Muon Collider Experimental Overview

Sergo Jindariani (Fermilab)
Northwestern workshop by the Lake

With material from **International Muon Collider Collaboration, US Muon Collider R&D Coordination Group, Snowmass Muon Collider Forum, MAP, etc**

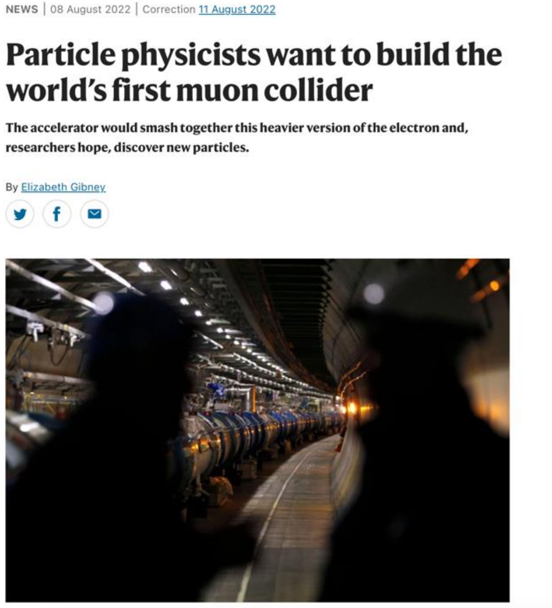
The Path to 10 TeV (excerpts from the 2023 P5 report)

- 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

BCG vaccination for cattle pp. 1410 & 1433

Steps toward regulating indoor air quality p. 1418

Landfills emit methane persistently p. 1499

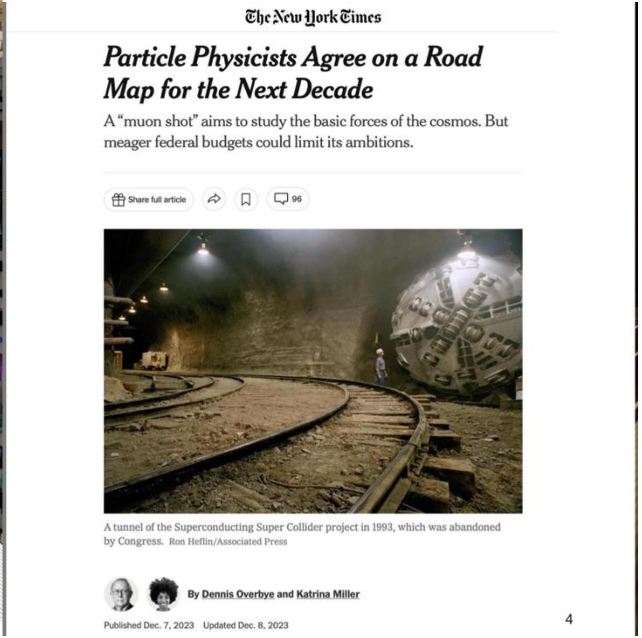
Science

$15
29 MARCH 2024
science.org
AAAS

A radical new particle accelerator concept emerges. Call it physicists'

MUON SHOT

p. 1405



The New York Times

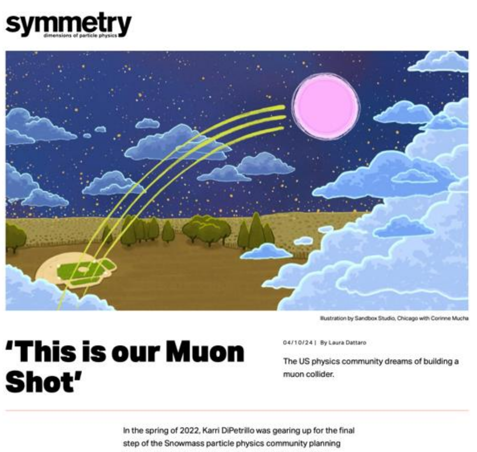
Particle Physicists Agree on a Road Map for the Next Decade

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

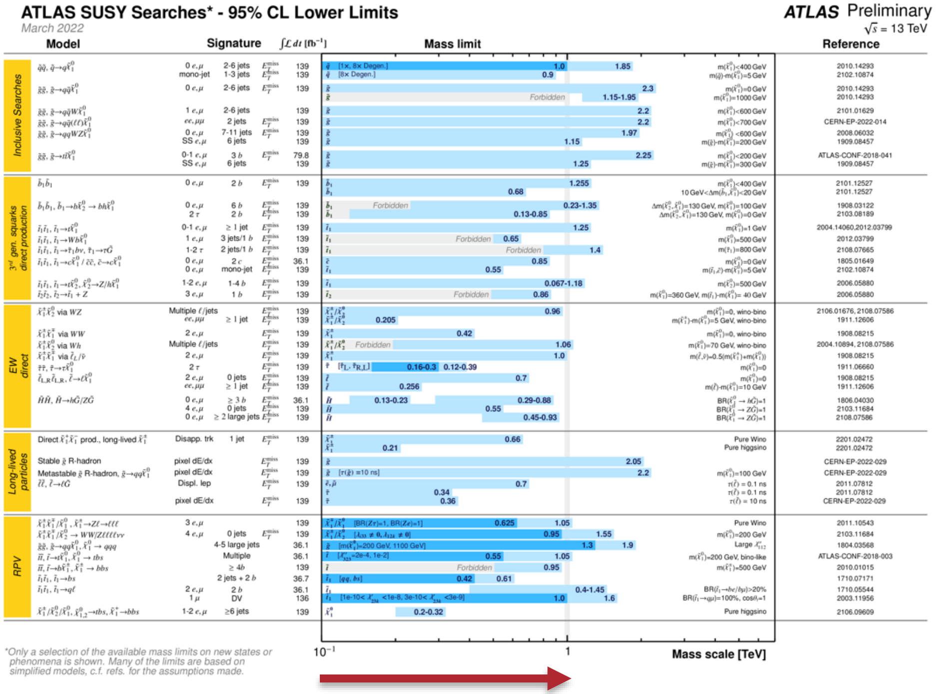
The US physics community dreams of building a muon collider.

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

Recent US Muon Collider history

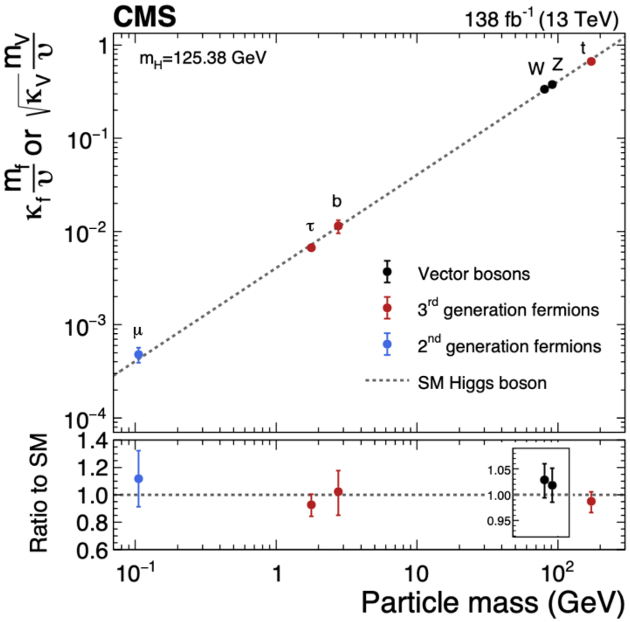
- **2021:** Following the 2019 European Strategy, Muon Colliders become part of the EU Accel. R&D Roadmap:
  - 3 Community meetings, followed by formation of the International Muon Collider Collaboration (IMCC), CERN is the host lab for IMCC
  - Regular working group meetings, large Annual Meetings, dedicated workshops, steady progress
- **2021 - 2022:** US Snowmass study reveals strong interest in 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
  - Input document submitted to P5: LINK
- **December 2023:** P5 Report released
- **February 2024:** Invitation-only PI meeting in Princeton focused on R&D Priorities. Summary document: LINK
- **August 2024:** First US Muon Collider Community meeting with 300+ participants

Why 10 TeV?



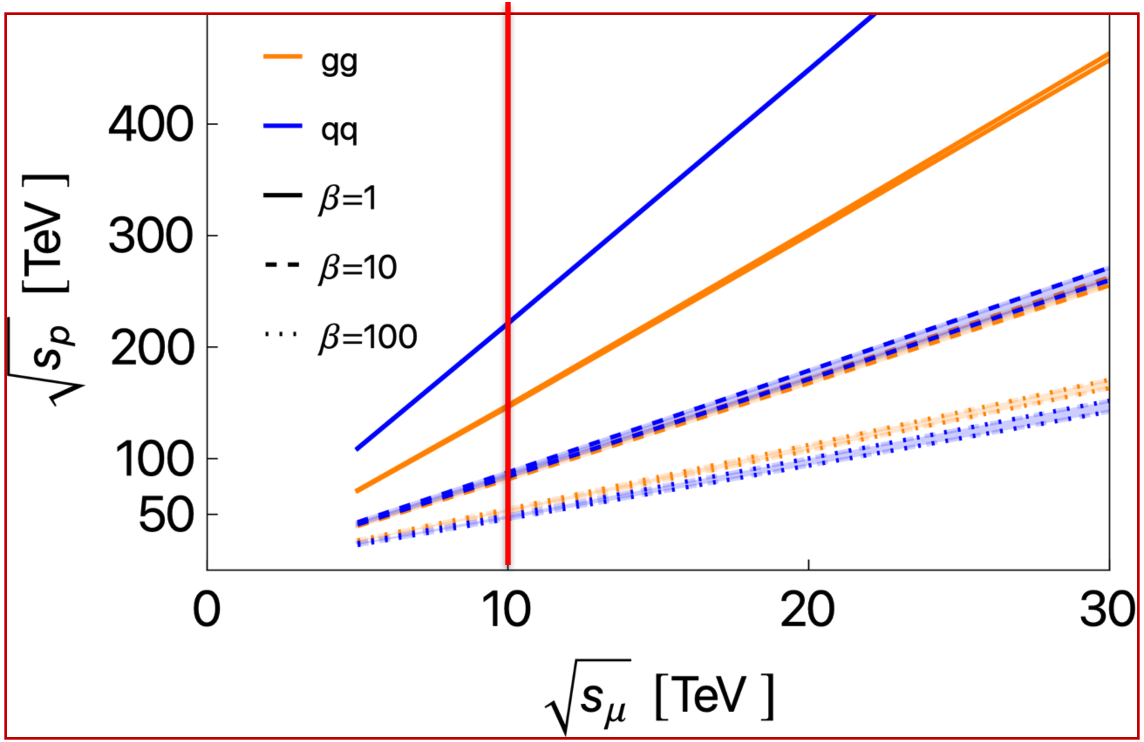
ATLAS Summary of SUSY Searches

CMS Higgs couplings

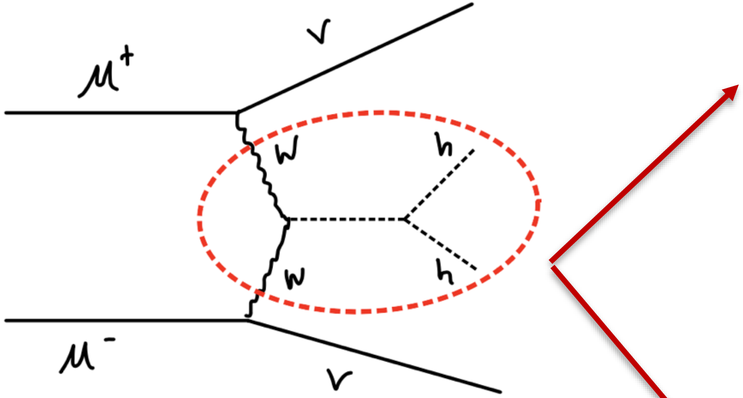


Several % coupling implies roughly the TeV scale for NP which could cause such a deviation

