



Muon Collider Forum Report

Diktys Stratakis

Snowmass Summer Meeting

19 July 2022

Special Thanks

- Muon Collider Forum Conveners
 - Derun Li (AF),
 - Fabio Maltoni and Patrick Meade (TF),
 - Kevin Black and Sergo Jindariani (EF)
- To all contributors to the Muon Collider Forum activities

Brief history

- Early mentions of Muon Colliders date back to 1960s with early design studies in 1990s-2000s
- Between 2011-2016 the Muon Accelerator Program (MAP) was formed to address key feasibility issues of a Muon Collider
 - Focused on a proton-driver based solution and considered a staged approach.
 - End-to-end design for a Neutrino Factory & a 125 GeV Higgs Factory.
Considered colliders at 1.5, 3 and 6 TeV
- In 2021, CERN Council has charged the EU Laboratory Directors Group to develop the Accelerator R&D Roadmap for next decade:
 - Several community meetings organized with the goal to define the needed muon R&D with deliverables and demonstrators. Strong participation from the US
- Muon Colliders are now part of the European Accel. R&D Roadmap
 - Formation of the International Muon Collider Collaboration (IMCC)
 - Consider a 10+ TeV collider

Muon Collider Forum

- Recently, there has been strong interest in Muon Colliders in the US HEP community
- In 2020, the Snowmass EF+AF+TF have created a Muon Collider Forum to provide input to Snowmass on the Muon Collider (MuC)
 - The intention of this informal organization is to not compete with other efforts but to have a US driven component.
 - Build a strong collaboration between the particle physics and accelerator communities for MuC research and make a strong physics case
- The forum has been very active:
 - Monthly meetings and dedicated workshops
 - 160 e-mail subscribers, 50-100 regular participants
 - 412 registrants and ~200 participants in the Muon Collider Agora
 - Inform community about the past and current developments
 - Exchange knowledge and ideas

Muon Collider Forum Report

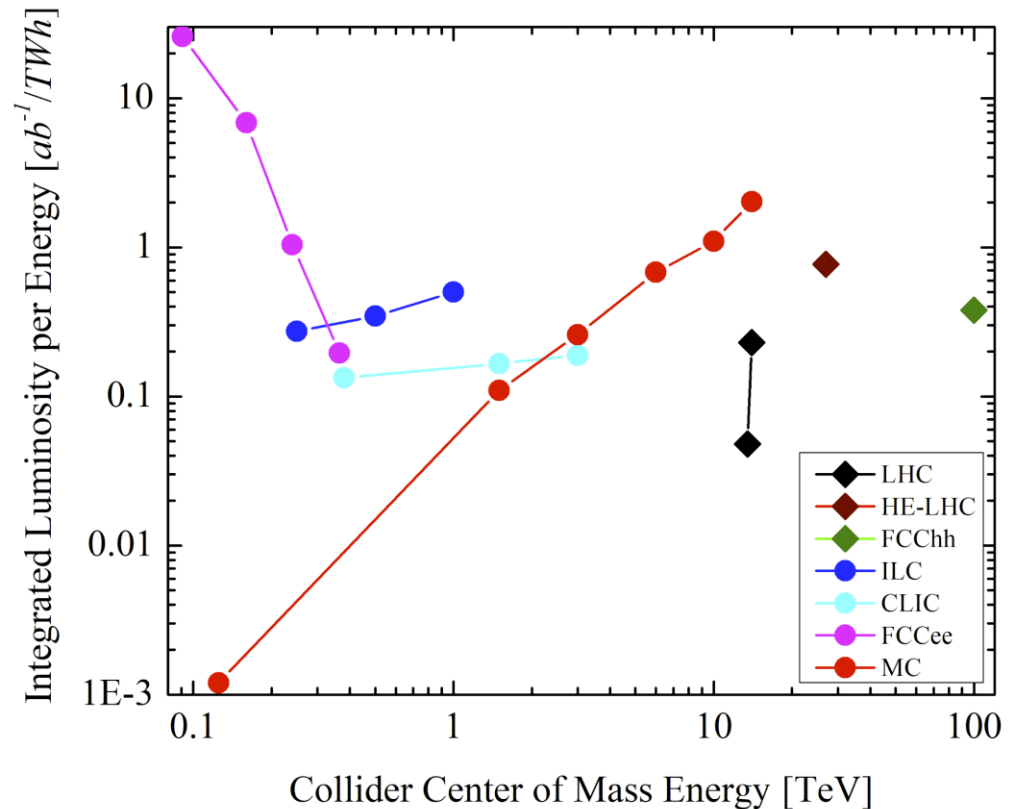
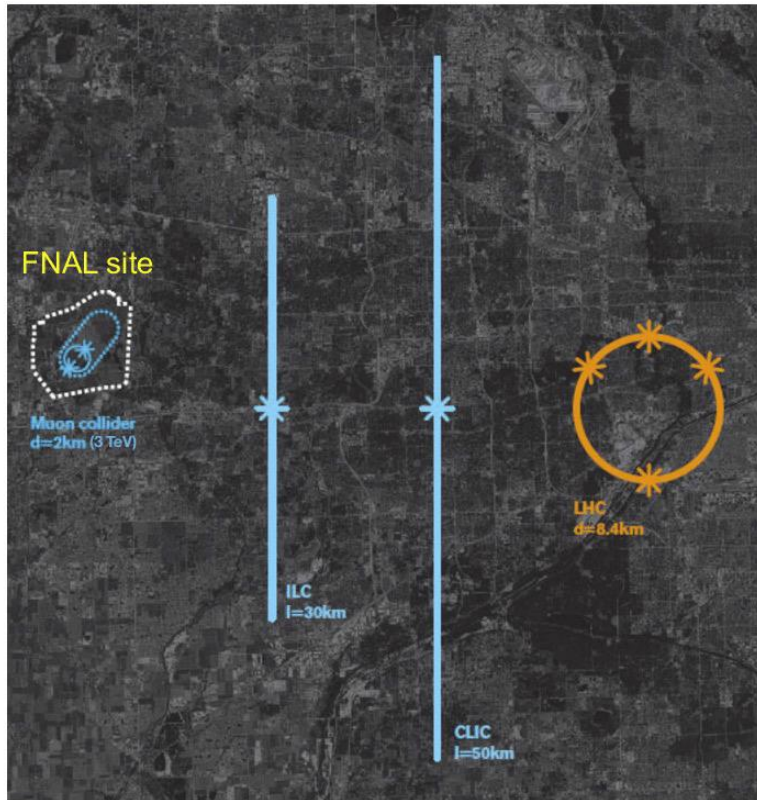
- Muon Collider Forum Report – a coherent vision for muon colliders from the US/ Snowmass perspective
 - Highlights of physics developments in theory, detector and accelerators
 - Identify key areas where US can provide critical contributions to the global MC R&D efforts.
 - Present a “US Site-Filler” as one of options for hosting a MC in the future.
- The primary focus of the report is a 10 TeV physics program
- Emphasize potential US role for R&D, explore US siting for a MC, and a vision of a US program by the next Snowmass



