(Highlights of) US Muon Collider Activities

Sergo Jindariani (Fermilab)

On behalf of the USMCC Leadership Team: T. Holmes (UTK), K. Kennedy (Princeton), P. Meade (Stony Brook), S. Pagan-Griso (LBNL), D. Stratakis (Fermilab)

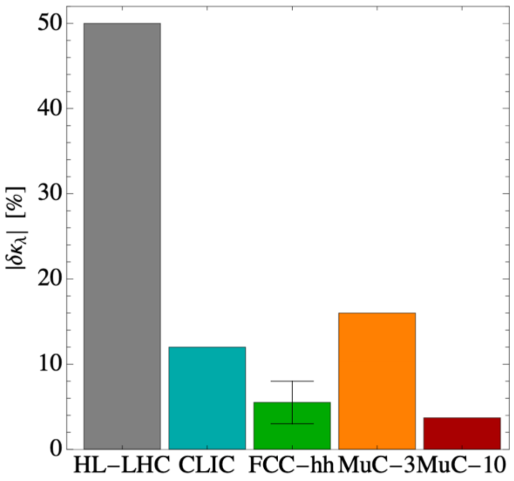
2nd USMCC meeting, University of Chicago, August 2025

Outline

- USMCC Formation and Next steps
- Engagement with IMCC and ESPPU process
- Recap of challenges, R&D plan and US activities
- Upcoming meetings and outreach activities
- Summary

Highlights of Muon Collider Physics

More in Liantao's talk

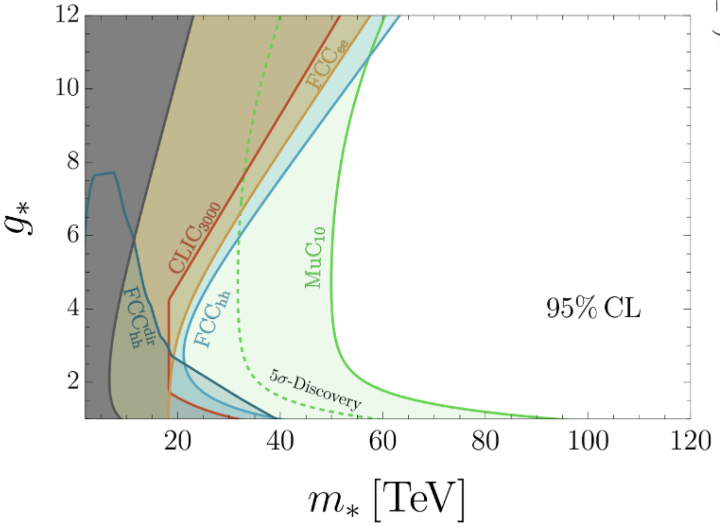


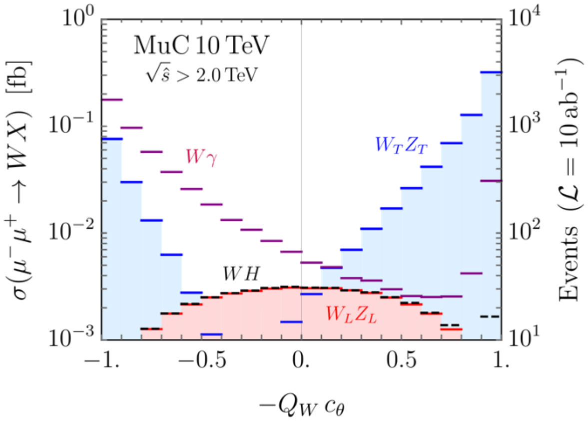
Multi-Higgs Factory

ESPPU Muon Collider Report
Arxiv: 2504.21417

Unprecedented reach for New Physics due to combination of energy+precision

ESPPU Muon Collider Report
Arxiv: 2504.21417





Opens door for studies of new SM phenomena such EWK symmetry restoration

R. Capdevilla, T. Han
Arxiv: 2412.12336

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Statements from the P5 and NAS panel reports

P5: 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… ***This is our muon shot***

NAS EPP Recommendation 1: The United States should host the world's highest-energy elementary particle collider around the middle of the century. This requires **the immediate creation of a national muon collider research and development program** to enable the construction of a demonstrator of the key new technologies and their integration.

The USMCC

USMCC

Core Purposes

- Define necessary work for mid-P5 panel
- Design a US demonstrator
- Engage with the international community
- Create a long-term vision for Fermilab that leads to a muon collider
- Build on a theory-driven physics case

Ratified a charter on May 8, 2025

Elected Leadership on July 31

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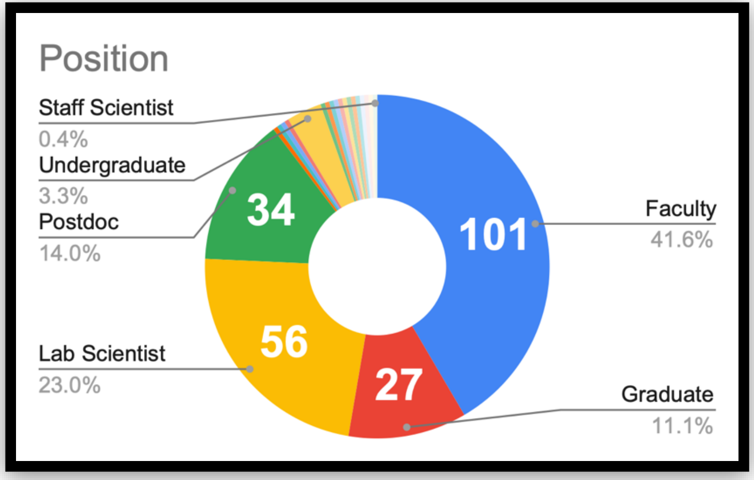
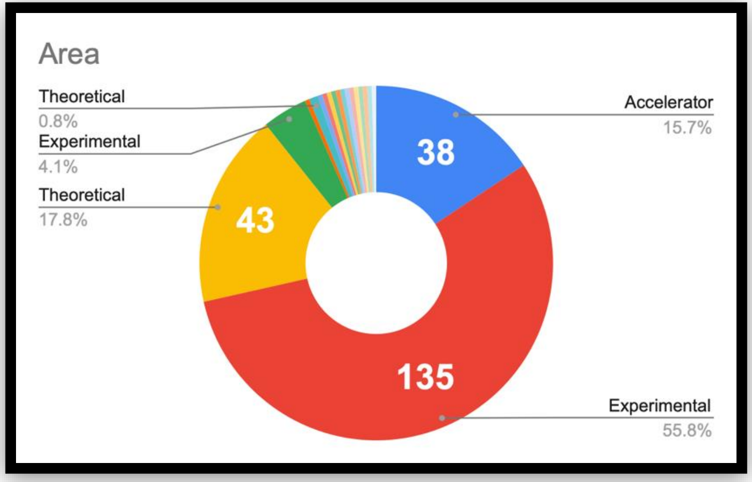
USMCC Demographics

- Currently have 244 members from 81 institutions
- **Please join - email Sergo+Tova**





USMCC Elected Leadership

Chair

Sergo Jindariani (FNAL)

Vice Chair

Tova Holmes (UTK)

Communications

Kiley Kennedy (Princeton)

Accelerator

Diktys Stratakis (FNAL)

Experiment

Simone Pagan Griso (LBNL)

Theory

Patrick Meade (SBU)

USMCC

- Formation of a broader Leadership Strategy Group (LSG)
- Welcome feedback from the collaboration about how we can serve you better LINK

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USMCC Communications Plans and Priorities

- **Broad Public Outreach**
  - Active social media (follow muoncollider.us !)
  - Programs/curricula for QuarkNet, AAPT
  - Presentations/demos at schools, especially in local Fermilab area
- **Government Relations and Advocacy**
  - Develop and update advocacy materials
  - Expand participation in the annual HEP DC Trip
  - Continued close collaboration with agencies
- **Cross-Disciplinary Communication**
  - Clear communication across technical areas (theory/accel/exp)
  - Strengthen partnerships with industry
  - Bolster physics case that appeals to non-collider/non-HEP physicists

If you are interested in getting involved, please reach out to Kiley & Larry (kileykennedy@princeton.edu, Lawrence.Lee.Jr@cern.ch)

Thank you!

USMCC

- **To everybody who helped us to guide the US effort from Snowmass/P5 to this stage:** D. Acosta (Rice), G. Apollinari (Fermilab), A. Apresyan (Fermilab), S. Belomestnykh (Fermilab), M. Begel (BNL), S. Berg (BNL), P. Bhat (Fermilab), K. Black (Wisconsin), P. Chang (Florida), C. Cesarotti (MIT), N. Craig (UCSB), M. Convery (Fermilab), S. Cousineau (ORNL), A. De Gouvea (NW), K. DiPetrillo (Chicago), J. Eldred (Fermilab), P. Ferracin (LBNL), M. Franklin (Harvard), M. Garcia-Sciveres (LBNL), S. Gessner (SLAC), S. Gourlay (Fermilab), T. Han (Pittsburgh), Matheus Hostert (Iowa), W. Hopkins (ANL), M. Kumar (BNL), L. Lee (UTK), Z. Liu (Minnesota), T. Luo (LBNL), N. Mokhov (Fermilab), E. Nanni (SLAC), S. Nagaitsev (BNL), M. Neubauer (UIUC), I. Ojalvo (Princeton), M. Palmer (BNL), K. Pedro (Fermilab), F. Pellemoine (Fermilab), S. Prestemon (LBNL), E. Prebys (UC Davis), Ben Rosser (Chicago), L. Sexton-Kennedy (Fermilab), E. Snively (SLAC), Z. Tabrizi (Pittsburgh), C. Tully (Princeton), R. Yohay (FSU), K. Yonehara (Fermilab), D. Wood (Northeastern), and many others …

We look forward to continuing to work with you !

Current Funding

At the labs

Fermilab demonstrator (LDRD)

Fermilab future collider software (LDRD)

Brookhaven collider R&D - RCS design and cooling cell (LDRD)

LBNL future collider detectors (LDRD)

SLAC high-field RF test stand (GARD)

At the universities

Princeton/Chicago/Tennessee Acc+Exp for MuC (Simons Foundation)

Tennessee Fellowships (Cottrell x2, Sloan)

UCSB/Princeton/Northeastern/UTK Interdisciplinary Seminar Series (Kavli Foundation)

+ start-ups, internal funding, and fractions of base grants/ECAs/CAREERs

also at labs

constrained by lack of significant R&D funding from gov't agencies

IMCC and US Engagement

More in Taylor's talk

- International Muon Collider R&D activities are led and coordinated by IMCC
  - Very active community since 2020
  - Over 50 institutions signed MoC
  - Funding in Europe comes from CERN + EU grant + smaller pots from member institutions
- US physicists have been actively engaged with IMCC
  - US representatives in IMCC leadership
  - 7 Universities signed MoC, more in the pipeline, **we encourage you to sign it!**
  - DOE – CERN collaborative agreement in progress, that will enable labs to official join
- Will revisit IMCC organization in the future, following ESPPU and USMCC ramp up

2025 IMCC Annual meeting @DESY

- 181 contributions showing new results across accelerator, experiment, theory
- 20% US participants

IMCC Input to European Strategy Process

arxiv:2504.21417

- The IMCC submitted input to the European Strategy Process
  - A comprehensive document *(over 400 pages)* summarizing technical progress made, future R&D plans, and timeline towards the collider realization
  - While IMCC is currently focusing on the green-field design, both US and CERN sites for the demonstrator and the final facility are mentioned and discussed

- The US is heavily involved in this effort:
  - Core editorial team for IMCC: Federico Meloni (chair), Chris Rogers (deputy chair), ***Kevin Black***, Christian Carli, ***Steve Gourlay***, ***Sergo Jindariani***, Roberto Losito, Donatella Lucchesi, ***Patrick Meade***, Elias Metral, ***Simone Pagan Griso***, Nadia Pastrone, Daniel Schulte, ***Diktys Stratakis***, Rebecca Taylor, Andrea Wulzer
  - Many additional chapter authors from US: Artur Apresyan, Sergey Belomestnykh, Scott Berg, Nathaniel Craig, Andre de Gouvea, Karri DiPetrillo, Jeff Eldred, Spencer Gessner, Eliana Gianfelice, Timon Heim, Tova Holmes, Walter Hopkins, Sergei Nagaitsev, Emilio Nanni, Mark Palmer, Kevin Pedro, Katsuya Yonehara

The Muon Collider

Supplementary report to the European Strategy for Particle Physics - 2026 update

The International Muon Collider Collaboration

The most up-to-date version of this document can be found at:
https://edms.cern.ch/document/3284682/1

Abstract
Muons offer a unique opportunity to build a compact high-energy electroweak collider at the 10 TeV scale. A Muon Collider enables direct access to the underlying simplicity of the Standard Model and unparalleled reach beyond it. It will be a paradigm-shifting tool for particle physics representing the first collider to combine the high-energy reach of a proton collider and the high precision of an electron-positron collider, yielding a physics potential significantly greater than the sum of its individual parts. A high-energy muon collider is the natural next step in the exploration of fundamental physics after the HL-LHC and a natural complement to a future low-energy Higgs factory. Such a facility would significantly broaden the scope of particle colliders, engaging the many frontiers of the high energy community.
The last European Strategy for Particle Physics Update and later the Particle Physics Project Prioritisation Panel in the US requested a study of the muon collider, which is being carried on by the International Muon Collider Collaboration. In this comprehensive document we present the physics case, the state of the work on accelerator design and technology, and propose an R&D project that can make the muon collider a reality.

