Future Colliders

Outcomes from Snowmass & Options for the US

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University of Chicago
Rencontres du Vietnam
11 August 2023

Future Colliders at Snowmass

A biased viewpoint

Developing a Strategic Plan

Snowmass Community Planning Exercise: define important questions for the field and identify promising opportunities to address them

Input to Particle Physics Project Prioritization Panel (P5): define a 10 year strategy, in the context of a 20-year global vision, with realistic budget scenarios

Important Questions

2014 Particle Physics Science Drivers

- Nature of the Higgs Boson
- Nature of neutrinos
- Dark Matter
- Origin, evolution, and stability of the Universe
- New particles, interactions, and physics principles

For the Energy Frontier

What changed since the previous P5

- Completion of LHC Run 2 at $\sqrt{s}$=13 TeV
- We've begun to measure Higgs properties with increasing precision
- No sign of Beyond the Standard Model Physics at LHC (or elsewhere)
- High Luminosity LHC is an approved project

What we knew going into Snowmass

- Nature is more complex than we expected
- We need to start planning for a future beyond the HL-LHC

Less clear

- What future collider(s) should we build?
- How can we convey the necessity of future colliders to ourselves, other scientists, and the public

Energy Frontier Conveners

Meenakshi Narain

Laura Reina

Alessandro Tricoli

The unique power of colliders

Most powerful tool to directly explore the smallest scales

The only place we can answer key questions raised by the Higgs discovery

What is preventing m_h from being pulled up to Plank scale?

New symmetry, new particles?

Composite Higgs, like the pion?

Does the Higgs interact with other particles as expected?

Couplings modified by new physics?

Implications for flavor, dark matter?

What is the Higgs potential realized in nature?

Does the Higgs self-interact?

Electroweak phase transition?

Connections to origin, evolution & stability of universe

What we'll learn at the HL-LHC

ATL-PHYS-PUB-2022-018

Explore the TeV scale with unprecedented luminosity

Tease out any rare processes/unconventional signatures

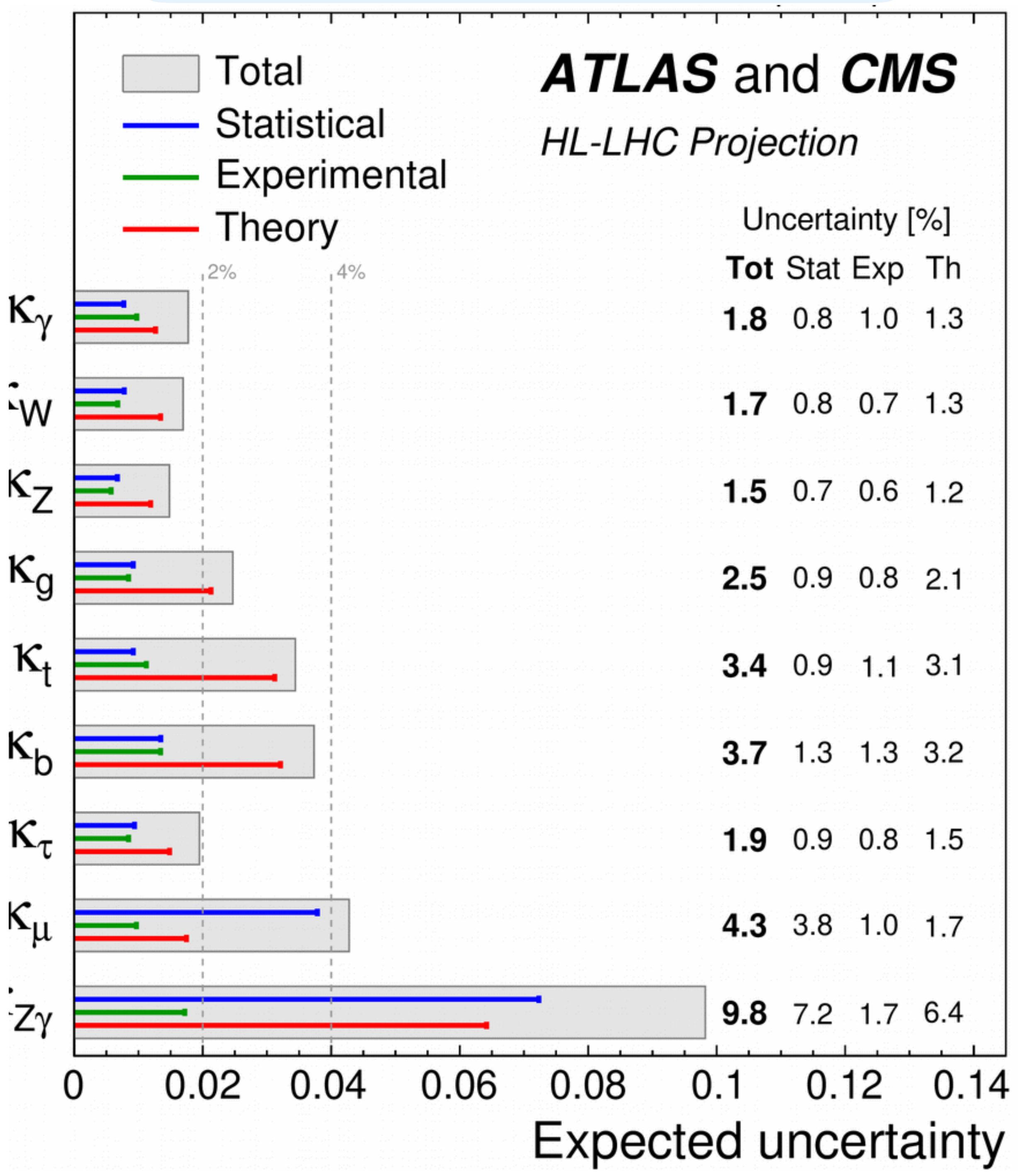
Put the Higgs under a microscope

M_h: 125 GeV ± 20 MeV

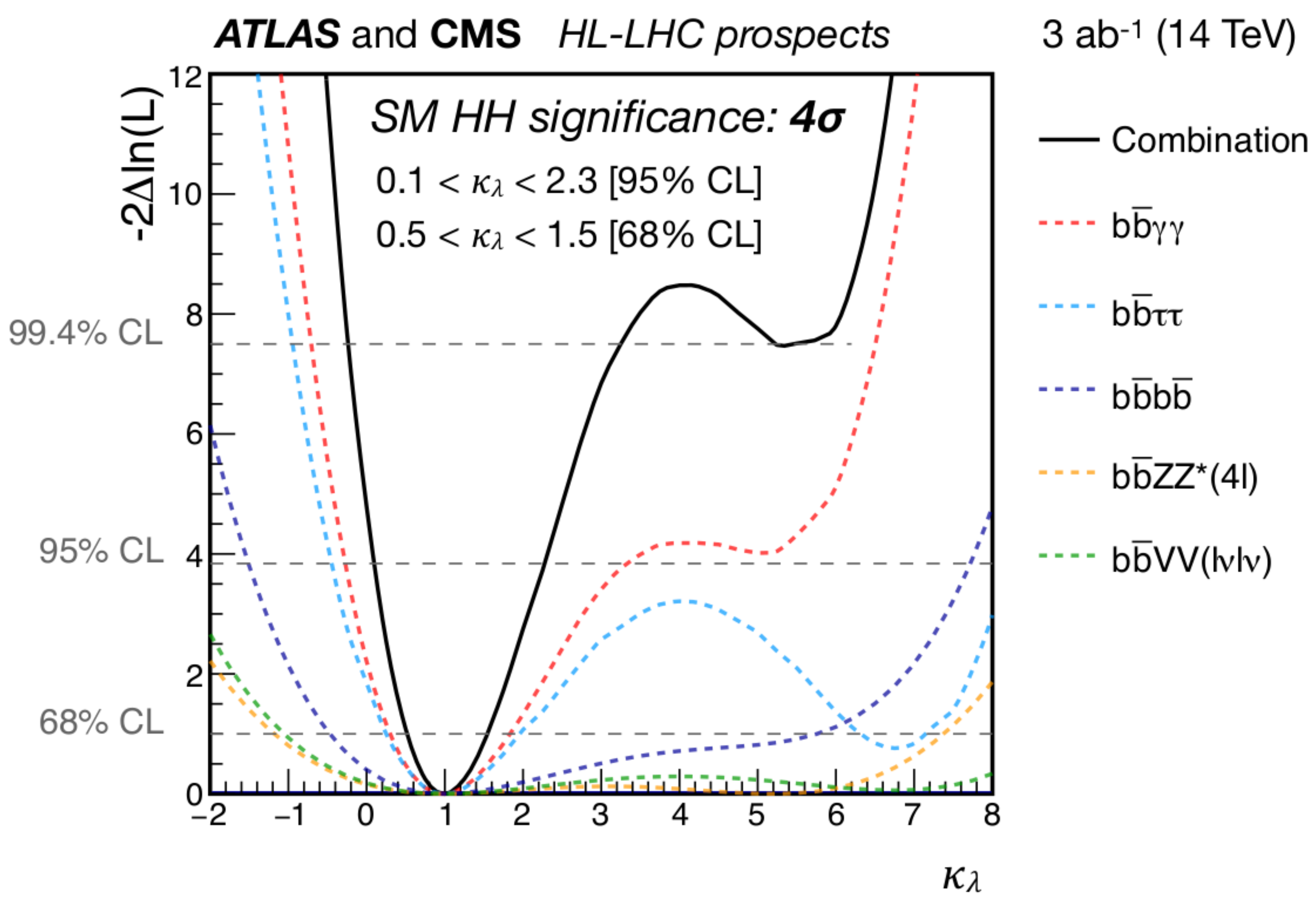
Γ_h : 4 MeV ± 5/20%
(model dependent)

Br(h→inv): < 5%

Couplings: ~few%



Self-coupling λ : ~50%



Higgs couplings

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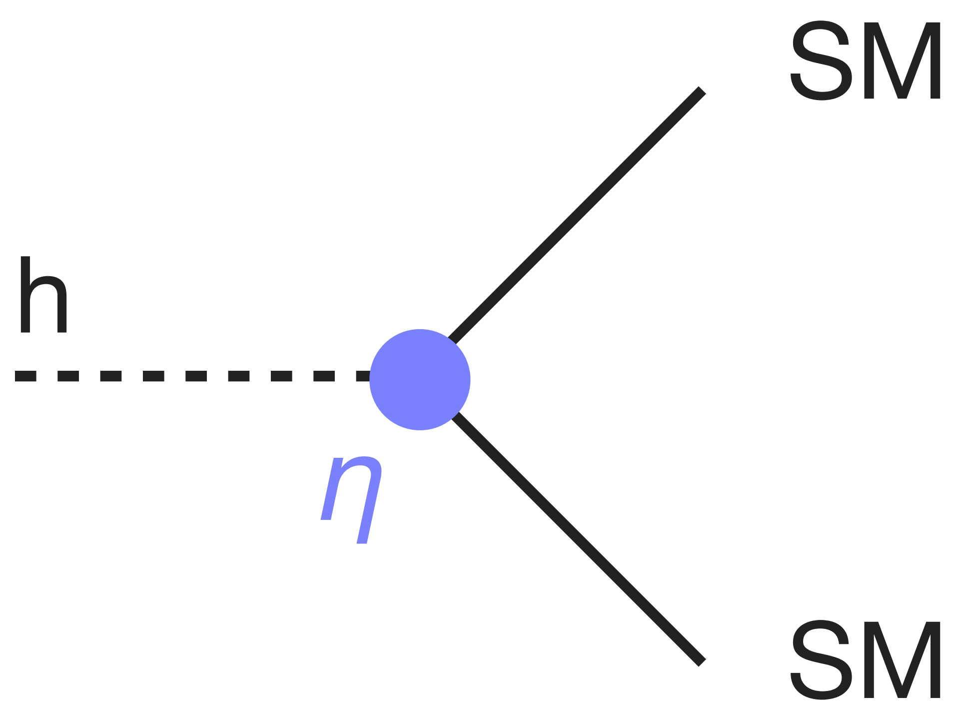
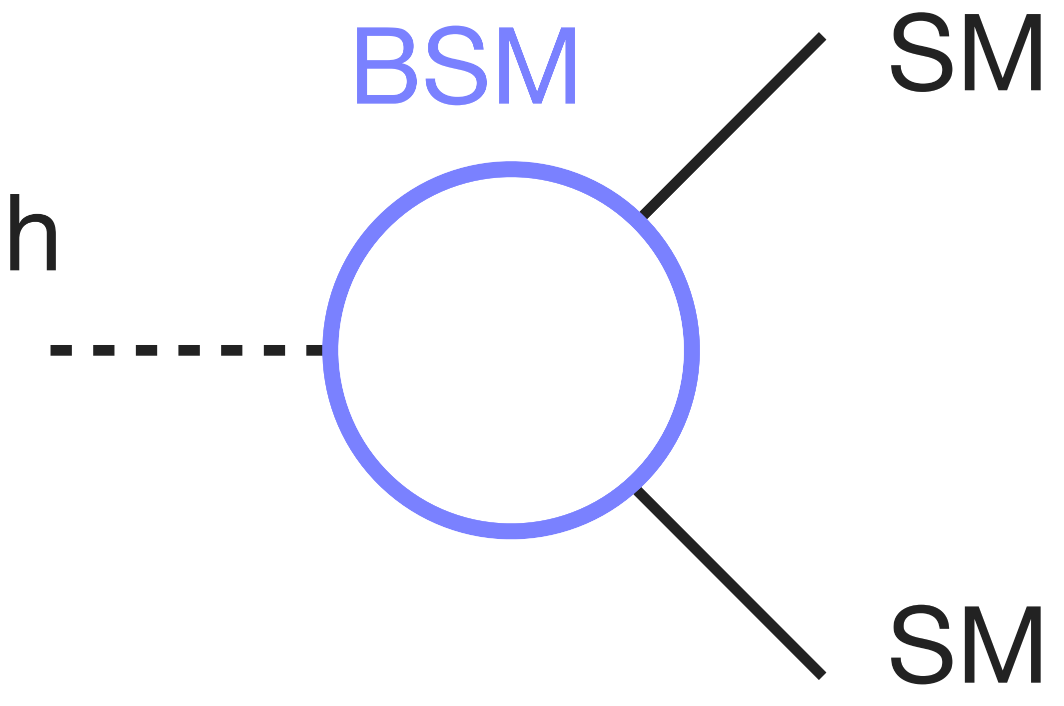
Indirectly probe BSM Physics at higher scales

Order of magnitude improvement requires ~1 million Higgs Bosons in a clean environment

Fastest way to do this is a 240 GeV e^+e^- Higgs Factory



$$\Delta\eta \sim \frac{v^2}{M^2}$$



For specific BSM scenarios

$$\Delta\eta \sim 1\,\% \longrightarrow 0.4 < M < 5.5 \text{ TeV}$$

$$\Delta\eta \sim 0.1\,\% \longrightarrow 0.1 < M < 1.7 \text{ TeV}$$

Does not necessarily exceed constraints from direct LHC searches
Ultimately we'll need to directly probe multi-TeV scale

Higgs potential

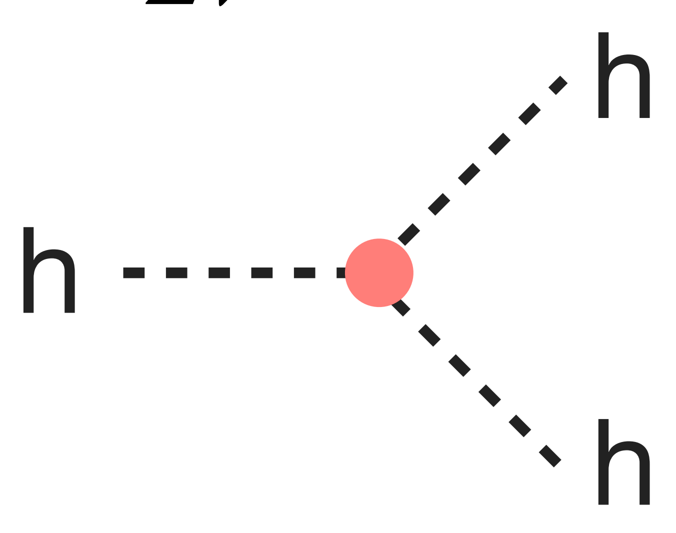
R. Petrossian-Byrne & N. Craig

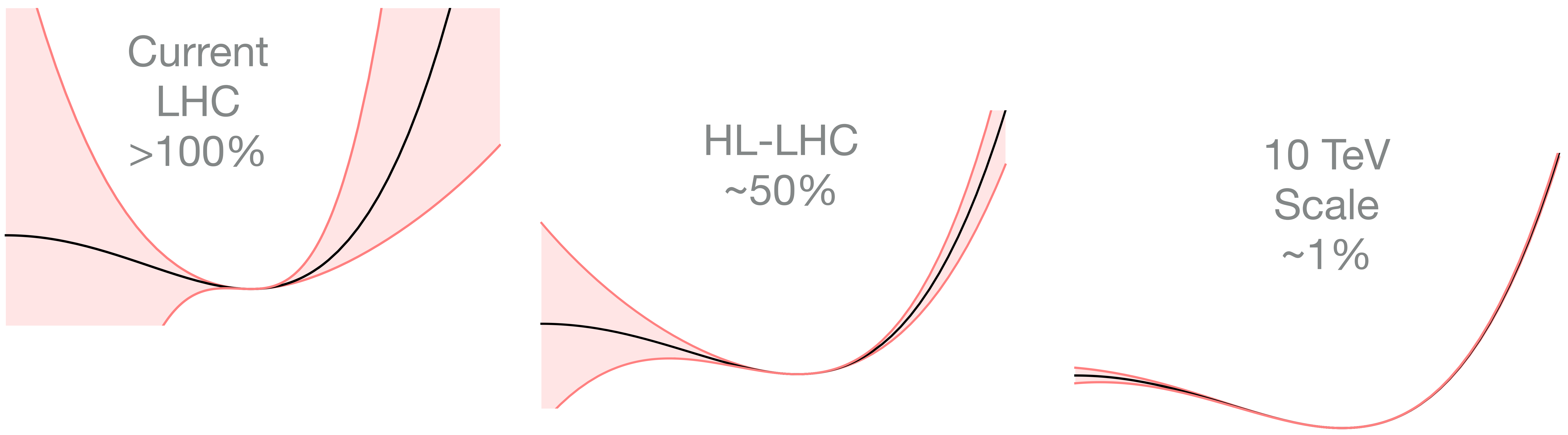
Meaningful tests towards understanding origin & stability of the universe

Is electroweak symmetry restored at high energies? Was there a phase transition?

