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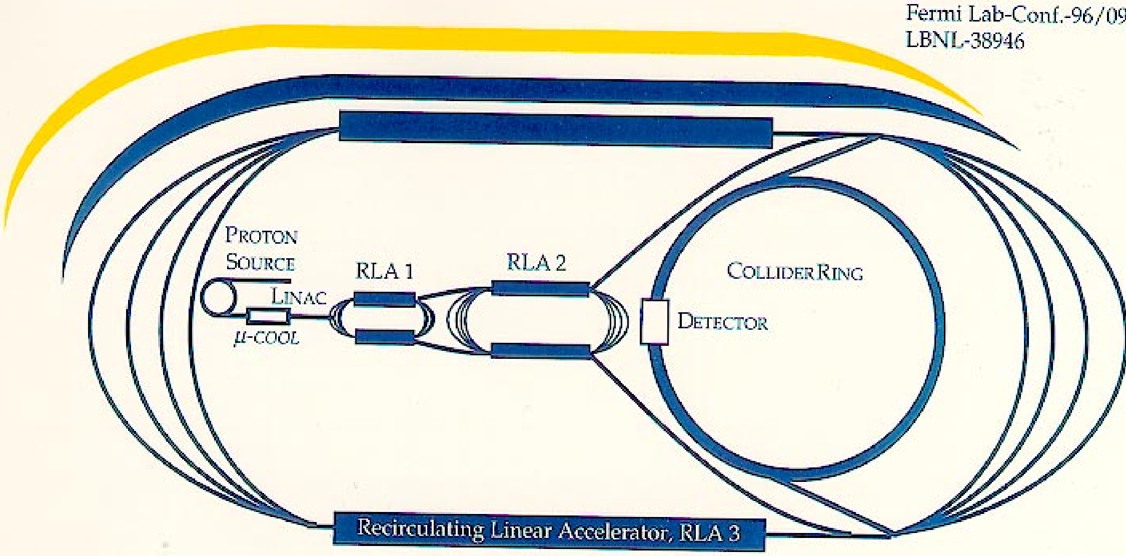

$\mu^+ \mu^-$ Collider
A Feasibility Study

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MUON MUON COLLIDER: A FEASIBILITY STUDY

The $\mu^+\mu^-$ Collider Collaboration[1]

September 27, 1996

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EXECUTIVE SUMMARY

Introduction

A feasibility study is presented of a $\mathbf{2+2}\,\mathrm{TeV}$ muon collider with a luminosity of $\mathcal{L}=\mathbf{10^{35}}\,\mathrm{cm}^{-\mathbf{2}}\mathrm{s}^{-\mathbf{1}}$. The resulting design is not optimized for performance, and certainly not for cost; however, it does suffice–we believe–to allow us to make a credible case, that a muon collider is a serious possibility for particle physics and, therefore, worthy of **R&D** support so that the reality of, and interest in, a muon collider can be better assayed. The goal of this support would be to completely assess the physics potential and to evaluate the cost and development of the necessary technology.

The muon collider complex consists of components which first produce copious pions, then capture the pions and the resulting muons from their decay; this is followed by an ionization cooling channel to reduce the longitudinal and transverse emittance of the muon beam. The next stage is to accelerate the muons and, finally, inject them into a collider ring wich has a small beta function at the colliding point. This is the first attempt at a point design and it will require further study and optimization. Experimental work will be needed to verify the validity of diverse crucial elements in the design.

Muons because of their large mass compared to an electron, do not produce significant synchrotron radiation. As a result there is negligible beamstrahlung and high energy collisions are not limited by this phenomena. In addition, muons can be accelerated in circular devices which will be considerably smaller than two full-energy linacs as required in an e^+-e^- collider. A hadron collider would require a CM energy 5 to 10 times higher than 4 TeV to have an equivalent energy reach. Since the accelerator size is limited by the strength of bending magnets, the hadron collider for the same physics reach would have to be much larger than the muon collider. In addition, muon collisions should be cleaner than hadron collisions.

There are many detailed particle reactions which are open to a muon collider and the physics of such reactions–what one learns and the necessary luminosity to see interesting events–are described in detail. Most of the physics accesible to an e^+-e^- collider could be studied in a muon collider. In addition the production of Higgs bosons in the s-channel will allow the measurement of Higgs masses and total widths to high precision; likewise, $t\bar{t}$ and W^+W^- threshold studies would yield m_t and m_W to great accuracy. These reactions are at low center of mass energy (if the MSSM is correct) and the luminosity and $\Delta p/p$ of the beams required for these measurements is detailed in the Physics Chapter. On the other hand, at $\mathbf{2+2}\,\mathrm{TeV}$, a luminosity of $\mathcal{L} \approx \mathbf{10^{35}}\,\mathrm{cm}^{\mathbf{-2}}\,\mathrm{s}^{\mathbf{-1}}$ is desirable for studies such as, the scattering of longitudinal W bosons or the production of heavy scalar particles. Not explored in this work, but worth noting, are the opportunities for muon-proton and muon-heavy ion collisions as well as the enormous richness of such a facility for fixed target physics provided by the intense beams of neutrinos, muons, pions, kaons, antiprotons and spallation neutrons.

