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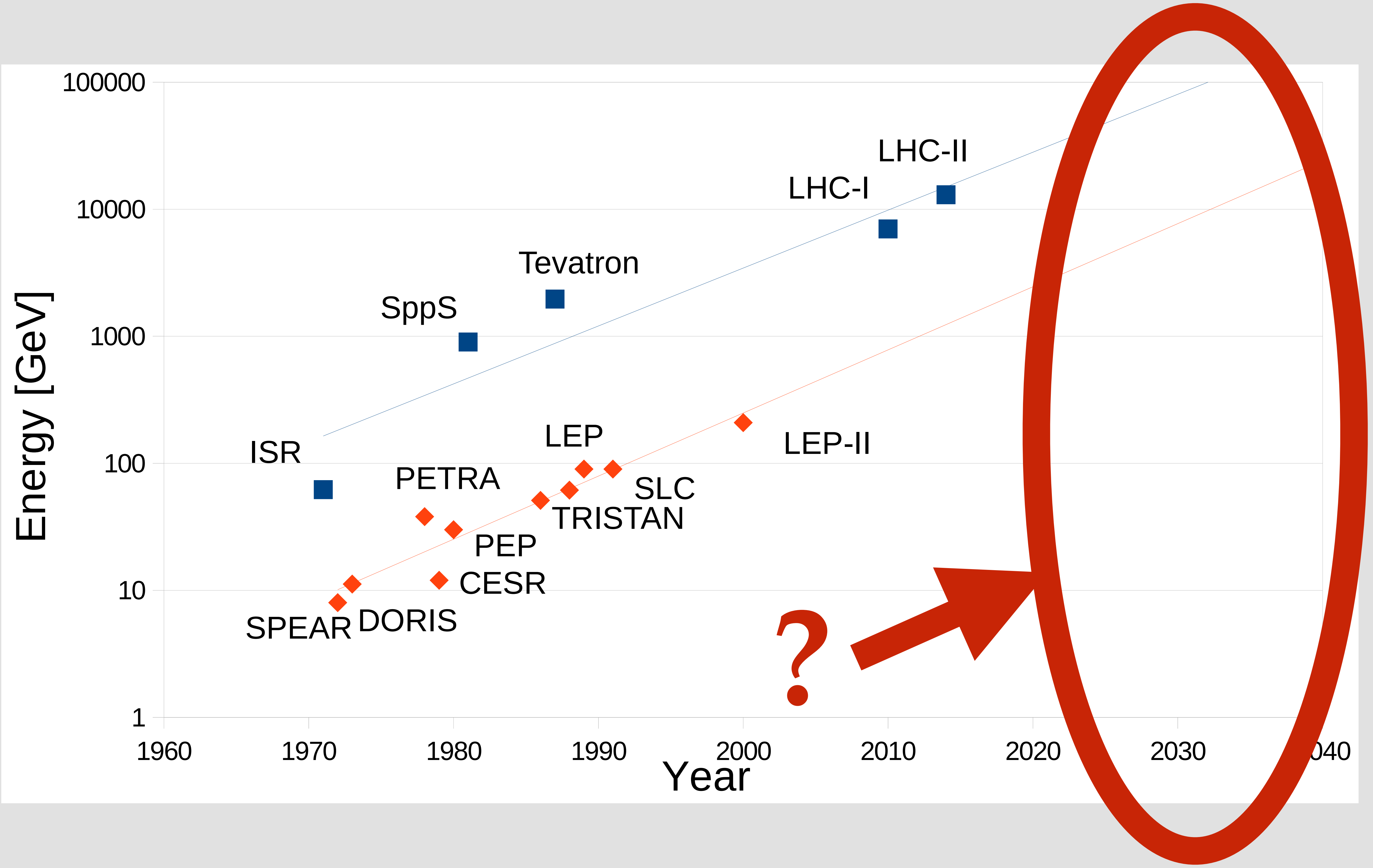
Muon colliders for a post-LHC HEP programme

J.B. Lagrange on behalf of the UK muon collaboration team
ISIS, RAL, STFC

29/06/2023

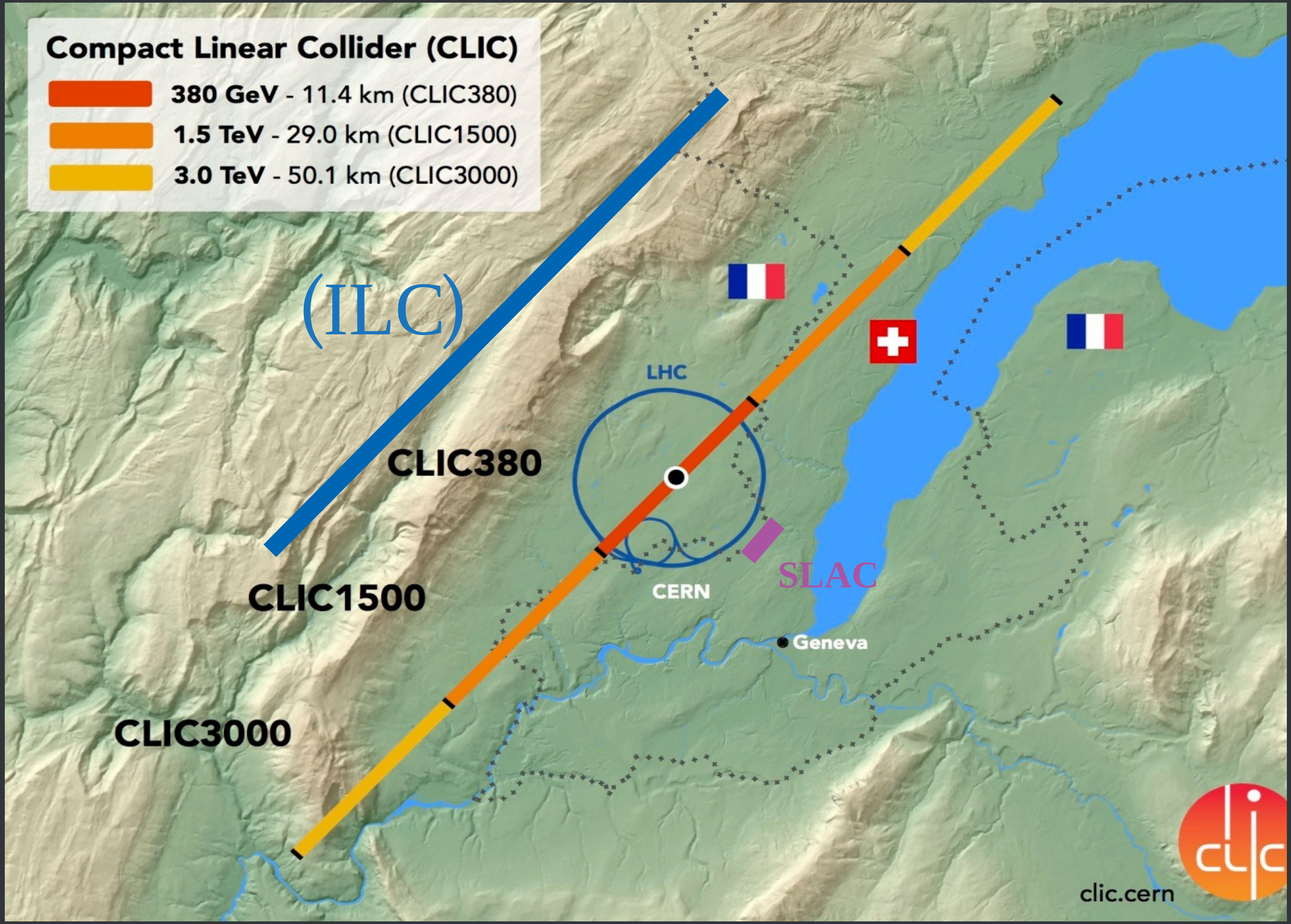
Past high energy physics

- Towards higher energy
- Bigger, more expensive, more power hungry (LHC performance already limited by electricity cost)
- Limit?
- What next?



