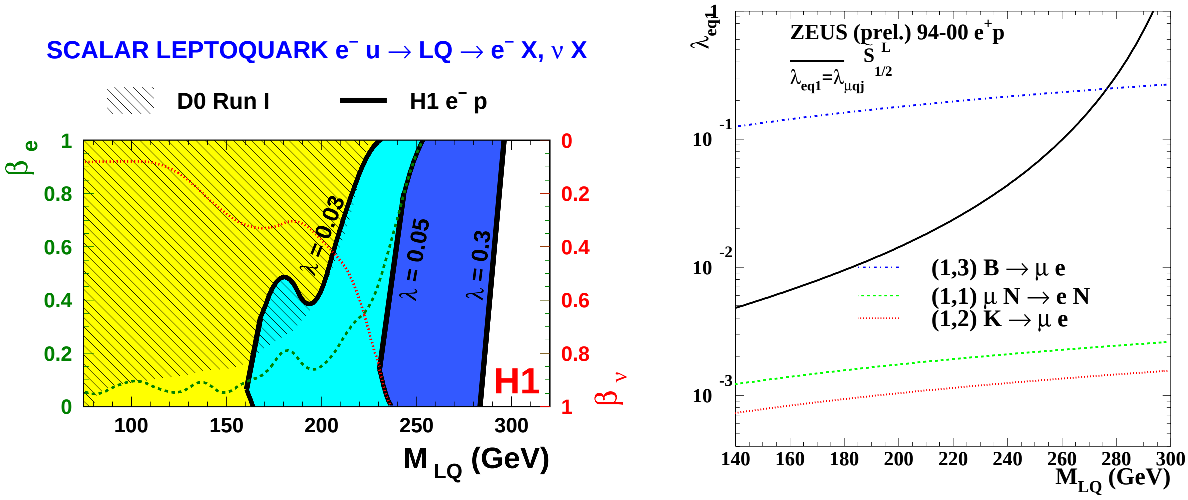

Figure 4: a) Leptoquark constraints a) in generic models; b) for LFV couplings.

COLLIDER CONSTRAINTS on $\mathbf{1^{st}}$ GENERATION LEPTOQUARKS					
β_e	Lower Mass Limits in GeV			Decays	Experiment
	any λ_{lq}	$\lambda_{lq} \geq 0.1$	$\lambda_{lq} \geq 0.3$		
1	242	-	-	$e^{\pm}q$	CDF⊕DØ
	-	276→282	295→298	$e^{\pm}u$	H1, ZEUS
	-	243→246	270→276	$e^{\pm}d$	H1, ZEUS
1/2	204	-	-	$e^{\pm}q$, νq	DØ
	-	271→275	292→294	$e^{\pm}u$ & (νd or invisible)	H1, ZEUS
	-	230→235	265→270	$e^{\pm}d$ & (νu or invisible)	H1, ZEUS
0	98	-	-	νq	DØ
	-	262	282	νd	H1
	-	237	262	νu	ZEUS

Table 3: Lower mass limits (95%CL) on scalar leptoquarks from direct searches at HERA and Tevatron colliders, for different decay branching fraction β_e.

observed. In the Standard Model, lepton flavours are separately conserved in every reaction but no fundamental motivation is provided for the exact additive conservation of electron, muon and tau numbers. But GUT theories [3, 31] could possibly allow for detectable LFV rates. At HERA, striking event topologies could result from s- or u-channel exchange of leptoquarks if $\lambda_{eq} \times \lambda_{\mu q} \neq 0$ or $\lambda_{eq} \times \lambda_{\tau q} \neq 0$.

Both the H1 [32] and ZEUS [33] experiments have searched for events with a high-P_T μ or τ balancing a hadronic jet. No outstanding candidate was found. Exclusion limits have been derived for the case of real production at $M_{LQ} < \sqrt{s_{ep}}$ and for virtual exchange with $M_{LQ} \gg \sqrt{s_{ep}}$. Limits in the former case are shown for instance in Fig. 4. The case of LFV in virtual exchange is reviewed in Ref.[2]. An exploration of a mass-coupling range beyond indirect constraints from rare processes is found possible at HERA in particular when involving also a combination of quark generations.

6 R-Parity Violating Supersymmetry

Squarks in R-parity violating supersymmetry can be produced in resonance at HERA via a $e - q$ fusion process involving a lepton number violating Yukawa coupling λ'_{1jk} [2]. The $\tilde{u}_L$, $\tilde{c}_L$ or $\tilde{t}_L$ squarks can be produced by e^+d fusion while the $\tilde{d}_R$, $\tilde{s}_R$ or $\tilde{b}_R$ squarks can be produced via e^-u fusion. The squarks might then decay "directly" via the $\not{R}_p$ coupling or undergo "indirect" decays initiated by gauge couplings and in which the $\not{R}_p$ couplings enter at a later stage in the decay chain. The coupling λ' allows for direct decays of sleptons into quark pairs, of squarks into lepton-quark pairs, and of gaugino-higgsinos into a lepton plus a quark pair.

