SEARCH FOR HORIZONTAL BOSONS AT THE SSC

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Summary

The production process $\overset{(-)}{p}p \to \ell^- \ell'^+ + X$, where the leptons belong to two different generations and X refers to spectator jets, provides a clear signature for horizontal (generation-changing) bosons when the leptons are emitted nearly back-to-back and $p_T^{miss} = 0$. Cross sections and p_T distributions for each lepton are presented, and discovery limits on M_H are extracted for several different channels.

Present experimental evidence suggests that flavor-changing neutral currents (FCNC's) are very rare. Their absence can be neatly interpreted to mean that the GIM mechanism operates at both the quark and lepton levels. However, since the replication of quark and lepton families is still not well understood, one cannot dismiss the possibility that neutral current interactions exist in nature which violate this apparent flavor conservation principle. In particular, the exchange of neutral "horizontal" bosons can directly couple two different generations and lead directly to FCNC's. The only restriction is that the coupling be weak enough that the effects of these interactions have so far escaped experimental detection.

In order to restrict the parameters of a horizontal boson theory, it is conventional[1] to assume that the overall gauge theory can be written as (or contains) the direct product $G_S \times G_H$, where G_S is the standard model gauge group for one generation and G_H is the horizontal group in question. Among the groups discussed in the literature[2] are $SU(2)_H$ and $SU(3)_H$. In the $SU(2)_H$ case, the 3 neutral generators effect the transitions $\Delta G = 0, \pm 1$ among the three generations of quarks and leptons belonging to the adjoint representation. In the latter case, the 8 generators effect transitions among the three generations belonging to the fundamental representation of $SU(3)_H$.

It is also convenient to classify[3] the horizontal boson exchange processes as diagonal or non-diagonal, according to whether the boson couples two neutral currents of the same type (UU, DD, NN or LL) or different types (UD, UN, UL, NL, etc.). To the extent that the horizontal boson masses are degenerate, $\Delta G \neq 0$ processes are forbidden in the limit that G is conserved and no generation mixing occurs. With generation-mixing angles present, $\Delta G = \pm 1$ and ± 2 processes are also allowed since G-conserving transitions can still take place at each vertex connected by the horizontal boson exchanged.

Present experimental lower limits on the horizontal boson masses taken from the paper by Cahn and Harari[2] are listed in Table I as functions of the horizontal coupling g_H and generation-mixing angles. In the limit of zero mixing, the processes $\mu N \to eN$, $\mu \to 3e$, $\mu \to e\gamma$ and the mass difference $\Delta M(K_L - K_S)$ yield no information. Limits for the two non-diagonal processes, $K_L \to e\mu$ and $K^+ \to \pi^+ e\mu$,

$$M_H > 4.6 \text{ TeV} \left| \frac{g_H}{g_W} \right| \cos \beta_{LD}$$
$$M_H > 18 \text{ TeV} \left| \frac{g_H}{g_W} \right| \cos \beta_{LD} \qquad (1)$$

are based on the experimental branching ratios[4]

$$B(K_L \to e\mu) < 6 \times 10^{-6}$$
$$B(K^+ \to \pi^+ e\mu) < (5\text{-}7) \times 10^{-9} \qquad (2)$$

respectively. The coupling g_H is scaled relative to the weak coupling g_W under the assumption that the $K_L \to e\mu$ process takes place through a V − A coupling, while the $K^+ \to \pi^+ e\mu$ decay occur through a pure V interaction. Here in both cases, the non-diagonal (DL) horizontal exchange process involves $\bar{d}s \to \bar{e}\mu^-$.

Table I. Present limits on horizontal boson masses M_H or Δ, where $\Delta^{-2} = M_s^{-2} - \bar{M}^{-2}$, cf. Ref. 3.

Process	$\lvert\Delta G\rvert$	Interaction	Lower Limit (TeV)
$K_L \to e^\mp \mu^\pm$	0	V−A	$M_H > 4.5 \left\lvert \frac{g_H}{g_W} \right\rvert \cos \beta_{LD}$
$K^+ \to \pi^+ e^- \mu^+$	0	V	$M_H > 18 \left\lvert \frac{g_H}{g_W} \right\rvert \cos \beta_{LD}$
$\mu N \to eN$	1	V	$M_H > 85 \left\lvert \frac{g_H}{g_W} \right\rvert \lvert\sin \beta_{LU} - \sin \beta_{LD}\rvert^{1/2}$
$\mu \to 3e$	1	V−A	$\Delta > 13 \left\lvert \frac{g_H}{g_W} \right\rvert \lvert\sin \beta_L \cos \beta_L\rvert^{1/2}$
$\mu \to e\gamma$	1	V	$\Delta > 11 \left\lvert \frac{g_H}{g_W} \right\rvert \lvert\sin \beta_L \cos \beta_L\rvert^{1/2}$
$\Delta M(K_L - K_S)$	2	V−A	$\Delta > 400 \left\lvert \frac{g_H}{g_W} \right\rvert \sin \beta_D$