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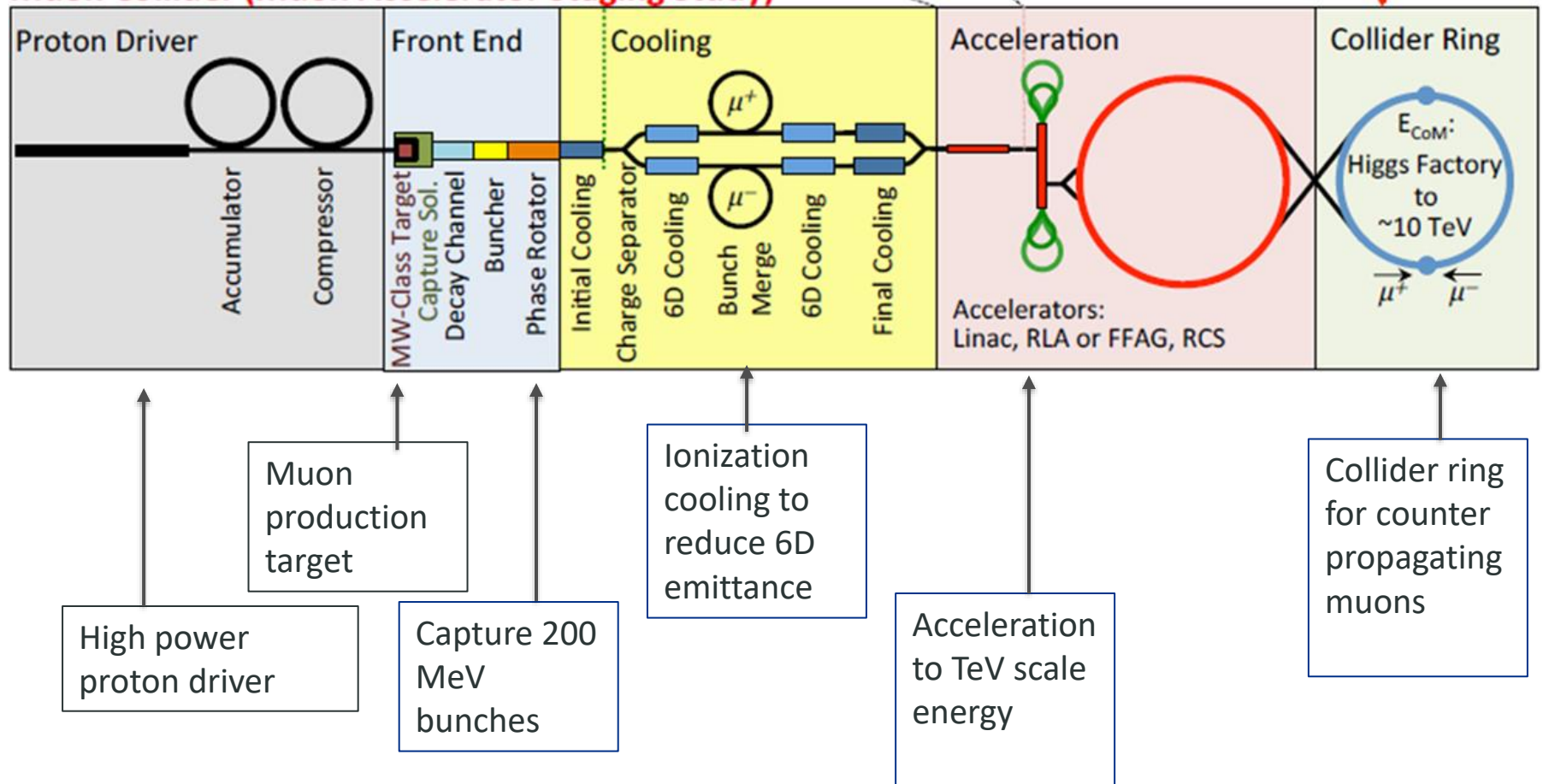
- Now public:
https://snowmass21.org/energy/muon_forum
- ~ 130 authors, 50% Early Career scientists