Requires measuring Higgs self-coupling λ with few % uncertainty

$$\lambda = \frac{m_h^2}{2v^2}$$



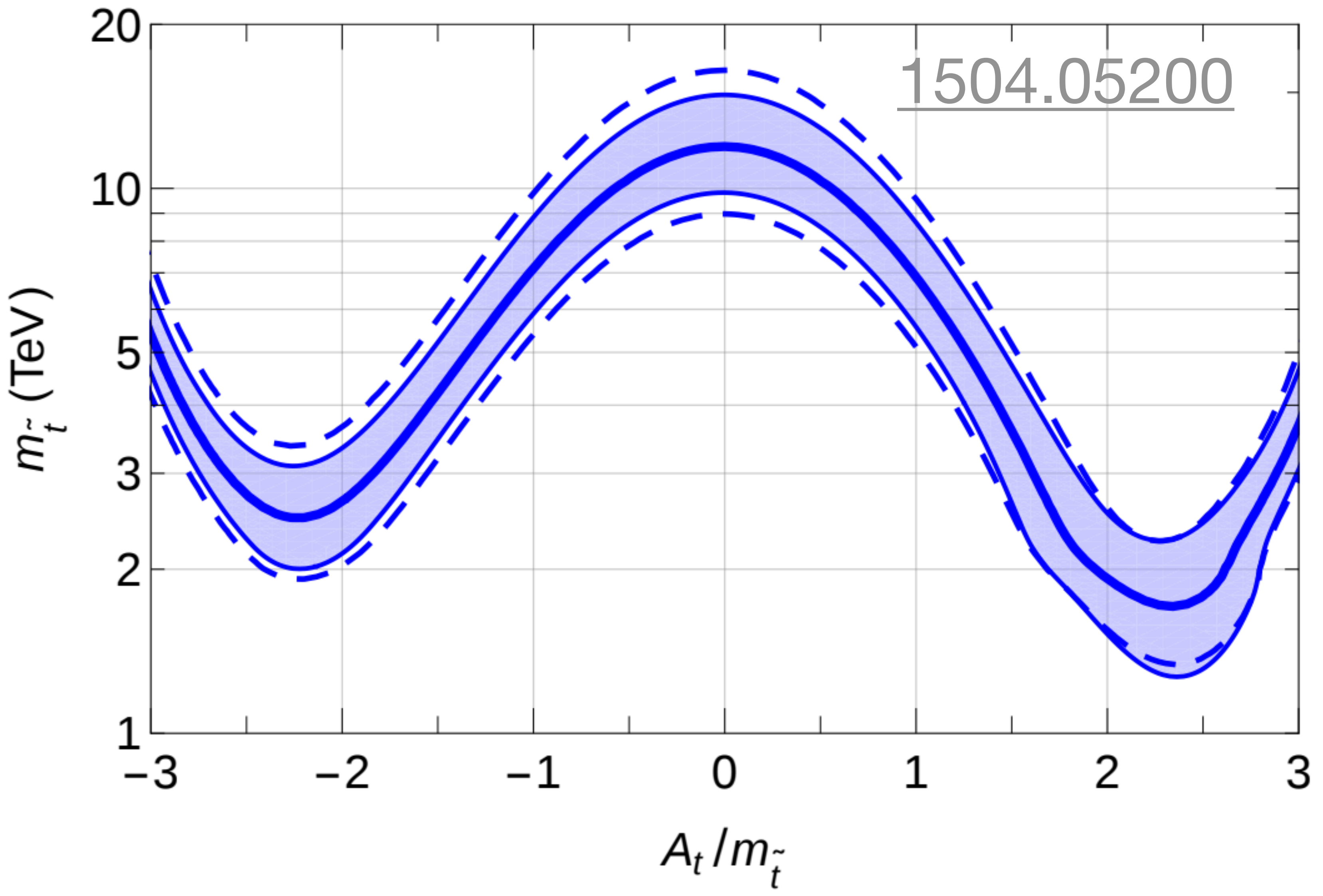


Producing enough multi-Higgs events <u>is only possible at a 10 TeV scale collider</u>

New Physics?

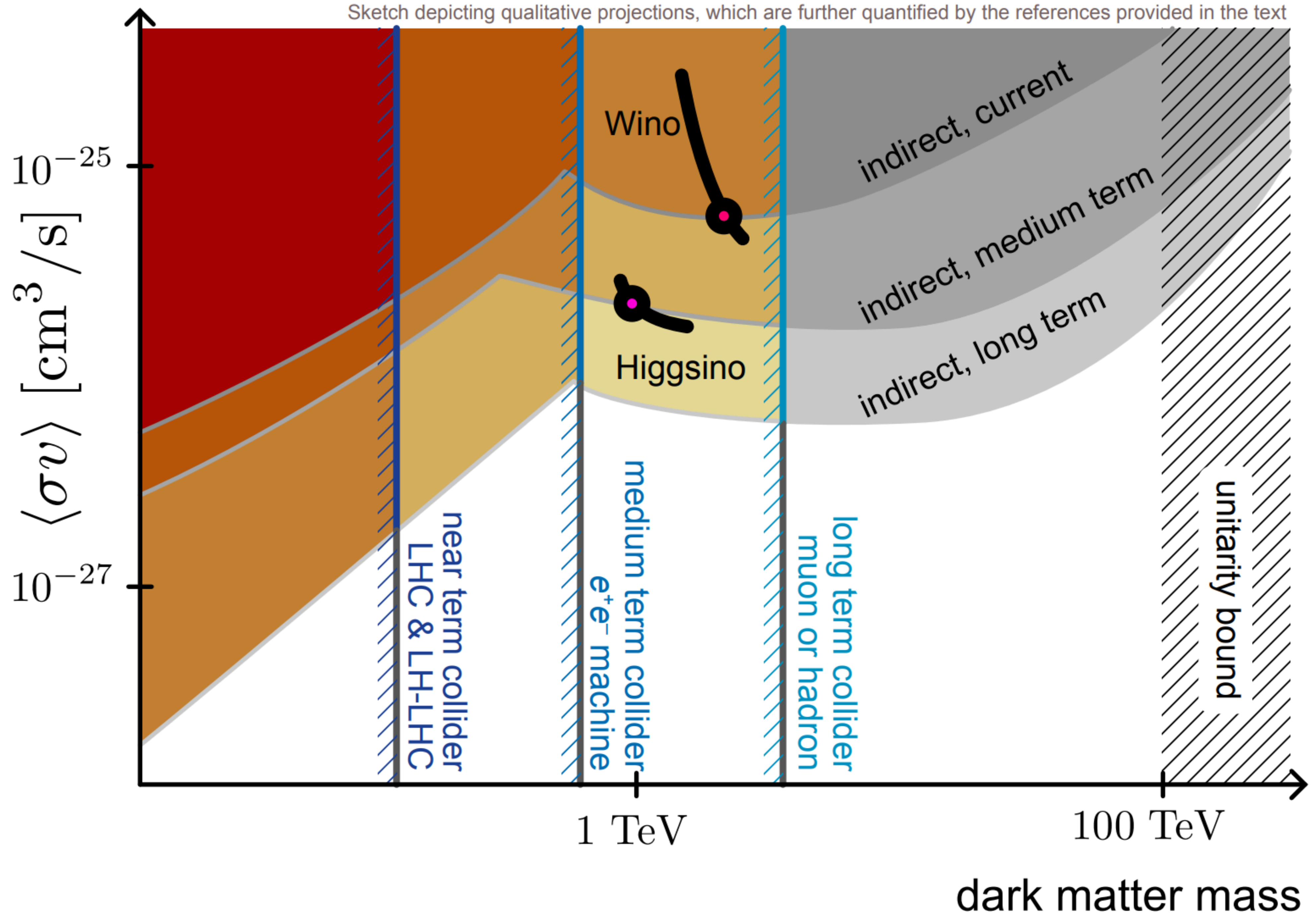
Simplest top down & bottom up approaches both require going to the 10 TeV scale or higher

Observed m_h sets direct targets for Supersymmetry



m_h =125 GeV
→ multi-TeV top-partners

WIMP dark matter



Pure Higgsino DM
is under neutrino floor!

How to get to higher energies

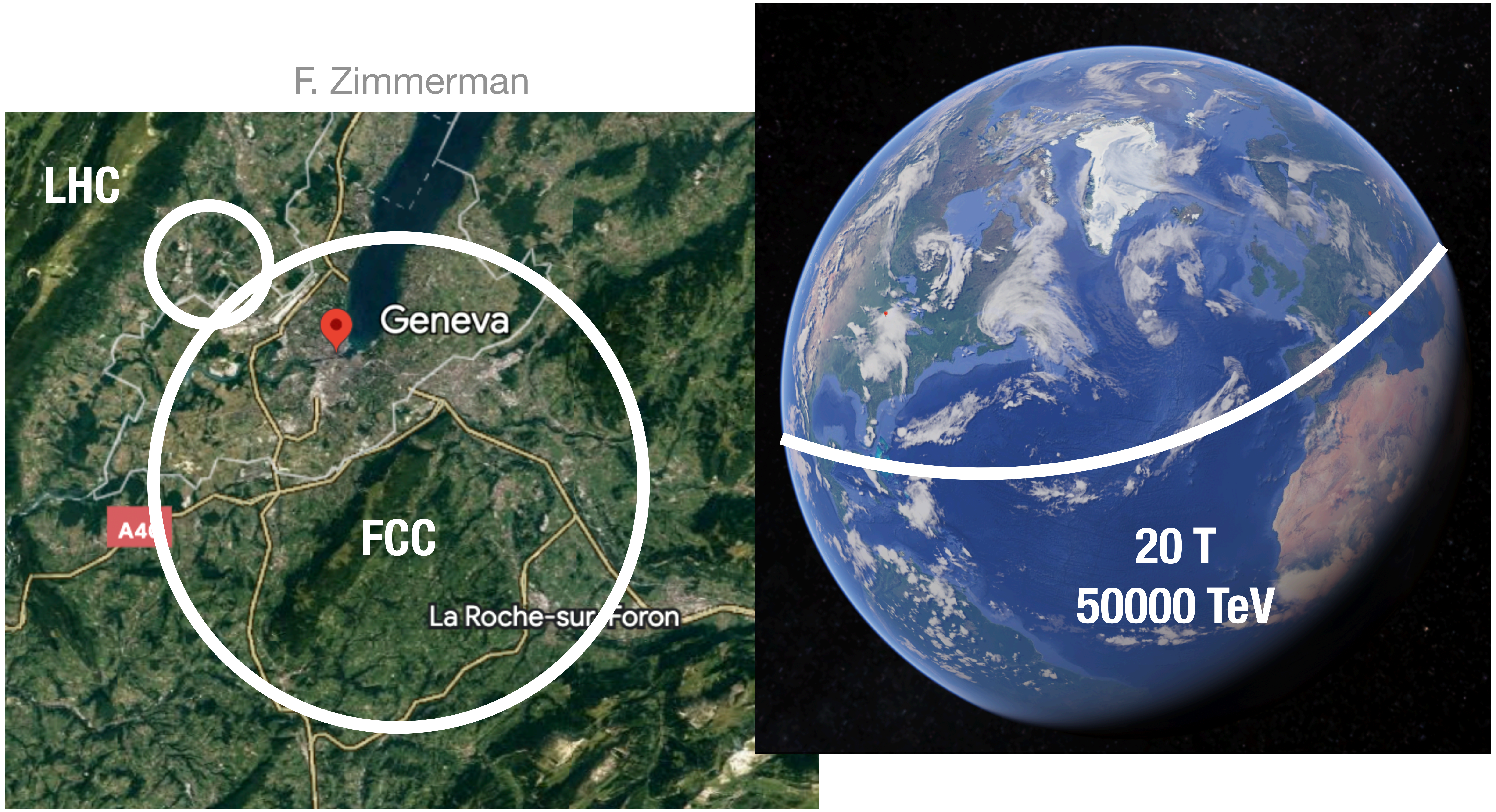
For a fixed technology
→ go bigger

$$E_{\text{beam}} \sim 0.3 \cdot R \cdot B_{\text{dipole}}$$

For 100 TeV pp-collisions

LHC NbTi	8 T	190 km
Record NbSn3	15 T	100 km
Future HTS	20 T	80 km

F. Zimmerman



However, even with next generation magnets we're approaching the limit of acceptable footprints, power consumption & costs

Or take a risk on new technology?

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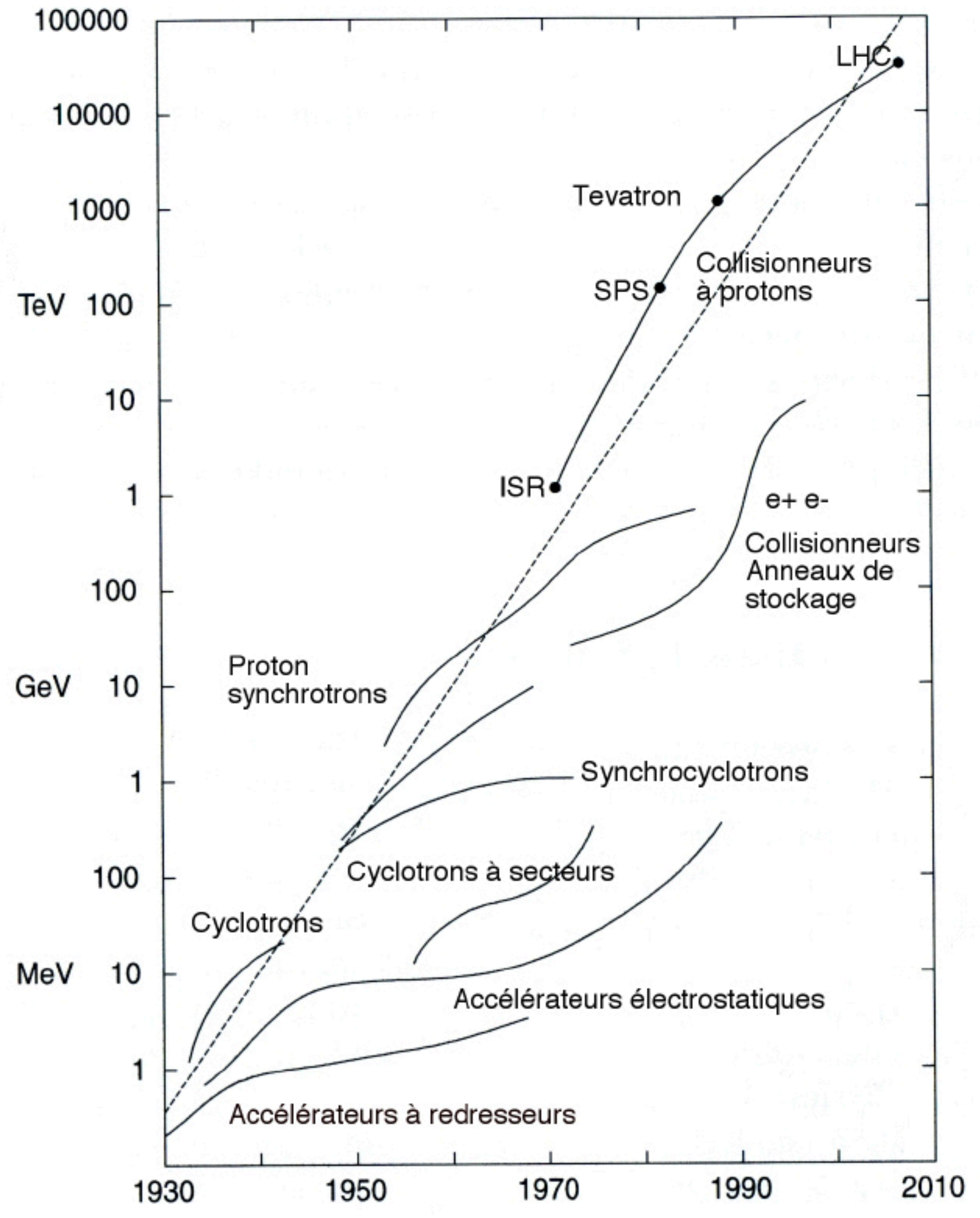
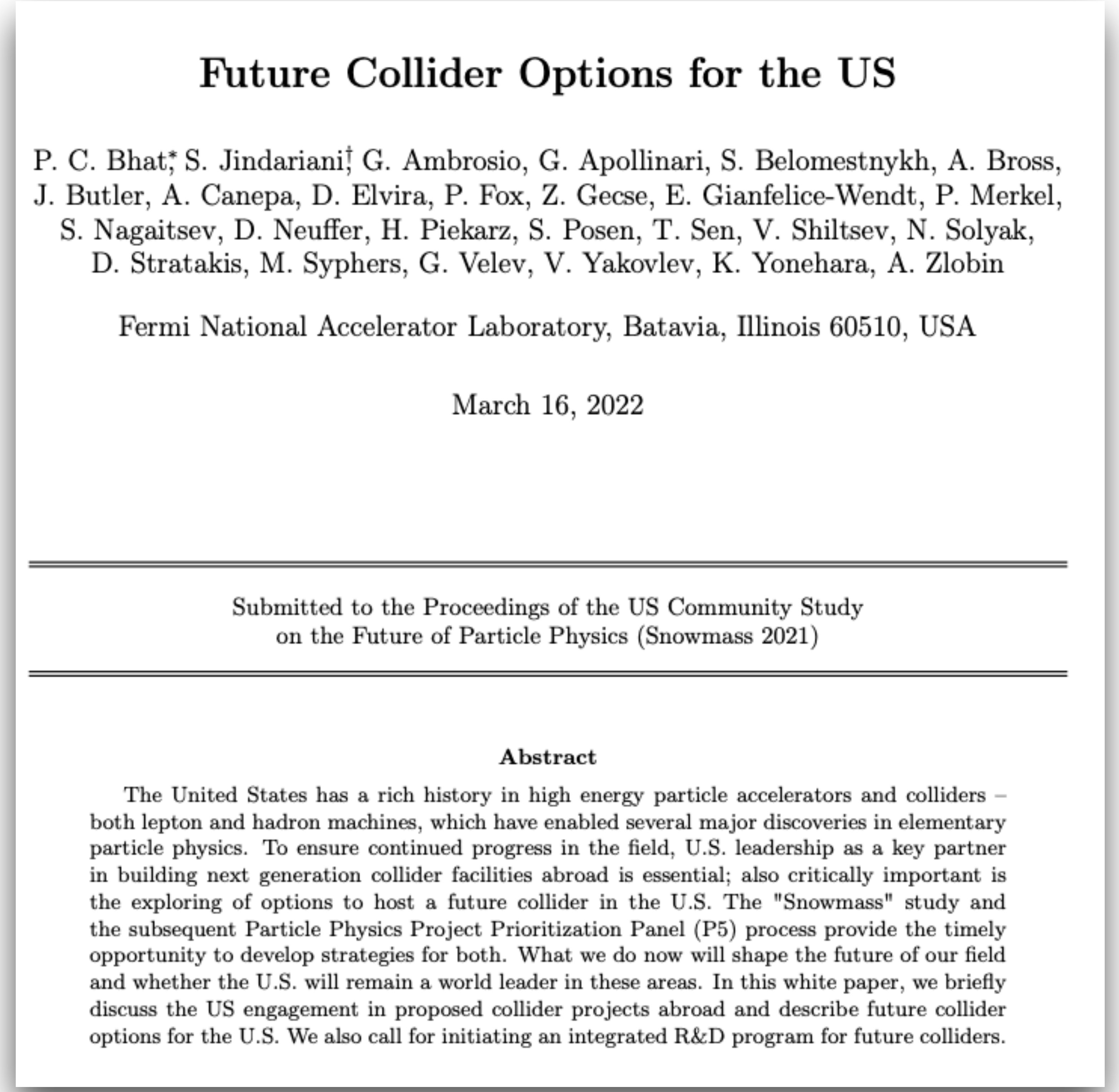
Enable breakthroughs with compact & power efficient options

Potential to bring the energy frontier back to US!





