International
MUON Collider
Collaboration

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

The Path to an Energy Frontier Muon Collider

Princeton Physics
Hamilton Colloquium

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February 22, 2024

@BrookhavenLab

ATRO – Accelerator Facilities Division

Acknowledgements

US Muon Accelerator Program (MAP)

International Design Study for a Neutrino Factory (IDS-NF)

International Muon Ionization Cooling Experiment (MICE)

International Muon Collider Collaboration (IMCC)

Participants in this Princeton Muon Collider Workshop

Snowmass Multi-TeV Collider Topical Group & Contributors

European Laboratory Directors Group – Accelerator R&D Roadmap

Snowmass Muon Collider Forum

2023 Particle Physics Project Prioritization Panel (P5)

Themes of this Talk

- **High Energy Colliders** → A Brief Perspective
- **Why Muons?** → A Vehicle for Discovery → The Physics Challenges
- **A Muon Collider** → Machine Concepts → **Charting a Path Forward**

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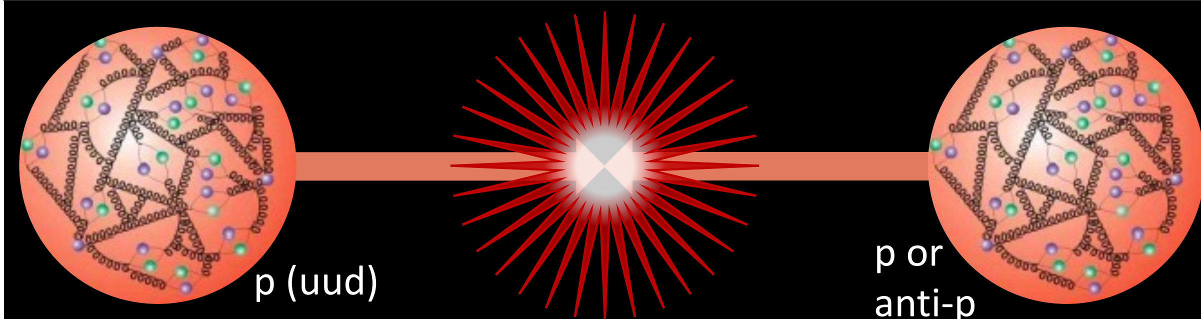
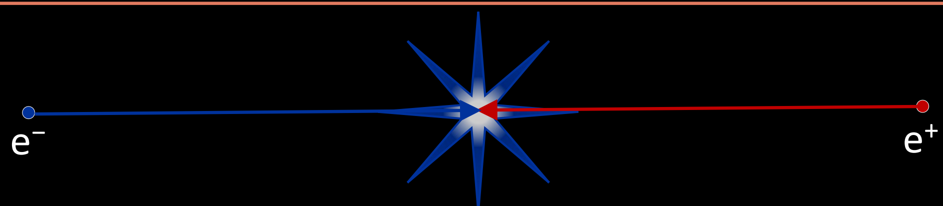
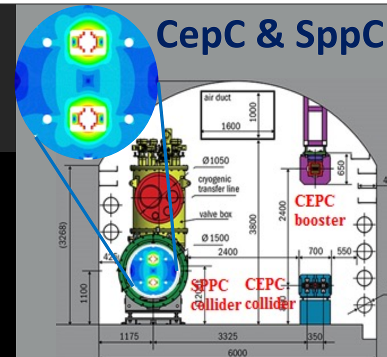
HEP Particle Colliders

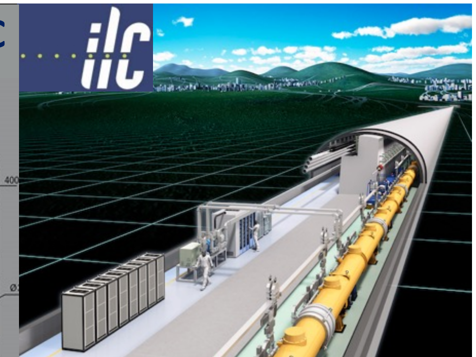


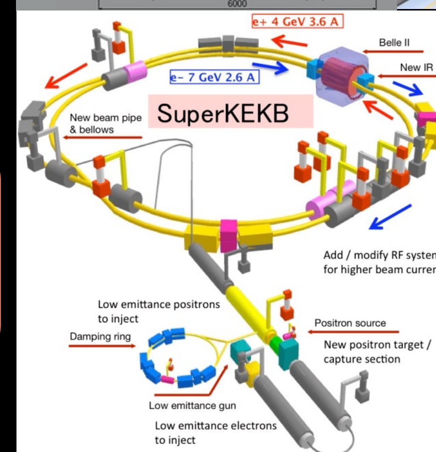
Proton-proton (or anti-proton) Collisions:
- Offer highest achievable center-of-mass collision energies
- Collisions of composite particles
- Discovery potential via Electroweak and Strong Interactions



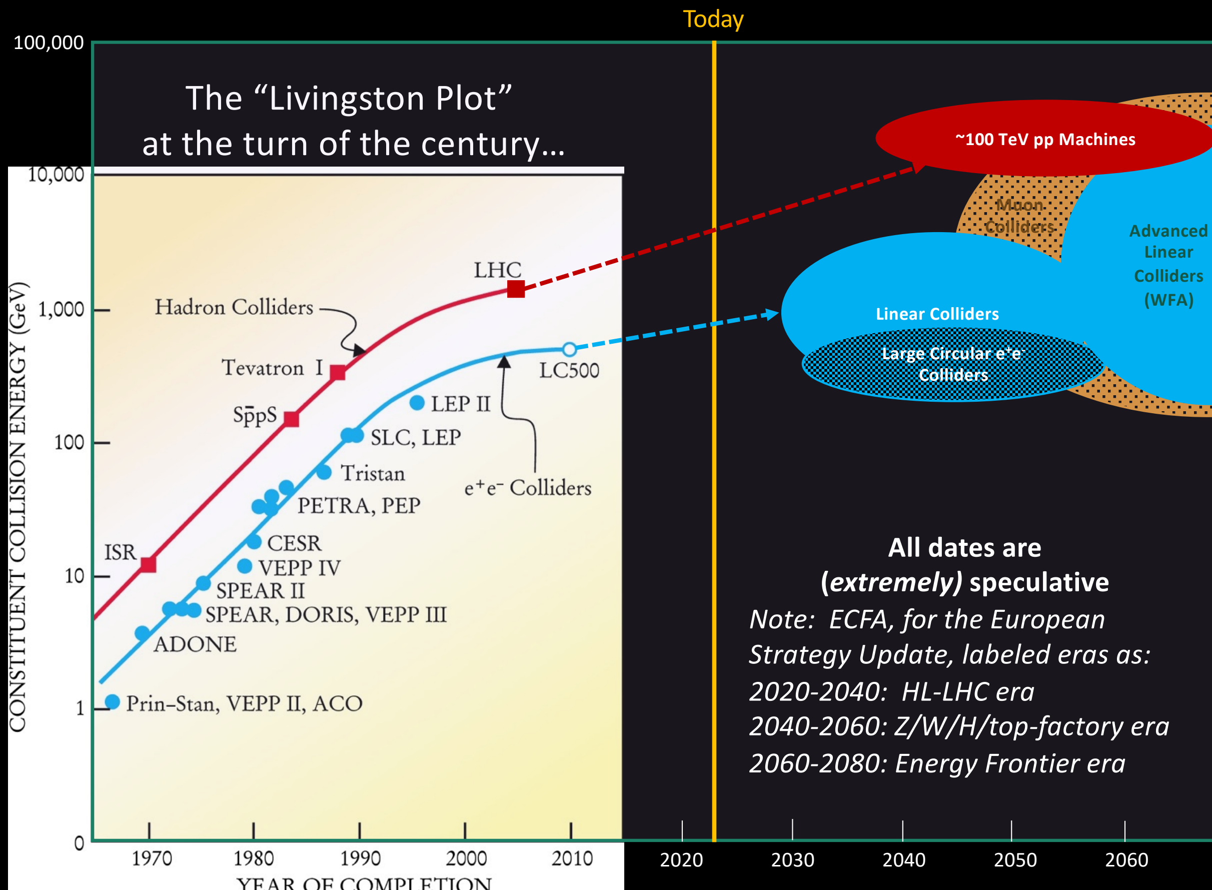
Electron-Positron Collisions:
- Collision of point-like fermions with well-defined initial state
- Precision measurements via Electroweak Interactions
- At multi-TeV energies – de facto electroweak boson colliders







A Look at Where We Are



- Livingston Plot in 2001
  [M. Tigner, Physics Today 54 , 1, 36 (2001)]
  - Through the 1900s, progress driven by critical technology developments for many decades (1940s –)
  - CoM Energies increasing by ***~2 orders of magnitude*** every ***25 years***
- Where are we now?
  - Progress has become much more challenging
    - Machine Complexity
    - Costs (R&D and capital)
  - ***What are our options and priorities for the next HEP machine?***

OVERVIEW OF MULTI-TEV MACHINE CONCEPTS

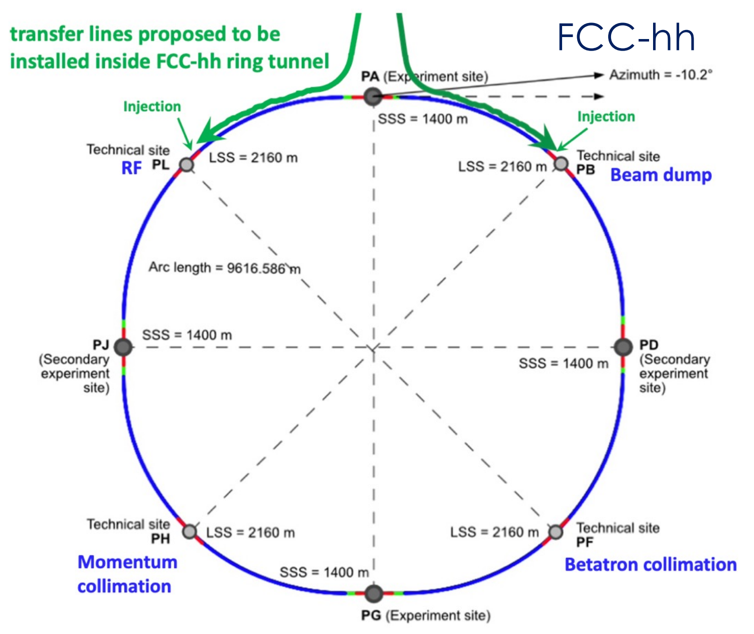
Snowmass 2021

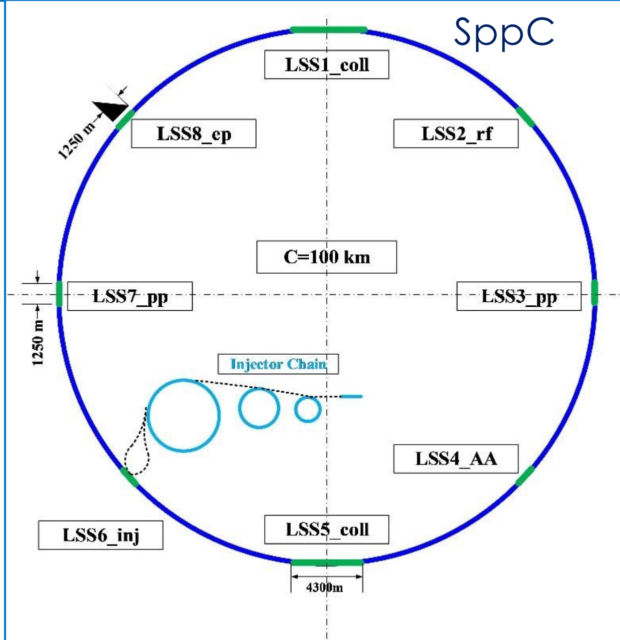
- TeV-class Conventional Linear Colliders
  - CLIC
  - ILC 1-TeV Nb
  - CCC
  - ILC Multi-TeV
  - RELIC
- Proton-proton Energy Frontier Machines
  - FCC-hh
  - SppC
  - Collider-In-Sea
- Lepton-Ion Machines
  - FCC-eh
  - MuIC
- Lepton Collider Energy Frontier Machines
  - MuC
  - WFA

