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## **Physics with a Millimole of Muons**

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# Physics with a Millimole of Muons

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**Abstract.** The eventual prospect of muon colliders reaching several TeV encourages us to consider the experimental opportunities presented by very copious stores of muons, approaching  $10^{21}$  per year. I summarize and comment upon some highlights of the *Fermilab Workshop on Physics at the First Muon Collider and at the Front End of a Muon Collider*. Topics include various varieties of  $\mu\mu$  colliders,  $\mu p$  colliders, and applications of the intense neutrino beams that can be generated in muon storage rings.

## INTRODUCTION

The initial appeal of a  $\mu^+\mu^-$  collider is that it may provide a possible path to a few-TeV lepton-lepton collider to address the great issue of our age, the character of the mechanism that breaks electroweak symmetry. It is a commonplace that lepton colliders and hadron colliders offer complementary means to explore the nature of electroweak symmetry breaking [1,2]. It is widely agreed that the rise of synchrotron radiation causes circular electron machines to become impractical for energies above a few hundred GeV. Linear colliders are therefore under development for c.m. energies from a few hundred GeV to about 1.5 TeV. I think it possible that linear-collider technology may only be interesting for about one decade in energy; the growth path beyond 1 to 2 TeV is not clear. But it is a very interesting decade in energy, over which we expect to learn the secrets of electroweak symmetry breaking. That is why there is such intense interest in the linear-collider approach. In contrast, the extrapolation of a  $\mu^+\mu^-$  collider to several TeV per beam seems straightforward—if a  $\mu^+\mu^-$  collider can be made to work at all [3,4]. If the small size of a  $\mu^+\mu^-$  collider is an indication of its cost, which is by no means

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established, a  $\mu^+\mu^-$  collider might even offer a less costly way to a modest-energy lepton collider. Taken together, these two possibilities offer a strong incentive to investigate the technology of a  $\mu^+\mu^-$  collider.

Once the technological possibility of a muon collider is raised, there are many interesting possibilities to contemplate [5]. On the way to the ultimate prize of a 2–4-TeV collider, we may consider a high-luminosity  $Z$  factory and machines to operate near the  $W^+W^-$  and  $t\bar{t}$  thresholds, as well as a machine with  $\sqrt{s} \approx \frac{1}{2}$  TeV to explore details of a supersymmetric or technicolor world for which the first indications have been found elsewhere. A  $\mu^+\mu^-$  collider also offers the unique possibility of a Higgs factory where detailed measurements not possible elsewhere could be undertaken. The front end of a muon collider offers a host of possibilities of its own, including intense low-energy hadron beams, a copious source of low-energy muons, and the neutrino beams of unprecedented intensity and unusual flavor composition that emanate from stored muons. A muon collider in the neighborhood of a hadron storage ring opens the possibility of high-luminosity  $\mu p$  collisions as well.

Many of these possibilities have been explored at this Workshop, which I found notable for the fact that the participants actually did some original work. My first—and most important—conclusion to the Workshop is that there are many *interesting* physics topics to think about.

## The Case for Muons

The muon is massive:  $m_\mu \approx 106 \text{ MeV}/c^2 \approx 207m_e$ . Compared to electrons in a circular machine of given radius, muons of the same energy lose far less energy to synchrotron radiation, by a factor  $(m_e/m_\mu)^4 \approx 5.5 \times 10^{-10}$ . A crippling problem for electron machines—and the reason we turn to linear colliders—is of negligible importance for a muon machine.

In common with the electron, the muon is an elementary lepton at our current limits of resolution. Its energy is not shared among many partons, so the muon is a more efficient delivery vehicle for high energies than is the composite proton.

Because the muon is massive, and can be accelerated efficiently in circular machines, and because we can probe the 1-TeV scale with muons of a few TeV, as opposed to protons of several tens of TeV, a muon collider can be small. If a muon collider proves technically feasible, we need to discover whether small translates to inexpensive—both in absolute terms and compared to other paths we might take to high energies.

Beyond the suggestion of these practical advantages, muons offer a possibly decisive physics advantage. The great seduction of a First Muon Collider is that the cross section for the reaction  $\mu^+\mu^- \rightarrow H$ , direct-channel formation of the Higgs boson, is larger than the cross section for  $e^+e^- \rightarrow H$  by a factor  $(m_\mu/m_e)^2 \approx 42,750$ . This is a very large factor. The tantalizing question

is whether it is large enough to make possible a “Higgs factory” with the luminosities that may be achieved in  $\mu^+\mu^-$  colliders. In  $e^+e^-$  collisions, of course, the  $s$ -channel formation cross section is hopelessly small. That is why the associated-production reaction  $e^+e^- \rightarrow HZ$  has become the preferred search mode at LEP-2.

