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Pursuing the Strange Stop Interpretation of the HERA Large- Q^2 Data

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Abstract

We explore the possible interpretation of the large- Q^2 anomaly reported by the H1 and ZEUS collaborations in terms of stop squark production off a strange quark in the proton via an R -violating interaction. This “strange stop” interpretation is constrained by LEP measurements of the $Z \rightarrow e^+e^-$ decay rate in addition to constraints from the electroweak ρ parameter and CDF and D0 searches for first-generation leptoquarks. We investigate the interplay between these constraints, taking full account of stop mixing effects. We find that if $m_{\tilde{t}} \leq 200$ GeV only relatively small domains of the chargino and neutralino parameters are consistent with these constraints, and explore the extent to which this scenario may be probed further by searches for contact interactions at LEP 2 and experiments with e^- and polarized beams at HERA.

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The surprisingly large number of high- x and $-Q^2$ deep-inelastic e^+p scattering events at HERA, reported recently by the H1 and ZEUS collaborations [1, 2], is currently exciting considerable theoretical speculation [3, 4, 5, 6]. It may well be that the excess reported is just a statistical fluctuation, and this may become apparent from the additional data being obtained during the current year’s run. However, unless and until this happens, it is the responsibility of theorists to pursue different possible interpretations of the excess, assuming it to be real, evaluate and combine the constraints imposed by other data, and propose additional signatures that may serve to discriminate between the surviving rival interpretations. Effective contact interactions from some energy scale beyond that of the Standard Model do not seem to match well the combined Q^2 distribution reported by the H1 and ZEUS collaborations. Interest has been piqued by the tendency of the H1 data to peak in an x range corresponding to the production of a narrow resonance with a mass around 200 GeV [1] and leptoquark quantum numbers, which is apparently not contradicted by the ZEUS data [4, 7].

If one chooses to speculate along this line, upper limits on the production cross section at the Fermilab Tevatron collider [8, 9] strongly suggest that any such leptoquark state must have spin 0, and hint that its branching ratio $\mathcal{B}(e^+q)$ into the observed final state should be significantly less than unity [4]. The latter is difficult, though not impossible, to arrange in a model without supersymmetry, but is natural if the “leptoquark” is actually a squark produced via an interaction that violates R parity [10, 11, 12]: $\lambda'_{ijk} L_i Q_j D_k^c$, where L_i, Q_j denote left-handed lepton and quark doublets, and D_k^c denotes left-handed charge-1/3 antiquark singlets. In such a supersymmetric scenario, there may be significant competition between the branching ratio \mathcal{B} for R -violating decays via the λ'_{ijk} production coupling and R -conserving decay modes such as χq followed by $\chi \rightarrow \ell \bar{q} q$ decay [4]. Within this general supersymmetric framework, three possible interpretations seem to emerge: $e_R^+ d_R \rightarrow \tilde{c}_L, e_R^+ d_R \rightarrow \tilde{t}$ and $e_R^+ s_R \rightarrow \tilde{t}$.

In this paper, we focus on the latter “strange stop” interpretation, which requires a relatively large R -violating coupling $\lambda'_{132} \sim 0.3/(\cos\phi\sqrt{\mathcal{B}})$, where ϕ is an angle describing mixing between the $\tilde{t}_{L,R}$ ², and possibly fine tuning of the chargino spectrum so as to have a significant, but not too dominant, branching ratio into $\chi^+ b$ [4]. As was pointed out in [4], this scenario must contend with LEP 2 constraints on virtual \tilde{t} exchanges from the OPAL collaboration [13], as well as with upper limits from precision electroweak physics on the possible contribution of the \tilde{t}, \tilde{b} sector to the ρ parameter. In addition, as was pointed out in [14], the measurement of the $Z \rightarrow e^+e^-$ decay rate provides an upper bound on the possible magnitude of any λ'_{13k} coupling, which is of particular interest because it is independent of the stop mixing angle and decay branching ratio. As we shall see, new data strengthen significantly the constraint found in the previous analysis, providing stimulus for the re-evaluation in this paper of all the phenomenological constraints on the “strange stop” interpretation of the HERA data, taking into account $\tilde{t}_{L,R}$ mixing effects³. We do not comment on possible stringent limits on R -parity violating interactions from cosmological considerations [15], as they can be avoided in various schemes, such as baryogenesis at the electroweak scale [16]. We analyze the restrictions imposed by the $Z \rightarrow e^+e^-$ and other constraints in the μ, M_2 plane that characterizes chargino and neutralino properties⁴, and hence stop decay modes. If the stop mass is 200 GeV or below,

²This must be significant, because of the electroweak ρ parameter [4].

³We also comment, where appropriate, on implications for the “down stop” interpretation.

⁴We assume universality at the supersymmetric GUT scale for the input soft supersymmetry-breaking gaug-

there is a restricted region of this plane where λ'_{132} is sufficiently small to satisfy the $Z \rightarrow e^+e^-$ constraint and $\mathcal{B}(e^+s)$ is sufficiently small to avoid the Tevatron production constraint. The latter imposes no constraint if the stop mass exceeds 210 GeV, in which case a significantly larger region of the μ, M_2 plane is allowed. We find that searches for effective contact interactions at LEP 2 may have a limited chance to probe further the “strange stop” scenario, and also comment on the possibilities for e^- or polarized beams at HERA to cast light on this scenario.

