OVERVIEW OF $\mu^+\mu^-$ COLLIDER OPTIONS

D. B. Cline, Center for Advanced Accelerators, Physics Department, University of California Los Angeles, Los Angeles, CA 90095-1547 USA

Two dedicated workshops have been held in California on $\mu^+\mu^-$ colliders: Napa in 1992 and Sausalito in 1994. As a result of this and a new round of simulations, as well as $\mu^\pm$ cooling experimental plans, it is possible to consider the feasibility of constructing a $\mu^+\mu^-$ collider. However, the energy range and required luminosity must be specified by the particle physics goals before proceeding. Also, the unique features of the physics potential vs LHC must be shown. We will describe the status of this field and the key problems that must be solved before a definite proposal can be made.

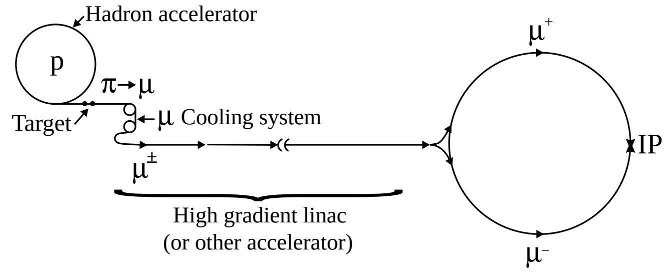


Figure 1: Schematic of a possible $\mu^+\mu^-$ collider scheme - few hundred GeV to few TeV.

I. INTRODUCTION

At Port Jefferson Advanced Accelerator Workshop in the Summer of 1992, a group investigating new concepts of colliders studied anew the possibility of a $\mu^+\mu^-$ collider since $e^+ e^-$ colliders will be very difficult, in the several TeV range[1]. A small group also discussed the possibility of a $\mu^+\mu^-$ collider[2]. A special workshop was then held in Napa, California, in the fall of 1992, for this study. There are new accelerator possibilities for the development of such a machine, possibly at an existing or soon to exist storage ring[3]. For the purpose of the discussion here, a $\mu^+\mu^-$ collider is schematically shown in Figure 1. In this brief note we study one of the most interesting goals of a $\mu^+\mu^-$ collider: the discovery of a Higgs Boson in the mass range beyond that to be covered by LEP I & II (~80-90GeV) and the natural range of the Super Colliders $\geq 2M_Z$ [4,5,6]. In this mass range, as far as we know, the dominant decay mode of the h^0 will be

$$h^0 \to b\bar{b} \tag{1}$$

whereas the Higgs will be produced by the direct channel

$$\mu^+\mu^- \to h^0 \tag{2}$$

which has a cross section enhanced by the ratio

$$\left[\frac{M_\mu}{M_e}\right]^2 \sim (200)^2 = 4\times 10^4 \tag{3}$$

much larger than the corresponding direct product at an $e^+ e^-$ collider. However, the narrow width of the Higgs partially reduces this enhancement. Recent results suggest that the low mass Higgs is preferred[5](Figure 2a).

In the low mass region the Higgs is also expected to be a fairly narrow resonance and thus the signal should stand out clearly from the background from[3]

$$\begin{aligned} \mu^+\mu^- &\to \gamma \to b\bar{b} \\ &\to Z_{tail} \to b\bar{b} \end{aligned} \tag{4}$$

If the resolution requirements can be met, the machine luminosity of ~10^{32}cm^{-2}sec^{-1} could be adequate to facilitate the discovery of the Higgs in the mass range of 100-180GeV.

Finally, another possibility is to use the polarization of the $\mu^+\mu^-$ particles orientated so that only scalar interactions are possible. However, there would be a trade-off with luminosity and thus a strategy would have to be devised to maximize the possibility of success in the energy sweep through the resonance (see Figure 2b for other physics issues)

II. RESULTS FROM THE NAPA AND SAUSALITO $\mu^+\mu^-$ COLLIDER WORKSHOP

At the Napa meeting (1992) a small group of excellent accelerator physicists struggled with the major concepts of a $\mu^+\mu^-$ collider; some results are published in NIM, Oct. 1994[3]. At the Sausalito (1994) meeting a larger group of accelerator, particle and detector physicists were involved. The proceedings will be published by AIP press in 1995.