Physics


gg
qq
β=1
β=10
β=100
400
300
200
100
50
0
10
20
30
$\sqrt{s_p}$ [TeV]
$\sqrt{s_\mu}$ [TeV]

Physics

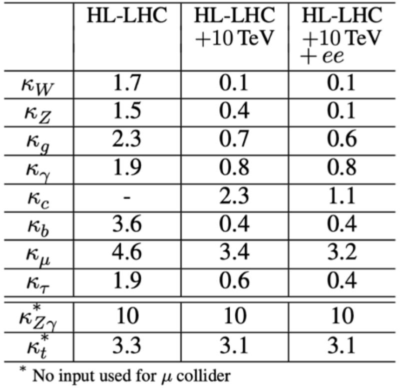


At 10 TeV:

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

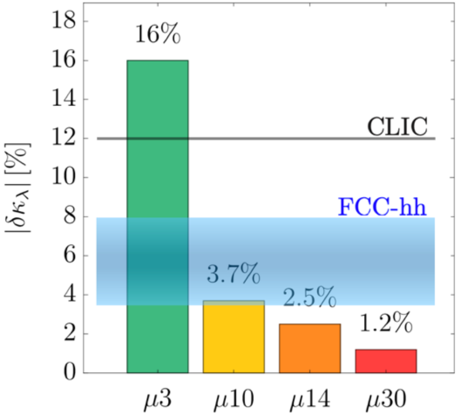
* No input used for μ collider

Order of magnitude in Higgs precision

and

can directly probe the scale implied in same machine!

Turn Higgs potential into precision science



Why Muons – size

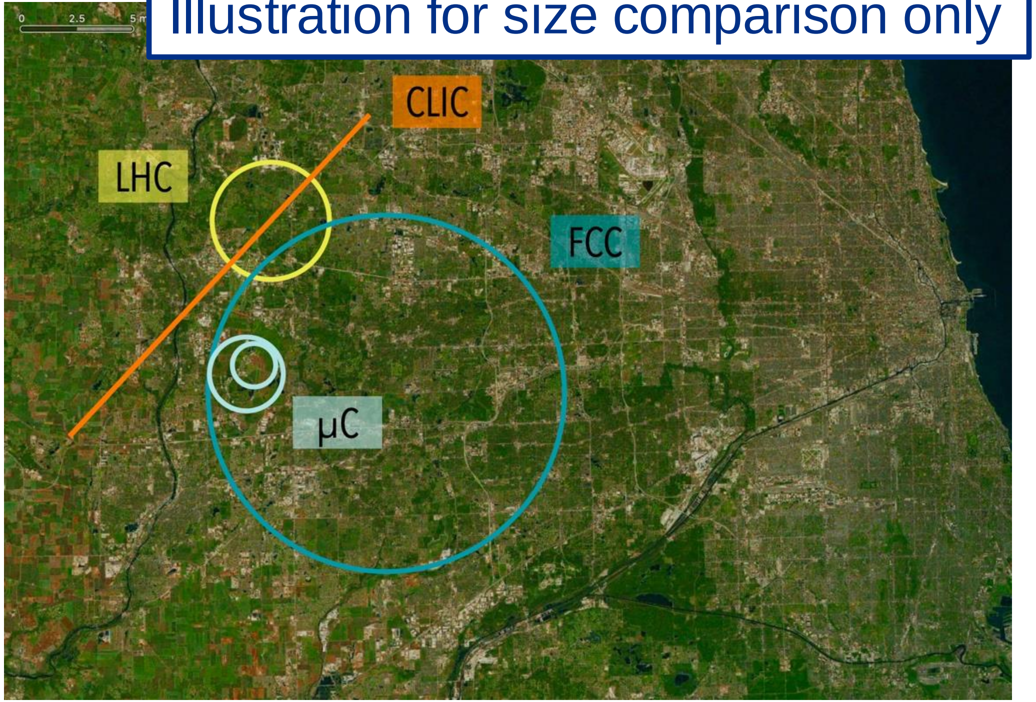
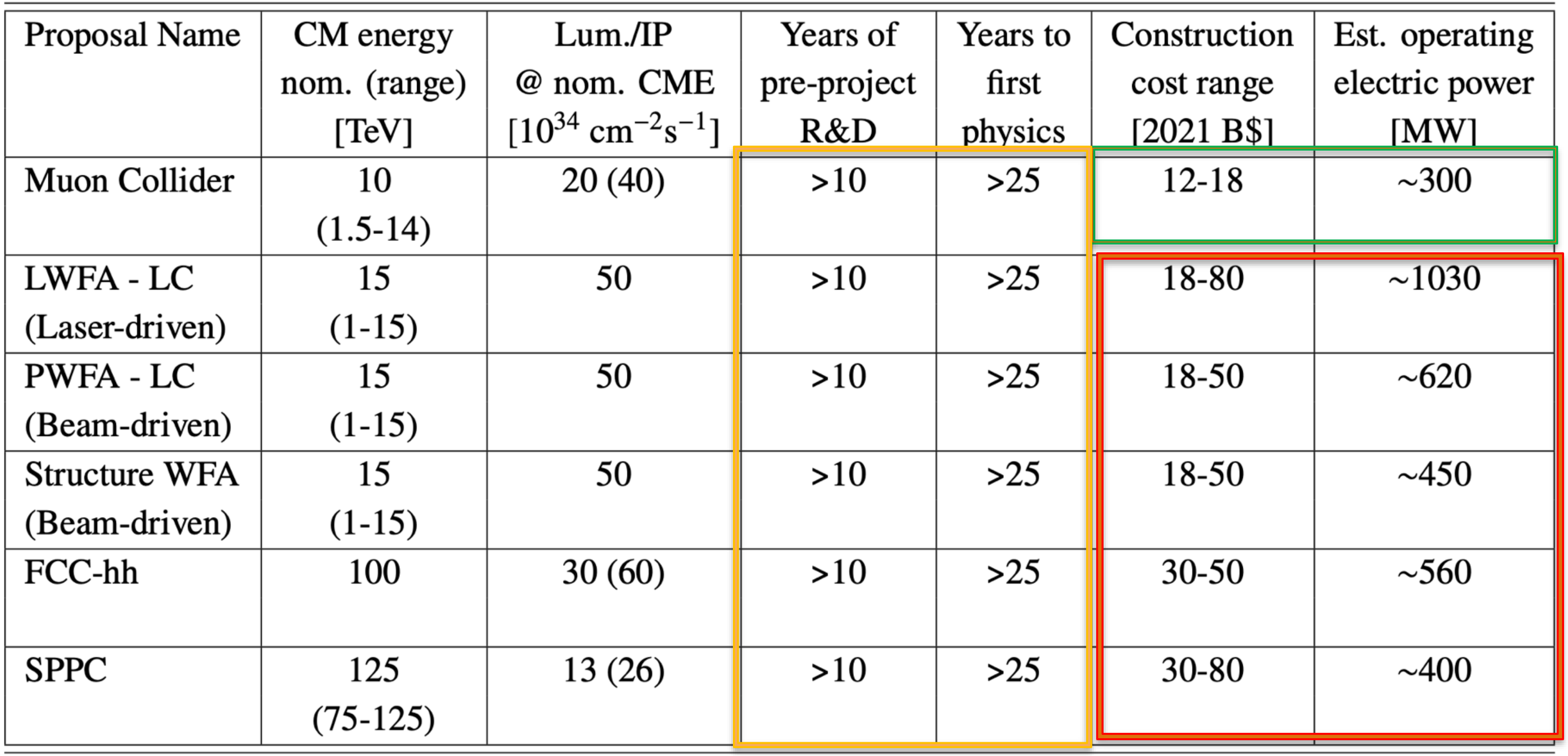


Illustration for size comparison only

Way smaller footprint than hadron colliders with equivalent physics reach

Why Muons – cost and power

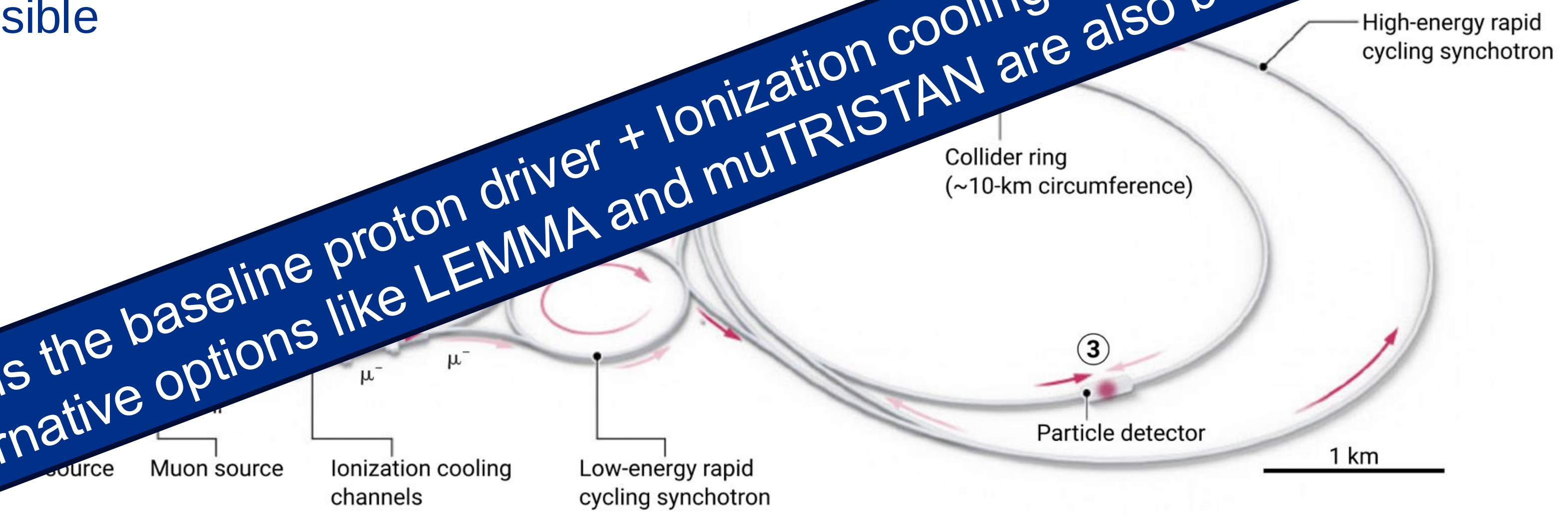
More details: Snowmass’21 ITF report



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} c driven by the Higgs physics requirements)
- **Staging in energy** (e.g. 3→10 TeV) or **in luminosi** LHC) are possible



