Muon Colliders

Daniel Schulte for
Jean-Pierre Delahaye, Marcella Diemoz, Ken Long, Bruno Mansoulie, Nadia Pastrone (chair), Lenny Rivkin, Alexander Skrinsky, Andrea Wulzer

Many thanks to Mark Palmer, Vladimir Shiltsev and the MAP and LEMMA teams
Also to Donatella Lucchesi, Christian Carli, Alexej Grudiev, Alessandra Lombardi, Gijs De Rijk, Mauricio Vretenar, ...
Findings

A first, high-level review of the two schemes with proton-based (MAP) and positron-based (LEMMA):

Muon-based technology represents a unique opportunity for the future of high energy physics research: the multi-TeV energy domain exploration.

First focus promising positron-based scheme, but identified need for consolidation

No showstopper found for proton scheme, but much more detailed understanding is required to judge performance, cost and power. No CDR exists.

Important progress of the technologies, addressing the feasibility of major technical issues with R&D performed by international collaborations.

In Europe, the reuse of existing facilities and infrastructure for a muon collider is of interest (e.g. LHC).

Documents: see first slide of the reserve
Motivation

High energy lepton colliders are precision and discovery machines

\[ V = \frac{1}{2} m_h^2 h^2 + (1 + k_3) \lambda_{hhh}^{SM} v h^3 + (1 + k_4) \lambda_{hhh}^{SM} h^4 \]

Precision potential

- Measure \( k_4 \) to some 10%
- With 14 TeV, 20 ab\(^{-1}\)

Discovery reach

- 14 TeV lepton collisions are comparable to 100 TeV proton collisions
- For s-channel physics target

Luminosity goal

- (Factor \( O(3) \) less than CLIC at 3 TeV)
Proposed Lepton Colliders (Granada)

CLIC can reach 3 TeV

- Cost estimate 18 GCHF
  - Largely main linac, i.e. energy
- Power 590 MW
  - Part in luminosity, a part in energy
- Similar to FCC-hh (24 GCHF, 580 MW)

Technically possible to go higher in energy

But is it affordable?

R&D required towards higher energies (or improvement of 3 TeV)

- Reduction of cost per GeV (improved NC acceleration, novel acceleration technologies)
- Improved power consumption (higher RF to beam efficiency, higher beam quality)
Proton-driven Muon Collider Concept

Short, intense proton bunches to produce hadronic showers

Pions decay into muons that can be captured

Muon are captured, bunched and then cooled

Acceleration to collision energy

Collision

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Muon Colliders, EPS, July 2019
## Target Parameter Examples

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Production Operation</th>
<th>From the MAP collaboration: Proton source</th>
<th>Accounts for Site Radiation Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CoM Energy</td>
<td>TeV</td>
<td>0.126</td>
<td>1.5</td>
<td>3.0</td>
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<tr>
<td>Avg. Luminosity</td>
<td>10^{34}cm^{-2}s^{-1}</td>
<td>0.008</td>
<td>1.25</td>
<td>4.4</td>
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<tr>
<td>Beam Energy Spread</td>
<td>%</td>
<td>0.004</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Higgs Production/10^{7}sec</td>
<td></td>
<td>13,500</td>
<td>37,500</td>
<td>200,000</td>
</tr>
<tr>
<td>Circumference</td>
<td>km</td>
<td>0.3</td>
<td>2.5</td>
<td>4.5</td>
</tr>
<tr>
<td>No. of IPs</td>
<td></td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>Hz</td>
<td>15</td>
<td>15</td>
<td>12</td>
</tr>
<tr>
<td>*</td>
<td>cm</td>
<td>1.7</td>
<td>1 (0.5-2)</td>
<td>0.5 (0.3-3)</td>
</tr>
<tr>
<td>No. muons/bunch</td>
<td>10^{12}</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Norm. Trans. Emittance,_{TN}</td>
<td>mm-rad</td>
<td>0.2</td>
<td>0.025</td>
<td>0.025</td>
</tr>
<tr>
<td>Norm. Long. Emittance,_{LN}</td>
<td>mm-rad</td>
<td>1.5</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Bunch Length,_{s}</td>
<td>cm</td>
<td>6.3</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>Proton Driver Power</td>
<td>MW</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Wall Plug Power</td>
<td>MW</td>
<td>200</td>
<td>216</td>
<td>230</td>
</tr>
</tbody>
</table>

