Physics at the High-Energy Frontier with Colliding Beams of Muons

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Speculation that we and our world is made from smaller “particles” is very ancient:

Mochus (Phoenicia) [identified by Newton as Moses]
Leucippis, Democritus, Epicurus, …, among the Greeks
Lucretius among the Romans

Leucippis and Democritus held a deterministic view, but Epicurus and Lucretius considered “swerving of the atoms”, i.e., that Nature has a fundamentally random character. However, even as late as 1900 people such as Mach doubted that atoms exist, perhaps because “seeing is believing”, and atoms are too small to be “seen” with visible light.

⇒ Need better microscopes!

[And need better vacuum, so individual atoms have a long mean free path.]

In memoriam: UT philosopher and “amateur” antenna physicist, L.B. Cebik (1939-2008).
The era of particle physics began in 1897 with the “discovery” of the electron by JJ Thomson. This effort followed many other studies of “rays” in partially evacuated tubes.

Thomson had the better vacuum pump, but poor enough that the glow of gas atoms struck by electrons circling in a magnetic field could still be “seen”.

The discovery that the nucleus of the atom is very small is due to Geiger, Marsden and Rutherford (1909). They used a “microscope” in which α-particles (helium nuclei), rather than light, reflected off a heavy nucleus, which latter was thereby “seen.”

Heisenberg (1927) transforms the resolving power of a microscope, \( \theta = \lambda / d \), into the “uncertainty principle: \( \Delta x = \hbar / \Delta p \),

⇒ Need high energy/momentum to “see” small objects.
A Century of Elementary Particle Physics

Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is a quantum field theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).

**Fermions**

- Matter constituents spin = 1/2, 3/2, 5/2, ...

**Leptons**

- Spin = 1/2

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass (GeV/c^2)</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>e^-</td>
<td>0.000511</td>
<td>1</td>
</tr>
<tr>
<td>μ</td>
<td>0.0000511</td>
<td>0</td>
</tr>
</tbody>
</table>

**Quarks**

- Spin = 1/2

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass (GeV/c^2)</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>0.0002</td>
<td>2/3</td>
</tr>
<tr>
<td>d</td>
<td>0.0003</td>
<td>1/3</td>
</tr>
</tbody>
</table>

**Neutrinos**

- Spin = 0

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass (GeV/c^2)</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>ν_e</td>
<td>0.0002</td>
<td>0</td>
</tr>
</tbody>
</table>

**Bosons**

- Force carriers spin = 0, 1/2, ...

**Unified Electroweak**

- Spin = 1

<table>
<thead>
<tr>
<th>Property</th>
<th>Mass (GeV/c^2)</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Strong (color)**

- Spin = 1/2

<table>
<thead>
<tr>
<th>Property</th>
<th>Mass (GeV/c^2)</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gluon</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Color Charge**

- Only quarks and gluons carry “strong charge” (also called “color charge”) and can have strong interactions. Each quark carries three types of color charge. Color charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.

**Properties of the Interactions**

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two or quarks separated by the specified distances.

<table>
<thead>
<tr>
<th>Property</th>
<th>Gravitational Interaction</th>
<th>Weak Interaction (Electroweak)</th>
<th>Electromagnetic Interaction</th>
<th>Strong Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acts on</td>
<td>Mass = Energy</td>
<td>Flavor</td>
<td>Electric Charge</td>
<td>Color Charge</td>
</tr>
<tr>
<td>Particles exp.</td>
<td>All</td>
<td>Quarks, Leptons</td>
<td>Electrically Charged</td>
<td>Quarks, Gluons</td>
</tr>
<tr>
<td>Particles mediating</td>
<td>Graviton (not yet observed)</td>
<td>W^+ W^- Z^0</td>
<td>Υ</td>
<td>Gluons</td>
</tr>
<tr>
<td>Strength</td>
<td>10^-1 m</td>
<td>10^-4</td>
<td>1</td>
<td>10^4</td>
</tr>
</tbody>
</table>

**Unsolved Mysteries**

- Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, mini-black holes, and evidence of string theory.

