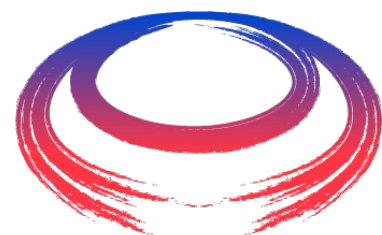


Introduction to the Muon Collider



International
Muon Collider
Collaboration

C. T. Rogers

Rutherford Appleton Laboratory

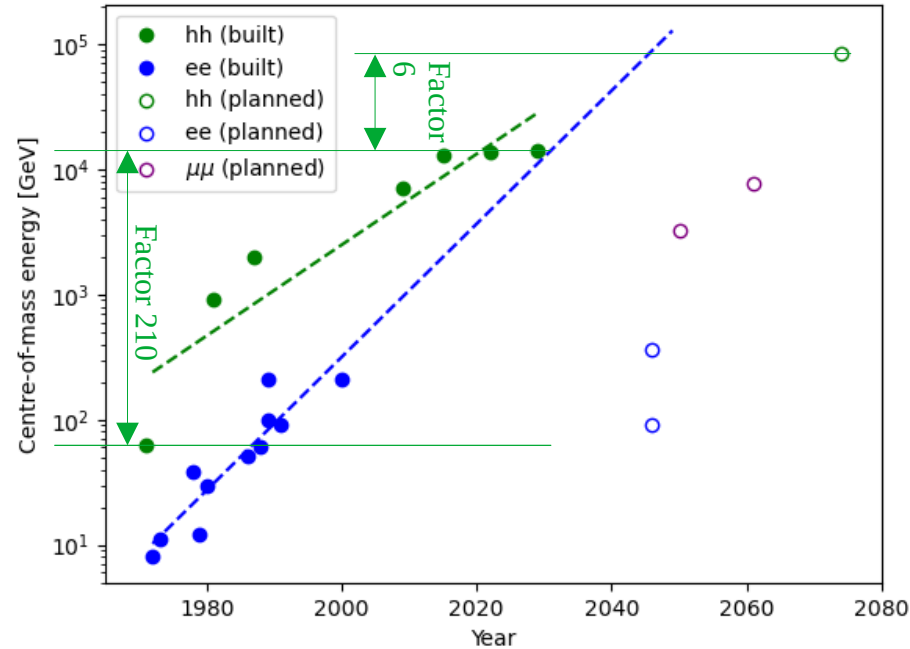
Funded by the European Union (EU). Views and opinions expressed are however those of the author only and do not necessarily reflect those of the EU or European Research Executive Agency (REA). Neither the EU nor the REA can be held responsible for them.



Science and
Technology
Facilities Council

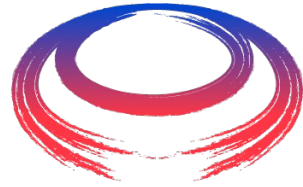
ISIS Neutron and
Muon Source

Particle Colliders



- Particle collider energy grew exponentially in 20th century
- E.g. proton collider energy grew by factor **210** in **last 50 years**
- Proton collider energy set to grow by factor **6.3** in **next 50 years**
 - Despite requirement of massive budget uplift
 - Is high energy physics sustainable?

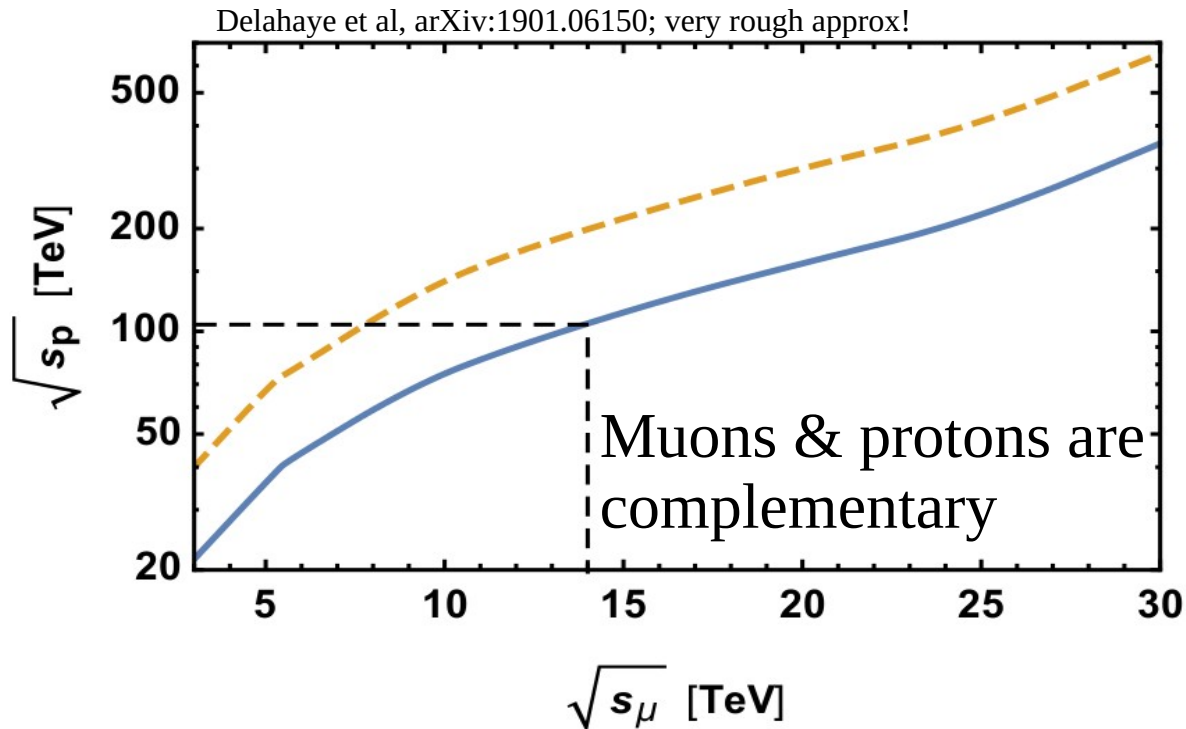
Can muons help?



International UON Collider Collaboration



Muon collider motivation



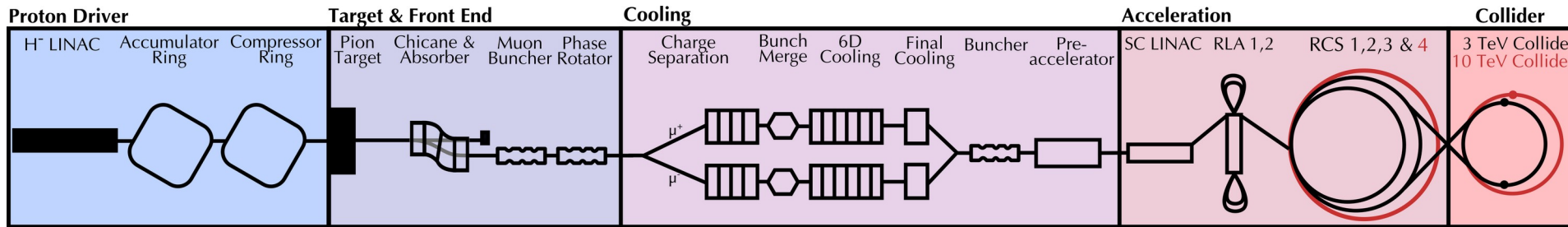
Energy at which cross-section is equal

- Assuming equal Feynman amplitude (EW)
- Assuming factor 10 enhancement in pp (EW+QCD)

- Muons → fundamental particle
 - Full energy available at collision
- Muons → much more massive than electrons
 - Synchrotron radiation is suppressed