International Muon Collider Collaboration
MuCol
Funded by the European Union

EDMS 3284682 v.1 status In Work access Public
ESPPU_Muon_Collider_Backup.pdf modified 2025-06-10 10:36

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US Muon Collider Submission to ESPPU

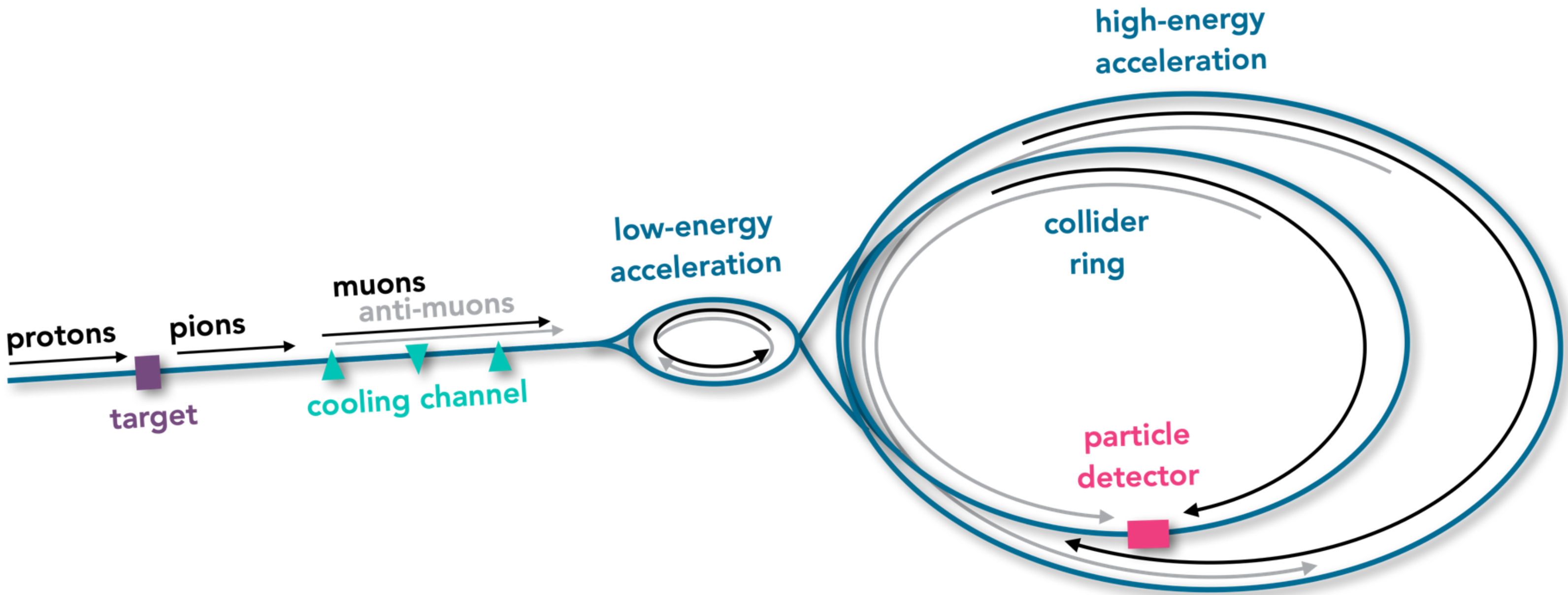
- A short 10-pager summarizing US plans and strategy
  - Over 300 signatories
  - arxiv: 2503.23695

- **Main messages:**
  - Close collaboration between the two regions regardless of where the machine is eventually realized ***(no region can do it alone!)***
  - Advocates for strong and sustained support for Muon Collider efforts in Europe
  - Expresses interest in hosting the demonstrator and potentially the collider in the US
  - Outlines goals for USMCC and how it interfaces with international efforts
  - Supports DOE-CERN collaborative agreement on Muon Collider R&D

- The main messages were propagated to the DPF national input document

The Machine Concept at ~10 TeV

- The goal is to get to **10 TeV center-of-mass** energy with $L \sim 10^{35}\ cm^{-2}\ s^{-1}$
- **Staging in energy** (e.g. 3→10 TeV) or **in luminosity** (a la LHC→HL-LHC) are possible and being studied



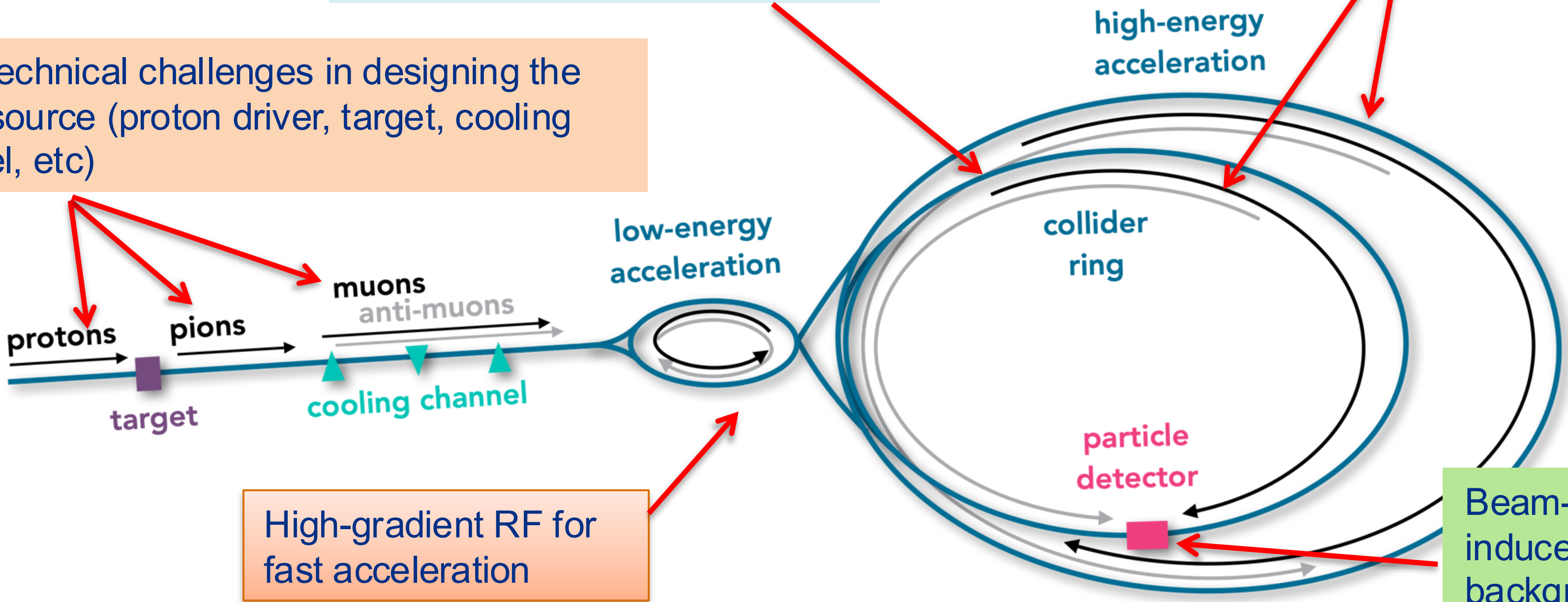
Muon Accelerator Challenges

More in Valdimir's talk

Challenging magnets in many places

Dense neutrino flux needs to be mitigated

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



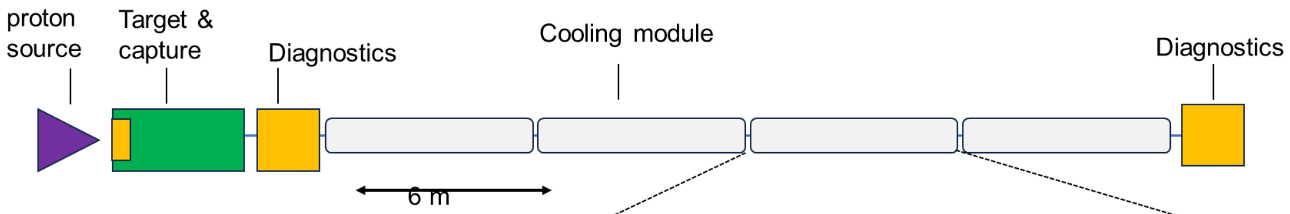
High-gradient RF for fast acceleration

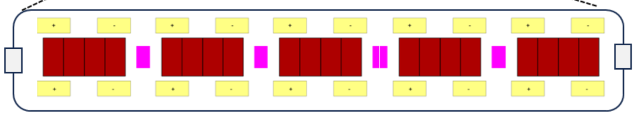
Beam-induced background in the detectors

These challenges should not be seen as show-stoppers but rather luminosity and cost risks

Ionization Cooling Demonstrator

More in Diktys's talk

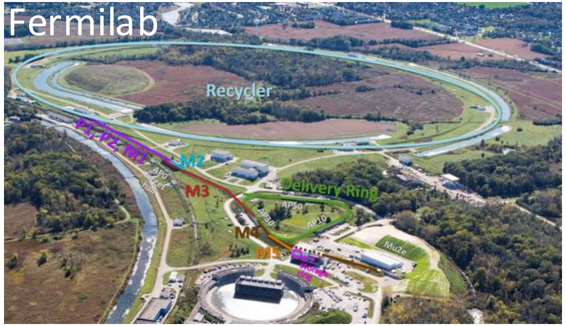


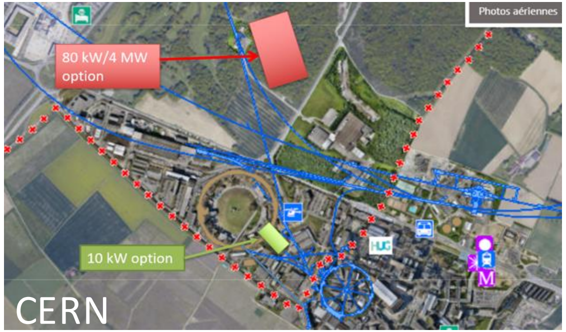


Demonstrator, example configuration:

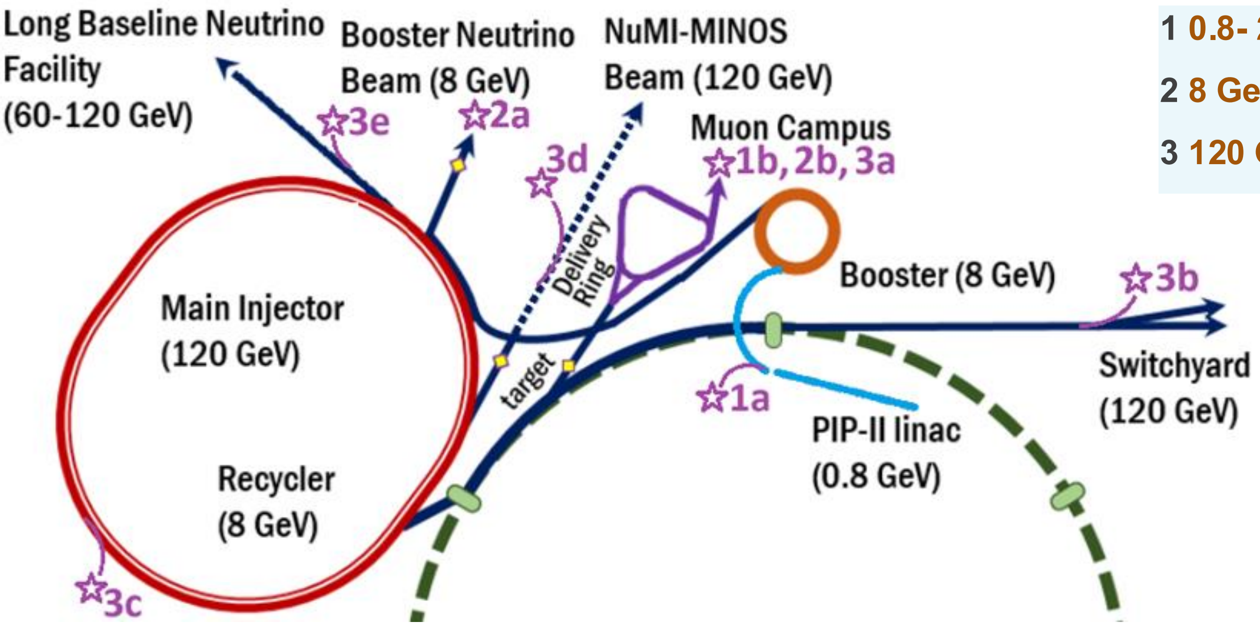
	Muon energy, MeV	Total length, m	Total # of cells	B_max, T	6D emm. reduction	Beam loss, %
Full scale MC	200	~980	~820	2-14	x $1/10^5$	~70%
Demonstrator	200	48	24	0.5-7	x 1/2	4-6%

Potential sites being explored:





Demonstrator Site exploration



1 **0.8- 2GeV** protons from the PIP-II linac

2 **8 GeV** protons from the Booster

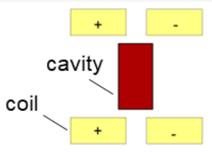
3 **120 GeV** protons from the Main Injector

- **GOAL:** Explore candidate sites for a Muon Ionization Cooling Technology Demonstrator within Fermilab. Compare available beam parameters, location, existing and needed infrastructure for each site.
- Two-year Fermilab LDRD approved to do this work!

