Muon Collider Collaboration

D. Schulte for the forming International Muon Collider Collaboration
Introduction

Muon collider had been studied mainly in the US (MAP), effort reduced after P5
Other activities mainly in UK (MICE: demonstration of ionisation cooling, EMMA: FFA) and at INFN (alternative muon production scheme)

The Laboratory Directors Group (LDG) appointed a working group (chair N. Pastrone) to review the muon collider for the European Strategy Update
• The report was very favorable

The updated strategy recommends R&D on muon beams

The LDG initiated an international muon collider collaboration
• kick-off meeting July 3rd, 272 participants

CERN will initially host the study and preparing a Memorandum of Understanding
Muon Collider Collaboration: Objective and Scope

Objective:
In time for the next European Strategy for Particle Physics Update, the study aims to establish whether the investment into a full CDR and a demonstrator is scientifically justified.
It will provide a baseline concept, well-supported performance expectations and assess the associated key risks as well as cost and power consumption drivers. It will also identify an R&D path to demonstrate the feasibility of the collider.

Deliverable:
Report assessing muon collider potential and describing R&D path to CDR

Scope:
• Focus on two energy ranges:
  – 3 TeV, if possible with technology ready for construction in 10-20 years
  – 10+ TeV, with more advanced technology
• Explore synergy with other options (neutrino/higgs factory)
• Define R&D path
Memorandum of Understanding

 Basically ready, waiting for final approval of DG

 CERN is initially hosting the study

 • International collaboration board (ICB) representing all partners
   – elect chair and study leader
   – can invite other partners to discuss but not vote (to include institutes that cannot sign yet)

 • Study leader

 • Advisory committee reporting to ICB

 Addenda to describe actual contribution of partners
Overall Context

Two main strategic processes are ongoing

- **Definition of European Accelerator R&D Roadmap** by LDG
  - Define scope of muon collider study until September 2021

- **Snowmass/P5** process in the US
  - Input until June 2021, decisions in 2022
    - will have to prepare white papers
  - Submitted several Letters Of Interest from the collaboration:
    
    International Muon Collider Collaboration (corresponding author: D. Schulte)
    Muon Collider Facility (c.a.: D. Schulte)
    Muon Collider Physics Potential (c.a.: A. Wulzer)
    Machine Detector Interface Studies at a Muon Collider (c.a.: D. Lucchesi)
    Muon Collider experiment: requirements for new detector R&D and reconstruction tools (c.a.: N.Pastrone)
    A Proton-Based Muon Source for a Collider at CERN (c.a.: Chr. Rogers)
    Issues and Mitigations for Advanced Muon Ionization Cooling (c.a.: Chr. Rogers)
    LEMMA: a positron driven muon source for a muon collider (c.a.: M.E. Biagini)
    Applications of Vertical Excursion FFAs(vFFA)and Novel Optics (c.a.: Sh. Machida)

- In addition, others refer to the muon collider, e.g. technologies, physics, ...
Test Facility
Collider Design
Baseline design Design optimisation Project preparation

Technologies
Design / models Prototypes / t. f. comp. Prototypes / pre-series

Test Facility
Design Construct Exploit

Exploratory phase
Definition phase

Ready to decide on test facility
Cost scale known

Ready to commit
Cost know

Ready to construct

Technically limited

ECFA Meeting 20/11/2020
D. Schulte: Muon Collider Collaboration
## Tentative Roadmap

<table>
<thead>
<tr>
<th>Exploratory Phase</th>
<th>Definition Phase</th>
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<tr>
<td></td>
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**Explore design**
- Identify critical issues
- Explore and prioritise issues
- Make design choices
- Define realistic goals

**Define design**
- Address feasibility issues
- Develop design, refine choices
- Develop R&D programme to demonstrate performances

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**Initial list ready**

**Prioritised list ready**

**Work**

**Go through full collider to complete and update tentative list**

**Study the most critical issues from initial list to find solutions, further refine understanding, iterate**
Exploratory Phase – Key Topics

• Physics potential evaluation

• Impact on the environment
  – The neutrino radiation and its impact on the site. This is known to require mitigation strategies for the highest energies.
  – Power consumption (accelerating RF, magnet systems, cooling)

• The impact of machine induced background on the detector, as it might limit the physics reach.