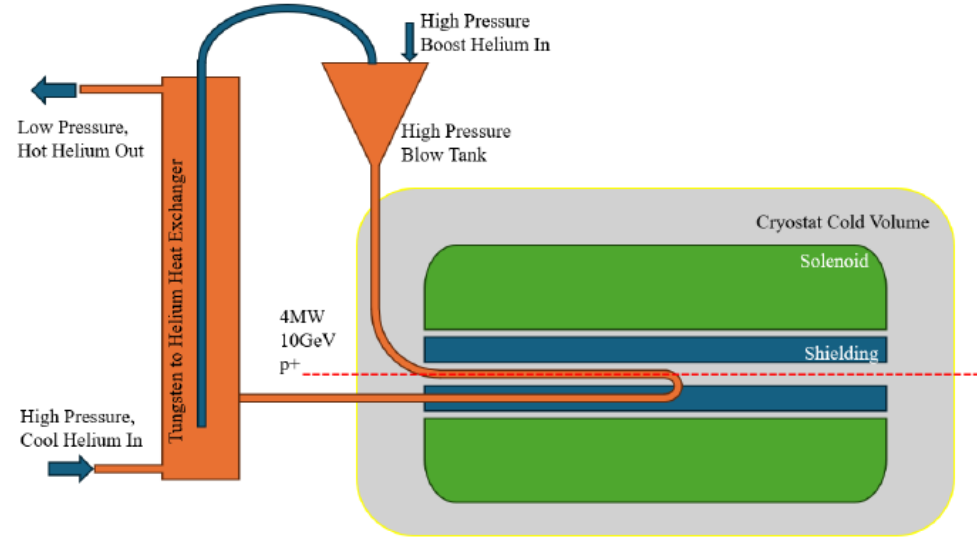
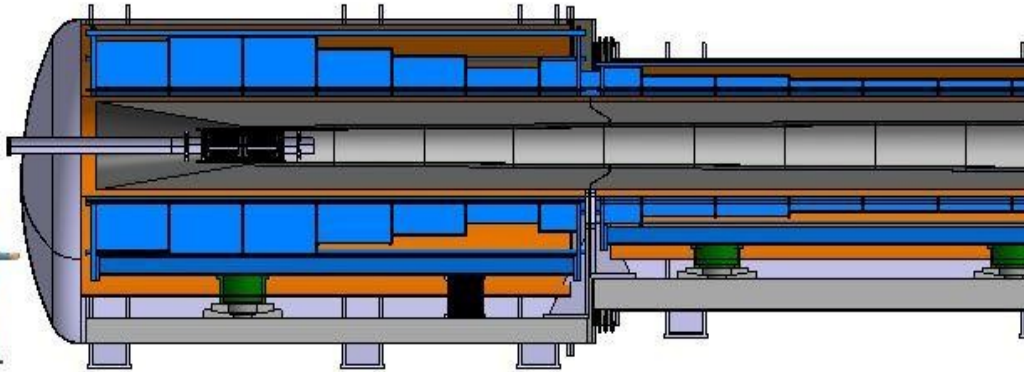
Muon Collider



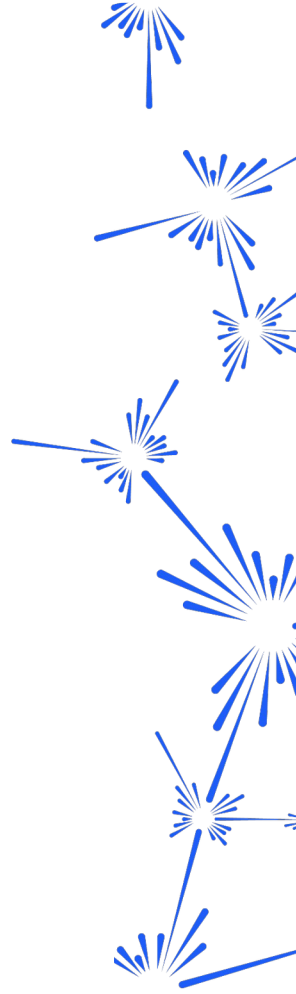
- MW-class proton driver → target
- Pions produced; decay to muons
- Muon capture and cooling
- Acceleration to TeV & Collisions
- Designed for high energy while **maximising luminosity**
 - Luminosity is key



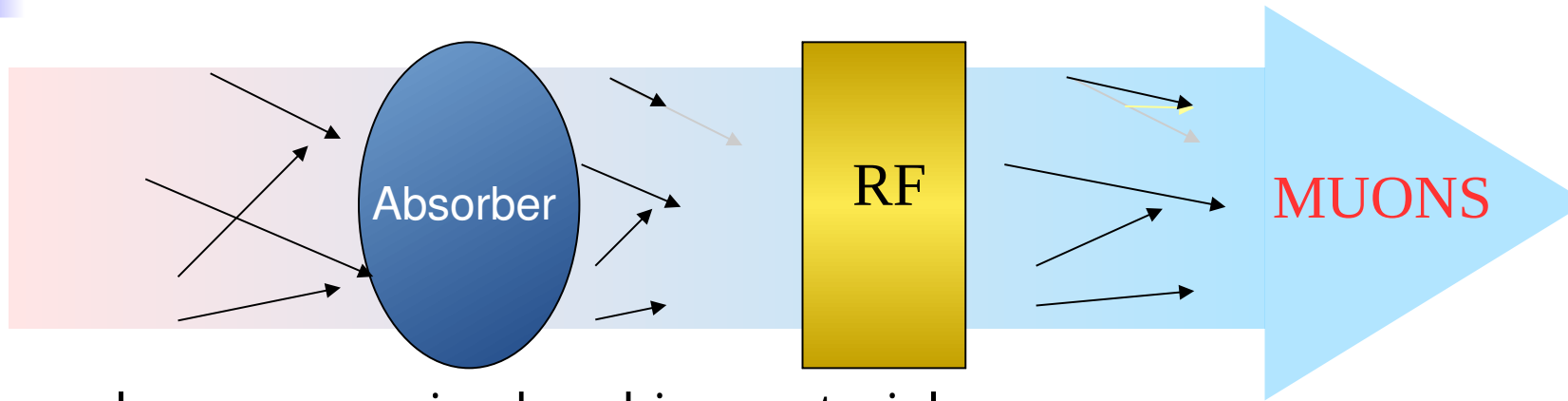
MuC Target



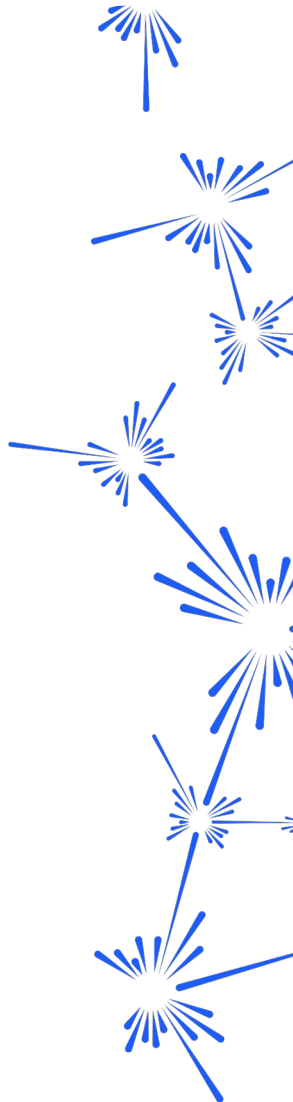
- Protons on target \rightarrow pions \rightarrow muons
 - Graphite target takes proton beam to produce pions
 - Heavily shielded, very high field solenoid captures π^+ and π^-
- Baseline graphite target similar to T2HK/Dune Phase 2
- UK developing alternative fluidised powder target to manage higher heat load
 - Possible application for neutron production
 - Warwick, RAL