The properties of the muon also raise challenges to the construction and exploitation of a  $\mu^+\mu^-$  collider. The muon is not free: it doesn’t come out of a bottle like the proton or boil off a metal plate like the electron. On the other hand, it is readily produced in the decay  $\pi \rightarrow \mu\nu$ . Still, gathering large numbers of muons in a dense beam is a formidable engineering challenge, and the focus of much of the R&D effort over the next few years. The muon is also not stable. It decays with a lifetime of  $2.2 \mu\text{s}$  into  $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$ . We must act fast to capture, cool, accelerate, and use muons, and must be able to replenish the supply quickly. Multiply  $2.2 \mu\text{s}$  by whatever Lorentz ( $\gamma$ ) factor you like for a muon collider, it is still a very short time.

The muon’s decay products complicate experimentation as well. Just to indicate the dimensions of the problem, in a  $2 \oplus 2$ -TeV collider with  $2 \times 10^{12}$  muons/bunch, every meter the bunch travels sees  $2 \times 10^5$  decays, with an average electron energy of about 700 GeV.

Finally, the neutrinos emitted in  $\mu$  decay may constitute a radiation hazard. You need not fear the neutrinos themselves. The interaction length of a 100-GeV neutrino is about 25 million kilometers in water, so it has only about 1 chance in  $10^{11}$  of interacting in the column depth of your body. The potential hazard comes from neutrino interactions in the Earth surrounding a  $\mu^+\mu^-$  collider, which generate hadronic showers. Estimates suggest that the potential radiation dose from these showers becomes a serious concern for  $E_\mu \approx 1 - 2 \text{ TeV}$ .

## The Big Questions for $\mu^+\mu^-$ colliders

When we discuss whether there should be muon colliders in our future, we must answer a number of important questions.

- What machines are possible? When? At what cost?
- What are the physics opportunities?
- Can we do physics in the environment? (What does it take?)
- How will these experiments add to existing knowledge not just in the abstract, but *when they are done*?

These questions are not the unique concern of a muon collider, but need to be addressed for any new accelerator we might contemplate. I would like to underscore the importance of the last question: it is crucially important to

try to judge what will be known from ongoing experiments and initiatives already launched at the moment that a new experimental tool could be ready. What seems like essential information—if we could have it today—may fade in significance a decade or more hence. Our goal must be to develop the means to do experiments that can change the way we think. It is worth keeping in mind Bob Palmer’s estimate that a First Muon Collider might be in operation around the year 2010 [6].

## The Focus of This Workshop

The Workshop on Physics at the First Muon Collider and at the Front End of a Muon Collider was organized around nine working groups. One dealt with accelerator issues, concentrating on the design of a proton driver for the Fermilab site. Progress on an RF system, longitudinal space-charge effects, the formation of short bunches a few ns in length, and instability questions was reported by Bob Noble [7]. Four working groups addressed physics prospects for muon colliders. They were organized around Higgs and  $Z$  factories [8], top physics [9], supersymmetry [10], and strong dynamics [11]. Four more working groups explored the physics interest of beams associated with the front end of a muon collider. Those groups considered low-energy hadron physics [12], neutrino physics [13], deep inelastic scattering [14], and low-energy muon physics [15].

## The Front End of a Muon Collider

The Front End of a Muon Collider consists of four basic elements.

- A high-intensity proton source. An example design developed for the Fermilab site ends in a rapid-cycling synchrotron that delivers 16-GeV protons at 15 Hz [16]. In each cycle, two bunches of  $5 \times 10^{13}$  protons are accelerated, for a total of  $1.5 \times 10^{22}$  protons per year. That is about  $10^3$  the number of protons delivered at 8 GeV by the Fermilab Booster.
- A system for pion production, collection, and decay. Charged pions created in the collision of the proton beam with a target are confined in a high-field solenoid and guided into a 20-meter-long decay channel within a 7-Tesla solenoid that keeps the muons from escaping. Such a system might yield about 0.2  $\mu^+$  and  $\mu^-$  per proton, or about  $10^{13}$   $\mu^+$  and  $\mu^-$  per cycle, for a total of about  $1.5 \times 10^{21}$   $\mu^+$  and  $\mu^-$  per year.
- A muon cooling channel to concentrate the muons in six-dimensional phase space. It is hoped that an “ionization cooling” system [17] could compress the muons’ phase space by a factor of  $10^5$ – $10^6$ , leading to dense