Future Collider Options for the US

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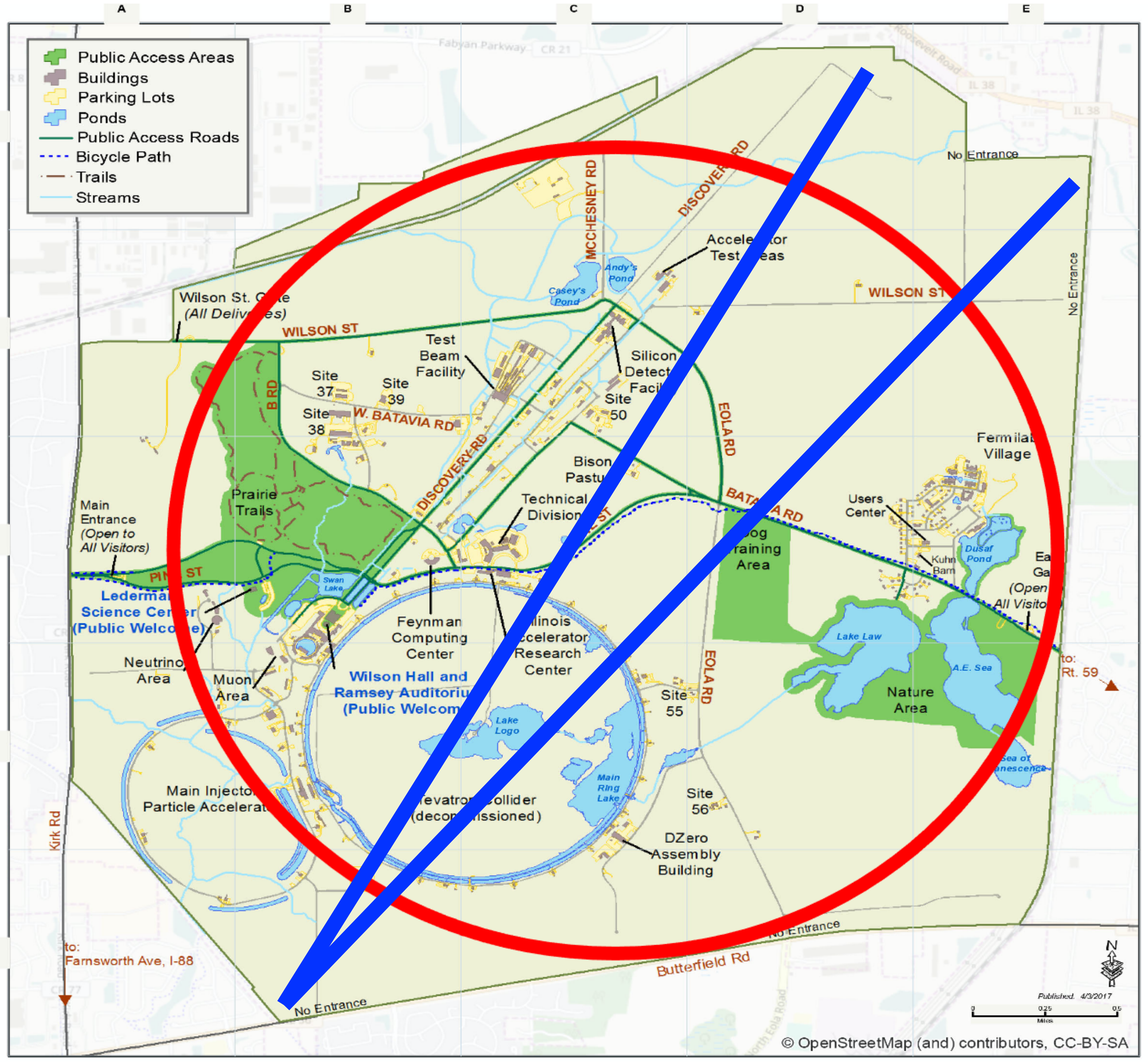
Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

March 16, 2022

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

Abstract

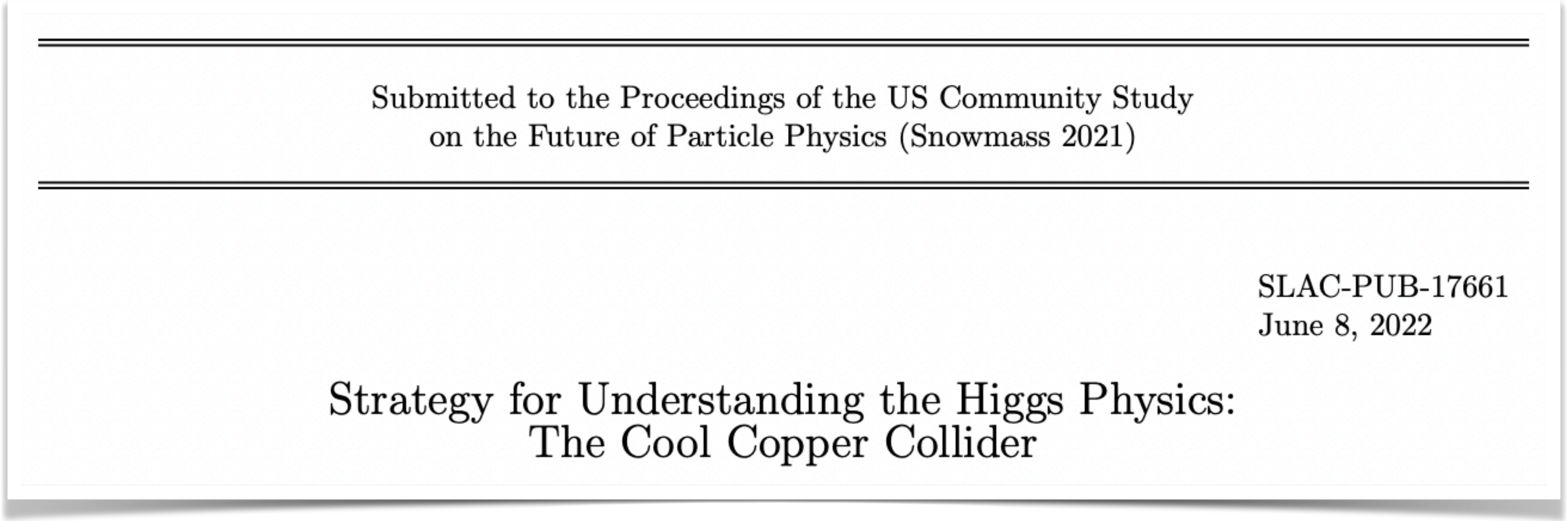
The United States has a rich history in high energy particle accelerators and colliders – both lepton and hadron machines, which have enabled several major discoveries in elementary particle physics. To ensure continued progress in the field, U.S. leadership as a key partner in building next generation collider facilities abroad is essential; also critically important is the exploring of options to host a future collider in the U.S. The "Snowmass" study and the subsequent Particle Physics Project Prioritization Panel (P5) process provide the timely opportunity to develop strategies for both. What we do now will shape the future of our field and where the U.S. will remain a world leader in these areas. In this white paper, we briefly discuss the US engagement in proposed collider projects abroad and describe future collider options for the U.S. We also call for initiating an integrated R&D program for future colliders.



Cool Copper Collider

2203.07646

- Normal conducting cavities, specifically optimized for efficiency
- Key: structure distributing power to each accelerating cell in parallel from a common RF manifold
- Liquid nitrogen is sufficient! Potentially cheaper, much easier
- Demonstrated gradients
  - peak 150 MV/m on small scale
  - robust at 120 MV/m


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

SLAC-PUB-17661
June 8, 2022

Strategy for Understanding the Higgs Physics:
The Cool Copper Collider

Multi-TeV Muon Collider

2209.01318

- Breaks paradigm of larger and larger e+e- and pp colliders
- Massive, fundamental particles:
  - 10 TeV $\mu^+\mu^-$ ~ 100 TeV pp
  - No synchrotron radiation ($1/m^4$)
  - →Compact and power efficient

Muon Collider Forum Conveners

Energy Frontier: Kevin Black, Sergo Jindariani

Accelerator: Derun Li, Diktys Stratakis

Theory: Fabio Maltoni, Patrick Meade

International MUON Collider Collaboration

Cross-Frontier Report Submitted to the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Prepared for submission to JINST

Muon Collider Forum Report

In memory of Meenakshi Narain, a friend and a colleague, who passed away on January 1, 2023. She fought tirelessly so that the next generation of particle physicists could continue the quest to discover the underlying laws of the universe. Her vision and support ensured the creation of the forum and this report. She will be deeply missed.

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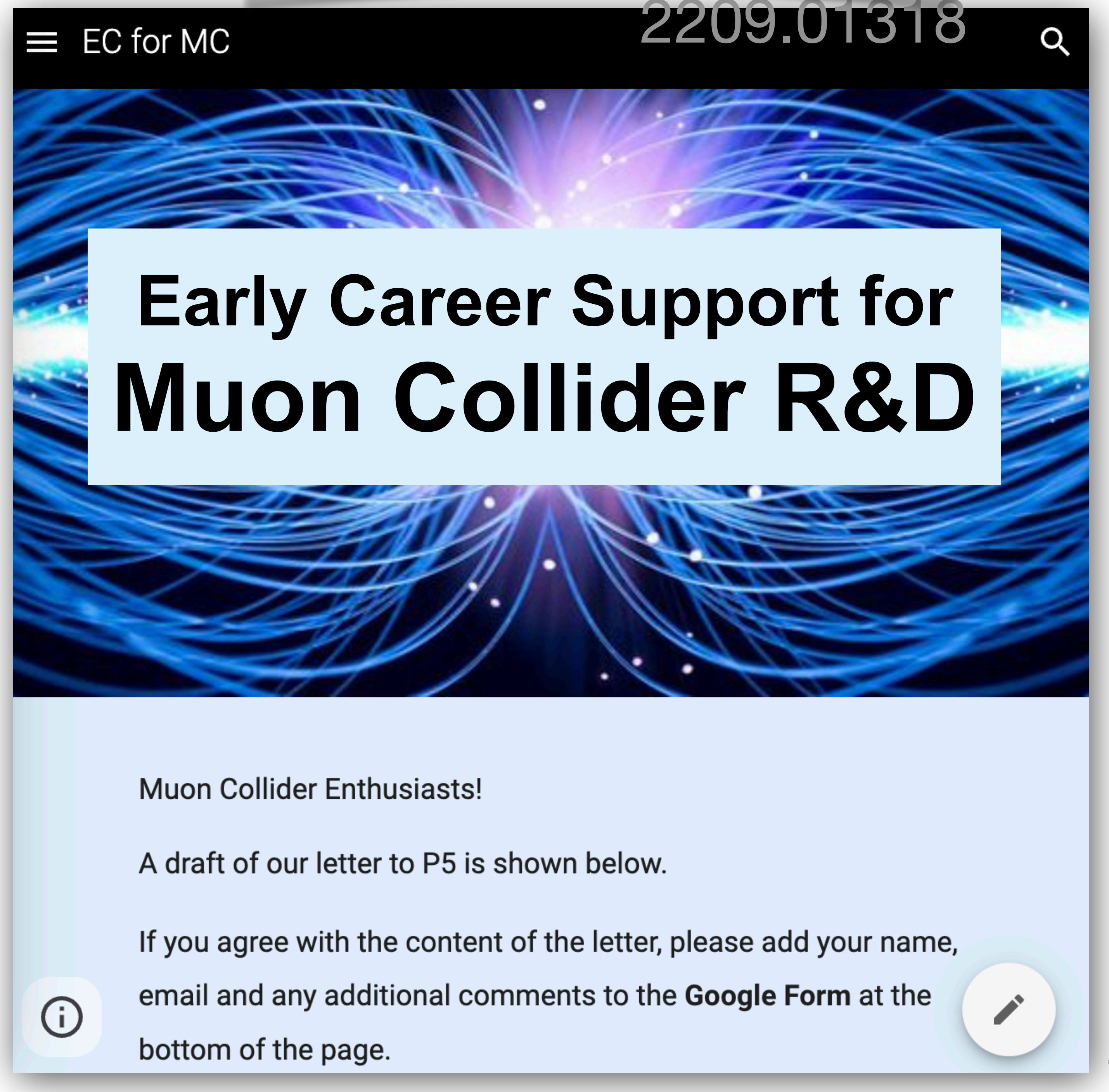


Realistic constraints?

2208.06030

Defer to accelerator experts

On the Feasibility of Future Colliders:
Report of the Snowmass’21 Implementation Task Force

Thomas Roser,[1] Reinhard Brinkmann,[2] Sarah Cousineau,[3] Dmitri Denisov,[1] Spencer Gessner,[4] Steve Gourlay,[5,6] Philippe Lebrun,[7] Meenakshi Narain,[8] Katsunobu Oide,[9] Tor Raubenheimer,[4] John Seeman,[4] Vladimir Shiltsev,[6] Jim Strait,[5,6] Marlene Turner,[5] Lian-Tao Wang.[10]

- Energy and Luminosity Reach, and Achievable Science
- Size, Complexity, and Environmental Impact
- Technical Risk and Technical Readiness
- Parametric Cost Estimates and Schedule

Collider Task Force Takeaways

2208.06030

- e+e- Higgs Factories "(nearly) shovel ready"
- For 10 TeV scale colliders
  - We don't have the technology today & we're not ready to make any decisions
  - We should begin R&D for $\mu^+\mu^-$ AND pp colliders as soon as possible
- "We urge to give high priority to the R&D topics aimed at the reduction of the cost and the energy consumption of future collider projects"

Collider	√s (TeV)	Tunnel (km)	Power (MW)	Cost ($B)	Time to start (yrs)
ILC e+e-	0.24	20	140	7-12	<12
FCC-ee	0.24	100	290	12-18	13-18
μ-3	3	10	230	7-12	19-24
CLIC	3	50	550	18-30	19-24
μ-10	10	16	300	12-18	>25
FCC-hh	100	100	560	30-50	>25

*Cost without contingency/escalation
**Technically limited timelines
***No staging assumed

Energy Frontier Vision

EF Report: 2211.11084

The US EF community has also expressed renewed interest and ambition to bring back energy-frontier collider physics to the US soil while maintaining its international collaborative partnerships and obligations.

For the five year period starting in 2025:

1. Prioritize the HL-LHC physics program, including auxiliary experiments,
2. Establish a targeted e^+e^- Higgs factory detector R&D program,
3. Develop an initial design for a first stage TeV-scale Muon Collider in the US,
4. Support critical detector R&D towards EF multi-TeV colliders.

For the five year period starting in 2030:

1. Continue strong support for the HL-LHC physics program,
2. Support construction of an e^+e^- Higgs factory,
3. Demonstrate principal risk mitigation for a first stage TeV-scale Muon Collider.

Plan after 2035:

1. Continuing support of the HL-LHC physics program to the conclusion of archival measurements,
2. Support completing construction and establishing the physics program of the Higgs factory,
3. Demonstrate readiness to construct a first-stage TeV-scale Muon Collider,
4. Ramp up funding support for detector R&D for energy frontier multi-TeV colliders.