The major issue confronting this collider development is the possible luminosity that is achievable. Two collider energies were considered: 200x200GeV and 2x2TeV. The major particle physics goals are the detection of the Higgs Boson(s) in the *s* channel for the low energy collider and

Table 1: Parameter list for 400GeV μ+μ- collider, Sausalito, 1994, 200x200GeV working group report.

Parameter	Symbol	Value
Collision energy	$E_c m$	400GeV
Energy/Beam	E_μ	200GeV
Luminosity	$L = \frac{f_n\ n_s\ n_b\ N_\mu^2}{4\pi\ \sigma^2}$	1×10^{31}cm^{-2}sec^{-1}
	Source Parameters	
Proton Energy	E_p	30GeV
Protons/Pulse	$N - p$	$2\times3\times10^{13}$
Pulse Rate	$f - o$	10Hz
μ (prod./accept.)	μ/p	0.03
μ survival	N_μ/N_{source}	0.33
	Collider Parameters	
Number of μ/bunch	$N_{\mu\pm}$	3×10^{11}
Number of bunches	n_B	1
Storage turns	$2n_s$	1500 (B=5T)
Normalized emittance	ε_N	10^{-4} m-rad
μ-beam emittance	$\varepsilon_t = \varepsilon_N / \gamma$	5×10^{-8} m-rad
Interaction focus	β_0	1cm
Beam size at interaction	$\sigma = (\varepsilon_t\ \beta_0)^{1/2}$	2.μm

WW scattering as well as supersymmetric particle discovery[3].

The workshop goal was to see if a luminosity of 10^{32} to 10^{34}cm^{-2}sec^{-1} for the two colliders might be achievable and useable by a detector. There were five working groups on the topics of (1) Physics, (2) 200x200GeV Collider, (3) 2x2TeV Collider, (4) Detector Design and Backgrounds, and (5) μ Cooling and production methods.

Table 1 gives the parameters and luminosity for the low energy collider. Table 2 gives the somewhat more optimistic parameter list for a 2x2TeV collider from the work of Neuffer and Palmer[7]!

The $\mu^+\mu^-$ collider has a powerful physics reach, especially if the $\mu^\pm$ polarization can be maintained. One interesting possibility is the observation of the super symmetric Higgs Boson(s) in the direct channel (see the report by V. Barger et al., from Sausalito meeting). The detector backgrounds will be considerable due to high energy μ decays upstream of the detector.

Table 2: Parameter list for 4TeV μ+μ- Colliders (Neuffer and Palmer)[7].

Parameter	Symbol	Value
Collision energy	$E_c m$	2TeV
Energy per beam	E_μ	200GeV
Luminosity	$L = f_n n_s n_b N_\mu^2 / 4\pi\sigma^2$	10^{34}cm^{-2}sec^{-1}
	Source Parameters	
Proton energy	E_p	30GeV
Protons/pulse	N_p	$2\times3\times10^{13}$
Pulse rate	f_0	10Hz
μ (prod./accept.)	μ/p	15
μ survival	N_μ/N_{source}	25
	Collider Parameters	
Number of μ/bunch	$N_{\mu\pm}$	10^{12}
Number of bunches	n_B	1
Storage turns	$2n_s$	500
Normalized emittance	ε_N	3×10^{-5} m-rad
μ-beam emittance	$\varepsilon_t = \varepsilon_N / \gamma$	1.5×10^{-9} m-rad
Interaction focus	β_0	0.3cm
Beam size at interaction	$\sigma = (\varepsilon_t\beta_0)^{1/2}$	2.1μm

In the summary of working group 4 it was concluded that these backgrounds might be manageable. One key to achieving a high luminosity collider is the collection of the $\mu^\pm$ from $\pi^\pm$ decays over nearly the full phase space over which they are produced. This is far from trivial and leads to conclusions from groups 2 and 3 that the present uncertainty in luminosity is of order $10^{2\pm1}$ (at most 4 orders of magnitude, but perhaps, realistically, 2 orders of magnitude, which, unfortunately, spans the range from being uninteresting to being very interesting). Hopefully, before the next meeting this uncertainty can be reduced. Perhaps the most interesting aspect of a $\mu^+\mu^-$ collider is the need to cool the $\mu^\pm$ beams over a very large dynamics range. Three experimental programs were discussed and are being initiated to study μ cooling: at BNL, FNAL, and a UCLA group is proposing to study cooling and acceleration in crystals at TRIUMF[8]. One major conclusion of the meeting is that $\mu^+\mu^-$ colliders are complimentary to both *pp* (LHC)[6] and e^+e^- (NLC) colliders, especially for the Higgs Sector and for the study of supersymmetric particles.