**TABLE 1.** Recirculating linear accelerator parameters.

	RLA 1	RLA 2	RLA 3
Input energy [GeV]	1.0	9.6	70
Output energy [GeV]	9.6	70	250
Turns	9	11	12
Linac length [m]	100	300	533.3
Arc length [m]	30	175	520
Bunch length [ps]	158	43	19
Revolution time [ $\mu$ s]	0.9	3.1	7.0
Decay losses	9.0%	5.2%	2.4%
Initial muons per bunch	$5 \times 10^{12}$	$4.6 \times 10^{12}$	$4.3 \times 10^{12}$
$\mu^+$ bunches per sec	15	15	15

bunches of  $5 \times 10^{12}$  muons at 200 MeV/c. In the simplest version of ionization cooling, passage through matter degrades a muon's longitudinal and transverse momentum in proportion. An RF cavity adds longitudinal momentum. Iterating these steps cools the beam in the transverse dimensions. An important refinement uses wedge-shaped degraders in a region of high dispersion, so that high-momentum muons see more material than low-momentum muons. By this device one can cool the beam in both longitudinal and transverse dimensions.

- A muon acceleration system to raise the captured muons quickly to the desired energy. An example presented at the Workshop consists of a series of three recirculating linear accelerators (RLAs), whose properties are summarized in Table 1. The muons are raised in steps from 1 to 10 GeV, from 10 to 70 GeV, and from 70 to 250 GeV. Notice that the number of turns in each RLA is quite small: 9, 11, and 12. The decay losses in the RLAs, while not crippling, are noticeable. From the acceleration system, the muons would be passed to a collider ring of quite modest dimensions.

We see that while the front end of a muon collider is small, it is also complex. The important questions to answer are whether the construction and operation of such a device is feasible, and whether the size or the complexity is decisive in determining its cost.

## A HIGGS FACTORY

The important possibility that a  $\mu^+\mu^-$  collider can operate as a Higgs factory has been studied extensively [18] and received considerable attention at the Workshop [8]. If the Higgs boson is light ( $M_H \lesssim 2M_W$ ), and therefore narrow, then the muon's large mass makes it thinkable that the reactions

$$\mu^+\mu^- \rightarrow H \rightarrow b\bar{b} \text{ and other modes}$$

will occur with a large rate that will enable a comprehensive study of the properties of the Higgs boson. We assume that a light Higgs boson has been found, and that its mass has been determined with an uncertainty of  $\pm(100-200)$  MeV/ $c^2$  [19]. Then suppose that an optimized machine is built with  $\sqrt{s} = M_H$ .

The muon's mass confers another important instrumental advantage: the momentum spread of a muon collider is naturally small, and can be made extraordinarily small. The Higgs factory can operate in two modes:

- modest luminosity ( $0.05 \text{ fb}^{-1}/\text{year}$ ) and high momentum resolution ( $\sigma_p/p = 3 \times 10^{-5}$ );
- standard luminosity ( $0.6 \text{ fb}^{-1}/\text{year}$ ) and momentum resolution ( $\sigma_p/p = 10^{-3}$ ).

At high resolution, the spread in c.m. energy is comparable to the natural width of a light Higgs boson:  $\sigma_{\sqrt{s}} \approx$  a few MeV  $\approx \Gamma(H \rightarrow \text{all})$ . At normal resolution,  $\sigma_{\sqrt{s}} \gg \Gamma(H \rightarrow \text{all})$ .

Parameters of the Higgs factories are given in Table 2, along with those of other candidates for a First Muon Collider [20]. It is worth remarking that the Higgs factory would be small, with a circumference of just 380 meters, and that the number of turns a muon makes in one lifetime is 820.

The first order of business is to run in the high-resolution mode to determine the Higgs-boson mass with exquisite precision. The procedure contemplated is to scan a large number of points (determined by  $2\Delta M_H/\sigma_{\sqrt{s}} \approx 100$ ), each with enough integrated luminosity to establish a three-standard-deviation excess. If each point requires an integrated luminosity of  $0.0015 \text{ fb}^{-1}$ , then the scan requires  $100 \times 0.0015 \text{ fb}^{-1} = 0.15 \text{ fb}^{-1}$ , about three nominal years of running.

**TABLE 2.** Parameters considered at the Fermilab workshop for narrow-band and broad-band Higgs factories, a LEP2 equivalent, a top factory, and a  $\frac{1}{2}$ -TeV FMC.