Demonstrator staging

More in Diktys's talk

Phase-I

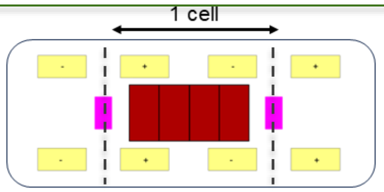


RF studies in B-fields

Material studies & cryogenics

600-800 MHz NC cavity, with coils making 10-14 T on axis

Phase-II

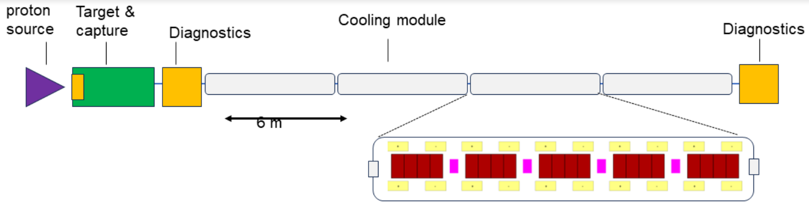


Cell integration studies

Cell resembles late 6D cooling stages

Reuse components from Phase I

Phase-III



Full demonstrator with beam

Coils producing 7-10 T axial fields

Potential to achieve 50% 6D cooling

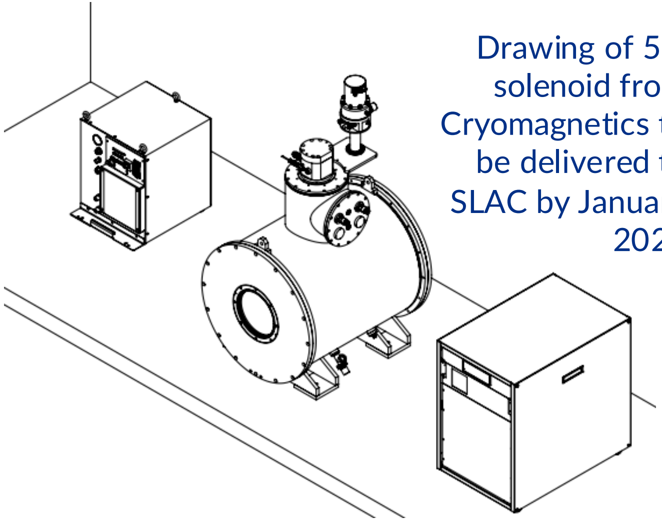
- Parameters may need to be adjusted
- Needs design studies for HTS coils under extreme forces (BNL LDRD, M.Palmer et al)
- Design of specialized RF cavities for the cooling channel – **more in talk by Dillon**

Testing RF Cavities in B field at SLAC

More in Emma's talk

Extending SLAC's high power RF testing capabilities to include external magnetic fields

- Measurements of the field emission and associated damage will be used to benchmark our simulated field emission in SLAC's ACE3P code suite.
- Test cavity geometries and materials relevant to muon cooling channel

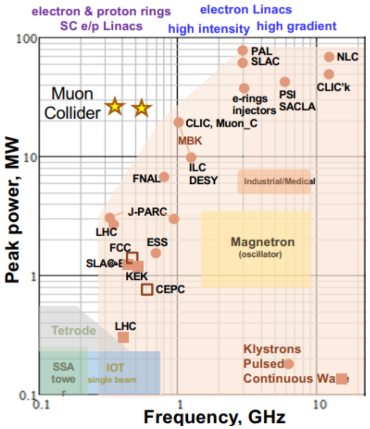


Drawing of 5 T solenoid from Cryomagnetics to be delivered to SLAC by January 2026

Benchmark high gradient results for frequency scaling with measurements at S-band and L-band available at NLCTA

Unique RF Source and Power Handling Requirements for MC

- Leverage SLAC expertise in design and fabrication of a wide range of rf sources
- Design and production of rf cavities, rf sources and rf components leading up to a future demonstrator



Additional beam dynamics expertise could be engaged for Machine Design

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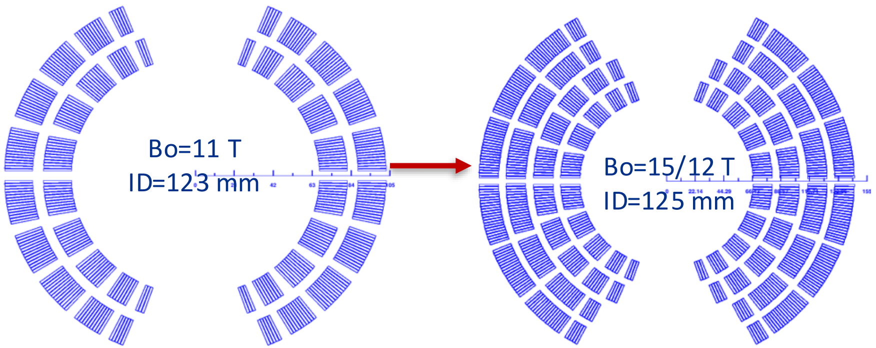
Magnet Developments

More in talks by Luca (Europe) and Ramesh (US)

Developing technology relevant to a future Muon Collider



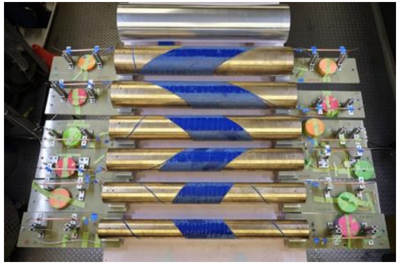
Combined function or higher field dipole

Muon collider territory!

World Record Field for an HTS (ReBCO) Dipole Magnet

Major <u>breakthrough</u> in reducing training in Nb_3Sn magnets

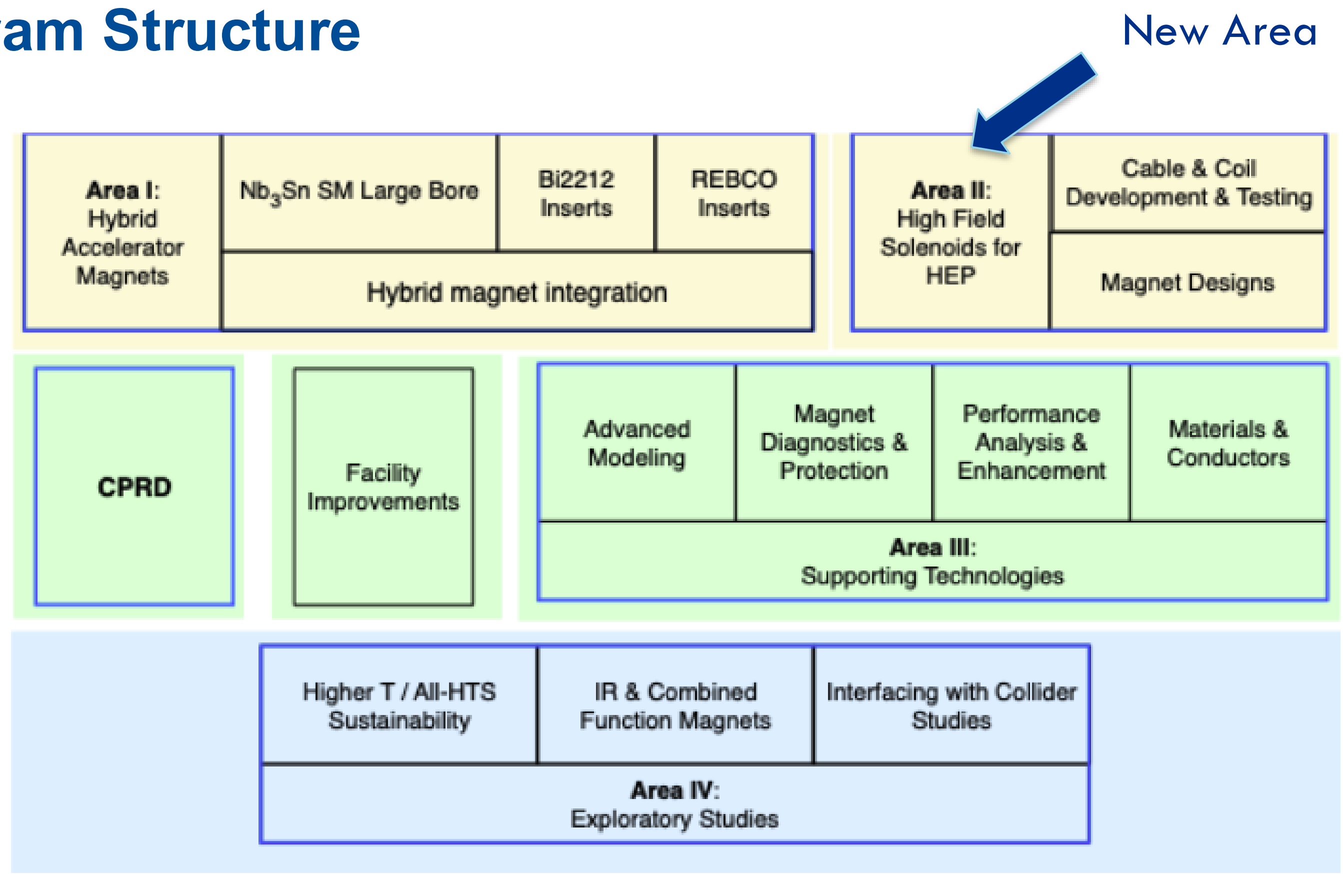
- Training & operating margin are major cost drivers
- Particularly relevant for future colliders



US MDP Program Structure

Improve integration for hybrid magnets

Strengthen linkage between technologies and magnets



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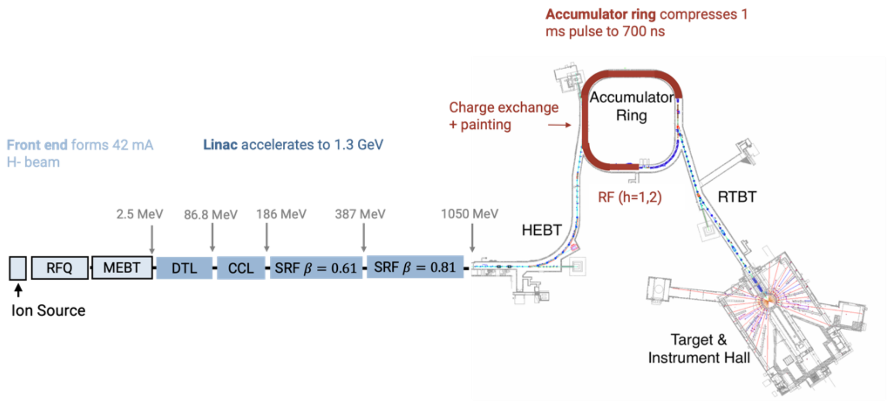
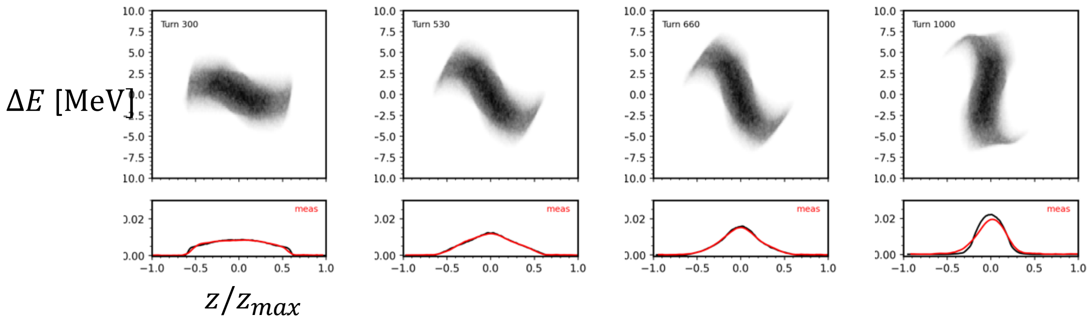
Bunch Compression Studies at SNS

More in talk by Austin

- ORNL SNS resembles proton driver and could probe relevant space charge regime.
- Experiments will test hardware limits, explore modifications for bunch compression.
- Initial experiment at low charge + simulation benchmark are shown on the slide.





