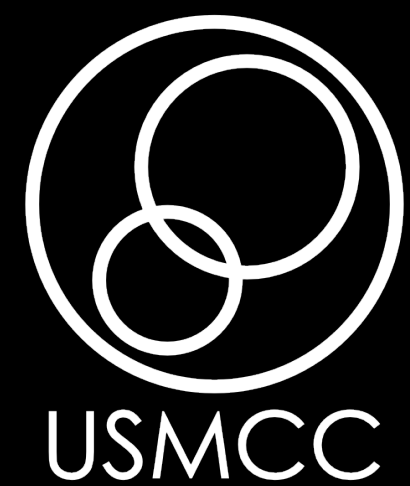




Lawrence Lee

MUON COLLIDER OVERVIEW

Tova Holmes (UTK)
On behalf of the US Muon
Collider Collaboration



New Science and Applications at the SNS
June 10, 2026

WHY COLLIDERS?

to make a collider

you must get (near) point-like particles
so focused and aligned that they can hit each other

WHY COLLIDERS?

to make a collider

you must get (near) point-like particles
so focused and aligned that they can hit each other

why not just hit a target?

center of mass energy much larger —————→ **goal: 10 TeV**

easier to understand without nuclear interactions —————→ **precision**

WHY MUONS?

Began with the logical choice: readily available, stable charged particles: **e**, **p**

can they continue to 10 TeV+?

circular e+e-:

$$P \approx 3 \times 10^{-7} \left(\frac{1 \text{ km}}{R} \right)^2 \left(\frac{E}{m} \right)^4 \text{eV/s}$$

huge power loss,
need a giant ring

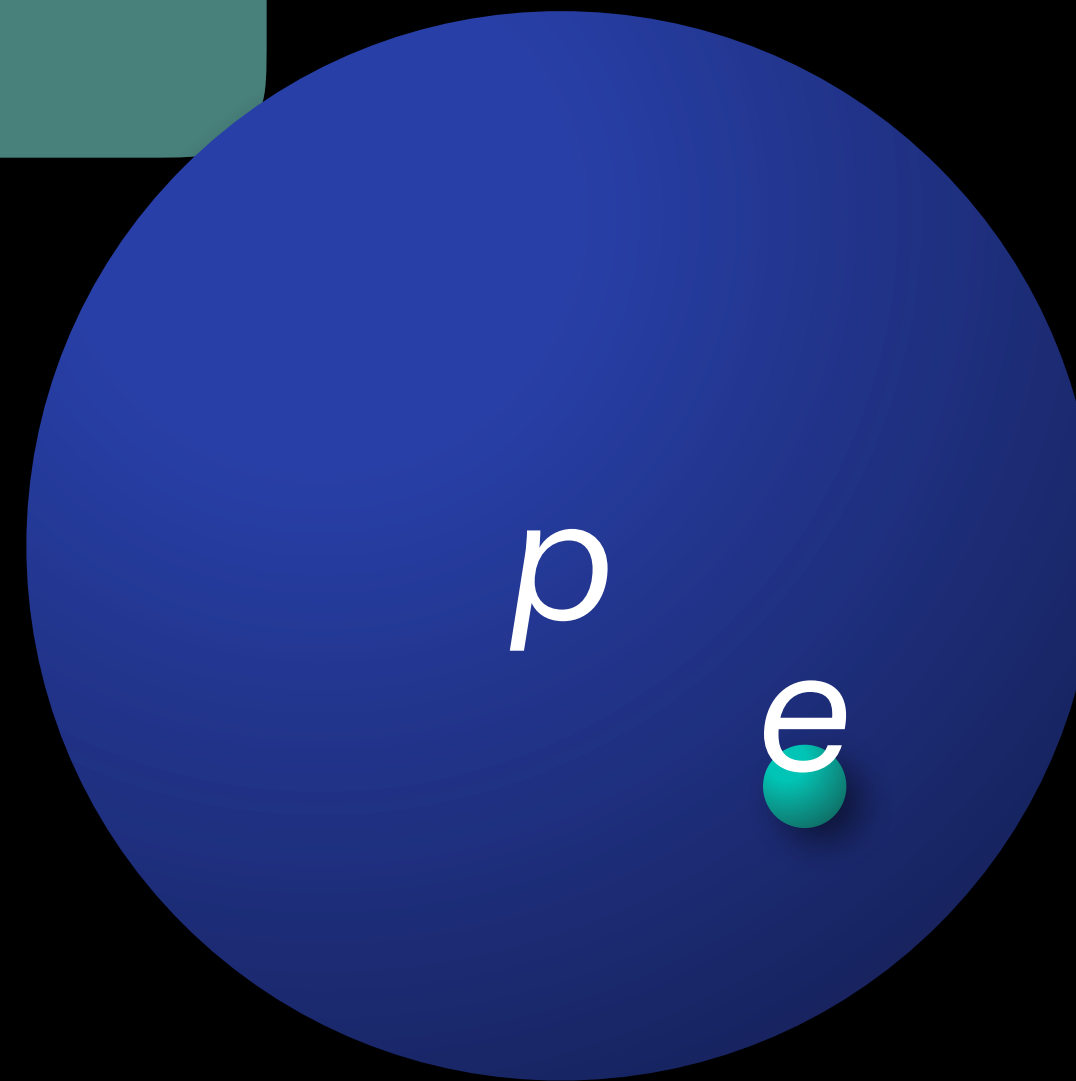
linear e+e-:

single pass; sufficient
luminosity requires high
power

circular pp:

$$B \approx 3 \left(\frac{E}{1 \text{ TeV}} \right) \left(\frac{1 \text{ km}}{R} \right) \text{ T}$$

energy reach \ll beam energy
giant ring/powerful magnets



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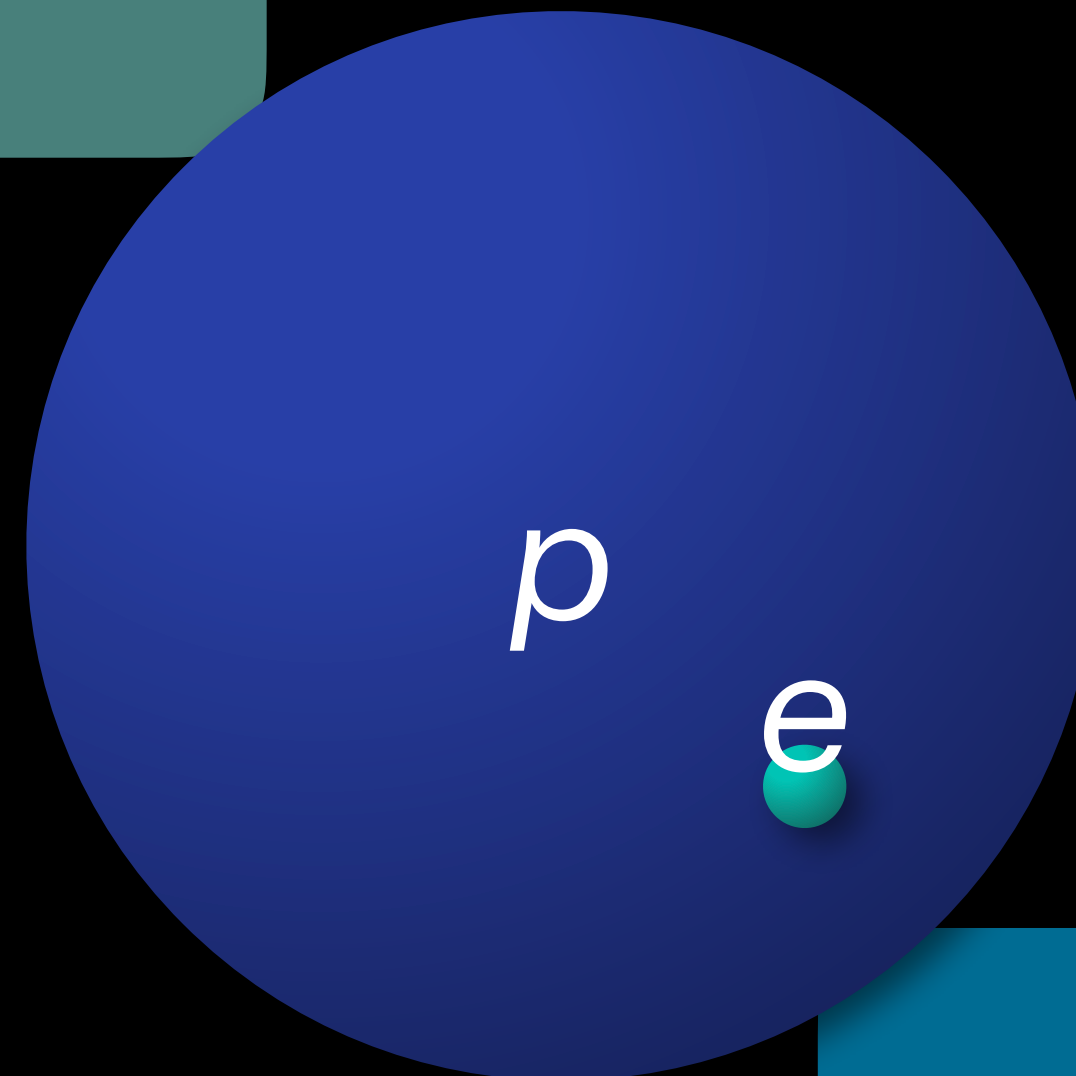
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energy reach \ll beam energy
giant ring/powerful magnets



use of these particles fundamentally
limits our reach:

next machine - **hard**
machine after that - **impossible**

in the past: overcame this
with a paradigm shift

switch to superconducting magnets
Tevatron explored new energy
huge success for physics, spin-off technology

government money well spent!

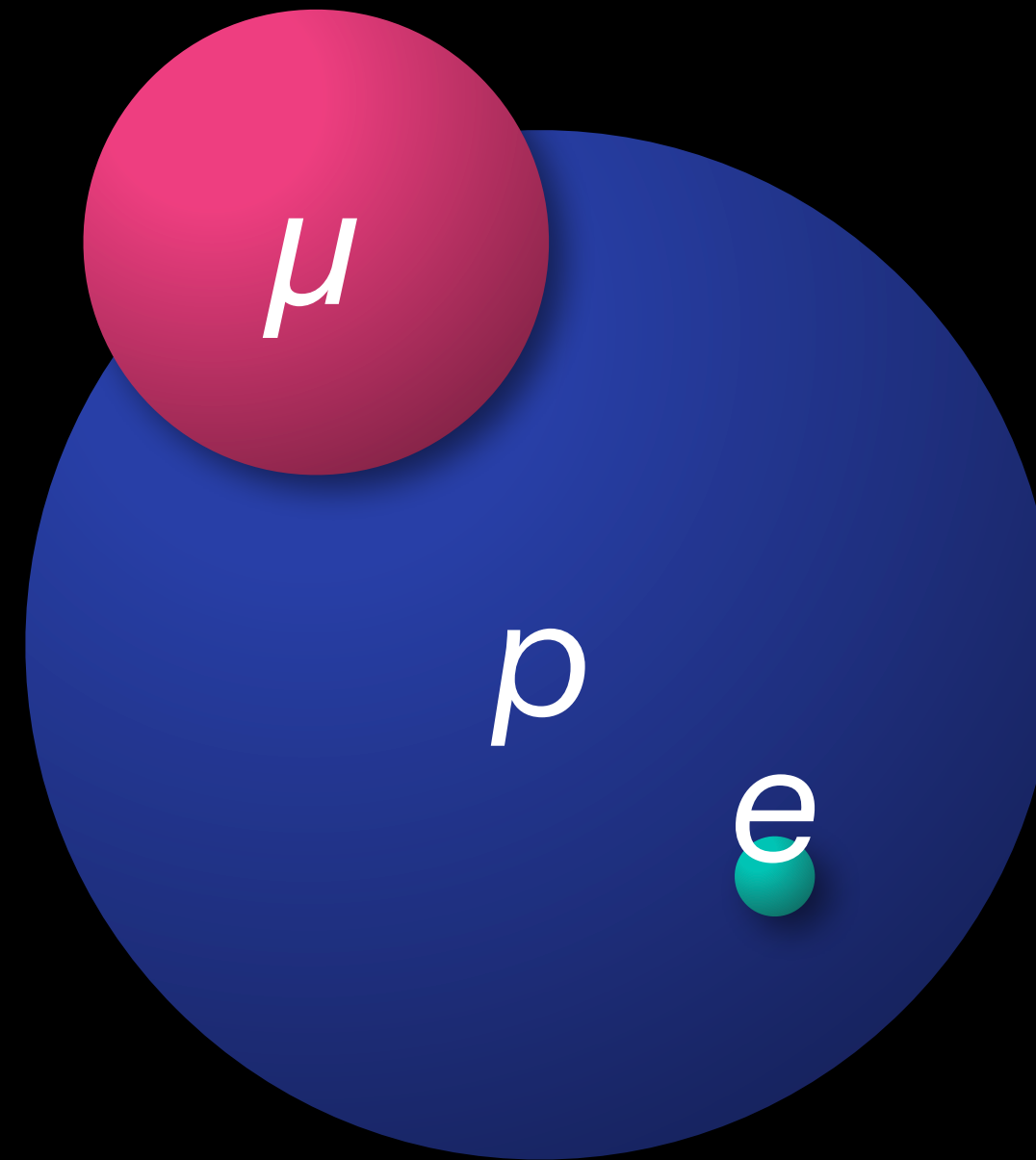
WHY MUONS?

we need more paradigm shifts
if we don't want to reach a **dead end**

one option:
a **muon collider**

Not a starter beam!

Muons aren't stable:
have to **produce** them
they **decay** in flight



but: fundamental
challenges get **easier** with energy

lifetime increases:

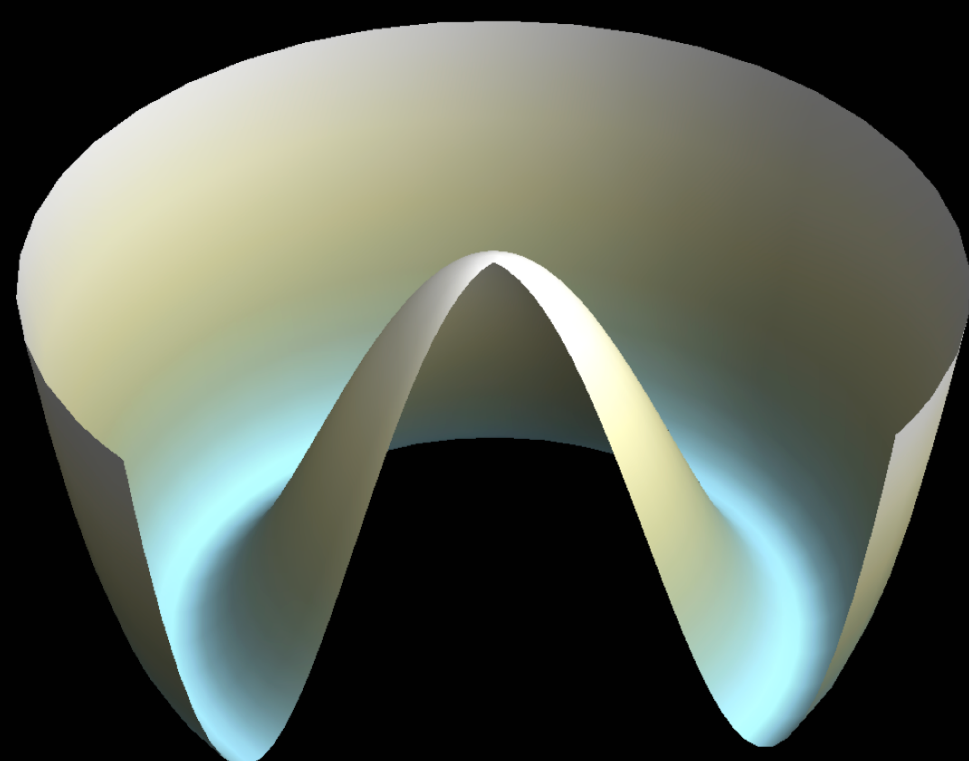
$$\tau'_\mu = 21 \text{ ms} \times \left(\frac{E}{1 \text{ TeV}} \right)$$

big consequences:
luminosity increases with E
beam **decays** decrease with E

as we contemplate higher energies, muons gain an advantage

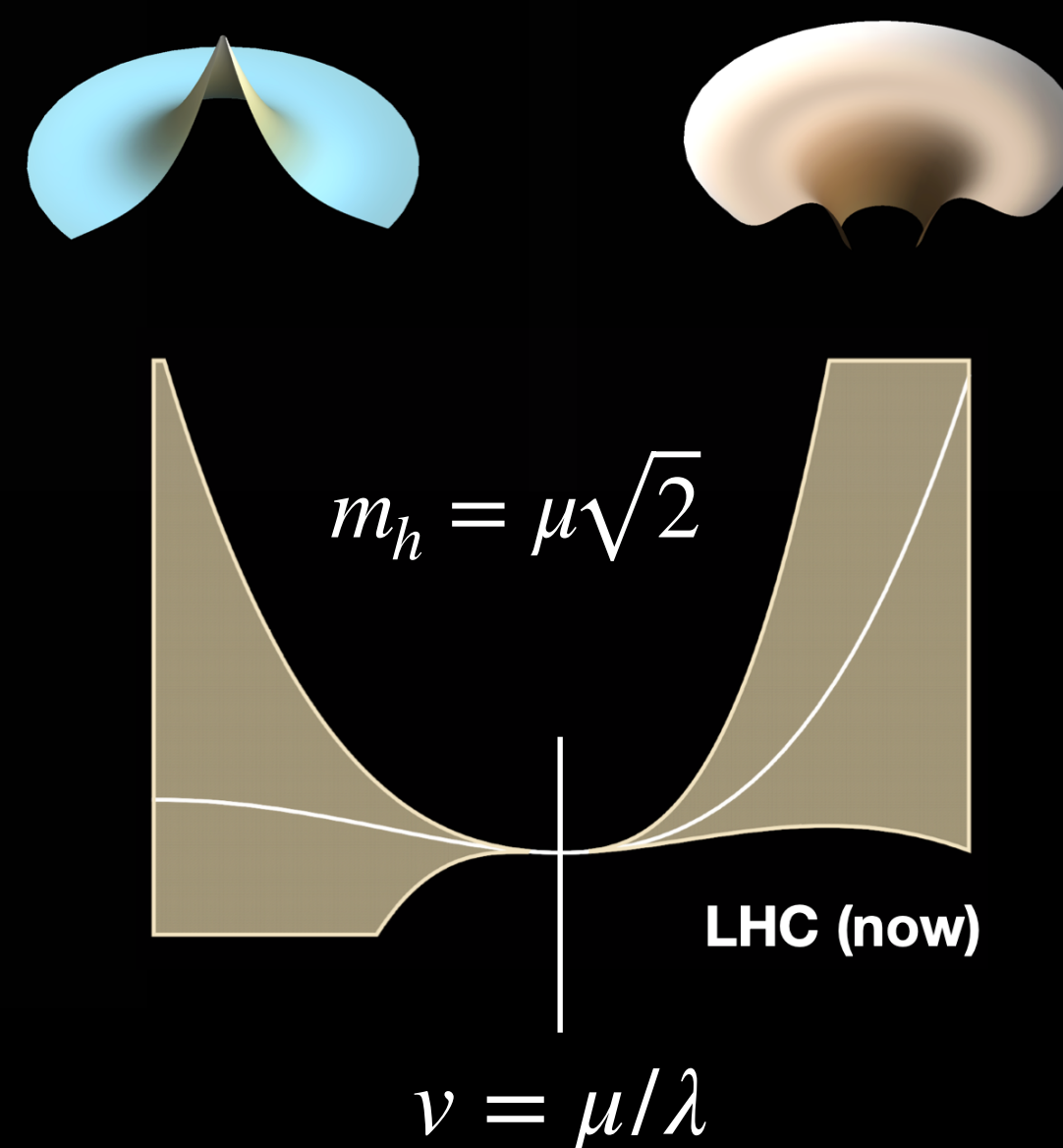
WHY HIGHER ENERGIES? UNDERSTANDING THE HIGGS

the theory



$$\mathcal{L} \supset \frac{1}{2} \partial_\mu \phi^* \partial^\mu \phi + \frac{1}{2} \mu^2 \phi^* \phi - \frac{1}{4} \lambda^2 (\phi^* \phi)^2$$

today's understanding



the future?

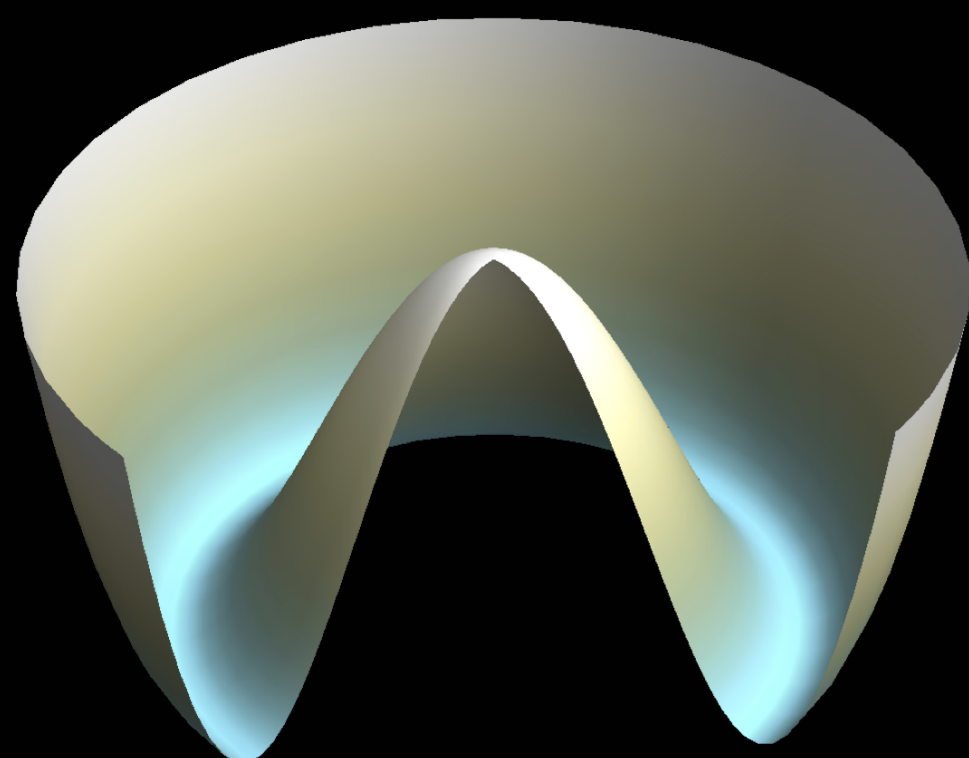


better understanding of birth (EWSB)
and possible death (metastability) of the universe

understanding what the Higgs potential is
is the first step to understanding *why* it is

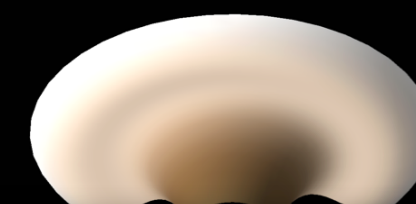
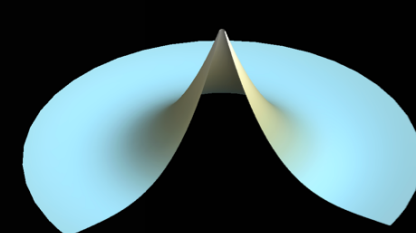
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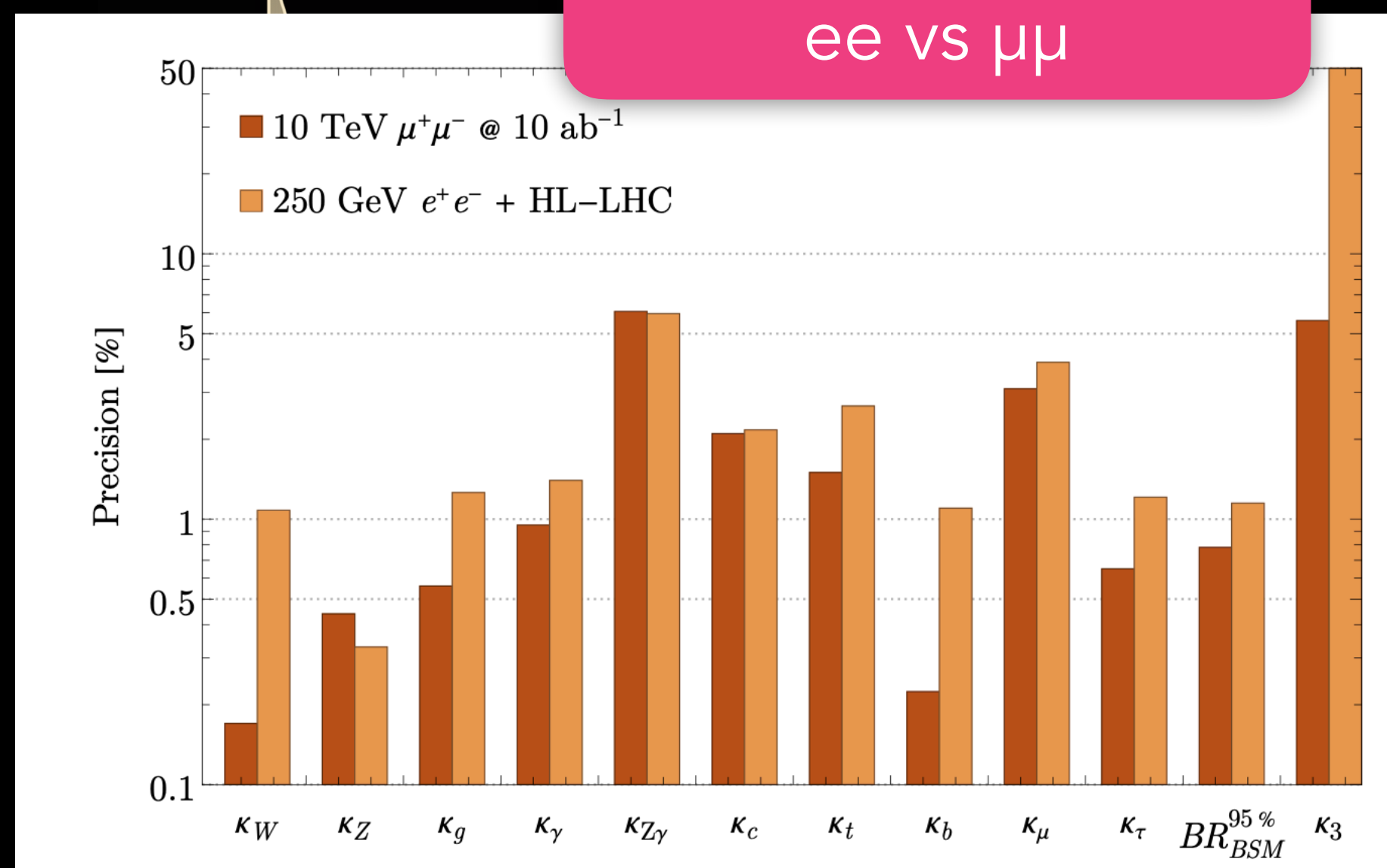


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today's understanding



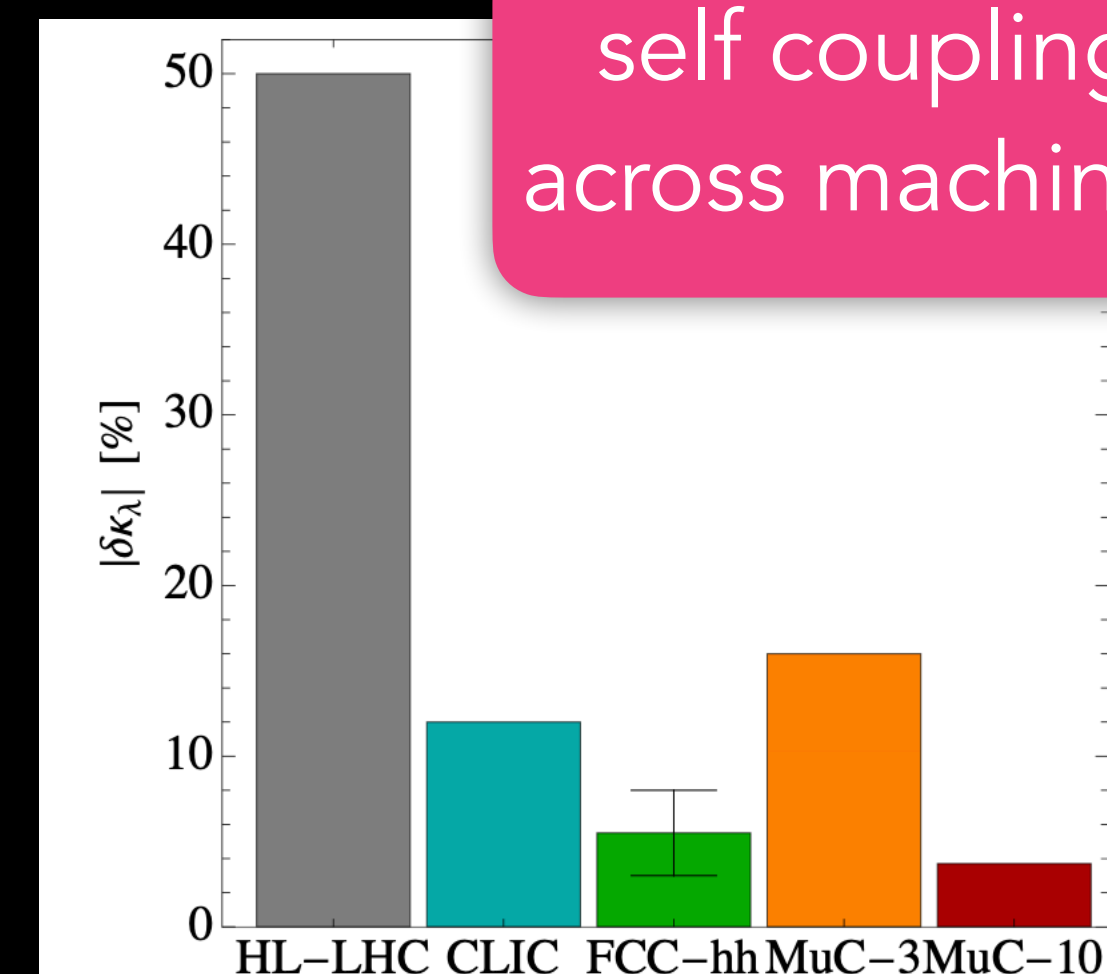
higgs parameters:
 ee vs μμ



the future?