This is the baseline proton driver + Ionization cooling based approach
Alternative options like LEMMA and muTRISTAN are also being studied

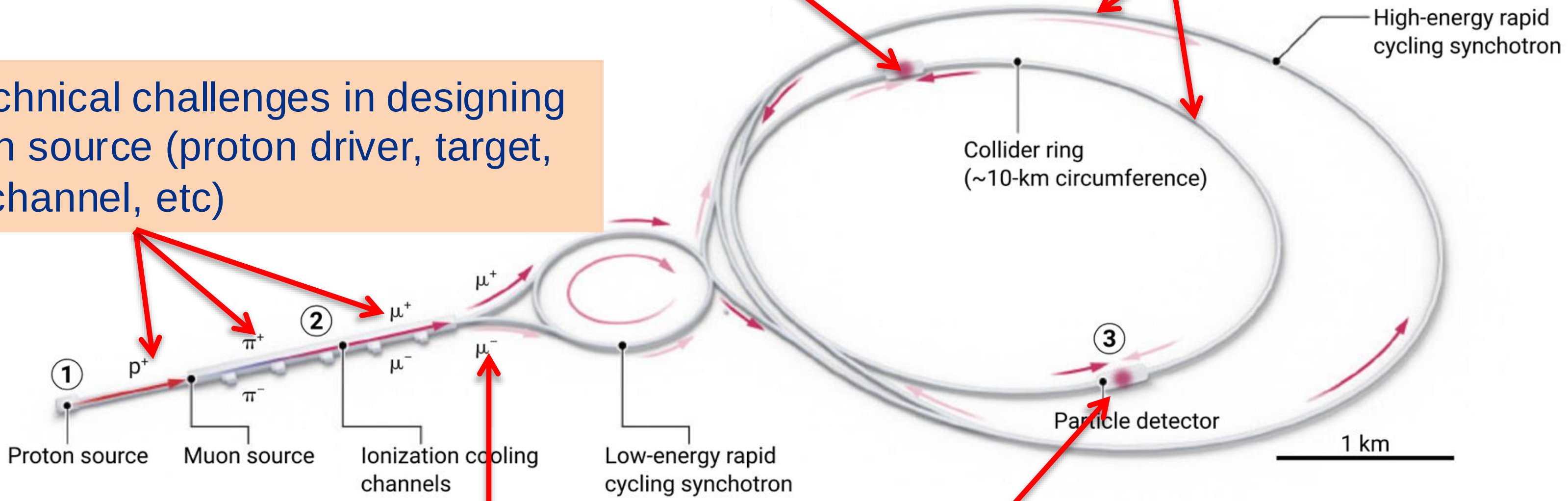
Image courtesy of A. Fisher and the Science magazine

Major Challenges

Dense neutrino flux needs to be mitigated

Challenging magnets in many places

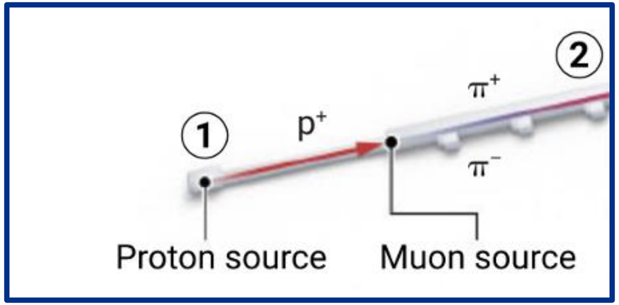
Many technical challenges in designing the muon source (proton driver, target, cooling channel, etc)



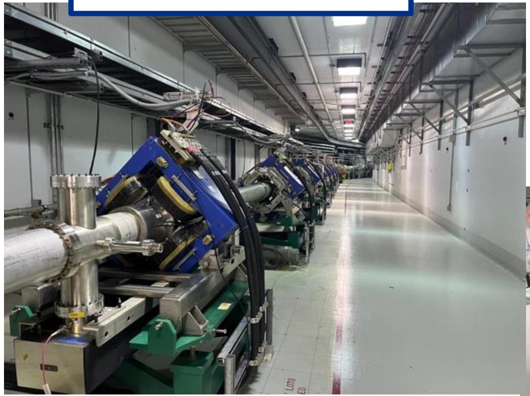
High-gradient RF for fast acceleration

Beam-induced background in the detectors

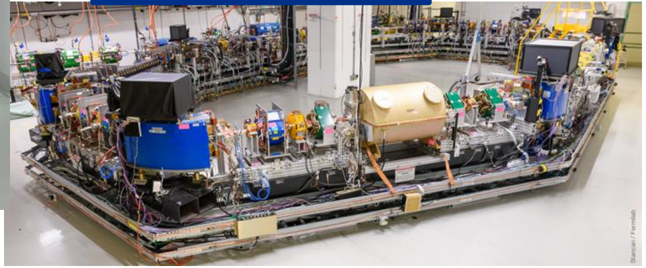
Proton Source



SNS at ORNL

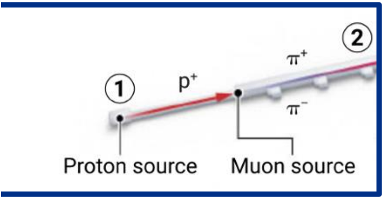


IOTA at FNAL

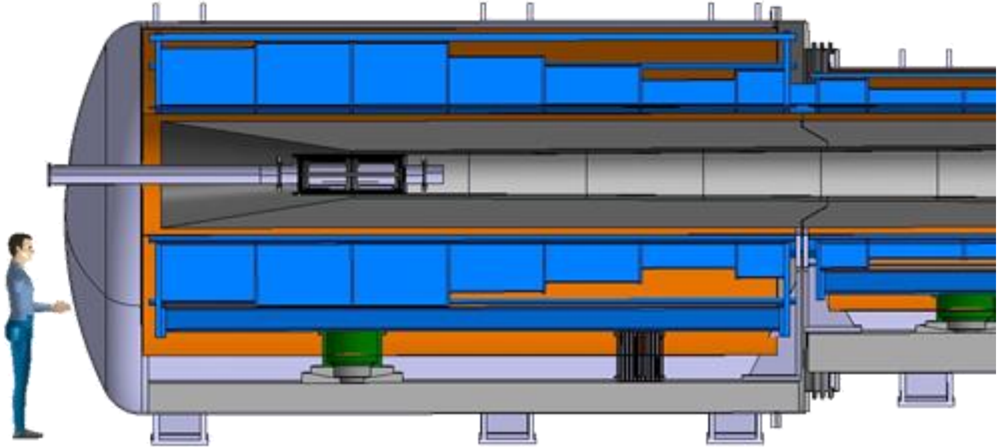


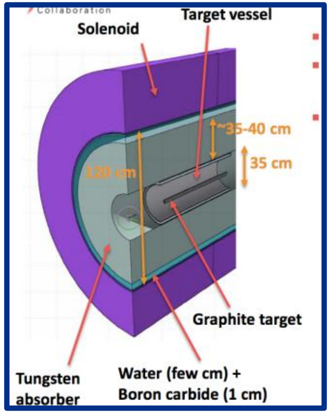
- Best performance: **1-4 MW** proton beam @ **5-20 GeV**, compressed to **1-3 ns** bunches at a **5-10 Hz** frequency
- Need to go from ranges to specific design and demonstrate that these proton beam parameters are achievable
- **Drive Fermilab Booster replacement design!**

Target and Capture



protons → in target → pions → decay → muons





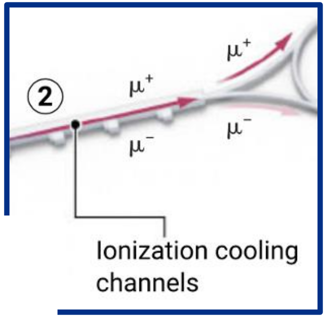
Graphite **Target**

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

Tungsten shielding
To protect magnet

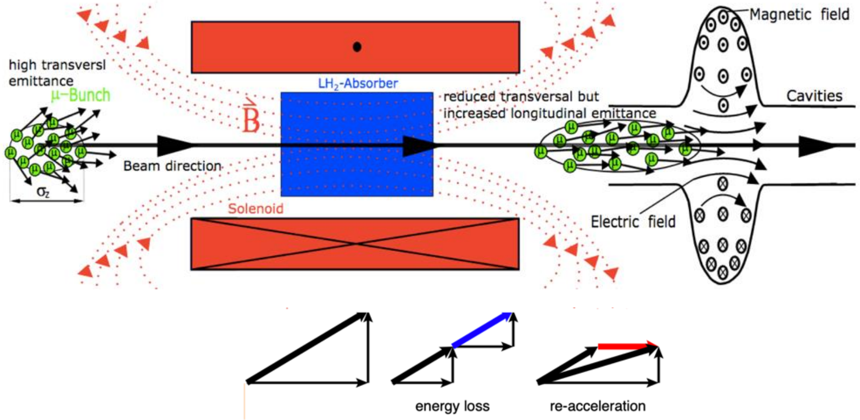
- Thermal and structural shock on the target due 2-4 MW and short proton bunches
- Study different materials, shapes, size optimization, advanced target concepts
- Focusing magnet is challenging due to field strength, size and radiation load

Ionization Cooling

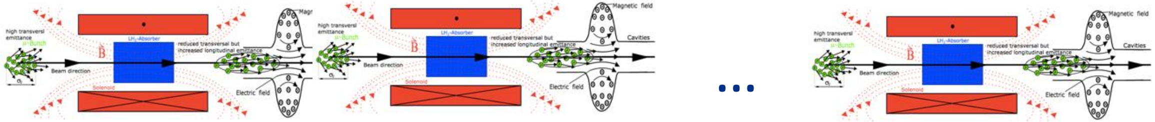


$$L = \frac{N_+ N_- n_C f}{4\pi\sigma_x\sigma_y}$$

Need to cool muons to achieve target luminosity!



