Muon Collider in the future of the Energy Frontier

Sergo Jindariani (Fermilab)

DPF-Pheno’2024

On behalf of the **US Muon Collider R&D Coordination Group**

and **the IMCC**

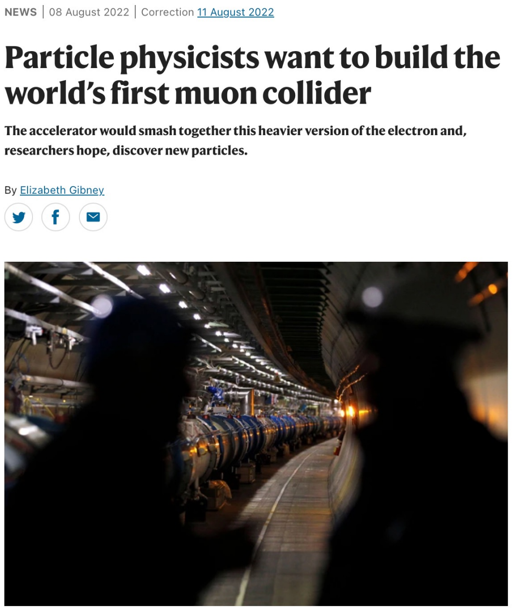
The Path to 10 TeV (excerpts from the 2023 P5 report)

- The proposed program aligns **with the long-term ambition of hosting a major international collider facility in the US, leading the global effort** to understand the fundamental nature of the universe.

- In particular, **a muon collider** presents an attractive option both for technological innovation and for bringing energy frontier colliders back to the US. The footprint of a **10 TeV muon collider is almost exactly the size of the Fermilab campus.**

- Although **we do not know if a muon collider is ultimately feasible**, the road toward it leads from current Fermilab strengths and capabilities to **a series of proton beam improvements and neutrino beam facilities**, ...

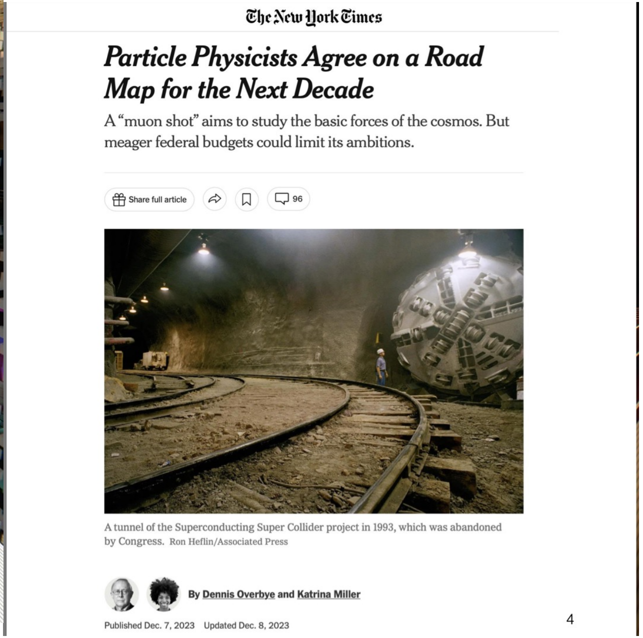
- At the end of the path is an unparalleled global facility on US soil.


NEWS | 08 August 2022 | Correction 11 August 2022

Particle physicists want to build the world's first muon collider

The accelerator would smash together this heavier version of the electron and, researchers hope, discover new particles.

By Elizabeth Gibney


The New York Times

Particle Physicists Agree on a Road Map for the Next Decade

A "muon shot" aims to study the basic forces of the cosmos. But meager federal budgets could limit its ambitions.

A tunnel of the Superconducting Super Collider project in 1993, which was abandoned by Congress. Ron Heflin/Associated Press

By Dennis Overbye and Katrina Miller

Published Dec. 7, 2023 Updated Dec. 8, 2023

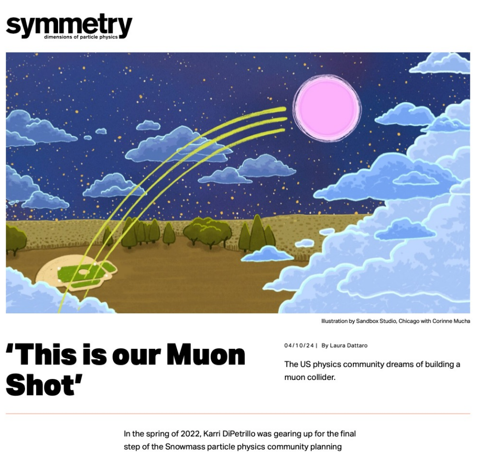

symmetry
dimensions of particle physics

Illustration by Sandbox Studio, Chicago with Corinne Mucha

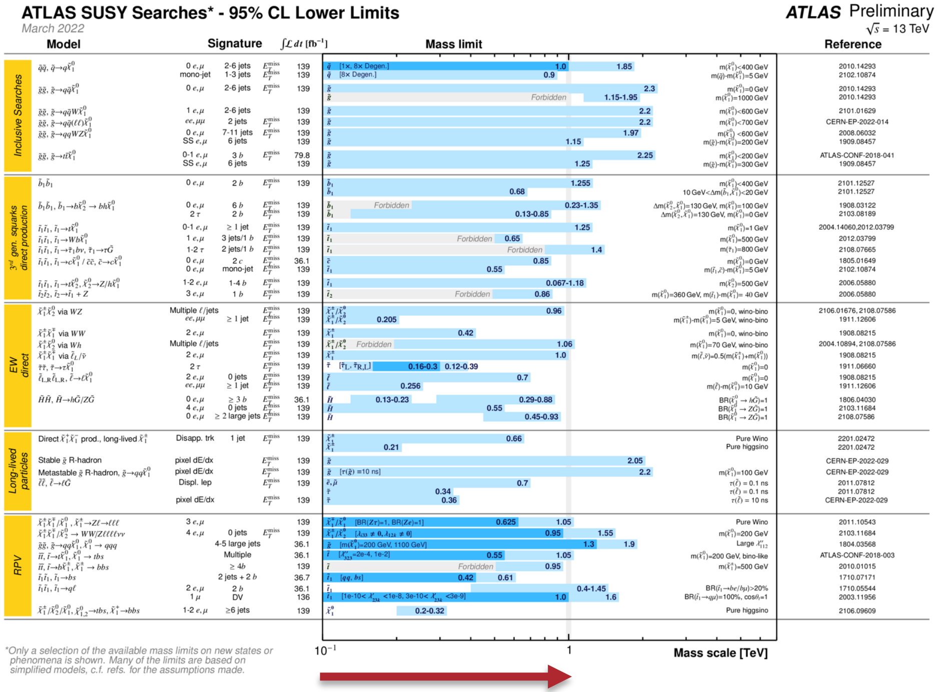
'This is our Muon Shot'

04/10/24 | By Laura Dattaro

The US physics community dreams of building a muon collider.

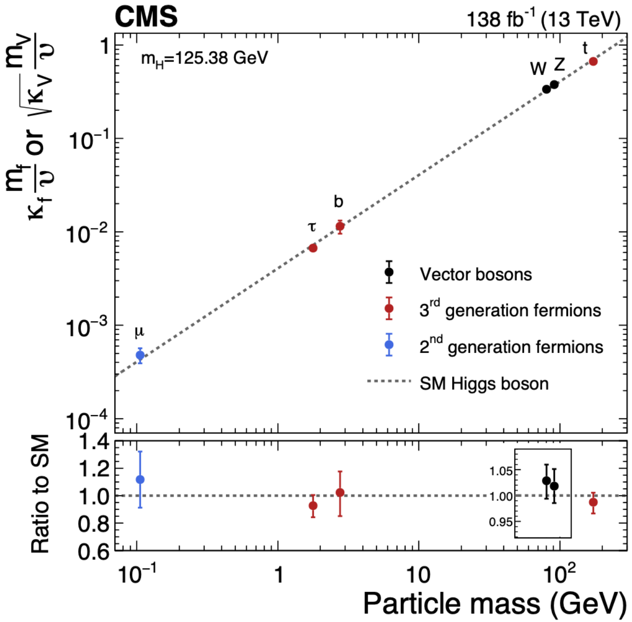
In the spring of 2022, Karri DiPetrillo was gearing up for the final step of the Snowmass particle physics community planning

Why 10 TeV?



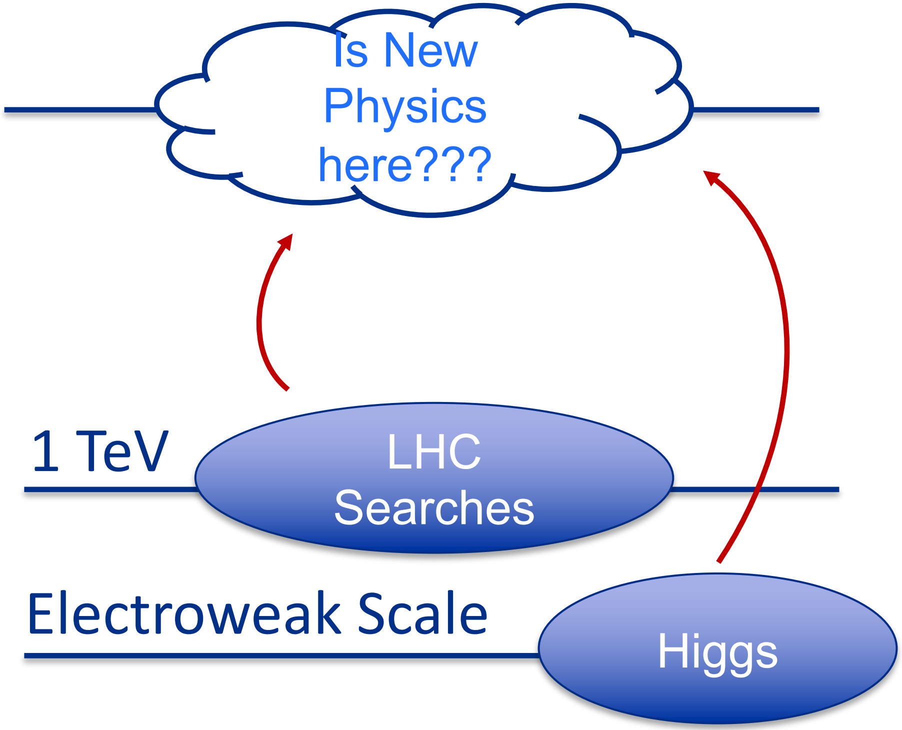
ATLAS Summary of SUSY Searches

CMS Higgs couplings



Several % coupling implies roughly the TeV scale for NP which could cause such a deviation

Why 10 TeV?



