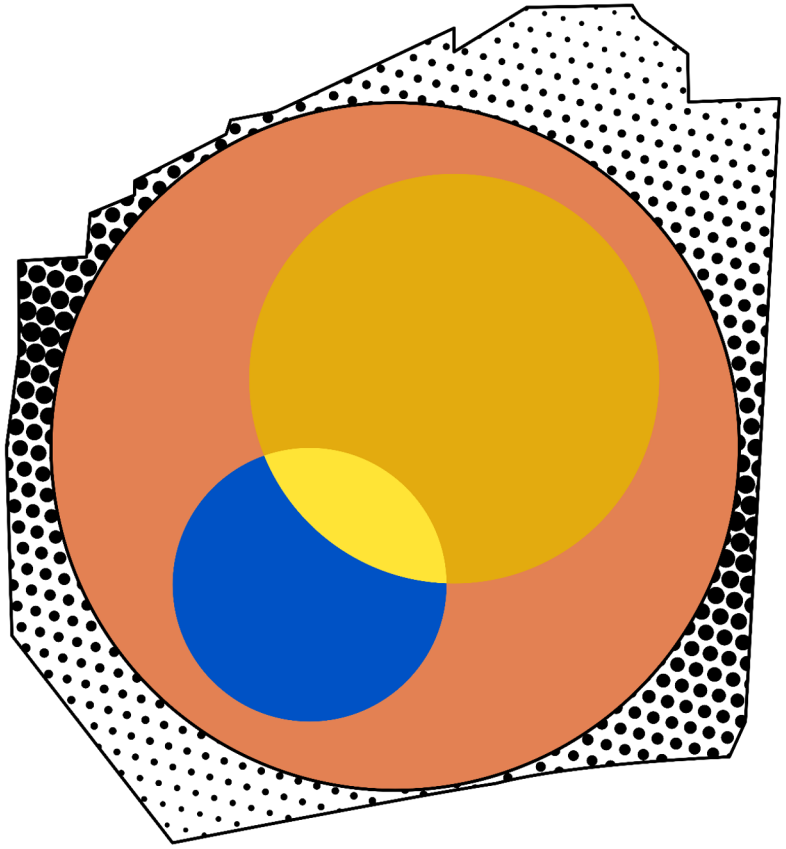


Update on **Muon Collider** activities in the US

HEPAP Meeting
December 5, 2024

US Muon Collider Collaboration Formation Team:
Michael Begel, Pushpa Bhat, Nathaniel Craig, Sridhara Dasu, Steve Gourlay, Tova Holmes, Sergo Jindariani, Patrick Meade, Mark Palmer, and Diktys Stratakis

Outline

- Recent activities in the US related to the “muon shot” of P5
- In progress formation of US Muon Collider Collaboration (USMCC)
- Interface with International Muon Collider Collaboration (IMCC) and European Strategy Process
- Goals for the future

Community Planning and P5 Process

- **2020 EPPSU:** led to **IMCC** formation (currently hosted by CERN)
- **2021-22 US Snowmass:**
  - Cross-Frontier ***Muon Collider Forum***
    - Accelerator (Derun Li, Diktys Stratakis)
    - Energy (Kevin Black, Sergo Jindariani)
    - Theory (Fabio Maltoni, Patrick Meade)
  - An enormous number of studies culminated in the following conclusions:
    - ***Physics case for 10 TeV is strong:*** *a* ***muon collider*** *offers a unique way to access both precision and direct probes* - particularly well-suited for answering EW questions
    - MC physics can be extracted with ***near-term detector advances***
    - ***No fundamental showstoppers*** identified for developing a 10 TeV MC, but technical challenges exist
    - Muon accelerator offers synergistic physics ***beyond the energy frontier***
- **2023 P5 Report:** Multiple recommendations to support ***US leadership*** and a ***robust US collider effort*** - expressed strong support for the R&D needed to enable our **"muon shot"**

