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Towards Muon Collider *detectors*

Sergo Jindariani (Fermilab)
Apr 13th, 2023

On behalf of US Muon Collider Community, International Muon Collider Collaboration, 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:

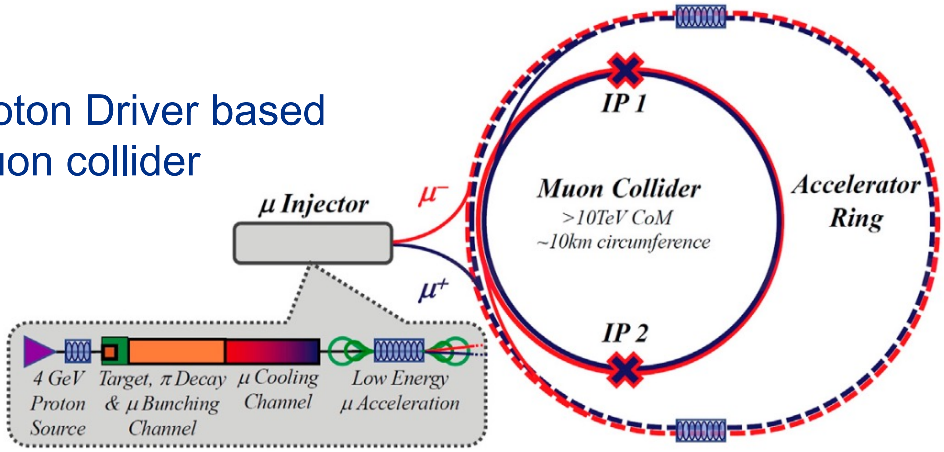
- Versatile machine with incredible EW reach (not just a muon collider, but a boson-boson collider)
- Higgs and understanding of Electroweak symmetry breaking
- Dark Matter
- And much more...

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)

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

Proton Driver based muon collider



Up to 2 interaction points but only one experiment assumed now

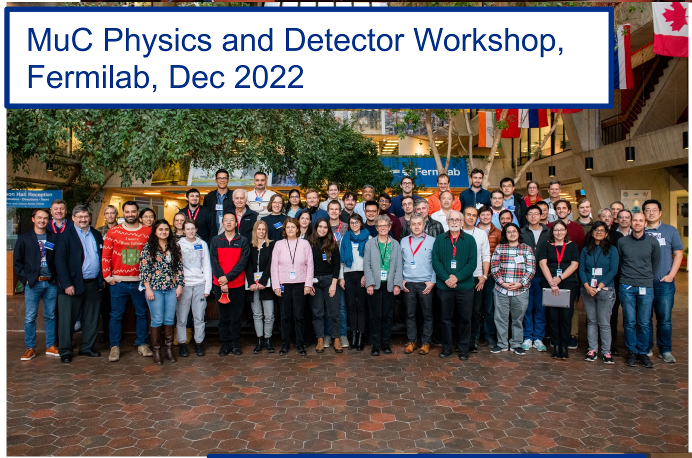
What changed since the last P5?

- **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], 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

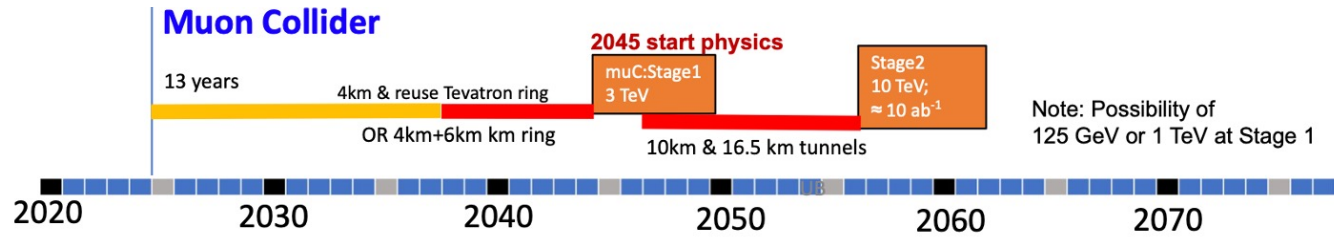
- Cross-frontier AF+EF+TF Muon Collider Forum :
  - Regular meetings with 50-100 participants in each, workshops
  - 40+ dedicated White Papers
  - Final report with ~180 authors, 50+% from Early Career (arxiv:2209.01318)
- **Conclusion of the Forum**: No fundamental showstoppers identified, but many engineering challenges exist, requiring a significant R&D investment

