Muon Test Facilities

Diktys Stratakis
Fermi National Accelerator Laboratory
Derun Li
Lawrence Berkeley National Laboratory

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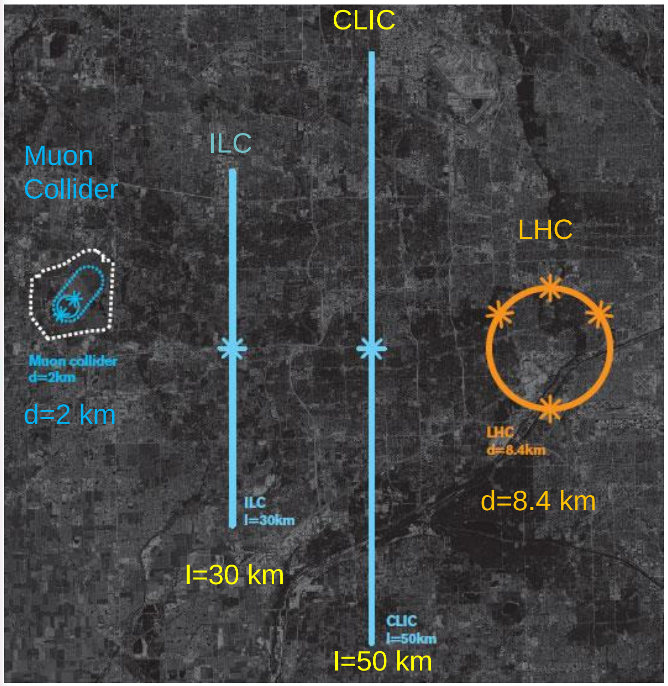
Outline

- Muon Collider (MC) overview
- Proposed MC parameters under Muon Accel. Program
- MC challenges
- Summary of past accomplishments
- Technology needs
- Current status
- Concluding comments and outlook of future work

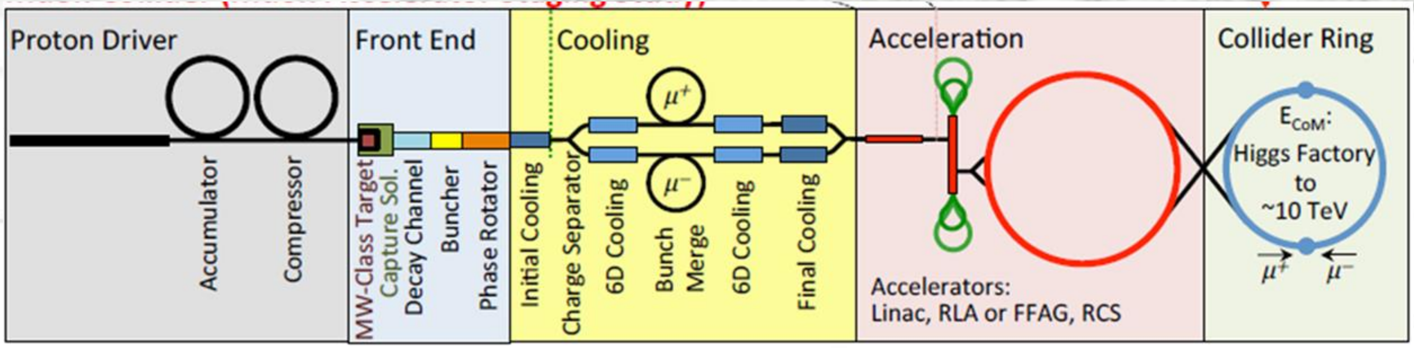
Muon Collider (MC) has a smaller footprint



- **Accelerator Physics and technology challenges associated with MC:**
  - **Muons are ~ 200 times heavier than electrons**
  - Allow for circular collider due to much less synchrotron radiation energy, impossible for e^-e^+ circular colliders at TeV scale and therefore smaller footprint.
  - **Muons decay and are produced with a very large transverse emittance**
  - Accelerator beam physics challenges;
  - Requires fast beam manipulation technologies (target and capture, cooling high gradient NC and SRF acceleration, SC magnets and etc.)
  - Must deal with decay particles and neutrino radiation.

A MC would offer a precision probe of fundamental interactions, in a smaller footprint as compared to electron or proton colliders

MC accelerator components



- High power (MW scale) proton driver
  - Considered 8 GeV H- SRF linac at 2-4 MW
- Pre-target accumulation & compression rings for 2 ns bunches
- Target & capture solenoid to create 200 MeV secondaries
  - Considered liquid Mercury targets at 20 T fields
- Ionization cooling line to reduce 6D phase-space by several orders of magnitude
  - Considered km scale channels with ~30 T magnets at the end
- Acceleration system to bring the beam at TeV scale energies
  - For multi-TeV scale, considered rapid cycling synchrotrons using SRF
- A collider ring where counter propagating muons collide

Current status

- Between 2011-2016 MAP collaboration was formed to address key feasibility issues of a Muon Collider. Leveraged prior decades of study to identify a design path. Focused on proton-driver based solution
- Meantime, increasingly growing interest in muon colliders from particle physics community, especially in Europe. Formation of International Muon Collaboration on the works.
- In Europe, CERN Council has charged the Laboratory Directors Group to develop the Accelerator R&D Roadmap for the next decade.
  - Three community meetings organized with the goal to define the needed Muon Collider R&D with deliverables and demonstrators
- From the US side, a Muon Collider Forum has been formed that meets monthly
  - AF is actively involved in the upcoming Snowmass process with the particle physics community to define the needed muon collider R&D.