Even at 6 TeV above target luminosity with reasonable power consumption, but have to confirm power consumption estimates.
The luminosity per beam power is about constant in linear colliders.

It can increase in proton-based muon colliders.

Strategy CLIC:
Keep all parameters at IP constant (charge, norm. emittances, betafunctions, bunch length)
⇒ Linear increase of luminosity with energy (beam size reduction)

Strategy muon collider:
Keep all parameters at IP constant
With exception of bunch length and betafunction
⇒ Quadratic increase of luminosity with energy (beam size reduction)
### Key Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>1.5 TeV</th>
<th>3 TeV</th>
<th>6 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>$10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>1.25</td>
<td>4.4</td>
<td>12</td>
</tr>
<tr>
<td>N</td>
<td>$10^{12}$</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>$f_r$</td>
<td>Hz</td>
<td>15</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>$P_{beam}$</td>
<td>MW</td>
<td>6.75</td>
<td>10.8</td>
<td>10.8</td>
</tr>
<tr>
<td>$&lt;B&gt;$</td>
<td>T</td>
<td>6.3</td>
<td>7</td>
<td>10.5</td>
</tr>
<tr>
<td>$\varepsilon_L$</td>
<td>MeV m</td>
<td>7.4</td>
<td>7.4</td>
<td>7.4</td>
</tr>
<tr>
<td>$\sigma_E / E$</td>
<td>%</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$\sigma_z$</td>
<td>mm</td>
<td>10</td>
<td>5</td>
<td>2(0.5)</td>
</tr>
<tr>
<td>$\beta$</td>
<td>mm</td>
<td>10</td>
<td>5</td>
<td>2.5</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>$\mu$m</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>$\sigma_{x,y}$</td>
<td>$\mu$m</td>
<td>5.9</td>
<td>3.0</td>
<td>1.5</td>
</tr>
</tbody>
</table>

*From the MAP collaboration: Proton source*
High power target (8 MW vs. 1.6-4 MW or even less required) has been demonstrated.

Maximum pulse tested $30 \times 10^{12}$ protons with 24 GeV
- $9 \times 10^{12}$ muons (loose 90%)

But radiation issues?

What could be made available at CERN (or elsewhere) as a proton driver for a potential test facility?

Maybe can use solid target
Transverse Cooling Concept

\[
\frac{d\epsilon_\perp}{ds} = -\frac{1}{(v/c)^2} \frac{dE}{ds} \frac{\epsilon_\perp}{E} + \frac{1}{2} \frac{1}{(v/c)^3} \left( \frac{14 \text{ MeV}}{E} \right)^2 \frac{\beta\gamma}{L_R}
\]
Cooling: The Emittance Path

- Specification
- Achieved (simulations)

For acceleration to multi-TeV collider

For acceleration to NuMAX (325MHz injector acceptance 3mm, 24mm)

Final

Initial

VCC & Hybrid

HCC

Bunch Merge

pre-merge 6D Cooling (original design)

post-merge 6D Cooling

Final

transverse emittance (microns)

longitudinal emittance (mm)

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MICE allows to address 4D cooling with low muon flux rate

\[
\frac{d\epsilon_\perp}{ds} = -\frac{1}{(v/c)^2} \frac{dE}{ds} \frac{\epsilon_\perp}{E} + \frac{1}{2} \frac{1}{(v/c)^3} \left( \frac{14\text{ MeV}}{E} \right)^2 \frac{\beta\gamma}{L_R}
\]