Muon Collider sustainability



- A MC would offer a precision probe of fundamental interactions, in a smaller footprint as compared to electron or proton colliders
- Most power efficient machine at high energies

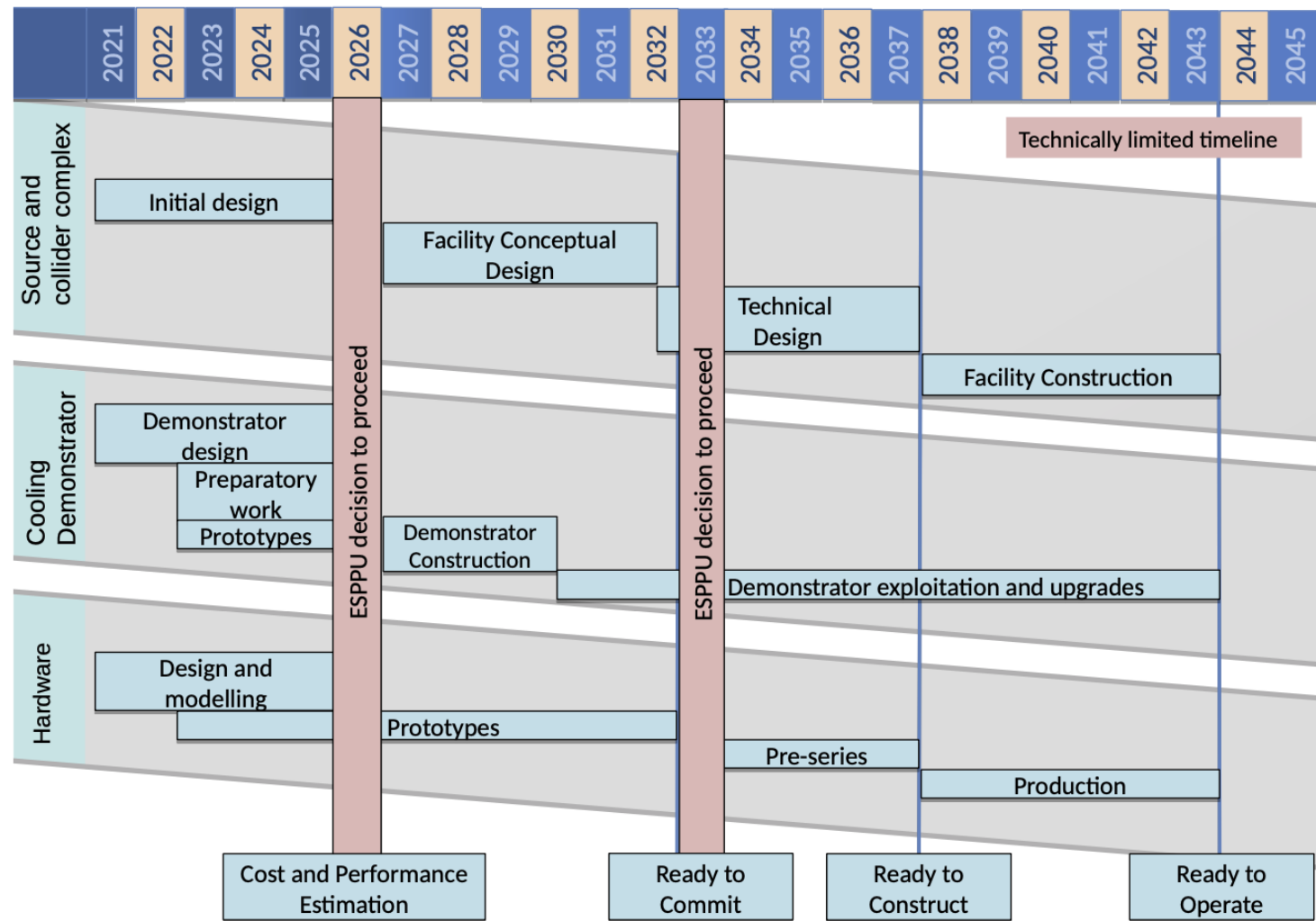
Machine overview



Energy Frontier Report – Resources and Timelines

- Five year period starting in 2025
 - Prioritize HL-LHC physics program,
 - Establish a targeted e+e- Higgs Factory detector R&D for US participation in a global collider
 - **Develop an initial design for a first stage TeV-scale MuC in the US (pre CDR)**
 - **Support critical detector R&D towards EF multi-TeV colliders**
- Five year period starting in 2030
 - Continue strong support for HL-LHC program
 - Support construction of an e+e- Higgs Factory
 - **Demonstrate principal risk mitigation and deliver CDR for a first stage TeV-scale MuC**
- After 2035
 - Evaluate continuing HL-LHC program to the construction of archival measurements
 - Begin support the physics program of the Higgs Factories
 - **Demonstrate readiness to construct and deliver TDR for a first TeV-scale MuC**
 - **Ramp up funding support for detector R&D for multi-TeV colliders**

IMCC Timeline



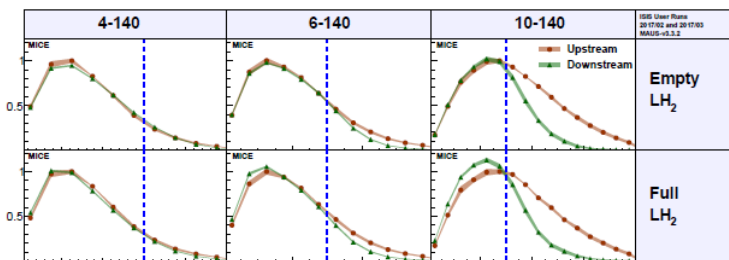
Required key accelerator technologies

- High power proton driver development
 - 2ns, 8 GeV bunches up to 4 MW with a 15 Hz rep. rate
- Target system capable of managing large instant power
 - 20 T capture solenoid with large bore that can withstand radiation