There *could* still be New Physics at LHC/HL-LHC…

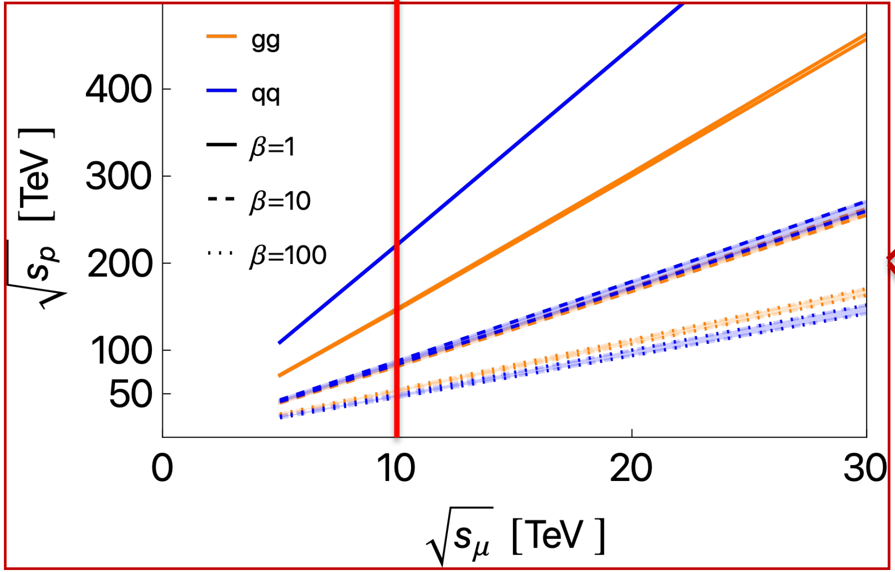
However, data suggests generically there maybe a *gap* from EW scale to scale of New Physics

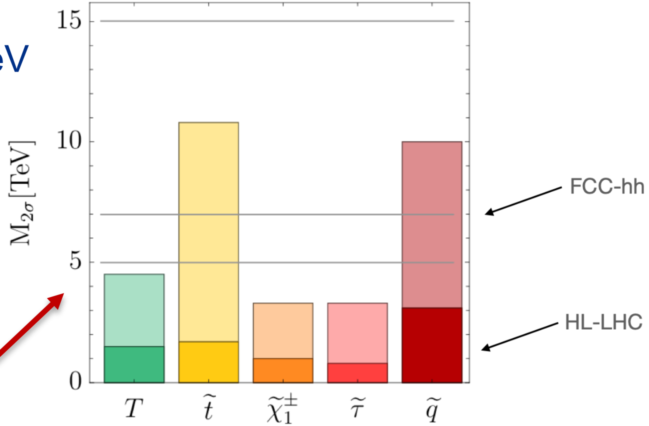
We need to be able to probe >>1 TeV

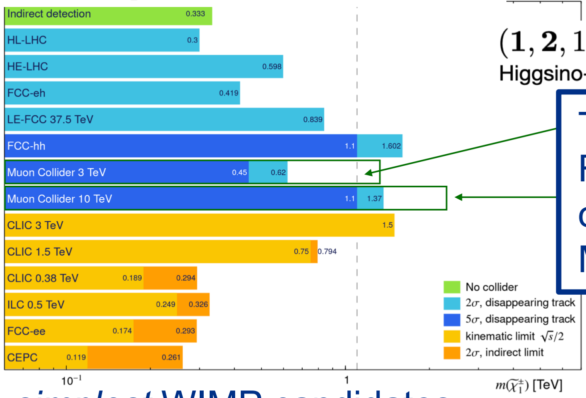
10 TeV is interesting as a step into unknown but also for *physics targets*

Physics

Direct production at higher scales - strongly motivated targets up to 10 TeV



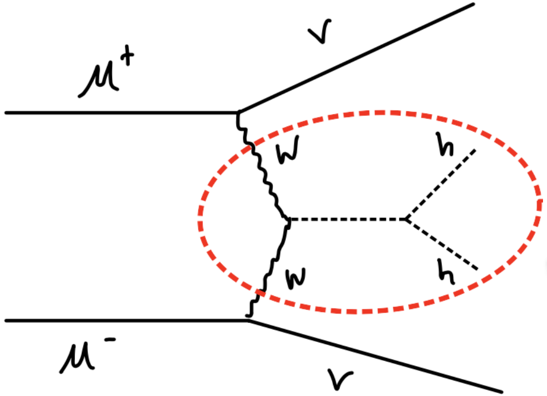




Talk by Rodolfo on Monday

Covers *simplest* WIMP candidates hard or impossible with next gen DM direct detection

Physics

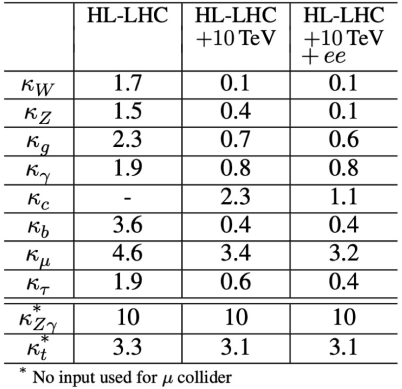


At 10 TeV:

10^7 single Higgs events

and

10^4 di-Higgs events



	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV + ee
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.4	0.1
κ_g	2.3	0.7	0.6
κ_γ	1.9	0.8	0.8
κ_c	-	2.3	1.1
κ_b	3.6	0.4	0.4
κ_μ	4.6	3.4	3.2
κ_τ	1.9	0.6	0.4
$\kappa^*_{Z\gamma}$	10	10	10
κ^*_t	3.3	3.1	3.1

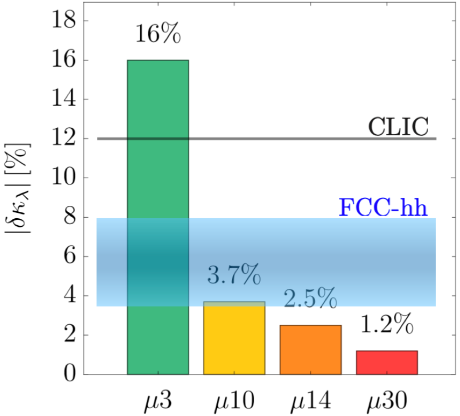
* No input used for μ collider

Order of magnitude in Higgs precision

and

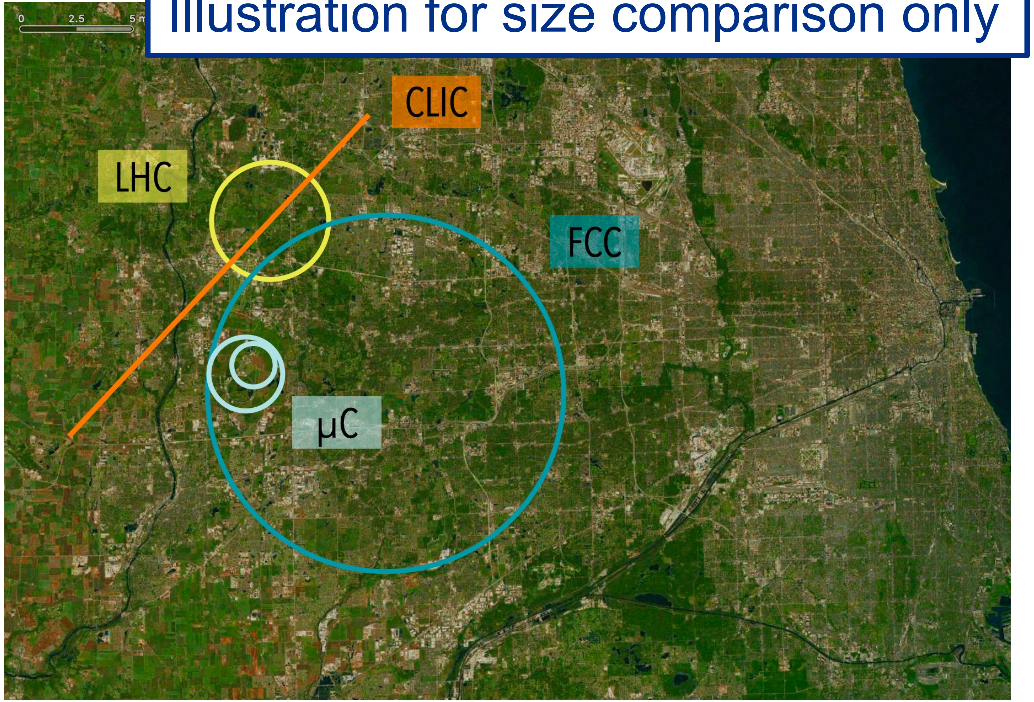
can directly probe the scale implied in same machine!