Muon Collider parameters under MAP

Parameter	Units	Higgs	Multi-TeV		
CoM Energy	TeV	0.126	1.5	3.0	6.0
Avg. Luminosity	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7 sec		13'500	37'500	200'000	820'000
Circumference	km	0.3	2.5	4.5	6
No. of IP's		1	2	2	2
Repetition Rate	Hz	15	15	12	6
$\beta^*_{x,y}$	cm	1.7	1	0.5	0.25
No. muons/bunch	10^{12}	4	2	2	2
Norm. Trans. Emittance, $\varepsilon_{\mathrm{TN}}$	μm-rad	200	25	25	25
Norm. Long. Emittance, $\varepsilon_{\mathrm{LN}}$	μm-rad	1.5	70	70	70
Bunch Length, σ_{S}	cm	6.3	1	0.5	0.2
Proton Driver Power	MW	4	4	4	1.6
Wall Plug Power	MW	200	216	230	270

$$\mathcal{L} = \frac{f_{col} \cdot n_{\mu_+} \cdot n_{\mu_-} \cdot \beta \cdot \gamma}{4\pi\left(\varepsilon_{x,n} \cdot \beta_x^*\right)^{1/2} \cdot \left(\varepsilon_{y,n} \cdot \beta_y^*\right)^{1/2}}$$

Beam components are designed to realize COM energy and Luminosity

Recent MC parameters under discussions at Snowmass MC forum

Target integrated luminosities

$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

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

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} $cm^{-2}s^{-1}$	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	μm	25	25	25
$\sigma_{x,y}$	μm	3.0	0.9	0.63

Snowmass process to give feedback on this

- **Continuing Muon Accelerator R&D requires a strong Physics case on MC and endorsement from Particle Physics Community;**
- **Future close collaboration between Accelerator and Particle Physics community is key;**
- **R&D efforts and funding likely after next P5.**

Key R&D Challenges for a MC

	Issues	Current status
Target	• Multi-MW Targets • High Field, Large Bore Capture Solenoid	• Ongoing >1 MW target development • Challenging engineering for capture solenoid
Front End	• Energy Deposition in Front-End Components • RF in Magnetic Fields (see Cooling)	• Current designs handle energy deposition
Cooling	• RF in Magnetic Field • High and Very High Field SC Magnets • Overall Ionization Cooling Performance	• MAP designs use 20 MV/m → 50 MV/m demo • > 30 T solenoid demonstrated for Final Cooling • Cooling design that achieves most goals
Acceleration	• Acceptance • Ramping System • Self-Consistent Design	• Designs in place for accel to 125 GeV CoM • Magnet system development needed for TeV-scale • Self-consistent design needed for TeV-scale
Collider Ring	• Magnet Strengths, Apertures, and Shielding • High Energy Neutrino Radiation	• Self-consistent lattices with magnet conceptual design up to 3 TeV • > ~ 5 TeV – ν radiation solution required
MDI/Detector	• Backgrounds from μ Decays • IR Shielding	• Further design work required for multi-TeV • Initial multi-TeV promising

Slide from Mark Palmer (MAP Director)

Highlights of past accomplishments

- Targetry R&D and proof-of-principle demonstration at CERN
- Demonstration of operation of normal conducting (NCD) RF cavities in the presence of strong magnetic fields
- Demonstration of transverse ionization cooling by the International Muon Ionization Cooling Experiment (MICE) hosted by RAL
- Muon emittance exchange demonstrated at the Fermilab Muon Campus and MICE
- Superconducting magnet development suitable for Muon Colliders
- End-to-end muon ionization cooling channel models that meet the MC requirements

Muon Collider Forum

- The Snowmass Energy, Theory and Accelerator Frontier Conveners created a Muon Collider Forum to provide input to Snowmass on the MC, based on the high level of interest.
- The intention is to not compete with the European effort but to have a US driven component.
- Monthly meetings with field experts
- More information:
- https://snowmass21.org/energy/muon_forum

Forum coordinators

Name	Institution	email	frontier
Derun Li	Lawrence Berkeley Lab	dli[at]lbl.gov	AF
Diktys Stratakis	Fermilab	diktys[at]fnal.gov	AF
Kevin Black	University of Wisconsin	kblack[at]hep.wisc.edu	EF
Sergo Jindariani	Fermilab	sergo[at]fnal.gov	EF
Fabio Maltoni	University of Bologna/CERN	maltoni.fabio[at]gmail.com	TF
Patrick Meade	Stony Brook University	patrick.r.meade[at]gmail.com	TF

Muon Collider Forum activities

- Delivery of a White paper for Snowmass
- Accelerator experts participate in the Snowmass process with the particle physics community to define the needed MC R&D
- The accelerator white paper goals are:
  - Highlight recent developments on accelerator technology that could lead to a Muon Collider
  - Report on the accelerator R&D needs
  - Discuss a timeline and siting options (including US sites)
  - Planned a dedicated accelerator workshop in January 2022

Muon Collider - a Dream Machine for Particle Physics.