Any coupling of the form λ'_{i3k} would make an extra contribution to the Z partial width $\Gamma_{l_i} \equiv \Gamma(Z \rightarrow l_i^+ l_i^-)$ via loop diagrams involving a t and a \tilde{d}_k , which is proportional to m_t^2 for large m_t . Since this may become quite large, precise determinations of the Γ_{l_i} at LEP can provide sensitive constraints on the possible magnitude of R violation in the top sector [14]. There are also contributions to $\delta\Gamma_l$ from diagrams with stops in the loops, but these are suppressed by a factor m_i^2/m_t^2 as compared to the dominant contribution, where $i = d, s$ for the couplings relevant to the interpretation of the HERA anomaly. These diagrams have negligible numerical impact on the bounds that we derive, so the effects of stop mixing on our bounds are also small. We note that the masses of the \tilde{d}_k could in principle be different from that of the \tilde{t} assumed to be produced at HERA. However, the numerical values of the loop diagrams are not very sensitive to $m_{\tilde{d}_k}$, which we assume for definiteness to equal $m_{\tilde{t}}$.

We evaluate the top- \tilde{d}_k loops using the full expressions for their contribution $\delta\Gamma_{l_i}$ given in Ref. [14]. It is clear that the dominant contributions come from diagrams with a top quark and a \tilde{d} or \tilde{s} squark in the λ'_{131} and λ'_{132} cases, respectively. The non-observation of flavour-changing decays such as $\mu \rightarrow e\gamma$ imposes upper limits on the possibility that the lepton-number violation induced by λ' couplings can be present simultaneously in both $e(i = 1)$ and $\mu(i = 2)$ channels: $\lambda'_{132}\lambda'_{232} < 0.015$ for $m_{\tilde{t}} \sim 200$ GeV [17]. This implies that these couplings cannot affect significantly both Γ_e and Γ_μ ⁵, so we improve the bounds on the λ'_{13k} couplings presented in Ref. [14], by considering the ratio Γ_e/Γ_μ ⁶. We have used the following experimental values for the leptonic widths [18]: $\Gamma_e = 83.94 \pm 0.15$ MeV and $\Gamma_\mu = 83.79 \pm 0.21$ MeV. The resulting bounds on λ'_{13k} are shown in Fig. 1. We see that the bound on λ' varies from about 0.52 to about 0.6 as the squark mass changes from 180 to 220 GeV. We emphasize that this bound is independent of stop mixing and the $\tilde{t} \rightarrow e^+q$ branching ratio \mathcal{B} , making it a valuable constraint on “strange stop” interpretation of the HERA anomaly.

The mass splitting in the stop-sbottom sector results in a contribution to the electroweak ρ parameter, which is constrained by precision Z measurements from LEP and the SLD, and by m_W/m_Z measurements from the Tevatron and elsewhere. These and the Tevatron measurement of m_t provide strong upper limits on any contribution to ρ from physics beyond the Standard Model, in particular from the stop-sbottom sector. In the absence of stop mixing [4], the \tilde{b}_L mass is given by $m_{\tilde{b}_L} = \sqrt{m_{\tilde{t}_L}^2 - \cos 2\beta M_W^2 - m_t^2 + m_b^2}$, and is about 100 to 130 GeV, which would result in a contribution $\Delta\rho$ larger than that allowed by the data at the 95 % C.L. [4]. We now evaluate the amount of mixing that is required to avoid any contradiction with the experimental upper limit on $\Delta\rho$.

We neglect the bottom quark mass, which also implies that we may neglect mixing in the

ino masses $M_{1,2}$.

⁵This also means that $\mathcal{B}(\mu^+s) \ll \mathcal{B}(e^+s)$ in the “strange stop” scenario.

⁶This is equivalent to considering the ratio R_e/R_μ , because the corrections the hadronic width Γ_h from loops with sleptons cancel when one takes the ratio.

