Muon Collider – Status and Plans

International
MUON Collider
Collaboration

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Science & Technology Facilities Council
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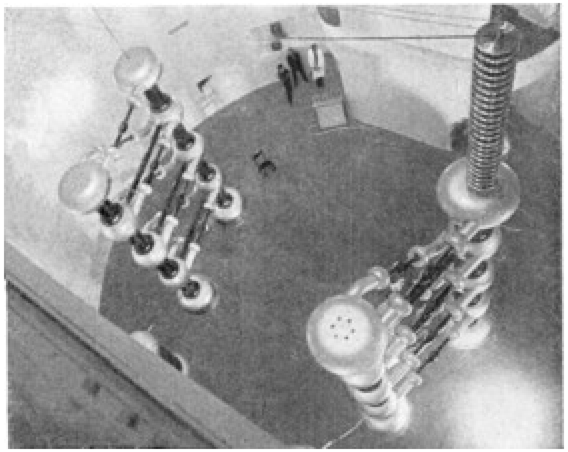
Funded by the European Union (EU). Views and opinions expressed are however those of the author only and do not necessarily reflect those of the EU or European Research Executive Agency (REA). Neither the EU nor the REA can be held responsible for them.

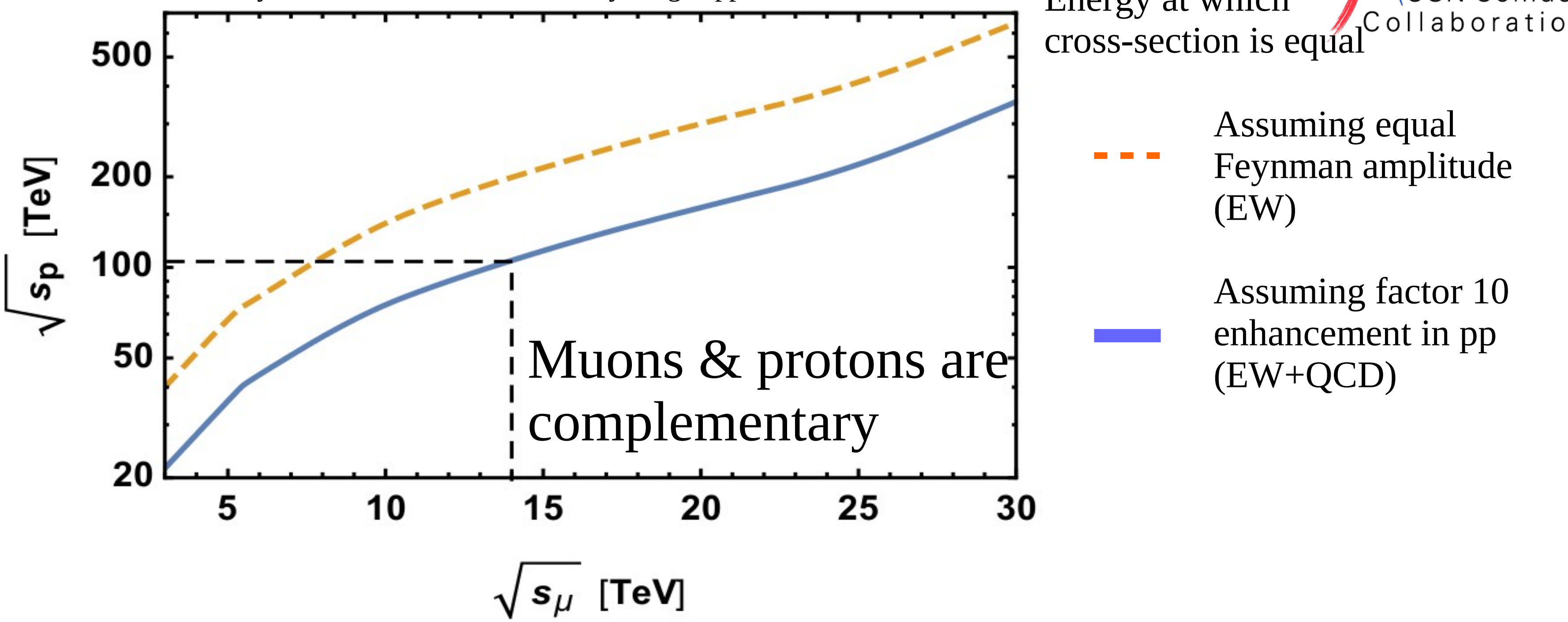
Accelerators in Physics

- First accelerators built in 1920s/30s
  - Accelerating protons, ions and electrons
  - Positrons in 1960s
  - Antiprotons in 1980s
- Tools for fundamental physics
- Hadron colliders
  - E.g. LHC
  - “Discovery machines”
- Electron positron colliders
  - E.g. Large Electron Positron Collider (LEP)
  - “Precision machines”
- Growing interest in building muon collider
  - Muons first accelerated in 2017 – new tech
  - Why muons? How?



Why Muons

Delahaye et al, arXiv:1901.06150; very rough approx!



- Proton collision energy is shared between quarks
  - Effective energy significantly reduced
- Electrons cannot reach high energy due to synchrotron radiation
  - Low mass particles emit x-rays when they are bent
- **Muons!**