$\sqrt{s}$ [GeV]	100	100	200	350	500
Momentum spread, $\sigma_p/p$	$3 \times 10^{-5}$	$1 \times 10^{-3}$	$1 \times 10^{-3}$	$1 \times 10^{-3}$	$1 \times 10^{-3}$
Muons per bunch	$3 \times 10^{12}$	$3 \times 10^{12}$	$2 \times 10^{12}$	$2 \times 10^{12}$	$2 \times 10^{12}$
Number of bunches	1	1	2	2	2
Repetition rate [Hz]	15	15	15	15	15
$\epsilon_{\perp}$ [mm·mrad]	$297\pi$	$85\pi$	$67\pi$	$56\pi$	$50\pi$
Circumference [m]	380	380	700	864	1000
$f_{\text{rev}}$ [Hz]	$7.9 \times 10^5$	$7.9 \times 10^5$	$4.3 \times 10^5$	$3.5 \times 10^5$	$3.0 \times 10^5$
Turns per lifetime	820	820	890	1260	1560
$\beta^*$ [cm]	13	4	3	2.6	2.3
$\sigma_z$ [cm]	13	4	3	2.6	2.3
$\sigma_r$ [ $\mu\text{m}$ ]	286	85	47	30	22
$\mathcal{L}_{\text{peak}}$ [ $\text{cm}^{-2}\text{s}^{-1}$ ]	$6 \times 10^{32}$	$7 \times 10^{33}$	$6 \times 10^{33}$	$1 \times 10^{34}$	$2 \times 10^{34}$
$\mathcal{L}_{\text{av}}$ [ $\text{cm}^{-2}\text{s}^{-1}$ ]	$5 \times 10^{30}$	$6 \times 10^{31}$	$1 \times 10^{32}$	$3 \times 10^{32}$	$7 \times 10^{32}$



The reward is that, after the scan, the Higgs-boson mass will be known with an uncertainty of  $\Delta M_H \approx \sigma_{\sqrt{s}} \approx 2 \text{ MeV}/c^2$ , which is quite stunning.

Extended running in the form of a three-point scan of the Higgs-boson line at  $\sqrt{s} = M_H, M_H \pm \sigma_{\sqrt{s}}$  would then make possible an unparalleled exploration of Higgs-boson properties. With an integrated luminosity of  $0.4 \text{ fb}^{-1}$  one may contemplate precisions of  $\Delta M_H \approx 0.1 \text{ MeV}/c^2$ ,  $\Delta \Gamma_H \approx 0.5 \text{ MeV} \approx \frac{1}{6} \Gamma_H$ ,  $\Delta(\sigma \cdot B(H \rightarrow b\bar{b})) \approx 3\%$ , and  $\Delta(\sigma \cdot B(H \rightarrow WW^*)) \approx 15\%$ .

These are impressive measurements indeed. The width of the putative Higgs boson is an important discriminant for supersymmetry, for it can range from the standard-model value to considerably larger values. Within the minimal supersymmetric extension of the standard model (MSSM), the ratio of the  $b\bar{b}$  and  $WW^*$  yields is essentially determined by  $M_A$ , the mass of the  $CP$ -odd Higgs boson. In the decoupling limit,  $M_A \rightarrow \infty$ , the MSSM reproduces the standard-model ratio. Deviations indicate that  $A$  is light. In the most optimistic scenario, this measurement could determine  $M_A$  well enough to guide the development of a second ( $CP$ -odd) Higgs factory using the reaction  $\mu^+ \mu^- \rightarrow A$ .

Again, these remarkable measurements exact a high price. At the Workshop luminosity of  $0.05 \text{ fb}^{-1}/\text{year}$ , it takes 8 years to accumulate  $0.40 \text{ fb}^{-1}$  *after the scan* to determine  $M_H$  within machine resolution. It is plain that this program becomes considerably more compelling if the Higgs-factory luminosity can be raised by a factor of 2 or 3—or more!

These projections are based on theorists' simulations; more attention is needed to experimental realities. Precision measurements at LEP and SLC have benefitted from excellent determinations of the luminosity  $\mathcal{L}$ , the beam energy, and the lepton polarization. For a muon collider, it has been shown that the muon spin tune  $\gamma(g_\mu - 2)/2$  offers a means of determining the beam energy to a few parts per million and the lepton polarization in real time [21]. Exploiting the fact that, for a muon collider ring with  $\sqrt{s} \approx M_Z$  the muon's spin approximately flips from turn to turn, one measures the decay-electron energy spectrum as a function of turn number. The frequency of the spin oscillations yields the Lorentz factor  $\gamma$ , and hence the beam energy, while the amplitude of the modulations in the energy spectrum is a measure of the beam polarization.

It is less clear how to make a precision determination of the luminosity. An analogue of the standard  $e^+e^-$  method of small-angle Bhabha monitors seems ruled out by the high flux of decay electrons. Indeed, the first-pass concepts for muon collider detectors do not instrument a cone of  $\pm(10-20)^\circ$  around the beam line [22]. For now we will assume that  $\delta\mathcal{L}/\mathcal{L} = 10^{-3}$ , but it is an important exercise to develop robust schemes for making this measurement.

Let us note finally that the flux of decay electrons challenges the operation of silicon detectors close to the interaction point [23].