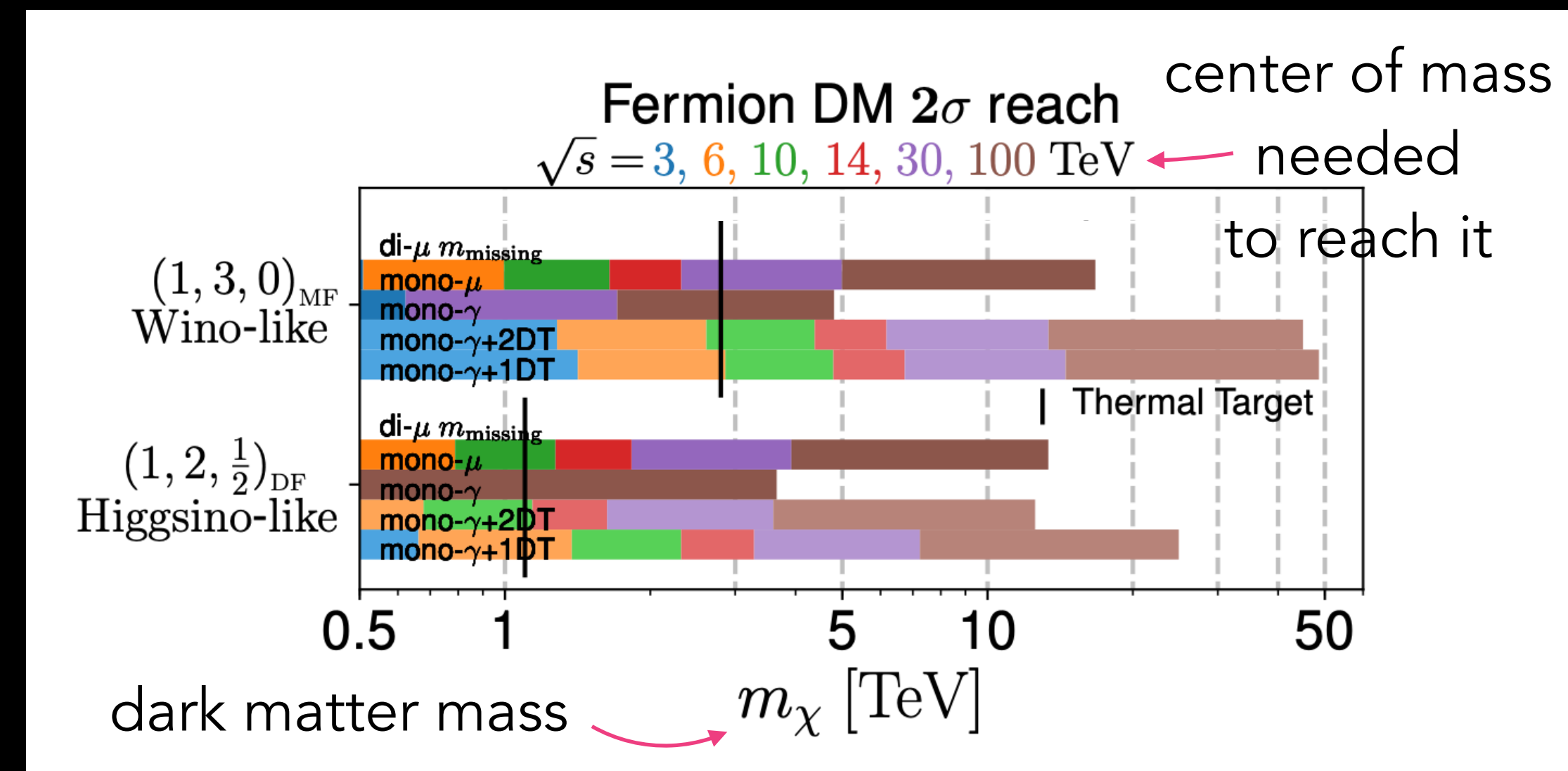
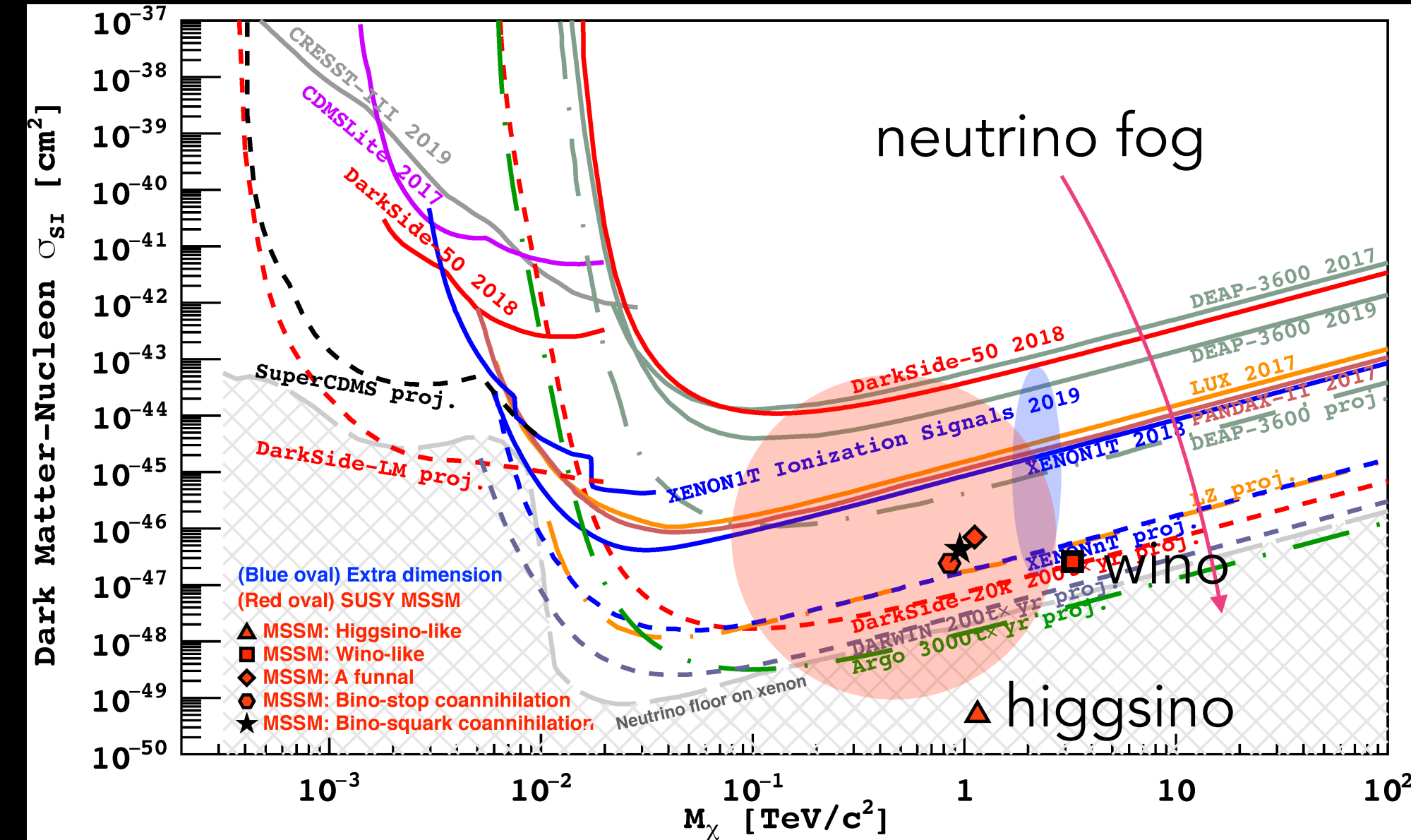
self coupling
 across machines



WHY HIGHER ENERGIES? DARK MATTER

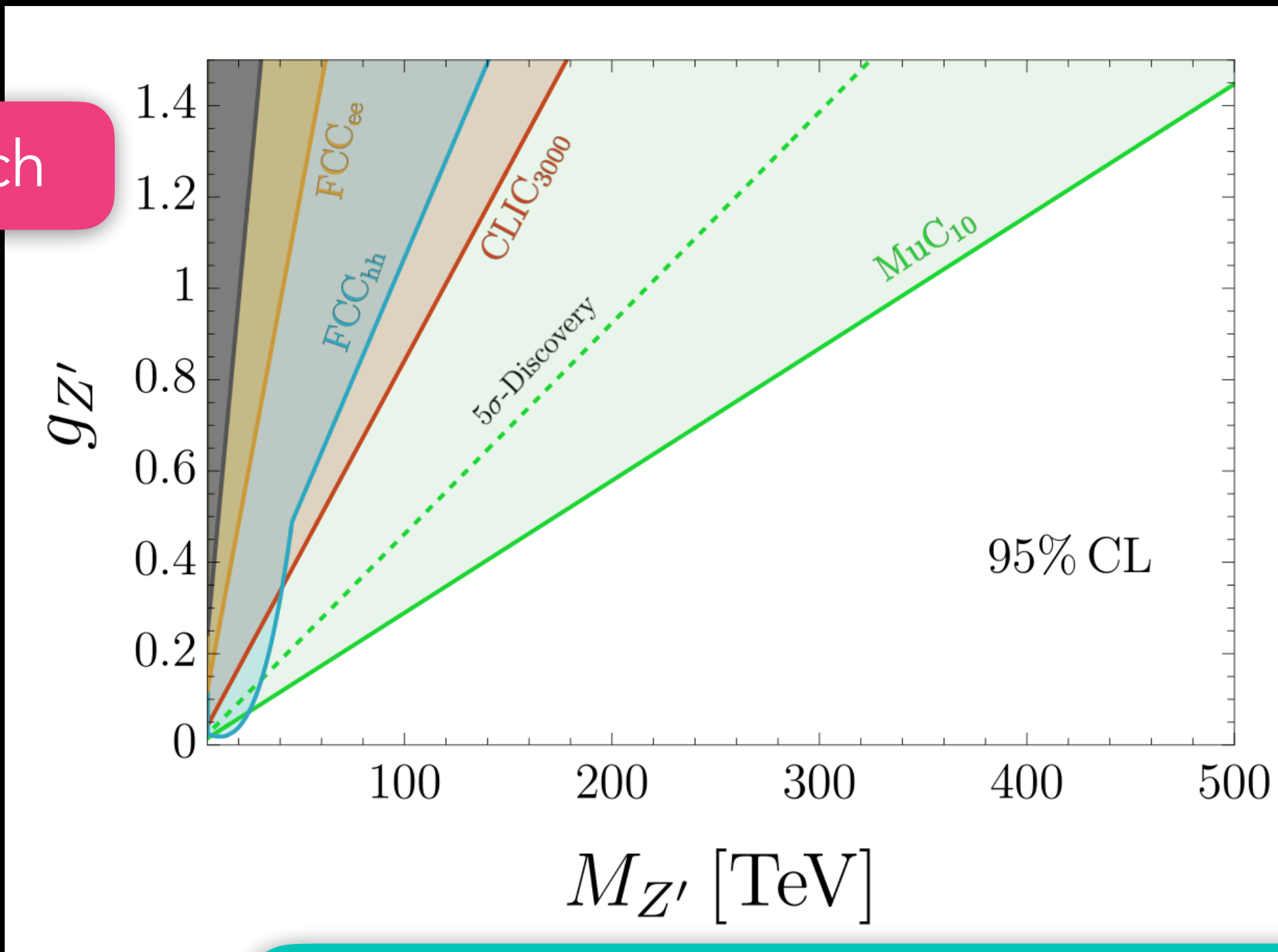
long-favored models of WIMP dark matter are within reach of a muon collider, but out of reach of direct detection

concrete targets that a μC can find or disprove

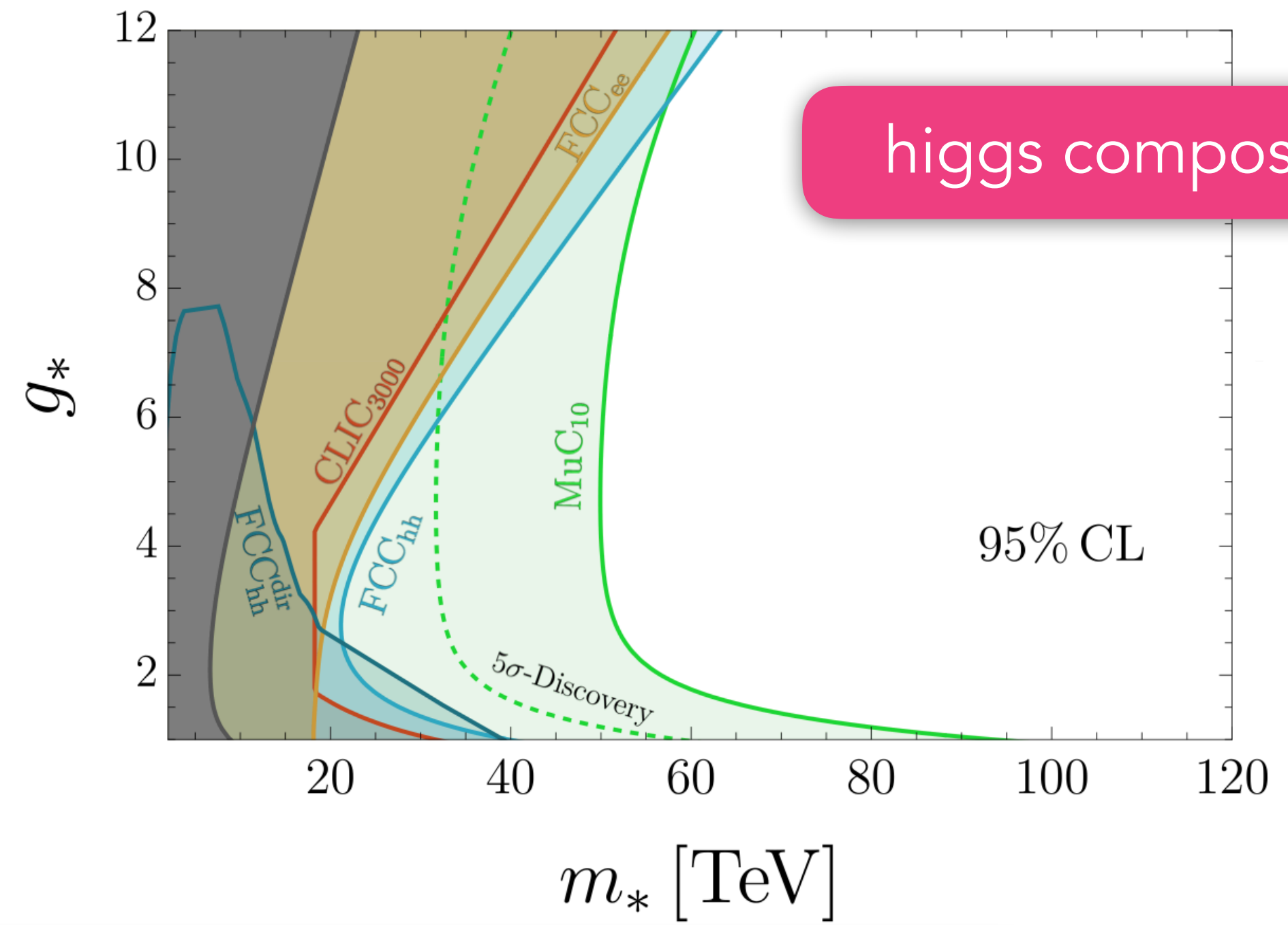


WHY HIGHER ENERGIES? PRECISION FROM ENERGY

Z' search

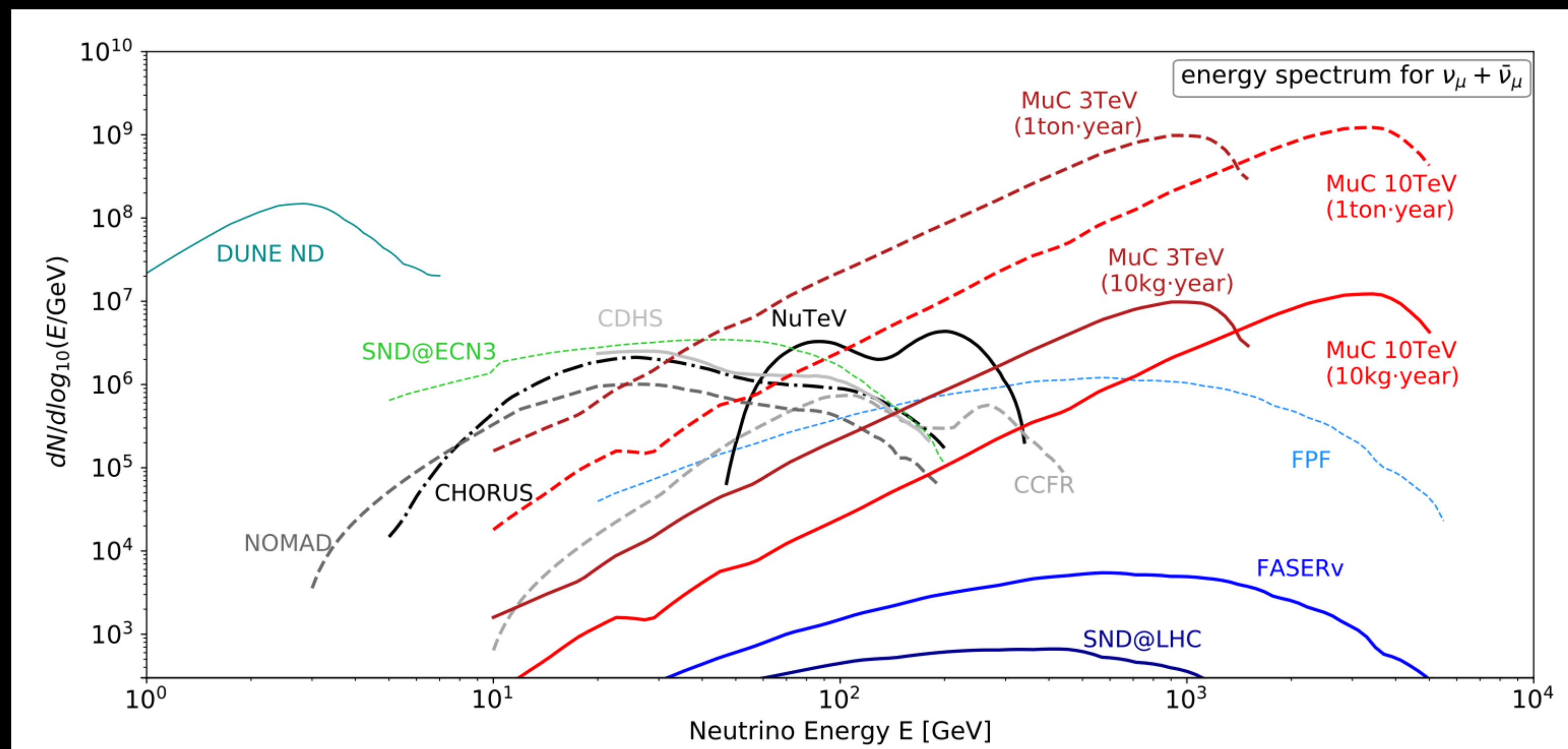


higgs compositeness



high E plus precision gives us access to higher dimensional EFT operators
— lets us extend far beyond the CoM energy in some areas

AT THE INTENSITY FRONTIER



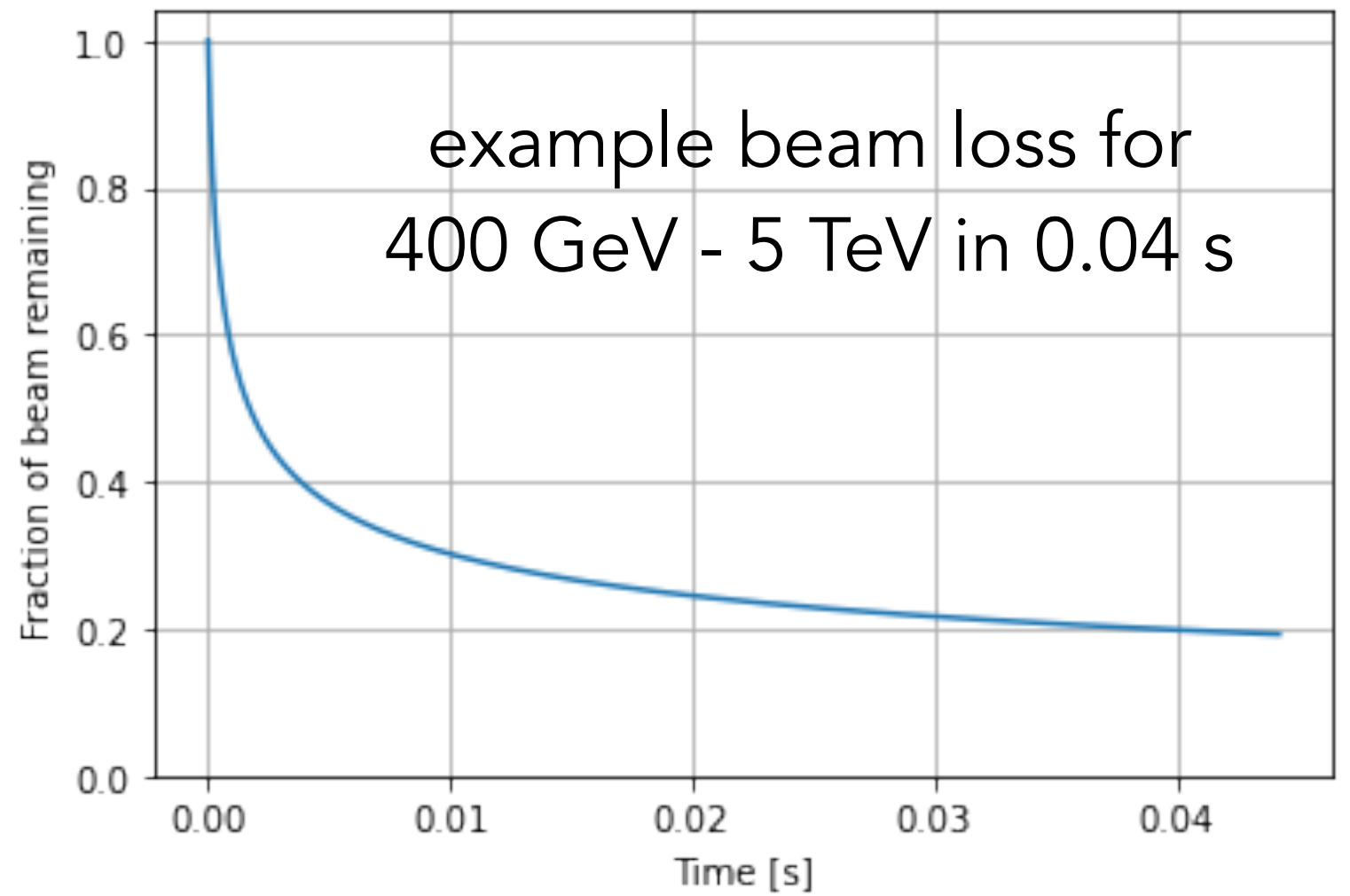
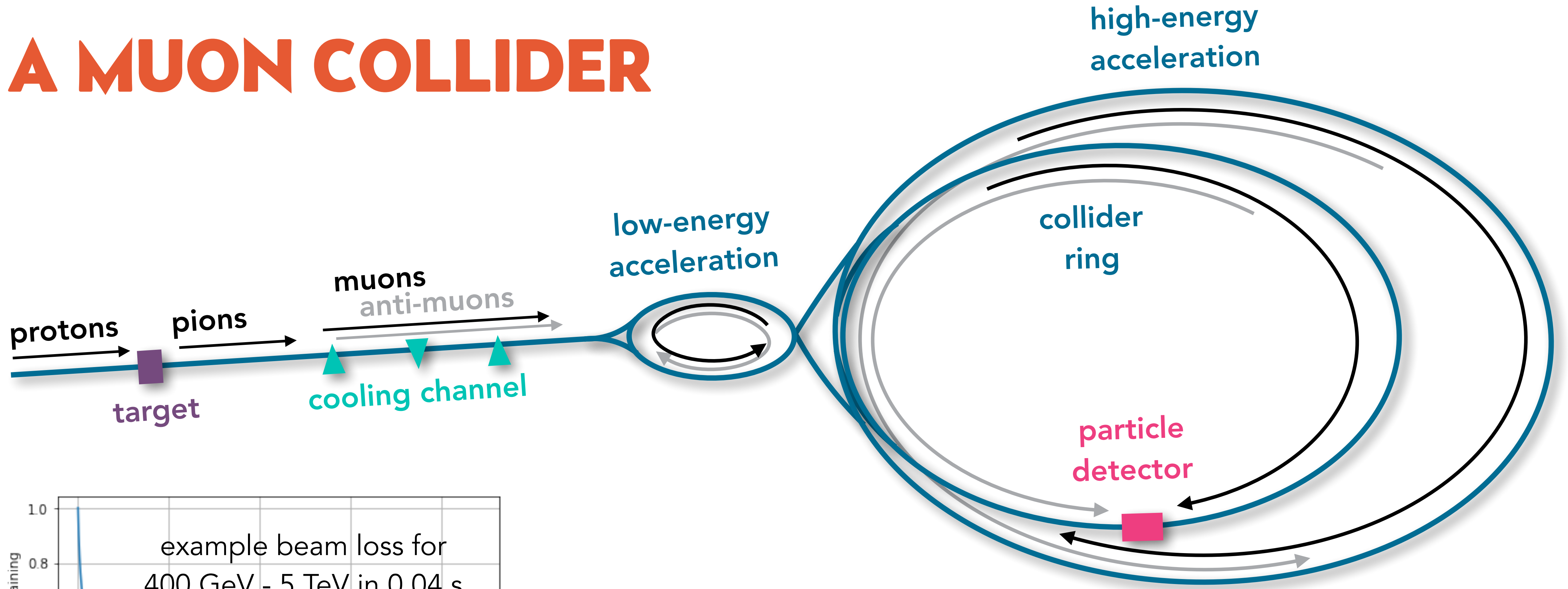
potential for precision high E cross section, ν DIS measurements

could also be possible to strip off neutrinos at an early stage for a lower E beam to study oscillations

more work needed to further develop neutrino program

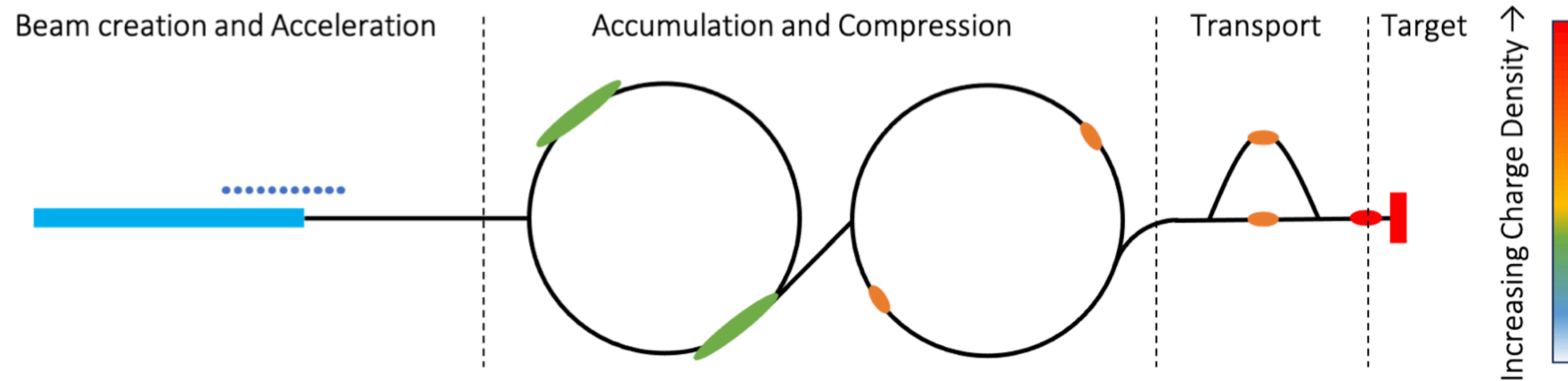
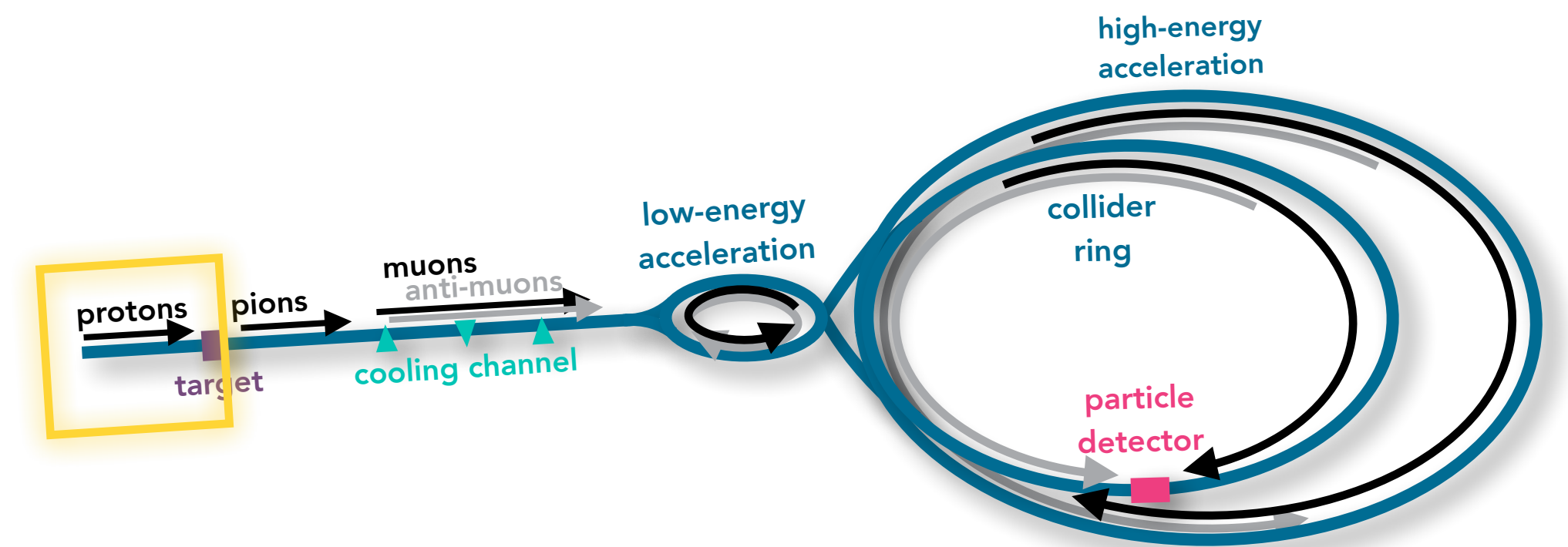
unprecedented number of high E neutrinos produced in well-understood, collimated beams

A MUON COLLIDER



overarching driver is luminosity:
create, cool, and collide muons as
fast as possible

A MUON COLLIDER



compare to:
spallation
sources

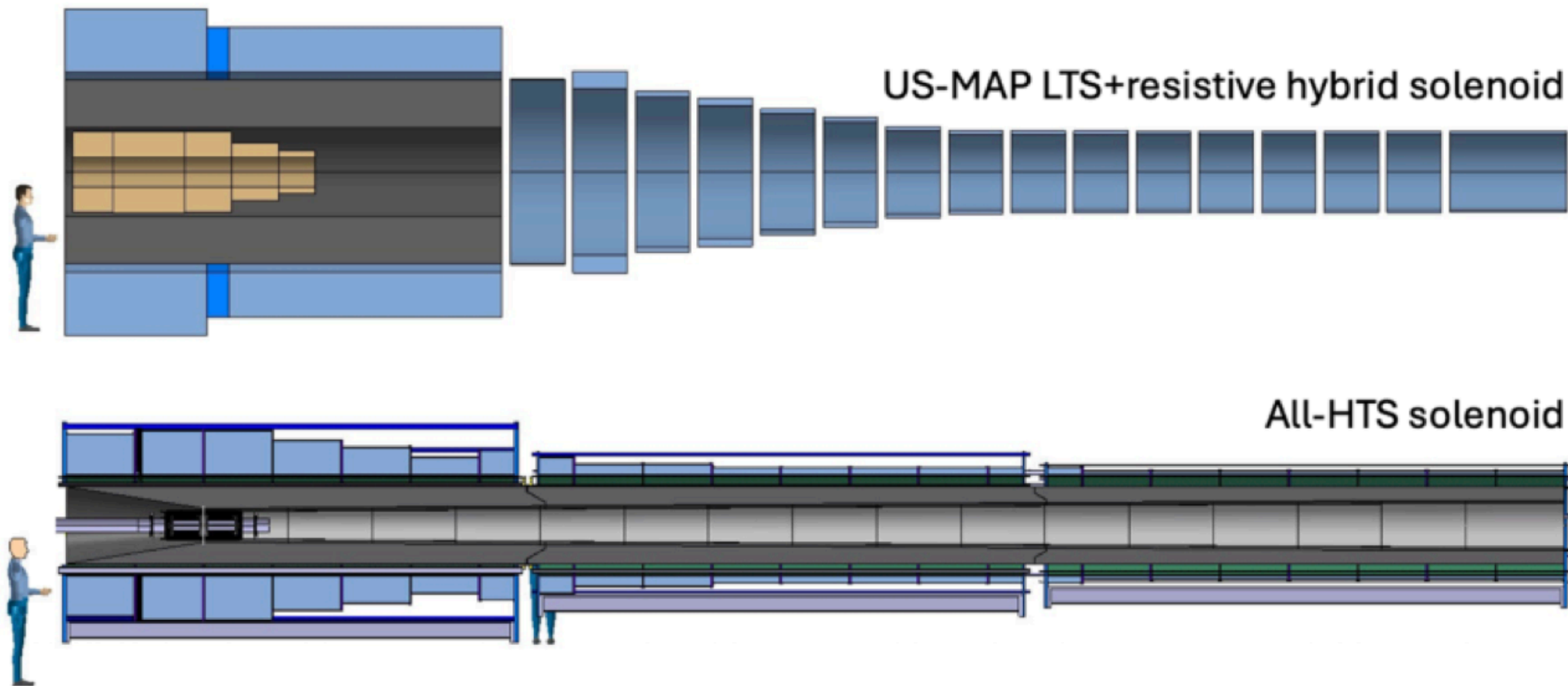
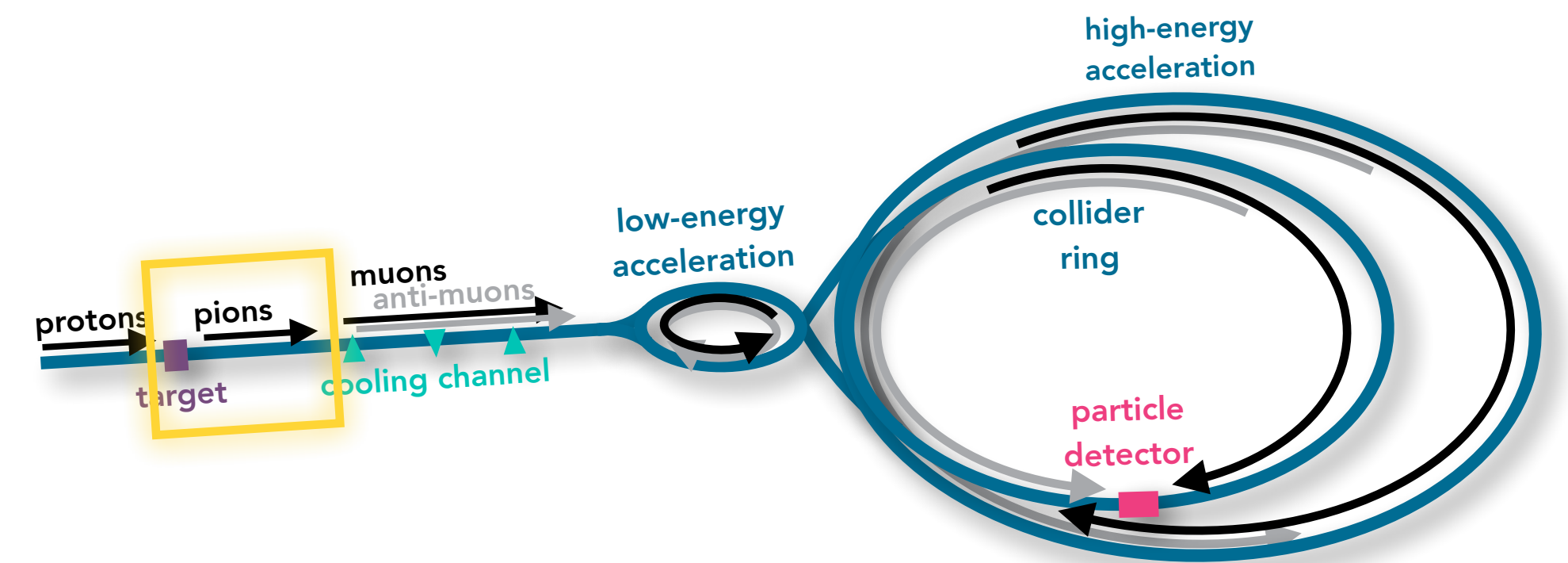
proton driver

- 2-4 MW → starting constraint on number of muons produced
- at 5-15 GeV → impacts proton to muon efficiency
- with 2-4 ns bunch size → small bunch size reduces initial muon emittance

space-charge is key constraint: must go to higher energies to increase bunch density

Most recent technical specs from "[The Muon Collider](#)" (input to ESPPU)

