Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Towards Muon Collider *detectors*

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Apr 13th, 2023

On behalf of US Muon Collider Community, IMCC, and Snowmass Muon Collider Forum

Thank you to everybody who provided input!

Physics Motivation

- We need to prepare for higher energies based on ***data*** from the LHC

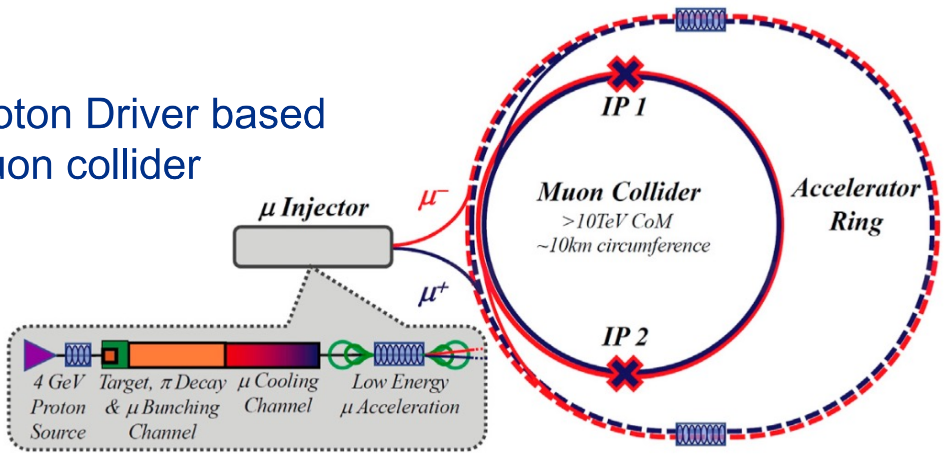
Muon Collider:

- Versatile machine with incredible EW reach (not just a muon collider, but a boson-boson collider)
- Higgs and understanding of Electroweak symmetry breaking
- Dark Matter
- And much more...

The Machine Concept

- The goal is to get to **10 TeV center-of-mass** energy
- Staging at 3 TeV is the current baseline, other scenarios possible
- Energy reach and precision in one machine
- Small footprint (can fit at Fermilab) and high energy efficiency
- Strong synergies with Neutrino program and other areas of HEP and Nuclear (see backup)

Proton Driver based muon collider



@ 3 TeV	~	1 ab^{-1}	5 years
@ 10 TeV	~	10 ab^{-1}	5 years

Up to 2 interaction points but only one experiment assumed now

What changed since the last P5?

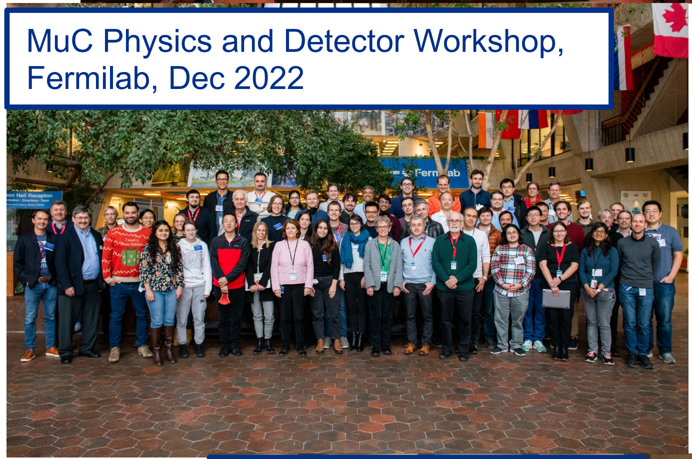
- **Physics:** Strong surge of interest in Muon Colliders within the theoretical and experimental communities. Shift of emphasis in Muon Colliders from 125 GeV to 10 TeV energy [ref]
- **Accelerator Technology (**more details at the SLAC townhall**)**:
  - Muon Accelerator Program (MAP) results completed and published, including designs of various subsystems [ref]
  - Key technological progress: multi-MW proton sources [ref], demonstration of RF in magnetic field [ref], high field solenoids [ref], targets [ref], good solution for neutrino flux mitigation, etc.
  - Muon Ionization Cooling Experiment (MICE) confirmed muon ionization cooling principle, results published [ref]
- **Detector:** Large leap in detector technologies in part from R&D done for HL-LHC upgrades. Feasibility of good quality physics in Muon Collider environment established in simulation [ref]
- International Muon Collider Collaboration (IMCC) established. MAP+IMCC put muon collider on a realistic path

Muon Collider in Snowmass

- Cross-frontier AF+EF+TF Muon Collider Forum :
  - Regular meetings with 50-100 participants in each, workshops
  - 40+ dedicated White Papers
  - Final report with ~180 authors, 50+% from Early Career (arxiv:2209.01318)

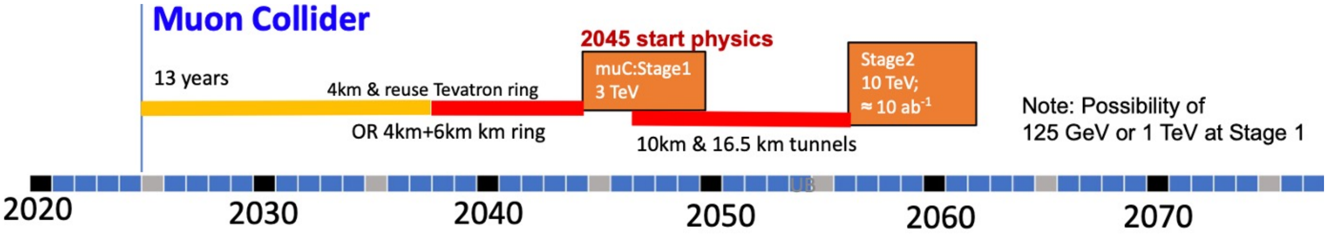
- **Conclusion of the Forum**: No fundamental showstoppers identified, but many engineering challenges exist, requiring a significant R&D investment

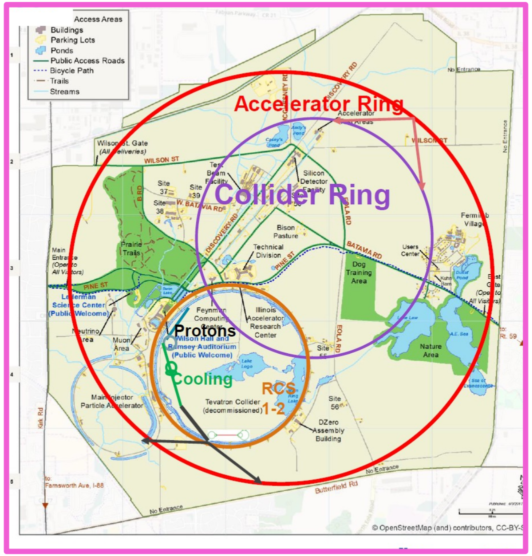

IMCC Meeting, CERN, Oct 2022


MuC Physics and Detector Workshop, Fermilab, Dec 2022


KITP Workshop, Santa Barbara, March 2023

The US timeline shown in Snowmass





- This is a highly optimistic **Technically Limited timeline**
  - not limited by resources/funding
  - does not account for R&D risks
  - assumes no delays in construction
- The actual project 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 – **need to start now!**

- Fermilab ACE+expansions could provide the accelerator frontend
- More at upcoming “ACE Science workshop”

