Muon Collider Demonstrator

D. Schulte for the International Muon Collider Collaboration

PBC
November 2022

Motivation and Goal

Previous studies in US (now very strong interest again), experimental programme in UK and alternatives studies by INFN

New strong interest:

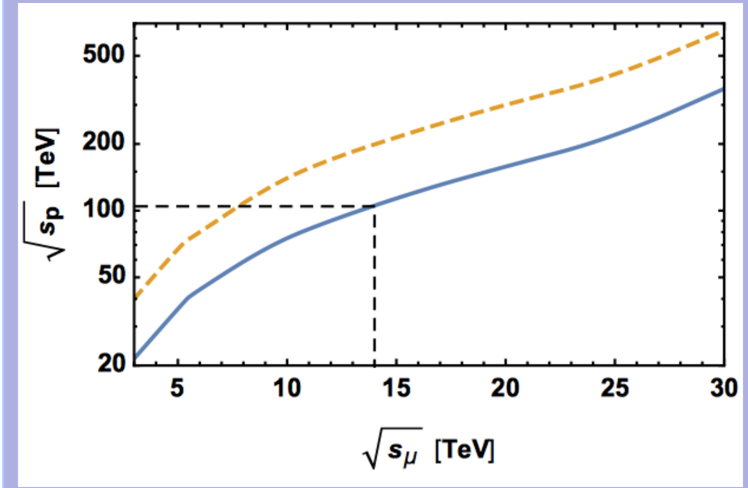
- Focus on **high energy** with **high luminosity**
  - 10+ TeV
  - potential initial energy stage (e.g. 3 TeV)
- **Technology** and **design advances**

Combines **precision physics** and **discovery reach**

Luminosity goal
(Similar to $L(E_{CM} > 0.99\ E_{CM,0})$ CLIC at 3 TeV)
$4\times10^{35}\ cm^{-2}s^{-1}$ at 14 TeV

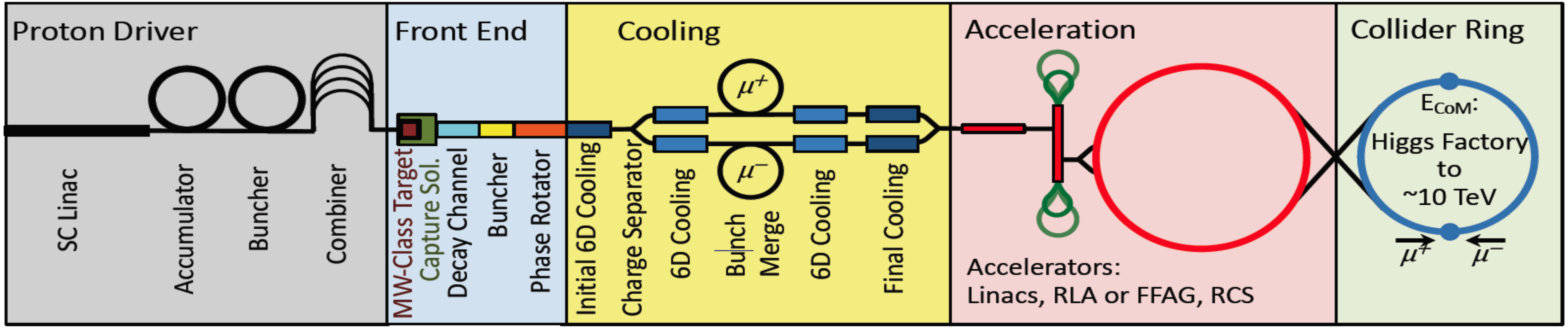
$$L \gtrsim \frac{5\,\text{years}}{\text{time}} \left(\frac{\sqrt{s_\mu}}{10\,\text{TeV}} \right)^2 2 \cdot 10^{35} \text{cm}^{-2}\text{s}^{-1}$$

Discovery reach
14 TeV lepton collisions are comparable to 100-200 TeV proton collisions for production of heavy particle pairs



