s-Channel Higgs Boson Production at a Muon-Muon Collider

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High luminosity muon-muon colliders would provide a powerful new probe of Higgs boson physics through *s*-channel resonance production. We discuss the prospects for detection of Higgs bosons and precision measurements of their masses and widths at such a machine.

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The feasibility of constructing high luminosity muon-muon colliders is currently under investigation [1,2] and a first overview of the phenomenology has been given [3]. The fact that the muon is 200 times more massive than the electron makes such colliders very attractive for both practical and theoretical reasons: (i) synchrotron radiation does not limit their circular acceleration and multi-TeV energies can be realized; (ii) the beam energy resolution is not limited by beamstrahlung smearing; (iii) the *s*-channel production of Higgs boson resonances ($\mu^+\mu^- \to h$) would make possible precision studies of the Higgs sector.

If electroweak symmetry breaking is realized via a scalar field Higgs sector, then one of the primary goals of future colliders must be to completely delineate the Higgs spectrum and measure the Higgs masses, widths, and couplings. In this Letter we present a quantitative study of the merits of *s*-channel Higgs production at a $\mu^+\mu^-$ collider with excellent beam energy resolution.

Two specific muon collider schemes are under consideration. A high energy machine with 4 TeV center-of-mass (c.m.) energy ($\sqrt{s}$) and luminosity of order 10^{35} cm^{-2}s^{-1} [4] would have an energy reach appropriate for pair production of heavy supersymmetric particles [3] or, in the absence of Higgs bosons, the study of strong scattering of longitudinally polarized W bosons [3,5,6]. A lower energy machine, hereafter called the First Muon Collider (FMC), could have c.m. energy around 0.5 TeV with a luminosity of order 2×10^{33} cm^{-2}s^{-1} [4] for unpolarized beams. It is the latter machine that may be most directly relevant to the *s*-channel Higgs process. The most costly component of a muon collider is the muon source (decays of pions produced by proton collisions) and the muon storage rings would comprise a modest fraction of the overall cost [7]. Consequently, full luminosity can be maintained at all c.m. energies where Higgs bosons are either observed or expected by constructing multiple storage rings optimized for c.m. energies centered on the observed masses or spanning the desired range.

For *s*-channel studies of narrow resonances, the energy resolution is an important consideration. A Gaussian shape for the energy spectrum of each beam is expected to be a good approximation, with an rms deviation most naturally in the range $R = 0.04\%$ to 0.08% [8]. By additional cooling or chromaticity corrections, this can either be decreased to $R = 0.01\%$ or increased to $R = 1\%$, respectively. The corresponding rms error σ in $\sqrt{s}$ is given by

$$\sigma = (0.04\ \text{GeV})\left(\frac{R}{0.06\%}\right)\left(\frac{\sqrt{s}}{100\ \text{GeV}}\right). \qquad (1)$$

The critical issue is how this resolution compares to the calculated total widths of Higgs bosons. Widths for the standard model Higgs $h_{\rm SM}$ and the three neutral Higgs bosons h^0, H^0, A^0 of the minimal supersymmetric standard model (MSSM) are illustrated in Fig. 1; for the MSSM Higgs bosons, results at $\tan\beta = 5$ and 20 are shown. The *s*-channel Higgs resonance would be found by scanning in $\sqrt{s}$ using steps of size $\sim\sigma$; its mass

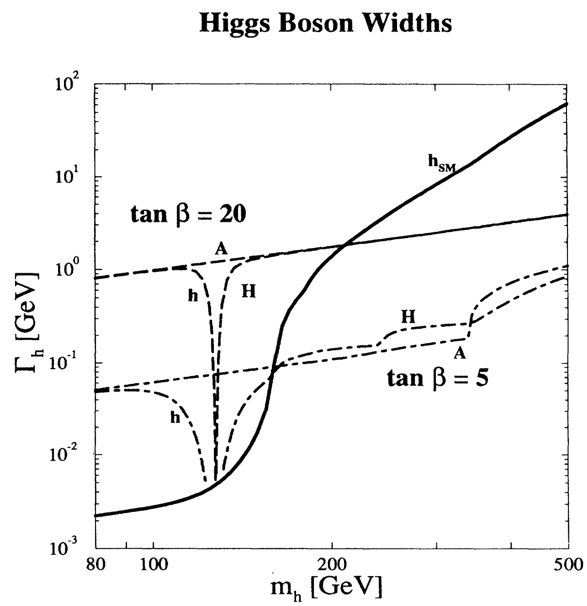

FIG. 1. Total width vs mass of the SM and MSSM Higgs bosons, for $\tan\beta = 5$ and 20 in the MSSM.