Turn Higgs potential into precision science
(Needed e.g for EW phase transition)



Why Muons – size

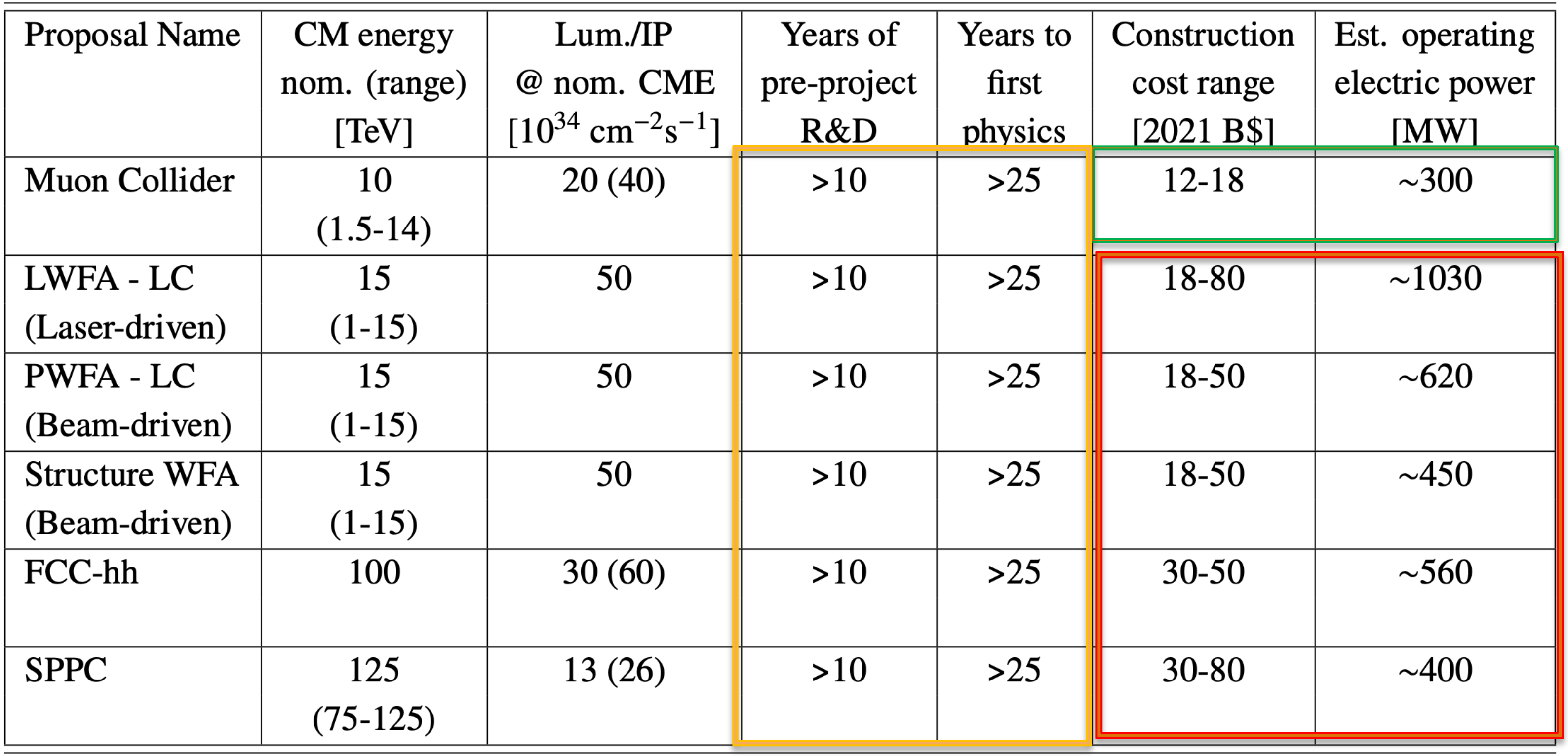
Illustration for size comparison only



Way smaller footprint than hadron colliders with equivalent physics reach

Why Muons – cost and power

More details: Snowmass’21 ITF report



Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
Muon Collider	10 (1.5-14)	20 (40)	>10	>25	12-18	~300
LWFA - LC (Laser-driven)	15 (1-15)	50	>10	>25	18-80	~1030
PWFA - LC (Beam-driven)	15 (1-15)	50	>10	>25	18-50	~620
Structure WFA (Beam-driven)	15 (1-15)	50	>10	>25	18-50	~450
FCC-hh	100	30 (60)	>10	>25	30-50	~560
SPPC	125 (75-125)	13 (26)	>10	>25	30-80	~400

The Machine Concept at ~10 TeV

- The goal is to get to **10 TeV center-of-mass** energy with L ~ 10^{35} cm^{-2} s^{-1} (driven by the Higgs physics requirements)
- **Staging in energy** (e.g. 3→10 TeV) or **in luminosity** (a la LHC→HL-LHC) are possible

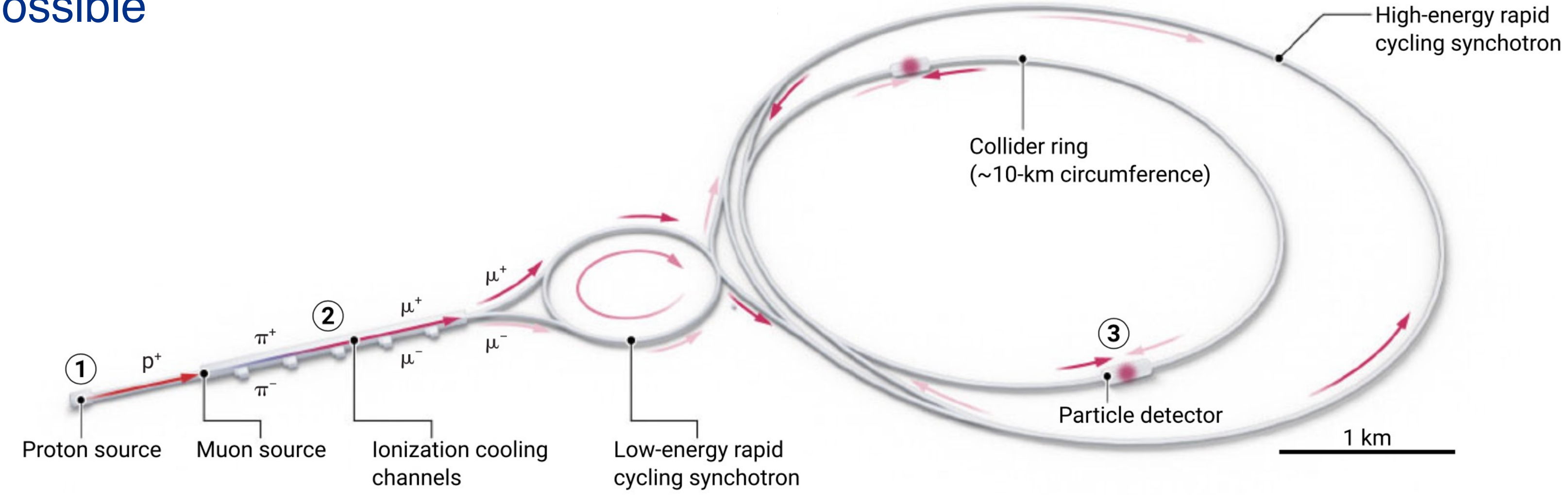


Image courtesy of A. Fisher and the Science magazine

Major Challenges

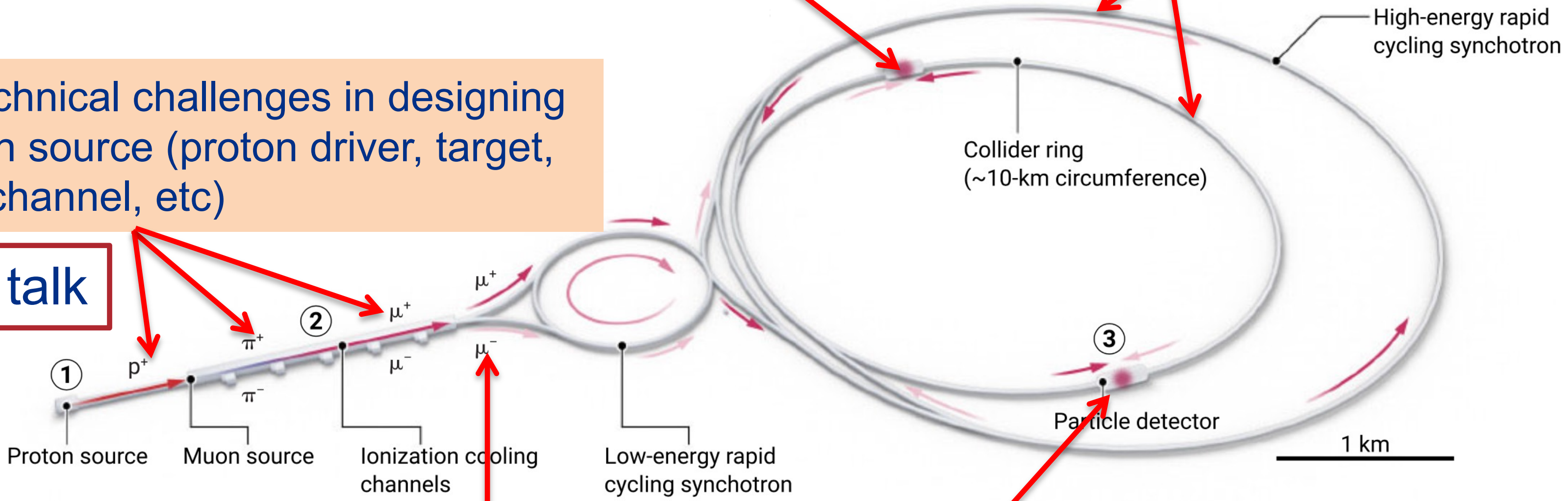
Scott's talk

Dense neutrino flux needs to be mitigated

Challenging magnets in many places

Many technical challenges in designing the muon source (proton driver, target, cooling channel, etc)