Post P5 - organizationally

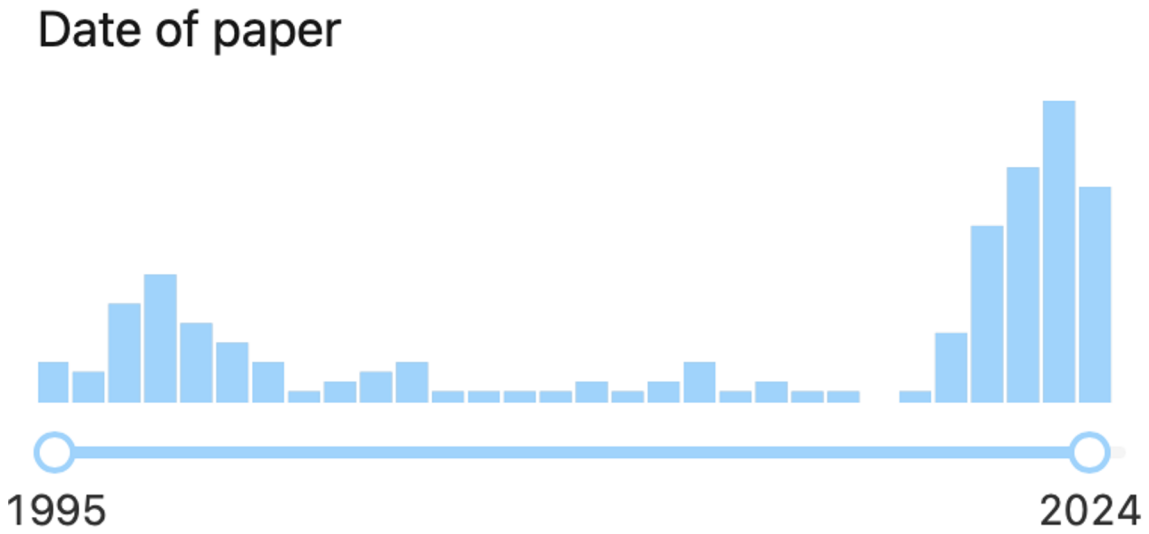
- Leveraging the successful MC Forum **accelerator+experiment+theory partnership**:
  - Community self-organize: invitation-only workshop at Princeton in February 2024
  - Delivered an R&D status & priorities report
  - Initiated elections for an interim organization
- Inaugural US Muon Collider Community Meeting hosted by Fermilab in August 2024
  - **300+ participants** with *over 260 attending in person*
  - IMCC Leadership participated
- Grassroots USMCC formation efforts
  - A concerted US community effort to realize the P5 timeline for the muon shot

Post P5 - scientifically

- Accelerator, Experimental and Theory communities have continued to make progress as well as working together in an unprecedented manner
- While awaiting an official response to relevant P5 recommendations from funding agencies, the US community has been proactive utilizing experimental/theory base grants, LDRD, university specific funding, private sources, and theory institutes for workshop funding
    - Important to note that currently the *majority* of funding for muon collider R&D efforts is European and we should maximize our efforts internationally
- The next few slides contain examples of recent progress in each frontier - but to make sufficient progress to match the P5 decision points requires directed muon collider funding (especially for accelerators)

Theory Progress

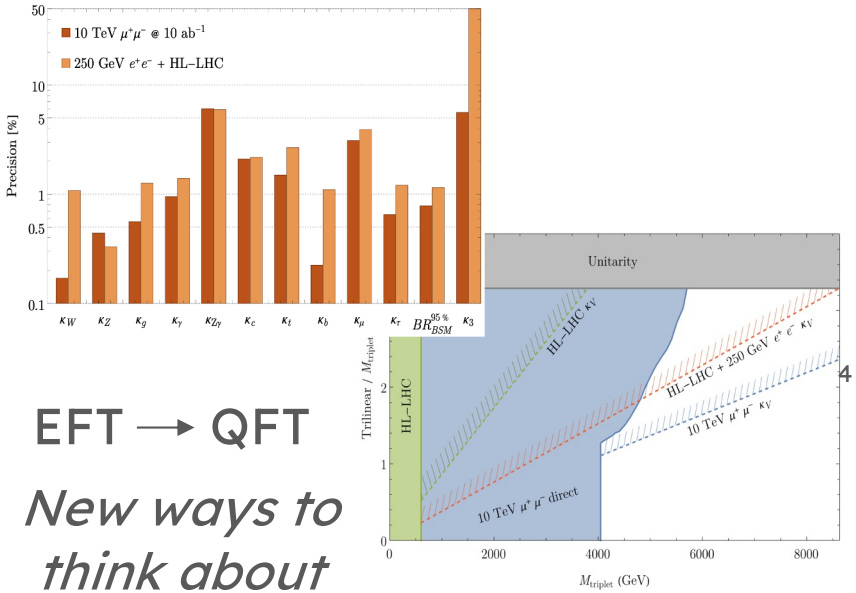
Strong recent theory engagement once 10 TeV scale+precision was viewed as realistic