- Ambition for a US hosted collider
- e+e- Higgs Factory AND multi-TeV
- Momentum for 10 TeV Muon Collider
- A sense of urgency
- Compact & Power Efficient
- Early Career Enthusiasm

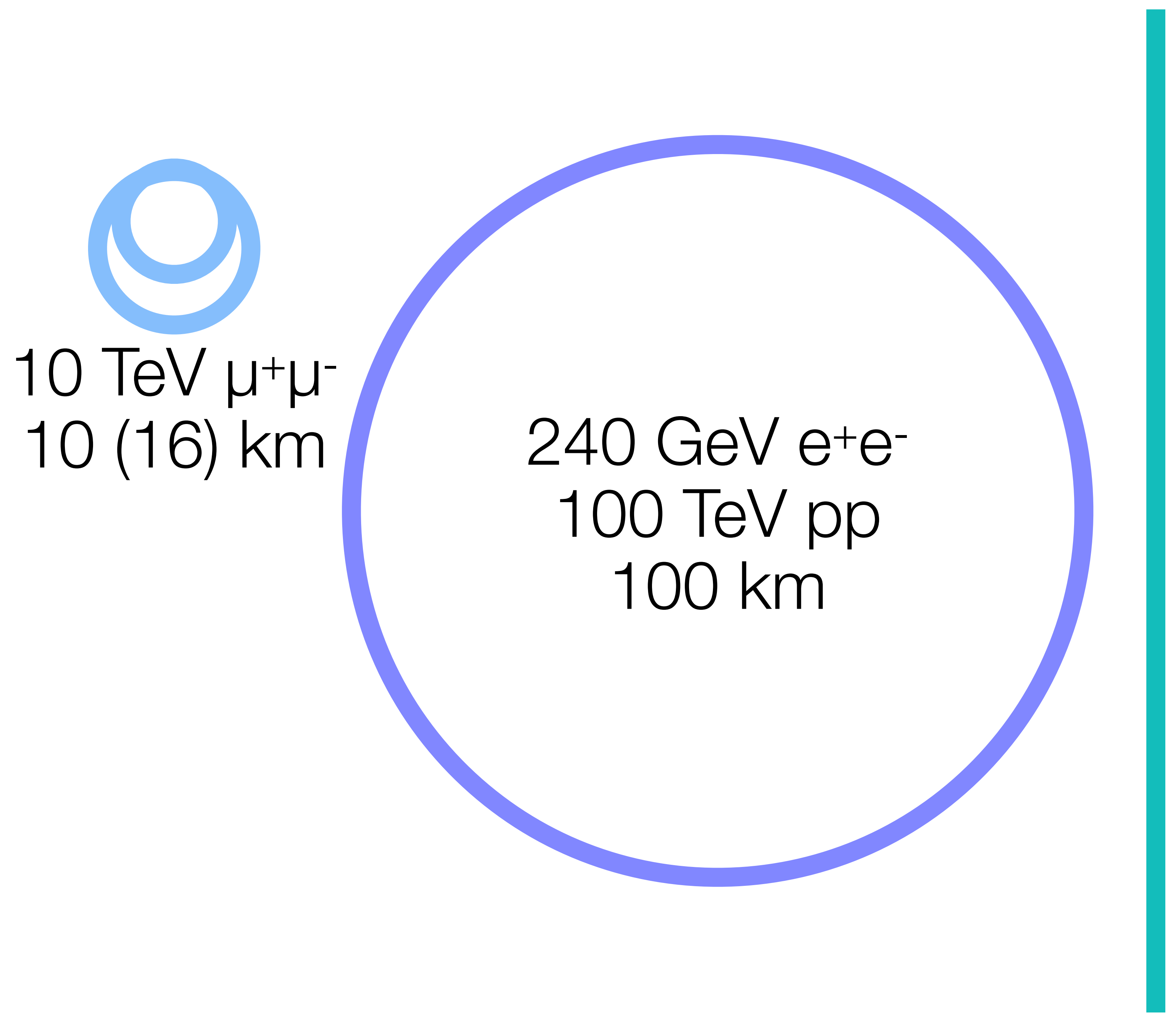
Why is there so much US interest in a Muon Collider?

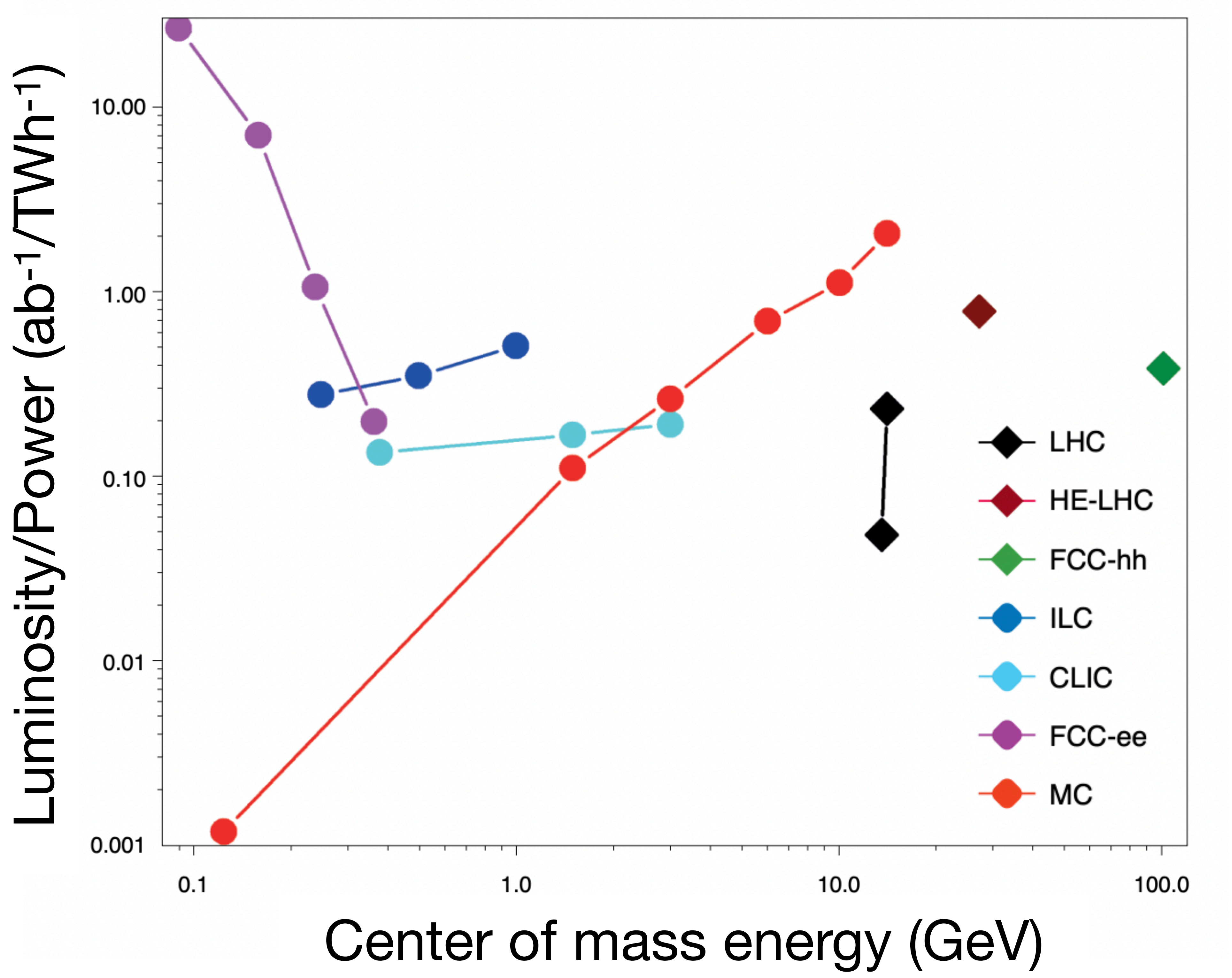
Compact and power efficient

Input to EPPSU 1901.06150

Muons break paradigm of larger and larger e^+e^- and pp machines

Colliding fundamental particles with no synchrotron radiation

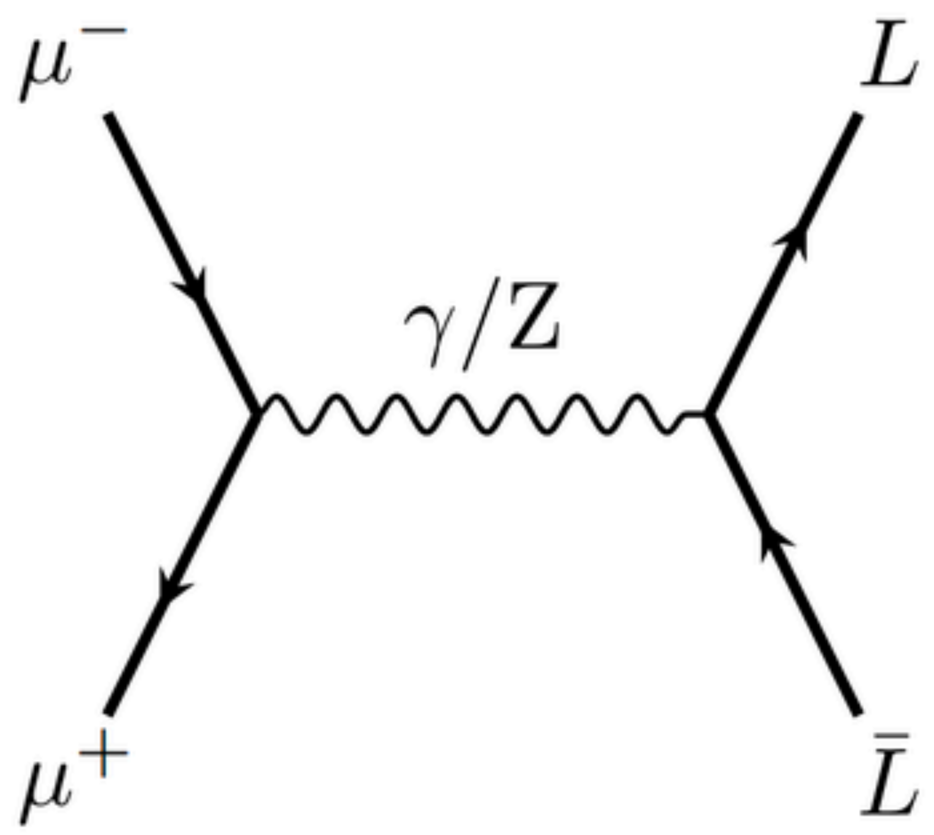




More than just a lepton collider

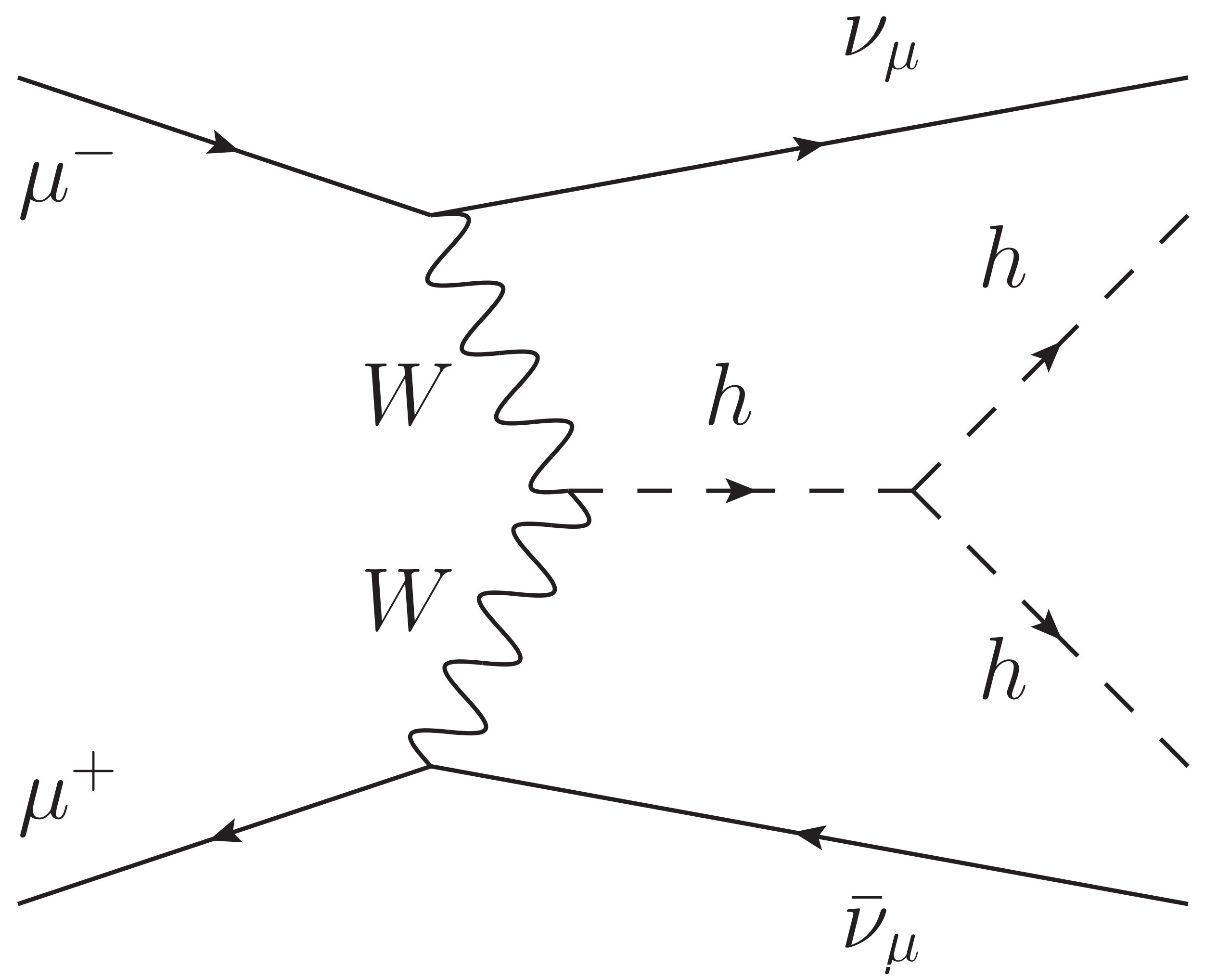
Also a gauge boson collider

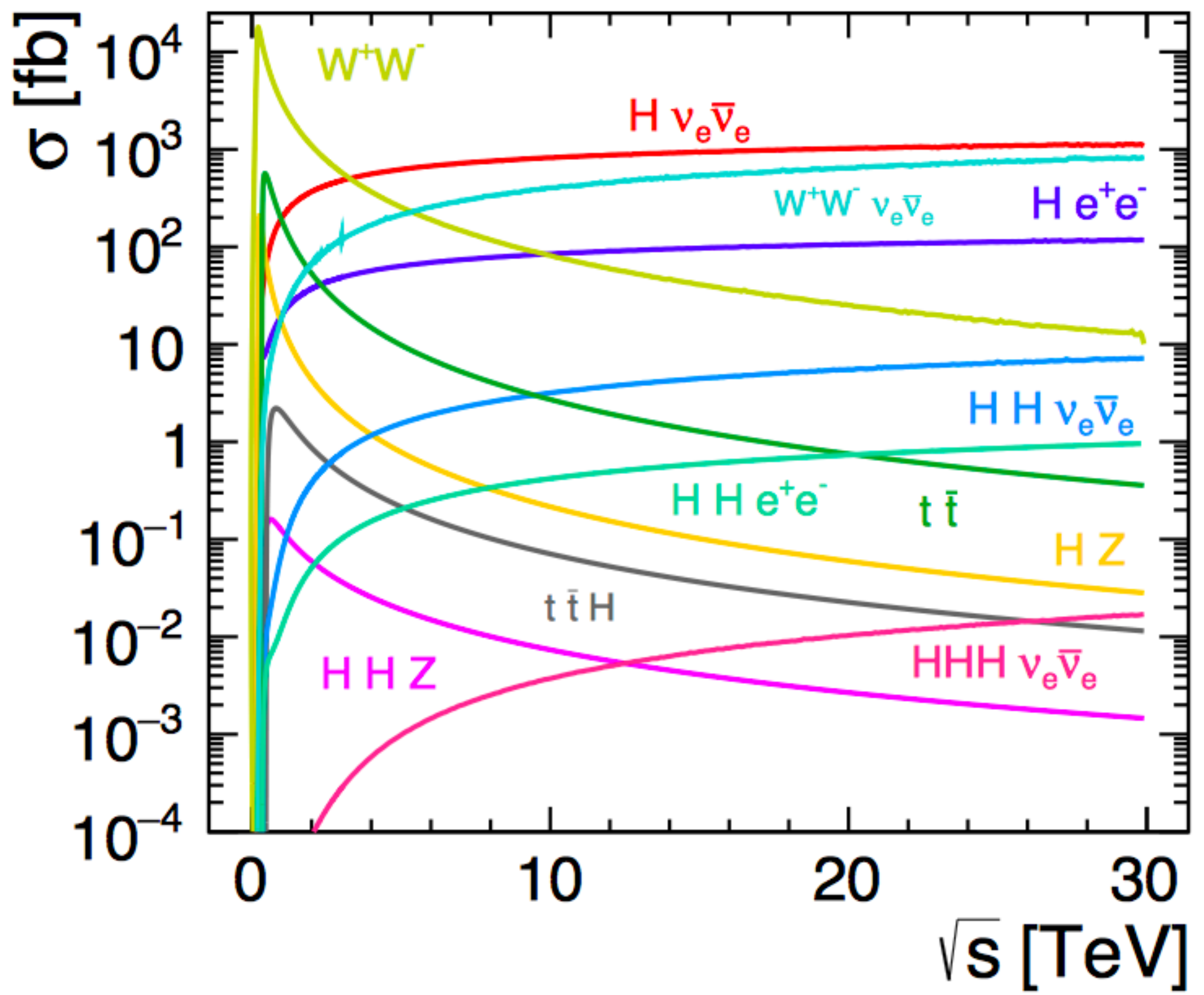
Energy reach & precision electroweak physics in same machine



