μC for EPP in the U.S. and the World

Based on Your Work Since the 90's

smaria@caltech.edu

University of Chicago
2nd Annual Muon Collider Meeting
August 7-8 2025

August 7, 2025

Table of Contents

Table of Contents

U.S. Tunnel Visions & Status

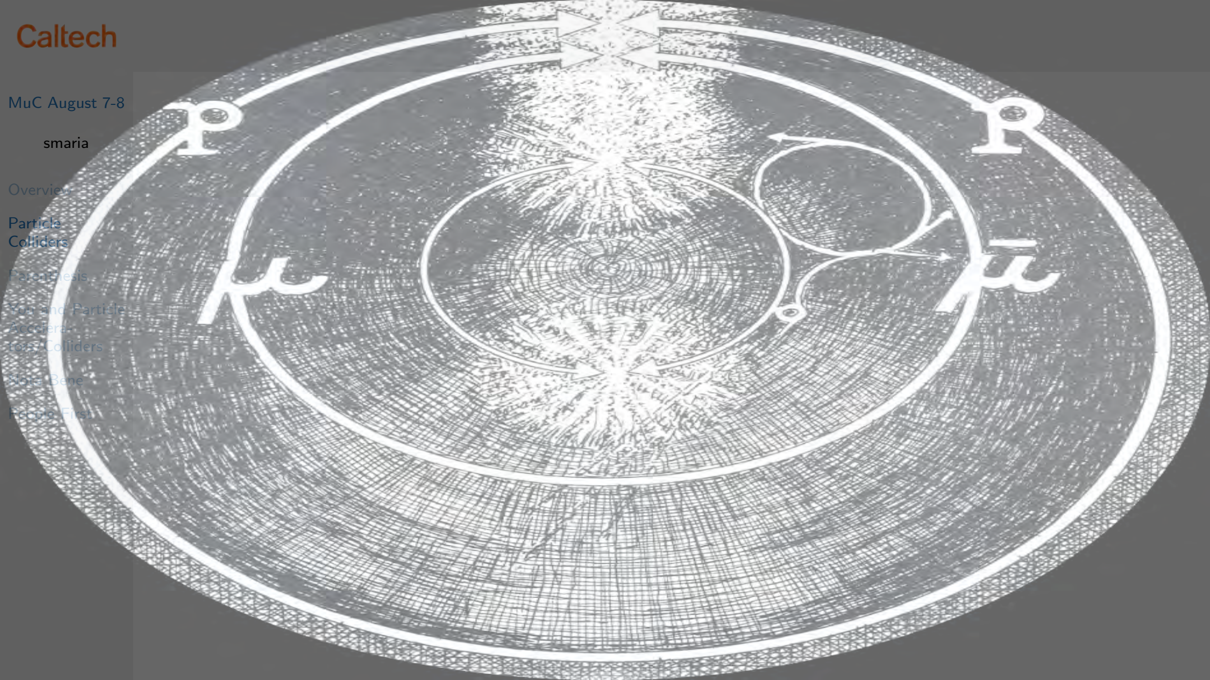
- **Vision:** U.S. involvement and leadership in new accelerator projects to realize stunning opportunities in particle physics.
- **Current Projects Under Construction:**
  - **LBNF/DUNE in the U.S.:** Expected to begin science operations around 2030.
  - **HL-LHC at CERN:** Also expected to begin science operations around 2030.
  - Both projects are anticipated to continue operations for 10 years or more.