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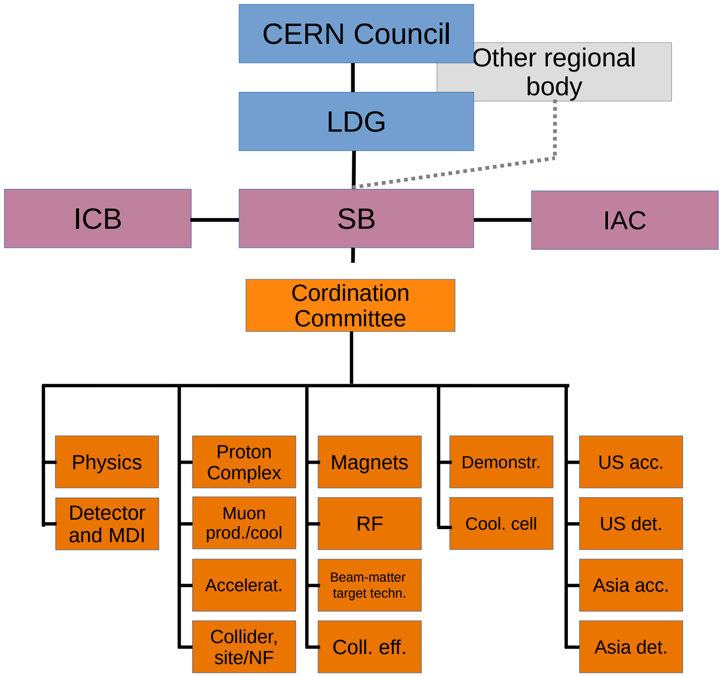
International Effort

- Following the 2018 European Strategy process, Laboratory Director's Group initiated a Muon Collider feasibility study
- International Muon Collider Collaboration (IMCC) was formed and hosted at CERN
- Several US universities joined IMCC, many more expressed interest
- IMCC welcomes broader US participation and development of siting options in both Europe and US



IMCC technical timeline is slightly shifted with respect to what was presented at Snowmass – will be better aligned if/when DOE/NSF join the effort

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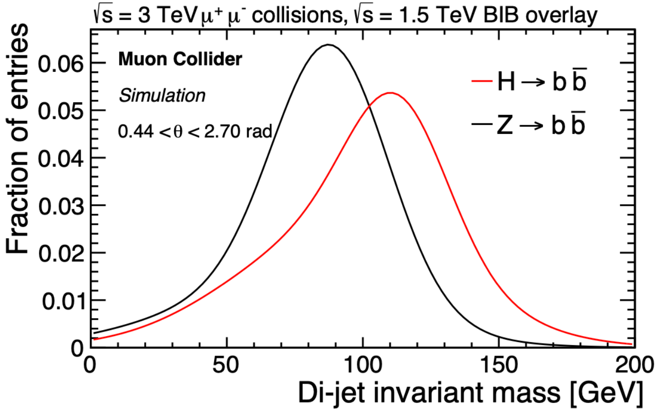
Detector Requirements

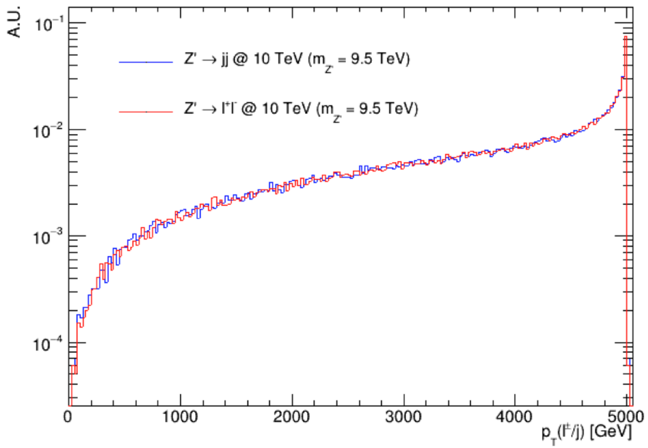
Precision Higgs program:

- High performance tracking for Particle Flow reconstruction
- + Good calorimetric energy resolution → need to separate W/Z from Higgs
- Performant heavy flavor tagging (e.g. H→bb/cc)

BSM program:

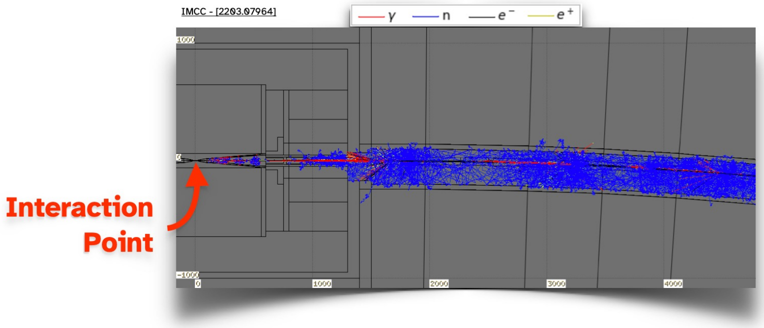
- Ability to reconstruct high energy leptons and jets
- Maintain acceptance/efficiency for unconventional signatures (disappearing tracks for DM searches, long-lived particles, etc)

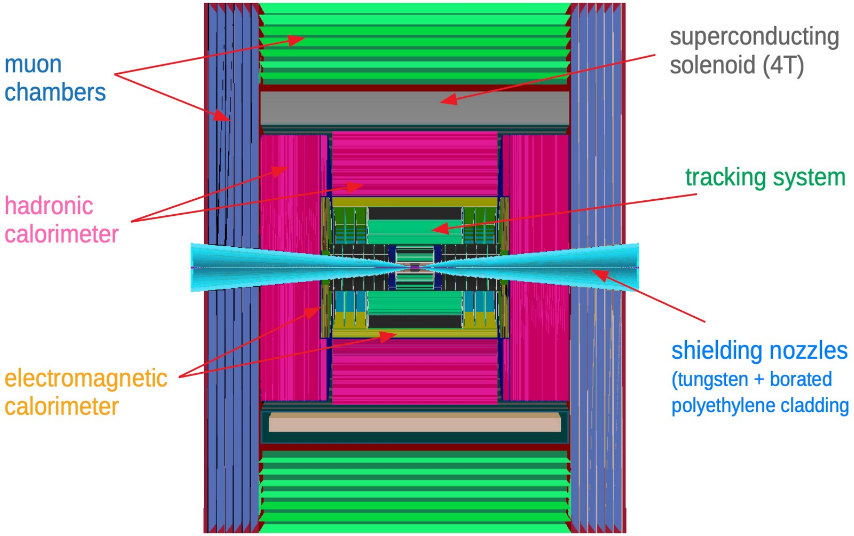




The Detector

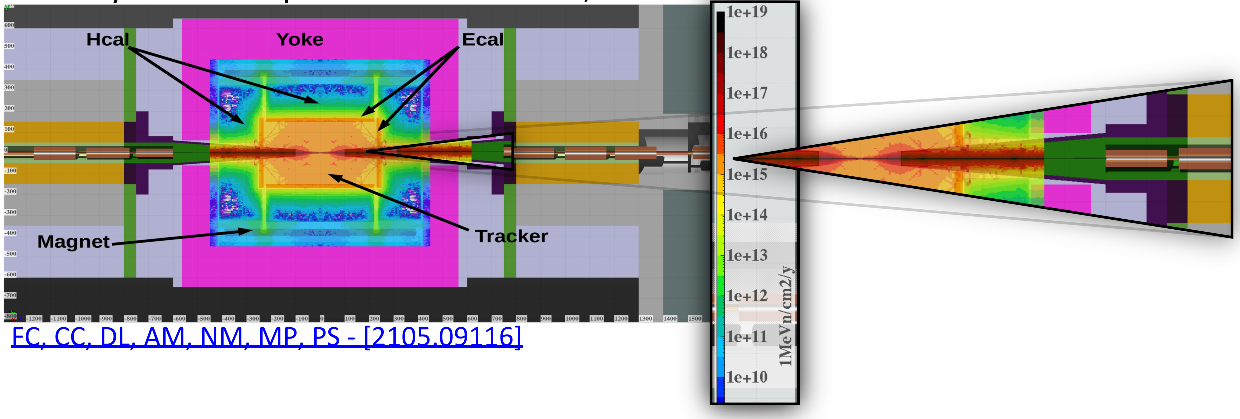
- Why do Muon Colliders need specialized detectors?
- Muons decay → Unique feature/challenge of Muon Collider detectors – beam induced background (BIB)
- Most of the energy in the detector is from muon decays that eventually result in a high rate of out-of-time neutrons and photons reaching the detector (BIB)→ major effect on the detector design



