
**FINDINGS and 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

......

**Carry out the R&D program toward the muon collider**
Facts

- June Council could possibly release the update of the EU Strategy
- U.S. Snowmass21 process was launched at: [https://snowmass21.org/start](https://snowmass21.org/start)
- Muon Collider community is ready to establish the international collaboration as announced at the General Meeting: [https://indico.cern.ch/event/886491/](https://indico.cern.ch/event/886491/)

A Muon Collider has the potential to largely extend the energy frontier:
- an immense physics reach ➔ to be further explored
- a start-to-end collider design faces challenges & requires key enabling technologies
- detector studies with beam induced background proved physics feasible @ 1-3 TeV ➔ new experiment design and studies at the energy frontier are needed
- possible re-use of existing infrastructures must be analyzed considering rad-hazard
multi-TeV circular muon colliders

have the unique potential to reach centre-of-mass energies of tens of TeV:
- direct searches for new particles over a wide range of unexplored masses
- accurate tests of the Standard Model
- Vector Boson Fusion and Vector Boson Scattering processes

unique and overwhelming physics reach

but

requirements for high instantaneous luminosity faces technical challenges due to:
- the short muon-lifetime
- the difficulty of producing large numbers of muons in bunches with small emittance

- Muon production beam source defines viable machine parameters
- Accelerator and collider rings require developments of key technologies
- Radiation hazard by neutrino’s fluxes must be carefully evaluated
- Machine detector interface constraints experiment design
- Beam-induced background requires detectors technology beyond status of the art
international collaboration

to develop an integrated muon collider design concept
that encompasses the physics, the detectors, and accelerator

• to develop fully the muon collider design study
  ➜ exploring the various options
• to pursue R&D priorities, according to an agreed upon work plan

Master plan:

• A start-to-end collider design ➜ this would be the first facility of its kind
• A machine detector interface that protects the detector from collider background while allowing good machine performance
• A physics and detector study to assess the physics reach of the collider
Technically Limited Potential Timeline

Briefing Book Tentative Timeline (2019)

- **12 March**
  - Design
  - Construction

- **20 March**
  - Test Facility

- **27 March**
  - Baseline design
  - Exploit

- **1 April**
  - Design/Models
  - Prototypes

- **3 April**
  - Prototypes/Pre-series
  - Prototypes/T.F. Comp.

- **5 April**
  - Ready to decide on test facility
  - Cost scale known

- **9 April**
  - Ready to commit to collider
  - Cost known

- **17 April**
  - Full project

- **1 May**
  - Higher cost for preparation

- **2 May**
  - Higher cost for technical design
  - Significant resources

- **3 May**
  - Higher cost for test facility
  - Specific prototypes
  - Significant resources

- **6 May**
  - MDI & detector simulations
  - Limited cost
  - Mainly paper design
  - And some hardware component R&D

- **8 May**
  - Machinery

- **9 May**
  - Technically limited

- **10 May**
  - CDRs
  - TDRs
  - Large Proto/Slice test

- **16 May**
  - Full project

- **17 May**
  - Limited cost
  - Mainly paper design
  - And some hardware component R&D
proton (MAP) vs positron (LEMMA) driven muon source

- **MAP**
  - 10^{13}-10^{14} \mu/sec

- **LEMMA**
  - e+ source

**arXiv:1905.05747v2 [physics.acc-ph]**

- **need consolidation** to overcome technical limitations to reach higher muon intensities
  - muons produced with low emittance ➔ “no/low cooling” needed
  - low production cross section: maximum \( \sigma(e^+e^- \rightarrow \mu^+\mu^-) \approx 1 \mu b \)
  - high heat load and stress in \( \mu \) production target
  - synchrotron power O(100 MW) ➔ available 45 GeV positron sources
Factor of merit

MAP studies addressed design issues from muon production to final acceleration:

- proton driver option: advanced studies for a 3-6 TeV machine
- however a 6D cooling TEST FACILITY is MANDATORY to demonstrate feasibility

A new idea not requiring 6D cooling – LEMMA – represent an appealing scheme:

- further studies and solid R&D program needed for such positron driven option
Effort for Baseline Design

- **Put together coherent design requires (mainly human) resources**
  - This goes beyond US effort
  - Consistent parameters and layouts
  - Integration of collider systems, trade-offs, choices, ...
  - May highlight additional important issues
  - Requires (mainly human) resources
  - Currently MAP is main option, LEMMA is alternative

- **Key R&D list with priorities**
  - Identify key / feasibility issues
    - i.e. largest technical risks
    - Key cost driver, if critical
    - Key power consumption, if critical
  - Entry point for collaborators

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Proposed MUST (MUon collider STudy network) submitted I.FAST EU project
Next steps