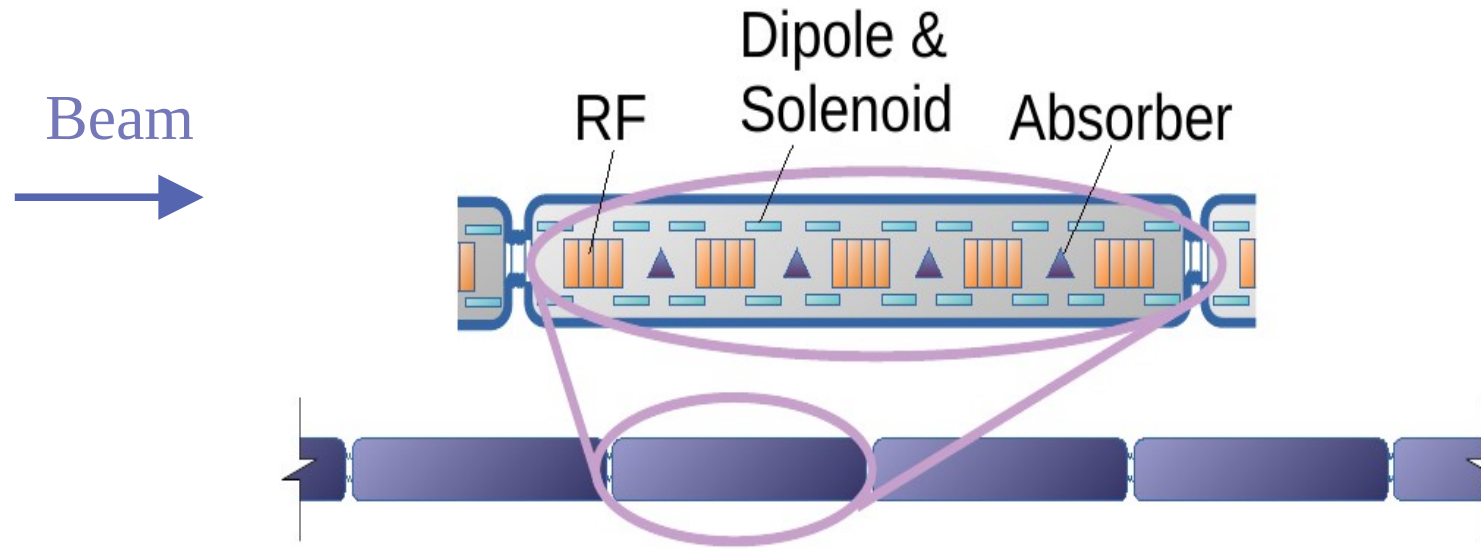
Ionisation Cooling



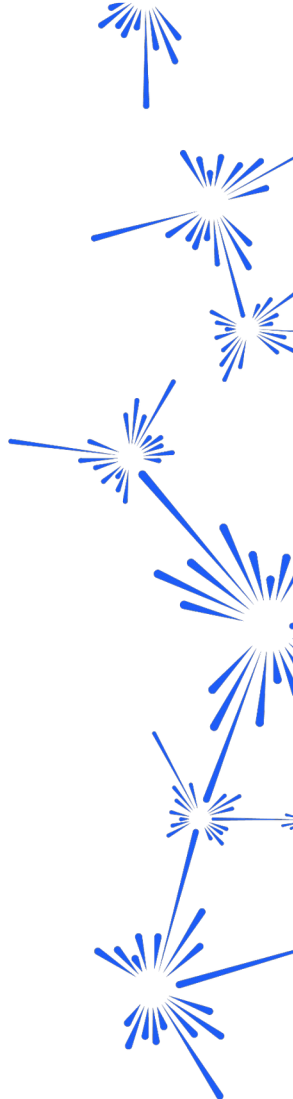
- Beam loses energy in absorbing material
 - Absorber removes momentum in all directions
 - RF cavity replaces momentum only in longitudinal direction
 - End up with beam that is more straight
- Multiple Coulomb scattering from nucleus ruins the effect
 - Mitigate with tight focussing
 - Mitigate with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



Rectilinear Cooling

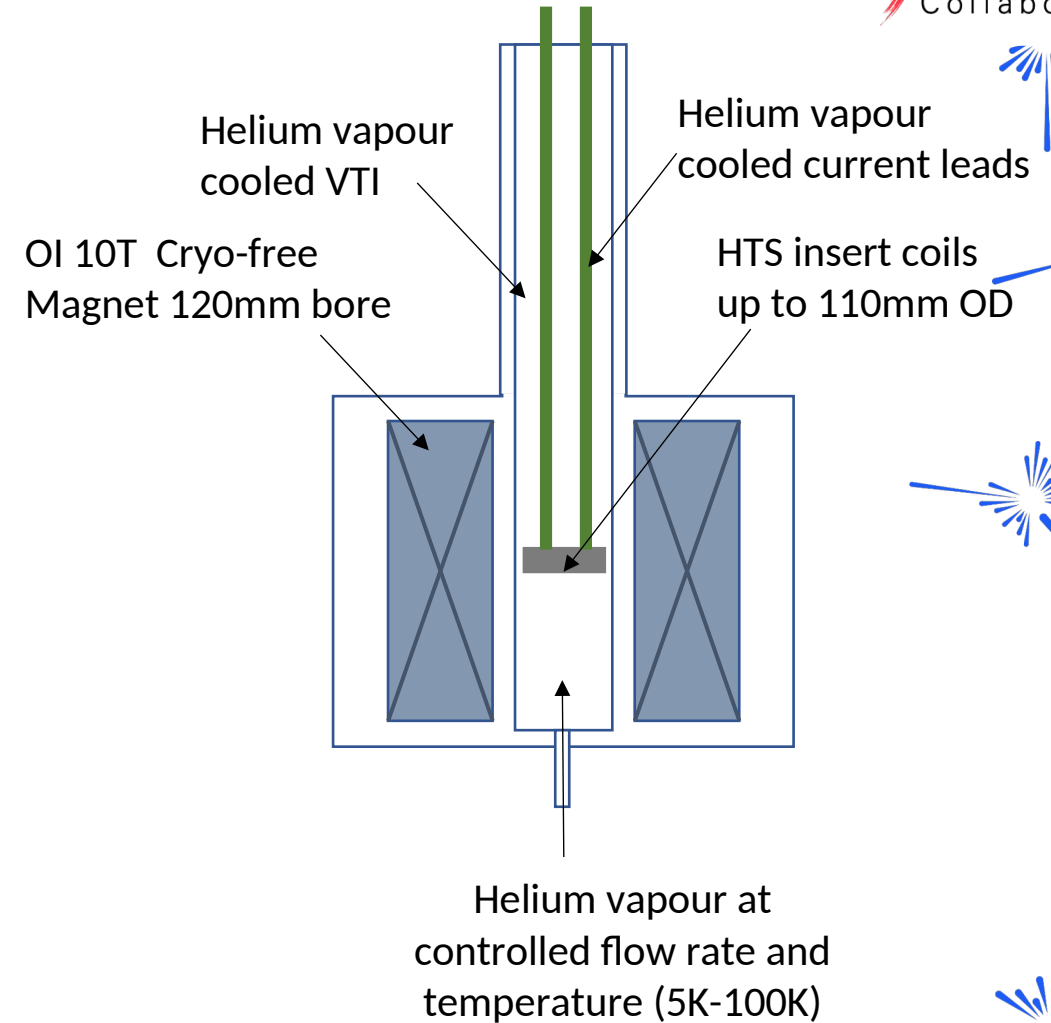


- 6D Cooling (RAL, Imperial)
 - Combined function dipole-solenoid magnets
 - Compact lattice – RF integrated into magnet cryostat
 - Lithium Hydride or IH₂ absorbers
 - Careful field shaping to control position of stop-bands



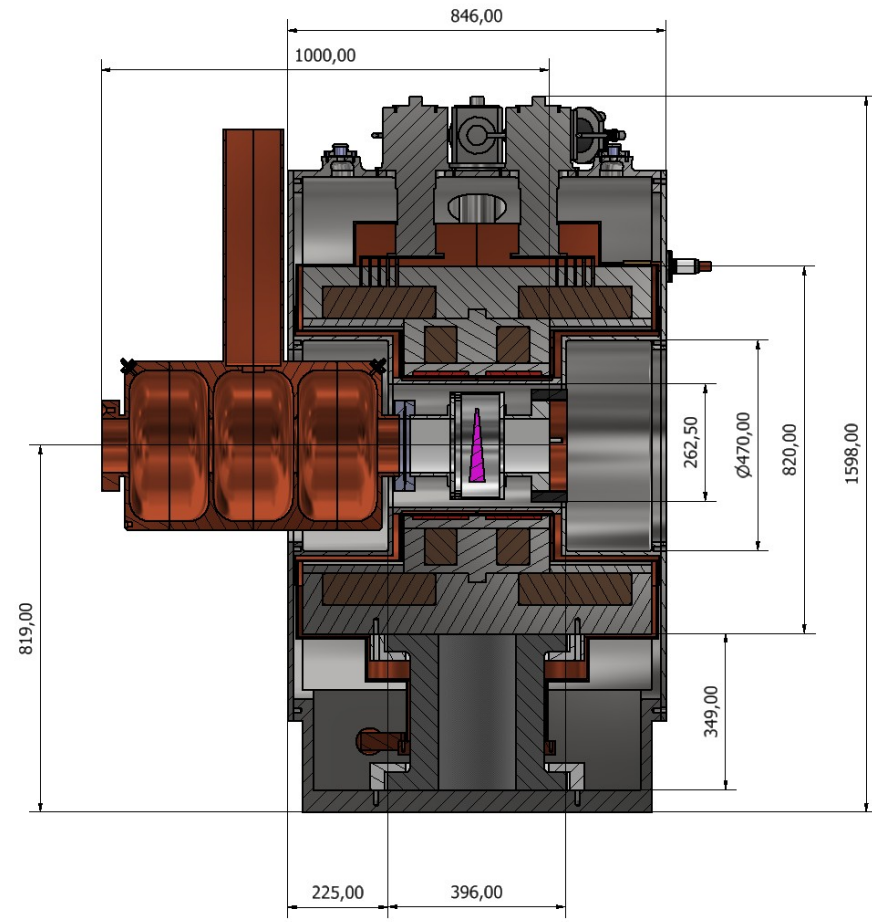
Magnet Design

- Challenging magnets
 - Non-insulated coils → improved ramp properties
 - Insulated coils → less sensitive to delamination
- Coil tested in 10 T magnet (Southampton)
 - Quench tests
 - Developing quench model