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would be simultaneously determined with roughly this same accuracy in the initial scan. For sufficiently small σ, the line shape would be that of a Breit-Wigner resonance and the Higgs width could be deduced.

The s-channel Higgs resonance cross section is

$$\sigma_h = \frac{4\pi\Gamma(h \to \mu\mu)\Gamma(h \to X)}{(s - m_h^2)^2 + m_h^2\Gamma_h^2}, \tag{2}$$

where h denotes a generic Higgs boson which decays to a final state X. The effective cross section $\overline{\sigma}_h$ is obtained by convoluting with the Gaussian distribution in $\sqrt{s}$:

$$\overline{\sigma}_h = \int \sigma_h(s') \frac{\exp[-(\sqrt{s'} - \sqrt{s})^2/2\sigma^2]}{\sqrt{2\pi}\sigma} d\sqrt{s'}. \tag{3}$$

For $\sigma \gg \Gamma_h$, $\overline{\sigma}_h$ at $\sqrt{s} = m_h$ is given by

$$\overline{\sigma}_h = \frac{\pi\Gamma_h}{2\sqrt{2\pi}\sigma}\sigma_h(\sqrt{s} = m_h), \tag{4}$$

and for $\Gamma_h \gg \sigma$

$$\overline{\sigma}_h = \overline{\sigma}_h(\sqrt{s} = m_h). \tag{5}$$

Since the backgrounds vary slowly over the expected resolution interval $\overline{\sigma}_B = \sigma_B$. In terms of the integrated luminosity L, total event rates are given by $L\overline{\sigma}$; roughly $L = 20$ fb^{-1}/yr is expected for the FMC. Predictions for $\overline{\sigma}_{h_{SM}}$ for inclusive SM Higgs production are given in Fig. 2 vs $\sqrt{s} = m_{h_{SM}}$ for resolutions of $R = 0.01\%$, 0.06%, 0.1%, and 0.6%. For comparison, the $\mu^+\mu^- \to Z^* \to Zh_{SM}$ cross section is also shown, evaluated at the value $\sqrt{s} = m_Z + \sqrt{2}m_{h_{SM}}$ for which it is a maximum.

SM Higgs boson.—The optimal strategy for SM Higgs *discovery* at a lepton collider is to use the $\mu^+\mu^- \to Zh$ mode (or $e^+e^- \to Zh$) because no energy scan is needed. Studies of e^+e^- collider capabilities indicate that the SM Higgs can be discovered if $m_{h_{SM}} < 0.7\sqrt{s}$. If $m_{h_{SM}} \lesssim 140$ GeV, its mass will be determined to a precision given by the event-by-event mass resolution of about 4 GeV in the $h + Z \to \tau^+\tau^- + q\overline{q}$ and $X + \ell^+\ell^-$ channels divided by the square root of the number of events in these channels, after including efficiencies [9,10]. A convenient formula is

$$\Delta m_{h_{SM}} \lesssim 0.4\ \mathrm{GeV}\left(\frac{10\ \mathrm{fb}^{-1}}{L}\right)^{1/2}, \tag{6}$$

yielding, for example, ± 180 MeV for $L = 50$ fb^{-1} [10]. At the Large Hadron Collider the $h_{SM} \to \gamma\gamma$ mode is deemed viable for $80 \lesssim m_{h_{SM}} \lesssim 150$ GeV, with a 1% mass resolution [11]. Once the h_{SM} signal is found, precision determination of its mass and measurement of its width become the paramount issues, and s-channel resonance production at a $\mu^+\mu^-$ collider is uniquely suited for this purpose.

For $m_{h_{SM}} < 2m_W$ the dominant h_{SM}-decay channels are $b\overline{b}$, WW^*, and ZZ^*, where the asterisk denotes a virtual weak boson. The light quark backgrounds to the $b\overline{b}$ signal can be rejected by b tagging. For the WW^* and ZZ^* channels we employ only the mixed leptonic-hadronic models ($\ell\nu 2j$ for WW^* and $2\ell 2j$, $2\nu 2j$ for ZZ^*, where $\ell = e$ or μ and j denotes a quark jet), and the visible purely leptonic ZZ^* modes (4ℓ and $2\ell 2\nu$), taking into account the major electroweak QCD backgrounds. For all channels we assume a general signal and background identification efficiency of $\epsilon = 50\%$, after selected acceptance cuts [12]. In the case of the $b\overline{b}$ channel, this is to include the efficiency for tagging at least one b. The signal and background channel cross sections $\epsilon\overline{\sigma}BF(X)$ at $\sqrt{s} = m_{h_{SM}}$ for $X = b\overline{b}$, WW^*, and ZZ^* are presented in Fig. 3 vs $m_{h_{SM}}$ for a resolution $R = 0.06\%$; $BF(X)$ includes the Higgs decay branching ratios for the signal, and the branching ratios for the

