Neutrino Physics at a Muon Collider

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Princeton U.
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CERN Muon Collider Workshop

Based on
Workshop on Potential for Neutrino Physics at Future Muon Colliders
BNL, 13-14 August, 1998

and
Workshop on Physics at the First Muon Collider and at the Front End of the Muon Collider
FNAL, November, 1998
The Path To a First Muon Collider

The simplest muon collider with luminosity sufficient to do frontier physics has CoM energy of 100 GeV: light Higgs, calibrate on $Z_0$.

Cost: > 1$B.

Could the case be strengthened by ancillary physics capabilities?

Interaction rate of $\nu$’s from $\mu$ decay in storage rings $\propto E^3$.

Intense ($> 10^{14}/s$), pulsed, low-energy $\mu$ (and $\nu$) beams exist in the early stages of a muon collider.
Summary of Ancillary Physics Capabilities

(My Impression)

• Higher-energy muon colliders will be the place to do neutrino physics. (But they are a long way off.)

• The duty factor of the low-energy muon beams (15 pps, each 2 ns wide) is not favorable to most muon physics: $\mu \rightarrow e\gamma$, $\mu \rightarrow ee^+e^-$, $\mu N \rightarrow eN$.

• A low-energy muon storage ring (not part of the basic muon-collider design) is of interest for muon physics, but perhaps not for neutrino physics. (Also, some muon cooling required.)

• The 20-T pion-capture solenoid does not produce a better low-energy neutrino beam than a horn.

Bottom line: Present understanding of ancillary physics capabilities does not provide a key justification for a muon collider.

⇒ A Challenge and an Opportunity!
Workshop on the Potential for Neutrino Physics at Future Muon Colliders

Thursday-Friday, 13-14 August, 1998

Brookhaven National Laboratory
Upton, New York, USA

Thanks to everyone who participated for making the workshop such a success!

- letter of invitation (2 July, 1998)
- workshop schedule
- registration form
- registered attendees
- travel & accommodation information
- follow-up nuMC book
- links to relevant papers, talks and other information

Organizing Committee:
Overview of Workshop

- 2 days long, 50 people
- plenary sessions + 3 working groups (WG's):
  (i) neutrino beam design
  (ii) long baseline experiments
  (iii) high rate experiments
Approx. Baseline vs. Energy Covered by WG’s

Radius of Earth

Baseline (km)

$10^{-1}$
$10^{0}$
$10^{1}$
$10^{2}$
$10^{3}$
$10^{4}$

long baseline osc. expts.

WG 2

high rate expts.  WG 3

dedicated storage rings

WG 1

at $\mu$ collider $E_\mu$ (GeV)

Overviews and Theory (plenary)

- Overview & status of muon colliders (Palmer)
- Overview of neutrino oscillations (Conrad)
- Neutrino - antineutrino transitions (Wang)*

(* = see slide)
$\nu_e$ or not $\nu_e$?

And Other Neutrino Oscillation Questions...

In principle the muon collider neutrino beams
Allow a comprehensive program
of Oscillation Measurements:

| $\nu_e \rightarrow \nu_e$ | Near/Far ratios of $\nu_e$ CC events
| $\nu_e \rightarrow \nu_\tau$ | $\nu_\tau$ appearance
| $\nu_\mu \rightarrow \nu_\tau$ | $\nu_\tau$ appearance
| $\nu_\mu \rightarrow \nu_e$ | Near/Far ratios of $\nu_e$ CC events and Near/Far ratios of NC/CC
| $\nu_\mu \rightarrow \nu_\mu$ | Near/Far ratios of $\nu_\mu$ CC events

... And CP violation tests by switching sign

The challenge to the Oscillation Working Group:
Can we design experiments with sensitivity
To cover the interesting regions

At $\sim 5\sigma$?
**Conclusion:**

**Effective $\nu \to \overline{\nu}$ transitions in 5 scenarios:**

<table>
<thead>
<tr>
<th>Model</th>
<th>Parameters</th>
<th>$\mu^+/\mu^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>pure Majorana, $m_{\nu}\sim 1\text{ keV}$</td>
<td>$10^{-10}$</td>
<td></td>
</tr>
<tr>
<td>Spin precession in $B_L$, $</td>
<td>\mu_\nu</td>
<td>&lt; 7 \times 10^{-10} \mu_B$</td>
</tr>
<tr>
<td>Neutrino decay, $</td>
<td>h^2 &lt; 2 \times 10^{-14} \Delta m^2 \sim 10^{-3} \text{ eV}$</td>
<td>$\sin^2 2\theta_{\mu} &lt; 0.02$</td>
</tr>
<tr>
<td>SU(2)$_R \times SU(2)_L \times U(1)$</td>
<td>$</td>
<td>\bar{\nu}_1 &lt; 0.003$, $</td>
</tr>
<tr>
<td>Exotic fermions, $</td>
<td>U_{\mu \mu}</td>
<td>&lt; 0.027$, $\Delta m^2 \sim 1.4 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