Integration

- Integration of such a compact lattice is tough
 - Overlapping magnet & RF fields → breakdown (Strathclyde)
 - Significant peak RF power required (Lancaster)
- Plan to demonstrate the cooling performance



Cooling Demonstrator



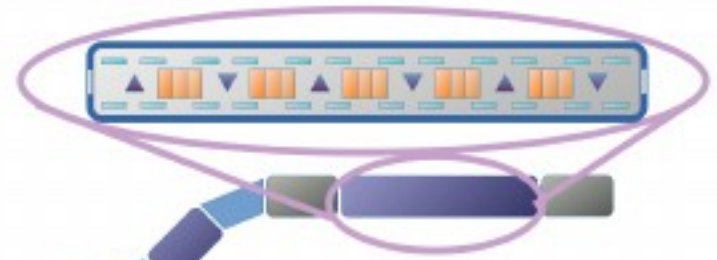
RF Test stands, to develop novel RF and magnet technologies



One-cell module to test RF in operational magnetic environment



Multi-cell module to demonstrate integration of absorber, RF and magnets



Demonstration of cooling module to show operation with beam



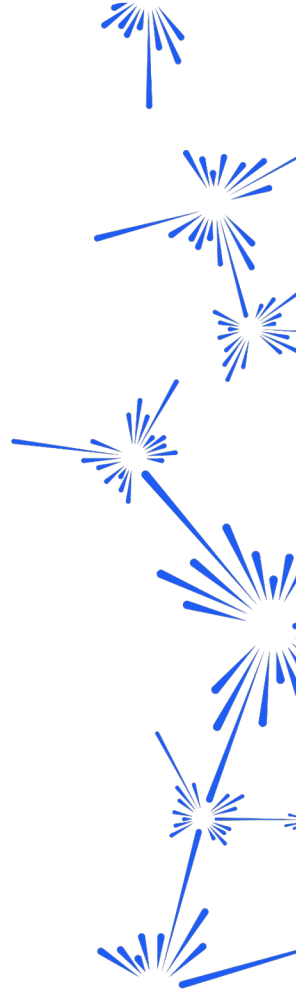
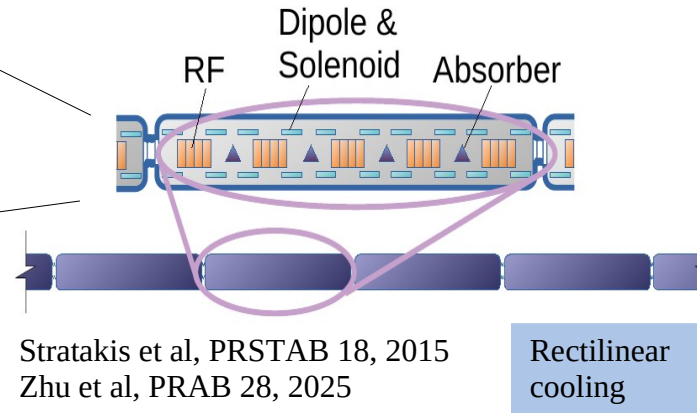
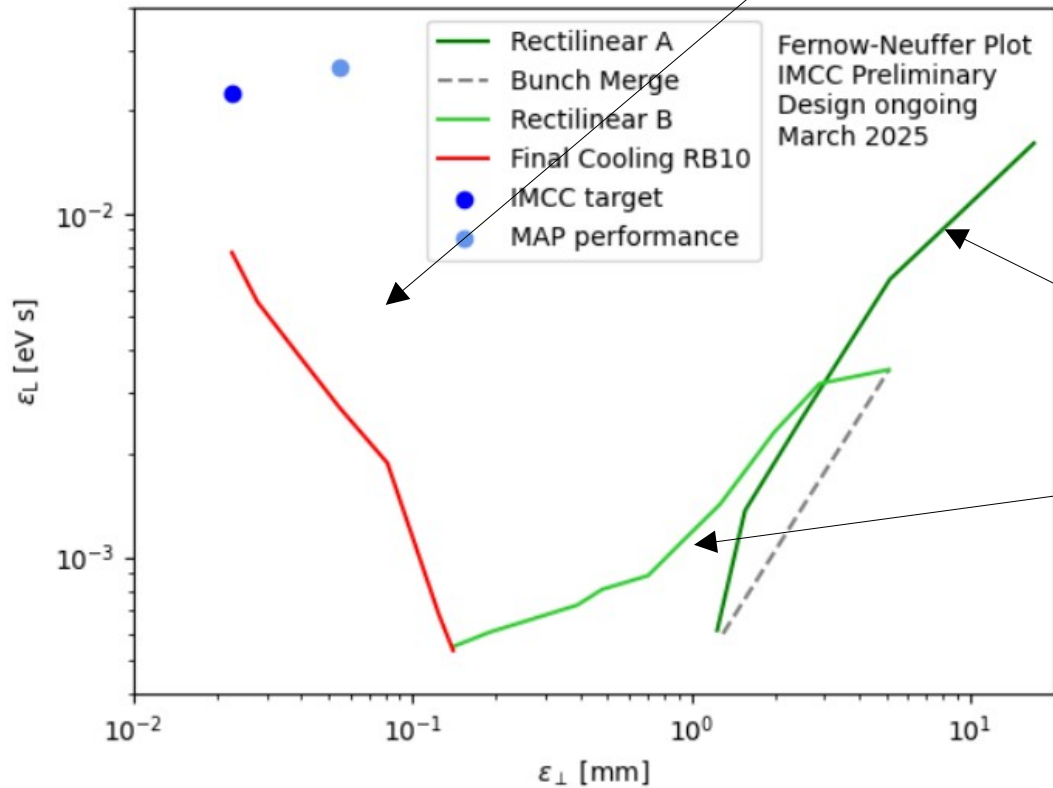
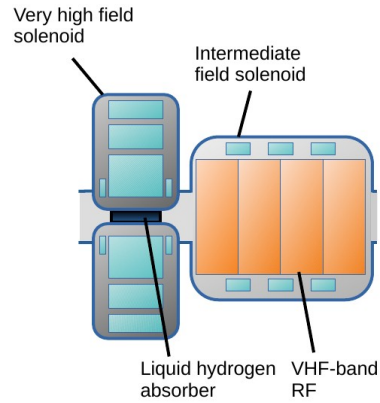
Demonstration of cooling to demonstrate beam physics performance



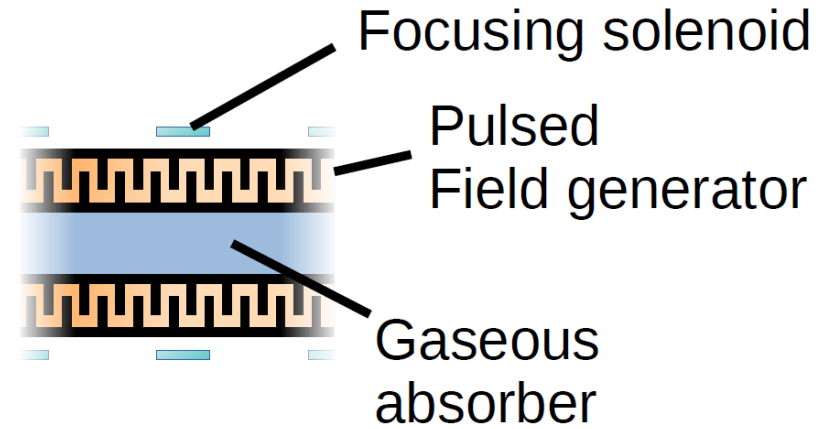
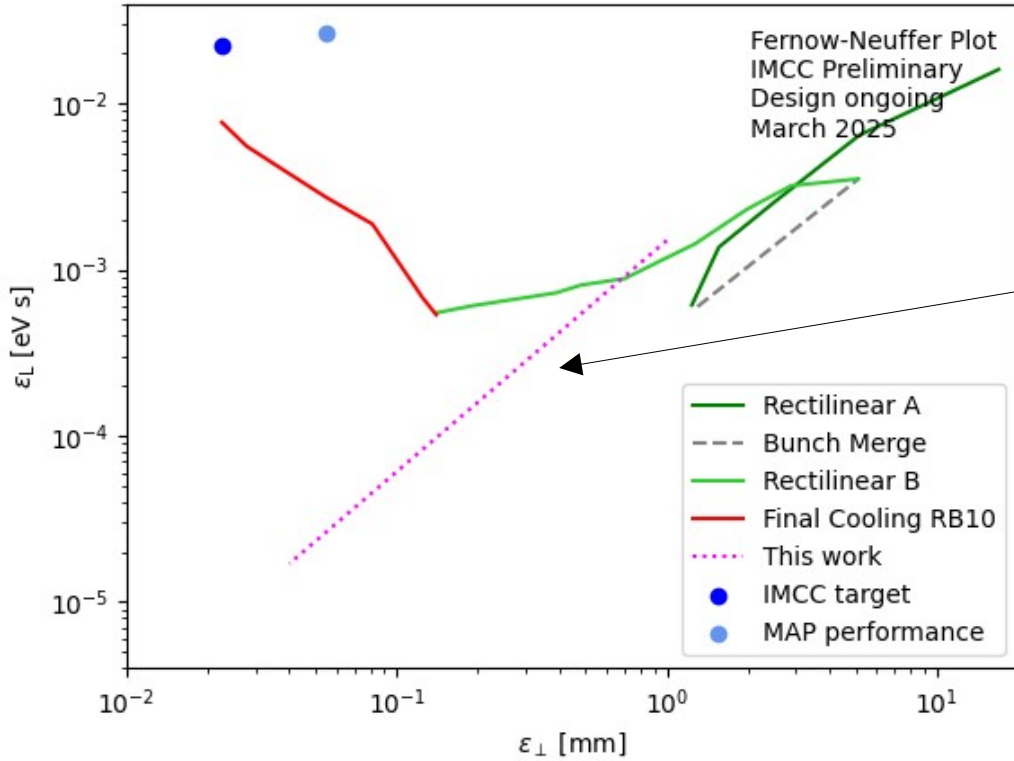
Muon Cooling