Chris's talk

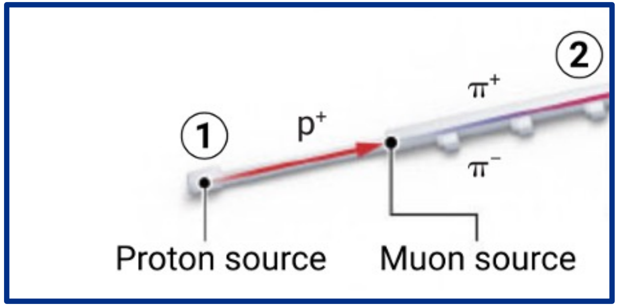


High-gradient RF for fast acceleration

Beam-induced background in the detectors

Tova's talk

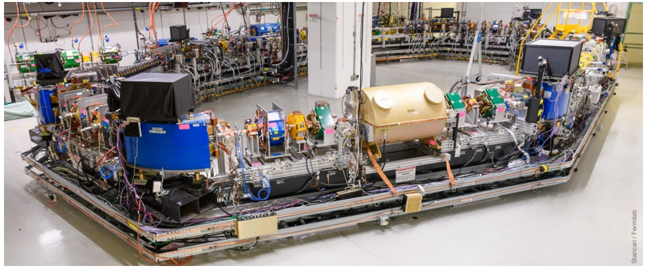
Proton Source



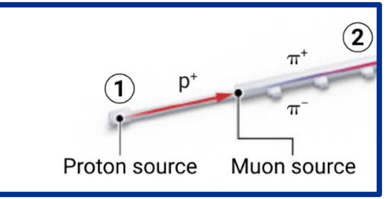
- Best performance: **1-4 MW** proton beam @ **5-20 GeV**, compressed to **1-3 ns** bunches at a **5-10 Hz** frequency
- Need to go from ranges to specific design and demonstrate that these proton beam parameters are achievable

SNS at ORNL

IOTA at FNAL

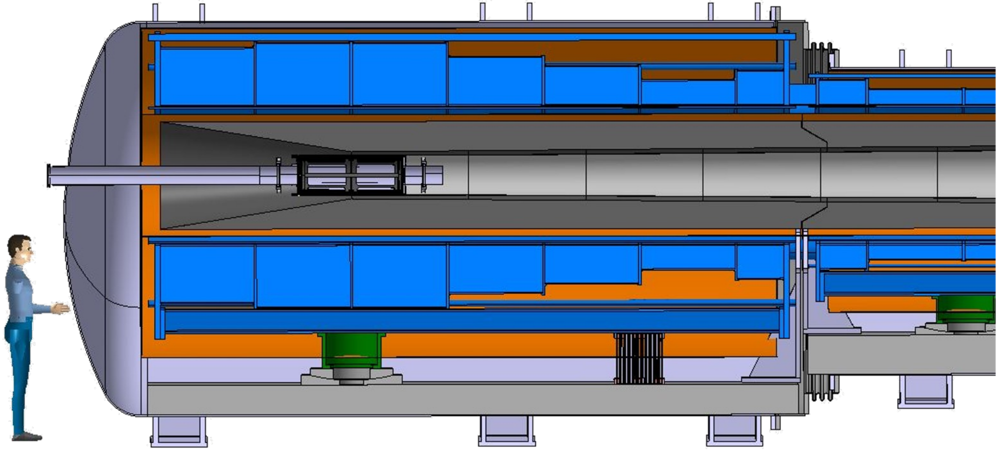


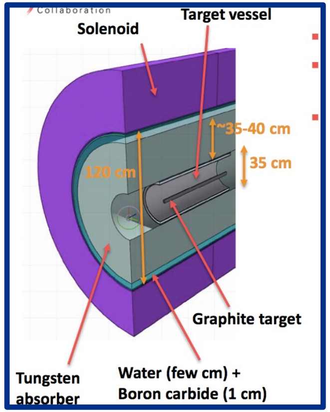
Target and Capture



in target → decay →

protons → pions → muons





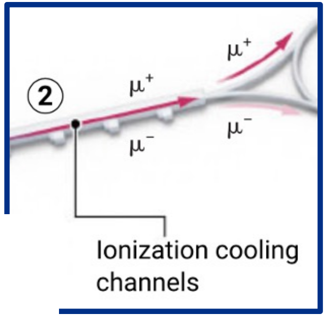
Graphite **Target**

20 T **solenoid**
to guide pions and muons

Tungsten shielding
To protect magnet

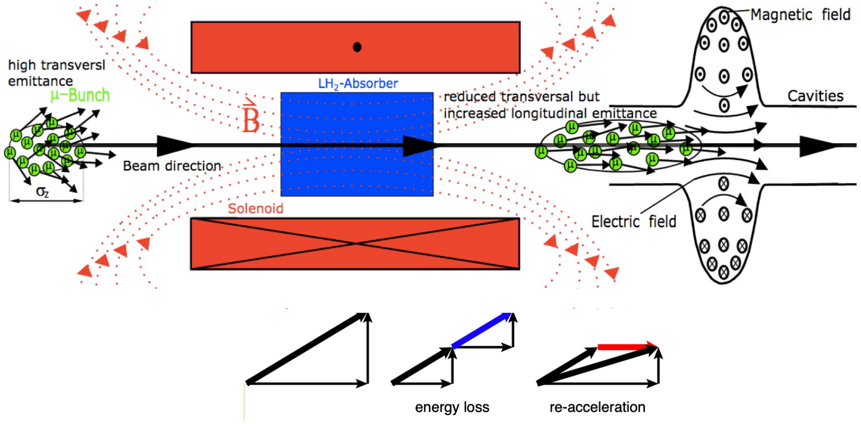
- Thermal and structural shock on the target due 2-4 MW and short proton bunches
- Study different materials, shapes, size optimization, advanced target concepts
- Focusing magnet is challenging due to field strength, size and radiation load

Ionization Cooling

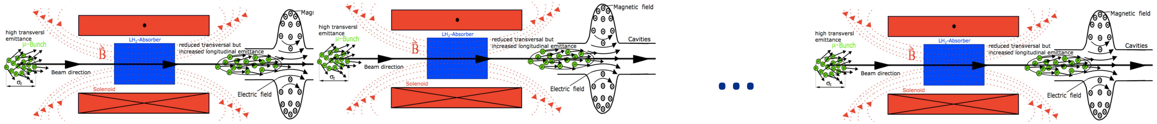


$$L = \frac{N_+ N_- n_C f}{4\pi\sigma_x\sigma_y}$$

Need to cool muons to achieve target luminosity!

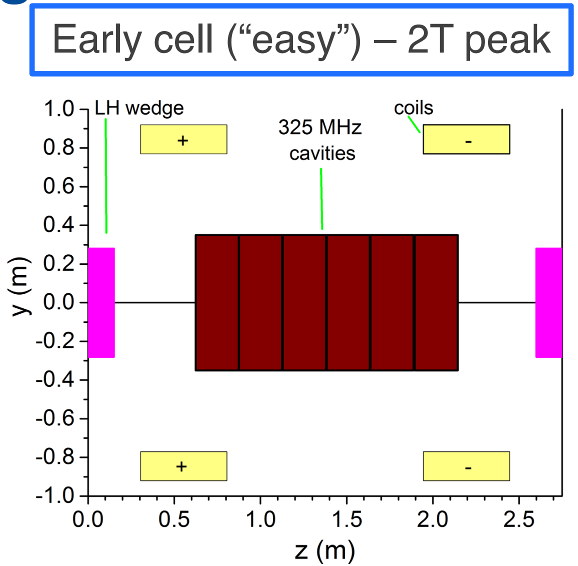


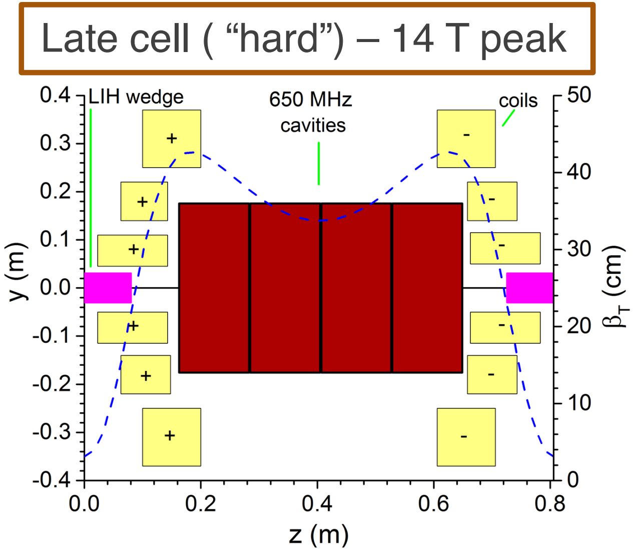
Each cell reduces emittance by ~10%. **Repeat O(100) times = cooling channel**



Not all cells identical

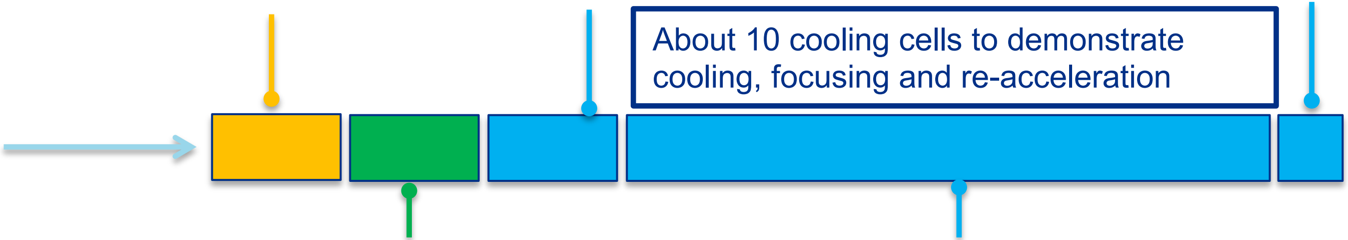
Cooling Cells





- Large bore solenoidal magnets: From 2 T (500 mm IR), to 14 T (50 mm IR)
- Normal conducting RF that can provide high-gradients within a multi-T fields
- Absorbers that can tolerate large muon intensities
- Need to further optimize the design considering engineering constraints

