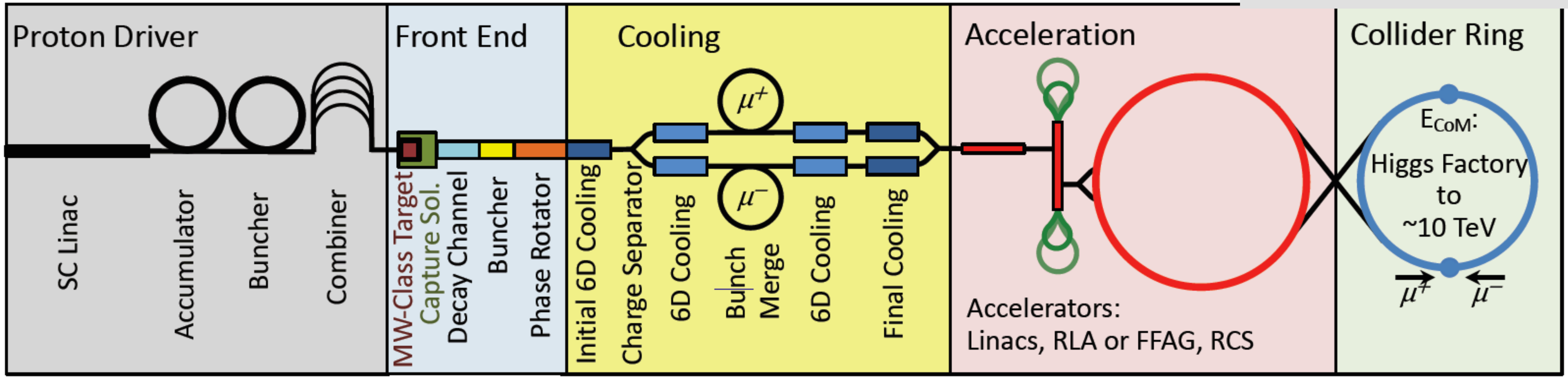
Roadmap Process of the Muon Beam Panel

Daniel Schulte and Mark Palmer for the Muon Beam Panel

Proton-driven Muon Collider Concept

The muon collider has been developed by the MAP collaboration mainly in the US
Muon cooling demonstration by MICE in the UK, some effort on alternative mainly at INFN

MAP collaboration



Short, intense proton bunches to produce hadronic showers

Protons produce pions
Pions decay to muons

Muon are captured, bunched and then cooled by ionisation cooling in matter

Acceleration to collision energy

Collision

Muon collider is unique for very high lepton collision

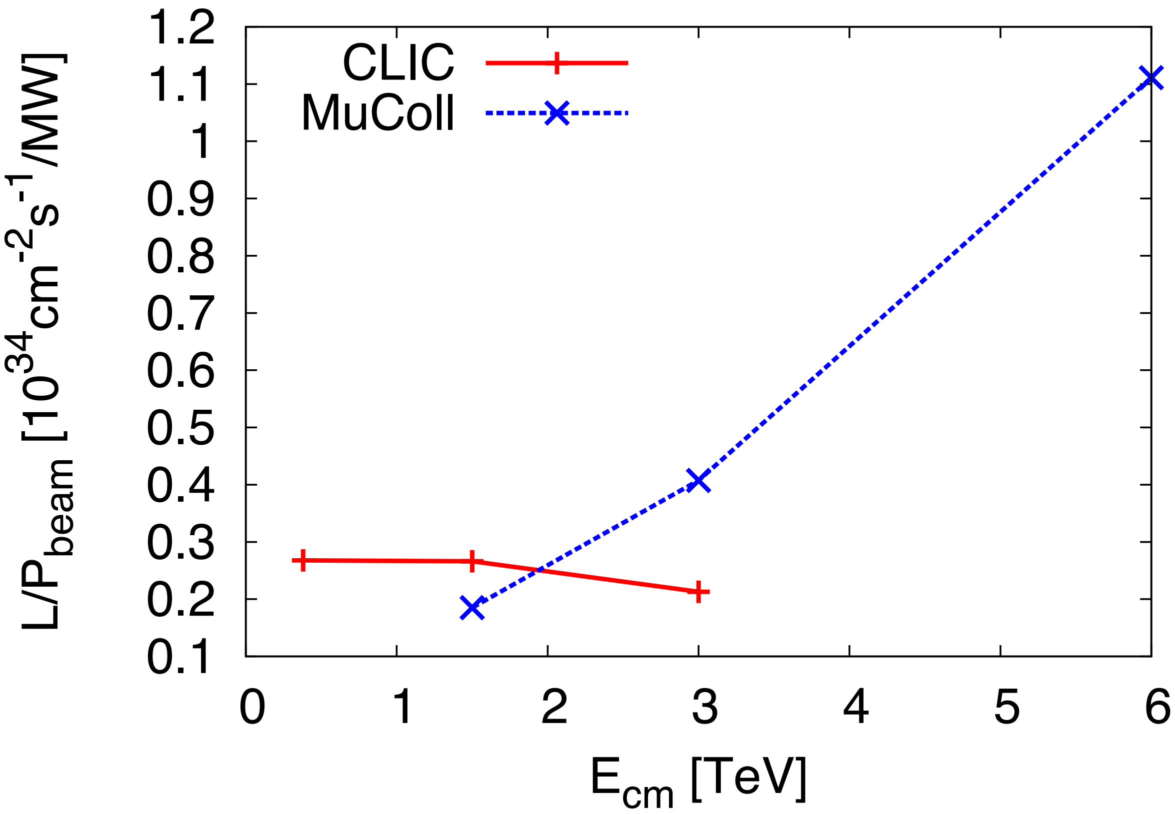
Comparing Luminosity in MAP vs. CLIC

In linear colliders luminosity per beam power is independent of collision energy for same technology

CLIC is at the limit of what one can do (decades of R&D)

No obvious way to improve

$$\mathcal{L} \propto \frac{N}{\sqrt{\beta_x \epsilon_x}} \frac{1}{\sqrt{\beta_y \epsilon_y}} P_{beam}$$



Luminosity per beam power increases with energy in muon collider

Muon colliders have the potential for high energies

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

International Muon Collider Collaboration

Objective:

In time for the next European Strategy for Particle Physics Update, the study aims to **establish whether the investment into a full CDR and a demonstrator is scientifically justified**.