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MICE Results

The absorber reduces the number of particle with large amplitude

They appear with smaller amplitude

Noticeable reduction of 9% emittance

But still some way to go
• 6D cooling
• Stages
• Small emittances
Other Tests

**MuCool**: >50 MV/m in 5 T field

A number of key components has been developed

**FNAL**
Breakthrough in HTS cables

**NHFML**
32 T solenoid with low-temperature HTS

**FNAL**
12 T/s HTS 0.6 T max

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Mark Palmer
Beam Acceleration

An important cost driver
Important for power consumption

A trade-off between cost and muon survival
Not detailed design, several approaches considered
- Linacs
- Recirculating linacs
- FFAGs
- Rapid cycling synchrotrons

Challenge is large bunch charge but single bunch

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Potential Approaches

Acceleration is important for cost and power consumption
No conceptual baseline design yet
But different options considered
A whole chain is needed from source to full energy

Recirculating linacs
- Fast acceleration but typically only a few passages through RF, hence high RF cost

Rapid cycling synchrotron (RCS)
- Potentially important acceleration range at affordable cost
- Could use combination of static superconducting and ramping normal-conducting magnets
- But have to deal with energy in fast pulsing magnets
- Efficient energy storage is required

FFAGs
- Static high field magnets, can reach factor up to 4 increase in energy, needs design work

Challenge to achieve a combination of high efficiency, low cost and good beam quality
Collider Ring

Strong focusing at IP to maximise luminosity
Becomes harder with increasing energy

High field dipoles to minimise collider ring size and maximise luminosity
Minimise distances with no bending

Proposal to combine last accelerator ring and collider ring (Neuffer/Shiltsev) might reduce cost but creates many specific challenges

Decaying muons impact accelerator components, detector and public
The latter becomes much worse with energy

Radiation to public in case LHC tunnel use

Might be best to use LHC tunnel to house muon accelerator and have dedicated new collider tunnel
Neutrino Radiation Hazard

Neutrinos from decaying muons can produce showers just when they exit the earth

Approximate dose
Particularly high in direction of straights

Potential mitigation by
- Owning the land in direction of experimental insertion
- Having a dynamic beam orbit so it points in different directions at each turn in the arcs
- Some gymnastics with beam in straights to make it point in different directions

\[ D_{\text{arc}} \approx 0.41 \text{ mSv} \frac{N_0 f_r T_{\text{operate}}}{10^{20}} \left( \frac{E}{\text{TeV}} \right)^3 \frac{m}{d} \frac{\langle B \rangle}{B} \]

\[ D_{\text{straight}} \approx 0.59 \text{ mSv} \frac{N_0 f_r T_{\text{operate}}}{10^{20}} \left( \frac{E}{\text{TeV}} \right)^3 \frac{m}{d} \frac{\langle B \rangle}{T} \frac{L}{m} \]

Need to study for higher energies (scaling \( E^3 \))

Dose is proportional to integrated luminosity times energy

Straights in LHC might increase problem
⇒ Another reason to consider this as accelerator
The LEMMA Scheme

Key concept:
Produce muon beam with low emittance using a positron beam
No cooling required

Muon current $10^{11}$ s$^{-1}$ is 300 times lower compared to $3 \times 10^{13}$ s$^{-1}$ for proton driver

Emittance $O(10^{-3})$ smaller than in proton scheme, 40 ns vs. 25 μm

In design of 2018 two important issues were found
- Muon multiple scattering
- Issue with phase space

Attempt to consolidate is ongoing
⇒ Nadia’s talk
Beam induced background studies on detector at $\sqrt{s} = 1.5$ TeV

MARS15 simulation in a range of $\pm 100$ m around the interaction point

750 GeV beam

Particle composition of the beam-induced background as a function of the muon decay distance from the interaction point