• High-energy systems that might limit energy reach or performance
  – Acceleration systems, beam quality preservation, final focus

• High-quality beam production, preservation and use
  – Target and target area
  – Cooling, in particular final cooling stage that does not yet reach goal
  – Proton complex
Comment on Resources

MUST in IFAST (WP 5.1, N. Pastrone)
• INFN, CERN, CEA, CNRS, KIT, PSI, UKRI, 300 kEUR request from EU

aMUSE contains relevant workpackages “Muon beams” and “Tools” (D. Lucchesi)
• uniPD, LIP, INFN, PSI, HZDR, Mainz, UniRM, TUD, Krakow, BNL, FNAL, integrated 117 pm over 4 years

Proposal to BMBF for funding of magnet and RF work (T. Arnd, U. van Rienen)
• KTI, Darmstadt University, Rostock University (9 py total)

JAI students worked on rapid cycling synchrotron as project (E. Tsesmelis)

Medium term plan at CERN has dedicated budget line
• Per year 5 FTE staff, 6 fellows, 4 students, 1 associate, 5 x 2 MCHF

Interest expressed in many institutes
• CEA, CNRS (IJClab), INFN, University of Chicago, IFIC, Jefferson Lab, Spanish Network, KIT, Darmstadt University, University of Rostock, Helmholtz-Zentrum Dresden-Rossendorf, Sofia University, Lund University, Uppsala University, Oslo University, LBL, EPSL, PSI, ESS, University of Mississippi, NIKHEF, HEPHY, FNAL, SLAC, ...

Actual work already ongoing (mainly volunteers)
Key Initial Steps

Define tentative collider energy and luminosity goals

Define tentative detector performance specifications to be able to launch physics potential studies

Start verification of detector performance
  • beam-induced background conditions
  • technologies

Start verification of accelerator performance, affordability and siting
  • also estimate (and mitigate if possible) beam-induced background
# Luminosity Goals

## Target integrated luminosities

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<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>$\int L dt$</th>
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<tr>
<td>3 TeV</td>
<td>1 ab$^{-1}$</td>
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<tr>
<td>10 TeV</td>
<td>10 ab$^{-1}$</td>
</tr>
<tr>
<td>14 TeV</td>
<td>20 ab$^{-1}$</td>
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</table>

Reasonably conservative
- each point in 5 years with tentative target parameters
- FCC-hh to operate for 25 years
- Aim to have two detectors
- But might need some operational margins

Note: focus on 3 and 10 TeV
Have to define staging strategy

## Tentative target parameters
Scaled from MAP parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>3 TeV</th>
<th>10 TeV</th>
<th>14 TeV</th>
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<tr>
<td>$L$</td>
<td>$10^{34}$ cm$^2$s$^{-1}$</td>
<td>1.8</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>$N$</td>
<td>$10^{12}$</td>
<td>2.2</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>$f_r$</td>
<td>Hz</td>
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<td>5</td>
<td>5</td>
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<tr>
<td>$P_{\text{beam}}$</td>
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<td>5.3</td>
<td>14.4</td>
<td>20</td>
</tr>
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<td>km</td>
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<td>14</td>
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<td>$\mu$m</td>
<td>3.0</td>
<td>0.9</td>
<td>0.63</td>
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</table>
Tentative Detector Performance Specification

10+ TeV collider enters uncharted territory
Need to establish physics case and detector feasibility

Established tentative detector performance specifications in form of DELPHES card (thanks to M. Selvaggi, Werner Riegler, Ulrike Schnoor, A. Sailer, D. Lucchesi, N. Pastrone M. Pierini, F. Maltoni, A. Wulzer et al.), based on FCC-hh and CLIC performances, including masks against beam induced background (BIB)

• For use by physics potential studies
  – Are the performances sufficient or too good?
• For detector studies to work towards
  – make sure technologies are reasonable
  – ensure background is OK
• Please find the card here: https://muoncollider.web.cern.ch/node/14

Detector simulation studies/design will now have to verify/ensure that this is realistic considering background and technologies
**Note: Delphes Simulation**

**Delphes** is a modular framework that simulates the response of a **multipurpose detector** in a parameterised way
- allows to easily scan key detector parameters
- perform preliminary key physics benchmark studies

**Muon Collider** aims at reconstructing **physics object** momenta up to 15 TeV
- Baseline concept is **hybrid** between **FCC-hh** and **CLIC**
Physics Potential

The muon collider physics potential emerges from a variety of measurements and searches that offer opportunities for new physics discoveries that are comparable or superior to “standard” future colliders.