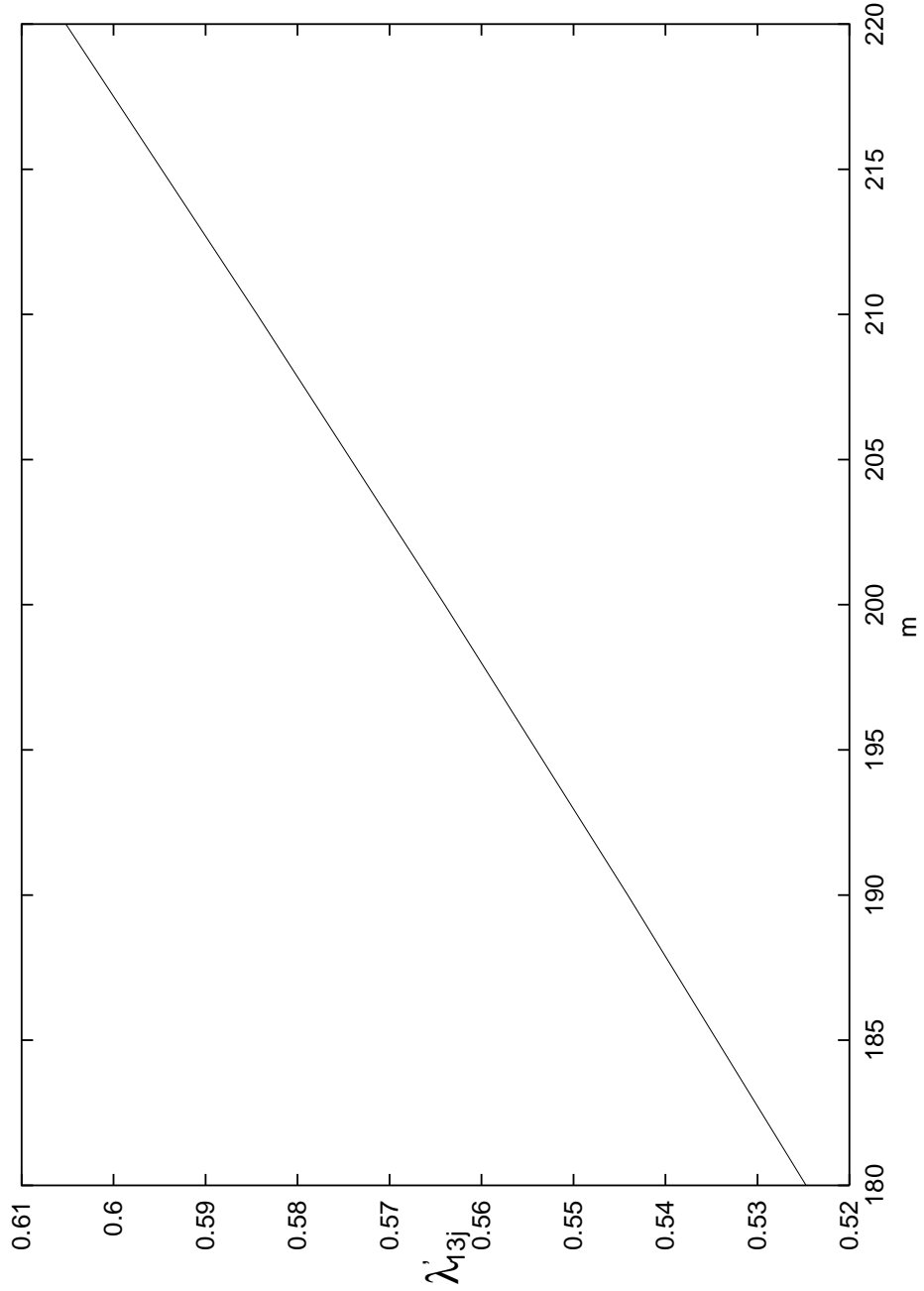


Figure 1: Upper bound on a generic R -violating coupling λ'_{13k} obtained from $Z \rightarrow e^+e^-, \mu^+\mu^-$ decays, using the data in [18] and the formulae in [14].

sbottom sector. The mixing in the stop sector may be expressed in terms of an angle ϕ given by

$$\tan\phi = \frac{m_{\tilde{t}_1}^2 - m_{\tilde{b}_L}^2 - m_t^2 - m_W^2 \cos 2\beta}{m_t m_{LR}}. \quad (1)$$

where $m_{\tilde{b}_L}$ is the mass of the physical left-handed sbottom, and we parametrize by $m_t m_{LR}$ the off-diagonal element in the stop mass-squared matrix where m_{LR} is a combination of the soft supersymmetry-breaking A parameter and the Higgs mixing parameter μ . We denote by $m_{\tilde{t}_{1,2}}$ the mass eigenstates that result from the mixing:

$$m_{\tilde{t}_{1,2}}^2 = \frac{1}{2}(m_{\tilde{b}_L}^2 + m_{\tilde{t}_R}^2 + 2m_t^2 + m_W^2 \cos 2\beta (1 + \frac{2}{3} \tan^2 \theta_W)) \mp \{[(m_{\tilde{b}_L}^2 - m_{\tilde{t}_R}^2 + m_W^2 \cos 2\beta (1 - \frac{2}{3} \tan^2 \theta_W))]^2 + 4m_t^2 m_{LR}^2\}^{\frac{1}{2}}, \quad (2)$$

where $m_{\tilde{t}_R}^2$ is the soft supersymmetry-breaking contribution to the right-handed stop mass. The contribution to $\Delta\rho$ coming from the $\tilde{t} - \tilde{b}$ mass-splitting is given in this notation by [19, 20]

$$\Delta\rho(\tilde{t} - \tilde{b}) = \frac{3\alpha}{8\pi m_W^2} \sin^2 \theta_W \left\{ \cos^2 \phi f_s(m_{\tilde{t}_1}^2, m_{\tilde{b}_1}^2) \sin^2 \phi f_s(m_{\tilde{t}_2}^2, m_{\tilde{b}_1}^2) - \cos^2 \phi \sin^2 \phi f_s(m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2) \right\}. \quad (3)$$

where

$$f_s(m_1^2, m_2^2) = \frac{m_1^2 m_2^2}{m_1^2 - m_2^2} \ln \frac{m_2^2}{m_1^2} + \frac{1}{2}(m_1^2 + m_2^2) \quad (4)$$

We note that the (t, b) -loop contribution to ρ is positive, as is the range of ρ indicated by the precision electroweak data.

We plot in Fig. 2 the \tilde{t}, \tilde{b} contribution to $\Delta\rho$ as a function of the mixing angle ϕ for different choices of $\tan\beta$ and m_{LR} for $m_{\tilde{t}_1} = 200$ GeV. The parameter m_{LR} cannot be much larger than $m_{\tilde{b}_L}$, because of the problem of false vacua [21]. As a rule of thumb, one may impose $0 \lesssim m_{LR} \lesssim 3m_{\tilde{b}_L}$, in which case $\sin\phi < 0$. For the purposes of this analysis we choose $m_{LR} = km_{\tilde{b}_L}$, with $k = 1, 2$. The curves marked (a) and (b) in Fig. 2 are for the case $k = 1$ and $\tan\beta = 1, 5$ respectively, whereas those marked (c) and (d) are for $k = 2$ and $\tan\beta = 1, 5$. Curve (e) represents the 95 % C.L. upper limit after subtracting the Standard Model reference value for $m_H = 100$ GeV, as is appropriate for the MSSM. We see that for $k = 1$ and $\tan\beta = 1$, values of $\phi > -0.6$ are excluded for $m_H = 100$ GeV.