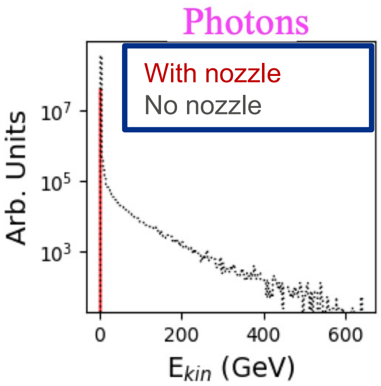


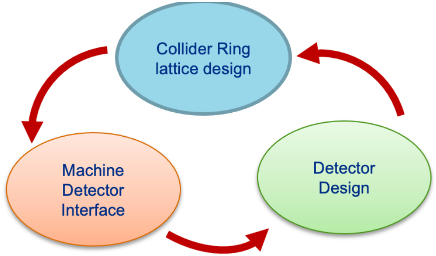
Machine-Detector Interface (MDI)

200-day 1-MeV-neq Fluence - √s=1.5 TeV, MARS15+FLUKA



FC, CC, DL, AM, NM, MP, PS - [2105.09116]





Forward region covered by coated tungsten nozzles:

- Reduces BIB in detector by many orders of magnitude
- Turns highly localized incident energy into diffuse detector energy
- Future nozzle optimization can bring further improvement:
  - materials/shapes/size, collaboration between accelerator and detector experts

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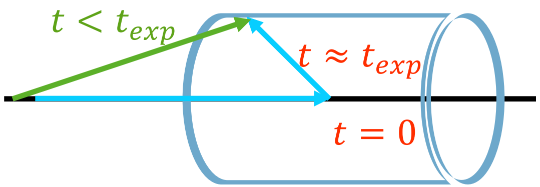
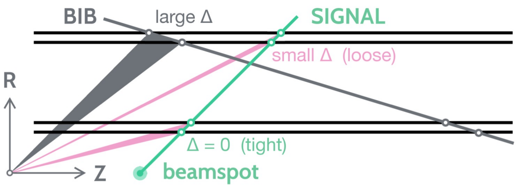
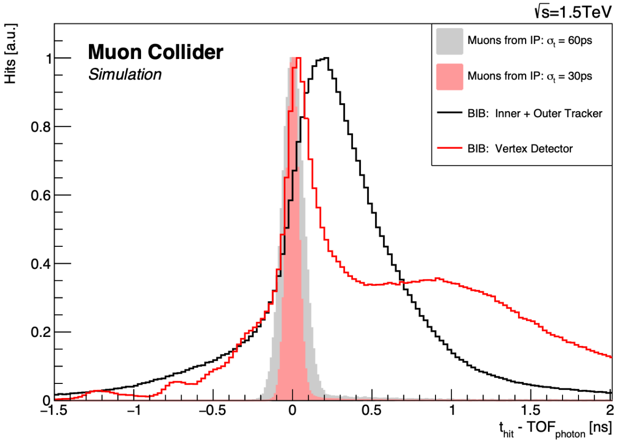
Tracker

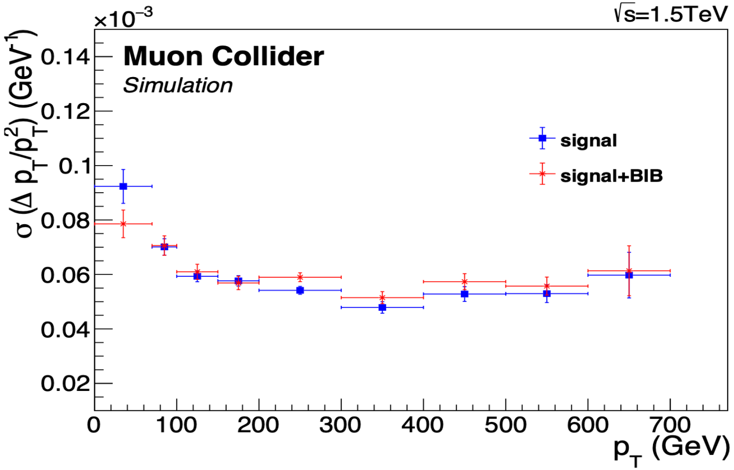
- Need to build detectors that can tell the difference between post-nozzle BIB and signal
- The BIB is mostly out of time and not pointing to the Interaction Point
- Some similarities with LHC pileup - **can build on that experience!**
- 4D tracker with precision timing (~30-60 ps), pointing, and local intelligence for on-chip BIB rejection







Track resolution



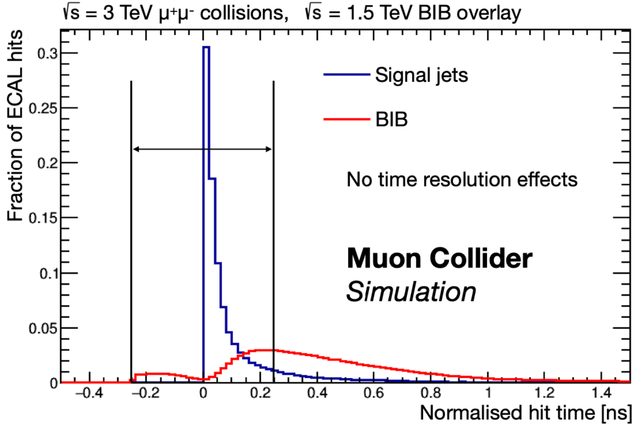
Calorimeter

- BIB dominated by low energy neutrals: photons (96%) and neutrons (4%)
- Current SiW ECAL + Iron/Scintillator HCAL design works reasonably well, but new ideas (e.g. dual readout) can bring better performance

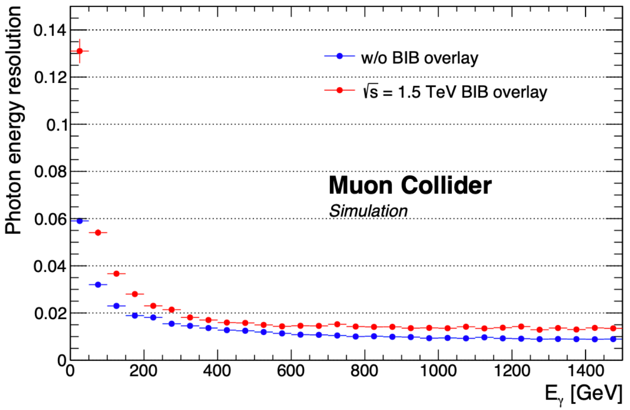
General Features:

- High granularity and shorter integration windows
- Hit time measurement O(100ps)
- Longitudinal segmentation

ECAL hit time

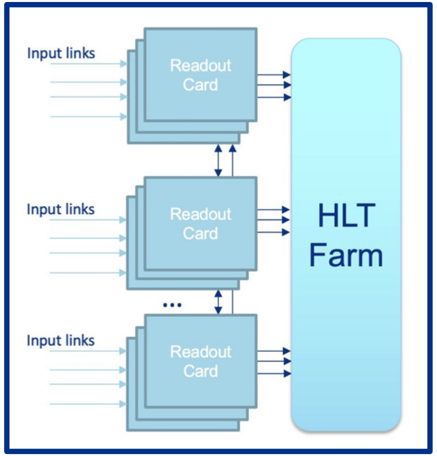


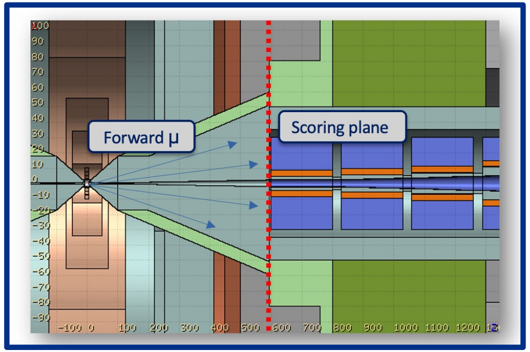
Photon Energy Resolution



Muons, DAQ and Forward Detectors

- **Muon system:** some technologies are reaching rate limits in the forward region. Also some contain gas mixture which has a high Global Warming Potential
- **DAQ:** Long time (10s of microseconds) between bunch crossings. Estimates indicate that a “streaming” architecture is possible. Various options for how to filter/store data
- **Forward Detectors:** Just started to investigate possibility of instrumenting the forward region for muon tagging, BSM physics, and for luminosity measurements