**Origin of Mass**

- In the Standard Model, for fundamental particles to have mass, there must exist a particle called the Higgs boson. Will it be discovered soon? Its supersymmetry theory correct in predicting more than one type of Higgs?
The Astrophysical Picture (WMAP)
Of these 4 questions, 3 can be addressed by experiments with particle-beam “microscopes”.

Why no antimatter?  Clues from neutrino mixing.
Dark Matter?  Search for production of new particles
Origin of Mass?  Search for evidence of the Higgs particle/field
Are Particles Really Quasiparticles?

Quasiparticles are “particles” whose mass is affected/determined by their interaction with a “background field.”

An early concept of a quasiparticle is a charged particle in a strong electromagnetic wave (Volkow, 1937), where
\[ m_{\text{eff}} = m \sqrt{1 + \eta^2}, \]
with \( \eta = eE / m_0 c. \)

In the Standard Model, a scalar background field is thought to affect (determine?) the masses of the “elementary” particles (Higgs, 1964).

⇒ Search for the Higgs boson.

SLAC E-144 was an experiment with electrons and a laser beam for which \( \eta \approx 0.3, \) such that a 10% electron mass shift occurred (and \( e^+e^- \) pairs were produced in light-by-light collisions.)

[Photon “solid:”
The number density of photons at the laser focus was 10 times the electron density in lead.]
“Microscopes” for Future Particle Physics

Since the time of Rutherford, “microscopes” for study of elementary particles do not use light/photons, but rather charged particles (electrons or protons) to illuminate/probe small objects.

Electron beams probe the electromagnetic structure of matter.

Proton (and neutron) beams probe the strong (quark/gluon) structure of matter.

Since ~ 1970, neutrino beams have also been used to probe the weak (hypercharge) structure of matter.

Since quarks are electrically charged, and have weak hypercharge as well, all 3 types of beams probe aspects of all known “matter.”

Protons are composed of quarks and gluons, so proton beams are in effect quark/gluon beams, in which the energy/momentum of the quarks and gluons has a broad spectrum.

⇒ Protons beams good for providing a “broad-brush” picture of elementary particles, whereas leptons beams (electrons and neutrinos) can provide finer detail.

The present major effort with high-energy particle beams is at the CERN Large Hadron Collider (LHC), which uses proton beams.
High-Energy Collisions Create Particles

An aspect of Nature not captured by the “microscope” analogy to its study is $E = mc^2$.

If the energy of a beam particle is a few times larger than its mass (or the mass of the target/illuminated particle, then the interaction of beam and target includes the creation of new particles.

This complication has become a central feature of “high-energy microscopes”, as it greatly expands the types of matter that can be studied.

If the goal is to produce new particles, it is advantageous that the center of mass energy of the beam and target particles be as large as possible.

⇒ Best to have both beam and target particles in motion, such that they collide head-on.

High-Energy Microscopes Are Beam-Beam Colliders

Hence the Large Hadron Collider is a proton-proton collider (with options for heavy-ion collisions.)
A New Type of Collider: $\mu^+\mu^-$

As far as we know, electrons (and positrons) are not composite particles, so an $e^+e^-$ collider provides a well-defined initial state in which all energy is concentrated in two fundamental particles.

However, electrons have relatively low mass, $m_e$, so the electric field $E$ of one beam can lead to substantial acceleration of electrons in the other beam.

$\Rightarrow$ Initial state radiation, with power $P \sim a^2 \sim E^2 / m_e^2$, which smears the energy of eventual $e^+e^-$ collisions.

This effect is much stronger at high energy, because the electric field $E$ of fast-moving charges is “flattened into a pancake” $\Rightarrow$ much larger $E$.

Solution: Use a beam particle that is not composite, but has higher mass than electron.

Enter the Muon ($\mu^\pm$)

$m_\mu / m_e \sim 207$, but otherwise their properties are very similar.

I.I. Rabi: “Who ordered that?”

One answer: Designers of better high-energy microscopes.
Physics Advantages of a $\mu^+\mu^-$ Collider

Narrower center-of-mass energy spread at high energies ($\Rightarrow$ precision studies of partners $Z'$ to the $Z^0$ vector boson, if these exist)

Since the coupling of the Higgs boson to particles is proportional to their mass, will have good rate for the process $\mu^+\mu^- \rightarrow h$, if the Higgs particle $h$ actually exists (Higgs Factory).