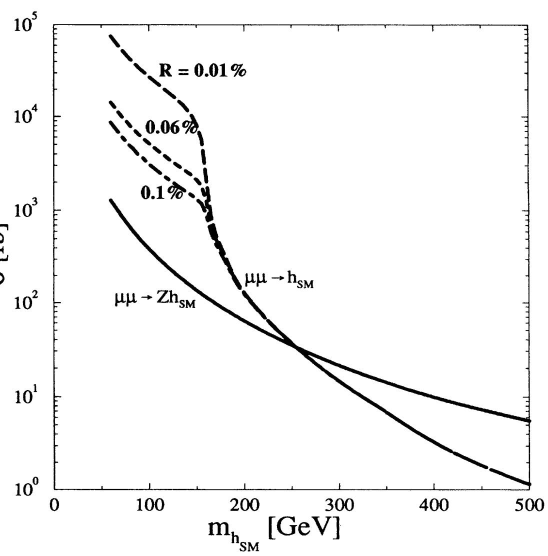

FIG. 2. Cross section vs $m_{h_{SM}}$ for inclusive SM Higgs production: (i) the s-channel $\overline{\sigma}_h$ [Eq. (3)] for $\mu^+\mu^- \to h_{SM}$ with $R = 0.01\%$, 0.06%, 0.1%, and 0.6% and (ii) $\sigma(\mu^+\mu^- \to Zh_{SM})$ at $\sqrt{s} = m_Z + \sqrt{2}m_{h_{SM}}$.

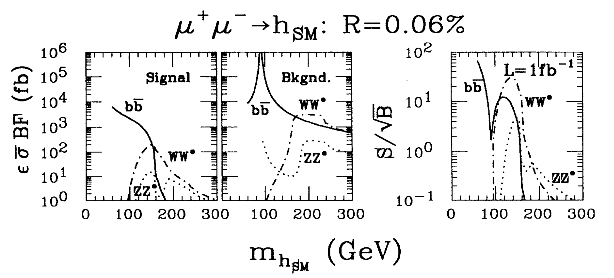

FIG. 3. The (a) h_{SM} signal and (b) background cross sections $\epsilon\overline{\sigma}BF(X)$ for $X = b\overline{b}$, and useful WW^* and ZZ^* final states (including a channel-isolation efficiency of $\epsilon = 0.5$) vs $m_{h_{SM}}$ for SM Higgs s-channel production with resolution $R = 0.06\%$. Also shown is (c) the luminosity required for $S/\sqrt{B} = 5$ in the three channels as a function of $m_{h_{SM}}$ for $R = 0.01\%$, 0.06%, and 1%.

W, W^* and Z, Z^* decays in the WW^* and ZZ^* final states for both the signal and the background. The background level is essentially independent of R, while the signal rate depends strongly on R as illustrated in Fig. 2.

The luminosity required to achieve $n_\sigma = S/\sqrt{B} = 5$ (where S and B are the signal and background rates) in the $b\overline{b}$, WW^*, and ZZ^* channels is also shown in Fig. 3—results for $R = 0.01\%$, 0.06%, and 1% as a function of $m_{h_{\rm SM}}$ are illustrated. For $R = 0.06\%$, $L = 1$ fb^{-1} would yield a detectable s-channel Higgs signal for all $m_{h_{\rm SM}}$ values between the current LEP I limit and $2m_W$ except in the region of the Z peak; a luminosity $L \sim 10$ fb^{-1} at $\sqrt{s} = m_{h_{\rm SM}}$ is needed for $85 \lesssim m_{h_{\rm SM}} \lesssim 100$ GeV. For $R = 0.01\%$, $n_\sigma = 5$ signals are achieved with only about $\frac{1}{25}$ of the luminosity required for $R = 0.06$. Note that a search for the $h_{\rm SM}$ (or any Higgs with width smaller than the achievable resolution) by scanning would be most efficient for the smallest possible R due to the fact that the L required at each scan point decreases as (roughly) $R^{1.8}$, whereas the number of scan points would only grow like $1/R$. If the Higgs resonance is broad, using small R is not harmful since the data from a fine scan can be rebinned to test for its presence.