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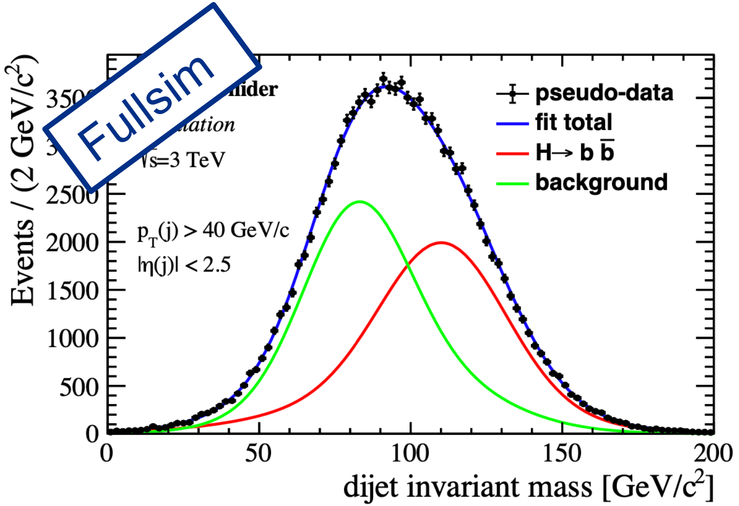
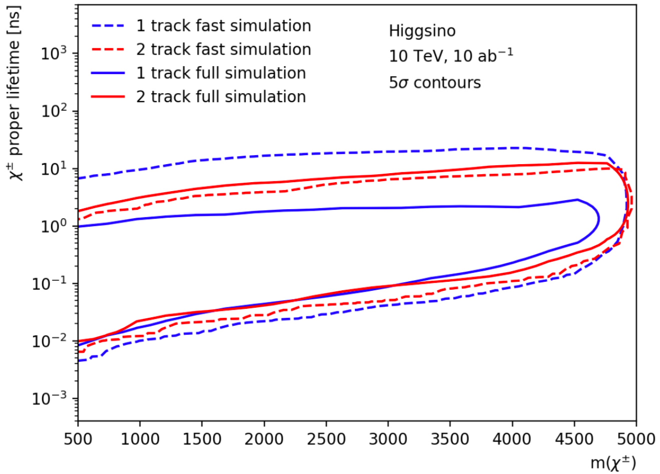
Full Simulation Physics Studies

- Detector requirements designed to meet physics goals
- Many measurements simulated with fully realistic background and reconstruction
- Two very different examples: Higgs→bb cross section and Dark Matter with disappearing tracks → Good agreement with FastSim



Higgs → bb cross-section:
FastSim: 0.73% vs Fullsim: 0.75%



Very good agreement in 2-track final state
1-track better in fastsim due to higher acceptance

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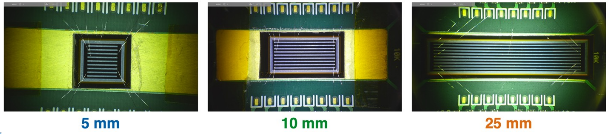
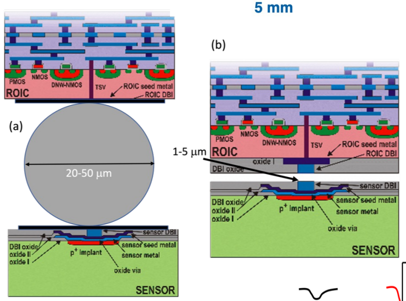
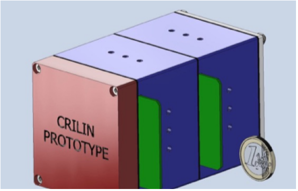
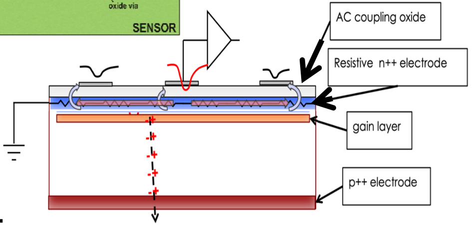
R&D Activities:

- 4D Trackers:
  - Design, Sensors, Data Transmission, Power, Mechanics
  - 3D Integration, ASIC, Intelligent Sensors/Modules
- Calorimeters:
  - Different technologies, design, reconstruction (with AI/ML)
  - Integration of precision timing
- Muons:
  - Qualification of new gases, fast timing,…
- TDAQ:
  - Architecture studies
  - Real-time reconstruction, novel readout technologies
- MDI+Forward:
  - MDI Design, Forward Muon Tagger
  - Luminosity Monitor
- Detector magnet









arXiv: 2203.07224

Promising Technologies and R&D Directions for the Future Muon Collider Detectors

Submitted to the Proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021)

Significant synergies with HL-LHC and EIC, e+e-, and pp detectors

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Software and Simulations

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

Towards the 10 TeV Detector

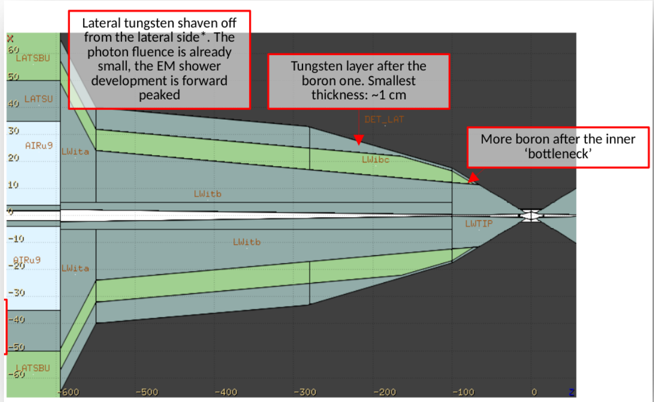
- Detector and MDI designs in early stages of development
- The backgrounds remain flat with energy
- Radiation at HL-LHC levels or lower, much lower than FCC-hh

With MAP nozzle design

Monte Carlo simulator	FLUKA	FLUKA	FLUKA
Beam energy [GeV]	750	1500	5000
μ decay length [m]	$46.7 \cdot 10^5$	$93.5 \cdot 10^5$	$311.7 \cdot 10^5$
μ decay/m/bunch	$4.3 \cdot 10^5$	$2.1 \cdot 10^5$	$0.64 \cdot 10^5$
Photons ($E_\gamma > 0.1$ MeV)	$51 \cdot 10^6$	$70 \cdot 10^6$	$107 \cdot 10^6$
Neutrons ($E_n > 1$ MeV)	$110 \cdot 10^6$	$91 \cdot 10^6$	$101 \cdot 10^6$
Electrons & positrons ($E_{e^\pm} > 0.1$ MeV)	$0.86 \cdot 10^6$	$1.1 \cdot 10^6$	$0.92 \cdot 10^6$
Charged hadrons ($E_{h^\pm} > 0.1$ MeV)	$0.017 \cdot 10^6$	$0.020 \cdot 10^6$	$0.044 \cdot 10^6$
Muons ($E_{\mu^\pm} > 0.1$ MeV)	$0.0031 \cdot 10^6$	$0.0033 \cdot 10^6$	$0.0048 \cdot 10^6$

[IMCC, Submitted to EPJC]

No dramatic change!