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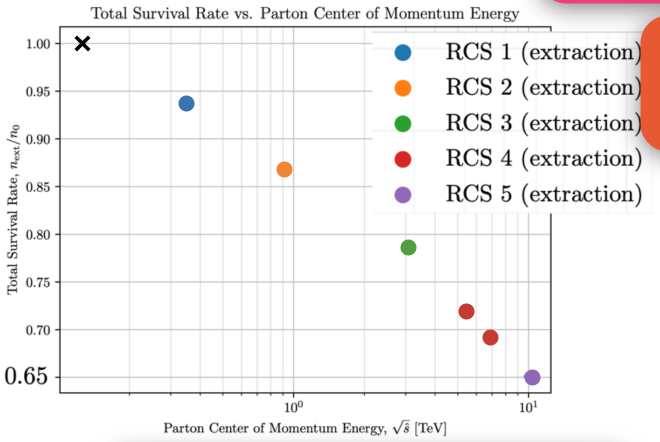
Fermilab Sited RCS Studies

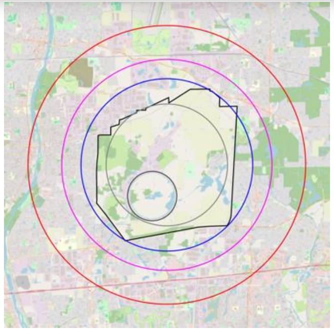
More in talk by Kyle

- **BNL LDRD Includes Two Muon Collider Thrusts:**
  - Rapid Cycling Synchrotron studies for the Fermilab siting option
  - Cooling Demonstrator module design studies (mentioned earlier)

RCS design for FNAL site



Highest current E w/i FNAL site is 5.42 TeV



Smallest current max ring size for 10 TeV is 21.9 km

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Training new Generation of Accelerator Experts

Please attend
Poster session

- Successful 3+ day Accelerator school this week with 70+ students
- Training clusters of new students in muon collider accelerator R&D, e.g.:
  - 6 students based at FNAL for the summer (Princeton, U Chicago, Wisconsin, Tennessee)
  - 4 students incorporated into BNL LDRD (Stony Brook, Princeton, Tennessee)
- Interested in expanding summer program in future years — needs funding for student and expert time!

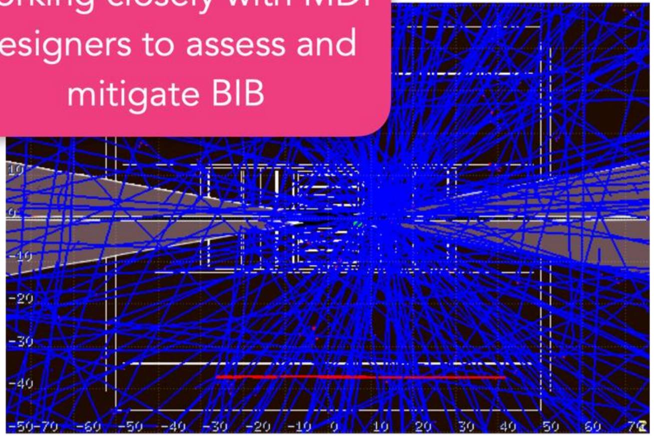
Muon Collider is an excellent motivator attracting a new generation to accelerator

Experimental Challenge

Exp. Parallel and Poster Sessions

- **Beam-Induced Backgrounds** dictate detector design and technologies
- Major progress in **suppressing** the backgrounds:
  - Improving the Interaction Region design
  - Optimizing shielding nozzles in forward region
  - 4D detector technologies and developing novel algorithms
- **Fundamentally reducible:** unlike *pp* the backgrounds are out-of-time and largely not from the IP
  - Can be mitigated with precision spatial and timing detectors and advanced algorithms

Working closely with MDI designers to assess and mitigate BIB



photons, electrons, positrons

(0.0003% of a BIB event)

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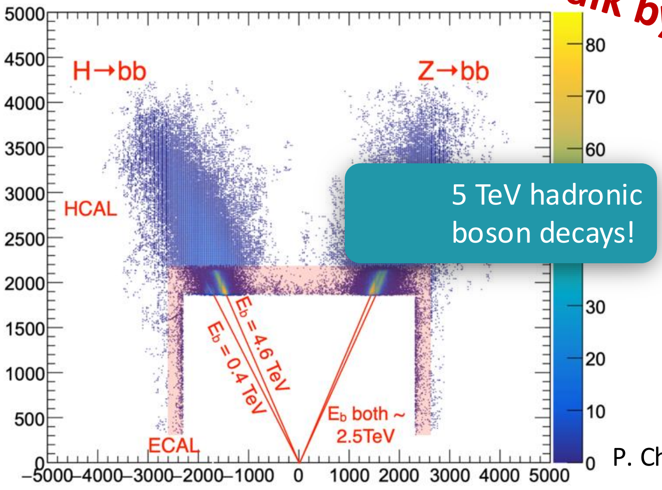
Detector Development

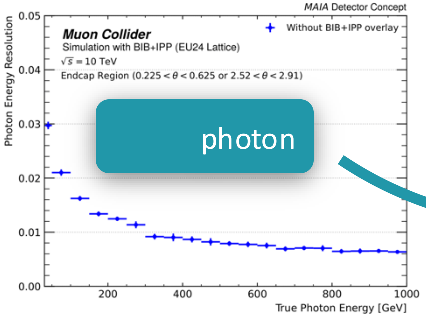
[2502.00181]

- Two design concepts (MAIA and MUSIC) for a 10 TeV detector:
  - Good physics performance achievable with both
  - One (MAIA) primarily developed by US institutions
- Modern and Flexible Software and Computing is Crucial!
- Detector **R&D needed:**
  - ***With investment***, should be ready to maximize physics potential by the time accelerator technology is ready

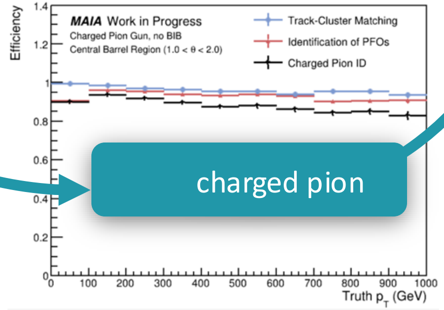
Talk by Simone



P. Chang

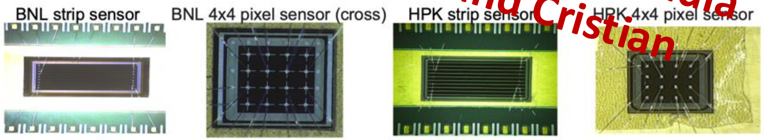


R. Powers



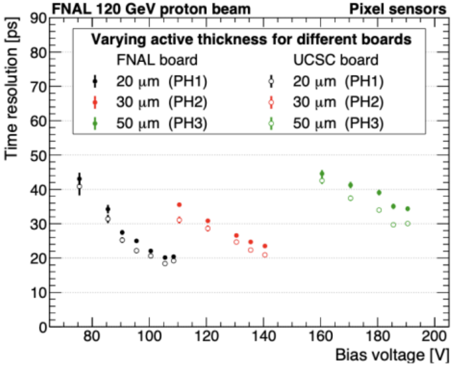
G. Penn

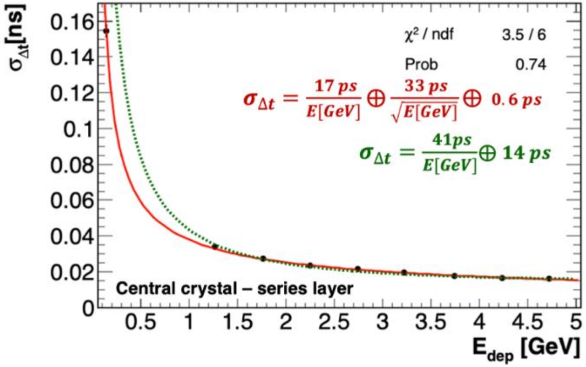
Detector Technologies



- Identify promising technologies
- Silicon based Sensor Technologies - very rapidly developing area – from LGADs to Quantum detectors
- PF and Dual Readout Calorimetry
- Novel DAQ architectures

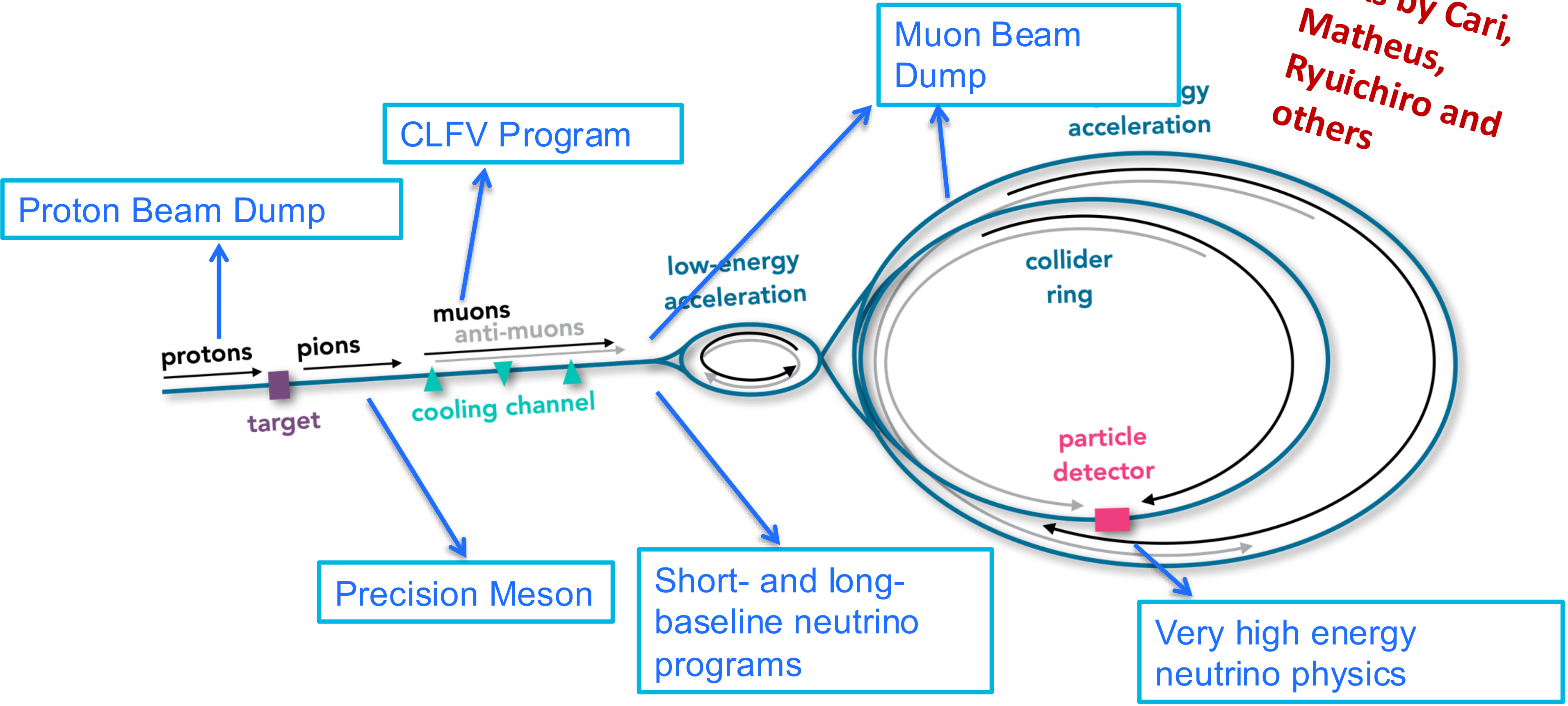
- Many opportunities for contributions:
  - ASIC and Magnet need long lead time
  - Power Distribution
  - Readout
  - Mechanics and Assembly
  - Forward detector, Luminosity, PID