We now calculate $\mathcal{B}(\tilde{t} \rightarrow e^+ s)$ in the context of the ‘‘strange stop’’ mechanism $e^+ s_R \rightarrow \tilde{t}$ studied in this paper, including stop mixing effects⁷. In the presence of mixing, the R -violating $\tilde{t}_1 \rightarrow e^+ s$ decay rate becomes

$$\Gamma_{\tilde{t}_1} = \frac{1}{16\pi} \lambda_{132}^2 m_{\tilde{q}} \cos^2 \phi \quad (5)$$

⁷In [4], the corresponding calculation of $\mathcal{B}(\tilde{t}_L \rightarrow e^+ d)$ was presented, neglecting stop mixing and under the alternative assumption that the \tilde{t}_L was produced off valence d quarks in the proton, with a much smaller value of the corresponding λ'_{131} coupling.

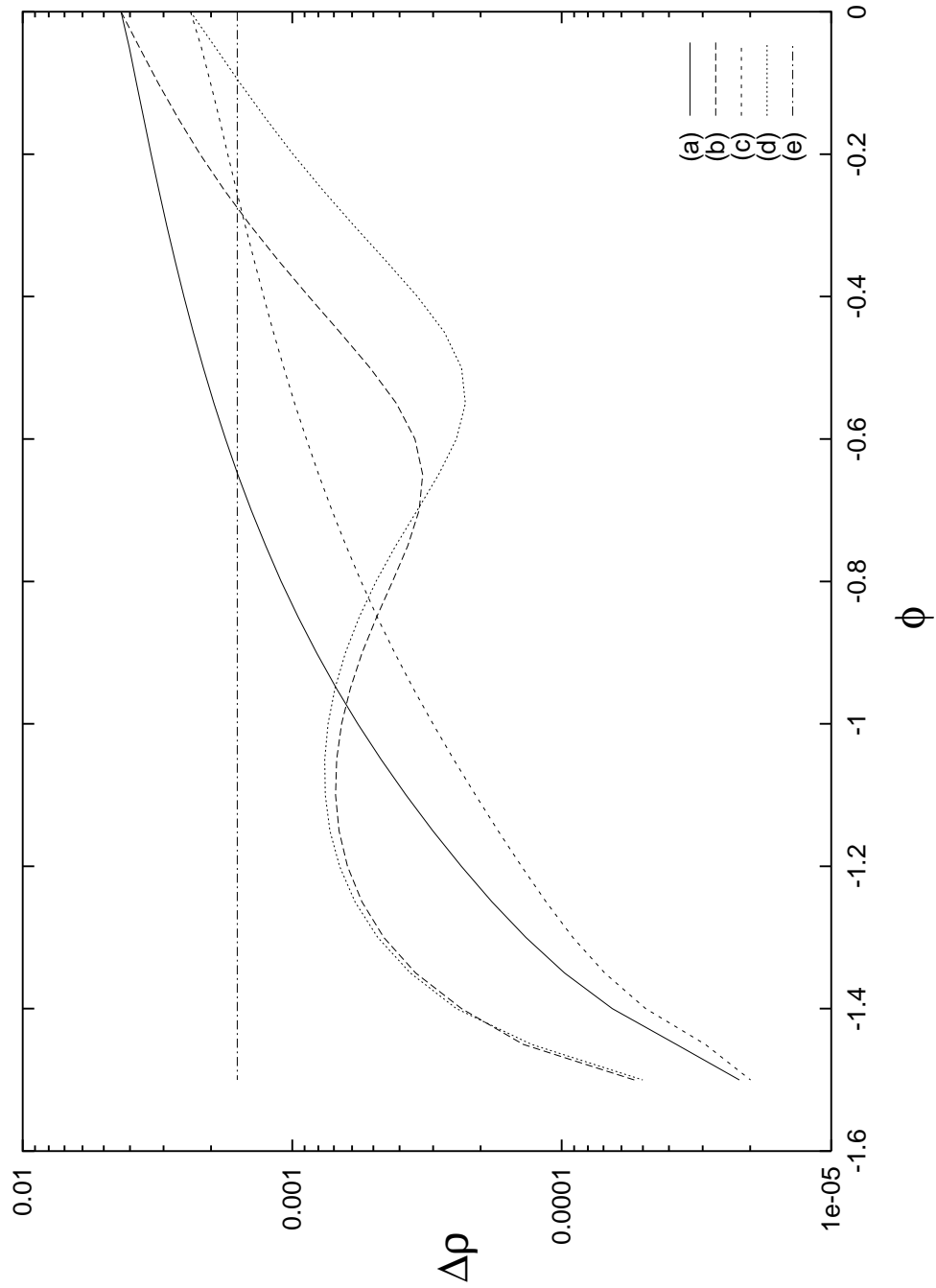


Figure 2: Contributions to the ρ parameter from $\tilde{t}-\tilde{b}$ loops, for the cases (a) $k = 1$ and $\tan\beta = 1$, (b) $k = 1$ and $\tan\beta = 5$, (c) $k = 2$ and $\tan\beta = 1$, (d) $k = 2$ and $\tan\beta = 5$, compared with (e) the 95 % C.L. after subtracting the Standard Model prediction for $m_H = 100$ GeV.

and the decay rate of \tilde{t}_2 is described by a similar equation, with $\cos\phi$ substituted by $\sin\phi$ ⁸. To illustrate our analysis, we choose values of the mixing angle ϕ that are consistent with the $\Delta\rho$ bound shown in Fig. 2.