A MUON COLLIDER



compare to:
spallation sources,
neutrino beams, and
fusion facilities

target and capture

2-4 MW on target in 20 T solenoid with 0.7 m radius

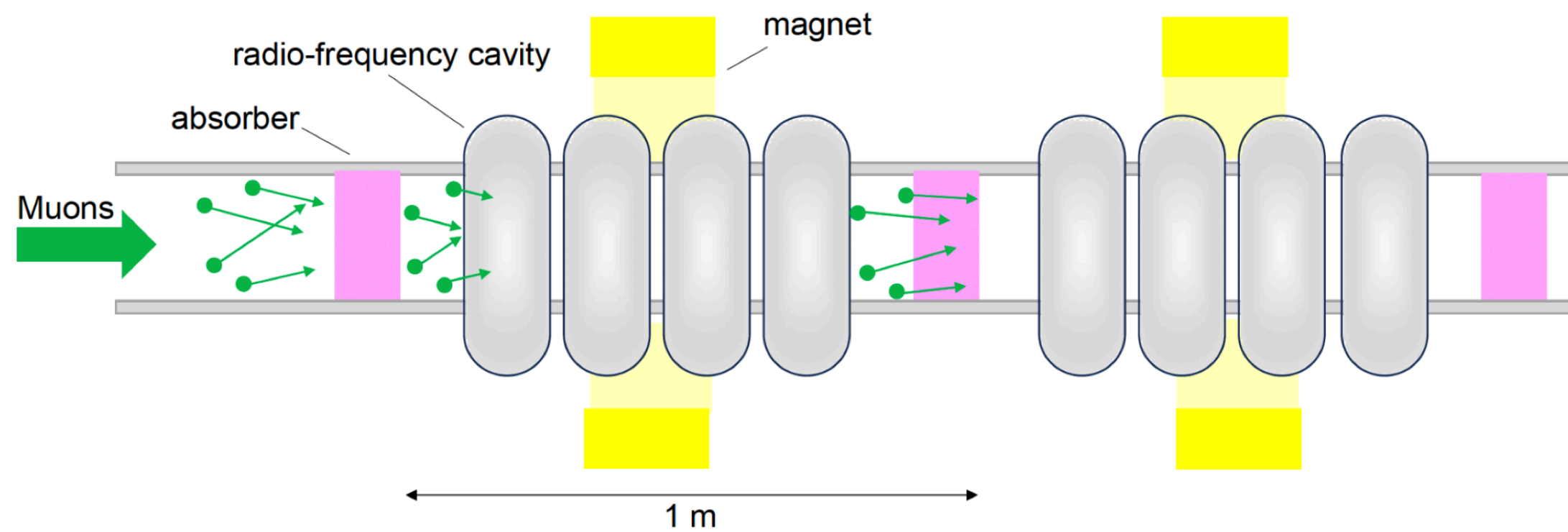
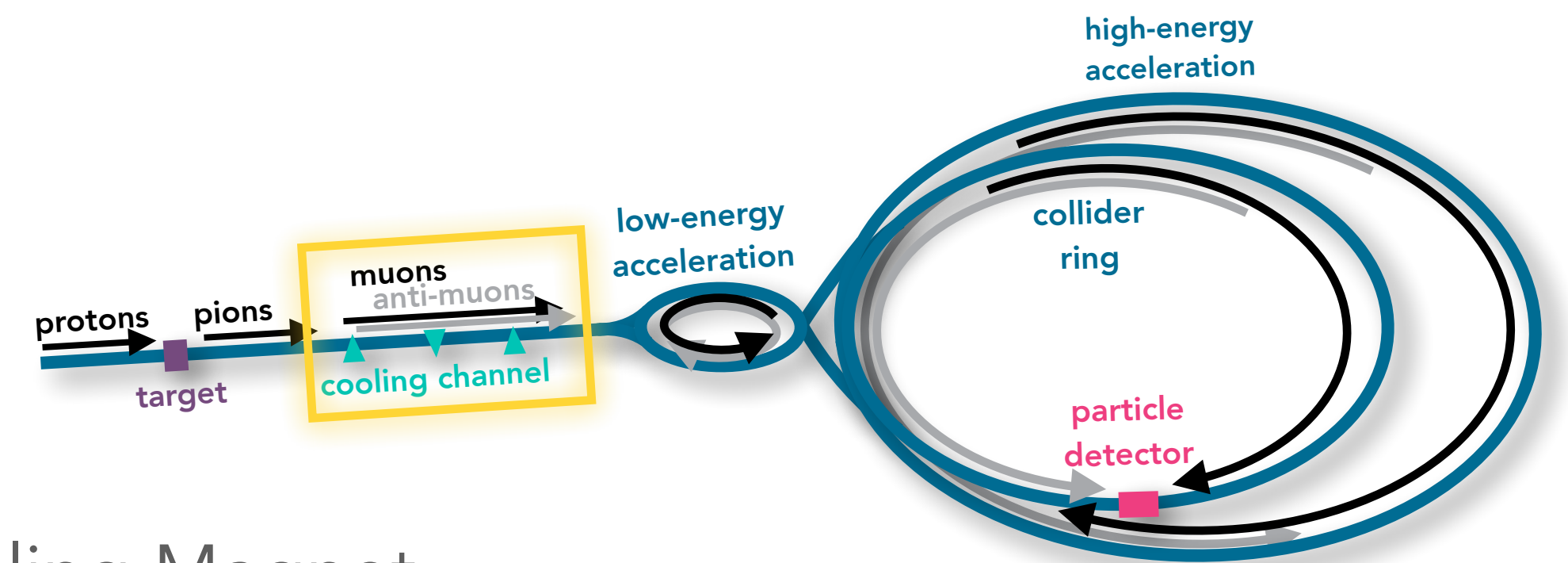
starting constraint on number of muons produced

high field captures more pions and muons; need large bore to accommodate shielding

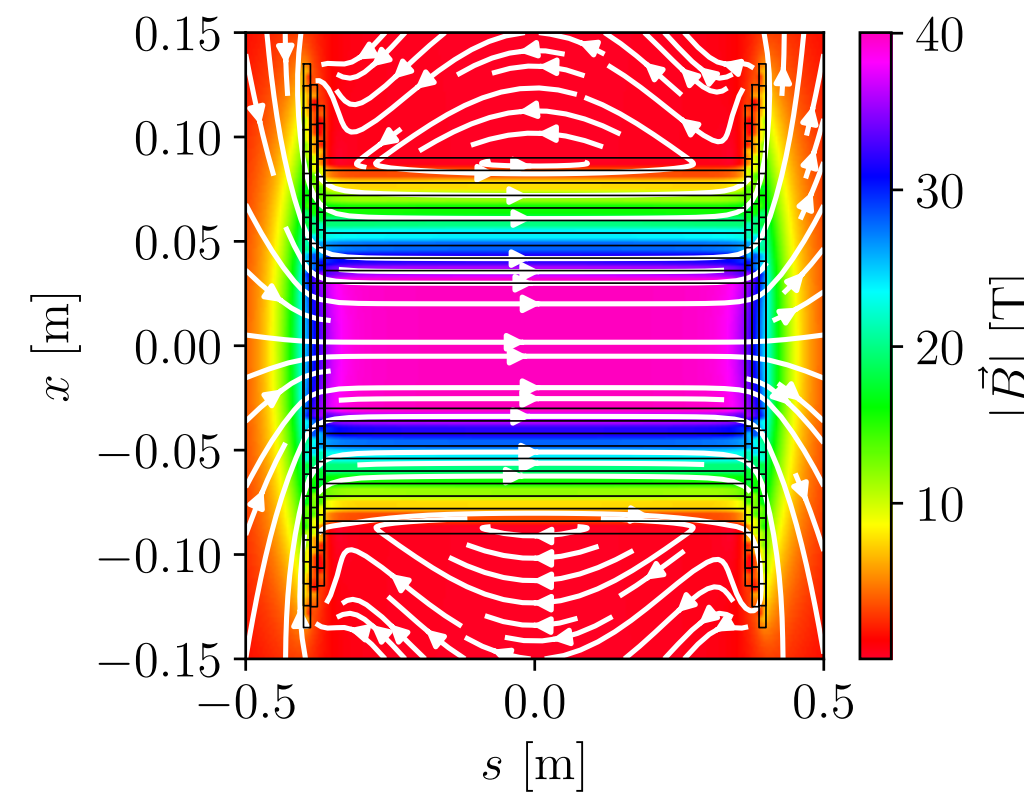
magnet and **target** materials and design push the limits of what can be done today

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A MUON COLLIDER



Final Cooling Magnet
B. Stechauner



novel for a muon collider!

cooling channel

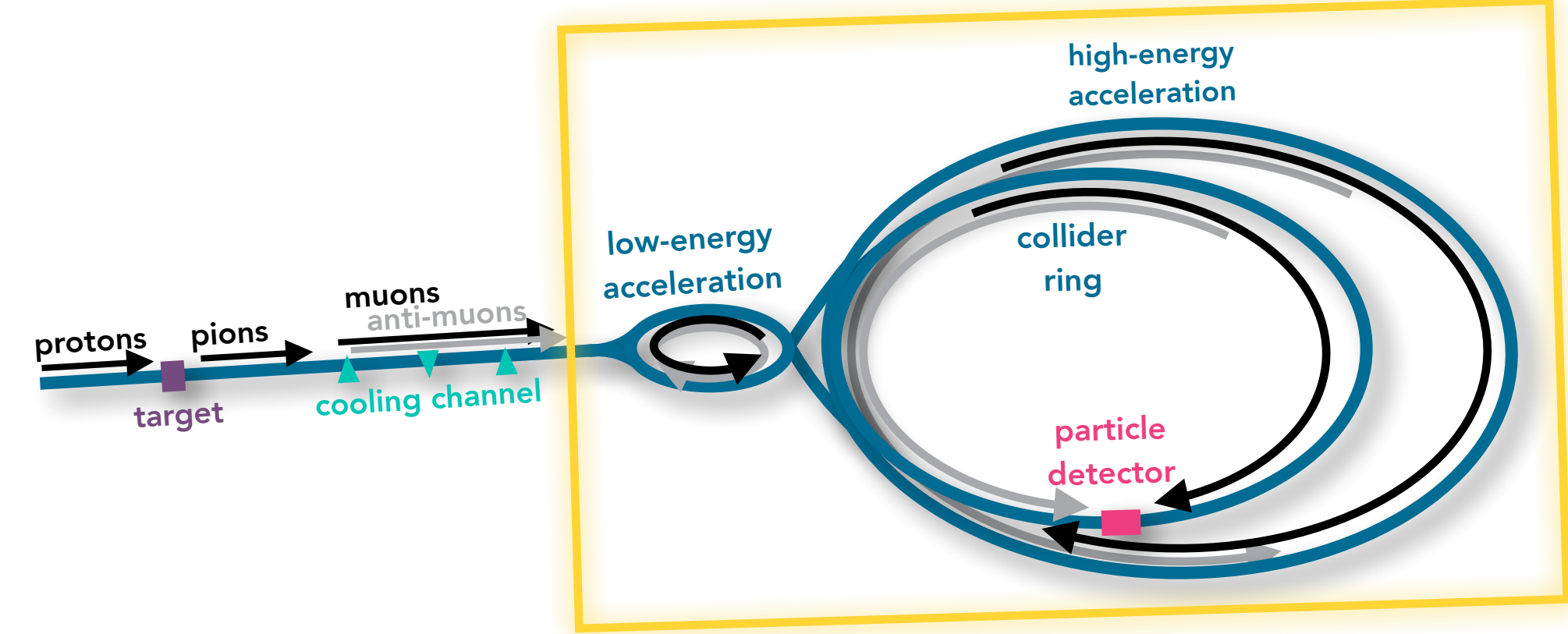
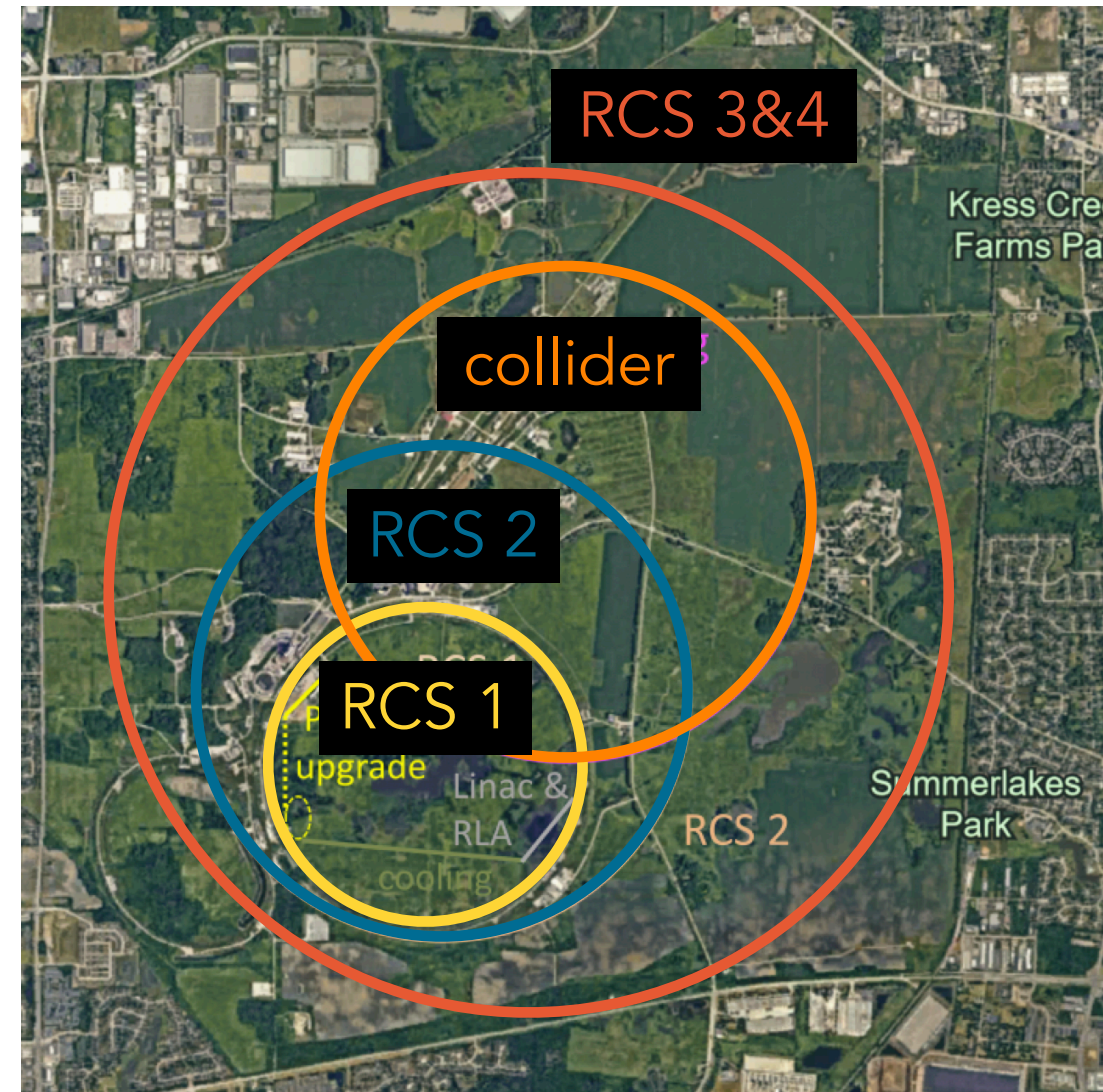
6 orders of magnitude of phase space reduction as compact as possible
peak B-field of up to 40 T

all parameters (x, y, z, px, py, pz) must shrink to allow collider to provide high luminosity
reduces loss of muons due to decays
gives strong focus, improves final cooling rate

cooling cells involve RF cavities in high fields, challenging solenoid engineering

Most recent technical specs from "[The Muon Collider](#)" (input to ESPPU)

A MUON COLLIDER



compare to: linear colliders for gradients, but ramp speed is unique for muC

rapid acceleration

avg. gradients up to 2.4 MV/m
magnet ramp speed O(kT/s)

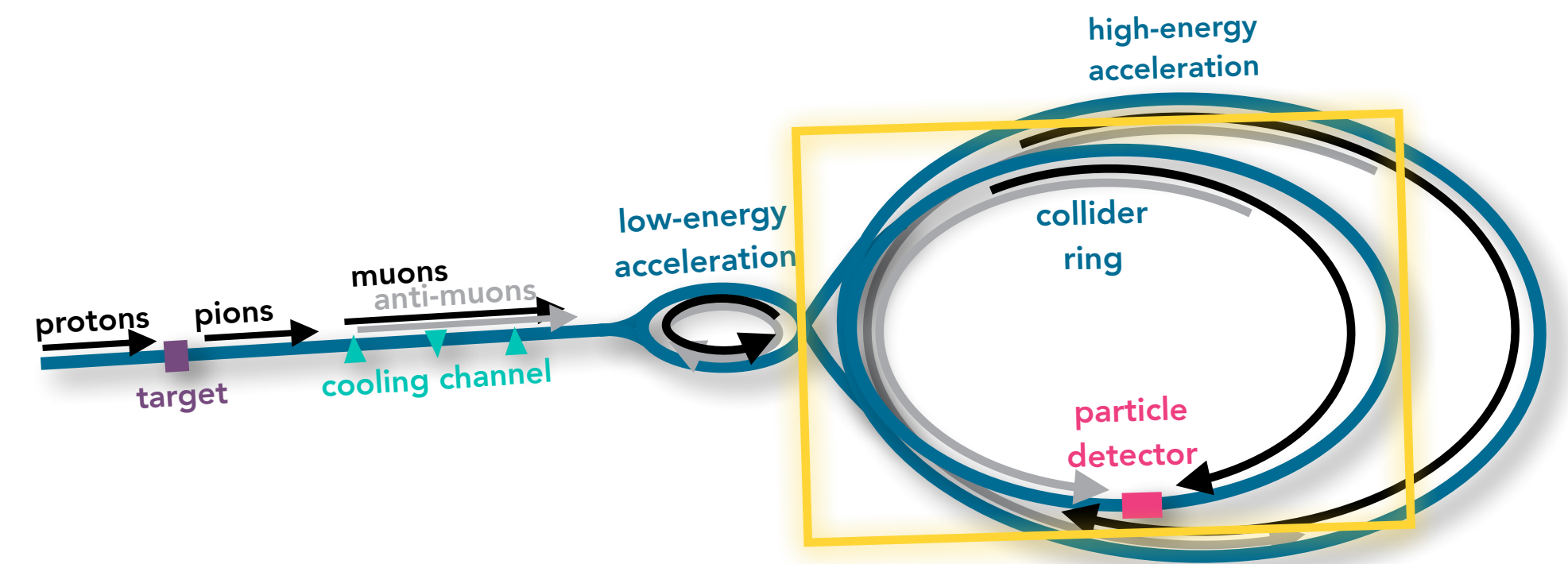
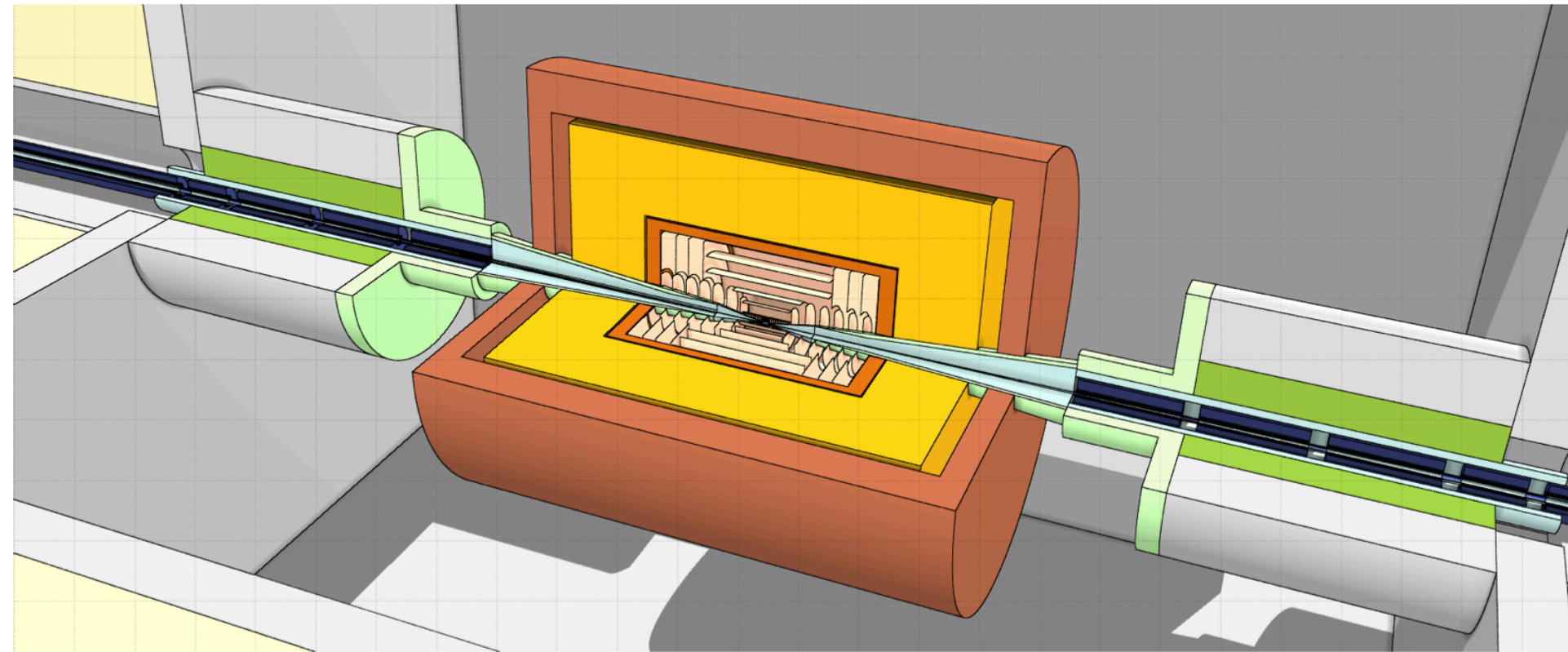


fast acceleration required to increase gamma before muons decay

use combination of **fixed-field** and ramping magnets to ease challenge

Most recent technical specs from "[The Muon Collider](#)" (input to ESPPU)

A MUON COLLIDER



compare to: dipole
needs for FCC-hh, but
neutrino mitigation is
unique

collider ring

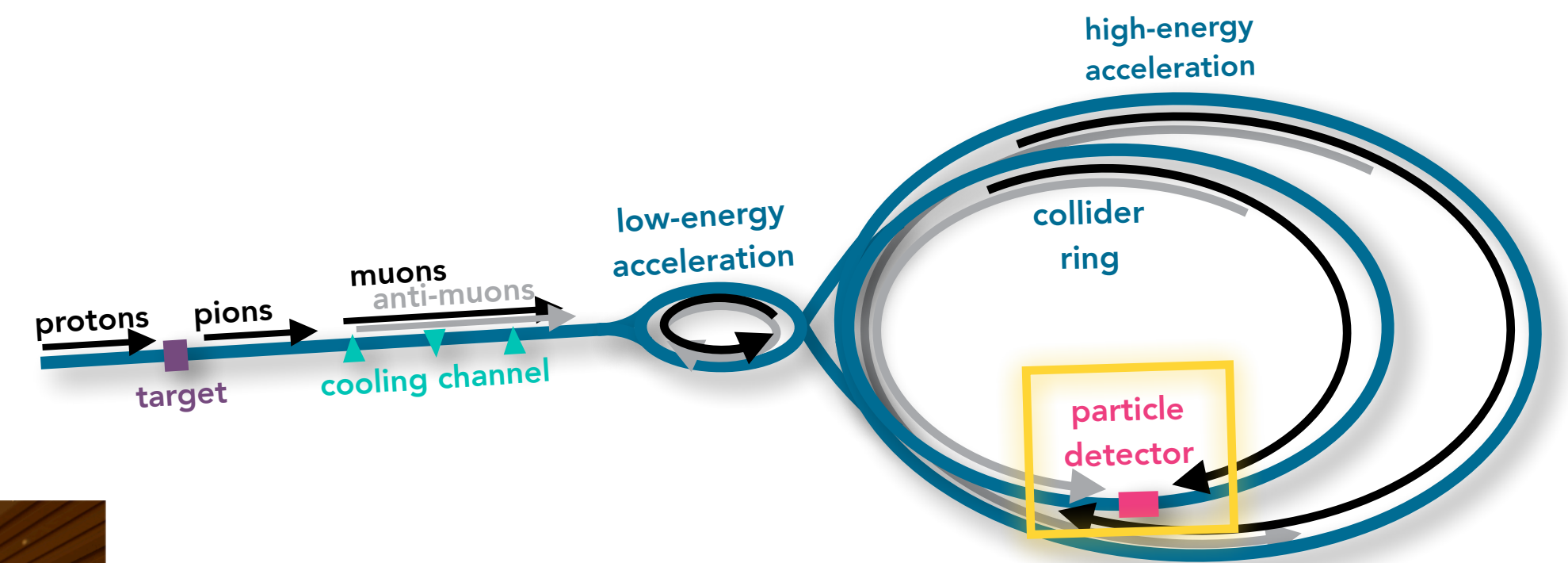
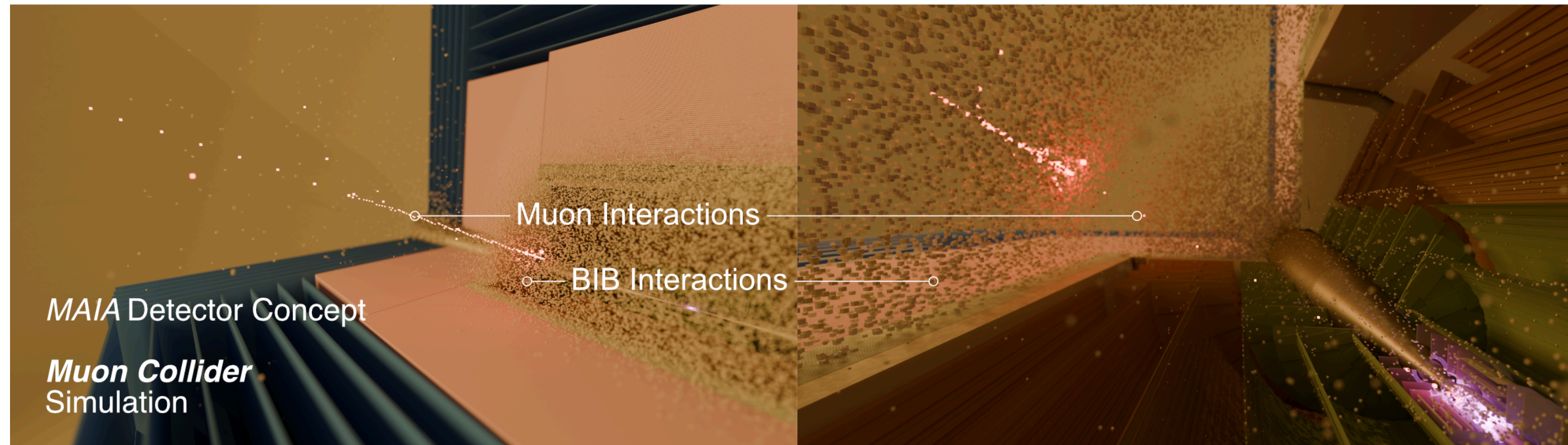
- dipoles ideally 16T → smaller ring size means higher luminosity
- integrated design of MDI → optimize focus and beam-induced background
- beam modulation and/or movers → neutrino mitigation around the ring

engineering and scalability of **HTS magnets** is the biggest constraint
energy staging option uses Nb₃Sn

Most recent technical specs from "[The Muon Collider](#)" (input to ESPPU)

A MUON COLLIDER

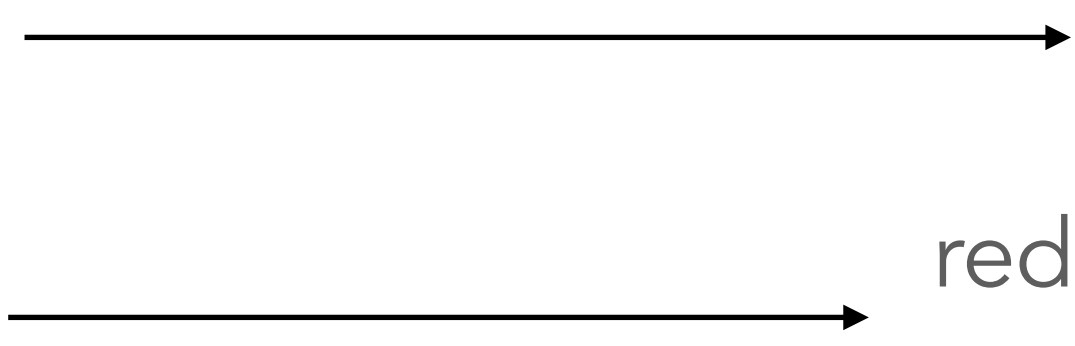
[2502.00181]



compare to: HL-LHC detectors, but biggest change is integrating timing

detector

up to $25 \times 25 \mu\text{m}$ feature size
 up to $O(10 \text{ ps})$ precision timing
 5 T solenoid w/ 1.5 m radius

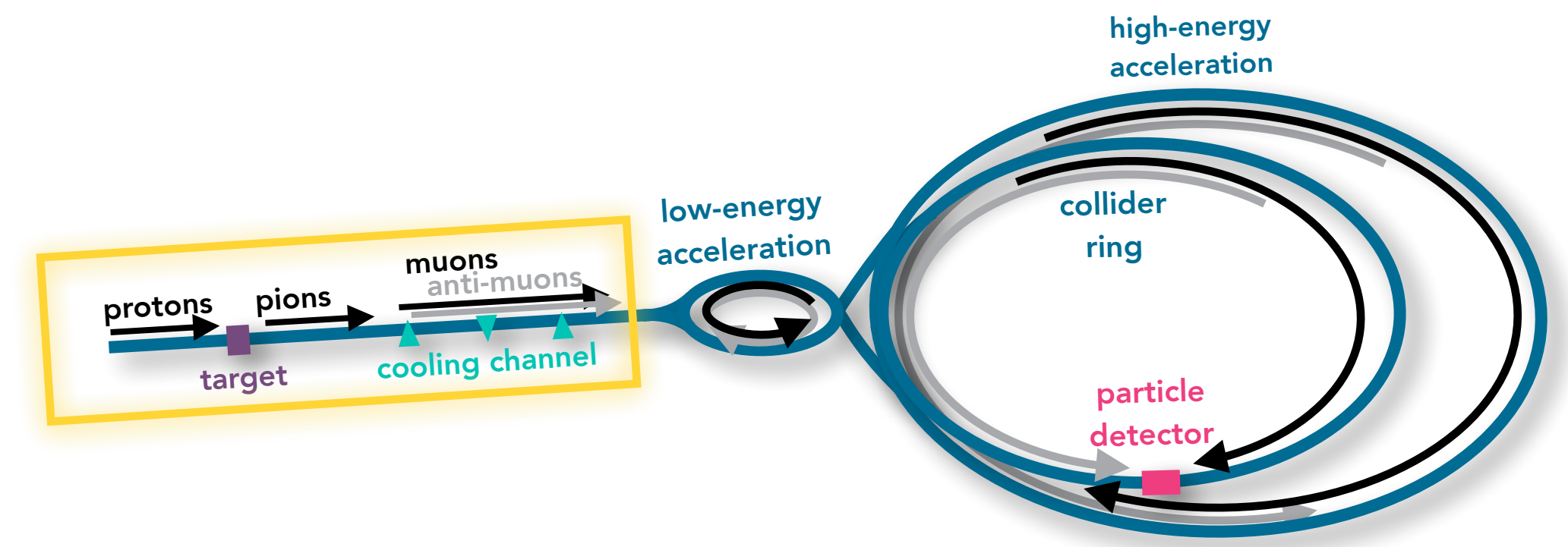


required to keep occupancy down and allow for signal - BIB discrimination
 reduces incoherent ee backgrounds and gives high- p_T precision

challenge is 4D precision while maintaining reasonable **power** and **read-out**

Most recent technical specs from "[The Muon Collider](#)" (input to ESPPU)

A MUON COLLIDER DEMONSTRATOR



ionization works! but can we engineer a system to take advantage of it?

need dedicated demonstrator program to show:

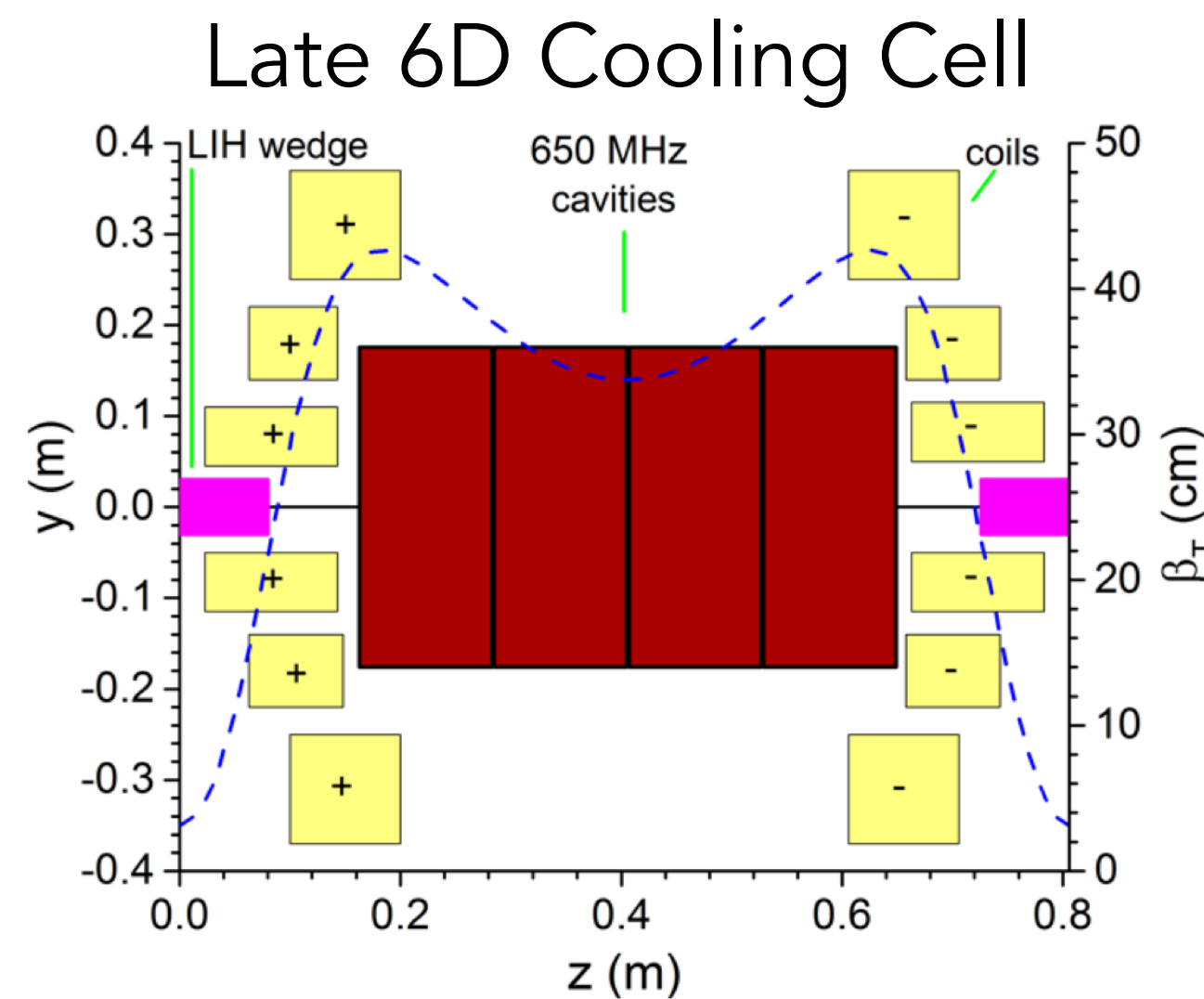
RF functionality in high B field

production of **solenoids** meeting our specs

integration of cooling cell components

operation of cells with **beam**

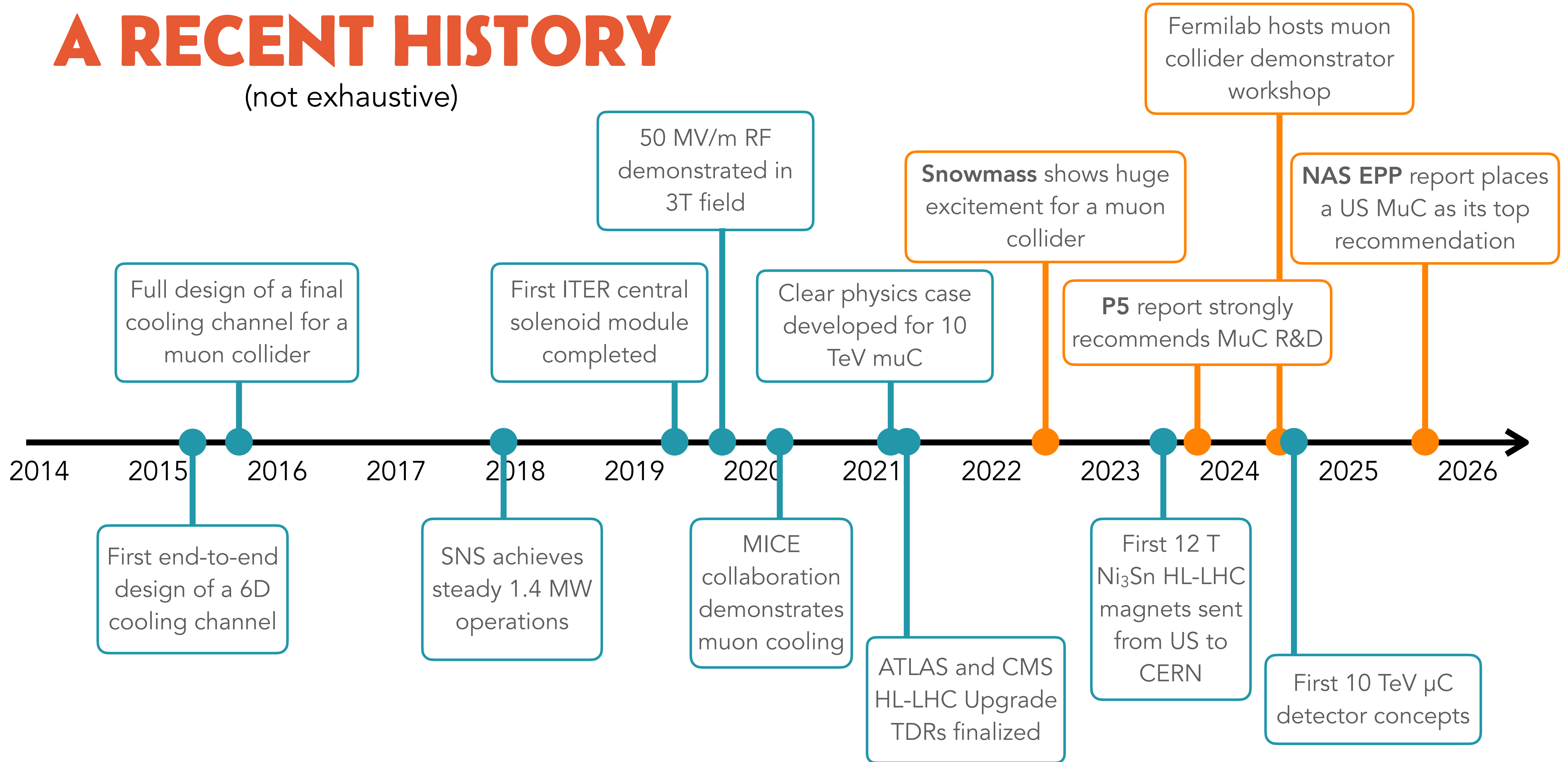
chain of cells cool according to simulation



Most recent technical specs from "[The Muon Collider](#)" (input to ESPPU)

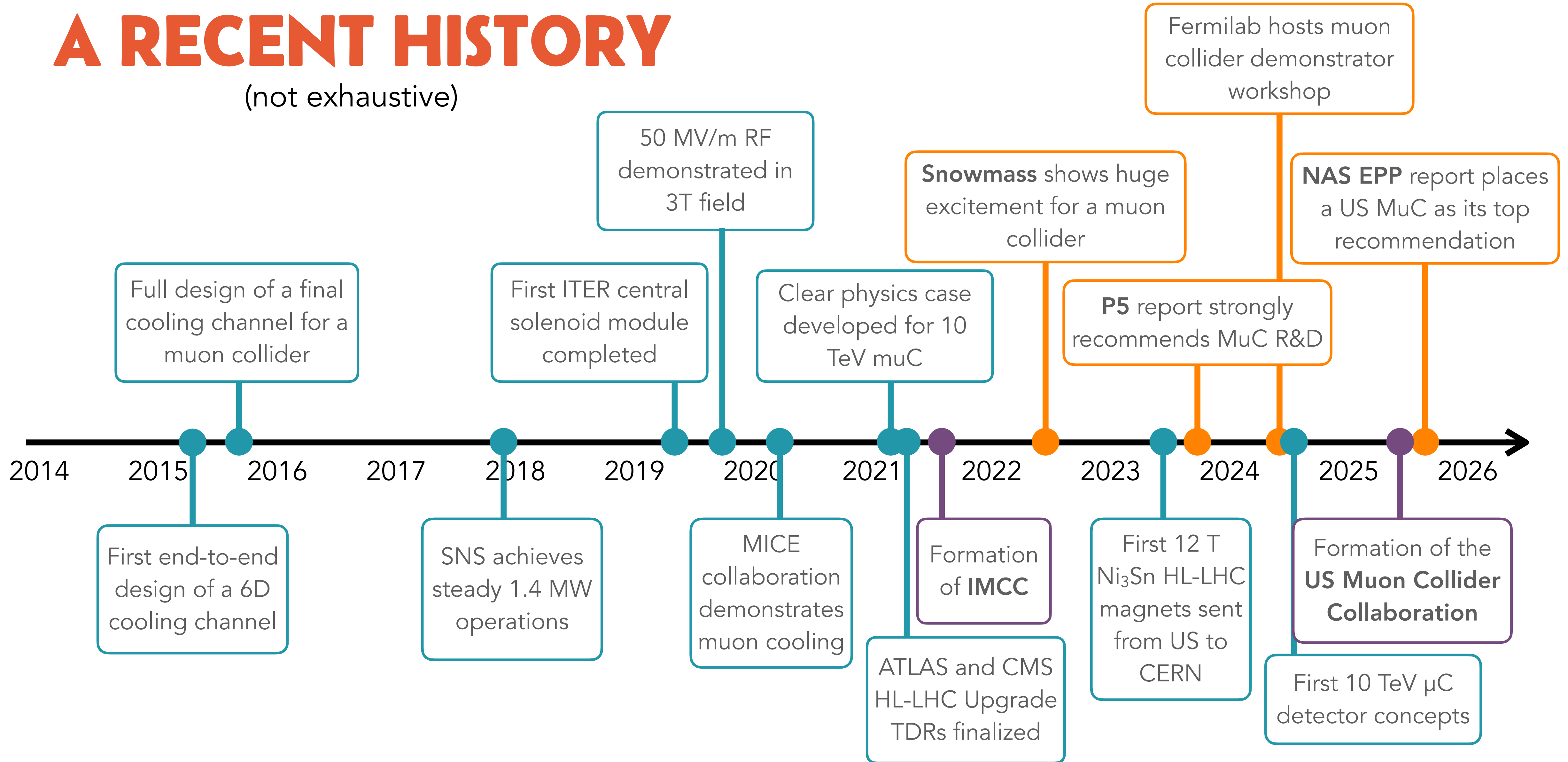
A RECENT HISTORY

(not exhaustive)



A RECENT HISTORY

(not exhaustive)



THE IMCC

IMCC Annual Meeting in 2 wks

Last year, 181 contributions showing new results across accelerator, experiment, and theory

training day with background for newcomers in all these areas

enthusiasm for increased US role

this ambitious program requires a global effort



~20% of participants from US

dedicated funding from CERN and EU, as well as national funding

Many meeting organizers, presenters from the US, presentation on USMCC status

THE IMCC



last year, compiled comprehensive documents for the European Strategy

10-page [summary](#)

400-page [report](#) with extensive description of R&D progress, status, and plans

The Muon Collider

Input to the European Strategy for Particle Physics - 2026 update

The International Muon Collider Collaboration

Contact persons:
Daniel Schulte* (daniel.schulte@cern.ch)
Federico Meloni¹ (federico.meloni@desy.de)
Chris Rogers² (chris.rogers@stfc.ac.uk)

Abstract

Muons offer a unique opportunity to build a compact high-energy electroweak collider at the 10 TeV scale. A Muon Collider enables direct access to the underlying simplicity of the Standard Model and unparalleled reach beyond it. It will be a paradigm-shifting tool for particle physics representing the first collider to combine the high-energy reach of a proton collider and the high precision of an electron-positron collider, yielding a physics potential significantly greater than the sum of its individual parts. A high-energy muon collider is the natural next step in the exploration of fundamental physics after the HL-LHC and a natural complement to a future low-energy Higgs factory. Such a facility would significantly broaden the scope of particle colliders, engaging the many frontiers of the high energy community.

The last European Strategy for Particle Physics Update and later the Particle Physics Project Prioritisation Panel in the US requested a study of the muon collider, which is being carried on by the International Muon Collider Collaboration. In this comprehensive document we present the physics case, the state of the work on accelerator design and technology, and propose an R&D project that can make the muon collider a reality.



*Organisation Européenne pour la Recherche Nucléaire (CERN), Geneva, Switzerland
¹Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany
²STFC Rutherford Appleton Laboratory (RAL), Harwell Oxford, United Kingdom

The Muon Collider

Supplementary report to the European Strategy for Particle Physics - 2026 update

The International Muon Collider Collaboration

The most up-to-date version of this document can be found at the following link:
<https://edms.cern.ch/document/3284682/1>

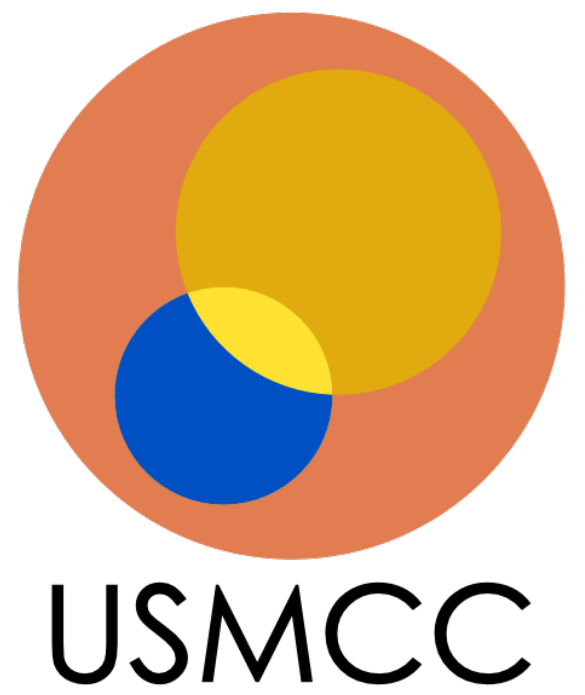
Abstract

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THE USMCC



Core Purposes

Define necessary work for mid-P5 panel

Design a US demonstrator

Engage with the international community

Create a long-term vision for Fermilab that leads to a muon collider

Build on a theory-driven physics case

Connections

Build a collaboration that continues to connect accelerator, experiment, and theory

Explore synergies with other areas of HEP (neutrino, CLFV, Beam Dump, etc)

Engage with all parts of the US scientific community interested in muon beam capabilities

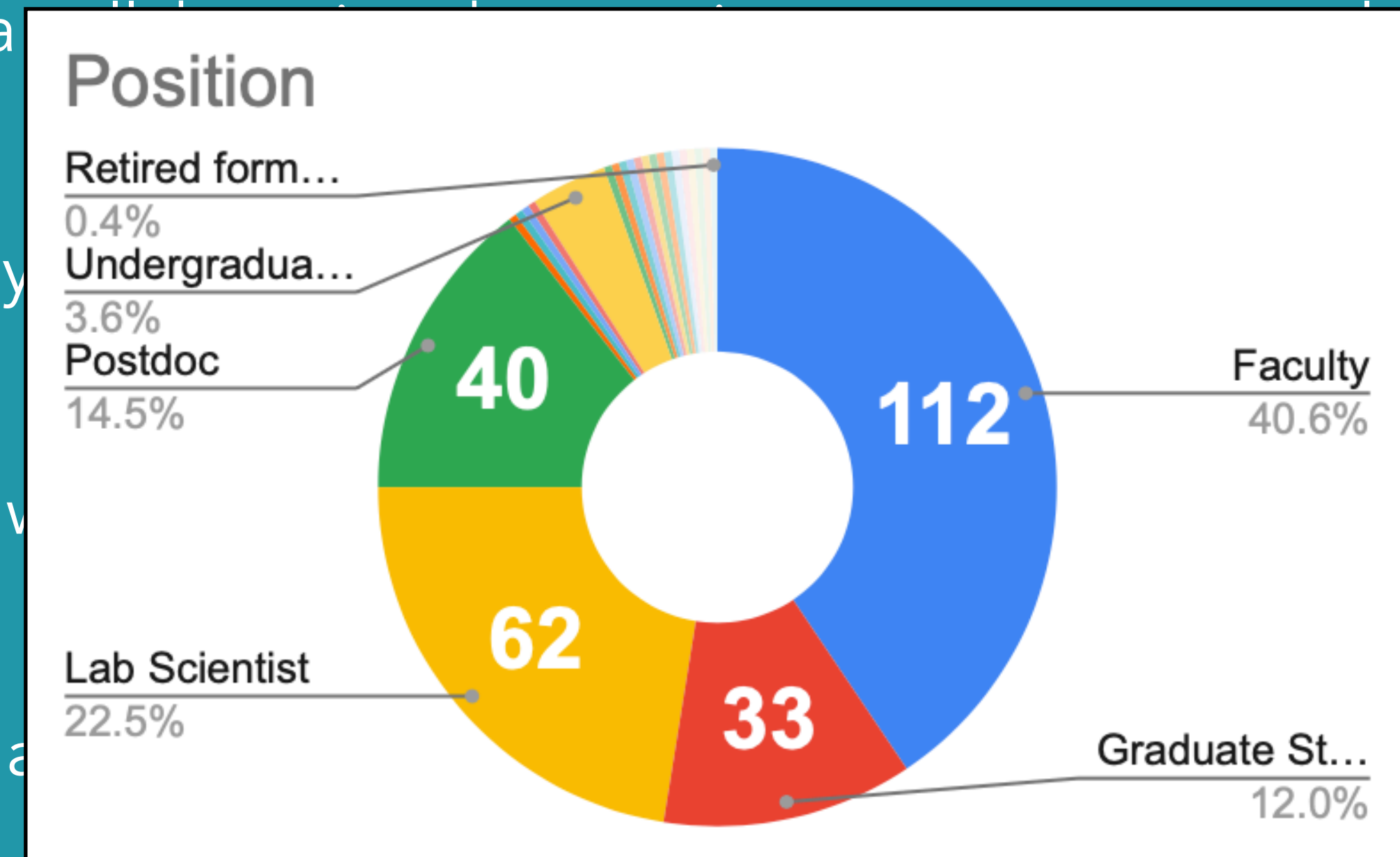
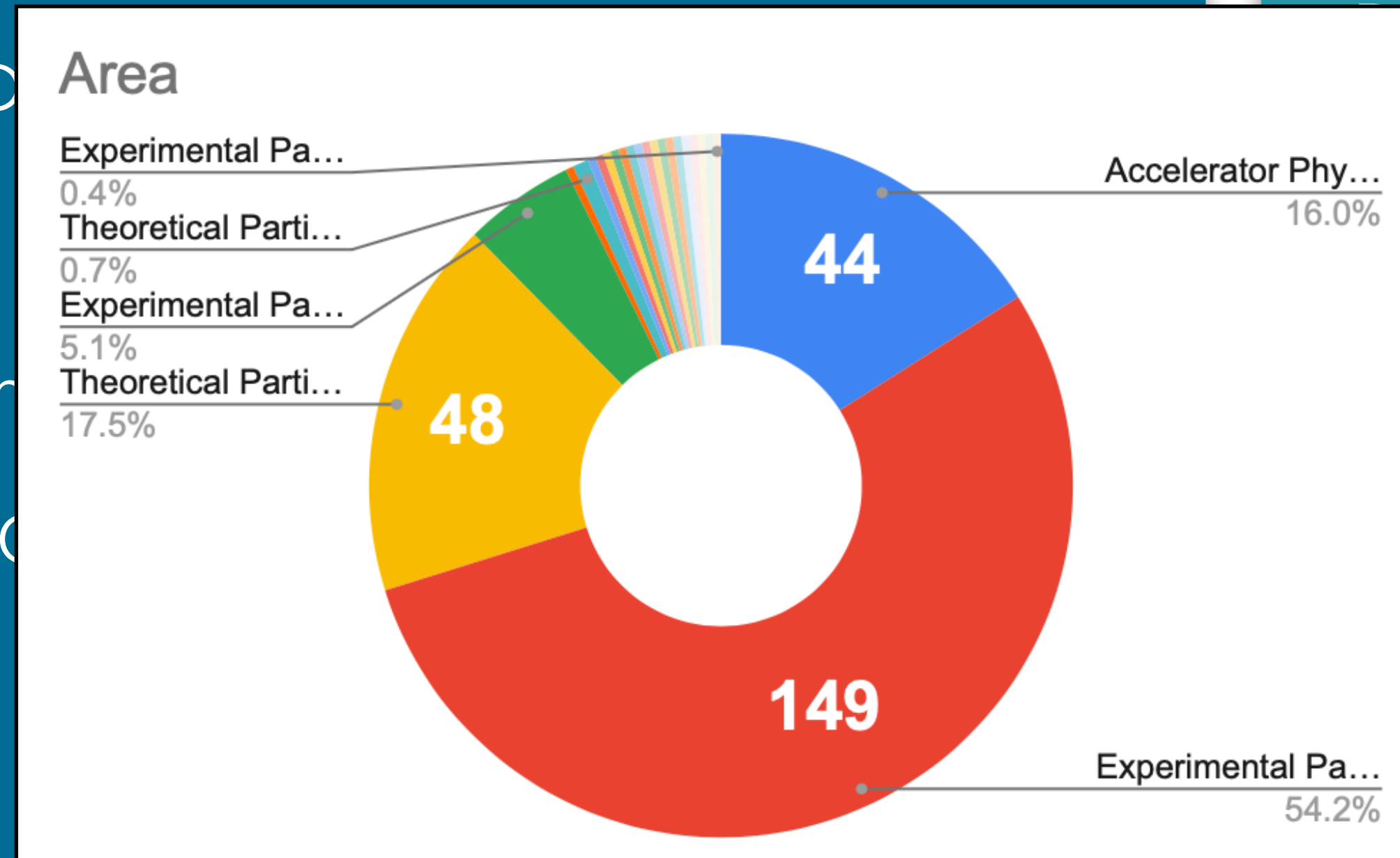
Provide a grassroots organization to interface with the funding agencies, strategy processes, and advocacy

THE USMCC



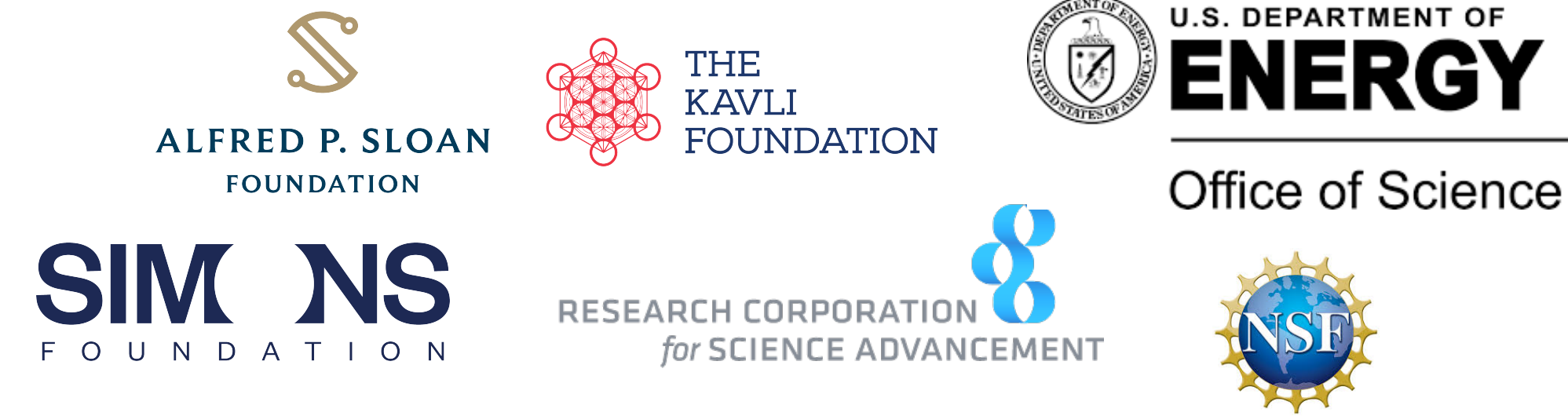
Core Purposes

Connections



Build a...
 core sy...
 age v...
 vide a...
 rator,
 V, Beam
 erested
 unding

US MUC FUNDING



At the labs

Fermilab demonstrator (LDRD)
Fermilab future collider software (LDRD)
Brookhaven collider R&D - RCS and cooling cell (LDRD)
LBNL future collider detectors (LDRD)
SLAC high-field RF test stand (GARD)
ORNL LDRD — this workshop

At the universities

Princeton/Chicago/Tennessee Acc+Exp for MuC (Simons Foundation)
Fellowships (Cottrell x2, Sloan x2)
UCSB/Princeton/Northeastern/UTK Interdisciplinary Seminar Series (Kavli Foundation)
Differentiable simulation for ionization cooling (DOE)
+ start-ups, internal funding, and fractions of base grants/ECAs/CAREERs

→ also at labs

LONG-TERM VISION

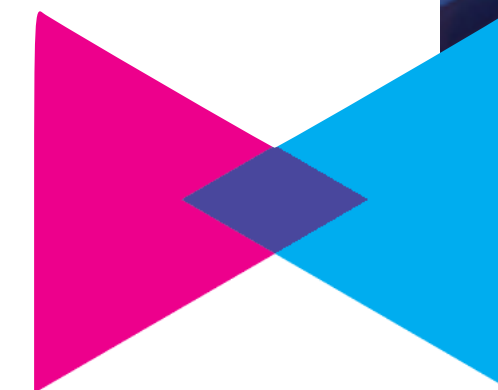
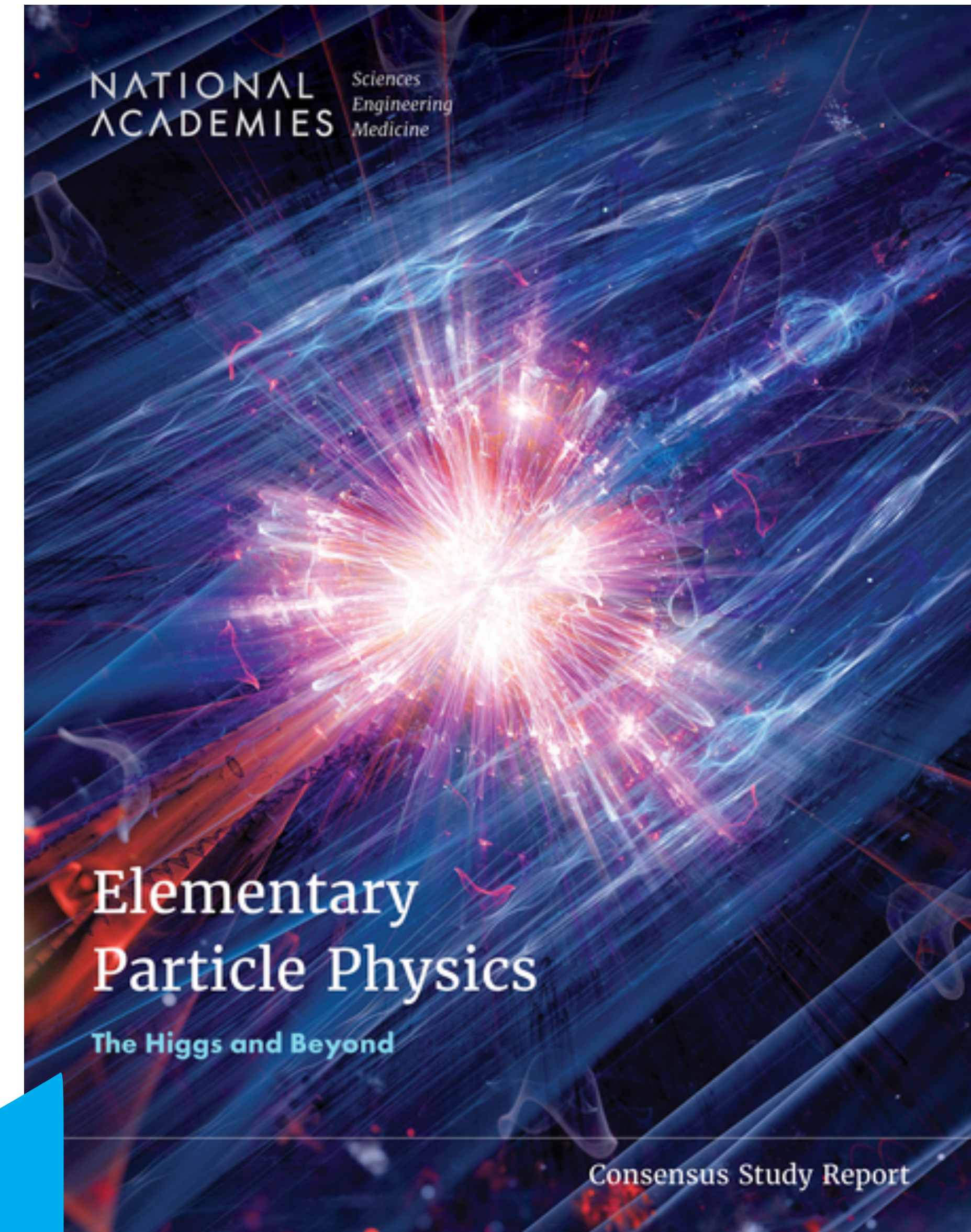
NAS Report released June 11, 2025

Recommendation 1: The United States should host the world's highest-energy elementary particle collider around the middle of the century. This requires the immediate creation of a national muon collider research and development program to enable the construction of a demonstrator of the key new technologies and their integration.

Reinforces and adds more urgency to 2023's P5

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, each producing world-class science while performing critical R&D toward a muon collider. At the end of the path is an unparalleled global facility on US soil. This is our Muon Shot.

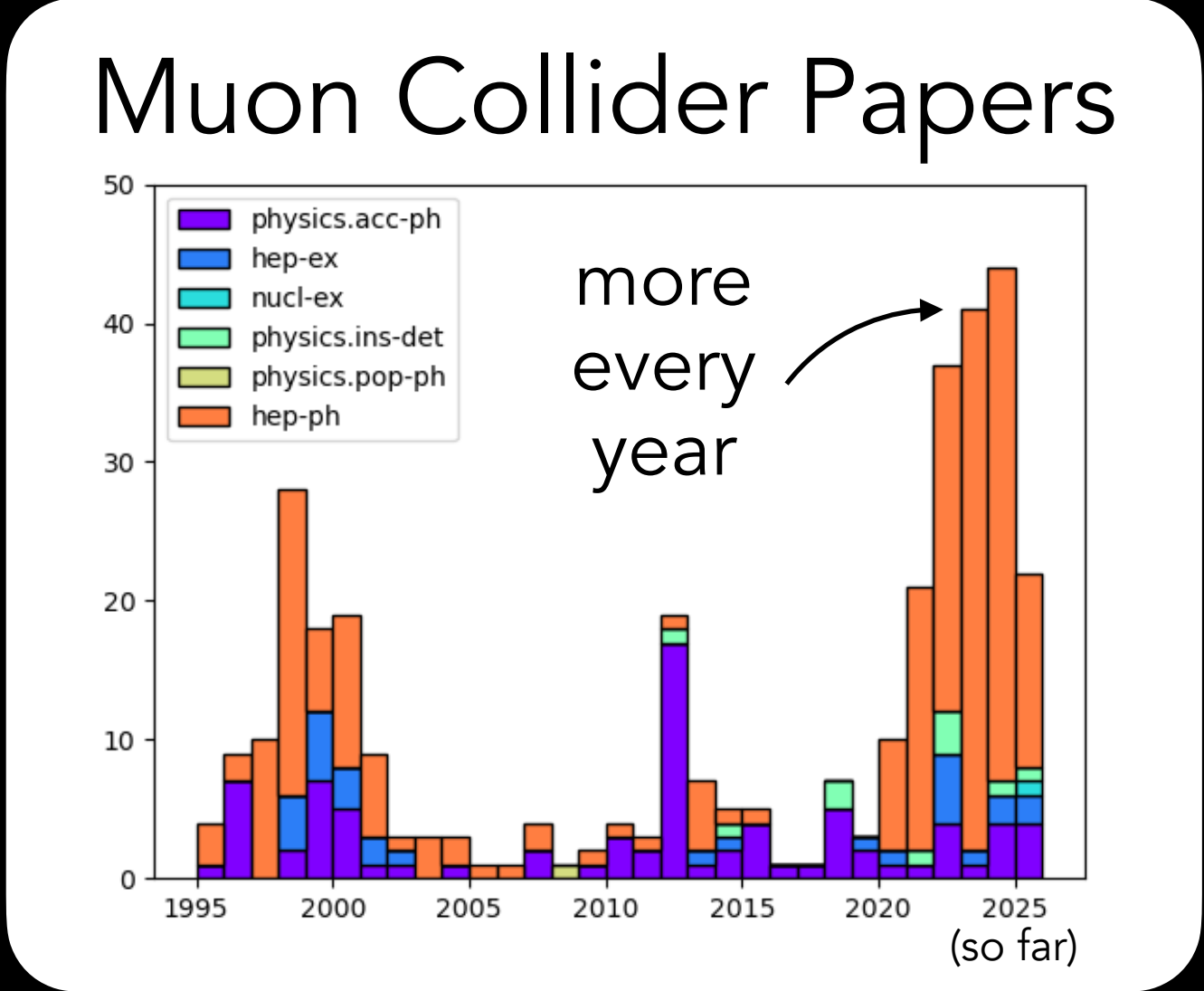
Recommendation 4: Support a comprehensive effort to develop the resources—theoretical, computational, and technological—essential to our 20-year vision for the field. This includes an aggressive R&D program that, while technologically challenging, could yield revolutionary accelerator designs that chart a realistic path to a 10 TeV pCM collider.