Muon Accelerator Synergies

Talks by Cari, Matheus, Ryuichiro and others



Upcoming Muon Collider Meetings

- International Muon Collider Demonstrator workshop:

  University of Milan, Italy, Nov 5-7th 2025, Indico will be available soon

- 2026 IMCC Annual Meeting:

  CERN, June 22-26th , 2026

- 2026 US MCC Meeting:

  planned at SLAC, dates TBD

- 2026 Muon Collider Accelerator School just starting to discuss – lessons learned from the school this week

- Will also plan detector and generator tutorials in 2026

Summary

- Muon Collider complex offers amazing physics opportunities.
- Requires significant *global R&D program – US community is ramping up*
- Big challenges to solve across accelerator/theory/experiment - need people, resources, creative ideas – please join the effort
- Stay in touch:
  - ***Self subscribe to the mailing list***
  - ***Join the SLACK channel***

Backup

Theory progress since last year

- Community focus was on the European Strategy Update
  - Many US theory participants were editors, chapter authors, PPG response contributors for IMCC submission
- Continued exploration of BSM models at energy frontier and precision EW studies – extending to exploration of phenomena tied to e.g. “EW restoration”
- Exploration of new opportunities specific to muon collider
  - Flavor physics isn’t just tied to muon-phillic operators but can be a powerful probe for *generic* flavor operators by combining energy with precision
  - High energy neutrinos with forward experiments could provide exquisite sensitivity for CKM elements (even compared to FCC-ee) and unparalleled PDF measurements at moderate to large x
- Many studies in progress adding more detailed background studies that will allow better benchmarking for detector development

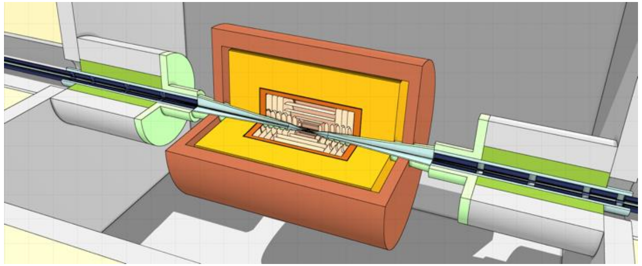
MDI Challenges

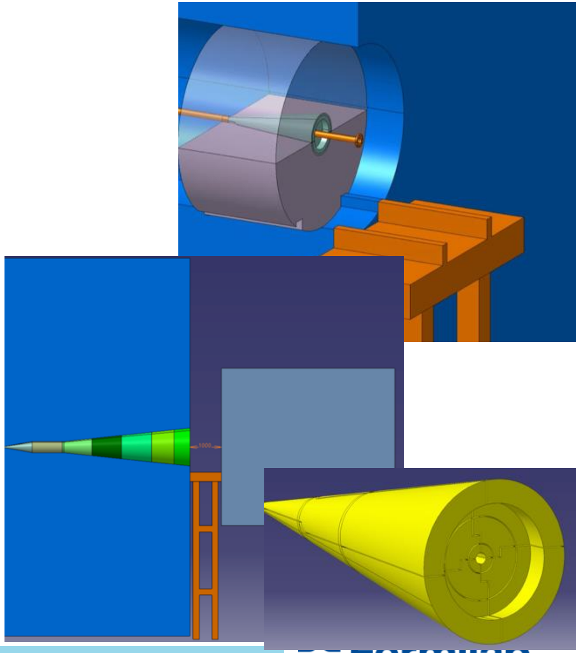
- Very challenging lattice design:
  - Key points: momentum acceptance, alignment requirements for IR magnets, IR magnet apertures vs achievable field strength

- Combined optimization of the interaction region, the nozzles and the detector

- Design, assembly, support, integration and alignment of the nozzles and central beam chamber

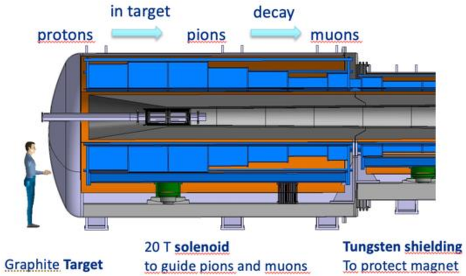
- Important to start with global MDI integration studies in order to define space requirements and interfaces

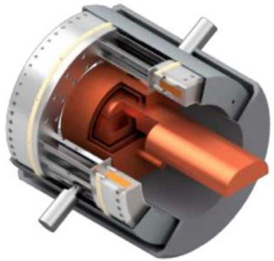


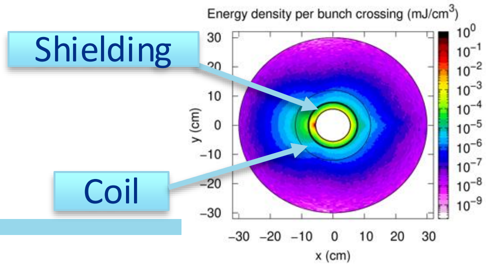


Muon Collider Needs: Accelerator Technology

- Optimal performance of a Muon Collider requires significant development in several areas of accelerator technology, including:
  - High Power Targets and Capture systems
    - Ability to withstand large thermal and structural shock
    - Large B superconducting magnets in high radiation environment
  - RF cavities:
    - High gradient NC cavities for cooling that have to operate in multi-T fields
    - High gradient SC cavities for acceleration that tolerate muon decay products
  - A variety of different Magnets:
    - High-field solenoids for the Cooling channel
    - Fast ramping dipoles for the muon acceleration
    - High-aperture and field dipoles and quadrupoles in the collider ring



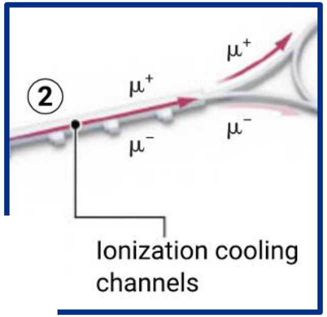




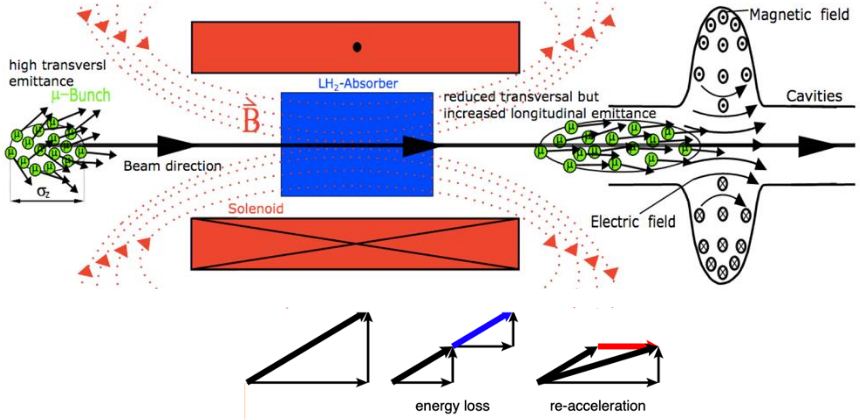
Muon Collider Needs: Accelerator End-to-end Design

- Muon Collider accelerator complex includes ~10 different sub-systems that are tightly interconnected due to non-stable nature of the colliding particles
- Designs for various sub-systems exist:
  - Developed by Muon Accelerator Program
  - Refined or revisited by IMCC, considering new ideas and evolution of accelerator technologies
- A full end-to-end simulation framework which puts all the sub-systems together in a coherent fashion is necessary in the next 5 for the “reference” design
  - Pin down performance of the machine in simulation
  - Study and compare various configurations and trade-offs for further developments

Muon Collider Needs: Ionization Cooling

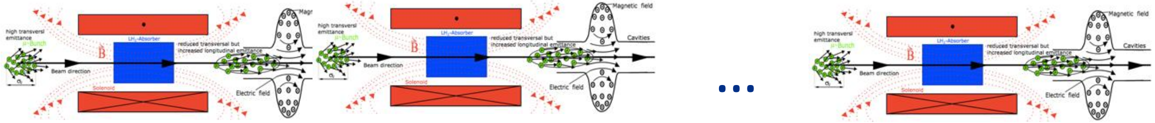


$$L = \frac{N_+ N_- n_C f}{4\pi\sigma_x\sigma_y}$$



Need to cool muons to achieve target luminosity!

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

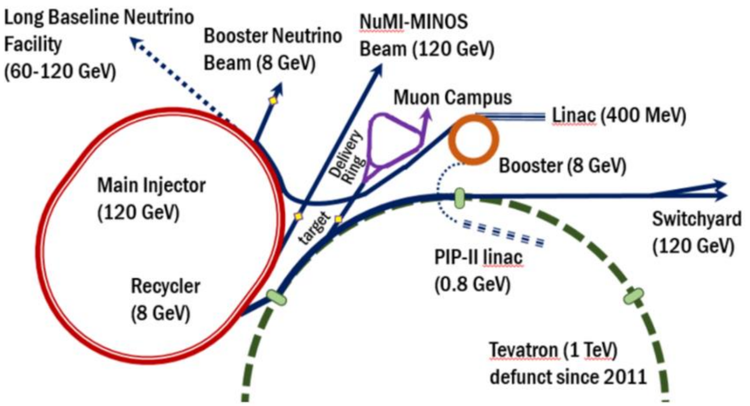


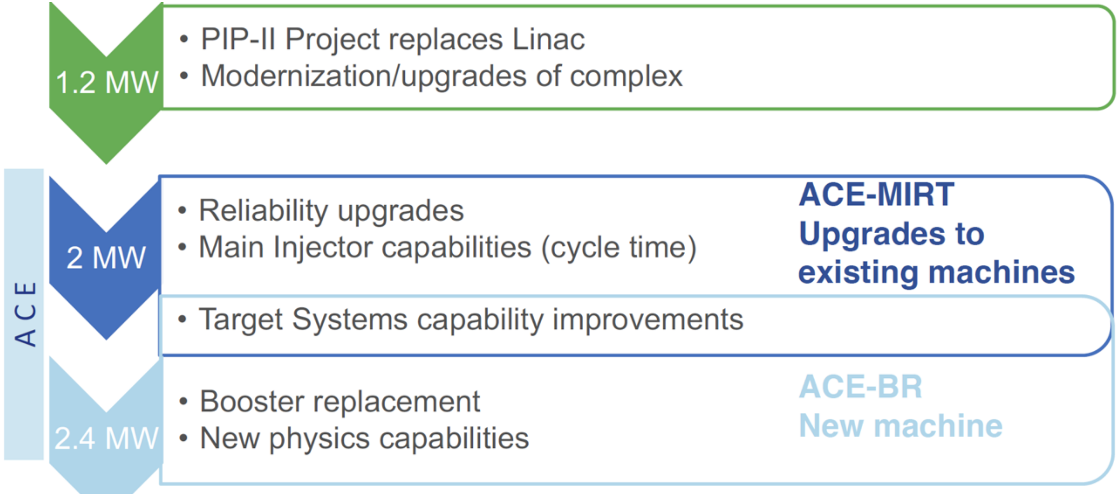
Not all cells identical

Fermilab

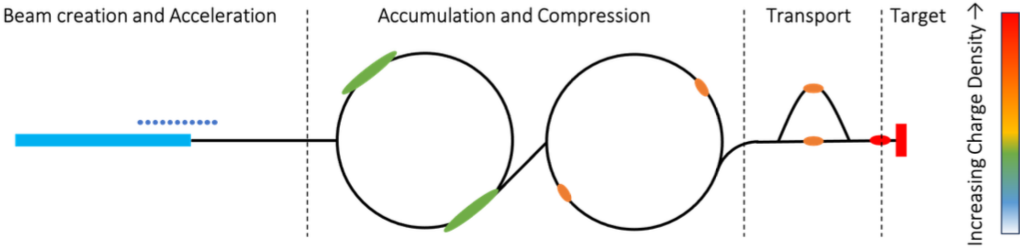
Fermilab Accelerator Complex Evolution (ACE)

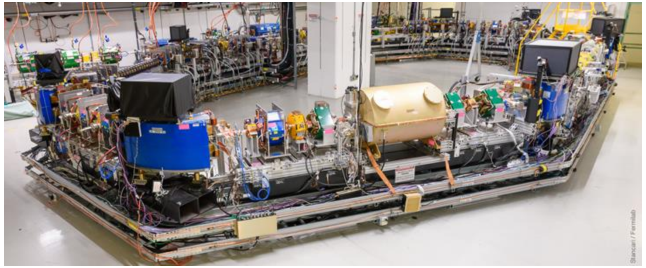
- Fermilab accelerator provides a variety of different beams to the user experiments
- Modernization and upgrades of the complex are ongoing or planned ***(more in Sasha's talk)***





Can ACE provide the Proton Source?