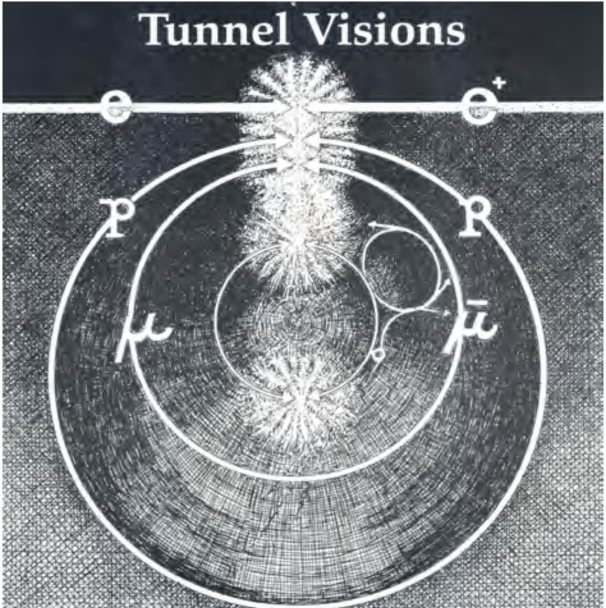
Future Collider Projects & Sequencing

- **Muon Collider:**
  - **R&D:** Essential to begin as soon as possible (estimated ≈7 years).
  - **Demonstrator Construction:** Ideally starts soon after DUNE begins science operations (lasts ≈10 years).
  - **Full Construction (if feasible):** Could begin around the time FCC-ee science operations start.
- **FCC-ee (CERN):**
  - **Construction:** Could begin around the same time as the muon-collider demonstrator.
  - **Role:** Ensures intensive Higgs studies and particle physics progress while a muon collider is being built in the U.S.
- **100-TeV Proton Collider:** Potential project beyond the 40-year horizon, extending discovery reach.
- **Urgency:** Scientific urgency and national imperative to act now to maintain U.S. momentum, leadership, and talent in a competitive and fast changing world.

Caltech

Table of Contents


p
p
μ
μ̄


Tunnel Visions
e
e+
p
p
μ
μ̄

Tunnel Visions is a series of eight two hour sessions on possible future accelerator options for Fermilab. The leading proponents of Linear Colliders, Muon Colliders, and Very Large Hadron Colliders will be challenged by a group of four conveners in each session.

Muon Collider: Scientific Potential

- Combines advantages of electron/positron and proton colliders.
- Enables precision measurements due to point-like muon collisions.
- Capable of reaching the 10 TeV energy frontier.
- Offers significant advantages in operating costs and energy consumption.
- Potentially fits on the Fermilab site, leveraging existing neutrino physics strength.

Muon Collider: Technical Challenges

- Novelty presents unknown operational challenges for colliding unstable particles in high numbers.
- Critical technical challenges in producing, compressing, controlling, and colliding muons.
- Muons decay rapidly (millionth of a second at rest), requiring extremely rapid acceleration and collision.
- Ionization cooling is a major challenge, requiring beam squeezing by a factor of a million.
- Diverse RF systems (room-temperature and superconducting) needed across a wide frequency range.

Muon Collider: Feasibility & Future Steps

- Immediate initiation of R&D towards feasibility is essential (estimated ≈7 years).
- Demonstrator construction to follow R&D (estimated ≈10 years), ideally after DUNE operations begin.
- A decision on feasibility is critical around the time FCC-ee science operations commence.
- The technology demonstrator is not yet precisely defined.
- Norbert Holtkamp: "12 [engineering] miracles need to be performed to make a muon collider feasible," with the 13th miracle probably being systems integration.
- Host the world's highest energy elementary particle collider by mid-century is no walk in the rose garden.

FCC-ee: Key Aspects

- A proposed "Higgs factory" at CERN, colliding electrons and positrons.
- Designed to produce millions of Higgs particles for high-precision measurements.
- Would occupy a new 90 km tunnel with four interaction points.
- Science operations could potentially begin as early as the mid-2040s.
- The tunnel could be repurposed for a 100 TeV proton-proton collider (FCC-hh) in the future.
- Considered the most advanced Higgs factory project in terms of implementation, with completed feasibility studies.
- Offers additional capabilities for precision electroweak measurements, top quark studies, and new physics searches.
- U.S. participation is crucial for scientific advancement, international collaboration, technological leadership, and training.

Caltech

Table of Contents

The Yellowstone Story: Wolves Return

- In 1995, wolves were reintroduced to Yellowstone National Park after a 70-year absence.
- Their reintroduction led to a significant decrease in the elk population, which had overgrazed the park.
- Less grazing allowed vegetation, particularly aspens and willows, to recover along riverbanks.