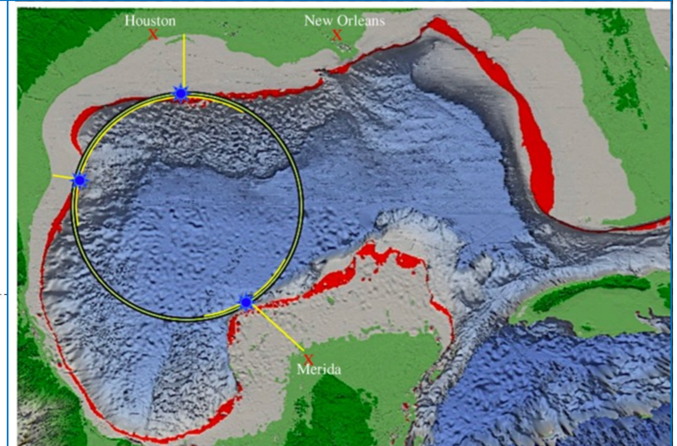
Potential Paths to the Energy Frontier

Proton-Proton
Energy Frontier Machines

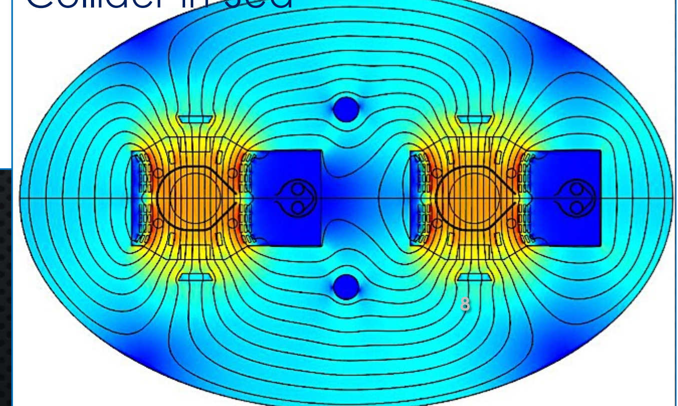
Snowmass 2021







Collider-in-Sea



FCC-hh
100 km
100 TeV
16T Dipoles

SppC
100 km
125 TeV
20T Dipoles

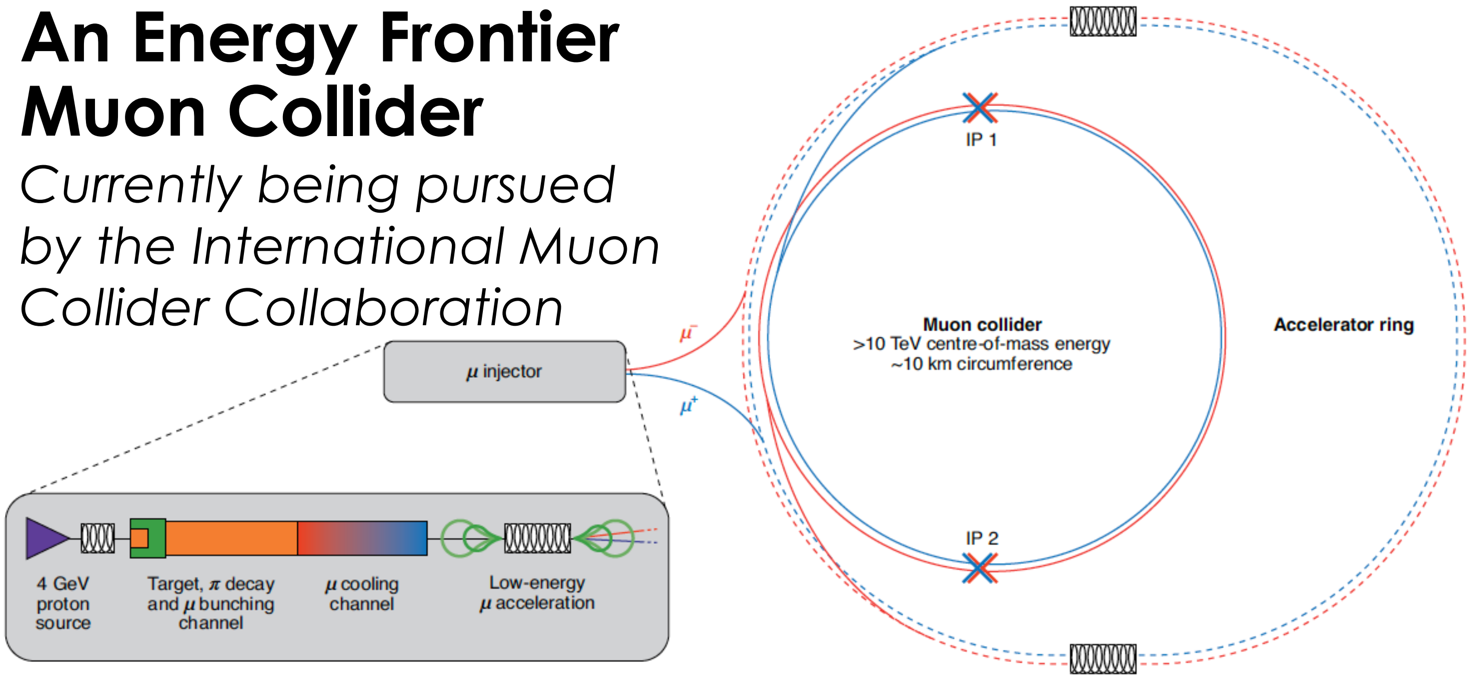
Collider-in-Sea
1,900 km
500 TeV
3.5T Dipoles

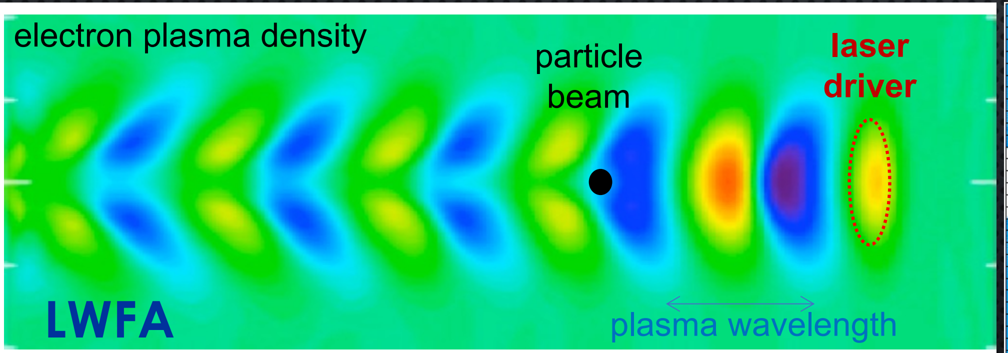
ENERGY FRONTIER LEPTON COLLIDER

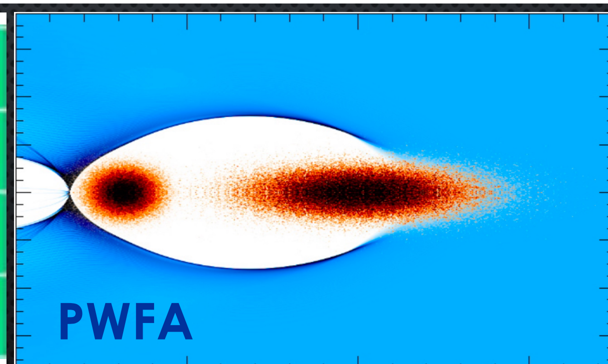
- EMERGING OPTIONS
  - MUON COLLIDER WITH STRONG DEPENDENCE ON ADVANCED MAGNET TECHNOLOGY
  - WAKEFIELD ACCELERATION
    - LASER-DRIVEN PLASMA
    - BEAM-DRIVEN PLASMA
    - BEAM-DRIVEN STRUCTURE

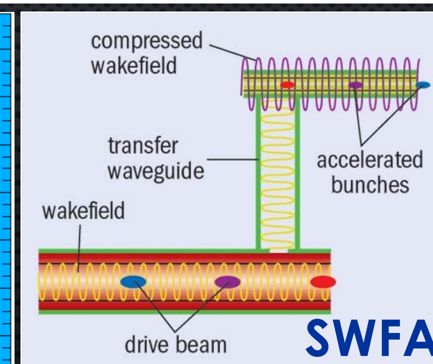
An Energy Frontier Muon Collider

Currently being pursued by the International Muon Collider Collaboration









MULTI-TEV CONCEPTS FROM SNOWMASS

Collider Concepts	Collider-In-Sea γ–γ	WFA MuC SppC CCC (TeV) ILC (multi-TeV) MuIC ReLiC (multi-TeV) FCC-eh SppC-eh	FCC-hh ILC (TeV) CLIC
Technical Maturity	• Low maturity conceptual development. • Proof-of-principle R&D required. • Concepts not ready for facility consideration.	• Emerging accelerator concepts requiring significant basic R&D and design effort to bring to maturity.	• Designs have achieved a level of maturity to have reliable performance evaluations based on prior R&D and design efforts. • Critical project risks have been identified and sub-system focused R&D is underway where necessary.
Funding Approach	• Funding for basic R&D required. • Availability of "generic" accelerator test facility access often necessary.	• Efforts would benefit from directed R&D funding to mature collider concepts. • Availability of test facilities to demonstrate a broad range of technology concepts required. • Some large-ticket demonstrators are generally necessary before a detailed "reference" design can be completed.	• Funding approach typically transitions to "project-style" efforts with significant dedicated investment required.

The AF4 evaluation of the maturity level of various concepts. Further details for the evaluation of the various concepts can be found in the "Concept Assessments" Section. The color code is that the concepts shown in blue offer a path to constituent center-of-mass energies >10 TeV, while those shown in orange are electron-hadron machines, and those shown in black are lepton collider concepts which will reach only into the 1-few TeV range.

Snowmass 2021

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Why Muons?

