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TWO GAUGE BOSON PHYSICS AT FUTURE COLLIDERS *

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Abstract

Electroweak unification suggests that there should be WW and ZZ physics analogous to $\gamma\gamma$ physics. Indeed, WW and ZZ collisions will provide an opportunity to search for the Higgs boson at future high energy colliders. Cross sections in the picobarn range are predicted for Higgs boson production at the proposed 40-TeV SSC. While other states may be produced by WW and ZZ collisions, it is the Higgs boson that looms as the most attractive objective.

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Bremsstrahlung is a ubiquitous feature of particle physics. Its most fundamental meaning is that of radiation emitted by an accelerated charged particle as when an electron scatters from the electric field surrounding a nucleus and emits a photon in the process. In its larger sense it includes processes where a charged particle simply emits a single virtual photon and has its trajectory modified as a result. Thus we can view inelastic electron-nucleon scattering as bremsstrahlung of a virtual photon by the electron, followed by the interaction of the virtual photon with the nucleon.

The purest bremsstrahlung process is then one in which both incident particles emits a virtual photon which subsequently collide. It is to such processes that we owe this meeting.

In bremsstrahlung the emitted virtual photon usually takes only a small fraction of the electron's energy and is emitted nearly along the electron's direction. This is easy to understand in old fashioned perturbation theory since this minimizes the difference between the energy of the initial electron and the sum of the energies of the electron and virtual photon. Typically the photon is emitted at an angle $\theta \approx m/E$.

Since electromagnetism and weak interactions are unified, it is natural to look for bremsstrahlung of W's and Z's. To be analogous to ordinary bremsstrahlung, such a process must be at such a high energy that the masses of the W and Z are small by comparison. Unfortunately this excludes all existing accelerators as locations for such an experiment.

The proposed Superconducting Supercollider (SSC) in the U.S. and Large Hadron Collider (LHC) at CERN with center-of-mass energies 40 TeV and 17 TeV would provide the means to use W and Z bremsstrahlung. Not only that, but the W and Z bremsstrahlung could be the key to the search for that Holy Grail of particle physics, the Higgs boson.

Let us pause briefly to review the status of the search for the Higgs boson[1]. First it must be stated that this search may be a quixotic one. The Higgs boson may not exist and if it does, it may be rather different from the version I will be discussing. I shall consider the orthodox Higgs boson that is part of the standard model with just one Higgs doublet. Supersymmetry requires at least two such

doublets and results in a much more complex spectrum. Technicolor banishes fundamental scalars altogether, but generates a plethora of pseudoscalars. The minimal Higgs model offers simplicity and specificity. Given the mass of the Higgs, all else follows from the model. Almost.

Searches for the Higgs boson can be conveniently divided into four categories. The first consists of completed experiments that cover the very lowest masses. The agreement between predicted and measured x-ray transitions in muonic atoms exclude Higgs bosons with masses less than about 6 MeV. The absence of Higgs bosons in the decays of the $J^P = 0^+$ state of O^{16} lying 6 MeV above the ground state sets a similar limit, while studies of the 20 MeV excitation of He^4 exclude masses up to about 11 MeV.

The second category includes current experiments looking for $K \to \pi H$, $B \to K^* H$ and $\Upsilon \to \gamma H$. None has found a sign of the Higgs boson. Despite a theory that is supposedly completely defined, each is the subject of a controversy. A Higgs boson with mass less than twice the mass of the τ may be excluded, or again it may not.

Theoretical guidance for the mass of the Higgs boson is lacking, for while there is the bound of Linde [2] and Weinberg [3], it is decreasingly stringent as the mass the of the t quark increases and disappears entirely if the t quark's mass is near 80 GeV.

The third category consists of tests to be conducted at e^+e^- colliders at the Z or somewhat above it. The decay $Z \to Hl^+l^-$ should give LEP the opportunity to find a Higgs boson up to 40 GeV or so, while LEP II will use $e^+e^- \to HZ$ to look as high as 80 GeV.

The fourth category is reserved to very high energy colliders, either hadron colliders like SSC or LHC, or e^+e^-colliders like TLC or CLIC. For the hadron collider, the dominant production processes are gluon fusion [4] and WW fusion [5]. At e^+e^- colliders, only the latter is available [6].

