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Status of Muon Collider Research and Development and Future Plans

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The status of the research on muon colliders is discussed and plans are outlined for future theoret-

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ical and experimental studies. Besides work on the parameters of a 3-4 and 0.5 TeV center-of-mass (CoM) energy collider, many studies are now concentrating on a machine near 0.1 TeV (CoM) that could be a factory for the s-channel production of Higgs particles. We discuss the research on the various components in such muon colliders, starting from the proton accelerator needed to generate pions from a heavy-Z target and proceeding through the phase rotation and decay ($\pi \rightarrow \mu \nu_\mu$) channel, muon cooling, acceleration, storage in a collider ring and the collider detector. We also present theoretical and experimental R & D plans for the next several years that should lead to a better understanding of the design and feasibility issues for all of the components. This report is an update of the progress on the R & D since the Feasibility Study of Muon Colliders presented at the Snowmass'96 Workshop [R. B. Palmer, A. Sessler and A. Tollestrup, *Proceedings of the 1996 DPF/DPB Summer Study on High-Energy Physics* (Stanford Linear Accelerator Center, Menlo Park, CA, 1997)].

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I. INTRODUCTION

The Standard Model of electroweak and strong interactions has passed precision experimental tests at the highest energy scale accessible today. Theoretical arguments indicate that new physics *beyond the Standard Model* associated with the electroweak gauge symmetry breaking and fermion mass generation will emerge in parton collisions at or approaching the TeV energy scale. It is likely that both hadron-hadron and lepton-antilepton colliders will be required to discover and make precision measurements of the new phenomena. The next big step forward in advancing the hadron-hadron collider energy frontier will be provided by the CERN Large Hadron Collider (LHC), a proton-proton collider with a center-of-mass (CoM) energy of 14 TeV which is due to come into operation in 2005. Note that in a high energy hadron beam, valence quarks carry momenta which are, approximately, between $\frac{1}{6}$ to $\frac{1}{9}$ of the hadron momentum. The LHC will therefore provide hard parton-parton collisions with typical center of mass energies of $2.3 - 1.5$ TeV.

The route towards TeV-scale lepton-antilepton colliders is less clear. The lepton-antilepton colliders built so far have been e^+e^- colliders, such as the Large Electron Positron collider (LEP) at CERN and the Stanford Linear Collider (SLC) at SLAC. In a circular ring such as LEP the energy lost per revolution in keV is $88.5 \times E^4/\rho$, where the electron energy E is in GeV, and the radius of the orbit ρ is in meters. Hence, the energy loss grows rapidly as E increases. This limits the center-of-mass energy that would be achievable in a LEP-like collider. The problem can be avoided by building a linear machine (the SLC is partially linear), but with current technologies, such a machine must be very long (30-40 km) to attain the TeV energy scale. Even so, radiation during the beam-beam interaction (beamstrahlung) limits the precision of the CoM energy [1].

For a lepton with mass m the radiative energy losses are inversely proportional to m^4. Hence, the energy-loss problem can be solved by using heavy leptons. In practice this means using muons, which have a mass ≈ 207 times that of an electron. The resulting reduction in radiative losses enables higher energies to be reached and smaller collider rings to be used [2,3]. Parameters for 10 to 100 TeV collider have been discussed [4,5]. Estimated sizes of the accelerator complexes required for 0.1-TeV, 0.5-TeV and 4-TeV muon colliders are compared with the sizes of other possible future colliders, and with the FNAL and BNL sites in Fig. 1. Note that muon colliders with CoM energies up to ≈ 4 TeV would fit on these existing laboratory sites. The cost of building a muon collider is not yet known. However, since muon colliders are relatively small, they may be significantly less expensive than alternative machines.

Since muons decay quickly, large numbers of them must be produced to operate a muon collider at high luminosity. Collection of muons from the decay of pions produced in proton-nucleus interactions results in a large initial phase volume for the muons, which must be reduced (cooled) by a factor of 10^6 for a practical collider. This may be compared with the antiproton stochastic cooling achieved in the Tevatron. In this case the 6-dimensional (6-D) phase space is reduced by approximately a factor of 10^6, while with stacking the phase space density [6,7] is increased by a factor of 10^{10}. The technique of ionization cooling is proposed for the $\mu^+\mu^-$ collider [8–11]. This technique is uniquely applicable to muons because of their minimal interaction with matter.

