Muon Collider Collaboration

Daniel 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 (demonstration of ionisation cooling) 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 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 host the study, we are finalising a Memorandum of Cooperation
International Muon Collider Collaboration

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:
  – $3 \text{ TeV}$, if possible with technology ready for construction in 10-20 years
  – $10+ \text{ TeV}$, with more advanced technology
• Explore synergy with other options (neutrino/higgs factory)
• Define R&D path
Potential Long-Term Timeline

1. Exploratory phase
2. Definition phase
3. Collider Design
4. Baseline design
5. Design optimisation
6. Project preparation
7. Approve
8. Test Facility
9. Design
10. Construct
11. Exploit
12. Technologies
13. Design / models
15. Prototypes / pre-series
16. Ready to decide on test facility
17. Cost scale known
18. Ready to commit
19. Cost known
20. Ready to construct
21. Technically limited

Muon Collider, March 23, 2021
Lepton Physics at High Energy

High energy lepton colliders are precision and discovery machines

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

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 production of heavy particle pairs

Luminosity goal

(Factor O(3) less than CLIC at 3 TeV) 4x10\(^{35}\) cm\(^{-2}\)s\(^{-1}\) at 14 TeV

\[ L \sim \frac{5 \text{ years}}{\text{time}} \left( \frac{\sqrt{s}}{10 \text{ TeV}} \right)^2 \cdot 2 \cdot 10^{35} \text{ cm}^{-2} \text{s}^{-1} \]
Proposed Lepton Colliders (ESU)

Maximum proposed energy CLIC 3 TeV

- Cost estimate total of 18 GCHF
  - In three stages
  - 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?

Cost roughly is linear with energy

Power consumption roughly goes with the square of energy

\[ L \propto P_{\text{synrad}} E_{\text{cm}}^{-3.5} \]

\[ L \propto P_{\text{RF}} \]

\[ L \geq \frac{5 \text{ years}}{\text{time}} \left( \frac{\sqrt{s} \mu}{10 \text{ TeV}} \right)^2 \cdot 2 \cdot 10^{35} \text{ cm}^{-2} \text{s}^{-1} \]
Energy Limit

Electron-positron rings are multi-pass colliders limited by synchrotron radiation.

Strong dependence on particle mass.

Hence proton rings are energy frontier.

Electron-positron linear colliders avoid synchrotron radiation, but single pass.

Energy challenge
Need full voltage in main linac which is costly.

Luminosity challenge
Need very small beam size at collision is required, leads to strong beam-beam effects, requires extremely tight tolerances.

\[ \Delta E \propto \left( \frac{E}{m} \right)^4 \frac{1}{R} \]
Linear Collider Cost

CLIC cost at 3 TeV is about 18 GCHF

CLIC additional cost at 14 TeV: around 40-50 GHCF
- upgrade 1.5 to 3 TeV about 8 GCHF
- (14 TeV - 3 TeV) / 1.5 TeV * 8 GCHF = **59 GCHF**
- some cost reduction due to large-scale production
- upgrade could be performed in affordable steps but might have limited interest in each step

Plasma technology might potentially lead to a cheaper accelerator once it is mature
- much higher gradients
- but many issues to be solved
Linear Collider Luminosity

For constant technology

• keep bunch charge and length constant

• emittances and betafunctions are constant
  – same beam quality and same focusing
  – these are not directly linked to the acceleration technology
    • emittance is determined by damping rings
    • and degradation during acceleration
    • betafunction is quality of the focusing system
  – actually becomes harder at higher energies
    • more emittance degradation
    • harder to focus beam because of synchrotron radiation in focusing system
    • actually already visible at CLIC at 3 TeV

$L \propto \frac{N}{\sqrt{\beta_x \epsilon_x}} \frac{1}{\sqrt{\beta_y \epsilon_y}} P_{beam}$

⇒ Luminosity per beam power independent of energy
Linear Collider Luminosity

CLIC requires about 300 MW of wall plug power for the RF to produce 28 MW of beam power and 300 about MW for other systems (e.g. magnets)

\[ \mathcal{L} \propto \frac{N}{\sqrt{\beta_x \epsilon_x}} \frac{1}{\sqrt{\beta_y \epsilon_y}} P_{beam} \]