Simulated time of arrival (TOF) of the beam background particles to the tracker modules with respect to the expected time ($T_0$) of a photon emitted from IP

arXiv:1905.03725
Conclusion

We think we can answer the following questions

• **Can muon colliders at this moment be considered for the next project?**
  • Enormous progress in the proton driven scheme and new ideas emerged
  • But at this moment not mature enough for a proposal

• **Is it worthwhile to do muon collider R&D?**
  • Yes, it promises the potential to go to very high energy
  • It may be the best option for very high lepton collider energies, beyond 3 TeV
  • It has strong synergies with other projects, e.g. magnet and RF development
  • Has synergies with other physics experiments
  • Should not miss this opportunity

• **What needs to be done?**
  • Muon production and cooling is key => A new test facility is required.
  • A conceptual design of the collider has to be made
  • Many components need R&D, e.g. fast ramping magnets, background in the detector
  • Site-dependent studies to understand if existing infrastructure can be used
    • limitations of existing tunnels, e.g. radiation issues
    • optimum use of existing accelerators, e.g. as proton source
Recommendations

Set-up an international collaboration to promote muon colliders and organize the effort on the development of both accelerators and detectors and to define the road-map towards a CDR by the next Strategy update.

Develop a muon collider concept based on the proton driver and considering the existing infrastructure.

Consolidate the positron driver scheme addressing specifically the target system, bunch combination scheme, beam emittance preservation, acceleration and collider ring issues.

Carry out the R&D program toward the muon collider. Based on the progress of the proton-driver and positron-based approaches, develop hardware and research facilities as well as perform beam tests. Preparing and launching a conclusive R&D program towards a multi-TeV muon collider is mandatory to explore this unique opportunity for high energy physics. A well focused international effort is required in order to exploit existing key competences and to draw the roadmap of this challenging project. The development of new technologies should happen in synergy with other accelerator projects. Moreover, it could also enable novel mid-term experiments.
Proposed Tentative Timeline

- **R&D detectors**
- **Prototypes**
- **MDI & detector simulations**

Design

1. Baseline design
2. Design optimisation
3. Project preparation
4. Approve

Test Facility

5. Design
6. Construct
7. Exploit
8. Exploit

Technologies

9. Design / models
11. Prototypes / pre-series

**MACHINE**

12. **CDRs**
13. **TDRs**
14. **Large Proto/Slice test**

**DETECTOR**

15. Ready to decide on test facility
16. Cost scale known
17. Ready to commit to collider
18. Cost known
19. Ready to construct

Technically limited

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Reserve
Muon Collider Working Group

Jean Pierre Delahaye, CERN, Marcella Diemoz, INFN, Italy, Ken Long, Imperial College, UK, Bruno Mansoulie, IRFU, France, Nadia Pastrone, INFN, Italy (chair), Lenny Rivkin, EPFL and PSI, Switzerland, Daniel Schulte, CERN, Alexander Skrinsky, BINP, Russia, Andrea Wulzer, EPFL and CERN appointed by CERN Laboratory Directors Group in September 2017

to prepare the Input Document to the European Strategy Update

“Muon Colliders,” arXiv:1901.06150

de facto it is the seed for a renewed international effort

Past experiences and new ideas discussed at the joint ARIES Workshop

July 2-3, 2018
Università di Padova - Orto Botanico
https://indico.cern.ch/event/719240/overview

Preparatory meeting to review progress for the ESPPU Symposium

April 10-11, 2019
CERN – Council Room
https://indico.cern.ch/event/801616
Recommendations

Set-up an international collaboration to promote muon colliders and organize the effort on the development of both accelerators and detectors and to define the road-map towards a CDR by the next Strategy update. As demonstrated in past experiences, the resources needed are not negligible in terms of cost and manpower and this calls for a well-organized international effort.

For example, the MAP program required an yearly average of about 10M$ and 20 FTE staff/faculty in the 3-year period 2012-2014.