Another angle

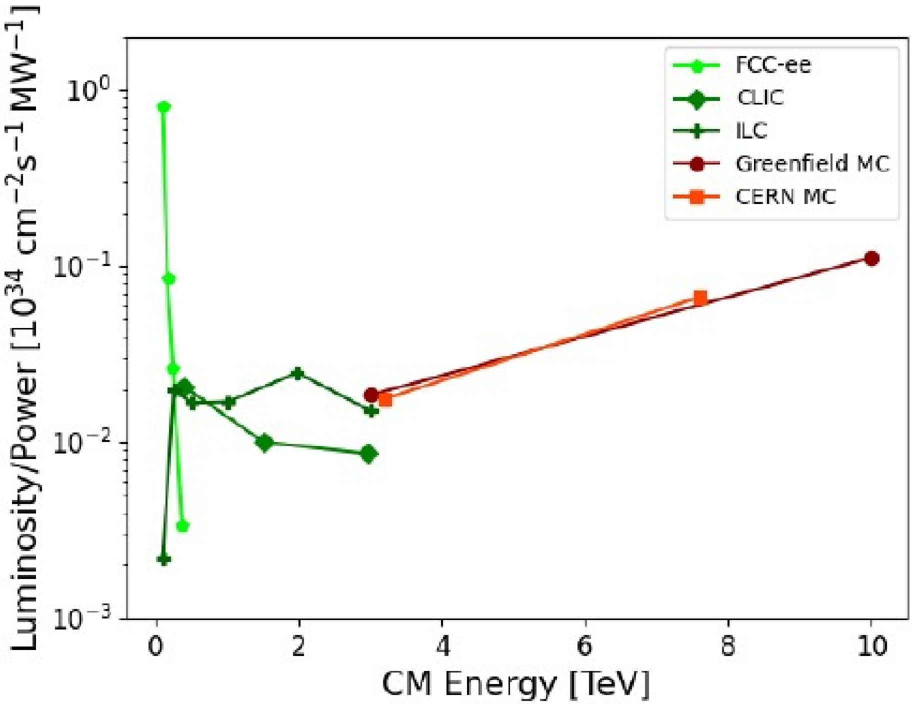
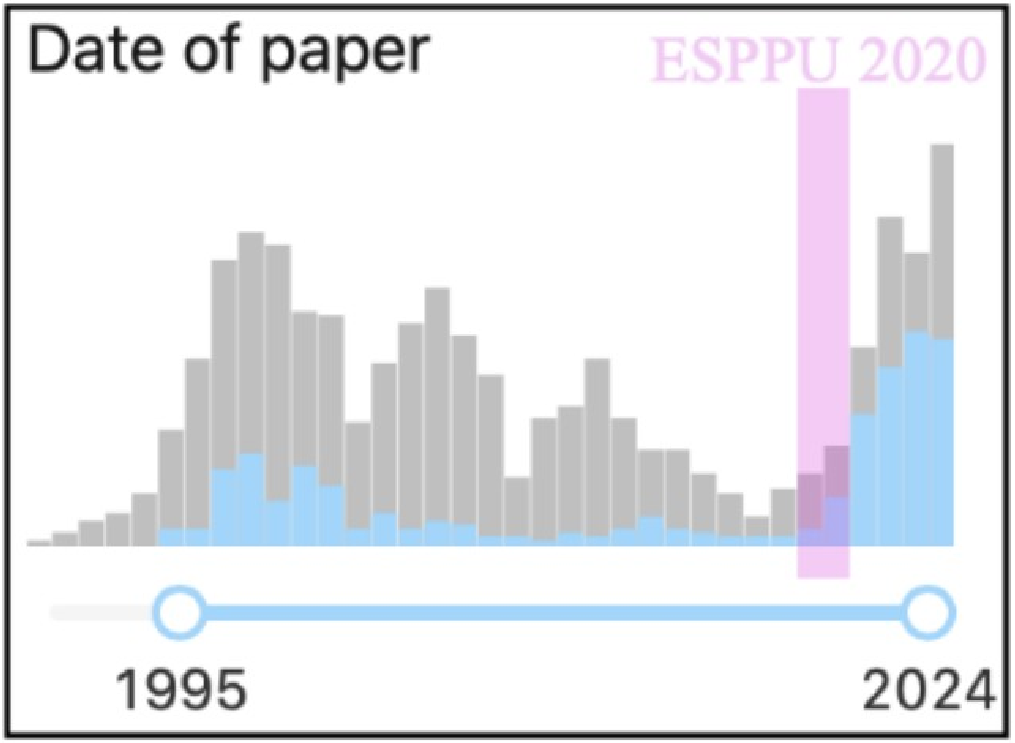
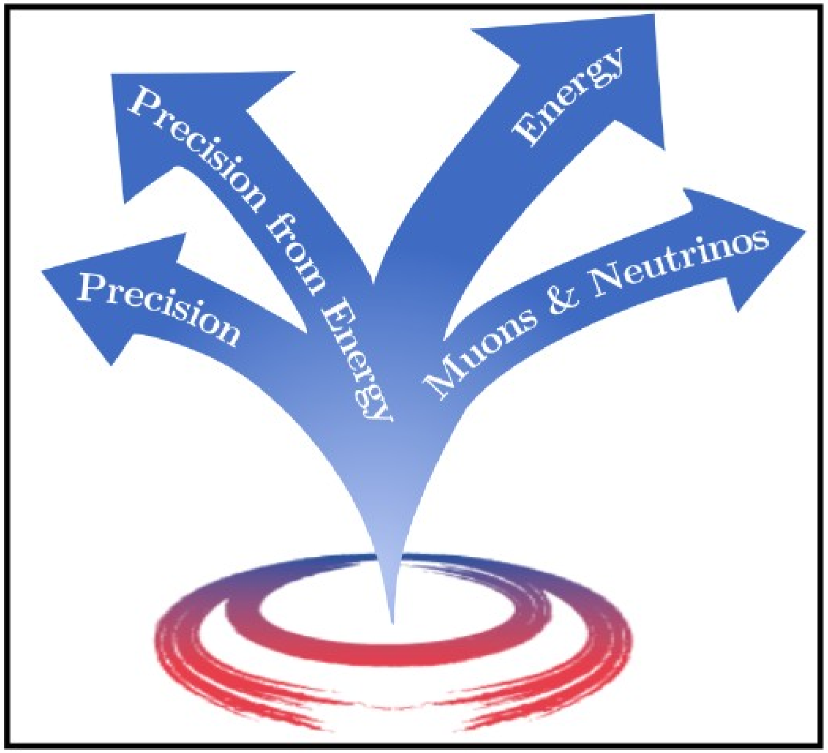


Figure 1.9.1: Ratio of luminosity to wall plug power compared to several e^+e^- machines.

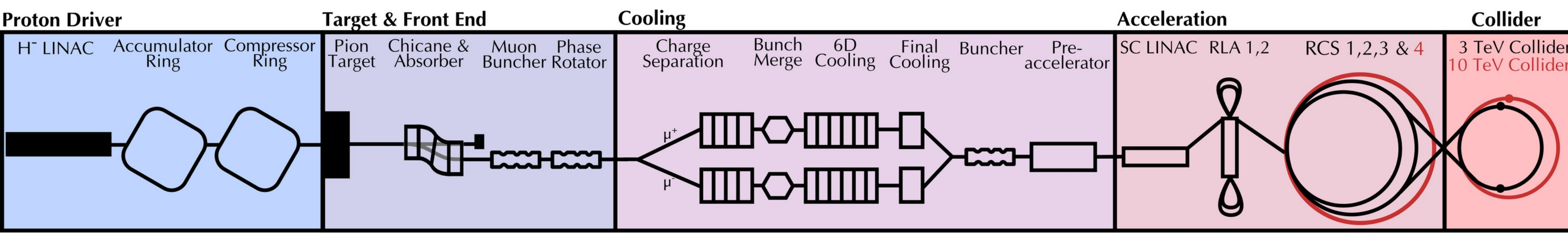
- Muons very efficient delivery of luminosity