100+ papers with muon collider in the title have appeared on the hep-ph arXiv since the start of the recent Snowmass

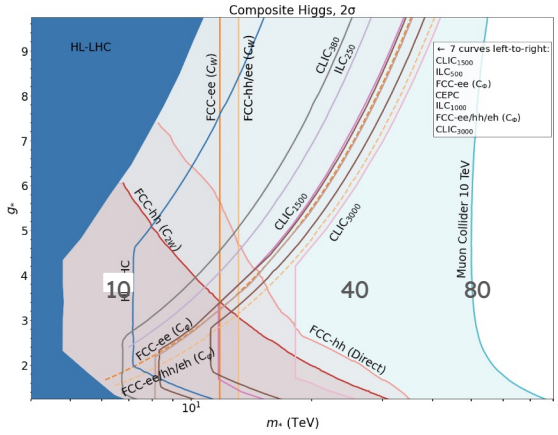
Theory progress post P5

- Prior focus on asking similar questions to e+e- or pp colliders @ muC
- Moving to unique capabilities muons offer and new questions that can be asked



EFT ⟶ QFT

New ways to think about precision



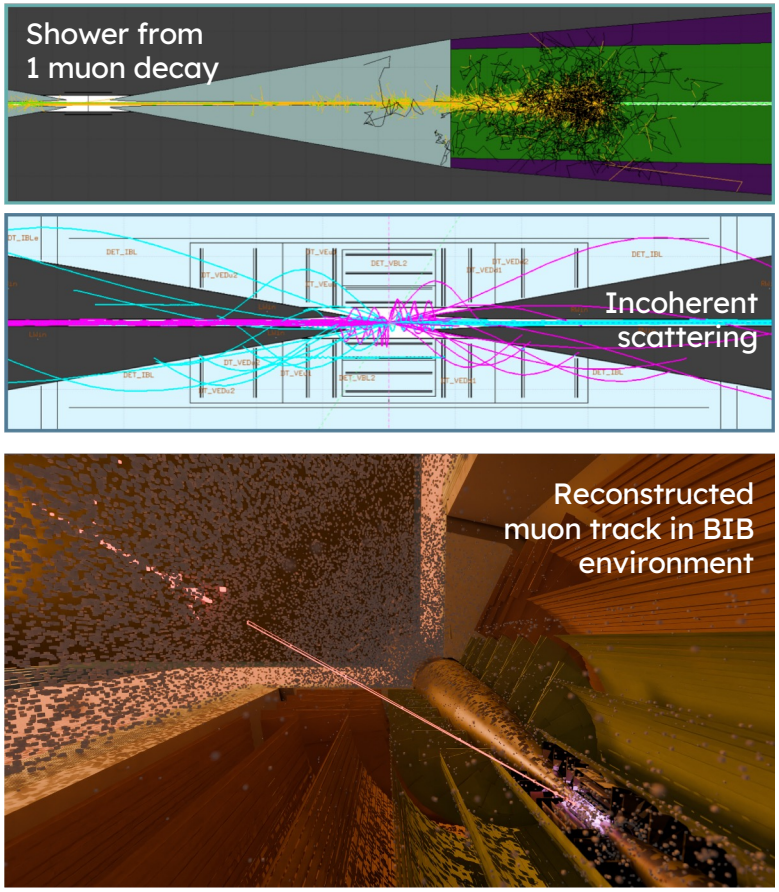
Indirect reach well beyond 10 TeV

Focus Topics:

Neutrinos
Dark Sectors
Flavor
New SM phenomena

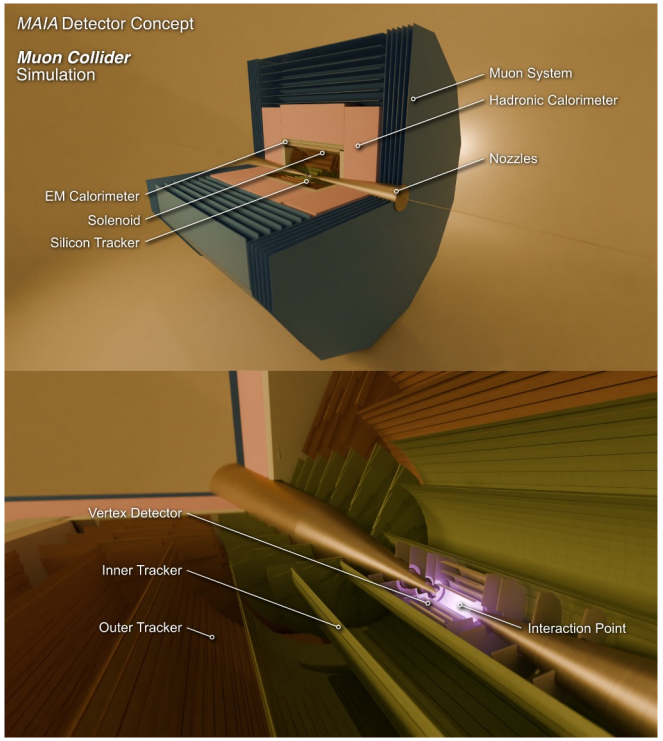
Experimental Challenge

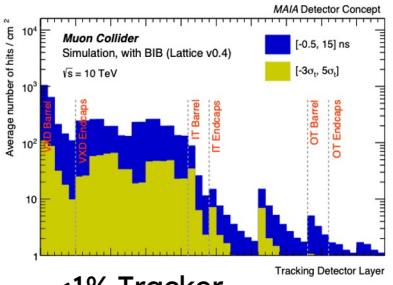
- **Beam-Induced Backgrounds** dictate detector design and technologies
- Major progress in the recent years in developing strategies on how to **suppress** the backgrounds:
  - Refining full-sim workflow to study impact
  - Improving the Interaction Region design
  - Optimizing shielding nozzles in forward region
  - Investigating high-resolution 4D detector technologies and developing novel algorithms to employ this info
  - Suppressing incoherent e+e- with magnetic fields
- **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



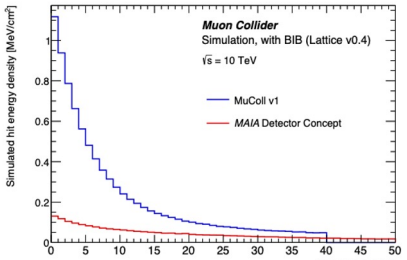
Experimental Progress and Needs

- Two design concepts (MAIA and MUSIC) for a 10 TeV detector
  - Good physics performance achievable with both
  - One (MAIA) primarily developed by US institutions
- Detector technologies are **near-term**:
  - Can reach assumed timing and feature-size specs individually, but further development needed to integrate, scale, and maintain low power
- Integrated doses similar to HL-LHC
- Rely on strong central solenoids: ~5T, ~1m radius, which require development
- Detector **R&D needed**:
  - *With investment*, should be ready to maximize physics potential by the time accelerator technology is ready