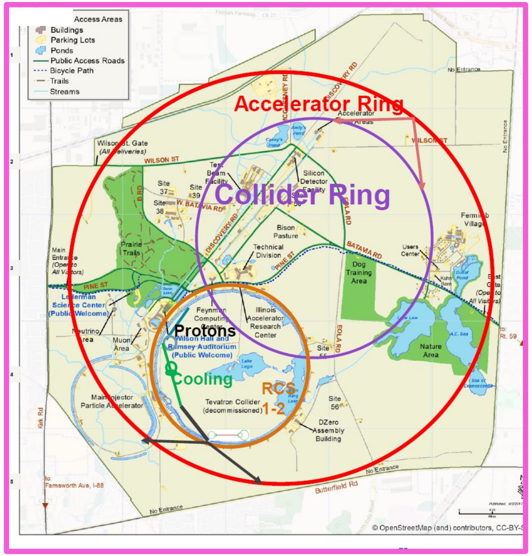

IMCC Meeting, CERN, Oct 2022


MuC Physics and Detector Workshop, Fermilab, Dec 2022


KITP Workshop, Santa Barbara, March 2023

The US timeline shown in Snowmass



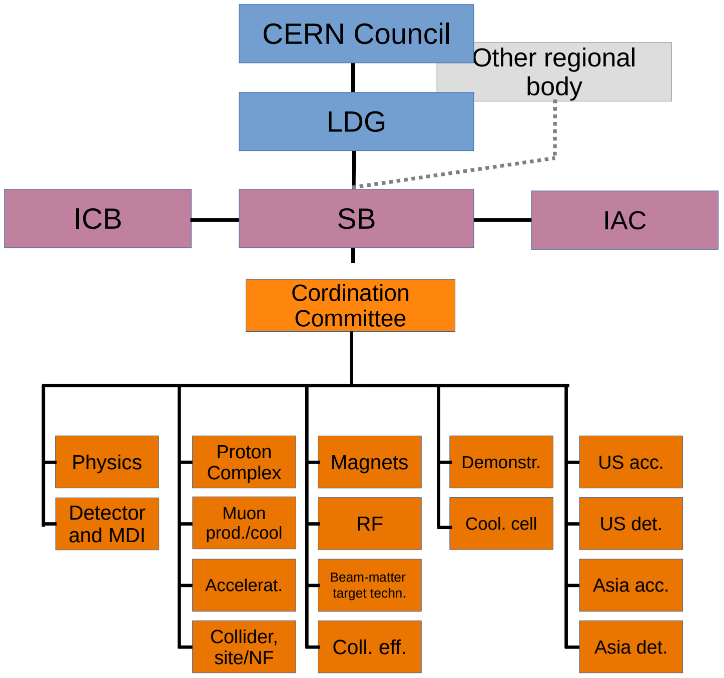


- This is a highly optimistic **Technically Limited timeline**
  - not limited by resources/funding
  - does not account for R&D risks
  - assumes no delays in construction
- The actual project start time is subject to:
  - Successful outcome of **the proposed extensive R&D program**
  - Availability 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”

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
- IMCC planning assumes a significant US participation to develop the baseline project and the best siting option (including US siting)
- Several US universities joined IMCC, many more expressed interest

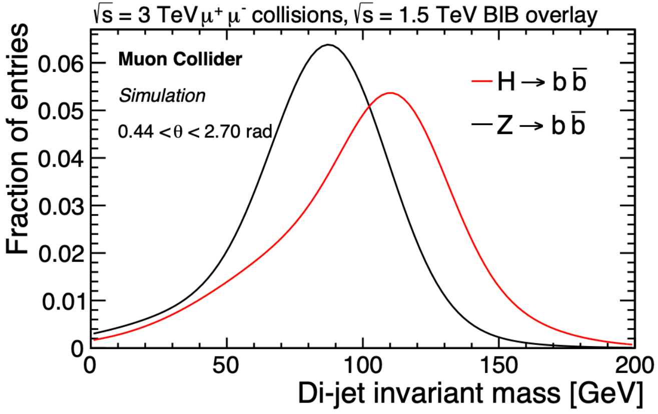


IMCC technical timeline will be reviewed periodically, including next year if/when DOE/NSF join the effort

Detector Requirements

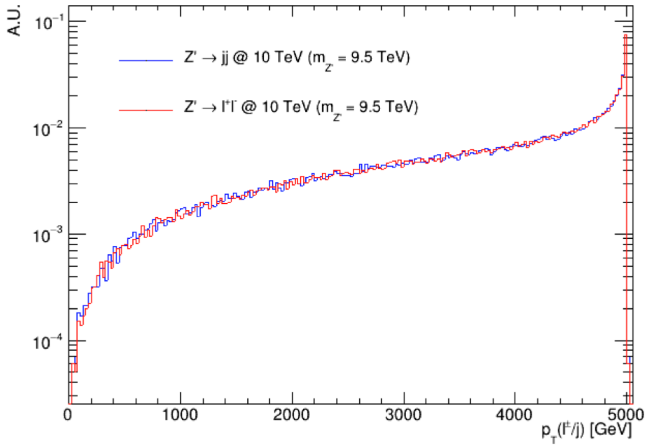
Precision Higgs program:

- 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)



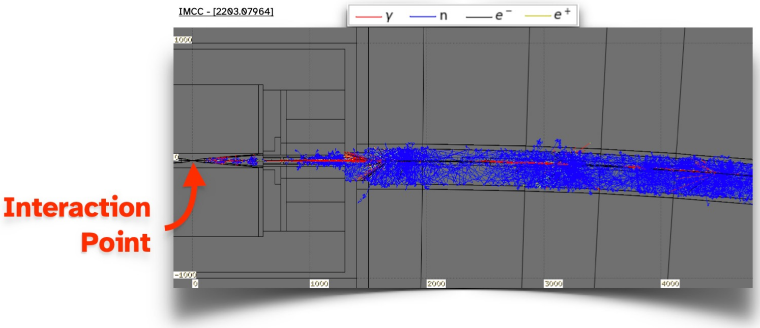
BSM program:

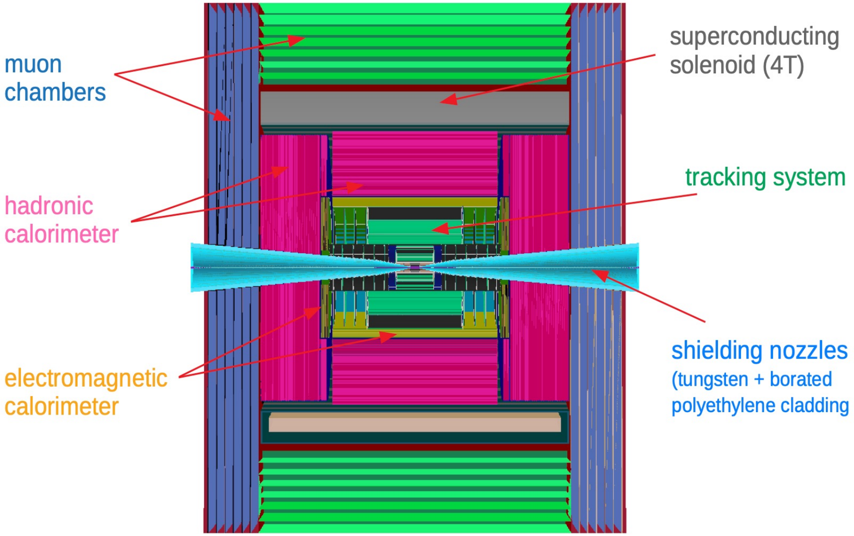
- Ability to reconstruct high energy leptons and jets
- Maintain acceptance/efficiency for unconventional signatures (disappearing tracks for DM searches, long-lived particles, etc)