Muon colliders also offer some significant physics advantages. The small radiative losses permit very small beam-energy spreads to be achieved. For example, momentum spreads as low as $\Delta P/P = 0.003\%$ are believed to be possible for a low-energy collider. By measuring the time-dependent decay asymmetry resulting from the naturally polarized muons, it has been shown [12] that the beam energy could be determined with a precision of $\Delta E/E = 10^{-6}$. The small beam-energy spread, together with the precise energy determination, would facilitate measurements of the masses and widths of any new resonant states scanned by the collider. In addition, since the cross-section for

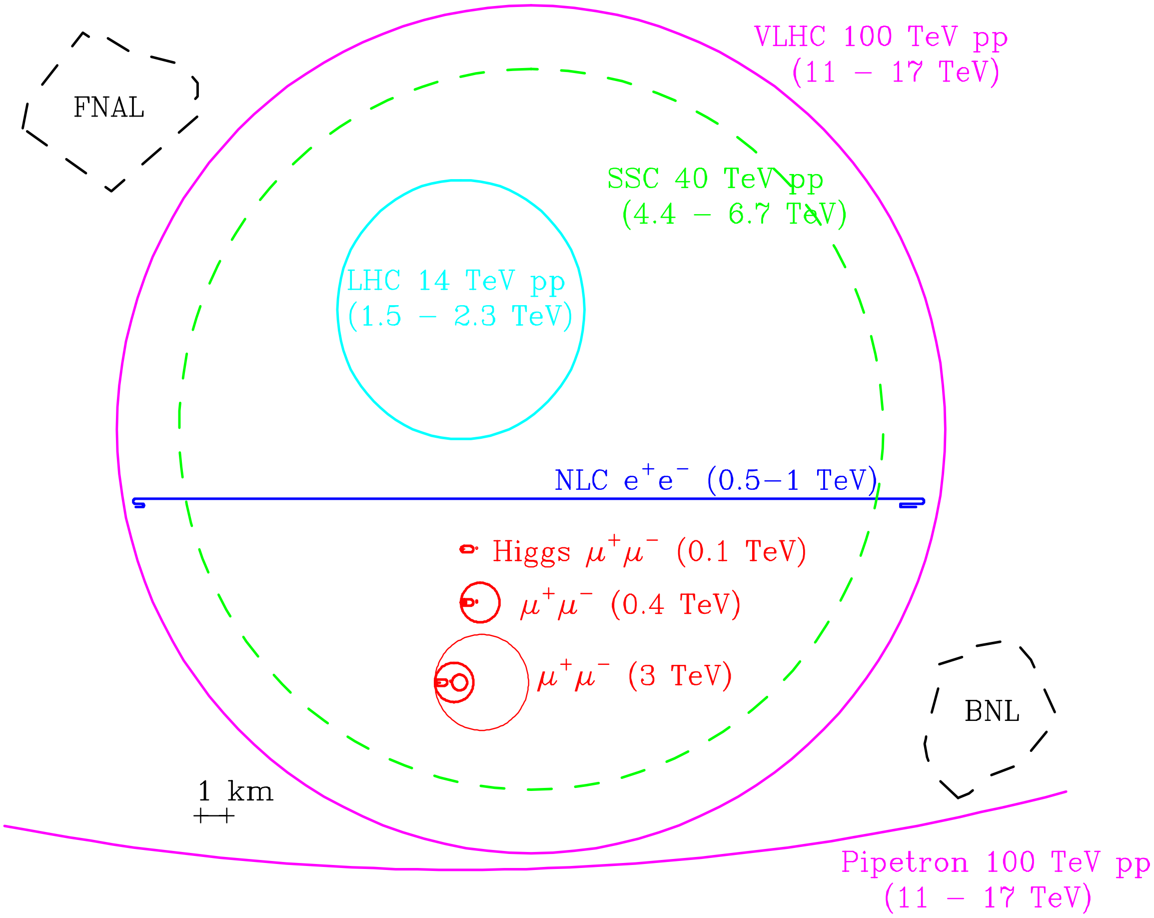

FIG. 1. Comparative sizes of various proposed high energy colliders compared with the FNAL and BNL sites. The energies in parentheses give for lepton colliders their CoM energies and for hadron colliders the approximate range of CoM energies attainable for hard parton-parton collisions.

producing a Higgs-like scalar particle in the s-channel (direct lepton-antilepton annihilation) is proportional to m^2, this extremely important process could be studied only at a muon collider and not at an e^+e^- collider [13]. Finally, the decaying muons will produce copious quantities of neutrinos. Even short straight sections in a muon-collider ring will result in neutrino beams several orders of magnitude higher in intensity than presently available, permitting greatly extended studies of neutrino oscillations, nucleon structure functions, the CKM matrix, and precise indirect measurements of the W-boson mass [14] (see section **II.I**).