## OTHER OPTIONS FOR THE FMC

Several other candidates for the First Muon Collider have been studied at this Workshop. In order of increasing energy, they are a  $Z$  factory, machines to explore the  $W$ -pair and top-pair thresholds, and a continuum machine operating at  $\sqrt{s} = 500$  GeV. The parameters assumed for these machines are displayed in Table 2. It is worth noting that the average luminosities considered at the Workshop are about an order of magnitude smaller than those projected for  $e^+e^-$  linear colliders [24]. Unless there are compensating advantages for a  $\mu^+\mu^-$  collider—the superior beam energy resolution, for example—the luminosity that can be achieved will be decisive.

A very-high-luminosity  $Z$  factory, say twenty times the luminosity of LEP, would be a superb device for  $B$  physics. There is also unfinished business in the precision measurement of electroweak observables, particularly in light of the discrepancy between the value of the weak mixing parameter  $\sin^2\theta_W$  inferred from the SLD measurement of  $A_{LR}$  and the value determined from a host of measurements at LEP. Alain Blondel [25] emphasized the desirability of controlling independently the polarizations of  $\mu^+$  and  $\mu^-$  for refining our understanding of  $\sin^2\theta_W$ . Apart from the challenge of attaining adequate luminosity, an open issue for precision electroweak measurements in a  $\mu^+\mu^-$  collider is how to monitor the luminosity to high precision.

Although a  $\mu^+\mu^-$  collider operating at  $W^+W^-$  threshold could make impressive measurements of the  $W$ -boson mass, with  $\delta M_W \approx 20$  MeV in  $10 \text{ fb}^{-1}$  [26], it is hard to imagine that this will be an important goal in the year 2010. Experiments at LEP2 and the Tevatron Collider may soon give us a world average uncertainty approaching 50 MeV, and future running at the LEP2, the Tevatron, and the LHC will push the precision further.

It is possible that extensive measurements near top threshold could hold greater interest [27,9]. In principle, such measurements might yield extraordinarily precise measurements of the top-quark mass  $m_t$ , and give information on the strong coupling constant  $\alpha_s$  and the Higgs- $t\bar{t}$  coupling  $\zeta_t$ . For those studies, the superb momentum spread of a  $\mu^+\mu^-$  collider—about an order of magnitude better than the momentum spread of a linear collider—could be a winning advantage. I have to say that I am not convinced that the advertised determinations of  $m_t$ ,  $\alpha_s$ , and  $\zeta_t$  are actually attainable. I fear that the statement that the ambiguity in defining  $m_t$  is no larger than  $\pm\Lambda_{\text{QCD}}$  may be too glib. I am also concerned that the theoretical link between the shape of the  $t\bar{t}$  excitation curve and  $m_t$ ,  $\alpha_s$ , and  $\zeta_t$  is more ambiguous than has generally been assumed [28]. It is important to look critically at these questions as we assess the capabilities of both a  $\mu^+\mu^-$  collider and a linear collider.

Let us now look briefly at some physics prospects of a 500-GeV  $\mu^+\mu^-$  collider. There are rich possibilities for detailed study of the spectrum and properties of superpartners. Strategies for constraining the (many) parameters of supersymmetric models in linear colliders have been documented extensively.

For the most part, the case for the study of supersymmetry in a  $\mu^+\mu^-$  collider is quite parallel to that for a linear collider [29,10]. (We have already noted the unique possibility to form the Higgs bosons in the  $s$ -channel reactions  $\mu^+\mu^- \rightarrow h, H, A$ .) Linear colliders and  $\mu^+\mu^-$  colliders have different possibilities for exploiting beam polarization; how best to use polarization in a muon collider is a good issue for further study. In specific cases considered at the Workshop, luminosity appeared to be a concern. This was especially the case for the discovery and study of sleptons. Since hadron colliders are not well suited to the search for sleptons, it is important that a lepton collider excel in slepton physics.

If evidence for new strong dynamics represented by light-scale technicolor is found elsewhere, a  $\mu^+\mu^-$  collider will also have very significant capabilities for following up that discovery [11,30,31]. Technivector mesons with masses in the range 200-400 GeV/ $c^2$  would be produced copiously even at a luminosity of  $10^{32}$  cm $^{-2}$ s $^{-1}$  [32]. A linear collider would offer similar possibilities, within the limitations of its  $\sim 3\%$  beam energy resolution. It was recognized at this Workshop that a  $\mu^+\mu^-$  collider could be an impressive technipion factory, forming  $\mu^+\mu^- \rightarrow \pi_T^0$  at an appreciable rate [11]. The rate for  $e^+e^- \rightarrow \pi_T^0$  is, of course, negligible.

A new element in the comparison with a linear collider is the claim by the DESY group [33] that it may be possible to increase the projected luminosity of a 500-GeV linear collider by more than an order of magnitude, perhaps to  $\sim 10^{35}$  cm $^{-2}$ s $^{-1}$ . We have an obligation to explore how physics reach depends on luminosity for  $e^+e^-$  linear colliders and  $\mu^+\mu^-$  colliders alike.

