Fermi National Accelerator Laboratory

FERMILAB-Conf-86/036-T

UCLA/86/TEP/34
September 1986

SIGNALS OF HORIZONTAL SYMMETRIES AT THE SSC*

N. G. DESHPANDE

University of Oregon, Eugene, Oregon 97403

and

J. GUNION

University of California, Davis, California 95616

and

D. KOSOWER,†

Harvard University, Cambridge, Massachusetts 02138

and

M. H. RENO

Fermi National Accelerator Laboratory, Batavia, Illinois 60510

and

A. SONI

University of California, Los Angeles, California 90024

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* To appear in the Proceedings of the 1986 Summer Study on the Physics of the Superconducting Super Collider, Snowmass, Colorado, June 23–July 11, 1986.

† Present address: Columbia University, New York, New York 10027

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N. G. Deshpande, University of Oregon, Eugene, Oregon 97403

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D. Kosower,* Harvard University, Cambridge, Massachusetts 02138

M. H. Reno, Fermi National Accelerator Laboratory, Batavia, Illinois 60510

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Summary

We show that the SSC can explore a region of parameter space that has not been accessible to low energy experiments, in particular a fairly low mass ($M_H \sim 500$ GeV) and small coupling constant ($g_H \sim 10^{-2} - 10^{-3} \times g_W$). As has been pointed out in the past, the clearest (but unfortunately not theoretically essential) signal of a new horizontal gauge boson involves two different flavors of charged leptons. The corresponding quark final states are hidden deep below the QCD backgrounds, unless the horizontal gauge group is such that low energy constraints do not apply so that $g_H \sim g_W$ at low M_H is possible.

Introduction

The standard model of strong, weak and electromagnetic interactions with gauge group $G = SU(3) \times SU(2) \times U(1)$ has been extremely successful in its description of the fundamental forces of nature. It lacks, however, even a qualitative explanation of why there are so many fermions. Motivated by our lack of understanding of why there is more than one family of quarks and leptons, theories such as certain composite,[1] family unified[2] and extended gauge theories[3] have been proposed. Our focus here is on models that can be written in terms of an effective gauge group $G \times H$ where H is a horizontal gauge group, either a simple or a product group, with bosons that mediate transitions between families of fermions. At least some of the known fermions transform non-trivially under H. Such models often predict extra fermions and scalars as well as gauge bosons. We leave the discussions of the first two to other Snowmass subgroups and concentrate only on the gauge interactions and how they would be manifest at the SSC.

Horizontal gauge couplings induce effective four-fermion interactions that are flavor violating. Stringent constraints from low energy experiments put lower bounds on the scale of H symmetry breaking. This translates to an exclusion of a region of parameter space of the coupling constant and horizontal gauge boson mass. Our plan here is to demonstrate the full range of this parameter space that is both consistent with low energy constraints and accessible at SSC energies. This will include a review of the results presented in the Snowmass 1984 proceedings.[4] To set the notation, we present an effective lagrangian for flavor-changing neutral currents (FCNC). The low energy experimental limits on rare processes are translated into parameter constraints following Cahn and Harari.[5] We schematically describe why purely hadronic FCNC are difficult to extract from QCD backgrounds. We concentrate on the process $pp \to \ell_1 \bar{\ell}_2$ where ℓ_1 and ℓ_2 are charged leptons of different flavors.

Effective Lagrangian

The effective four fermion operator is parameterized in terms of the coupling constant g_H and the gauge boson mass M_H:

$$\mathcal{M} = \frac{g_H^2}{(2\sqrt{2})^2} \bar{f}_1 \gamma_\mu [R_{12}(1+\gamma_5) + L_{12}(1-\gamma_5)] f_2 \cdot \frac{1}{s - M_H^2 + i\Gamma_H M_H} \bar{f}_4 \gamma^\mu [R_{34}(1+\gamma_5) + L_{34}(1-\gamma_5)] f_3$$

for $\bar{f}_1 f_2 \to H \to \bar{f}_3 f_4$. Purely V–A horizontal interactions with $R_{12} = R_{34} = 0$ and $L_{12} = L_{34} = 1$ are normalized identically to the weak interactions. Defining the symmetry breaking scale Λ such that $M_H = g_H \Lambda$, the Cahn–Harari limits are shown in Table 1. We have included in Table 1 the limit on Λ that would arise from a bound $B(D \to \mu e) < 10^{-4}$. Presently, there are no such published limits. In models allowing tree graph contributions, the $K_L - K_S$ mass difference calculation depends on $\Delta^{-2} = M^{-2} - M'^{-2}$, where M and M' are the masses of gauge bosons that couple non–diagonally to the strange and down quarks. Without a specific model, it is difficult to translate the limit on Δ to one on Λ. The angles β and β' are related to the rotation angles required to diagonalize the quark mass matrices. We assume that these angles are on the order of the Cabibbo angle, so all cosines have been set to unity.