Muons decay to neutrinos, so the technology of a $\mu^+\mu^-$ collider also leads to a so-called Neutrino Factory.

Technical Advantage

A muon collider can circular, and much smaller than $pp$ or $e^+e^-$ colliders of comparable center of mass energies.

(V. Shiltsev, 6/9/09)

(R.B. Palmer, 6/27/11)
A Muon Collider is an energy-frontier particle-physics facility (that also produces lots of high-energy ν's).

Higher mass of muon  
⇒ Better defined initial state than e⁺e⁻ at high energy.

A muon lives ≈ 1000 turns.

Need lots of muons to have enough luminosity for physics.

Need a production target that can survive multimegawatt proton beams.
START WITH PROJECT X at Fermilab

Neutrinos
Muons
Kaons
Nuclei

“simultaneously”

2 MW (60-120 GeV)
1300 km

2 MW at ~3 GeV, flexible time structure and pulse intensities

(S. Geer, 6/30/11)
ADD
NEUTRINO
FACTORY

Enhanced Neutrinos
Enhanced Muons
Muon Collider test bed
Kaons
Nuclei

“simultaneously”

4MW protons
5 GeV muons
1300 km
But, is it as easy as 1-2-3?
Muon Collider Technical Challenges (1)

- **Muons created as tertiary beam \((p \rightarrow \pi \rightarrow \mu)\)**
  - low production rate
    - need target that can tolerate multi-MW beam
  - large energy spread and transverse phase space
    - need emittance cooling
    - high-acceptance acceleration system and decay ring

- **Muons have short lifetime (2.2 \(\mu\)s at rest)**
  - puts premium on rapid beam manipulations
    - high-gradient radio-frequency (RF) cavities (in magnetic field for cooling)
    - presently untested *ionization cooling* technique
    - fast acceleration system
Ionization Cooling (1)

- Ionization cooling analogous to familiar synchrotron radiation (SR) damping process in electron storage rings
  - energy loss (SR or $dE/dx$) reduces $p_x$, $p_y$, $p_z$
  - energy gain (RF cavities) restores only $p_z$
  - repeating this reduces $p_x, y/p_z$
Ionization Cooling (2)

• There is also a heating term
  — for synchrotron radiation (in electron rings) it is quantum excitation [aka Hawking/Unruh thermal bath seen by accelerated observers (J.S. Bell, 1982)]
  — for ionization cooling it is multiple scattering

• Balance between heating and cooling gives equilibrium emittance

\[
\frac{d\varepsilon_N}{ds} = - \frac{1}{\beta^2} \left. \frac{dE_\mu}{ds} \right|_\varepsilon_N + \frac{\beta_\perp (0.014 \text{ GeV})^2}{2 \beta^3 E_\mu m_\mu X_0}
\]

- **Cooling**
- **Heating**

\[
\varepsilon_{x,N,\text{equil.}} = \frac{\beta_\perp (0.014 \text{ GeV})^2}{2 \beta m_\mu X_0 \left. \frac{dE_\mu}{ds} \right|_\varepsilon_N}
\]

— prefer low \( \beta_\perp \) (strong focusing), large \( X_0 \) and \( dE/ds \) (\( \text{H}_2 \) is best)
Muon Collider Technical Challenges (2)

- Proton beam parameters
  - desired proton intensity for Neutrino Factory is 4 MW
    - e.g., $3.1 \times 10^{15} \text{ p/s at 8 GeV}$ or $6.2 \times 10^{13} \text{ p/pulse at 50 Hz}$
  - desired rms bunch length is 1-3 ns to minimize intensity loss
    - not easily done at high intensity and moderate energy

![Graph showing relationship between proton beam acceptance and rms bunch length.](image)

Difficult requirement at low beam energy (5-10 GeV)
Muon Collider Technical Challenges (3)