Because plans for high energy hadron colliders are much more advanced than those for e^+e^- colliders, I begin with the former. The gluon fusion and WW fusion mechanism compete and for very large Higgs boson mass, it is the WW fusion that is most important. The cross-over point depends on the mass of the t quark

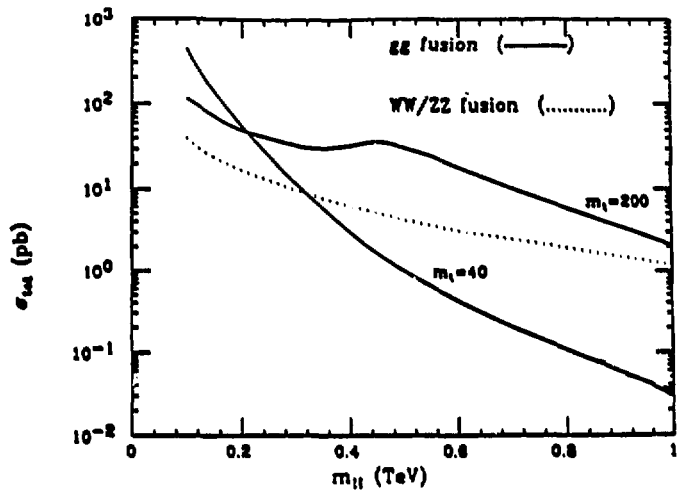

Figure 1: The cross section for Higgs boson production at $\sqrt{s} = 40$ TeV due to gluon fusion and WW (or ZZ) fusion. Adapted from [7].

as seen in Fig. 1 taken from Ref. [7].

Although gluon fusion is surely two gauge boson physics, I think this meeting is intended to focus on the electroweak sector so I shall concentrate on WW fusion. In Fig. 2 we see the standard diagram for two-photon physics, but is just as well represents the fusion of two W's or Z's to make a Higgs boson. A comparison of $\gamma\gamma$ collisions and WW collisions is illuminating.

The most surprising difference between WW collisions and $\gamma\gamma$ collisions is that in the former it is the longitudinally polarized W's play a dominant role. While in two-photon collisions there is a large flux of longitudinal photons, their effects are minimal because they decouple as their mass squared goes to zero. This is central to the analysis of spin-one resonances produced in $\gamma\gamma$ collisions as has been discussed at length at this meeting. Because the W and Z are massive, their longitudinal polarization states, which arise through spontaneous symmetry

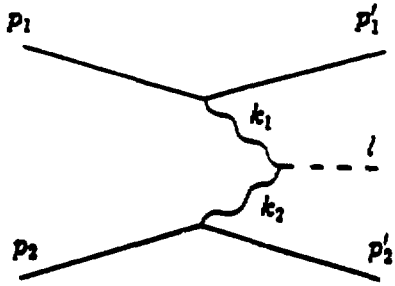

Figure 2: The diagram for WW (or ZZ) fusion production of the Higgs boson.

breaking, play an especially vital role. In particular, the coupling of the standard model Higgs boson to W's and Z's is due to an interaction

$$\frac{g^2}{4} W^{+\mu} W_\mu^- \phi^2 \tag{1}$$

where $\phi = H + v$ and H is the Higgs field while v is its vacuum expectation value. Expanding we have the term that gives mass $gv/2$ to the W's

$$\frac{g^2 v^2}{4} W^{+\mu} W_\mu^- \tag{2}$$

and a term that couples the Higgs boson to two W's

$$\frac{g^2 v}{2} W^{+\mu} W_\mu^- H = g M_W W^{+\mu} W_\mu^- H. \tag{3}$$

The decay of a very massive Higgs boson is dominantly to longitudinal W or Z pairs. Writing

$$\begin{aligned} H(p) &\rightarrow W(q_1) + W(q_2) \\ \epsilon_L(q_1) &= (|\vec{q}\,|, 0, 0, q_0)/M_W \\ \epsilon_L(q_2) &= (|\vec{q}\,|, 0, 0, -q_0)/M_W \end{aligned} \tag{4}$$

the amplitude for the decay to longitudinal W's is

$$\mathcal{M} = g M_W \epsilon_L(q_1) \cdot \epsilon_L(q_2)$$

$$= gM_W(q_0^2 + |\vec{q}|^2)/M_W^2. \tag{5}$$

If the Higgs boson is much more massive than the W, $q^0 \approx |\vec{q}| \approx M_H/2$ and the decay amplitude is

$$\mathcal{M} \approx g\frac{M_H^2}{2M_W}. \tag{6}$$

There is another way to look at the same process. Before spontaneous symmetry breaking, the W and Z are massless and lack longitudinal degrees of freedom. These degrees of freedom ultimately come from the scalar fields. There are four scalar fields, ϕ_1, ϕ_2, ϕ_3, and ϕ_4. They interact through a potential

$$V = \frac{1}{2}\mu^2(\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2) + \frac{\lambda}{4}(\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2)^2. \tag{7}$$