The Detector

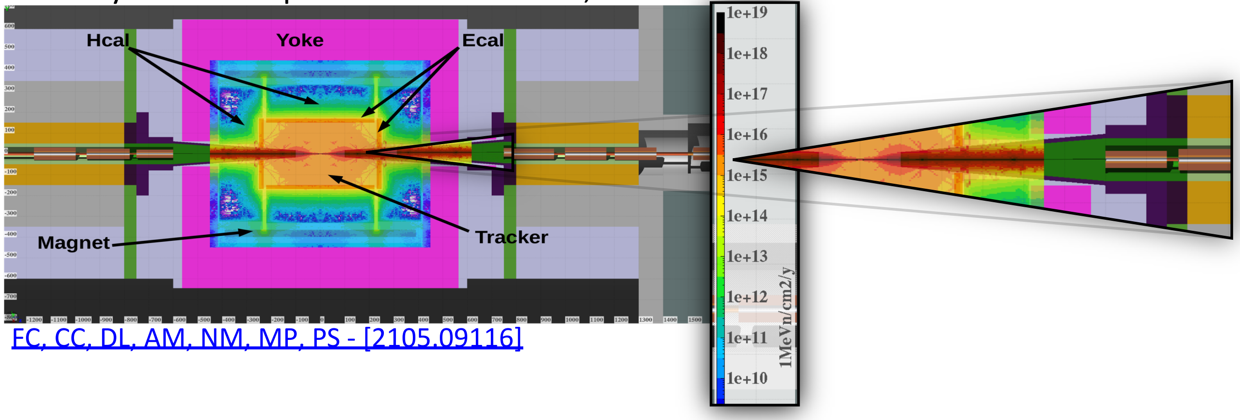
- Why do Muon Colliders need specialized detectors?
- Muons decay → Unique feature/challenge of Muon Collider detectors – beam induced background (BIB)
- Most of the energy in the detector is from muon decays that eventually result in a high rate of out-of-time neutrons and photons reaching the detector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



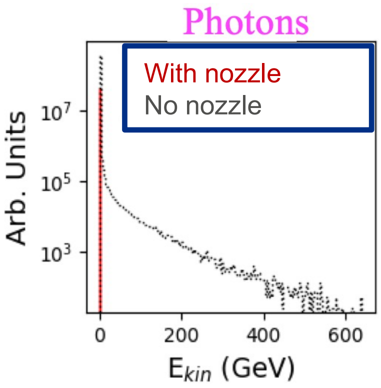


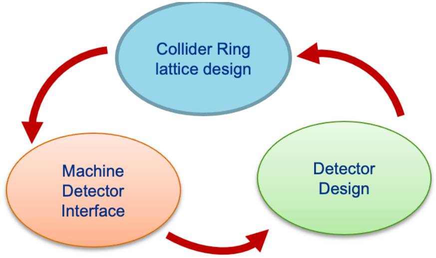
Machine-Detector Interface (MDI)

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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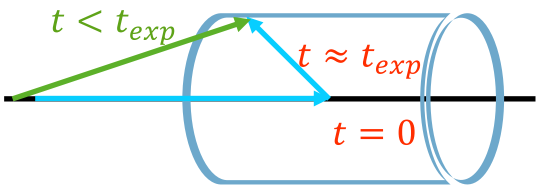
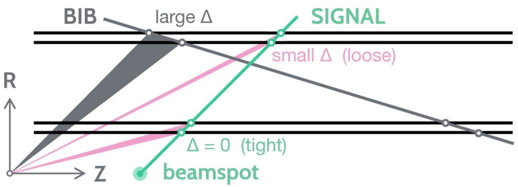
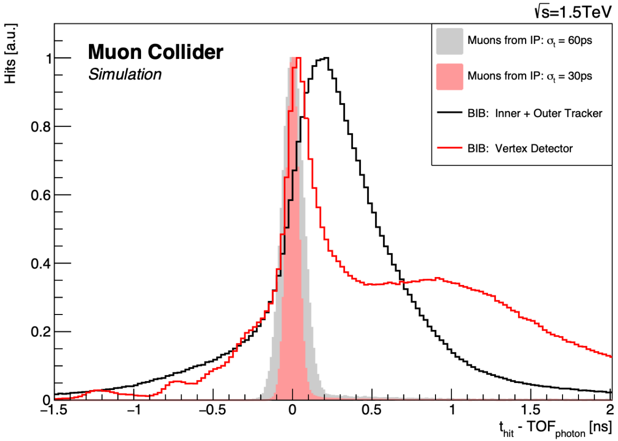
Tracker

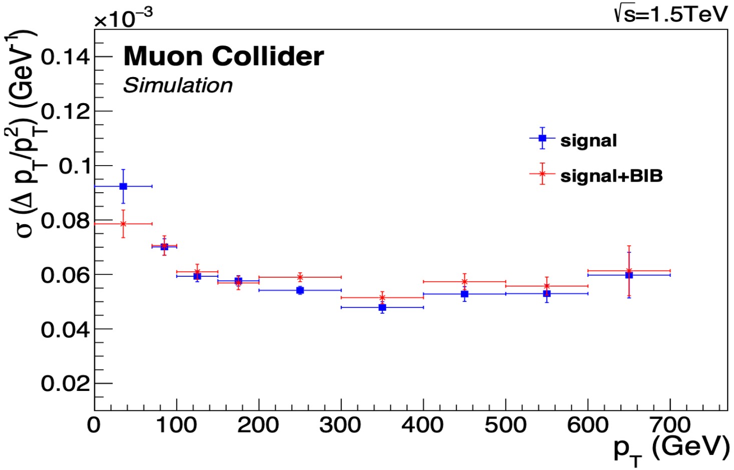
- Need to build detectors that can tell the difference between post-nozzle BIB and signal
- The BIB is mostly out of time and not pointing to the Interaction Point
- Some similarities with LHC pileup - **can build on that experience!**
- 4D tracker with precision timing (~30-60 ps), pointing, and local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







Track resolution



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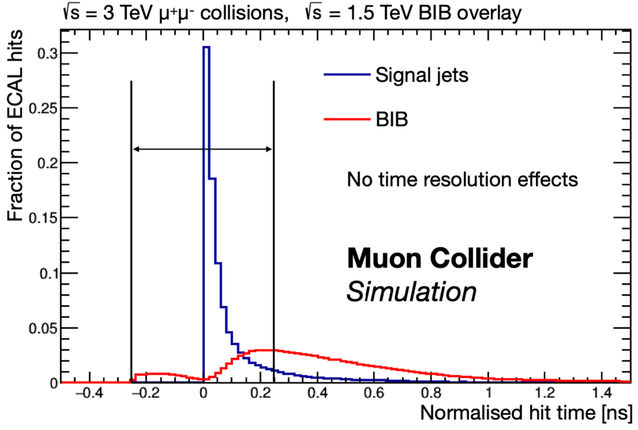
Calorimeter

- 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. Crilin, dual readout) can bring better performance