- Cooling system to reduce 6D emittance by 6 orders of magnitude
 - Demand for high B-fields @ 30-40 T range
 - Placement of NC RF cavities within multi-T B-fields
- Acceleration scheme towards TeV scale energy before decay
 - Fast ramping magnets to deliver ramp times of several T on a ms timescale
- Collider ring
 - 12-16 T dipole magnets with a 150 mm aperture
 - Neutrino flux mitigation system

An important outcome of MAP was that progress in each of the above areas was sufficient to suggest that there exist a viable path forward

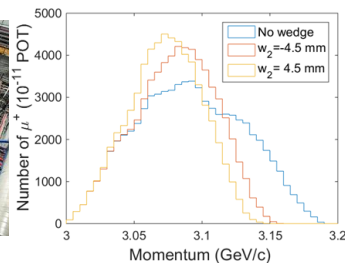
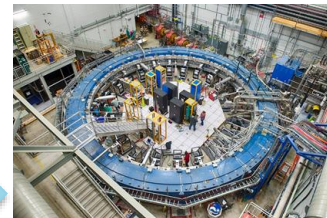
Feasibility: Ionization Cooling

- Sufficient progress was made in all ionization cooling section designs over the last years
 - Design of cooling lattices in place with realistic assumptions [\[ref\]](#)
 - They came only by a factor of two to the MuC requirement [\[ref\]](#). With latest technology considerable improvements are expected (next slide)
- Ionization cooling has been **demonstrated** in two occasions
 - MICE demonstrated transverse cooling with different absorbers [\[ref\]](#)
 - Fermilab demonstrated longitudinal cooling for the Muon g-2 Experiment [\[ref\]](#)
 - Full demo of ionization cooling is a key part of the proposed R&D program



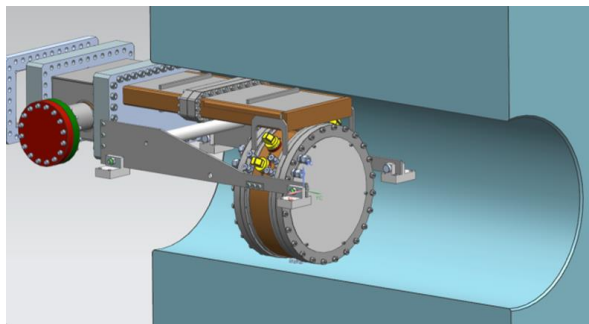
Transverse cooling demo in MICE

Longitudinal cooling for Muon g-2



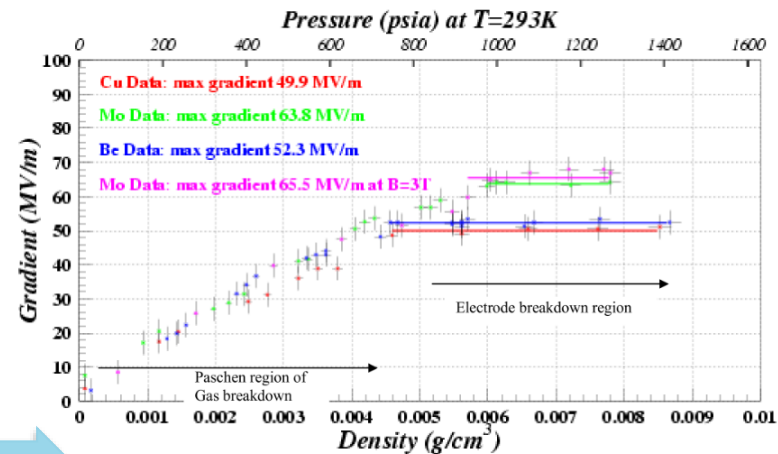
Feasibility: RF cavities in magnetic field