Once the Higgs is observed, the highest priority will be to determine its precise mass and width. This can be accomplished by scanning across the Higgs peak. The luminosity required for this is strongly dependent upon R (i.e., σ) and the width itself. For a SM Higgs with $m_{h_{\rm SM}} = 120$ GeV the width, $\Gamma_{h_{\rm SM}} \sim 0.005$ GeV, will be smaller than σ, and a set of carefully chosen measurements is required. The minimal set is three measurements separated in $\sqrt{s}$ by 2σ; the first would be taken at $\sqrt{s}$ equal to the current best central value of the mass (from the initial detection scan). The second and third would be at $\sqrt{s}$ values 2σ below and 2σ above the first, with about 2.5 times the integrated luminosity expended on the first. In this way, a $\delta\Gamma/\Gamma = 1/3$ measurement of the width in the $b\overline{b}$ channel for $m_{h_{\rm SM}} = 120$ GeV requires total luminosity of at least $L = 0.6$, 5, 20, and 65 fb^{-1} for $R = 0.01\%$, 0.02%, 0.03%, and 0.04%, respectively. Actual luminosity requirements can be up to 50% larger, depending upon luck in placement of the first scan point. Note that in this way the Higgs mass is also determined to the accuracy of $\delta\Gamma$.

In addition, the event rate in a given channel measures $\Gamma(h_{\rm SM} \to \mu^+\mu^-)BF(h_{\rm SM} \to X)$. Then, using the branching fractions (most probably already measured in $Zh_{\rm SM}$ associated production), the $h_{\rm SM} \to \mu\mu$ partial width can be determined, providing an important test of the Higgs coupling.

MSSM Higgs bosons.—The MSSM has three neutral Higgs bosons h^0 (CP even), H^0 (CP even), and A^0 (CP odd). There is a theoretical upper bound on the mass of the lightest state h^0 of $m_{h^0} \lesssim 130$ to 150 GeV [13,14]. If $m_{A^0} \gtrsim 2m_Z$ (typical of grand unified models), the couplings are approximately [15]

	$\mu^+\mu^-, b\overline{b}$	$t\overline{t}$	ZZ, W^+W^-
h^0	1	-1	1
H^0	$\tan\beta$	$-1/\tan\beta$	0
A^0	$-i\gamma_5\tan\beta$	$-i\gamma_5/\tan\beta$	0

times the SM-Higgs couplings. Thus the h^0 couplings are SM-like, while H^0, A^0 have negligible WW and ZZ couplings and, for $\tan\beta > 1$, enhanced $\mu^+\mu^-$ and $b\overline{b}$ couplings. If $m_{A^0} \lesssim m_Z$, then H^0 is SM-like, while h^0 has couplings like those for H^0 above.

A $\mu^+\mu^-$ collider provides two particularly unique probes of the MSSM Higgs sector. First, the couplings of the SM-like MSSM Higgs boson deviate sufficiently from exact SM Higgs couplings that it may well be distinguishable from the $h_{\rm SM}$ by measurements of Γ_h and $\Gamma(h \to \mu^+\mu^-)$ at a $\mu^+\mu^-$ collider, using the s-channel resonance process. For instance, in the $b\overline{b}$ channel Γ_h and $\Gamma(h \to \mu^+\mu^-)BF(h \to b\overline{b})$ can be measured with sufficient accuracy so as to distinguish the h^0 from the $h_{\rm SM}$ for m_{A^0} values as high as 500 GeV [12].

The second dramatic advantage of a $\mu^+\mu^-$ collider in MSSM Higgs physics is the ability to study the non-SM-like Higgs bosons, e.g., for $m_{A^0} \gtrsim 2m_Z$ the H^0, A^0. An e^+e^- collider can study these states only via $Z^* \to A^0H^0$ production, which could easily be kinematically disallowed since grand unified theory scenarios typically have $m_{A^0} \sim m_{H^0} \gtrsim 200$–250 GeV. In s-channel production the H^0, A^0 can be even more easily observable than a SM-like Higgs. This is because the partial widths $\Gamma(H^0, A^0 \to \mu^+\mu^-)$ grow rapidly with increasing $\tan\beta$, implying [see Eqs. (4) and (5)] that $\overline{\sigma}_{H^0,A^0}$ will become strongly enhanced relative to SM-like values. $BF(H^0, A^0 \to b\overline{b})$ is also enhanced at large $\tan\beta$, implying an increasingly large rate in the $b\overline{b}$ final state. Thus we concentrate here on the $b\overline{b}$ final states of H^0, A^0 although the modes $H^0, A^0 \to t\overline{t}$, $H^0 \to h^0h^0, A^0A^0$, and $A^0 \to Zh^0$ can also be useful [12].