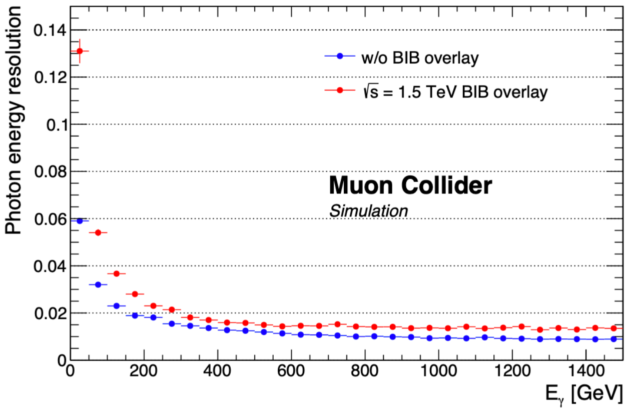
General Features:

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

ECAL hit time



Photon Energy Resolution

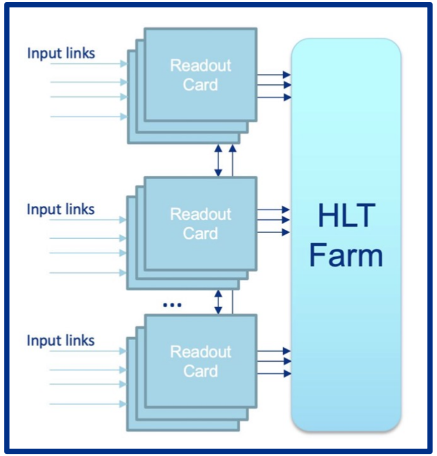


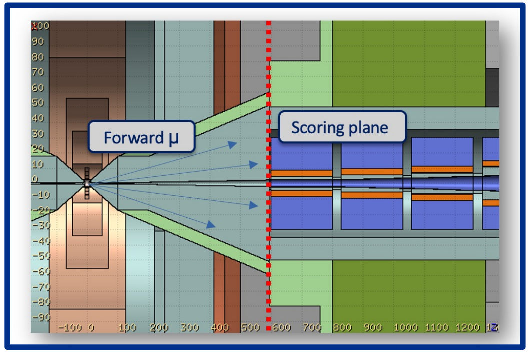
Muons, DAQ and Forward Detectors

- **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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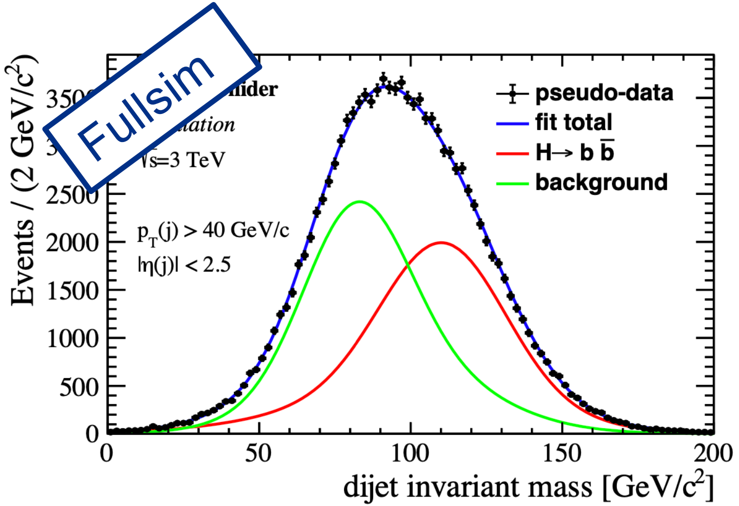
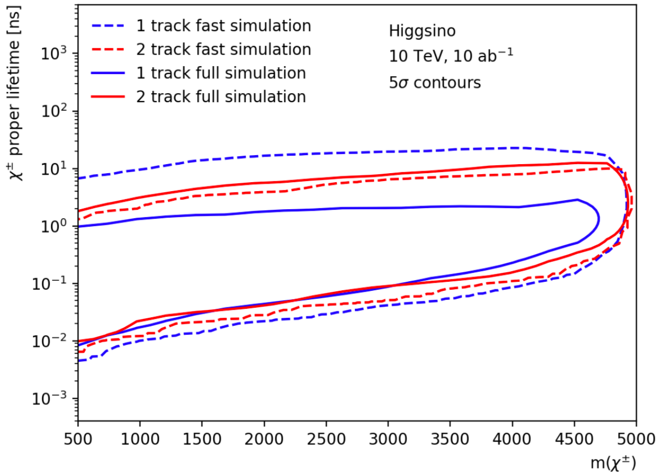
Full Simulation Physics Studies

- 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



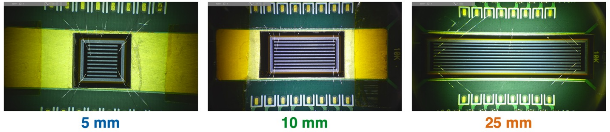
Higgs → bb cross-section:
FastSim: 0.73% vs Fullsim: 0.75%

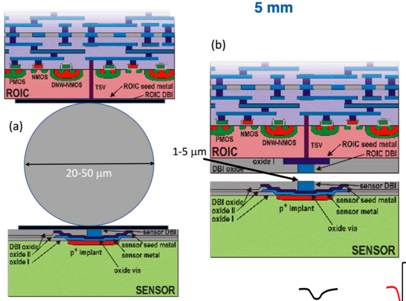


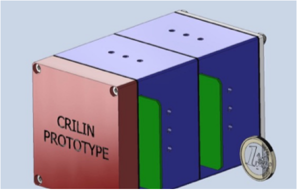
Very good agreement in 2-track final state
1-track better in fastsim due to higher acceptance

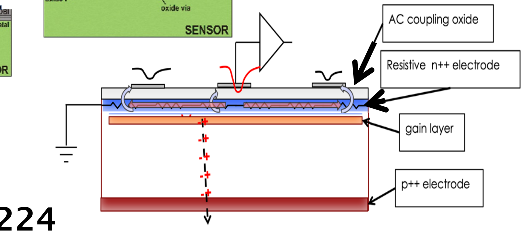
R&D Activities in US and Europe:

- 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

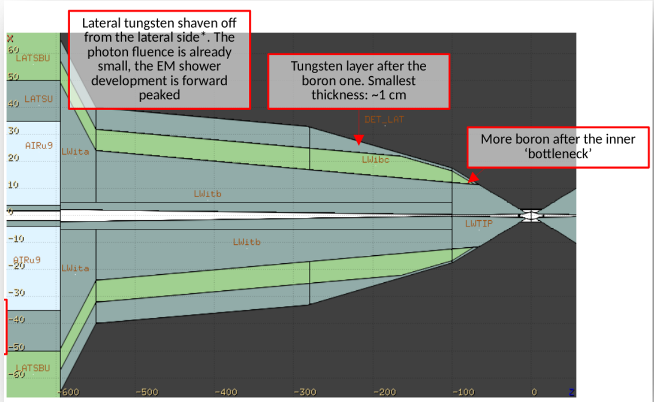
- Detector and MDI designs in early stages of development
- The backgrounds remain flat with energy
- Radiation at HL-LHC levels or lower, much lower than FCC-hh