The concept of muon colliders was introduced by G. I. Budker [2,3], and developed further by A. N. Skrinsky *et al.* [15–22] and D. Neuffer [13,23–25]. They pointed out the significant challenges in designing an accelerator complex that can make, accelerate, and collide μ^+ and μ^- bunches all within the muon lifetime of $2.2\,\mu$s ($c\tau = 659$ m). A concerted study of a muon collider design has been underway in the U.S. since 1992 [26–42]. By the Sausalito workshop [30] in 1995 it was realized that with new ideas and modern technology, it may be feasible to make muon bunches containing a few times 10^{12} muons, compress their phase space and accelerate them up to the multi-TeV energy scale before more than about 3/4 of them have decayed. With careful design of the collider ring and shielding it appears possible to reduce to acceptable levels the backgrounds within the detector that arise from the very large flux of electrons produced in muon decays. These realizations led to an intense activity, which resulted in the muon-collider feasibility study report [43,44] prepared for the 1996 DPF/DPB Summer Study on High-Energy Physics (the Snowmass'96 workshop). Since then, the physics prospects at a muon collider have been studied extensively [45–47], and the potential physics program at a muon collider facility has been explored in workshops [39] and conferences [40].

Encouraged by further progress in developing the muon-collider concept, together with the growing interest and involvement of the high-energy-physics community, the *Muon Collider Collaboration* became a formal entity in May of 1997. The collaboration is led by an executive board with members from Brookhaven National Laboratory (BNL), Fermi National Accelerator Laboratory (FNAL), Lawrence Berkeley National Laboratory (LBNL), Budker Institute for Nuclear Physics (BINP), University of California at Los Angeles (UCLA), University of Mississippi and Princeton University. The goal of the collaboration is to complete within a few years the R&D needed to determine whether a Muon Collider is technically feasible, and if it is, to design the First Muon Collider.

TABLE I. Baseline parameters for high- and low-energy muon colliders. Higgs/year assumes a cross section $\sigma = 5 \times 10^4$ fb; a Higgs width , = 2.7 MeV; 1 year = 10^7 s.

CoM energy	TeV	3	0.4		0.1	
p energy	GeV	16	16		16	
p's/bunch		2.5×10^{13}	2.5×10^{13}		5×10^{13}	
Bunches/fill		4	4		2	
Rep. rate	Hz	15	15		15	
p power	MW	4	4		4	
μ/bunch		2×10^{12}	2×10^{12}		4×10^{12}	
μ power	MW	28	4		1	
Wall power	MW	204	120		81	
Collider circum.	m	6000	1000		350	
Ave bending field	T	5.2	4.7		3	
Rms $\Delta p/p$	%	0.16	0.14	0.12	0.01	0.003
6-D $\epsilon_{6,N}$	$(\pi \mathrm{m})^3$	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}
Rms ϵ_n	π mm-mrad	50	50	85	195	290
β^*	cm	0.3	2.6	4.1	9.4	14.1
σ_z	cm	0.3	2.6	4.1	9.4	14.1
σ_r spot	μm	3.2	26	86	196	294
σ_θ IP	mrad	1.1	1.0	2.1	2.1	2.1
Tune shift		0.044	0.044	0.051	0.022	0.015
n_{turns} (effective)		785	700	450	450	450
Luminosity	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$	7×10^{34}	10^{33}	1.2×10^{32}	2.2×10^{31}	10^{31}
Higgs/year				1.9×10^3	4×10^3	3.9×10^3