Despite the enhanced $b\overline{b}$ partial widths, the suppressed (absent) coupling of the H^0 (A^0) to WW and ZZ means that, unlike the SM Higgs boson, the H^0 and A^0 remain relatively narrow at high mass, with widths $\Gamma_{H^0}, \Gamma_{A^0} \sim 0.1$ to 3 GeV. Since these widths are generally comparable to or broader than the expected $\sqrt{s}$ resolution for $R = 0.06\%$ and $\sqrt{s} \gtrsim 200$ GeV, measurements of these Higgs widths could be straightforward with a scan over several $\sqrt{s}$ settings, provided that the signal rates are sufficiently high. The results of a fine scan can be combined to get a coarse scan appropriate for broader widths.

The cross section for $\mu^+\mu^- \to A^0 \to b\overline{b}$ production with $\tan\beta = 2$, 5, and 20 (including an approximate cut and b-tagging efficiency of 50%) is shown vs m_{A^0} in Fig. 4 for beam resolution $R = 0.06\%$. Also shown is the significance of the $b\overline{b}$ signal for delivered luminosity $L = 0.1$ fb^{-1} at $\sqrt{s} = m_{A^0}$. Discovery of the A^0 and H^0 will require an energy scan if $Z^* \to H^0 + A^0$ is

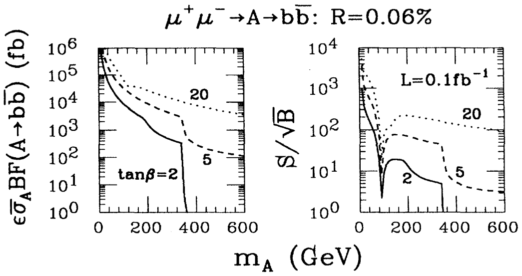

FIG. 4. (a) The effective $b\bar{b}$-channel cross section $\epsilon\bar{\sigma}_{A^0} \times BF(A^0 \to b\bar{b})$ for s-channel production of the MSSM Higgs boson A^0 vs $\sqrt{s} = m_{A^0}$, for $\tan\beta = 2$, 5, and 20, beam resolution $R = 0.06\%$ and channel isolation efficiency $\epsilon = 0.5$ and (b) corresponding statistical significance of the $A^0 \to b\bar{b}$ signal for $L = 0.1\ \mathrm{fb}^{-1}$ delivered at $\sqrt{s} = m_{A^0}$.

kinematically forbidden; a luminosity of 20 fb^{-1} would allow a scan over 200 GeV at intervals of 1 GeV with $L = 0.1\ \mathrm{fb}^{-1}$ per point. The $b\bar{b}$ mode would yield a 5σ signal at $\sqrt{s} = m_{A^0}$ for $\tan\beta \gtrsim 2$ for $m_{A^0} \lesssim 2m_t$ and for $\tan\beta \gtrsim 5$ for all m_{A^0}. For $m_{A^0} \gtrsim m_Z$ ($m_{A^0} \lesssim m_Z$), the H^0 (h^0) has very similar couplings to those of the A^0 and would also be observable in the $b\bar{b}$ mode down to similar $\tan\beta$ values. Discovery of *both* the H^0 and A^0 MSSM Higgs bosons would be possible over a large part of the $m_{A^0} \gtrsim m_Z$ MSSM parameter space.

Polarized beams would allow a reduction in backgrounds relative to signals in the discovery and study of any Higgs boson. If polarization P is possible for *both* beams, then, relative to the unpolarized case, the signal is enhanced by the factor $1 + P^2$ while the background is suppressed by $1 - P^2$ [16]. The luminosity required for a signal of given statistical significance is then proportional to $(1 - P^2)/(1 + P^2)^2$. For example, if 85% polarization could be achieved with less than a factor of 10 decrease in luminosity, Higgs studies would benefit.

In summary, $\mu^+\mu^-$ colliders offer significant new opportunities for probing the Higgs sector. The s-channel resonance production process is especially valuable for precision Higgs mass measurements, Higgs width measurements, and the search for Higgs bosons with negligible hZZ couplings, such as the H^0, A^0 Higgs bosons of the MSSM. For an extremely narrow Higgs boson, such as a light SM Higgs, excellent energy resolution is mandatory for the width measurement and could allow us to distinguish between the SM Higgs and the SM-like Higgs of the MSSM. The techniques discussed here in the SM and MSSM theories are generally applicable to searches for any Higgs boson or other scalar particle that couples to $\mu^+\mu^-$.

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