Our studies must be illustrative of the MC potential for new physics exploration in multiple directions.

Direct search of heavy particles
- SUSY-inspired, WIMP, VBF production, 2->1

High energy measurements
- difermion, diboson, EFT, Higgs compositeness

High rate Higgs production
- Higgs single and self-couplings, rare Higgs decays, exotic decays

A. Wulzer et al.
The muon collider physics potential emerges from a variety of measurements and searches that offer opportunities for new physics discoveries that are comparable or superior to “standard” future colliders.

Our studies must be illustrative of the MC potential for new physics exploration in multiple directions.

Our plans for Snowmass21:

https://indico.cern.ch/event/944012/contributions/3989516/attachments/2091456/3518021/Physics_SnowMass_LoI.pdf

Letter of Interest: Muon Collider Physics Potential


On behalf of the forming muon collider international collaboration [1]

We describe the plan for muon collider physics studies in order to provide inputs to the Snowmass process. The goal is a first assessment of the muon collider physics potential. The target accelerator design center of mass energies are 3 and 10 TeV or more [2]. Our study will consider energies $E_{CM} = 3,10,14$, and the more speculative $E_{CM} = 30$ TeV, with reference integrated luminosities $\mathcal{L} = (E_{CM}/10$ TeV)$^2 \times 10^{ab^{-1}}$ [3]. Variations around the reference values are encouraged, aiming at an assessment of the required luminosity of the project based on physics performances. Recently, the physics potentials of several future collider options have been studied systematically [4], which provide reference points for comparison for our studies.
Physics Potential

The muon collider physics potential emerges from a variety of measurements and searches that offer opportunities for new physics discoveries that are comparable or superior to “standard” future colliders.

Our studies must be illustrative of the MC potential for new physics exploration in multiple directions.

And we are not alone

**MUON COLLIDER: A WINDOW TO NEW PHYSICS**

Douglas Brey1, Kevin Black2, Anadi Casepe3, Sasana Chatopadhyay1,7, Matteo Sonnens1, Srilatha Dasu4, Dmitri Denisov5, Karri Di Pippillo6, Michel Greco6, Miklos Hall7, Ulrich Heintze5, Christian Herwig3, James Hirschauer7, Tavo Holzer4, Andrew Ivanov5, Bodhittha Jayatilaka, Sengo Jindariani, Young-Kee Kim5, Jacobo Konigsmark9, Lawrence Lue10, Masayasu Liu11, Zhen Liu12, Chang-Seong Moon13, Manabu Naranji14, Saeed Norberg15, Isabel Ojeda16, Katherine Patidar17, Simone Pagan Grimi18, Kevin Pedgo20, Alexa Perdik21, Elodie Besse21, Stefan Spanier19, Maciej Swiatkowski19, Ann Miao Wang1, Tian-Tao Wang2, Xing Wang2, HannsJung Weber19, David Yu16

1 Fermilab National Accelerator Laboratory, 2 University of Wisconsin, Madison, 3 Northern Illinois University, 4 Brookhaven National Laboratory, 5 Harvard University, 6 Brown University, 7 University of Tennessee, Knoxville, 8 Kansas State University, 9 University of Chicago, 10 University of Florida, 11 Purdue University, 12 University of Maryland, 13 Kyungpook National University, 14 University of Puerto Rico, Mayaguez, 15 Princeton University, 16 Duke University, 17 Lawrence Berkeley National Laboratory, 18 University of Colorado, Boulder, 19 TRIUMF, 20 University of California, San Diego

Electroweak multiplets at the Muon Collider

R. Capdevilla, D.Curtin, Y. Kahn, G. Krnjaic, F. Meloni, J. Zurita

August 2020

Letter of Interest: EW effects in very high-energy phenomena

C. Arina, G. Cuomo, T. Han, Y.Ma, F. Maltoni, A. Manohar, S. Prestel, R. Ruiz, L. Vecchi, R. Verheyen, B. Webber, W. Waalewijn, A. Wulzer, K. Xie

to be submitted to the Theory Frontier (TF07) and Energy Frontier (EF04)