III. THE POSSIBLE LUMINOSITY OF A $\mu^+\mu^-$ COLLIDER

The luminosity is given by

$$L = M \frac{N_{\mu^+} \ N_{\mu^-} \ f}{4\pi \ \varepsilon_N \ \beta^*} \gamma \qquad (5)$$

The $N_{\mu\pm}$ depend directly on the $\mu^\pm$ production and capture rate (μ/p), f is related to the magnetic field of the collider, ε_N the final μ invariant emittance from the final stage of cooling, and β^* will depend on the bunch length (and the longitudinal cooling of the $\mu^\pm$ beams), as well as the collider lattice.

We can rewrite the luminosity as

$$L \propto \frac{\left(\mu \ / \ p\ \right)^2 B_{\text{collider}} \, \gamma}{\varepsilon_N \ \left(\text{final } \beta^*\right)} \qquad (6)$$

In order to increase L we must increase (μ/p) and B and decrease ε_N and β^*. At the Napa meeting the best judgment of the group was that $(\mu/p) \sim 10^{-3}$ and $\varepsilon_N \sim 1 \text{ x } 10^{-5}\ \pi$m-rad, $\beta^* \sim$ 1cm. For the case of $\gamma = 200$, $L = 2\text{x}10^{30}\text{cm}^{-2}\text{sec}^{-1}$. If, on the other hand, we use the optimistic values of $(\mu/p) = 0.2$[7], $\beta^* = 1/3$cm, and $\varepsilon_N = 3\text{x}10^{-5}$m-rad, we find

$$\begin{aligned} L &= \left[2x\left(4x10^4\right)x3\right] \, L_0 \\ &= 4.8x10^{35} \text{cm}^{-2} \text{sec}^{-1} \end{aligned} \qquad (7)$$

a very large luminosity, never before achieved by any collider! Clearly this must be far too optimistic. It is clear that the (μ/p) ratio is the key parameter of the machine. Table 1 and 2 give some parameters of low energy and high energy colliders.

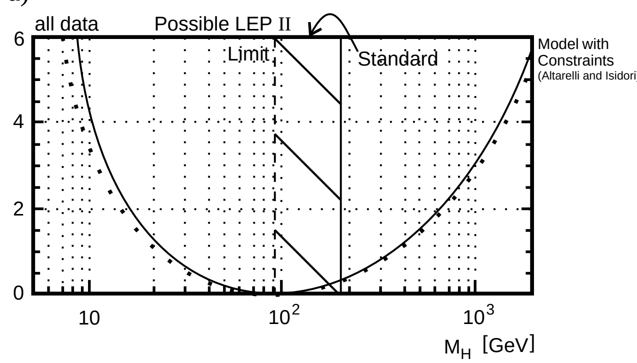
IV. MUON COOLING EXPERIMENT AT TRIUMF

This phase, the first phase of the experiment TRIUMF, will test the cooling mechanisms summarized in the proposal to TRIUMF. The beam momentum will be about 250MeV/c unchanneled muons will penetrate the 4cm crystal and the cooling process can be compared for the two. In addition, a higher energy beam tests cooling at the energies considered for realistic collider schemes. The first step of Phase II is to measure initial and final emittances of an unmodified crystal.

To enhance the cooling, we will generate a strain modulation of the planar channels. An acoustic wave of 1GHz is excited via a piezoelectric transducer. We will also detect predicted channeling radiation by surrounding the crystal with CsI scintillation detectors, which are sensitive to X-rays. Recent ideas on crystals and beams are very interesting.[9,10]

The M11 beamline is presently a source of high energy pions[11,12]. Straightforward modification of the beamline will provide a collimated beam of forward-decay muons at high intensity – about 10^6 per second at 250MeV/c. The longitudinal momentum spread is about 2% FWHM. Assuming optimum tuning of the final focus quadrupole doublet in M11, we can achieve a spot size of 3x2cm with horizontal and vertical divergences of 10m-rad and 16m-rad respectively. The critical angle for planar channeling of μ^+ at 250MeV/c in silicon is about 7m-rad, extrapolating from proton channeling data. A sizable fraction of the muons should channel through a few centimeters of the crystal.

a)



b)