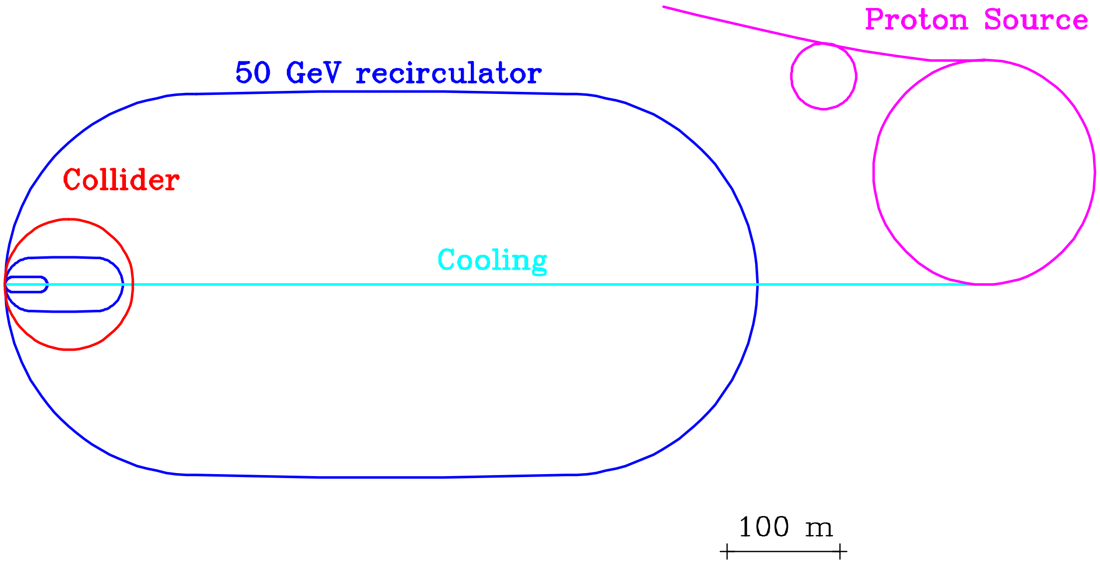

FIG. 2. Plan of a 0.1-TeV-CoM muon collider.

Table I gives the parameters of the muon colliders under study [48–55], which have CoM energies of 0.1 TeV, 0.4 TeV and 3 TeV and Figs. 2 and 3 show possible outlines of the 0.1 TeV and 3 TeV machines. In the former case, parameters are given in the table for operation with three different beam-energy spreads: $\Delta p/p = 0.12$, 0.01, and 0.003%. In all cases, proton bunches containing 2.5-5 $\times 10^{13}$ particles are accelerated to energies of 16 GeV. The protons interact in a target to produce $\mathcal{O}(10^{13})$ charged pions of each sign. A large fraction of these pions can be captured in a high-field solenoid. Muons are produced by allowing the pions to decay into a lower-field solenoidal

