Muon Collider Collaboration

Daniel Schulte for the forming international muon collider collaboration
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

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

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
Energy Limit

Electron-positron rings are multi-pass colliders limited by synchrotron radiation
Hence proton rings are energy frontier

Electron-positron linear colliders avoid synchrotron radiation, but single pass
Typically cost proportional to energy and power proportional to luminosity,
e.g. CLIC at 14 TeV \( O(60 \text{ GCHF}) \) and \( O(1.7-2.8 \text{ GW}) \)

Novel approach: muon collider
Large mass suppresses synchrotron radiation => multi-pass
Fundamental particle requires less energy than protons
But lifetime at rest only 2.2 \( \mu \text{s} \)
Proportional to energy

\[ \Delta E \propto \left( \frac{E}{m} \right)^4 \frac{1}{R} \]
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
In linear colliders, 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.

**European Strategy advised to consider muon collider**
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
Potential Long-Term Timeline

Collider Design
- Baseline design
- Design optimisation
- Project preparation

Test Facility
- Design
- Construct
- Exploit

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

Exploratory phase
- Ready to decide on test facility
- Cost scale known

Definition phase
- Ready to commit
- Cost known

Technically limited

D. Schulte
Muon Collider, JUAS, March 10, 2021
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

LDG created panels to provide the input for the Roadmap, one for muon beams

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.
Luminosity Goals

Target integrated luminosities

<table>
<thead>
<tr>
<th>√s (TeV)</th>
<th>(\int L dt)</th>
</tr>
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<tbody>
<tr>
<td>3</td>
<td>1 ab(^{-1})</td>
</tr>
<tr>
<td>10</td>
<td>10 ab(^{-1})</td>
</tr>
<tr>
<td>14</td>
<td>20 ab(^{-1})</td>
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</tbody>
</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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<td>N</td>
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<td>Hz</td>
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</tr>
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<td>7.5</td>
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<td>(\varepsilon)</td>
<td>(\mu m)</td>
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<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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</tbody>
</table>

Comparison: CLIC at 3 TeV: 28 MW
Muon Collider Luminosity Scaling

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

Constant current for required luminosity
Better scaling than linear colliders

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

These systems will drive the beam quality

Currently assume that we use the same production complex at all energies

We assume that we will got to the limit of technologies

But there are still ideas that need to be explored for further improvement

These systems will be the cost and power consumption drivers (for 10 TeV accelerator ring could be LHC size, collider ring is half LHC size)

They will limit the energy reach

Can imagine to implement accelerator for 3 TeV in the LHC tunnel or a smaller new one
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 $O(1.3 \text{ MW})$
- radiation in solenoid
- need to cool
- need to take care of debris for downstream systems

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

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

Maximise gradient in a magnetic field to limit muon decay
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
- Final Cooling
- 6D Cooling
- Charge Separator
- Bunch Merge
- Final Cooling
- MAP collaboration

**Target**
- Exit Front End (15mm, 45mm)
- Pre-merge 6D Cooling (original design)
- Bunch Merge
- Post-merge 6D Cooling

**Front End**
- Target
- Phase Rotator

**Initial Cooling**
- Inlet

**For acceleration to Higgs Factory**
- Exit Front End

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

**Initial Cooling**
- Inlet
Cooling: The Emittance Path

- **Specification**: For acceleration to multi-TeV collider
- **Achieved (simulations)**: For acceleration to Higgs Factory

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

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

**Initial**
- (X)
- (Y)

**MAP collaboration**

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Muon Collider, JUAS, March 10, 2021
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 Cooling**
  - For acceleration to Higgs Factory
  - Maybe can improve this

- **Initial (X) & Initial (Y)**

- **Post-merge 6D Cooling**

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

- **Bunch Merge**

- **Target**
  - Phase Rotator

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

- **MAP collaboration**

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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

FNAL
Breakthrough in HTS cables

NHFML
32 T solenoid with low-temperature HTS

MuCool: >50 MV/m in 5 T field

FNAL
12 T/s HTS
0.6 T max

Mark Palmer

D. Schulte
Muon Collider, JUAS, March 10, 2021
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
Beam Acceleration

An important cost driver
Important for power consumption

A trade-off between cost and muon survival
Not detailed design, several approaches considered

- Linacs
- Recirculating linacs
- FFAFs (static superconducting magnets)
- Rapid cycling synchrotrons (pulse magnets)
High-energy Acceleration

**Rapid cycling synchrotron (RCS)**
- Ramp magnets to follow beam energy
- Could use 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))
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

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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 $O(400 \text{ W/m})$ **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
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
Neutrino Radiation

Neutrinos from decaying muons 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
- maybe 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 $E^3$

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

B. King
Arc Estimates

Formulae by B. King

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

For our parameters and d = 500 m
10 TeV : 100 µSv/year
14 TeV : 280 µSv/year

With 20 cm gap between 15 T magnets
<B> = 10.5 T
10 TeV : 340 µSv/year
14 TeV : 940 µSv/year

Higher field, shorter gaps in collider
Denser beam
Larger energy spread acceptance

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Neutrino Radiation Mitigation

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

Opening angle ± 1 mrad

Even at 14 TeV 200 m deep tunnel would stay below 5 μSv/year

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

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
• Ensure that BIB is not an obstacle
• Through European Roadmap for Accelerator R&D

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
LEMA team
Muon collider working group
European Strategy Update
LDG
Muon collider collaboration
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