Initial 10 TeV nozzle optimization = 40-50% lower BIB

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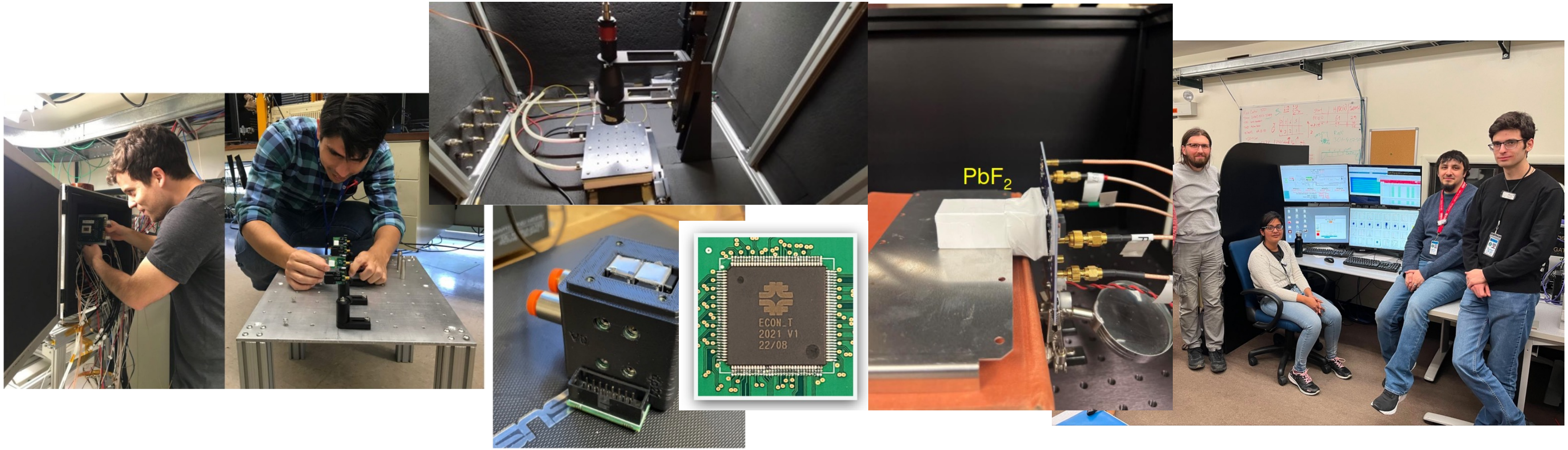
Training Opportunities

- Cutting edge technology + highly impactful research = Draw the best talent
- Unique training ground for future generations of particle physicists:
  - Great opportunities for labs and universities to engage in exciting R&D
- Strong interest amongst Early Career community – build a diverse community of future US particle physics leadership!



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US Muon Collider R&D Coordination Group

- In March, R&D Coordination Group was assembled to provide input to P5
- Focus on key elements of 10 TeV accelerator and detector design
- Develop R&D plan, activities, budget and deliverables

Chairs: Sergo Jindariani, Diktys Stratakis (FNAL), Sridhara Dasu (Wisconsin)

Detector R&D Focus Areas:
Tracking Detectors:
Maurice Garcia-Sciveres (LBNL), Tova Holmes (Tennessee)

Calorimeter Systems
Chris Tully (Princeton), Rachel Yohay (FSU)

Muon Detectors
Melissa Franklin (Harvard), Darien Wood (Northeastern)

Electronics/TDAQ
Darin Acosta (Rice), Michael Begel (BNL), Isobel Ojalvo (Princeton),

MDI+Forward Detectors:
Kevin Black (Wisconsin), Karri DiPetrillo (Chicago), Nikolai Mokhov (Fermilab)

Detector Software/Simulations/ML:
Simone Pagan Griso (LBNL), Walter Hopkins (ANL), Liz Sexton-Kennedy (Fermilab)

Physics Case Development:
Patrick Meade (Stony Brook), Nathaniel Craig (UCSB)

Accelerator R&D Focus Areas:
Muon source:
Mary Convery (Fermilab), Jeff Eldred (Fermilab), Sergei Nagaitsev (JLAB), Eric Prebys (UC Davis)

Machine design:
Frederique Pellemoine (Fermilab), Scott Berg (BNL), Katsuya Yonehara (Fermilab)

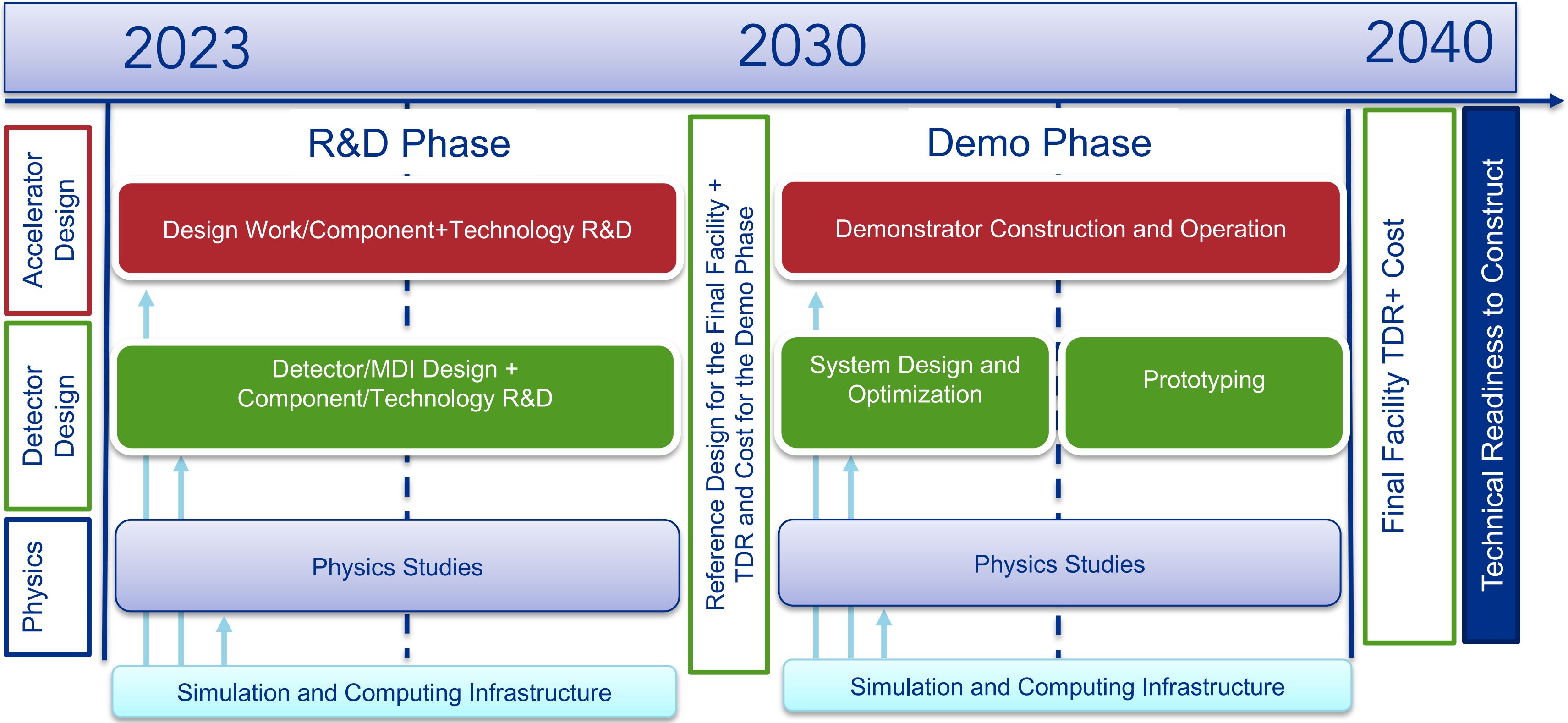
Magnet systems:
Steve Gourlay (Fermilab), Giorgio Apollinari (Fermilab), Soren Prestemon (LBNL)