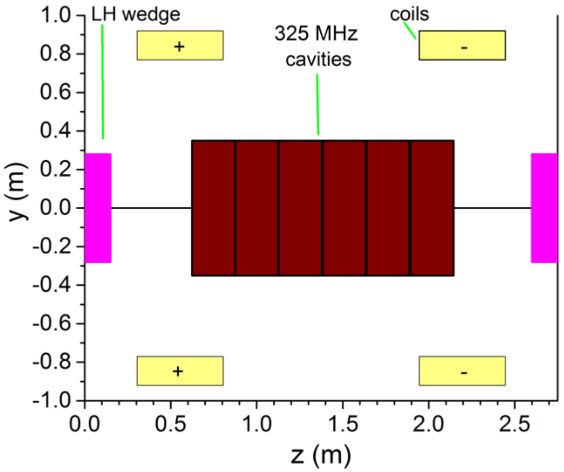
Each cell reduces emittance by ~10%. **Repeat O(100) times = cooling channel**



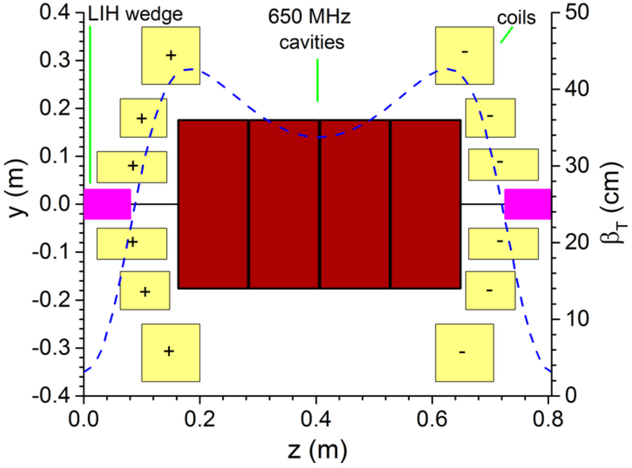
Not all cells identical

Cooling Cells

Early cell (“easy”) – 2T peak

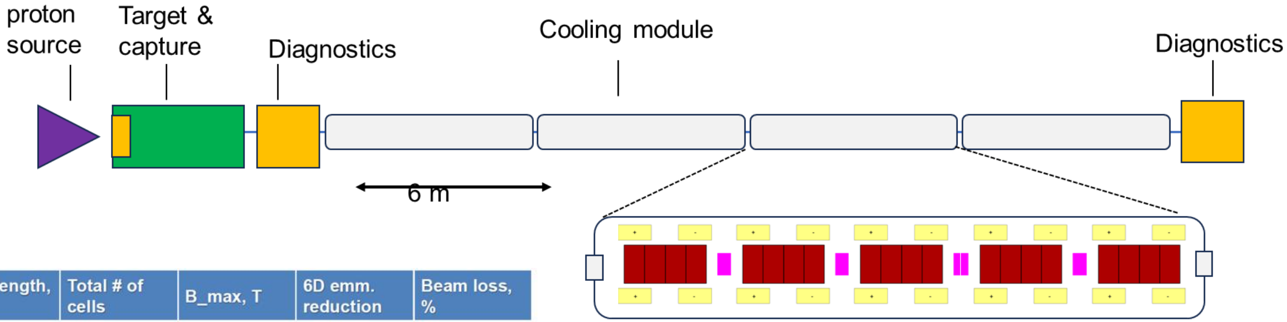


Late cell (“hard”) – 14 T peak

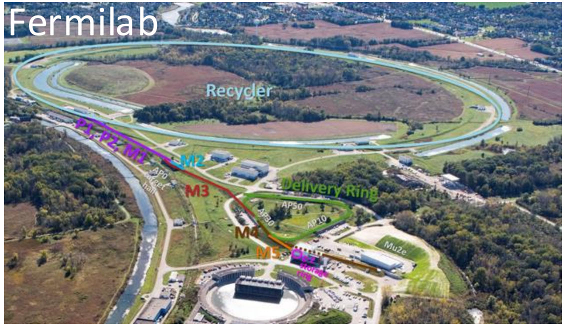


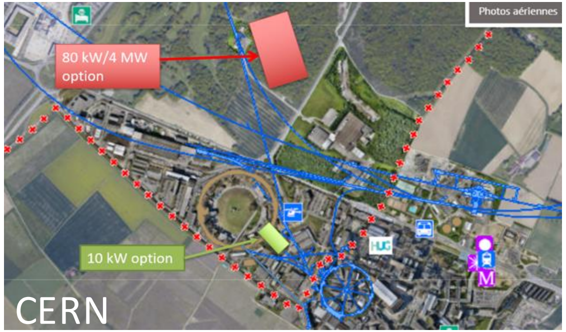
- Large bore solenoidal magnets: From 2 T (500 mm IR), to 14 T (50 mm IR)
- Normal conducting RF that can provide high-gradients within a multi-T fields
- Absorbers that can tolerate large muon intensities
- Need to further optimize the design considering engineering constraints

Cooling Demonstrator



	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%



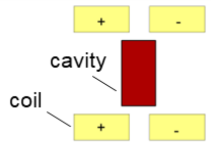


Need to have advanced demonstrator design in 3-5 years for the P5 “collider panel”

Demonstrator staging

- Parameters are aspirational and may need modifications based on available funding and resources

Phase-I

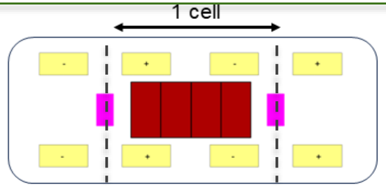


RF studies in B-fields

Material studies & cryogenics

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

Phase-II

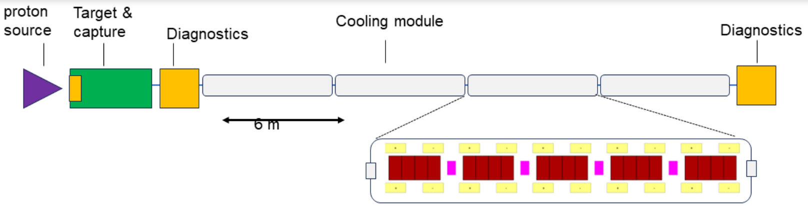


Cell integration studies

Cell resembles late 6D cooling stages

Reuse components from Phase I

Phase-III

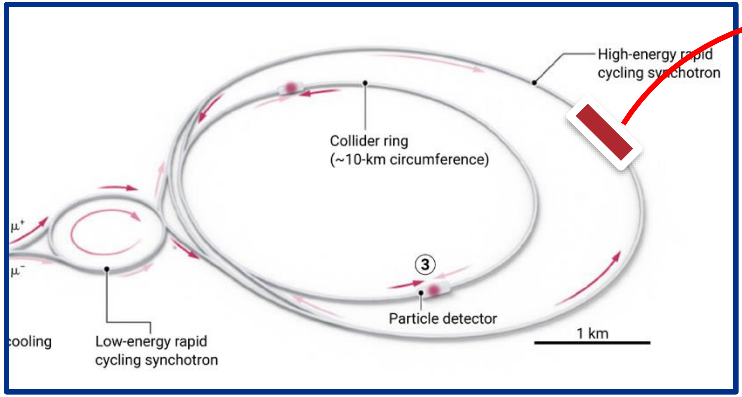


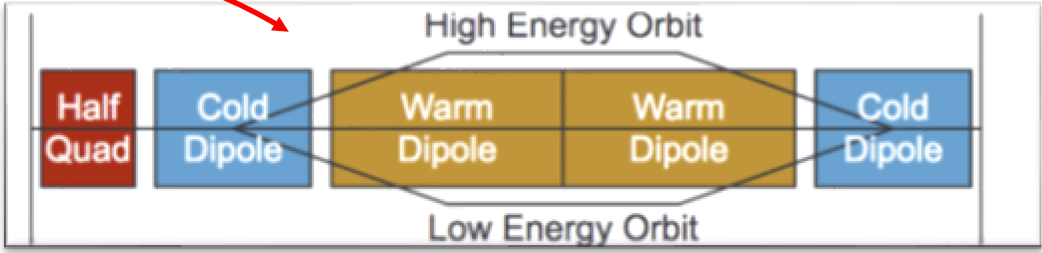
Full demonstrator with beam

Coils producing 7-10 T axial fields

Potential to achieve 50% 6D cooling

Acceleration of Muons

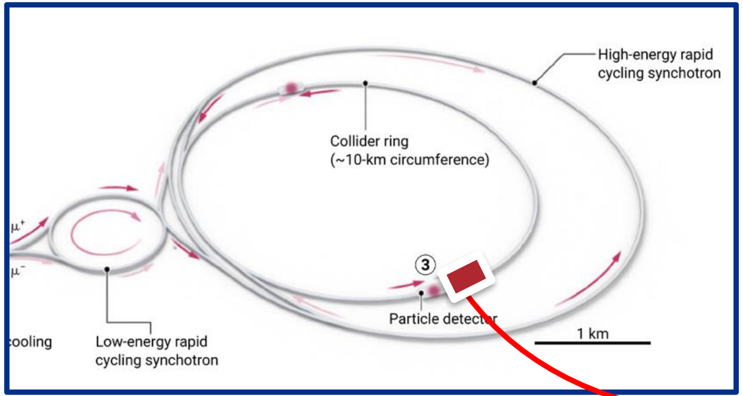




DC field   Pulsed from $-B_w$ to $+B_w$

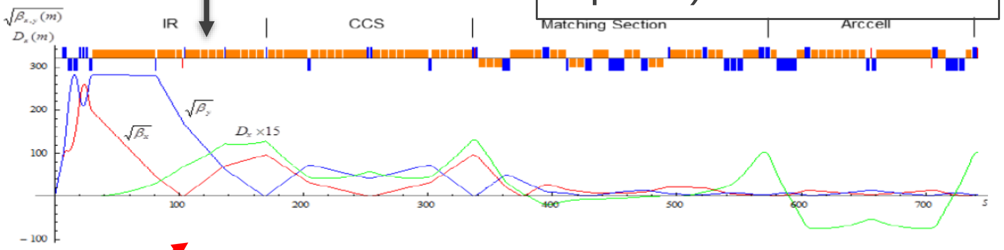
- Rapid Cycling Synchrotron accelerators
- Fast ramping magnets (up to 1000 T/s) accompanied with 16 T DC magnet
- Design of efficient energy sources with good power management (10s of GW) for pulsed magnets is the key