$$\sigma \sim \frac{1}{E^2}$$

$$\sigma \sim \frac{1}{M^2} \log^2 \frac{E^2}{M}$$





The perfect neutrino beam

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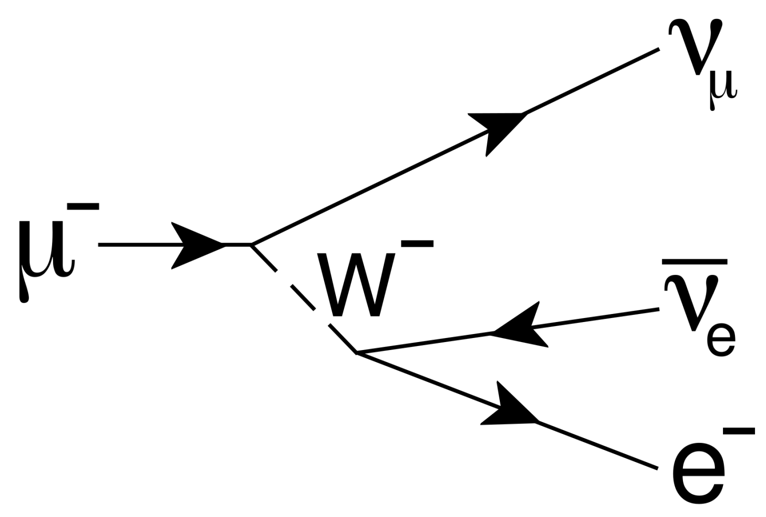
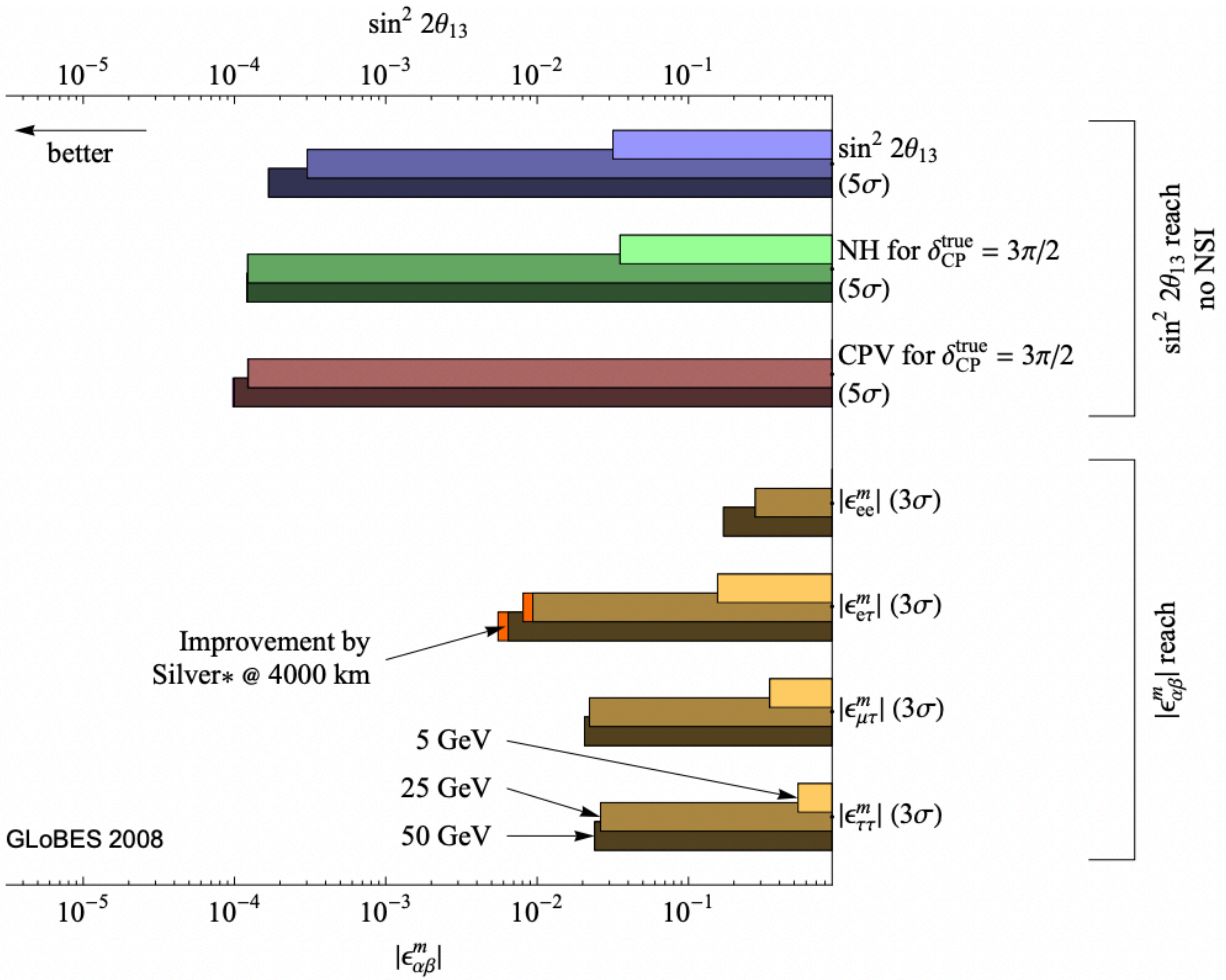
Equal numbers of e/μ (anti-)neutrinos
Precisely known energy spectra & intensity



- At low energy:
  - precision cross sections
  - sterile neutrino searches
  - δ_{CP}, Δm^2_{31}, θ_{13}, θ_{23}, ν_τ appearance
  - Over constrain PMNS paradigm
- At high energy: not fully prepared to say
- An appealing future after Dune/Hyper-K?



Why now

Muon Collider interest comes in waves

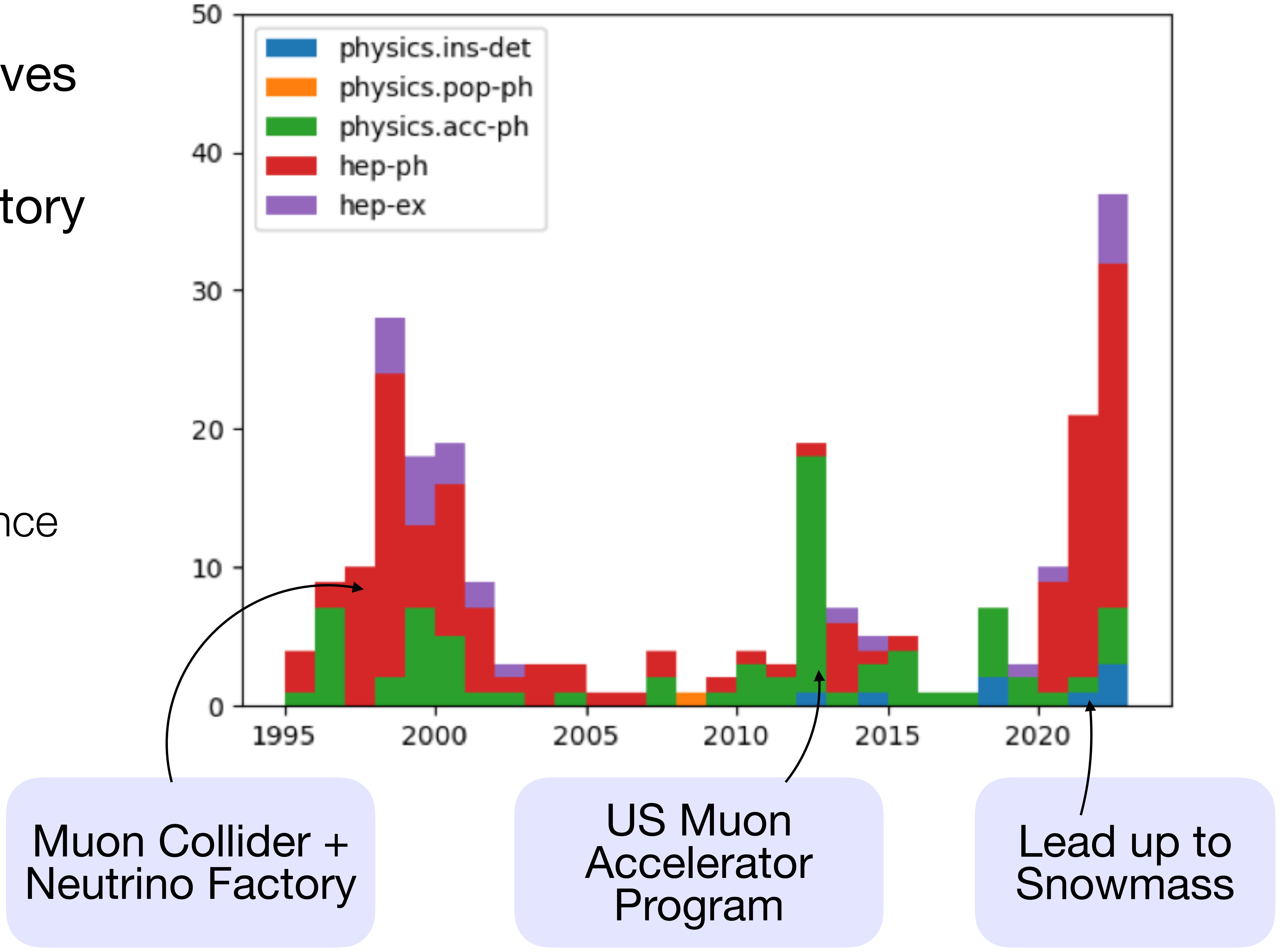
Previous waves 125 GeV Higgs Factory

Extremely challenging & hard to compete with e+e-!

This wave's focus is multi-TeV

Physics case for 10 TeV strengthened since Higgs Discovery.

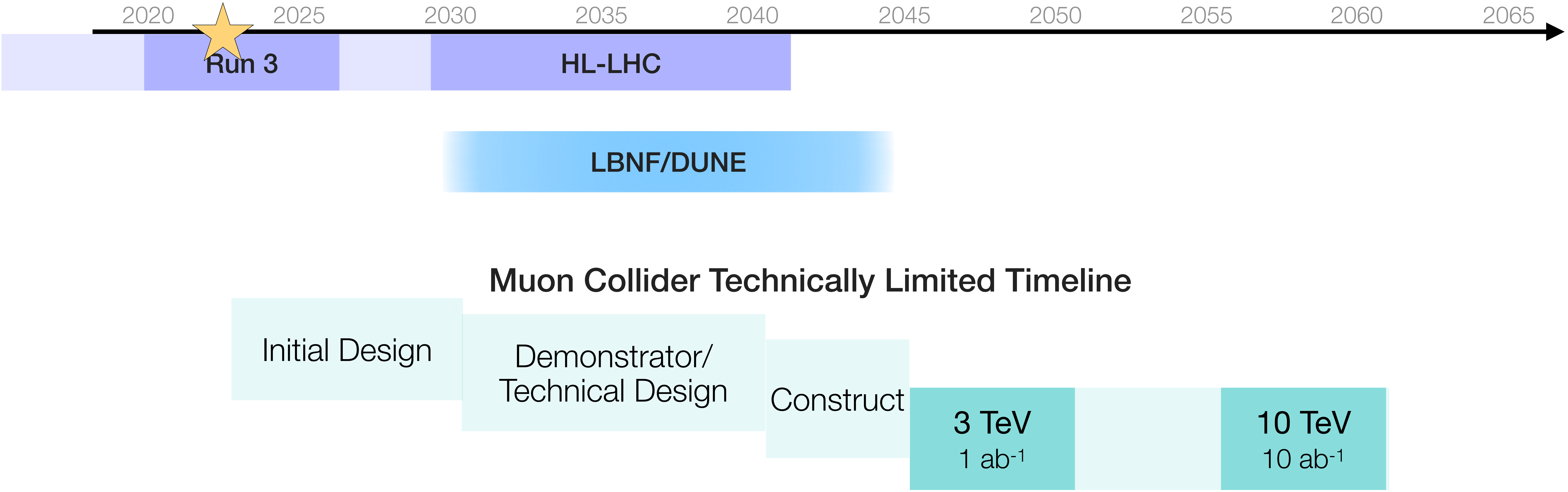
The time is right for R&D!



Why now

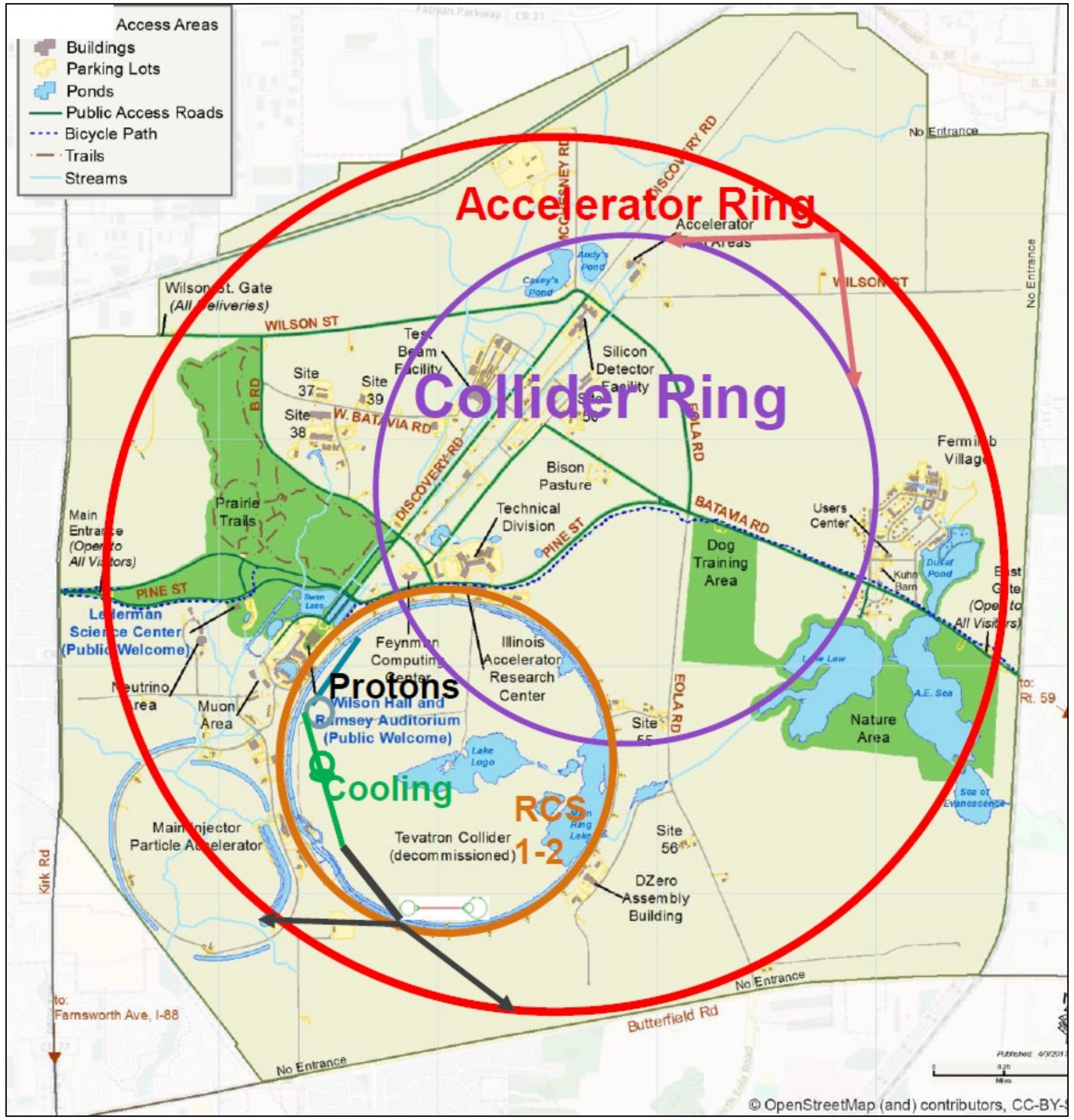
MuC Forum Report: 2209.01318

Recent design & technical progress → “no showstoppers identified”
Estimates from accelerator experts put a Muon Collider within early career lifetimes



The perfect fit Fermilab

- A 10 TeV Muon Collider fits within Fermilab site
- Builds on existing/proposed accelerator infrastructure
- Timescales and neutrino synergies align nicely with the lab's long term vision & US funding profile
- A US hosted collider enables collaboration & competition with our global partners = best science



> "Leveraging PIP-II and ACE, the US is well positioned to host a world-leading energy frontier collider as the next major facility at Fermilab, conceived and executed as a global endeavor"
>
> <u>- Lia Merminga @EPP Townhall</u>

Collider Challenges & Opportunities

What you might have heard

“A Muon Collider will never happen in our lifetimes”

“There still 10 or 12 miracles needed for a Muon Collider”

“Yeah but the neutrino radiation”

“Just a bunch of naive kids at Snowmass!”

My goal: give you a sense of the challenges, current status, why accelerator experts think there are no showstoppers

The muon lifetime challenge

Need to produce, cool, accelerate, and collide muons before they decay

Rest frame $\tau = 2.2\ \mu s$

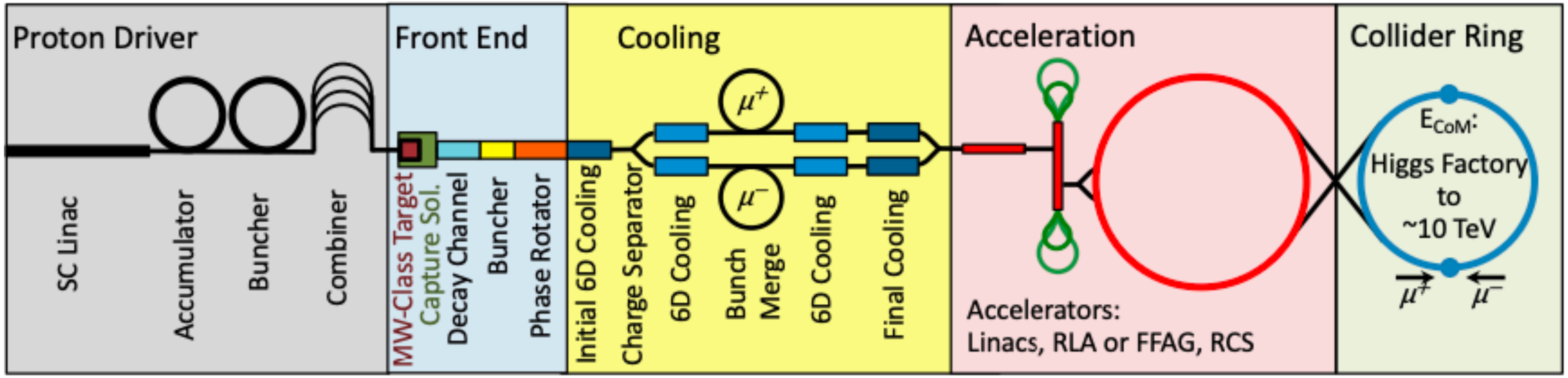
Multi-MW proton source on target

High field Solenoid for muon capture

6D Ionization Cooling

Accelerate to nominal energy ~16 km

Collider ring ~10 km



R&D History

Perception: “no progress in past 50 years”

First mentions in literature

Various Initial Collaborations & Designs

MAP: self consistent designs with existing or near term technology (2011-2016)

International Muon Collider Collaboration Formed (2020)

1965 … 2010 2015 2020

32-T Superconducting Magnet (2016)

Normal Conducting RF in B-field (2018)

MICE: First demonstration of 4D ionization cooling (2001-2018)

3 TeV detector concept

300 T/s fast ramping magnets

Multi-MW proton sources and targets (SNS, ESS, PIP-II)