For CLIC about **190 MW beam power** to reach \( 40 \times 10^{34} \text{cm}^{-2}\text{s}^{-1} \) at 14 TeV

If we consider only luminosity above 99% of nominal centre-of-mass energy, we need about **570 MW beam power**

Efficiency from wall plug power into RF systems to beam power is \( O(10\%) \)
- so **O(2-6 GW)** of total power consumption

Need to add the other systems (which also will increase compared to 300 MW)
Muons are much heavier than electrons
⇒ strongly suppressed synchrotron radiation
⇒ can use a ring and profit from multi-pass

Less RF voltage required
Can collider beams repeatedly

But muon lifetime is limited to 2.2 μs at rest
⇒ need to rapidly accelerate to increase lifetime
⇒ can only obtain limited number of collisions
⇒ need to deal with decay products (electrons/positrons and neutrinos)
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 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

D. Schulte
Muon Collider, March 23, 2021
Comparing Luminosity in MAP vs. CLIC

Luminosity per beam power increases with energy in a muon collider

Overall muon colliders have the potential for high energies

May overcome the luminosity limitations of linear colliders

European Strategy advised to consider muon collider
## Luminosity Goals

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

**Parameter** | **Unit** | **3 TeV** | **10 TeV** | **14 TeV** |
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>$L$</td>
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<td>1.8</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>$N$</td>
<td>$10^{12}$</td>
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<tr>
<td>$f_r$</td>
<td>Hz</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$P_{beam}$</td>
<td>MW</td>
<td>5.3</td>
<td>14.4</td>
<td>20</td>
</tr>
<tr>
<td>$C$</td>
<td>km</td>
<td>4.5</td>
<td>10</td>
<td>14</td>
</tr>
<tr>
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<tr>
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<td>7.5</td>
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<tr>
<td>$\sigma_E/E$</td>
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<td>0.1</td>
<td>0.1</td>
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<td>$\sigma_z$</td>
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<td>1.5</td>
<td>1.07</td>
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<tr>
<td>$\beta$</td>
<td>mm</td>
<td>5</td>
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<td>1.07</td>
</tr>
<tr>
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<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>3.0</td>
<td>0.9</td>
<td>0.63</td>
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</table>

### Target integrated luminosities

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

Comparison: CLIC at 3 TeV: 28 MW
## Target Parameter Scaling

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Scaled from MAP parameters

- Emittance is constant
  \[ \sigma_E \sigma_z = \text{const} \]
- Collider ring acceptance is constant
  \[ \frac{\sigma_E}{E} = \text{const} \]
- Bunch length decreases
  \[ \sigma_z \propto \frac{1}{\gamma} \]
- Betafunction decreases

\[ L \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\varepsilon \varepsilon_L} f_r N_0 \gamma \]
Muon Collider Luminosity Drivers

Fundamental limitation
Requires emittance preservation and advanced lattice design

\[ L \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon L} f_r N_0 \gamma \]

- High energy
- Large energy acceptance
- Dense beam
- High beam power

Luminosity per power increases with energy
Provided all technical limits can be solved

\[ L \gtrsim \frac{5 \text{ years}}{\text{time}} \left( \frac{\sqrt{s}}{10 \text{ TeV}} \right)^2 2 \cdot 10^{35} \text{ cm}^{-2} \text{s}^{-1} \]

- Constant current for required luminosity
- Better scaling than linear colliders

D. Schulte
Muon Collider, March 23, 2021
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
Overall Considerations

Drives the beam quality similar to MAP design still challenging design with challenging components

Cost and power consumption drivers, limit energy reach e.g. 30 km accelerator for 10/14 TeV, 10/14 km collider ring
Also impacts beam quality
Drives neutrino radiation and beam induced background
Intense proton beam is challenging

Need to make choices for the target

Ambitious high-field solenoid

Target has to withstand stress
• liquid mercury target successfully tested at CERN (MERIT)
• but solid target better for safety
• or beads
• or ...