Muon Colliders is a unique opportunity at the high-energy frontier

- Several teams from different countries already contributed to present knowledge
- The on-going work is fostering the preparation of an organized study:
  - identification of feasibility issues and potential incremental steps
  - resurrect studies of Muon Colliders taking advantage of the enormous progress already done
  - identify resources required to address most critical issues
  - launch international collaboration on Muon Colliders covering Physics, Detector and Accelerator
- Synergies with other future accelerators can be easily identified for example on:
  - high field magnets and fast ramping magnets with efficient energy recovery
  - efficient RF power production and high field cavities
  - robust targets
  - techniques for the large acceptance, rapid acceleration (RLA, LEMMA and other applications)
Conclusions

• INFN plays a crucial role on many activities

• This meeting was planned to briefly review:
  • work done
  • work in progress
  • plans

• A general international meeting will be help June 29-30 (2-6 pm) to agree on the new work plan and future steps of the international collaboration

• To be noted a renew interest on Muon Colliders in the SnowMass21 on-going US process
e-groups
towards an international collaboration

E-group: MUONCOLLIDER-DETECTOR-PHYSICS
MUST-phydet@cern.ch

E-group: MUONCOLLIDER-FACILITY
MUST-mac@cern.ch

Thanks to the 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 Directorate in September 2017
to prepare an Input Document to the European Strategy Update
de facto the seed of a renewed on-going international effort
extras
Why a multi-TeV Muon Collider?

cost-effective and unique opportunity for lepton colliders @\(\sqrt{s} > 3\) TeV

The luminosity per beam power is independent of collision energy in linear colliders, but increases linearly for muon colliders.

Full collision energy available for particle production: 14 TeV lepton collisions are comparable to 100 TeV proton collisions for selected new physics process, if sufficient luminosity is provided \(\sim 10^{35} \text{cm}^{-2}\text{s}^{-1}\).

Strong interest to reuse existing facilities and infrastructure (i.e. LHC tunnel) in Europe

D. Schulte

A. Wulzer
Proton-driven Muon Collider Concept

**US Muon Accelerator Program – MAP**, launched in 2011, wound down in 2014

MAP developed a proton driver scheme and addressed the feasibility of the novel technologies required for Muon Colliders and Neutrino Factories

<table>
<thead>
<tr>
<th>Proton Driver</th>
<th>Front End</th>
<th>Cooling</th>
<th>Acceleration</th>
<th>Collider Ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC Linac</td>
<td>Accumulator</td>
<td>Buncher</td>
<td>Combiner</td>
<td></td>
</tr>
</tbody>
</table>

Short, intense proton bunches to produce hadronic showers

Muons are captured, bunched and then cooled

Acceleration to collision energy

Collision

Design is not complete but did not find anything that does not work

No CDR exists No coherent baseline No reliable cost estimate

### Muon Collider Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Higgs Factory</th>
<th>Top Threshold Options</th>
<th>Multi-TeV Baselines</th>
<th>Accounts for Site Radiation Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CoM Energy</td>
<td>TeV</td>
<td>0.126</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>0.0017</td>
<td>0.008</td>
<td>0.07</td>
<td>0.6</td>
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<tr>
<td>Beam Energy Spread</td>
<td>%</td>
<td>0.003</td>
<td>0.004</td>
<td>0.01</td>
<td>0.1</td>
</tr>
<tr>
<td>Higgs* or Top* Production/10^7sec</td>
<td></td>
<td>3,500*</td>
<td>13,500*</td>
<td>7,000*</td>
<td>60,000*</td>
</tr>
<tr>
<td>Circumference</td>
<td>km</td>
<td>0.3</td>
<td>0.3</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>No. of IPs</td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>Hz</td>
<td>30</td>
<td>15</td>
<td>15</td>
<td>15</td>
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<tr>
<td>β*</td>
<td>cm</td>
<td>3.3</td>
<td>1.7</td>
<td>1.5</td>
<td>0.5</td>
</tr>
<tr>
<td>No. muons/bunch</td>
<td>10^{12}</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>3</td>
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<tr>
<td>No. bunches/beam</td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Norm. Trans. Emittance, ε_{TN}</td>
<td>π mm-rad</td>
<td>0.4</td>
<td>0.2</td>
<td>0.2</td>
<td>0.05</td>
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<tr>
<td>Norm. Long. Emittance, ε_{LN}</td>
<td>π mm-rad</td>
<td>1</td>
<td>1.5</td>
<td>1.5</td>
<td>10</td>
</tr>
<tr>
<td>Bunch Length, α_s</td>
<td>cm</td>
<td>5.6</td>
<td>6.3</td>
<td>0.9</td>
<td>0.5</td>
</tr>
<tr>
<td>Proton Driver Power</td>
<td>MW</td>
<td>4^#</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

* Could begin operation with Project X Stage II beam

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Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