To *see* all the interesting physics described herein requires a careful study of the operation of a detector in the very large background. Three sources of background have been identified. The first is from any halo accompanying the muon beams in the collider ring. Very carefully prepared beams will have to be injected and maintained. The second is due to the fact that on average 35 % of the muon energy appears in its decay electron. The energy of the electron subsequently is converted into EM showers either from the synchrotron radiation they emit in the collider magnetic field or from direct collision with the surrounding material. The decays that occur as the beams traverse the low beta insert are of particular concern for detector backgrounds. A third source of background is $e^+ - e^-$ pair creation from $\mu^+ - \mu^-$ interaction. Studies of how to shield the detector and reduce the background are addressed in the Detector Chapter.

Polarization of the muons allows many very interesting measurements which are discussed in the Physics Chapter. Unlike the electron collider in which the electron beam is highly polarized and the positron beam unpolarized, both muon beams may be partially polarized. It is necessary to select forward moving muons from the pion's decay and thus reduce the available number of muons and hence the luminosity. The necessary machine technology needed to achieve such a collider is discussed in the Option Chapter; at the moment it is not part of our point design, although such capability would almost certainly be incorporated into an actual device.

The Machine

A major portion of this report is devoted to the details of a muon collider complex. The *driver* of a muon collider is a 30 GeV proton synchrotron capable of providing 2.5×10^{13} protons per bunch with four bunches per pulse and 15 Hz pulse rate. The repetition rate, but not the number of protons, is beyond that of any existing machine, but not so far beyond as to seem unrealistic. In fact, the criteria are almost met by the design of KAON. The protons are driven into a target, most likely a liquid target, where copious pions are produced (about one pion per proton). Questions of target survivability are discussed in the

Target Chapter. The target is surrounded by a 20 T solenoidal field, which is adiabatically matched to a 5 T solenoid in the decay channel. The captured pions have a wide range of energy, with a useful range from 100 MeV up to 1 GeV. A strong *phase-rotating* rf field is used to reduce this energy spread as well as the longitudinal extent of the beam. This results in approximately 0.3 muons per proton with mean energy of 150 MeV and a $\pm 20\,\%$ rms energy spread. The muons (about 8×10^{12}) are subsequently cooled by means of ionization cooling which is achieved in a periodic channel consisting of focusing elements, solenoids and/or lithium lenses and absorber at places of small beam size (but corresponding large transverse beam angles) and rf cavities to make up for the energy loss. In some locations along the channel, dispersion is introduced and wedge shaped absorbers are used to produce longitudinal cooling. This is described in the Cooling Chapter. We allow for further loss, beyond natural decay, between the number of captured muons and the final number of muons at the collider ring; at the entrance of the acceleration system is 3×10^{12} per bunch.

After cooling, the muons are accelerated in a cascaded series of recirculating linear accelerators, as described in the Acceleration Systems Chapter. A conventional synchrotron cannot be used as the acceleration is too slow and the muons will decay before reaching the design energy. On the other hand, it is possible to consider synchrotron-like pulsed magnets in the arcs of a recirculator. It should be noted that the primary cost of a muon collider complex is in the acceleration, so care and attention must be devoted to this matter. However, the process is reasonably straight-forward.

The collider ring is injected with two bunches of each sign of 2×10^{12} high energy muons. Approximately 1000 turns occur within a luminosity lifetime, thus making a ring (in contrast with a single collision) advantageous. In order to reach the desired high luminosity, it is necessary to have a very low beta, of the order of 3 mm, (and associated very large betas in the focusing quadrupoles) at the insertion point. Since the muons only live about 1000 turns, numerical simulations can easily provide us with quantitatively correct information. It is necessary to run the ring nearly isochronously so as to prevent bunch spreading and yet keep the rf impedance low enough as to prevent collective instabilities. Space charge effects, and beam-beam effects, in the collider ring are being studied and some conclusions are presented in the Collider Ring Chapter. Such a ring has never been built, but should be possible to construct and operate.

The muon complex requires numerous superconducting magnets. These are needed in the capture section, in the decay channel, in the arcs of the recirculating accelerators, and in the collider ring. Attention has been given to these magnets, as well as to the very special magnets required for the interaction region, and these various considerations may be found in the appropriate chapters.