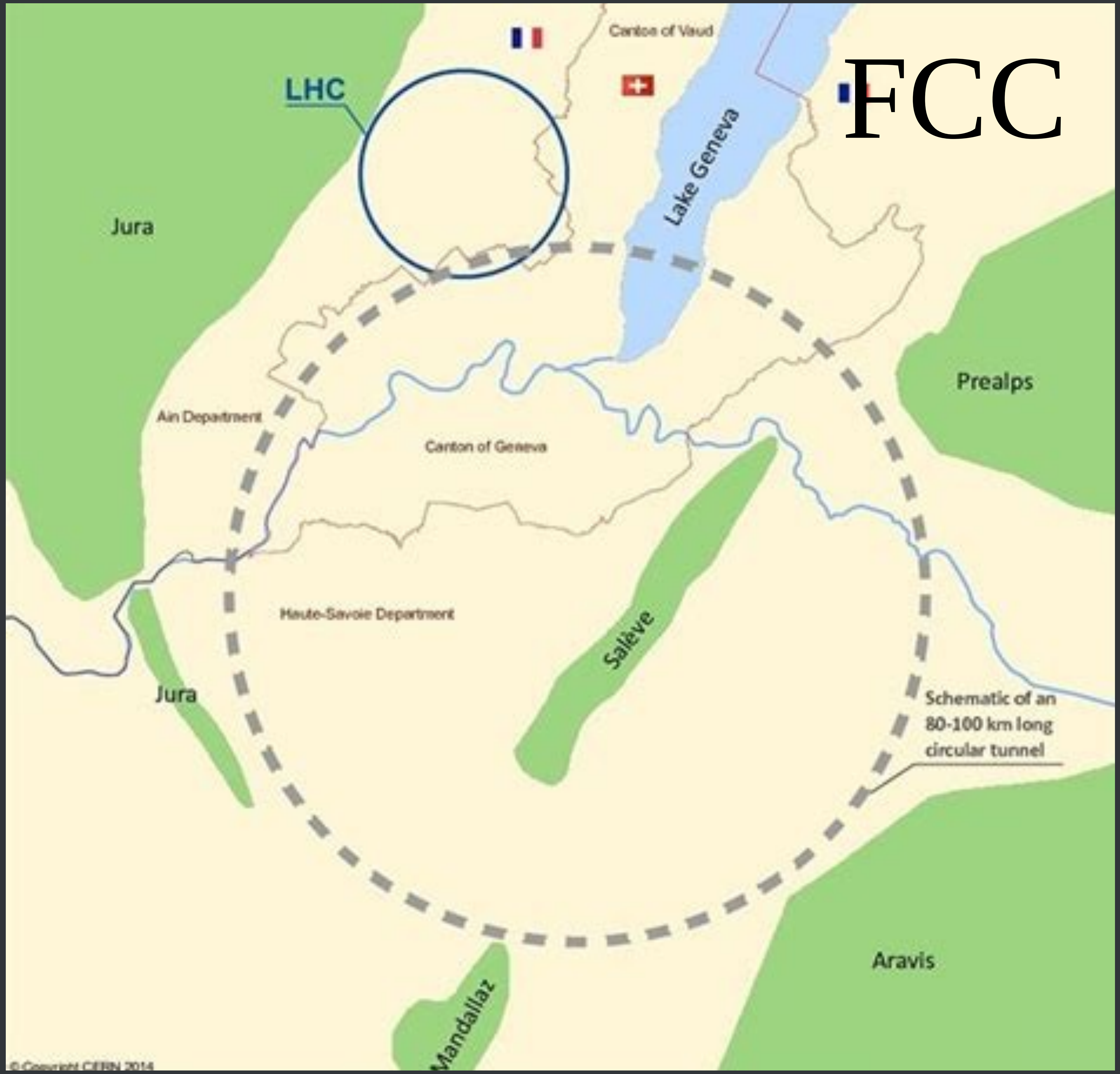
Linear colliders

- ILC:
  - 20 — 31 km
  - 250 — 500 GeV e^+e^-
- CLIC:
  - 11 — 50 km
  - 380 — 3000 GeV e^+e^-



Circular colliders

- FCC / CEPC
- 90-100 km circumference
- 90 – 350 GeV e+e-
- 50 – 100 TeV proton-proton



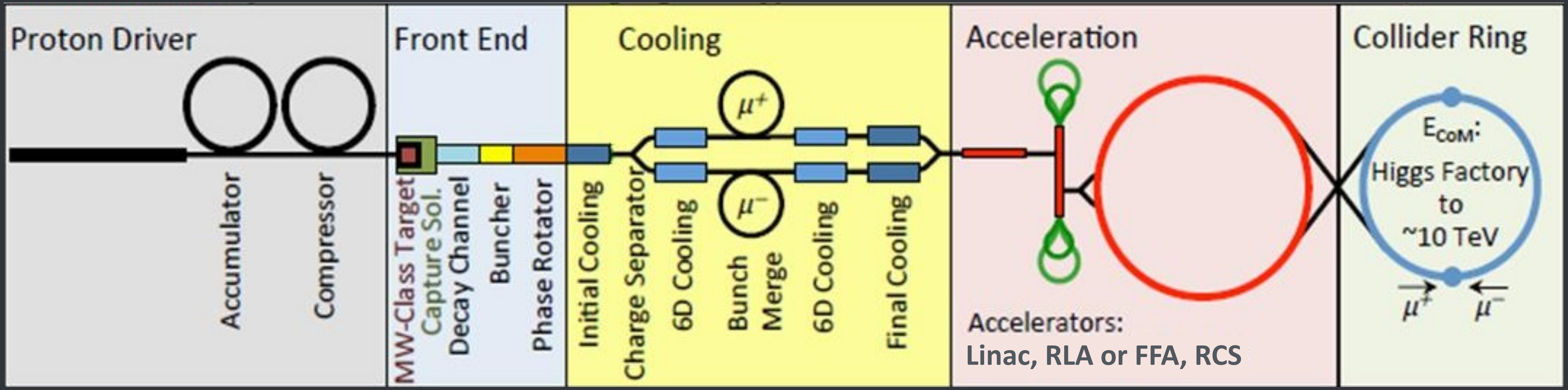
Conventional approach limitations

- e^+e^-:
  - Synchrotron radiation (ring)
  - Available RF acceleration (linear)
- Proton-proton:
  - Not a fundamental particle, need to go to higher energies (~x10) for the same physics reach

Muons

- Fundamental particle
- 207 times electron mass
- But… Not a primary particle, and 2.2 μs life time

Muon collider concept



- MW-class proton driver sent to a target
- Pions produced that decay into muons
- Muon capture and cooling
- Acceleration to TeV & Collisions