## A $\mu p$ COLLIDER?

If an energetic muon beam is stored in proximity to a high-energy proton beam, it is natural to consider the possibility of bringing them into collision. One concept considered at the Workshop was to collide a 200-GeV muon beam with the Tevatron's 1-TeV proton beam, with a mean luminosity of  $1.3 \times 10^{33}$  cm $^{-2}$ s $^{-1}$ , for an annual integrated luminosity of about 10 fb $^{-1}$  [34]. Such a machine would have an impressive kinematic reach, with  $\sqrt{s} \approx 0.9$  TeV and  $Q_{\max}^2 \approx 8 \times 10^5$  GeV $^2$ . For comparison, the  $e^\pm p$  collider HERA currently operates with 27.5-GeV electrons on 820-GeV protons, for  $\sqrt{s} \approx 0.3$  TeV and  $Q_{\max}^2 \approx 9 \times 10^4$  GeV $^2$ . The energy of the proton beam will increase over the next two years to 1 TeV, raising the c.m. energy by about 10%. The lifetime integrated luminosity of HERA is projected as 1 fb $^{-1}$ .

Because of the high luminosity and the large kinematic reach, physics at high  $Q^2$  is potentially very rich. In one year of operation (*i.e.*, at 10 fb $^{-1}$ ), the  $\mu p$  collider would yield about a million charged-current  $\mu^- p \rightarrow \nu_\mu + \text{anything}$  events with  $Q^2 > 5000$  GeV $^2$ . The ZEUS detector at HERA has until now recorded 326 charged-current events in that régime. The search for new phe-

nomena, including leptoquarks and squarks produced in  $R$ -parity-violating interactions, would be greatly extended.

On the other hand, the study of low- $x$  collisions appears very difficult because of the asymmetric kinematics and the angular cutoffs foreseen for detectors in the muon-storage-ring setting. A general question is what kind of detectors would survive the harsh environment of the  $\mu p$  collider.

## NEUTRINO BEAMS FROM STORED MUONS

The idea of using stored muons to produce neutrino beams of a special character has arisen repeatedly. A neutrino beam derived from the decay

$$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$$

is very different from the traditional beams derived from the decays of pions and kaons. The neutrino beam generated in  $\mu^-$  decay contains  $\nu_\mu$  and  $\bar{\nu}_e$ , but no  $\bar{\nu}_\mu$ ,  $\nu_e$ ,  $\nu_\tau$ , or  $\bar{\nu}_\tau$ . It is much richer in electron (anti)neutrinos than a traditional neutrino beam, and muon *neutrinos* are accompanied by electron *antineutrinos*. A neutrino beam derived from muon decay has therefore been seen as a way to remedy the absence of  $\nu_e$  and  $\bar{\nu}_e$  beams at high-energy accelerators. The idea of storing very large quantities of muons—about a millimole per year—adds an important new element to the discussion, for now we can consider muon storage rings as extremely intense neutrino sources.

Neutrino beams generated by the decay of  $10^{20}$  -  $10^{21}$  stored muons per year would make possible investigations of an entirely unprecedented nature: studies of deeply inelastic scattering in thin targets, and neutrino-oscillation studies over a wide range of distance/energy and at very great distances.

In the rest frame of the decaying muon, the distribution of muon-type neutrinos produced in the decays ( $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$ ,  $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$ ) is

$$\frac{d^2 N_{(\nu_\mu, \bar{\nu}_\mu)}}{dx d\Omega} = \frac{x^2}{2\pi} [(3 - 2x) \pm (1 - 2x) \cos \theta] ,$$

where  $\theta$  is the angle between the neutrino momentum and the muon spin and  $x = 2E_\nu/m_\mu$  is the scaled energy carried by the neutrino. The distribution favors  $x = 1$  with ( $\nu_\mu$  opposite,  $\bar{\nu}_\mu$  along) the muon spin direction. The distribution of electron-type neutrinos produced in  $\mu^\mp$  decay is somewhat softer; it is given by

$$\frac{d^2 N_{(\bar{\nu}_e, \nu_e)}}{dx d\Omega} = \frac{3x^2}{\pi} [(1 - x) \pm (1 - x) \cos \theta] ,$$

which peaks at  $x = \frac{2}{3}$  for ( $\bar{\nu}_e$  along,  $\nu_e$  opposite) the muon spin direction. In a neutrino beam generated by  $\mu^-$  decay, we would study at the same time, and in approximately equal proportions, the charged-current reactions  $\nu_\mu N \rightarrow$

$\mu^- + \text{anything}$  and  $\bar{\nu}_e N \rightarrow e^+ \rightarrow \text{anything}$ , along with the corresponding neutral-current reactions in a statistical mixture.