Collider Concept

Fuly driven by muon lifetime, otherwise would be easy



Short, intense proton bunch

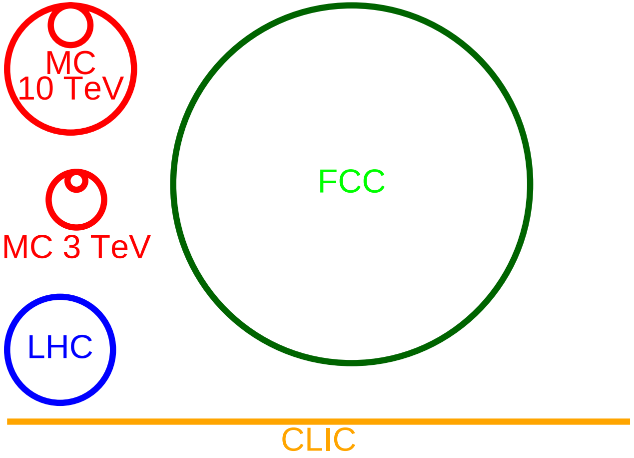
Protons produce pions which decay into muons
muons are captured

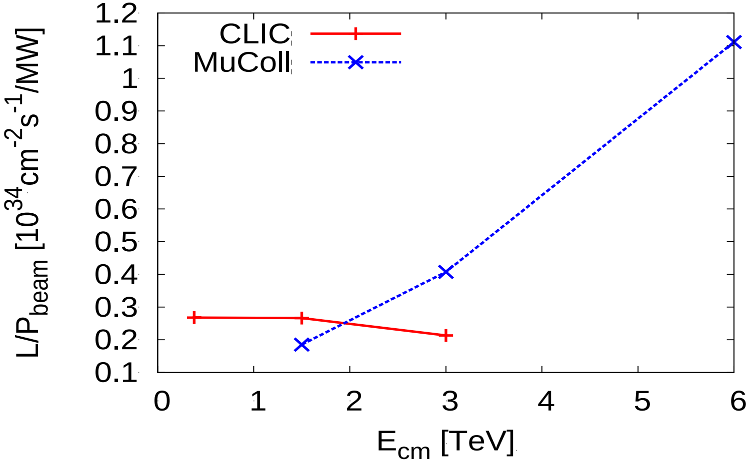
Ionisation cooling of muon in matter

Acceleration to collision energy

Collision

Sustainability





CLIC is highest energy proposal with CDR

- No obvious way to further improve linear colliders (decades of R&D)
- Cost 18 GCHF, power 590 MW

Rough rule of thumb:

- cost proportional to energy
- power proportional to luminosity

Muon Collider goals (10 TeV), challenging but reasonable:

- Much **more luminosity** than CLIC at 3 TeV **($L=20\times10^{34}$, CLIC: $L=2\times10^{34}/6\times10^{34}$)**
- **Lower power consumption** than CLIC at 3 TeV ($P_{beam,MC}=0.5P_{beam,CLIC}$)
- **Lower cost**

Staging is possible

Synergies exist (neutrino/higgs)

Unique opportunity for a **high-energy, high-luminosity lepton collider**

Accelerator R&D Roadmap

International MUON Collider Collaboration

On request of CERN Council but **global roadmap**

No insurmountable obstacle found for the muon collider

- but important need for R&D
- developed two funding scenarios

Full scenario deliverables by next ESPPU/other processes

- **Project Evaluation Report**
- **R&D Plan** that describes a path towards the collider; key element is **demonstrator concept**

Allows to make **informed decisions**

http://arxiv.org/abs/2201.07895

Label	Begin	End	Description	Aspirational		Minimal	
				[FTEy]	[kCHF]	[FTEy]	[kCHF]
MC.SITE	2021	2025	Site and layout	15.5	300	13.5	300
MC.NF	2022	2026	Neutrino flux mitigation system	22.5	250	0	0
MC.MDI	2021	2025	Machine-detector interface	15	0	15	0
MC.ACC.CR	2022	2025	Collider ring	10	0	10	0
MC.ACC.HE	2022	2025	High-energy complex	11	0	7.5	0
MC.ACC.MC	2021	2025	Muon cooling systems	47	0	22	0
MC.ACC.P	2022	2026	Proton complex	26	0	3.5	0
MC.ACC.COLL	2022	2025	Collective effects across complex	18.2	0	18.2	0
MC.ACC.ALT	2022	2025	High-energy alternatives	11.7	0	0	0
MC.HFM.HE	2022	2025	High-field magnets	6.5	0	6.5	0
MC.HFM.SOL	2022	2026	High-field solenoids	76	2700	29	0
MC.FR	2021	2026	Fast-ramping magnet system	27.5	1020	22.5	520
MC.RF.HE	2021	2026	High Energy complex RF	10.6	0	7.6	0
MC.RF.MC	2022	2026	Muon cooling RF	13.6	0	7	0
MC.RF.TS	2024	2026	RF test stand + test cavities	10	3300	0	0
MC.MOD	2022	2026	Muon cooling test module	17.7	400	4.9	100
MC.DEM	2022	2026	Cooling demonstrator design	34.1	1250	3.8	250
MC.TAR	2022	2026	Target system	60	1405	9	25
MC.INT	2022	2026	Coordination and integration	13	1250	13	1250
			Sum	445.9	11875	193	2445