UK collaboration

ROYAL HOLLOWAY UNIVERSITY OF LONDON

University of Southampton

Lancaster University

UKRI Science and Technology Facilities Council

University of Oxford

Imperial College London

University of Strathclyde Glasgow

University of Huddersfield

WARWICK THE UNIVERSITY OF WARWICK

US UNIVERSITY OF SUSSEX

UKRI Innovate UK

UNIVERSITY OF BIRMINGHAM

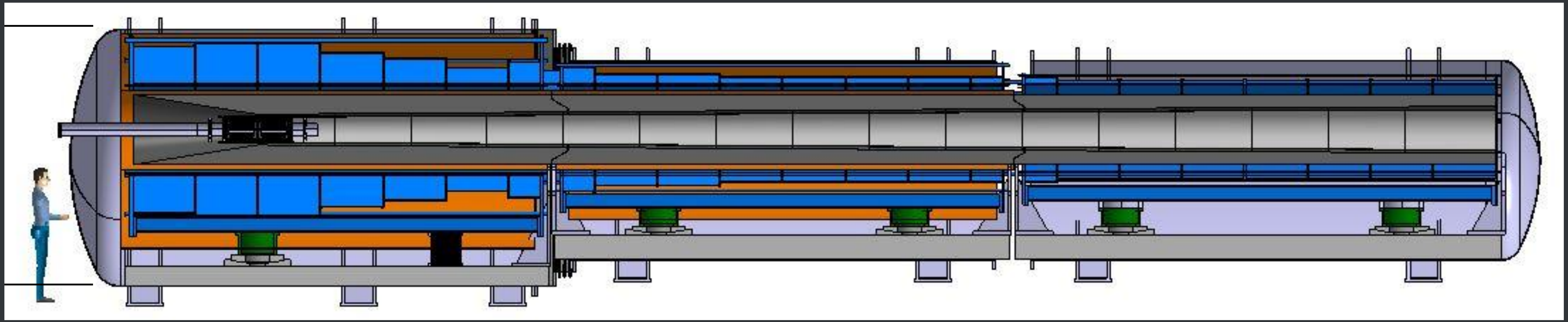
THE UNIVERSITY of MANCHESTER

Parameters

Parameter	Symbol	Unit	Target value		
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	$\mathfrak{L}$	$1 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	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	$\varepsilon_\perp$	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

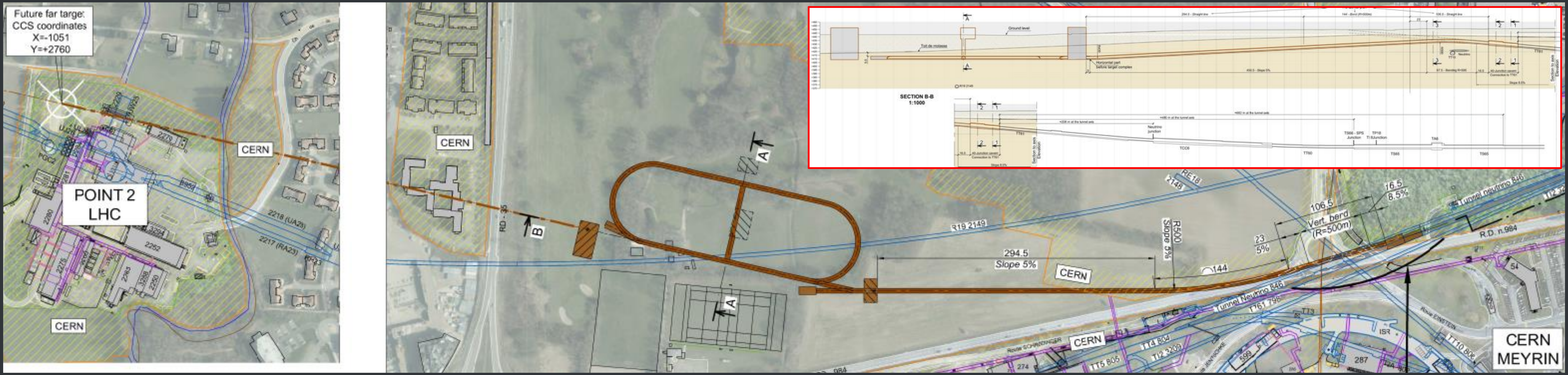
Proton driver & Target

- Protons on target → pions → muons
- Challenges:
  - Short bunch (few ns)
  - Energy deposition in high field solenoid at target
  - Target window life time



C. Accettura et al., IMCC Annual meeting 2023

nuSTORM

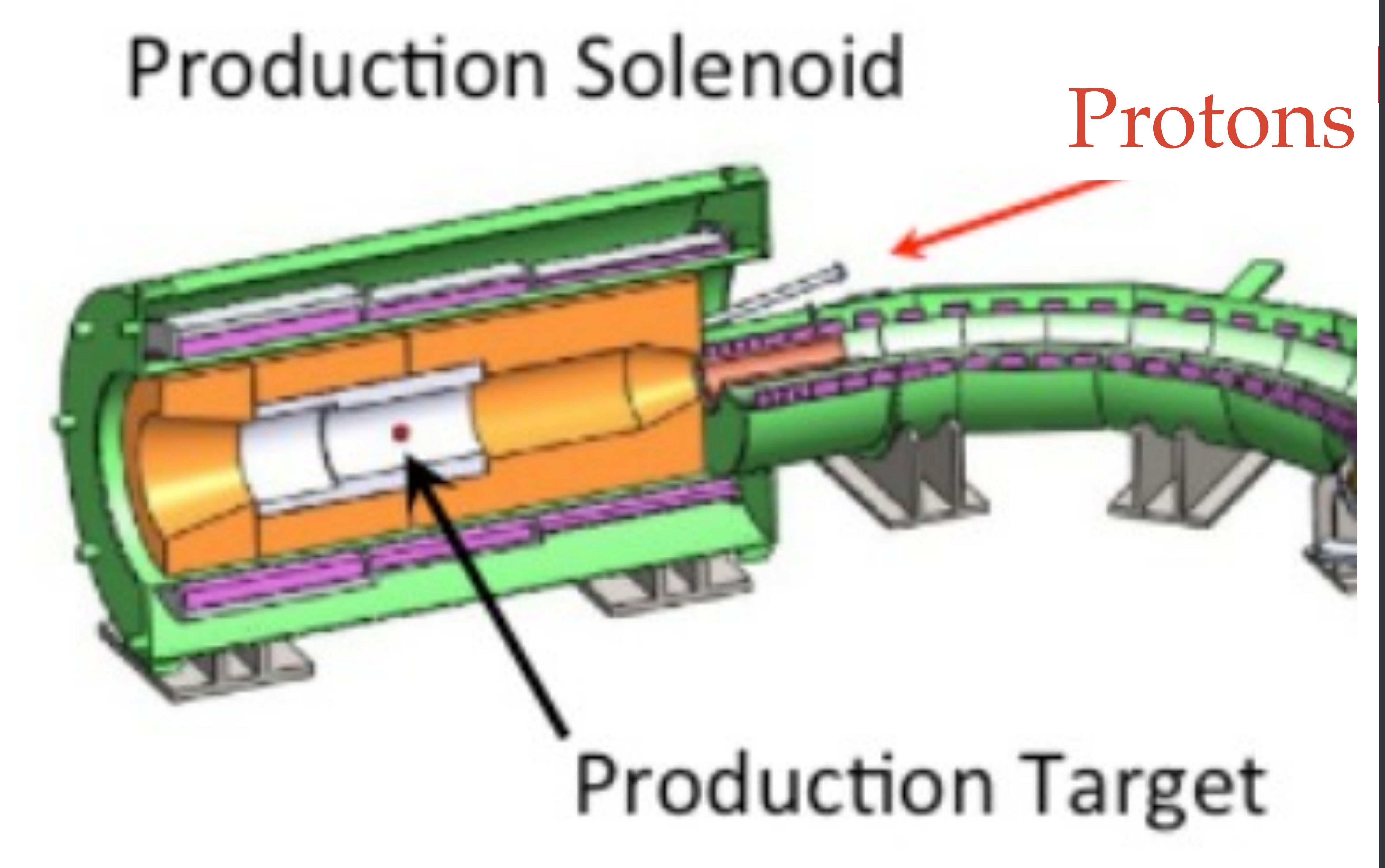


- 100 GeV protons from SPS into ~250 kW target
- Pion transport line with charge selection
- Stochastic muon injection into storage ring
- Precise neutrino scattering measurement & study of sterile neutrinos