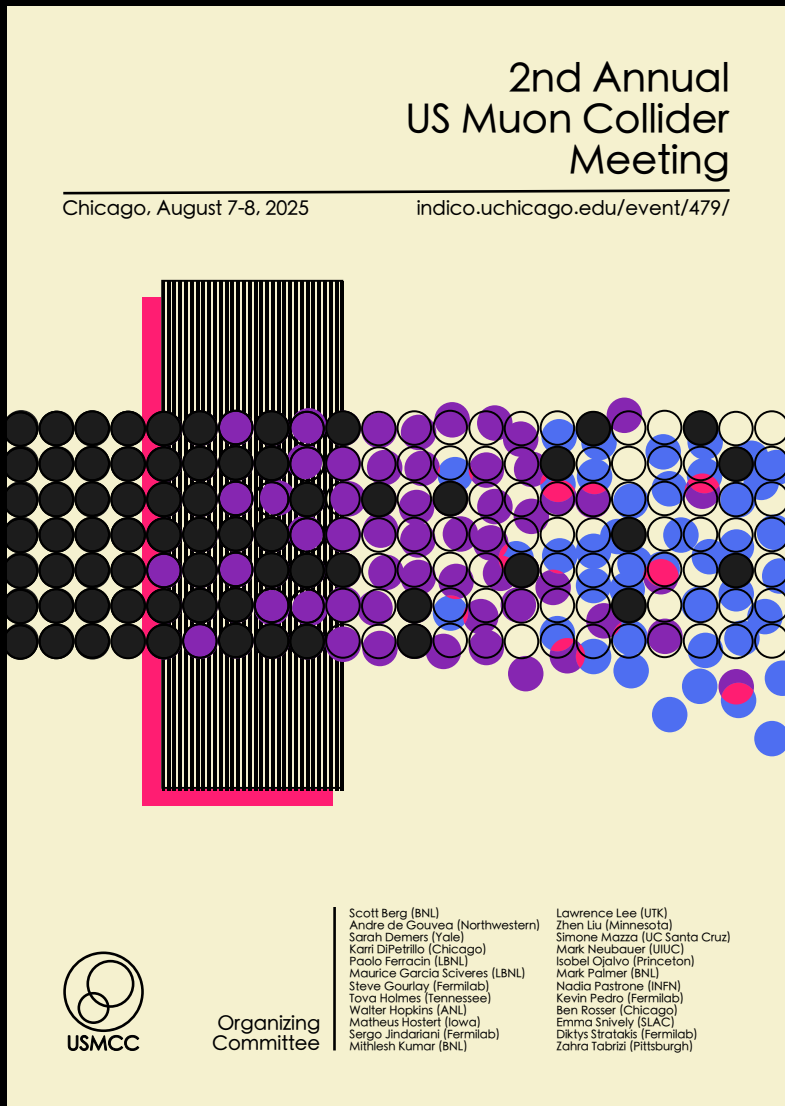
TAKE-AWAYS

the reports are in: muon colliders hold huge potential for the US and the future of particle physics

the US community is engaged and eager to ramp up



from arxiv



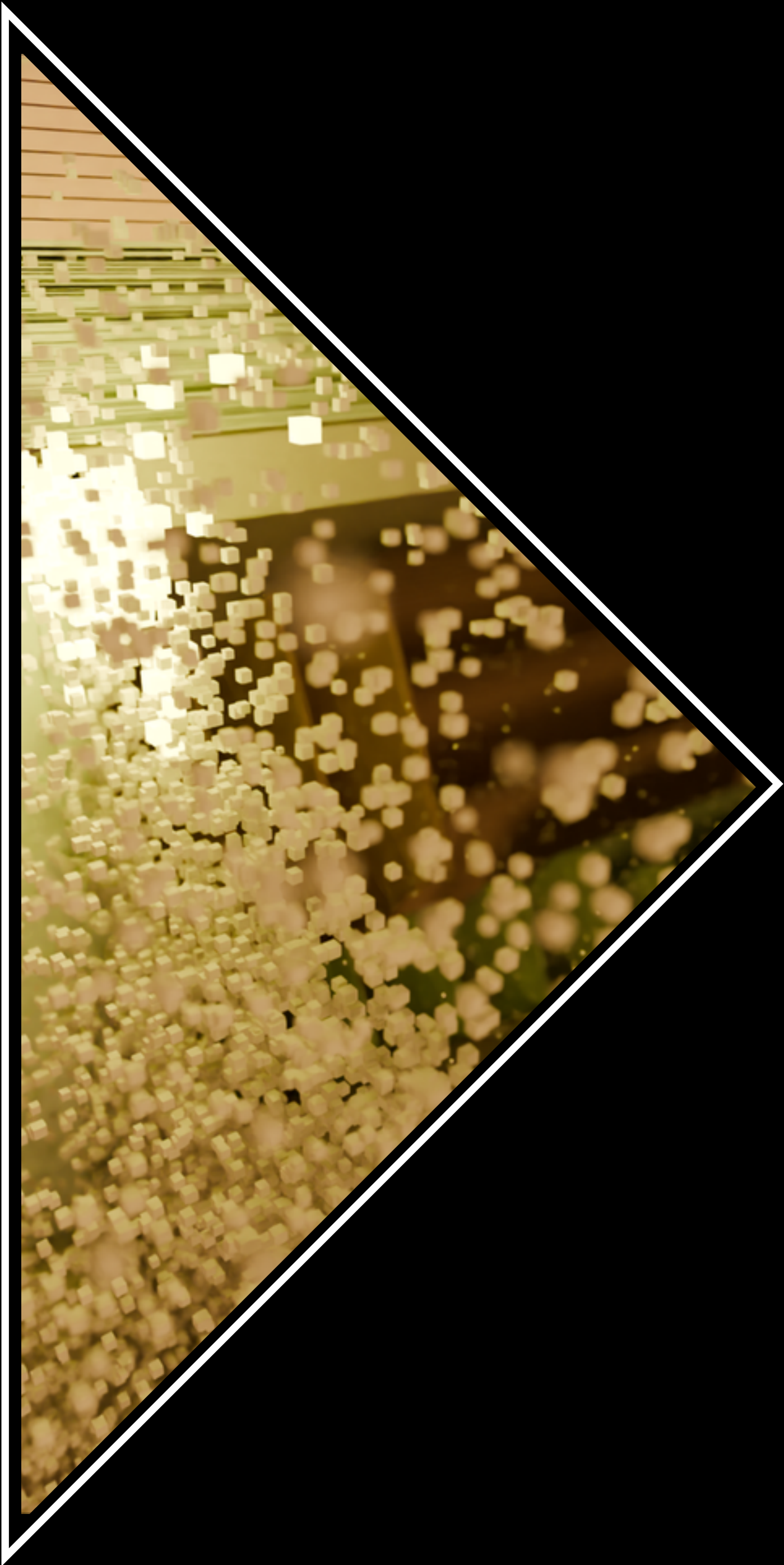
big challenges still to solve — need people and resources to make it happen

GET INVOLVED

muoncollider.us

[self-subscribe to our mailing list](#)

email me to join the collaboration



BACK-UP

EUROPEAN STRATEGY INPUT

- Main IMCC document had many US editors:
 - Core editorial team: Federico Meloni (chair), Chris Rogers (deputy chair), **Kevin Black**, Christian Carli, **Steve Gourlay**, **Sergo Jindariani**, Roberto Losito, Donatella Lucchesi, **Patrick Meade**, Elias Metral, **Simone Pagan Griso**, Nadia Pastrone, Daniel Schulte, **Diktys Stratakis**, Rebecca Taylor, Andrea Wulzer
- Many additional **chapter authors** from US: Artur Apresyan, Sergey Belomestnykh, Scott Berg, Nathaniel Craig, Andre de Gouvea, Karri DiPetrillo, Jeff Eldred, Spencer Gessner, Eliana Gianfelice, Timon Heim, Tova Holmes, Walter Hopkins, Sergei Nagaitsev, Emilio Nanni, Mark Palmer, Kevin Pedro, Katsuya Yonehara

The Muon Collider

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<https://edms.cern.ch/document/3284682/1>

Abstract

Muons offer a unique opportunity to explore the Standard Model at the 10 TeV scale. A Muon Collider at this energy scale will be a paradigm-shifting tool for exploring the underlying simplicity of the Standard Model. It will combine the high-energy reach of a muon collider with the precision of an electron-positron collider, offering a natural next step in the exploration of fundamental physics after the HL-LHC and a natural complement to a future low-energy Higgs factory. Such a facility would significantly broaden the scope of particle colliders, engaging the many frontiers of the high energy community.

The last European Strategy for Particle Physics Project Prioritisation Panel report identified a muon collider, which is being carried out by the International Muon Collider Collaboration. In this comprehensive report, we present the state of the work on accelerator R&D project that can make the muon

400 page [IMCC Update](#) summarizing status

United States (US) Muon Collider Community White Paper for the European Strategy for Particle Physics Update

Drafting Team: M. Beigel (Brookhaven National Laboratory), P. Bhat (Fermilab), N. Craig (University of California, Santa Barbara), S. Dasu (University of Wisconsin), K. DiPetrillo (University of Chicago), S. Gourlay (Fermilab), T. Holmes (University of Tennessee), S. Jindariani (Fermilab), P. Meade (Stony Brook University), S. Pagan-Griso (Lawrence Berkeley National Laboratory), M. Palmer (Brookhaven National Laboratory), D. Stratakis (Fermilab)

The list of endorsers is included at the end of the document.

Abstract:

This document is being submitted to the 2024-2026 European Strategy for Particle Physics Update (ESPPU) process on behalf of the US Muon Collider community, with its preparation coordinated by the interim US Muon Collider Coordination Group. The US Muon Collider Community comprises a few hundred American scientists. The purpose of the document is to inform ESPPU about the US plans for Muon Collider research and development (R&D), explain how these efforts align with the broader international R&D initiatives, and present the US community vision for the future realization of this transformative project.

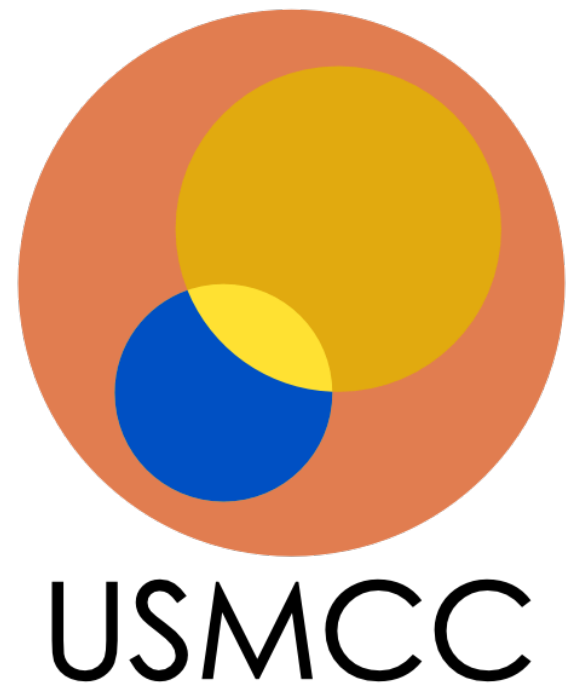


EDMS 3284682 v.1 status In Work access Public
ESPPU_Muon_Collider_Backup.pdf modified 2025-06-10 10:36

12 page [US supplement](#) detailing regional plans

¹ Corresponding author sergo@fnal.gov

THE USMCC LEADERSHIP



Chair



Sergo Jindariani

Vice Chair



Tova Holmes

Communications



Kiley Kennedy

Accelerator



Diktys Stratakis

Experiment



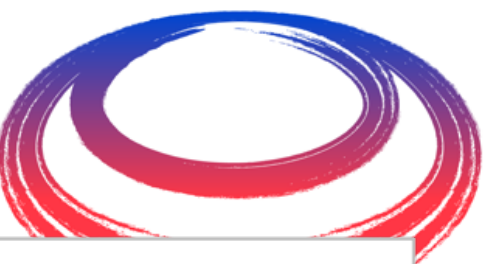
Simone Pagan Griso

Theory



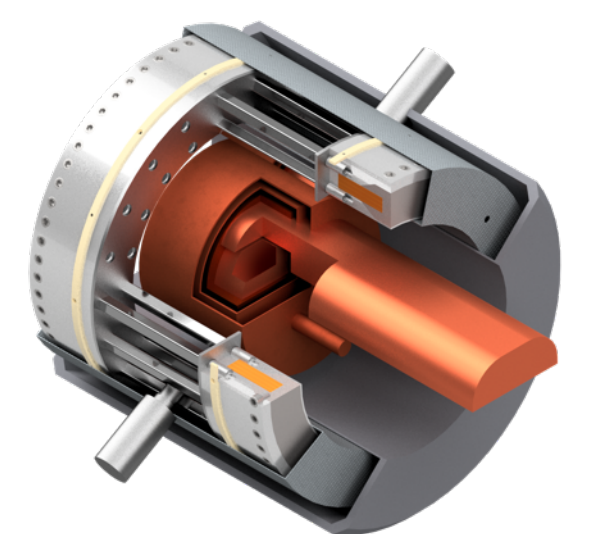
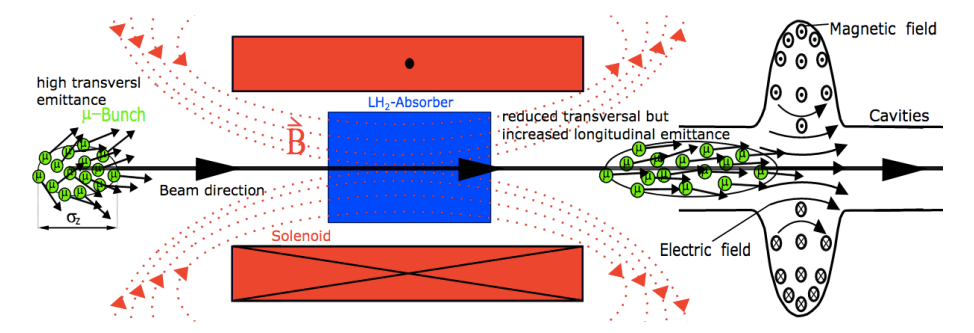
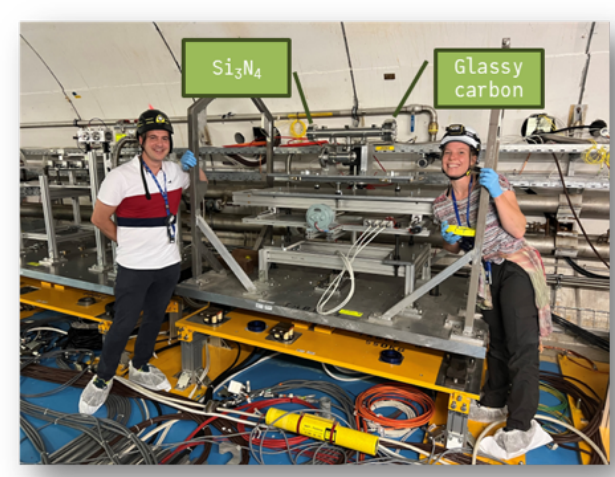
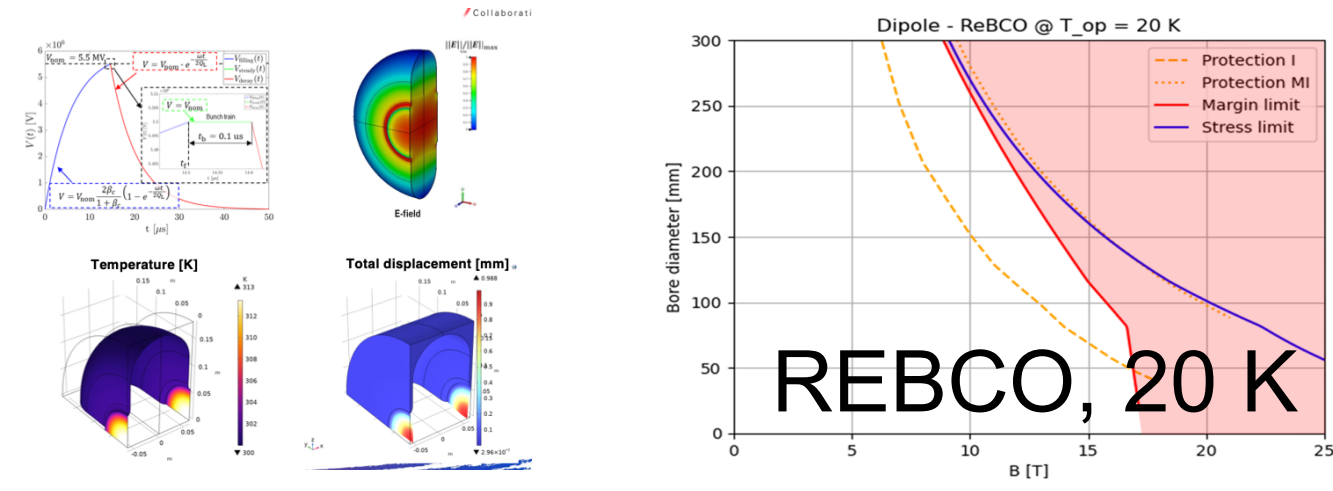
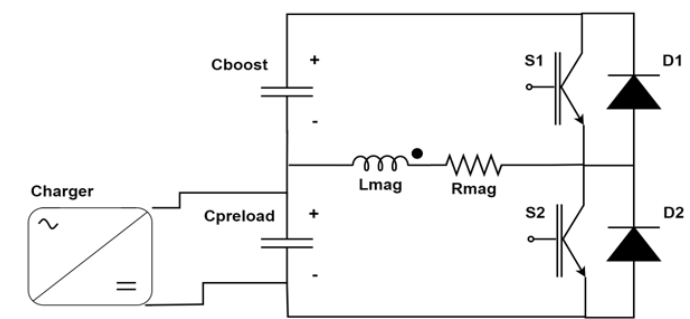
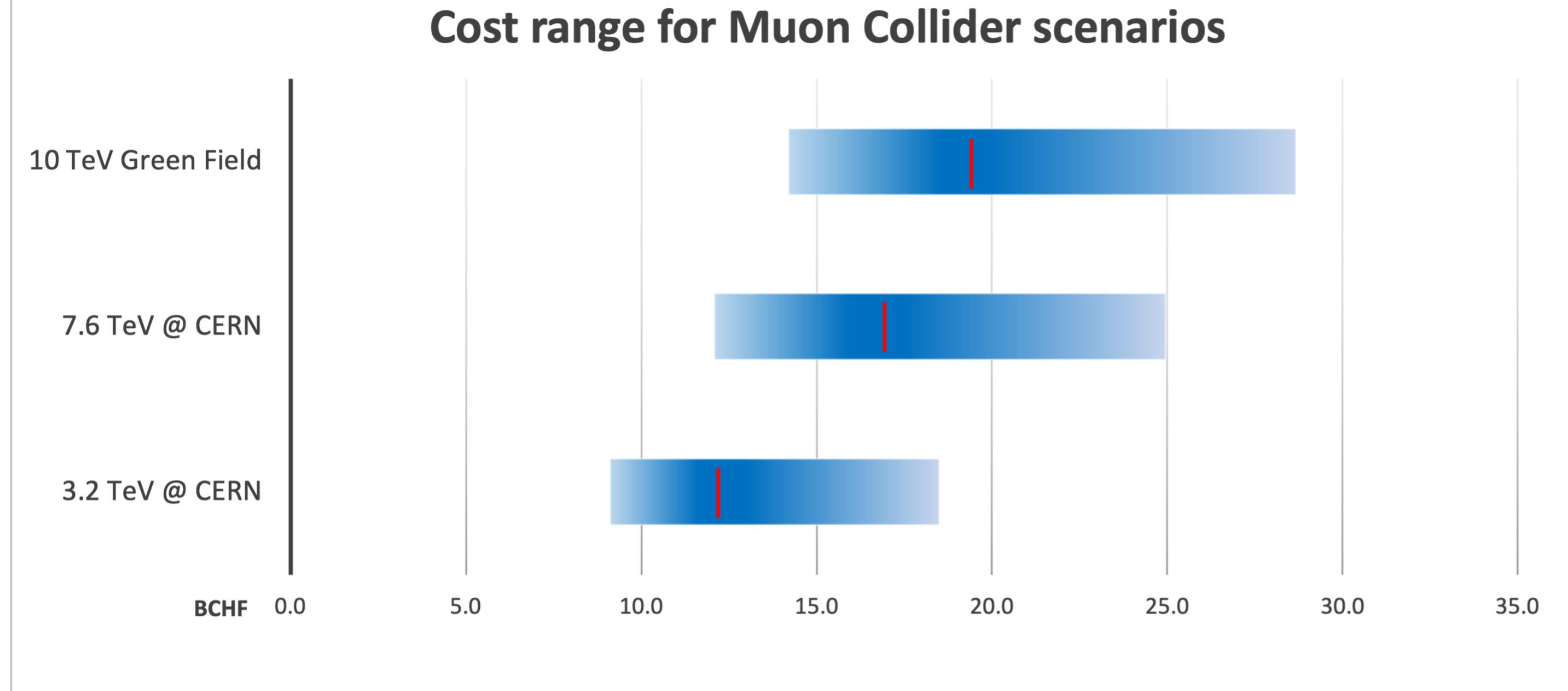
Patrick Meade

R&D Progress



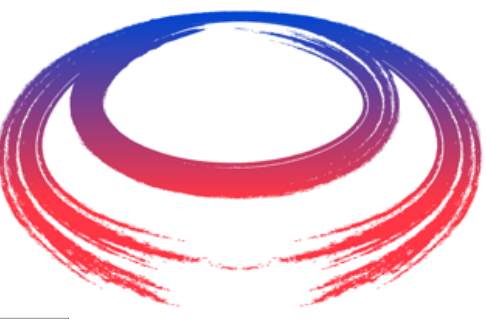
Design of many collider areas has progressed

- Lattice designs
- Technologies
- Detectors and MDI
- Demonstrator scope and design
- **Cost and power consumption scale**



	Unit	CERN 3.2 TeV	CERN 7.6 TeV	Green Field 10 TeV
Proton Driver	MW	16.70	16.70	16.70
6D Cooling	MW	11.76	11.76	11.76
RLAs	MW	10.77	10.77	10.77
RCSs	MW	44.19	108.93	124.68
Collider	MW	10.00	4.10	4.10
General Cooling and Ventilation	MW	20.00	20.00	20.00
Total Power consumption	MW	113.42	172.26	188.01

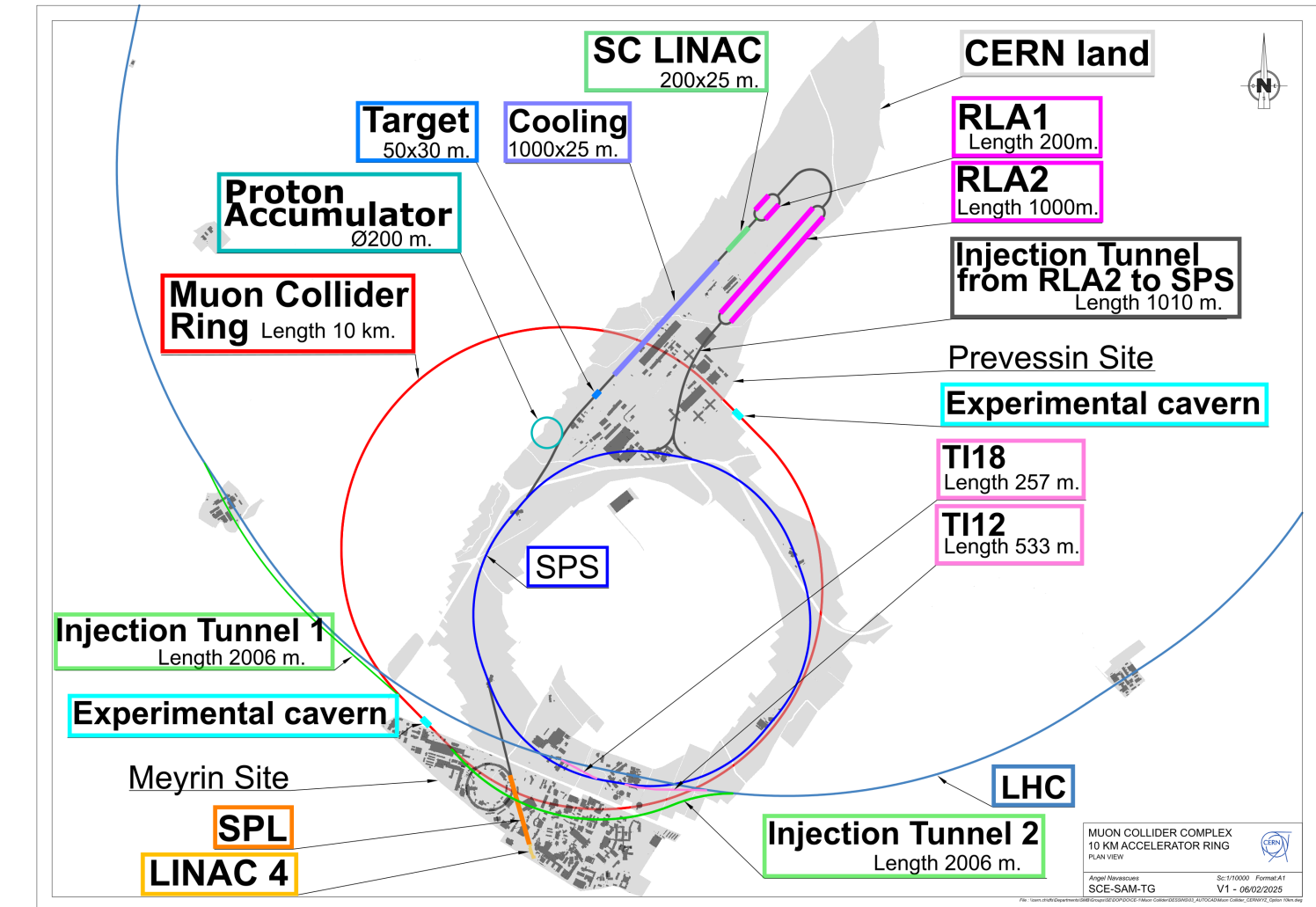
Site Specific Designs



International
MUON Collider
Collaboration

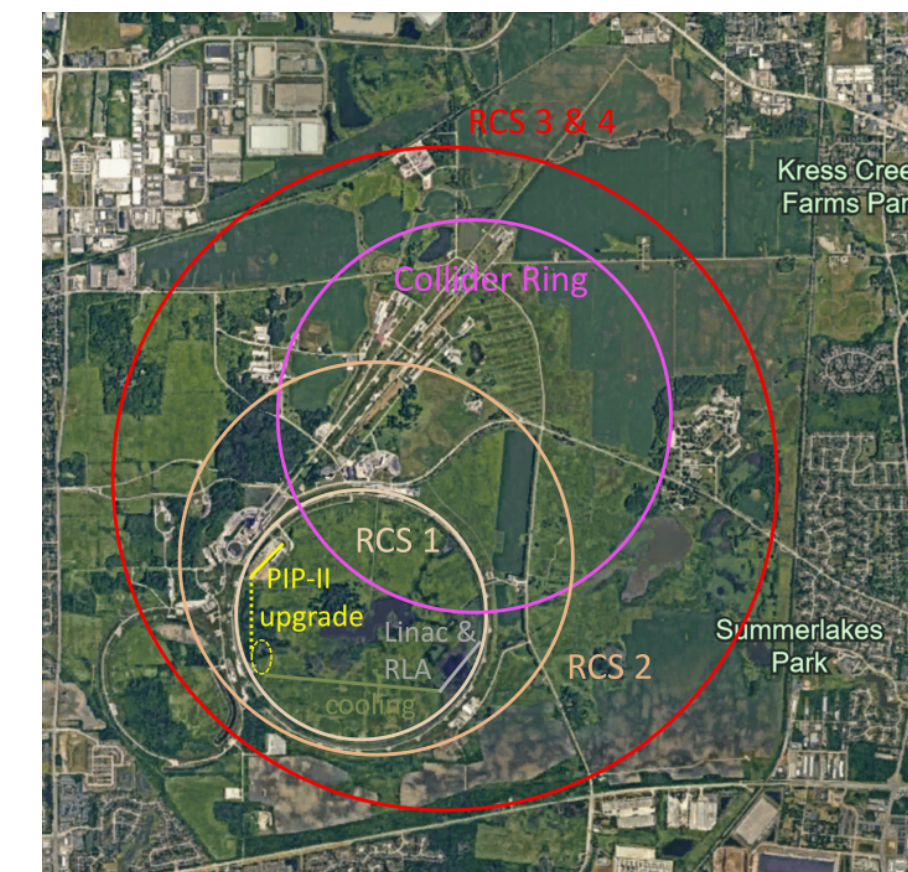
Started studies for concrete site at CERN and Fermilab

- At CERN re-use SPS and LHC and construct facility on CERN land
- Neutrino flux appears solvable
- Adjusted parameters (3.2 and 7.6 TeV)
- Stage with one tunnel or two different tunnels
 - Use of different technologies

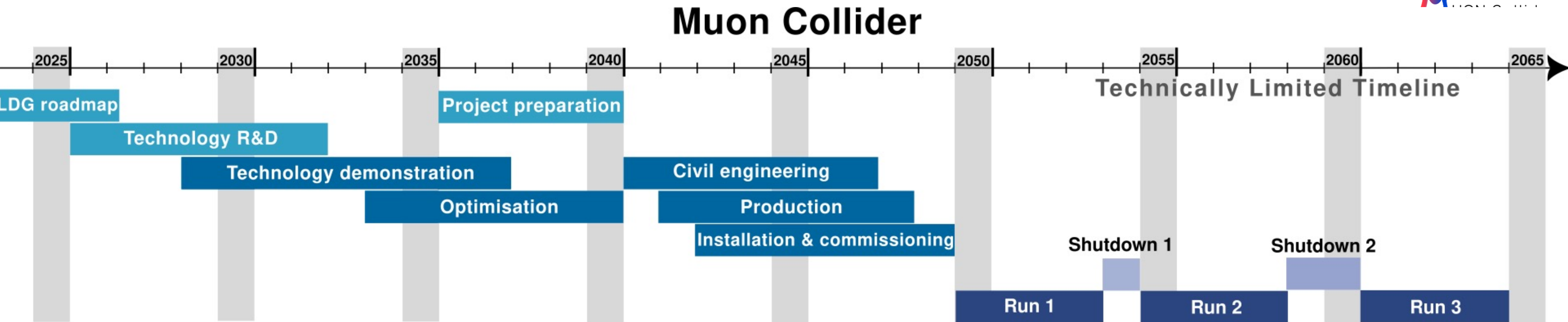


CERN-specific muon collider parameters

Parameter	Symbol	unit	Scenario 1		Scenario 2	
			Stage 1	Stage 2	Stage 1	Stage 2
Centre-of-mass energy	E_{cm}	TeV	3.2	7.6	3.2	7.6
Target integrated luminosity	$\int \mathcal{L}_{target}$	ab^{-1}	1	10	1	10
Estimated luminosity	$\mathcal{L}_{estimated}$	$10^{34} cm^{-2} s^{-1}$	0.9	7.9	2.0	10.1
Collider circumference	C_{coll}	km	11	11	4.8	8.7
Collider arc peak field	B_{arc}	T	4.8	11	11	14
Collider dipole technology			NbTi	Nb ₃ Sn or HTS	Nb ₃ Sn	HTS



Timeline and R&D Programme

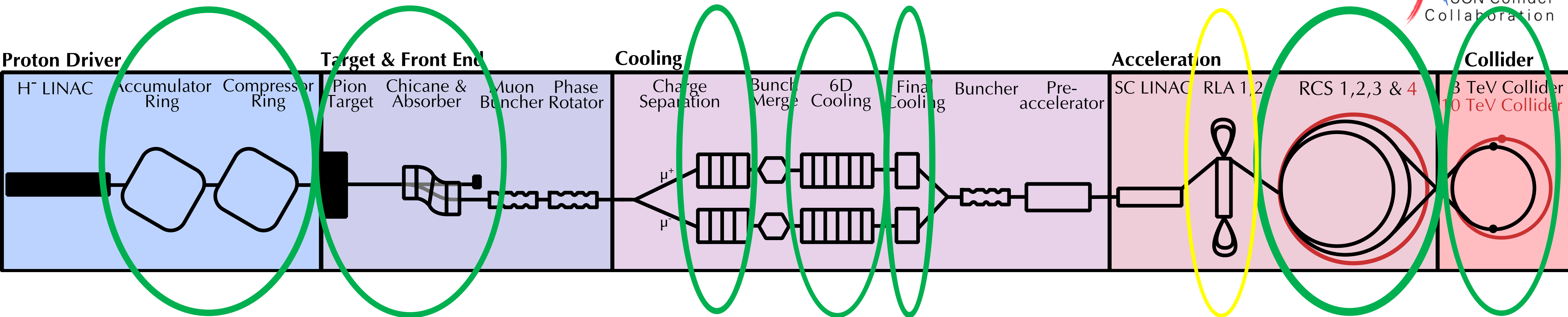


Goal is to be able to commit to a muon collider in 2036 to enable collider by 2050

- Considering the timeline drivers:
 - Magnet technologies: this excludes high-field HTS dipoles
 - Muon cooling technologies
 - Start-to-end design
 - Detector optimization

Ramping up of programme to rapidly gain confidence and balance risk vs R&D cost

Muon Collider CTEs and R&D Plan



- Proton driver
bunch compression

- Graphite target
- Target solenoid

- Muon cooling design
- 6D cooling solenoids
- 6D cooling RF cavities
- Final cooling solenoids

- Pulsed magnets and
power converters
- RCS RF system

- Collider ring dipoles
- Final focus quadrupoles
- Mover system

R&D programme key ingredients:

- Start-to-end design and optimization
- Magnet technologies
- RF technologies
- Cooling technology

- Demonstrator
- Detector R&D and optimization
- Other technologies

R&D Deliverables and Resources



Technologies	Deliverables	Key parameters and goals
Magnets		
Target solenoid	Develop conductor, winding and magnet technology	1 m inner / 2.3 m outer diameters, 1.4 m length, 20 T at 20 K
Split 6D cooling solenoid	Demonstration of solenoid with cell integration	510 mm bore, gap 200 mm, 7 T at 20 K
Final cooling solenoid	Build and test HTS prototype	50 mm bore, 15 cm length, 40 T at 4 K

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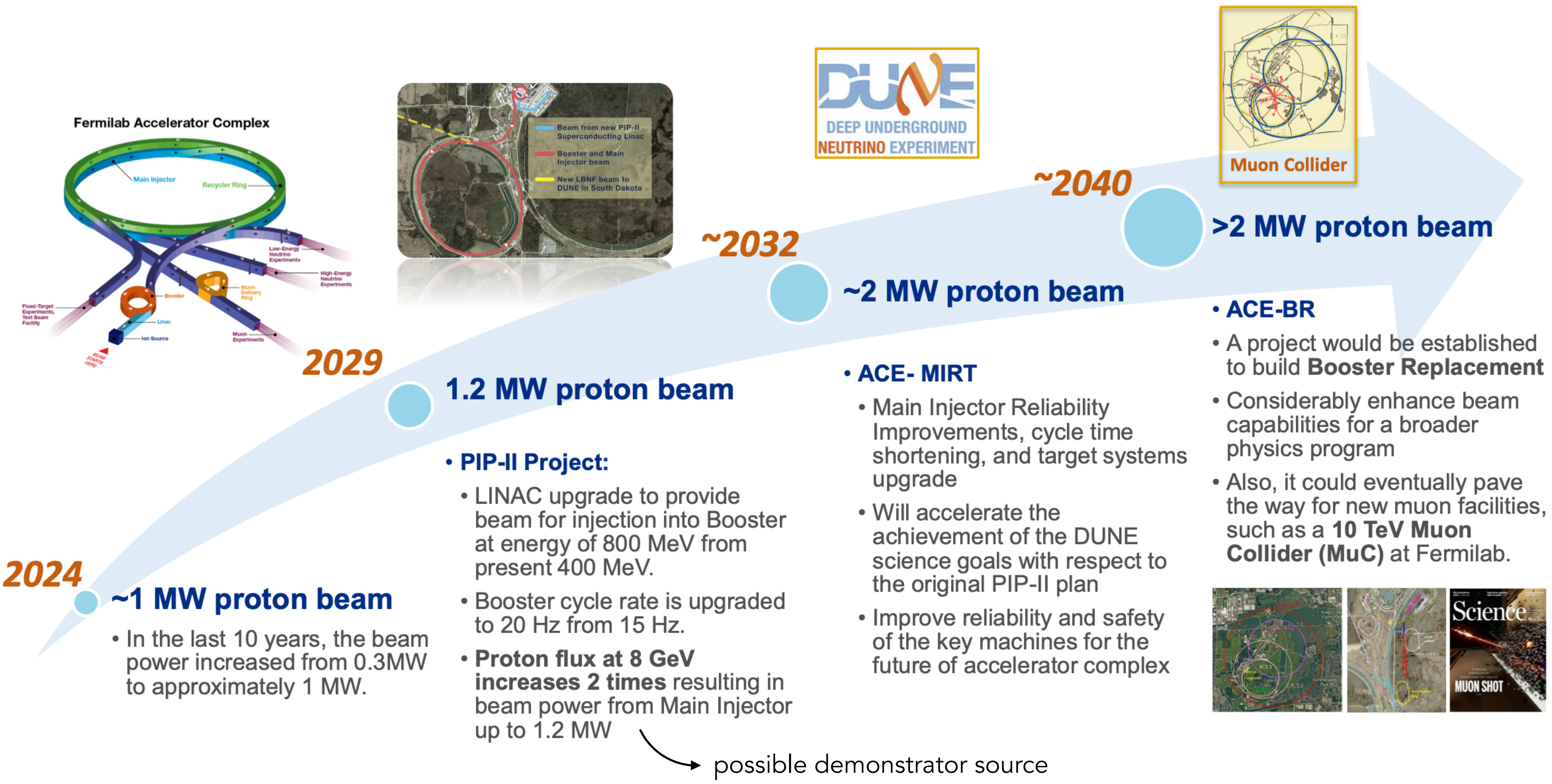
Fast ramping magnet system	Prototype magnet string and power converter	30 mm x 100 mm, 1.8 T, 3.3 T/s
LTS collider dipole	Demonstrate Nb ₃ Sn collider dipole	160 mm diameter, 11 T, 4.5 K, 5 m long
HTS RCS dipole	Demonstrate RCS HTS dipole	30 mm x 100 mm, 10 T, 20 K, 1 m long
HTS collider dipole	Demonstrate HTS collider dipole	140 mm diameter, 14 T, 20 K, 1 m long
HTS collider quadrupole	Demonstrate HTS IR quadrupole	140 mm diameter, 300T/m, 4.5K, 1m long
Radiofrequency		
Muon cooling RF cavities	Design, build and test RF cavities	352 MHz and 704 MHz in 10 T field
Klystron prototype	Design/build with Industry 704 MHz (and later 352 MHz) klystron	20 MW peak power, 704 MHz / 352 MHz
RF test stands	Assess cavity breakdown rate in magnetic field	20-32 MV/m, 704 MHz-3 GHz cavities in 7-10 T
SCRf cavities	Design SRF cavities, FPC and HOM couplers, fast tuners, cryomodules	352 MHz, 1056 MHz, 1.3 GHz, 1 MW peak power (FPC)