($E_{\nu} \sim 1\text{ GeV}$, $L \sim 1\text{ km}$)

Present statistics on high energy $\nu N$ scattering: (CC)

- $\sim 1.7 \times 10^5$ CDHS/CHARM
- $\sim 1.1 \times 10^6$ CCFR

+ Background: $\pi^- \to \bar{\nu}_\mu \mu^-$; $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$ in the beam.

⇒ Not possible to observe in lab.

- New theoretical scenarios for $\nu \leftrightarrow \bar{\nu}$ transitions
- Small transition probabilities ⇒ need intense $\nu$ beams from $\mu$ colliders
Neutrino Beam Design (WG 1)

- Improved sub-GeV beams from solenoidal capture & focus (Kahn)*
- Siting a muon collider at Fermilab (Finley)
- 2 GeV μSR with NO cooling (Palmer)*
- Low energy μSR as ν̄e sources (Cline)
- Neutrino beams at muon colliders (Geer)*

(* = see slide)
\textit{"perfect" beam}
Looks promising for low $E_y$... but needs to be optimized.
Three ideas at the workshop on physics at the first muon collider & front end of a muon collider, FNAL, November 1997:

1. Use dedicated storage ring to maximize neutrino flux (S. Geer).

2. Use straight sections in Recirculating LINACS (RLAs) .... fun because the pulses scan the RLA energy interval (C. Ankenbrandt & S. Geer).

3. Use straight sections in muon collider ring (B. King).
Low Energy Scenario

- Consider a 1.5 GeV/c unpolarized muon beam stored in a ring with a straight section pointing at an experiment 1 km away:
  - $1.4 \times 10^{16}$ $\nu_e$ m$^{-2}$ yr$^{-1}$
  - $1.4 \times 10^{16}$ $\nu_\mu$ m$^{-2}$ yr$^{-1}$
  - $6 \times 10^6$ $\nu$ CC interactions KT$^{-1}$ yr$^{-1}$
  - $3 \times 10^6$ $\overline{\nu}$ CC interactions KT$^{-1}$ yr$^{-1}$

*S. Geer, PRD 57,6989 (1998)*
Recent Work on a Capture, Acceleration, & Muon Storage Ring Scenario – (1)

B. Autin, S. Geer, C. Johnstone & D. Neuffer

Dont need all the muons in a single bunch ->

STAGE 1: Capture & begin acceleration with 800 MHz rf, \( V_{rf} = 15 \text{ MV/m}, \phi_S = 30^\circ \), linac length = 140m.

STAGE 2: Continue acceleration up to 10 GeV with 800 MHz rf, \( V_{rf} = 20 \text{ MV/m}, \phi_S = 60^\circ \), linac length = 500m.
- 2 GeV μ ring
  with NO cooling.

5. Put into 200 m arc storage ring.

low $\beta$
$\rho_0 \approx 10 cm$
$P_0 \approx 50$ MeV/c
$\gamma \approx 25$ m/rod

high $\beta$:
$\rho_0 \approx 30$ cm
$P_0 \approx 15$ MeV/c

$\nu_e - \nu_x$

Little solution $\checkmark$

$\approx 100 \times \frac{1}{20} = 5 m$
Possible Acc

Accel to 2 GeV:

\[ \frac{\Delta p}{p} = 15\% \rightarrow 1.5\% \quad \text{(same O}\_2\text{)} \]

\[ \rightarrow \sim 3\% \quad \text{(half bunch length)} \]

A "trick" for accelerating μ's to 2 GeV with only \( \frac{2}{3} \) GeV of rf linac.
Impressive "Free" Beams from μ Colliders

General purpose detector

250+250 GeV muon collider

Long baseline detector for oscillations

\[
\frac{M[\text{kg}]}{(L[\text{km}])^2} \times \frac{3 \times 10^7 \times 1}{L[\text{g.cm}^2] \text{ events/year}^*} = \frac{L[\text{g.cm}^2] \text{ events/year}^*}{(L[\text{km}])^2}
\]