If $\mu^2 < 0$ there is spontaneous symmetry breaking and

$$\frac{\langle\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2\rangle}{2} = -\frac{\mu^2}{2\lambda} > 0. \tag{8}$$

Let us say $\langle\phi_4\rangle^2 = -\mu^2/\lambda$, $\langle\phi_4\rangle = v = \sqrt{-\mu^2/\lambda}$. Now writing $\phi_4 = H + v$, $(\phi_1, \phi_2, \phi_3) = \boldsymbol{\phi}$

$$V = \frac{\mu^2}{2}\left[\boldsymbol{\phi}\cdot\boldsymbol{\phi} + (H+v)^2\right] + \frac{\lambda}{4}\left[\boldsymbol{\phi}\cdot\boldsymbol{\phi} + (H+v)^2\right]^2. \tag{9}$$

This gives H a mass squared $m_H^2 = -2\mu^2$ and an interaction

$$-\lambda\boldsymbol{\phi}\cdot\boldsymbol{\phi}Hv = -\frac{m_H^2}{2v}\boldsymbol{\phi}\cdot\boldsymbol{\phi}H \tag{10}$$

we can write $\boldsymbol{\phi}\cdot\boldsymbol{\phi}$ suggestively in terms of scalar particles $\boldsymbol{\phi}\cdot\boldsymbol{\phi} = 2w^+w^- + z^2$ so the matrix element for the decay $H \to w^+w^-$ is

$$\mathcal{M} = \frac{m_H^2}{v} = \frac{gm_H^2}{2M_W} \tag{11}$$

just as we found directly. This demonstrates the dual identity of the longitudinal part of the W: It can be thought of as the scalar field from which it came.

This decay amplitude has an important consequence. If the mass of the Higgs boson is large compared to that of the W or Z, the width of the Higgs boson is also very large:

$$\Gamma \approx 500\,\text{GeV}\,[m_H(\text{TeV})]^3 \tag{12}$$

The interaction $W^{+\mu}W^{-}_{\mu}H$ could not arise in electrodynamics because it is not gauge invariant. There is of course a coupling of two photons and two charged scalars:

$$e^2 A^2_\mu \phi^+ \phi^- \tag{13}$$

which is analogous to $g^2 W^{+\mu} W^{-}_{\mu} \phi^2$. The spontaneous breakdown that gives $\phi \to H + v$ and $\phi^2 \to H^2 + 2Hv + v^2$ which generates the coupling $W^{+\mu}W^{-}_{\mu}H$ and there can be no analogous transformation in electrodynamics. It is the unique longitudinal coupling of the Higgs boson to W's and Z's that makes W and Z fusion so effective.

The fluxes of virtual Ws in the transverse and longitudinal modes are given by [8,9]

$$f_T = \frac{g_V^2 + g_A^2}{8\pi^2} \frac{dx}{x} [2 - 2x + x^2] \int \frac{dQ^2 Q^2}{(Q^2 + M_V^2)^2} \tag{14}$$

$$f_L = \frac{g_V^2 + g_A^2}{8\pi^2} \frac{dx}{x} [2 - 2x] \int \frac{dQ^2 M_V^2}{(Q^2 + M_V^2)^2} \tag{15}$$

The expressions are very similar, but the longitudinal distribution does not vanish as Q^2 goes to zero, i.e. in the forward direction, as the transverse must by angular momentum conservation. After integration over Q^2, the longitudinal expression has no logarithmic term of the sort so familiar in two-photon physics. The cut-off provided by the electron mass in two-photon physics is replaced by the mass of the W - a very major difference!