• Target
  - favored target concept based on Hg jet in 20-T solenoid
    - jet velocity of ~ 20 m/s establishes “new” target each beam pulse
      - magnet shielding is daunting, but appears manageable
  - alternative approaches (powder or solid targets) also being pursued within EUROnu

Hg-jet target (MERIT)

2011 target system concept

Superconducting magnets

tungsten-carbide beads + water

tungsten-carbide beads + water

proton beam and mercury jet

mercury pool proton dump beam window

1. Suction / Lift
2. Load Hopper
3. Pressurise Hopper
4. Powder Ejection and Observation
Muon Collider Technical Challenges (4)

- Normal conducting RF in magnetic field
  - cooling channel requires this
    - 805-MHz experiments indicate substantial degradation of gradient in such conditions
      - initial 201-MHz tests show similar behavior
    - gas-filled cavities avoid performance degradation in magnetic field
      - effects of intense ionizing radiation traversing gas now under study
        - first indications are that beam loading is severe

\[ N_2 \text{ 500 psi} \]
\[ H_2 \text{ 900 psi} \]
In the USA, an R&D consortium has existed since 1997 [first called the Muon Collider (and Neutrino Factory) Collaboration] and now called the Muon Accelerator Program. http://map.fnal.gov/

The Neutrino Factory is pursued in a worldwide context via the International Design Study for a Neutrino Factory. https://www.ids-nf.org/wiki/FrontPage
Example: Challenges in the Target System

- 5-50 GeV beam energy appropriate for Superbeams, Neutrino Factories and Muon Colliders.  
  \(0.8-2.5 \times 10^{15}\) pps; \(0.8-2.5 \times 10^{22}\) protons per year of \(10^7\) s.

- MW energy dissipation requires liquid coolant somewhere in system!

  ⇒ No such thing as “solid-target-only” at this power level.

- Rep rate 15-50 Hz at Neutrino Factory/Muon Collider, as low as \(\approx 2\) Hz for Superbeam.
  ⇒ Protons per pulse from \(1.6 \times 10^{13}\) to \(1.25 \times 10^{15}\).
  ⇒ Energy per pulse from 80 kJ to 2 MJ.

- Small beam size preferred:
  \(\approx 0.1\) cm\(^2\) for Neutrino Factory/Muon Collider.

- Pulse width: \(< 2\) ns desired for Neutrino Factory/Muon Collider.

  ⇒ Severe materials issues for target AND beam dump.
  - Radiation Damage.
  - Melting.
  - Cracking (due to single-pulse “thermal shock”).
Target and Capture Topology: Solenoid

Desire $\approx 10^{14} \mu/s$ from $\approx 10^{15}$ p/s ($\approx 4$ MW proton beam).

Highest rate $\mu^+$ beam to date: PSI $\mu E 4$ with $\approx 10^9 \mu/s$ from $\approx 10^{16}$ p/s at 600 MeV.

$\Rightarrow$ Some R&D needed!

R. Palmer (BNL, 1994) proposed a solenoidal capture system.

Low-energy $\pi$'s collected from side of long, thin cylindrical target.

Collects both signs of $\pi$'s and $\mu$'s, $\Rightarrow$ Shorter data runs (with magnetic detector).

Solenoid coils can be some distance from proton beam. $\Rightarrow$ $\geq$ 4-year life against radiation damage at 4 MW.

Liquid mercury jet target replaced every pulse.

Proton beam readily tilted with respect to magnetic axis. $\Rightarrow$ Beam dump (mercury pool) out of the way of secondary $\pi$'s and $\mu$'s.

Shielding of the superconducting magnets from radiation is a major issue.

Magnet stored energy $\sim 3$ GJ!

Use of “magnetic bottles” around production targets proposed by Djilkibaev and Lobashev,

Why 20 T?

The baseline scenario has pions produced (almost) on axis of a 20-T solenoid, followed by an “adiabatic” field taped down to 1.5 T = field strength of front-end $\pi/\mu$ beam transport.

We desire to capture all pions with $p_\perp \leq 200$ MeV/c.

If used a 1.5-T solenoid around the target, would need aperture of radius 80 cm to capture these pions.

But, if use a 20-T solenoid these pions fit within an aperture of 7.5 cm.