Develop a muon collider concept based on the proton driver and considering the existing infrastructure. This includes the definition of the required R&D program, based on previously achieved results, and covering the major issues such as cooling, acceleration, fast ramping magnets, detectors, . . . .

Consolidate the positron driver scheme addressing specifically the target system, bunch combination scheme, beam emittance preservation, acceleration and collider ring issues.

Carry out the R&D program toward the muon collider. Based on the progress of the proton-driver and positron-based approaches, develop hardware and research facilities as well as perform beam tests. Preparing and launching a conclusive R&D program towards a multi-TeV muon collider is mandatory to explore this unique opportunity for high energy physics. A well focused international effort is required in order to exploit existing key competences and to draw the roadmap of this challenging project. The development of new technologies should happen in synergy with other accelerator projects. Moreover, it could also enable novel mid-term experiments.
Scope of the Working Group

• Performed a first, high-level review of the two muon collider schemes: one based on protons to produce muons (MAP) and one on positrons (LEMM)

• The focus has been on the positron-based scheme, which it was really promising but it has been found to require consolidation

• The proton scheme
• This year a more in depth investigation can provide a better assessment for the European Strategy Process about the potential value of the technology for a collider and the R&D programme that would be required. Dedicated work is being carried out on a positron driven new scheme

Note:

• Not ready to draft a CDR
• To pursue the promising muon collider option, a strong R&D effort should be supported to take ownership of a conceptual design or develop a better one
Findings

Muon-based technology represents a unique opportunity for the future of high energy physics research: the multi-TeV energy domain exploration.

The development of the challenging technologies for the frontier muon accelerators has shown enormous progress in addressing the feasibility of major technical issues with R&D performed by international collaborations.

In Europe, the reuse of existing facilities and infrastructure for a muon collider is of interest. In particular the implementation of a muon collider in the LHC tunnel appears promising, but detailed studies are required to establish feasibility, performance and cost of such a project.

A set of recommendations at the end will allow to make the muon collider technology mature enough to be favorably considered as a candidate for high-energy facilities in the future.
Potential Key R&D Items

- **Integrated design**
  - E.g. lose 90% of muons before collision, can this be reduced?
  - Important cross effects, e.g. beam emittance

- **Neutrino radiation**
  - How can it be reduced? (Better cooling, orbit variations, ...)
  - What can be defended to the public?

- **Experimental conditions**

- **Beam production and cooling**
  - Emittance drives design
  - Lower emittance: less radiation to public, detector, ...; less power; less risk
  - Proton beam production / compression
  - Paper design of cooling does not reach full performance
  - Robust targets
  - Robust high gradient RF
  - Height field solenoids
  - Take full advantage of MICE (data, installation)
  - Likely will find need to improve test compared to MICE
    - 6-D cooling, stages to reach significant emittance reduction, radiation effect on equipment, ...
    - Likely the core of the experimental programme

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Potential Key R&D Items, cont.

• Acceleration complex design
  – Is it affordable (cost and power)?
  – Fast ramping magnets (for RCS)
  – High field superconducting magnets
  – Beamline design
  – Collimation
  – ...

• Collider ring design
  – Is it affordable (cost)?
  – High field superconducting magnets, with radiation
  – Improved lattice design beyond 3 TeV
  – Injection, safety concept

• Reuse of existing infrastructure
  – Proton facilities
  – Tunnels (maybe more for acceleration than collision)

• LEMMA concept
  – Consolidation
  – Alternative low-emittance sources
Note: Total Power Consumption

Power consumption estimates are based on a table calculated by R. Palmer
• Leaves out a number of components, e.g. magnets
• Quote: “These numbers are preliminary, with large uncertainties”

J.-P. Delahaye added a constant value

Need to have conceptual start-to-end design to estimate power correctly
Efficiency of wall plug to beam is not very different from CLIC
Key to Luminosity