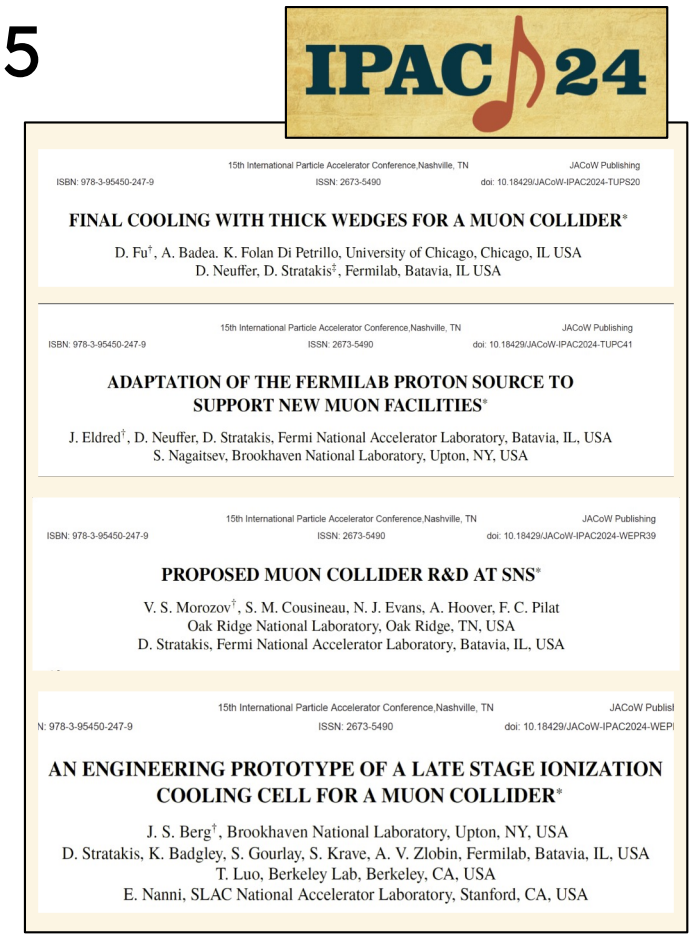
<1% Tracker Occupancy



Reduced ECAL Backgrounds

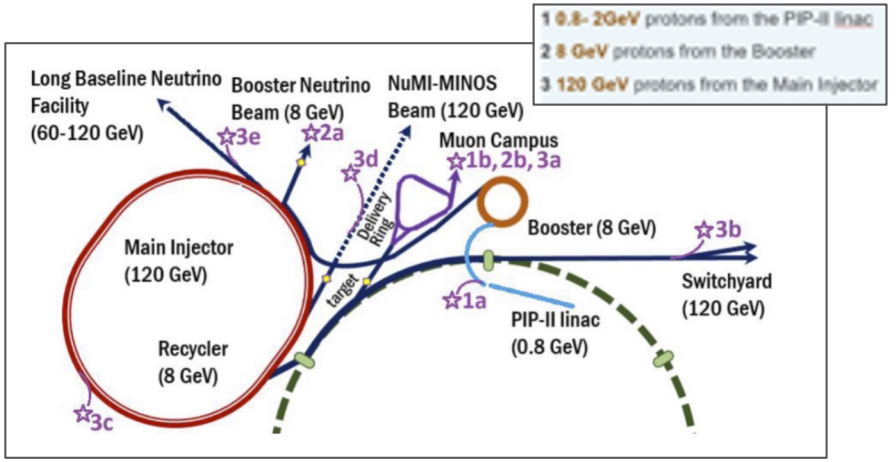
US Accelerator Engagement post P5

- Significant progress in Final cooling
  - New schemes have been proposed and simulated
- A study towards prototyping one of the late 6D cooling cells has begun
- Tie-ins with **existing infrastructure**:
  - Studying ways for adapting the Fermilab proton source towards a Muon Collider
  - Exploring use of the ORNL SNS linac for Muon Collider proton driver R&D



Accelerator Progress

- A study towards a Muon Collider Demonstrator at Fermilab has begun (LDRD proposal)
- BNL AS&T LDRD 25-042 (Collider R&D)
  - Palmer/Nagaitsev/Fischer
  - MC Topics:
    - RCS Design (focus on FNAL siting)
    - Cooling Cell Engineering Concept (for a MC Demonstrator)
- Hosted the IMCC Demonstrator Workshop at Fermilab
  - 100+ participants from around the world
  - Exchanged ideas over a Muon Collider Demonstrator Program



Organized scientific progress - Formation of USMCC

- Formation of USMCC to help execute the **P5 MC recommendations**
  - Define necessary work for mid-P5 panel
  - Engage with the international community
  - Design a US demonstrator
  - Create a long-term vision for Fermilab that leads to a muon collider
  - Build on a theory-driven physics case
- **Goal:** Maintain the strong coupling between acc/exp/th to realize the P5 vision
  - ***But additional organization and funding is required***
- *The US community is clearly ready to make rapid progress given the grassroots advances made since P5*

The USMCC Vision

- **Core Purposes:**
  - Help organize US activities
  - Serve as an interface with the international community (IMCC)
  - Prepare a US site proposal for a cooling demonstrator
  - Prepare a US site proposal for a collider in line with the P5 recommendations

- **Key Goals:**
  - Build on the progress demonstrated during Snowmass of the joint Accelerator, Experimental and Theory community effort
    - Create an organization that continues to maximize these joint efforts
  - Engage with all parts of the US scientific community interested in muon beam capabilities
    - Build on the exponential growth seen in recent years
  - Provide a grassroots organization to interface with the funding agencies, oversight panels, and strategy processes
  - Explore synergies with other areas of HEP (neutrino, CLFV, Beam Dump, etc)

Input to European Strategy Process

- The IMCC is preparing a submission to the European Strategy Process
  - A comprehensive document 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 will be 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