The adiabatic taper down to 1.5 T has the adiabatic invariant $\Phi_0 = \pi R_0^2 B_0 = \pi c^2 p_{0\perp}^2 / e^2 B_0$, which implies that at the end of the taper the pions fit in an aperture of only 30 cm.

That is, the use of an initial strong solenoid provides a kind of “transverse cooling”.

In principle, this “cooling” would be even stronger if we could use a field higher than 20 T.
CERN MERIT Experiment (Nov 2007)

Proof-of-principle demonstration of a mercury jet target in a strong magnetic field, with proton bunches of intensity equivalent to a 4-MW beam. Performed in the TT2A/TT2 tunnels at CERN.
MERIT Beam Pulse Summary

Integrated beam intensity [10^{13} protons]

Hg target OFF
Hg target IN


MERIT was not to exceed $3 \times 10^{15}$ protons on Hg to limit activation.

30 Tp shot @ 24 GeV/c
- 115 kJ of beam power
- a PS machine record!

1 Tp = $10^{12}$ protons
Disruption Length Analysis (H. Park, PhD Thesis)

Observe jet at viewport 3 at 500 frames/sec, measure total length of disruption of the mercury jet by the proton beam.

Images for 10 Tp, 24 GeV, 10 T:

Disruption length never longer than region of overlap of jet with proton beam.

No disruption for pulses of < 2 Tp in 0 T (< 4 Tp in 10 T).

Disruption length shorter at higher magnetic field.
Filament Velocity Analysis (H. Park)

Measure position of tip of filament in each frame, and fit for \( t_v \) and \( v \).

\[ \text{Slope} \propto \text{velocity} \]

\[ t_v = \text{time at which filament is first visible} \]

Filament velocity suppressed by high magnetic field.

Filament start time \( \gg \) transit time of sound across the jet.

\( \Rightarrow \) New transient state of matter???
Pump-Probe Studies

Is pion production reduced during later bunches due to disruption of the mercury jet by the earlier bunches?

At 14 GeV, the CERN PS could extract several bunches during one turn (pump), and then the remaining bunches at a later time (probe).

Pion production was monitored for both target-in and target-out events by a set of diamond diode detectors.

Results consistent with no loss of pion production for bunch delays of 40 and 350 µs, and a 5% loss (2.5-σ effect) of pion production for bunches delayed by 700 µs.
Cavitation pitting of (untreated) SS wall surrounding Hg target after 100 pulses (SNS):

Avoid this issue with free jet. But, is damage caused by mercury droplets from jet dispersion by the beam?

Numerical model by T. Davenne (RAL) suggests that droplets can cause damage.

Preliminary survey of MERIT primary containment vessel shows no damage.

Further studies to be made with Zeiss surface profiler.
The MERIT experiment established proof-of-principle of a free mercury jet target in a strong magnetic field, with proton bunches of intensity equivalent to a 4 MW beam.

- The magnetic field stabilizes the liquid metal jet and reduces disruption by the beam.
- The length of disruption is less than the length of the beam-target interaction, \( \Rightarrow \) Feasible to have a new target every beam pulse with a modest velocity jet.
- Velocity of droplets ejected by the beam is low enough to avoid materials damage.
- The threshold for disruption is a few \( \times 10^{12} \) protons, permitting disruption-free operation at high power if can use a high-rep-rate beam.
- Even with disruption, the target remains fully useful for secondary particle production for \( \approx 300 \mu s \), permitting use of short bunch trains at high power.
- No apparent damage to stainless-steel wall only 1 cm from interaction region.
Overall Summary

The opportunity for a Muon Collider/Neutrino Factory is associated with many challenges.

[No pain, no gain!]
Destruction of Nuclear Bombs Using

Ultra-High Energy Neutrino Beam

— dedicated to Professor Masatoshi Koshiba —

Hirotaka Sugawara*    Hiroyuki Hagura†    Toshiya Sanami‡

Abstract

We discuss the possibility of utilizing the ultra-high energy neutrino beam ($\sim 1000\,\text{TeV}$) to detect and destroy the nuclear bombs wherever they are and whoever possess them.