Prospects for a Muon Collider

Kirk T. McDonald

Princeton U.
mcdonald@puphep.princeton.edu

July 17, 1998

BNL AGS/RHIC User’s Meeting

Muon Collider main page:

Muon Collider R&D Status Report:

Princeton muon collider page:
http://puhep1.princeton.edu/mumu/
Future Frontier Facilities
(Will the U.S. have one?)

- Hadron collider (LHC, SSC): \( \approx 100k/m \) [magnets].
  \( \approx 2 \) km per TeV of CM energy.
  Ex: LHC has 14-TeV CM energy, 27 km ring, \( \approx 3B \).

- Linear \( e^+ e^- \) collider (SLAC, NLC(?)): \( \approx 200k/m \) [rf].
  \( \approx 20 \) km per TeV of CM energy;
  But a lepton collider needs only \( \approx 1/10 \) the CM energy
  to have equivalent physics reach to a hadron collider.
  Ex: NLC, 1.5-TeV CM energy, 30 km long, \( \approx 6B (?) \).

- Muon collider: \( \approx 1B \) for source/cooler + \( 100k/m \) for rings
  Well-defined leptonic initial state.
  \( m_\mu/m_e \approx 200 \Rightarrow \) Little beam radiation.
  \( \Rightarrow \) Can use storage rings.
  \( \Rightarrow \) Smaller footprint.
  Technology: closer to hadron colliders.
  \( \approx 6 \) km of ring per TeV of CM energy.
  Ex: 3-TeV muon collider \( \approx 3B (?) \).
Ingredients of a Muon Collider

An accelerator complex in which

- Muons (both $\mu^+$ and $\mu^-$) are collected from pion decay following a $pN$ interaction.
- Muon phase volume is reduced by $10^6$ by ionization cooling.
- The cooled muons are accelerated and then stored in a ring.
- $\mu^+\mu^-$ collisions are observed over the useful muon life of $\approx 1000$ turns at any energy.
- Intense neutrino beams and spallation neutron beams are available as byproducts.

Muons decay: $\mu \rightarrow e\nu \quad \Rightarrow$

- Must cool muons quickly (stochastic cooling won’t do).
- Detector backgrounds at LHC level.
- Potential personnel hazard from $\nu$ interactions.
Footprints

A First Muon Collider to study light-Higgs production:

50 GeV recirculator

Collider

Cooling

Proton Source

FNAL

VLHC (60 TeV p-p)
$E_{\text{eff}} = 4 \text{ TeV}$

LHC (14 TeV p-p)
$E_{\text{eff}} = 1.4 \text{ TeV}$

NLC (0.5 - 1 TeV e$^+$-e$^-$)

FMC (0.5 TeV $\mu$)

NMC (4 TeV $\mu$)

BNL

10 km

100 m
The Case for a Muon Collider

- More affordable than an $e^+e^-$ collider at the TeV (LHC) scale.
- More affordable than either a hadron or an $e^+e^-$ collider for (effective) energies beyond the LHC.
- Precision initial state superior even to $e^+e^-$.  

![Effect of Beam Smearing](image)

- Initial machine could produce light Higgs via $s$-channel:
  Higgs coupling to $\mu$ is $(m_\mu/m_e)^2 \approx 40,000 \times$ that to $e$.
  Beam energy resolution at a muon collider $< 10^{-5}$,
  $\Rightarrow$ Measure Higgs width.
  Add rings to 3 TeV later.
- Neutrino beams from $\mu$ decay about $10^4$ hotter than present.
Recommendation on R&D for a Muon Collider

The Subpanel recommends that an expanded program of R&D be carried out on a muon collider, involving both simulation and experiments. This R&D program should have central project management, involve both laboratory and university groups, and have the aim of resolving the question of whether this machine is feasible to build and operate for exploring the high-energy frontier. The scale and progress of this R&D program should be subject to additional review in about two years.

CERN-EP/98-03
CERN-SL 98-004 (AP)
CERN-TH/98-33

Options for Future Colliders at CERN

J. Ellis, E. Keil, G. Rolandi

January 23, 1998

6 RECOMMENDATIONS

3. CERN should launch technical studies of $\mu^+\mu^-$ colliders, notably in the areas of the source and beam cooling, and should explore the possibility of locating such machines on or in the neighbourhood of the CERN site.