Reality: Recent design progress and advances in technology

Proton driver

2209.01318

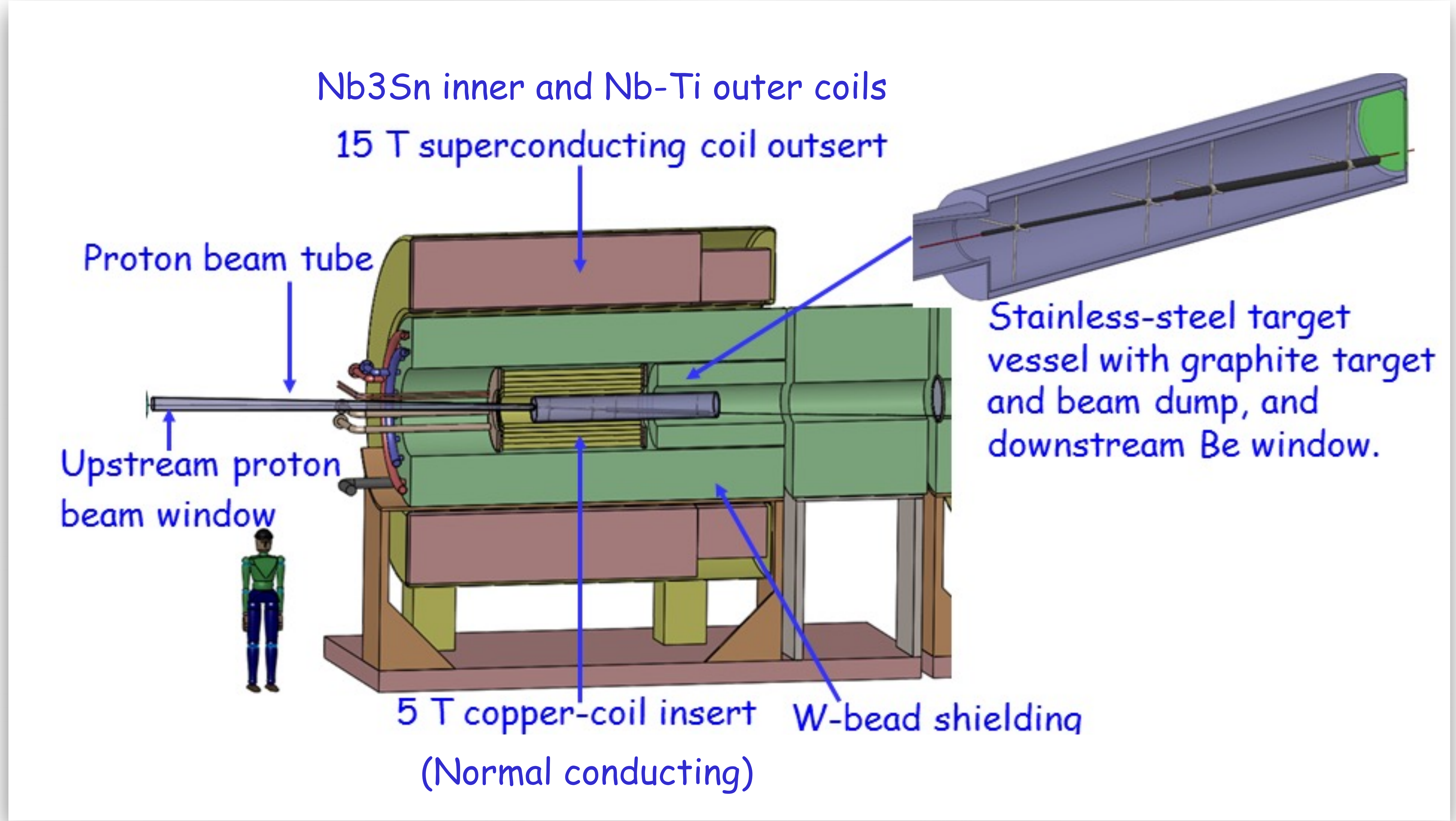
Goal is to deliver ~2e14 protons at 5-8 GeV and rate of ~10 Hz

Requirements:

- Proton source: 1-2 MW
- Accumulator & compressor: ~2ns bunches
- Target: shifted focus from liquid to solid (graphite)
- 20 T capture solenoid

Synergies:

- Spallation neutron and neutrino sources
- Charged lepton flavor violation experiments



Ionization Cooling

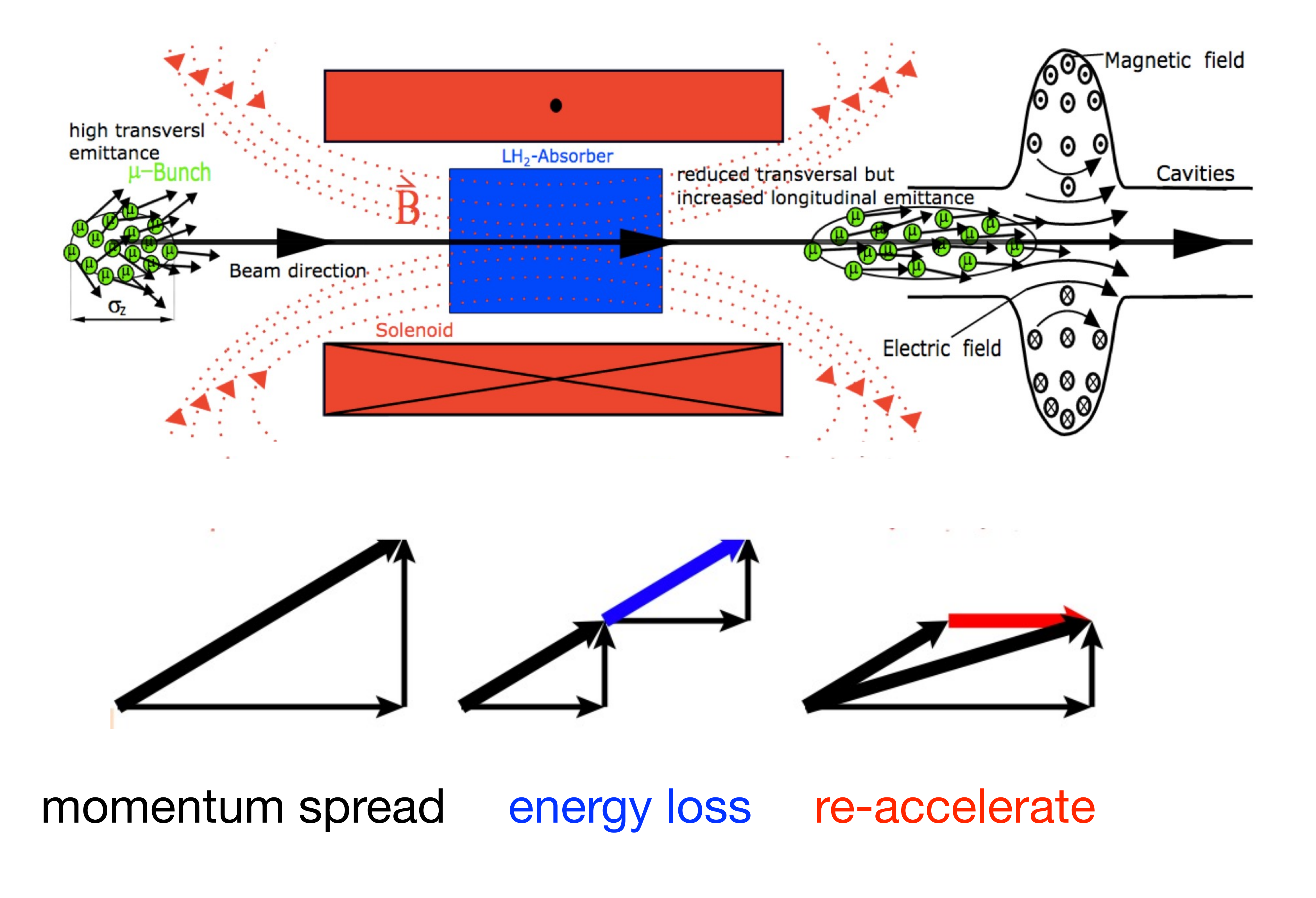
2209.01318

Rough concept: progressively reduce transverse momentum with low density absorber and restore lost longitudinal momentum with RF cavities

Status

- MAP end-to-end cooling design & simulation with realistic constraints within a factor of 2 of requirements
- MICE: Demonstration of single 4D cooling element
- Muon g-2: Demonstration of longitudinal cooling
- FNAL MuCool Test: RF-cavities in B-fields
- IMCC: improved lattice, test stands, demonstrator designs in progress

6D Cooling demonstrator critical if we want to move forwards with a Muon Collider



Accelerator and Collider Rings

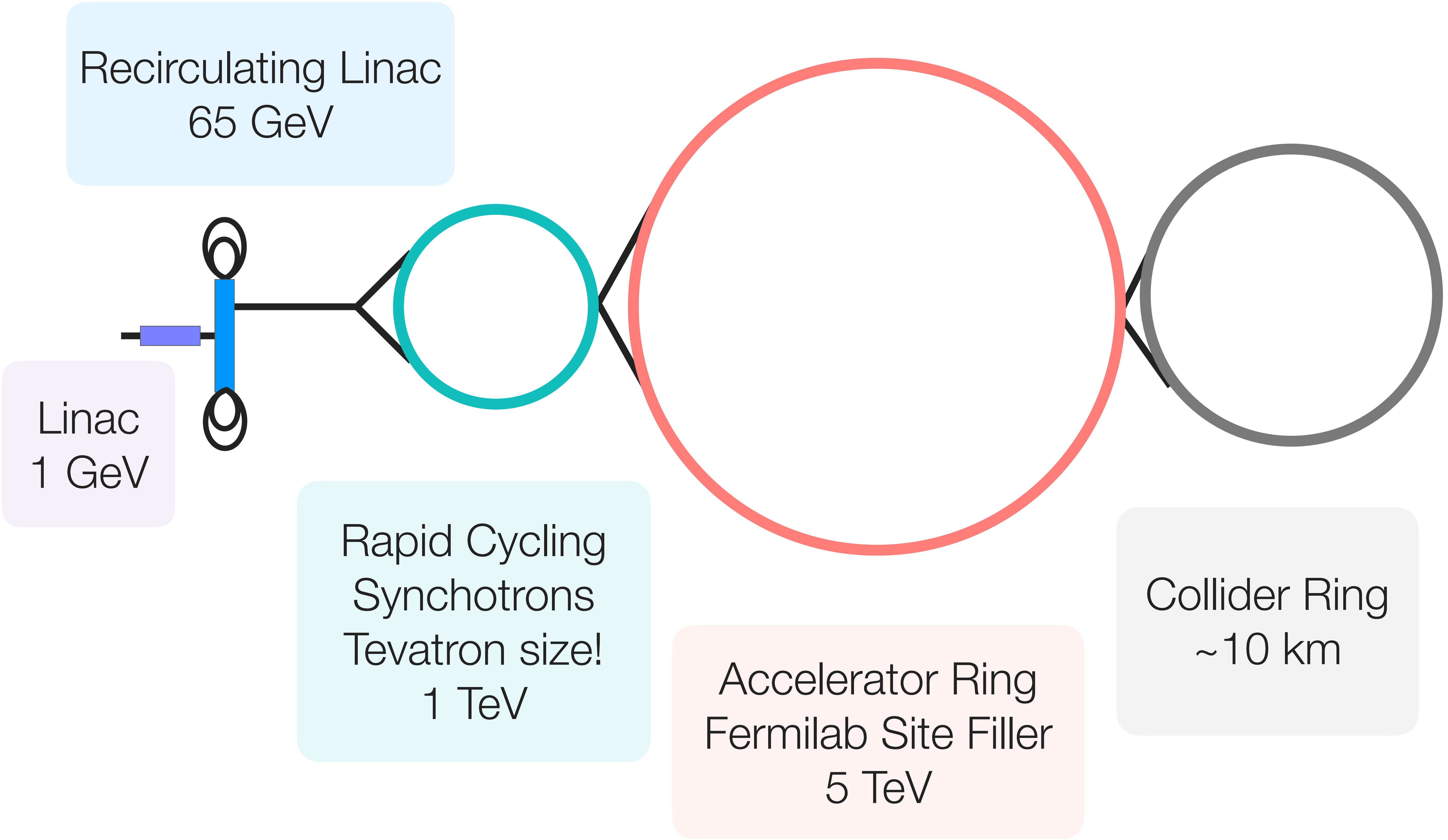
2209.01318

Accelerator

- Normal conducting fast ramping dipoles: ~1.5 T in around 1 ms
- Challenge: max field & power supplies

Collider:

- Circulate two bunches
- Re-fill when depleted
- Minimize size to maximize $N_{collisions}$
- 10 km ring, 16 T dipoles, ~2000 turns
- Large aperture magnets (15-20 cm) to accommodate shielding & prevent quenches



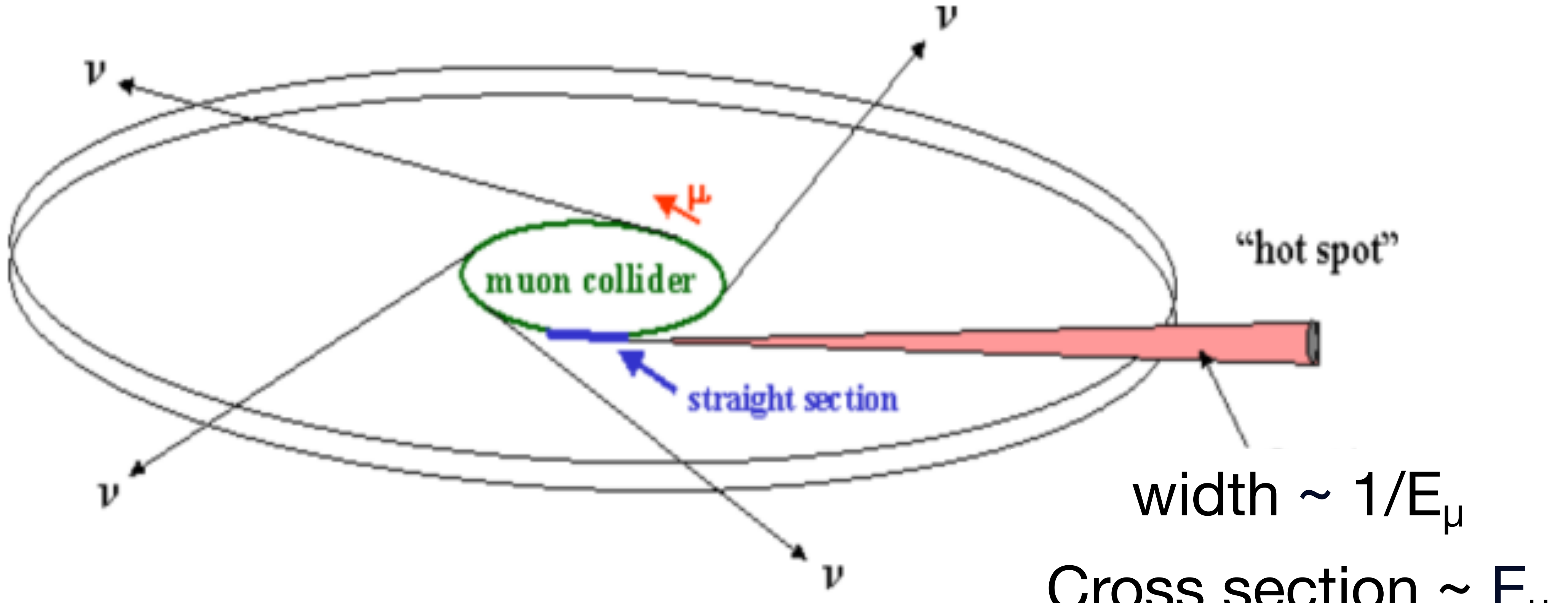
Neutrino Flux

2209.01318

Challenge: TeV neutrinos interacting between beam and you

Mitigation strategies for 10 TeV scenario exist!

- Depth 200 m
- Minimize field free regions
- "Beam wobbling" with B-field or high precision movers
  - ~1 cm 10x reduction
  - ~10 cm 100x reduction
- Better cooling/final focusing



width ~ $1/E_\mu$

Cross section ~ E_μ

Off-site yearly limit: 1000 μSv/year
Commercial flight: 3 μSv/hour
Large Hadron Collider : <5 μSv/year
Muon Collider Goal: <10 μSv/year

Detector Environment

- **Circulate two bunches & re-fill when depleted**
  - Event rate: 30 kHz
  - Muons survive ~2000 turns
- **Beam induced background**
  - Decays w/in 20 m of interaction point: $\sim 10^7$
  - Tungsten nozzles block high E decay products from entering detector region
  - Diffuse, low E, non-pointing, out of time hits
  - R&D Needs: radiation hard, highly granular detectors with precision timing