November 15, 2021

Abstract

1 Introduction

1.1 Big Physics Questions , Fabio/Patrick

General introduction with big questions in particle physics and how a Muon Collider can help address them. Difference wrt the last Snowmass when 13 TeV LHC was just about to start and HL-LHC was not a project.

1.2 Recent Developments in Theory , Fabio/Patrick

Overview of recent advancements in theory since the last Snowmass.

1.3 Recent Developments in Accelerator , Derun/Diktys

Overview of recent advancements in accelerator technology since the last Snowmass.

1.4 Recent Developments in Detectors , Kevin/Sergo

Overview of recent advancements in detector technology since the last Snowmass.

1.5 Global Efforts and Plans , Derun/Diktys

Briefly describe past (MAP), present (IMCC), etc

1.6 Working Assumptions , Kevin/Sergo

Energy and luminosity assumptions and how they were chosen.

2 Physics Highlights Fabio/Patrick

2.1 Higgs Boson

Higgs couplings, total width, mass, trilicar and quartic couplings,

Exploring site fillers (in progress)

- Fermilab site filler study:
  - 5 TeV is relatively accessible
  - 10 TeV is a stretch goal. <u>It requires 16 T dipoles and 4 T rapid cycling magnets</u>
  - Preliminary results. More studies in progress.

~4 TeV (2 x 2) Muon Collider (~2005)

- **Muon Collider**
  - **•2 TeV ring (~8T magnets)**
  - **•RLA accelerator**
    - **~18 turns**
      2km linacs -50 GeV each
      ~30 MV/m rf
      Arcs are ~8T magnets each
- **Not quite site filler**
  - **•Easily expand to 2.5x2.5**
  - **•(5 TeV)**

- **Double gradients, B_{max}**
  - **•10 TeV (5 x 5) – (16 T – 60 MV/m)**

Slide from David Neuffer (Fermilab)

State of the art technology and future MC RF and magnets (in progress)

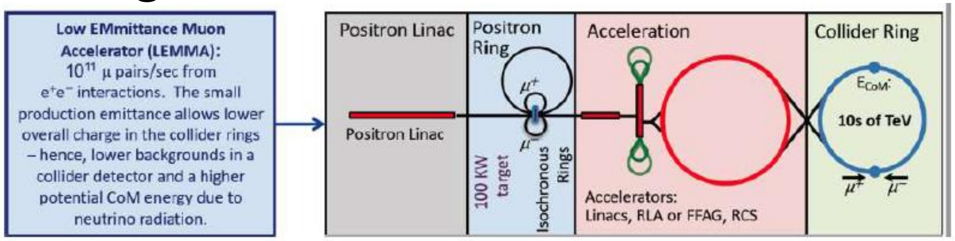
- **Conventional magnets**
  - ~ 2 Tesla
- **Superconducting – NbTi**
  - Tevatron at Fermilab ~ 4 Tesla
  - LHC at CERN ~ 8 Tesla
- **Superconducting Nb_3Sn**
  - HL– LHC+ ~ 16 Tesla
- **Pulsed magnets**
  - Achieved of 20 T/s HTS record
  - +/- 2 Tesla peak
  - +/- 4 Tesla peak (needed)

- **SRF technology**
  - 17 MV/m (650 MHz for PIP-II)
  - 30+ MV/m (1.3 GHz ILC)
- **Future advance**
  - 40 ~ 50 MV/m → 80+ MV/m (?)
- **Pulsed NC RF**
  - ~ 50 MV/m (805 MHz)
  - ~ 15 MV/m (201 MHz)
- **NCRF in a strong magnetic field**
  - 50 MV/m at 3 T (805 MHz)
  - Significant R&D needed

Slide from David Neuffer (Fermilab)

Areas of further research

- Magnet technology: High field, multi-Tesla SC magnets for muon production, cooling, acceleration and collision.
- RF technology: High gradient, robust normal conducting rf cavities for cooling and power-efficient superconducting rf for acceleration.
- Lattice designs: Shorter cooling channel designs, end-to-end lattice designs for acceleration towards TeV-scale energies, collider ring lattice designs for > 3 TeV CoM
- Detector technology: Concepts that can sustain muon decay background for multi-Tev energies
- Alternative concepts:
  - 45 GeV $e^+e^- \rightarrow$ muons



Concluding comments and Outlook

- Increasingly growing interest in muon collider from particle physics community, especially in Europe;
- Joining the international muon collider collaboration efforts under discussions
  - As individual institute or coordinated US efforts?
  - Leveraging and resuming previous US MAP R&D?
- A breakthrough towards a proton driven MC through MICE:
  - A successful muon cooling demonstration, but took nearly two decades;
  - Future R&D should take advantages of existing infra-structures and resources of collaboration institutes.
- Actively participate in the upcoming Snowmass process with particle physics community to define the needed muon collider R&D