**HIGGS AND ELECTROWEAK PHYSICS AT THE MUON COLLIDER: AIMING FOR PRECISION AT THE HIGHEST ENERGIES**

Asan Ayhan1, Jeff Berryhill3, Pushpa Bhat1, Kevin Black2, Elisabeth Brown3, Anadi Casepe3, Srilatha Dasu4, Dmitri Denisov5, Karri Di Pippillo6, Michel Greco6, Tavo Holzer4, Ulrich Heintze5, Rachel Hyams13, Young-Kee Kim5, Du Liu1, Mia Liu4, Zhen Liu12, Ian Lou10,11,12, Sengo Jindariani, Chang-Seong Moon13, Isabel Ojeda16, Manabu Naranji14, Maximilian Swiatkowski19, Marco Valente17, Tian-Tao Wang2, Xing Wang2, HannsJung Weber19, David Yu16

Muon Collider: Study of Higgs couplings and self-couplings precision


Beyond the Standard Model with High-Energy Lepton Colliders

Hind Al Ali1, Nima Arkani-Hamed2, Ian Banta1, Sean Benevides1, Tianji Cai, Junyi Cheng, Tim Cohen1, Nathaniel Craig1, Ji Ju Fan1, Isabel Garcia Garcia5, Seth Koren6, Giacomo Koszegi1, Zhen Liu12, Kunfeng Lyu3, Amara McCune3, Patrick Meade3, Isabel Ojeda16, Umut Oktem1, Matthew Reece11, Raman Sundrum2, Dave Sutherland12, Timothy Trott10, Chris Tully10, Ken Van Tilburg13, Tian-Tao Wang2, and Menghang Wang1

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Few Preliminary Results

Higgs 3-linear coupling: $\delta k_\lambda = (5\%, 3.8\%, 1.6\%)$ for $E = (10, 14, 30) \text{ TeV}$


[FCC reach is from 3.5 to 8.1\% depending on systematics assumptions]

Higgs compositeness scale: $(38, 53, 115) \text{ TeV}$ for $E = (10, 14, 30) \text{ TeV}$

[Buttazzo, Franceschini, Wulzer, to appear]

[other F.C.: from 20 to 40 TeV depending on model]
Detector Studies

Verify/ensure that target performance can be reached

Detector simulation infrastructure is mostly in place (D. Lucchesi et al., S. Jindariani et al.)

Background data for 125 GeV and 1.5 TeV available, hope to have 3 TeV in time for Snowmass

Are working to develop higher energy lattice but will take time

Try to characterise background to identify mitigation strategy

Consider snapshot DELPHES card for CLIC-like detector and reconstruction to see how far we have to go to reach tentative performance
Detector Simulations

BIB available for $\sqrt{s}=1.5$ TeV and $\sqrt{s}=125$ GeV

Prepare a new tool based on Fluka to generate new BIB:
- at different $\sqrt{s}$
- Modifying the detector and the interaction region

N. Mokhov et al. Fermilab-Conf-11-094-APC
Beam-induced Background

Event Full Simulation ⇒ no issues
Event track reconstruction:
- It takes a long time to do it with full BIB
- Reduce the combinatorial:
  - cutting harder on timing
  - exploit double layer to remove tracks not coming from primary interaction
Jet Reconstruction:
- Subtract “average” BIB energy
- Optimize ParticleFlow algorithm
Jet b-tag: to be optimized
Detector Technologies

Will rely largely on European Detector R&D Roadmap
- Will provide link persons to relevant working groups

Currently consider the following most important (N. Pastrone)
- solid state tracking
- calorimetry
- emerging technologies
- electronics and in detector processing

Will also include other regions

Physics potential studies and machine background studies will verify if performances similar to CLIC and FCC-hh are sufficient
Ongoing Accelerator Work

Muon collider is new in Europe
• Have to get up to speed

Together with US colleges are starting to take (shared) ownership of design
• Detailed presentations and discussions in serious of Design Meetings
• Transfer of lattice decks
• As new partners are forming own opinions
• Identifying issues that have been neglected
• Already part of generating the critical issues list
• Understanding the challenges and the resource needs

An important phase, excellent time to identified overlooked issues because of fresh view

Also have to find consensus on sometimes diverging opinions or define way to arrive at agreement
Muon Collider Baseline Concept

Proton Driver and Front End, Cooling and First part of Acceleration have same challenge level as in MAP designs.

Final cooling misses transverse emittance target by factor 2.

Still a challenging design with challenging components.

Started to review to complete R&D item list and prepare priority.