It will provide a baseline concept, well-supported performance expectations and assess the associated key risks as well as cost and power consumption drivers. It will also identify an R&D path to demonstrate the feasibility of the collider.

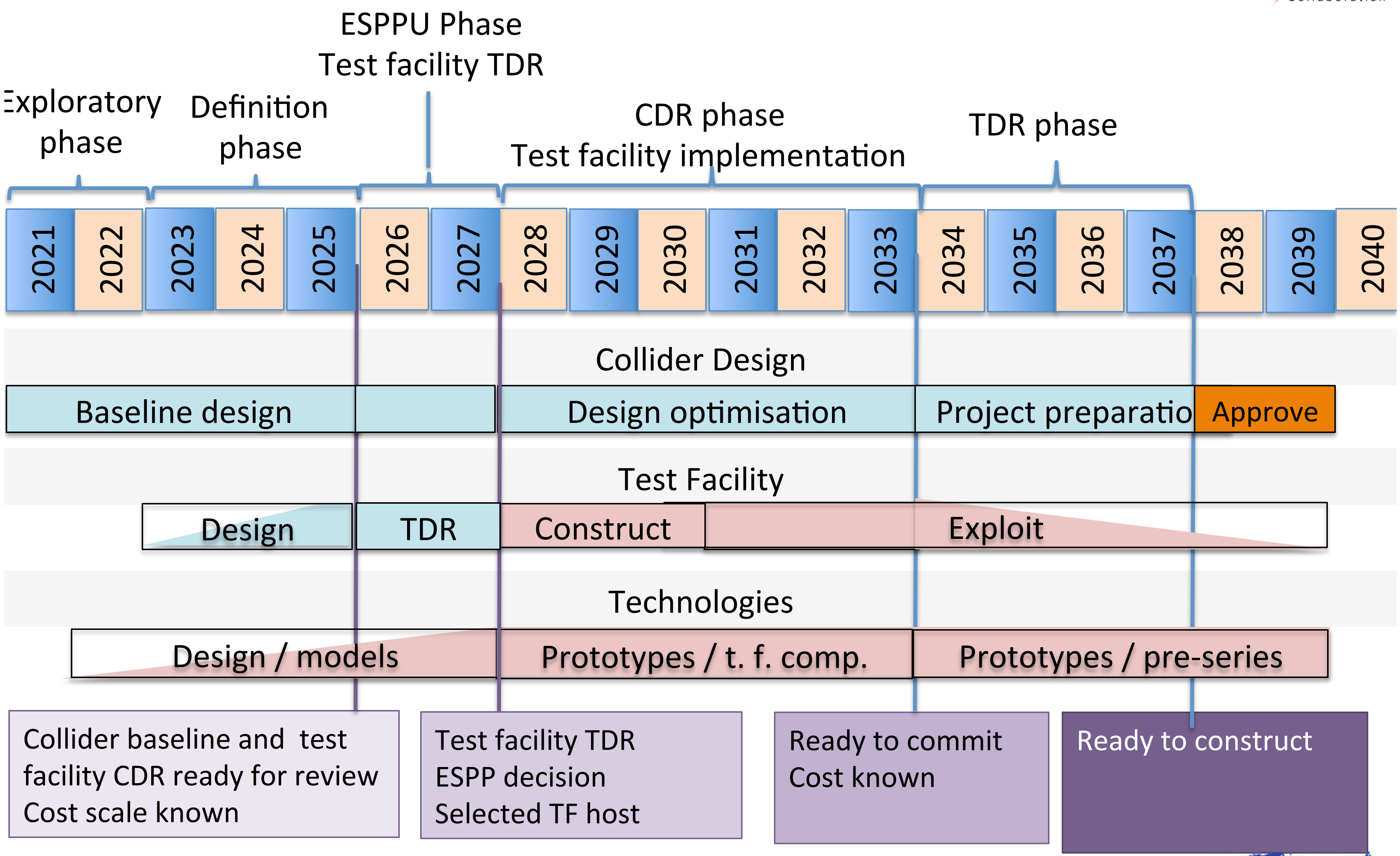
Scope:

- Focus on two energy ranges:
  - **3 TeV**, if possible with technology ready for construction in 10-20 years
  - **10+ TeV**, with more advanced technology, **the reason to do muon colliders**
- Explore synergy with other options (neutrino/higgs factory)
- Define **R&D path**

Deliverable:

- Report supporting that the muon collider is a realistic option, including description of required R&D programme to arrive at CDR
- Conceptual design report for test facility

Technically Limited Long-Term Timeline



Luminosity Goals

Target integrated luminosities

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

Note: currently no staging
Would only do 10 or 14 TeV

- Tentative parameters achieve goal in 5 years
- FCC-hh to operate for 25 years
- Might integrate some margins
- Aim to have two detectors

Now study if these parameters lead to realistic design with acceptable cost and power

Tentative target parameters
Scaled from MAP parameters

Comparison:
CLIC at 3 TeV: 28 MW

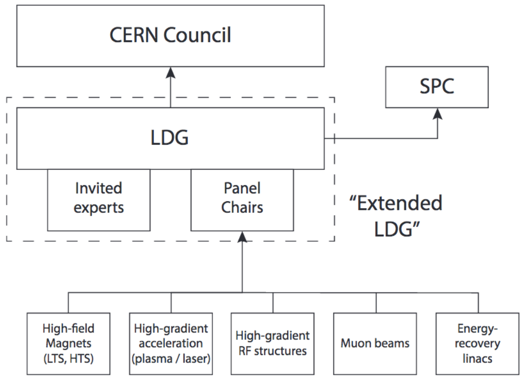
Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} $cm^{-2}s^{-1}$	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