Muon Cooling		
First 6D cooling cell	Build and test first cooling cell	
5-cell module	Build and test first 5-cell cooling module	
Cooling demonstrator	Design and build cooling demonstrator facility	Infrastructure to test cooling modules with muon beam
Final cooling absorber	Experimental determination of final cooling absorber limit	3×10^{12} muons, 22.5 μm emittance, 40 T field

Design & Other Technologies		
Neutrino flux mover system	Prototype components and tests as needed	Range to reach O(±1mradian)
Beam Instrumentation	Instrumentation component designs	Prototype components and tests as needed
Target Studies	Target design and test of relevant components	0.4 MJ/pulse, 5 Hz
Start-to-End Facility Design	A start-to-end model of the machine consistent with realistic performance specifications	Lattice designs of all beamlines, simulation codes with relevant beam physics, tuning and feedback procedures

Year	I	II	III	IV	V	VI	VII	VIII	IX	X
Accelerator Design and Technologies										
Material (MCHF)	1.6	3.2	4.8	6.4	9.6	10.8	12.0	12.0	12.0	12.0
FTE	47.1	60.6	75.0	85.0	100.0	120.0	150.0	174.6	177.2	185.1
Demonstrator										
Material (MCHF)	0.6	2.2	3.9	5.4	7.8	15.1	25.9	32.4	31.8	12.6
FTE	9.5	11.0	12.5	29.2	29.7	30.5	25.5	27.7	26.7	25.5
Detector										
Material (MCHF)	0.5	1.1	1.6	2.1	2.1	2.1	2.1	2.6	3.1	3.1
FTE	23.4	46.5	70.0	93.0	93.0	93.0	93.0	116.4	139.5	139.5
Magnets										
Material (MCHF)	3.0	4.9	10.1	10.0	11.0	13.4	11.7	7.2	6.6	4.7
FTE	23.3	28.4	36.4	40.9	44.3	47.1	46.2	37.7	36.1	29.4
TOTALS										
Material (MCHF)	5.7	11.4	20.3	23.9	30.6	41.4	51.7	54.2	53.5	32.4
FTE	103.3	146.5	194.0	248.1	267.0	290.6	314.8	356.3	379.4	379.6

SITING AT FERMILAB: ROADMAP



Future of US MuC is integrated with the future of FNAL

US MuC Coordination team met with FNAL director search to discuss priorities



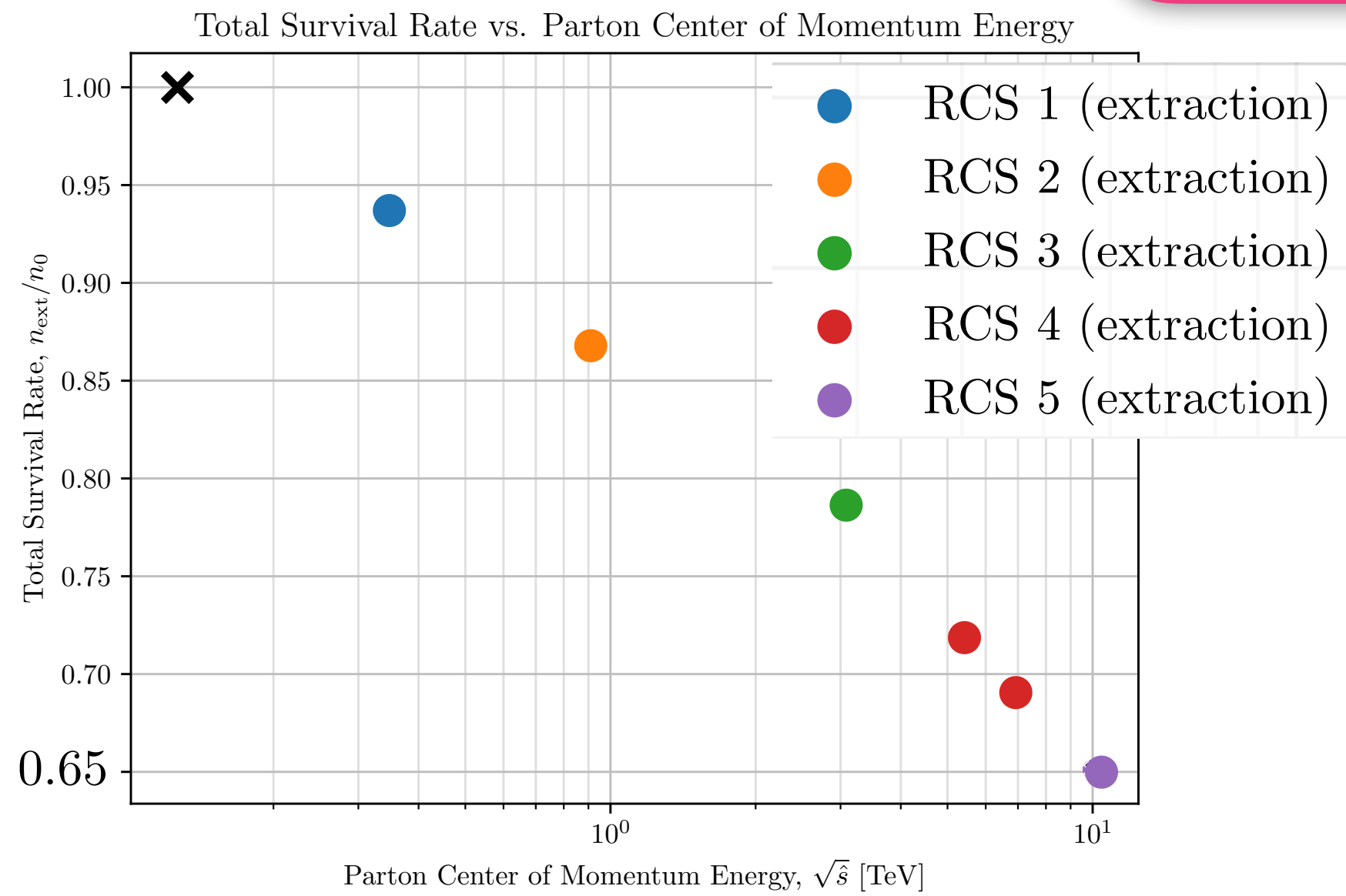
RECENT HIGHLIGHTS: PUSHING COMPACTNESS

charge-agnostic cooling channel studies

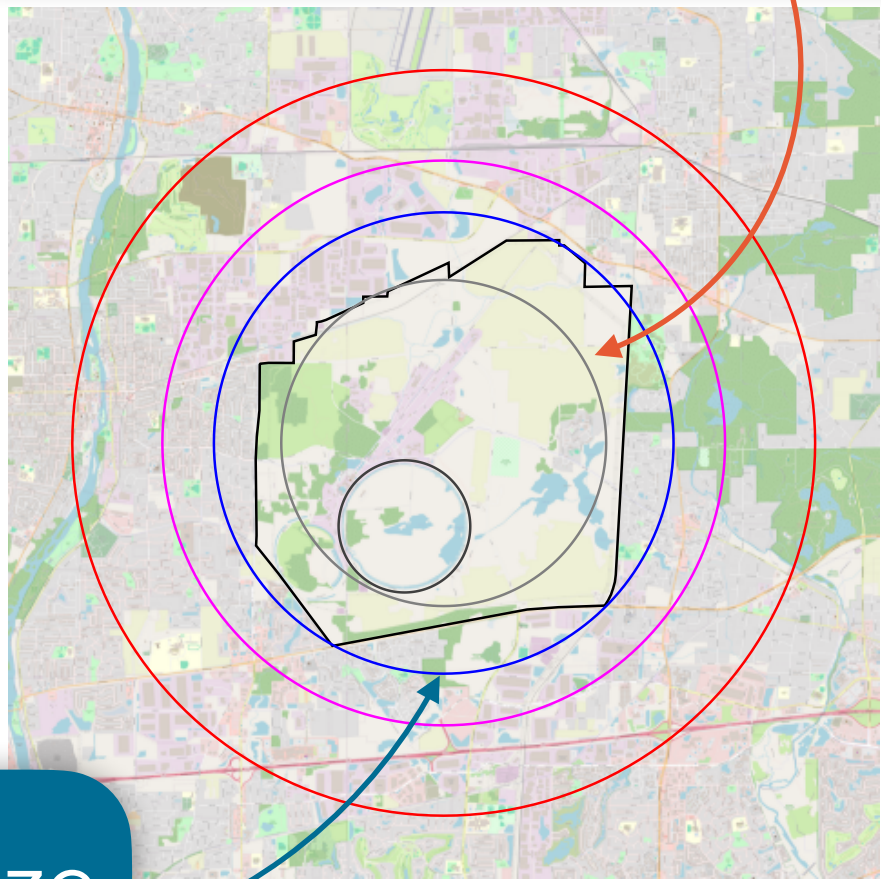
reducing size and cost of cooling channel

RCS design for FNAL site

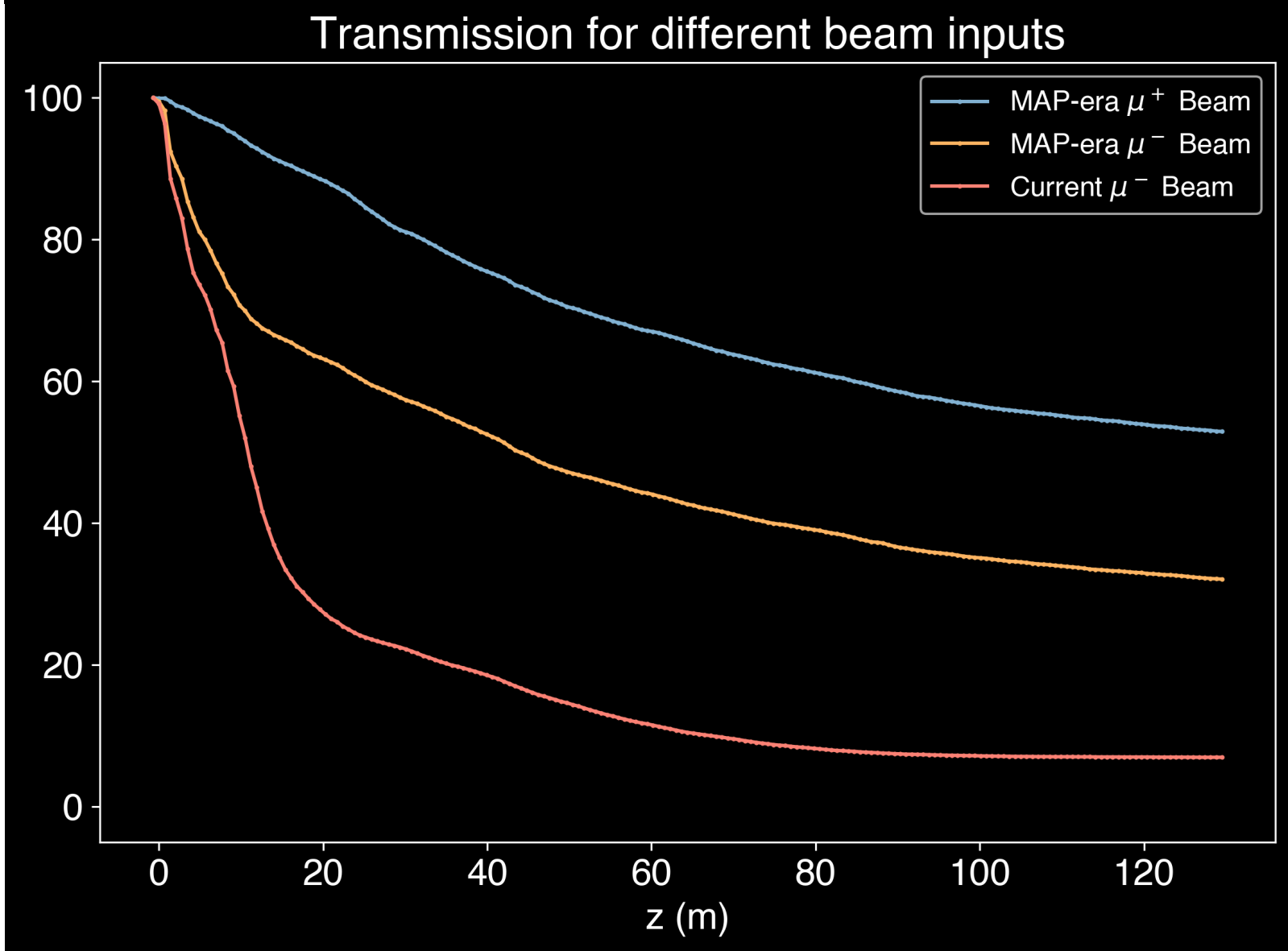
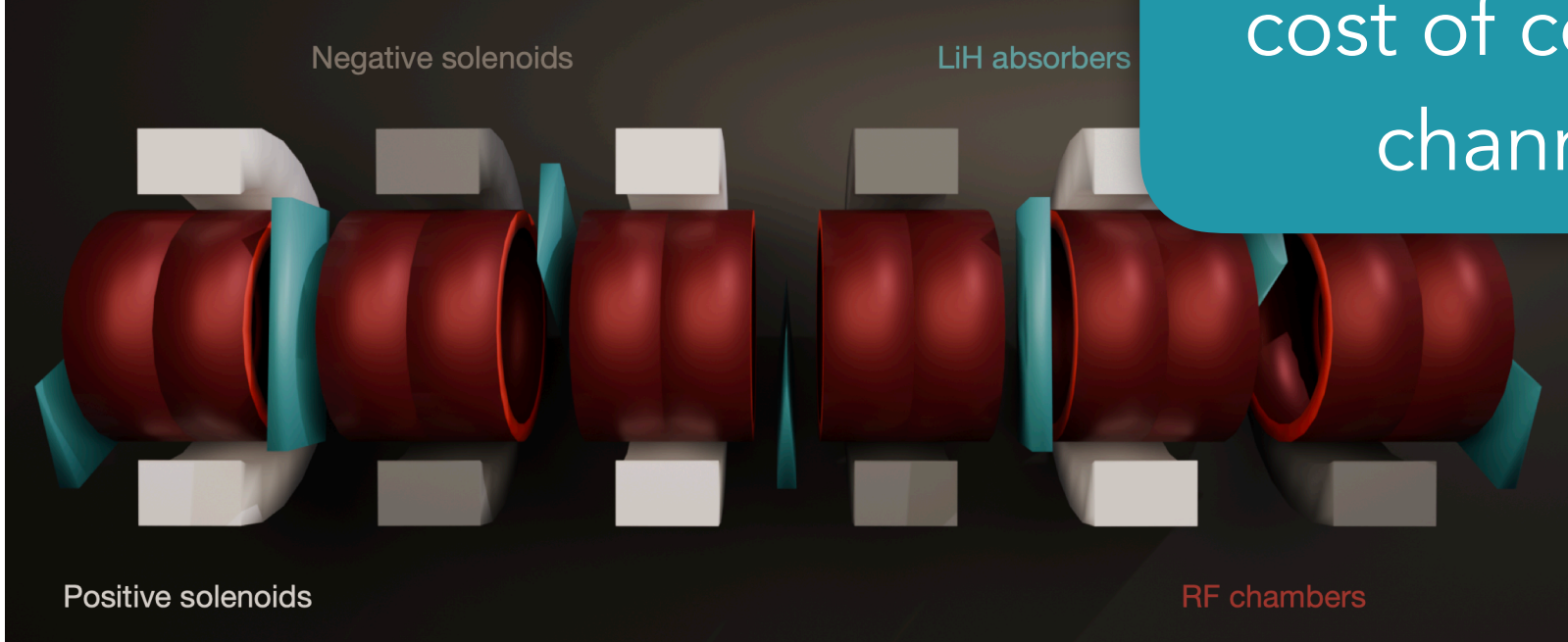
Highest current E w/i FNAL site is 5.42 TeV



Smallest current max ring size for 10 TeV is 21.9 km



K. Capobianco-Hogan



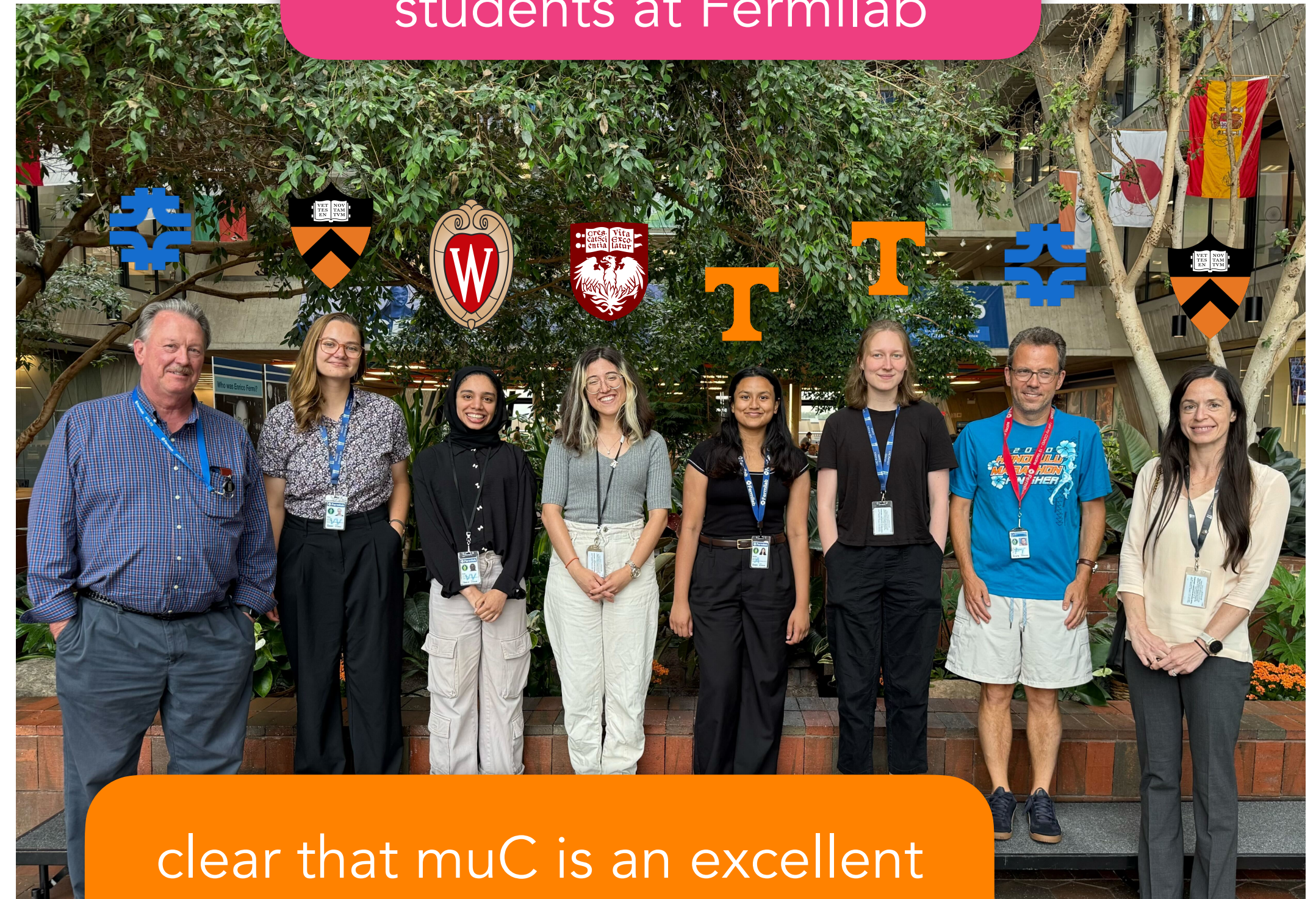
C. Riggall, R. Ganesan

RECENT HIGHLIGHTS: THE NEXT GENERATION

- Training clusters of new students in muon collider accelerator R&D, e.g.:
 - 6 students based at **FNAL** for the summer (Princeton, U Chicago, Wisconsin, Tennessee)
 - 4 students incorporated into **BNL LDRD** (Stony Brook, Princeton, Tennessee)
- Interested in expanding summer program in future years — needs funding for student and expert time!

work on previous slide
done within these groups!

summer accelerator
students at Fermilab



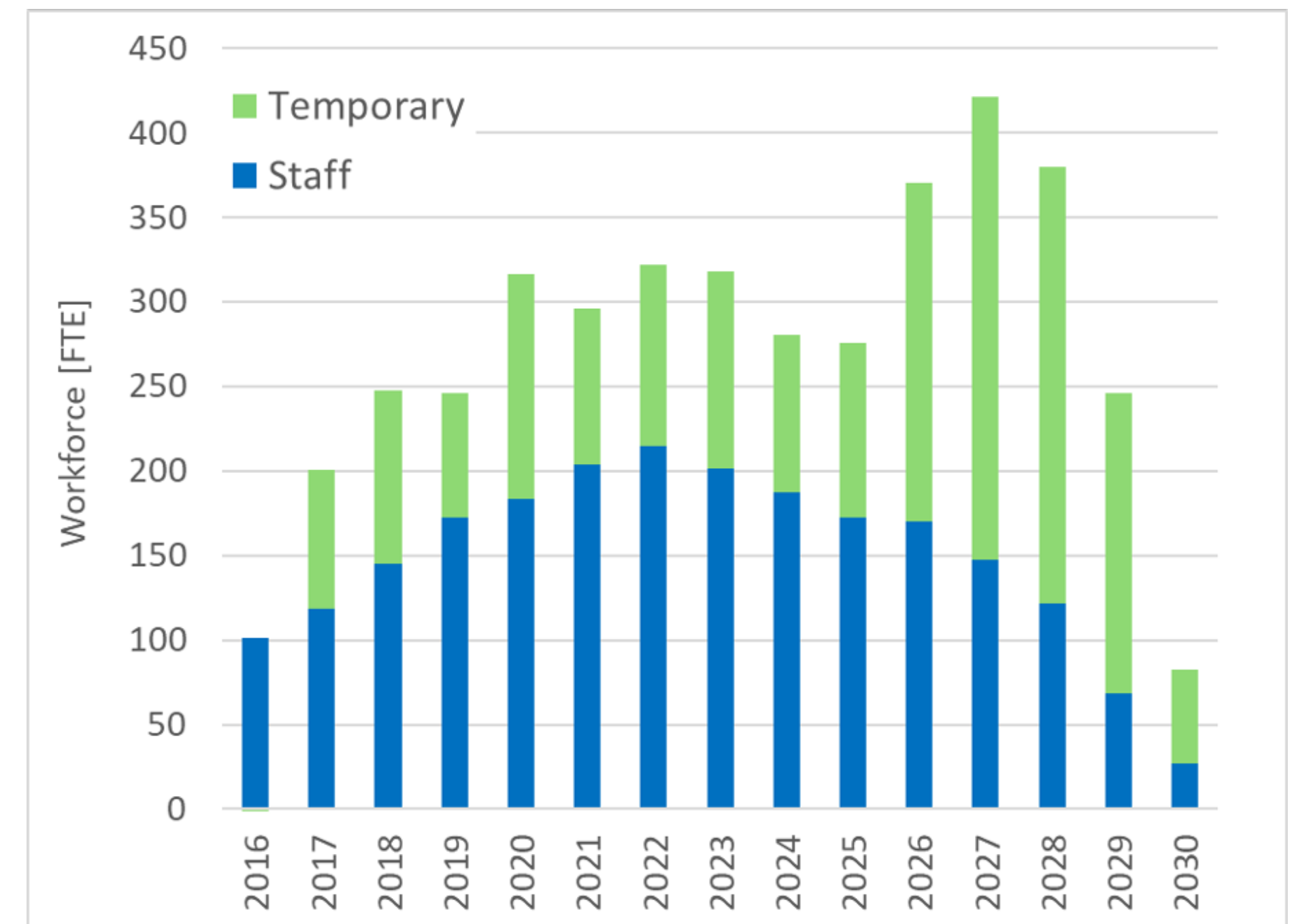
clear that muC is an excellent
motivator attracting a new
generation to accelerator

~100 attendees at Muon Collider
Accelerator School [next week!](#)

RECENT HIGHLIGHTS: THE NEXT GENERATION

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- Interested in expanding summer program in future years — needs funding for student and expert time!

HL-LHC Project FTE



[B. Di Girolamo](#)

Need real growth in accelerator physics
to enable a large-scale US collider

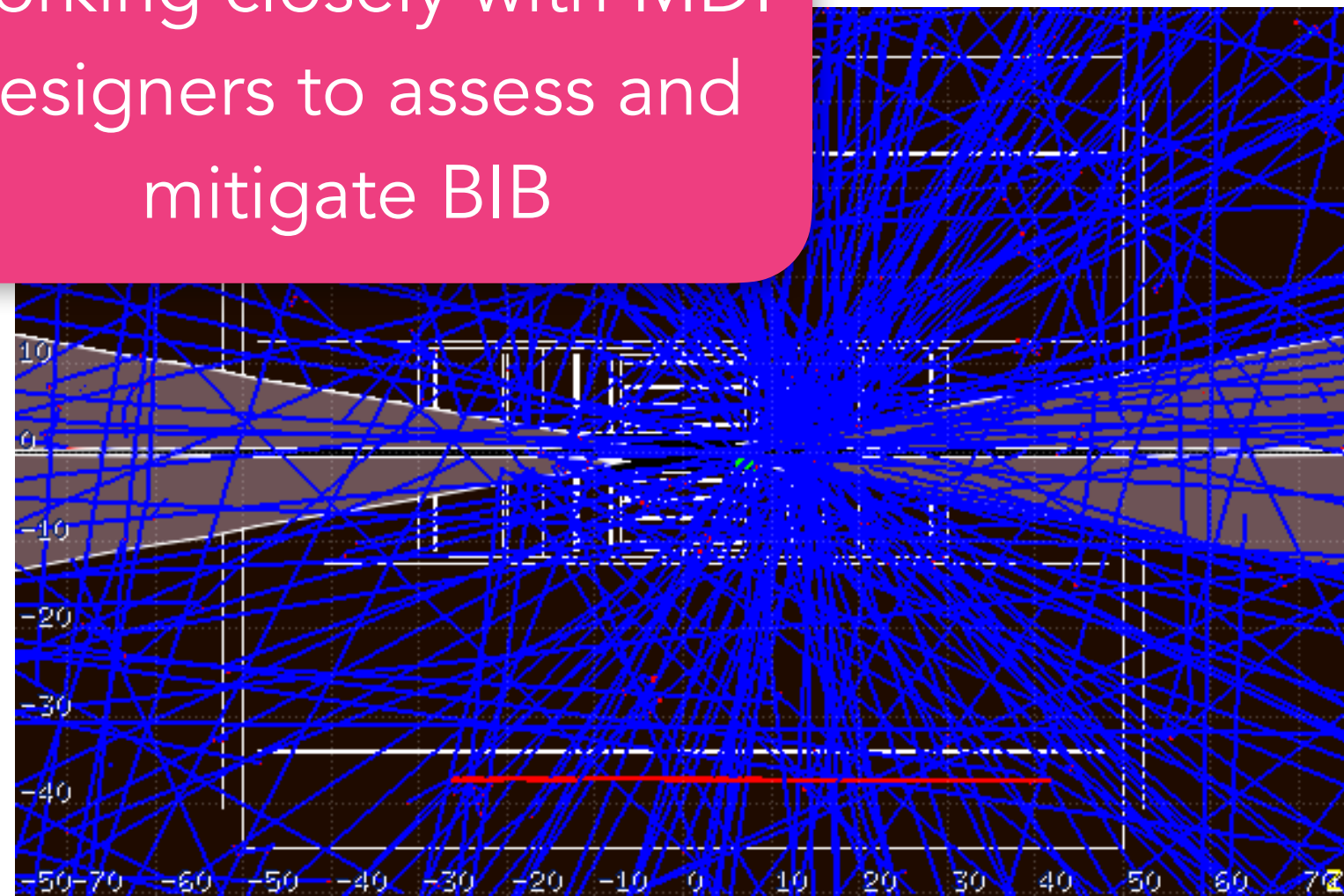
RECENT HIGHLIGHTS: 10 TEV DETECTOR CONCEPTS



2 detector concepts developed for 10 TeV, MAIA led by US + DESY

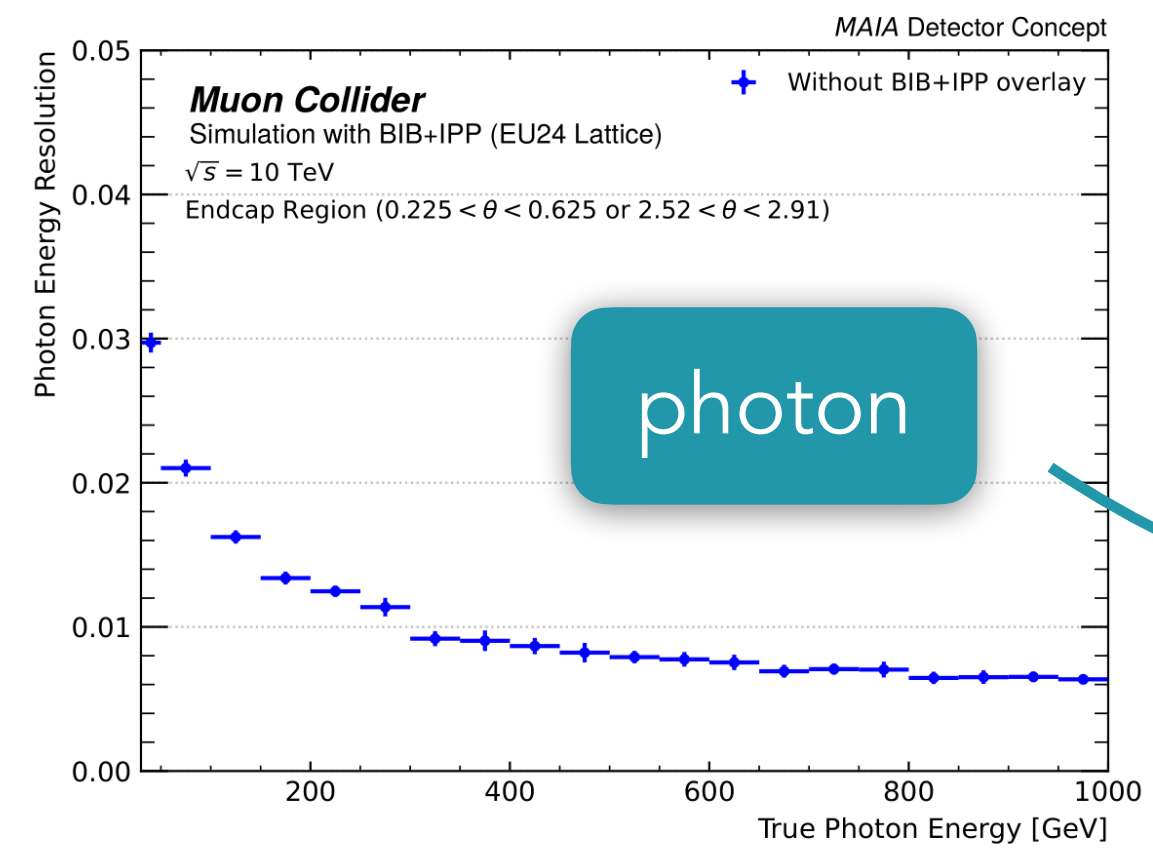
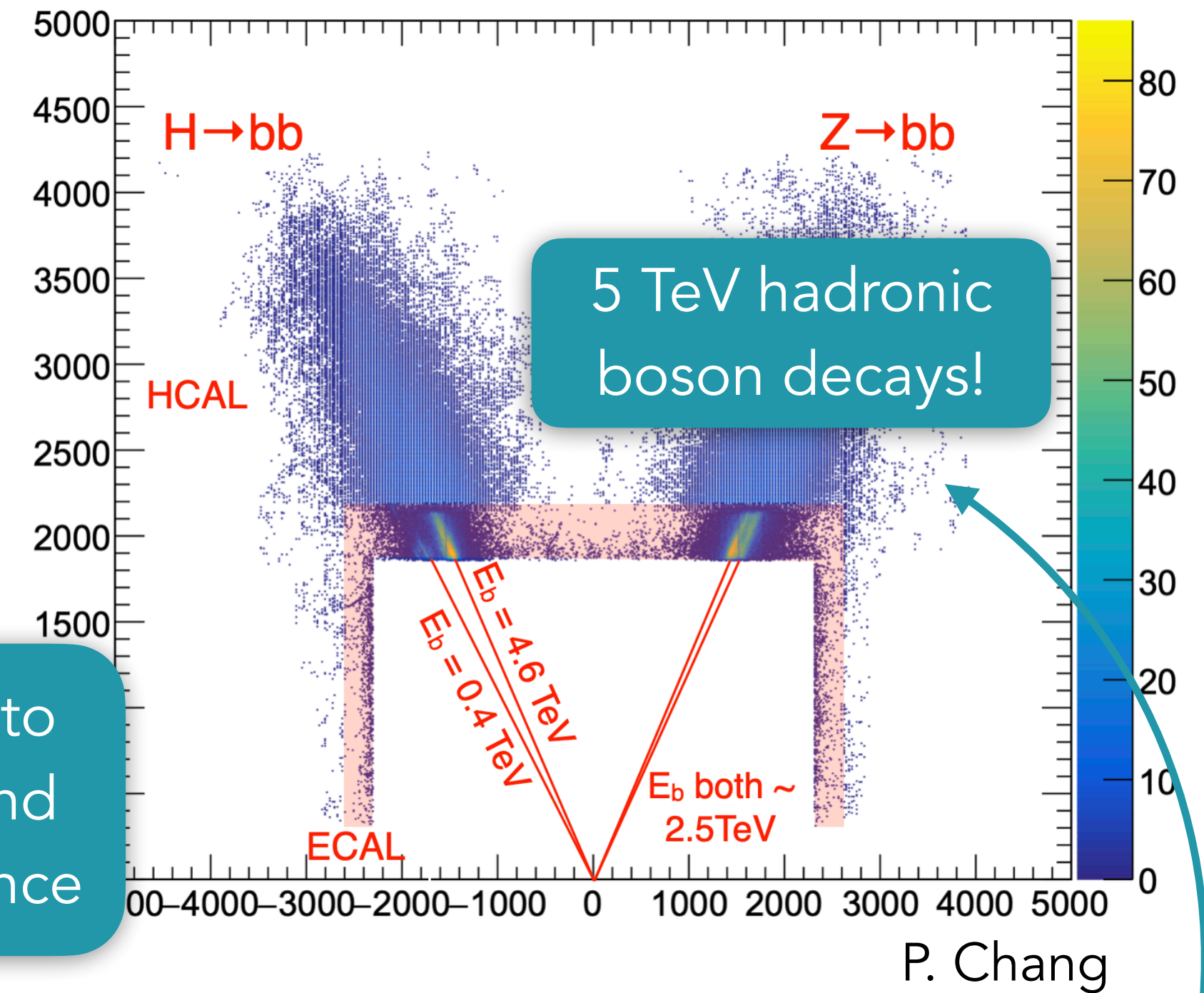
Working closely with MDI designers to assess and mitigate BIB