The SSC will prove to be a very useful tool to extend these limits to other non-diagonal processes involving $q\bar{q}' \to \ell^- \ell'^+$ transitions. In particular, lepton pairs such as $e^\mp \mu^\pm$, $e^\mp \tau^\pm$, $\mu^\mp \tau^\pm$ emitted nearly back-to-back by a massive real or virtual horizontal boson produced in the s channel would provide an exceptionally clear signal. This is especially so for $e\mu$ events since $p_T^{miss} = 0$ and the events are expected to be very quiet hadronically. No conventional theoretical background will contribute to pair production of different generation leptons with no missing p_T. For example, Drell-Yan production of τ pairs followed by τ decay into a μ which carries most of the τ momentum, while mimicing the signal, is orders of magnitude smaller in cross section in the Jacobian peak region even when the coupling g_H is of order g_W. Since the "alignment" of the quark and lepton families into a given generation is not fully understood, we shall present results for quark pair annihilations of the type $d\bar{s}$, $d\bar{b}$, $s\bar{b}$, $u\bar{c}$, $u\bar{t}$, $c\bar{t}$ and their conjugates into the various lepton channels listed above.

The matrix element for the subprocess $q\bar{q}' \rightarrow H^\circ \rightarrow \ell^- \ell'^+$, where H is the horizontal boson, is written in anology to the weak interaction case as

$$\mathcal{M} = \frac{g_H^2}{2} \frac{1}{(s-M_H^2)+iM_H\Gamma_H} \bar{u}_\ell \gamma_\mu A v_{\ell'} \bar{v}_{q'} \gamma_\mu A \, u_q \,, \quad (3)$$

where A = 1 or $1/2(1+\gamma_5)$ for a pure V or V - A interaction, respectively, and a standard resonance denominator is introduced. From this one obtains the color-averaged differential cross section

$$\frac{d\hat{\sigma}}{d\hat{t}} = \frac{\pi}{3} \frac{\alpha_H^2}{(s-M_H^2)^2+M_H^2\Gamma_H^2} \begin{cases} 1/2 \ (\hat{t}^2+\hat{u}^2)/\hat{s}^2, & V \\ \hat{u}^2/\hat{s}^2 \,, & V-A \end{cases} \quad (4)$$

for the subprocess. The corresponding H° partial decay rate is given by

$$W(H\rightarrow a\bar{b}) = \begin{cases} 1/6 \ \alpha_H \, M_H, & V \\ 1/12 \ \alpha_H \, M_H, & V-A \end{cases} \quad (5)$$

where $a\bar{b}$ represents a lepton pair. A color factor of 3 must be included for each quark pair channel. The total width for the horizontal boson then involves 2 quark and 2 lepton channels or a factor of 8 for the $SU(3)_H$ group and 4 quark and 4 lepton channels or a factor of 16 for the $SU(2)_H$ group.

In computing the inclusive cross section for horizontal gauge boson production followed by decay to a specific leptonic channel, one convolutes the cross section $d\hat{\sigma}/d\hat{t}$ of (4) with quark distribution functions (we employ EHLQ[5] structure functions with Λ_{QCD}=200 MeV). We compute[6]

$$\sigma = \int_{-Y}^{Y} dy_1 \int_{-Y}^{Y} dy_2 \int_{p_T^{min}}^{p_T^{max}(y_1,y_2)} \frac{d\sigma}{dy_1 dy_2 dp_T} \quad (6)$$

where $d\sigma/dy_1dy_2dp_T$ is the inclusive cross section for production of lepton 1 at rapidity and transverse momentum y_1 and p_T and lepton 2 at rapidity and transverse momentum y_2 and $-p_T$ (intrinsic quark k_T is neglected). We have chosen Y = 3 in order to guarantee that both leptons appear in a moderate sized detector. We have used p_T^{min} = 50 GeV in order to reduce large lepton backgrounds.[7]

Qualitatively, one finds σ rises smoothly as a function of $\sqrt{s}$ and shows very little structure. We therefore quote results only for the $\sqrt{s}$ = 40 TeV design energy of the SSC. In Fig. 1 the pp cross sections are plotted as functions of M_H with V or A coupling at the production and decay vertices. The results for V-A coupling are nearly identical and are not shown. Fig. 1a depicts σ for the two channels[8]

$$d\bar{s} + u\bar{c} \rightarrow e^- \mu^+ \quad (7a)$$

and

$$s\bar{d} + c\bar{u} \rightarrow \mu^- e^+ \,, \quad (7a')$$

for three choices of α_H = 1.0, 0.1 and α_W = 0.035.