- Two promising solutions for sustaining cavity gradient in B-fields
 - Use low density materials (like Be) to reduce damage from field-emission [ref]
 - Use high-pressure gas inside the cavity [ref]
- Both techniques have been experimentally verified with a 3 T field
- **No degradation in achievable gradient for the applied B-field**
- This opens the path for further improvement in cooling performance



Demo of 50 MV/m at 0 T and 3T with vacuum

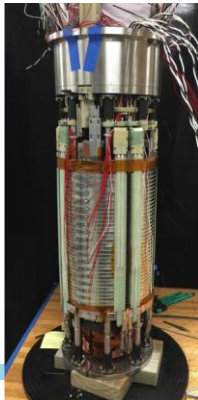
Demo of 50 MV/m at 0 T and 3T with gas



Feasibility: Magnet technology

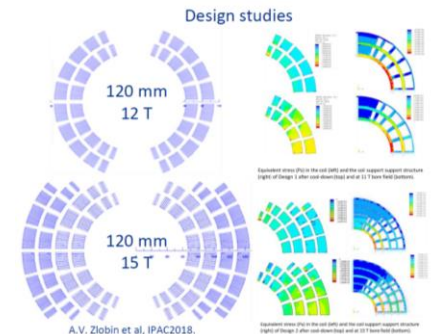
- **Cooling:** Designs consider B-fields in the 30-40 T range
 - This field has been demonstrated with commercial MRI 29 T magnets
 - Record 32 T achieved at NHMFL. A funded proposal to design purely SC 40 T magnet in place [\[ref\]](#)
- **Acceleration:** Designs considered rapid cycling synchrotrons with fast cycling magnets
 - Demonstrated record ramp rate of 300 T/s with HTS – upgrades for higher fields proposed [\[ref\]](#).
- **Col. Ring:** 6 TeV designs consider >100 mm bore, 16 T arc dipoles
 - US-MDP plans in 4-5 years demonstration of a 12-15 T (120 mm) Nb₃Sn dipole

Record SC
32 T @
NHMFL



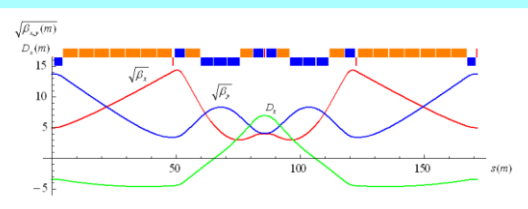
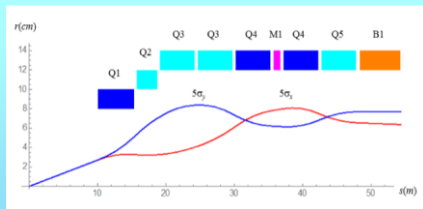
~ 300 T/s
HTS demo

US-MDP future
magnet developments



Feasibility: Collider Ring design & neutrino flux

- Lattice designs for a 3 and 6 TeV Colliders are in place
 - Optics and magnet parameters have been specified [\[ref\]](#)
 - Addressed the challenges associated with radiation loads on magnets as well as particle background in the collider detector [\[ref\]](#)
- The decay of muons in the collider ring produces a dense flux of neutrinos at significant distance from the collider
 - Several solutions in place to mitigate the problem: Examples include situating the collider at ~ 100 m depth [\[ref\]](#) or move lattice overtime (IMCC approach) [\[ref\]](#).
 - These solutions illustrate that neutrino flux can be manageable, similar to LHC.



6 TeV
lattice
design



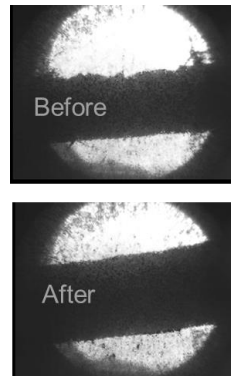
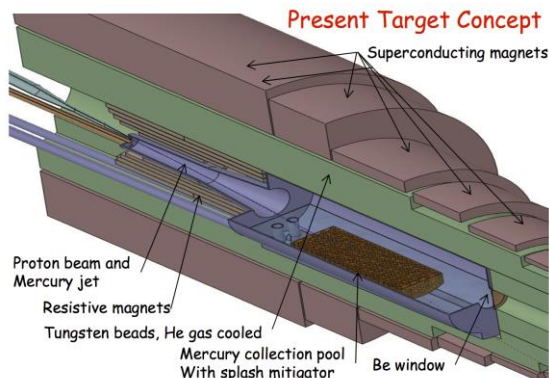
Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