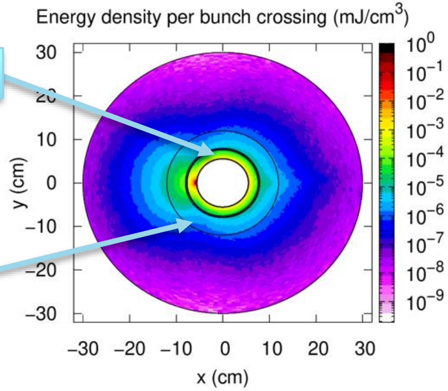
Collider Ring Needs



IR region (high-B quads)

bend region (high-B dipoles)



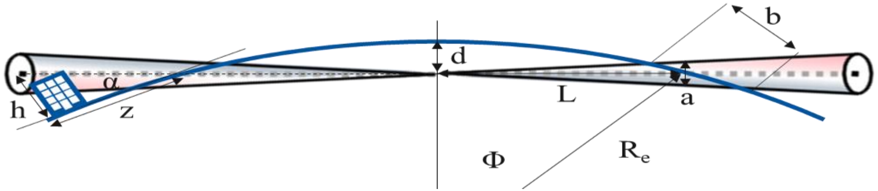


Shielding

Coil

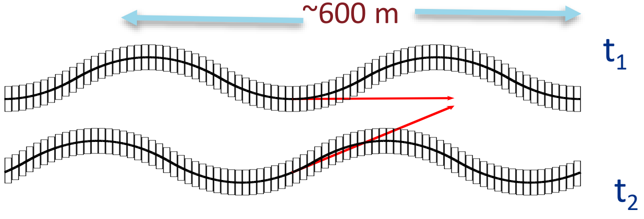
- Dipoles with strong field (12-16 T for 10 TeV) and large aperture
- Quadrupoles with strong fields for the IR (15-20 T fo 10 TeV)
- Power loss due to muon decay 500 W/m → requires tungsten shielding + cooling

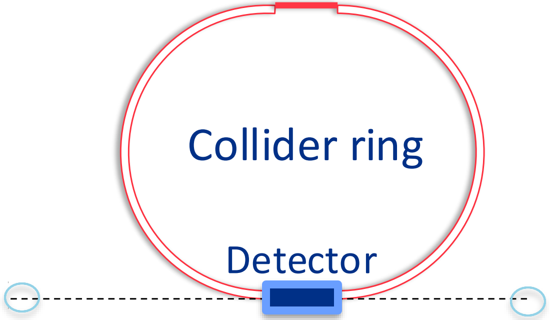
Neutrino Flux Mitigation



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

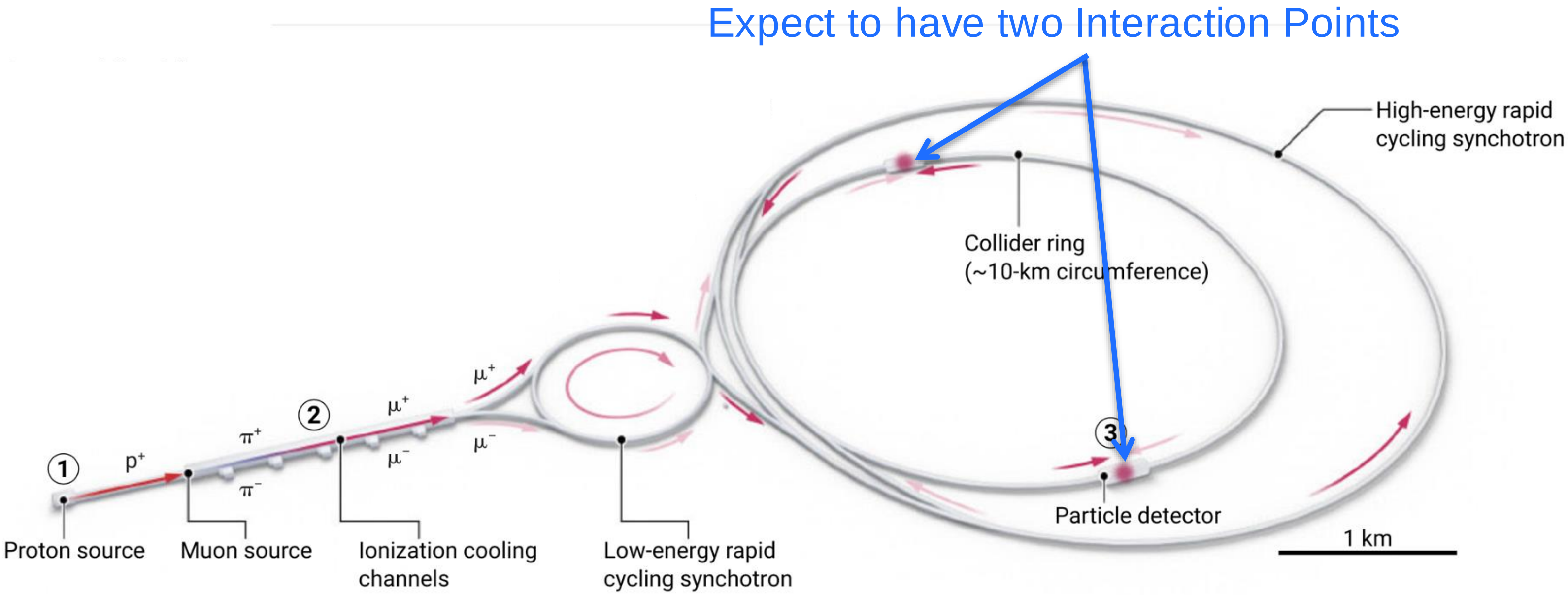
- Arcs:
  - 3 TeV at 200m depth – acceptable
  - 10 TeV needs 200m + “wobble” the beam
- The straights may require acquisition of small land



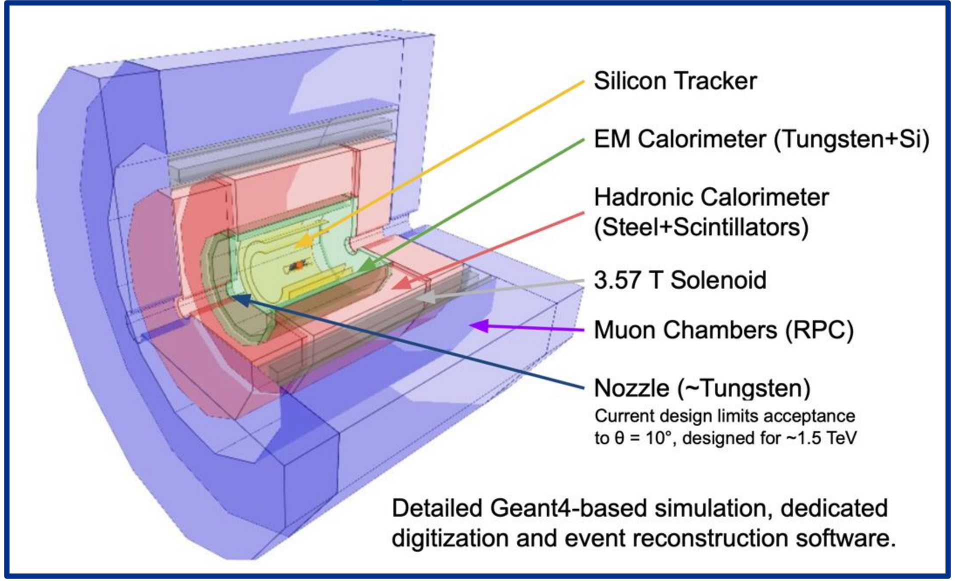


- Need to further develop the mitigation strategy, investigate impacts on the beam dynamics, … and study opportunities with high energy neutrino beams

