Muon Colliders:
Status of R&D and Future Plans

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[For the Muon Collider Collaboration]
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PAC’99 Invited Paper WEBR4

Muon Collider main page:

Muon Collider R&D Status Report:

Princeton Muon Collider page:
http://puhep1.princeton.edu/mumu/
The Y2K Problem for Particle Physics

• Can elementary particle physics prosper for a 2nd century with laboratory experiments based on innovative particle sources?

• Can a full range of new phenomena be investigated:
  – Neutrino mass ⇒ a 2nd $3 \times 3$ (or larger?) mixing matrix.
  – Precision studies of Higgs bosons.
  – A rich supersymmetric sector (with manifestations of higher dimensions).
  – ... And more ....

• Will our investment in future accelerators result in more cost-effective technology, that is capable of extension to 10’s of TeV of constituent center-of-mass energy?

The Solution...

• A Muon Collider is the best option to accomplish the above!
What is 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: $\mu \rightarrow e\nu$    $\Rightarrow$

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

For muon colliders at 3 TeV, 400 GeV (top factory) and 100 GeV (light Higgs factory).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>3 TeV</th>
<th>0.4 TeV</th>
<th>0.1 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>CoM energy (TeV)</td>
<td>3</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>$p$ energy (GeV)</td>
<td>16</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>$p$'s/bunch</td>
<td>$2.5 \times 10^{13}$</td>
<td>$2.5 \times 10^{13}$</td>
<td>$5 \times 10^{13}$</td>
</tr>
<tr>
<td>Bunches/fill</td>
<td>4</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Rep. rate (Hz)</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>$p$ power (MW)</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>$\mu$/bunch</td>
<td>$2 \times 10^{12}$</td>
<td>$2 \times 10^{12}$</td>
<td>$4 \times 10^{12}$</td>
</tr>
<tr>
<td>$\mu$ power (MW)</td>
<td>28</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Wall power (MW)</td>
<td>204</td>
<td>120</td>
<td>81</td>
</tr>
<tr>
<td>Collider circum. (m)</td>
<td>6000</td>
<td>1000</td>
<td>350</td>
</tr>
<tr>
<td>Ave. bending field (T)</td>
<td>5.2</td>
<td>4.7</td>
<td>3</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>500</td>
<td>100</td>
<td>10</td>
</tr>
<tr>
<td>Rms $\Delta P/P$ (%)</td>
<td>0.16</td>
<td>0.14</td>
<td>0.003-0.12</td>
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<tr>
<td>$6d \epsilon_6$ ($\pi$ m)$^3$</td>
<td>$1.7 \times 10^{-10}$</td>
<td>$1.7 \times 10^{-10}$</td>
<td>$1.7 \times 10^{-10}$</td>
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<tr>
<td>Rms $\epsilon_n$ (π mm-mrad)</td>
<td>50</td>
<td>50</td>
<td>85-290</td>
</tr>
<tr>
<td>$\beta^*$ (cm)</td>
<td>0.3</td>
<td>2.6</td>
<td>4.1-14.1</td>
</tr>
<tr>
<td>$\sigma_z$ (cm)</td>
<td>0.3</td>
<td>2.6</td>
<td>4.1-14.1</td>
</tr>
<tr>
<td>$\sigma_r$ spot (μm)</td>
<td>3.2</td>
<td>26</td>
<td>86-294</td>
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<tr>
<td>$\sigma_\theta$ IP (mrad)</td>
<td>1.1</td>
<td>1.0</td>
<td>2.1</td>
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<tr>
<td>Tune shift</td>
<td>0.044</td>
<td>0.044</td>
<td>0.051-0.022</td>
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<tr>
<td>$n_{\text{turns}}$ (effective)</td>
<td>785</td>
<td>700</td>
<td>450</td>
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<tr>
<td>Luminosity (cm$^{-2}$s$^{-1}$)</td>
<td>$7 \times 10^{34}$</td>
<td>$10^{33}$</td>
<td>$10^{31}$-1.2 $\times 10^{32}$</td>
</tr>
<tr>
<td>Higgs/year</td>
<td>$2-4 \times 10^5$</td>
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</table>