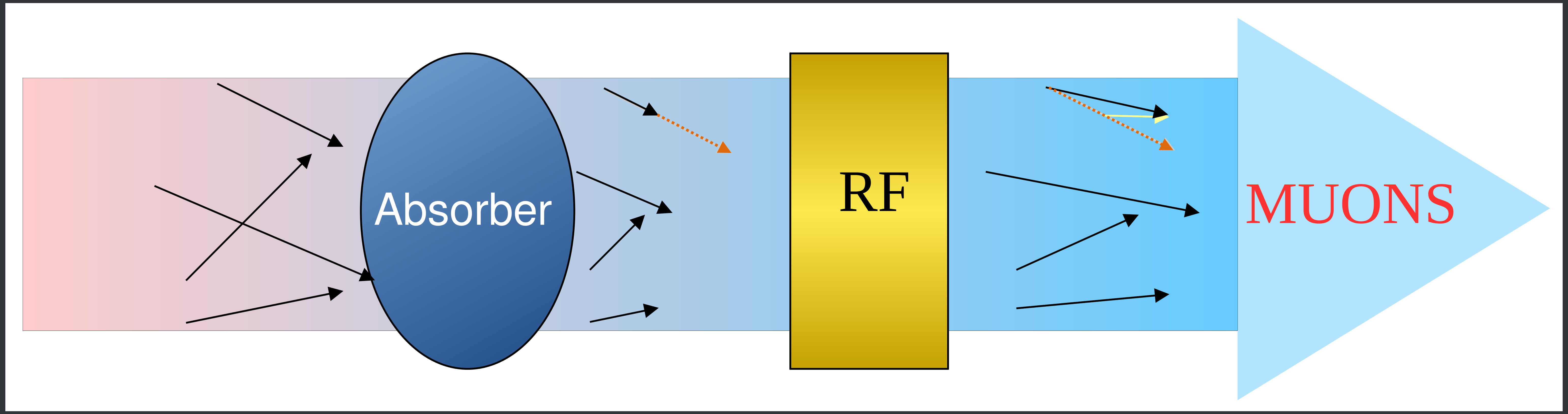
Science and Technology Facilities Council

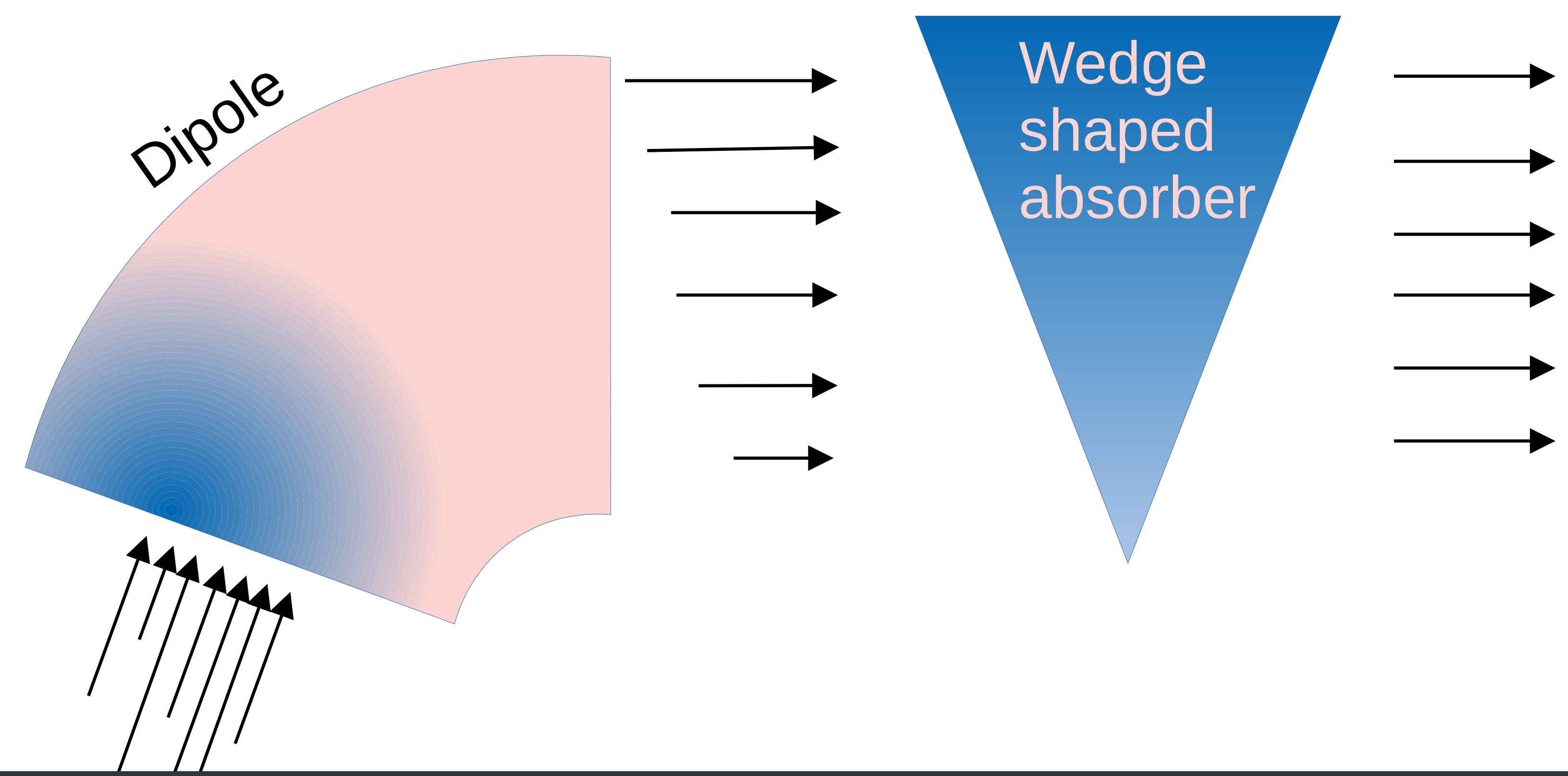
CLFV: COMET & mu2e

- Muon-to-electron conversion experiments
- Strong synergy with MC
  - Similar target station
  - Build collaboration