Accelerator ring, collider ring, interaction region, MDI, neutrino radiation become more challenging with energy. Also will drive cost and power.

They will limit energy reach.

Challenging design with challenging components.
Interaction Region (IR)

- Typical design example to be used as starting point for our design
  6 TeV design by M-H. Wang, Y. Nosochkov, Y. Cai and M. Palmer

Bendings close to IP for dispersion
Doublet for final focus
“local” correction of vertical chromaticity
Octupoles and local correction of hor. chromaticity
Straight for RF, injection …
Matching to (negative momentum compaction) arc

Very challenging design

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Collider Ring

**Challenging optics** (short bunch, long ring, minimal RF)
Important **collective effects** (beam-beam etc.)

**High-field, large aperture dipoles** to minimise collider ring size and maximise luminosity

**Combined function magnets** replace quadrupoles to avoid straights

O(400 W/m) **beam loss**
- 5 MW total at 10 TeV
- Need to shield magnets
  - MAP at 3 TeV: 30-50 mm shielding
- Large apertures
  - MAP at 3 TeV: 150 mm

Will consider different technology options at different energies (NbTi, Nb$_3$Sn, HTS)
Balance performance, cost and timescale
Muon Acceleration

Design of initial acceleration (A. Bogacz) looks very solid

Does not change with collider energy

Main question is if we can further optimise

Accelerator ring is cost driver

Changes with collider energy

• potential energy limit

Two options are considered (presented by S. Berg, S. Machida, D. Summers)

• RCS (Rapid Cycling Synchrotron) with fast-ramping magnets

• FFAG with static magnets and special optics

**Optics design** (Interest: RCS: A. Chance, CEA, FFAG: S. Machida, Rutherford Lab)

**Fast-pulsing magnets** (normal-conducting or HTS (Interest: L. Rossi, INFN))

**Efficient energy recovery** of fast pulsing magnets (Interest: CERN)

**Efficient superconducting RF** for short, intense bunches (Interest: U. van Rienen, Rostock, A. Grudiev, CERN)
Muon Cooling

Presentations: Chr. Rogers, D. Neuffer, D. Bowring, P. Jurj, D. Summers

6D cooling can probably be better than foreseen
- Review integration aspects (superconductive magnet coils next to normal-conducting RF)
- Optimise the design

Final cooling misses target transverse emittance by factor 2
- Higher field solenoids should help (>> 30 T), KTI proposal to BMFT (T. Arndt)
- Equilibrium emittance proportional to 1/B

Chopping and recombining bunch as alternative to final cooling suggested (D. Summers)
- To be reviewed

Experimentally proven RF gradients are higher than in design
- More muons will survive
- Can have more cooling
- Maybe can reuse some CLIC drive beam hardware for tests of RF
Proton Complex and Front-end

**Intense proton beam** is challenging

Need to make choices for the **target**

Ambitious **high-field solenoid**

**Radiation** in magnet

**Downstream radiation** from MW proton beam
Alternative: The LEMMA Scheme

45 GeV positrons to produce muon
Accumulate muons from several passages

Goal: produce low emittance muon beam, no cooling required

Challenge to get enough charge into the bunch

Will try to put together target parameter list based on fundamental limitations (e.g. target and collider ring) to identify potential and R&D issues
Neutrino Radiation and Site Considerations

Neutrino radiation from collider ring is key for site and layout
- At 3 TeV 40 m deep tunnel arcs stay below 10% of legal limit, have to own land in direction of straights
- At 14 TeV with 500 m deep tunnel arc stays below legal limit

Tentative considerations on reuse of LHC tunnel:
- Too long for 3 TeV collider (need 4.5-6 km)
- 14 TeV collider ring suffers from neutrino radiation
- Use for 3 TeV accelerator ring appears possible

Want to minimise radiation as much as possible
CERN civil engineering will develop tool to optimise orientation of collider ring (J. Osborn)
Discussion started with neutrino experts on potential use of neutrinos in direction of long straight (A. De Roeck et al.)
Development of lattice is starting
Discussion with HSE-RS (radiation safety) started
Consider mitigation techniques, even challenging ones
Example Neutrino Radiation Mitigation

Mitigation by varying beam orbit in collider is limited and costly (more space in magnets needed)

Vary vertical beam angle at $s_1$ in time

Relevant length of arc at $s_1$ is $O(10 \text{ cm})$

Move collider ring components, e.g. vertical bending with 1% of main field

Opening angle $\pm 1 \text{ mrad}$

$O(100)$ larger than decay cone $\Rightarrow$ gain $O(100)$ in radiation

In straights, additional improvement in horizontal

Need to study impact on beam and operation, e.g. dispersion control

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Demonstrator and Neutrinos

Need to develop R&D programme for implementation after next ESU

Key will be demonstrator facility to produce useful muon beam

Risk not being that cheap

Can this be combined with a neutrino facility such as NuSTORM?