Muon Beam Panel

Daniel Schulte (CERN, chair)
Mark Palmer (BNL, co-chair)
Tabea Arndt (KIT)
Antoine Chance (CEA/IRFU)
Jean-Pierre Delahaye (retired)
Angeles Faus-Golfe (IN2P3/IJClab)
Simone Gilardoni (CERN)
Philippe Lebrun (European Scientific Institute)
Ken Long (Imperial College London)
Elias Metral (CERN)
Nadia Pastrone (INFN-Torino)
Lionel Quettier (CEA/IRFU), Magnet Panel link
Tor Raubenheimer (SLAC)
Chris Rogers (STFC-RAL)
Mike Seidel (EPFL and PSI)
Diktys Stratakis (FNAL)
Akira Yamamoto (KEK and CERN)

Contributors:
Alexej Grudiev (CERN), RF panel link
Roberto Losito (CERN), Test Facility link
Donatella Lucchesi (INFN) MDI link

https://muoncollider.web.cern.ch/organisation



Work with collaboration, panel and community meetings:

- May 20+21: Identify R&D challenges, first scope
- July 12-14: Identify the R&D for next five years, internal priorities, resource estimates
- July 16: Submission of Interim Report to LDG
- September: Final R&D list, scenarios, may still answer questions of LDG
- September LDG submits Interim Report to Council
- December Final Report submitted to Council

Community Meeting Conveners

Updated conveners list

- **Radio-Frequency (RF):** Alexej Grudiev, Jean-Pierre Delahaye, Derun Li, Akira Yamamoto, (suggestion from Alexej).
- **Magnets:** Lionel Quettier, Toru Ogitsu, Soren Prestemon, Sasha Zlobin, (Riccardo Musenich, Stefania Farinon).
- **High-Energy Complex (HEC):** Antoine Chance, J. Scott Berg, Alex Bogacz, Christian Carli, , Angeles Faus-Golfe, Eliana Gianfelice-Wendt, Shinji Machida.
- **Muon Production and Cooling (MPC):** Chris Rogers, Marco Calviani, Chris Densham, Diktys Stratakis, Akira Sato, Katsuya Yonehara.
- **Proton Complex (PC):** Simone Gilardoni, Hannes Bartosik, Frank Gerigk, Natalia Milas, (Sarah Couisineau for September).
- **Beam Dynamics (BD):** Elias Metral, Tor Raubenheimer, Rob Ryne.
- **Radiation Protection (RP):** Claudia Ahdida.
- **Parameters, Power and Cost (PPC):** Daniel Schulte, Mark Palmer, Philippe Lebrun, Mike Seidel, Vladimir Shiltsev, Jingyu Tang, Akira Yamamoto
- **Machine Detector Interface (MDI):** Donatella Lucchesi, Christian Carli, Anton Lechner, Nicolai Mokhov, Nadia Pastrone.
- **Synergy:** Kenneth Long, Roger Ruber, Koichiro Shimomura.
- **Test Facility (TF):** Roberto Losito, Alan Bross, Tord Ekelof.

Key Challenge Areas

10+ TeV is uncharted territory

- **Physics potential** evaluation

- Impact on the environment
  - The **neutrino flux mitigation** and its impact on the site

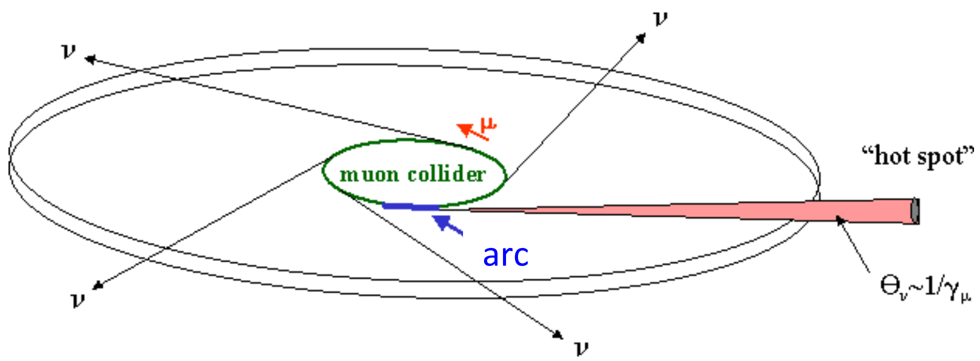
- The impact of **machine induced background** on the detector, as it might limit the physics reach.

- **High-energy systems** after the cooling (acceleration, collision, …)
  - This can limit the energy reach via cost, power and beam quality

- **High-quality beam production** of cooled muon beam
  - MAP did study this in detail
  - First experimental verification in MICE
  - Need to optimise and prepare test facility

- **Integrated Collider Design** with choices, parameters, trade-offs
  - need to cover all accelerator areas