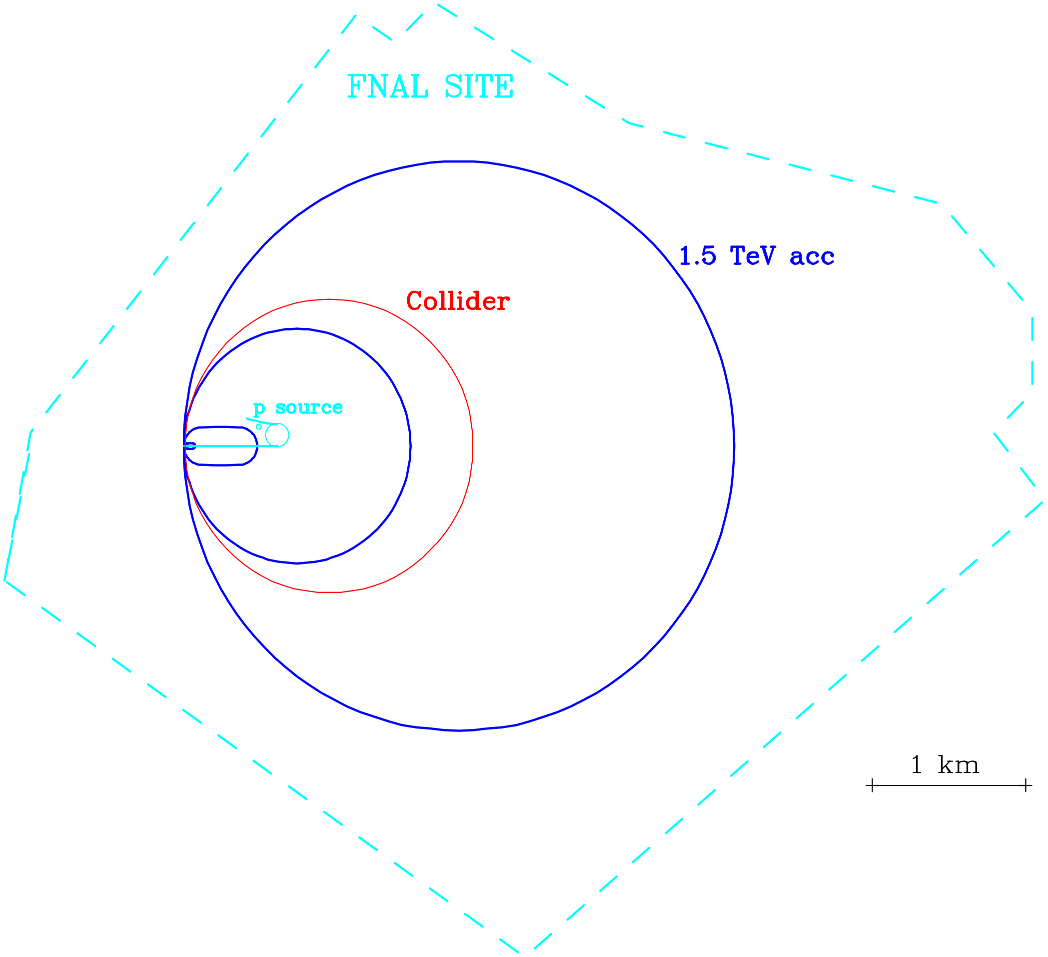

FIG. 3. Plan of a 3-TeV-CoM muon collider shown on the Fermi National Laboratory site as an example.

channel. To collect as many particles as possible within a useful energy interval, rf cavities are used to accelerate the lower-energy particles and decelerate the higher-energy particles (so-called phase rotation). With two proton bunches every accelerator cycle, the first used to make and collect positive muons and the second to make and collect negative muons, there are about 10^{13} muons of each charge available at the end of the decay channel per accelerator cycle. If the proton accelerator is cycling at 15 Hz, then in an operational year (10^7 s), about 10^{21} positive and negative muons would be produced and collected.

As stated before, the muons exiting the decay channel populate a very diffuse phase space. The next step in the muon-collider complex is to *cool* the muon bunch, *i.e.*, to turn the diffuse muon cloud into a very *bright* bunch with small longitudinal and transverse dimensions, suitable for accelerating and injecting into a collider. The cooling must be done within a time that is short compared to the muon lifetime. Conventional cooling techniques (stochastic cooling [56] and electron cooling [16]) take too long. The technique proposed for cooling muons is called ionization cooling [8,10,11], and will be discussed in detail in sec. V. Briefly, the muons traverse some material in which they lose both longitudinal and transverse momentum by ionization losses (dE/dx). The longitudinal momentum is then replaced using an rf accelerating cavity, and the process is repeated many times until there is a large reduction in the transverse phase space occupied by the muons. The energy spread within the muon beam can also be reduced by using a wedge-shaped absorber in a region of dispersion (where the transverse position is momentum dependent). The wedge is arranged so that the higher-energy particles pass through more material than lower-energy particles. Initial calculations suggest that the 6-D phase space occupied by the initial muon bunches can be reduced by a factor of 10^5-10^6 before multiple Coulomb scattering and energy straggling limit further reduction. We reiterate that ionization cooling is uniquely suited to muons because of the absence of strong nuclear interactions and electromagnetic shower production for these particles at energies around 200 MeV/c.

Rapid acceleration to the collider beam energy is needed to avoid excessive particle loss from decay. It can be achieved, initially in a linear accelerator, and later in recirculating linear accelerators, rapid-cycling synchrotron, or fixed-field-alternating-gradient (FFAG) accelerators. Positive and negative muon bunches are then injected in opposite directions into a collider storage ring and brought into collision at the interaction point. The bunches circulate and collide for many revolutions before decay has depleted the beam intensities to an uninteresting level. Useful luminosity can be delivered for about 800 revolutions for the high-energy collider and 450 revolutions for the low-energy one.