Ripple, W. J., & Beschta, R. L. (2012). "Trophic cascades in Yellowstone: The first 15 years after wolf reintroduction". Biological Conservation, 145(1), 205-213. https://www.sciencedirect.com/science/article/abs/pii/S0006320711004046

The Yellowstone Story: Ecosystem Restoration

- The regrowth of trees stabilized riverbanks, reducing erosion and creating new habitats.
- Beaver populations increased due to more willow trees, building dams that further diversified the landscape.
- This led to a rise in various species, including birds, fish, and other mammals.
- The entire ecosystem, from plants to rivers, was transformed and restored through this trophic cascade.

Caltech

Interdependence in Particle Physics

- International collaboration is vital for a thriving particle physics ecosystem.
- The program of activities needed to address the agenda of particle physics is beyond the resources – human and fiscal – of any single nation, and planning and coordination are essential to success.
- Particle physics programs of CERN and the United States have become interdependent to the mutual benefit of both. American involvement at CERN is now a major element in the U.S. program.
- The United States must work to strengthen international planning and coordination on all levels.It is important for the United States to be more involved in the decision-making process.
- Without the international collaboration as successfully demonstrated at CERN, maintained with critical FCC-ee contributions and leadership, it will be impossible to build the muon collider in the U.S.

Particle Physics: A Complex Adaptive System

- Particle physicists gave birth to the World Wide Web (WWW).
- The field itself operates as a Complex Adaptive System (CAS):
  - **Interdependent Components:** Researchers, experimental facilities (e.g., LHC, detectors), data analysis tools, theoretical frameworks, and funding bodies.
  - **Dynamic Interactions:** Continuous feedback between theoretical predictions and experimental results, leading to new discoveries and refined understanding.
  - **Adaptation & Evolution:** The field constantly adapts to and invents technological advancements (e.g., accelerator, detector upgrades), new data, and evolving scientific questions.
  - **Emergent Properties:** Breakthroughs (e.g. Higgs boson discovery) and revolutionary technologies emerge from these complex, collaborative interactions.
  - **Resilience & Vulnerability:** Its health relies on sustained international collaboration, funding, and the continuous development of new talent and technologies.

Table of Contents

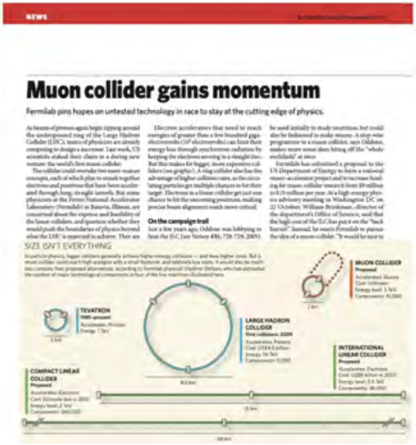
Navigating Your Particle Physics Trajectory

- As a junior faculty member, your career builds on 7-10 years of intensive graduate and postdoctoral work.
  - This includes experience with modern data analysis (including ML/AI), and operating/upgrading cutting-edge detectors.
  - You have contributed to the current EPP program, extracting science results and publishing papers.
- Your next 10-15 years offer a rich trajectory in current and upcoming experiments with googles and googles of data, yielding significant scientific output.
- Concurrently, for the next 10-20 years, you have the opportunity to **design, build, and guide students** in the ambitious projects you are passionate about (e.g., Muon Collider, FCC).
- This path is a chance for challenging "marshots" and beyond – lots of learning and invention.

Navigating Your Particle Physics Trajectory

- Your greatest reward will likely be the students and postdocs you train, who will hopefully surpass you in capacities, if not also in wisdom.
- This serious work contributes to the resilience and sustained growth of the complex adaptive particle physics system.

I want my μC.