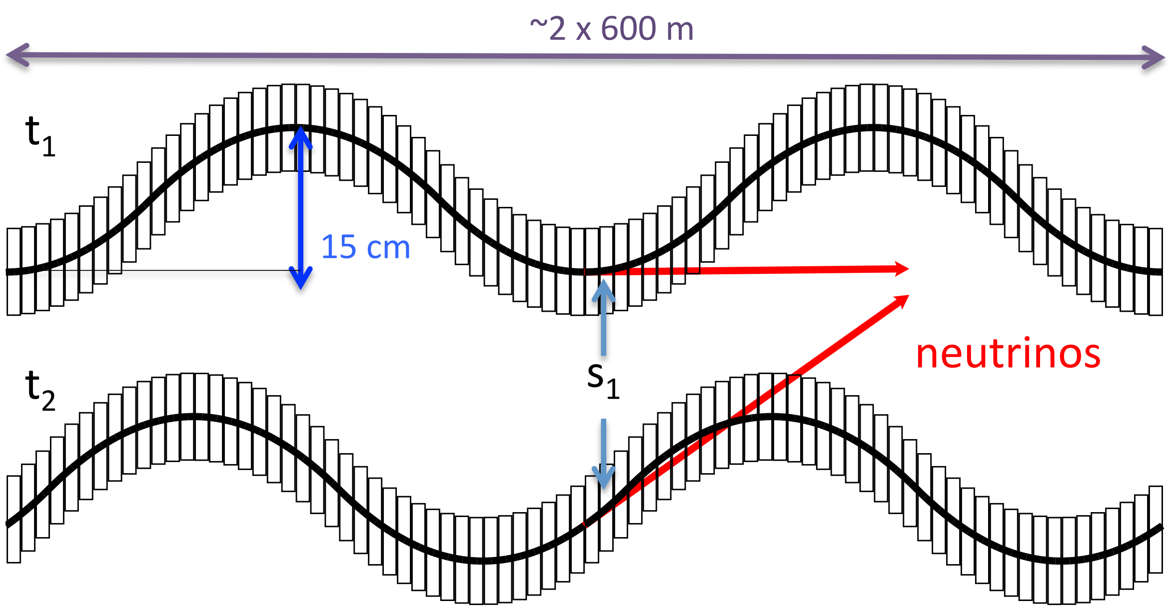
Neutrino Flux Mitigation



Legal limit 1 mSv/year
MAP goal < 0.1 mSv/year
Our goal: arcs below threshold for legal procedure < 10 μSv/year
LHC achieved < 5 μSv/year

3 TeV, 200 m deep tunnel is about OK

Need mitigation of arcs at 10+ TeV: idea of Mokhov, Ginneken to move beam in aperture
our approach: move collider ring components, e.g. vertical bending with 1% of main field



Opening angle ± 1 mradian

14 TeV, in 200 m deep tunnel comparable to LHC case

Need to study mover system, magnet, connections and impact on beam

Working on different approaches for experimental insertion

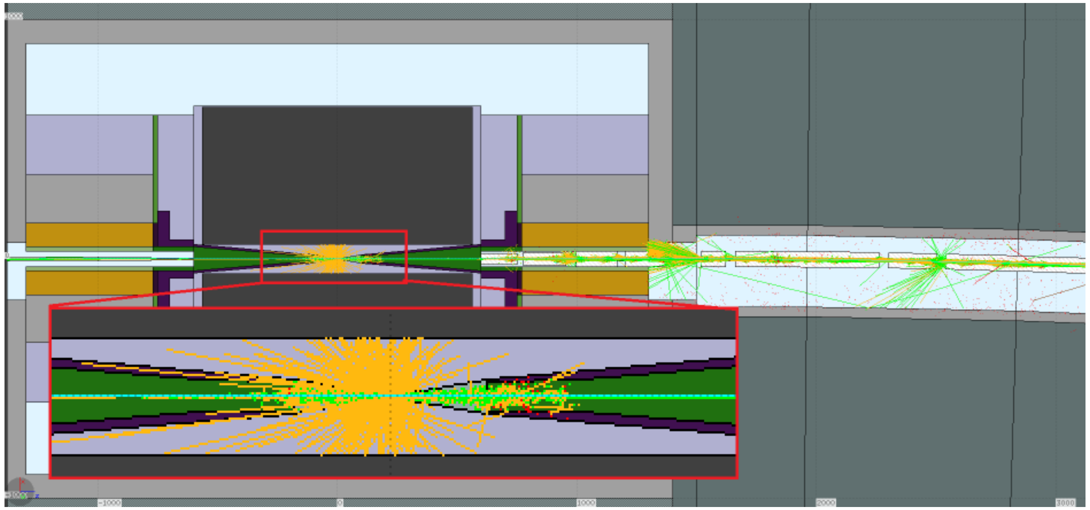
MDI

Main background sources
- Muon decay products (40,000 muons/m/crossing at 14 TeV)
  - tertiary muons produced far from collision point
  - showers products produced in final triplets
- Beam-beam background

Background reduces while beam decays
- part luminosity delivered with lower background
- consider worst condition

Mitigation methods
- masks
- detector granularity
- detector timing
- solenoid field
- event reconstruction strategies
- …