Muon cooling

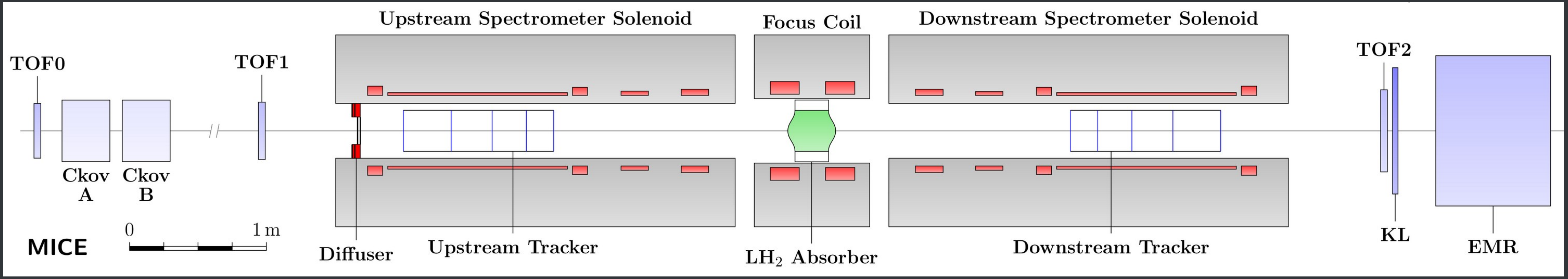


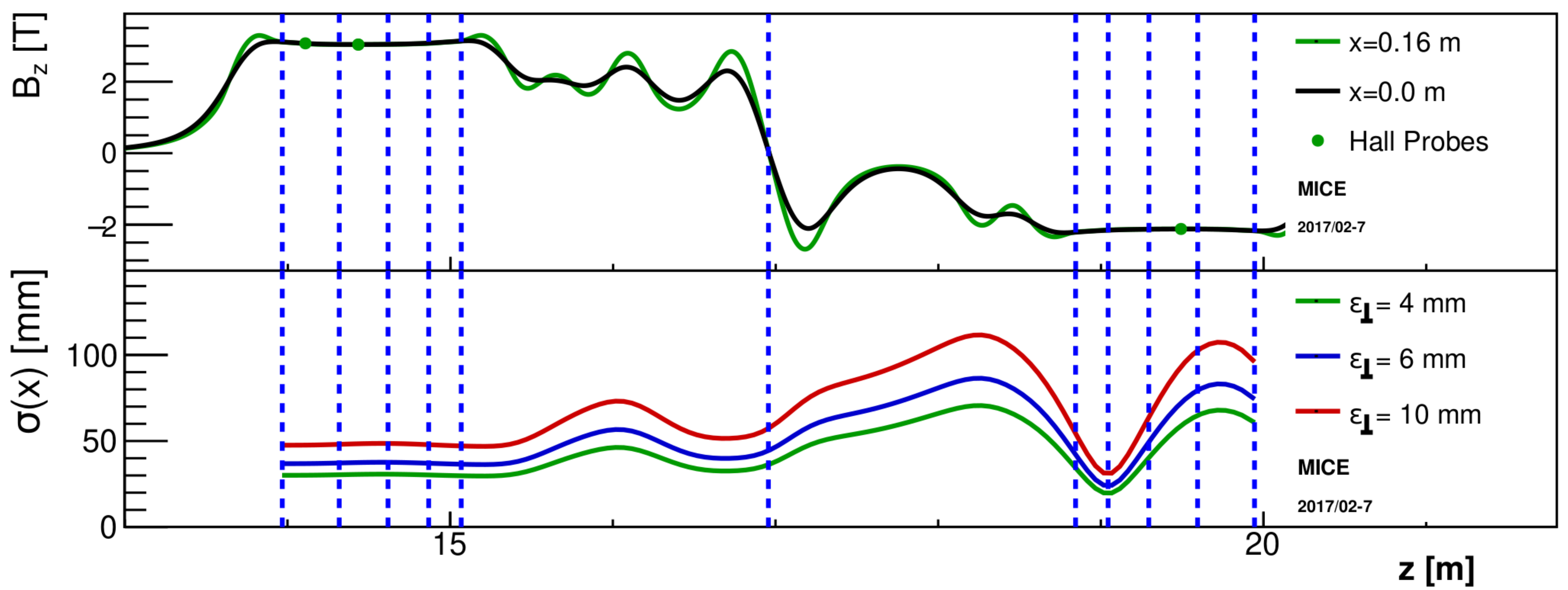


- Ionisation cooling:
  - Energy loss in absorber, reaccelerating in RF cavity
- Multiple Coulomb Scattering mitigated with tight focusing and low-Z absorber
- 6D cooling can be done with emittance exchange