Physics Engagement



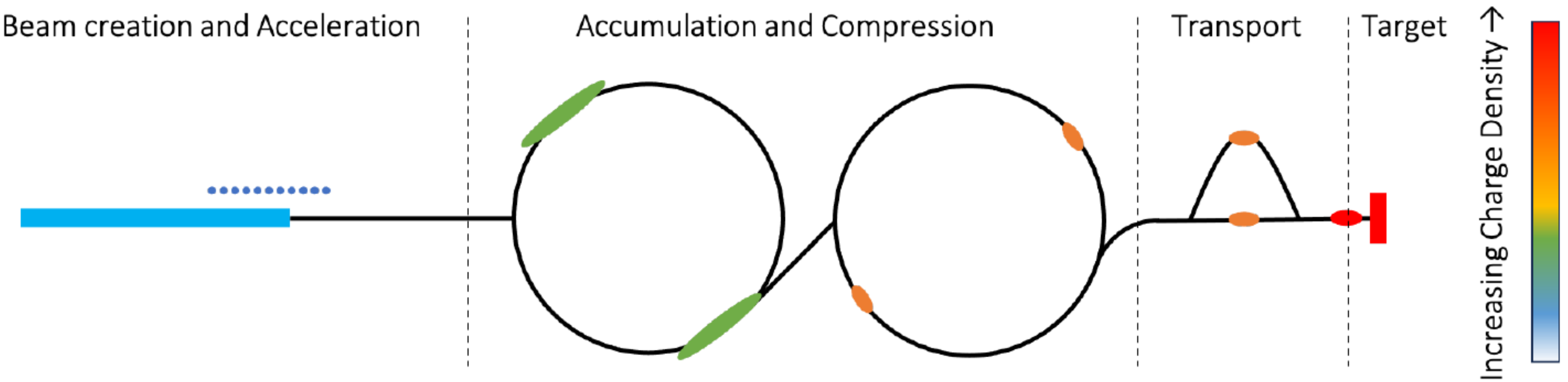


Muon Collider



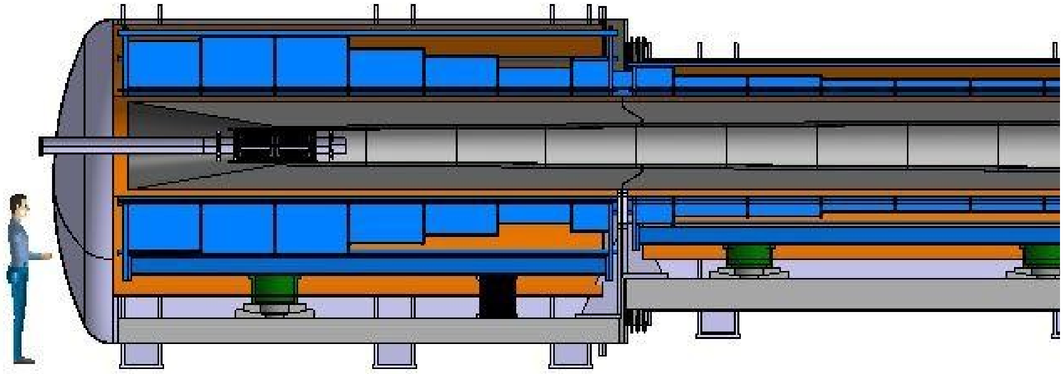
- MW-class proton driver → target
- Pions produced; decay to muons
- Muon capture and cooling
- Acceleration to TeV & Collisions
- Designed for high energy while **maximising luminosity**
  - Luminosity is key

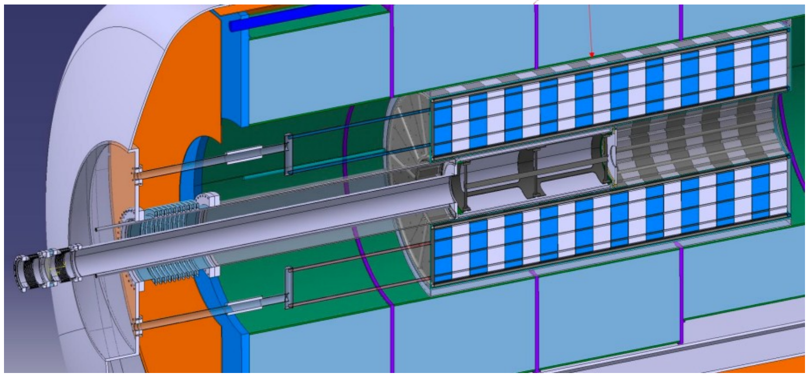
Proton Driver



- Current proton driver design
  - Linac → ~ O(millisecond) H- pulse
  - Accumulator → O(microsecond) proton pulse
  - Compressor → O(nanosecond) proton pulse

MuC Target





- Protons on target → pions → muons
  - Graphite target takes proton beam to produce pions
  - Heavily shielded, very high field solenoid captures π^+ and π^-
- Target similar to T2HK/Dune Phase 2
- Solenoid comparable to spherical tokamak solenoids
- Alternatives for higher power
  - Liquid metal
  - Tungsten Powder

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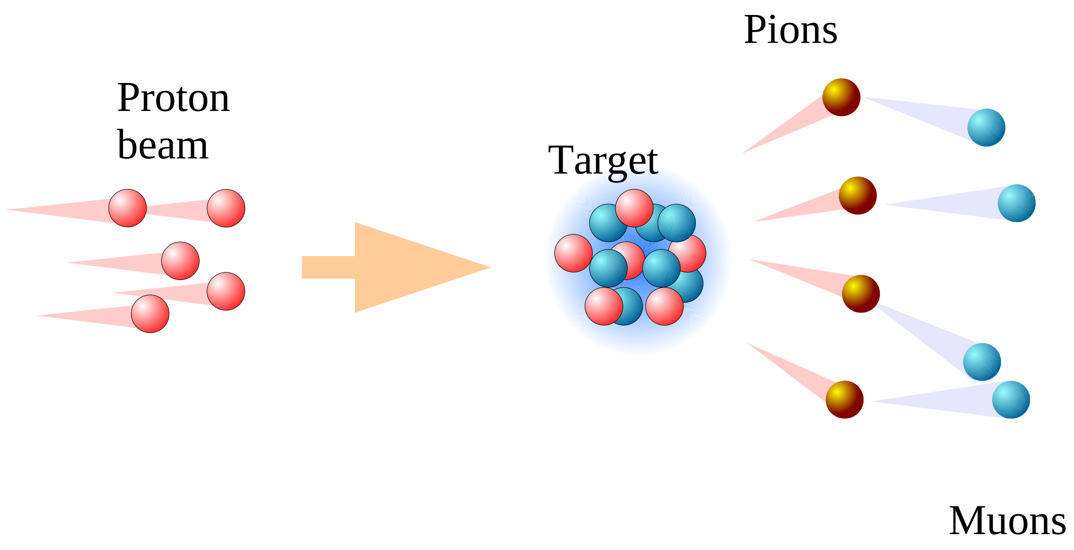
Beam brightness



- Orderly beam of protons
- Pions leave the target in many directions
- Pions decay in many different positions
- Low brightness beam
- High emittance beam