Will explore synergies

Also explore if the neutrinos from the straights of the collider could be used for physics
First suggestion (A. De Roeck, E. Tsesmelis)
Deep-sea installations in Mediterranean (KM3NeT-Fr, KM3NeT-It, KM3NeT-Gr)
But could be too deep, maybe interesting for test facility

Ideas are very welcome
Conclusion

Started to address the R&D on muon collider as requested by European Strategy

Formal collaboration at any moment

Actual work started with meetings on design and specialised topics
• Accelerator design
• Physics and detectors

Topical meetings
• Physics potential, Detector simulations, Muon cooling

Will have project meeting with everyone
• Every few months, half day long

Web page: [http://muoncollider.web.cern.ch](http://muoncollider.web.cern.ch)
• Find meeting link in menu “Organisation”

Mailing lists: [MUONCOLLIDER_DETECTOR_PHYSICS@cern.ch](mailto:MUONCOLLIDER_DETECTOR_PHYSICS@cern.ch), [MUONCOLLIDER_FACILITY@cern.ch](mailto:MUONCOLLIDER_FACILITY@cern.ch)

Many thanks to all that contributed
MAP collaboration, M. Palmer
MICE collaboration
LEmma team
Muon collider working group
European Strategy Update
LDG
...

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Reserve
Critical Issues Include:

- **Advanced detector concepts and technologies**, requiring excellent timing, granularity and resolution, able to reject the background induced by the muon beams.
- **Advanced accelerator design** and beam dynamics for high luminosity and power efficiency.
- **Robust targets and shielding** for muon production and cooling as well as collider and detector component shielding and possibly beam collimation.
- **High field, robust and cost-effective superconducting magnets** for the muon production, cooling, acceleration and collision. High-temperature super-conductors would be an ideal option.
- **High-gradient and robust normal-conducting RF** to minimise muon losses during cooling.
- High rate **positron production** source and high current positron ring (LEMA).
- **Fast ramping normal-conducting, superferric or superconducting magnets** that can be used in a rapid cycling synchrotron to accelerate the muons and efficient power converters.
- **Efficient, high-gradient superconducting RF** to minimise power consumption and muon losses during acceleration.
- **Efficient cryogenics systems** to minimise the power consumption of the superconducting components and minimise the impact of beam losses.
- Other accelerator technologies including high-performance, compact **vacuum systems** to minimise magnet aperture and cost as well as fast, robust, **high-resolution instrumentation**.
In linear collider, the luminosity per beam power is about constant.

In muon collider, luminosity can increase linearly with energy.

A linear collider is single-pass so need full voltage in main linac.

Muon collider is multi-pass so have lower voltage.

But have to carefully verify this.

Overall muon colliders have the potential for high energies.

May overcome the energy limitations of linear colliders.

The working group concluded that an International collaboration should be formed to study the muon collider.
**Intense proton beam** is challenging

Need to make choices for the **target**

**Ambitious high-field solenoid**

Target has to withstand **strong shock**
- liquid mercury target successfully tested at CERN (MERIT)
- but solid target better for safety
- or beads
- or ...

Important power of proton driver O(MW)
need to take care of debris for downstream systems
need to cool

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

See previous presentation by J. Pasternak

Superconducting solenoids
High-field normal conducting RF
Liquid hydrogen targets
Compact design

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

- **Specification**
  - For acceleration to multi-TeV collider
  - Final Cooling
  - For acceleration to Higgs Factory
  - post-merge 6D Cooling
  - pre-merge 6D Cooling (original design)
  - Bunch Merge