RF systems:
Sergey Belomestnykh (Fermilab), Spencer Gessner (SLAC), Tianhuan Luo (LBNL)

International Liaisons:
Donatella Lucchesi (INFN), Federico Meloni (DESY), Chris Rogers (RAL), Daniel Schulte (CERN),

+ communication with DOE, CPAD, ECFA

US Muon Collider R&D timeline



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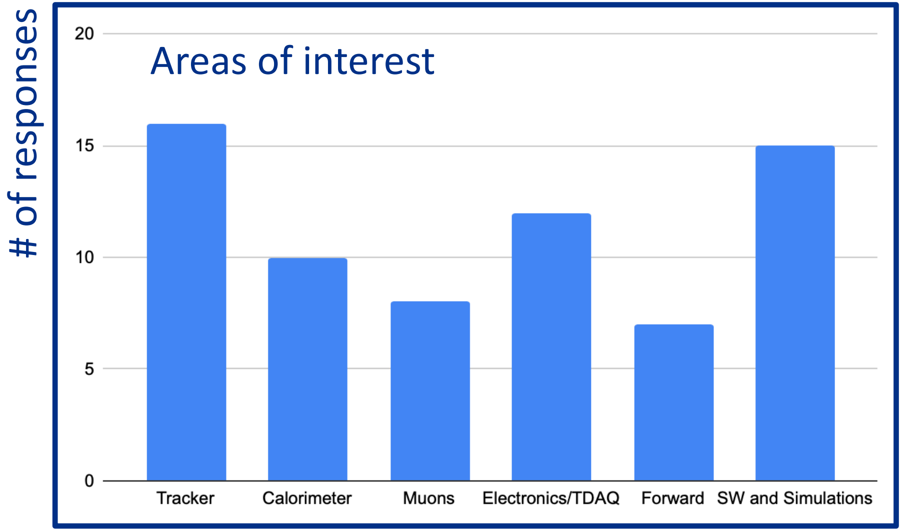
Detector R&D Scope and Interest:

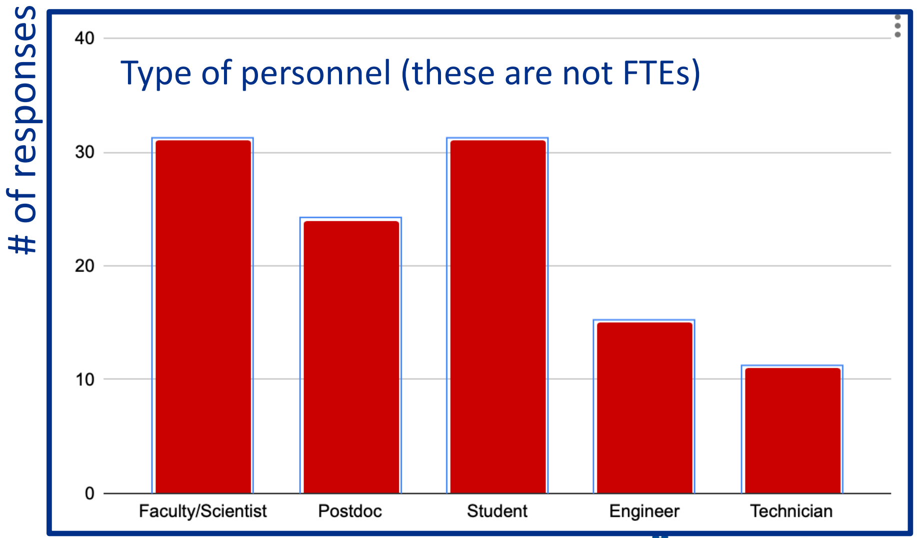
List of work areas and activities

The scope of detector work:

- Support and enhancement of the fullsim framework and tools
- Develop detector + MDI design, simulate the performance, refine detector specs
- Conduct hardware R&D to establish technology feasibility

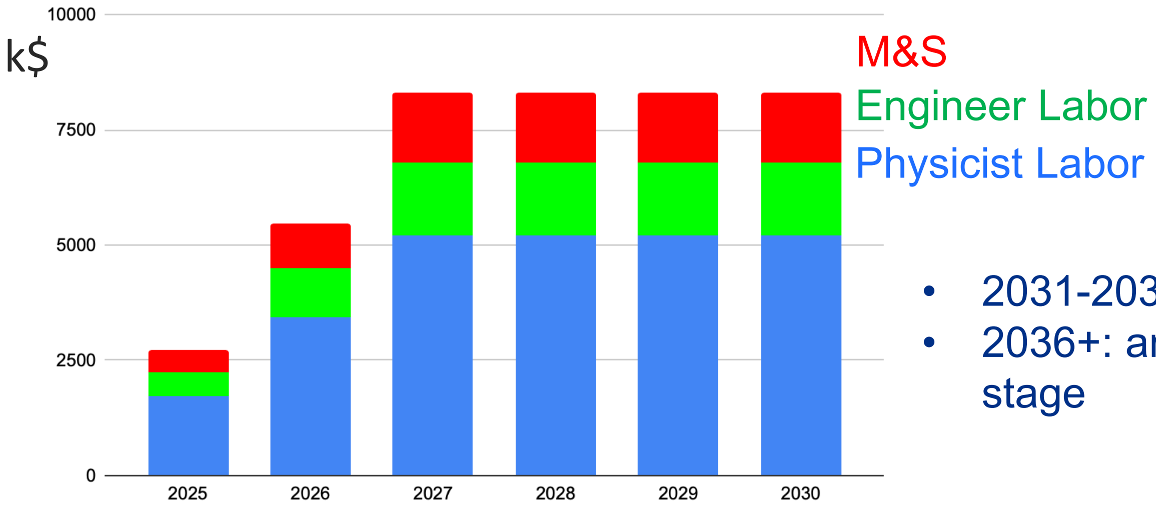
Expression of interest from 31 PIs from 24 US institutions (does not include theorists and accelerator physicists)





US R&D Budget Estimate (Detector only)

- Bottom-up estimate: assumes ~50% of needed work done by US and another ~50% by international partners → equal partnership with European efforts
- 2025-2030: ramp up to ~ 30-35 FTE/y + M&S for computing and early hardware
  - 1 FTE = $200k, no escalation included
  - Significant overlaps exist with generic detector R&D efforts



- 2031-2035: estimate to increase by ~50%
- 2036+: another increase, hard to quantify at this stage

Summary

- Muon colliders open an exciting window into the future of particle physics
- We have a well-organized and highly motivated group ready to address challenges of Muon Collider
- We are asking P5 to:
  - Recommend establishing a Muon Collider R&D program with the goal for technical readiness by ~2040
  - Recommend that DOE and NSF recognize muon collider work within the EF base program proposals, including software and simulations
  - Support the formation of a US Muon Collider effort to coordinate US impact while engaging in global efforts
  - Enable US to compete for hosting a global Muon Collider
- We are also asking for support of the theory community for Muon Collider studies

Extras

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

Fermilab ACE and Muon Collider

- ACE is a step in right direction (power increase at 120 GeV requires power increase at 8 GeV – as muon collider needs).
- ACE infrastructure is compatible with the Muon Collider R&D needs (though needs to be expanded)
- ACE will provide an excellent platform for Muon Collider accelerator and detector R&D
- ACE Booster replacement is to be designed such that it is compatible with the Muon Collider Facility needs (also, will need to be expanded)