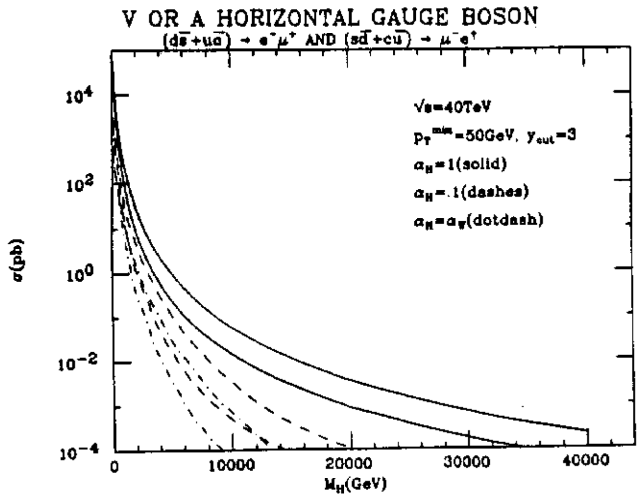

FIG. 1a. σ of Eq. (6) as a function of M_H for reaction (7a) and (7a') with V or A horizontal boson couplings. The higher curves of a given type are always those for process (7a).

Generation-mixing angles will be ignored throughout. The curves for (7a) lie higher due to the additional valence quark contributions which are not present in the (7a') case. With an integrated luminosity of $10^{40}cm^{-2}$, the 35 event level corresponds to M_H values of 20, 10 and 7.8 TeV for (7a), while the charge conjugate process (7a'), involving only sea quarks, yields only 15, 7 and 5.5 TeV, for α_H = 1.0, 0.1 and α_W, respectively. At the 5 event level, one is sensitive to M_H values 33, 15 and 11 TeV for (7a) and 24, 10 and 7.5 TeV for (7a'). Values for (7a) are listed in detail in Table II. The unequal discovery limits for two charge-conjugate channels in pp collisions can lead to an apparent charge asymmetry, i.e., $e^-\mu^+$ vs. $e^+\mu^-$, and will help to confirm the nature of the signal. Such a charge asymmetry does not occur in $p\bar{p}$ reactions.

In Fig. 1b we compare the cross sections as a function of M_H for the three $SU(3)_H$ channels (7a),

$$d\bar{b} + u\bar{t} \rightarrow e^- \tau^+ \quad (7b)$$

and

$$s\bar{b} + c\bar{t} \rightarrow \mu^- \tau^+ \,. \quad (7c)$$

Table II. Discovery limits on horizontal boson masses M_H with $\sqrt{s}$=40 TeV and $\int \mathcal{L}\, dt = 10^{40} cm^{-2}$.

Process	g_H	35 Events	5 Events
$d\bar{s} + u\bar{c} \rightarrow e^-\mu^+$	1.0	20 TeV	33 TeV
	0.1	10	15
	α_W	7.8	11
$d\bar{b} + u\bar{t} \rightarrow e^-\tau^+$	1.0	16	25
	0.1	8.3	12
	α_W	6.4	9
$s\bar{b} + c\bar{t} \rightarrow \mu^-\tau^+$	1.0	9.7	16
	0.1	5	6.8
	α_W	3.9	5
$d\bar{s} \pm s\bar{b} \pm u\bar{c} + c\bar{t}$ $\rightarrow e^-\mu^+ + \mu^-\tau^+$	1.0	19	30
	0.1	11	17
	α_W	8.1	12