6. These studies should be carried out in collaborations with other laboratories, since most technical problems do not depend on the site. CERN's goal in these collaborations should be to contribute to the global pool of technologies for future collider options. It should confirm its reputation as a valuable and reliable partner in the international collaborations that will form to develop proposals for future collider projects.
The Muon Collider Collaboration

Charles M. Ankenbrandt1, Giorgio Apollinari2, Muzaffer Atac1, Bruno Autin3, Valeri I. Balbekov1, Vernon D. Barger4, Odette Benary5, Scott Berg6, Michael S. Berger6, S. Alex Bogacz7, T. Bolton8, Shlomo Caspi9, Christine Celata9, Yong-Chul Chae10, David B. Cline11, John Corlett9, Lucien Cremaldi12, H. Thomas Diehl1, Alexandr Drozdhin1, Richard C. Fernow13, David A. Finley1, Yasuo Fukui14, Miguel A. Furman9, Tony Gabriel15, Juan C. Gallardo13 Alper A. Garren11, Stephen H. Geer1, Ilya F. Ginzburg16, Michael A. Green9, John F. Gunion17, Ramesh Gupta9, Tao Han17, Katherine C. Harkay1, Colin Johnson3, Carol Johnstone1, Stephen A. Kahn13, Bruce J. King13, Harold G. Kirk13, Masayuki Kumada18, Yoshitaka Kuno14, Paul LeBrun1, Kevin Lee11, Derun Li19, David Lissauer13, Laurence S. Littenberg13, Changguo Lu19, Alfredo Lucchio13, Kirk T. McDonald19, Alfred D. McInturff9, Frederick E. Mills1, Nikolai V. Mokhov1, Alfred Moretti1, David V. Neuffer1, King-Yuen Ng1, Robert J. Noble1, James H. Norem10,1, Blaine E. Norum20, Hiromi Okamoto21, Yasar Onel22, Robert B. Palmer13, Zohreh Parsa13, Jack M. Peterson9, Yuriy Pischalnikov11, Milorad Popovic1, Eric J. Prebys19, Zubao Qian1, Rajendran Raja1, Pavel Rehak13, Thomas Roser13, Robert Rossmanith23, Jack Sandweiss24, Ronald M. Scanlan9, Lindsay Schachinger9, Andrew M. Sessler9, Quan-Sheng Shu7, Gregory I. Silvestrov25, Alexandr N. Skrinsky25, Panagiotis Spentzouris1, Ray Stefanski2, Sergei Strigavin1, Iuliu Stumer13, Don Summers12, Valery Tayursky25, Valeri Tchermitiane13, Lee C. Teng10, Alvin V. Tollestrup1, Yağmur Turm13,26, Dejan Trbojevic13, William C. Turner9, Andy Van Ginneken1, Tatiana A. Vsevolozhskaya25, Masayoshi Wake14, Weishi Wan1, Haipeng Wang13, Robert Weggel13, Erich H. Willen13, David R. Winn27, Jonathan S. Wurtele28, Yongxiang Zhao1, David B. Cline, John F. Gunion, Ramesh Gupta, David Neuffer, King-Yuen Ng, Robert J. Noble, James H. Norem, Blaine E. Norum, Hiromi Okamoto, Yasar Onel, Robert B. Palmer, Zohreh Parsa, Jack M. Peterson, Yuriy Pischalnikov, Milorad Popovic, Eric J. Prebys, Zubao Qian, Rajendran Raja, Pavel Rehak, Thomas Roser, Robert Rossmanith, Jack Sandweiss, Ronald M. Scanlan, Lindsay Schachinger, Andrew M. Sessler, Quan-Sheng Shu, Gregory I. Silvestrov, Alexandr N. Skrinsky, Panagiotis Spentzouris, Ray Stefanski, Sergei Strigavin, Iuliu Stumer, Don Summers, Valery Tayursky, Valeri Tchermitiane, Lee C. Teng, Alvin V. Tollestrup, Yağmur Turm, Dejan Trbojevic, William C. Turner, Andy Van Ginneken, Tatiana A. Vsevolozhskaya, Masayoshi Wake, Weishi Wan, Haipeng Wang, Robert Weggel, Erich H. Willen, David R. Winn, Jonathan S. Wurtele, Yongxiang Zhao, Max Zolotorev