D. Calzolari

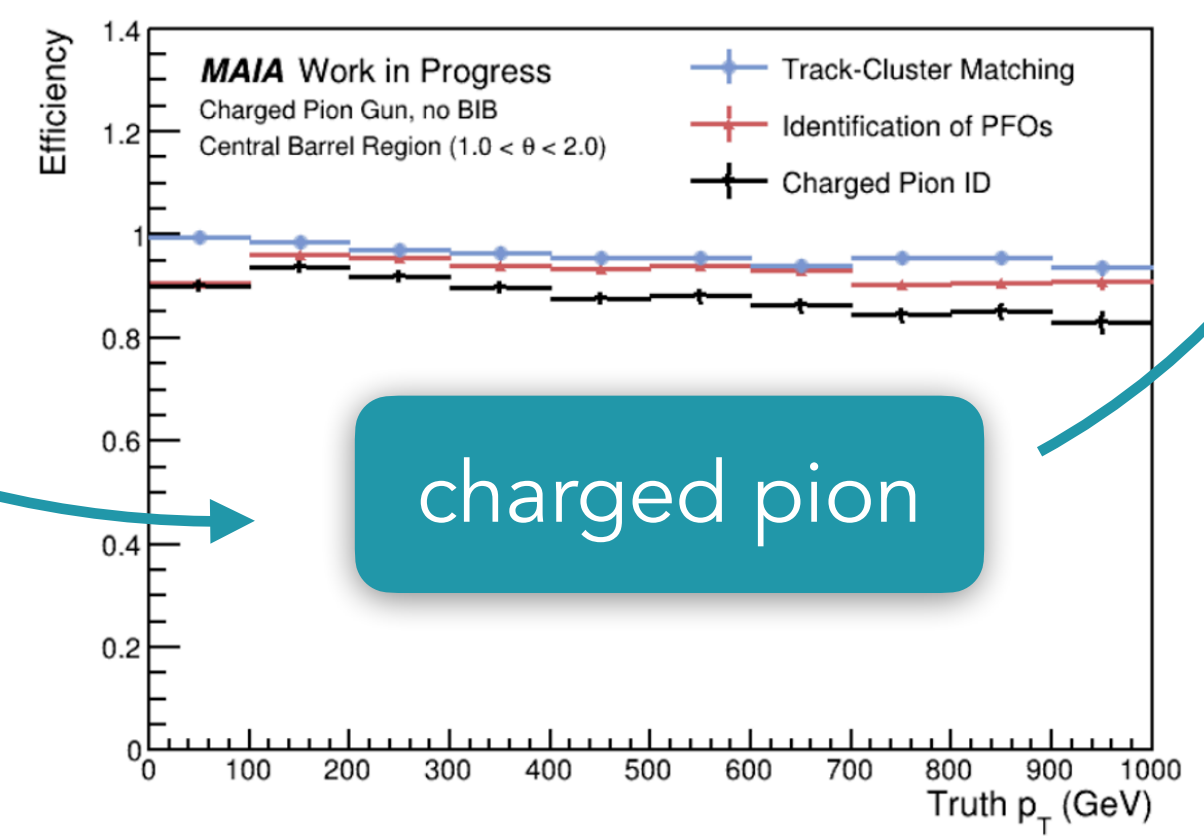


photons, electrons, positrons
(0.0003% of a BIB event)

Moving from simple to complex object ID and quantifying performance



R. Powers



G. Penn

RECENT HIGHLIGHTS: HIERARCHY OF RATES

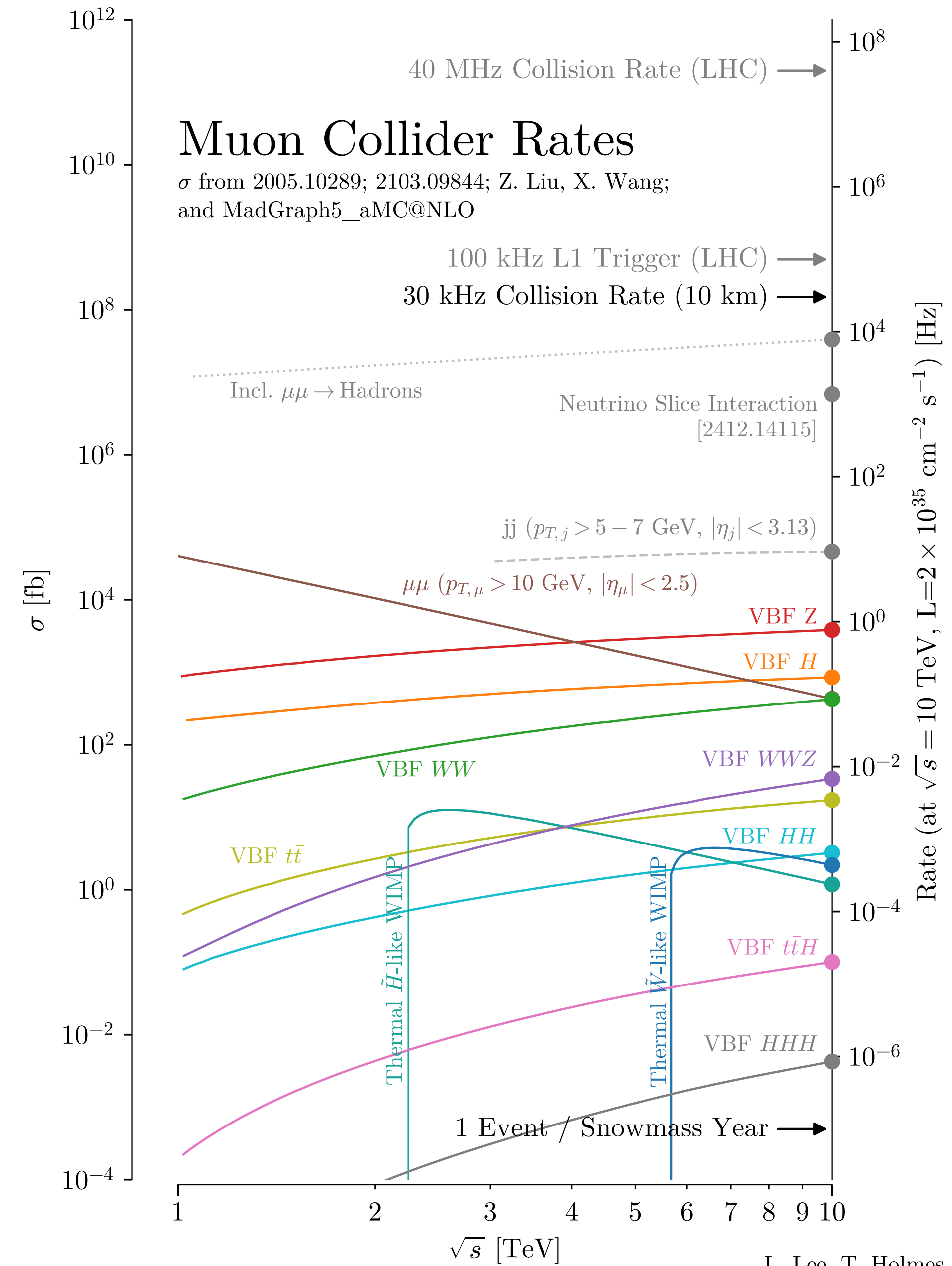
- Unique interplay at a muon collider
 - $O(0.1)$ /crossing neutrino interactions
 - 4 OoM between crossing rate and key processes
 - Possibility for trigger, but trade-offs and possible designs need to be studied
 - Which are most viable for luminosity?

event info reduction



of events reduction

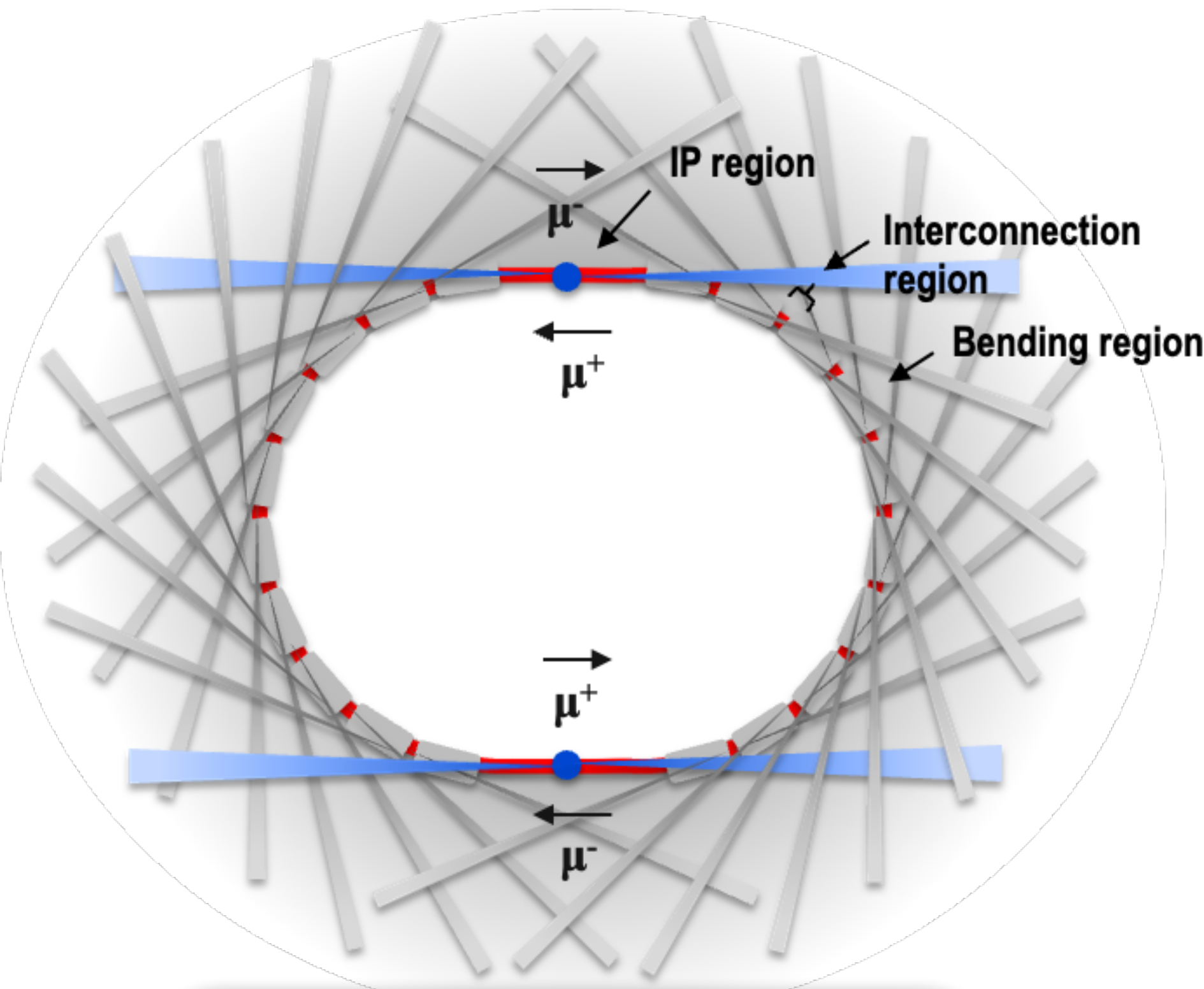
huge amount of work to be done further understanding BIB mitigation and its impact on these questions



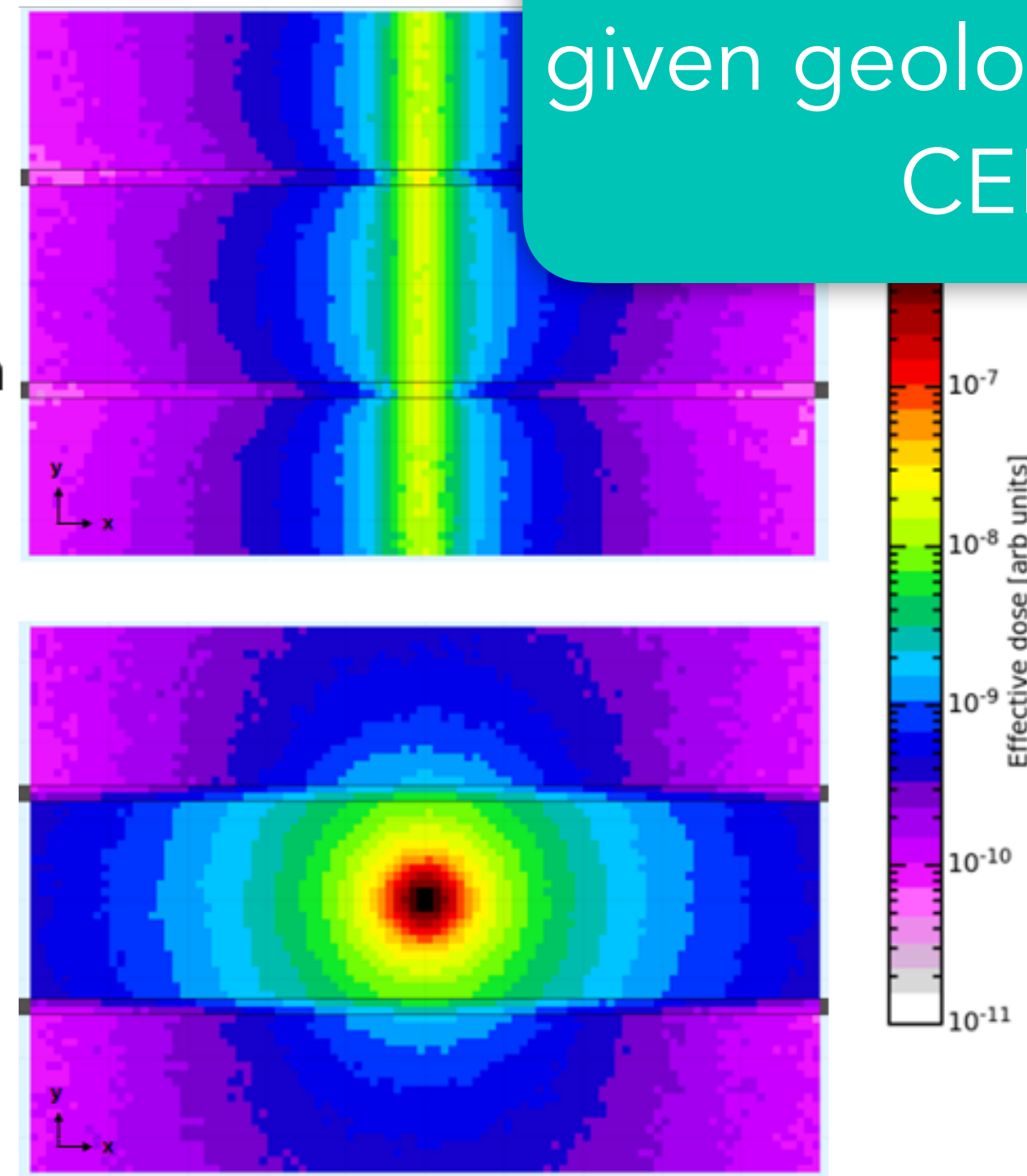
NEUTRINO RADIATION MITIGATION

C. Ahdida

detailed evaluation given geology done for CERN



variety of intensities from different portions of the collider



impact of movers

Risk of ν -induced activation?

could also cause activation of soil and radiation, persons could then be activated at the location where ν break the ground

- It can be assumed that the collider is deep underground inside the impermeable molasse \rightarrow no contact with shallower aquifers and not suitable for exploitation of drinking water
- Therefore, only activation in the more shallow moraine region would be relevant
- What levels of radiation would cause a substantial soil activation?

Example of siting in the Geneva area

Table 6.12.1: Effective dose of neutrino-induced radiation for an underground building structure at different distances from the muon decay when the vertical deformation by the movers is applied. The muon beam energy is 5 TeV.

Distance	μ^- Mitigated dose [pSv/decay]	μ^+ Mitigated dose [pSv/decay]
15 km	$6.6 \cdot 10^{-9}$	$6.7 \cdot 10^{-9}$
20 km	$4.8 \cdot 10^{-9}$	$4.9 \cdot 10^{-9}$
30 km	$3.0 \cdot 10^{-9}$	$3.1 \cdot 10^{-9}$
60 km	$1.3 \cdot 10^{-9}$	$1.4 \cdot 10^{-9}$

much more to do at FNAL site

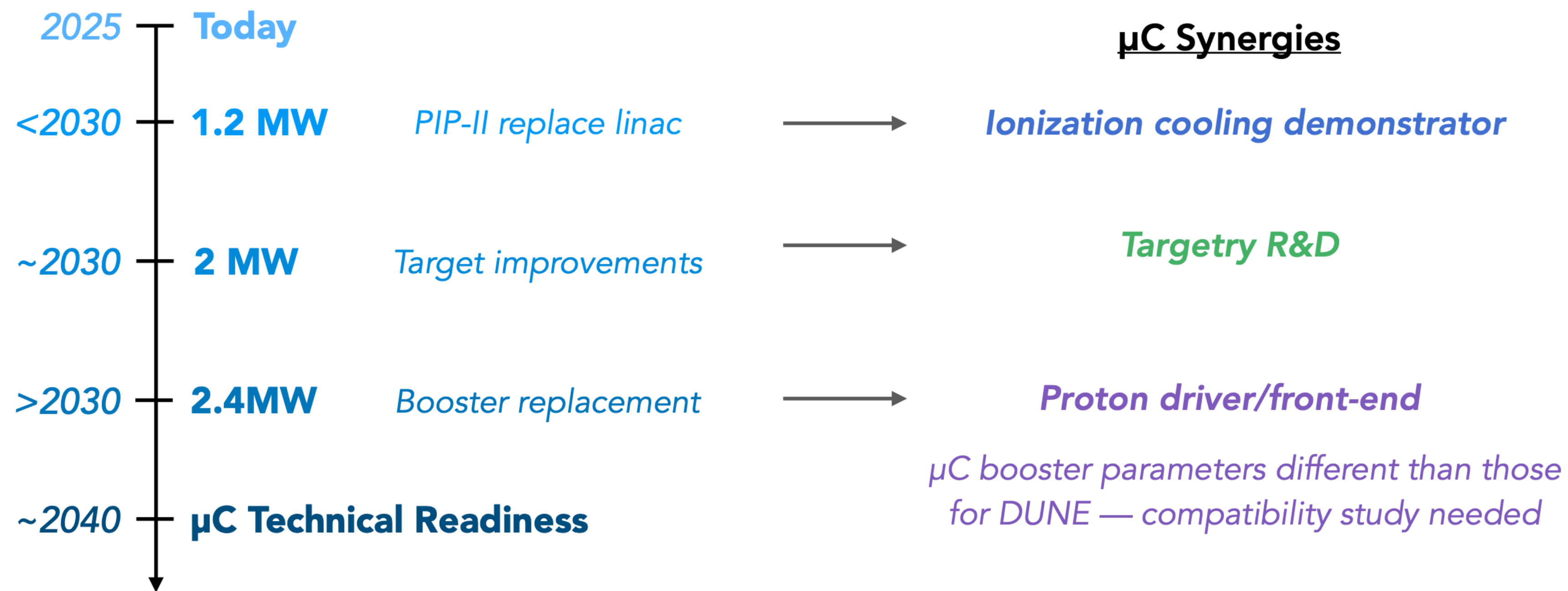
Most recent technical specs from "The Muon Collider" (input to ESPPU)

FNAL DEMONSTRATOR + ACE

D. Stratakis

Synergies with Fermilab's ACE Plan

Accelerator Complex Evolution (ACE) Plan could become the basis for μ C infrastructure

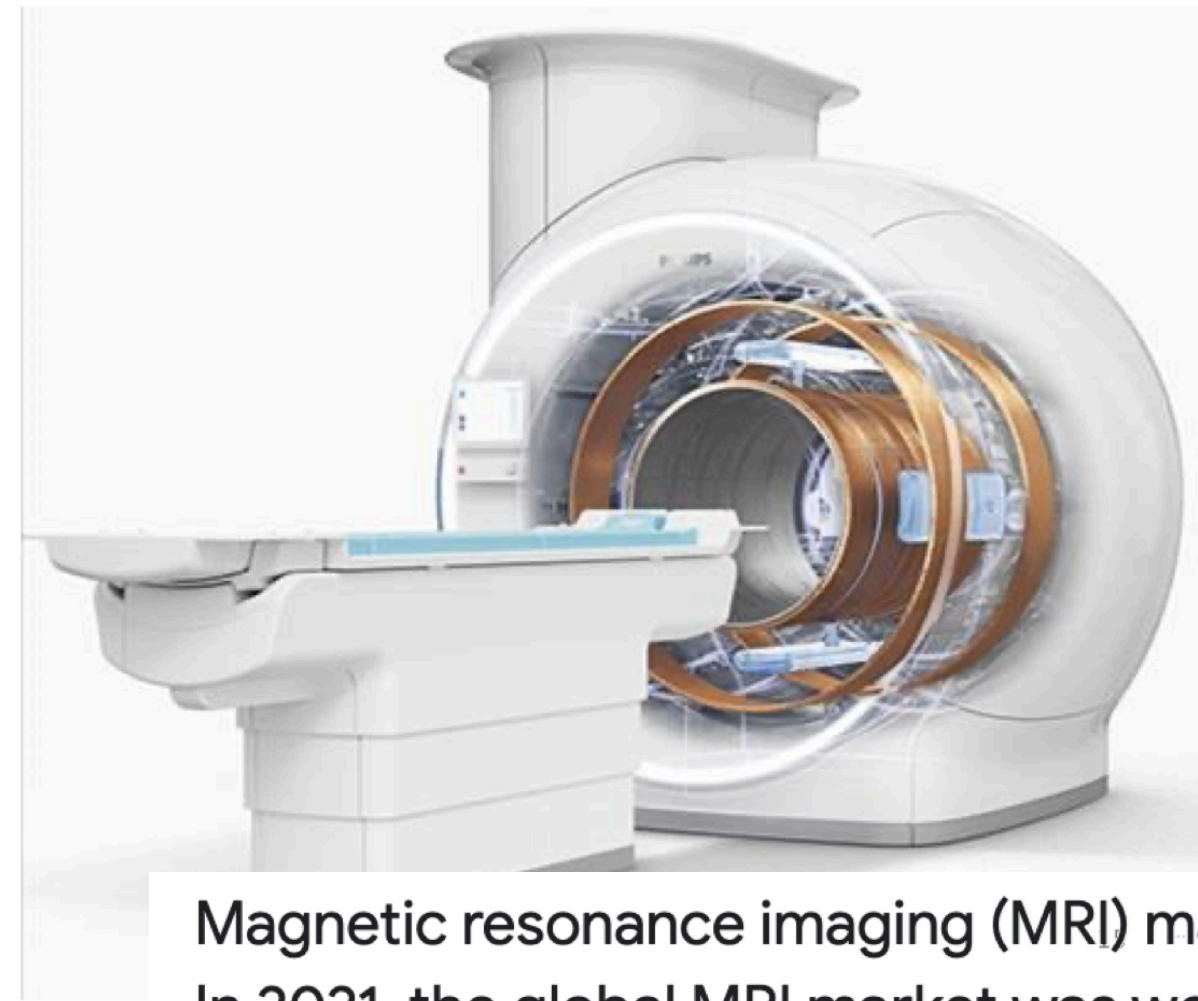
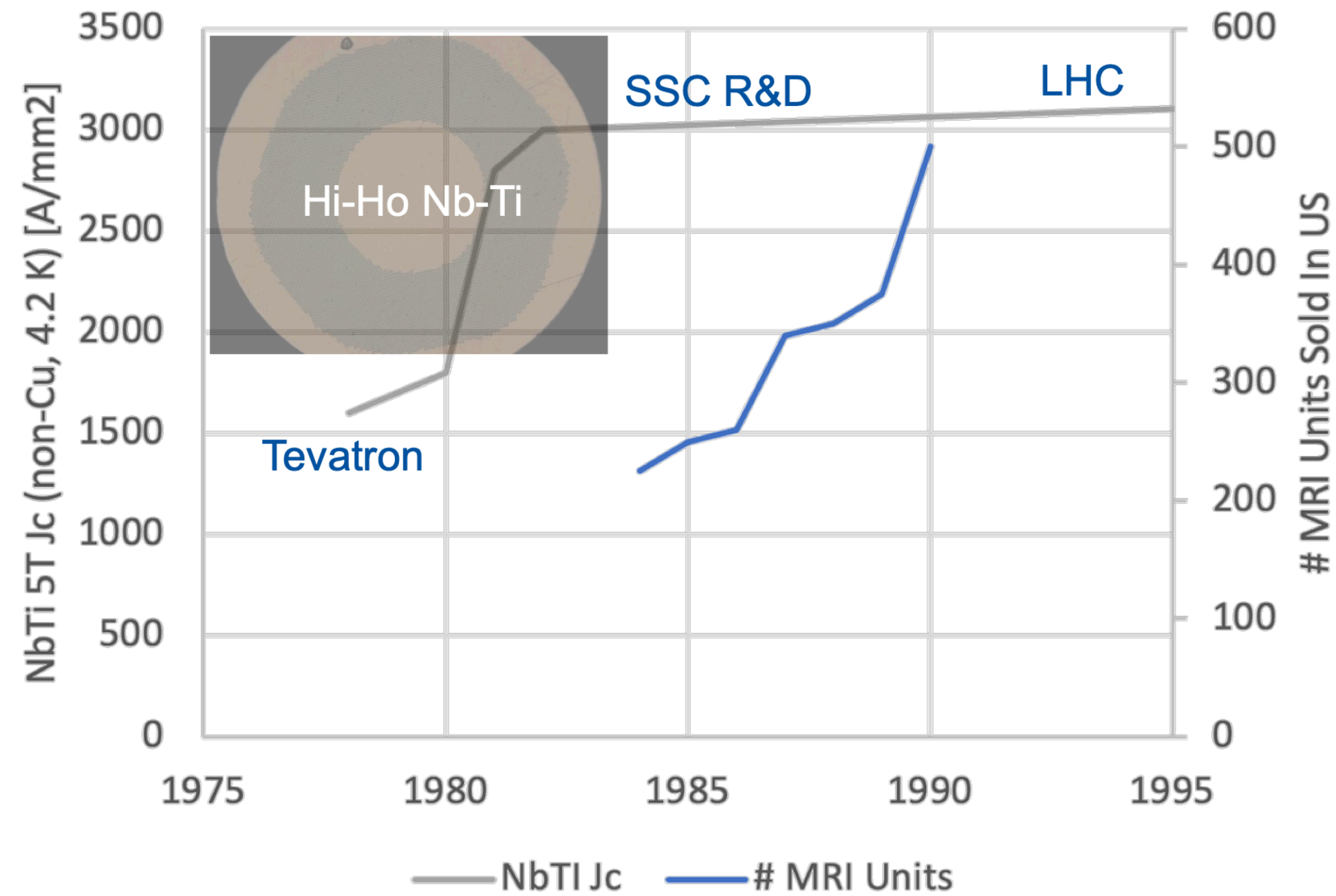


K. Kennedy

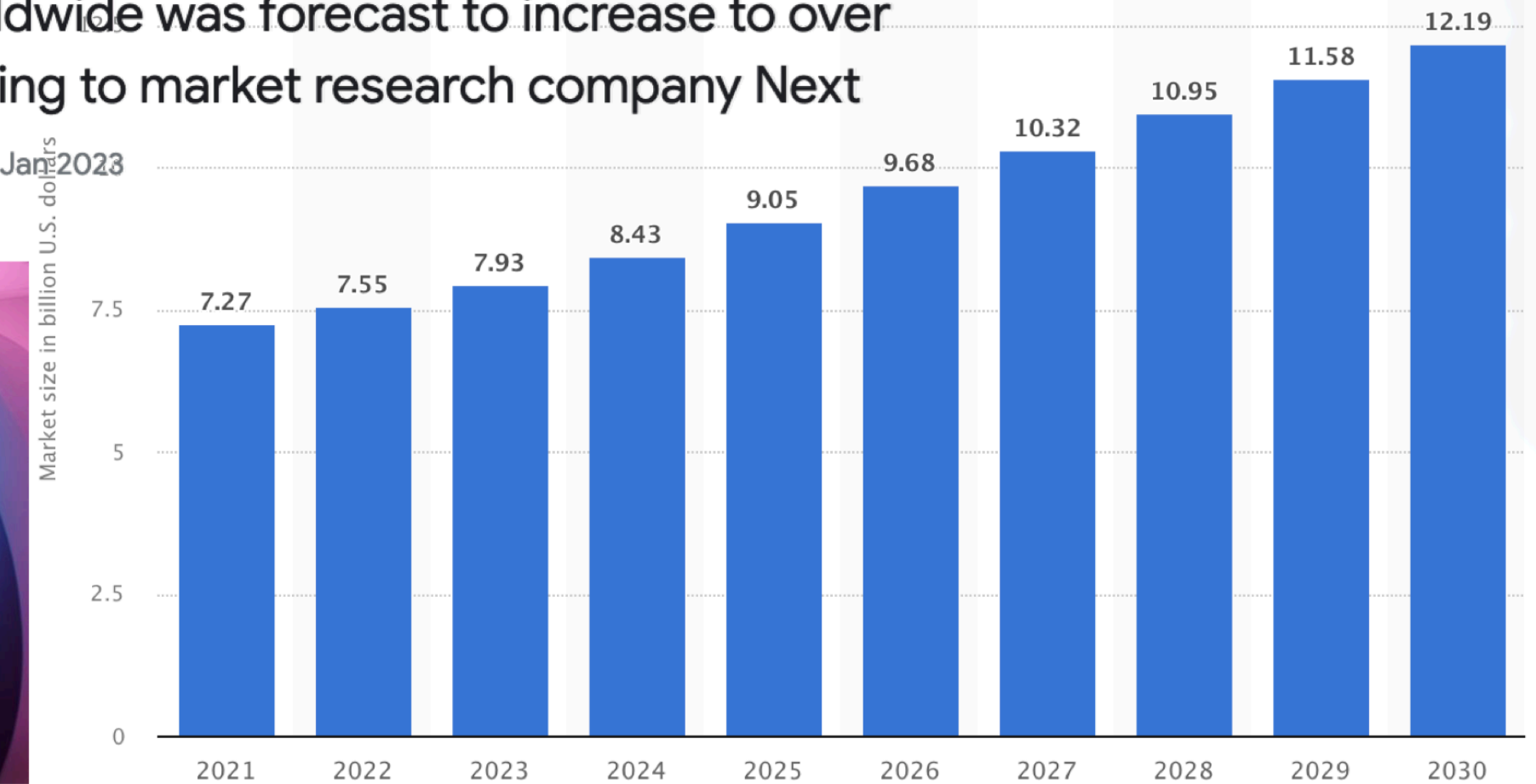
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Fermilab Annual Meeting 2025