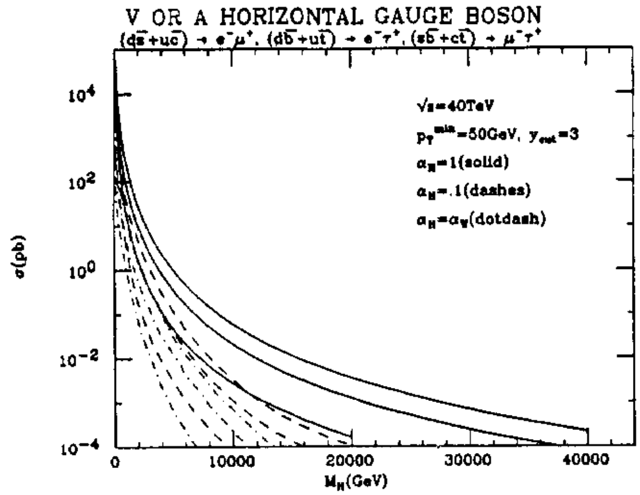

FIG. 1b. σ of Eq. (6) as a function of M_H for reaction (7a), (7b) and (7c) (V or A couplings). Curves of a given type follow the above process order.

The M_H discovery limits for (7b) and (7c) are somewhat smaller than those for (7a); on the other hand rare K decays yield no information for the (7b) and (7c) channels. Curves and limits for the $SU(2)_H$ process involving

$$d\bar{s} + s\bar{b} + u\bar{c} + c\bar{t} \to e^-\mu^+ + \mu^-\tau^+ \quad (8)$$

are similar to those for (7a); we give only the limits in Table II.

In order to be sensitive at the quoted M_H levels in reactions (7b), (7c) and (8), it is necessary that τ identification be possible with good efficiency. For high mass horizontal bosons this can be achieved through vertex detection. At lower masses reconstructable τ decay channels must be employed. Needless to say, e/μ discrimination is required in order to distinguish horizontal gauge boson signals from those of new Z's.

In Fig. 2 the single lepton cross section, $d\sigma/dy_1 dp_T(|y_2|<Y)$, is shown for process (7a) for y_1 = 0 and 2 and three different pairings of α_H and M_H chosen to correspond to the 35 event level in Table II. The p_T spectra for y_1 = 0 clearly reflect the Jacobian peak at $M_H/2$ for the more weakly coupled cases α_H = 0.1 and $\alpha_H = \alpha_W$ for which the H width is significantly smaller than its mass. In general the distributions (which include effects from the full H propagator) are broad and demonstrate that the leptons carry off sizeable momentum, yielding hadronically quiet events and providing clear signatures for the horizontal boson processes.

In summary, the SSC will significantly extend the lower limits for the masses of hypothesized horizontal gauge bosons or, in fact, lead to their discovery as indicated above. However, the stringent limits on $K_L \to \mu e$ imply that a horizontal gauge boson which mediates $d\bar{s} \to e^-\mu^+$ can not be observed at the SSC. Nonetheless, many other channels exist (such as $u\bar{c} \to e\mu$, $d\bar{s} \to \mu\tau$, etc.) for which the SSC can either discover new FCNC's or significantly improve limits on the strength of FCNC transitions. Moreover, the present weak limits on FCNC's involving third generation fermions suggest that the tau has the potential of being a window of new physics beyond the standard model. As such, the large number of taus

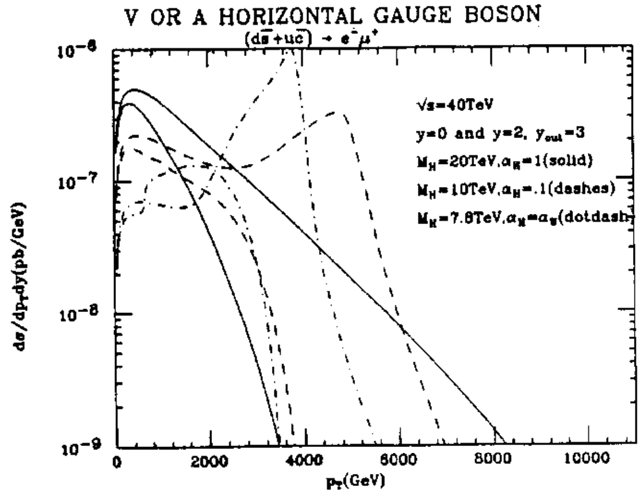

FIG. 2. Single lepton p_T distributions for reaction (7a) for three discovery limit pairings of α_H and m_H (taken from Table II) at lepton rapidity y = 0 and y = 2. The curves with the more restricted p_T range correspond to y = 2.

produced at the SSC could allow more stringent limits (or discovery) of rare decays, which would give an additional handle on the search for new horizontal gauge bosons.

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8. In many models the two processes $d\bar{s} \to e\mu$ and $u\bar{c} \to e\mu$ are roughly equal numerically, but this need not be the case in general.