Let us examine the capabilities of a high-energy neutrino beam for deeply inelastic scattering experiments. Two variants were considered at the Workshop [20]. In the first, the 533-m straight section of RLA 3, the final recirculating linear accelerator in the Front End, provides the decay region. Muons enter RLA 3 at 70 GeV and are accelerated in 12 turns to 250 GeV. The muon energy is therefore different on each turn, and increasing along the linac. The mean neutrino energy  $\langle E_\nu \rangle \approx 135$  GeV. The resulting neutrino beam is well collimated; at 600 meters downstream, half the neutrinos lie within 25 cm of the linac axis. In the second scheme, a 10-meter straight section in a 250-GeV  $\mu^+\mu^-$  collider ring yields neutrinos with  $\langle E_\nu \rangle \approx 178$  GeV during 1560 turns. This beam is even better collimated, with about half the neutrinos within 15 cm of the axis 600 meters downstream. The neutrino flux per year is prodigious, about a thousand times the flux the NUTEV detector received in a year of running with a traditional neutrino beam.

The gigantic flux of neutrinos from a millimole of stored muons means that the familiar massive neutrino detectors would be inappropriate devices [35]. Thin targets, instead of extremely massive target calorimeters, become the order of the day. For example, a 1-meter liquid hydrogen target 600 meters downstream of RLA 3 would record  $10^7$  deeply inelastic events per year. We could therefore measure parton distributions of the proton directly, instead of inferring them from measurements made on heavy (typically, iron) targets. The high rates and light targets should also make it possible to extend measurements of the parton distributions to smaller values of  $x_{\text{Bjorken}}$  than has been possible before in neutrino scattering. The neutral-current / charged-current ratio could be measured with tiny statistical error, making possible an indirect measurement of the  $W$ -boson mass with  $\delta M_W = (20-50)$  MeV/ $c^2$ . By reconstructing  $10^5$  charmed particles per year, we could make improved measurements of the quark-mixing matrix element  $|V_{cd}|$  and significantly advance our knowledge of the strange quark and antiquark distributions within the nucleon.

There are other possibilities as well. Polarized targets might make it possible to probe details of the distribution of spin within the proton, perhaps even to study the polarization of minority components like the  $s$  and  $\bar{s}$  sea. And we could consider the uses of high-resolution silicon detectors for special studies involving heavy flavors.

Neutrino beams from muon decay offer dramatic new possibilities for the study of neutrino oscillations. The paucity of electron neutrinos and antineutrinos in traditional neutrino beams is the reason why we have limited knowledge of  $\nu_e \leftrightarrow \nu_\tau$  oscillations: the  $\bar{\nu}_e$  available at reactors are too low in energy to permit  $\tau$ -lepton appearance experiments. That limitation would be removed with muon-decay neutrino beams. In addition, the intense fluxes will permit flexible experimentation over great distances.

Consider a beam of  $\nu_\mu$  and  $\bar{\nu}_e$  produced in  $\mu^-$  decay. In a detector that can measure the charge of leptons produced in charged-current interactions, it will be possible to distinguish the expected reactions

$$\nu_\mu N \rightarrow \mu^- + \text{anything} \text{ and } \bar{\nu}_e N \rightarrow e^+ + \text{anything}$$

from the oscillation-induced reactions

$$(\nu_\mu \rightarrow \nu_e)N \rightarrow e^- + \text{anything} \text{ and } (\bar{\nu}_e \rightarrow \bar{\nu}_\mu)N \rightarrow \mu^+ + \text{anything} .$$

In addition to these appearance experiments (of a new and interesting kind), we can look for distortions of the charged-lepton energy spectra that might signal oscillations. For beams of sufficiently high energy, it will also be possible to perform appearance experiments in search of

$$(\nu_\mu \rightarrow \nu_\tau)N \rightarrow \tau^- + \text{anything} \text{ and } (\bar{\nu}_e \rightarrow \bar{\nu}_\tau)N \rightarrow \tau^+ + \text{anything} .$$

Steve Geer has made a preliminary study of the fluxes and event rates that could be anticipated from a muon storage ring [36]. A rough optimization of a storage ring to maximize the neutrino flux in a given direction results in a ring that consists of two semicircular arcs and two straight sections, with all segments of equal length. In this way, 25% of the muons decay while pointing at the detector. In the conceptual designs under consideration, the typical length of an arc (hence, of a straight section) is about

$$\ell = 75 \text{ m} \times \left( \frac{p_\mu}{40 \text{ GeV}/c} \right) ,$$

which is short. Accordingly, it is reasonable to consider installing a ring sloped at a steep angle to point to a distant detector [37]. Some interesting possibilities are presented in Table 3. In the case of conventional neutrino beams from meson decay, which require a decay region about a kilometer long, tunneling costs threaten to become prohibitive for dip angles greater than a few degrees.