Physics Frontiers

- **Intense and cold muon beams ⇨ unique physics reach**
  - Tests of Lepton Flavor Violation
  - Anomalous Magnetic Moment (g-2)
  - Precision sources of neutrinos
  - Next generation lepton collider

$$m_\mu = 105.7\,MeV/c^2$$
$$\tau_\mu = 2.2\,\mu s$$

Colliders

- **Opportunities**
  - s-channel production of scalar objects ⇨ strong coupling to Higgs → $\sim\left(\frac{m_\mu^2}{m_e^2}\right) \cong 4\times10^4$
  - Reduced synchrotron radiation (**E^4/m^4**) ⇨ multi-pass acceleration feasible
  - Beams can be produced with small energy spread
  - Beamstrahlung effects (**E^4/m^4**) are suppressed at the collider IP relative to e^+e^- colliders
- ***BUT* the accelerator complex and detector must be able to handle the impacts of μ decays**

Collider Synergies

- High intensity beams required for a long-baseline Neutrino Factory are readily provided in conjunction with a Muon Collider Front End
- Such overlaps offer unique staging strategies to guarantee physics output while developing a muon accelerator complex capable of supporting collider operations
- Applications beyond HEP

$$\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$$
$$\mu^- \rightarrow e^-\bar{\nu}_e\nu_\mu$$

$\mu^+\mu^-$ Collider Luminosity

Detector and Physics Performance at a Muon Collider
N. Bartosik et al 2020 JINST 15 P05001

- For a muon collider, we can write the luminosity as:

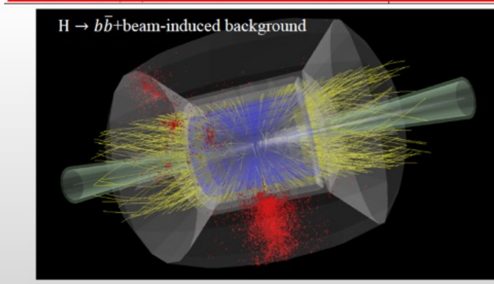
$$\mathcal{L} = \frac{N^2 f_{coll}}{4\pi\sigma_x\sigma_y} = \frac{\langle N^2 \rangle_{n_{turns}} n_{turns} f_{bunch}}{4\pi\sigma_\perp^2}$$

- For the 1.5 TeV muon collider design, we have
  - N = 2×10^{12} particles/bunch
  - $\sigma_{x,y}$ ~ 5.9 µm, β^* = 10 mm, $\varepsilon_{x,y}(norm)$ = 25 µm-rad
  - n_{turns}~$10^3 \propto 150 \langle B[T] \rangle$
  - f_{bunch}=15 Hz (rate at which new bunches are injected)

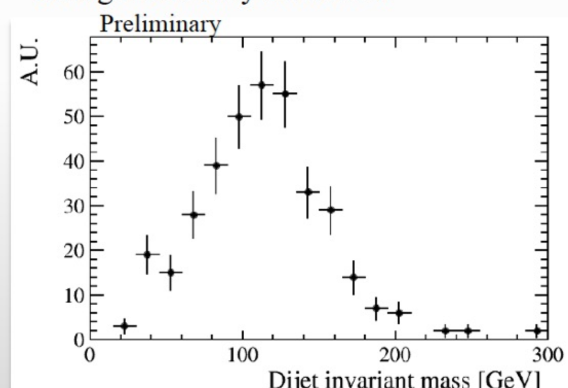
$$\mathcal{L} \approx \frac{N_0^2 n_{turns} f_{bunch}}{4\pi\sigma_\perp^2} \approx 1.4\times10^{34}\, cm^{-2} s^{-1}$$

$b\bar{b}$ Studies at $\sqrt{s}$ =1.5 TeV

Process	cross section [pb]
$\mu^+\mu^- \to \gamma^*/Z \to b\bar{b}$	0.046
$\mu^+\mu^- \to \gamma^*/Z\gamma^*/Z \to b\bar{b}$ +X	0.029
$\mu^+\mu^- \to \gamma^*/Z\gamma \to bb\gamma$	0.12
$\mu^+\mu^- \to HZ \to b\bar{b}$ +X	0.004
$\mu^+\mu^- \to \mu^+\mu^- H\ H \to b\bar{b}$ (ZZ fusion)	0.018
$\mu^+\mu^- \to \nu_\mu\nu_\mu H\ H \to bb$ (WW fusion)	0.18 Signal

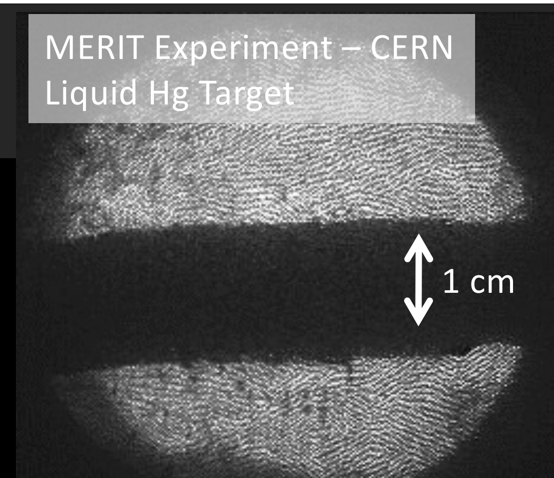


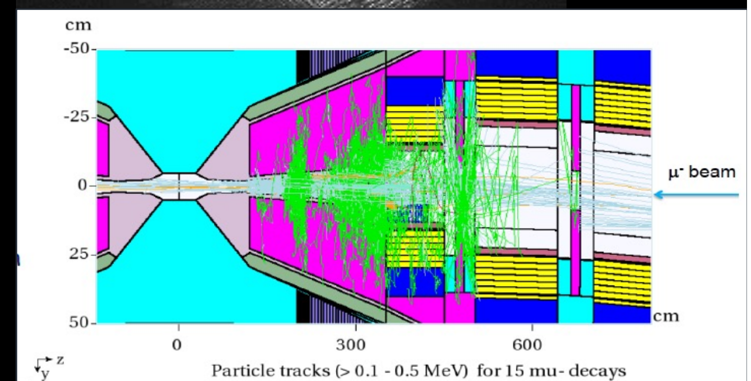
$\mu^+\mu^- \to H\nu\bar{\nu} \to b\bar{b}\nu\bar{\nu}$ + beam-induced background fully simulated

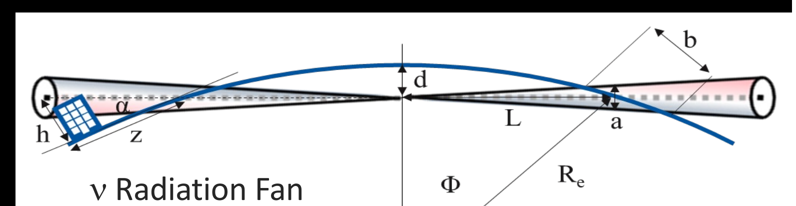


The Physics Challenges

- Muons are difficult to produce
  - Most effective route is tertiary production from a multi-MW proton beam on a target: $\mathbf{p} \longrightarrow \pi \longrightarrow \mu$
  - Beams must be bunched and cooled to produce luminosity in a collider
- Muons decay
  - All beam manipulations must be rapidly carried out to deliver useable beams to a collider
    - Bunching
    - Cooling
    - Acceleration
  - Electrons from the muon decays deposit significant energy in the accelerator components and physics detector
  - Neutrinos from the muon decays can produce ionizing radiation far from the accelerator complex







High Energy Physics

- A Brief Perspective

Why Muons?

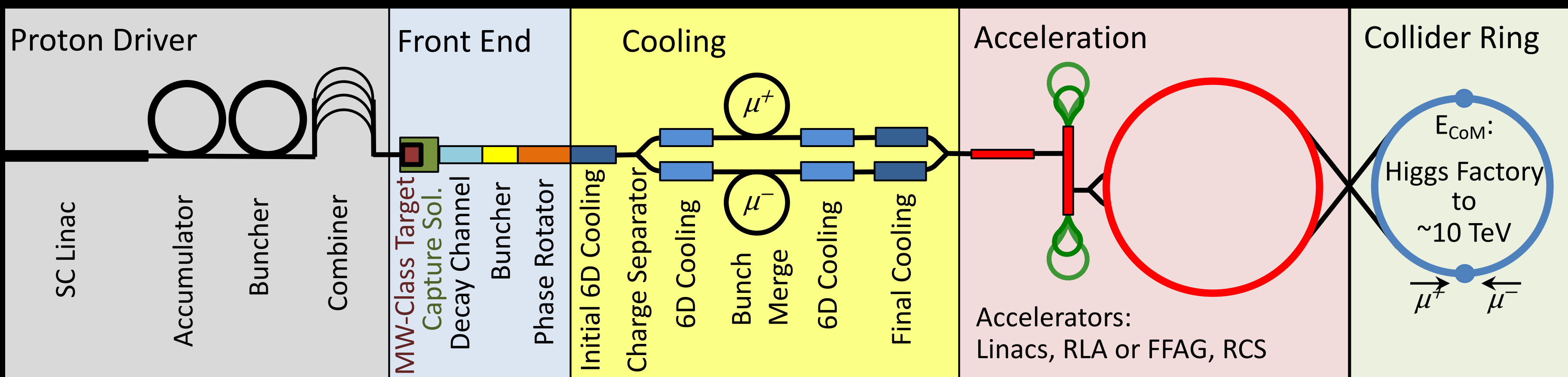
- A Vehicle for Discovery
- The Physics Challenges

A Muon Collider

- Machine Concepts
- **Charting a Path Forward**

Proton-Driven MC Concept

Muon Collider



Short & intense proton bunches to deliver hadronic showers

p→π→μ → bunched beams

Ionization cooling reduces the transverse & longitudinal emittance

Rapid acceleration to high energy to avoid μ losses. Multi-pass acceleration offers energy efficiency.

μ-Collider Goals:
126 GeV ⇨ ~14,000 Higgs/yr
Multi-TeV ⇨ Lumi > 10^{34}cm^{-2}s^{-1}

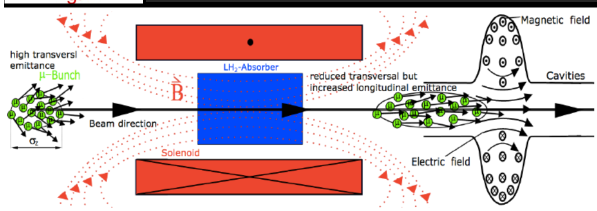
Accelerator design is driven by the short muon lifetime

After the 2014 P5, the MAP effort concluded. What has changed?