Some theories have a single gauge group, either SU(2) or SU(3) with some fermions of each charge transforming in the adjoint or fundamental representation, respectively.[3] In these

Table 1. Cahn–Harari[5] limits on horizontal symmetry breaking scale $\Lambda = M_H/g_H$. The parameter Δ is defined such that $\Delta^{-2} = M^{-2} - M'^{-2}$.

Limit	Interaction	Min. $\Lambda = M_H/g_H$ (TeV)
$B(K^+ \to \pi^+ e\mu) < 5 \cdot 10^{-9}$	$L_{sd} = L_{e\mu} = 1$, $R_{sd} = R_{e\mu} = 0$	$\Lambda > 15.8$
	$L_{sd} = L_{e\mu} = 1$, $R_{sd} = R_{e\mu} = 1$	$\Lambda > 26.6$
$B(K_L \to e\mu) < 6 \cdot 10^{-6}$	$L_{sd} = L_{e\mu} = 1$, $R_{sd} = R_{e\mu} = 0$	$\Lambda > 6.0$
$B(D \to e\mu) < 10^{-4}$	$L_{cs} = L_{e\mu} = 1$, $R_{sd} = R_{e\mu} = 0$	$\Lambda > 3.0$
$\sigma_{\mu e}/\sigma_{\mu\nu} < 1.5 \cdot 10^{-10}$	$L_{qq} = L_{e\mu} = 1$, $R_{qq} = R_{e\mu} = 1$	$\Lambda > 130 \sin^{\frac{1}{2}} \beta$
$\Delta M_K/M_K \simeq 7 \cdot 10^{-15}$	$L_{sd} = L_{ds} = 1$, $R_{sd} = R_{ds} = 0$	$\Delta/g_H > 592 \sin\beta'$

* Present address: Columbia University, New York, New York 10027.

cases, one expects a single gauge coupling constant to enter the calculation. The SSC signatures of the model of Hou and Soni[3] in which the horizontal gauge symmetry is designed to account for the observed CP violation in the kaon system, have been considered in detail by Bengtsson *et al.*[6] Our conclusions below are consistent with their analysis.

We need not assume that there is a simple gauge group, however. Certain composite models, for example, suggest that there should be separate gauge groups for the quark doublets Q_i, the lepton doublets L_i and each of the singlet fermions: u_i, d_i and e_i. (This is a type of techni–GIM mechanism.[7]) In the absense of any gauge boson mixing, flavor violating effects will only occur within a given hypercharge sector and will depend on Δ^{-2} of the gauge bosons that couple to that sector. One can imagine symmetry breaking schemes that may maintain a nearly degenerate set of gauge bosons for each sector, but that mixes the sectors slightly. In this way, it is possible to satisfy, say, the constraints from ΔM_K and rare kaon decays. The effective coupling for the former process will be the gauge coupling for that sector, whereas the coupling for the latter will be a combination of quark and lepton gauge coupling constants together with a mixing angle. This may yield an extremely small effective coupling constant. Furthermore, in these schemes it is possible to have fairly large flavor–violating effects only in the charge 2/3 sector where the limits are less restrictive. We shall consider the coupling constants for each process to be independent.

Quark FCNC

In general, it would be desirable to be sensitive to horizontal gauge bosons in quark, as well as lepton, final state channels. In particular, if the horizontal gauge bosons that couple to quarks do not couple to leptons, quark final states would be the only probe of these bosons at a hadron collider. We briefly describe the experimental requirements for distinguishing quark FCNC from the QCD backgrounds.

The processes we have in mind are those involving a heavy and light quark: $pp \to ct$ and $pp \to sb$. Also possible, of course, are $pp \to uc$, ds, but these are more difficult to extract from the very large QCD two–jet background. Consider the ct final state with $M_H \sim 500$ GeV. We imagine that there is a t–quark trigger, an isolated charged lepton trigger, for example, to select a sample of candidate events. If we assume that the horizontal gauge boson couples to both quark and lepton channels, then Table 1 is applicable in many models and would imply that the coupling constant $g_H \ll 1$. In this case, the H decay width and total cross section are small. The total cross section for $pp \to ct$, without cuts and assuming the number of H decay channels is 16 (including ν channels), is less than a few tenths of a picobarn.