1Fermi National Laboratory, P. O. Box 500, Batavia, IL 60510
2Rockefeller University, New York, NY 10021
3CERN, 1211 Geneva 23, Switzerland
4Department of Physics, University of Wisconsin, Madison, WI 53706
5Tel-Aviv University, Ramat-Aviv, Tel-Aviv 69978, Israel
6Physics Department, Indiana University, Bloomington, IN 47405
7Jefferson Laboratory, 12000 Jefferson Ave., Newport News, VA 23606
8Kansas State University, Manhattan, KS 66502-2601
9Lawrence Berkeley National Laboratory, 1 Cyclotron Rd., Berkeley, CA 94720
10Argonne National Laboratory, Argonne, IL 60439
11University of California Los Angeles, Los Angeles, CA 90095
12University of Mississippi, Oxford, MS 38677
13Brookhaven National Laboratory, Upton, NY 11973
14KEK High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba 305, Japan
15Oak Ridge National Laboratory, Oak Ridge, TN 37831
16Institute of Mathematics, Prosp. ac. Koptyug 4, 630090 Novosibirsk, Russia
17Physics Department, University of California, Davis, CA 95616
18National Institute of Radiological Sciences, 4-9-1 Anagawa, Inage, Chiba, Japan
19Joseph Henry Laboratories, Princeton University, Princeton, NJ 08544
20University of Virginia, 205 McCormick Road, Charlottesville, VA 22901
21National Institute of Radiological Sciences, 1-1 Oho, Tsukuba 305, Japan
22Physics Department, Van Allen Hall, University of Iowa, Iowa City, IA 52242
23DESY, Hamburg, Germany
24Physics Department, Yale University, CT 06520
25Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russia
26Department of Physics and Astronomy, SUNY, Stony Brook, NY 11790
27Fairfield University, Fairfield, CT 06430
28University of California Berkeley, Berkeley, CA 94720

Spokesperson: R.B. Palmer
# Meetings and Workshops

<table>
<thead>
<tr>
<th>Subject</th>
<th>Organizer</th>
<th>Place</th>
<th>Date</th>
<th>Additional Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Targetry</td>
<td>H. Kirk and K. McDonald</td>
<td>BNL</td>
<td>Aug. 3, 1998</td>
<td>Contact K. McDonald (<a href="mailto:mcdonald@puphep.princeton.eduH">mcdonald@puphep.princeton.eduH</a>)/ Kirk (<a href="mailto:hkirk@bnl.gov">hkirk@bnl.gov</a>)</td>
</tr>
<tr>
<td>Acceleration</td>
<td>S. Berg and D. Neuffer</td>
<td>Bloomington, IN</td>
<td>Aug. 10-11, 1998</td>
<td>Contact S. Berg (<a href="mailto:jsberg@indiana.edu">jsberg@indiana.edu</a>)</td>
</tr>
<tr>
<td>Neutrino Physics</td>
<td>B. King</td>
<td>BNL</td>
<td>Aug. 13-14 1998</td>
<td>Contact B. King (<a href="mailto:bking@bnl.gov">bking@bnl.gov</a>)</td>
</tr>
<tr>
<td>Cooling Theory &amp; Expt</td>
<td>R. Fernow and S. Geer</td>
<td>BNL</td>
<td>Aug. 31-Sep. 2, 1998</td>
<td>Contact R. Fernow (<a href="mailto:fernow@bnl.gov">fernow@bnl.gov</a>) or S. Geer (<a href="mailto:sgeer@fnal.gov">sgeer@fnal.gov</a>)</td>
</tr>
<tr>
<td>Collaboration Meeting</td>
<td>A. Sessler</td>
<td>LBNL</td>
<td>Oct. 8-13, 1998</td>
<td>Contact A. Sessler (<a href="mailto:amsessler@lbl.gov">amsessler@lbl.gov</a>)</td>
</tr>
<tr>
<td>Cooling Theory &amp; Expt</td>
<td>R. Fernow and S. Geer</td>
<td>FNAL</td>
<td>Dec. 7 - 9, 1998</td>
<td>Contact R. Fernow (<a href="mailto:fernow@bnl.gov">fernow@bnl.gov</a>) or S. Geer (<a href="mailto:sgeer@fnal.gov">sgeer@fnal.gov</a>)</td>
</tr>
<tr>
<td>Collaboration Meeting</td>
<td>B. Palmer</td>
<td>BNL</td>
<td>Tentative May 19-26, 1999</td>
<td>Contact J. Gallardo (<a href="mailto:gallardo@bnl.gov">gallardo@bnl.gov</a>)</td>
</tr>
</tbody>
</table>