Need to ensure they do not compromise physics

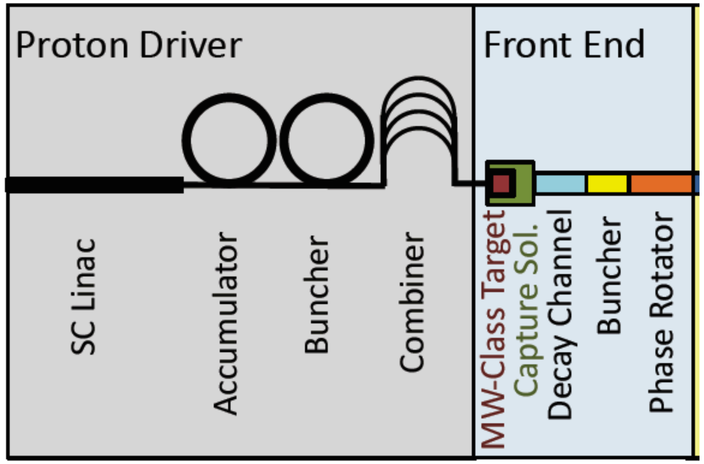


Simulation tools exist

First studies at lower energies (125 GeVand 1.5 TeV are encouraging

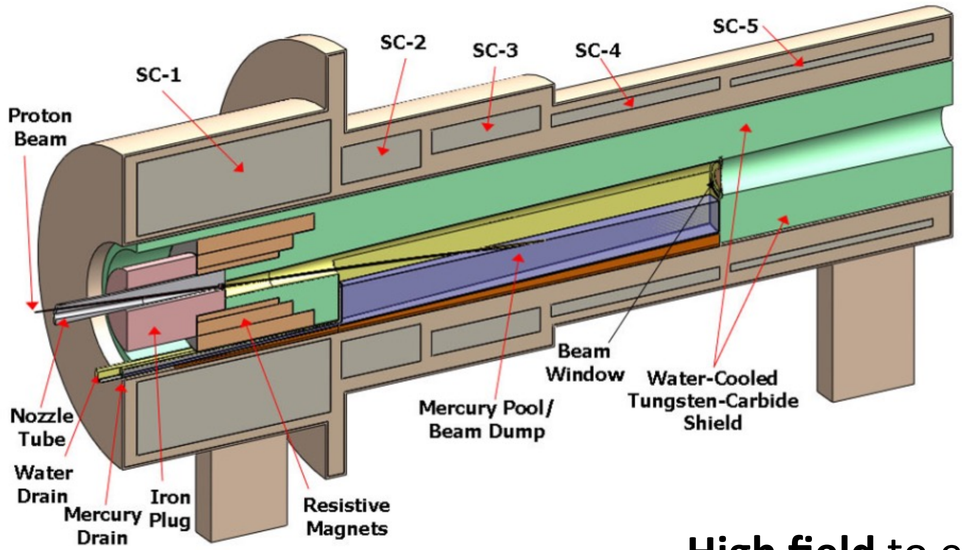
Will develop systems for higher energies

Proton Complex and Target Area



Proton beam power is no issue, some look required at
H- source and **accumulator complex**

2 MW proton beam
requires radiation protection

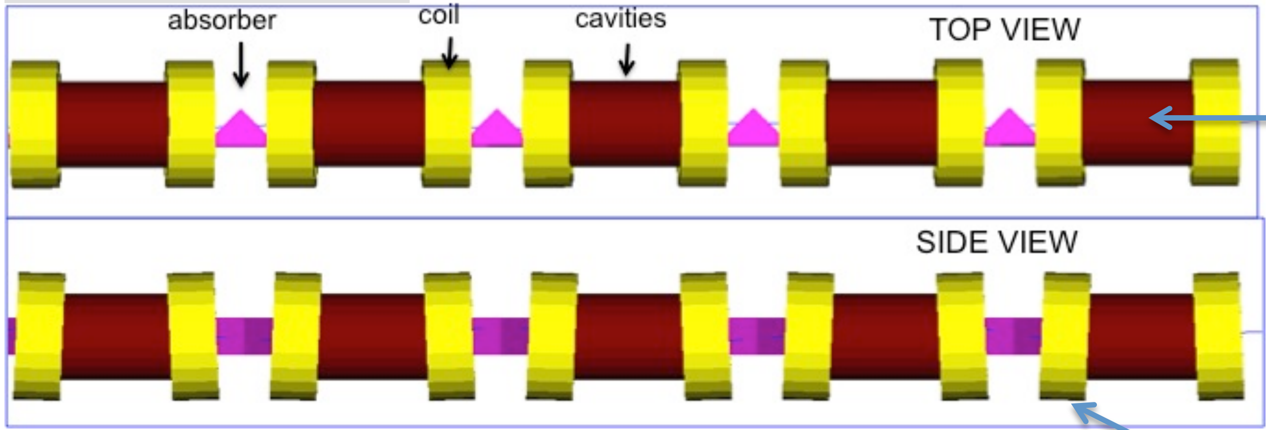


Large aperture O(1m)
to allow shielding

High field to efficiently collect pions/muons:
20 T then tapering

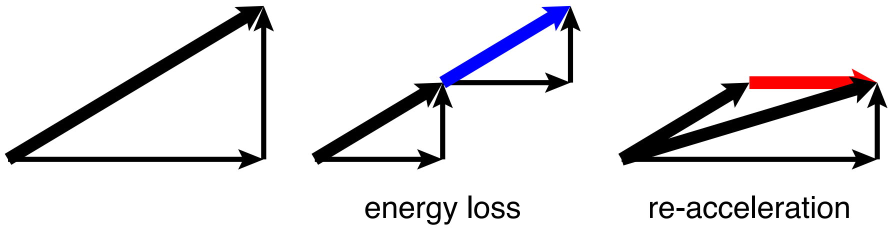
Cooling Concept

MAP collaboration

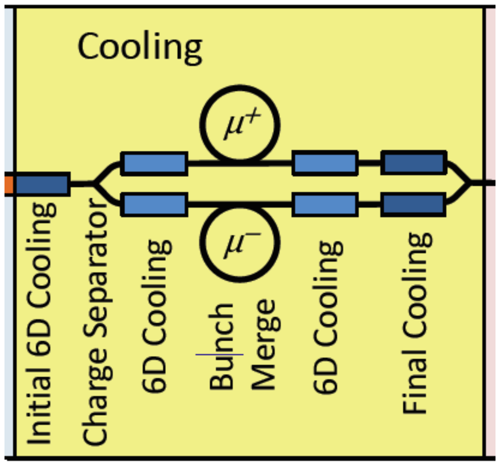


Limit muon decay, cavities with **high gradient in a magnetic field**
tests much better than design values but need to develop

Compact integration to minimise muon loss



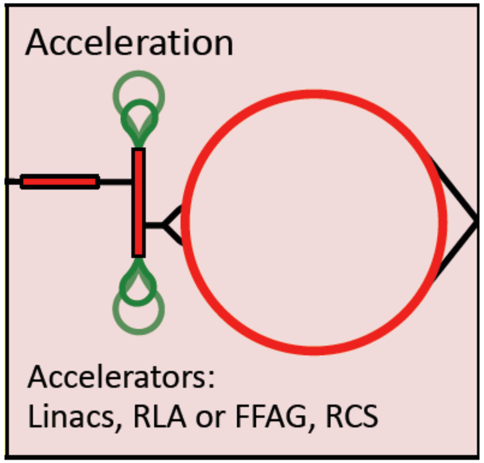
Minimise betafunction with **strongest solenoids (40+ T)**
32 T achieved, 40+ T planned