Experiments



Detector Designs

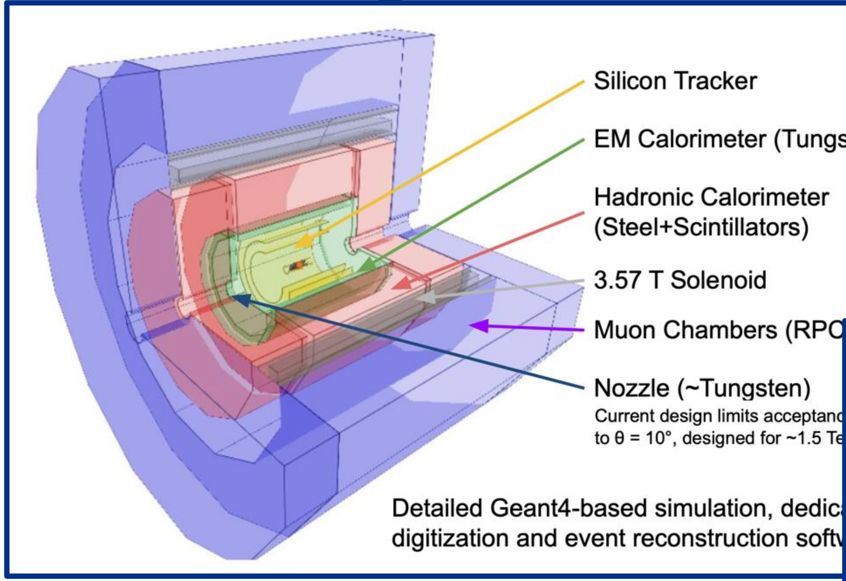


Current design limits acceptance to θ = 10°, designed for ~1.5 TeV

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



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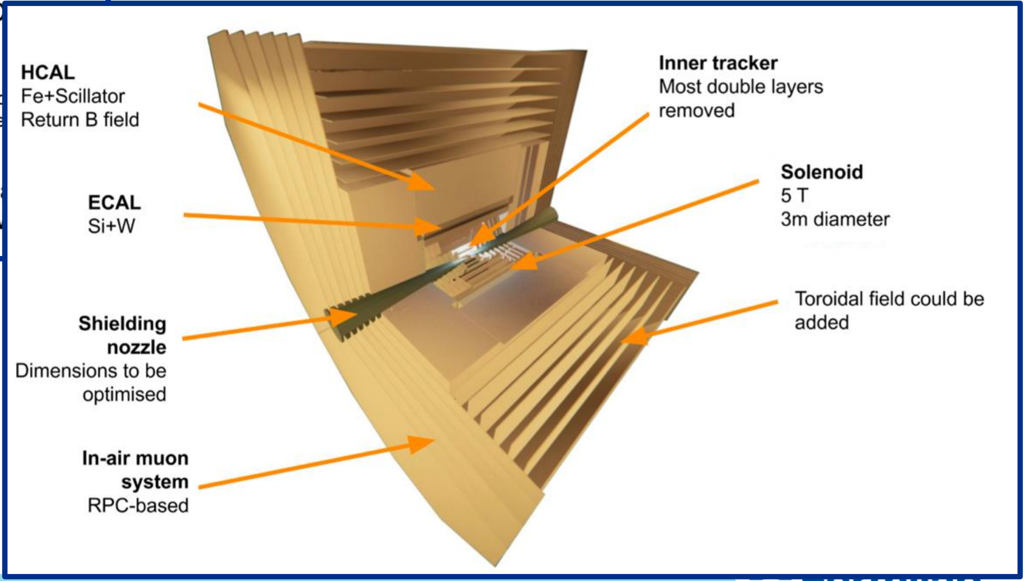
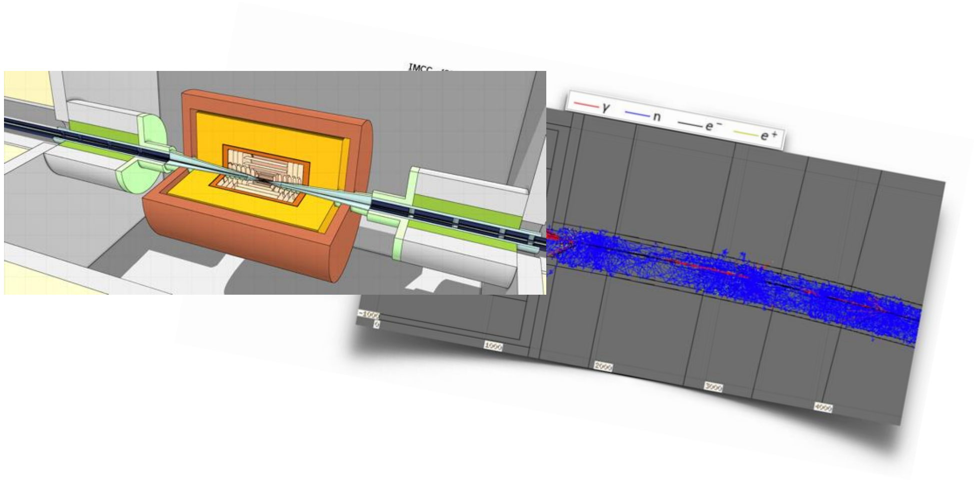
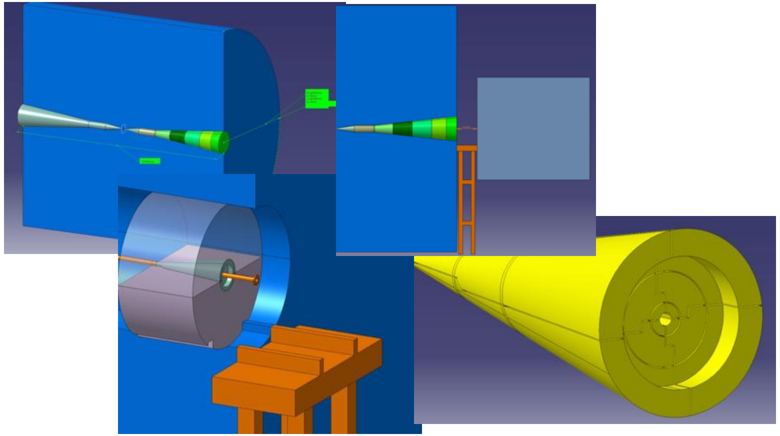


Multiple 10 TeV design concepts are newly emerging

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

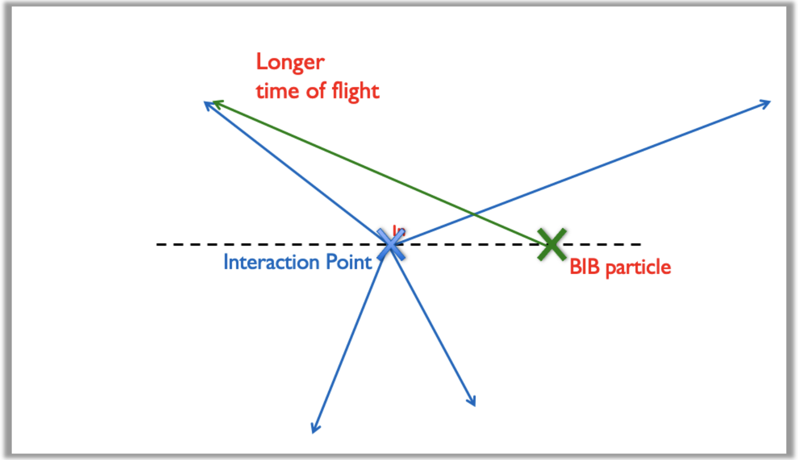


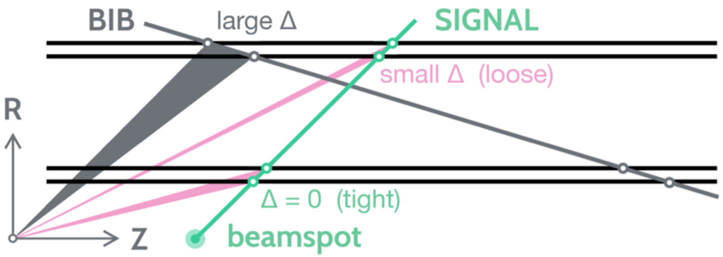


- Machine-Detector Interface requires careful design optimization and engineering studies
- Next step in evolution of detectors, hybrid of LHC and Higgs Factory needs. Requires novel detectors - opportunities for innovative detector designs and technology!

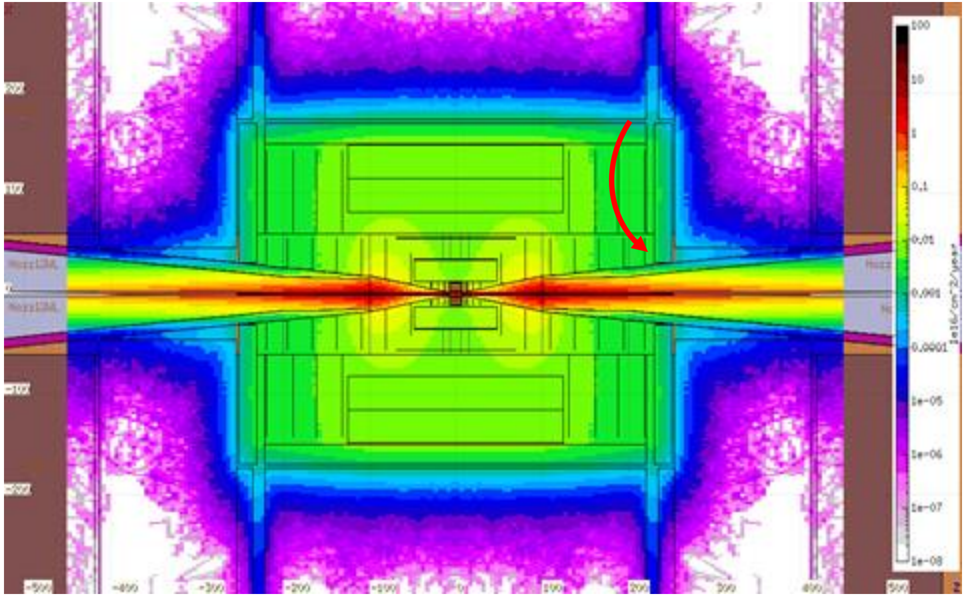
BIB Suppression

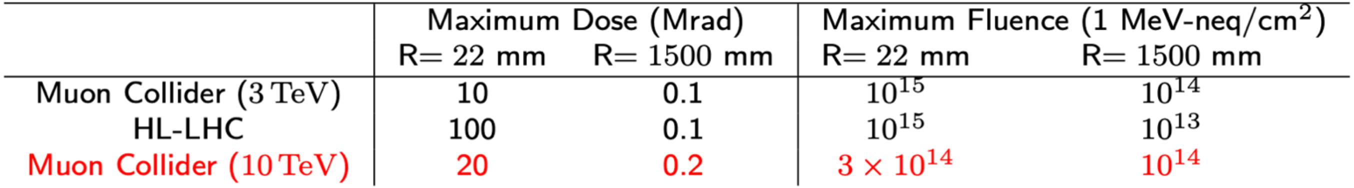
- The BIB is mostly low energy, out of time and not pointing to the Interaction Point
- Some similarities with LHC pileup - **can build on that experience!**