The two jet background is comprised of three components. For jet–jet invariant mass $M_{jj} \lesssim$ a few TeV, gg final states account for the majority of the total two jet cross section, σ_{jj}. At higher masses, but below $M_{jj} \sim 10$ TeV, gq scattering dominates, until at higher masses still, the qq process takes over.[8] For $M_{jj} \sim 500$ GeV, $\sigma_{jj} \sim 5 \cdot 10^4$ pb in a 25 GeV invariant mass bin. (This is much larger than the decay width of H, but we take the energy resolution to be $5\% \times M$.) Of this total, approximately 2% are gt final states.[8] This accounts for approximately 10^3 pb, three orders of magnitude above the signal. A discrimination between charm quarks and gluon jets and/or detection of the associated top quark in the spectator

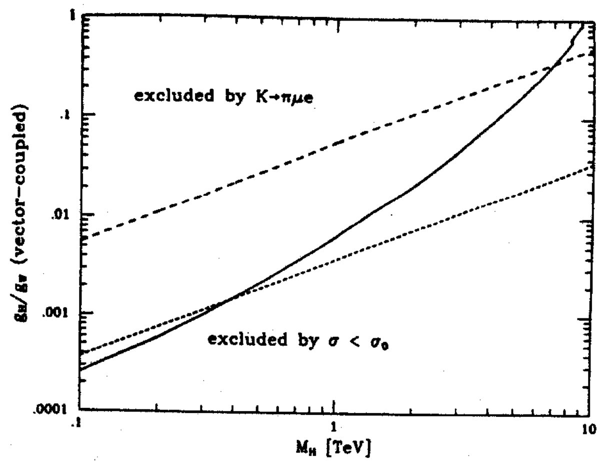

Figure 1. For vector coupled horizontal gauge bosons, the region below the solid line is inaccessible to SSC experiments because the uncut cross–section is less than $\sigma_0 = 10^{-3}$ pb. Above the dashed line, the parameters predict $K \to \pi\mu e$ at a level above the present experimental upper bound. The dotted line indicates the parameters allowing $B(K \to \pi\mu e)$ at the 10^{-13} level.

jet in the background process is required at a level of 1/1000. For invariant masses on the order of a TeV, the QCD two jet cross section is reduced by a factor of 1/3, but the gq processes are beginning to dominate the cross section, so backgrounds are as difficult to exclude as they are at lower energies.

Only if the coupling g_H were larger than allowed by the Table 1 constraints could quark final states probe the horizontal gauge boson sector Since $\sigma \sim g_H^4$, a factor of 10 increase in g_H over the Table 1 limits would make FCNC observable in the quark sector. Such a large value of g_H cannot be ruled out in models where the horizontal gauge bosons that couple to the quarks are different from those that couple to leptons, or where there is a mismatch between the familiy mixing structure in the lepton sector and that in the quark sector.

Leptonic FCNC

The observation of the leptonic flavor–violating signal of H production and decay would be an unambiguous signal of new physics. The process is virtually background–free. There is no missing energy as there are only charged leptons in the final state. Furthermore, the leptons reconstruct to the mass M_H. A standard model source of such a signal is $pp \to W^+W^- \to \ell_1\bar{\ell}_2\bar{\nu}_1\nu_2$ where the $\bar{\nu}_1$ and ν_2 momenta are anti–aligned. For fairly low invariant masses, where the background cross–section $(d\sigma/dM_{\ell_1\bar{\ell}_2})$ is largest, the width of H must be extremely small compared to its mass ($g_H \ll 1$), so the peak from H production should stand out. For higher invariant masses of ℓ_1 and $\bar{\ell}_2$, the background cross–section decreases significantly.

The cross-sections for $pp \to \ell_1\bar{\ell}_2$ are displayed in the 1984 *Snowmass Proceedings*[4] for various coupling constants with $M_H \lesssim 40$ TeV. Bengtsson *et al.*[6] have also computed the cross–section, including both the Drell–Yan horizontal gauge boson production and "Compton production" with $gq \to qH$ for M_H between 1 and 10 TeV. At SSC energies and for masses above 1 TeV, the latter account for as much as 20% of the cross–section.

In view of the rather complete analysis of the total cross–section presented elsewhere, we instead focus our attention on the range of parameters accessible to the SSC, and how the low energy constraints on these parameters come in. Figures

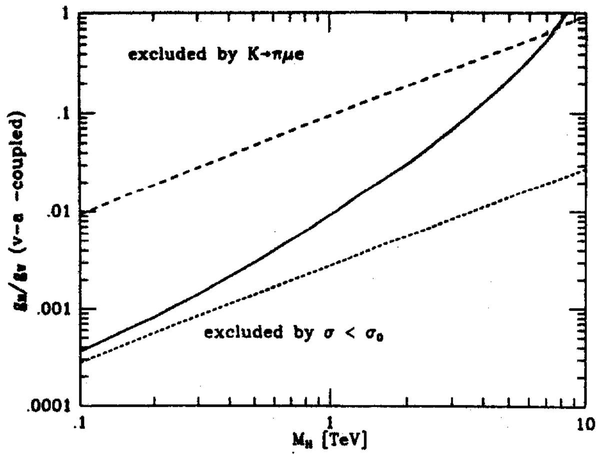

Figure 2. For $V - A$ coupled horizontal gauge bosons, the region below the solid line is inaccessible to SSC experiments because the uncut cross-section is less than $\sigma_0 = 10^{-3}$ pb. Above the dashed line, the parameters predict $K \to \pi\mu e$ at a level above the present experimental upper bound. The dotted line indicates the parameters allowing $B(K \to \mu e)$ at the 10^{-13} level.