Important power of proton driver $O(1.3 \text{ MW})$
• radiation in solenoid
• need to cool
• radiation in downstream systems
• power level considered feasibility but not a huge margin
Cooling Concept

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

Limit muon decay, cavities with very gradient in a magnetic field
Minimise betafunction with strongest solenoids

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

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

- **Initial 6D Cooling**
  - Bunch Merge
  - Charge Separator
  - 6D Cooling

- **Final 6D Cooling**
  - 6D Cooling
  - Final Cooling

- **Pre-merge 6D Cooling (original design)**
  - Bunch Merge

- **Post-merge 6D Cooling**
  - 6D Cooling

- **MAP collaboration**

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

- **Target Phase Rotator**

- **For acceleration to Higgs Factory**

- **D. Schulte**
  - Muon Collider, March 23, 2021
Cooling: The Emittance Path

- Specification
- Achieved (simulations)

For acceleration to multi-TeV collider

Final Cooling

For acceleration to Higgs Factory

VCC & Hybrid

HCC

Initial (X)

Initial (Y)

Post-merge 6D Cooling

Pre-merge 6D Cooling (original design)

Bunch Merge

MAP collaboration

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Cooling: The Emittance Path

- Specification
  For acceleration to multi-TeV collider

- Achieved (simulations)
  Several ideas to improve final cooling
  Need to work out the solution
  - Highest field HTS helps
  - Phase space manipulations of beam

- Final
  For acceleration to Higgs Factory

- Initial (X)
- Initial (Y)
  post-merge 6D Cooling

- VCC & Hybrid
  pre-merge 6D Cooling (original design)

- HCC
  Bunch Merge

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

- MAP collaboration

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Muon Collider, March 23, 2021
Cooling Challenges and Status

Cavities with very high accelerating gradient in strong magnetic field

Very strong solenoids (> 30 T) for the final cooling
- simplified: Luminosity is proportional to the field

Integrated system test

MuCool: >50 MV/m in 5 T field

Two solutions
- Copper cavities filled with hydrogen
- Be end caps

NHFML
32 T solenoid with low-temperature HTS

We would like to push even further

MICE (UK)
MICE (in the UK)

- Principle of ionisation cooling has been demonstrated
- More particles at smaller amplitude after absorber is put in place
- More complete experiment with higher statistics, more than one stage required
- Integration of magnets, RF, absorbers, vacuum is engineering challenge

Nature volume 578, pages 53-59 (2020)
Beam Acceleration

Trade-off between cost and muon survival
- Linacs
- Recirculating linacs

Final acceleration
- FFAG (static superconducting magnets)
- or RCS (rapid cycling synchrotron)

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**High-energy Acceleration**

**Rapid cycling synchrotron (RCS)**
- Ramp magnets to follow beam energy
- Combination of static and ramping magnets
- Possible circumference
  - 14-26.7 km at 3 TeV
  - O(30 km) for 10 and 14 TeV

**Fast-pulsing magnets** (O(ms) ramps))

**FFAG**
Lattice with high-field magnets that are static and accommodates different energies at different location in the magnets
- Challenging lattice design for large bandwidth and limited cost
- Complex high field magnets
- Challenging beam dynamics

**EMMA** proof of FFA principle

In hybrid design, need 5 km of 2 T of fast-ramping, normal-conducting magnets per TeV beam energy

O(30 km) for 1.5-5/7 TeV
• two rings in same tunnel
• or higher field HTS ramping magnets

Started to work on power converters (efficient recovery of energy in ramping magnets, O(200 MJ) at 14 TeV

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**RCS**

<table>
<thead>
<tr>
<th>Acceleration 0.3 to 1.5 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
</tr>
<tr>
<td>8 T dipole</td>
</tr>
<tr>
<td>L&lt;sub&gt;ramp&lt;/sub&gt;</td>
</tr>
<tr>
<td>B&lt;sub&gt;ramp&lt;/sub&gt;</td>
</tr>
</tbody>
</table>

Test of fast-ramping normal-conducting magnet design

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

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FNAL
12 T/s HTS
0.6 T max
Need to push in field and speed

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Muon Collider, March 23, 2021
Collider Ring

**High field dipoles** to minimise collider ring size and maximise luminosity
4.5 km at 3 TeV, 10/14 at 10/14 TeV

Need to protect from $O(500 \text{ W/m})$ **beam loss**
- 1/3 of beam energy
- large aperture and shielding
  - 150 mm in MAP at 3 TeV, 30-50 mm shielding
- open mid-plane magnets
- efficient cooling

Strong focusing at IP to maximise luminosity
Becomes harder with increasing energy
Divergence independent of energy
Challenging triplet design

Maintaining very short bunch (1 mm) in large ring
- Careful control of longitudinal motion
- Beam dynamics of frozen beam
Important progress on high-field magnets for many projects, HL-LHC, FCC, ...