The Physics Landscape

Muon Collider R&D Progress

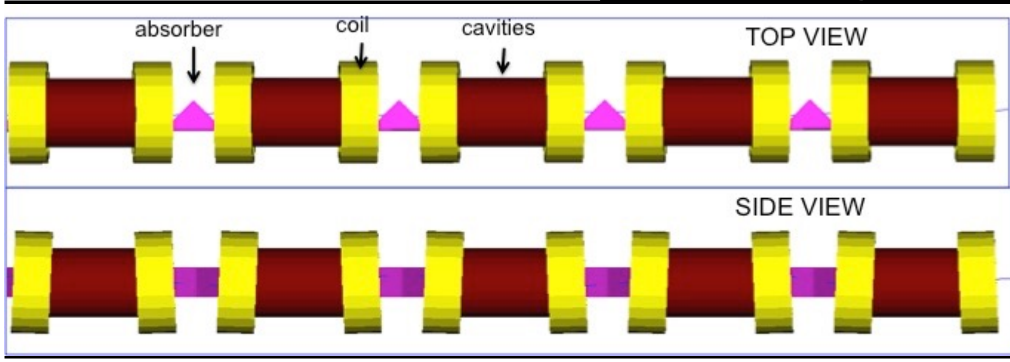
What has changed? *Concept Maturity*

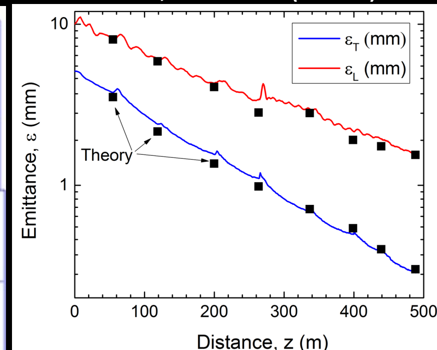


One Example: Ionization Cooling

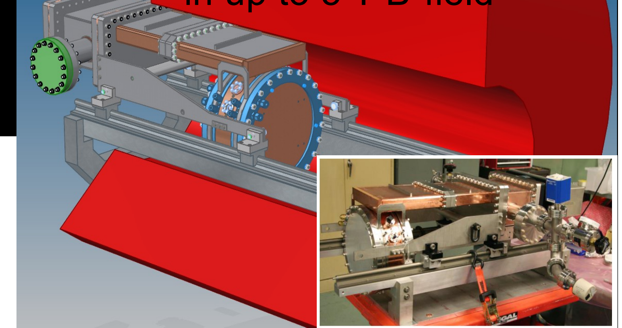
Cooling designs with good performance and significant room for improvement based on recent R&D

Rectilinear Cooling Channel – PRSTAB 18, 031003 (2015)

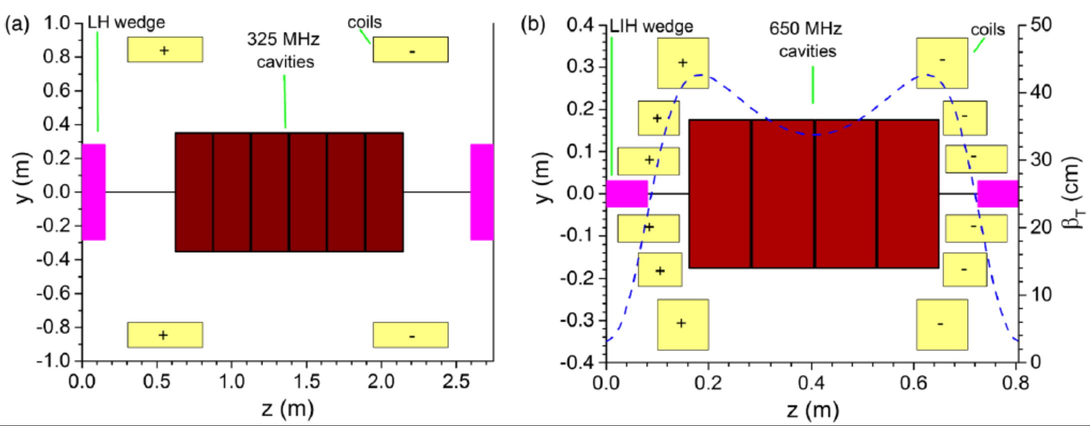




>50MV/m operation in up to 5 T B-field



MICE Cooling Channel



MICE Demo of Ionization Cooling

Nature **578,** 53–59 (2020)

RF in Magnetic Fields

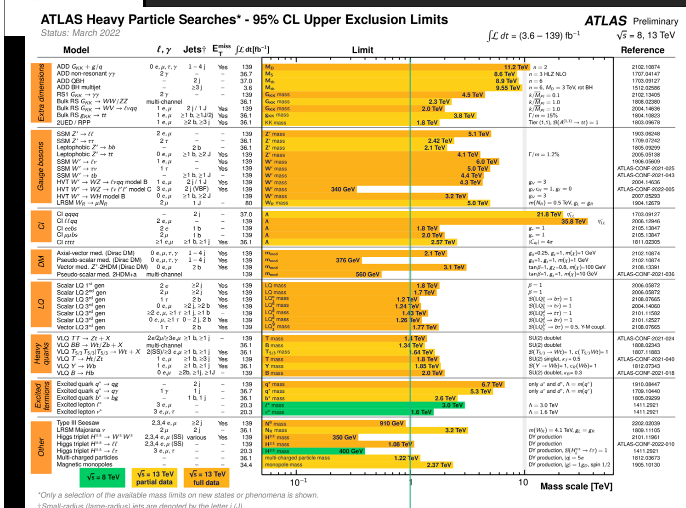
~2.5x improvement over current designs

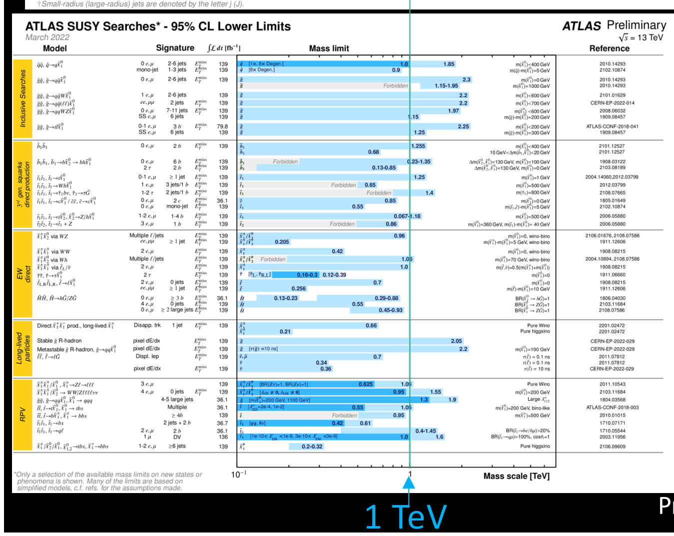
- Phys. Rev. Accel. Beams 23, 072001
- 2018 JINST 13 P01029

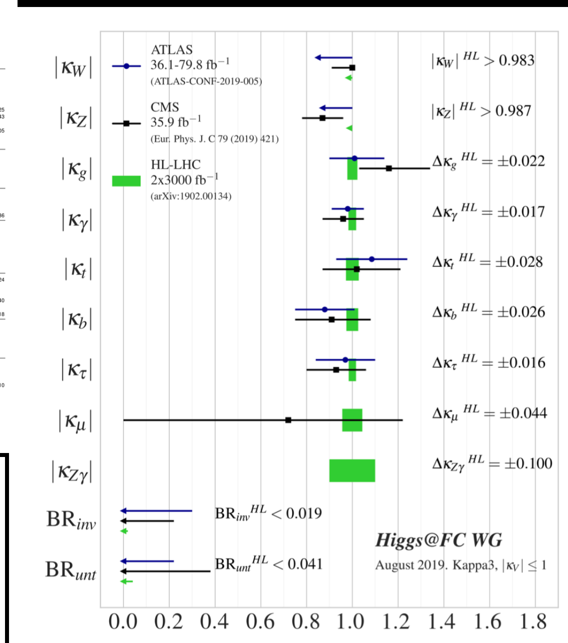
What has changed? *MC R&D Progress*

Area	Issues	Status
Target	• Multi-MW Targets • High Field, Large Bore Capture Solenoid	Ongoing >1 MW target development Solenoid specs similar to ITER Central Solenoid
Front End	• Energy Deposition in FE Components • RF in Magnetic Fields (see Cooling)	Current designs handle energy deposition
Cooling	• RF in Magnetic Field • High and Very High Field SC Magnets • Overall Ionization Cooling Performance	MAP designs use ~20 MV/m → 50 MV/m demo >30 T solenoid demonstrated for Final Cooling Cooling design that achieves most goals
Acceleration	• Acceptance • Ramping System • Complete design concept to all energies	Designs in place for accel to 125 GeV CoM Magnet system development needed for TeV-scale Additional design work needed for TeV-scale
Collider Ring	• Magnet Strengths, Apertures, & Shielding • High Energy Neutrino Radiation	Lattices with magnet conceptual design to 3 TeV ν radiation at 10 TeV currently under study
MDI/Detector	• Backgrounds from μ Decays • IR Shielding	Physics studies show good performance (2020 *JINST* **15** P05001) Further design work required for multi-TeV

What has changed? The Physics Landscape – *Generic Lessons from the LHC*







~1% tests on the Higgs

Implies roughly the ~ TeV scale for New Physics which could cause such a deviation

There *could* still be New Physics at LHC/HL-LHC…

However, data suggests generically there is a gap from EW scale to scale of New Physics

We need to be able to probe **>>1 TeV**

10 TeV is interesting as a step into the unknown but also for ***physics targets***

Courtesy Patrick Meade (SBU)

Physics Reach of a 10 TeV Muon Collider

10 TeV MC →

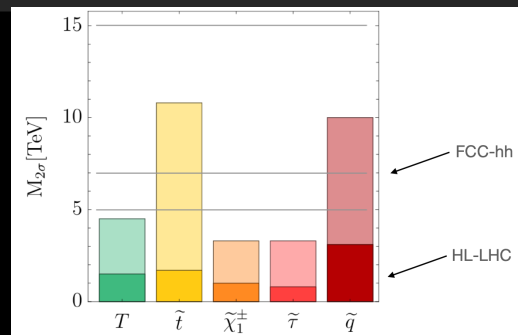
	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV + ee
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.4	0.1
κ_g	2.3	0.7	0.6
κ_γ	1.9	0.8	0.8
κ_c	-	2.3	1.1
κ_b	3.6	0.4	0.4
κ_μ	4.6	3.4	3.2
κ_τ	1.9	0.6	0.4
$\kappa^*_{Z\gamma}$	10	10	10
κ^*_t	3.3	3.1	3.1

* No input used for μ collider

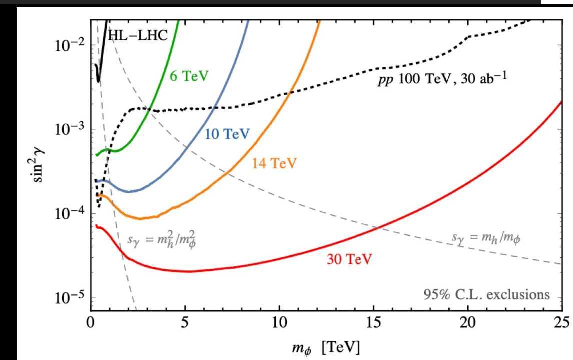
Order of magnitude in Higgs precision

and

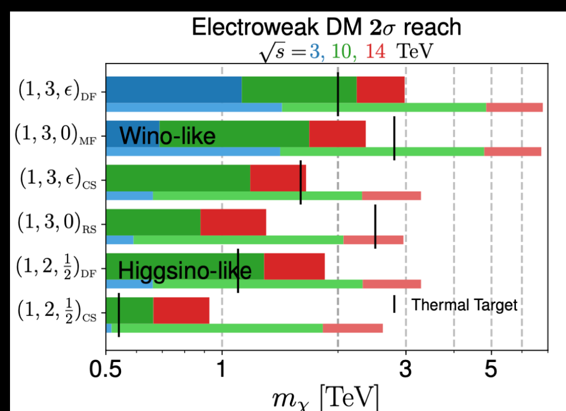
can directly probe the scale implied in same machine!



