a capability to search for any missing neutral state such as the Higgs boson via the missing mass technique. We are investigating methods to improve our forward muon detection capability.

X. CONCLUSIONS

Unlike protons, muons are point-like but, unlike electrons, they emit relatively little synchrotron radiation and therefore can be accelerated and collided in rings.

Another advantage resulting from the low synchrotron radiation is the lack of beamstrahlung and the possibility of very small collision energy spreads. A beam energy spread of ΔE/E of 0.003% is considered feasible for a 100 GeV machine. It has been shown that by observing spin precession, the absolute energy could be determined to a small fraction of this width. These features become important in conjunction with the large s-channel Higgs production ($\mu^+\mu^- \to h$, 43000 times larger than for $e^+e^- \to h$), allowing precision measurements of the Higgs mass, width and branching ratios. A higher energy muon collider can also distinguish the nearly degenerate heavy Higgs bosons H^0 and A^0 of the minimal supersymmetric extension of the standard model, since these states can also be produced in the s channel. We have also examined the ability of the muon collider to study techni-resonances, do a high luminosity study of Z boson physics, scan the W and $t\bar{t}$ thresholds to make precision mass measurements as well as SUSY and strongly interacting W boson physics. The high luminosity proton driver and the cold low energy muons permit the study of rare kaon and muon decays. Muon storage rings will permit low-systematics studies of neutrino oscillations for a wide range of mixing angle and δm^2 phase space with hitherto unattainable sensitivity.

Such machines are clearly desirable. The issues are:

- whether they can be built and physics done with them
- what they will cost.

Much progress has been made in addressing the first question and the answer, so far, appears to be yes. It is too early to address the second.

We have studied machines with CoM energies of 0.1, 0.4 and 3 TeV, defined parameters and simulated many of their components. Most recent work has been done on the 0.1 TeV *First Muon Collider*, the energy taken to be representative of the actual mass of a Higgs particle. A summary of progress and challenges follows:

a. Proton driver The specification of the proton driver for the three machines is assumed the same: 10^{14} protons/pulse at an energy above 16 GeV and 1-2 ns *rms* bunch lengths. There have been three studies of how to achieve these parameters. The most conservative, at 30 GeV, is a generic design. Upgrades of the FNAL (at 16 GeV) and BNL (at 24 GeV) accelerators have also been studied. Despite the very short bunch requirement, each study has concluded that the specification is attainable. Experiments are planned to confirm some aspects of these designs.

b. Pion production and capture Pion production has been taken from the best models available, but an experiment (BNL-E910) that has taken data, and is being analyzed, will refine these models. The assumed 20 T capture solenoid will require state-of-the-art technology. Capture, decay and phase rotation have been simulated, and have achieved the specified production of 0.3 muons per initial proton. The most serious remaining issues for this part of the machine are:

- The nature and material of the target: The baseline assumption is that a liquid metal jet will be used, but the effects of shock heating by the beam, and of the eddy currents induced in the liquid as it enters the solenoid, are not yet fully understood.
- The maximum rf field in the phase rotation: For the short pulses used, the current assumptions would be reasonably conservative under normal operating conditions, but the effects of the massive radiation from the nearby target are not known.

Both these questions can be answered in a target experiment planned to start within the next two years at the BNL AGS.

Polarization of the muon beams represents a significant physics advantage and is an important feature of a muon collider. Polarized muon beams are possible. Muons are produced with 100% polarization in the rest frame of the pion, but they travel in all directions. By accepting the forward going muons, it is easy to obtain 25% polarization in either beam easily. The amount of polarization can be increased with an accompanying price in luminosity.

c. Cooling The required ionization cooling is the most difficult and least understood element in any of the muon colliders studied. Ionization cooling is a phenomenon that occurs whenever there is energy loss in a strong focusing environment.

But achieving the nearly 10^6 reduction required is a challenge. Cooling over a wide range has been simulated using lithium lenses and ideal (linear matrix) matching and acceleration. Examples of limited sections of solenoid lattices with realistic accelerating fields have now been simulated, but the specification and simulation of a complete system has not yet been done. Much theoretical work remains: space charge and wakefields must be included; lattices at the start and end of the cooling sequences must be designed; lattices including liquid lithium lenses must be studied, and the sections must be matched together and simulated as a full sequence. The tools for this work are nearly ready, and this project should be completed within two years.