NEWS

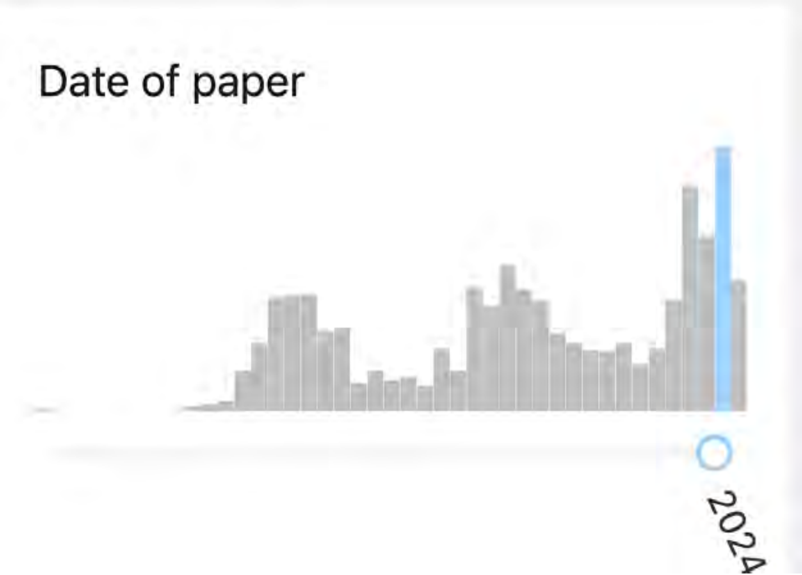
Muon collider gains momentum

Fermilab pins hopes on untested technology in race to stay at the cutting edge of physics.

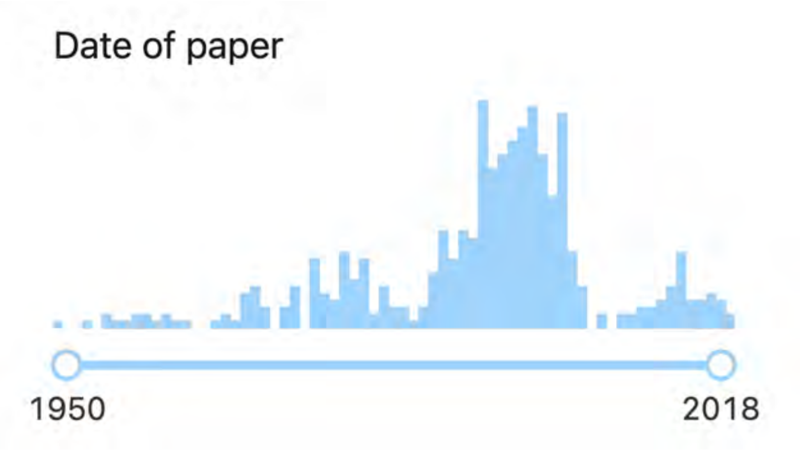
On the campaign trail

SIZE ISN'T EVERYTHING

I want my μC.



157,μC


Date of paper
1950
2018

Caltech

I want my μC.

MuC August 7-8

smaria

$\mu^+\mu^-$ Collider: Feasibility Study

J.C. Gallardo (Brookhaven), R.B. Palmer (Brookhaven), A.V. Tollestrup (Fermilab), A.M. Sessler (LBL, Berkeley), A.N. Skrinsky (Novosibirsk, IYF)

Jul, 1996

481 pages

Part of 1996 DPF / DPB Summer Study On New Directions For High-Energy Physics: Proceedings, Snowmass 1996

Published in: eConf C960625 (1996) R4

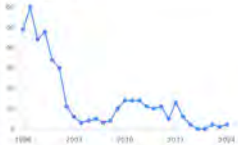
Contribution to: Snowmass 96

Report number: SLAC-R-988, BNL-52503, FERMILAB-CONF-96-092, LBL-38946, LBNL-38946

View in: OSTI Information Bridge Server

pdf links cite reference search 416 citations

Citations per year



Abstract:

A feasibility study is presented of a 2+2 TeV muon collider with a luminosity of $L=10^{35} cm^{-2} s^{-1}$. The resulting design is not optimized for performance, and certainly not for cost; however, it does suffice--the authors believe--to allow them to make a credible case, that a muon collider is a serious possibility for particle physics and, therefore, worthy of R and D support so that the reality of, and interest in, a muon collider can be better assayed. The goal of this support would be to completely assess the physics potential and to evaluate the cost and development of the necessary technology. The muon collider complex consists of components which first produce copious pions, then capture the pions and the resulting muons from their decay; this is followed by an ionization cooling channel to reduce the longitudinal and transverse emittance of the muon beam. The next stage is to accelerate the muons and, finally, inject them into a collider ring which has a small beta function at the colliding point. This is the first attempt at a point design and it will require further study and optimization. Experimental work will be needed to verify the validity of diverse crucial elements in the design.