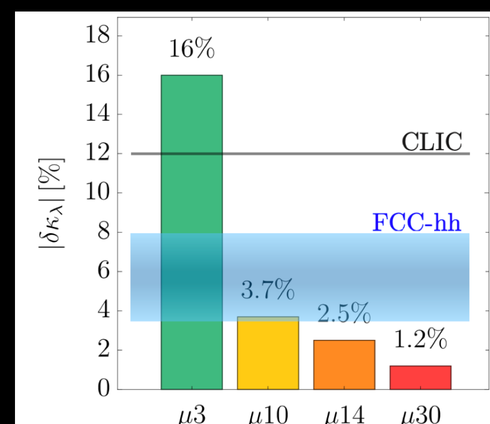
Direct production at higher scales – strongly motivated targets up to 10 TeV



Qualitatively improved reach into Higgs Portal



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



Turn Higgs potential into precision science (e.g., needed for EW phase transition)

Courtesy Patrick Meade (SBU)

Transition Initiated with the European Strategy Update

European Strategy Update

- Prior to the 2020 European Strategy Update
  - Considerable interest in LEMMA approach
  - European colleagues pursued the detector and physics analysis utilizing MAP background studies (Mokhov, et al.)
- ESPP Update supported pursuit of R&D towards a MC
- Accelerator R&D Roadmap
  - Described a technically limited program to validate MC concepts
  - Goal: Readiness for a construction decision in <20 yrs

arXiv:2201.07895 [physics.acc-ph]

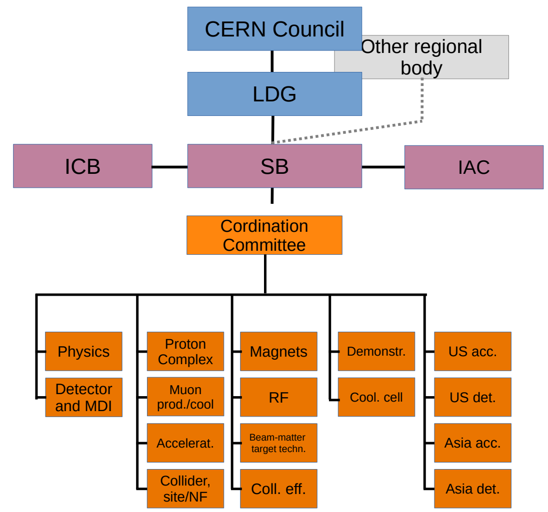
Formation of the International Muon Collider Collaboration (IMCC)

Annual meetings CERN October 2022 and Orsay June 2023

Many other meetings

- e.g. synergy meeting Orsay June 2023, …
- Design meetings on Mondays, …

Next Annual Meeting at CERN March 12-15, 2024



Governance is active: ICB 4 times, SB once, MuCol GB twice, …

Publication policy defined (Publication and Speakers Committee)

Web site to collect information on resources of partners

- Are now in “grey book”
- Started signing addenda to MoC

Courtesy D. Schulte

IMCC and MuCol Efforts

IMCC Technically Limited Timeline in Accel R&D Roadmap

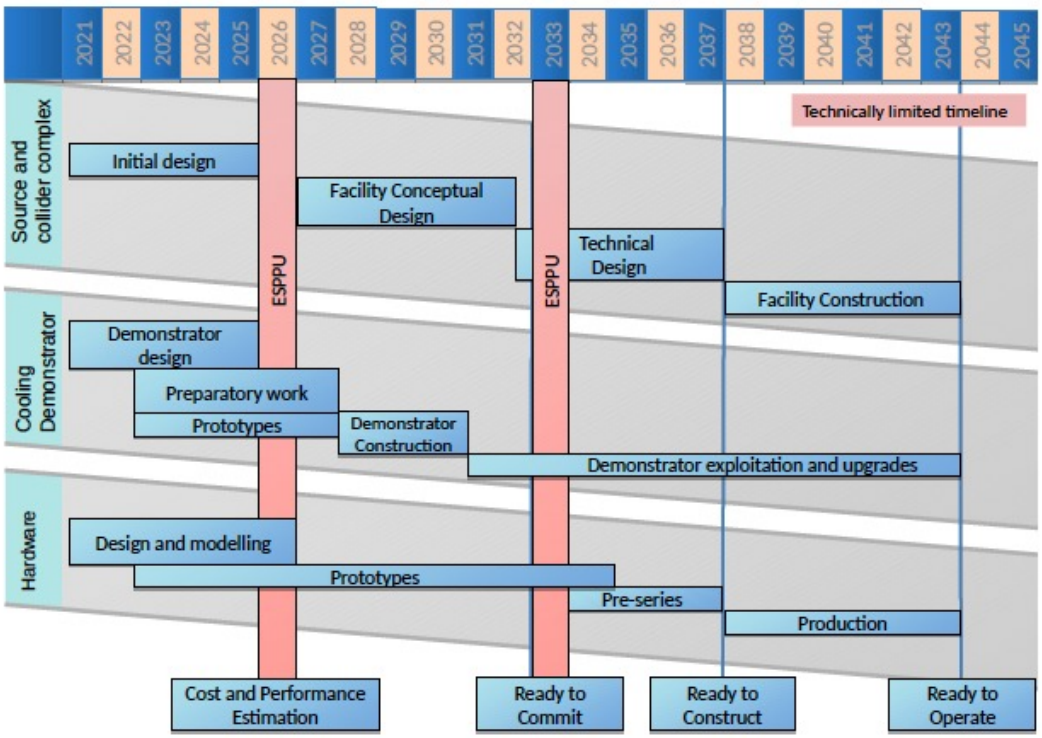
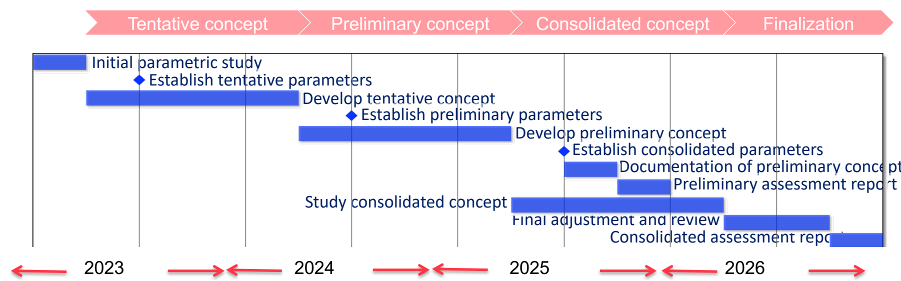


Fig. 5.3: A technically limited timeline for the muon collider R&D programme.

- [MuCol Project](#)
  - EU HORIZON funded support for MC development



Courtesy D. Schulte

A Lightning Survey of Recent Progress

MC Parameters as Developed by MAP

RAST, Vol 10, No. 01, pp. 189-214 (2019)

Table 3. Main parameters of the various phases of an MC as developed by the MAP effort.

Parameter	Units	Higgs	Top-high resolution	Top-high luminosity	Multi-TeV		
CoM energy	TeV	0.126	0.35	0.35	1.5	3.0	6.0*
Avg. luminosity	10^{34} cm$^{-2}s^{-1}$	0.008	0.07	0.6	1.25	4.4	12
Beam energy spread	%	0.004	0.01	0.1	0.1	0.1	0.1
Higgs production/10^7 sec		13,500	7000	60,000	37,500	200,000	820,000
Circumference	km	0.3	0.7	0.7	2.5	4.5	6
Ring depth [1]	m	135	135	135	135	135	540
No. of IPs		1	1	1	2	2	2
Repetition rate	Hz	15	15	15	15	12	6
$\beta^*_{x,y}$	cm	1.7	1.5	0.5	1 (0.5–2)	0.5 (0.3–3)	0.25
No. muons/bunch	10^{12}	4	4	3	2	2	2
Norm. trans. emittance, ε_T	π mm-rad	0.2	0.2	0.05	0.025	0.025	0.025
Norm. long. emittance, ε_L	π mm-rad	1.5	1.5	10	70	70	70
Bunch length, σ_s	cm	6.3	0.9	0.5	1	0.5	0.2
Proton driver power	MW	4	4	4	4	4	1.6
Wall plug power	MW	200	203	203	216	230	270

* Accounts for off-site neutrino radiation

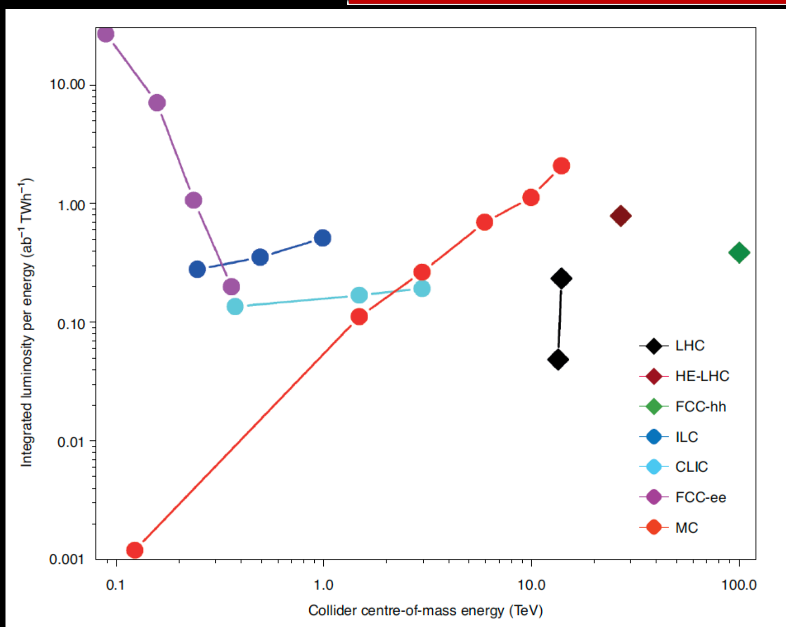
Where would the most interesting physics be for a staging option?

Parameter Sets for the International MC Collaboration

- Performance Aims:
  - Achieve the target integrated luminosity in ~5 years of running

$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

Energy Efficiency



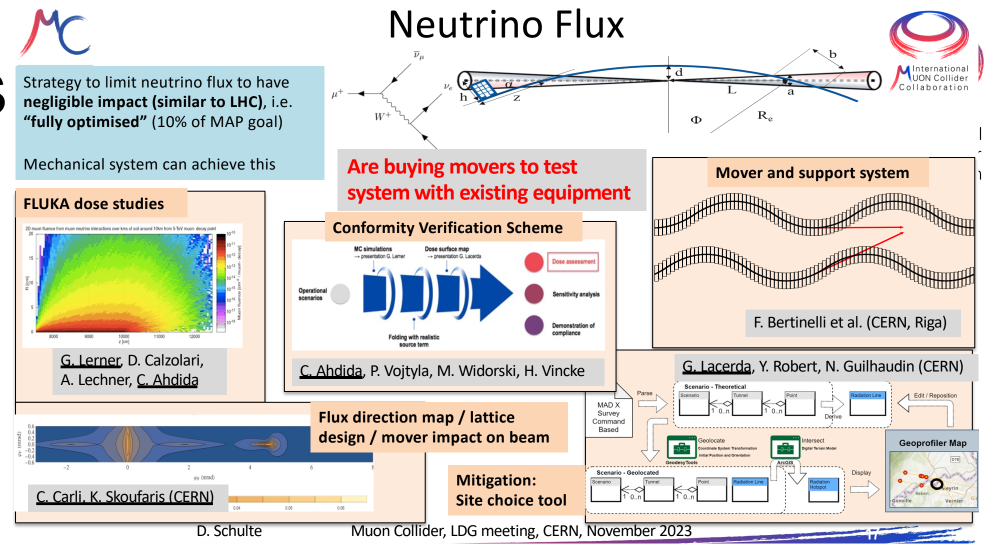
Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} $cm^{-2}s^{-1}$	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