Neutrino Flux around Muon Colliders and 7 Ways to Mitigate it

Nikolai Mokhov, Fermilab
Workshop Muon-Driven Colliders
January 27, 2022

Feasibility: Target station

- MAP considered 2-4 MW liquid mercury or Gallium jets @ 20 T
 - MERIT exp. demonstrated liquid Mercury jet in high field solenoid. Technology is OK for beam power up to 8 MW but some safety concerns [\[ref\]](#)
- As an alternative IMCC is exploring a Graphite target concept
 - 2 MW target could be acceptable, opening a path for solid targets [\[ref\]](#)
 - Mature technology for ~ 1 MW targets @ Fermilab with plans to expand > 2 MW for its neutrino program in the following years
- SC solenoid design very demanding and needs R&D
 - Experience with ITER center solenoid can be used – size and field strength are comparable.



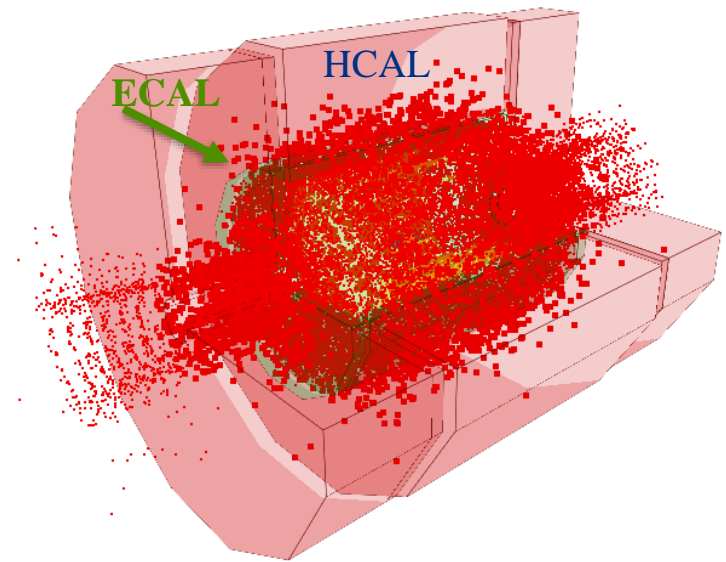
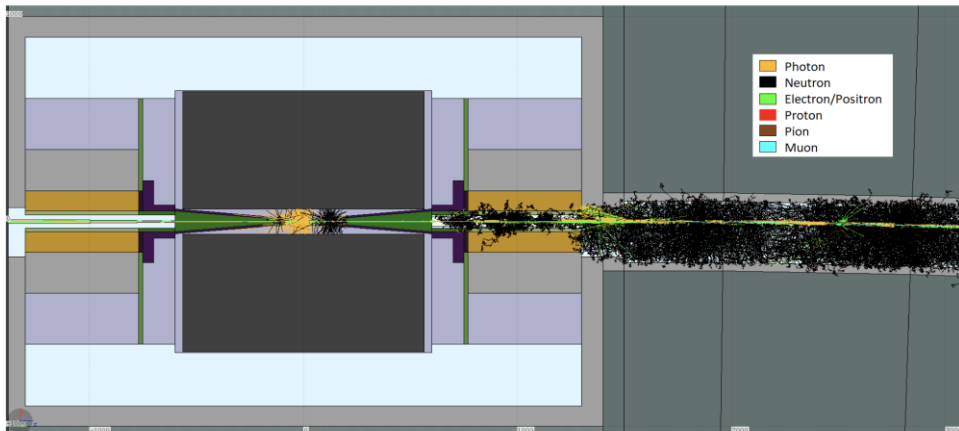
ITER 13 T
solenoid

Liquid
Mercury jet
demo



Beam Induced Background

- Beam background is one of the unique features/challenges of Muon Colliders
- Main Source of Beam Induced Background (BIB) are showers produced by electrons originating in beam muon decays
- Muons decay with an average lifetime of $2.2 \cdot 10^{-6}$ seconds at rest, at $\sqrt{s} = 3$ TeV they live for about $3.1 \cdot 10^{-2}$ seconds
- The challenge is to separate collision particles from the BIB



Detectors: Key Developments

◆ Detector Environment:

- ✓ Radiation levels similar to HL-LHC and much smaller than at the future hadron colliders

◆ Beam induced background evolution studied:

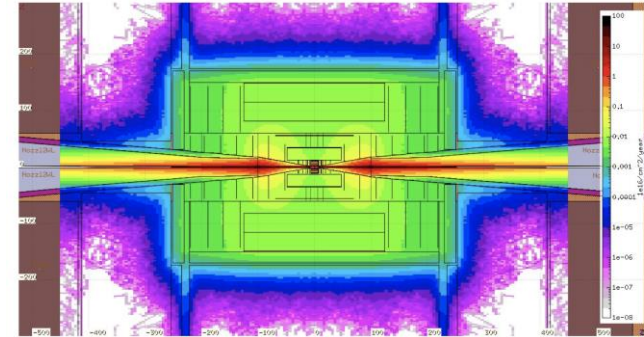
- ✓ The BIB in detector volume is approximately constant with COM energy (even without MDI optimization) → higher energies possible