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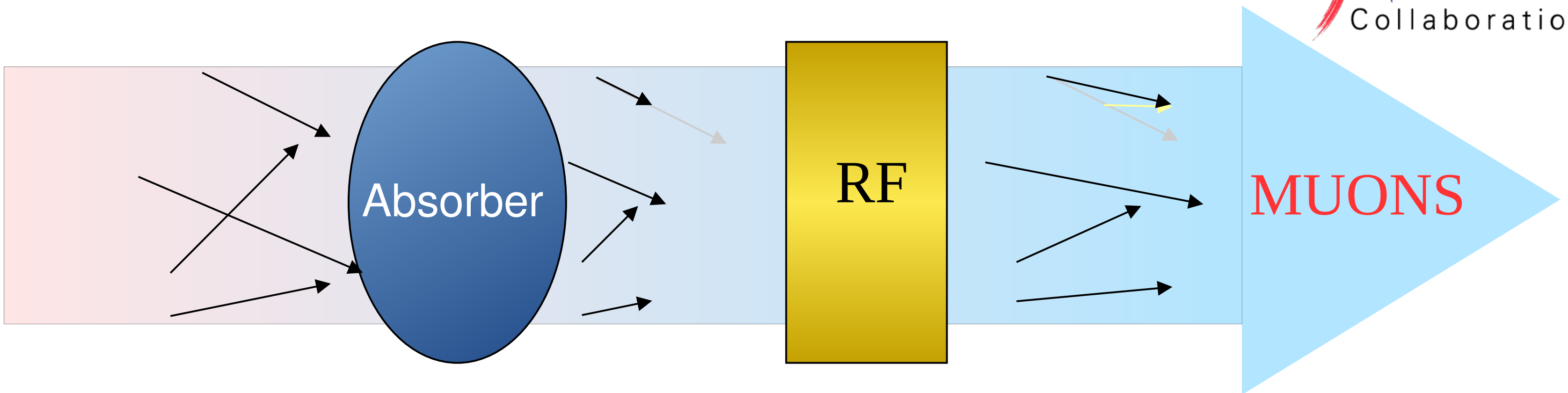
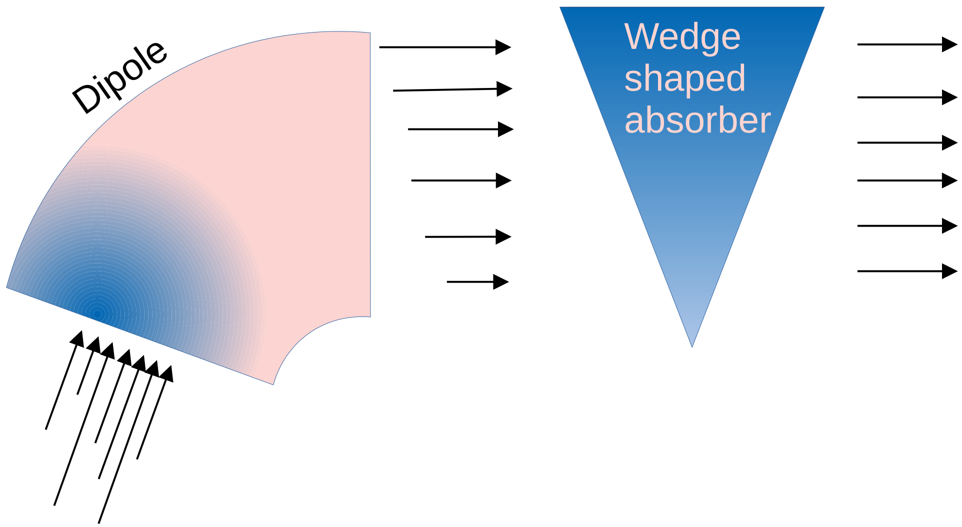
Ionisation Cooling



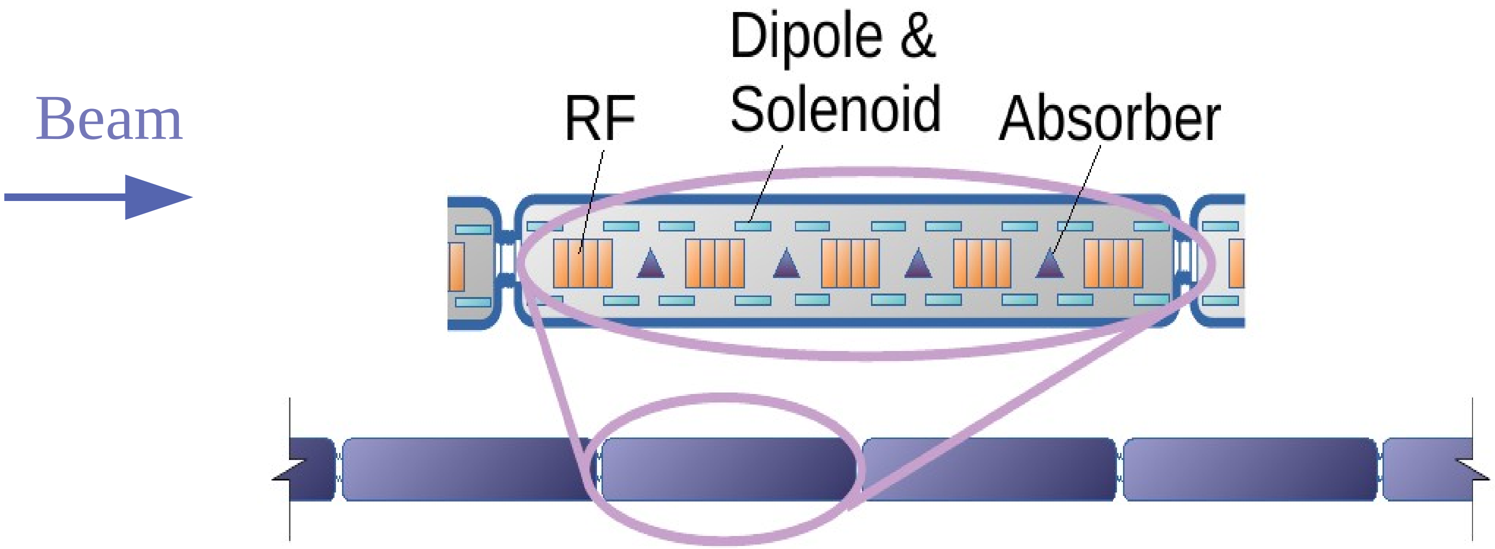
- Beam loses energy in absorbing material
  - Absorber removes momentum in all directions
  - RF cavity replaces momentum only in longitudinal direction
  - End up with beam that is more straight
- Multiple Coulomb scattering from nucleus ruins the effect
  - Mitigate with tight focussing
  - Mitigate with low-Z materials
  - Equilibrium emittance where MCS completely cancels the cooling

Emittance exchange



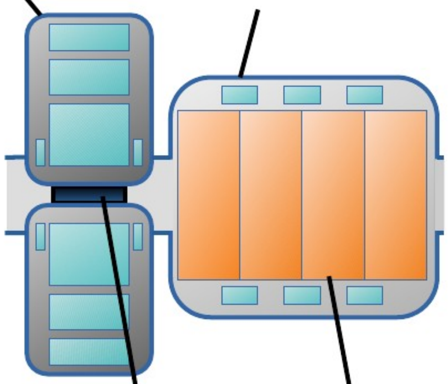
- Initial beam is narrow with some momentum spread
  - Low transverse emittance and high longitudinal emittance
- Beam follows curved trajectory in dipole
  - Higher momentum particles have higher radius trajectory
  - Beam leaves dipole wider with energy-position correlation
- Beam goes through wedge shaped absorber
  - Beam leaves wider without energy-position correlation
  - High transverse emittance and low longitudinal emittance

Rectilinear Cooling



- 6D Cooling
  - Combined function dipole-solenoid magnets
  - Compact lattice – RF integrated into magnet cryostat
  - Lithium Hydride or lH2 absorbers
  - Careful field shaping to control position of stop-bands

Final cooling



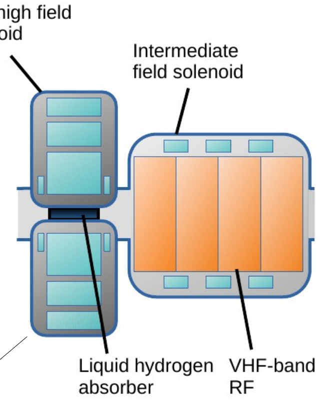
H. Sayed et al., High field – low energy muon ionization cooling channel, Phys. Rev. ST Accel. Beams 18, 2015
Fol et al, IPAC22