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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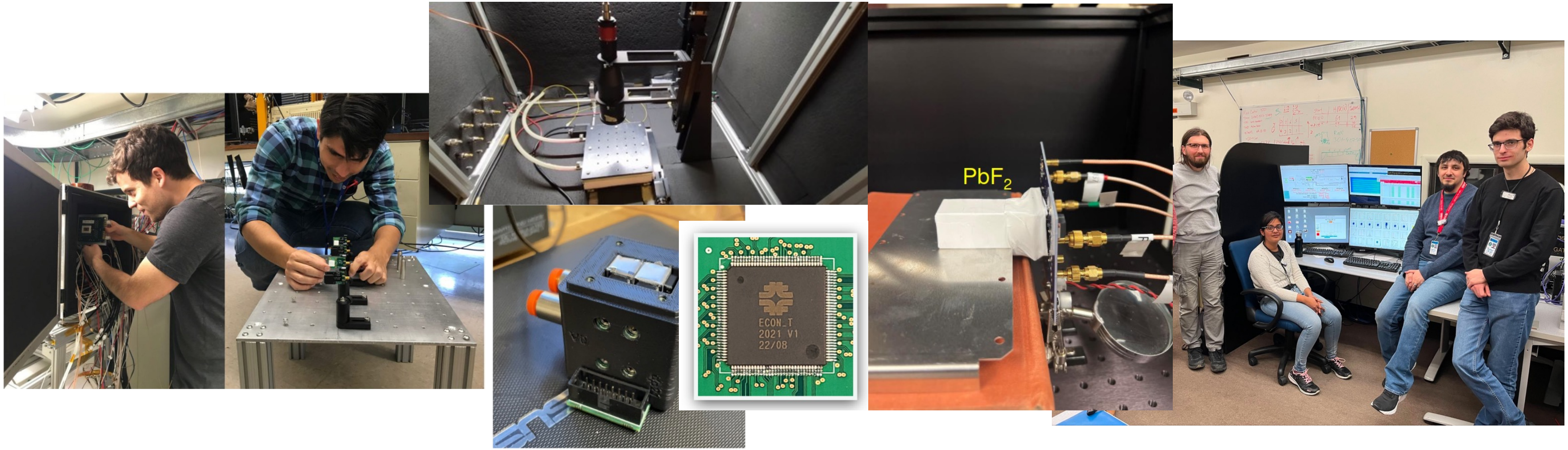
Training Opportunities

- Cutting edge technology + highly impactful research = Draw the best talent
- Unique training ground for future generations of accelerator and particle physicists:
- Strong interest amongst Early Career – build a diverse community of future US particle physics leadership!



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)

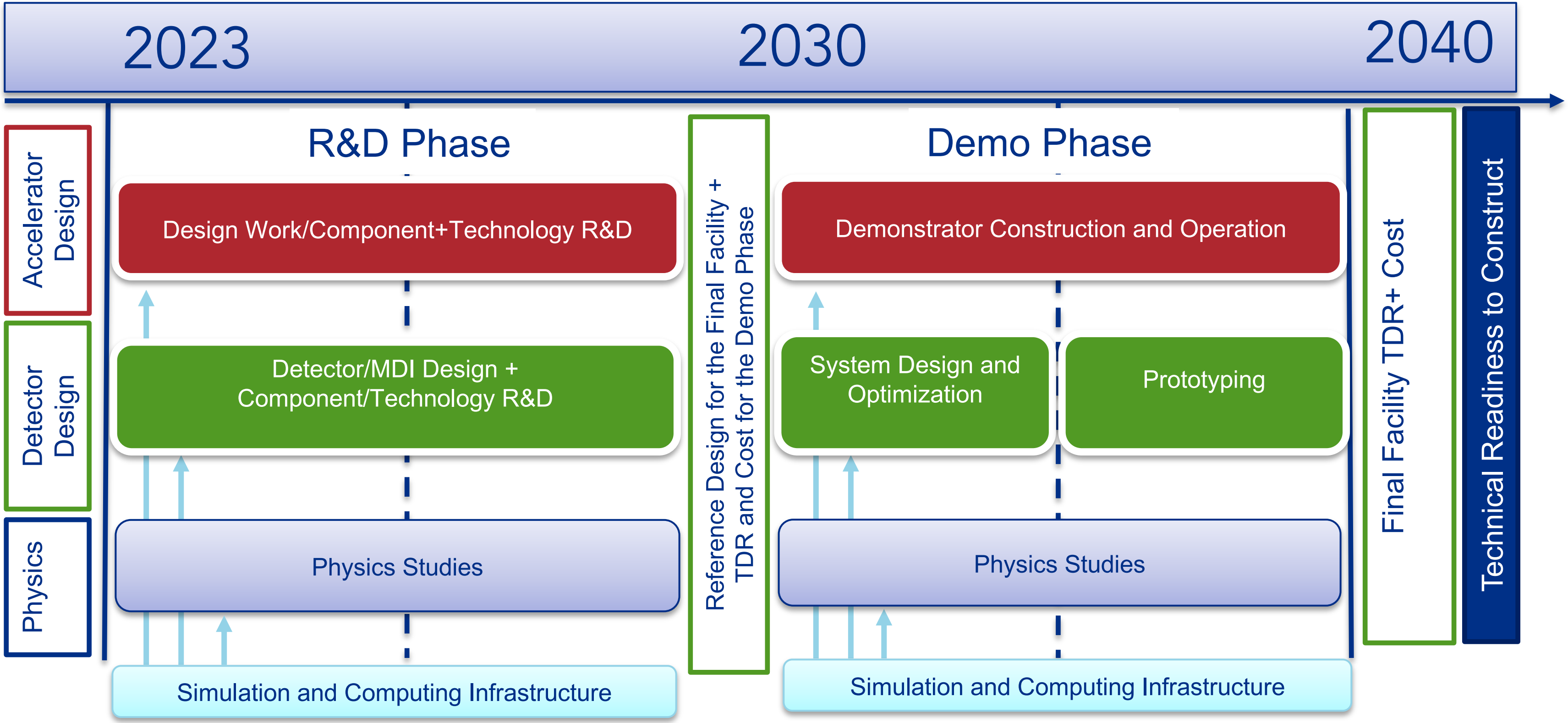
Magnet systems:
Steve Gourlay (Fermilab), Giorgio Apollinari (Fermilab), Soren Prestemon (LBNL)