The cross section for producing a Higgs boson via WW fusion is given approximately by [10]

$$\begin{aligned} \sigma &= \frac{1}{16 m_W^2} \left(\frac{\alpha}{x_W}\right)^3 \left[(1+\tau)\ln\frac{1}{\tau} - 2 + 2\tau\right] \\ &\approx 0.13 \text{ pb } \left[(1+\tau)\ln\frac{1}{\tau} - 2 + 2\tau\right] \end{aligned} \tag{16}$$

where $x_W = \sin^2\theta_W \approx 0.22$ and $\tau = M_H^2/s$.

Now in a high energy hadron collider the quarks have variable momenta so the value of τ depends on which quarks are colliding, but still the typical cross sections are in the pb range. For the SSC with $\sqrt{s} = 40$ TeV the cross section for a 200 GeV Higgs is about 10 pb while that for a 1 TeV Higgs is about 1 pb. The

detection of the produced Higgs will be enormously challenging. If the Higgs has a mass greater than $2M_Z$, the decay $H \to ZZ$ followed by $Z \to e^+e^-$ or $\mu^+\mu^-$ will provide the cleanest signal but with a depressingly low branching ratio since $B(H \to ZZ) \lesssim 1/3$, $B(Z \to e^+e^-) = B(Z \to \mu^+\mu^-) \approx 0.033$. As a result, even with the design luminosity of the SSC of $\mathcal{L} = 10^{33}\text{cm}^{-2}\text{s}^{-1}$ and 10^7s of running, each picobarn of cross section will yield just 14 of these "gold-plated" events.

These events are "gold plated" because their nature is unmistakable. Of course there is background to the Higgs signal from the $q\bar{q} \to ZZ$ continuum. For a relatively light Higgs boson, a peak in the ZZ invariant mass distribution would stand out over the background. As the mass approaches 800 GeV, the width of the Higgs becomes so large that there is no distinct structure. This is seen in Fig. 3.

The second best signature is $H \to ZZ$ followed by $Z \to e^+e^-$, $\mu^+\mu^-$ and $Z \to \nu\bar{\nu}$ [12,13]. The neutrinos result in large massing transverse momenta since the Z's are emitted isotropically from the spin-zero Higgs boson. The combined branching ratio is about 6 times larger for these "silver-plated" events. The critical requirement for studying this decay mode is that the detector not miss an important amount of "transverse energy": The detector must be hermetic.

Since the invariant mass of the ZZ pairs cannot be measured, a variable like the transverse mass

$$M_T = 2\sqrt{P_T^2 + M_Z^2} \tag{17}$$

must be used. This would have been the mass of the Higgs boson if it emitted the Z at 90 degrees to the beam line and if the Higgs boson itself had no transverse momentum. Some Monte Carlo results for a Higgs mass of 800 GeV are shown in Fig. 4. The transverse momenta of the observed Z will not exactly balance the missing transverse momenta since the produced Higgs itself has transverse momentum. Indeed, the transverse momenta can be quite substantial.

In two photon processes, the virtual photons have a transverse momentum spectrum

$$\sim \frac{dk_\perp^2}{k_\perp^2 + x^2 m_e^2} \tag{18}$$

where x is the fraction of the electron's energy given to the virtual photon. Thus $k_\perp^2$ is typically of order m_e, but the distribution has a long tail extending to