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

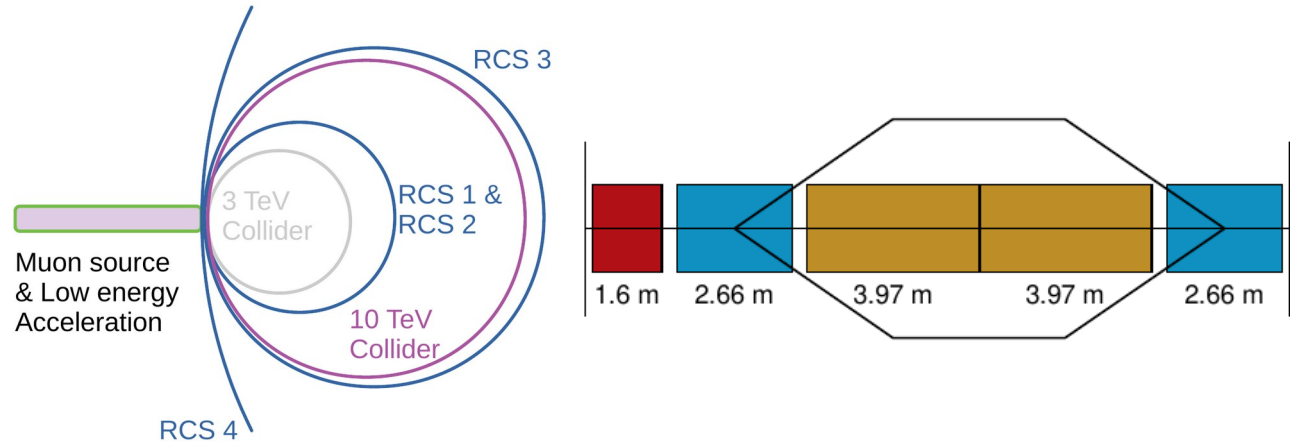
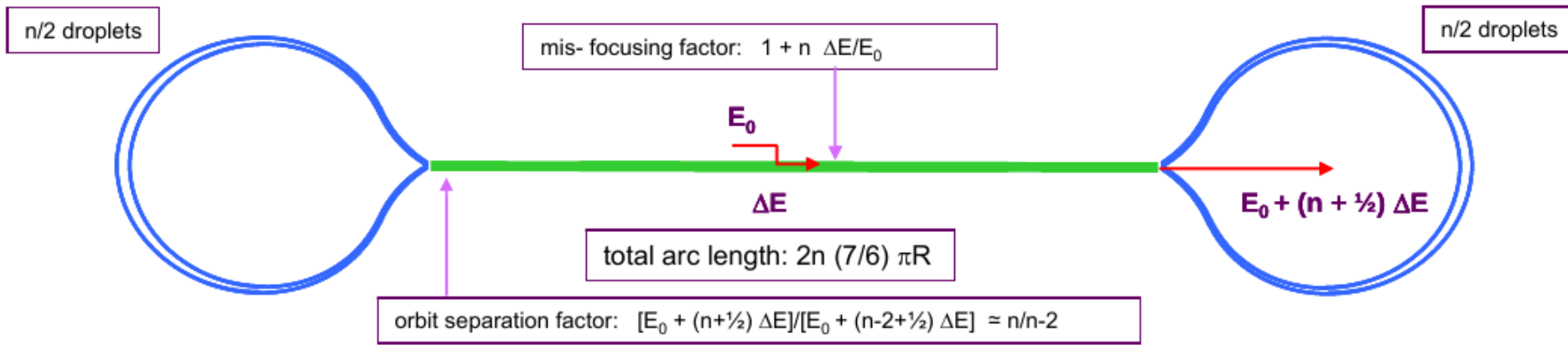
4D Final cooling



Low Energy Muon Cooling



Pulsed Synchrotrons



- Acceleration using linacs, recirculating linacs and synchrotrons
- Collision in dedicated collider ring
- Can FFAs help here?
 - RAL, Huddersfield



Muon Collider Detector (3 TeV)

hadronic calorimeter

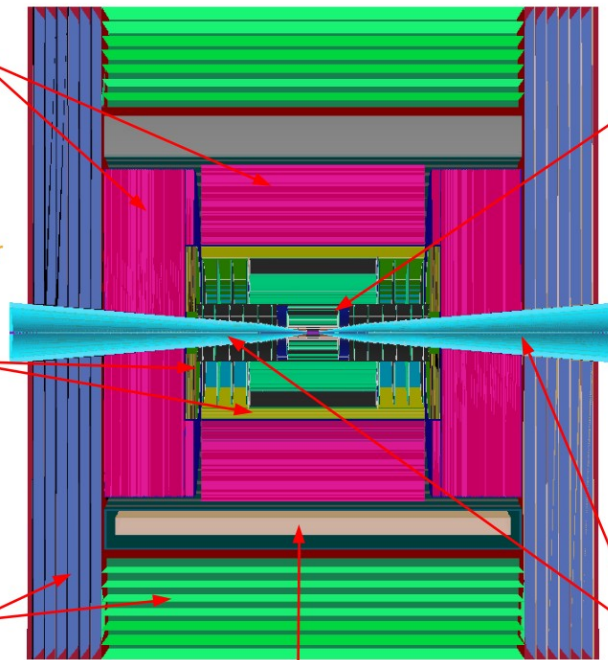
- ◆ 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- ◆ 30x30 mm² cell size;
- ◆ 7.5 λ_I .

electromagnetic calorimeter

- ◆ 40 layers of 1.9-mm W absorber + silicon pad sensors;
- ◆ 5x5 mm² cell granularity;
- ◆ 22 $X_0 + 1 \lambda_I$.

muon detectors

- ◆ 7-barrel, 6-endcap RPC layers interleaved in the magnet's iron yoke;
- ◆ 30x30 mm² cell size.



superconducting solenoid (3.57T)

tracking system

- ◆ **Vertex Detector:**
 - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
 - 25x25 μm^2 pixel Si sensors.
- ◆ **Inner Tracker:**
 - 3 barrel layers and 7+7 endcap disks;
 - 50 μm x 1 mm macro-pixel Si sensors.
- ◆ **Outer Tracker:**
 - 3 barrel layers and 4+4 endcap disks;
 - 50 μm x 10 mm micro-strip Si sensors.

shielding nozzles

- ◆ Tungsten cones + borated polyethylene cladding.

Two detector proposals (analogous to CMS and ATLAS)

- MUSIC
- MAIA
- UK: Warwick, Birmingham, Cambridge, RAL



Muon Collider – Facility Parameters



Parameter	Symbol	Unit	Target value		
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	\mathcal{L}	$1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	1.8	20	40
Collider circumference	C_{coll}	km	4.5	10	14
Muons/bunch	N	1×10^{12}	2.2	1.8	1.8
Repetition rate	f_r	Hz	5	5	5
Beam power	P_{coll}	MW	5.3	14.4	20
Longitudinal emittance	ε_l	MeV m	7.5	7.5	7.5
Transverse emittance	ε_{\perp}	μm	25	25	25
IP bunch length	σ_z	mm	5	1.5	1.07
IP beta-function	β	mm	5	1.5	1.07
IP beam size	σ	μm	3	0.9	0.63



Technology applications

- High field solenoids have many important applications
 - 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!