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



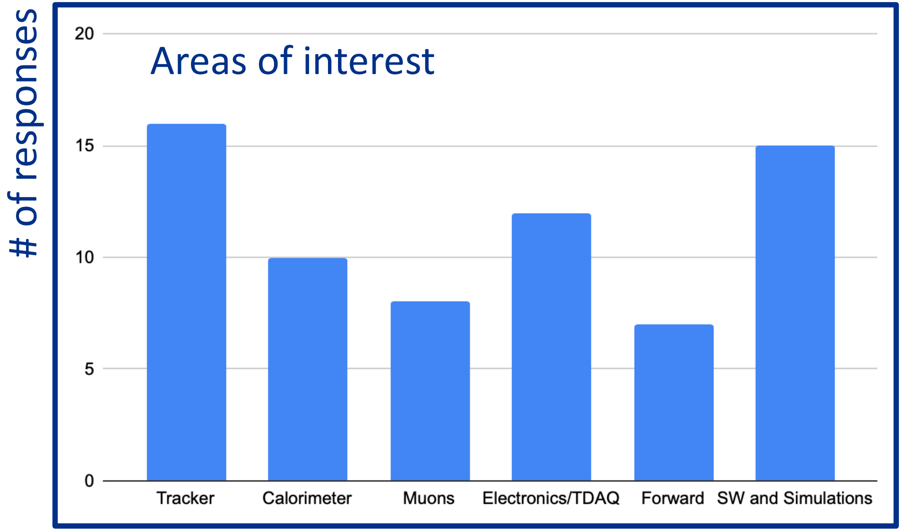
Detector R&D Scope and Interest:

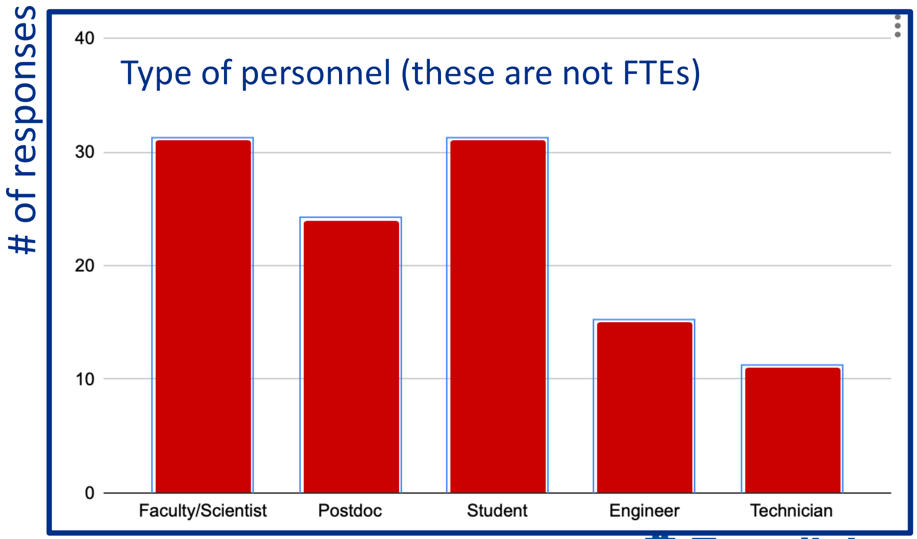
List of work areas and activities

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)





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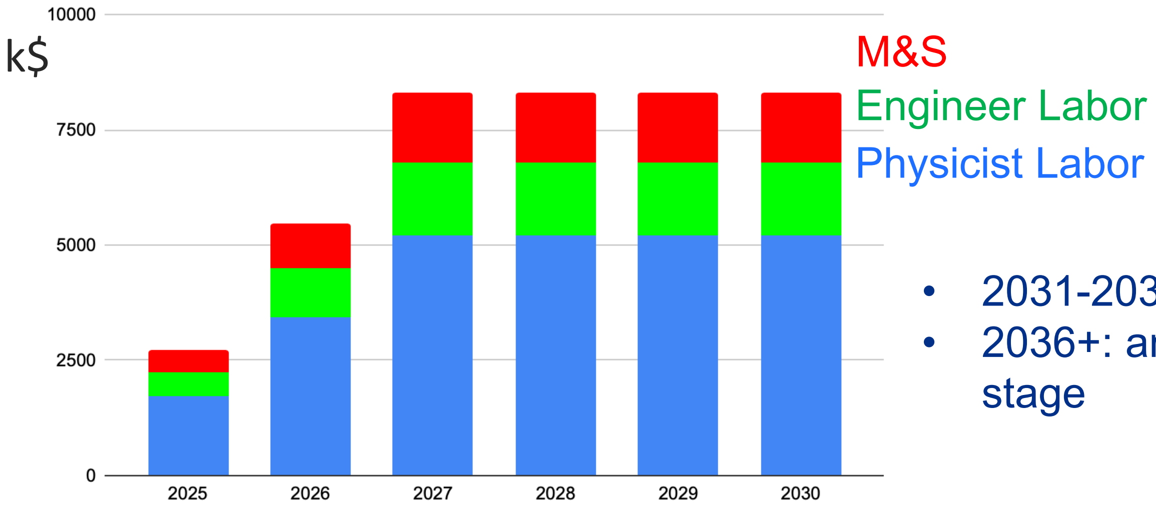
US R&D Budget Estimate (Detector only)

- 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

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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

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 at FNAL up to 0.5T peak field	Design and demonstration work to achieve higher ramp rates (up to 1000 T/s) and peak fields of ~2T
Very Rapid Cycling Synchrotron Dynamics	Lattice design in place for a 3 TeV accelerator ring	Develop lattice design for a 10 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

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)