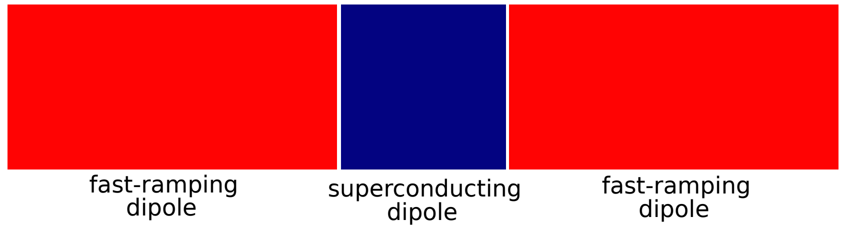
Need to **optimise lattice design** to gain factor 2 in emittance integrating demonstrated better hardware performances

This is the **unique** and **novel** system of the muon collider
Will need a **test facility**
The principle has been demonstrated in MICE

High-energy Acceleration



System of linacs followed by sequence of RCS and/or FFA



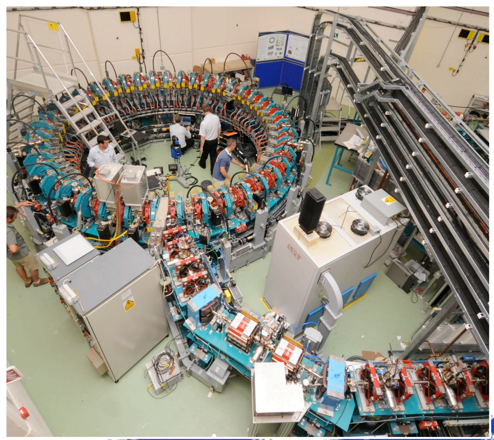
Rapid cycling synchrotron (RCS)
- Combine static and ramping magnets
- **Ramp magnets** to follow beam energy
  - normal conducting
  - or novel HTS
- **Power consumption** of fast-ramping systems is important

RF system
- **Important single-bunch beam loading**

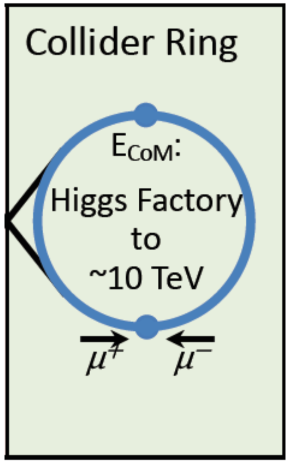
FFAG
- Fixed (high-field) magnets but large energy acceptance
- Challenging **lattice design** for large bandwidth and limited cost
- **Complex high-field magnets**
- Challenging beam dynamics

EMMA proof of FFA principle

Nature Physics 8, 243–247 (2012)



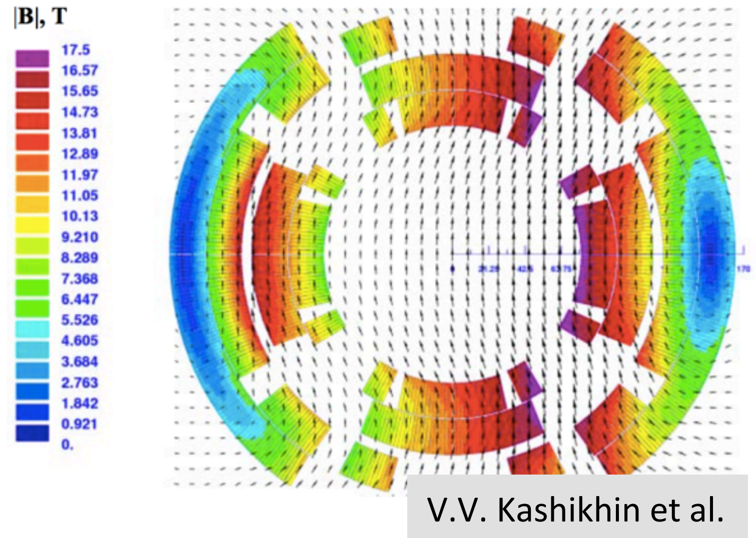
Collider Ring



High field dipoles to minimise collider ring size and maximise luminosity
4.5 km at 3 TeV, 10/14 at 10/14 TeV

Beam loss protection O(500 W/m)

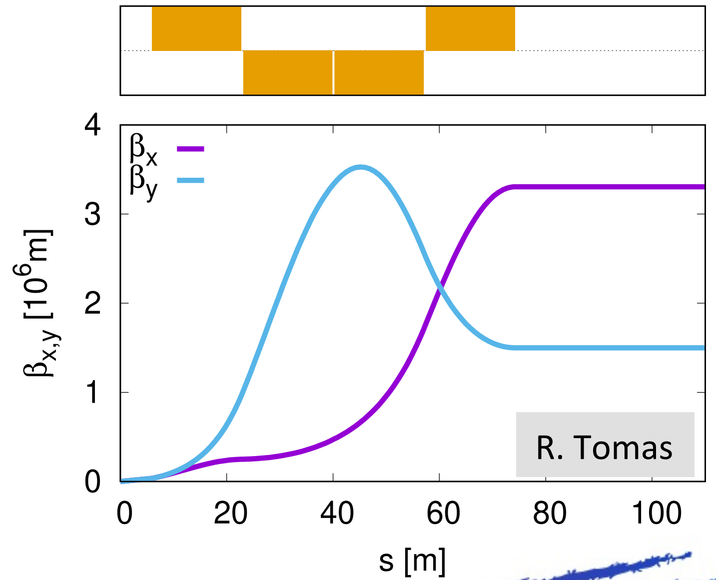
- MAP shielding solution for 3 TeV: 150 mm aperture and 30-50 mm shielding



Strong focusing at IP to maximise luminosity
HL-LHC type performance for 3 TeV
Large aperture HTS required at high energy

Lattice design/beam dynamics
e.g. Short bunch preservation (1 mm) in large ring

- Careful control of longitudinal motion
- Beam dynamics of frozen beam
- Synergy with light sources might exist



Tentative Potential Workpackages

Workpackages potentially including hardware

- Fast-ramping magnet systems
- Cooling RF
- Neutrino radiation mitigation system