General development of superconducting magnets with advanced technologies (Nb$_3$Sn and HTS) in all regions

For the first energy stage could stay with more conventional performance and use more advanced technologies for high-energy upgrades

Development of conductors (FCC)
Neutrino Radiation

Neutrinos can produce showers just when they exit the earth

Due to narrow neutrino beam, radiation can become relevant
Particularly high in direction of the straights

Buy the land concerned, to be worked out with civil engineers

Arcs remain important limit
Dose increases with energy x luminosity, i.e. proportional to $E^3$
Arrows

Typical legal limit 1 mSv/year
MAP goal < 0.1 mSv/year
No legal procedure < 10 μSv/year
LHC achieved < 5 μSv/year

Mitigate radiation to a level as low as reasonably possible
Similar to LHC

Higher field, deeper tunnel in collider
Shorter gaps
Denser beam
Larger energy spread and acceptance

More efficient physics
More years of running

Tricks

Expected scaling laws:

Ring: \( N \propto P^3 \) from Energy*cross section*1/J

Straight: \( N \propto P^4 \), from Energy*cross section*1/J*1/Jarc

\[\frac{D}{\int \mathcal{L}} \propto aE \left( \frac{T}{B} + \frac{L}{0.7 \text{ m}} \right) \frac{1}{d} \frac{e_T e_L}{N_0} \frac{1}{\sigma_\delta}\]
Neutrino Radiation Mitigation

Mokhov, Ginneken: move beam in collider aperture
Investigate: move collider ring components, e.g. vertical bending with 1% of main field

Opening angle ± 1 mradian
Even at 14 TeV
200 m deep tunnel would be comparable to LHC case
Need to study impact on beam and operation, e.g. dispersion control
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
Detector

Detector is based on CLIC detector

Nozzles added to protect from beam-induced background (BIB)

Each beam contains one bunch crossing every 15 μs (3 TeV) or 47 μs (14 TeV)

Muon decay rate at 3 TeV: 200,000 bx⁻¹ m⁻¹

Rate decreases with energy but energy in each decays increases

Simulations for 1.5 TeV with LineBuilder and FLUKA comparing to previous MAP results (MARS)

Will study higher energies as machine designs become available
Alternative: The LEMMA Scheme

45 GeV positrons to produce muon pairs
Accumulate muons from several passages

Low-emittance muon beam can reduce radiation

Less mature than proton-driven scheme
Large positron current required
Target is challenging
Large positron production rate \( [O(10^{17}/s)] \)
Currently do not reach luminosity goal
European Roadmap on Accelerator R&D

LDG has been charged by Council to deliver an Accelerator R&D Roadmap for Europe by the end of the 2021.

The extended LDG will deliver a report to council:

• The scientific drivers for R&D, and the progress needed to enable future facilities
• The current state-of-the-art, and the further steps to be taken over the next decade
• Potential deliverables and demonstrators for the next decade
• A prioritised work plan, taking into account the capabilities and interests of stakeholders
• A range of scenarios for engagement, ranging from ‘minimal investment’ to ‘maximum possible rate of progress’, with a first estimate of resources and timeline.

LDG created panels to provide the input for the Roadmap.
Muon Beam Panel

Members: Daniel Schulte (CERN), Mark Palmer (BNL), Tabea Arndt (KIT), Antoine Chance (CEA/IRFU) Jean-Pierre Delahaye (retired), Angeles Faus-Golfe (IN2P3/IJClab), Simone Gilardoni (CERN), Philippe Lebrun (European Scientific Institute), Ken Long (Imperial College London), Elias Metral (CERN), Nadia Pastrone (INFN-Torino), Lionel Quettier (CEA/IRFU), Tor Raubenheimer (SLAC), Chris Rogers (STFC-RAL), Mike Seidel (EPFL and PSI), Diktys Stratakis (FNAL), Akira Yamamoto (KEK and CERN)

Foresee three community meetings
• First in May, date to be defined
• Please contribute

Will profit from workshop on the muon collider testing opportunities (with physics potential of test facility):

https://indico.cern.ch/event/1009746/.