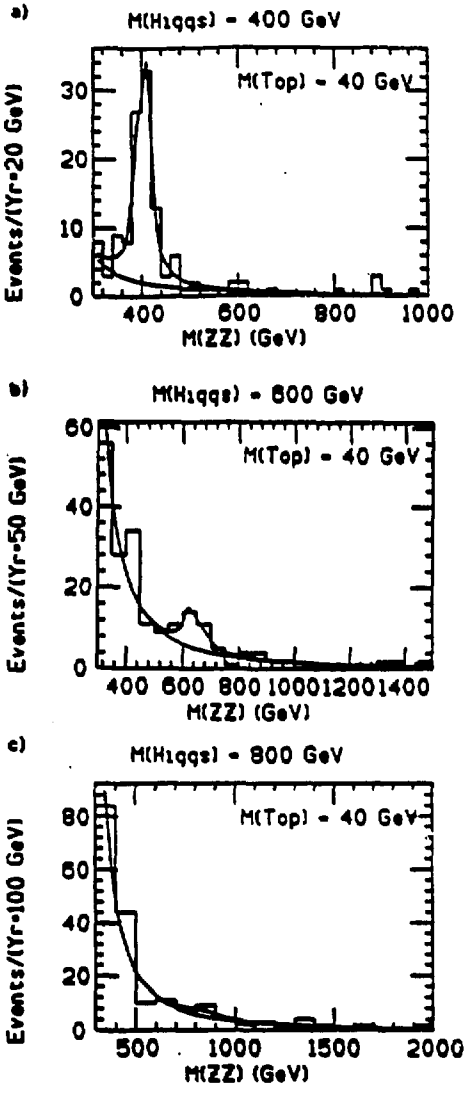

Figure 3: Monte Carlo results for the ZZ invariant mass distribution from the continuum background and the Higgs boson for SSC parameters. The t quark mass is set to 40 GeV. The figure is taken from Ref. [11].

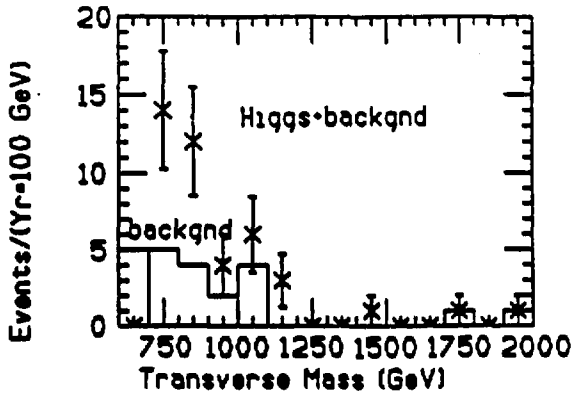

Figure 4: The transverse mass distribution for $pp \to ZZ$ with one Z decaying into charge leptons and the other into neutrinos. The parameters of the SSC are used. The background, shown as the blocked histogram, is taken just from $q\bar{q} \to ZZ$. It would be increased by about 60% if $gg \to ZZ$ were included. The figure is from Ref. [11]

$k_\perp^2 \sim E^2$ and the integrated spectrum has a factor $\ln E^2/m_e^2$.

For WW fusion the distribution of longitudinal bosons is

$$\frac{dk_\perp^2}{\left(\frac{k_\perp^2}{1-x} + M_W^2\right)^2} \tag{19}$$

with the consequence that $k_\perp^2$ is typically of order M_W^2. The produced Higgs bosons thus have transverse momentum of this same order.

While this transverse momenta is an unwanted effect for the $\ell^+\ell^-\nu\bar{\nu}$ signature there is some possibility of exploiting it through the analogue of double tagged two-photon events [14,15]. The WW fusion events could be tagged by observing the quarks recoiling against the bremsstrahlung W's. Such tagging could discriminate against various backgrounds. If we insist on observing a jet with $p_\perp > aM_W$, the

signal should be reduced by about the square of

$$\frac{\int_{a^2M_W^2}^{\infty} \frac{dp_\perp^2}{(p_\perp^2+M_W^2)^2}}{\int_0^{\infty} \frac{dp_\perp^2}{(p_\perp^2+M_W^2)^2}} = \frac{1}{1+a^2}. \tag{20}$$

Such a reduction cannot be afforded for the meager signal ($Z \to \ell^+\ell, \mu^+\mu^-)(Z \to \ell^+\ell^-, \mu^+\mu^-$) but it might make it possible to work with the much more frequent sequence $H \to W^+W^-$, $(W \to \ell\nu)(W \to q\bar{q})$.

Why isn't this the best signature with its large combined branching ratio? The backgrounds can be divided into two categories: "real" and "fake". A real background to $H \to W^+W^-$ is $q\bar{q} \to W^+W^-$. The W pairs from the real background do not peak at a fixed invariant mass. Moreover, they tend not to have as much transverse momenta as those from $H \to W^+W^-$. If one of the W's is observed in a hadronic decay, it is the "fake" background that dominates. An example is $q\bar{q} \to Wgg$, where the two gluon jets look like a hadronically decaying W. This background is 50-100 times as large as the "true" background [16,17].

An event $q\bar{q} \to Wgg$ would not have the additional tagging jets that $qq \to qqH \to qqWW$ would. Thus tagging is potentially a means of overcoming the background. Naturally there are additional backgrounds to consider, for example, $q\bar{q} \to gWgyg$. The calculation of such processes has been carried out only approximately. The results are open to differing interpretations[18].