Technically, one of the most challenging aspects of the cooling system appears to be:

- High gradient rf (e.g. 36 MV/m at 805 MHz) operating in strong (5-10 T) magnetic field, with beryllium foils between the cavities.

An experiment is planned that will test such a cavity, in the required fields, in about two years time. On an approximately six year time scale, a *Cooling Test Facility* is being proposed that could test ten meter lengths of different cooling systems. If they are required, then an urgent need is to develop:

- Lithium Lenses: (e.g. 2 cm diameter, 70 cm long, liquid lithium lenses with 10 T surface fields and a repetition rate of 15 Hz).

The use of 31 T solenoids could avoid their need, at least in the low energy *First Muon Collider*, which would ease the urgency of this rather long term R&D, but both options would require long-term R&D. Meanwhile a short lithium lens is under construction at BINP (Novosibirsk, Russia).

d. Acceleration The acceleration system is probably the least controversial, although possibly the most expensive, part of a muon collider. Preliminary parameters have been specified for acceleration sequences for a 100 GeV and a 3 TeV machine, but they need refinement. In the low energy case, a linac is followed by three recirculating or FFAG accelerators. In the high energy accelerator, the recirculating or FFAG accelerators are followed by three fast ramping synchrotrons employing alternating pulsed and superconducting magnets. The parameters do not appear to be extreme, and it does not appear as if serious problems are likely.

e. Collider The collider lattices are challenging because of the requirement of very low beta functions at the interaction point, high single bunch intensities, and short bunch lengths. However, the fact that all muons will decay after about 800 turns means that slowly developing instabilities are not a problem. Feasibility lattices have been generated for a 4 TeV case, and more detailed designs for 100 GeV machines are been studied. In the latter case, but still without errors, 5σ acceptances in both transverse and longitudinal phase space have been achieved in tracking studies. Beam scraping schemes have been designed for both the low energy (collimators) and high energy (septum extractors) cases.

The short bunch length and longitudinal stability problems are avoided if the rings, as specified, are sufficiently isochronous, but some rf is needed to remove the impedance generated momentum spread. Transverse instabilities (beam breakup) should be controlled by rf BNS damping.

The heating of collider ring superconducting magnets by electrons from muon decay can be controlled by thick tungsten shields, and this technique also shields the space surrounding the magnets from the induced radioactivity on the inside of the shield wall. A conceptual design of magnets for the low energy machine has been defined.

Although much work is yet to be done (inclusion of errors, higher order correction, magnet design, rf design, etc), the collider ring does not appear likely to present a serious problem.

f. Neutrino radiation and detector background Neutrino radiation, which rises as the cube of the energy, is not serious for machines with center of mass energies below about 1.5 TeV. It is thus not significant for the First Muon Collider; but above 2 TeV, it sets a constraint on the muon current and makes it harder to achieve desired luminosities. However, advances in cooling and correction of tune shifts may still allow a machine at 10 TeV with substantial luminosity ($> 10^{35}$ cm^{-2}s^{-1}).

Background in the detector was at first expected to be a very serious problem, but after much work, shielding systems have evolved that limit most charged hadron, electron, gamma and neutron backgrounds to levels that are acceptable. Muon background, in the higher energy machines, is a special problem that can cause serious fluctuations in calorimeter measurements. It has been shown that fast timing and segmentation can help suppress this background, and preliminary studies of its effects on a physics experiment are encouraging. The studies are ongoing.

g. Detector scenarios We have considered several options for the experimental detector components for various CoM energy colliders. Much work needs to be done to optimize the physics reach at each energy by feeding back the results of detailed simulations of backgrounds and signal to the detector design. Only then will the feasibility of doing physics with a muon collider be fully explored.

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[1] M. Tigner, *Imperatives for Future High Energy Accelerators*, AIP Conf. Proc. **279**, p. 1 (1993).

[2] G. I. Budker, *Accelerators and Colliding Beams* (in Russian), in *Proc. 7^{th} Int. Conf. on High Energy Accel.* (Yerevan, 1969), p. 33; extract: AIP Conf. Proc. **352**, p. 4 (1996).

[3] G. I. Budker, Int. High Energy Conf. (Kiev, 1970), unpublished; extract: AIP Conf. Proc. **352**, p. 4 (1996).