◆ Detector technologies have been rapidly advancing (in large due to HL-LHC needs):

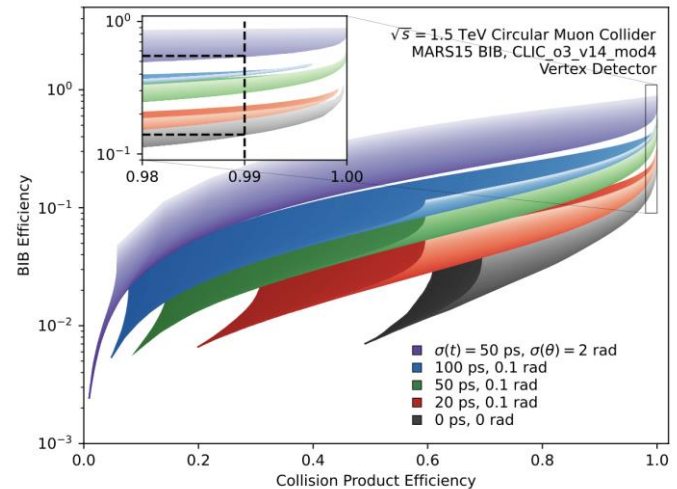
- ✓ Particle Flow detectors with excellent position, energy and timing resolution
- ✓ Advanced on- and off- detector data processing
- ✓ Using reconstruction from pp makes a huge difference

◆ Minimum muon collider detector requirements are within reach or already technologically available.

1-MeV-neq fluence for one year of operation (200 days)

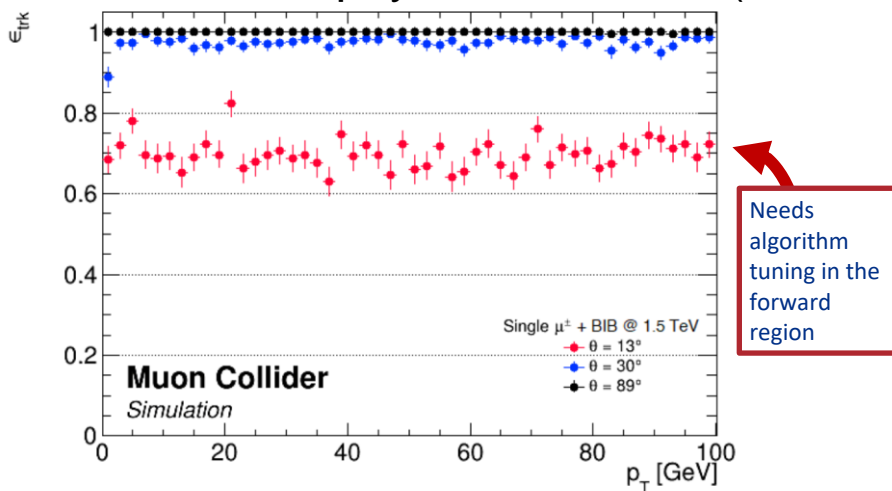


Expected (FLUKA simulation) to be approximately: $\sim 10^{14-15}/\text{cm}^2/\text{y}$ in the tracker
 $\sim 10^{14}/\text{cm}^2/\text{y}$ in the ECAL

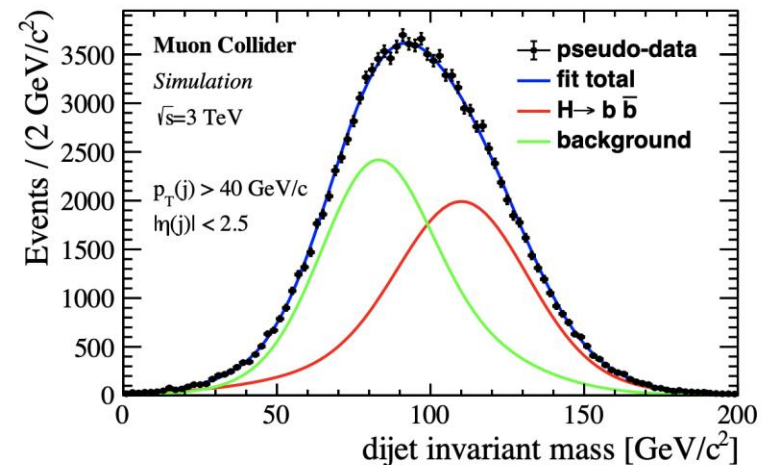


Preliminary Detector Performance

- ◆ Reconstruction feasibility demonstrated using simple algorithms
 - ✓ Detector occupancy and energy density are manageable
 - ✓ Performance similar to LHC is already achieved. Many avenues for improvements
- ◆ Fast simulation performance **validated** against full simulation using a set of benchmark physics scenarios ($H \rightarrow b\bar{b}$ cross-section Dark Matter search)