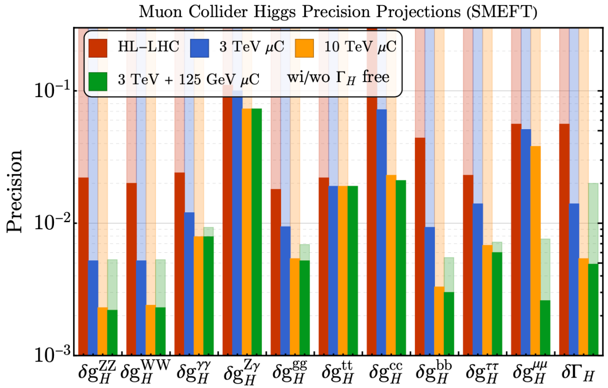
Booster Replacement Scenarios

- Initial scenarios under explorations included cases where available 8 GeV power is in 1-2 MW range
- Exact parameters still to be defined, including input from the upcoming ACE physics workshops

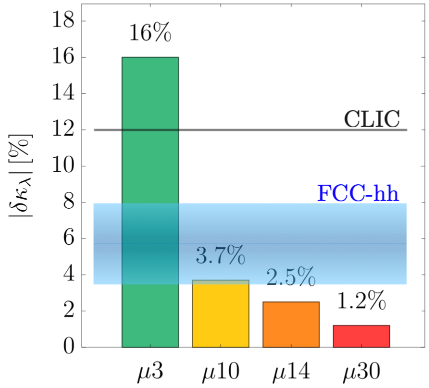
	Nominal	New RCS Scenarios			8 GeV Linac Scenarios		
Parameter		**v1**	**v2**	**v3**	**v1**	**v2**	**v3**
Linac Energy	0.8 GeV	2 GeV	2 GeV	2 GeV	8 GeV	8 GeV	8 GeV
Linac Current	2 mA	2 mA	2 mA	5 mA	2.7 mA	5 mA	5 mA
Rep. Rate	20 Hz	10 Hz	20 Hz	20 Hz	10 Hz	10 Hz	20 Hz
8 GeV Beam Power	160 kW	320 kW	960 kW	960 kW	320 kW	760 kW	1600 kW

Parameter	PIU scenarios	MuC-PD scenarios
Energy	8 GeV	8-16 GeV
Rep. rate	10-20 Hz	5-20 Hz
Avg. beam power	0.3-1.6 MW	1-4 MW
Proton structure	25-40 e12 over 2 μs ring	40-120 e12 in four 1-3 ns bunches

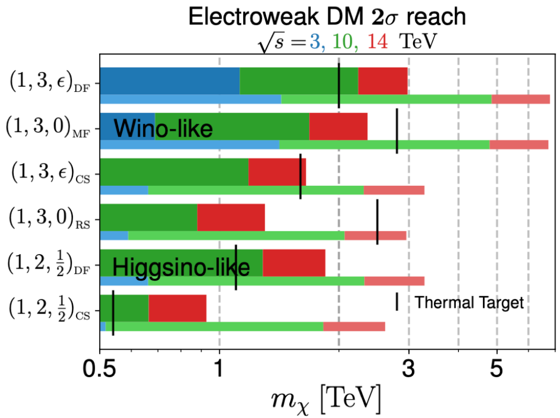
Muon Collider Physics



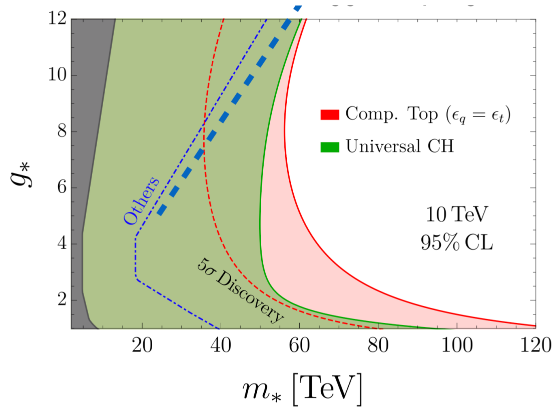
Order of magnitude in Higgs precision wrt HL-LHC and can directly probe *the scale implied in same machine!*



Self-coupling: at 3 TeV better than LHC. At 10 TeV similar or better than FCC-hh.



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



Unprecedented reach for strongly motivated BSM scenarios

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Muon Collider at Fermilab

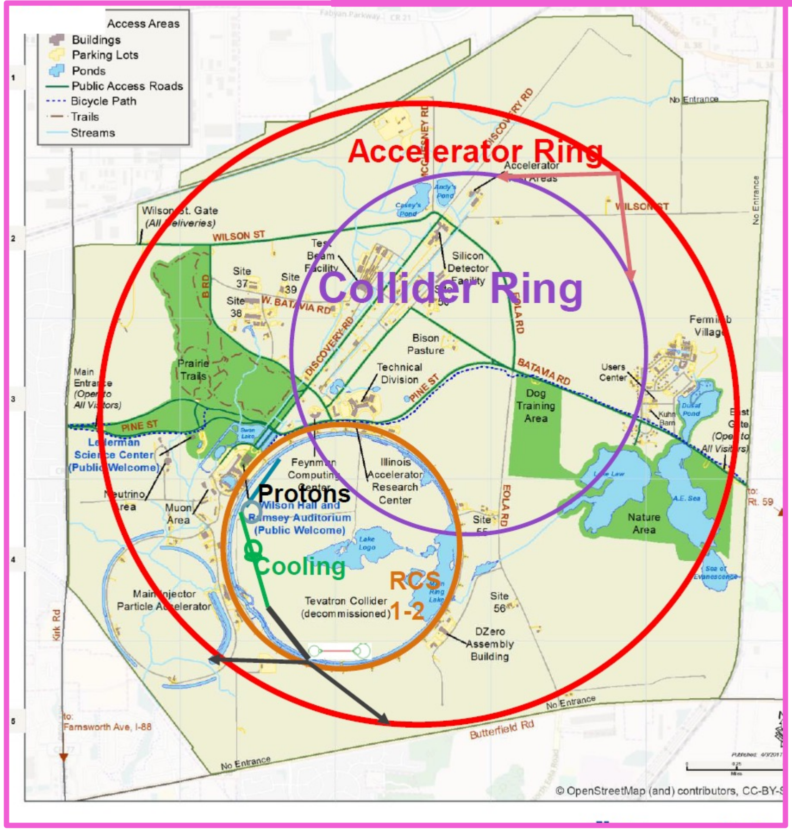
A concept of 10 TeV Muon Collider at Fermilab developed

Proton source
- PIP-II → PIU → Target → Cooling

Acceleration (3 stages)
- Linac + Recirculating Linac → 65 GeV
- Rapid Cycling Synchrotrons #1, #2 → 1 TeV (Tevatron tunnel?)
- RCS #3 → 5 TeV (site filler)
- 10 km collider ring

Various staging scenarios possible

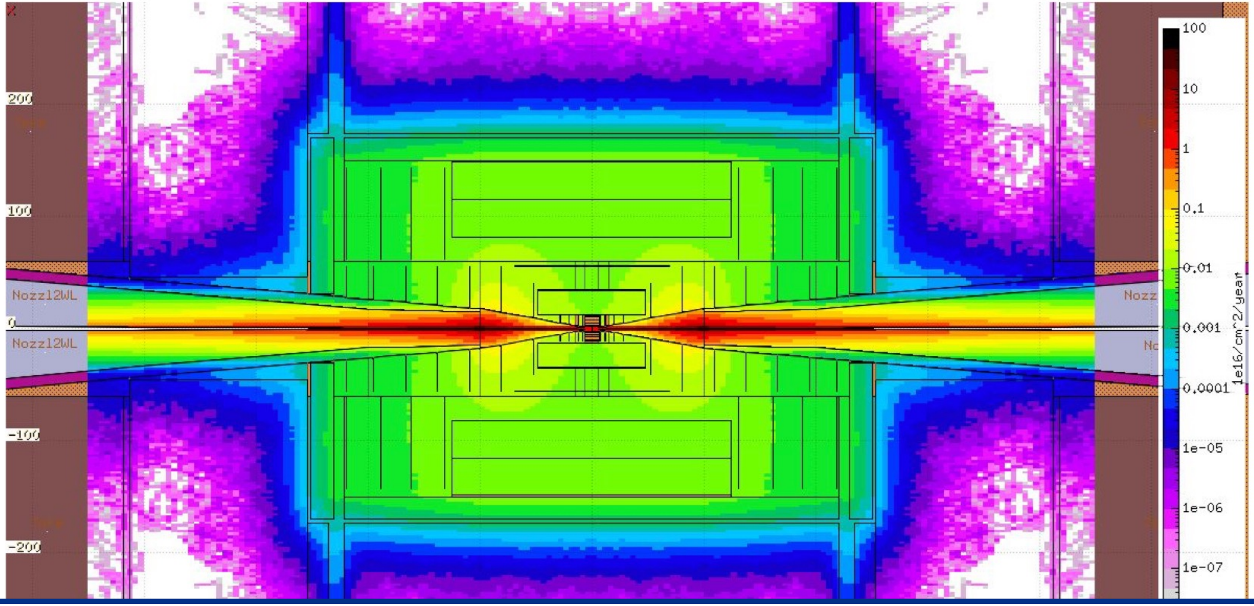
By D. Neuffer, [Details]