The most important R -conserving decay is presumably that into a chargino: $\tilde{t} \rightarrow \chi^+ b$. To understand this, we first note that the decay $\tilde{t} \rightarrow \chi t$, where χ is the lightest neutralino, is presumably excluded by LEP 2 lower limits on m_χ , though a thorough analysis in the appropriate R -violating framework has not yet been published. Secondly, the kinematically-allowed $\tilde{t} \rightarrow \chi c$ decay is suppressed by typical loop factors, and three-body decays are also expected to be small [4]. Since the value of the λ'_{132} coupling required in the ‘‘strange stop’’ interpretation studied here ($\gtrsim 0.3$) is much larger than that of the corresponding λ'_{131} coupling in the ‘‘down stop’’ interpretation ($\gtrsim 0.04$) pursued in [4], it is easier for the R -violating decay mode to become competitive with the R -conserving chargino decay mode, even when the latter is not kinematically suppressed.

In the presence of mixing, the $\tilde{t} \rightarrow \chi^+ b$ decay rate becomes [11]

$$\Gamma'_{\tilde{t}_1} = \frac{\alpha}{4\sin^2\theta_W} m_{\tilde{t}_1} \lambda^{1/2}\left(1, \frac{m_b^2}{m_{\tilde{t}_1}^2}, \frac{m_{\chi^\pm}^2}{m_{\tilde{t}_1}^2}\right) \cdot \left\{ \left(|G_L|^2 + |G_R|^2 \right) \left(1 - \frac{m_b^2}{m_{\tilde{t}_1}^2} - \frac{m_{\chi^\pm}^2}{m_{\tilde{t}_1}^2} \right) - \frac{4m_b m_{\chi^\pm}}{m_{\tilde{t}_1}^2} \text{Re}(G_R G_L^*) \right\}, \quad (6)$$

$$G_L \equiv -\frac{m_b U_{k2}^* \cos\phi}{\sqrt{2}m_W \cos\beta}, \quad G_R \equiv V_{k1} \cos\phi + \frac{m_t V_{k2} \sin\phi}{\sqrt{2}m_W \sin\beta} \quad (7)$$

where $\lambda(x, y, z) \equiv x^2 + y^2 + z^2 - 2xy - 2yz - 2zx$ is the usual phase space factor, and the V_{kl} and U_{kl} are the chargino mixing angles, determined in the usual way by μ , the ratio $\tan\beta$ of supersymmetric Higgs vacuum expectation values, and M_2 . As compared to zero mixing, we see that the vertex involving \tilde{t}_L changes by a factor $\cos\phi$ like the R -violating coupling. However, now we also have the vertex that couples the chargino to \tilde{t}_R , which is dependent on $V_{1,2}$, m_t , and $\sin\phi$. Note also that the branching ratios of the stop decays to charginos depend on the sign of ϕ , which is sensitive in particular to the soft supersymmetry-breaking parameter A and the Higgs mixing parameter μ .

The presence of the additional vertex suggests at first sight that large stop mixing might tend to favour the R -conserving decay mode relative to the R -violating one. Indeed, this feature is manifest in the region of parameter space where μ is small. However, there is also the possibility of a cancellation that may amplify the R -violating branching ratio in some specific regions of parameter space. To see this, note that, when stop mixing is taken into account, besides the squared couplings of the $\tilde{t}_{L,R}$ vertices, there also exists a term in the decay rate arising from the cross product of the parts of the \tilde{t}_R and \tilde{t}_L vertices that have the same helicity⁹. This ‘‘cross term’’ is proportional to

$$2 \cos\phi \sin\phi \frac{m_t V_{k2} V_{k1}}{\sqrt{2}m_W \sin\beta} \quad (8)$$

⁸This decay would be relevant if \tilde{t}_2 were light enough to have been produced at HERA, as proposed in [6].

⁹The additional term involving $\text{Re}(G_R G_L^*)$ gives a much smaller contribution, except in the small region with $m_{\tilde{t}_1}^2 - m_{\chi^\pm}^2 \sim m_b^2$, on which we do not comment further.

This is significant, and can be destructive if either (i) $\sin\phi$ is negative and V_{11} and V_{12} have the same sign, or (ii) $\sin\phi$ is positive and V_{11} and V_{12} have opposite signs.

It is clear that the stop branching ratio $\mathcal{B}(e^+q)$ must be non-negligible, if H1 and ZEUS are to have seen this decay mode without being drowned by other stop decay signatures. On the other hand, the D0 [8] and CDF [9] collaborations at the Fermilab $\bar{p}p$ collider have both established upper limits on $\sigma_{LQ}\mathcal{B}(e^+q)^2$, where LQ is a generic scalar particle with decays into e^+q , which may for our purposes be taken as the \tilde{t}_1 . In particular, CDF [9] establishes that $m_{LQ} > 210$ GeV if $\mathcal{B}(e^+q) = 1$, corresponding to $\mathcal{B}(e^+q) \lesssim 1/\sqrt{1 + 9\ln(210 \text{ GeV}/m_{LQ})}$ for values of the leptoquark mass below 210 GeV. The CDF limit [9] corresponds, in particular, to $\mathcal{B}(e^+q) < 0.73(0.87)$ for $m_{LQ} = 190(200)$ GeV, but provides no constraint for $m_{LQ} \geq 210$ GeV.