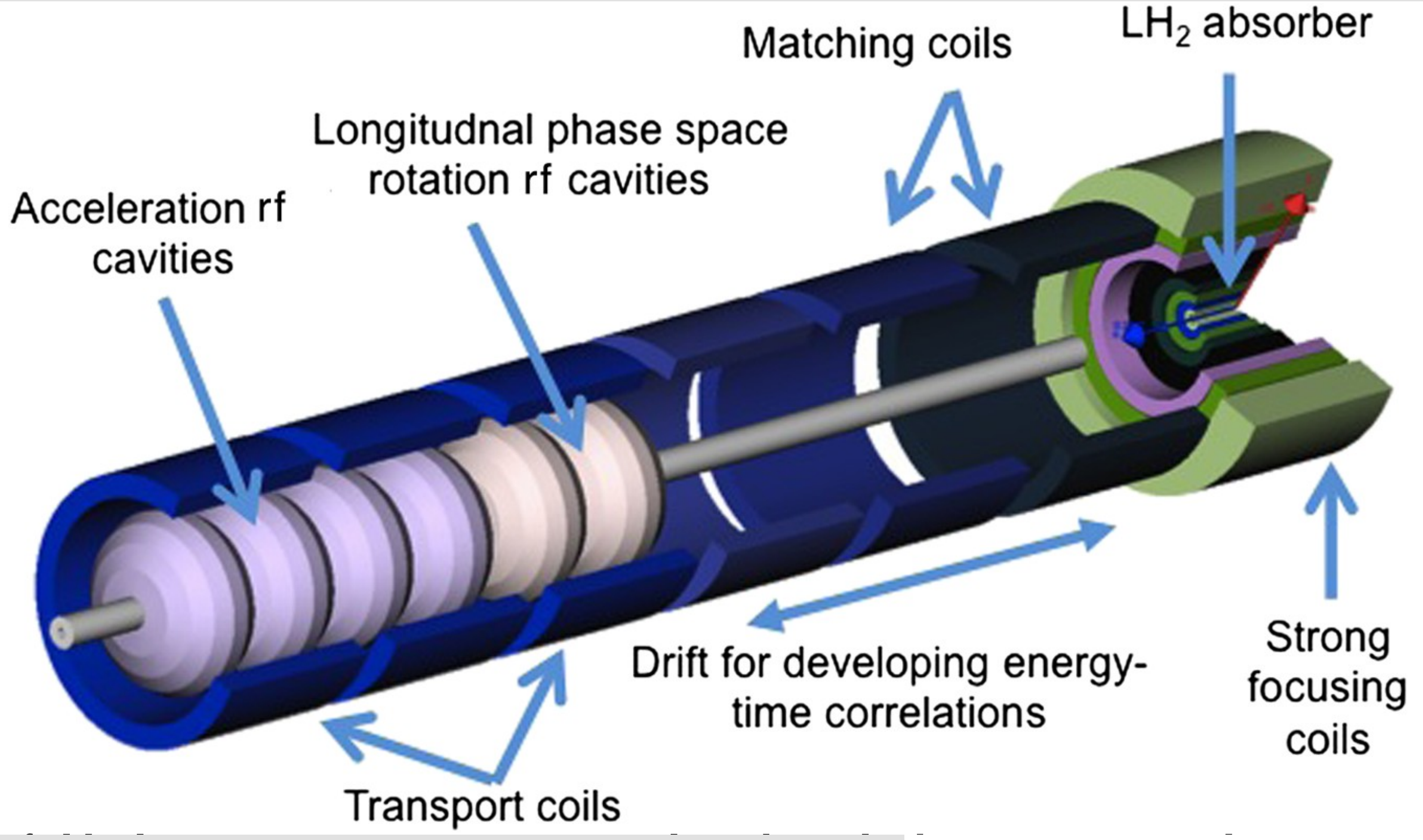
MICE

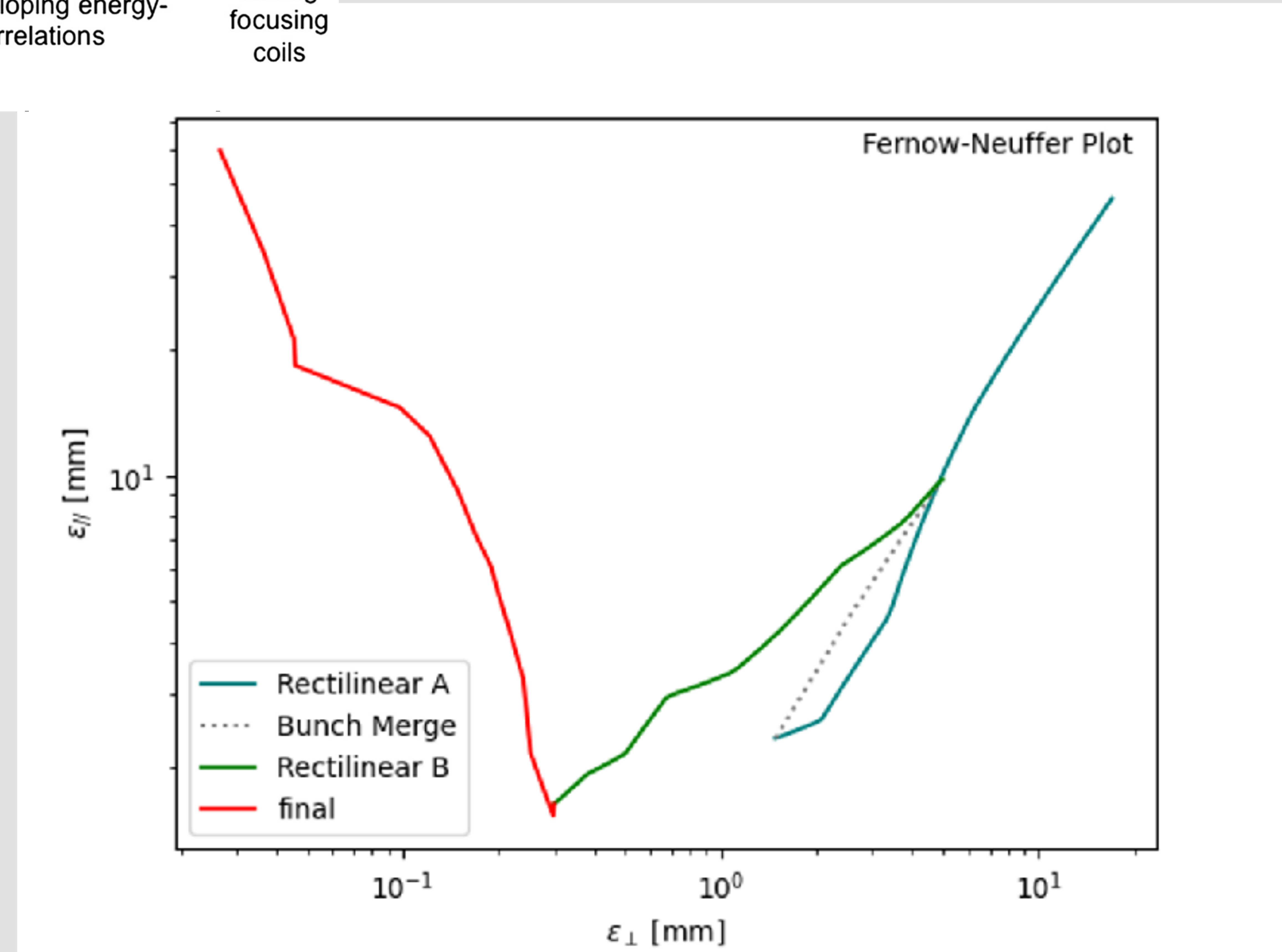
Built at RAL, UK





Muon cooling goal



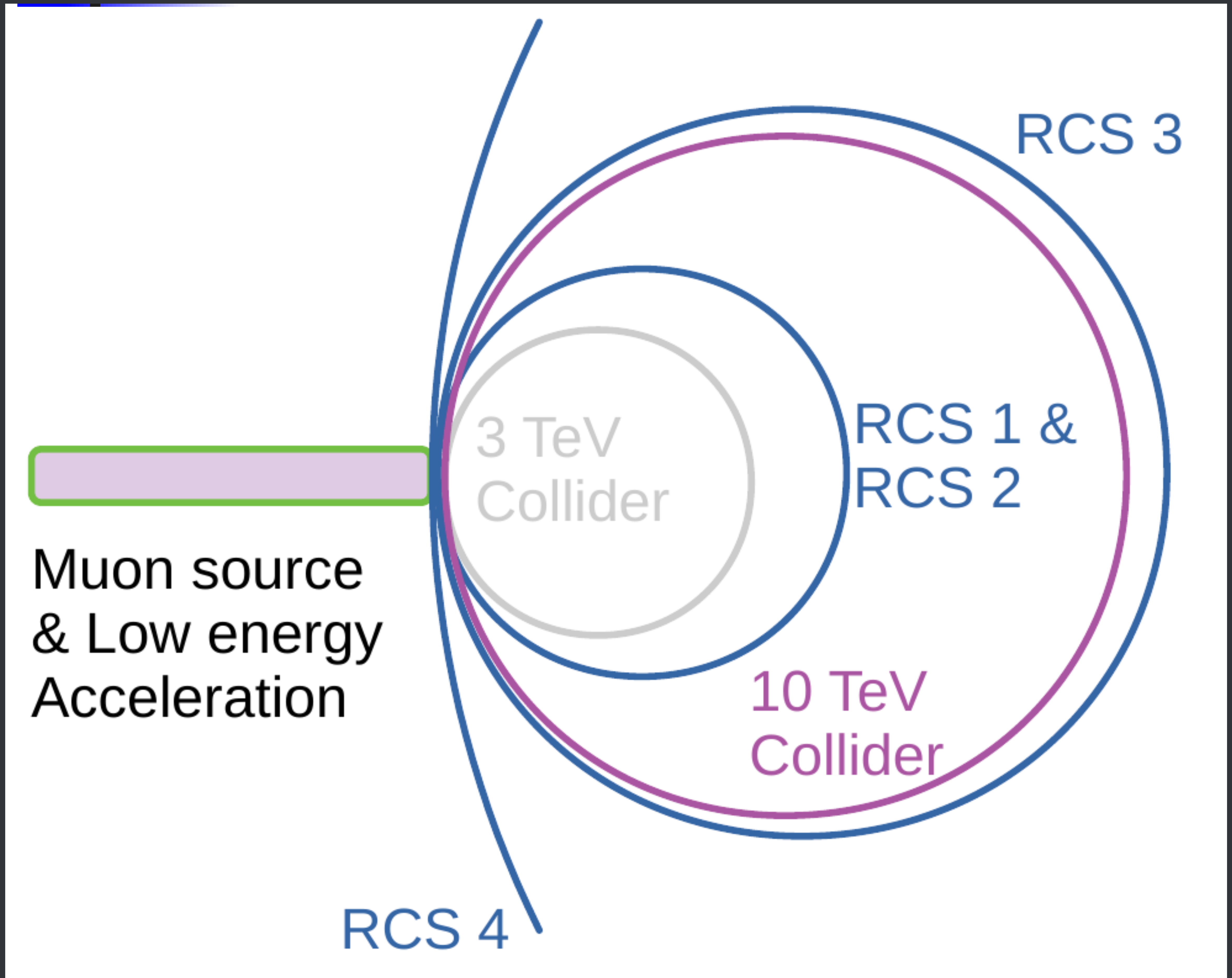


Challenges:

- Very tight focusing in final cooling
- Chromatic aberrations

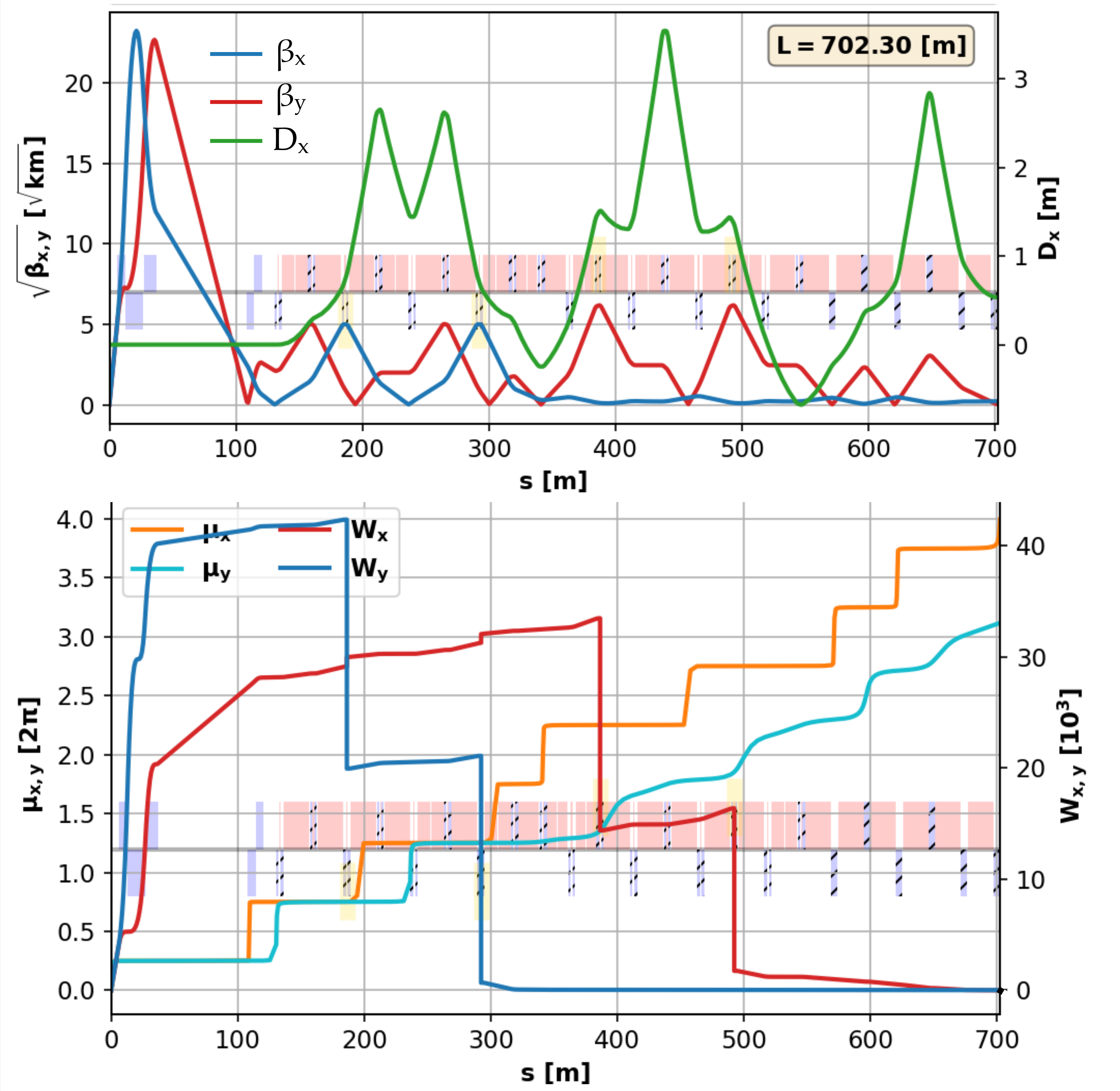
Muon acceleration

- Linac and RLA at low energy (highest energy gradient)
- Synchrotrons at higher energies
  - Very fast ramp RCS or FFAs



Collider ring

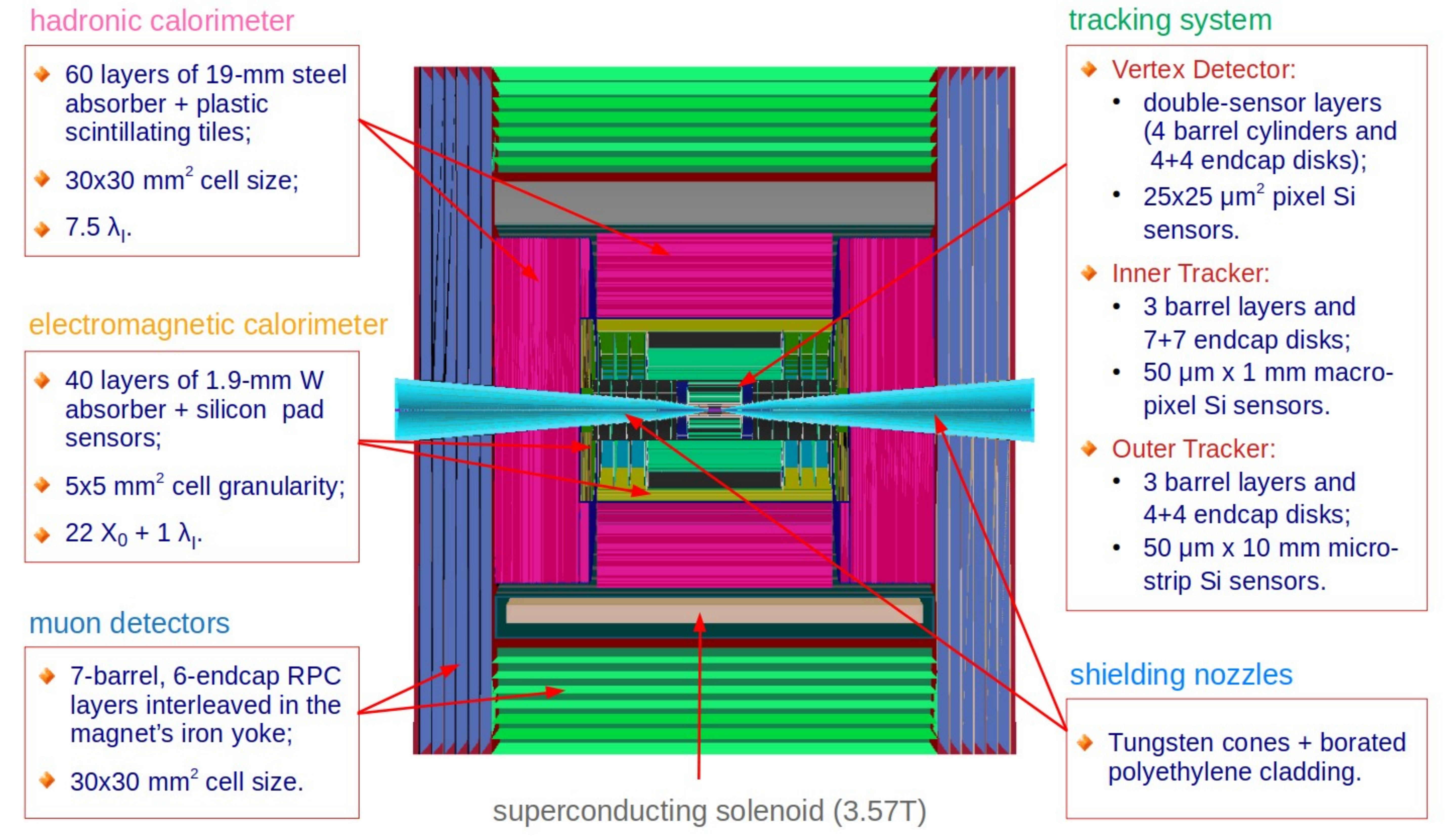
- Luminosity increases for shorter ring and with tight focusing
- Challenges:
  - Very high mean dipole field
  - Very short bunches
  - Chromatic abberations
  - Neutron showering from neutrinos