A study of the scaling laws governing muon colliders is presented in the Options Chapter. Naturally, one would, if the concept is shown to be of interest, initially construct a lower energy machine (perhaps in the hundreds of GeV region) and thus the scaling laws are of special interest. In particular, a *lower energy demonstration machine* of $\mathcal{L} = \mathbf{10^{33}}\,\mathrm{cm}^{\mathbf{-2}}\mathrm{s}^{\mathbf{-1}}$ at $250 + 250\,\mathrm{GeV}$ could serve as a breadboard for exploring the properties and technologies needed for this class of colliders while providing useful physics.

Conclusions

We suggest that to make sensible decisions about the future, the potential of a muon collider must be explored as rapidly and aggressively as possible. The accompanying document furnishes a solid base for identifying areas where more study and/or innovations are needed. In particular, **R&D** needs to be done related to the muon cooling channel, recirculating superconducting magnets or pulsed magnets for the accelerator in order to arrive at a design that minimizes cost. The magnets for the collider ring have a high heat load from muon decay electrons. Configurations other than a $\cos(\theta)$ magnet, such as a C-magnet, require study and modeling. The performance of rf cavities in the presence of intense radiation needs to be measured.

A sustained, extensive and integrated program of component development and optimization will have to be carried out in order to be assured that the design parameters can be attained and the cost minimized. The technology for the most part already exists within the High Energy Physics community and the work should involve the US, Europe, Russia, Japan and the international HEP community as a whole.

FOREWORD

This is a first attempt to gather in a single document the technical options and status of an ever evolving prospective high-energy (2+2 TeV), high-luminosity ($\mathcal{L} = 2 \times 10^{35} cm^{-2} s^{-1}$) $\mu^+\mu^-$ Collider.

This report is the compendium of the collaborative effort of scientists from Brookhaven National Laboratory (BNL), Fermi National Accelerator Laboratory (Fermilab) and Lawrence Berkeley National Laboratory (LBNL) with significant contributions from individual researchers from SLAC, KEK, CERN and US universities.

The first organizational meeting took place in October 1995, during the *9th Advanced ICFA Beam Dynamics Workshop* held in Montauk, NY. After some discussions, a steering committee was named to write and edit the various chapters of this *book*.

Three steering committee meetings were held (BNL, February; Fermilab, April and LBNL, May) to assess the progress of the chapters and to consider new promising technical alternatives.

A system connected to the INTERNET was implemented in a server (`http://www.bnl.gov/`), which can be easily reached with a WEB browser, with entry at the BNL Muon Collider Study Group WEB site:

`http://www.bnl.gov/~cap/mumu/mu_home_page.html`

Studies of the physics goals and requeriments of a $\mu^+\mu^-$ Collider began formally, with several workshops and symposiums, after the Port Jefferson Third Advanced Accelerator Concepts Workshop, June 14-20, 1992, where a working group on *Physics Opportunities* considered the merits of such a collider.[1] Inmediately after Port Jefferson, a special workshop was held in Napa, California, in the fall of 1992.[2] This was followed by the second workshop

[1]P. Chen and K. MacDonald, *Summary of the Physics Opportunities Working Group*, AIP Conference Proceedings **279**, Advanced Accelerator Concepts, Ed. J. Wurtele, 853 (1993)

[2]*Proceedings of the Mini-Workshop on $\mu^+\mu^-$ Colliders: Particle Physics and Design*, Napa CA, Nucl. Inst. and Meth., **A350** (1994); Ed. D. Cline

on *Physics Potential and Development of* $\mu^+\mu^-$ *Colliders*, Sausalito California, 1994.[3], the 9th Advanced ICFA Beam Dynamics Workshop, Montauk, New York in October 1995[4] and the Symposium on Physics Potential and Development of $\mu^+\mu^-$ Colliders at San Francisco, CA December 1995.[5]

I would like to acknowledge the contribution of Kathleen Tuohy, Patricia Tuttle and "Sam" Vanecek for their attention to details, that contributed greatly to making this report readable.

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For the $\mu^+\mu^-$ Collaboration

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[3] *Physics Potential and Development of* $\mu^+\mu^-$ *Colliders, 2*nd *Workshop*, Sausalito, CA, Ed. D. Cline, AIP Press, Woodbury, New York (1995)

[4] *Proceedings of the 9th Advanced ICFA Beam Dynamics Workshop*, Ed. J. Gallardo, AIP Press (1996)

[5] *Proceedings Symposium on Physics Potential and Development of* $\mu^+\mu^-$ *Colliders*, San Francisco, CA December 1995, Supplement to Nucl.Phys. B, Ed. D. Cline and D. Sanders, to be published

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