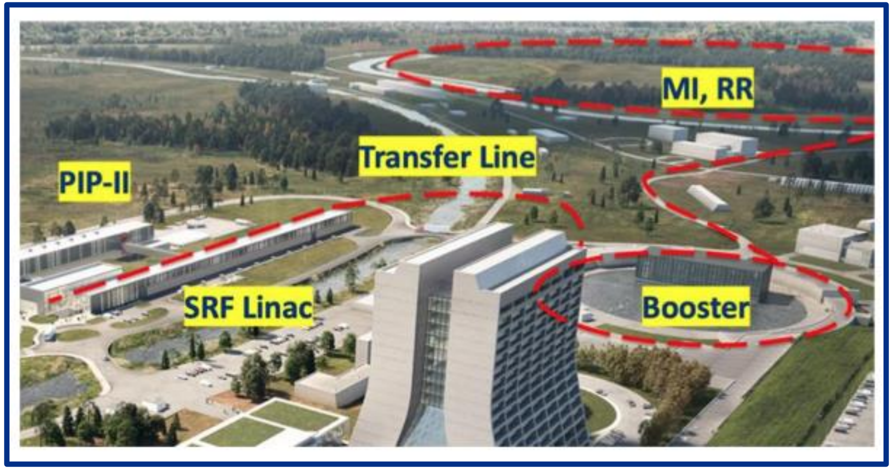


- Proton beam ranges for optimal performance :
  - **1-4 MW @ 5-20 GeV**,
  - Narrow bunches **1-3 ns**
  - **5-10 Hz** frequency
- Requires work to study bunch accumulation, compression and collective effects to convert ranges into specific set of parameters

PIP-II as part of the Muon Collider Proton Driver

PIP-II Project provides

- New SRF linac for injection into Booster at 800 MeV (present 400 MeV)
- New Beam Transfer Line (BTL) from Linac to 8 GeV Booster,
- Booster cycle rate upgraded to 20 Hz from 15 Hz
- Increased proton beam intensity at 8 GeV for 1.2 MW beam power from MI



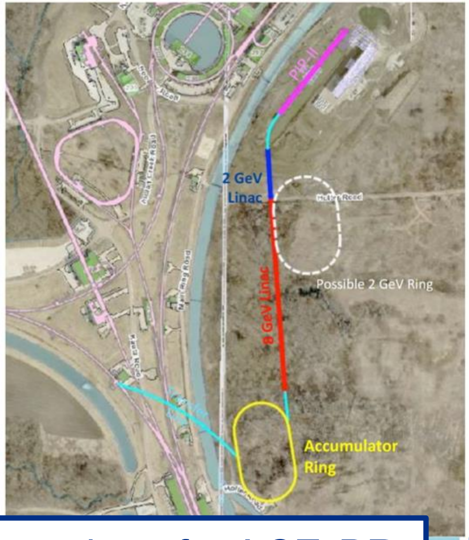
- The present PIP-II linac current appears too low for the MC Proton Driver
- There are ideas on how to adopt/adjust the PIP-II linac design, but requires a detailed study

New Booster as part of the Muon Collider Proton Driver

- Past Booster Replacement designs focused almost entirely on DUNE needs
- Muon Collider adds a new goal for the ACE-BR design choices
- Need to evaluate compatibility with potential modifications for the PIP-II linac

2GeV Linac + 2-8GeV RCS

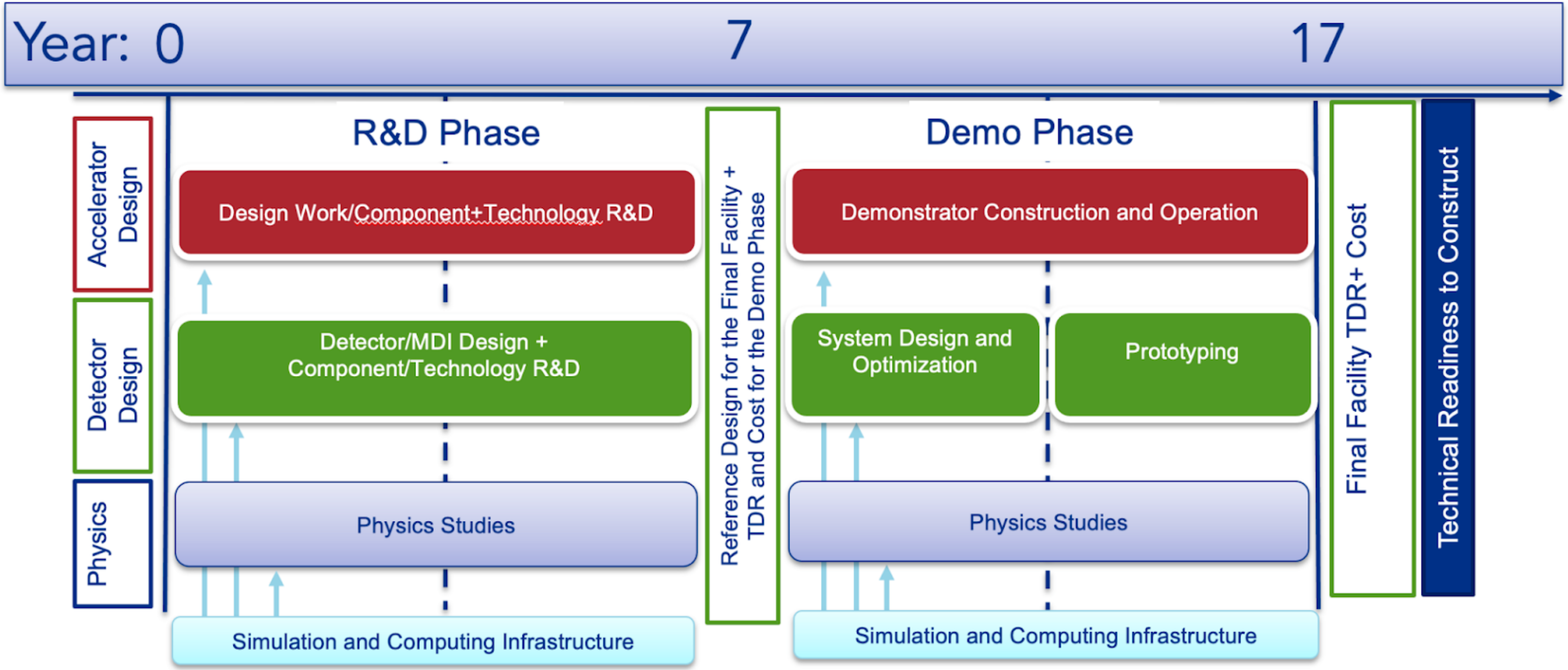
8GeV Linac + 8GeV AR



Sketches of potential configurations for ACE-BR

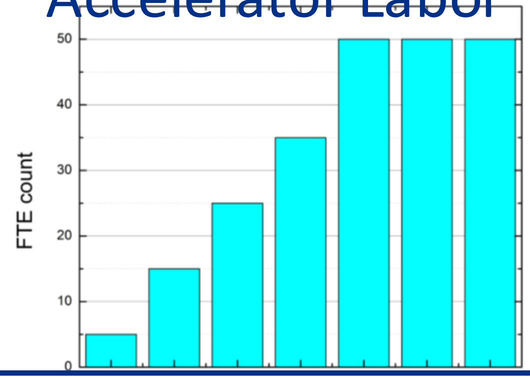
Potential US timeline shown to P5

- The timeline is slightly shifted (but not inconsistent) with IMCC timeline due to ***US specific budgetary and resource constraints***



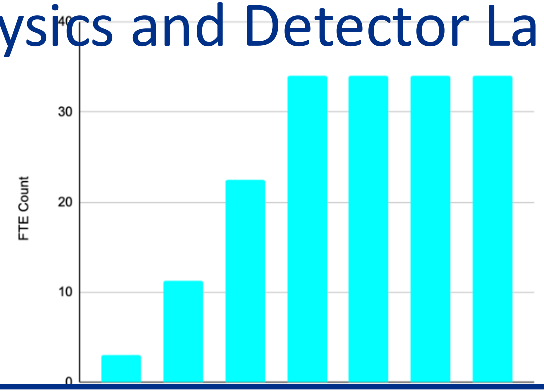
Resource Request to P5 – R&D Phase (first 7 year)

Accelerator Labor



Year: 1 2 3 4 5 6 7

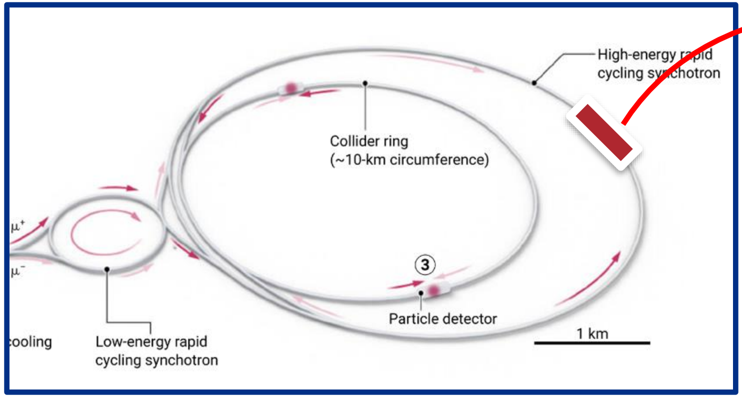
Physics and Detector Labor

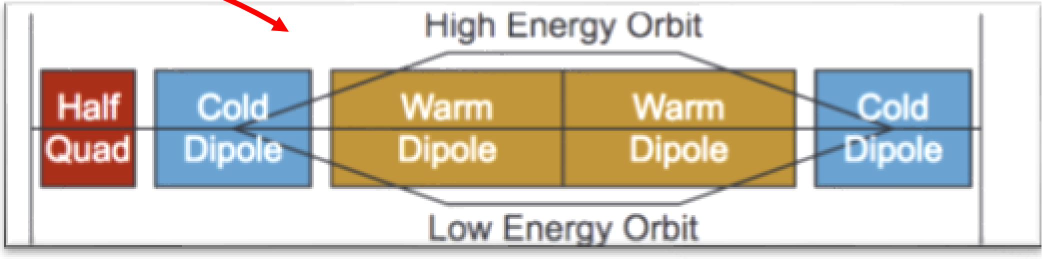


Year: 1 2 3 4 5 6 7

- M&S ramp up to at least ~5M/year for the accelerator and ~1.5M/year for detector R&D
- **Assumed equal contribution from Europe to maintain the current R&D plan**
- Detailed profile for the Demonstrator Phase (2030+) was not provided, only top-down estimates were made
- Work is ongoing with IMCC to develop such profile