We combine the above constraints in the μ, M_2 plane as shown in Fig. 3, using the following procedure. We first choose values of $\tan\beta$ and of ϕ , the latter compatible with the $\Delta\rho$ upper bound shown in Fig. 2. We then use (5) and (7) to calculate $\mathcal{B}(e^+s)$, employing self-consistently the value of λ'_{132} suggested by the HERA observations: $\lambda'_{132} = 0.3/(\cos\phi\sqrt{\mathcal{B}})$. We then apply the $Z \rightarrow e^+e^-$ constraint of Fig. 1 - which excludes models with low \mathcal{B} , in particular at small M_2 and/or $|\mu|$, and the CDF constraint [9] - which excludes models with large \mathcal{B} if $m_{\tilde{t}_1} < 210$ GeV. As we see in Figs. 3(a,b), only restricted regions of the μ, M_2 plane are compatible with these constraints if $m_{\tilde{t}_1} = 190$ GeV, and these are not greatly expanded if one chooses $m_{\tilde{t}_1} = 200$ GeV as in Figs. 3(c,d). On the other hand, it is clear that the entire upper part of the μ, M_2 plane is allowed if $m_{\tilde{t}_1} \geq 210$ GeV, since the CDF constraint [9] then imposes no restriction. Comparing Figs. 3(a,c) with Figs. 3(b,d), we see that the allowed regions are of similar size, but more symmetric between positive and negative μ , if one chooses $\tan\beta = 5$.

As was pointed out in [4], one of the potentially interesting constraints on leptoquark or R -violating squark interpretations of the large- Q^2 HERA anomaly could come from LEP 2 limits on effective contributions to $e^+e^- \rightarrow \bar{q}q$ due to crossed-channel exchanges. Formulae have been given in [4] and elsewhere for the case of single leptoquark or R -violating squark exchange. However, the LEP 2 constraint is potentially most relevant for the ‘‘strange stop’’ interpretation with its relatively large coupling: $\lambda'_{132} \sim 0.3/(\cos\phi\sqrt{\mathcal{B}})$, in which case stop mixing should be taken into account in estimating the exchange contributions. Accordingly, we now present for completeness the simple generalization of the standard formulae available previously to the case in which two mixed stops $\tilde{t}_{1,2}$ are exchanged:

$$\begin{aligned} \sigma = & \sigma_{SM} + \frac{3\lambda'^4(I_1\cos^4\phi + I_2\sin^4\phi)}{64\pi s} + \frac{3\lambda'^4(I_3\cos^2\phi\sin^2\phi)}{64\pi s} + \\ & + \frac{3\lambda'^2\alpha_{em}(I'_1\cos^2\phi + I'_2\sin^2\phi)}{4s} \left[e_e e_d + a_L^e a_R^d \frac{s(s - M_Z^2)}{(s - M_Z^2)^2 + \Gamma_Z^2 M_Z^2} \right] \end{aligned} \quad (9)$$

where

$$I_{1,2} = \frac{1 + 2x_{\tilde{t}_{1,2}}}{1 + x_{\tilde{t}_{1,2}}} - 2x_{\tilde{t}_{1,2}} \ln\left(\frac{1 + x_{\tilde{t}_{1,2}}}{x_{\tilde{t}_{1,2}}}\right) \quad (10)$$

$$I_3 = 1 + \frac{x_{\tilde{t}_1}^2}{-x_{\tilde{t}_1} + x_{\tilde{t}_2}} \ln\left(\frac{1 + x_{\tilde{t}_1}}{x_{\tilde{t}_1}}\right) - \frac{x_{\tilde{t}_2}^2}{-x_{\tilde{t}_1} + x_{\tilde{t}_2}} \ln\left(\frac{1 + x_{\tilde{t}_2}}{x_{\tilde{t}_2}}\right) \quad (11)$$

$$I'_{1,2} = -\frac{1}{2} + x_{\tilde{t}_{1,2}} - x_{\tilde{t}_{1,2}}^2 \ln\left(\frac{1 + x_{\tilde{t}_{1,2}}}{x_{\tilde{t}_{1,2}}}\right) \quad (12)$$