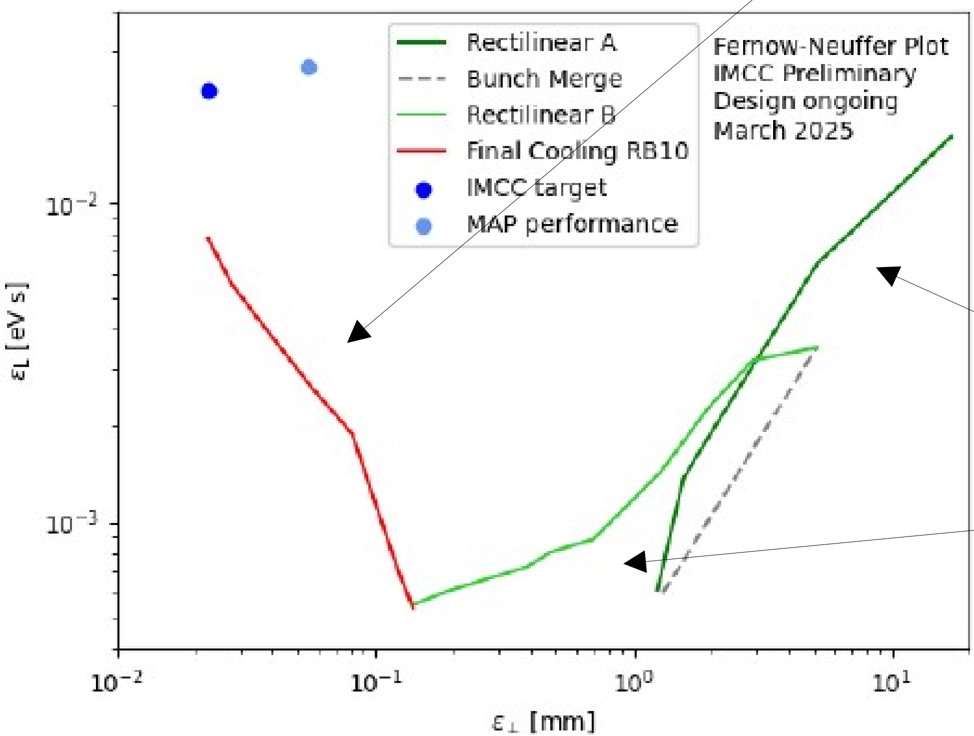
- Challenge is to get very tight focussing
- Go to high fields (~40 T) and lower momenta
  - Causes longitudinal emittance growth
  - Chromatic aberrations introduce challenges
    - Elaborate phase rotation required to keep energy spread small
    - Move to low RF frequency to manage time spread

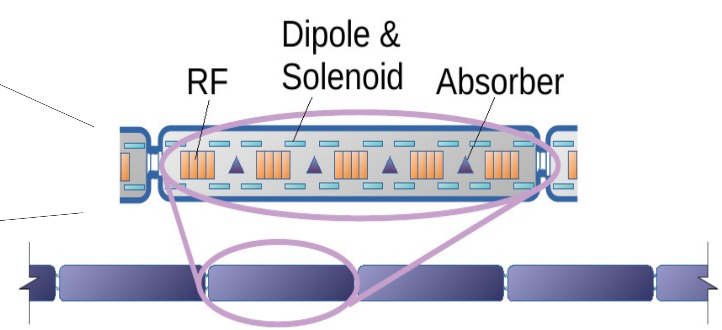
Muon Cooling

Sayed et al, PRSTAB 18, 2015
Fol et al, IPAC22

4D Final cooling







Stratakis et al, PRSTAB 18, 2015
Zhu et al, PRAB 28, 2025

Rectilinear cooling

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Muon cooling Demonstrator

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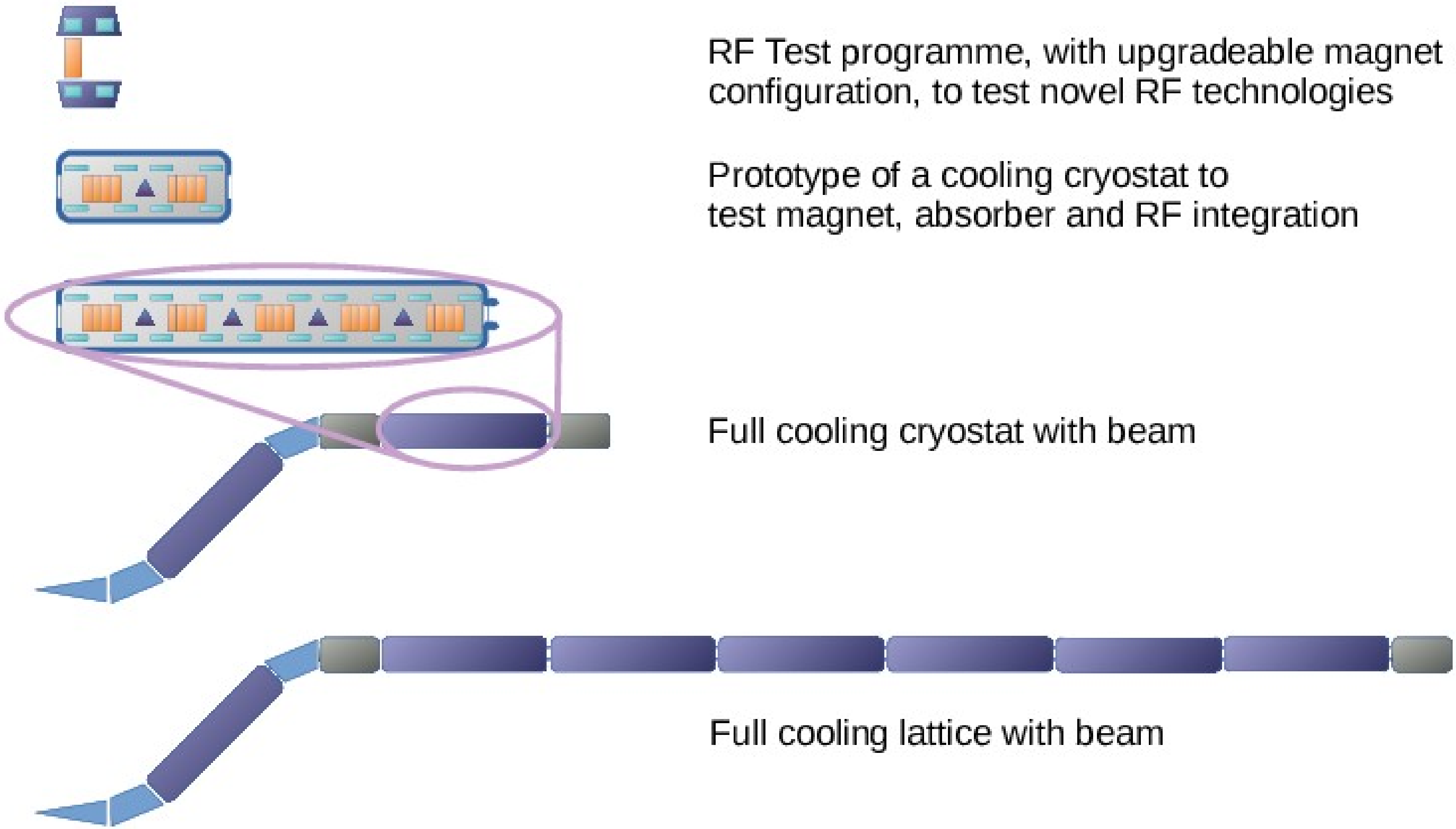