Report ready in September, given to Council in December
Detector Technologies

Will rely largely on European Detector R&D Roadmap (ECFA)
• 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
US Snowmass/P5

Submitted a number of proposals for white papers
• physics potential
• detector
• accelerator

Growing interest in the community
Aiming to coordinate the regional efforts

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)
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.

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 $L = (E_{CM}/10\ \text{TeV})^2 \times 10\ \text{ab}^{-1}$ [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 Berry1, Kevin Black2, Anadi Canepa1, Sagar Chattopadhyay3,4, Matteo Croceoni2, Shrillur Das2, Dimitri Derri3,4, Karri Di Pietro1, Melina Franklin1, Zosia Grzes1, Allison Hall, Ulrich Heintz3, Christian Herrig4, James Hirschauer2, Tom Holme1, Andrew Ivanov3, Bodhitri Jayasthika4, Sergio Jedrecat1, Young-Kee Kim1, Jacobo Kinoshita1, Lawrence Lan1, Minyoung Liu2, Zhan Liu4, Chang-Song Moon4, Memakshi Narula4, Scarlett Norberg4, Isabel Ojalvo4, Katherine Pathai4, Simone Pagan Grillo1, Kevin Pedro4, Alex Perlick4, Efthie, Bossagan1,2, Stefan Spahn2, Maximilian Swierzcholski3,4, Ann Miao Wang2, Lian-Tao Wang2, Xing Wang2, Hannsjoerg Weber1, David Yu5

1 Fermi 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

Beyond the Standard Model with High-Energy Lepton Colliders

Hind Al Ali1, Nima Arkani-Hamed2, Ian Banta1, Sean Benevides1, Tianji Cai1, Junyi Cheng1, Tim Cohen1, Nathaniel Craig1, Ilji Fun1, Isabel Garcia Garcia1, Seth Koren2, Giacomo Koszegi4, Zhen Liu2, Kunfeng Lyu2, Amara McCune1, Patrick Meade1, Isabel Ojalvo4, Umut Oktem1, Matthew Reece11, Raman Sundrum2, Dave Sutherland12, Timothy Trot11, Chris Tully10, Ken Van Tilburg5, Lian-Tao Wang2, and Menghang Wang1

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

Arzu Ayyan1, Jeff Berryhill2, Pushpa Bhat1, Kevin Black3, Elisabeth Brunet3, Anadi Canepa1, Shrillur Das2, Dimitri Derri3, Karri Di Pietro1, Melina Franklin1, Zosia Grzes1, Allison Hall, Ulrich Heintz3, Christian Herrig4, James Hirschauer2, Tom Holme1, Andrew Ivanov3, Bodhitri Jayasthika4, Sergio Jedrecat1, Young-Kee Kim1, Du Liu4, Mia Liu5, Zhan Liu4, Ian Low11,12, Sergio Jadach1, Chang-Song Moon4, Isabel Ojalvo4, Memakshi Narula4, Maximilian Swierzcholski13,14, Marco Valente15, Lian-Tao Wang2, Xing Wang2, Hannsjoerg Weber1, David Yu5

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

C. Aimé2, F. Ball3, N. Bartosik1, L. Buonincontri1, M. Casarza1, M. Chiesa1, F. Collamatii3, C. Curtolo2, D. Lucchesi3, B. Melet4, F. Maltoni3, B. Mansoulie5, A. Nisati6, N. Pastrone1, F. Piccinini1, C. Riccardi1, P. Sala1, P. Salvini1, L. Sestini2, I. Vai1, D. Zuliani4

ECFA Meeting 20/11/2020

D. Schulte: Muon Collider Collaboration
The muon is a unique promising option at highest lepton energies

We need to fully explore the physics case, which goes well beyond 3 TeV (studied for CLIC)

Have to address the feasibility

A great challenge but also a great opportunity

Workshop on the muon collider testing opportunities (with physics case):
https://indico.cern.ch/event/1009746/.