[4] A. N. Skrinsky, *Towards Ultimate Luminosity Polarized Muon Collider (Problems and Prospects)*, AIP Conf. Proc. **441**, p. 249 (1998).

[5] B. J. King, *Discussion on Muon Collider Parameters at Center of Mass Energies from 0.1 TeV to 100 TeV*, BNL-CAP-223-MUON-98C; to appear in Proc. EPAC98 Conf. (Stockholm, June 1998).

[6] V. Bharadwaj, et al., *Fermilab Collider Run 1b Accelerator Performance*, Fermilab-TM-1970, (1995). See in particular Chapter 4, Table I (page 12) and Figure 8 (page 19);
http://fnalpubs.fnal.gov/archive/1996/tm/TM-1970.html

[7] M. D. Church and J. P. Marriner, *The Antiproton Sources: Design and Operation* Annu. Rev. Nucl. Sci., **43**, p. 253 (1993)

[8] A. A. Kolomensky, *On the Oscillation Decrements in Accelerators in the Presence of Arbitrary Energy Losses*, Sov. Atomic Energy **19**, p. 1511 (1965);
http://puhep1.princeton.edu/mumu/physics
/kolomensky/1.html

[9] G. I. Budker, *An Effective Method of Damping Particle Oscillations in Proton and Antiproton Storage Rings*, Sov. Atomic Energy **22**, p. 438 (1967);
http://puhep1.princeton.edu/mumu/physics/budker/1.html

[10] Yu. M. Ado and V. I. Balbekov, *Use of Ionization Friction in the Storage of Heavy Particles*, Sov. Atomic Energy **31**, p. 731 (1971);
http://puhep1.princeton.edu/mumu/physics/ado/1.html

[11] V. I. Balbekov, *Achievable Transverse Emittance of Beam in Muon Collider*, AIP Conf. Proc. **372**, p. 140 (1996);
ftp://ftp.mumu.bnl.gov/pub/documents/balbekov.ps

[12] Rajendran Raja and Alvin Tollestrup, *Calibrating the energy of a 50×50 GeV Muon Collider using $g-2$ spin precession*, Phys. Rev. D **58**, 013005 (1998);
http://xxx.lanl.gov/ps/hep-ex/9801004

[13] D. Neuffer, *Multi-TeV Muon Colliders*, AIP Conf. Proc. **156**, p. 201 (1987);
http://www-ppd.fnal.gov/muscan/munotes/mc-006.pdf

[14] S. Geer, *Workshop on physics at the first muon collider and front end of a muon collider: A brief summary*, in Ref. [40], p. 18.

[15] A. N. Skrinsky, *Intersecting Storage Rings at Novosibirsk*, Proc. Int. Seminar on Prospects of High-Energy Physics (Morges, Mar. 1971), unpublished; extract: AIP Conf. Proc. **352**, p. 6 (1996).

[16] G. I. Budker and A. N. Skrinsky, *Electron cooling and new possibilities in elementary particle physics*, Sov. Phys. Usp. **21**, p. 277 (1978).

[17] A. N. Skrinsky, *Acceleration and Instrumentation Prospects of Elementary Particle Physics*, AIP Conf. Proc. **68**, p. 1056 (1980).

[18] A. N. Skrinsky and V. V. Parkhomchuk, *Methods of cooling beams of charged particles*, Sov. J. Part. Nucl. **12**, p. 223 (1981).

[19] A. N. Skrinsky, *Accelerator and detector prospects of elementary particle physics*, Sov. Phys. Usp. **25**, p. 639 (1982), sec. 3n.

[20] V. V. Parkhomchuk and A. N. Skrinsky, *Ionization Cooling: Physics and Applications*, in *Proc. 12^{th} Int. Conf. on High Energy Accel.*, ed. by F. T. Cole and R. Donaldson (Fermilab, 1983), p. 485;
http://www-ppd.fnal.gov/muscan/munotes/mc-003.pdf

[21] A. N. Skrinsky, *Ionization Cooling and Muon Collider*, AIP Conf. Proc. **372**, p. 133 (1996).

[22] A. N. Skrinsky, *Polarized Muons Beams for Muon Collider*, Nucl. Phys. B (Proc. Suppl.) **51A**, p. 201 (1996).

[23] D. Neuffer, *Colliding Muons Beams at 90 GeV*, Fermilab report FN-319 (July 1979);
http://www-ppd.fnal.gov/muscan/munotes/mc-001.pdf