TECHNOLOGY SPIN-OFFS: MRIS

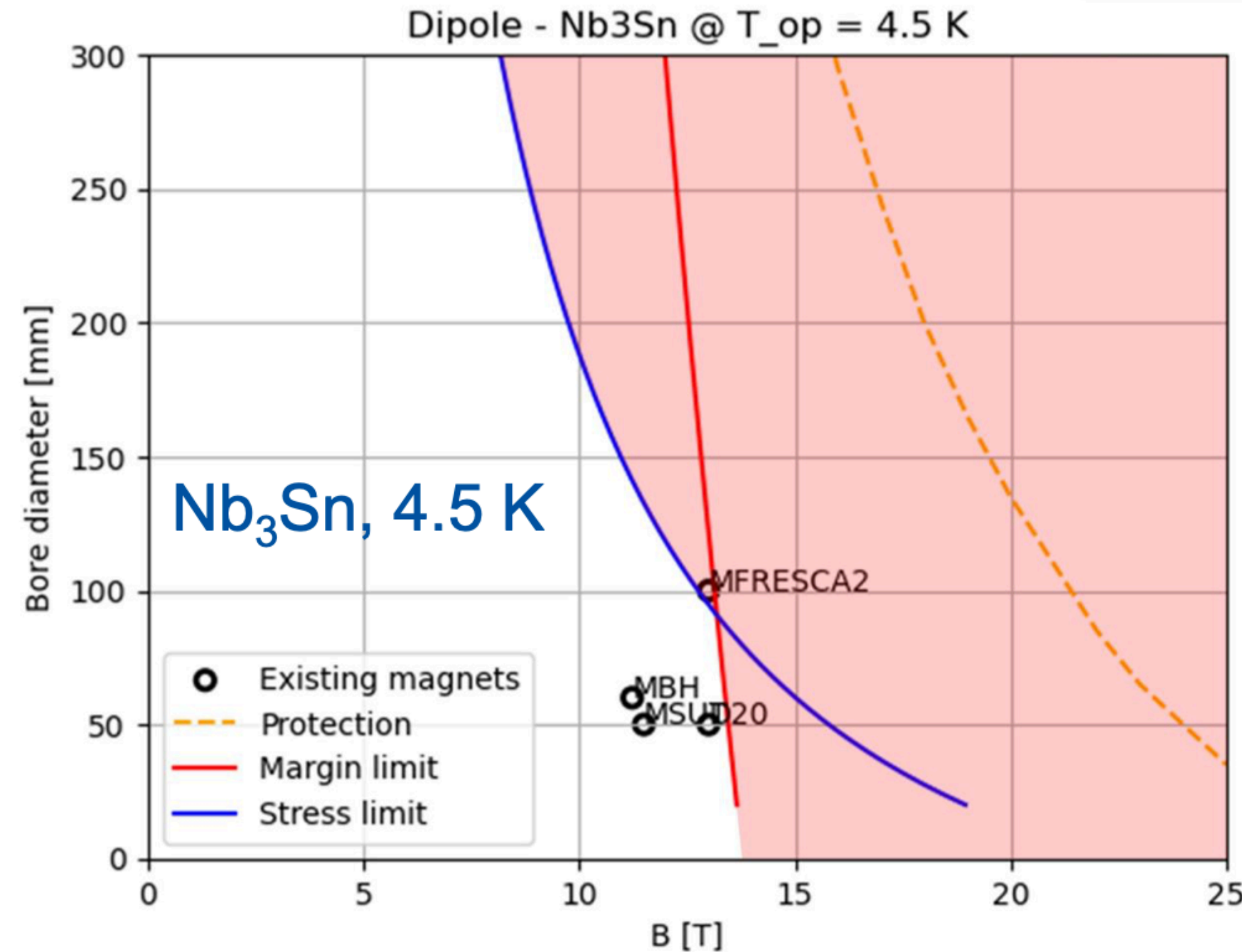


Magnetic resonance imaging (MRI) market size worldwide 2021-2030. In 2021, the global MRI market was worth around 7.3 billion U.S. dollars. By 2030, the MRI market worldwide was forecast to increase to over 12.1 billion U.S. dollars, according to market research company Next Move Strategy Consulting. 20 Jan 2023

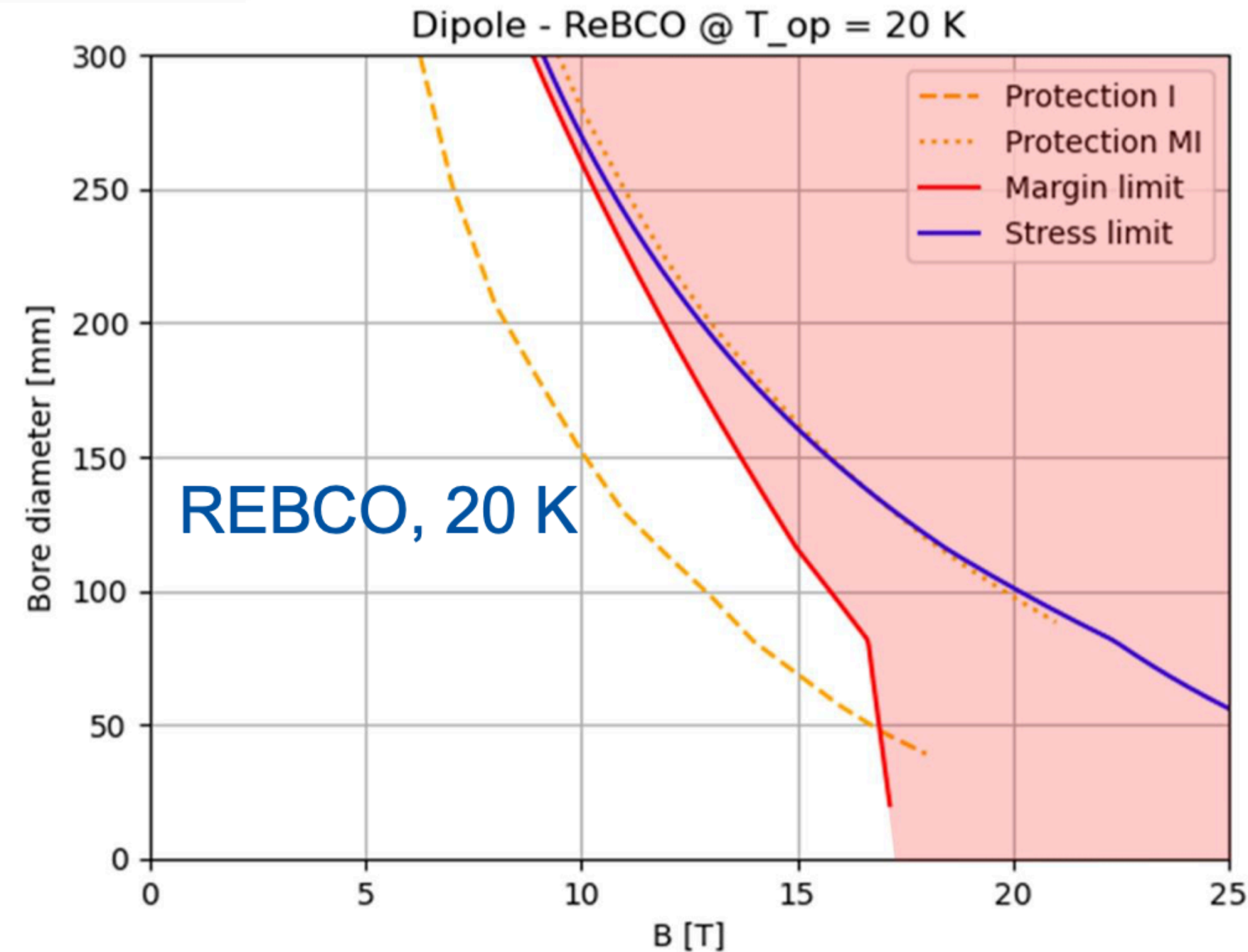


MAGNET LIMITATIONS

A-B plots

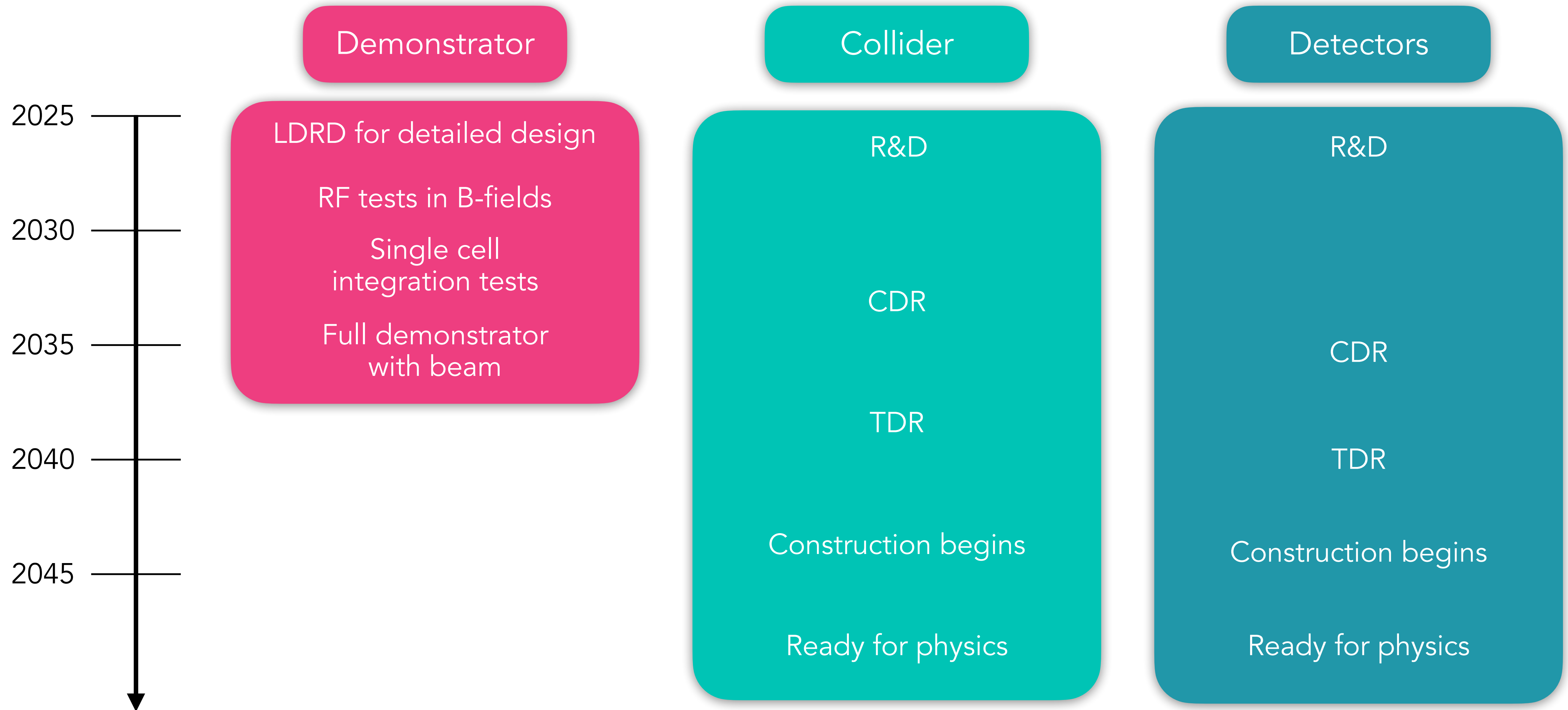


Nb₃Sn performance at 4.5 K is limited by **operating margin** and **peak stress**. There is not much we can do to break these limits



REBCO performance is limited by **quench protection**, NI winding may give the solution, **provided we master it in engineered accelerator magnets**

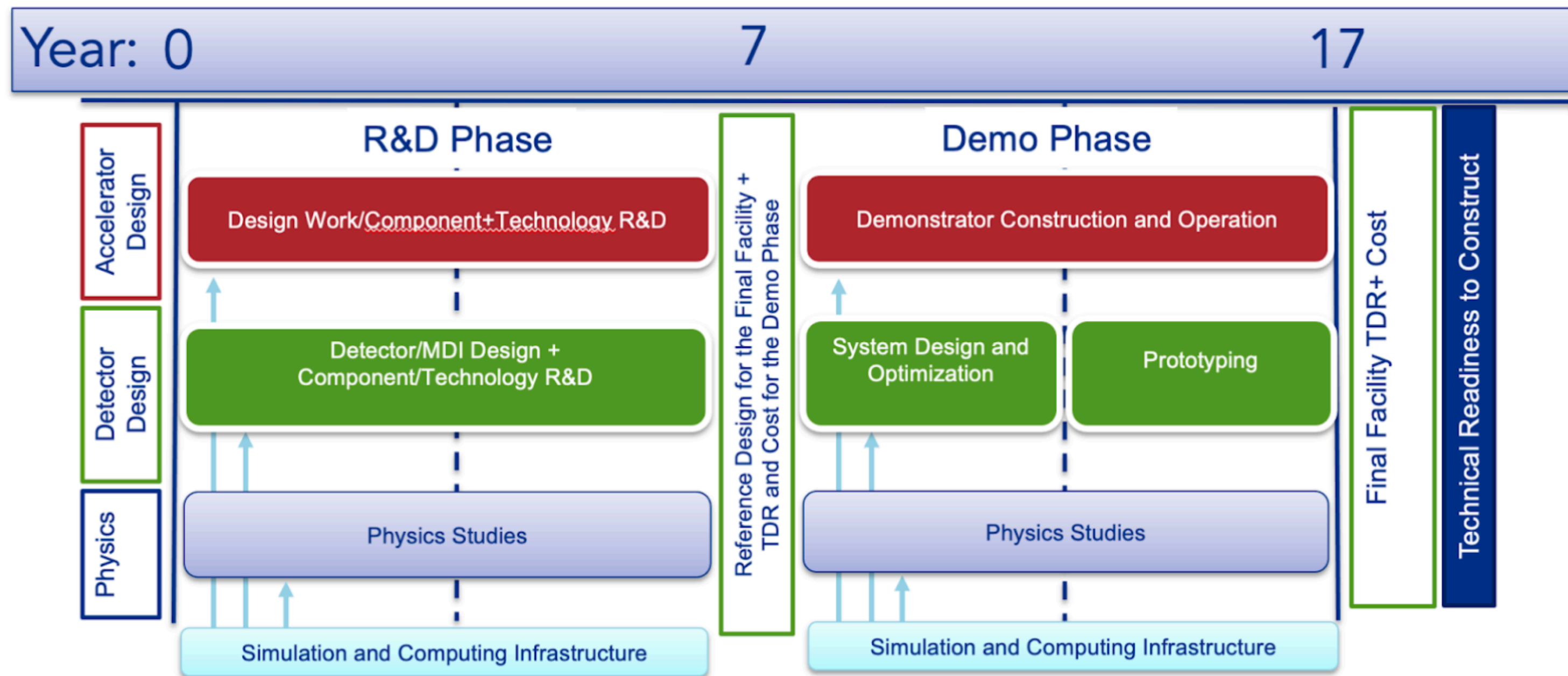
A TECHNICALLY LIMITED TIMELINE SKETCH



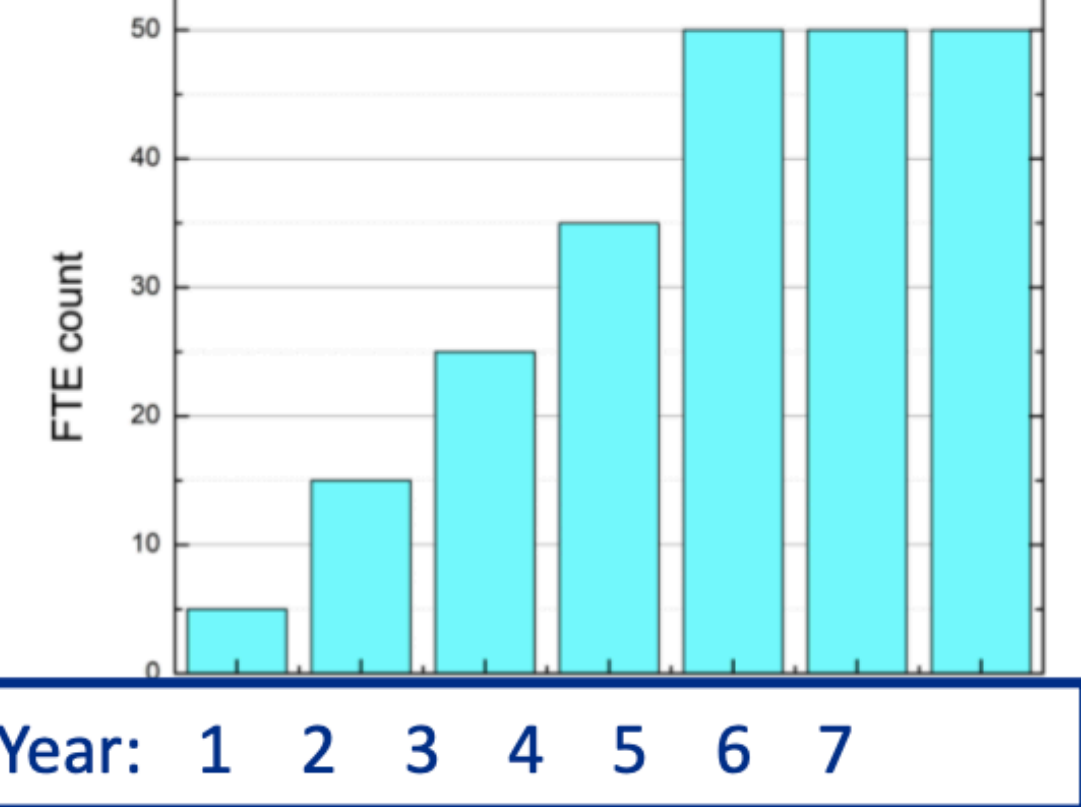
P5 TIMELINE

Potential US timeline shown to P5

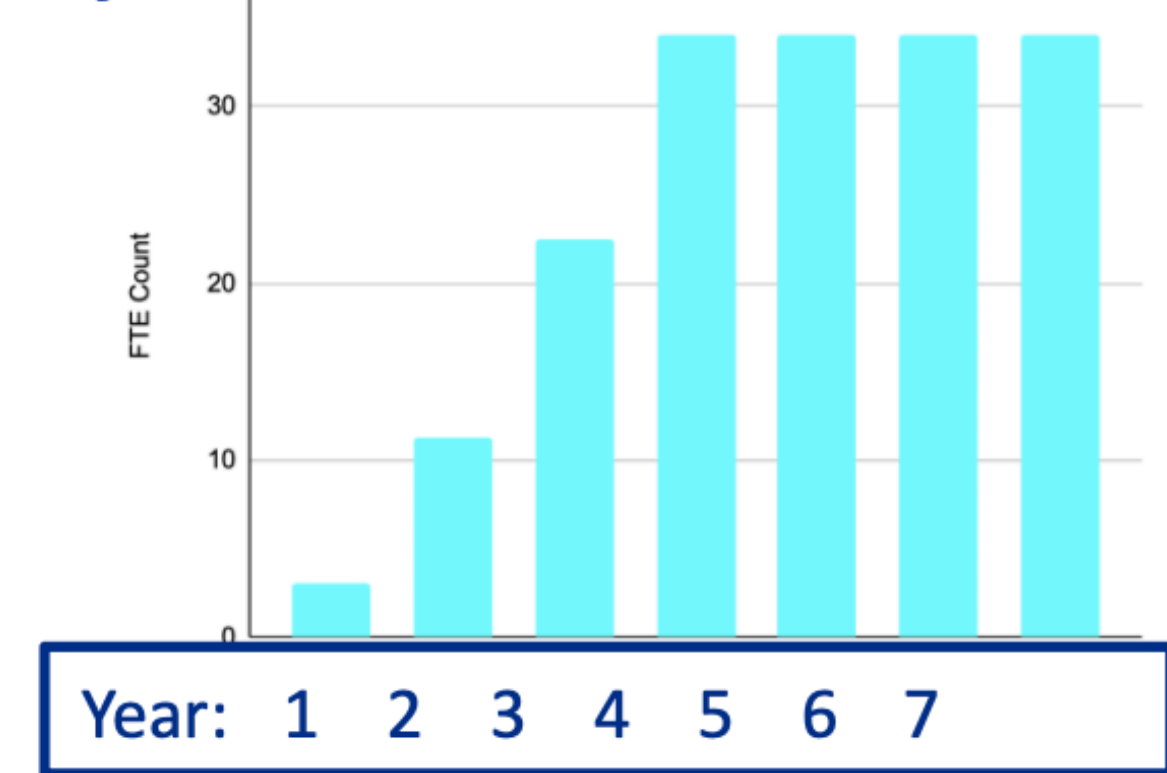
- The timeline is slightly shifted (but not inconsistent) with IMCC timeline due to **US specific budgetary and resource constraints**



Accelerator Labor



Physics and Detector Labor



EUROPEAN STRATEGY TIMELINE

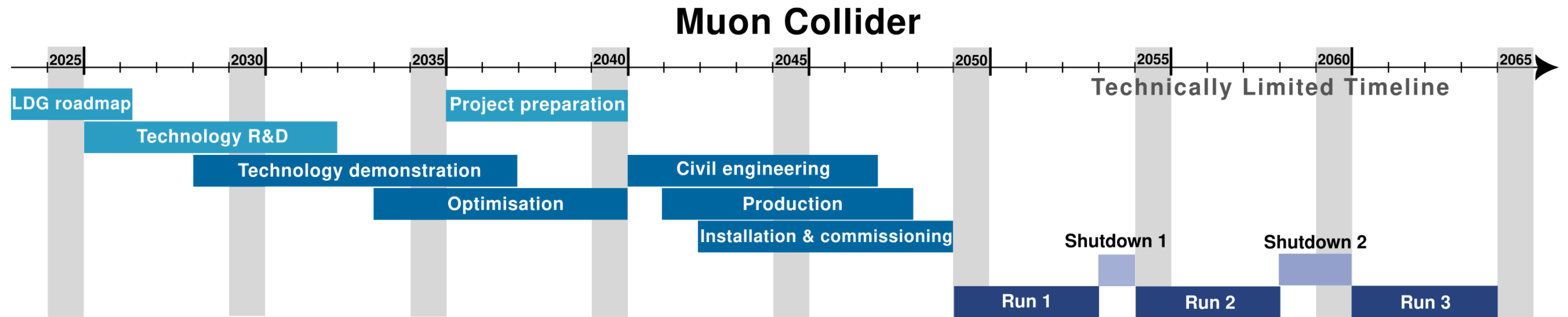


Figure 1.8.1: Technically limited muon collider timeline.

US and European siting have slightly different timing constraints due to interplay with existing projects, but are consistent within error bars

“The [R&D] programme requires approximately 300 MCHF material budget and about 1800 FTEy of personnel for the accelerator and about 20 MCHF and 900 FTEy for detectors. With timely funding, the programme spans about 10 years.”

Most recent technical specs from [“The Muon Collider”](#) (input to ESPPU)

COMPLEMENTARITY WITH HH

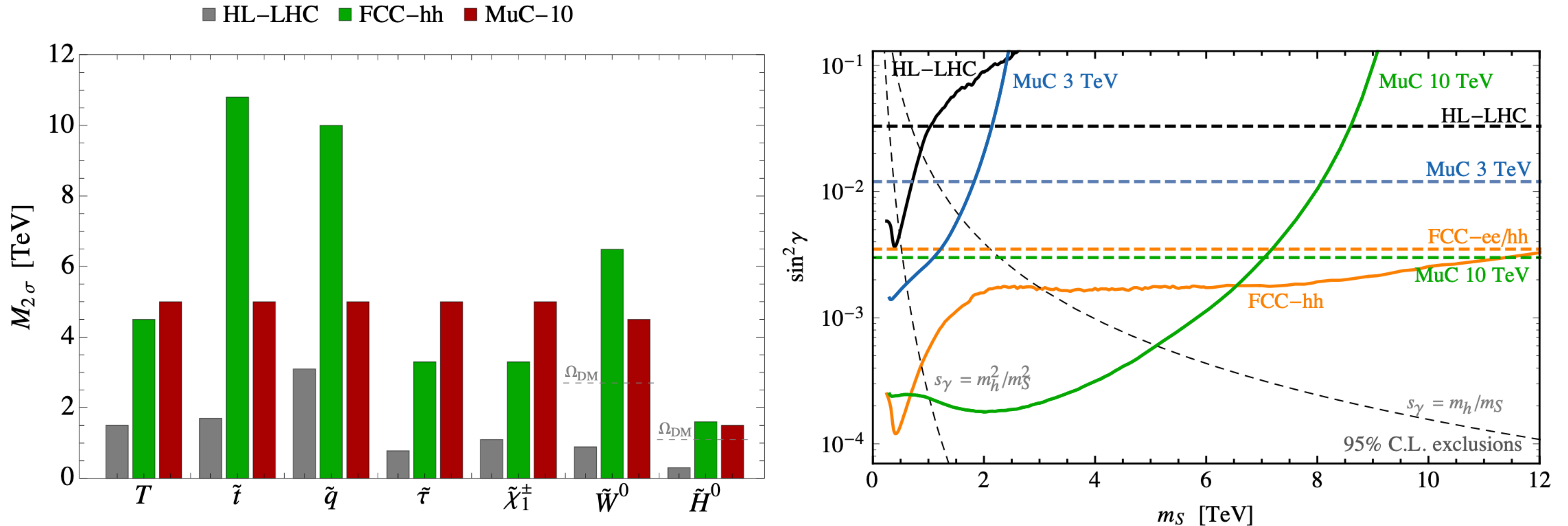


Figure 2.2.2: Left: 95%CL exclusion reach on the mass of several BSM particles at future colliders [13, 80, 82, 199–201]. Only EW pair production is considered to assess the MuC sensitivity. This underestimate the reach in models where single-production is possible (see e.g. [47]). For the wino and the Higgsino, we label as “ Ω_{DM} ” the mass required to reproduce the observed dark matter abundance. Right: exclusion contour [1] for a scalar singlet of mass m_S mixed with the Higgs boson with strength $\sin \gamma$.

Most recent technical specs from “[The Muon Collider](#)” (input to ESPPU)

POWER CONSUMPTION

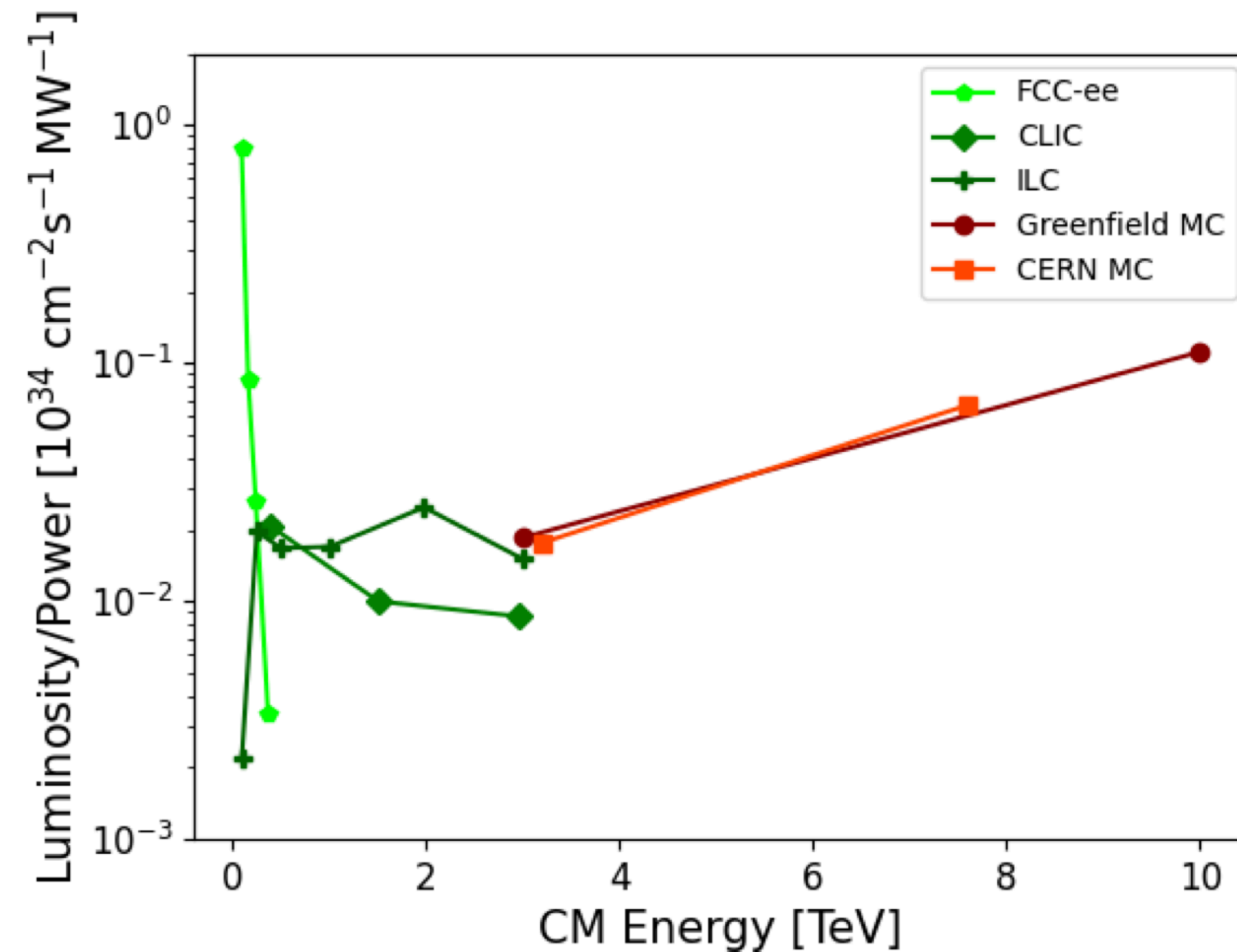


Figure 1.9.1: Ratio of luminosity to wall plug power compared to several e^+e^- machines.

Most recent technical specs from "[The Muon Collider](#)" (input to ESPPU)

STAGING OPTIONS

Table 1.1.1: Tentative target parameters for a muon collider at different energies. Scenario 1 corresponds to Energy Staging, and Scenario 2 corresponds to Luminosity Staging. Both are defined in Section 1.8. The estimated luminosity refers to the value that can be reached if all target specifications can be reached, including beam-beam effects.

Parameter	Symbol	Unit	Scenario 1		Scenario 2	
			Stage 1	Stage 2	Stage 1	Stage 2
Centre-of-mass energy	E_{cm}	TeV	3	10	10	10
Target integrated luminosity	$\int \mathcal{L}_{\text{target}}$	ab^{-1}	1	10	10	10
Estimated luminosity	$\mathcal{L}_{\text{estimated}}$	$10^{34} \text{cm}^{-2} \text{s}^{-1}$	2.1	21	5 (tbc)	14
Collider circumference	C_{coll}	km	4.5	10	15	15
Collider arc peak field	B_{arc}	T	11	16	11	11
Luminosity lifetime	N_{turn}	turns	1039	1558	1040	1040
Muons/bunch	N	10^{12}	2.2	1.8	1.8	1.8
Repetition rate	f_{r}	Hz	5	5	5	5
Beam power	P_{coll}	MW	5.3	14.4	14.4	14.4
RMS longitudinal emittance	ε_{\parallel}	eVs	0.025	0.025	0.025	0.025
Norm. RMS transverse emittance	ε_{\perp}	μm	25	25	25	25
IP bunch length	σ_z	mm	5	1.5	tbc	1.5
IP betafunction	β	mm	5	1.5	tbc	1.5
IP beam size	σ	μm	3	0.9	tbc	0.9
Protons on target/bunch	N_{p}	10^{14}	5	5	5	5
Proton energy on target	E_{p}	GeV	5	5	5	5

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BEAM TARGETS

Table 1.1.2: Tentative target beam parameters along the acceleration chain. A 10 % emittance growth budget has been foreseen in the transverse and longitudinal planes, both for 3 and 10 TeV. This assumes that the technology and tuning procedures will have been improved between the two stages. The very first acceleration is assumed to be part of the final cooling. This choice allows optimisation of the energy in the last absorber with no strong impact on the acceleration chain.

Parameter	Symbol	Unit	Final cooling	at 3 TeV	at 10 TeV
Beam total energy	E_{beam}	GeV	0.255	1500	5000
Muons/bunch	N_b	10^{12}	4	2.2	1.8
Longitudinal emittance	ε_{\parallel}	eVs	0.0225	0.025	0.025
RMS bunch length	σ_z	mm	375	5	1.5
RMS rel. momentum spread	σ_P/P	%	9	0.1	0.1
Transverse norm. emittance	ε_{\perp}	μm	22.5	25	25
Aver. grad. 0.2–1500 GeV	G_{avg}	MV/m	—	2.4	
Aver. grad. 1.5–5 TeV	G_{avg}	MV/m	—		1.1

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DETECTOR TARGETS

Table 1.3.1: Preliminary summary of the “baseline” and “aspirational” targets for selected key metrics for a 10 TeV muon collider.

Requirement	Baseline	Aspirational
Angular acceptance $\eta = -\log(\tan(\theta/2))$	$ \eta < 2.5$	$ \eta < 4$
Minimum tracking distance [cm]	~ 3	< 3
Forward muons ($\eta > 5$)	tag	$\sigma_p/p \sim 10\%$
Track σ_{p_T}/p_T^2 [GeV^{-1}]	4×10^{-5}	1×10^{-5}
Photon energy resolution	$0.2/\sqrt{E}$	$0.1/\sqrt{E}$
Neutral hadron energy resolution	$0.4/\sqrt{E}$	$0.2/\sqrt{E}$
Timing resolution (tracker) [ps]	$\sim 30 - 60$	$\sim 10 - 30$
Timing resolution (calorimeters) [ps]	100	10
Timing resolution (muon system) [ps]	~ 50 for $ \eta > 2.5$	< 50 for $ \eta > 2.5$
Flavour tagging	b vs c	b vs c , s -tagging
Boosted hadronic resonance identification	h vs W/Z	W vs Z

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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



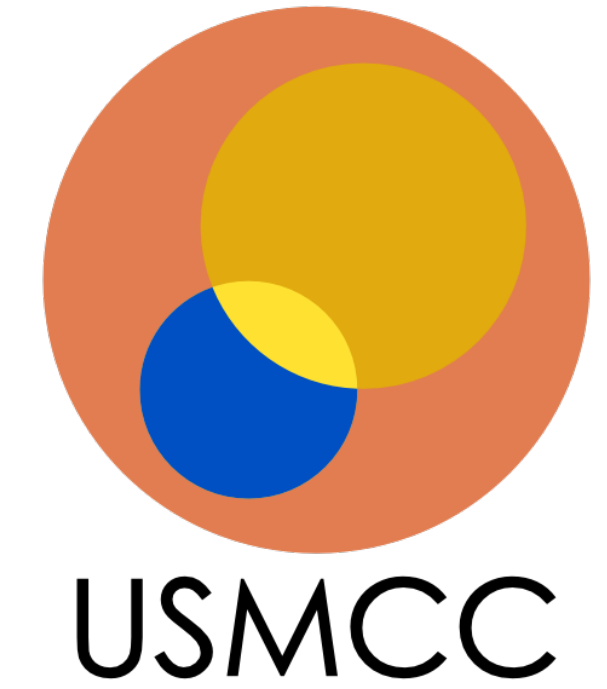
Muon Collider Challenges and Progress

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 processes ($\mu 2e$, $\mu 2e\gamma$, $\mu 3e$, etc)	MW class proton source, muon production and collection, storage ring
Beam dump experiments	Searches for exotic particles (dark photons, $L\mu$ - $L\tau$, 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

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will soon also begin naming members of a broader leadership strategy group