Efficiency of reconstructing tracks



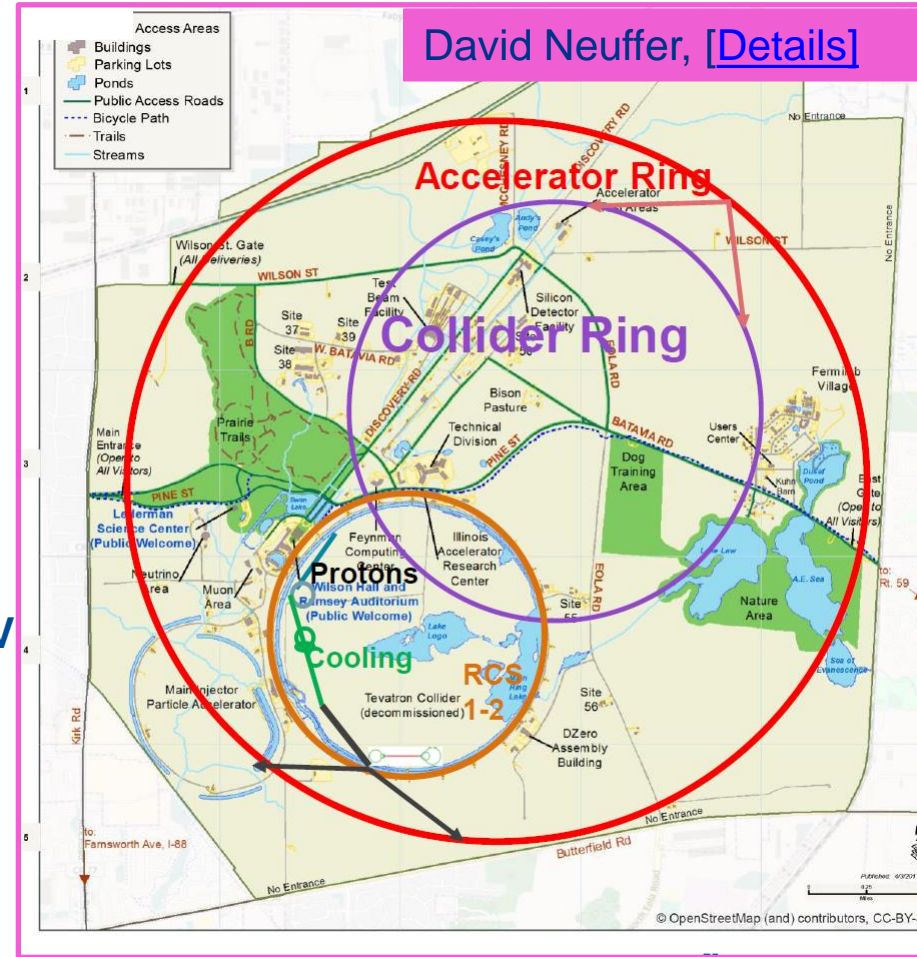
Higgs \rightarrow $b\bar{b}$ cross-section precision:
FastSim: 0.73% vs Fullsim: 0.75%

Moving forward

- No fundamental show-stoppers have been identified.
 - Nevertheless, engineering challenges exist in many aspects of the design and targeted R&D is necessary in order to make further engineering and design progress
 - **Cooling can substantially relax proton driver and neutrino flux specs**
- Demonstrations are required for both the muon source and the high-energy complex
 - Demonstration of radiation and shock resistance of materials
 - Demonstration of high field multi-Tesla magnets for muon production, cooling, acceleration and collision
 - Demonstration of high gradient, normal conducting rf cavities for cooling and power-efficient superconducting rf for acceleration
 - Demonstration of an integrated ionization cooling module as an engineering prototype
- IMCC is exploring demonstrator sites internationally

A path for a Muon Collider at Fermilab

- A conceptual design is in place
- Proton source
 - PIP-II upgrade -> Target
- Ionization cooling channel
- Acceleration (3 stages)
 - Linac + Recirculating Linac → **65 GeV**
 - Rapid Cycling Synchrotrons #1, #2 → **1 TeV (Tevatron size)**
 - RCS #3 → **5 TeV (site filler)**
- 10 TeV collider
 - Collider radius: 1.65 km
- Staging @125 GeV (Higgs), 1 TeV, and 3 TeV possible



Fermilab new formed *Future Colliders Group* is actively exploring filler option

Summary

- Physics & technology landscape has significantly changed since 2013
 - Explosion of interest in muon colliders as indicated by the number of publications, activities in IMCC, Muon Forum etc
 - Outstanding physics program
 - Minimum muon collider accelerator and detector requirements are within reach or technologically available
- There has been a recent considerable growth of interest about MuC from the particle physics community:
 - Significant growth of related publications & related workshops
 - Formation of the IMCC
- We are asking Snowmass/ P5 to support a MuC program in the US
 - Enable collaboration with IMCC
 - Provide funding for accelerator and detector R&D
 - Further develop the site-filler concept for the next Snowmass process