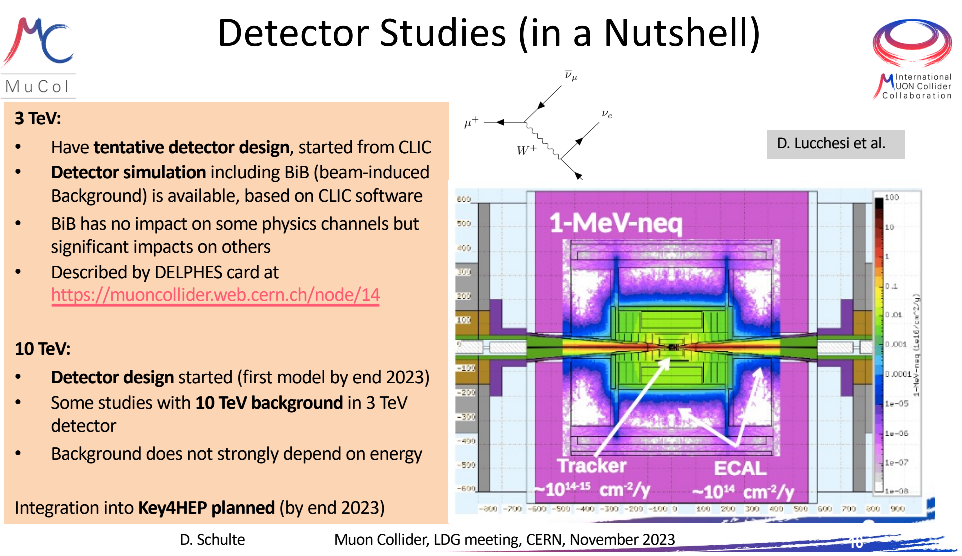
Compare: 28 MW for 3 TeV CLIC

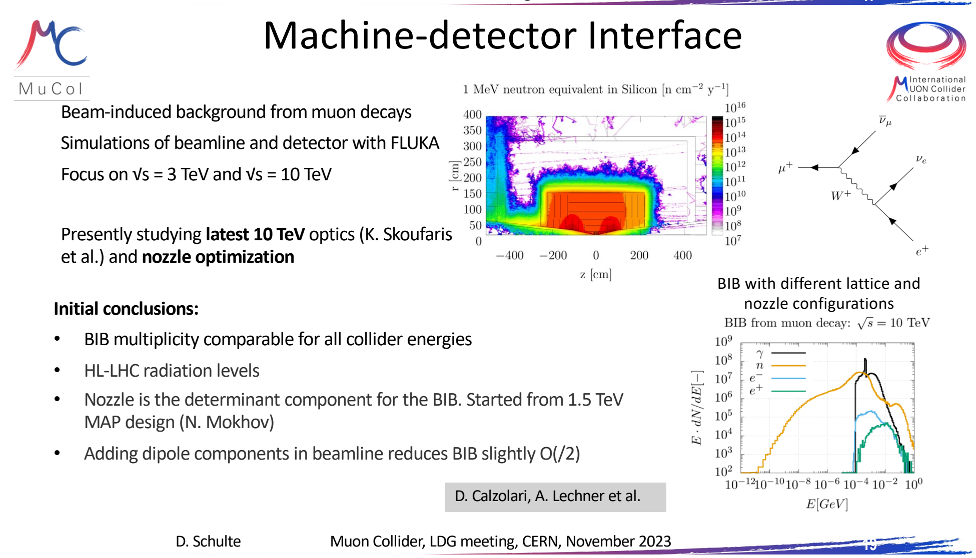
IMCC Technical Progress

MuCol

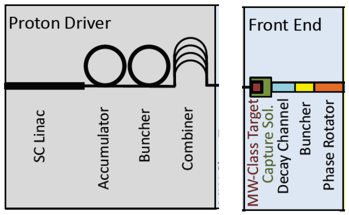
The IMCC (with MuCol) has continued development of the proton-driven MC concept from the starting point of the US MAP studies





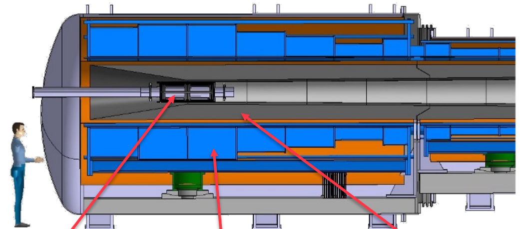


Proton Complex and Target



protons → (in target) pions → (decay) muons

400 kJ protons to produce 5 x 10^{13} captured muon pairs



5 GeV proton beam, 2 MW = 400 kJ x 5 Hz
Power is at hand

ESS and Uppsala will focus on merging beam into high-charge pulses

Optimisation of parameters planned

N. Milas, A. Lombardi et al.

Graphite **Target**

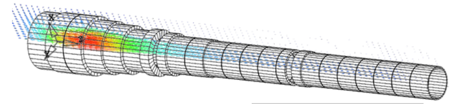
20 T **solenoid**
to guide pions and muons

Tunsten shielding
To protect magnet

D. Schulte Muon Collider, LDG meeting, CERN, November 2023

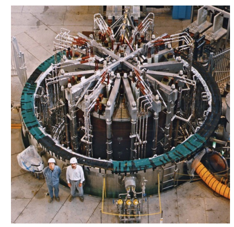
Target Studies

Target solenoid ongoing
Either large bore 20 T HTS or 15 T LTS with 5 T insert



HTS target solenoid: 20 T, 20 K

A Portone, P. Testoni, J. Lorenzo Gomez, F4E

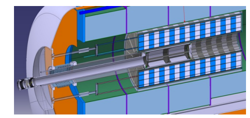


ITER model coil: 13 T
Nb_3Sn 1.7 m diameter

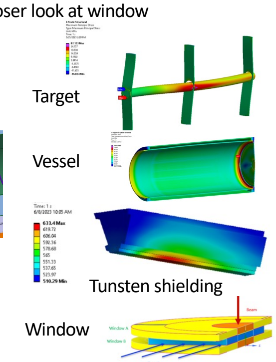
Our work is relevant for fusion

FLUKA studies:
2 MW target: stress in target, shielding, vessel OK
Need to have closer look at window
Cooling OK

Integration



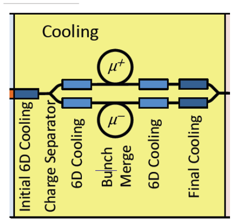
Cooling, vacuum, mechanics, …



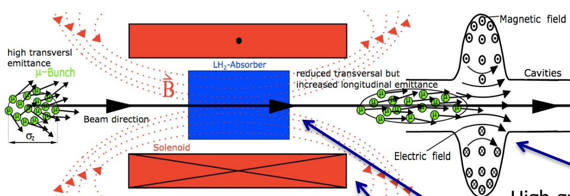
A. Lechner, R. Franqueira Ximenes et al.

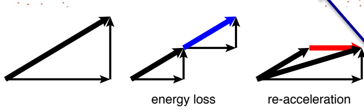
D. Schulte Muon Collider, LDG meeting, CERN, November 2023

Muon Cooling Principle (for Reference)



C. Rogers, B. Stechauner, E. Fol et al. (RAL, CERN)

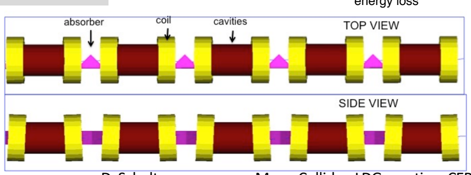




High-gradient normal-conducting cavities

Robust absorbers

High-field, superconducting solenoid



D. Schulte Muon Collider, LDG meeting, CERN, November 2023

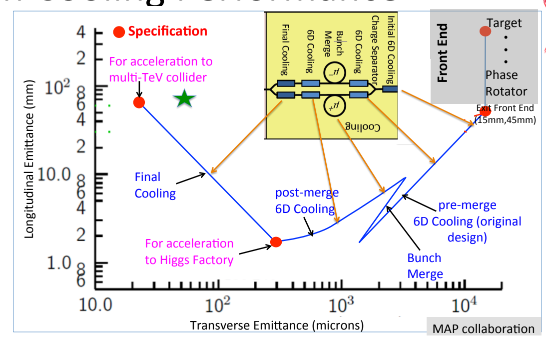
Muon Cooling Performance

MAP design achieved 55 um based on achieved fields

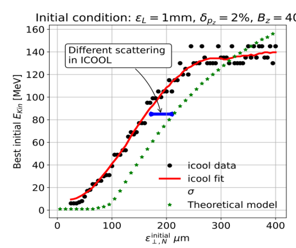
Can expect better hardware

Integrating physics into **RFTRACK**, a CERN simulation code with single-particle tracking, collective effects, …

A. Latina, E. Fol, B. Stechauner at al.

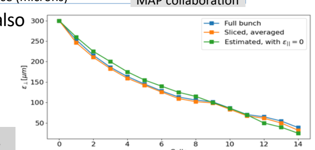


MAP collaboration



Working on **improved, systematic design**, also using better magnets and RF

Currently improved from 55 um to 33 um, 25 um is the goal



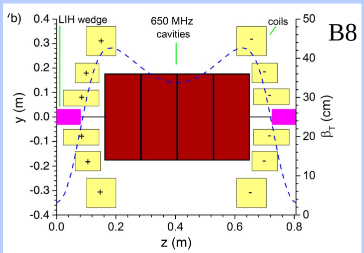
Ch. Rogers, Zhu Ruihu, B. Stechauner, E. Vol et al.

D. Schulte Muon Collider, LDG meeting, CERN, November 2023

Cooling Cell Technology

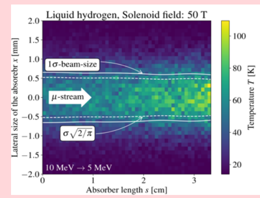
Develop example **cooling cell with integration**
- tight constraints
- additional technologies (**absorbers**, instrumentation,...)
- early preparation of **demonstrator facility**

L. Rossi et al. (INFN, Milano, STFC, CERN), J. Ferreira Somoza et al.

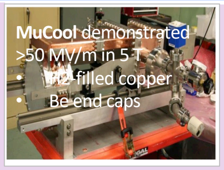


Most complex example 12 T

Windows and absorbers for high-density muon beam
- Pressure rise mitigated by gas density
- Plan window test in HiRadMat



RF cavities in magnetic field
MAP demonstrated higher than goal gradient
Improve design based on theoretical understanding
Preparation of **new test stand**, but needs funding
- Test stand at CEA (700 MHz, need funding)
- Test at other frequencies in the UK considered
- Use of CLIC breakdown experiment considered



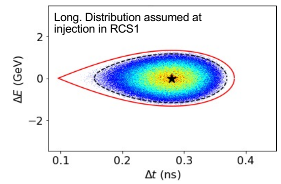
C. Marchand, Alexej Grudiev et al. (CEA, Milano, CERN, Tartu)

Collective Effects and RF Design

Longitudinal dynamics and RF important due to high bunch charge

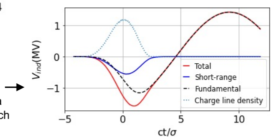
- > 30 RF stations needed
- Orbit length changes require frequency tuning required
- Single-bunch HOM power loss up to 10 kW during pulse
- CW average is lower, development of high-capacity couplers needed

A. Chance, H. Damerell, F. Batsch, U. van Rienen, A. Grudiev et al. (CEA, Rostock, Milano, CERN)
E. Metral, D. Amorim et al. (CERN)

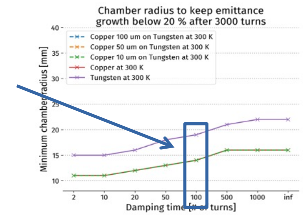


1.3 GHz appears possible for longitudinal effects and stability

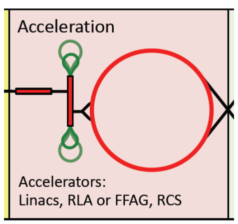
Induced voltages in RCS1 for a single bunch

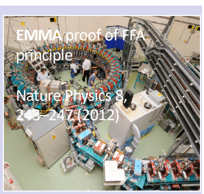


Collider ring single beam instability limits
Conservative feedback
Copper coating beneficial (few microns)
Beam-beam studies started

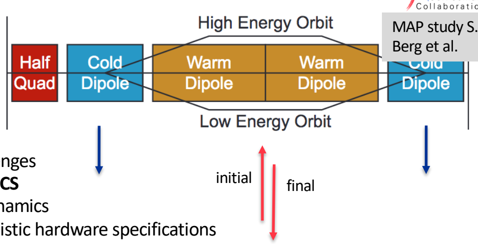


Acceleration Complex





Core is sequence of hybrid pulsed synchrotron (0.4-11
- Alternative FFA



MAP study S. Berg et al.