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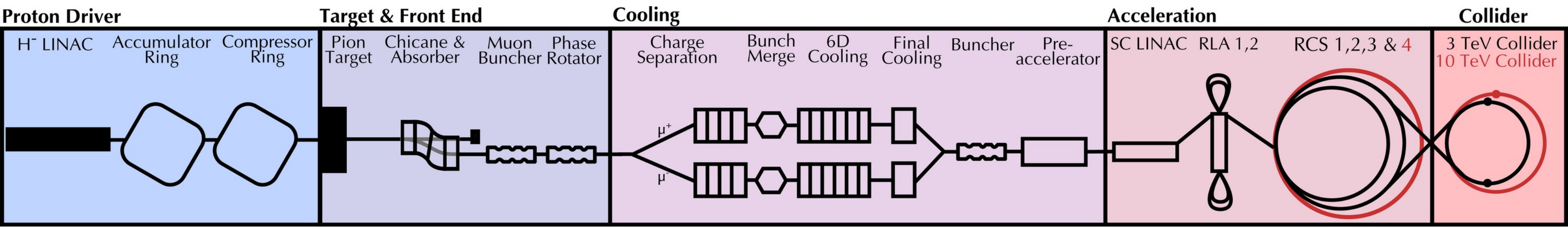
Muon Collider



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Pulsed Synchrotrons

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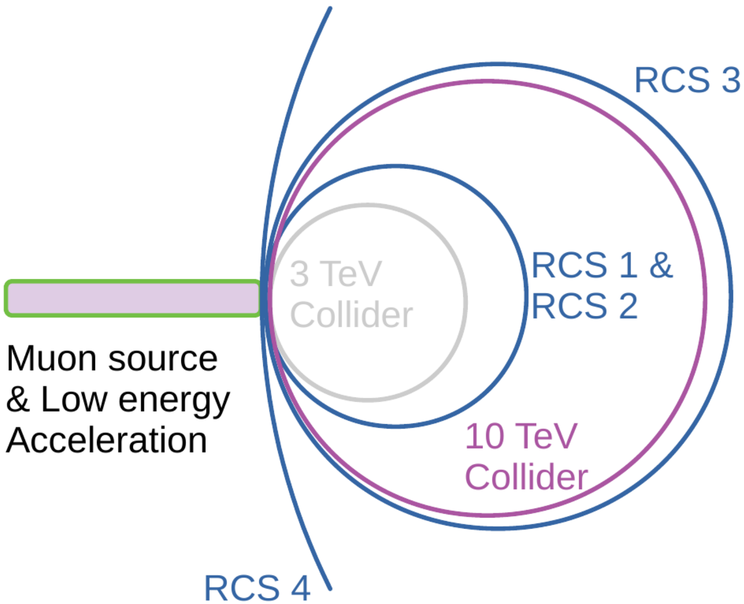
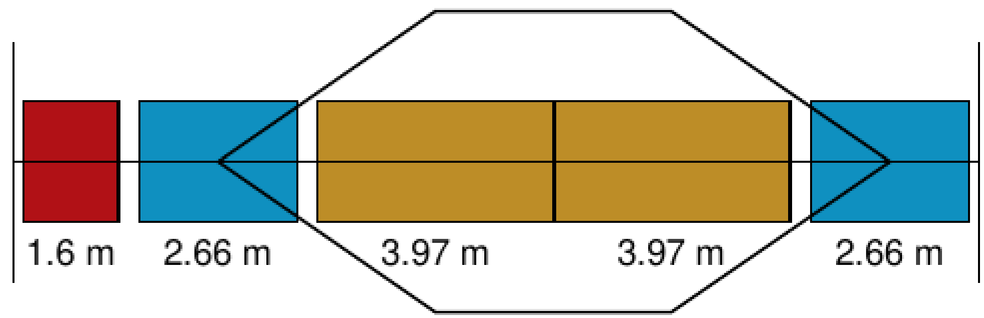
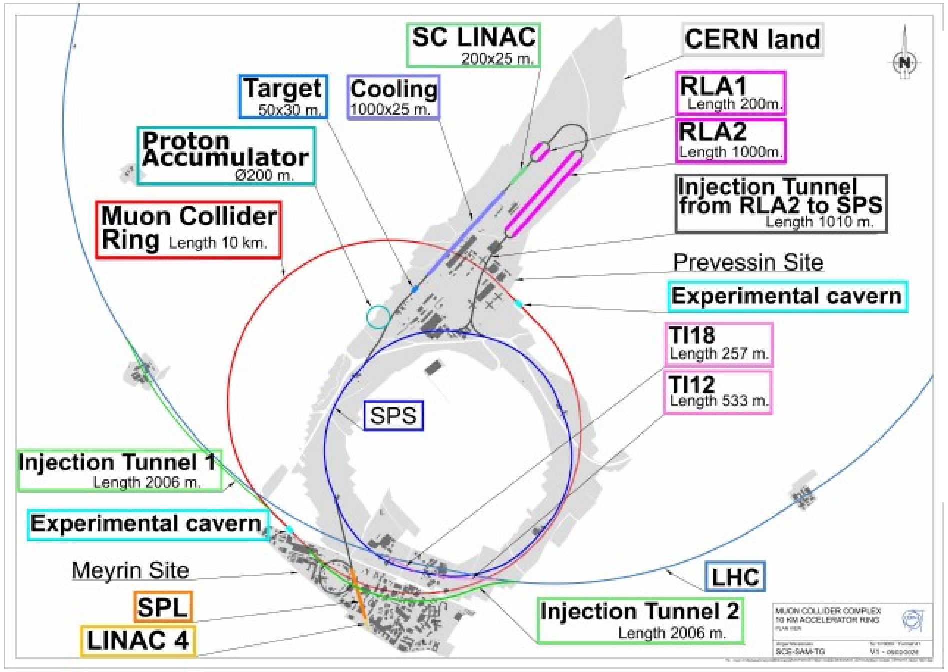




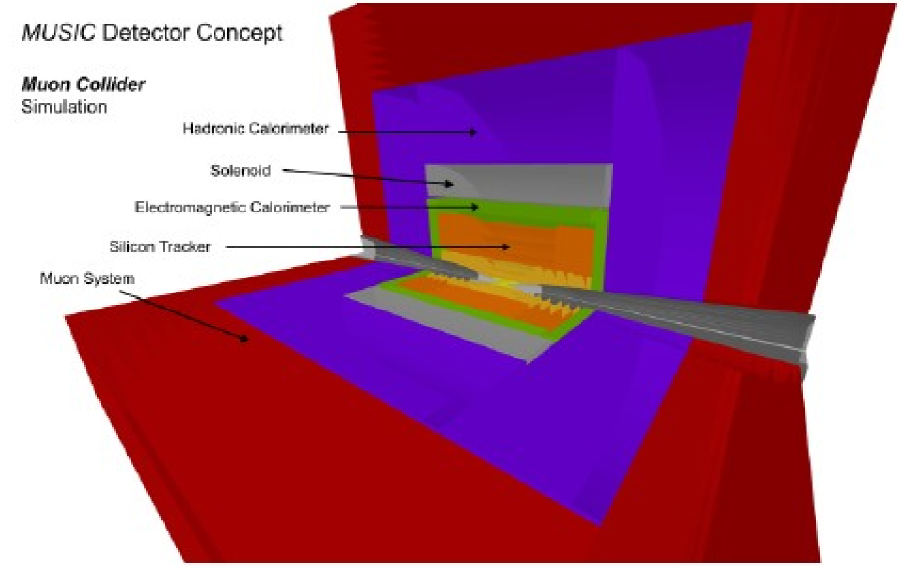
- At higher energy, can use synchrotrons
  - Ramp magnets in synchronisation with increasing beam energy
  - Need extremely fast ramp < few ms
  - To keep ring compact, use combination of
    - Fixed superconducting and
    - Pulsed normal conducting magnets
  - Shielding components from decay losses