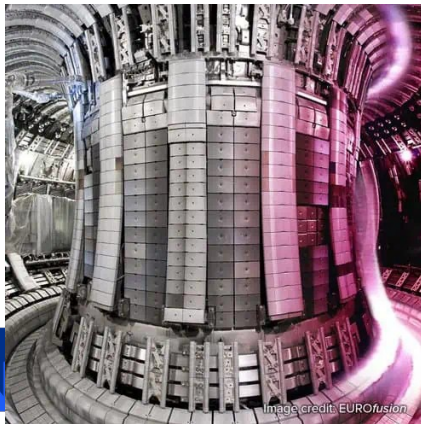


Image credit: EUROfusion



2026 European Strategy for Particle Physics Update

Accelerator science and technology

Advanced accelerators rely on detailed beam physics models, powerful simulations and key technologies such as high-field magnets, high-gradient normal-conducting and superconducting RF accelerating systems, high-gradient plasma-wakefield acceleration, bright muon beams and energy recovery linacs (ERLs). Several technology approaches directly address the requirement of greater sustainability for future accelerator-based facilities. These include superconducting magnets and resonators operated at higher cryogenic temperature, superconducting current links, use of permanent magnets, and more efficient RF power sources, complemented by a more extensive use of robotics and artificial intelligence.

- B. In order to realise the visionary plan presented, the highest priority must be the development and industrialisation of key technologies: advanced superconducting and normal-conducting RF structures, efficient RF power sources and accelerator-quality magnets in the 14–20 T range, including those based on high-temperature superconductors.*
- C. Demonstration of high-current multi-turn energy recovery in linacs constitutes an important step towards power-efficient lepton accelerators for a broad range of applications and should be pursued.*
- D. The longer-term development of advanced technologies, such as high-gradient wakefield acceleration and those underpinning bright muon beams, should be supported at an appropriate level. Synergies with the US initiative on muon collider R&D should be exploited.*



P5 Report (2023)

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.

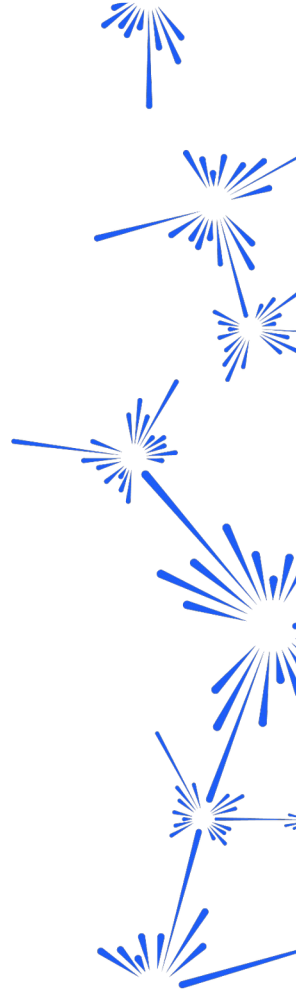
Recommendation 6: Convene a targeted panel with broad membership across particle physics later this decade that makes decisions on the US accelerator-based program at the time when major decisions concerning an off-shore Higgs factory are expected, and/or significant adjustments within the accelerator-based 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.



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**.





US National Academy of Sciences



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.

A muon collider is a bold and innovative approach to getting to the 10 TeV energy scale. Its origins trace to the United States, and it could be sited in the United States at Fermilab. The significant technological challenges in determining whether or not a muon collider can be built demand the initiation of an R&D phase (circa 7 years), followed by a demonstrator phase (circa 10 years), as quickly as possible. Doing so will ensure that making a decision on the feasibility of a muon collider and whether or not to build one in the United States will not delay getting to the 10 TeV frontier.

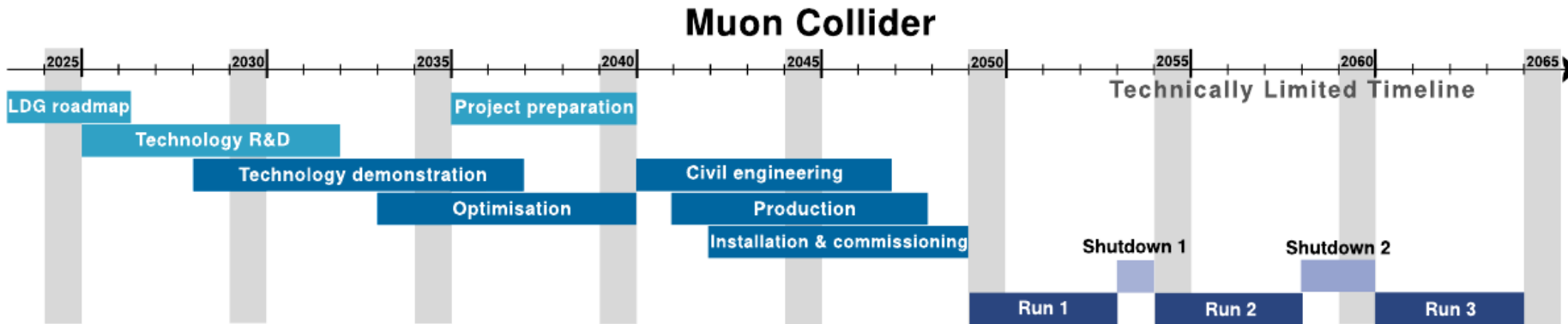
From Elementary Particle Physics: The Higgs and Beyond (2025)



ISIS Neutron and
Muon Source



Time scale

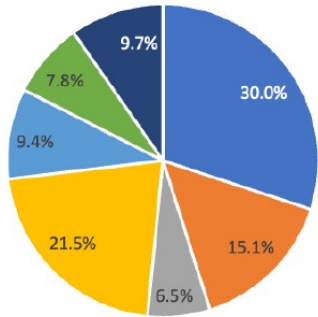


- “Technically Limited Timeline”
 - Needs full support of major lab
 - Until that time, expect slip

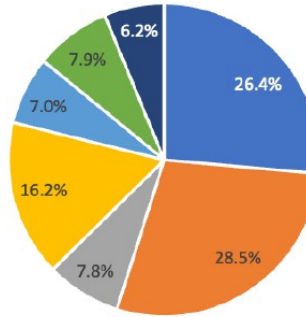


Cost

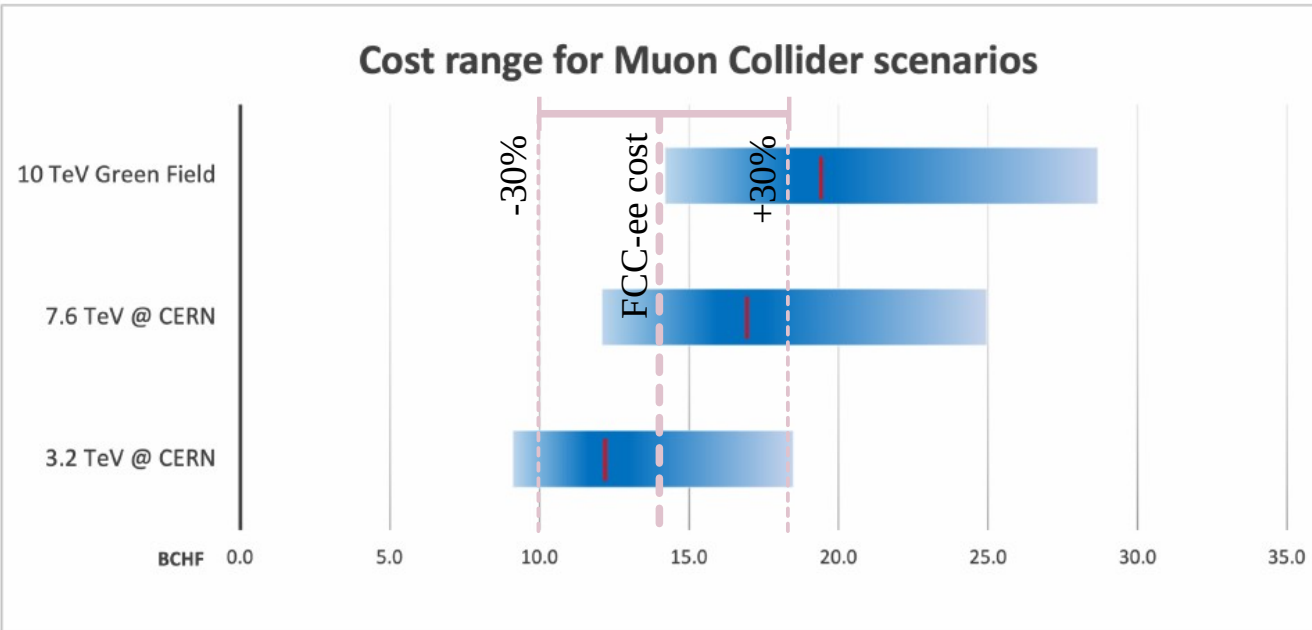
Relative cost for 3.2 TeV



Relative cost for 7.6 TeV



Cost range for Muon Collider scenarios



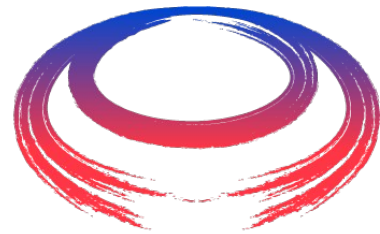
Final Word

- The muon collider
 - Far higher energy than e^+e^- colliders
 - Far smaller footprint than equivalent proton colliders
- 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