Success of advanced cooling concepts $\Rightarrow$ several $\times$ $10^{32}$

Site Radiation mitigation with depth and lattice design: $\leq 10$ TeV

M. Palmer: [https://map.fnal.gov/](https://map.fnal.gov/)
## Recent Tentative Target Parameters

D. Schulte – CERN Muon Collider Meeting [https://indico.cern.ch/event/886491/](https://indico.cern.ch/event/886491/)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>3 TeV</th>
<th>3 TeV*</th>
<th>10 TeV</th>
<th>10 TeV*</th>
<th>14 TeV</th>
<th>14 TeV*</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>$10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>1.8</td>
<td>1.8</td>
<td>20</td>
<td>20</td>
<td>40</td>
<td>40</td>
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<tr>
<td>N</td>
<td>$10^{12}$</td>
<td>-2–2.2</td>
<td>-2–2.2</td>
<td>1.8</td>
<td>1.8</td>
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<tr>
<td>$f_r$</td>
<td>Hz</td>
<td>-6–5</td>
<td>35 29</td>
<td>-4–5</td>
<td>-10–12</td>
<td>-4–5</td>
<td>-7–9</td>
</tr>
<tr>
<td>$p_{beam}$</td>
<td>MW</td>
<td>5.8 5.3</td>
<td>34 32</td>
<td>12.8–14.4</td>
<td>32–35</td>
<td>18–20</td>
<td>32–37</td>
</tr>
<tr>
<td>C</td>
<td>km</td>
<td>4.5</td>
<td>26.7</td>
<td>10</td>
<td>26.7</td>
<td>14</td>
<td>26.7</td>
</tr>
<tr>
<td>$&lt;B&gt;$</td>
<td>T</td>
<td>7</td>
<td>1.2</td>
<td>10.5</td>
<td>3.9</td>
<td>10.5</td>
<td>5.5</td>
</tr>
<tr>
<td>$\varepsilon_L$</td>
<td>MeV m</td>
<td>7.5</td>
<td>7.5</td>
<td>7.5</td>
<td>7.5</td>
<td>7.5</td>
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<td>$\sigma_E/E$</td>
<td>%</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
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<td>$\sigma_z$</td>
<td>mm</td>
<td>5</td>
<td>5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.07</td>
<td>1.07</td>
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<tr>
<td>$\beta$</td>
<td>mm</td>
<td>5</td>
<td>5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.07</td>
<td>1.07</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>$\mu$m</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>$\sigma_{x,y}$</td>
<td>$\mu$m</td>
<td>3.0</td>
<td>3.0</td>
<td>0.9</td>
<td>0.9</td>
<td>0.63</td>
<td>0.63</td>
</tr>
</tbody>
</table>

Adjust for staging, $G = 1$ MV from 1.5 to 5 TeV, or 1.3 MV from 1.5 TeV to 7 TeV

*Use of LHC tunnel for collider
Recent LEMMA effort

M.Antonelli, M.E.Biagini, M.Boscolo, S.Guiducci, P.Raimondi, A.Variola et al.

Asymmetric collisions $e^+ e^- \to \mu^+ \mu^-$ at the $\mu^+ \mu^-$ threshold ($\sqrt{s} \approx 0.212$ GeV)

- maximize $\mu^+ \mu^-$ pairs production cross section
- minimize the $\mu^+ \mu^-$ beam angular divergence and energy spread

Extremely promising:
- muons produced with low emittance $\Rightarrow$ “no/low cooling” needed

But difficult:
- low production cross section: maximum $\sigma(e^+ e^- \to \mu^+ \mu^-) \sim 1 \mu$b
- high heat load and stress in $\mu$ production target
- synchrotron power $O(100 \text{ MW}) \Leftarrow$ available 45 GeV positron sources

$\Rightarrow$ need consolidation to overcome technical limitations to reach higher muon intensities

LEMMA

arXiv:1905.05747
Components and in the walls of the tunnel produce a high flux of secondary particles (see figure 1).

As it was shown in the recent study \[1\], the appropriately designed interaction region and machine detector interface (including shielding nozzles, figure 2 and figure 3) can provide the reduction of muon beam background by more than three orders of magnitude for a muon collider with a collision energy of 1.5 TeV.

Figure 1. A MARS15 model of the Interaction Region (IR) and detector with particle tracks $>1$ GeV (mainly muons) for several forced decays of both beams.

Figure 2. The shielding nozzle, general RZ view (W — tungsten, BCH2 – borated polyethylene).

Figure 3. The shielding nozzle, zoom in near IP (Be — beryllium).

The amount of MARS15 simulated data was limited to 4.6% of the $\mu^+\mu^-$ decays on the 26 m beam length yielding total of $1.6 \times 10^6$ background particles per bunch crossing (BX).