- **PROSPECTIVE STUDY OF MUON COLLIDERS**
  
  Introductory meeting  
  Monday, July 20 1998 at 14 hrs  
  CERN PS Auditorium, Bdg 6-2-024
Technical Challenges

- 16-GeV proton driver, 15 Hz, 4-MW beam power, 1-ns bunch length (C. Ankenbrandt, T. Roser...).

- **Targetry and Capture**

- **Muon Cooling**

  - Acceleration – more work needed (S. Berg...)
  
  - Storage rings have beautiful, highly corrected solutions due to heroic work of Al Garren, Carol Johnstone and Dan Trbojević.
  
  - Interaction region and detector design – more work needed (I. Stumer...)

A muon’s view of the interaction region:
Overview of Targetry for a Muon Collider

- $1.2 \times 10^{14} \mu^\pm/s$ via $\pi$-decay from a 4-MW proton beam.
- Cooling jacket around stationary target would absorb too many pions.
- Liquid-metal jet target: Ga, Hg, or solder (Bi/In/Pb/Sn).
- 20-T capture solenoid followed by a 1.25-T $\pi$-decay channel with phase-rotation via rf (to compress energy of the muon bunch).
Targetry Issues

• 1-ns beam pulse ⇒ shock heating of target.
  – Resulting pressure wave may disperse liquid (or crack solid).
  – Damage to target chamber walls?
  – Magnetic field will damp effects of pressure wave.

• Eddy currents arise as metal jet enters the capture magnet.
  – Jet is retarded and distorted, possibly dispersed.
  – Hg jet studied at CERN, but not in beam or magnetic field:

  ![High-speed photographs of mercury jet target for CERN-PS-AA. Laboratory test.](image)
  4,000 frames per second, Jet speed: 20 m/s, diameter: 3 mm, Reynolds Number: >100,000

• Targetry area also contains beam dump.
  – Need 4 MW of cooling.
  – Harsh radiation environment for magnets and rf.
An R&D Program for Targetry

at a Muon Collider

A Proposal to the BNL AGS Division


Argonne National Laboratory, Argonne, IL 60439
Brookhaven National Laboratory, Upton, NY 11973
University of California, Los Angeles, CA 90095
CERN, 1211 Geneva, Switzerland
Fermi National Laboratory, Batavia, IL 60510
Lawrence Berkeley National Laboratory, Berkeley, CA 94720
Michigan State University, East Lansing, MI 48824
Oak Ridge National Laboratory, Oak Ridge, TN 37831
Princeton University, Princeton, NJ 08544

To be submitted Sept. 1, 1998.

1Project Manager. Email: kirk@electron.cap.bnl.gov
2Spokesperson. Email: mcdonald@puphep.princeton.edu
Studies to be performed in the AGS F.E.B. U-line.
Ionization Cooling

- Ionization: takes momentum away.
- RF acceleration: puts momentum back along $z$ axis.

$\Rightarrow$ Transverse cooling.

Particles are slowed along their path ($dE/dx$)

Particles are accelerated longitudinally

- Use channel of LH$_2$ absorbers, rf cavities and alternating solenoids (to avoid buildup of angular momentum).
• But the **energy spread rises**.

• ⇒ Must exchange longitudinal and transverse emittance frequently to avoid beam loss due to bunch spreading.