Integrated luminosity of one bunch

\[ \Delta \int \mathcal{L} \approx \sum_{i=0}^{\infty} \left( \frac{N_0 e^{-i\Delta t/\gamma \tau}}{4\pi \sigma_x \sigma_y} \right)^2 \]

High bunch charge

High energy

For constant longitudinal emittance

High field in collider ring

Small emittance

High beam power

Win luminosity per power as the energy increases

In linear colliders, luminosity per power tends to be energy independent

• except if one changes technology (very short bunches, smaller vertical emittance)

In circular electron-positron colliders luminosity drops rapidly with energy (power \( \approx 3.5 \))
Key to Luminosity

Integrated luminosity of two colliding bunches with charge $N_0$

$$\Delta \int \mathcal{L} \approx \sum_{i=0}^{\infty} \frac{(N_0 e^{-i \Delta t / \gamma \tau})^2}{4 \pi \sigma_x \sigma_y}$$

Size of the ring scales as

Hence

$$\sum_{i=0}^{\infty} \left( N_0 e^{-i \Delta t / \gamma \tau} \right)^2 \propto N_0^2 B$$
Key to Luminosity

\[ \Delta \int L \propto \frac{B N_0^2}{4\pi \epsilon \beta / \gamma} \]

Geometric emittance shrinks with energy
Assumption: normalised emittance is preserved
Key to Luminosity

Assumption:
Longitudinal emittance is preserved

Collider ring can tolerate the same relative energy spread

Hence bunch length can shrink

Hence beta-function can shrink (provided we have a technical solution)

\[ \sigma_E \sigma_z = \text{const} \]

\[ \frac{\sigma_E}{E} = \text{const} \]

\[ \sigma_z \propto \frac{1}{\gamma} \]

\[ \beta \approx \sigma_z \quad \beta \propto \frac{1}{\gamma} \]

\[ \Delta \int \mathcal{L} \propto \frac{BN_0^2}{4\pi \epsilon \beta / \gamma} \]

\[ \Delta \int \mathcal{L} \propto B \frac{N_0^2 \gamma^2}{\epsilon} \]
Key to Luminosity

\[ \Delta \int \mathcal{L} \propto B \frac{N_0^2 \gamma^2}{\epsilon} \]

\[ \mathcal{L} \propto B \frac{N_0}{\epsilon} \gamma P_{\text{beam}} \]
Key Challenges

- **Neutrino radiation**
  - What can be defended to the public?
  - How can it be reduced?

- **Experimental conditions**
- **Beam production and cooling**
  - No paper design with full performance
  - Improve test compared to MICE
    - 6-D cooling, stages to reach significant emittance reduction, radiation effect on equipment, ...

- **Acceleration complex design**
  - Is it affordable (cost and power)?
  - Fast ramping magnets
  - High field superconducting magnets
  - Beamline design
  - Collimation
  - ...

- **Collider ring design**
  - Is it affordable?
  - High field magnet design
  - Improved lattice design beyond 3 TeV required
  - Injection, safety concept

- **Reuse of existing infrastructure**
  - Proton facilities
  - Tunnels (maybe more for acceleration than collision)

- **LEMMMA concept**
  - Consolidation
  - Alternative low-emittance sources
Key Technologies

• High-field, robust magnets
  – Dipoles, solenoids, ...

• Efficient fast ramping magnets
  – For the beam acceleration
  – Integrated field is approx. 0.25 x 21 Tm x collision energy / GeV

• Efficient energy storage of magnet energy
  – Cannot afford to lose energy in fast ramping magnets

• Efficient cryogenics systems

• High field cavities
  – In a solenoid for the cooling system

• Robust superconducting cavities

• Efficient RF power production

• Robust targets

• Beamdynamics
  – Start-to-end design and simulations
Carlo Rubbia: The experimental realization of the presently described $\mu+\mu$- Ring Collider may represent the most attractive addition of the future programs on the Standard Model to further elucidate the physics of the $\Delta o$, requiring however a substantial amount of prior R&D developments, which must be experimentally confirmed by the help of the Initial Muon Cooling Experiment(al) program.