Fermilab

Radiation Levels

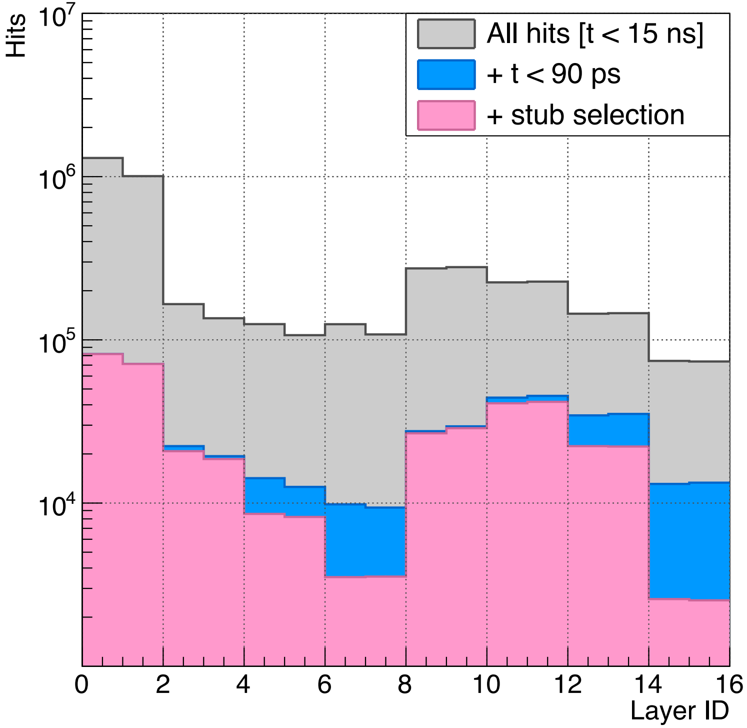
1-MeV-neq fluence for one year of operation (200 days)



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

Fermilab

Timing and Pointing in the Pixel detector



Muon Collider Synergies

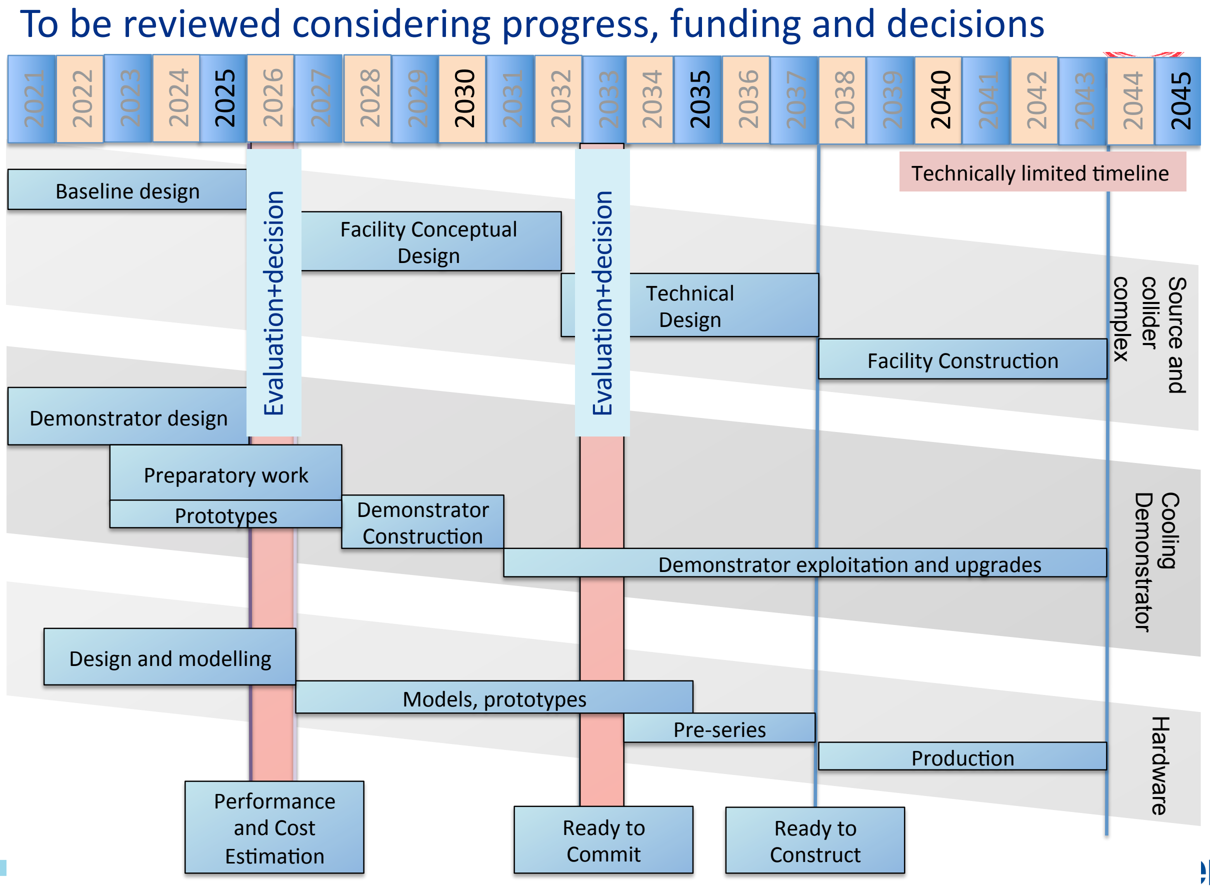
- Variety of Neutrino synergies:
  - Short baseline (x-sections, sterile) → Production + Storage ring
  - Long baseline neutrino factory → Production + Partial Cooling + Partial Acceleration
  - High energy neutrino cross sections → needs Collider beam
  - BSM physics → FASERν like experiment with smaller flux uncertainties → needs Collider beam
- Dark Sectors → High intensity proton beam
- Charged Lepton Flavor Violation → Muon production target and solenoid, possibly storage
- Beam dump experiments → Production + Cooling + Acceleration
- Muon-Ion collider → Full chain with one beam

IMCC Technically Limited Timeline

Muon collider important in the long term

Prudently explore if MuC can be **option as next project**

- e.g. in Europe if higgs factory built elsewhere
- **sufficient funding required now**
- very **strong ramp-up required** after 2026
- might require compromises on initial scope and performance
  - 3 TeV



rmilab

IMCC Collaboration Organisation

- **Collaboration Board (ICB)**
  - Chair: **Nadia Pastrone**

- **Steering Board (ISB)**
  - Chair **Steinar Stapnes**
  - Reports to LDG but could add DOE

- **Advisory Committee (IAC)**
  - To be defined

- **Coordination committee (CC)**
  - Study Leader **Daniel Schulte**
  - Deputies: **Andrea Wulzer, Donatella Lucchesi, Chris Rogers**
  - **Sergo Jindariani, Mark Palmer** as US links
  - Will strengthen physics and detectors