Web page: http://muoncollider.web.cern.ch

Mailing lists:
MUONCOLLIDER_DETECTOR_PHYSICS@cern.ch,
MUONCOLLIDER_FACILITY@cern.ch

go to https://e-groups.cern.ch and search for groups with “muoncollider” to subscribe

Many thanks to all that contributed
MAP collaboration
MICE collaboration
LEMAA team
Muon collider working group
European Strategy Update
LDG
Muon collider collaboration
...
Memorandum of Cooperation

Basically ready, waiting for final polishing

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
High-energy Frontier Proposals

European Strategy Process just finished

Four main high-energy facilities proposed
• two at CERN
• two in Asia

FCC (Future Circular Collider):
FCC-hh
• pp collider with 100 TeV cms
• ion option
FCC-ee
• Potential e⁺e⁻ first stage
FCC-eh
• additional option

ILC
• 250 GeV electron-positron linear collider
• Japan might host
• limited in energy reach

CLIC
• 380 GeV, 1.5 TeV and 3 TeV electron positron collider

CEPC / SppC
CEPC
• e⁺e⁻ collider 90-240 GeV
SppC
• 75-150 TeV hadron collider later in the same tunnel
## Proposed Projects (ESU)

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>ILC</td>
<td>ee</td>
<td>0.25</td>
<td>2</td>
<td>11</td>
<td>129 (upgr. 150-200)</td>
<td>4.8-5.3 GILCU + upgrade</td>
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<tr>
<td></td>
<td></td>
<td>0.5</td>
<td>4</td>
<td>10</td>
<td>163 (204)</td>
<td>7.8 GILCU</td>
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<tr>
<td></td>
<td></td>
<td>1.0</td>
<td></td>
<td></td>
<td>300</td>
<td>?</td>
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<tr>
<td>CLIC</td>
<td>ee</td>
<td>0.38</td>
<td>1</td>
<td>8</td>
<td>168</td>
<td>5.9 GCHF</td>
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<tr>
<td></td>
<td></td>
<td>1.5</td>
<td>2.5</td>
<td>7</td>
<td>(370)</td>
<td>+5.1 GCHF</td>
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<tr>
<td></td>
<td></td>
<td>3</td>
<td>5</td>
<td>8</td>
<td>(590)</td>
<td>+7.3 GCHF</td>
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<tr>
<td>CEPC</td>
<td>ee</td>
<td>0.091+0.16</td>
<td>16+2.6</td>
<td>149</td>
<td>5 G$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.24</td>
<td>5.6</td>
<td>7</td>
<td>266</td>
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<tr>
<td>FCC-ee</td>
<td>ee</td>
<td>0.091+0.16</td>
<td>150+10</td>
<td>4+1</td>
<td>259</td>
<td>10.5 GCHF</td>
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<tr>
<td></td>
<td></td>
<td>0.24</td>
<td>5</td>
<td>3</td>
<td>282</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.365 (+0.35)</td>
<td>1.5 (+0.2)</td>
<td>4 (+1)</td>
<td>340</td>
<td>+1.1 GCHF</td>
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<tr>
<td>LHeC</td>
<td>ep</td>
<td>60 / 7000</td>
<td>1</td>
<td>12</td>
<td>(+100)</td>
<td>1.75 GCHF</td>
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<tr>
<td>FCC-hh</td>
<td>pp</td>
<td>100</td>
<td>30</td>
<td>25</td>
<td>580 (550)</td>
<td>17 GCHF (+7 GCHF)</td>
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<tr>
<td>HE-LHC</td>
<td>pp</td>
<td>27</td>
<td>20</td>
<td>20</td>
<td>7.2 GCHF</td>
<td></td>
</tr>
</tbody>
</table>
Combined with transverse cooling at beginning

Several options considered

Allows 6-D cooling
**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**.

<table>
<thead>
<tr>
<th>Direct search of heavy particles</th>
<th>High energy measurements</th>
<th>High rate Higgs production</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUSY-inspired, WIMP, VBF production, 2-&gt;1</td>
<td>difermion, diboson, EFT, Higgs compositeness</td>
<td>Higgs single and self-couplings, rare Higgs decays, exotic decays</td>
</tr>
</tbody>
</table>
Few Preliminary Results

Higgs 3-linear coupling: $\delta \kappa = (5\%, 3.8\%, 1.6\%)$ for $E = (10, 14, 30)$ TeV


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

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

[Buttazzo, Franceschini, Wulzer, to appear]

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