*assumes 250-250 GeV collider, 200 m straight section & 6 x 10^7 /year

Long Baseline Experiments (WG 2)

(This WG dealt largely with detector technologies)

- **ICARUS**: a fully-active tracking detector (Cline)
- **MINOS**: a sampling calorimetric detector (Michael)
- Emulsion detectors for $\nu_\tau$ appearance expts. (Para)
- Beam comparisons for $\nu_\tau$ appear. expts. (Shaevitz)*

(* = see slide)
Long Baseline Options

<table>
<thead>
<tr>
<th>EV (GeV)</th>
<th>L/E (Km/GeV)</th>
<th>FNAL-Soudan</th>
<th>KEK-Kam.</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>73.2</td>
<td>25.0</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>36.6</td>
<td>12.5</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>24.4</td>
<td>8.3</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>18.3</td>
<td>6.3</td>
<td></td>
</tr>
</tbody>
</table>

Intercontinental ν experiments!
A first look at

A long-baseline muon storage ring experiment: $\nu_\tau$ appearance

- A 1kton emulsion experiment (50% detection efficiency)
- 730 km baseline
- Flux from Geer, FNAL-Pub-971389 (on workshop web page)
- For $\sin^22\theta = 1$
- Events for two years of running

Since $L$ dependence is weak and energy dependence of rate is faster than $E^2$ plus $\tau$ xsec suppression $\Rightarrow$ 50 GeV $\mu$SR is best.

**Conclusion:** Muon storage rings ($\mu$SR) give big gains over conventional $\nu$ beams only at higher energies.
High Rate Experiments (WG 3)

- High rate, high performance $\nu$ detectors (King)*
- QCD studies (Harris)
- Precision EW physics (McFarland/Yu)
- Rare & exotic processes (Bolton)
- CKM quark mixing matrix (King)*

potential for huge improvements over existing analyses + new contributions to precision HEP

- Charm factory (Summers) $O(10^8)$ charm decays + unique event-by-event $c\bar{c}$ production tag: $\nu \rightarrow l^-c$; $\bar{\nu} \rightarrow l^+\bar{c}$

$\Rightarrow$ can be competitive/superior to current & proposed charm factories

(* = see slide)
High Rate, High Performance ν Detector

- HUGE statistics: $50 \text{ g/cm}^2$ target $\Rightarrow 3 \times 10^9$ events/year
- outstanding reconstruction of CC & NC event kinematics
- possibility of interchangeable/multiple targets: Si CCD’s, $\text{H}_2/D_2$, ...
CKM Matrix: current uncertainties in $|V_{qq'}|^2$ & guesses at uncertainties with $10^{10}$ interactions

$d \rightarrow c$
$O(10^8)$ events

$s \rightarrow c$
$O(10^8)$ events
$s(x)$ from NC needs $s$ tagging

$u \rightarrow b$
$O(10^4)$ events with $b$ threshold

c$\rightarrow b$
$O(10^4)$ events(?) threshold very imp.
c$\rightarrow b$ from NC

d, s$\rightarrow t$
dramatic improvements possible at very high $E_{\nu}$

Not bad!!

Conclusions

- Physics program is rich, complementary to energy frontier
  - "No home runs"
  - Now need detailed studies of best processes
- Detectors/Targets open up possibilities for novel processes

Would you build a muon collider solely for v experiments?  
[ ] yes  [ ] maybe  [x] no

Do you build an experiment for high rate physics if the beams are there?  
[x] yes  [ ] maybe  [ ] no

Does it significantly strengthen the case for a heavy lepton collider?  
[ ] yes  [ ] maybe  [x] no
Follow-up Activities

- Book of transparencies (available from tuohy@bnl.gov)
- Contributed write-ups (optional - probably not many)
- Book &/or PRD overview of $\nu$ physics possibilities at muon colliders: plan to complete in November, authors: Bigi, Bolton, Harris, King, McFarland, Morfin, Para, Schellman, Spentzouris, Summers, Yu
- Possibility of future workshops e.g. Aspen '99 summer study
Workshop Summary

• Will eventually have a wide range of exciting physics possibilities with "free" intense $\nu$ beams at muon colliders

• Dedicated $\mu$SR could possibly help with $\nu$ oscillation studies on a shorter timescale. Can they be built quickly and affordably? (A major challenge!)

• Follow-up studies are needed & some are underway