Complementary $\not{R}_p$ SUSY searches have been performed at HERA, LEP and Tevatron colliders under the hypothesis of a single dominant λ'_{1jk} coupling. The constraints obtained [34] by the H1 experiment at HERA from a search for resonant squark production via λ'_{1jk} are shown in Fig. 5. Similar results were obtained [35] by the ZEUS experiment. Also shown on Fig. 5 are the best existing indirect bounds [36] from low-energy experiments. The λ'_{111} coupling is severely constrained by the non-observation of neutrinoless double beta decay. The most severe low-energy constraints on λ'_{121} and λ'_{131} come from APV measurements. When analysed in the framework of $\not{R}_p$ minimal Supergravity [34], the HERA constraints are found to extend beyond LEP and Tevatron constraints towards

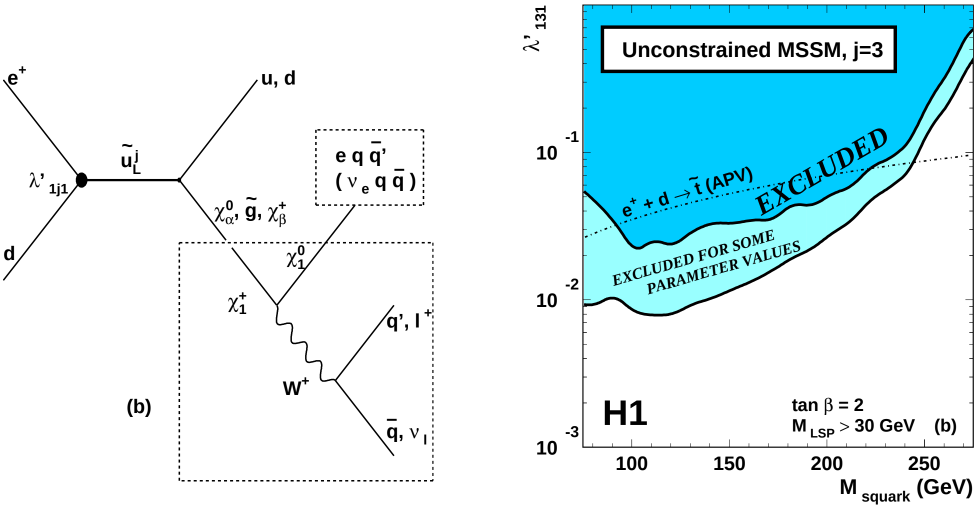

Figure 5: R-parity violating supersymmetry constraints.

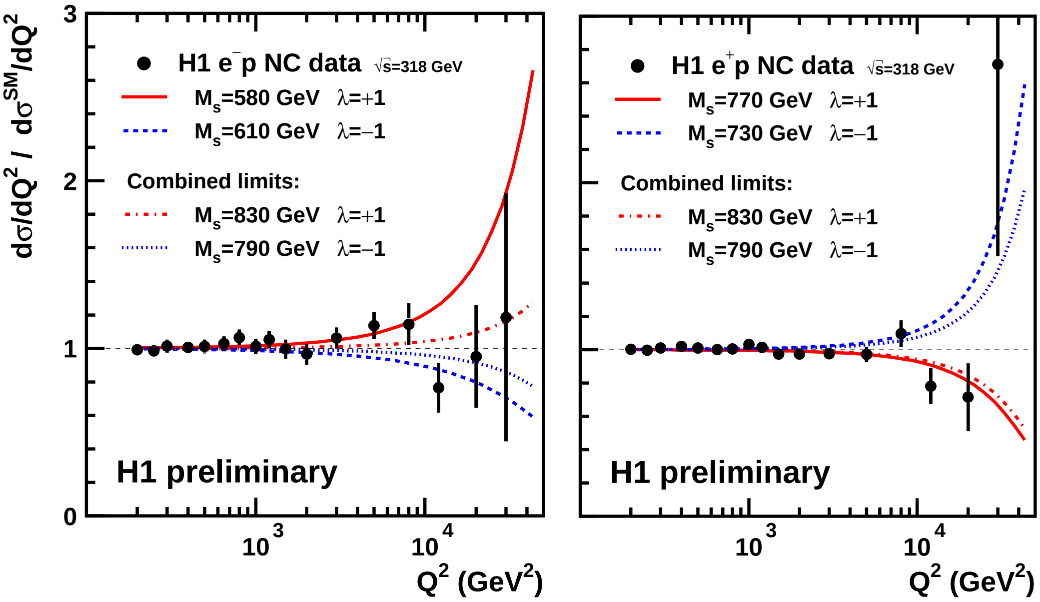

Figure 6: Constraints for models with large extra dimensions.

larger $\tan\beta$ for a coupling of electromagnetic strength, (i.e. $\lambda'_{131} = 0.3$).