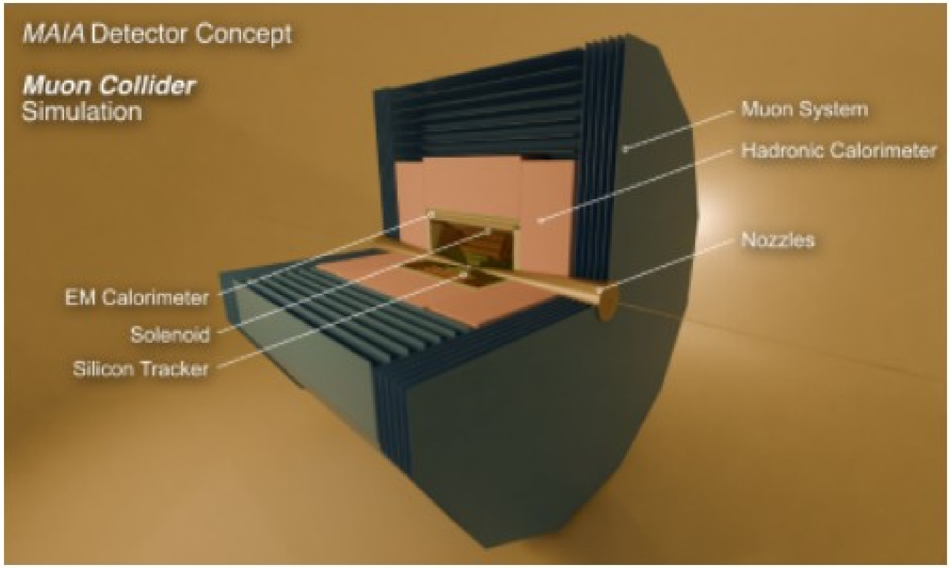
Muon Collider - Siting



- CERN siting has been done
  - Muon production system on Prevessin site
  - RCS in SPS and LHC rings
  - 3.2 TeV and 7.6 TeV options available
  - New collider tunnel
  - 15 km of new tunnel length required
- Highly desirable to go above 7.6 TeV – possible with FFAs?

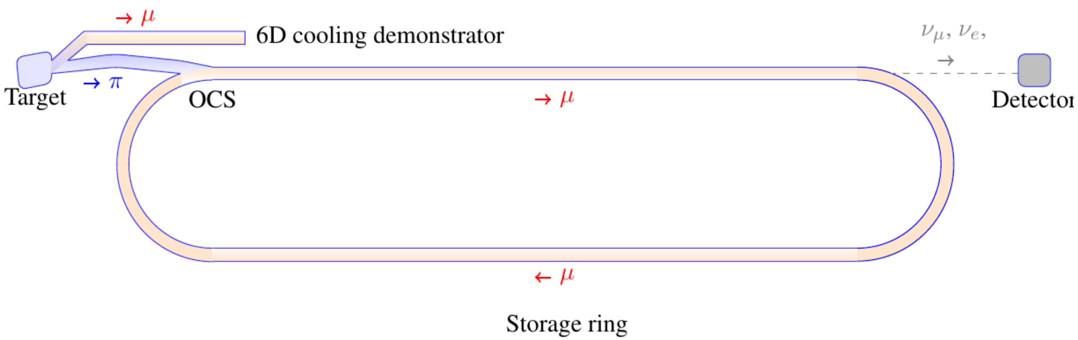
Detector

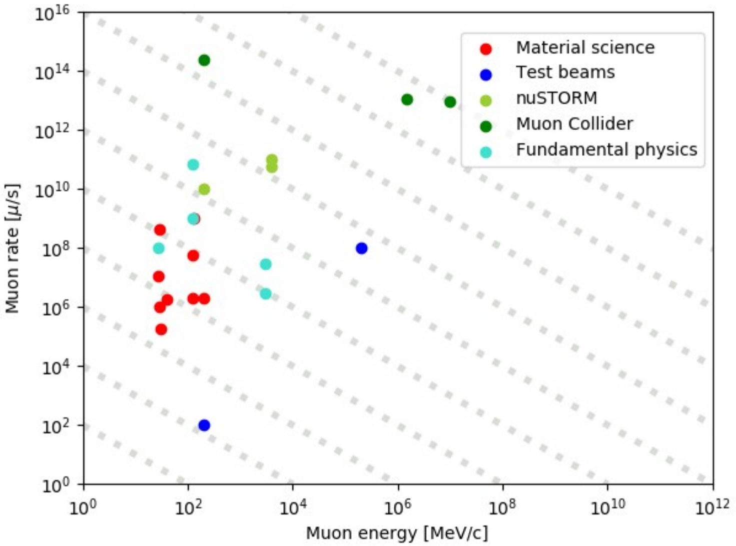




- Two detector concepts
- Differ in placement of the solenoid
- Many other differences

Synergy with nuSTORM





- NuSTORM → "next scale" muon facility
  - FFA-based storage ring (no acceleration)
  - Muon production target and pion handling
  - Possibly shared with cooling demonstrator
- Aim to measure neutrino-nucleus cross-sections
  - E.g. reduce neutrino oscillation experiment resolutions
  - Nuclear physics studies
  - Sensitivity to Beyond Standard Model physics

Collaboration

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	Technical University of Darmstadt
	University of Rostock
	KIT
IT	**INFN**
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	INFN, Univ. Milano
	INFN, Univ. Padova
	INFN, Univ. Pavia
	INFN, Univ. Bologna
	INFN Trieste
	INFN, Univ. Bari
	INFN, Univ. Roma 1
	ENEA
Mal	**Univ. of Malta**
BE	***Louvain***

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	University of Southampton
	University of Strathclyde
	University of Sussex
	Imperial College London
	Royal Holloway
	University of Huddersfield
	University of Oxford
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PT	**LIP**
NL	**University of Twente**
FI	**Tampere University**
LAT	**Riga Technical Univers.**

US	**Iowa State University**
	Wisconsin-Madison
	Pittsburg University
	Old Dominion
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	Peking University
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New Collaborators Welcome!

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University of HUDDERSFIELD

2020 Update to the European Strategy for Particle Physics

International MUON Collider Collaboration

High-priority future initiatives

A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

• ***the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;***

• ***Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.***

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

B. Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry. The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs. ***The European particle physics community must intensify accelerator R&D and sustain it with adequate resources. A roadmap should prioritise the technology, taking into account synergies with international partners and other communities such as photon and neutron sources, fusion energy and industry. Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes.***

P5 Report

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Recommendation 1: As the highest priority independent of the budget scenarios, complete construction projects and support operations of ongoing experiments and research to enable maximum science.

Recommendation 2: Construct a portfolio of major projects that collectively study nearly all fundamental constituents of our universe and their interactions, as well as how those interactions determine both the cosmic past and future.

Recommendation 3: Create an improved balance between small-, medium-, and large-scale projects to open new scientific opportunities and maximize their results, enhance workforce development, promote creativity, and compete on the world stage.

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.

Recommendation 5: Invest in initiatives aimed at developing the workforce, broadening engagement, and supporting ethical conduct in the field. This commitment nurtures an advanced technological workforce not only for particle physics, but for the nation as a whole.