US Muon Collider Community Input to the ESPPU

- The US Muon Collider Community is planning a short submission to the European Strategy process
- Goals of this input:
  - Summarize US activities and plans - reflecting recent community wide meetings
  - Describe the requested US resources/Demo proposal
  - Emphasize that common goal is worldwide R&D effort for realization anywhere
- The document will be aligned with the 2023 P5 report
- Initial drafting has started, to be followed by further feedback from the community and IMCC in time for March submission

Goals for the future

USMCC goals:

- Finalize collaboration to ensure accelerator, experimental and theory communities stay coupled and engaged
- Stay on track with P5 recommendations:
  - Advance designs for a demonstrator to meet mid-P5 decision point (~ few years)
  - Accelerate work on other R&D needs
  - Dedicated funding is *required* to follow P5 plan
- Balance MuC-specific efforts with applicable generic R&D
- Continue on path towards a US Energy Frontier future

Can't do it alone:

A US-CERN agreement regarding participation in IMCC needs to be finalized ASAP

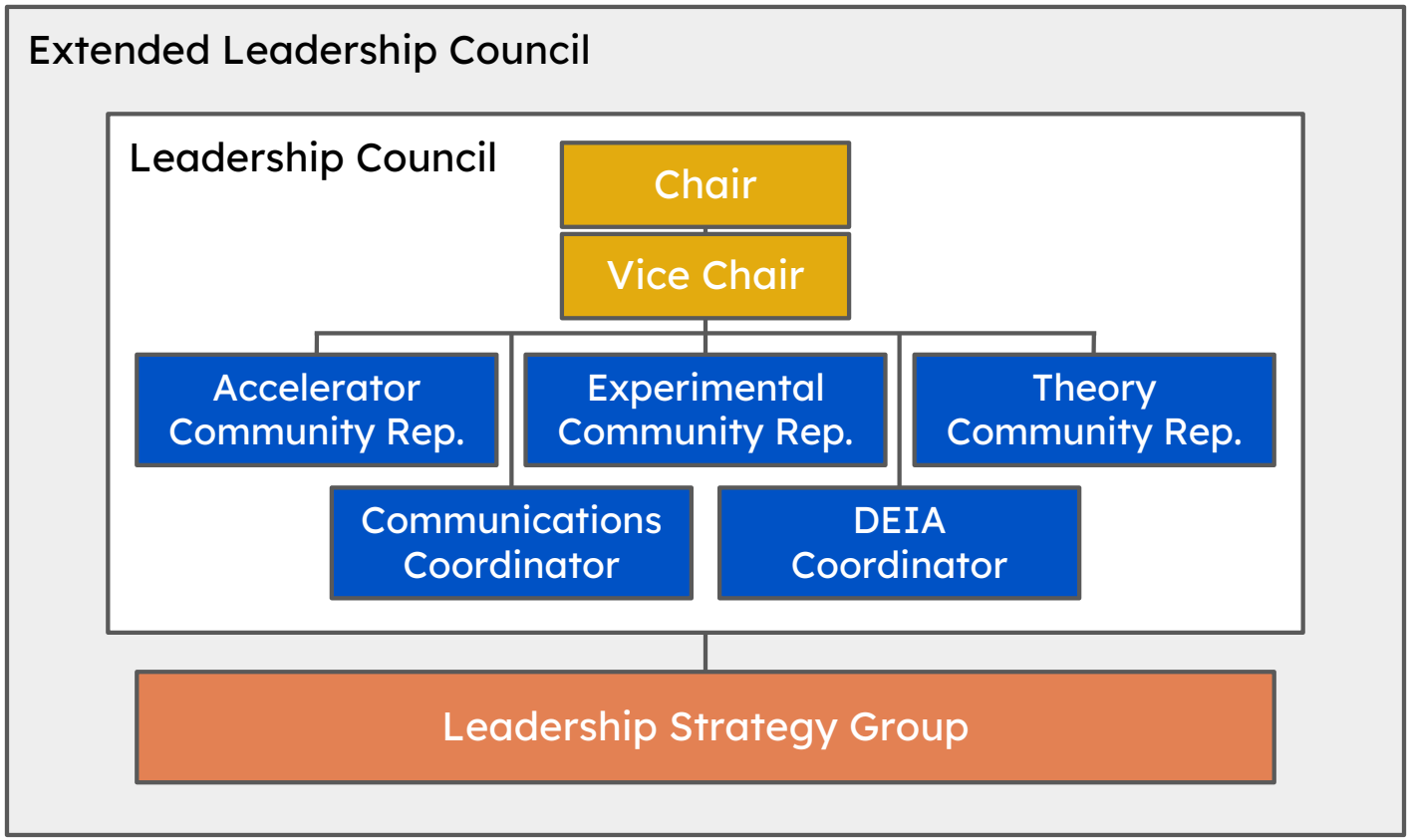
We need R&D support from both the US and abroad simultaneously to realize this vision