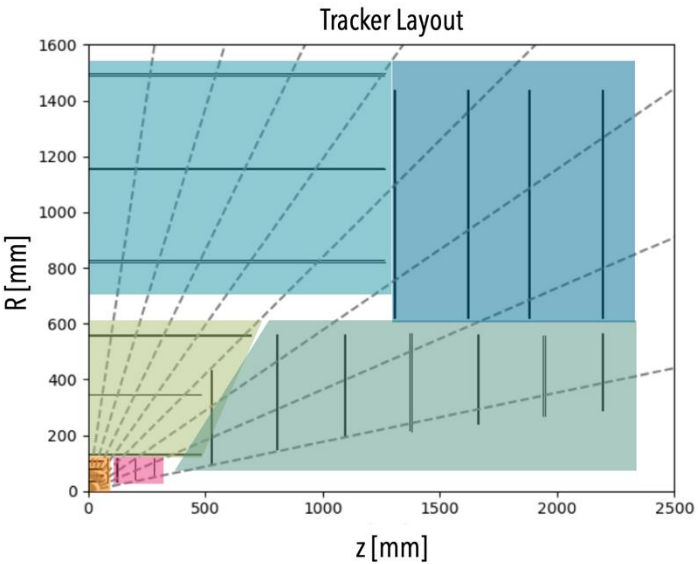
Detector Design – radiation environment

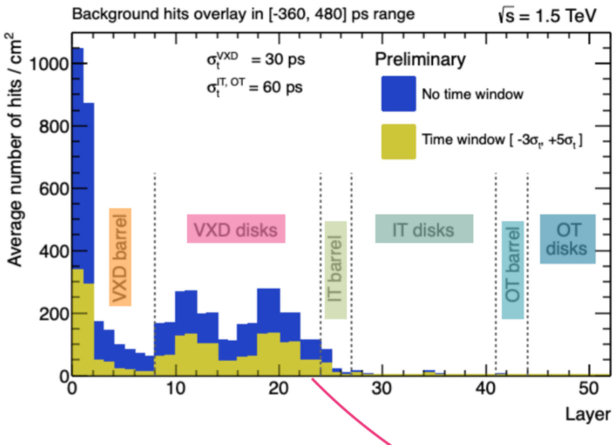


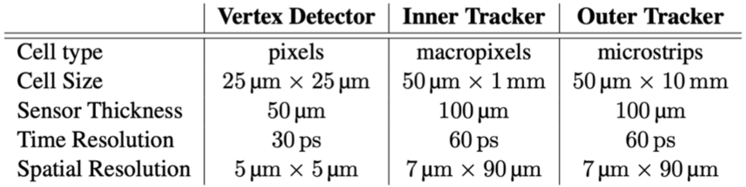


	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm	R= 22 mm	R= 1500 mm
Muon Collider (3 TeV)	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}
Muon Collider (10 TeV)	20	0.2	3×10^{14}	10^{14}

Tracker Challenges



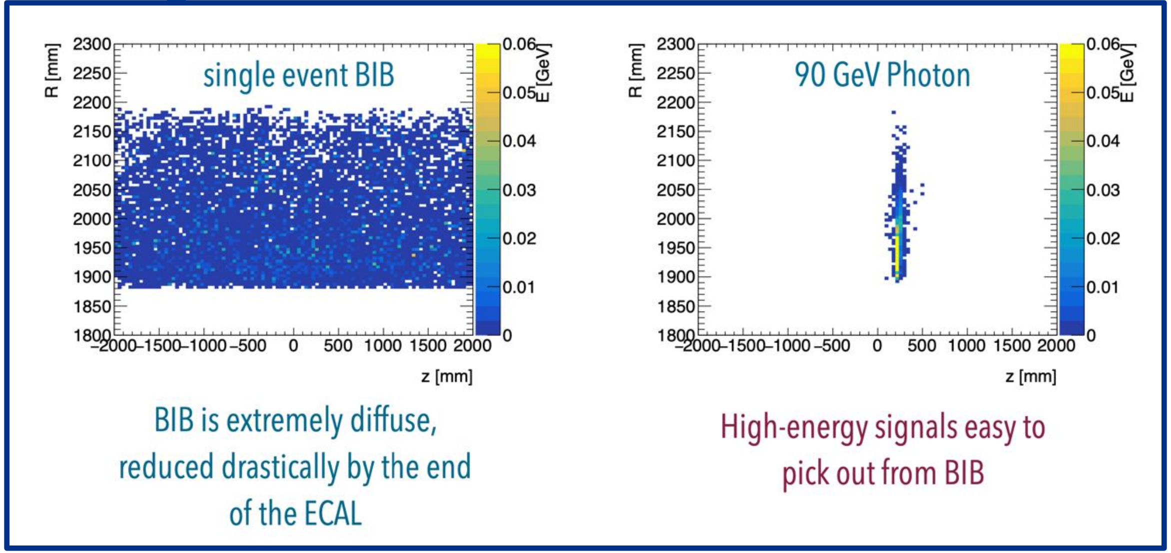




	Vertex Detector	Inner Tracker	Outer Tracker
Cell type	pixels	macropixels	microstrips
Cell Size	25 µm × 25 µm	50 µm × 1 mm	50 µm × 10 mm
Sensor Thickness	50 µm	100 µm	100 µm
Time Resolution	30 ps	60 ps	60 ps
Spatial Resolution	5 µm × 5 µm	7 µm × 90 µm	7 µm × 90 µm

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

Calorimeter Design



single event BIB

90 GeV Photon

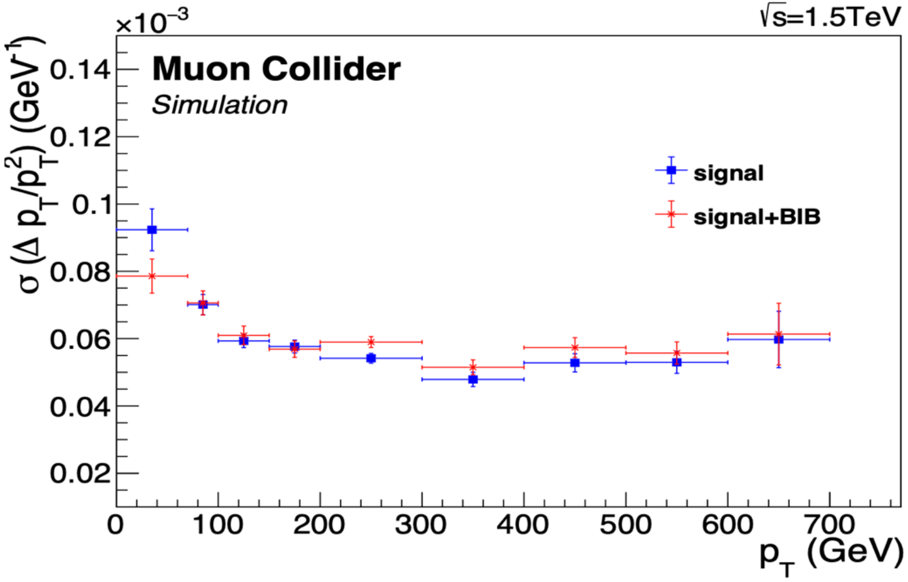
BIB is extremely diffuse, reduced drastically by the end of the ECAL

High-energy signals easy to pick out from BIB

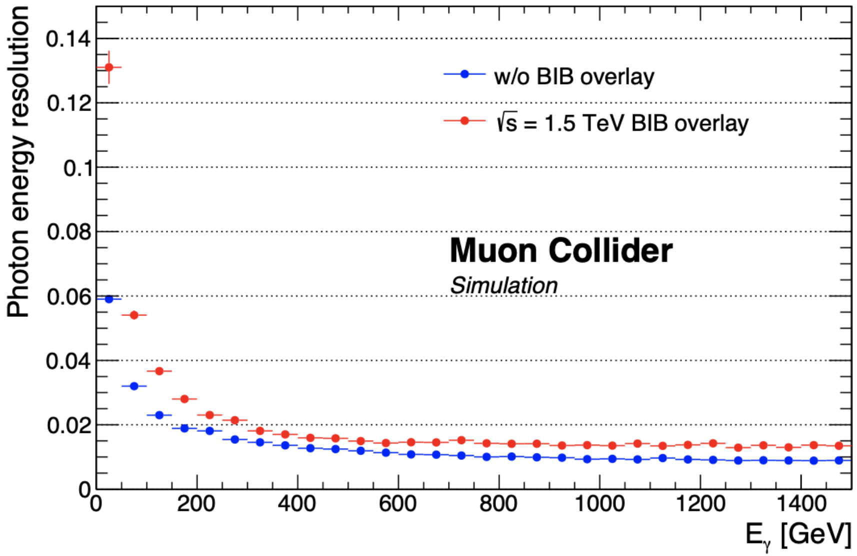
- High granularity and shorter integration windows
- Hit time measurement O(100ps)
- Longitudinal segmentation
- Perfect application for AI-based clustering and reconstruction algorithms