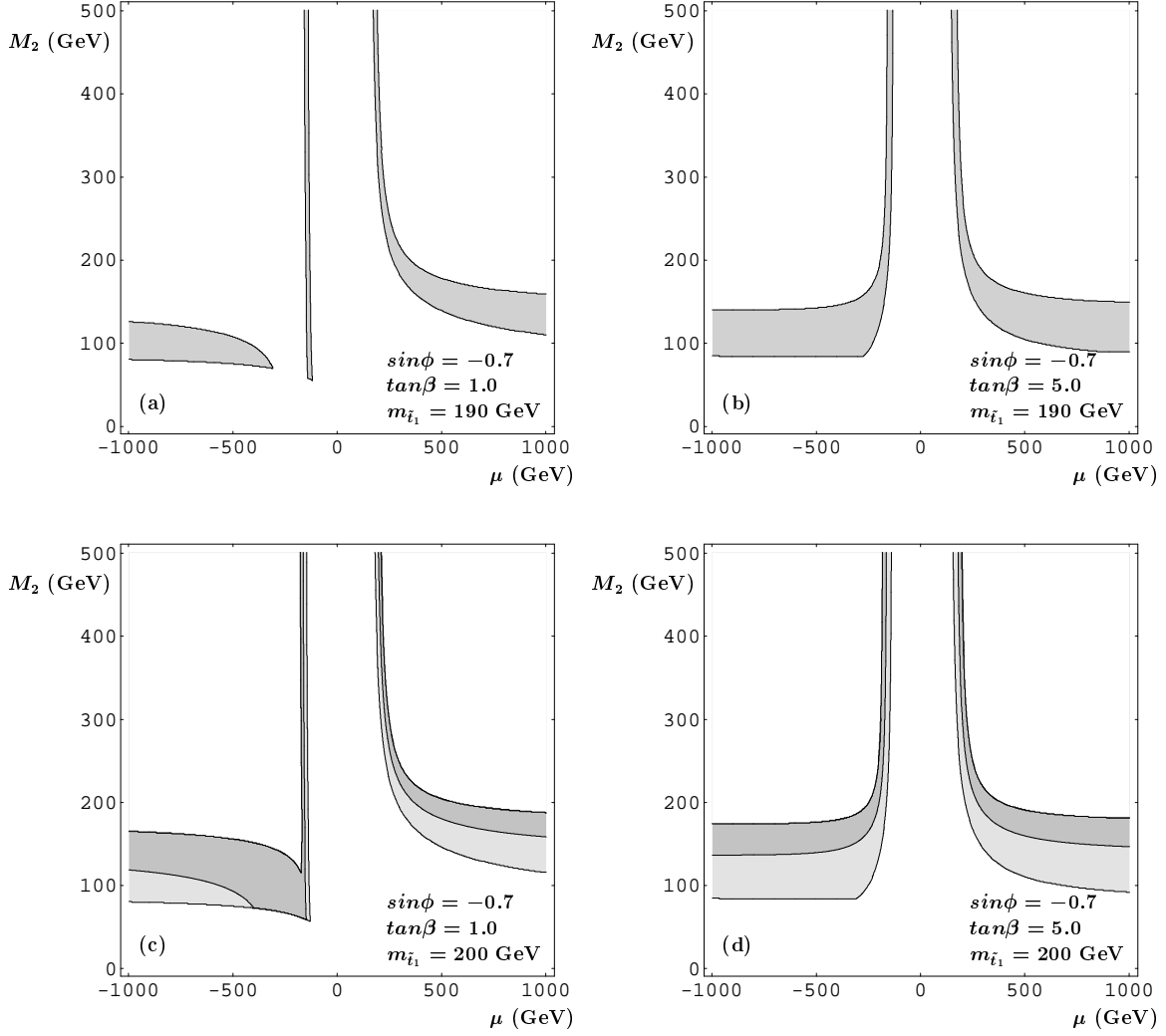


Figure 3: Regions of the μ, M_2 plane that are consistent with the upper bound on λ'_{132} shown in Fig. 1 and the CDF upper limit on $\mathcal{B}(e^+q)$ [9] for the R -violating decay of \tilde{t}_1 , for (a) $\sin\phi = -0.7$, $\tan\beta = 1.0$ and $m_{\tilde{t}_1} = 190$ GeV, (b) $\sin\phi = -0.7$, $\tan\beta=5.0$ and the same value of $m_{\tilde{t}_1}$, (c) $\sin\phi = -0.7$, $\tan\beta = 1.0$ and $m_{\tilde{t}_1} = 200$ GeV, and (d) $\sin\phi = -0.7$, $\tan\beta=5.0$ and the same value of $m_{\tilde{t}_1}$.

with $a_{L,R}^f = (T_3^f - e^f \sin^2 \theta_W) / (\sin \theta_W \cos \theta_W)$ and $x_{\tilde{t}_{1,2}} \equiv \frac{m_{\tilde{t}_{1,2}}^2}{s}$. The contributions proportional to $I_{1,2}$ in eq.(9) arise from the squared amplitudes of the diagrams with the R -violating vertices, for \tilde{t}_1 and \tilde{t}_2 exchange respectively, and I_3 is the interference term between the \tilde{t}_1 and \tilde{t}_2 exchange diagrams. Finally, the terms proportional to $I'_{1,2}$ are interference terms with the Standard Model s -channel γ and Z exchanges, for both stop exchanges ¹⁰.

The interference of the new diagrams with the Standard Model processes is in our case destructive. In the case we discussed previously [4] with $\lambda'_{131} = 0.04$, interference gave the dominant deviation from the Standard Model prediction. However, in the case studied in this paper with $\lambda'_{132} \lesssim 0.3$, the squares of the new diagrams are also large, and cancellations occur between them and the negative interference terms. Moreover, when mixing is introduced, the squared terms and the destructive interference ones are multiplied by different factors, in such a way that the cancellation is *enhanced*. Thus the bounds derivable from LEP 2 bounds may be relaxed significantly compared to the unmixed case. Indeed, for any given value of λ'_{132} , there is even a value of ϕ where no bound is obtained, since the cancellation becomes exact. More generally, when two light stops are exchanged, the cancellation occurs over a wider range of mixing angle ϕ , and the LEP 2 bounds are relaxed. The numbers for some representative parameter choices are shown in the Table. For various different values of $m_{\tilde{t}_2}$ and ϕ , the magnitudes of the destructive interference terms and the new squared amplitude contributions are shown, and we see how they conspire to leave small net contributions to the cross section for $e^+e^- \rightarrow \bar{s}s$.