1 and 2 show the horizontal gauge boson mass versus coupling constant (with the weak coupling constant scaled out) for vector- and $V - A$ coupled horizontal symmetries. For g_H/g_W above the dashed lines, the parameters predict rare kaon decays above the experimental limits. The solid lines indicate the boundary of observability: for g_H below the solid lines, $\sigma(pp \to H \to e\mu) < \sigma_0 = 10^{-3}$ pb. This assumes an annual integrated luminosity of 10^4 pb^{-1}yr^{-1}. We used the narrow width approximation for the H propagator, and set the number of H decay channels to 8 ($H \to uc$, ds, $e\mu$, $\nu_e\nu_\mu$). No cuts were imposed.

One can imagine models in which $uc \to \mu e$ but $ds \not\leftrightarrow \mu e$. The cross-sections are reduced by approximately 0.5, so the solid line in figures 1 and 2 drop by a factor of $(1/2)^{\frac{1}{4}} \simeq 0.8$.

The dotted lines are the boundaries that would be fixed by improving the rare decay limits to $B < 10^{-13}$ branching ratio. Rare kaon decay experiments presently underway expect to reach a sensitivity of order 10^{-12}.[9] According to figures 1 and 2, branching ratios for $K \to \pi\mu e$ and $K \to \mu e$ at 10^{-13} would imply signals at the SSC below the level of observability. We emphasize, however, that this is only true for models in which u, c, d, s, e and μ all couple to the same gauge bosons with the same coupling constant. For models in which this is not the case, the dashed and dotted lines are relocated.

Discussion

There are many different models of horizontal gauge symmetry. In most models a given horizontal gauge boson couples both to leptons and to quarks. In this class of model the discussions given above and in ref. 4 show that it is most favorable to search for the horizontal gauge boson in leptonic final states at the SSC—the quark states have large, possibly insurmountable, backgrounds. These backgrounds also imply that, if the horizontal group is such that the horizontal gauge bosons that couple to quarks are different from those that couple to leptons, prospects for discovery at the SSC are not promising unless the associated coupling g_H is much larger than anticipated. The constraints on the size of g_H in this latter type of model have not been thoroughly investigated, but are certainly much weaker than those discussed below.

Turning to those theories in which the horizontal gauge bosons have couplings to both quark and lepton channels, the range of horizontal gauge boson masses and couplings allowed by low energy constraints is strongly model dependent. Low energy constraints are most severe when the horizontal gauge boson mediates the process $\bar{s}d \to \bar{\mu}e$. This process is allowed when the transformation properties of (d, s, b) are identical to (e, μ, τ) under the horizontal group. If we presume that detection of a horizontal gauge boson requires 10 events in the $\bar{\mu}e + \bar{e}\mu$ final state, then the range of g_H and m_H values accessible in a standard operating year (10^4 pb^{-1}) at the SSC is such that horizontal bosons with large m_H can only be detected if the associated value of g_H is so large that it is ruled out by the low energy constraints. In fact, the range of m_H that can be probed at allowed values of g_H lies below ≈ 10 TeV. In this range figures 1 and 2 show that there is a large region of $m_H - g_H$ space that is not excluded by current low energy limits and can be fruitfully explored at the SSC.

However, it is possible to imagine more general horizontal gauge groups. For instance, (d, s, b) could be identified with (μ, τ, e). This leads to $\bar{s}d \to \bar{\tau}\mu$ rather than $\bar{\mu}e$. The constraints on horizontal gauge bosons are then rather weak and arise, for example, from $B \to \bar{\mu}e$. The principle limitation upon horizontal gauge boson discovery in this latter type of model is event rate. The values of g_H allowed by low energy constraints can be large enough that detection of very heavy,[4] as well as very light, horizontal gauge bosons is possible at the SSC. For instance, the solid curves of figs. 1 and 2, covering the low M_H region, are only slightly altered, depending upon which initial quarks couple to the horizontal gauge boson that gives rise to the $\bar{\mu}e + \bar{e}\mu$ final state, whereas the constraint lines move to much higher levels. We see that a wide range of weakly coupled light horizontal gauge bosons can be searched for at the SSC.

Acknowledgments

This work was supported in part by the Department of Energy and the National Science Foundation. Fermilab is operated by the Universities Research Association for the Department of Energy.

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