Performance Examples

Track relative momentum resolution
BIB effects are small

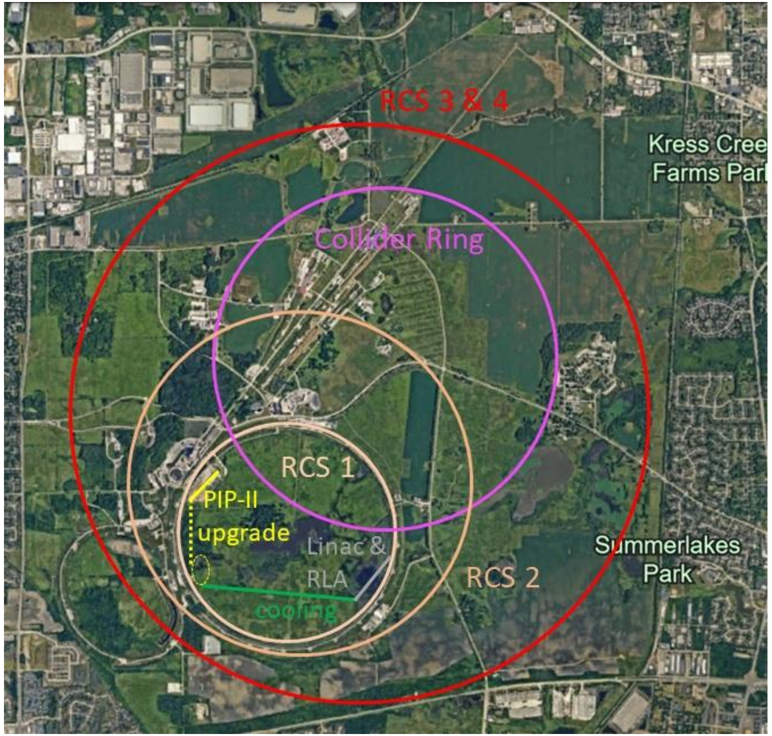


Few % Photon Energy Resolution
Improvements possible at low E_T



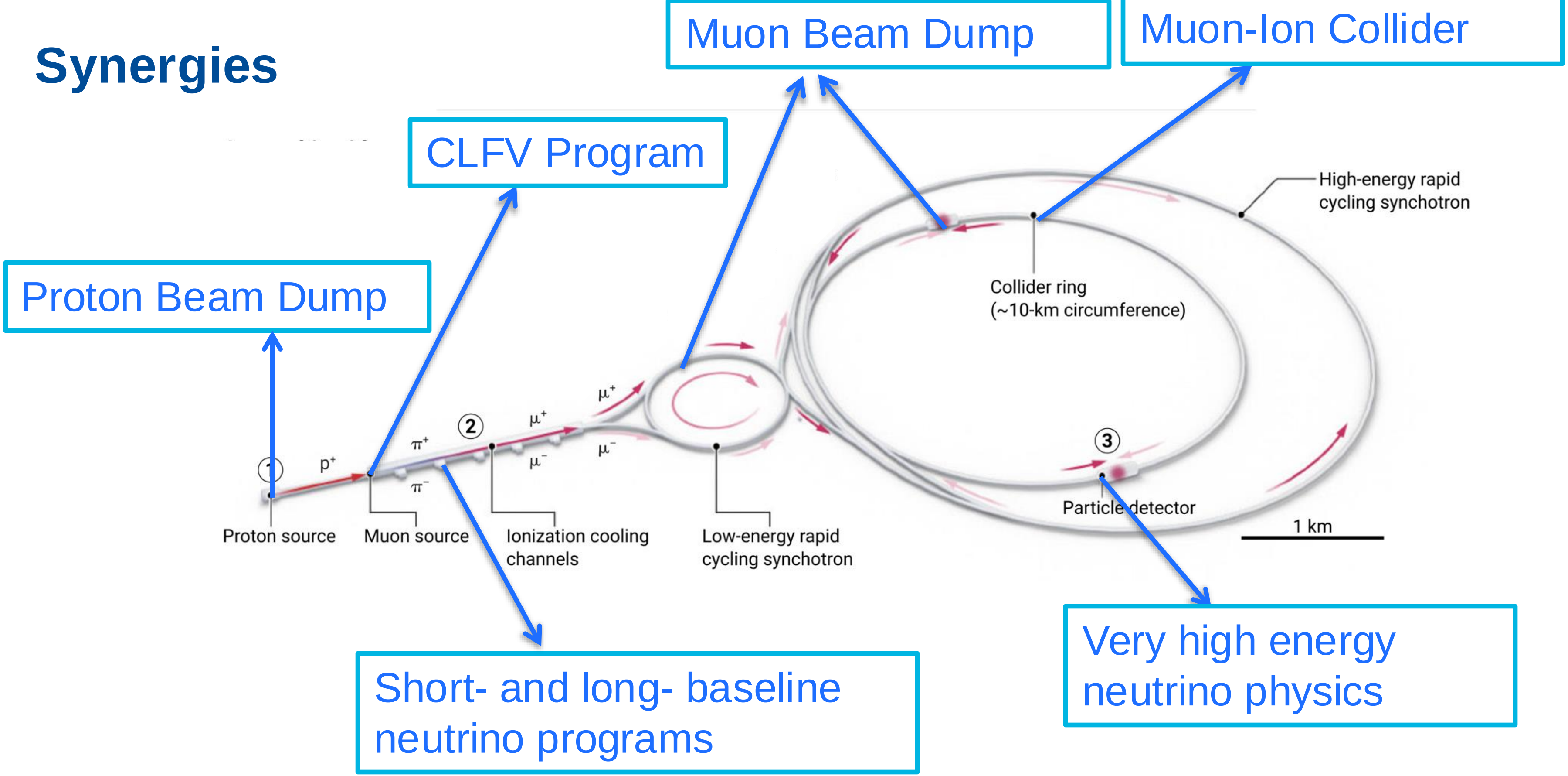
Muon Collider at Fermilab

- 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

Synergies



Muon Beam Dump

Muon-Ion Collider

CLFV Program

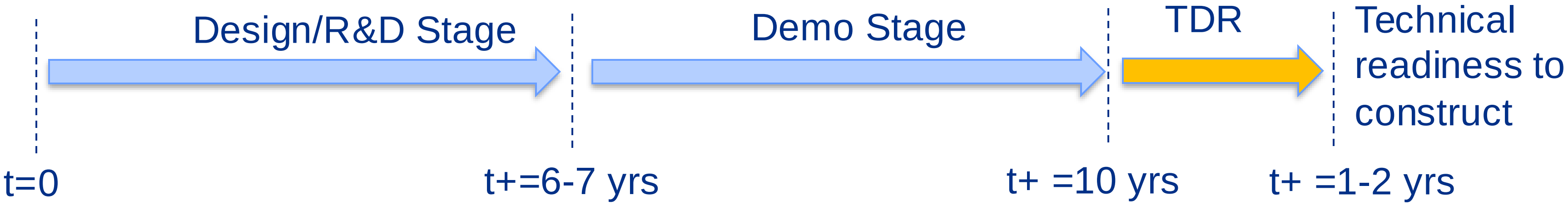
Proton Beam Dump

Short- and long- baseline neutrino programs

Very high energy neutrino physics

+ many more spinoffs such as muSR, muon imaging, technology synergies , algorithms etc

“Sketch” Timeline



- 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!**

Muon Collider Meetings

- US Muon Collider Community Meeting August 7-9th, 2024 at Fermilab: https://indico.fnal.gov/e/usmc2024

- IMCC Demonstrator Workshop:

  Fermilab Oct 30th – Nov 1st, https://indico.fnal.gov/event/64984/

- 2025 IMCC Annual Meeting at DESY, May 2025

  Indico will be available soon

- Muon Collider Accelerator School and 2nd US Muon Collider Meeting, August 3-8th, 2025 in Chicagoland – more information by Young Kee Kim

Outlook

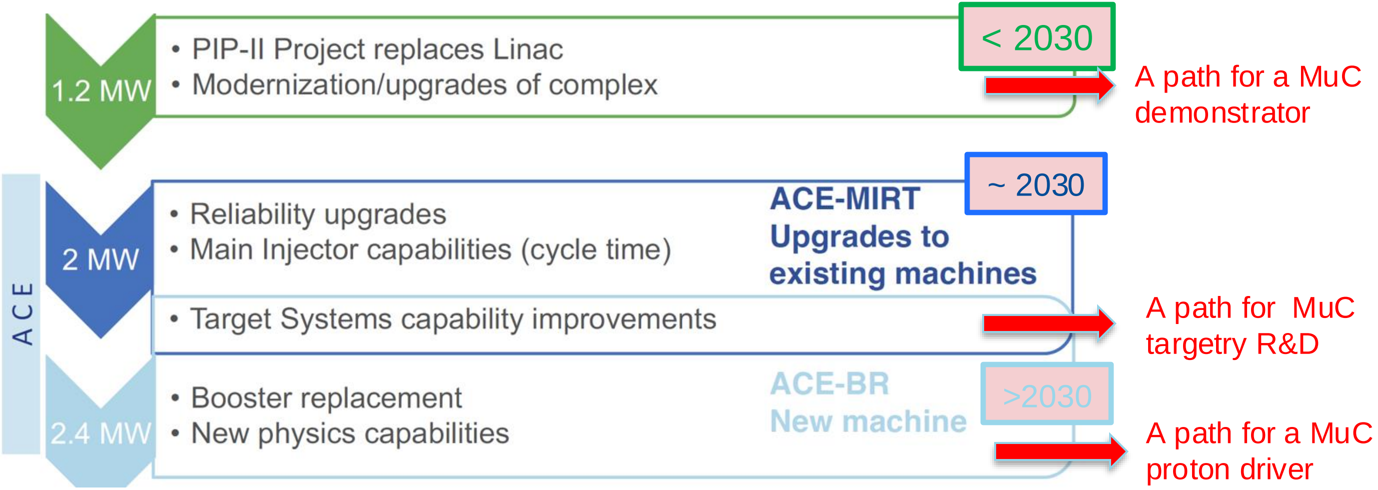
- Muon Collider is an exciting future collider option. A machine that can be a paradigm changer in particle physics
- However, realization of such a collider **requires significant international R&D and demonstrator program stretching over the next 2 decades**
- Strong synergies with neutrino, CLFV, beam dump etc

- Active ongoing effort in Europe under IMCC. Starting to get organized in the US:
  - Join Listserv mailing list USMCC-info@listserv.fnal.gov + SLACK channel: LINK

Backup

Fermilab acceleration evolution plan

- **Fermilab's ACE program** could become the basis for developing a proton driver and a target station for a MuC
  - Includes a rigorous target R&D program for 2+ MW beams in the next decade
  - Can serve as a basis for a MuC demo facility and a MuC front-end



ACE

1.2 MW
- PIP-II Project replaces Linac
- Modernization/upgrades of complex

< 2030

A path for a MuC demonstrator

2 MW
- Reliability upgrades
- Main Injector capabilities (cycle time)

ACE-MIRT Upgrades to existing machines

~ 2030

- Target Systems capability improvements

A path for MuC targetry R&D

2.4 MW
- Booster replacement
- New physics capabilities

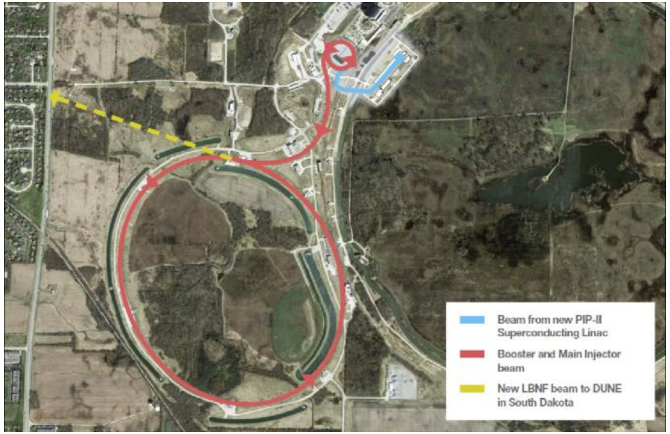
ACE-BR New machine

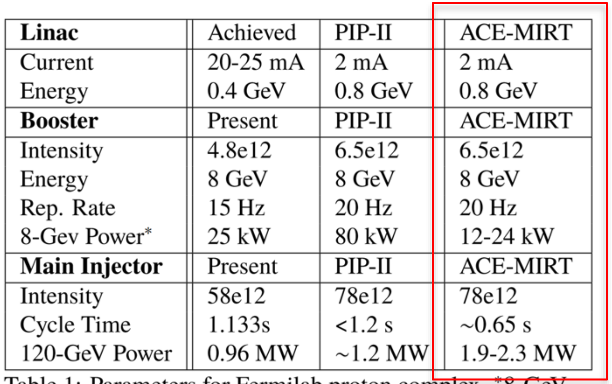
>2030

A path for a MuC proton driver

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.

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.

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

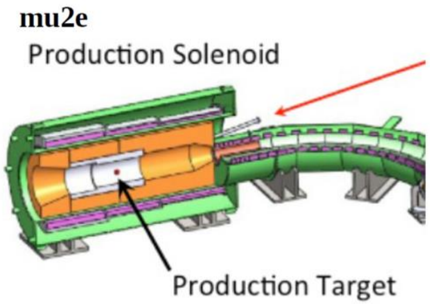
  - An order of magnitude improvement in precision SM physics wrt the LHC

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

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