We have seen in the above analysis that the “strange stop” scenario may survive the available constraints, at the price of requiring a relatively restricted region in the μ, M_2 plane if $m_{\tilde{t}_1} \leq 200$ GeV. It is disappointing that partial cancellations between negative interference and positive squared-amplitude terms may hinder attempts to pin down this scenario at LEP 2. In principle, the decay modes and branching ratios observable at HERA could discriminate between the “down” and “strange stop” scenarios. There are also possibilities for discriminating between these scenarios by using different beams at HERA.

One clear distinction could be drawn by comparing stop production in e^+p and e^-p collisions. In the “down stop” case, one predicts $\sigma(e^+p) \gg \sigma(e^-p)$, since production occurs off valence quarks in e^+p collisions, and off sea quarks in e^-p collisions. One does not expect such a large ratio in the “strange stop” interpretation, since production occurs off sea quarks with either beam. However, it is not necessarily the case that the production cross sections must be exactly equal, since the s and \bar{s} distributions may have different shapes, though their integrals must be equal. If the strange sea in the proton is extrinsic, e.g., generated by perturbative QCD, one would expect strict equality in the cross sections, but this need not be the case if there is an intrinsic [22] strange component ¹¹. Thus, we predict only that $\sigma(e^+p) \sim \sigma(e^-p)$ in the “strange stop” interpretation.

Another tool for discriminating between models could be provided by polarized beams at

¹⁰Note that, as well as the different coupling factors, because of fermionic Wick ordering there is a difference in the sign of the interference term for charge-1/3 $\bar{q}q$ final states such as the $\bar{s}s$ case considered here, as compared to charge-2/3 final states such as the $\bar{c}c$ case considered in [4]. This has the consequence that the interference terms are numerically negative in both cases, as shown in [5]: we thank P. Zerwas for discussions on this point.

¹¹There is no indication of this in the data available so far, but we do note that there are indications of other flavour asymmetries in the $\bar{q}q$ sea [23].

$\lambda'_{132} = 0.4, m_{\bar{t}_1} = 200 \text{ GeV}, m_{\bar{t}_2} \text{ very heavy}$			
$ \sin\phi $	cross section (pb)	squared amplitude (pb)	negative interference(pb)
0.0	0.082	0.415	-0.333
0.2	0.063	0.383	-0.320
0.4	0.013	0.293	-0.280
0.6	-0.043	0.170	-0.213
0.8	-0.066	0.054	-0.120

$\lambda'_{132} = 0.4, m_{\bar{t}_1} = 200 \text{ GeV}, m_{\bar{t}_2} = 205 \text{ GeV}$			
$ \sin\phi $	cross section (pb)	squared amplitude (pb)	negative interference (pb)
0.0	0.082	0.415	-0.333
0.2	0.066	0.399	-0.333
0.4	0.025	0.356	-0.331
0.6	-0.016	0.313	-0.329
0.8	-0.020	0.306	-0.326

Table 1: The contribution additional to the Standard Model cross section for $e^+e^- \rightarrow s\bar{s}$ at $E_{CM} = 192 \text{ GeV}$, for different values of the stop mixing angle ϕ . The second column gives the net additional contribution to the cross section due to the new terms. The third column presents the positive contributions due to the new squared amplitude terms in the first line of (9), and the fourth column presents the negative terms due to the destructive interference in the second line of (9).

HERA. Both the “down stop” and “strange stop” mechanisms involve the component of the e^+ beam with right-handed longitudinal polarization. This means that dramatic effects should be seen once longitudinal *lepton* beam polarization is commissioned at HERA: both models predict that $\sigma(e_L^+p) \ll \ll \sigma(e_R^+p)$ and $\sigma(e_R^-p) \ll \ll \sigma(e_L^-p)$. Polarized *proton* beams [24] would also be very interesting. In the case of “down stop” model, since most models predict that valence down quarks should mainly be polarized *opposite* to the proton spin, one would expect that $\sigma(e_R^+p_R) \ll \ll \sigma(e_R^+p_L)$.

The predictions for polarized proton beams in the “strange stop” model are currently less clear, since there is no consensus on the amount of polarization Δs of the $\bar{s}s$ sea in the proton. The most straightforward interpretation of the available data on polarized deep-inelastic ℓN scattering is that $\Delta s < 0$ [25], though this suggestion is subject to possible gluonic reinterpretation [26]. However, the available data give no clear indication on the *degree* of polarization $\Delta s/(\bar{s} + s)$, particularly not at the large x values probed by the HERA experiments, nor do we know how Δs might be shared between the \bar{s} and s in the proton. One particularly naive model suggests that the s quarks may have a large degree of polarization, particularly at large x , and that the same *might* also be true of the \bar{s} [27]. In this case, one might expect that

$$\sigma(e_R^+p_R) < \sigma(e_R^+p_L), \sigma(e_L^-p_L) < (?)\sigma(e_L^-p_R) \quad (13)$$

with much smaller cross sections for the other beam polarizations, as mentioned above.

It is very likely that the mystery of the large- Q^2 HERA anomaly will be resolved by the time such polarized experiments become possible. However, these examples serve to illustrate that both beam polarizations could be useful analysis tools.

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