• Can reduce energy spread by a wedge absorber at a momentum dispersion point:

  ![Absorber wedge diagram](image)

  - Energy too high
  - Nominal energy
  - Equal energies
  - Energy too low

• Emittance exchange via wedges + bent solenoids:
PROPOSAL

Ionization Cooling Research and Development Program for a High Luminosity Muon Collider

Charles M. Ankenbrandt\textsuperscript{a}, Muzaffer Atac\textsuperscript{a}, Giorgio Apollinari\textsuperscript{b}, Valeri I. Balbekov\textsuperscript{a}, Morris Binkley\textsuperscript{a}, S. Alex Bogacz\textsuperscript{c}, Christine Celata\textsuperscript{d}, David B. Cline\textsuperscript{e}, John Corlett\textsuperscript{d}, Lucien M. Cremaldi\textsuperscript{f}, Richard C. Fernow\textsuperscript{g}, David Finley\textsuperscript{a}, Yasuo Fukui\textsuperscript{h}, Juan C. Gallardo\textsuperscript{g}, Stephen H. Geer\textsuperscript{a,†}, Gail G. Hanson\textsuperscript{o}, Ahmed Hassanein\textsuperscript{i}, Carol Johnstone\textsuperscript{a}, Stephen A. Kahn\textsuperscript{g}, Bruce J. King\textsuperscript{g}, Harold G. Kirk\textsuperscript{g}, Thomas R. Kobilarcik\textsuperscript{a}, Yoshitaka Kuno\textsuperscript{h}, Paul LeBrun\textsuperscript{a}, Kevin Lee\textsuperscript{e}, Derun Li\textsuperscript{d}, Changguo Lu\textsuperscript{j}, Kirk T. McDonald\textsuperscript{j}, Alfred D. McInturff\textsuperscript{d}, Frederick E. Mills\textsuperscript{a}, Nikolai V. Mokhov\textsuperscript{a}, Alfred Moretti\textsuperscript{a}, Yoshiharu Mori\textsuperscript{h}, David V. Neuffer\textsuperscript{a}, Robert J. Noble\textsuperscript{a}, James H. Norem\textsuperscript{a,i}, Stephen C. O’Day\textsuperscript{a}, Yasar Onel\textsuperscript{k}, Robert B. Palmer\textsuperscript{g}, Zohreh Parsa\textsuperscript{g}, Yuriy Pischalnikov\textsuperscript{e}, Milorad Popovic\textsuperscript{a}, Eric J. Prebys\textsuperscript{j}, Zubao Qian\textsuperscript{a}, Rajendran Raja\textsuperscript{a}, Claude Reed\textsuperscript{i}, Pavel Rehak\textsuperscript{g}, Andrew M. Sessler\textsuperscript{d}, Gregory I. Silvestrov\textsuperscript{l}, Alexandr N. Skrinsky\textsuperscript{l}, Dale Smith\textsuperscript{i}, Panagiotis G. Spentzouris\textsuperscript{a}, Ray Stefanski\textsuperscript{a}, Sergei Striganov\textsuperscript{a}, Donald J. Summers\textsuperscript{f}, Lee C. Teng\textsuperscript{i}, Alvin V. Tollestrup\textsuperscript{a}, William C. Turner\textsuperscript{d}, Andreas Van Ginneken\textsuperscript{a}, Tatiana A. Vsevolozhskaya\textsuperscript{l}, David R. Winn\textsuperscript{m}, Jonathan S. Wurtele\textsuperscript{n}, Takeichiro Yokoi\textsuperscript{h}, Yongxiang Zhao\textsuperscript{g}, Max Zolotorev\textsuperscript{d}

The MUCOOL Collaboration

† Spokesperson
Cooling Demonstration Experiment

Test basic cooling components:

- Alternating solenoid lattice, RF cavities, LH$_2$ absorber
- Lithium lens (for final cooling).
- Dispersion + wedge absorbers to exchange longitudinal and transverse phase space.

Track individual muons; simulate a bunch in software.

Possible site: Meson Lab at Fermilab:

![Diagram of cooling apparatus and site layout]
Summary

• A muon collider offers the prospect of a more cost-effective technology for high-energy accelerators.

• Cooling the beams is the key.

• The concepts of a muon collider are still in a formative stage.

⇒ Join us in exploring the physics opportunities and solving the technical challenges of a muon collider!