Initial Cooling Experiment
Use 100 ns ESS pre-pulse with $3 \times 10^{11}$ protons
Yields $3 \times 10^7 \mu^-$ and $6 \times 10^7 \mu^+$ around 250 MeV
Linear Collider Scaling with Energy

\[ \mathcal{L} \propto H_D \frac{n_\gamma^{\frac{3}{2}}}{\sqrt{\sigma_z}} \frac{1}{\sqrt{\epsilon_y \beta_y}} \frac{R+1}{R} \frac{\eta P_{wall}}{mc^2} \]

At high energy

\[ n_\gamma \propto \left( \frac{\sigma_z}{\gamma} \right)^\frac{1}{3} \left( \frac{N}{\sigma_x + \sigma_y} \right)^\frac{2}{3} \]

For unchanged technologies:
Luminosity per power remains constant with energy
Provided we can focus the beam accordingly

\[ R = \frac{\sigma_x}{\sigma_y} \]
Muon Collider Luminosity Scaling

Key assumptions:
Emittance are preserved from source to collision
Higher energy allows shorter bunches and hence smaller betafunctions

\[ \mathcal{L} \propto B \frac{N_0}{\varepsilon \ell L} \gamma f_r N_0 \gamma \]

High field in collider ring
Dense beam
High beam power
High energy

For mostly unchanged technologies:
Luminosity per power naturally increases with energy
Provided we can focus the beam accordingly
Longitudinal Cooling/Emittance Exchange

Combined with transverse cooling at beginning

Several options considered

Allows 6-D cooling
Key concept (original numbers in brackets)

Produce muon beam with low emittance using a positron beam (40 nm vs. 25 \( \mu m \) in proton scheme)

• No cooling required, use lower muon current

• Positron beam (45 GeV, \( 3 \times 10^{11} \) particles every 200 ns) passes through target and produces muon pairs

• Muon bunches are circulated through target \( O(2000) \) times accumulating more muons (\( 4.5 \times 10^7 \))

• Every 0.5 ms, the muon bunches are extracted and accelerated

• They are combined in the collider ring, where they collide

Muon current \( 10^{11} \text{ s}^{-1} \) is 300 times lower compared to \( 3 \times 10^{13} \text{ s}^{-1} \) for proton driver
Key Issues

Small efficiency of converting positrons to muon pairs
• Muon pair production is only small fraction of overall cross section ($O(10^{-5})$)
• Most positrons lost with no muon produced
• Have to produce many positrons (difficult)
• $O(100\text{MW})$ synchrotron radiation
• High heat load and stress in target (also difficult)

Two additional severe issues were identified in the review
– The multiple scattering of the muons in the target
  • Theoretical best emittance of 600 nm instead of assumed 40 nm
  • Reduction of luminosity by factor 15
– Small bunches were accelerated and later merged but no design exists for the merger
  • The combination factor is proportional to beam energy
  • If the combination does not work, lose a large factor of luminosity

Working on a better design but have to wait and see the outcome
Ongoing LEMMA Effort

Ongoing effort to address identified challenges

• Positron production
  • Rotating target (like ILC)
  • Use of positron beam for production

• Positron ring challenge
  • larger ring, pulsed ring, lower energy accumulator ring

• Large emittance from target
  • use sequence of thin targets, H₂ targets, ...
  • Increased muon bunch charge, e.g. better capturing, ...
  • muon cooling (crystals, stochastic, ...)

• Difficulty of combining muon bunches at high energy
  • Increasing charge at the source (producing bunches in pulsed fashion)
  • increase muons per positron bunch

More detailed studies needed to understand what does work and how well