Cooling Demonstrator



Target
+ horn (1st phase) /
+ superconducting solenoid (2nd phase)

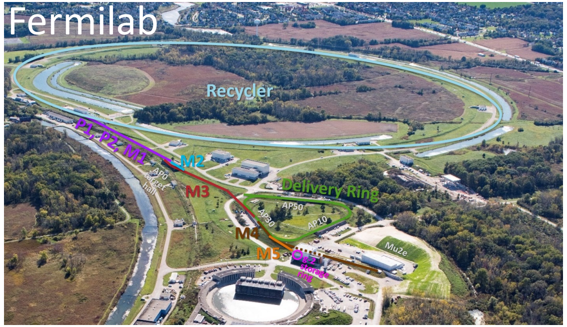
Collimation and **upstream diagnostics** area, 10 m

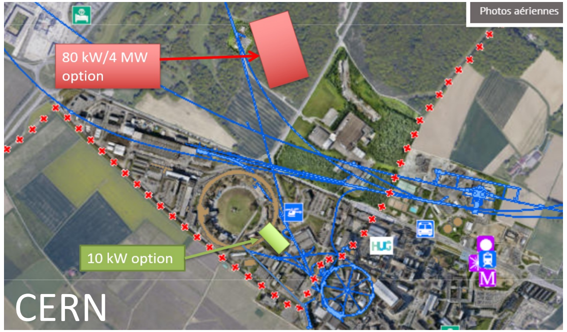
Downstream diagnostics area, 5 m

About 10 cooling cells to demonstrate cooling, focusing and re-acceleration

Momentum selection chicane, 10 m

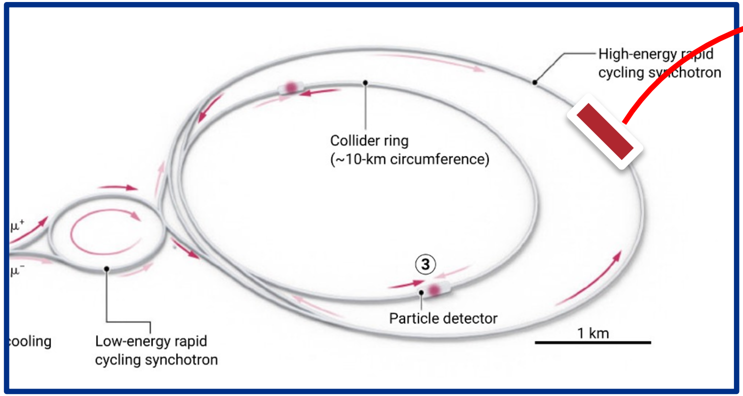
Cooling area, 50 m

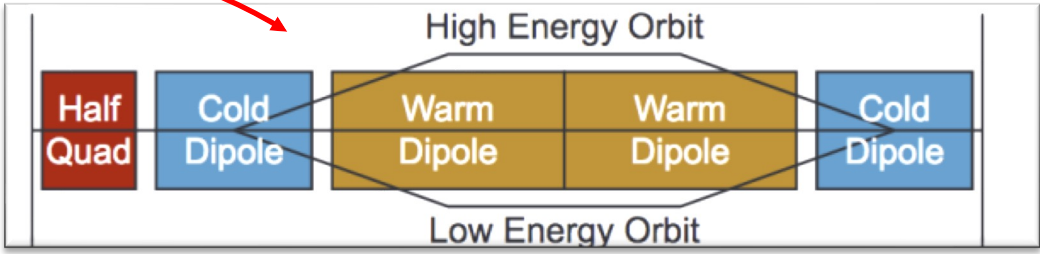




Need to have advanced demonstrator design in 3 years for the P5 "collider panel"

Acceleration of Muons

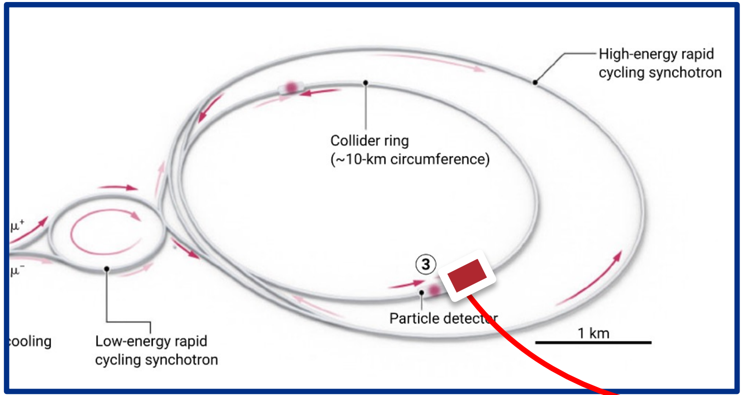




DC field Pulsed from $-B_w$ to $+B_w$

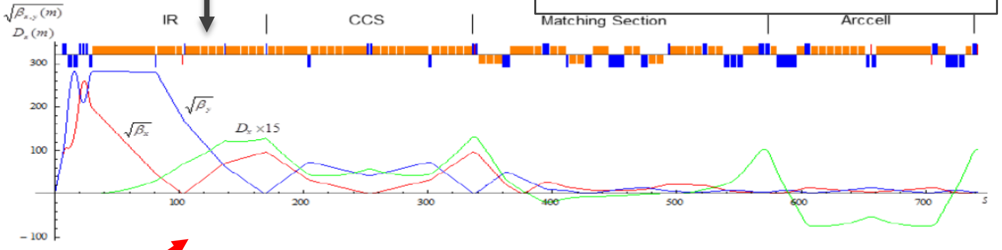
- Rapid Cycling Synchrotron accelerators
- Fast ramping magnets (up to 1000 T/s) accompanied with 16 T DC magnet
- Design of efficient energy sources with good power management (10s of GW) for pulsed magnets is the key

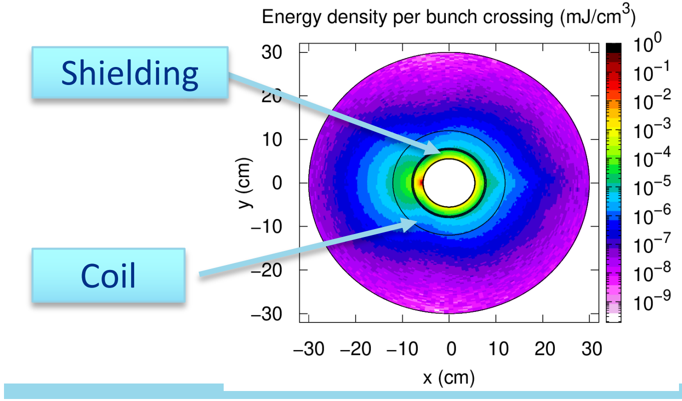
Collider Ring Needs



IR region (high-B quads)

bend region (high-B dipoles)

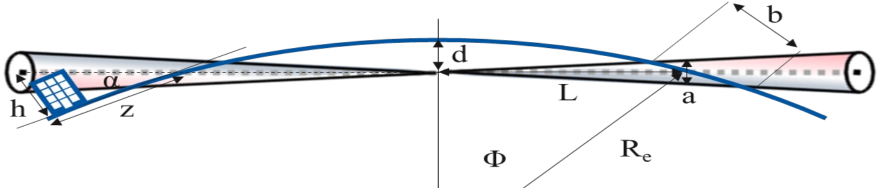




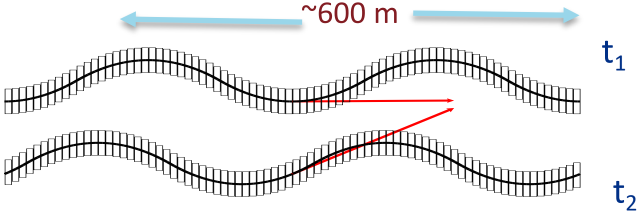
- Dipoles with strong field (12-16 T for 10 TeV) and large aperture
- Quadrupoles with strong fields for the IR (15-20 T for 10 TeV)
- Power loss due to muon decay 500 W/m → requires tungsten shielding + cooling

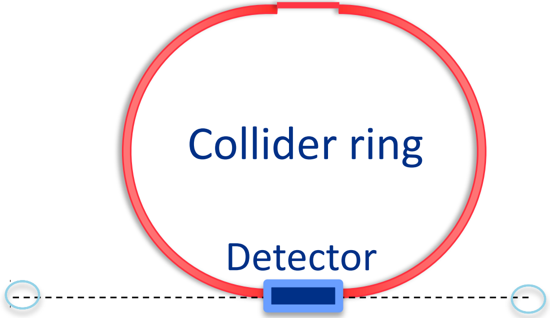
Neutrino Flux Mitigation

Aim to have **negligible impact from arcs** (<10 μSv/year). For comparison airline flight 3 μSv/hour



- Arcs:
  - 3 TeV at 200m depth – acceptable
  - 10 TeV needs 200m + “wobble” the beam
- The straights may require acquisition of small land