Acceleration of Muons

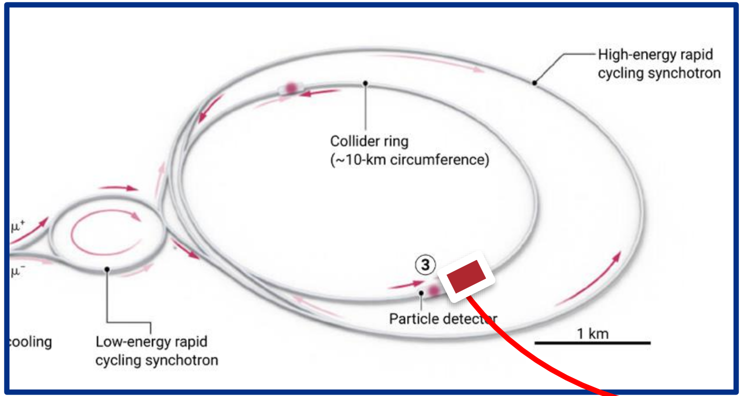


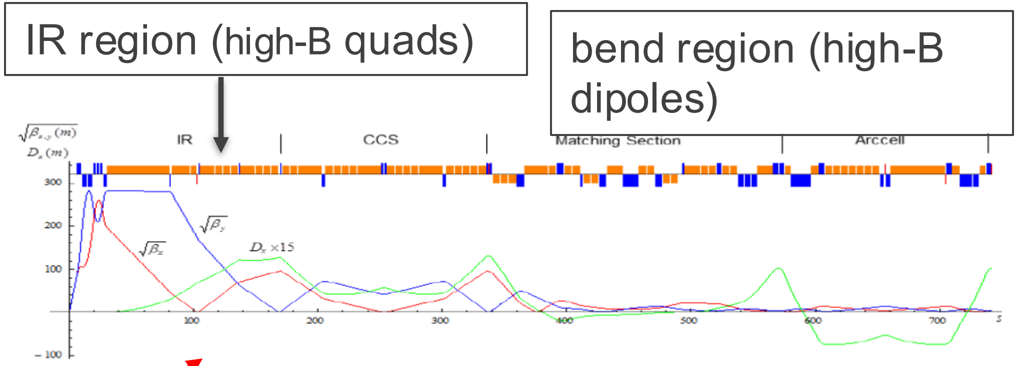


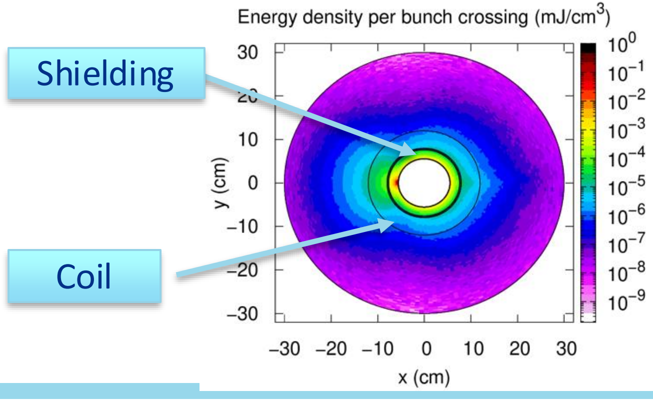
DC field Pulsed from $-B_w$ to $+B_w$

- 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







- 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

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.

Share full article 96

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

4

symmetry
dimensions of particle physics

Illustration by Sandbox Studio, Chicago with Corinne Mucha

'This is our Muon Shot'

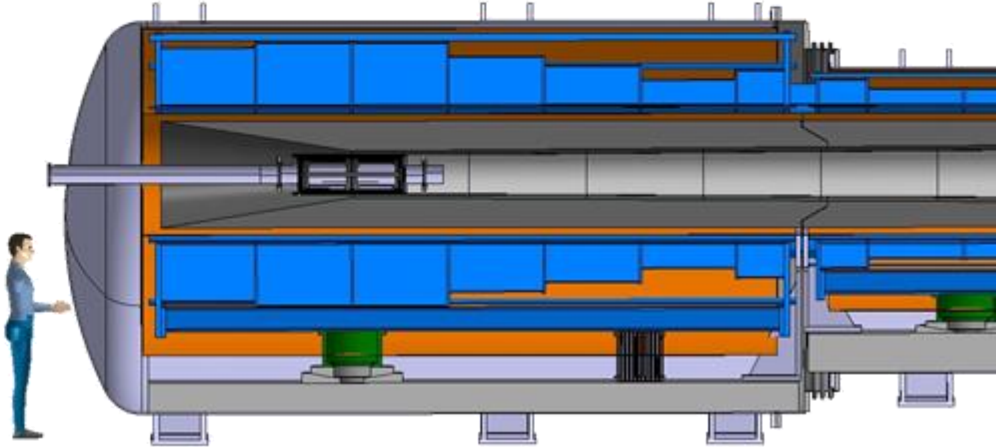
04/10/24 | By Laura Dattaro

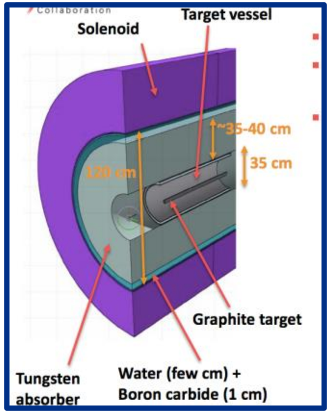
The US physics community dreams of building a muon collider.

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

Fermilab

protons → (in target) → pions → (decay) → muons





Graphite **Target**

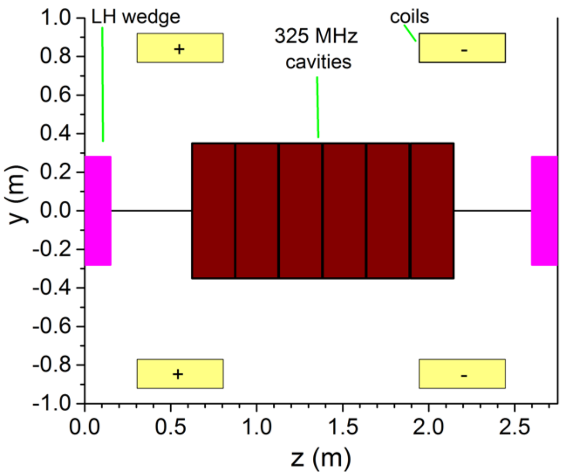
20 T **solenoid**
to guide pions and muons

Tungsten shielding
To protect magnet

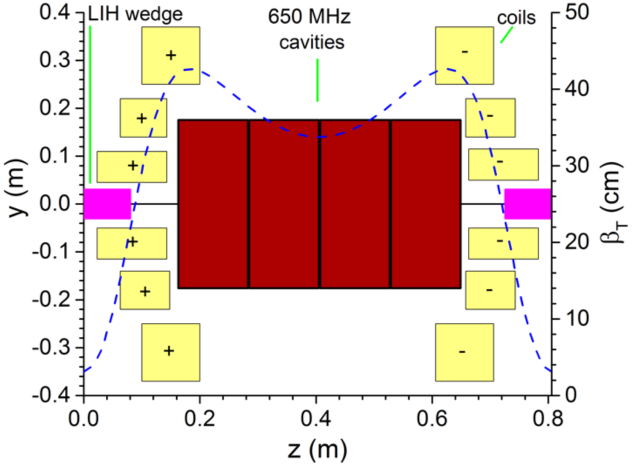
- Thermal and structural shock on the target due 2-4 MW and short proton bunches
- Study different materials, shapes, size optimization, advanced target concepts
- Focusing magnet is challenging due to field strength, size and radiation load

Cooling Cells

Early cell ("easy") – 2T peak



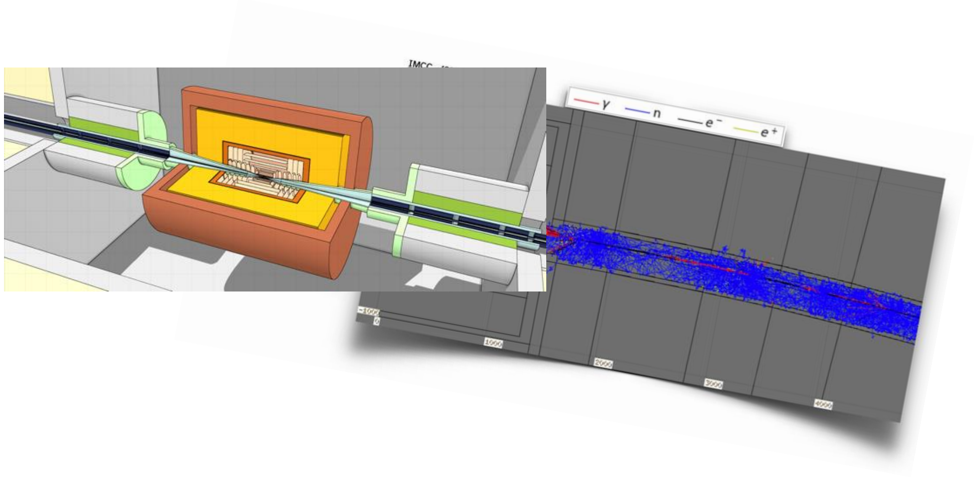
Late cell ("hard") – 14 T peak

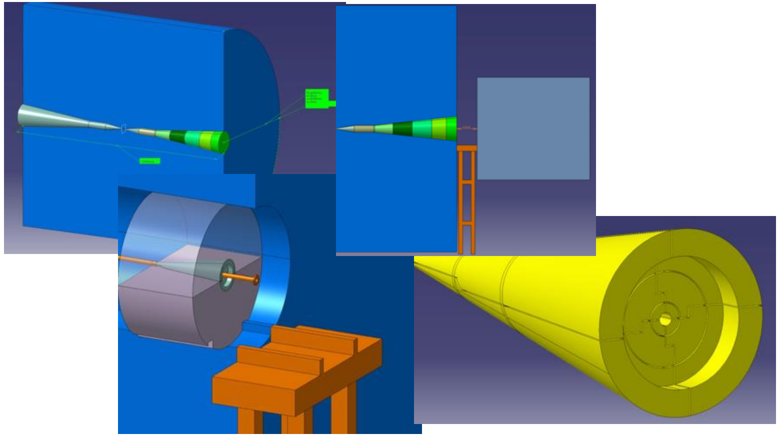


- Large bore solenoidal magnets: From 2 T (500 mm IR), to 14 T (50 mm IR)
- Normal conducting RF that can provide high-gradients within a multi-T fields
- Absorbers that can tolerate large muon intensities
- Need to further optimize the design considering engineering constraints

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

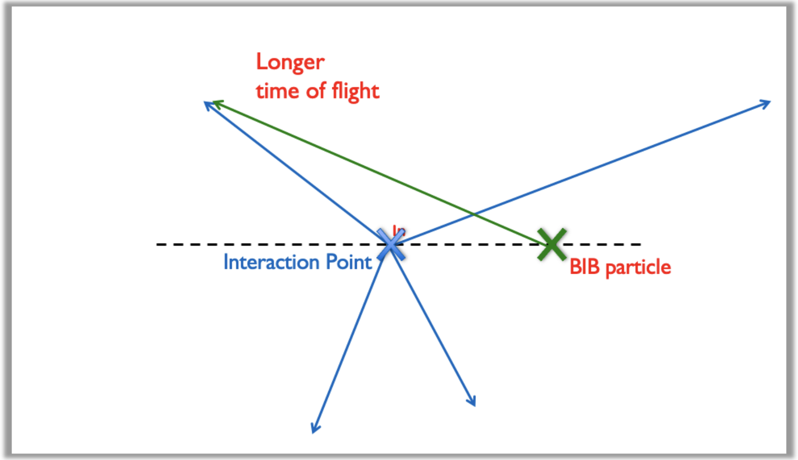


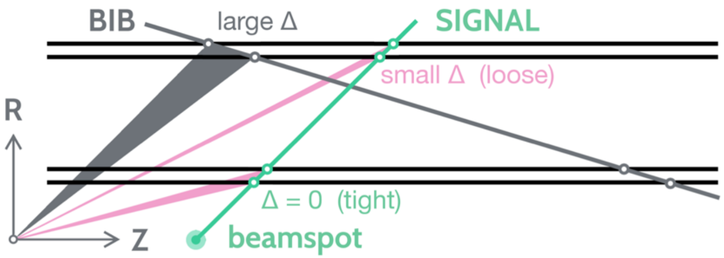


- Machine-Detector Interface requires careful design optimization and engineering studies
- Next step in evolution of detectors, hybrid of LHC and Higgs Factory needs. Requires novel detectors - opportunities for innovative detector designs and technology!