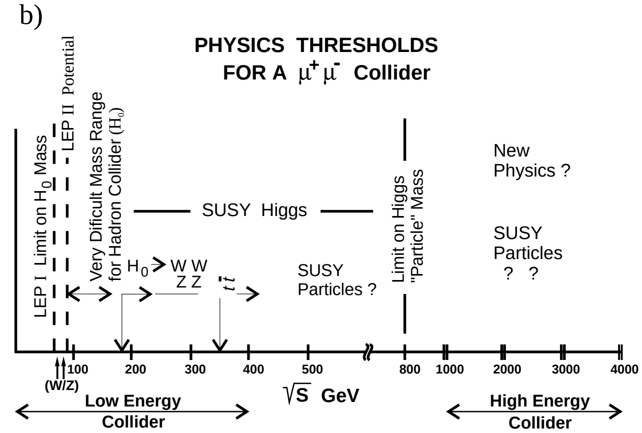


Figure 2 a) Upper and lower bound s on m_{ϕ_0} as a function of m_t, coming from the requirement of a perturbative theory[4]. b) Physics threshold for a μμ collider.

V. HOW TO GET A $\mu^+\mu^-$ COLLIDER STARTED

There are many problems and also possibilities to start a $\mu^+\mu^-$ collider in the USA. For example, if crystal cooling could be used a collider of the type shown in Figure 3 might be constructed[13]. We list the major issues in the development of a collider in Table 3. In the past the only example of such an innovative machine is the $p\bar{p}$ collider initiated by Cline, McIntyre and Rubbia in 1976[14]. In Table 3 we attempt to make a comparison between these two projects! In my opinion the key problem is comparison with the NLC and LHC.

I wish to thank W. Barletta, D. Neuffer, A. Sessler, R. Palmer, F. Mills, and the other participants of the Napa and Sausalito workshops for may interesting discussions. Thanks also to A. Bogacz and P. Sandler for help with this paper.

Table 3:

	For a $\mu^+\mu^-$ Collider Development	Example in Past $p\bar{p}$ Collider (1976-1987)[14] (Cline,McIntyre, Rubbia proposal)
1)	Strong Physics Motivation Higgs, SUSY, etc. etc. (Higgs mass unknown - but it may be at low mass)	*W/Z* Discovery (M_W, *Z* known)
2)	Parameters Study Are they realistic? How can we make a convincing argument	FNAL/CERN Studies (1976-1981)
3)	Beam Manipulation and Cooling Rapid Acceleration Possibility? (μ lifetime constraint)	AA Ring and Beams ($\bar{p}$ production yield)
4)	Demonstration of $\mu^\pm$ Cooling (Experiments) (New Ideas)	p / $\bar{p}$ Cooling ICE Ring Novosibirsk, FNAL (1976-1981)
5)	Detector Concepts and Feasibility Study	UA1/UA2 CDF/D0 Designs 1977-1987

V. REFERENCES

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New Scheme for a $\mu^+\mu^-$ Collider

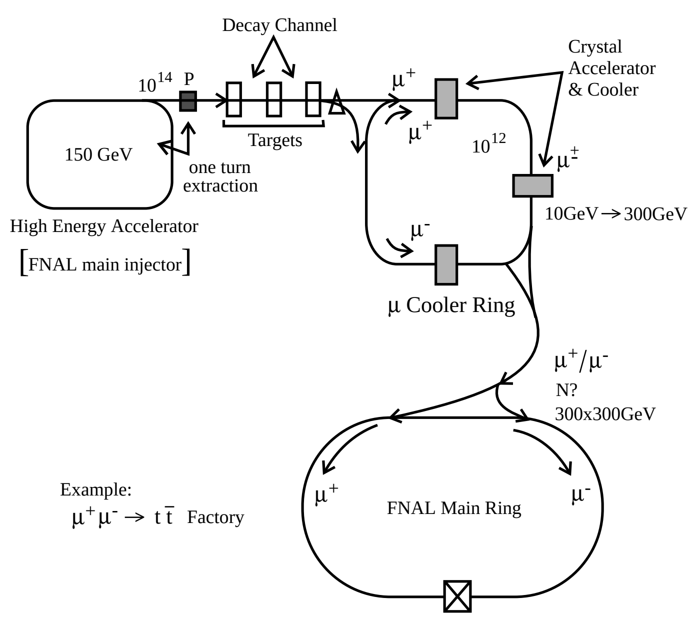

Figure 3: A scheme for a $\mu^+\mu^-$ collider using crystal cooling.