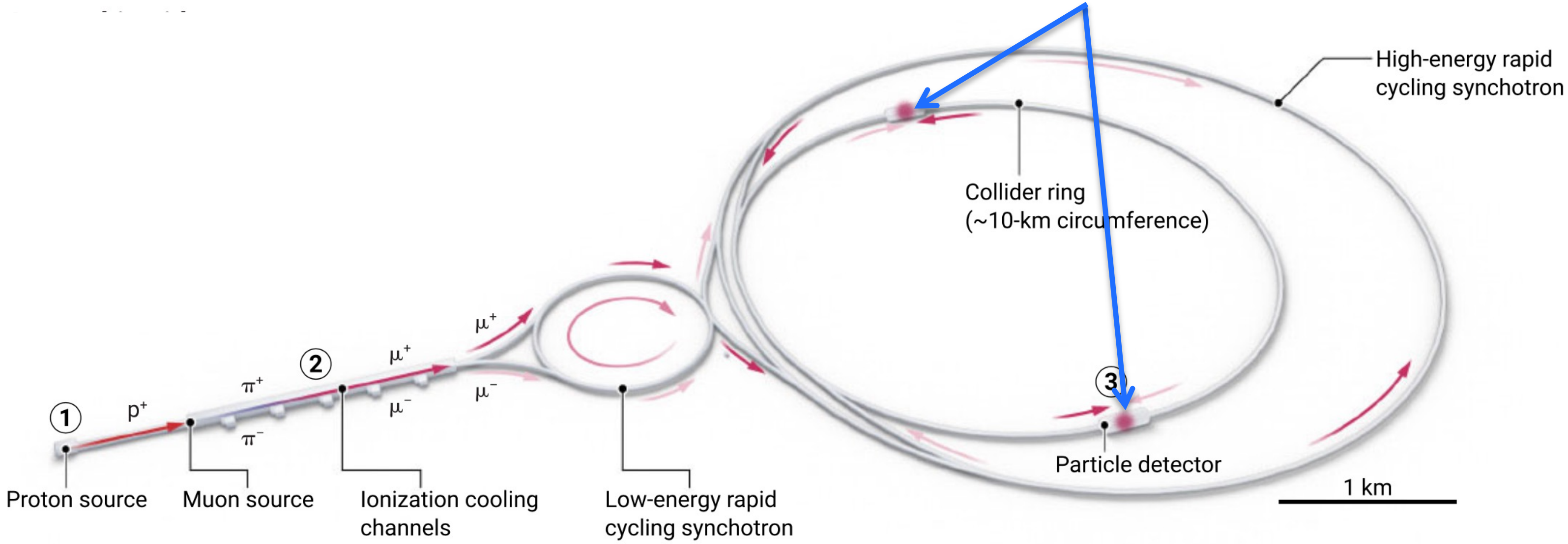




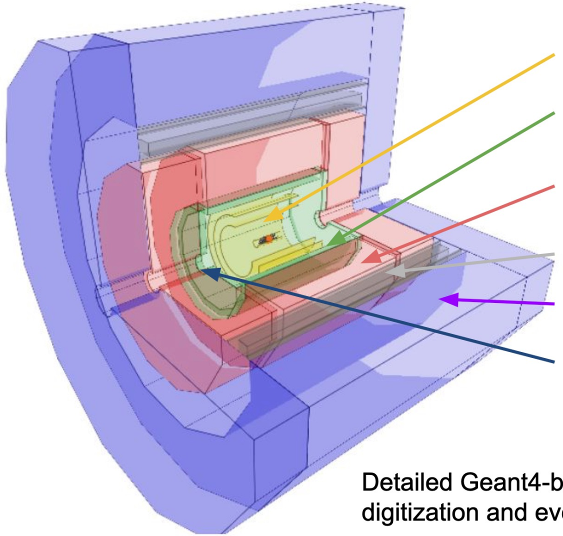
- Need to further develop the mitigation strategy, investigate impacts on the beam dynamics, … and study opportunities with high energy neutrino beams

Experiments

Expect to have two Interaction Points



Detector Designs

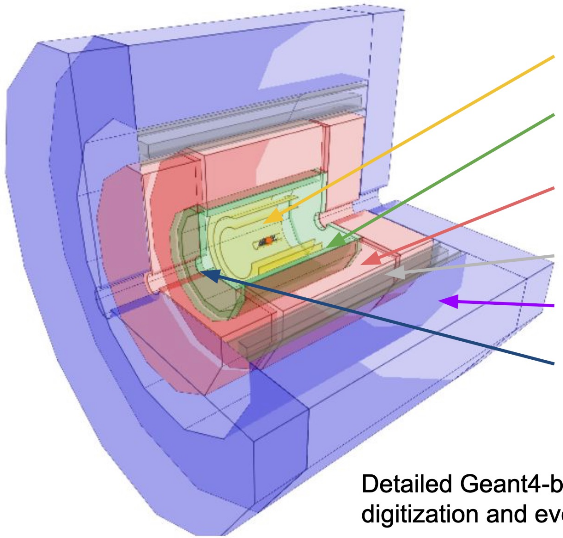


Current design limits acceptance to θ = 10°, designed for ~1.5 TeV

Detailed Geant4-based simulation, dedicated digitization and event reconstruction software.

The 3 TeV design stemming from CLIC has been extensively studied for Snowmass

Detector Designs



Silicon Tracker

EM Calorimeter (Tungsten+Si)

Hadronic Calorimeter
(Steel+Scintillators)

3.57 T Solenoid

Muon Chambers (RPC

Nozzle (~Tungsten)

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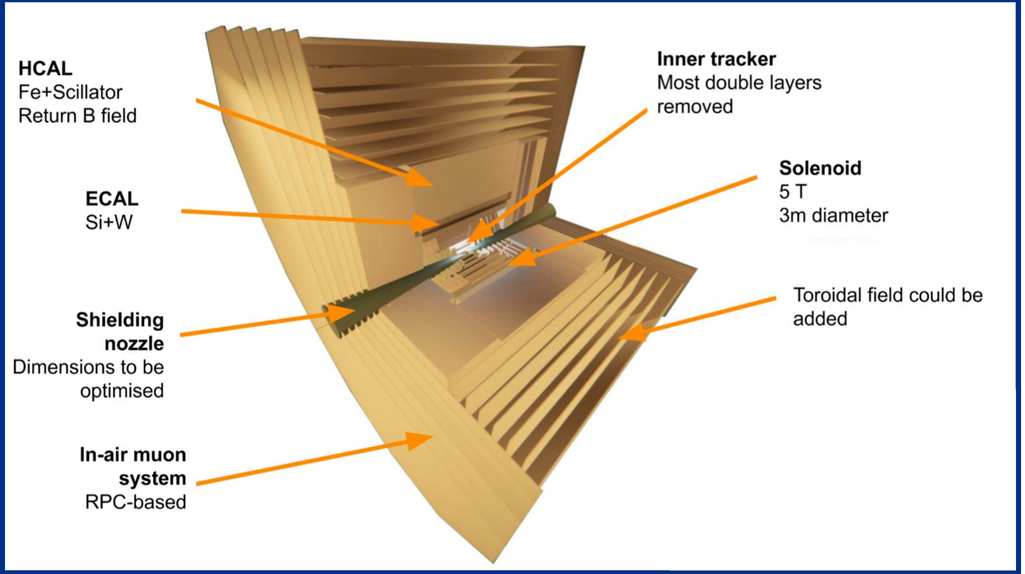