The "gold-plated" events might enable the SSC to find a Higgs boson upon 600 or 700 GeV. Above that, the "silver-plated" events are still the best bet. As the mass range is raised, not only do the cross sections fall, but more importantly the width of the Higgs boson increases as m_H^3. A 1 TeV Higgs boson would have a width of about 500 GeV. Such a heavy Higgs boson would not appear as a peak but only as an elevated cross section. The identification of such a signal would require a thorough understanding of the "real" background.

It is possible to consider models with ever increasing Higgs boson mass. Now to speak of the Higgs boson as a particle when its width is comparable to its mass, as it is for $m_H \approx 1.4$ TeV, is misleading. Still, we can think of m_H as simply a parameter of the model. Now it might be thought that as m_H increases indefinitely, it could be ignored. This is certainly not so. Referring to the interaction of the

scalar bosons w and z that represent the longitudinal W and Z, and eliminating the coupling λ in favor of m_H and v, we find

$$\mathcal{L} = -\frac{m_H^2}{8v^2}\left[\phi\cdot\phi + (H+v)^2\right]^2 \tag{21}$$

Remembering that $\phi\cdot\phi = 2w^+w^- + z^2$, we see that this will lead, for $W^+W^- \to ZZ$, to two diagrams, one with a four-point coupling and one with a Higgs boson in the s-channel. The latter cannot be dropped since the coupling grows in just such a way to compensate for the decrease due to the large mass in the propagator. The four-point diagram gives

$$\mathcal{M}_{four\ point} = m_H^2/v^2 \tag{22}$$

while the diagram with the Higgs boson in the s-channel gives

$$\mathcal{M}_{Higgs} = (m_H^2/v^2)\frac{m_H^2}{s-m_H^2} \tag{23}$$

and the sum is

$$\mathcal{M} = \frac{m_H^2}{v^2}\frac{s}{s-m_H^2} \tag{24}$$

At energies much below $\sqrt{s} = m_H$, the amplitude is

$$\mathcal{M}_{low\ energy} = -s/v^2 \tag{25}$$

while at energies above the Higgs boson mass it is

$$\mathcal{M}_{high\ energy} = m_H^2/v^2 \tag{26}$$

The low energy result is quite general [12,19] and follows from symmetry considerations. It is the analog of the $\pi\pi$ scattering length result of Weinberg based on current algebra. Written in terms of the partial wave amplitude a which must satisfy the elastic unitarity conditions $|a| \le 1$; $-\mathrm{Im}(1/a) = 1$, this model gives a real amplitude

$$a_{w^+w^-\to zz} = -\frac{m_H^2}{16\pi v^2}\frac{s}{s-m_H^2} \tag{27}$$

Now if we wish to consider arbitrarily large values of m_H, we have simply

$$a_{w^+w^-\to zz} = \frac{s}{16\pi v^2} \tag{28}$$

Certainly this cannot hold indefinitely. By $\sqrt{s} = 1.7$ TeV this naive form violates $|a| \leq 1$. As the energy increases, the interactions become stronger and stronger and the result will show up in WW and ZZ scattering [12]. This would be reflected in the process $pp \to ZZX$ and would be similar to the case of a 1 TeV Higgs boson. Perhaps the best bet to see it would be to use the channel with one Z decaying to charged leptons and one to neutrinos. The signal might amount to fifteen events or so, over a background of similar size [31]. An intriguing possibility is a search for W^+W^+ as a final state. The rate again is governed by a low energy theorem. There is no direct background from $q\bar{q}$ annihilation [12]. These are very demanding challenges for our experimental colleagues!

While the prospects for a very high energy hadron collider seem closer than for a TeV e^+e^- collider, one can never be sure since the future actions of the U. S. Congress and the CERN Council may not be any easier to predict than what we will find at a new accelerator. It thus behooves us to consider the possibilities for gauge boson fusion at a very high energy e^+e^- machine [6,20,21,22,23,24].

The very much cleaner environment in an e^+e^- collider would permit the observation of relatively light Higgs bosons that decay into $b\bar{b}$ or $t\bar{t}$ as well as heavier ones that decay to ZZ or WW. Moreover, the latter could be distinguished even in their hadronic decay modes.