Higgs/year assumes a cross section $\sigma = 5 \times 10^4$ fb; a Higgs width $\Gamma = 2.7$ MeV; 1 year = $10^7$ s.
A First Muon Collider to study light-Higgs production:
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 $e^+e^-$. Muon polarization $\approx 25\%$,

  \[ \Rightarrow \text{Can determine } E_{\text{beam}} \text{ to } 10^{-5} \text{ via } g-2 \text{ spin precession.} \]

**$t\bar{t}$ threshold:** Nearly degenerate $A^0$ and $H^0$:

- 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 $< 10^{-5}$,
  \[ \Rightarrow \text{Measure Higgs width.} \]

Add rings to 3 TeV later.
• Neutrino beams from $\mu$ decay about $10^4$ hotter than present.

Initial scenario in a low-energy muon storage ring.

Study $CP$ violation via $CP$-conjugate initial states:

\[
\begin{align*}
\mu^+ &\rightarrow e^+\nu_\mu\nu_e \\
\mu^- &\rightarrow e^-\nu_\mu\bar{\nu}_e
\end{align*}
\]
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. Ankenbrandt, Giorgio Apollinari, Muzaffer Atac, Bruno Autin, Valeri I. Balbekov, Vernon D. Barger, Odette Benary, Scott Berg, Michael S. Berger, S. Alex Bogacz, T. Bolton, Shlomo Caspi, Christine Celata, Yong-Chul Chae, David B. Cline, John Corlett, Lucien Cremaldi, H. Thomas Diehl, Alexandr Drozdhin, Richard C. Fernow, David A. Finley, Yasuo Fukui, Miguel A. Furman, Tony Gabriel, Juan C. Gallardo, Alper A. Garren, Stephen H. Geer, Ilya F. Ginzburg, Michael A. Green, John F. Gunion, Ramesh Gupta, Tao Han, Katherine C. Harkay, Harold G. Kirk, IEEE, Harold G. Kirk, Physics Department, Indiana University, Bloomington, IN 47405, Valery Tayursky, N.S.R.F., Institute for Chemical Research, Kyoto University, Gokanoshou, Uji, Kyoto 611, Japan, David V. Neuffer, Stephen H. Geer, Dejan Trbojevic, Panagiotis Spentzouris, Yasuo Fukui, Tao Han, Hiromi Okamoto, Derun Li, Masayoshi Wake, Shlomo Caspi, KEK High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba 305, Japan, 14KEK, National Institute for Radiological Sciences, 4-9-1 Anagawa, Inage, Chiba, Japan, David R. Winn, Physics Department, Van Allen Hall, University of Iowa, Iowa City, IA 52242, 15Oak Ridge National Laboratory, Oak Ridge, TN 37831, 16Department 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, Joseph Henry Laboratories, Princeton University, Princeton, NJ 08544, 19University of Virginia, 205 McCormick Road, Charlottesville, VA 22901, 20Brookhaven National Laboratory, Upton, NY 11973, 21Argonne National Laboratory, 1 Cyclotron Rd., Berkeley, CA 94720, 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
# Scheduled Muon Collider Mini-Workshops and Conferences