Not only are the dimensions (including the maximum depth) of the muon storage ring reasonable, the fluxes at distant detectors are impressively large. Geer has estimated that a 20-GeV muon beam would generate a flux of a few  $\times 10^{10}$   $\nu/\text{m}^2/\text{year}$  at the Gran Sasso Laboratory, some 7332 km from Fermilab. [A useful comparison may be that the NUTEV detector saw a flux of

**TABLE 3.** Possible sites for long-baseline neutrino experiments using beams generated in a muon storage ring at Fermilab.

Location	Distance [km]	Dip Angle	Heading
Soudan Mine, Minnesota	729	3°	336°
Gran Sasso, Italy	7332	35°	50°
Kamioka Mine, Japan	9263	47°	325°

about  $10^9$   $\nu/\text{m}^2/\text{minute}$  in the 1997 run.] The fluxes at the Soudan Mine in Minnesota would be about a hundred times larger, and ten times the flux planned for the MINOS experiment.

Since an important figure of merit for neutrino-oscillation searches is  $L/E$ , the ratio of path length to neutrino energy, it may be advantageous to keep the muon energy low. For 20-GeV muons, about 100 charged-current events would occur per kiloton per year in the Gran Sasso. Both the fluxes and the rates rise with muon-beam energy, but there is a price to pay in  $L/E$ .

The properties of neutrino beams produced in the decay of large numbers of muons are altogether very remarkable. The possibilities for experiments are quite astounding. We need to ask what a plausible experimental program might be, and whether the experiments are merely amazing, or truly interesting. We also need to ask the important practical question: can this really be done?

## SUMMARY REMARKS

We do not yet know whether a  $\mu^+\mu^-$  collider will be a practical tool for particle physics, but the animated discussions at this Workshop and the diversity of ideas reported in this volume are evidence that the prospect of a  $\mu^+\mu^-$  collider gives us much to think about. Some of the possibilities I have discussed in this short summary, as well as others to be found elsewhere in these Proceedings, represent opportunities that are both unique and remarkable. This has been an unusually stimulating workshop, for the novelty and reach of the ideas we have discussed. An important conclusion is that the campaign to explore the feasibility and utility of a  $\mu^+\mu^-$  collider is serious—and fun.

The original motivation for the  $\mu^+\mu^-$  collider remains the central goal: a practical lepton collider with multi-TeV beams.

I would like to conclude with a few general observations inspired by what we have heard during the Workshop.

- The various machines discussed as the First Muon Collider (which some have called the Next Lepton Collider) all are luminosity poor. The interesting—and unique—program that has been outlined for a Higgs factory would be a far more compelling prospect if it could be carried out over a few years, rather than a decade.
- A program that includes many collider rings dedicated to specific studies: a Higgs factory, a top factory, a  $\frac{1}{2}$ -TeV collider, etc., appears very rich. We have to keep in mind the realities of the muon economy: not all elements of a multiring complex will operate at once. That means that different kinds of experiments will necessarily be sequential or interleaved. We cannot ignore *when* experiments might be done when we try to assess the impact they will have on physics.

- Even modest polarization can be highly useful, especially if it can be controlled flexibly, and separately for  $\mu^+$  and  $\mu^-$ . It is an advantage if polarization can be reversed on demand.
- Single-muon-ring devices do not seem to lack intensity. The capabilities of the intense neutrino beams produced in the decays of stored leptons appear very well matched to the demands of the physics.

It is important for us to learn whether a  $\mu^+\mu^-$  collider should be part of our future. I see four important short-term goals. ¶ Determine the overall feasibility of the muon-collider idea, with the goal of a high-performance, low-cost lepton collider that reaches several TeV. ¶ Learn whether it is possible to build a  $\mu^+\mu^-$  collider as a Higgs factory, with adequate luminosity to carry out the initial survey in only a few years and growth potential to make it worthwhile to exploit Higgs physics for a decade. ¶ Make serious designs of muon storage rings as neutrino sources and investigate their potential for transforming neutrino physics. It is possible that this approach to neutrino physics might make sense even before we know whether a muon collider is viable. ¶ Develop realistic conceptual designs for muon-collider detectors, paying careful attention to the challenges of the experimental environment, especially for heavy-flavor tagging. Explore adventurous designs for neutrino detectors that would take advantage of the unique character of muon-produced neutrino beams.

In assessing all the possibilities for muon-collider physics and for the physics opportunities that arise from the front end of a muon collider, we must judge as carefully as we can what will be the scientific impact of experiments we could carry out using these adventurous new devices. The idea of a  $\mu^+\mu^-$  collider is bold indeed; it calls for bold experiments that can change the way we think.

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