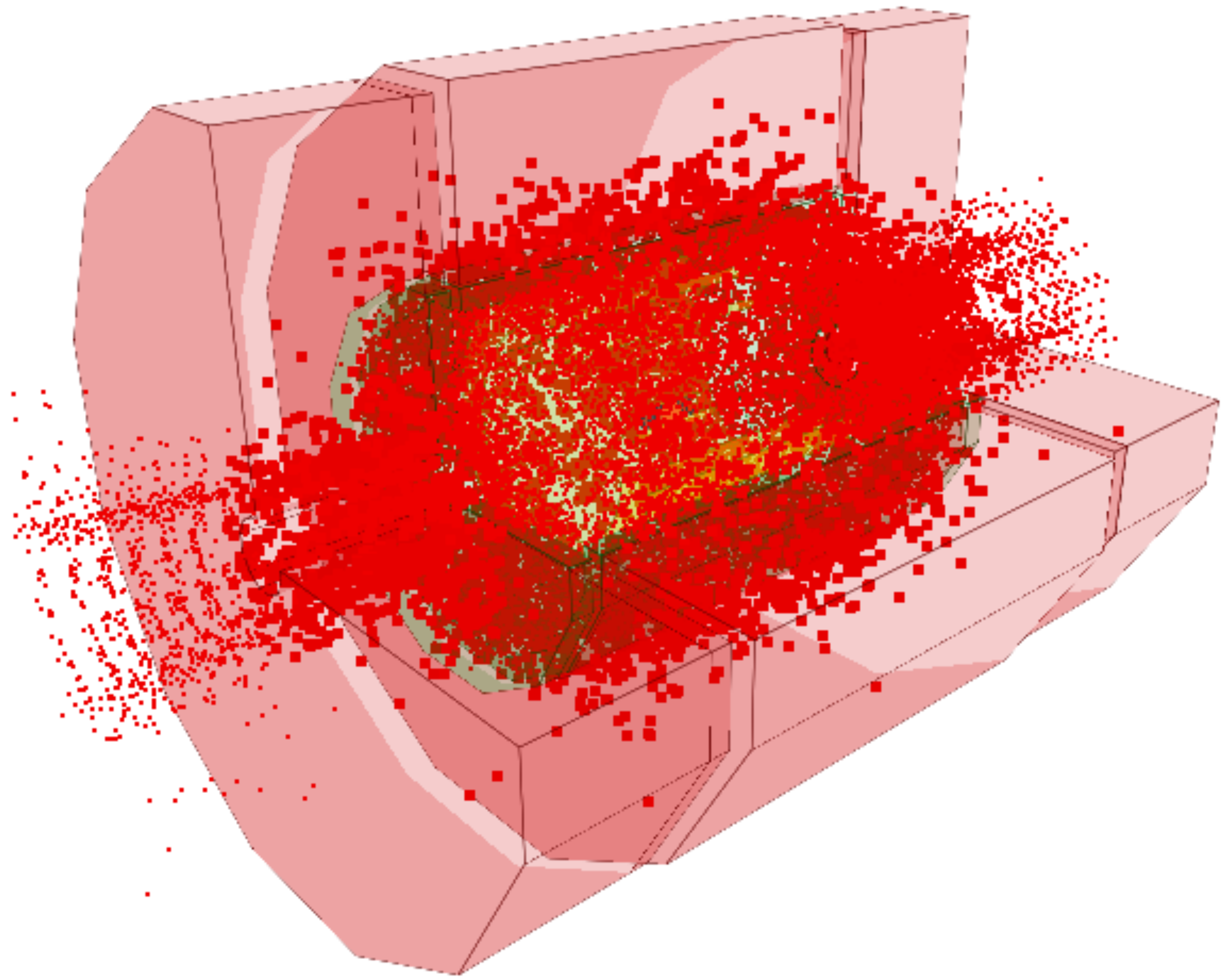
1000 x lower event rate than LHC

N_{decay} decrease with Energy

Total E_{decay} doesn't depend on Energy

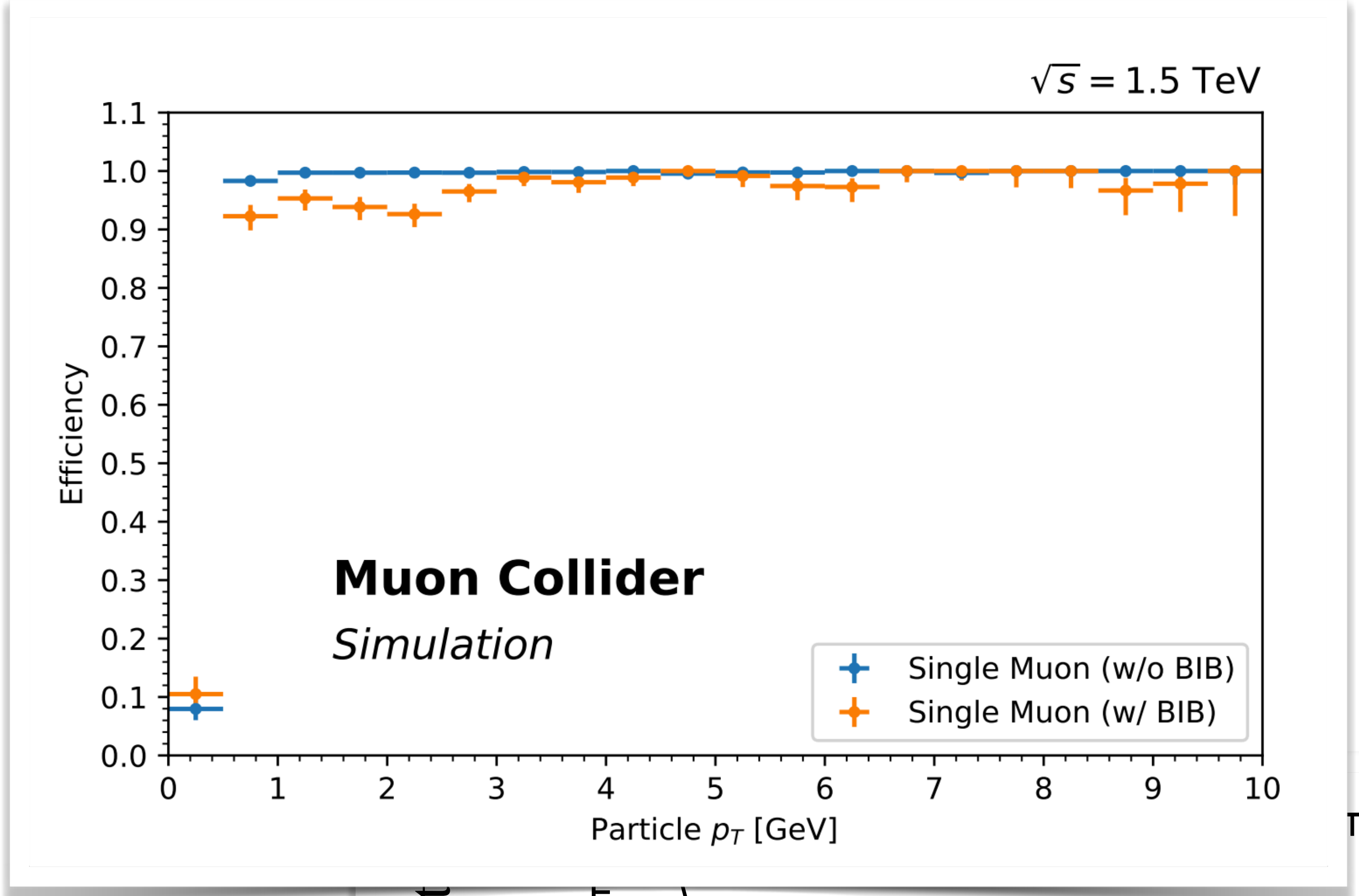
Dose & fluence ~HL-LHC

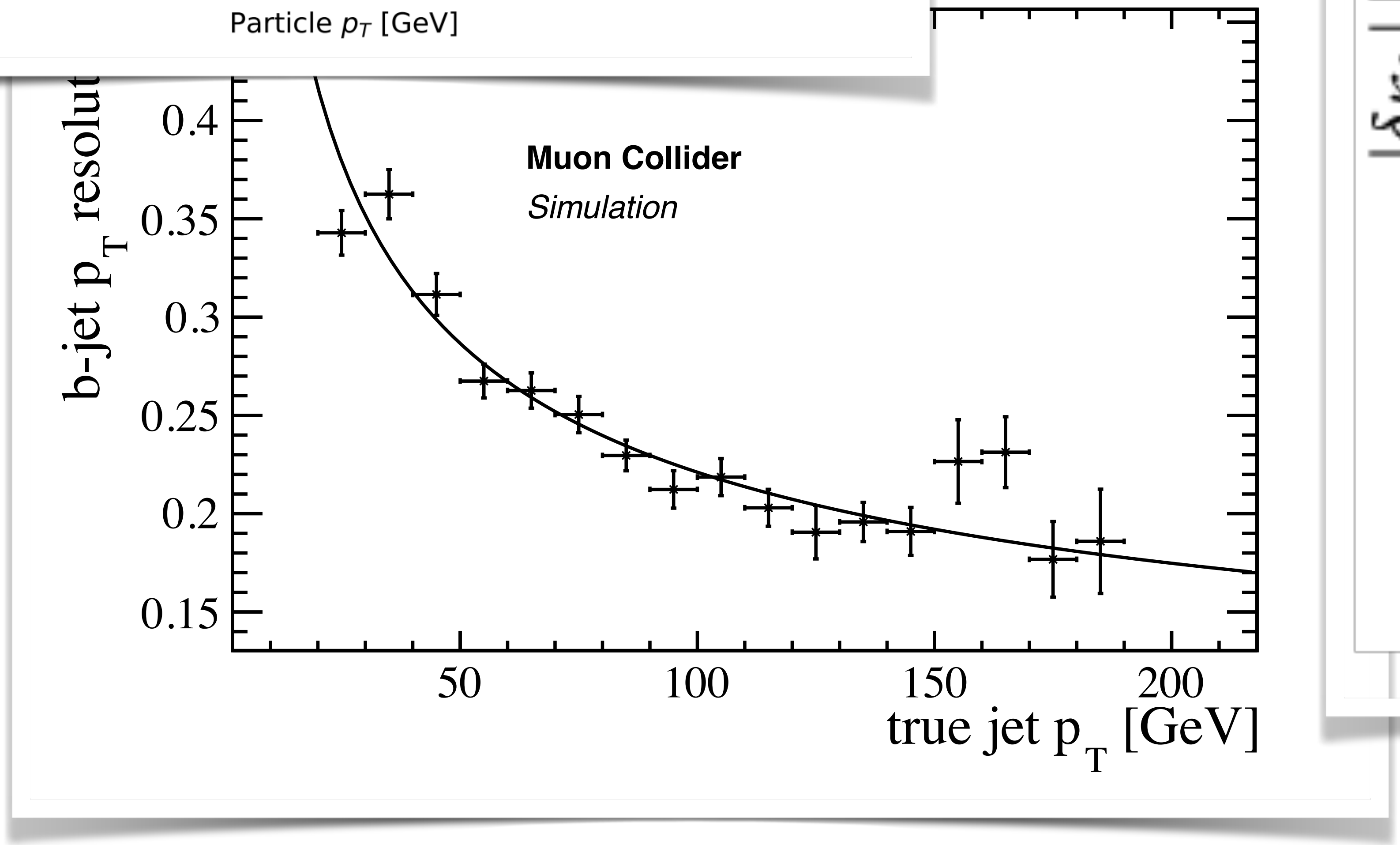
Hit rates ~10x HL-LHC

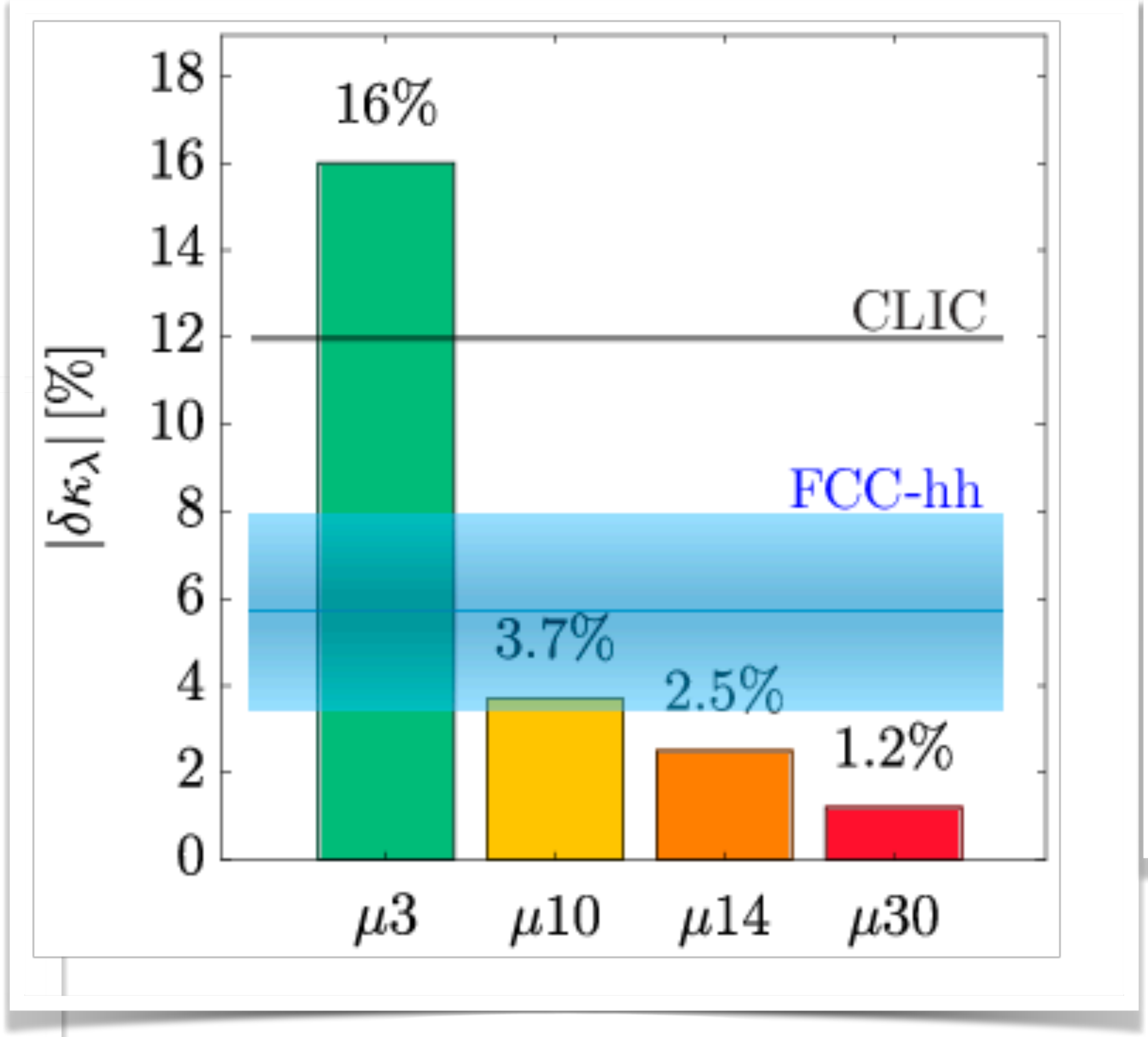


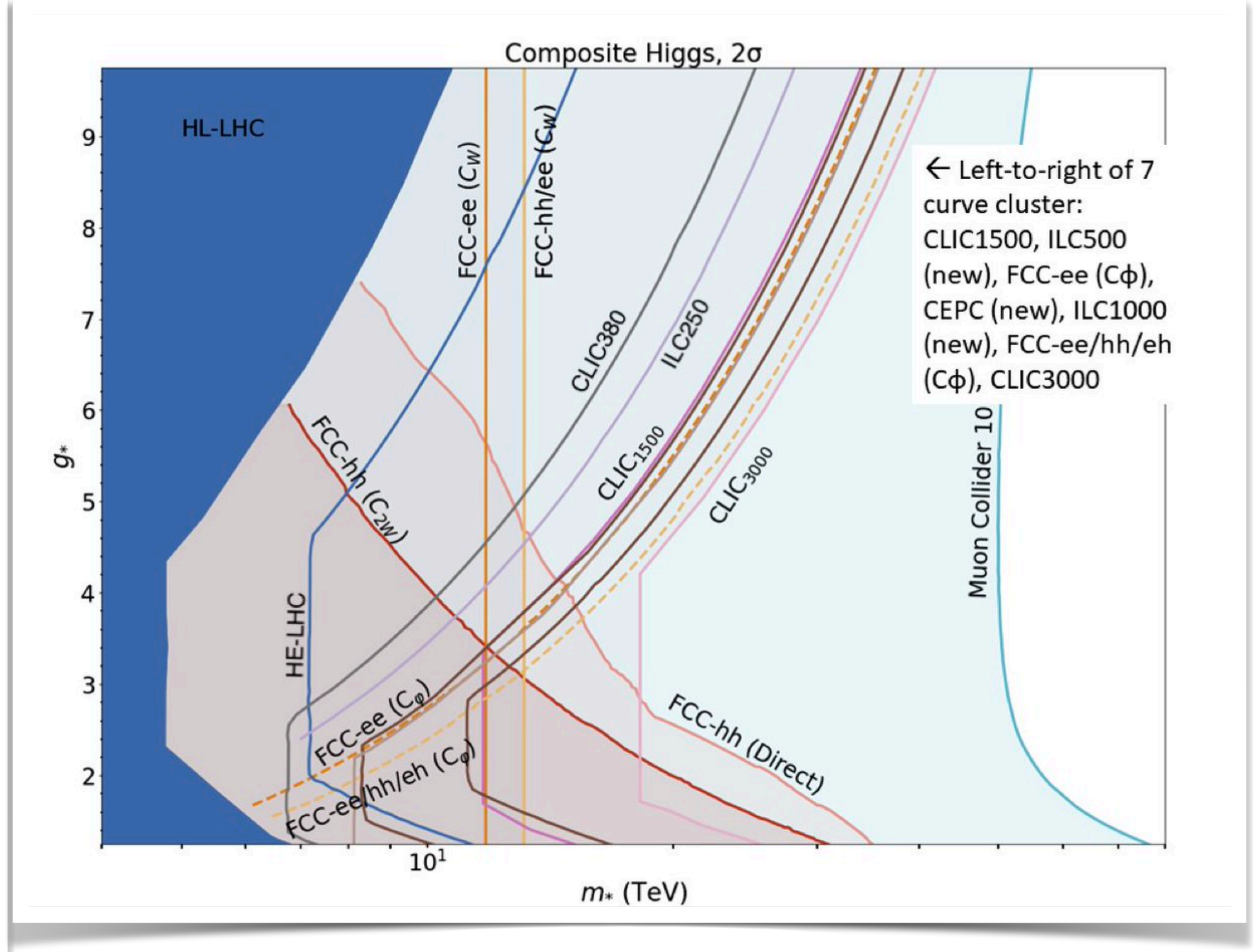
Extracting Physics

IMCC + Snowmass: high quality physics demonstrated in full simulation @3 TeV





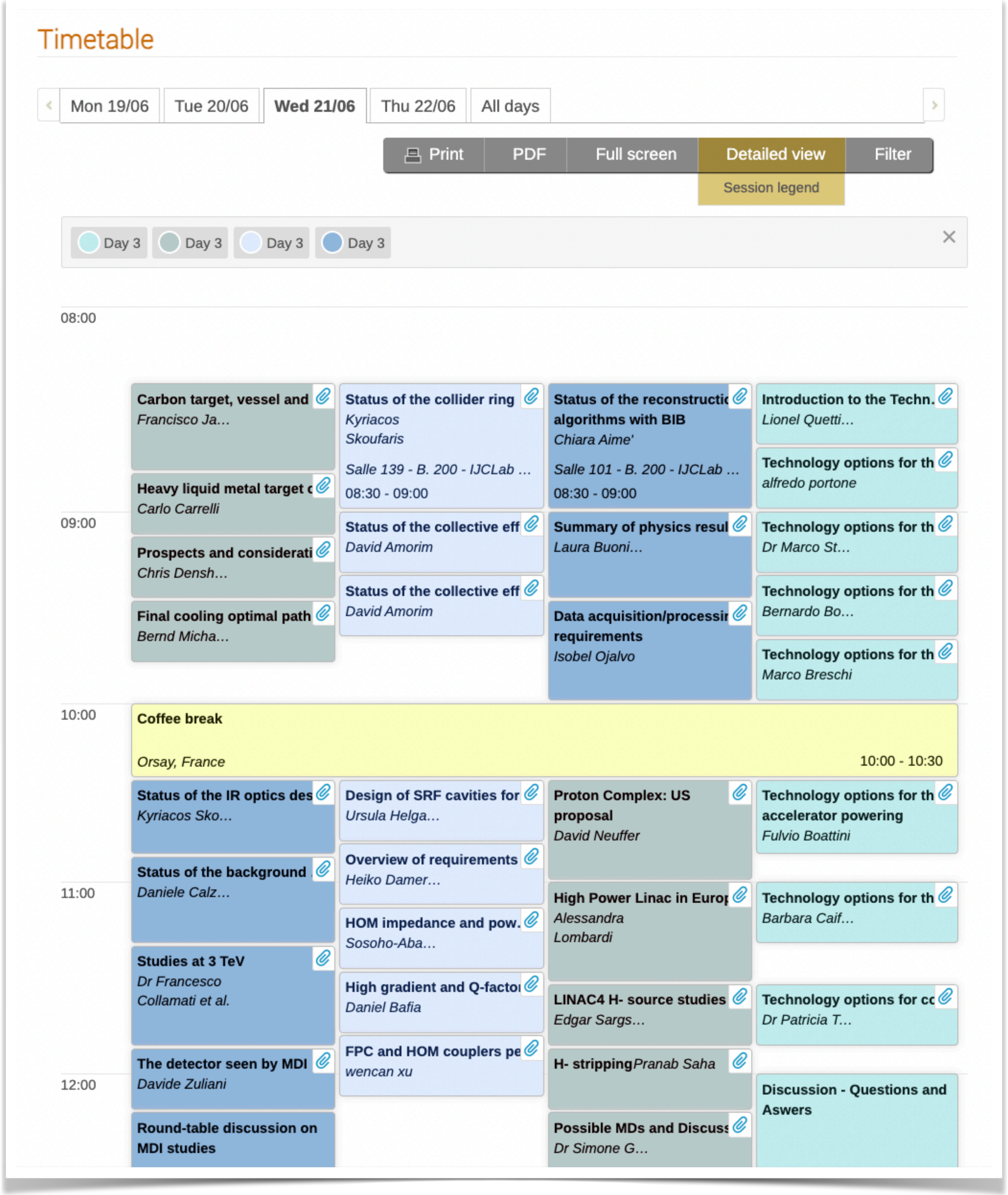




It's an exciting time!