Backup



International
Muon Collider
Collaboration
C. T. Rogers

Rutherford Appleton Laboratory



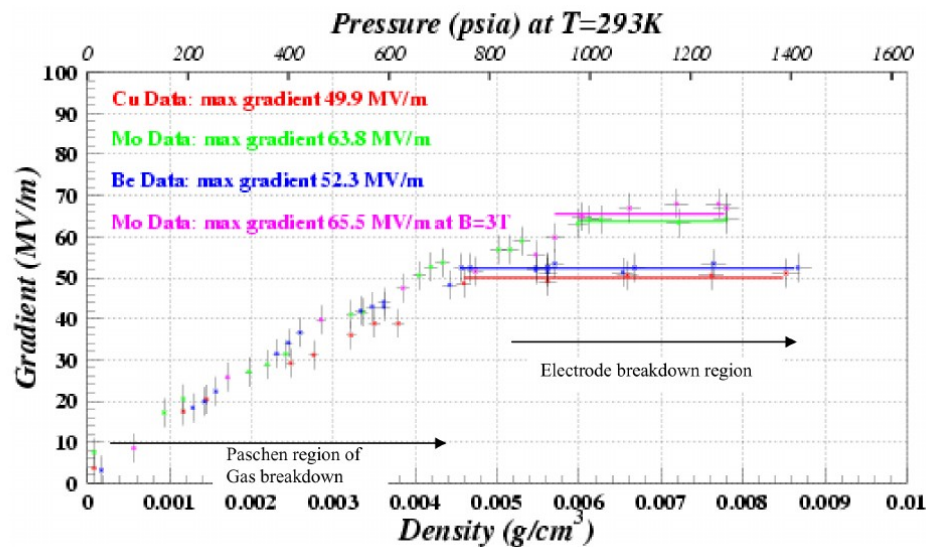
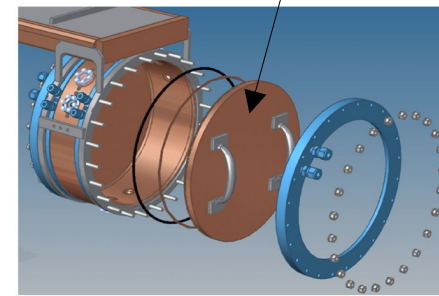
Cavity R&D

- Cooling requires strong B-field overlapping RF
 - B-field → sparking in RF cavities
- Two technologies have demonstrated mitigation

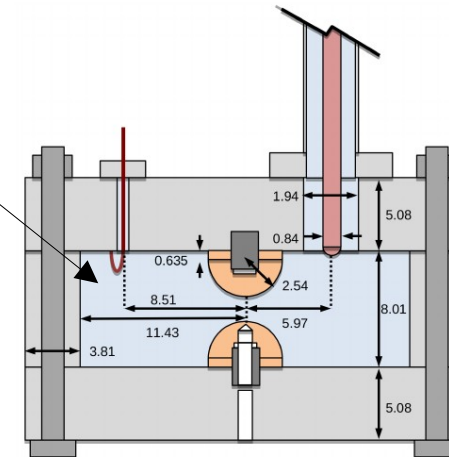
Bowring et al, PRAB 23 072001, 2020

Material	B-field (T)	E-field (MV/m)	
Cu	0	24.4 ± 0.7	Double vs Cu cavity in 0 T
Cu	3	12.9 ± 0.4	
Be	0	41.1 ± 2.1	
Be	3	$> 49.8 \pm 2.5$	

Changeable Cu/Be walls



High Pressure gas



Freemire et al, JINST 13 P01029, 2018



Luminosity

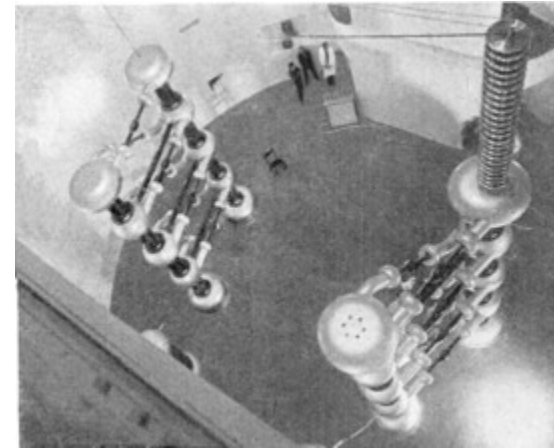
$$\mathcal{L} \approx \underbrace{\frac{e\tau_\mu}{(4\pi m_\mu c)^2}}_{K_L} \underbrace{\frac{f_{hg}\sigma_\delta \bar{B}}{\varepsilon_\perp \varepsilon_L n_b f_\tau}}_{\substack{4 \\ 3}} \underbrace{\eta_+ \eta_- (\eta_\tau P_p \gamma m_\mu c^2)^2}_{\substack{4 \\ 5 \\ 1 \\ P_+ P_-}} \quad 2$$

- 1) Luminosity increases with the square of muon energy/beam power
 - Beam size decreases as energy increases (geometric emittance)
 - 2) High field, low circumference collider ring → more luminosity
 - Shorter path length, more collisions before muon decay
 - 3) Low repetition rate, few bunches is best
 - Assume that the bottleneck is in the number of protons
 - Fewer collisions, but each collision is more intense
 - 4) High quality muon source is essential
 - Low emittance, good capture efficiency
 - 5) Good efficiency acceleration is essential
 - High voltage systems
- The whole muon collider is designed to maximise luminosity!



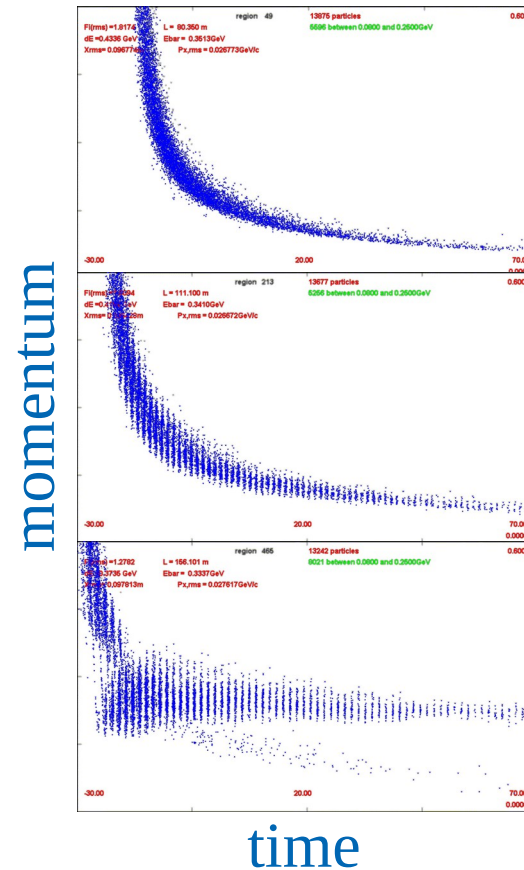
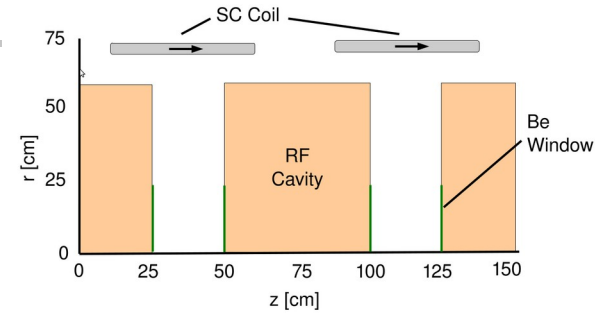
Accelerators in Physics