7 Extra Dimensions

It has been realized recently that the problem of the hierarchy between the EW scale and the Planck scale, two seemingly fundamental scales in Nature, could be solved in theories with extra dimensions. Viable quantum-gravity scenarios have been constructed [37, 38] in which the gravitational force is expected to become comparable to the gauge forces close to the EW scale, eventually leading to (model dependent) effects in the TeV range observable at high energy colliders [39, 40]. In the string-inspired Arkani-Hamed, Dimopoulos and Dvali (ADD) scenario [37] with $n \geq 2$ "large" compactified extra dimensions, a gravitational "string" scale is introduced $(4+n)$ dimensions which is related to the usual (effective four-dimentional) Planck scale via $M_p^2 = R^n M_s^{2+n}$, where R is a characteristic (large) size of the n compactified extra dimensions. The graviton is allowed to propagate in these extra dimensions of finite size R which implies that it will appear in our familiar 4-dimensional universe as a "tower" of massive Kaluza-Klein (KK) excitation states. The exchange of KK towers between SM particles leads to an effective contact interaction with a coupling coefficient $\eta_G = \lambda / M_S^4$ [41].

The contributions of virtual graviton exchange to deep inelastic scattering in *ep* collisions have been derived in Refs. [41, 42]. Searches for virtual graviton exchange in theories with large extra dimensions have been performed by the H1 [24] and ZEUS [25] experiments. A typical result is shown in Fig. 6. The high-Q^2 NC DIS events are presented as a ratio to the SM prediction, together with the effect of Kaluza-Klein graviton exchange

95% CL limit on M_S [TeV]					
λ	H1	ZEUS	CDF[a]	D0[b]	LEP Combined[c]
$+1$	0.83	0.81	0.96	1.21	1.26
-1	0.79	0.82	0.94	1.13	0.96

Table 4: Collider results from searches for virtual effects from theories with large extra dimensions expressed in the formalism of Giudice, Rattazzi and Wells [41].

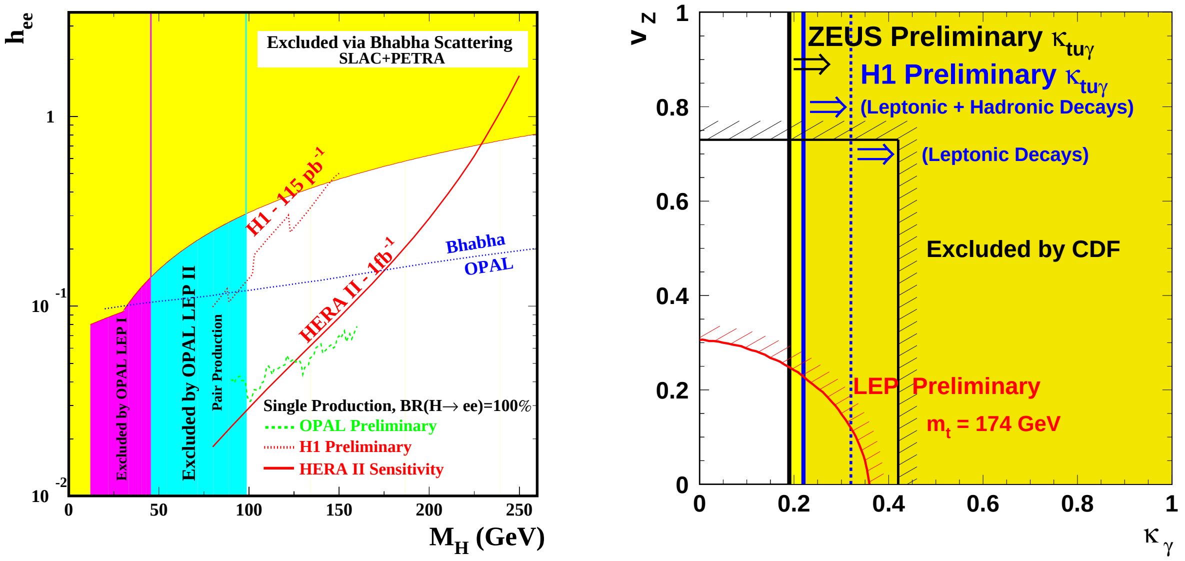

Figure 7: a) Constraints on doubly charged higgses. b) Constraints on FCNC top anomalous couplings from high-energy colliders.

for a mass excluded at 95% CL.