Backup

Things the USMCC is not

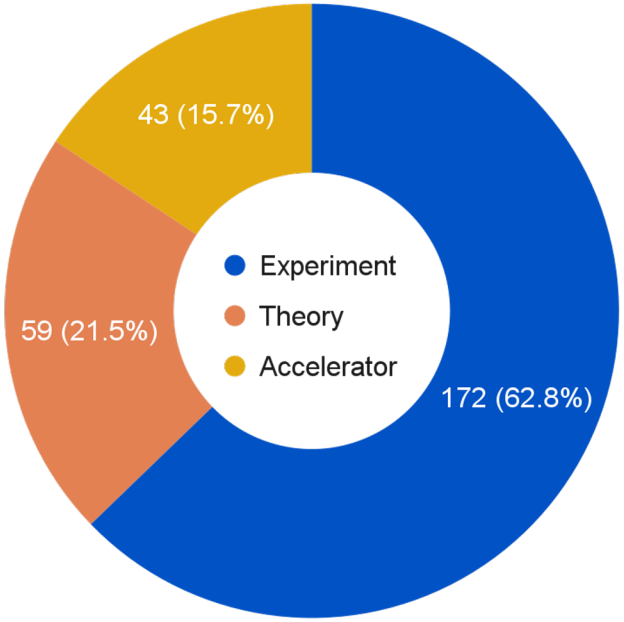
- USMCC does not replace the IMCC
  - In the future the IMCC could potentially be hosted in the US depending on outcome of future European strategy processes and implemented plans
- Future US pre-projects or projects are entirely separate but this community organization can be helpful for scientific advisory purposes. Future collaborations e.g. detector collaborations are entirely distinct
- Given that a muon collider would be unique and present new technological and physics opportunities, this organization would continue to tie together acc/exp/th communities unlike prior colliders and persist into the future alongside other organizations