- First accelerators built in 1920s/30s
 - Accelerating protons, ions and electrons
- Antiproton acceleration in 1980s
 - Made possible by stochastic cooling
- Accelerators were originally a tool for fundamental physics
 - Now many uses
- Hadron colliders
 - E.g. LHC
 - “Discovery machines”
- Lepton colliders
 - E.g. Large Electron Positron Collider (LEP)

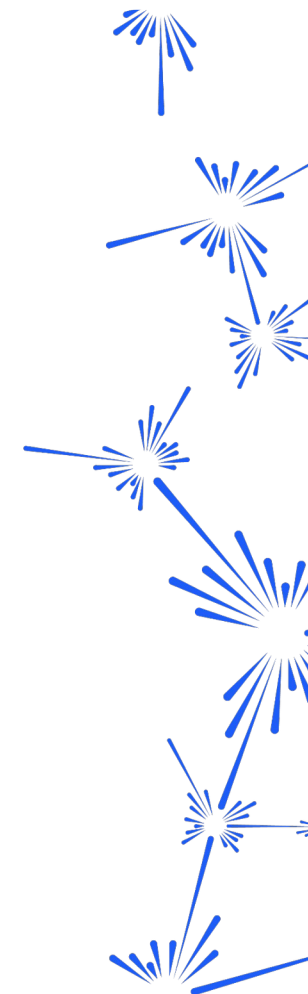
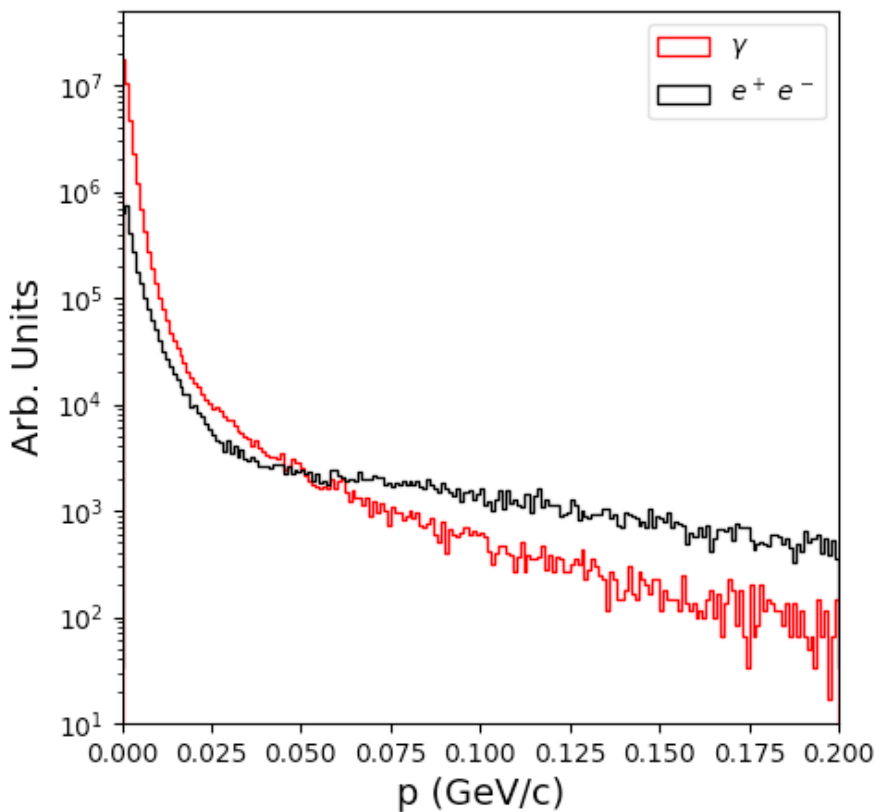
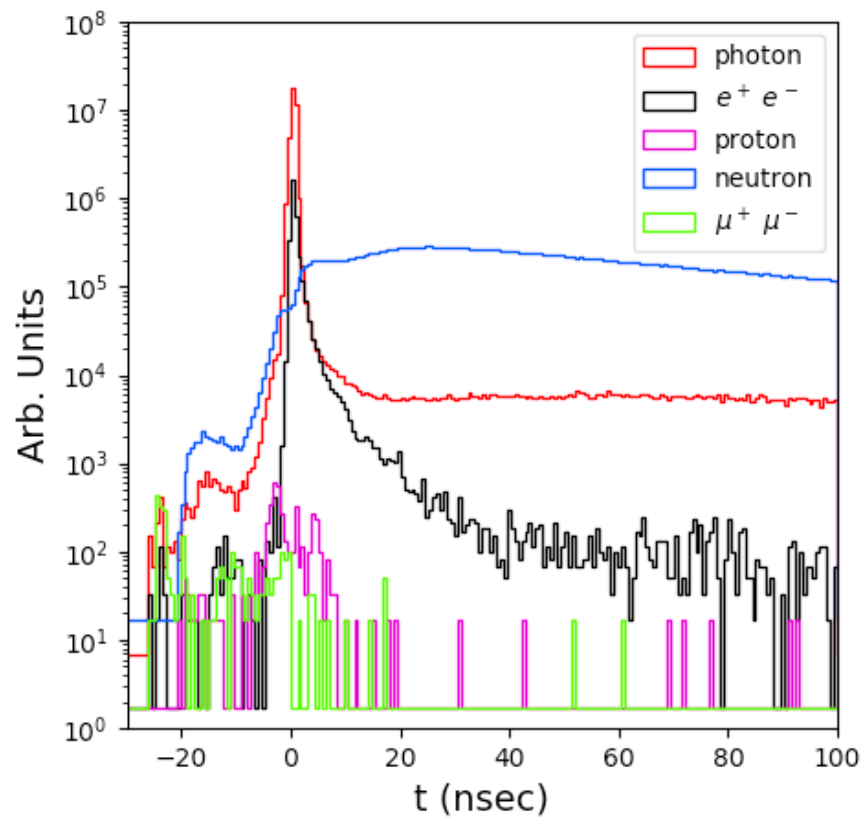


Buncher/Phase Rotator

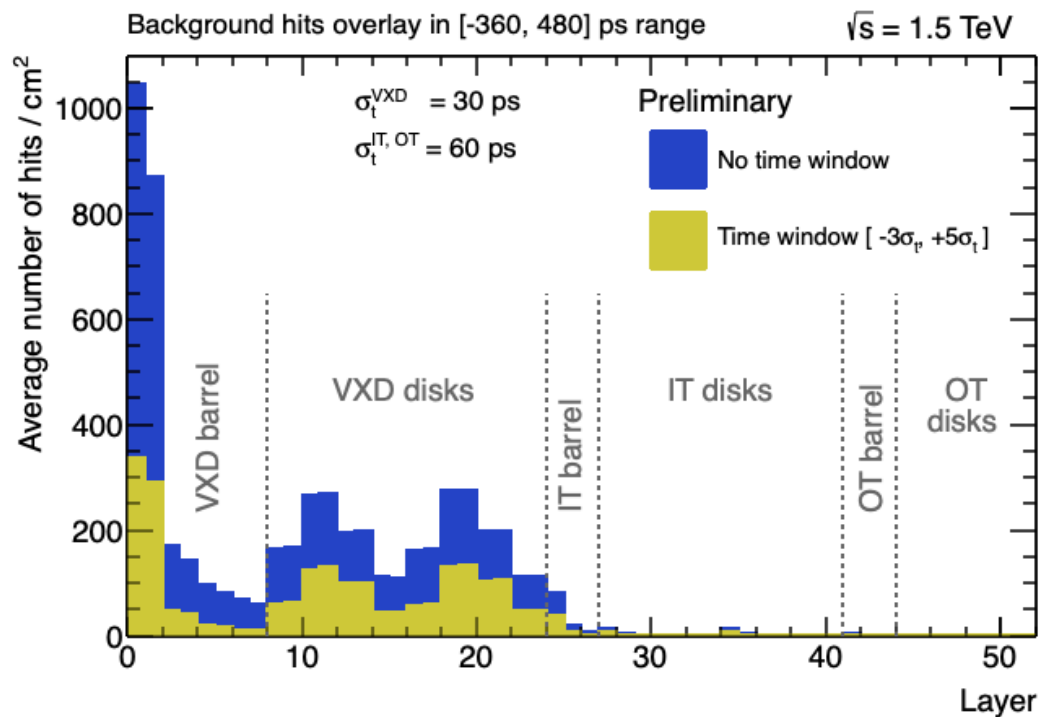
- E.g. longitudinal bunch capture
- Drift to develop energy-time relation
- Buncher adiabatically ramp RF voltages
- Phase rotator misphase RF
 - High energy bunches decelerated
 - Low energy bunches accelerated
- Challenge: Control of losses



BIB Characteristics



BIB Rejection



- Beam induced background (BIB) arising due to muon decays