Recommendation 6: Convene a targeted panel with broad membership across particle physics later this decade that makes decisions on the US accelerator-based program at the time when major decisions concerning an off-shore Higgs factory are expected, and/or significant adjustments within the accelerator-based R&D portfolio are likely to be needed. A plan for the Fermilab accelerator complex consistent with the long-term vision in this report should also be reviewed.

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P5 Report – Muon Shot

2.3

The Path to 10 TeV pCM

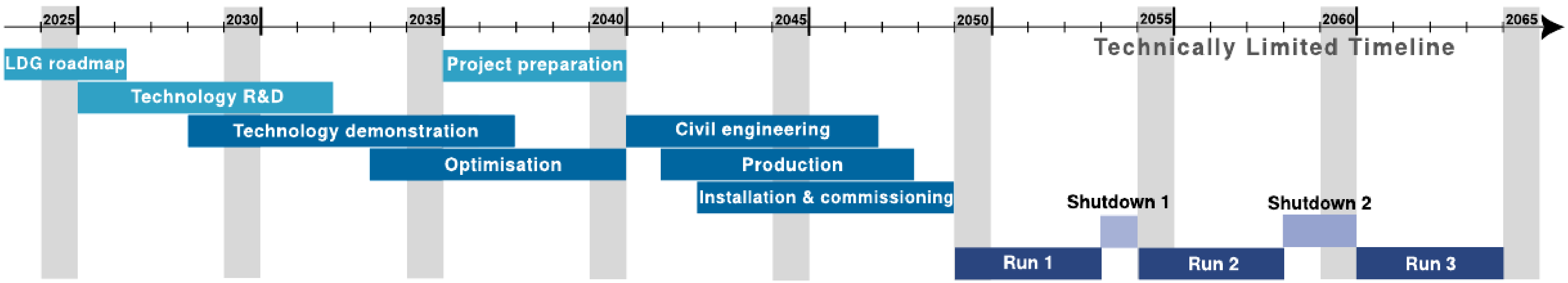
Although we do not know if a muon collider is ultimately feasible, the road toward it leads from current Fermilab strengths and capabilities to a series of proton beam improvements and neutrino beam facilities, each producing world-class science while performing critical R&D towards a muon collider. At the end of the path is an unparalleled global facility on US soil. This is our Muon Shot.

Submissions to 2026 ESPPU

- MuC ESPPU submission
  - 451 authors
- UK - Discussion of not-FCCee concepts in second round submission (meeting on Monday 28th)
- My opinion:
  - Strong consensus to keep open other options
  - Concept of “straight to FCChh” presented by UK-ECFA
  - Strongly challenged by the community
- Document to be submitted end of May

Cost and time scale

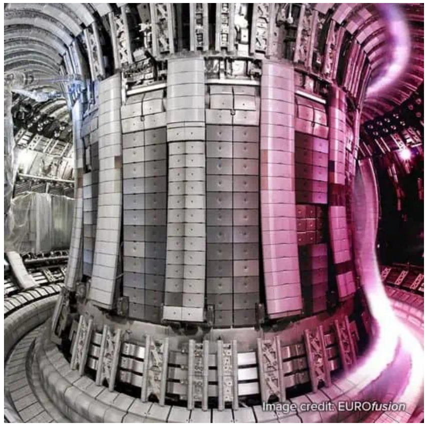
Muon Collider



Project	Particle species	CM Energy [TeV]	Wall plug power [MW]	New Tunnel	Cost [GCHF]	Luminosity [10^34]
CLIC	e+e-	0.38	166	11.4	7.2	4.5
		1.5	287	29	7.2+6.5	3.7
CEPC @ 30 MW SR	e+e- → Z	0.091	203	100	4.6	115
	e+e- → tt	0.36	358	100	4.6	0.5
C^3	e+e-	0.25	110	8		1.3
		3	320	33		14
Muon Collider @ CERN	mu+mu-	3.2	113		12.2	0.9
		7.6	172	15	16.9	7.9
FCCee	e+e-	0.091	222	97	15.32	144
		0.365	357	97	15.32	1.45
FCChh	pp	84.6	355	97	18.9+FCCee	30
HALHF	e+e-	0.25	106	4.9	3.8	1.2
		0.55	218	8.4	6.3	2.5
LEP3	e+e-	0.091	250	0	3.2	44
		0.23	250	0	3.2	1.8
LHeC	pe-	0.05+7	220		1.6	2.3

Technology applications

- High field solenoids have many important application
  - Developing collaboration with fusion experts
  - MRI magnets
- Muon beam techniques have application in many other fields
  - Muon spin resonance (muSR)
  - Muon tomography
- Delivery of such a muon beam is a unique achievement – we don’t know what is the impact!



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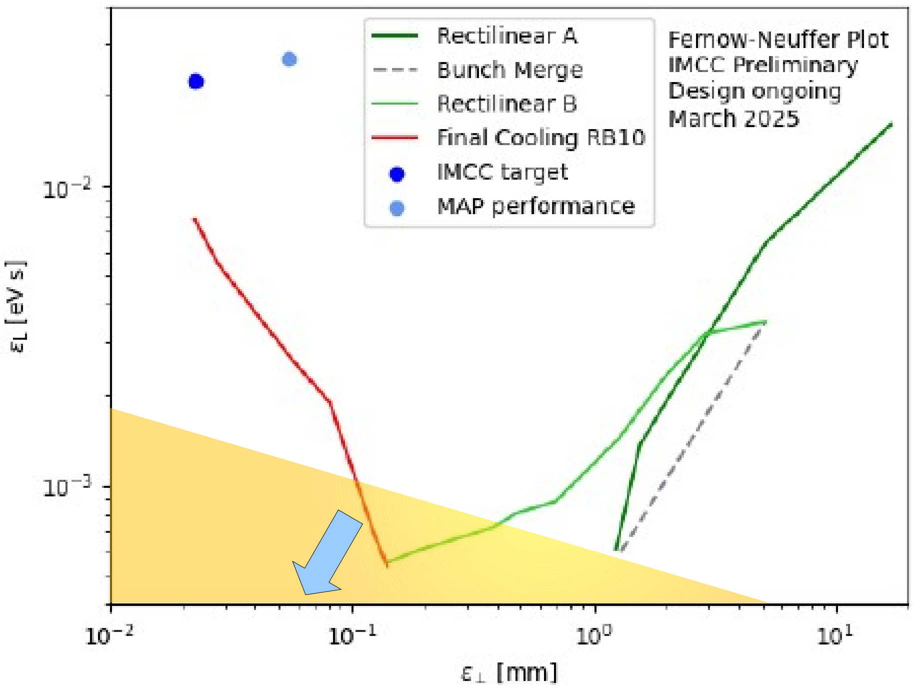
Synergy with ISIS

- Low energy, low emittance cooling system under study with ISIS
- Potential for significant gains in cost and performance of the muon cooling system
- Applicable to muSR and other beamlines
  - Potential significant gain in effectiveness of these instruments



Final Word

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- The muon collider
  - Far higher energy than e^+e^- colliders
  - Far smaller footprint than equivalent proton colliders
  - More power efficient, more cost efficient
- Many technical challenges
  - All are manageable with current or near-to-current technologies
  - Must demonstrate practical solutions
- Muon collider has potential to advance particle physics by many decades
  - We must now deliver it

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