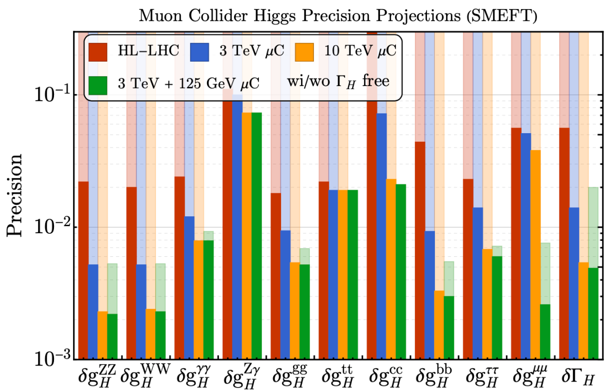
Booster Replacement Scenarios

- 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

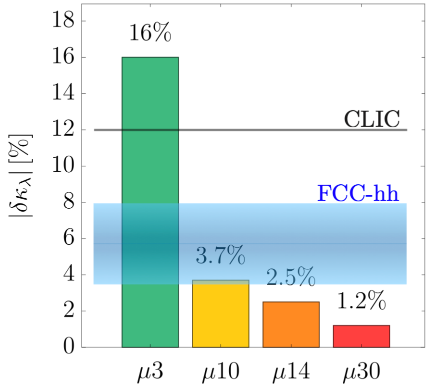
	Nominal	New RCS Scenarios			8 GeV Linac Scenarios		
Parameter		**v1**	**v2**	**v3**	**v1**	**v2**	**v3**
Linac Energy	0.8 GeV	2 GeV	2 GeV	2 GeV	8 GeV	8 GeV	8 GeV
Linac Current	2 mA	2 mA	2 mA	5 mA	2.7 mA	5 mA	5 mA
Rep. Rate	20 Hz	10 Hz	20 Hz	20 Hz	10 Hz	10 Hz	20 Hz
8 GeV Beam Power	160 kW	320 kW	960 kW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

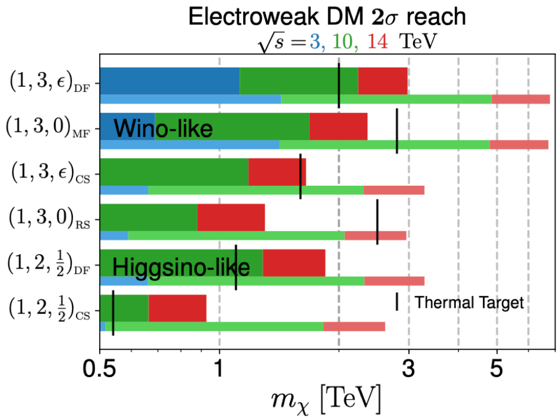
Muon Collider Physics



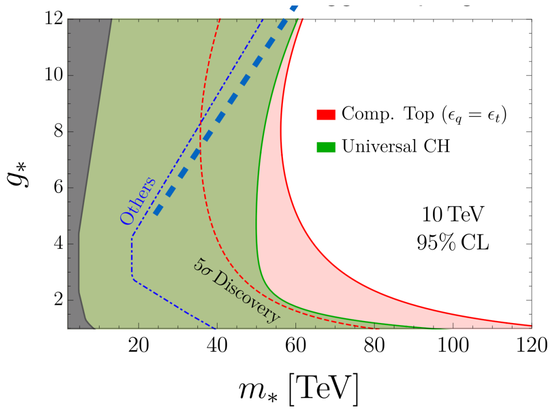
Order of magnitude in Higgs precision wrt HL-LHC and can directly probe *the scale implied in same machine!*



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

Muon Collider at Fermilab

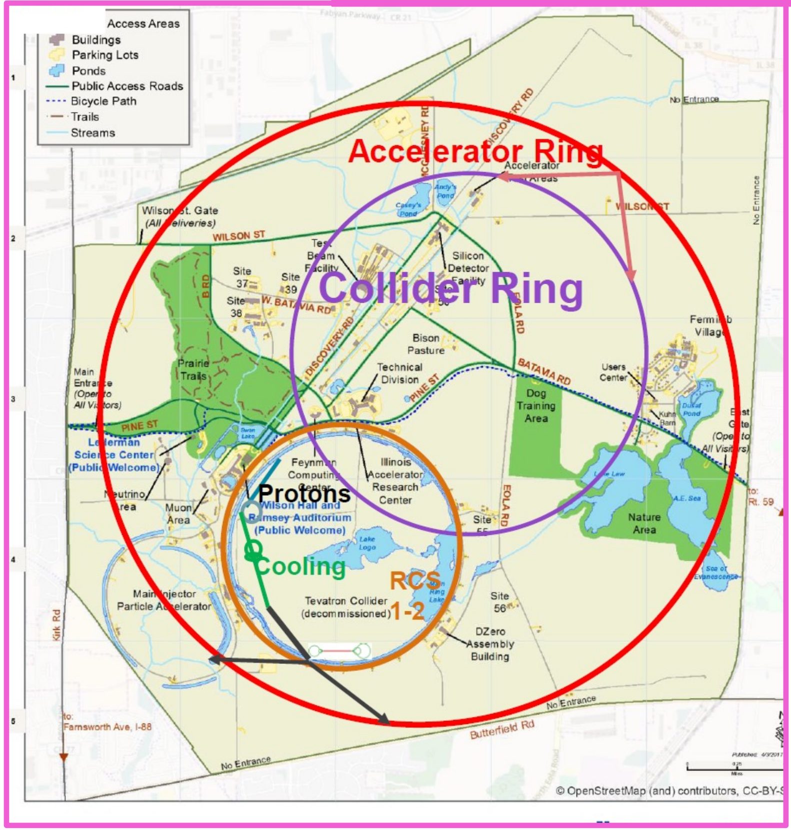
By D. Neuffer, [Details]