In just the past year

- International Muon Collider Collaboration (CERN)
  - Second Annual Meeting June 2023 in Orsay
  - Rapid progress beyond MAP designs
- "MuCol" project funded by EU
  - Design study for collider complex at 10 TeV
  - Brings in ~7M Euro
- US Muon Collider Coordination Group formed to coordinate funding request to P5
- 4+ major meetings dedicated to muon colliders



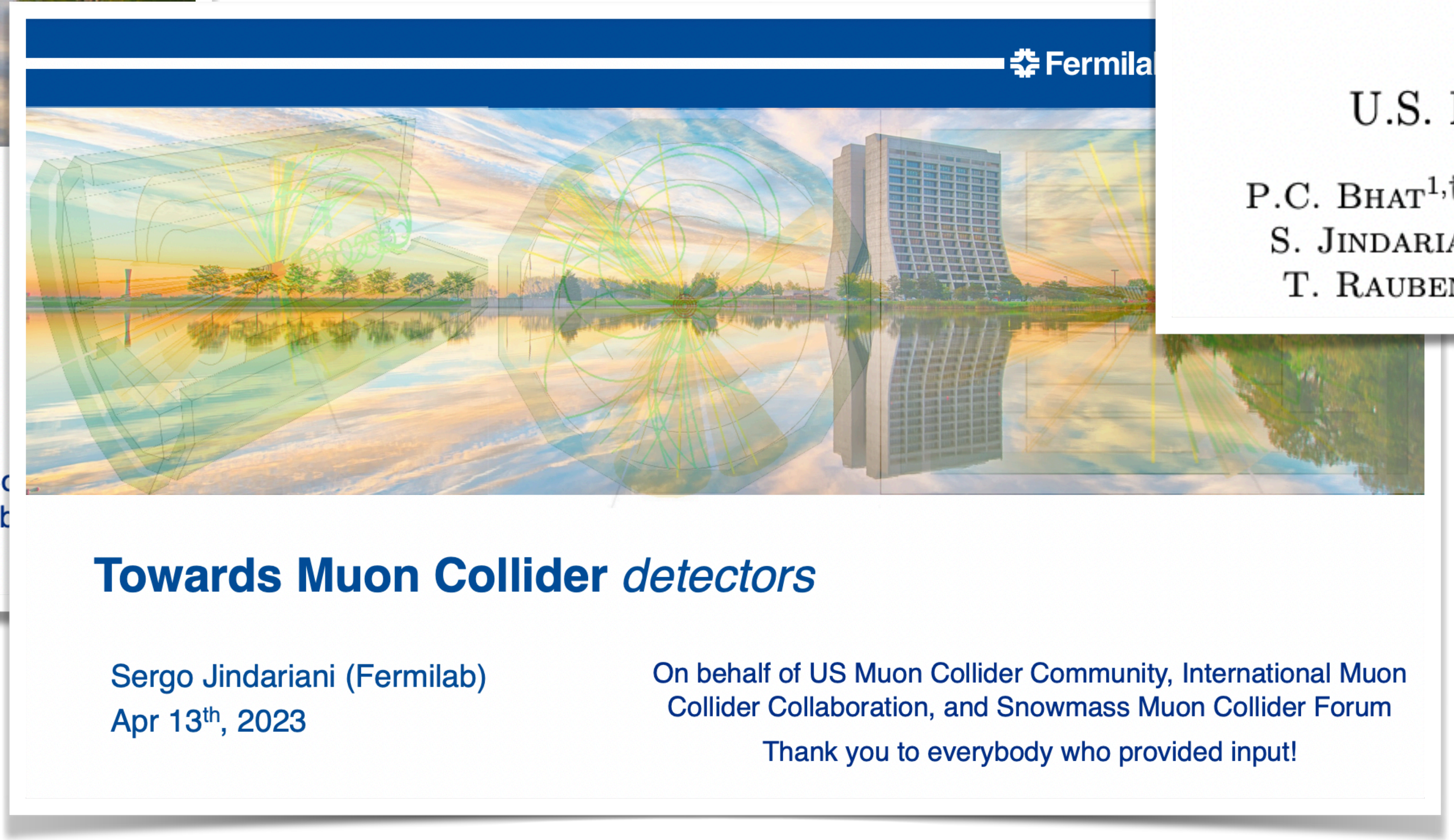
Next steps for the US

Proposed Muon Collider R&D program presented to P5

Should hear back soon!

P5 Accelerator Ask

P5 Detector Ask



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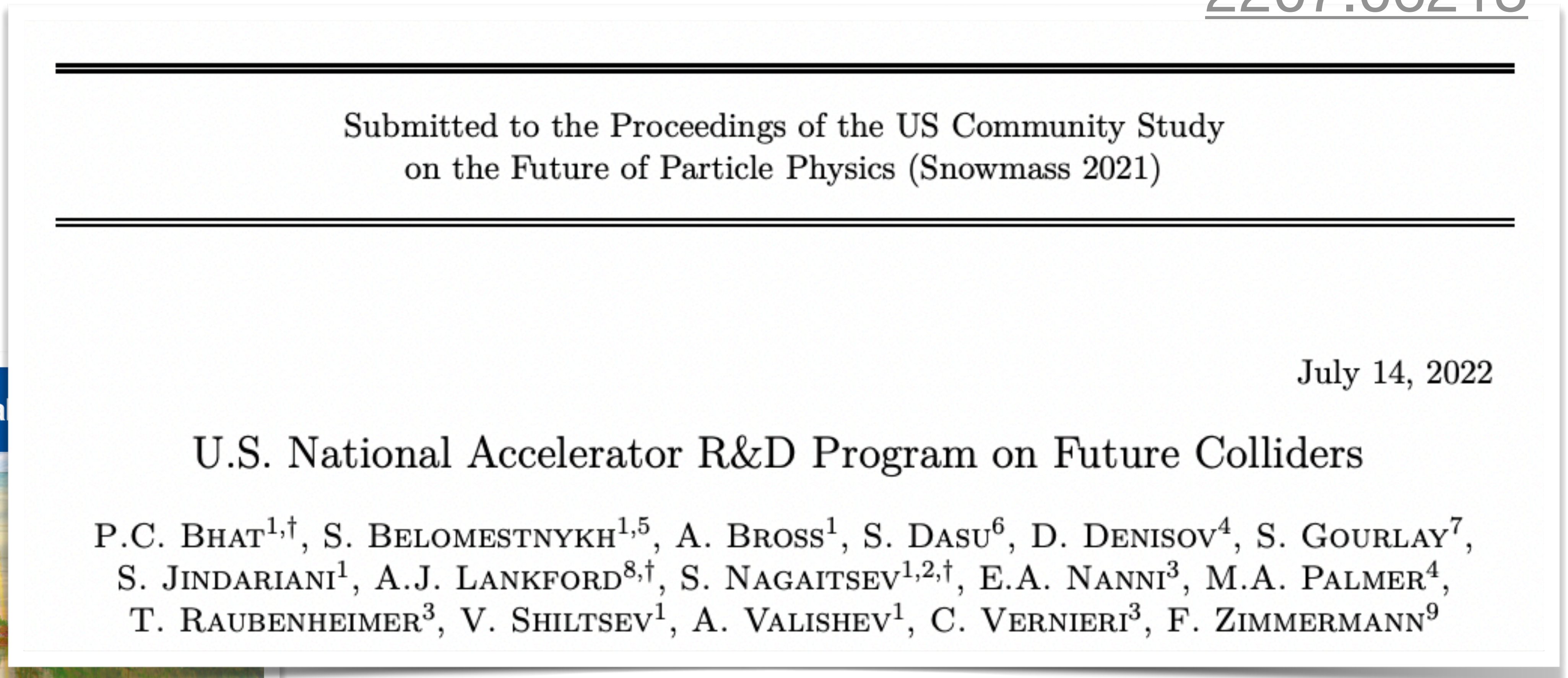

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

July 14, 2022

U.S. National Accelerator R&D Program on Future Colliders

P.C. Bhat[1,†], S. Belomestnykh[1,5], A. Bross[1], S. Dasu[6], D. Denisov[4], S. Gourlay[7], S. Jindariani[1], A.J. Lankford[8,†], S. Nagaitsev[1,2,†], E.A. Nanni[3], M.A. Palmer[4], T. Raubenheimer[3], V. Shiltsev[1], A. Valishev[1], C. Vernieri[3], F. Zimmermann[9]

How the future could look

We could be on our way to prototypes, a demonstrator, and designing a muon collider front-end

https://indico.fnal.gov/event/59663/

D. Stratakis

FERMILAB-FN-1229

Elements of a MuC US R&D program (2024-2030)

	Some examples
Design and Simulation work	• Optimize ACE for MuC proton driver needs • Accelerator & collider designs for a FNAL MuC • Neutrino flux mitigation for a FNAL MuC • Ionization cooling design work
Prototyping & tests	• Bunch compression & proton stripping • Target material & performance studies • Fast ramping magnet prototypes • Low-frequency SRF cavity prototyping & testing
Demonstrator	• Explore facility options for a full demo • Design & prototype (if possible) 1.5 cooling cell • Deliver a TDR for a demo facility with costs

- **This plan is pending P5 decision and will be modified after consultation with the IMCC AND knowledge of the US funding profile**

Fermilab

14 IMCC Annual Meeting

Report from the Fermilab Proton Intensity Upgrade Central Design Group

Robert Ainsworth, Giorgio Apollinari, Tug T. Arkan, Sergey Belomestnykh, Pushpalatha C. Bhat, S.J. Brice, Brian Chase, Mary E. Convery, Steven J. Dixon, Jeff Eldred, Grigory Eremeev, Brenna Flaugher, Jonathan D. Jarvis, Sergo Jiindariani, David Johnson, Jonathan Lewis, Richard Marcum, Sergei Nagaitsev, David Neuffer, Donato Passarelli, Frederique Pellemoine, William A. Pellico, Sam Posen, Eduard Pozdeyev, Alexander Romanenko, Arun Saini, Kiyomi Seiya, Vladimir Shiltsev, Nikolay Solyak, James M. Steimel, Diktys Stratakis, Alexander A. Valishev, Mayling L. Wong-Squires, Slava Yakovlev, Katsuya Yonehara, Robert Zwaska

Fermilab ACE Science Workshop

Jun 14 – 15, 2023
America/Chicago timezone

Enter your search term

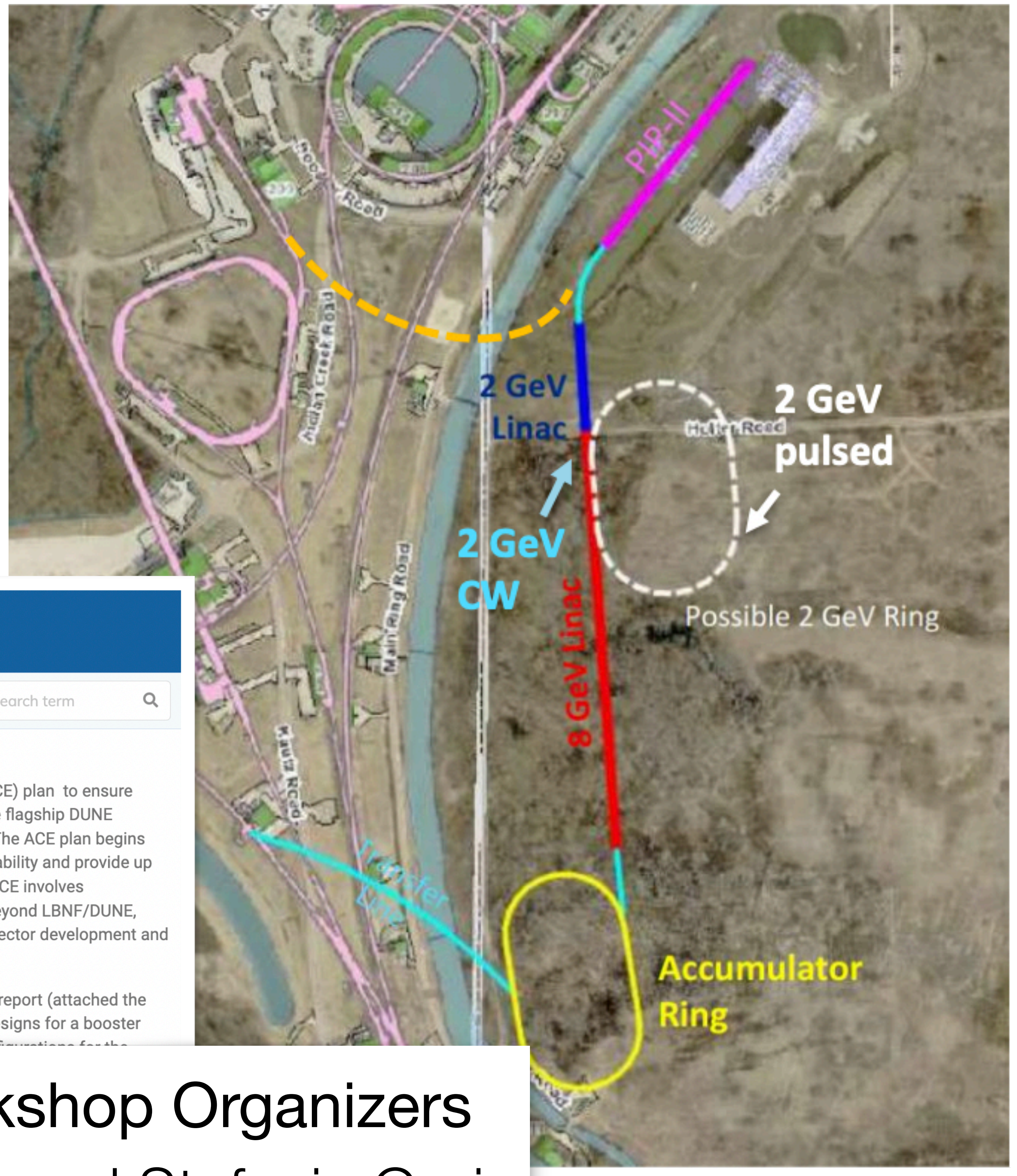
- Overview
- Call for Abstracts
- Timetable
- Registration
- Participant List
- Local Accommodations
- Zoom Information

For more info
ntran@fnal.gov
2575

Over the past year Fermilab has developed the Accelerator Complex Evolution (ACE) plan to ensure quality, high intensity beam delivery for a diverse set of experiments, including the flagship DUNE experiment, and for upgrades necessary for a potential future multi-TeV collider. The ACE plan begins with modifications to the Main Injector and the DUNE Target that will improve reliability and provide up to 2.1 MW of beam for DUNE through the mid-late 2030s. The second phase of ACE involves replacement of the booster to expand the scientific capabilities of the complex beyond LBNF/DUNE, improve overall complex capacity and reliability while providing a platform for detector development and serving as a front end for future colliders.

The Proton Intensity Upgrade Central Design Group (PIU-CDG) recently finished a report (attached the indico page) that focused on the most promising technologies and accelerator designs for a booster replacement. They defined the main a… Fermilab complex.

This workshop is intended to take the … community input which can be enable… expanded science capabilities in the P… could be realized. Experimental requir… considerations for the machine design…



ACE workshop Organizers
Nhan Tran and Stefania Gori

Conclusions

- US Long Term Planning
  - Snowmass made the case for an e+e- Higgs Factory and a 10 TeV-scale collider
  - Enthusiasm for compact, power efficient, and US-hosted options
  - We should hear more from P5 soon
- Momentum for a Multi-TeV Muon Collider
  - Energy and precision in a single machine
  - Interesting synergies & staging opportunities
  - No show stoppers identified, R&D should start now!
- Do your homework & decide for yourself!
  - Collider Implementation Task Force
  - International Muon Collider Collaboration
  - Towards a Muon Collider