With a 1 TeV center of mass energy, the Higgs boson production cross section is 0.25 pb for $m_H = 100$ GeV and 0.028 pb for $m_H = 500$ GeV. In a nominal year with $\int \mathcal{L}\, dt = 10^{40}\,\mathrm{cm}^{-2}$, this gives 2500 and 280 events respectively. A detailed study [25] showed that for Higgs boson masses between 150 GeV to 500 GeV the search was possible. A Higgs boson with a mass near 100 GeV would be confused with the background process $e^+e^- \to \nu eW$, but it may be possible to overcome this problem.

The gauge boson fusion mechanism can create final states other than the Higgs boson. A possible application at a hadron collider would be the production of a very heavy quark antiquark pair, $U, \overline{D}$. Suppose the D is much lighter than the U. Then is it cheaper to create $U\overline{D}$ than $U\overline{U}$. This can be done through W-gluon fusion. The process has been considered by Willenbrock and Dicus [26] and by Dawson and Willenbrock [27]. Some results are shown in Fig. 5. As expected, the W-gluon fusion mechanism has the advantage if the D quark is light enough.

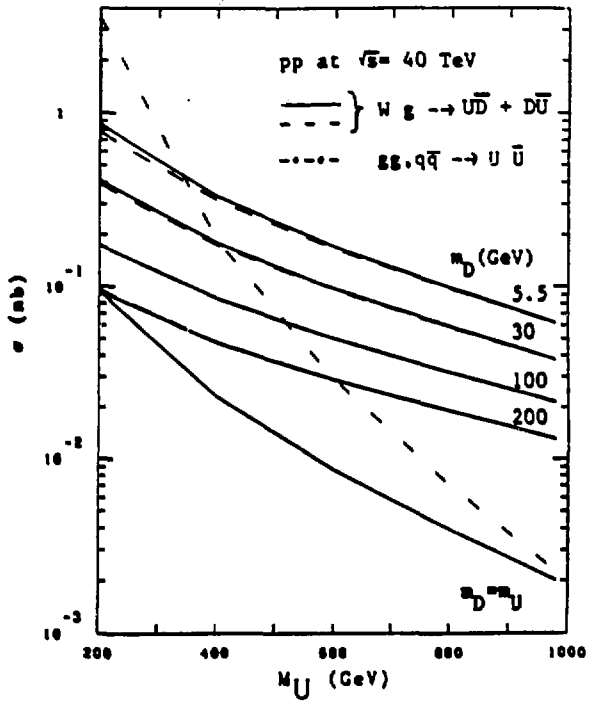

Figure 5: Cross section for $pp \to U\overline{D}X + \overline{U}DX$ at the SSC as a function of the U quark mass, for various values of the D quark mass. The dashed lines show exact calculations, the solid lines the effective W approximation. The dash-dot line shows the cross section for $U\overline{U}$ production. The figure is from Ref. [27].

However, the splitting between the U and D quarks is limited [28,29] because it gives rise to a deviation from the predicted ratio of the W to Z mass. A representative limit is

$$\left|m_U^2 - m_D^2\right|^2 < (350\text{GeV})^2 \tag{29}$$

When this is considered, the conventional sources, $gg \to U\overline{U}$ and $q\overline{q} \to U\overline{U}$ are seen to dominate everywhere.

An analogous process is the creation of the lepton pair, $L\overline{N}$, where the neutral lepton N is possibly massive [30,27]. The competition is between the gauge boson

fusion $WZ \to L\overline{N}$ and the Drell-Yan process $q\overline{q} \to L\overline{N}$ through a W. The restriction on the mass splitting is less stringent

$$\left|m_L^2 - m_N^2\right|^2 < (600\text{GeV})^2 \tag{30}$$

Moreover, the competing process is not so effective. In fact if the neutral and charged heavy leptons have equal masses, the gauge boson fusion mechanism is more important than the Drell-Yan mechanism if the lepton mass exceeds 500 GeV. While gauge boson fusion production of new fermions is an interesting possibility, it can't be said to rival its importance in the study of electroweak symmetry breaking.

Gauge boson fusion seems destined to play a central role at future high energy colliders. In the past two-photon physics has been practiced by a relatively small group of theorists and experimenters. Now two-gauge boson physics is discussed before Congressional committees as a partial justification for spending billions of dollars for the SSC. In the past our modest meetings have been held in places like Lake Tahoe and Jerusalem. Our future may be in Waxahachie, Texas.

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