HCAL
Fe+Scillator
Return B field

ECAL
Si+W

Shielding nozzle
Dimensions to be optimised

In-air muon system
RPC-based

Inner tracker
Most double layers removed

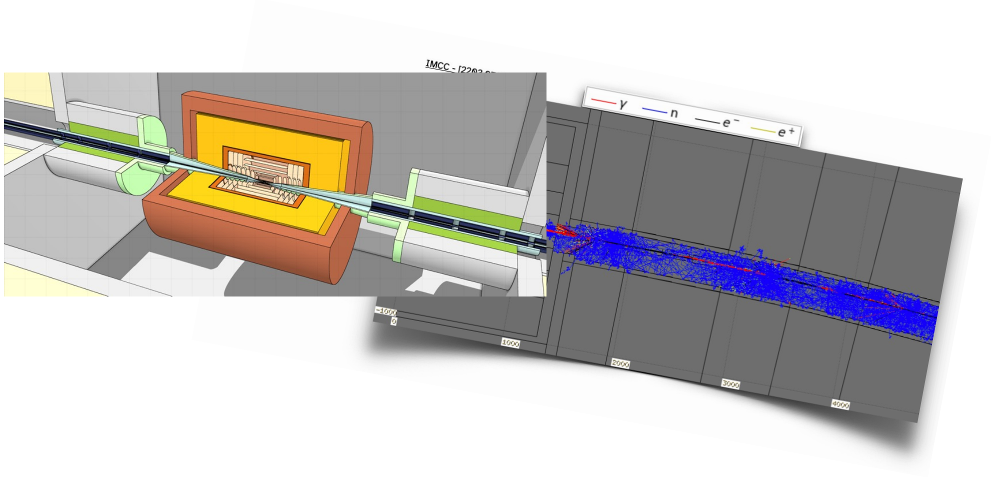
Solenoid
5 T
3m diameter

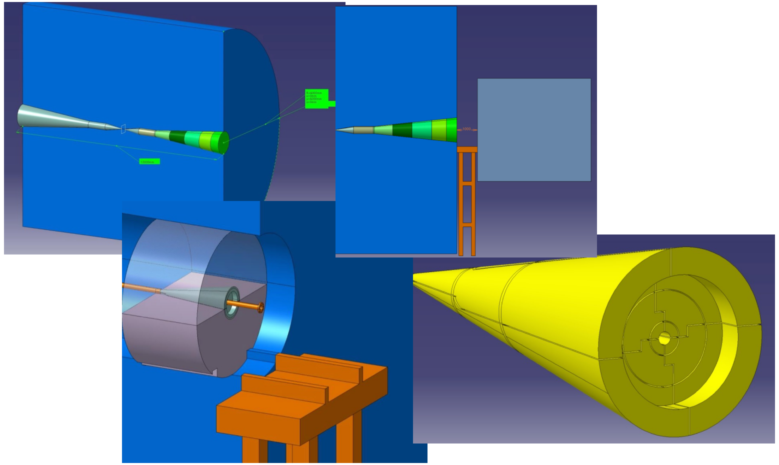
Toroidal field could be added

Multiple 10 TeV design concepts are newly emerging

BIB Challenges

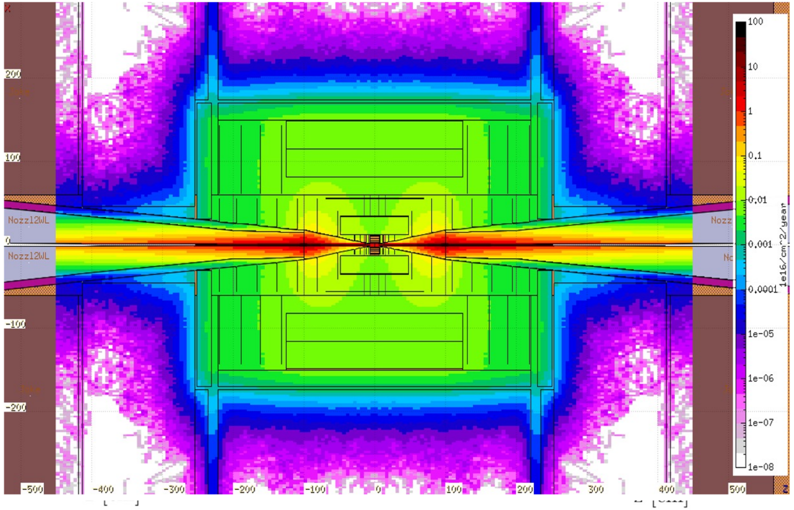
- Beam background is one of the unique features/challenges of Muon Colliders
  - 10^6 muon decays per meter Simulating the BIB is a computational challenge

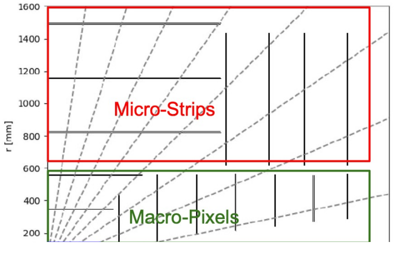


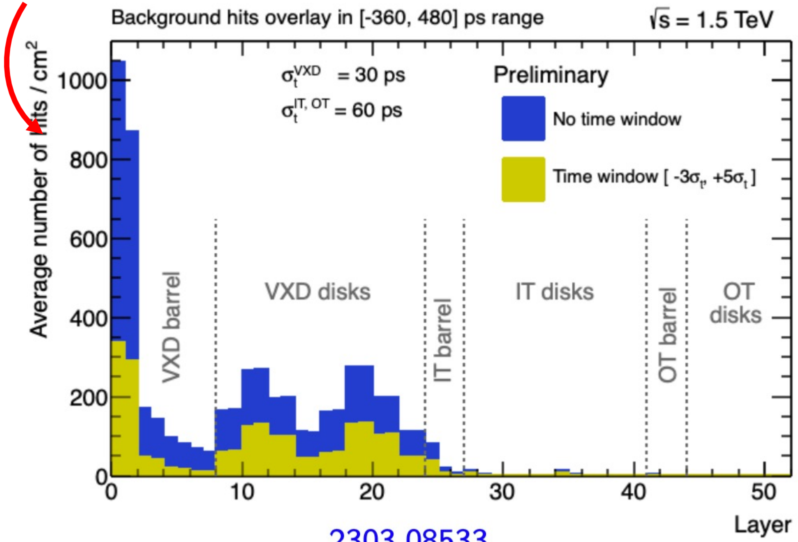


- Forward shielding is necessary to convert energetic particles from the BIB into a cloud of mostly soft neutrons and photons
- Machine-Detector Interface requires careful design optimization and engineering studies

Detector Design







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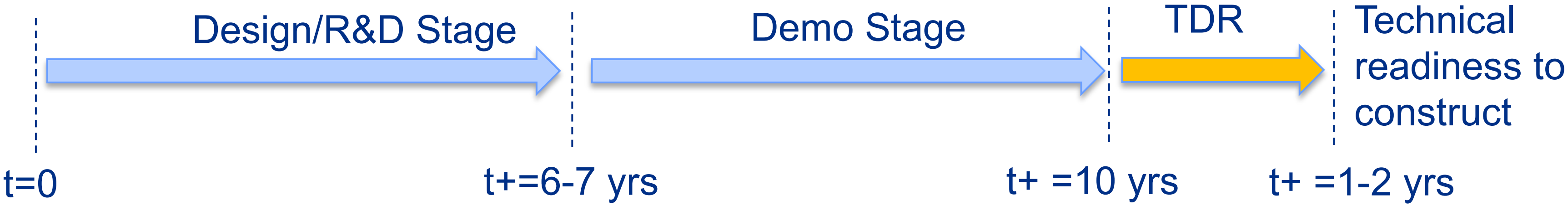
	Maximum Dose (Mrad) R= 22 mm	Maximum Dose (Mrad) R= 1500 mm	Maximum Fluence (1 MeV-neq/cm^2) R= 22 mm	Maximum Fluence (1 MeV-neq/cm^2) R= 1500 mm
Muon Collider (3 TeV)	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}
Muon Collider (10 TeV)	20	0.2	3×10^{14}	10^{14}

Next step in evolution of detectors, hybrid of LHC and Higgs Factory needs. Requires novel detectors - opportunities for innovative detector designs and technology!

“Sketch” Timeline


Design/R&D Stage

Demo Stage

TDR

Technical readiness to construct

t=0

t+=6-7 yrs

t+ =10 yrs

t+ =1-2 yrs

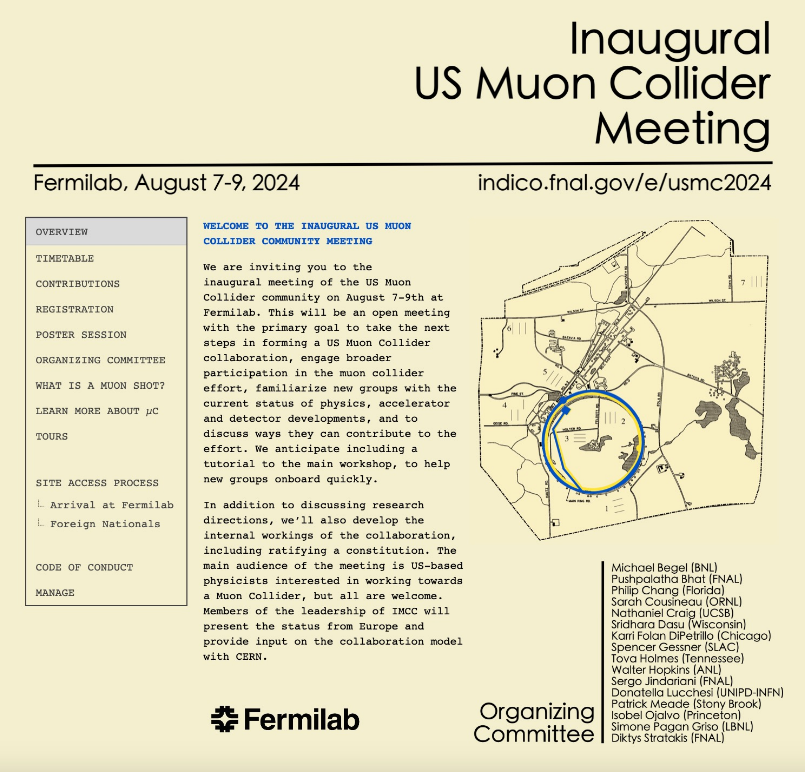
- The actual construction start time is subject to:
  - Successful outcome of **the proposed extensive R&D program**
  - Availability of funding + resources
  - Host laboratory, and international agreements
- Development will take a long time:
  - LHC concept was born in early 1980s, first operation in 2009
  - **Need to start R&D now!**

Outlook

- Muon Collider is an exciting future collider option. A machine that can be a paradigm changer in particle physics
- However, realization of such a collider **requires significant international R&D and demonstrator program stretching over the next 2 decades**
- **Many places to contribute to cutting-edge research and technology development**
- **Opportunity for HEP physicists to contribute to accelerator simulations and development**
- Active ongoing effort in Europe under IMCC. Starting to get organized in the US:
  - Email muon-collider@googlegroups.com if you are interested in contributing to the effort
  - Join Listserv mailing list mucUS@listserv.fnal.gov + SLACK channel: LINK

1st US Muon Collider Community Meeting

- August 7-9th, 2024 at Fermilab: https://indico.fnal.gov/e/usmc2024



Inaugural
US Muon Collider
Meeting

Fermilab, August 7-9, 2024
indico.fnal.gov/e/usmc2024

OVERVIEW
TIMETABLE
CONTRIBUTIONS
REGISTRATION
POSTER SESSION
ORGANIZING COMMITTEE
WHAT IS A MUON SHOT?
LEARN MORE ABOUT μC
TOURS

SITE ACCESS PROCESS
  └ Arrival at Fermilab
  └ Foreign Nationals

CODE OF CONDUCT
MANAGE

WELCOME TO THE INAUGURAL US MUON COLLIDER COMMUNITY MEETING

We are inviting you to the inaugural meeting of the US Muon Collider community on August 7-9th at Fermilab. This will be an open meeting with the primary goal to take the next steps in forming a US Muon Collider collaboration, engage broader participation in the muon collider effort, familiarize new groups with the current status of physics, accelerator and detector developments, and to discuss ways they can contribute to the effort. We anticipate including a tutorial to the main workshop, to help new groups onboard quickly.

In addition to discussing research directions, we'll also develop the internal workings of the collaboration, including ratifying a constitution. The main audience of the meeting is US-based physicists interested in working towards a Muon Collider, but all are welcome. Members of the leadership of IMCC will present the status from Europe and provide input on the collaboration model with CERN.

