LEMMA approach for the production of low-emittance muon beams

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The LHC will operate until about 2040 according to the current schedule

→ a new machine needed to explore physics beyond the LHC reach

Current studies concentrate on two conceptually different scenarios:

1. **high energy** (*FCC-hh*)
   - very heavy particles can be produced (~few TeV)
   - lots of additional radiation produced in hadronic collisions
   - kinematics of interacting partons uncertain (limited by PDF)

2. **high precision** (*FCC-ee, ILC, CLIC*)
   - extremely clean final states with minimum of additional radiation
   - kinematics of interacting particles known precisely
   - limited energy reach (up to 0.5 TeV at FCC) due to synchrotron radiation

Each of the two scenarios requires a dedicated accelerator complex

→ can only be implemented one after another if using the same tunnel

Increased time and cost requirements for the accelerator construction
Advantages of both $pp$ and $e^+e^-$ colliders can be combined in a $\mu^+\mu^-$ collider

- same clean final states as in $e^+e^-$ collisions
- initial state kinematics precisely known
- collisions at a multi-TeV level can be achieved
- may profit from the high $\mu^+\mu^- \rightarrow H$ cross section at dedicated $\sqrt{s}$
- much less synchrotron radiation
  - more compact layout
  - lower power consumption

Serious challenges to be addressed:
- accelerating and colliding muons before they decay
- suppressing background from the $\mu$ beam decay products ($e^-, \nu$)
- producing a low-emittance muon beam
**Classical scheme: MAP**

**Major effort towards a multi-TeV Muon Collider design made by:**
- U.S. Muon Accelerator Program (MAP)
- International Muon Ionization Cooling Experiment (MICE)

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**Proton Driver**
- Accumulator
- Compressor

**Target**
- Proton Driver
- Target

**Front End**
- Decay Channel
- Buncher
- Phase Rotator

**Cooling**
- 6D Cooling
- Bunch Merge
- 6D Cooling
- Final Cooling

**Acceleration**
- Accelerator Types: Linac, Recirculating Linacs (RLAs), Rapid Cycling Synchrotrons (RCS)
- \( E_{\text{COM}} \)
- 126 GeV
- 1.5 TeV
- 3 TeV

**Collider Ring**
- \( \mu^+ \rightarrow \mu^- \)
- \( \mu^+ + \mu^- \rightarrow X \)

**A series of RF cavities + solenoid coils to reduce the transverse beam divergence**

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**Figure 27:** Functional elements of a Higgs Factory/Muon Collider complex

They can be listed as follows:

- A proton driver producing a high-power multi-GeV bunched proton beam.
- A pion production target operating in a high-field solenoid. The solenoid confines the pions radially, guiding them into a decay channel.
- A "front end" consisting of a solenoid \( \pi^+ \rightarrow \mu^+ \) channel, followed by a system of RF cavities to capture the muons longitudinally and phase rotate them into a bunch train suitable for use in the cooling channel.
- A cooling channel that uses ionization cooling to reduce the longitudinal phase space occupied by the beam by about six orders of magnitude from the initial volume at the exit of the front end.
- A series of acceleration stages to take the muon beams to the relevant collider energies. Depending on the final energy required, this chain may include an initial linac followed by recirculating linear accelerators (RLAs) and/or fixed-field alternating gradient (FFAG) rings.
- A compact collider ring, having a circumference of ~300 m for a Higgs Factory and several kilometers for a TeV-scale collider, along with the associated detector(s). At present, the baseline Higgs Factory design assumes 1 detector while the TeV-scale colliders can readily accommodate at least 2 detectors.
A new approach has been proposed recently: Low Emittance Muon Accelerator producing muons at the $e^+e^- \rightarrow \mu^+\mu^-$ threshold ($\sqrt{s} \approx 45$ GeV)

- divergence of the $\mu^\pm$ beams very small and tunable via $\sqrt{s}$
- long $\mu^\pm$ beam lifetime ($\sim 500$ µs) $\rightarrow$ reduced losses from the $\mu^\pm$ decays