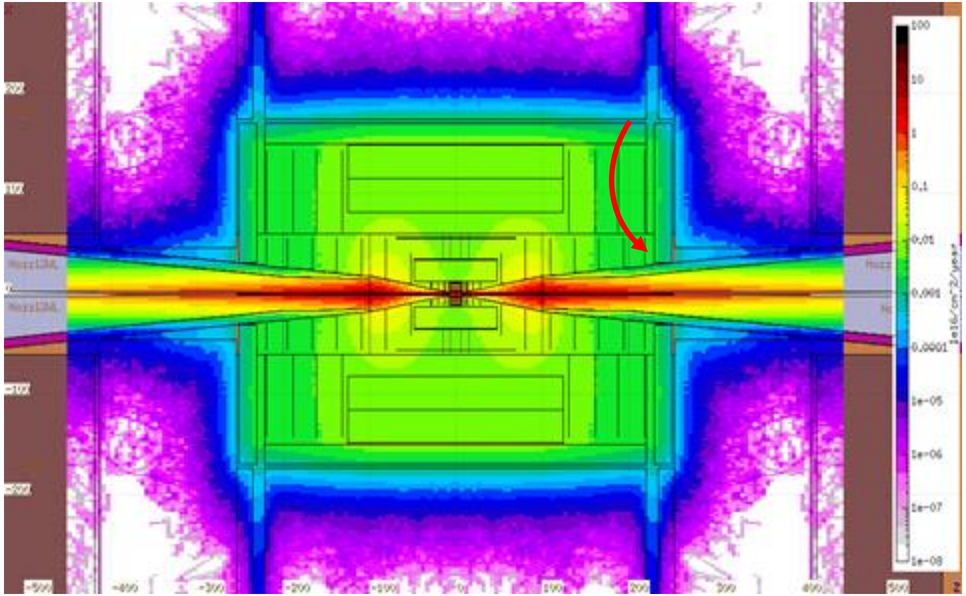
BIB Suppression

- The BIB is mostly low energy, out of time and not pointing to the Interaction Point
- Some similarities with LHC pileup - **can build on that experience!**



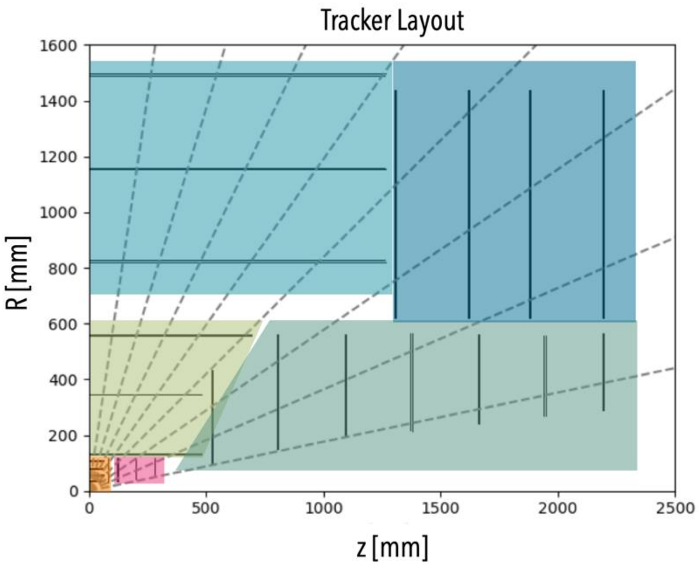


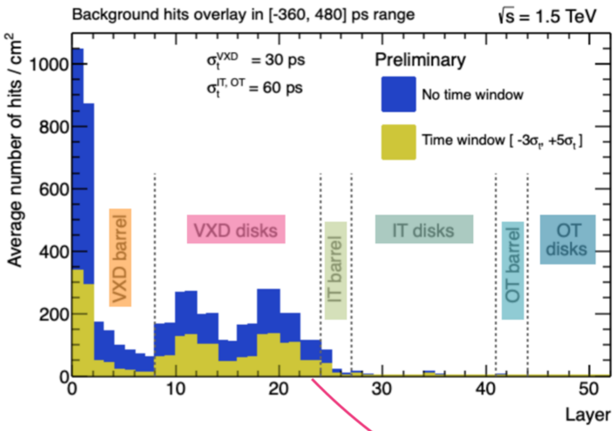
Detector Design – radiation environment



	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm	R= 22 mm	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}

Tracker Challenges

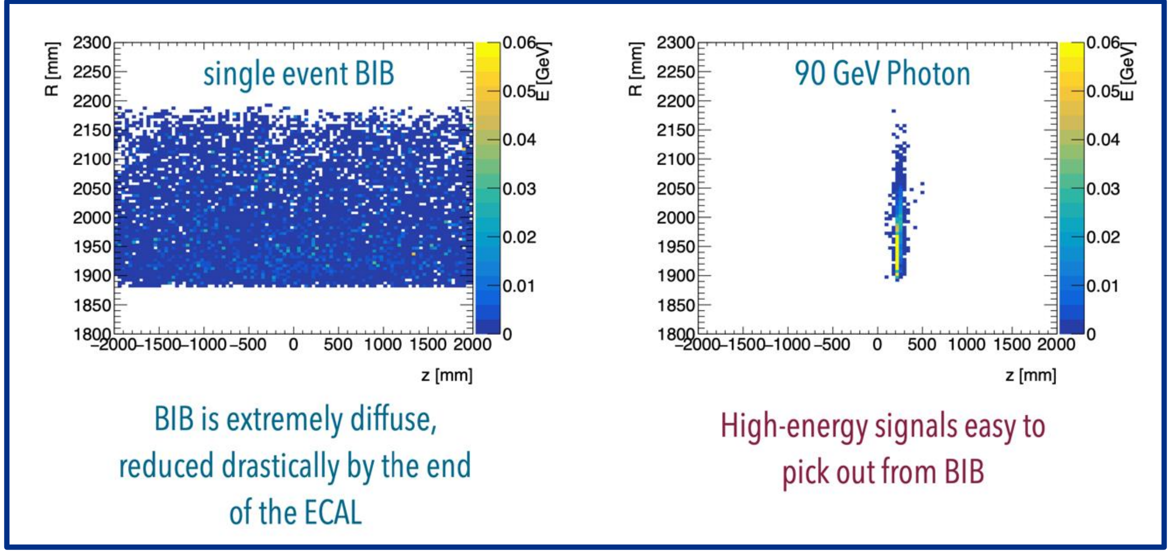




	Vertex Detector	Inner Tracker	Outer Tracker
Cell type	pixels	macropixels	microstrips
Cell Size	25 µm × 25 µm	50 µm × 1 mm	50 µm × 10 mm
Sensor Thickness	50 µm	100 µm	100 µm
Time Resolution	30 ps	60 ps	60 ps
Spatial Resolution	5 µm × 5 µm	7 µm × 90 µm	7 µm × 90 µm

- Occupancy per layer with 1% target directly translates into feature size and timing resolution
- On detector data suppression is important

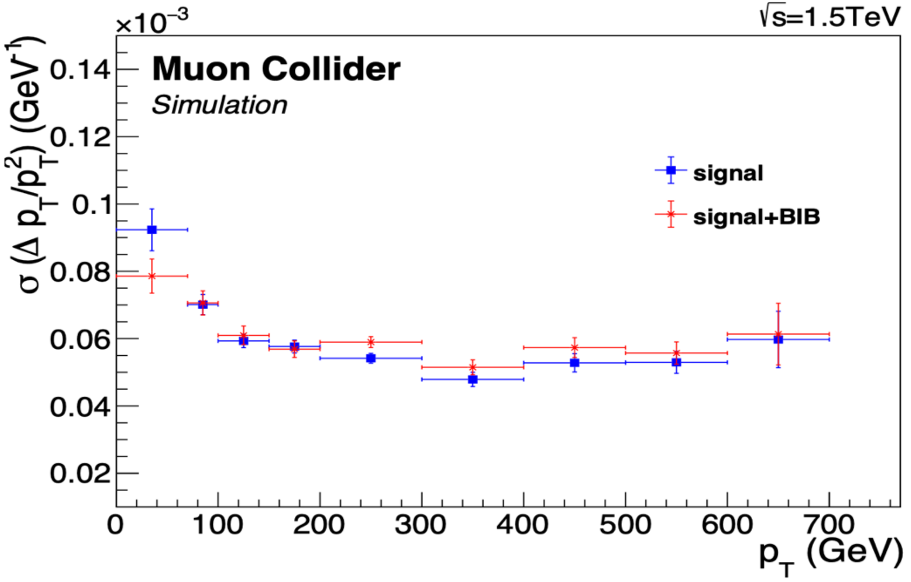
Calorimeter Design



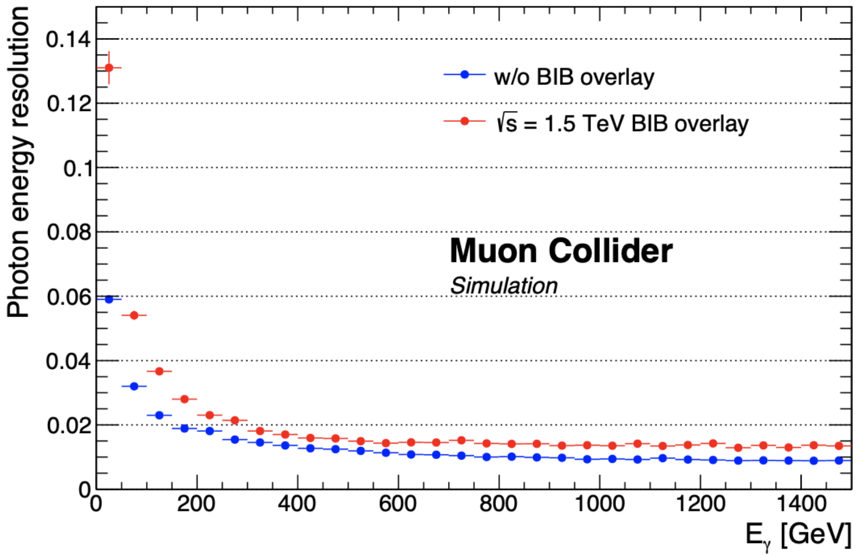
- High granularity and shorter integration windows
- Hit time measurement O(100ps)
- Longitudinal segmentation
- Perfect application for AI-based clustering and reconstruction algorithms

Performance Examples

Track relative momentum resolution
BIB effects are small



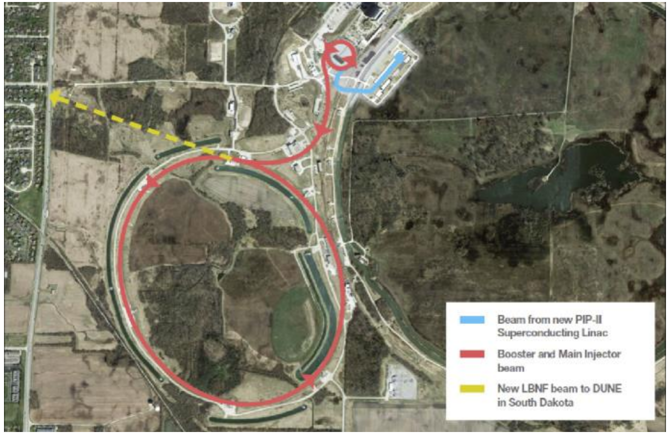
Few % Photon Energy Resolution
Improvements possible at low E_T



Fermilab

Possibilities during the ACE-MIRT phase

- The PIP-II proton accelerator will provide the intensity sufficient to power a new generation of high energy facilities at Fermilab
  - Proton flux at 8 GeV increases during PIP-II era
  - The 12-24 kW available for 8 GeV program would be suitable for a muon cooling demonstrator
  - Other options at lower or higher energies should be explored

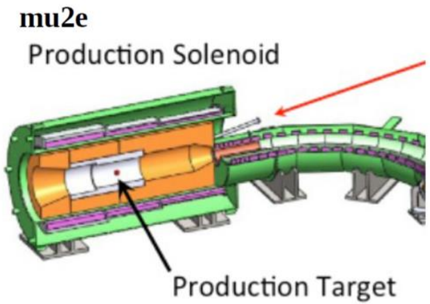


Linac	Achieved	PIP-II	ACE-MIRT
Current	20-25 mA	2 mA	2 mA
Energy	0.4 GeV	0.8 GeV	0.8 GeV
Booster	Present	PIP-II	ACE-MIRT
Intensity	4.8e12	6.5e12	6.5e12
Energy	8 GeV	8 GeV	8 GeV
Rep. Rate	15 Hz	20 Hz	20 Hz
8-Gev Power*	25 kW	80 kW	12-24 kW
Main Injector	Present	PIP-II	ACE-MIRT
Intensity	58e12	78e12	78e12
Cycle Time	1.133s	<1.2 s	~0.65 s
120-GeV Power	0.96 MW	~1.2 MW	1.9-2.3 MW

Table 1: Parameters for Fermilab proton complex. *8-GeV beam power given for what is available simultaneous with 120-GeV program.

Site at Fermilab: Muon Campus

- Designed to provide beam for the Muon g-2 and Mu2e experiments
  - Capable to deliver **8 kW** beam at **8 GeV** to the Mu2e production target
  - Available tunnel space to run the demonstrator without interfering with Mu2e
  - Production target is similar to the MuC target



Excellent opportunity to examine targets under 5 T field

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