There are many interesting and challenging problems that need to be resolved before the feasibility of building a muon collider can be demonstrated. For example, (i) heating from the very intense proton bunches may require the use of of a liquid-jet target, and (ii) attaining the desired cooling factor in the ionization-cooling channel may require the development of rf cavities with thin beryllium windows operating at liquid-nitrogen temperatures in high solenoidal fields. In addition, the development of long liquid-lithium lenses may be desirable to provide stronger radial focusing for the final cooling stages.

This article describes the status of our muon-collider feasibility studies, and is organized as follows. Section **II** gives a brief summary of the physics potential of muon colliders, including physics at the accelerator complex required for a muon collider. Section **III** describes the proton-driver specifications for a muon collider, and two site-dependent examples that have been studied in some detail. Section **IV** presents pion production, capture, and the pion-decay channel, and section **V** discusses the design of the ionization-cooling channel needed to produce an intense muon beam suitable for acceleration and injection into the final collider. Sections **VI** and **VII** describe the acceleration scenario and collider ring, respectively. Section **VIII** discusses backgrounds at the collider interaction point and section **IX** deals with possible detector scenarios. A summary of the conclusions is given in section **X**.

II. THE PHYSICS POTENTIAL OF MUON COLLIDERS

A. Brief overview

The physics agenda at a muon collider falls into three categories: First Muon Collider (FMC) physics at a machine with center-of-mass energies of 100 to 500 GeV; Next Muon Collider (NMC) physics at 3–4 TeV center-of-mass energies; and front-end physics with a high-intensity muon source.

The FMC will be a unique facility for neutral Higgs boson (or techni-resonance) studies through s-channel resonance production. Measurements can also be made of the threshold cross sections for production of W^+W^-, $t\bar{t}$, Zh, and pairs of supersymmetry particles — $\chi_1^+\chi_1^-$, $\chi_2^0\chi_1^0$, $\tilde{\ell}^+\tilde{\ell}^-$ and $\tilde{\nu}\bar{\tilde{\nu}}$ — that will determine the corresponding masses to high precision. A $\mu^+\mu^- \to Z^0$ factory, utilizing the partial polarization of the muons, could allow significant improvements in $\sin^2\theta_{\rm w}$ precision and in B-mixing and CP-violating studies. In Fig. 4, we show the cross sections for standard model (SM) processes versus the CoM energy at the FMC. For the unique s-channel Higgs boson production, where $\sqrt{s}_{\mu\mu} = m_H$, results for three different beam energy resolutions are presented.

The NMC will be particularly valuable for reconstructing supersymmetric particles of high mass from their complex cascade decay chains. Also, any Z' resonances within the kinematic reach of the machine would give enormous event rates. The effects of virtual Z' states would be detectable to high mass. If no Higgs bosons exist below ~1 TeV, then the NMC would be the ideal machine for the study of strong WW scattering at TeV energies.

At the front end, a high-intensity muon source will permit searches for rare muon processes sensitive to branching ratios that are orders of magnitude below present upper limits. Also, a high-energy muon-proton collider can be constructed to probe high$-Q^2$ phenomena beyond the reach of the HERA ep collider. In addition, the decaying muons will provide high-intensity neutrino beams for precision neutrino cross-section measurements and for long-baseline experiments [57–66]. Plus, there are numerous other new physics possibilities for muon facilities [44,39] that we will not discuss in detail in this document.

B. Higgs boson physics

The expectation that there will be a light (mass below $2M_W$) SM-like Higgs boson provides a major motivation for the FMC, since such a Higgs boson can be produced with a very high rate directly in the s-channel. Theoretically, the lightest Higgs boson h^0 of the most general supersymmetric model is predicted to have mass below 150 GeV and to be very SM-like in the usual decoupling limit. Indeed, in the minimal supersymmetric model, which contains the five Higgs bosons h^0, H^0, A^0, $H^{\pm}$, one finds $m_{h^0} \lesssim 130$ GeV and the h^0 is SM-like if $m_{A^0} \gtrsim 130$ GeV. Experimentally, global analyses of precision electroweak data now indicate a strong preference for a light SM-like Higgs boson. The goals of the FMC for studying the SUSY Higgs sector via s-channel resonance production are: to measure the light Higgs mass, width, and branching fractions with high precision, in particular sufficient to differentiate the minimal