Started work on key challenges
- **Integrated design of RCS**
  - Longitudinal dynamics
  - Lattice with realistic hardware specifications
  - Collective effects
- **Concept of key components**
  - Fast-ramping normal magnets
  - HTS alternative
  - Efficient power converters
  - RF with transient beam loading

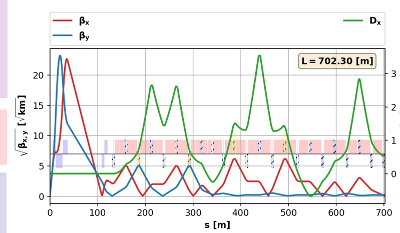
Lattice and integration: A. Chance et al. (CEA)
Long. dynamics and RF systems: H. Damerell, U. van Rienen, A. Grudiev et al. (Rostock, Milano, CERN)
Power converter: F. Boattini et al.
Magnets: L. Bottura et al. (LNCMI, Darmstadt, Bologna, Twente)
FFA: S. Machida et al. (RAL)

Collider Ring

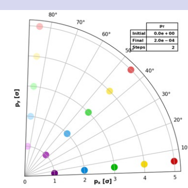
Challenges:
- Very small beta-function (1.5 mm)
- Large energy spread (0.1%)
- Maintain short bunches

MAP developed 4.5 km ring for 3 TeV with Nb_3Sn
- magnet specifications in the HL-LHC range

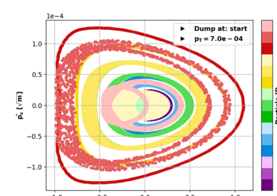
Important progress on **10 TeV collider ring**
- around 16 T HTS dipoles (lower Nb_3Sn to come)
- final focus based on HTS



K. Skoufaris, Ch. Carli, support from P. Raimondi, K. Oide, R. Tomas



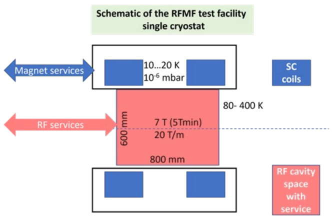
pT [%]	DAmin [σ]
0.07	5
0.08	4
0.09	3
0.1	<1



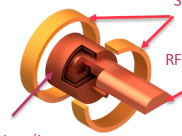
V0.6 good dynamic aperture at almost 0.1% off-energy, approaching the target

RF Test Stand

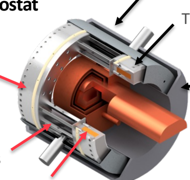
Module work currently focuses on RF test stand
- Important ensure timely R&D plan
  - Simple module example
  - To test cavities for prototype cooling modules
- Try to identify **infrastructure** for this
  - CEA, INFN, Cockroft, CERN, ...
  - Will not be cheap so need to find resources



Bare coils and RF cavity



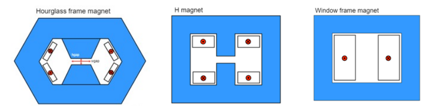
With cryostat



L. Rossi, C. Marchand, D. Giove, A. Gurdiev, G. Ferrand, M. Castoldi, S. Sorti et al.

Fast-ramping Magnet System (-> Luca)

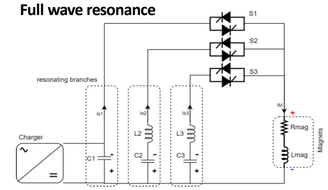
F. Boattini et al.



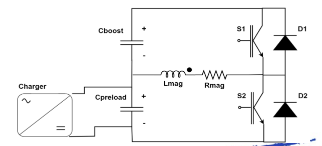
Management of the **power in the resistive dipoles** (several tens of GW):
- Minimum stored magnetic energy
- Highly efficient energy storage and recovery

Differerent power converter options investigated

Full wave resonance



Commutated resonance (new)



FNAL 300 T/s HTS magnet

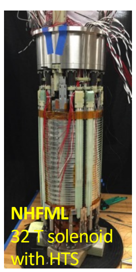
Could also use HTS driven dipoles

Simple HTS racetrack dipole could match the beam requirements and aperture for static magnets

Solenoid R&D

Started **HTS solenoid** development for high fields
Synergies with fusion reactors, NRI, power generators for windmills, ...

A Portone, P. Testoni, J. Lorenzo Gomez, F4E



32 T LTS/HTS solenoid demonstrated

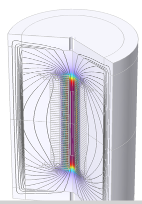
Target solenoid, 20 T, 20 K

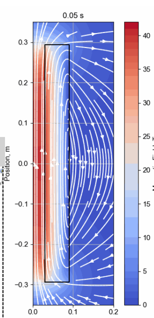
Final Cooling solenoid

$$B_{max} = 2\cdot\sqrt{\sigma_{max}\cdot\mu_0}$$

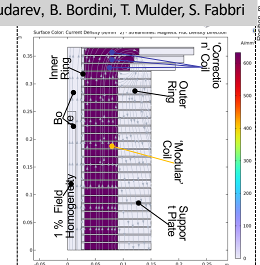
σ_{max} = 600 MPa

$B_{max} \approx$ **55 T**





A. Dudarev, B. Bordini, T. Mulder, S. Fabbri



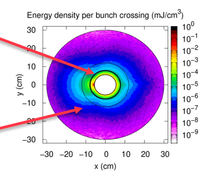
Collider Ring Technology

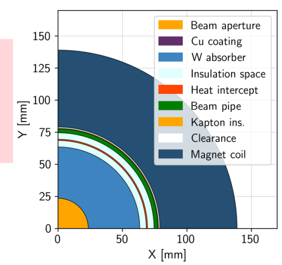
Power loss due to muon decay 500 W/m
FLUKA simulation of **shielding:**
Require 30-40 mm tungsten
- Few W/m in magnets
- No problem with radiation dose

Shielding

A. Lechner
D. Calzolari
(CERN)

Coil

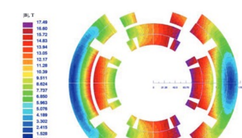


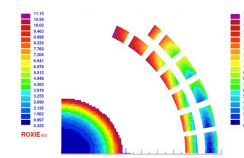


K. Skoufaris, Ch. Carli, D. Amorim, A. Lechner, R. Van Weelderen, P. De Sousa, L. Bottura et al.

L. Bottura et al.

Initial **estimate of magnet field limits**:
9 T for NbTi, 14 T for Nb_3Sn
Need **stress management**





Different **cooling scenarios** studied
< 25 MW power for cooling possible
Shield with CO_2 at 250 K (preferred) or water
Support of shield is important for heat transfer
Discussion on options for magnet cooling

R. Van Weelderen, P. De Sousa

High Energy Physics — A Brief Perspective

Why Muons? — A Vehicle for Discovery — The Physics Challenges

A Muon Collider — Machine Concepts — **Charting a Path Forward**

International MUON Collider Collaboration

Brookhaven National Laboratory

P5 "Ask" from the US MC Community

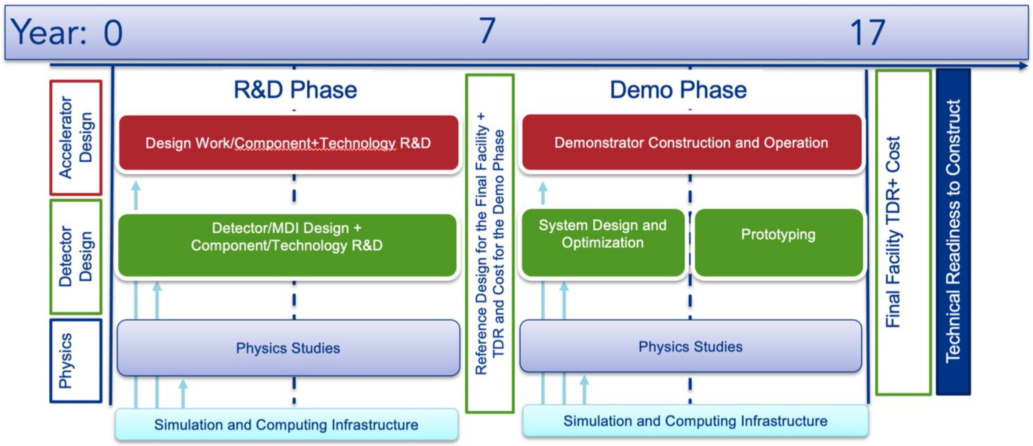


Figure 1: A sketch of the proposed muon collider R&D timeline, along with high-level activities, milestones, and deliverables.

S. Jindariani, D. Stratakis, Sridhara Dasu et al.

- Aims for the US to be a co-equal partner with Europe in an International Effort
- Timeline trails the European "technically-limited" roadmap somewhat

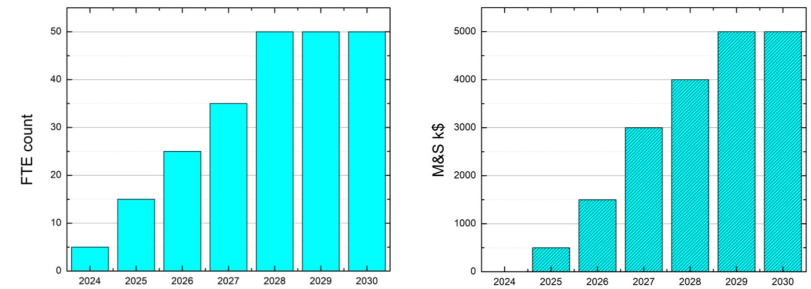


Figure 2: FTE and M&S profiles for accelerator R&D corresponding to the first phase of the program. We assume here that funding can start in 2024. The M&S is in FY23 dollars and escalation is not included in these estimates.