Here the coupling λ, which depends on the full theory and is expected to be of order unity, has been fixed by convention to $\lambda = \pm 1$. A combined analysis of the $e^- p$ and $e^+ p$ data yields very similar lower limits on M_S for both $\lambda = +1$ and $\lambda = -1$ of about 0.8 TeV.

8 Doubly Charged Higgs

The symmetries of the Standard Model could be merely the low-energy remains of an extended theory which would lie at some intermediate high energy scales, still far below GUT scale. This is the case in left-right symmetric (LRS) models. Besides possessing additional gauge bosons, LRS models require an extension of the Higgs sector and predict the existence of doubly charged Higgs physical states [43, 44, 45]. Doubly charged Higgs are also present in other scenarios [2] containing triplet Higgs fields but not necessarily incorporating left-right symmetry. In LRS models, the doubly charged Higgs are members of so-called “left-” and “right-handed” triplets $(\Delta^0, \Delta^-, \Delta^{--})_{L,R}$ and carry the quantum number $\mid B - L \mid = 2$. The triplets of scalars act solely in the leptonic sector but are not involved in the mass-generation mechanism for the ordinary charged leptons. Hence, the Δ^{--} could possess comparable decay branching ratio into like-sign charged leptons of each of the three generations.

HERA allows for single production of doubly charged scalars via a h_{ee} coupling by the fusion of the incoming beam electron with an electron emerging from the splitting of a photon radiated off the proton [2]. The reactions $e^- p \to e^+ p \Delta^{--}$ followed by the decays $\Delta^{--} \to e^- e^-$; $(\mu^- \mu^-, \tau^- \tau^-)$ or, for non-diagonal couplings, $e^- p \to \mu^+ p \Delta^{--}$ followed by the decays $\Delta^{--} \to e^- \mu^-$; $(e^- \tau^-, \mu^- \tau^-)$ constitute an almost background-free search environment. A most promising signal at high masses would be three leptons with two of them of the same sign at large invariant mass values.

The constraints obtained at HERA$_I$ by the H1 experiment [46] are shown on Fig. 7 together with other existing direct and indirect constraints (here for a h_{ee} coupling). Masses $M_{\Delta^{\pm\pm}} \lesssim 98.5$ GeV (95% CL) have been excluded by the LEP$_{II}$ experiments [2] by searching for pair production in the s-channel. Also shown on Fig. 7 are the LEP$_{II}$ constraints [2] from indirect effects on measurements of Bhabha scattering. For a coupling of electromagnetic strength, $h_{ee} = e$ with $e \equiv \sqrt{4\pi\alpha}$, doubly charged Higgses which would decay with 100% branching into like-sign and like-flavour charged leptons have been probed at HERA$_I$ for masses $M_\Delta \gtrsim 130$ GeV. The sensitivity at HERA$_{II}$ will be competitive with the one of LEP$_{II}$, extending the mass reach to $M_\Delta \gtrsim 200$ GeV.

9 Anomalous Top Couplings

In the SM the neutral currents are flavour diagonal. Flavour-changing neutral currents (FCNC) are not contained at tree level and can happen only from higher-order loop contributions. Sizeable rates can arise only when the top quark appears in the loop. Therefore, no detectable rate is predicted in the SM for FCNC processes between the top and charm or up quarks. However, considerable enhancement are expected, especially a large top FCNC [2], in various new models such as models with two or more Higgs doublets, supersymmetric models with or without R-parity conservation, or models with a composite top quark. The top-quark phenomenology is less tightly constrained than that of lighter quarks and can be tested at current colliders. In the absence of a specific predictive theory, a most general effective Lagrangian was proposed in Ref. [47] to describe FCNC top interactions involving electroweak bosons The ep collisions at HERA are most sensitive to the $\kappa_{\gamma,u}$ coupling, leading to a u-quark in the proton changing to a top quark with a t-channel photon exchange with the electron. The process involving the Z-boson is much suppressed due to the large mass in the t-channel propagator. The anomalous coupling to the c-quark is also suppressed by the small charm density in the proton.

The single-top production at HERA would yield a high-P_T W boson accompanied by an energetic b-quark jet. When the W decays leptonically, the event topology will contain an energetic isolated lepton and large missing transverse momentum, as well as large hadronic transverse momentum. For the hadronic decays of W, the topology will be a three-jet event with a resonant structure in dijet and three-jet invariant masses. Both the H1 [48] and ZEUS [49] collaborations derived limits on $\kappa_{\gamma,u}$ as shown in Fig. 7. The H1 limits based on leptonic decay channels only [48] are less stringent due to a slight excess of isolated-lepton events observed in the data [50]. The Fig. 7 also shows limits from LEP and the Tevatron [2] experiments which are sensitive to both γ and Z couplings both to u- and c-quark couplings.

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