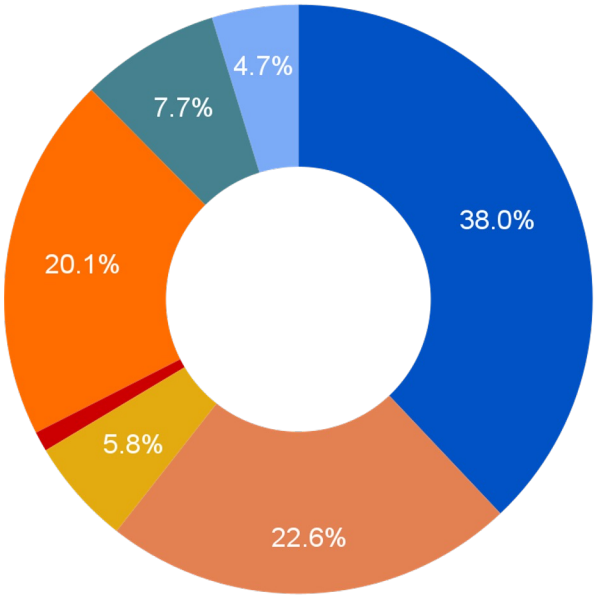
USMCC structure

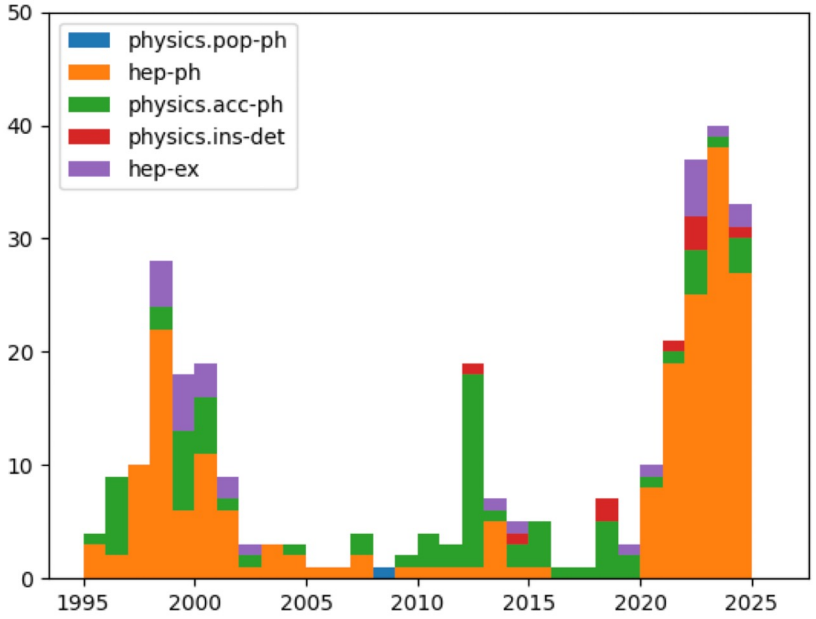


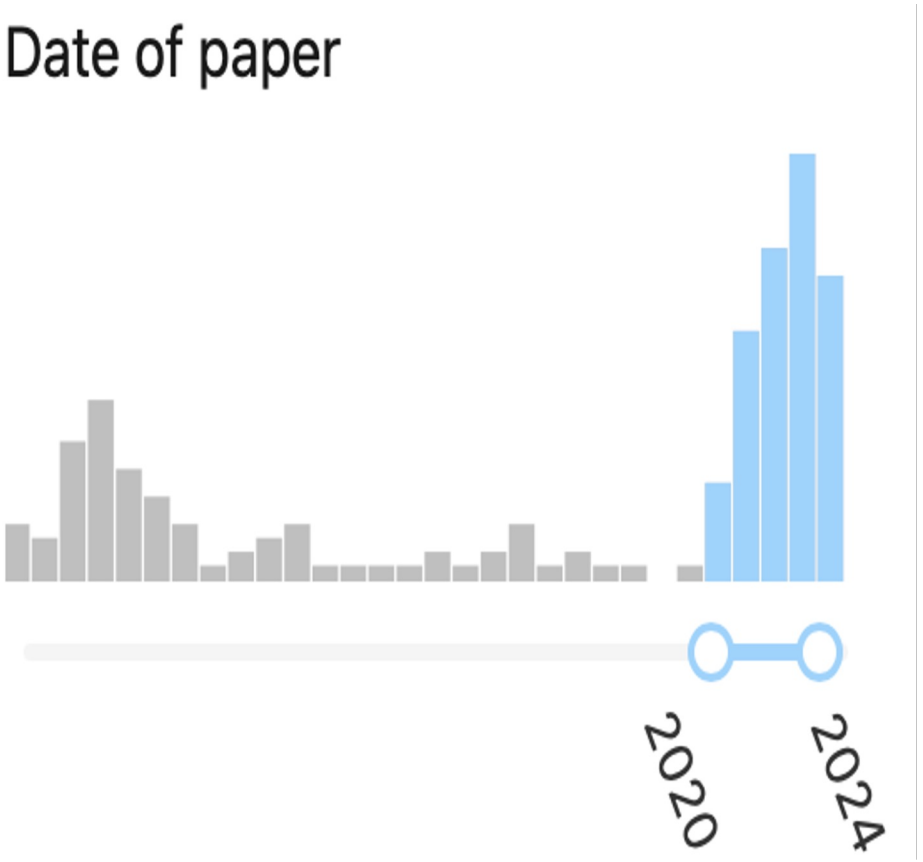
Inaugural Meeting Participants

274 Registrants
+25 Remote






physics.pop-ph
hep-ph
physics.acc-ph
physics.ins-det
hep-ex
50
40
30
20
10
0
1995
2000
2005
2010
2015
2020
2025


Date of paper
2020
2024

Theory-Experiment & Theory-Accelerator Synergies

- Theory - Experiment interplay for detector design
  - Design strongly influenced by BIB mitigation
  - Performance targets set by diverse set of physics targets
    - EW/Higgs Precision, High pT searches, and exotic signatures (e.g. LLP)
  - Special detector needs set out by theory for high energy muC
    - E.g Inclusive cross sections, Invisible Higgs decays -> Forward muon detectors, luminosity monitors, etc
- Theory - Accelerator interplay for accelerator design
  - Accelerator staging, both energy and luminosity targets
    - What are optimal energy targets before 10 TeV
    - What are ranges of luminosity possible for physics goals
  - What physics can be done with demonstrator facilities and auxiliary experiments e.g:
    - Neutrino factory possibilities
    - Beam dump experiments