<table>
<thead>
<tr>
<th>Subject</th>
<th>Organizer</th>
<th>Place</th>
<th>Date</th>
<th>Additional Information</th>
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<tbody>
<tr>
<td><strong>Expt. rf systems</strong></td>
<td>N. Holtkamp</td>
<td>FNAL</td>
<td>Mar. 18-19, 1999</td>
<td>Contact Norbert Holtkamp (<a href="mailto:holtkamp@fnal.gov">holtkamp@fnal.gov</a>)</td>
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<tr>
<td><strong>Cooling Theory &amp; MUCOOL</strong></td>
<td>R. Fernow and S. Geer</td>
<td>LBNL</td>
<td>April 12-14, 1999</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>) or John Corlett (<a href="mailto:jncorlett@LBL.gov">jncorlett@LBL.gov</a>)</td>
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<tr>
<td><strong>Muon Neutrino Sources</strong></td>
<td>J. Wurtele</td>
<td>LBNL</td>
<td>April 15, 1999</td>
<td>Contact J. Wurtele (<a href="mailto:wurtele@socrates.berkeley.edu">wurtele@socrates.berkeley.edu</a>)</td>
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<tr>
<td><strong>Collaboration Meeting</strong></td>
<td>B. Palmer</td>
<td>St. Croix (USVI)</td>
<td>May 20-26, 1999</td>
<td>Contact J. Gallardo (<a href="mailto:gallardo@bnl.gov">gallardo@bnl.gov</a>)</td>
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<tr>
<td><strong>Neutrino Factories based on Muon Accumulators</strong></td>
<td>B. Autin and A. Blondel</td>
<td>Lyon (France)</td>
<td>July 5-9, 1999</td>
<td>Contacts Autin (<a href="mailto:Bruno.Autin@cern.ch">Bruno.Autin@cern.ch</a>); J. Wurtele (<a href="mailto:wurtele@socrates.berkeley.edu">wurtele@socrates.berkeley.edu</a>) and S. Wojcicki</td>
</tr>
<tr>
<td><strong>Muon Colliders at the Highest Energies</strong></td>
<td>C. Johnson, B. King, J. Lykken</td>
<td>Montauk (NY)</td>
<td>Sep 27 - Oct 1, 1999</td>
<td>Contact the organizers (<a href="mailto:Colin.Johnson@cern.ch">Colin.Johnson@cern.ch</a>;<a href="mailto:bking@bnl.gov">bking@bnl.gov</a>;lykken@fnal)</td>
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<tr>
<td><strong>Physics Potential &amp; Development of mu⁺-mu⁻ Colliders</strong></td>
<td>D. Cline</td>
<td>Fairmont Hotel San Francisco (CA)</td>
<td>Dec 15 - 17, 1999</td>
<td>Contact Kevin Lee (<a href="mailto:klee@physics.ucla.edu">klee@physics.ucla.edu</a>)</td>
</tr>
</tbody>
</table>
Technical Challenges

• Proton Driver, 16-GeV, 15 Hz, 4MW, 1-ns bunch: WEA163

• Targetry and Capture: THP34, THP38, THP41, THP55, THP57, THP59

• Muon Cooling: MOP98, THA130, THP31, THP33, THP35, THP39, THP40, THP42, THP48, THP54, THP56, THP58, THP60, THP83, THP85, TUA147, TUP101, WEBR5

• Acceleration: MOP86, THP37, THP50, THP86
• Storage rings: THP43, THP44, THP45, THP46, THP47, THP49, THP53, TUP129, TUP154

• Interaction region and detector design.

A muon’s view of the interaction region:
- Neutrino beams: THP32, THP36, THP51, THP52, WEBR6
• $1.2 \times 10^{14} \mu^\pm/s$ 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 $\Rightarrow$ 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 tests)](image)

  4,000 frames per second, Jet speed: 20 ms$^{-1}$, diameter: 3 mm, Reynold’s Number:$>$100,000

A. Porcel

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

**Long Term:** Provide a facility to test key components of the front-end of a muon collider in realistic beam conditions.

**Near Term** (1-2 years): Explore viability of a liquid metal jet target in intense, short proton pulses and (separately) in strong magnetic fields.

(Change target technology if encounter severe difficulties.)

**Mid Term** (3-4 years): Add 20-T magnet to AGS beam tests; Test 70-MHz rf cavity (+ 1.25-T magnet) downstream of target; Characterize pion yield.
Ionization Cooling
(An Idea So Simple It Might Just Work)

- Ionization: takes momentum away.
- RF acceleration: puts momentum back along $z$ axis.
- $\Rightarrow$ Transverse “cooling”.


But won’t work for electrons or protons.

So use muons: Balbekov, Budker, Skrinsky, late 1960’s.
The Details are Delicate

Use channel of LH$_2$ absorbers, rf cavities and alternating solenoids (to avoid buildup of angular momentum).

\[ \text{Absorber wedge} \]

Nominal energy

Energy too high

Energy too low

Equal energies

The Energy Spread Rises due to “Straggling”

⇒ 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:
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:
3 cells of the cooling channel:

Emittance diagnostics via a bent solenoid spectrometer:
Summary

- A muon collider offers the prospect of a more cost-effective technology for high-energy accelerators.
- The concepts of a muon collider are still in a formative stage.
- Cooling the beams is the key.
- Significant technical challenges in producing enough muons.
- ⇒ Join us in exploring the physics opportunities and solving the technical challenges of a muon collider!