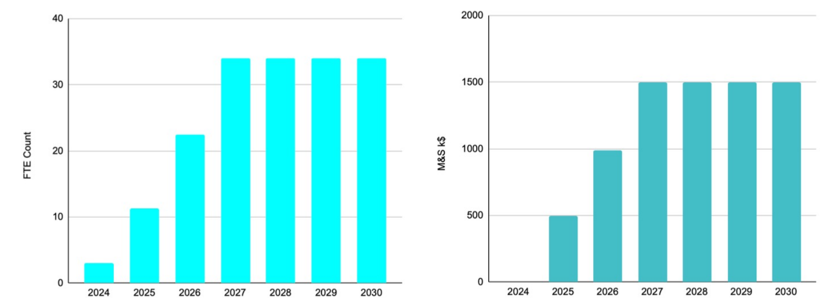
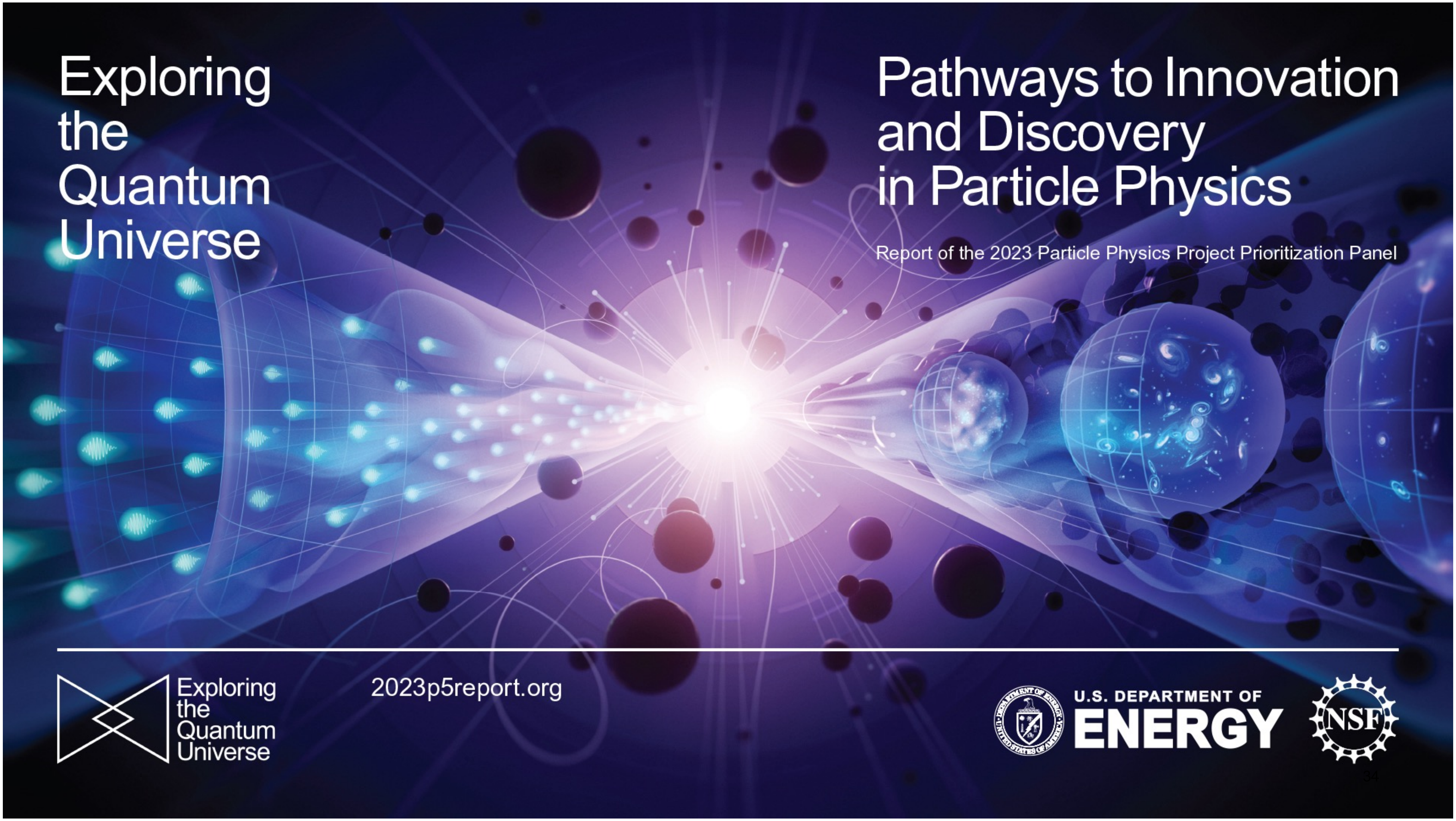


Figure 3: FTE and M&S profiles for detector R&D corresponding to the first phase of the program. We assume here that funding can start in 2024. The M&S is in FY23 dollars and escalation is not included in these estimates.

Brookhaven National Laboratory


Exploring
the
Quantum
Universe
Pathways to Innovation
and Discovery
in Particle Physics
Report of the 2023 Particle Physics Project Prioritization Panel
Exploring
the
Quantum
Universe
2023p5report.org
U.S. DEPARTMENT OF
ENERGY
NSF

Exploring the Quantum Universe

2.3 The Path to a 10 TeV pCM

Realization of a future collider will require resources at a global scale and will be built through a world-wide collaborative effort where decisions will be taken collectively from the outset by the partners. This differs from current and past international projects in particle physics, where individual laboratories started projects that were later joined by other laboratories. The proposed program aligns with **the long-term ambition of hosting a major international collider facility in the US, leading the global effort** to understand the fundamental nature of the universe.

…

In particular, a muon collider presents an attractive option both for technological innovation and for bringing energy frontier colliders back to the US. The footprint of **a 10 TeV pCM muon collider is almost exactly the size of the Fermilab campus**. A muon collider would rely on a powerful multi-megawatt proton driver delivering very intense and short beam pulses to a target, resulting in the production of pions, which in turn decay into muons. This cloud of muons needs to be captured and cooled before the bulk of the muons have decayed. Once cooled into a beam, fast acceleration is required to further suppress decay losses.

…

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 towards a muon collider. At the end of the path is an unparalleled global facility on US soil. **This is our Muon Shot.**

P5 Presentation to HEPAP Excerpt

Exploring the Quantum Universe

Recommendation 4

Not Rank-Ordered

a. Support **vigorous R&D toward a cost-effective 10 TeV pCM collider** based on proton, muon, or possible wakefield technologies, including an evaluation of options for US siting of such a machine, with a goal of being ready to build **major test facilities and demonstrator facilities within the next 10 years** (sections 3.2, 5.1, 6.5, and Recommendation 6).
b. Enhance research in **theory** to propel innovation, maximize scientific impact of investments in experiments, and expand our understanding of the universe (section 6.1).
c. Expand the **General Accelerator R&D (GARD)** program within HEP, including stewardship (section 6.4).
d. Invest in R&D in **instrumentation** to develop innovative scientific tools (section 6.3).
e. Conduct **R&D** efforts to define and enable new projects in the next decade, including detectors for an e^+e^- Higgs factory and 10 TeV pCM collider, Spec-S5, DUNE FD4, Mu2e-II, Advanced Muon Facility, and line intensity mapping (sections 3.1, 3.2, 4.2, 5.1, 5.2, and 6.3).
f. Support key **cyberinfrastructure** components such as shared software tools and a sustained R&D effort in computing, to fully exploit emerging technologies for projects. Prioritize **computing and novel data analysis techniques** for maximizing science across the entire field (section 6.7).
g. Develop plans for improving the **Fermilab accelerator complex** that are consistent with the long-term vision of this report, including neutrinos, flavor, and a 10 TeV pCM collider (section 6.6).

We recommend specific budget levels for enhanced support of these efforts and their justifications as **Area Recommendations** in section 6.

P5 Presentation to HEPAP Excerpt

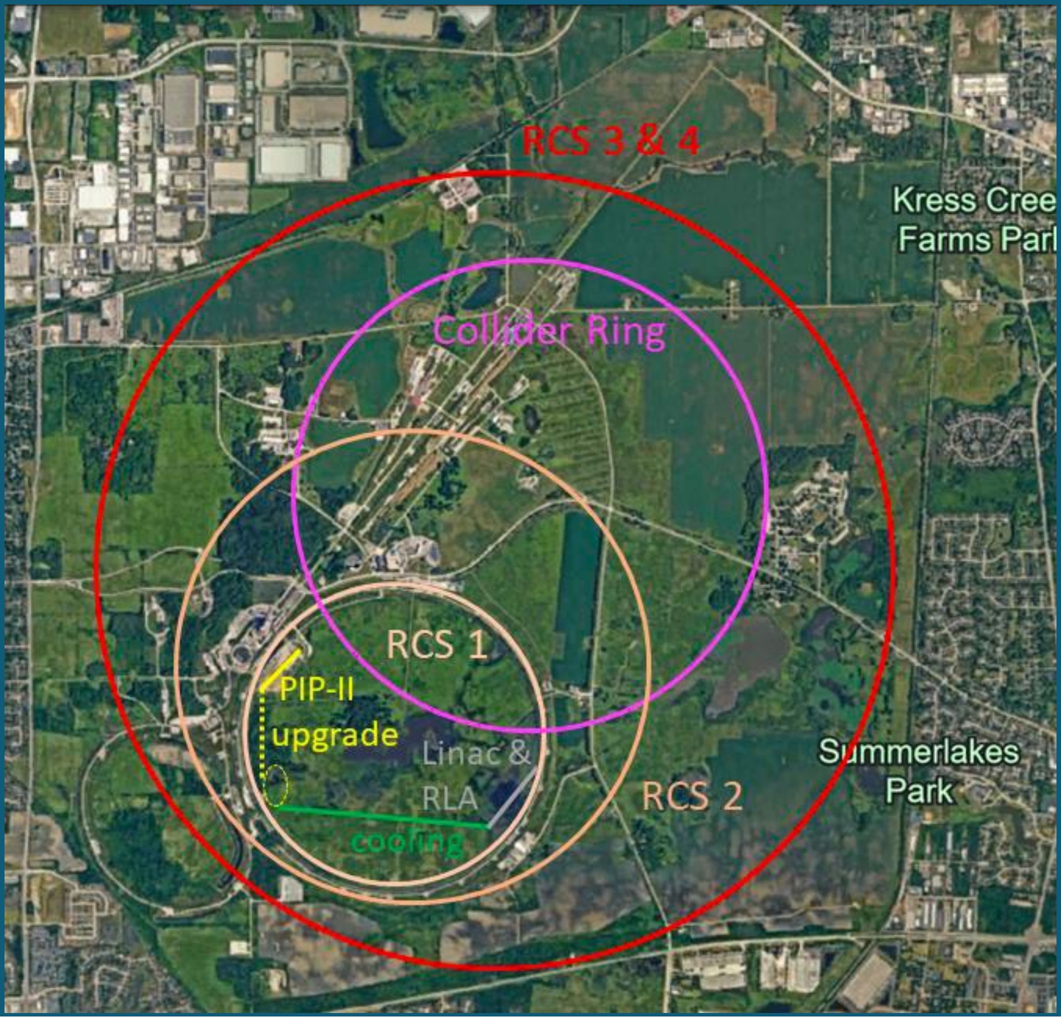
Conclusion

- A 10 TeV pCM Muon Collider R&D and design effort is currently underway!
- The 2023 P5 Report recommends establishment of a robust US Collider R&D Program
  - Both for a Higgs Factory and towards future 10 TeV pCM machines
  - With the aspiration for the US to host a future machine
  - Any of these machines will be a global endeavor
- For the US MC community, engagement with the international effort is the next critical step
  - Provide a critical mass of world-wide expertise for the R&D and Design efforts
  - Ensure that R&D and design schedules can deliver results that support a machine decision within the 20-year time frame
- Challenges do exist…
  - DOE-HEP funding is not presently at the levels assumed in the P5 Scenarios
  - Time will be required to ramp up a well-managed effort
  - International agreements need to be put in place
  - The shape of the US Collider R&D Program needs to be defined

⇨ ***Looking forward to growing a US team to engage in the Muon Shot!***

Thank you for your attention!

The potential scale of the accelerator complex for a 10 TeV MC at Fermilab



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International MUON Collider Collaboration