The corresponding statistical weight ($\sim 22.3$) was taken into account in the following ILCRoot simulation. For each particle output by MARS15, 22 or 23 particles were generated by choosing a new azimuthal angle at random. This provided a total of $3.24 \times 10^8$ particles entering the detector in the ILCRoot simulation. The most abundant background consists of photons and neutrons. Table 1 lists these background yields together with kinetic energy thresholds used in the MARS15 simulation for different types of particles.

On-going simulations and studies for mitigation even with existing/future tunnels
Next steps

- **Move to use the Future Collider Framework**
  - Description of the detector already done including the nozzle
  - A new, up to the state of the art detector is needed

- **Simulate the beam-induced background with FLUKA**
  - MDI and IR descriptions provided by MAP collaboration for 1.5 and 3 TeV $\sqrt{s}$
  - Importing the description in FLUKA and generate new beam-induced background

- **Re-evaluate Physics performance** @ $\sqrt{s}=1.5$ TeV as double check then study Physics performance @ $\sqrt{s}=3$ TeV with full simulation

- **Collaborate with MAP to have MDI and IR @ $\sqrt{s}=10$ TeV to evaluate Physics performance**

- Determine physics objects efficiency and resolution for each configuration and parametrize them to estimate broad physics reaches smearing Monte Carlo generated process
Use of Existing Infrastructure

Might be able to reuse much of the proton and general infrastructure
- Needs detailed study
- Much of the expertise is available

Use of the largest tunnels, i.e. LHC or potentially FCC
- Can house positron ring in the LEMMA case
  - In FCC, even lepton equipment might exist from FCC-ee
  - Large rings means less synchrotron radiation and power consumption
- Consider to use ring as a collider
  - But means to have larger ring for acceleration
  - Or to use combined final accelerator / collider
    - This compromises luminosity and generates technical challenges but may save cost
- **Use tunnel for final accelerator**
  - Have a small optimised collider ring
  - Seems natural solution

Some proposals made, e.g. LEMMA team, V. Shiltsev, D. Neuffer, F. Zimmermann, ...
**Other Options**

**Variations of the muon sources were suggested**
- E.g. use of channeling in crystals
- Use of gamma factory to produce muons
- Use of gamma factory to produce positrons for LEMMA

But all at a very tentative level for now

Also suggested were use of LHC and FCC tunnel for the collider ring
- Obviously something that needs to be explored
- Come back to this later

**Combination of final accelerator stage and collider ring**
- Could maybe save some cost
- But likely will compromise performance
- And generate its own challenges
- So trade-off has to be understood

Also some other ideas
- But too early ......
Tentative Considerations on Baseline

- **Focus on first stage with energy of $O(1.5 + 1.5 = 3$ TeV)**
  - To come after higgs factory and matching highest CLIC energy
  - Using the high-energy strength of muon colliders
  - Realistic design for implementation at CERN, with cost power and risk scale
  - If successful, feasibility demonstration for CDR

- **Explore 14 TeV as further step**
  - To match FCC-hh discovery potential
  - Mainly exploration of parameters to guide choices
  - Provide evidence for feasibility, maybe cost frame

- **Some exploration of lower energies / Higgs factory**
  - Scaling from higher energies
  - Not a main focus, except if other projects do not cover lower energies

- Open for input
Some synergies ➔ Key Accelerator Technologies

- High-field, robust collider magnets with minimum gap
  - Dipoles, solenoids, ... for collider ring
- Efficient fast ramping magnets with efficient energy recovery — magnet powering
  - For the beam acceleration
- Efficient cryogenics, vacuum and shielding systems
  - Significant beam loss
- Robust targets and beam cleaning
- High field cavities
  - In a solenoid for the cooling system
- Efficient RF power production
- Civil engineering
- Other systems (instrumentation)
- Beam-dynamics and accelerator design
  - Start-to-end design and simulations, source design, ...
Letters of Interest (submission period: April 1, 2020 – August 31, 2020)
Letters of interest allow Snowmass conveners to see what proposals to expect and to encourage the community to begin studying them. They will help conveners to prepare the Snowmass Planning Meeting that will take place on November 4 - 6, 2020 at Fermilab. Letters should give brief descriptions of the proposal and cite the relevant papers to study. Instructions for submitting letters are available at https://snowmass21.org/loi.
Authors of the letters are encouraged to submit a full writeup for their work as a contributed paper.

Contributed Papers (submission period: April 1, 2020 – July 31, 2021)
Contributed papers will be part of the Snowmass proceedings. They may include white papers on specific scientific areas, technical articles presenting new results on relevant physics topics, and reasoned expressions of physics priorities, including those related to community involvement. These papers and discussions throughout the Snowmass process will help shape the long-term strategy of particle physics in the U.S. Contributed papers will remain part of the permanent record of Snowmass 2021. Instructions for submitting contributed papers are available at https://snowmass21.org/submissions/.