Paper studies exploiting synergies

- Superconducting RF
- Efficient RF power systems
- High-field solenoids
- High-field dipoles / combined function magnets
- Target system

Other theoretical studies

- Accelerator design and beam dynamics
- Integrated cooling cell design
- Radiation protection and accelerator radiation (target, collider ring)
- MDI
- Other technologies

Test facility design

- Application of above workpackages to test facility (should be the same people)
- Studies for test facility implementation: civil engineering, proton complex, …

Conclusion

- Muon colliders are a unique opportunity for a high-energy, high-luminosity lepton collider
  - high luminosity to power ratio
  - cost efficiency to be assessed
- Not as mature as ILC or CLIC
  - have to address important R&D items
  - but now showstopper identified
- Need to develop concept to a maturity level that allows to make informed choices by the next ESPPU and other strategy processes
  - Baseline design
  - Demonstration programme with test facility
- An important opportunity that we should not miss

Many thanks to the Muon Beam Panrel, the collaboration, the MAP study, the MICE collaboration, Mark Palmer, Chris Rogers and many others

Reserve

Memorandum of Cooperation

Basically ready, waiting for final polishing

CERN is initially hosting the study

- International collaboration board (ICB) representing all partners
  - elect chair and study leader
  - can invite other partners to discuss but not vote (to include institutes that cannot sign yet)
- Study leader
- Advisory committee reporting to ICB

Addenda to describe actual contribution of partners

Key Muon Production and Cooling

- Lattice design optimisation
  - Do not yet reach the target transverse emittance
  - Most muons are lost here
  - Room to optimise the cooling system for emittance and muon survival

- Highest-field solenoid for final cooling
  - Aim for 40+ T
- Target solenoid
  - High field, large aperture, high radiation
- Other cooling magnets
  - High field, large aperture, required for test facility

- High-gradient, RF in strong magnetic field
- Have to limit peak power

- Cooling cell design
  - Tight integration of components

- Target
  - Energy per pulse (also power, but muons per bunch is critical and cannot be mitigated by multiple targets)
  - Challenge depends on muon survival, scaling of MAP parameter tables 1.3 MW, other estimates up to 4 MW
  - ⇒ Best to plan for some reserve

- Radiation from target

- Proton complex
  - Challenge is to compress proton pulse

Key High-energy Systems

- Lattice designs
  - in particular IP and collider ring, accelerator rings, also linacs
- Longitudinal beam dynamics along complex
  - including single bunch beam loading
- Collective effects estimates
  - not sure that they were explored completely

- Final triplet magnets
  - drive the luminosity, require large aperture and high gradient
- Collider arc magnets
  - key cost driver, large aperture, radiation load, vertical bending field, impact of mover system?
- RCS fast-ramping magnets and power system
  - Cost driver
  - Efficient energy recovery from magnetic field, low losses
- FFA magnet and optics design

- Mitigation of beam loss
  - Interaction region and detector shielding
  - In collider ring at 10 TeV about 5 MW (500 W/m), leads to 35 MW of cryo power for 1% shielding inefficiency
  - O(200) kW in cold accelerator parts, goal 10% inefficiency or better

- RF
  - very high single-bunch beam loading
  - efficiency

- Mover system
  - also impact on components

Cooling Challenges and Status

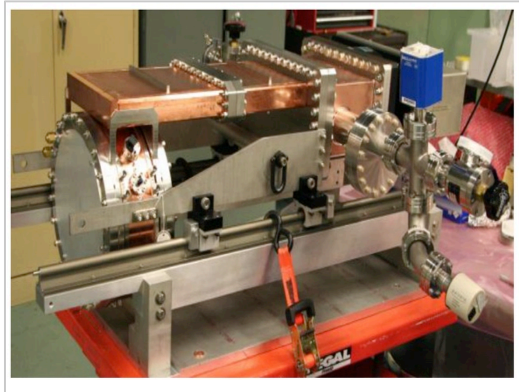
FNAL
12 T/s
HTS
0.6 T max

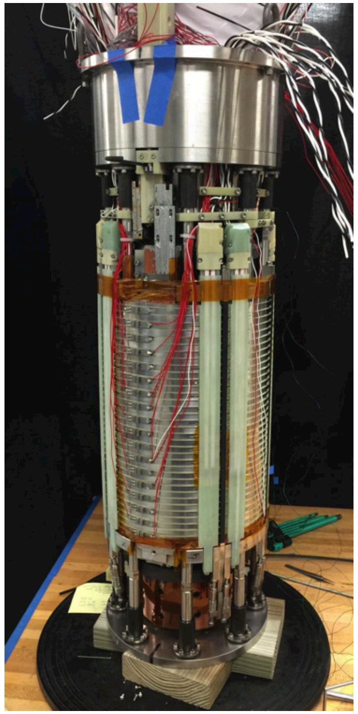
Need to push in field and speed

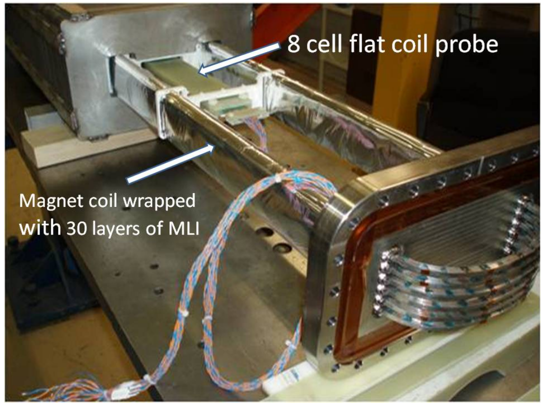
Test of **fast-ramping normal-conducting magnet** design