**Final Cooling post-merge**

**Initial 6D Cooling**

**Bunch Merge**

**Exit Front End** (15mm,45mm)

**Front End**

**Target**

**Phase Rotator**

**MAP collaboration**

ECFA Meeting 20/11/2020

D. Schulte: Muon Collider Collaboration
Cooling: The Emittance Path

- **Specification**
  - For acceleration to multi-TeV collider

**Longitudinal Emittance** vs. **Transverse Emittance** (microns)

- **Final Cooling**
  - For acceleration to Higgs Factory
- **Initial (X)**
- **Initial (Y)**
- **Post-merge 6D Cooling**
- **Pre-merge 6D Cooling (original design)**
- **Bunch Merge**
- **VCC & Hybrid**
- **HCC**

**Front End**: Target Phase Rotator
- Exit Front End (15mm,45mm)

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Cooling: The Emittance Path

- Specification
- Achieved (simulations)

Several ideas to improve final cooling:
- Highest field HTS helps
- Phase space manipulations of beam

For acceleration to multi-TeV collider

Final Cooling

For acceleration to Higgs Factory

VCC & Hybrid

HCC

Initial (X)
Initial (Y)

pre-merge 6D Cooling (original design)

post-merge 6D Cooling

Bunch Merge

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High-energy Acceleration

Rapid cycling synchrotron (RCS)
- Inject beam at low energy and ramp magnets to follow beam energy
- Could use combination of static superconducting and ramping normal-conducting magnets

Fast-pulsing magnets (O(ms) ramps))
Field defines size of accelerator ring
- normal-conducting
- HTS is interesting

Important energy in fast pulsing magnets
- O(200 MJ) @ 14 TeV
- need very efficient energy recovery

FFAG
Challenging lattice design for large bandwidth and limited cost
High field magnets

RF challenge:
High efficiency for power consumption
High-charge, single-bunch beam (10 x HL-LHC)
Maintain small longitudinal emittance
RF Challenge

**Acceleration and collider ring RF**
14 TeV: 1 mm long bunch with 0.1 % energy spread in collider ring
Almost same longitudinal emittance as after muon cooling
High bunch charge of $2 \times 10^{12}$ muons
Start with long bunch that is subsequently compressed
Need concept of longitudinal dynamics all along the accelerator
Challenging to maintain emittance

**Muon cooling RF**
Proof of principle in US (gas-filled copper and vacuum beryllium cavities)

**Other RF**
e.g. proton complex RF
making contact, may need more effort later

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

Need smaller betafunctions at higher energy
Or smaller longitudinal emittance / larger energy acceptance

$$\beta^* \propto \frac{1}{E}$$

And focusing of higher energy beam is more difficult

FCC-hh example (R. Martin)

First look from Rogelio Tomas on final triplet at 14 TeV ($L^* = 6$ m):
Challenging system
Need to add shielding
Key systems designed for 3 TeV in US
A number of key components has been developed
Cooling test performed according to theory

But no CDR, no integrated design, no reliable cost estimate
More work to be done, e.g. substantial, 6D cooling
The LEMMA Scheme

Progress in design
• Fluid targets
• Combination of bunches into single bunch
• Novel design of muon accumulator rings with very large energy acceptance [-10%; +15%]
• Sequence of targets to keep beta-function small

However, emittance are not so small:
• 1 - 20 μm (normalised)

Will assess LEMMA based on first principles
• target and collider ring
• to develop target parameters
• to judge feasibility
• to devise a strategy of how to continue
Physics and Detector Studies

10+ TeV collider enters uncharted territory
Need to establish physics case and detector feasibility

Established tentative detector performance specifications in form of DELPHES card (thanks to M. Selvaggi, Werner Riegler, Ulrike Schnoor et al.), based on FCC-hh and CLIC performances, including masks against beam induced background (BIB)

• For use by physics potential studies
  – Are the performances sufficient or too good?
• For detector studies to work towards
  – make sure technologies are reasonable
  – ensure background is OK
• Please find the card here: https://muoncollider.web.cern.ch/node/14

Detector simulation studies
• Currently at 1.5 TeV and 125 GeV (because we have background data)
• To understand background characteristics
  – develop mitigation strategy (e.g. origin of tracks for rejection, timing)
• To check how far we have to go to arrive at target performance
  – Snapshot DELPHES card to motivate further R&D
• Note: reconstruction tailored to beam-induced background might become important
Muon Collider Baseline Concept

Short, intense proton bunches to produce hadronic showers

Pions decay into muons that can be captured

Muon are captured, bunched and then cooled by ionisation cooling in matter

No CDR exists, no coherent baseline of machine
No cost estimate
Need to extend to higher energies (10+ TeV)
But did not find something that does not work