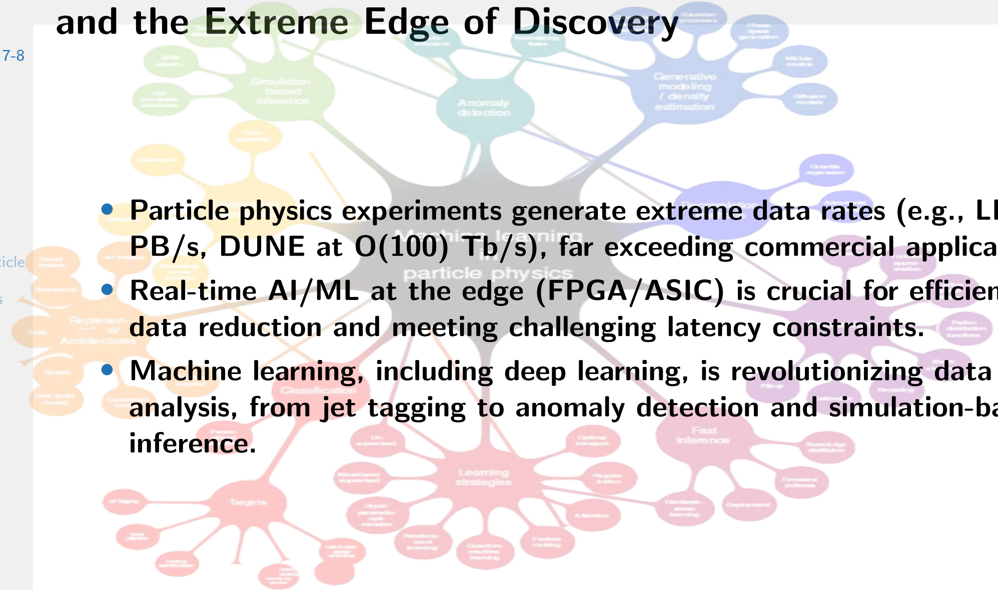
Caltech

Table of Contents

Particle Accelerators: Pillars of Discovery and Innovation

- Particle accelerators are foundational to discovery science, enabling breakthroughs from the Higgs boson to new states of matter.
- Future endeavors include the development of a U.S.-based muon collider and contributions to the Higgs Factory at CERN (FCC) – and EIC.
- Beyond fundamental physics, accelerator science drives innovation in diverse fields, including medical treatments, advanced materials, and semiconductor manufacturing (e.g., EUV lithography).

Artificial Intelligence and Machine Learning at the Center and the Extreme Edge of Discovery



- Particle physics experiments generate extreme data rates (e.g., LHC at PB/s, DUNE at O(100) Tb/s), far exceeding commercial applications.
- Real-time AI/ML at the edge (FPGA/ASIC) is crucial for efficient data reduction and meeting challenging latency constraints.
- Machine learning, including deep learning, is revolutionizing data analysis, from jet tagging to anomaly detection and simulation-based inference.

Table of Contents

Recruit, Train, Retain

- Success of the field is reliant on recruiting and retaining the very best students and postdocs from across the nation and around the world to the U.S. particle physics effort.
- These researchers form an important part of the trained technical and entrepreneurial talent that helps the United States maintain its influence in advanced technology innovation, as well as in science.
- Non-traditional funding sources such as philanthropic organizations and industry present new opportunities to support early-career scientists.

Thank You


Scott Berg (BNL)
Andre De Gouvea (Northwestern)
Karri DiPetrillo (Chicago)
Paolo Ferracin (LBNL)
Steve Gourlay (Fermilab)
Tova Holmes (Tennessee)
Walter Hopkins (ANL)
Matheus Hostert (Iowa)
Sergo Jindariani (Fermilab)
Mithlesh Kumar (BNL)
Zhen Liu (Minnesota)
Mark Neubauer (UIUC)
Isobel Ojalvo (Princeton)
Mark Palmer (BNL)
Kevin Pedro (Fermilab)
Ben Rosser (Chicago)
Emma Snively (SLAC)
Diktys Stratakis (Fermilab)
Zahra Tabrizi (Pittsburgh)
Organizing Committee

Extra

Caltech

I want the ILC!

https://www.youtube.com/hashtag/mylinearcollider