MuCool: >50 MV/m in 5 T field

Two solutions
- Copper cavities filled with hydrogen
- Be end caps



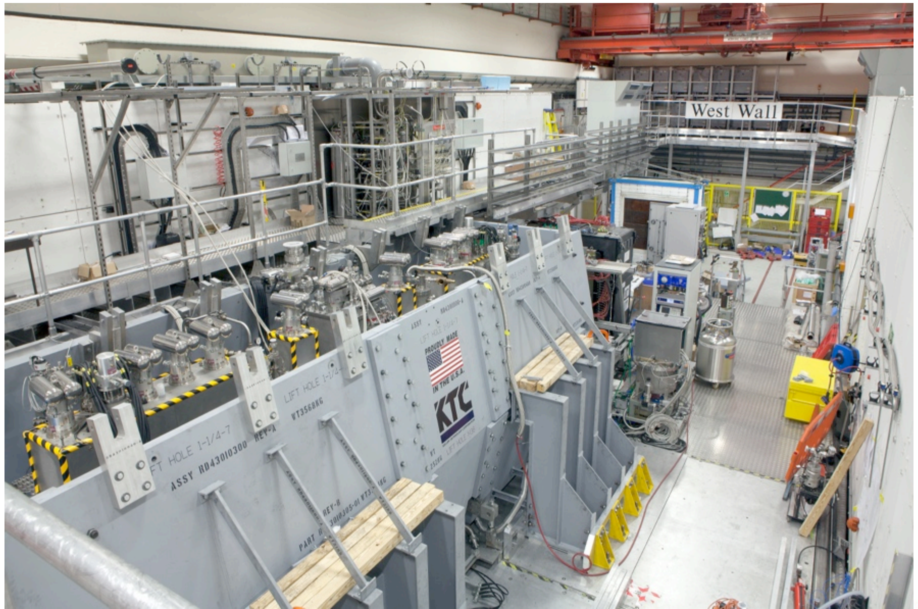




NHFML
32 T solenoid with HTS

Planned efforts to push even further

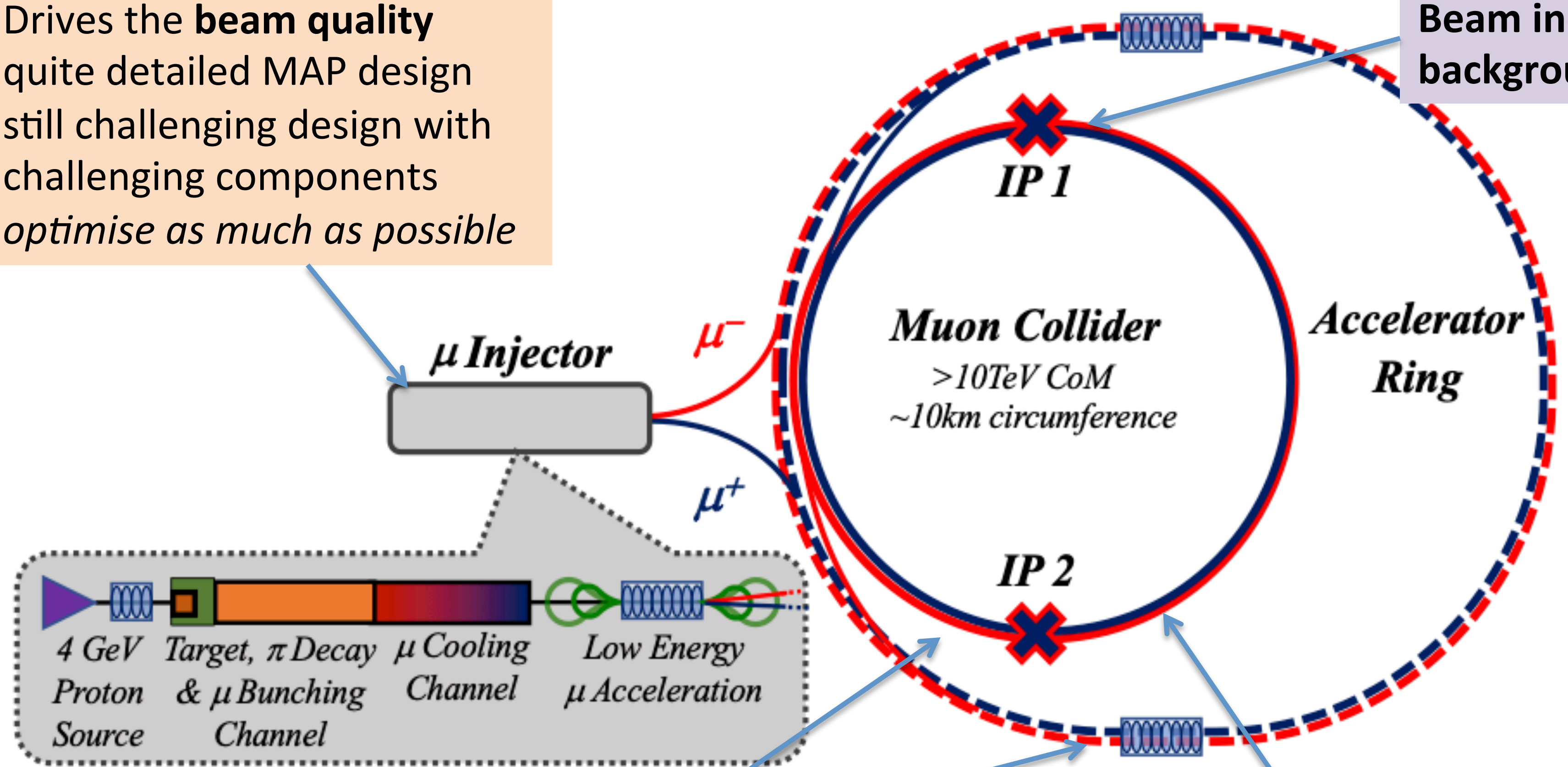
MICE (UK) Muon cooling principle



Key Challenges

Drives the **beam quality**
quite detailed MAP design
still challenging design with
challenging components
optimise as much as possible

Beam induced background



Dense neutrino flux
mitigated by mover system and site selection

Cost and **power** consumption drivers, limit energy reach
e.g. 30 km accelerator for 10/14 TeV, 10/14 km collider ring
Also impacts **beam quality**