Very elegant and technically simpler design $\rightarrow$ has to be experimentally proven
The LEMMA concept put to a test in a series of testbeam campaigns in 2017/2018

• using the CERN SPS beam line as a positron source \((5 \times 10^6 \text{ } e^+/\text{spill})\)

The main goal of the testbeam: understand if the LEMMA approach is feasible

\[
N(\mu^+\mu^-) = N(e^+) \cdot \rho(e^-) \cdot \sigma(e^+e^- \rightarrow \mu^+\mu^-) \cdot L
\]

\(L\) – target length

A number of measurements foreseen to answer this question:

• kinematic properties of the produced muons (emittance, momentum, ...)
• cross section of the \(e^+e^- \rightarrow \mu^+\mu^-\) production (depends on the \(e^+\) energy)
• effect of the target material/thickness

Data taking performed with a number of different configurations:

• target materials: \(Be, C\)
• Target thickness: 2 cm, 6 cm
• positron-beam energies: 45 GeV, 46.5 GeV, 49 GeV
A combination of detectors used to measure the $\mu^\pm$ trajectories and energies

Experimental setup:

- **target**: Be or C
- **Si microstrip stations**
- **vacuum beam pipe**
- **dipole magnet**
- **CAL**
- **DT**

Scintillators used as external trigger for the Silicon stations and Calorimeter

$e^+ \rightarrow \mu^\pm$

DT chambers acquired with trigger-less readout

\[ B = 2 \text{ T} \]

Iron blocks
Several calibration runs were performed without a target:

- **µ⁻ beam**: for alignment of the Calorimeters and DT muon chambers
- **e⁺ beam**: for alignment of the Silicon stations + calibration of the Calorimeters

First version of muon analysis performed: *calorimeter information not considered*

- reconstructing e⁺ and µ± trajectories and selecting good µ⁺µ⁻ candidate events
  - µ⁺ and µ⁻ tracks intersecting inside the magnet
  - \( m(\mu^+\mu^-) = 2 \cdot 106 \text{ MeV} \land p(\mu^+) + p(\mu^-) = p(e^+) \)
Reconstructed hits from Silicon stations and DT chambers in a signal event (August 19th, 2018)

Reconstructed hit positions in silicon stations before and after the beam pipe

- good agreement with the MC simulation

X in det30

X in det31
Silicon stations and DT chambers used for the muon track reconstruction
• providing ~6% momentum resolution

Significant improvement in 2018 compared to 2017
• low statistics due to hardware problems in 2017
Reconstructed muon kinematics in a good agreement with the MC simulation

Not all setup features implemented in MC yet
Alignment of the detectors not perfect yet
DT muon chambers have a trigger-less readout: all channels acquired every 25ns
- can detect $\mu^+\mu^-$ events without the external trigger
- similar design considered by the LHCb/CMS/ATLAS for HL-LHC

Each of the 4 chambers contains 64 cells arranged in 4 layers

Measuring time of a charge carrier reaching the wire
$\rightarrow$ reference time $t_0$ needed to convert time to a hit position

A triplet of hits sufficient to determine $t_0$ *(meantimer method)*
$\rightarrow$ separate equation for each type of pattern

The determined $t_0$ found to be more precise than the external trigger due to a $\sim3$ ns jitter in the trigger electronics

The number of events identified with DT data: $\sim10000$
- trigger efficiency: $\sim2$-$20\%$ *(preliminary estimate)*
Summary

A Muon Collider is a promising project that could replace or complement the rather well studied $e^+e^-$ and $pp$ collider options.

LEMMA is an elegant solution for producing low-emittance muon beams.

The LEMMA scheme has been implemented using the $e^+$ beam at CERN.

A number of open questions remain:
1. Can the desired $\mu$ production rate of $\sim 10^{11}$ be achieved?
2. What is the actual luminosity vs emittance dependence?
3. What is the effect of the target material and length?

The obtained testbeam data is the first step in providing the answers.

A lot of work has already been done: experimental setup + data analysis.

Main ingredients of the analysis chain already in place:
$\rightarrow$ conclusive numerical results are a matter of time + our devoted work.