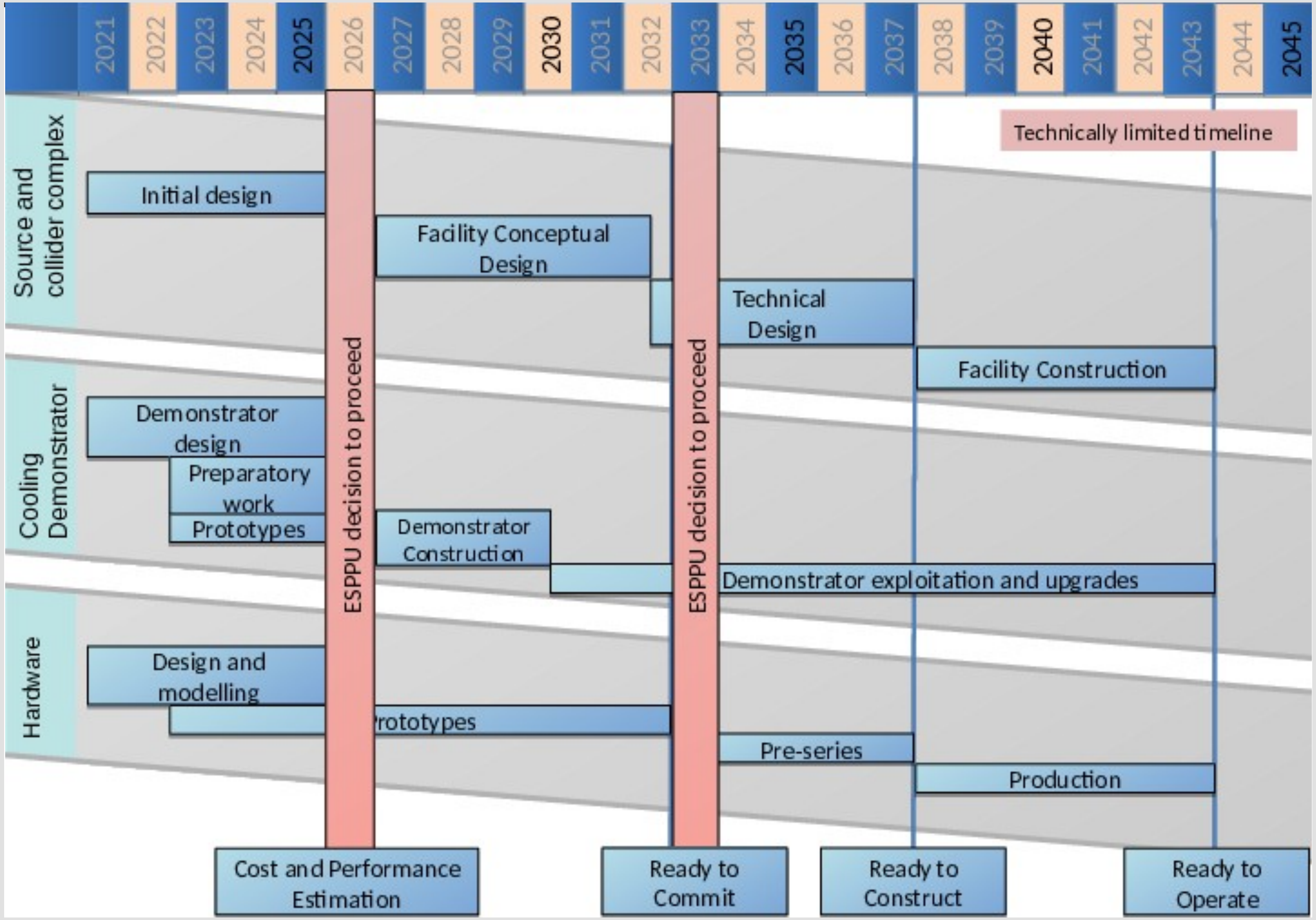
K. Skoufaris et al., IMCC Annual meeting 2023

Collider detectors

- Standard detector arrangement
- Based on e+e- detector
- Challenges:
  - Beam induced background arising due to muon decays



Timeline



2021
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2038
2039
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Technically limited timeline
Source and collider complex
Initial design
Facility Conceptual Design
Technical Design
Facility Construction
Cooling Demonstrator
Demonstrator design
Preparatory work
Prototypes
Demonstrator Construction
Demonstrator exploitation and upgrades
Hardware
Design and modelling
Prototypes
Pre-series
Production
ESPPU decision to proceed
ESPPU decision to proceed
Cost and Performance Estimation
Ready to Commit
Ready to Construct
Ready to Operate

Conclusion

- Muon collider can go to **much higher energy** than e^+e^- colliders, and **much smaller footprint** than equivalent proton-proton colliders
- Many technical challenges, **but no show-stopper** with current technologies
- **Physics opportunities** at each stage of R&D
  - CLFV
  - Neutrinos
  - Top & Higgs factories
  - Energy frontier

Thank you for your attention

Questions?

International collaboration

IEIO	**CERN**
FR	**CEA-IRFU**
	CNRS-LNCMI
DE	DESY
	Technical University of Darmstadt
	University of Rostock
	KIT
IT	**INFN**
	INFN, Univ., Polit. Torino
	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***

UK	**RAL**
	UK Research and Innovation
	University of Lancaster
	University of Southampton
	University of Strathclyde
	University of Sussex
	Imperial College London
	Royal Holloway
	University of Huddersfield
	University of Oxford
	University of Warwick
	University of Durham
SE	**ESS**
	University of Uppsala
PT	**LIP**
NL	**University of Twente**
FI	**Tampere University**
LAT	**Riga Technical Univers.**

US	**Iowa State University**
	Wisconsin-Madison
	Pittsburg University
	Old Dominion
	BNL
China	***Sun Yat-sen University***
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CH	**PSI**
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KO	**KEU**
	Yonsei University
India	***CHEP***
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	INFN, Univ. Ferrara
	INFN, Univ. Roma 3
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	INFN Laboratori del Sud
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