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

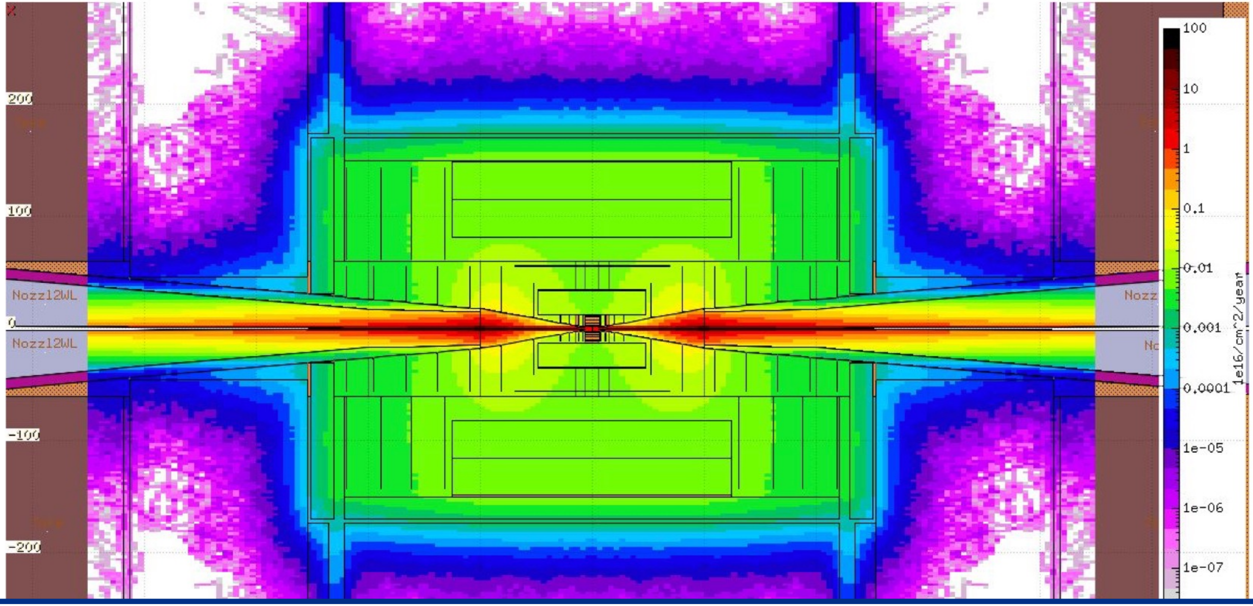
Various staging scenarios possible



Fermilab

Radiation Levels

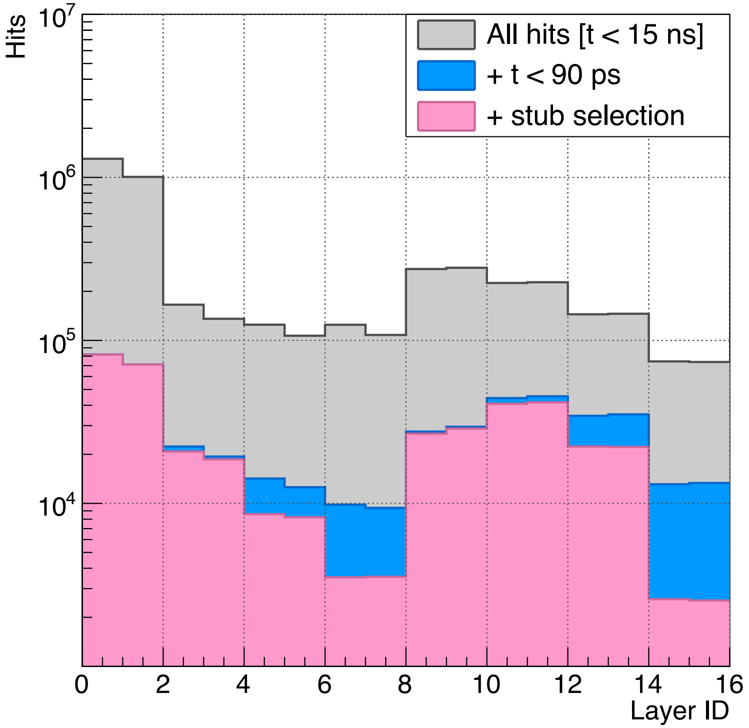
1-MeV-neq fluence for one year of operation (200 days)



	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

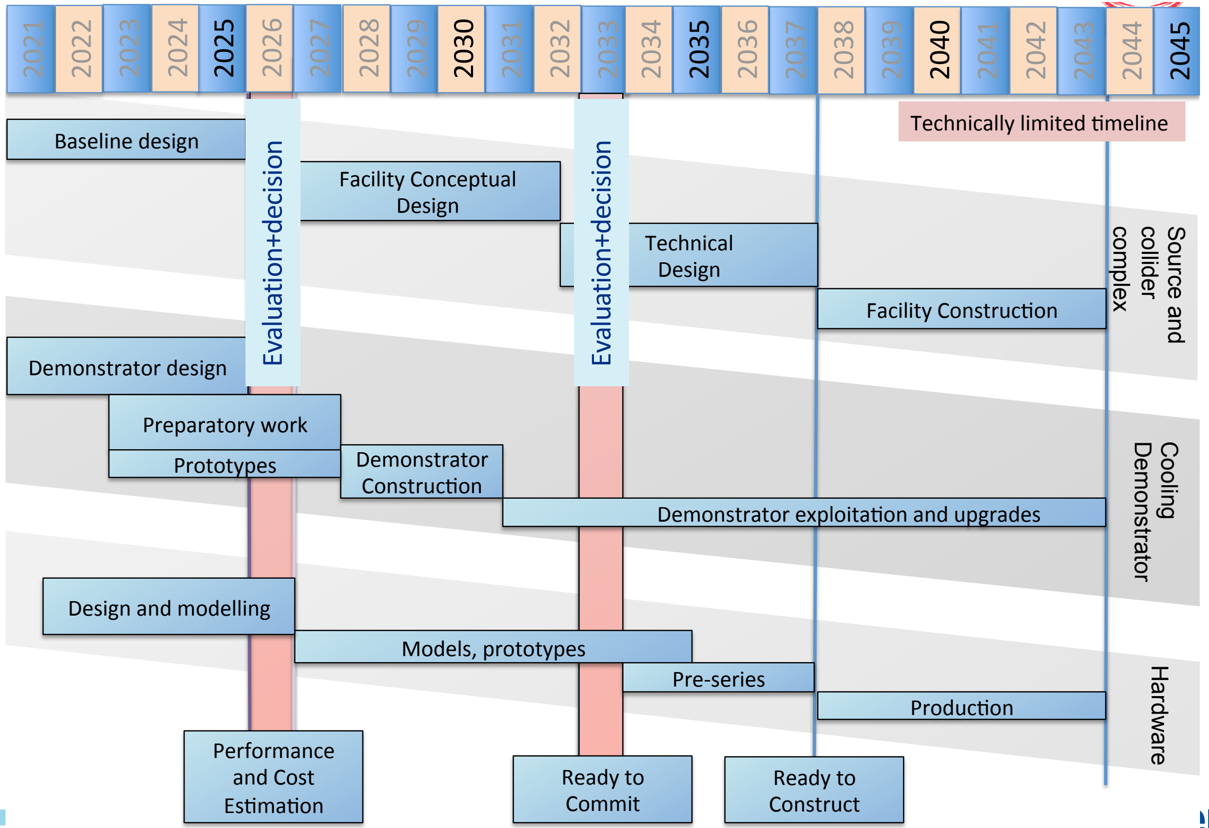
IMCC Technically Limited Timeline

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

To be reviewed considering progress, funding and decisions



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