Fermilab

Organizing
Committee

Michael Begel (BNL)
Pushpalatha Bhat (FNAL)
Philip Chang (Florida)
Sarah Cousineau (ORNL)
Nathaniel Craig (UCSB)
Sridhara Dasu (Wisconsin)
Karri Folan DiPetrillo (Chicago)
Spencer Gessner (SLAC)
Tova Holmes (Tennessee)
Walter Hopkins (ANL)
Sergo Jindariani (FNAL)
Donatella Lucchesi (UNIPD-INFN)
Patrick Meade (Stony Brook)
Isobel Ojalvo (Princeton)
Simone Pagan Griso (LBNL)
Diktys Stratakis (FNAL)

Excellent opportunity to learn more about muon colliders

Registration will open soon

Please join us at this event!

Backup

Muons – blessing and curse

- **Muons are much heavier than electrons → no synchrotron radiation issues, can accelerate to high energies**
- **Muons are elementary particles – the whole energy is available for probing new physics**
- **No QCD background - precision and energy in one machine**

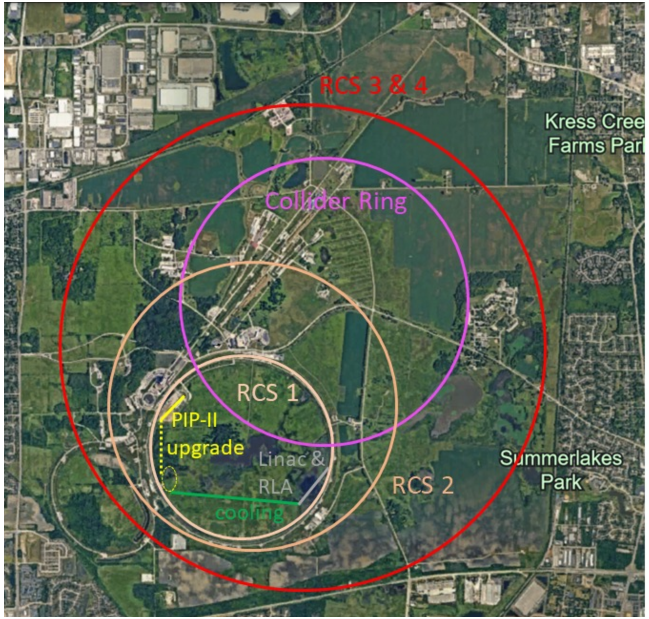
  - **Muons decay (in 2 μs at rest!)**
    - All beam manipulations must be done **fast**
    - Particles from muon decays deposit significant energy in the accelerator components and physics detectors

What changed since the last P5?

- **Physics:** Strong surge of interest in Muon Colliders within the theoretical and experimental communities. Shift of emphasis in Muon Colliders from 125 GeV to 10 TeV energy [ref]
- **Accelerator Technology**:
  - Muon Accelerator Program (MAP) results completed and published, including designs of various subsystems [ref]
  - Important technological progress: multi-MW proton sources [ref], demonstration of RF in magnetic field [ref], high field solenoids [ref], good solution for neutrino flux mitigation, etc.
  - Muon Ionization Cooling Experiment (MICE) confirmed muon ionization cooling principle, results published [ref]
- **Detector technology :** Large leap in detector technologies in part from R&D done for HL-LHC upgrades. Feasibility of good quality physics established in simulation [ref]
- International Muon Collider Collaboration (IMCC) established. The process of forming US organization is ongoing.

Muon Collider at Fermilab

- Initial concept for 10 TeV machine
- Proton source
    - PIP-II → ACE-BR → Target
- Ionization cooling channel
- Acceleration (4 stages)
    - Linac + RLA → **173 GeV**
    - RCS #1 → **450 GeV (Tevatron size)**
    - RCS #2 → **1.7 TeV (col. ring size)**
    - RCS #3, 4 → **5 TeV (site fillers)**
- Collider ring, 10.5 km long



This design is very preliminary. Need further, more detailed development

Software and Simulation Challenges

- Realistic simulation of the BIB is crucial for quantifying the detector performance
- Complex event features due to beam-induced background
- The design, optimization, performance estimation and physics case of a muon collider are expected to require moderate dedicated computational resources.
  - Core software frameworks and analysis tools. Focus on multi-threading; synergies with other future accelerators projects and HL-LHC
  - BIB and shielding simulations (FLUKA, MARS, GEANT) are CPU/disk-intensive. Need accuracy and efficiency. Ideal case for in-development GPU simulation engines
  - Detector layout design and technology evaluation require iterations.
  - Digitization and reconstruction algorithms require detailed studies and production of large samples for realistic physics projections. Balance full/fast simulations.

A bit of history

- **1960s:** First mention of Muon Colliders in the literature
- **1990s-2010:** Design studies through US institutional collaborations
- **2011-2016:** Muon Accelerator Program was approved by DOE
  - Focused on a proton-driver solution; studied 125 GeV and 1.5, 3 and 6 TeV colliders
- **2021:** Muon Colliders become part of the EU Accel. R&D Roadmap
  - International Muon Collider Collaboration (IMCC) formed, CERN currently the host lab
- **2022:** US Snowmass study reveal strong interest on Muon Colliders
  - Muon Collider Forum Report: a vision from the US perspective
- **March 2023:** Formation of the US Muon Collider R&D coordination group
  - Provide input to the P5 panel on US-based Muon Collider research
- **December 2023:** P5 Report released, with strong support for Muon Collider R&D

Why 10 TeV?

- Direct and indirect searches at the LHC exclude many models up to 1 TeV. Need to be able to probe >> 1 TeV

- Data suggests generically there is a *gap* from EW scale (~100 GeV) to scale of New Physics

- 10 TeV is ***a major step forward into unknown*** but also interesting for well-motivated concrete physics targets

    - Determination of the Higgs potential via measurements of self-coupling

    - Probe simplest Dark Matter models up to the thermal targets

    - An order of magnitude improvement in precision SM physics wrt the LHC

Useful References

- Useful references for this Effort:
  - Muon Smasher’s Guide: Link
  - IMCC Facility overview white paper: Link
  - IMCC Simulated Performance white paper: Link
  - IMCC Promising Detector Technologies white paper: Link
  - Muon Collider Forum Report: Link

Muon Collider Challenges and Progress

Challenge	Progress	Future work
Multi MW proton sources with short bunches	Multi-MW proton sources have been and are being produced for spallation neutron sources and neutrino sources (SNS, ESS, J-PARC, Fermilab)	Refine design parameters, including proton acceleration to 5-10 GeV. Accumulation and compression of bunches.
Multi MW targets	Neutrino targets have matured to 1+MW. RADIATE studies of novel target materials and designs aim at 2.4MW.	Develop target design for 2 MW and short muon collider bunches. Produce a prototype in 2030s.
Production solenoid	ITER Nb3Sn central solenoid with similar specifications and rad levels produced	Study cryogenically stabilized superconducting cables and validate magnet cooling design. Investigate possibility of HTS cables.
Cooling channel solenoids	Solenoid with 30+T field now exists at NHMFL. Plans to design 40+T solenoids in place.	Extend designs to the specs of the 6D cooling channel, fabrication for the demo experiment
Ionization cooling	MICE transverse cooling results published. Longitudinal cooling via emittance exchange demonstrated at g-2.	Optimize with higher fields and gradients. Demonstrate 6D cooling with re-acceleration and focusing
RF in magnetic field	Operation of up to 50 MV/m cavity in magnetic field demonstrated, results published	Design to the specs of the 6D demo, experiment; fabrication

Muon Collider Challenges and Progress

Challenge	Progress	Future work
Fast Ramping Magnets	Demonstrated with 290 T/s up to 0.5T peak field at FNAL. Ramps up to 5000 T/s demonstrated with small magnets.	Design and demonstration work to achieve higher ramp rates (up to 1000 T/s) and peak fields of ~2T with large magnets
Very Rapid Cycling Synchrotron Dynamics	Lattice design in place for a 3 TeV accelerator ring	Develop lattice design for a 5 TeV accelerator ring
Neutrino Flux Effects	Mitigation strategies based on placing the collider ring at 200m and introducing beam wobble has been shown to achieve necessary reduction up to 10-14 TeV	Study mechanical feasibility, stability and robustness of the mover's system and impact on the accelerator and the beams
Detector shielding and rates	Demonstrated to be manageable in simulation with next generation detector technologies	Further develop and optimize 3 and 10 TeV detector concepts and MDI. Perform detector technology R&D and demonstration.
Open aperture storage ring magnets	12-15T Nb3Sn magnets have been demonstrated	Design and develop larger aperture magnets 12-16T dipoles and HTS quads
Low-beta IR collider design and dynamic aperture	Lattice design in place for a 3 TeV collider with optics and magnet parameters within existing technology limits	Develop lattice design for a 10 TeV collider

Muon Collider Synergies

Facility/Experiment	Physics Goals	Synergy
nuStorm	Short baseline neutrino program, including searches for sterile neutrino and cross section measurements	100kW proton source, muon production and collection, storage ring operation
Neutrino Factory (e.g. nuMax)	Better CP, mixing angles, mass splitting, non-standard interactions	MW class proton source, muon production and collection, 6D partial cooling and muon acceleration (up to ~5 GeV)
Dark Sector searches	Searches for particles from Dark Sectors produced in fixed target experiments using high intensity proton beam	MW class high-intensity proton beams
Charged Lepton Flavor Violation (e.g. AMF)	Searches for rare lepton flavor violating proceses (mu2e, mu2eg, mu3e, etc)	MW class proton source, muon production and collection, storage ring
Beam dump experiments	Searches for exotic particles (dark photons, Lmu-Ltau, etc) in muon beam dump experiments	100kW – MW proton source, muon production and collection, partial cooling and acceleration
Neutrinos from collider beam muon decays	DIS in neutrino-nucleus interactions, better nuclear PDF, atmospheric neutrinos FASERv like experiment with smaller flux uncertainties	Everything up to multi-TeV energy collider beams
Muon Ion Collider	A broad program addressing many fundamental questions in nuclear and particle physics	Everything up to multi-TeV energy collider beams