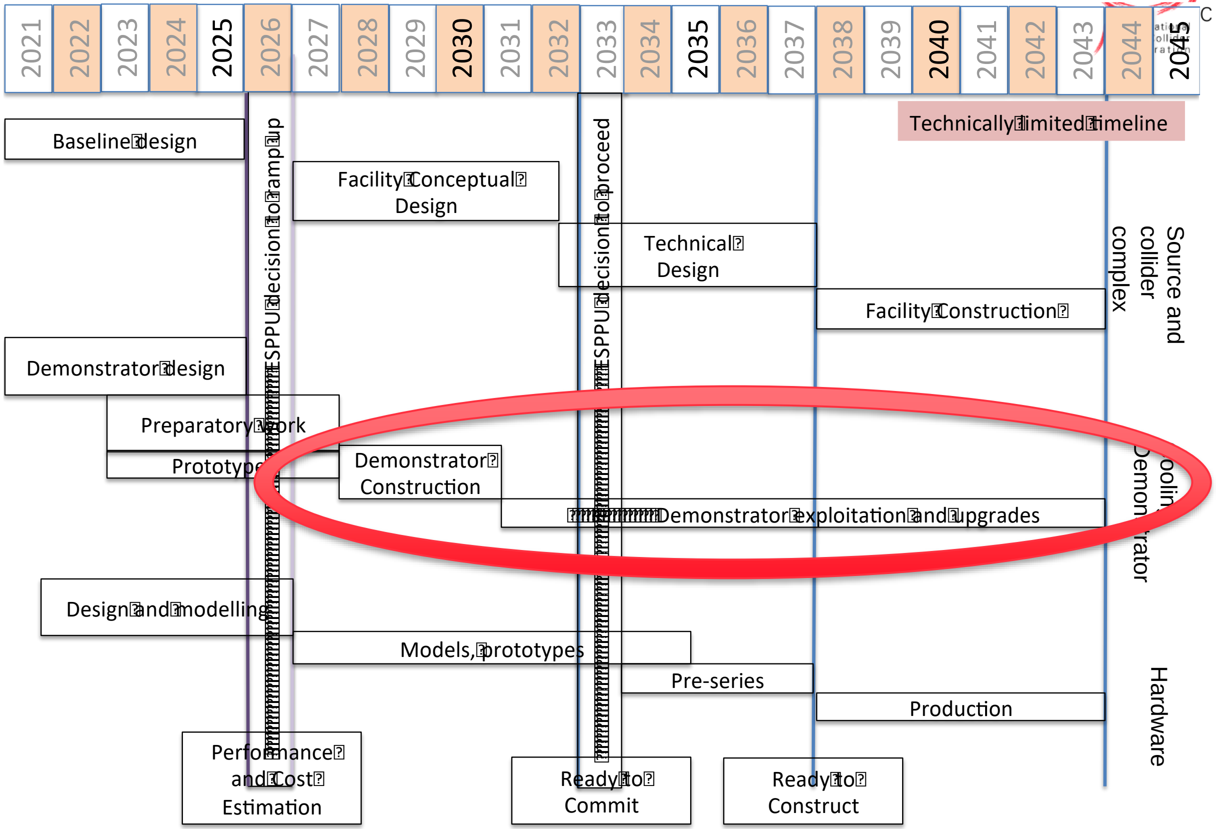
Table 5.5: The resource requirements for the two scenarios. The personnel estimate is given in full-time equivalent years and the material in kCHF. It should be noted that the personnel contains a significant number of PhD students. Material budgets do not include budget for travel, personal IT equipment and similar costs. Colours are included for comparison with the resource profile Fig. 5.7.

Technically Limited Timeline

Muon collider important in the long term

Prudently explore if MuC can be **option as next project**

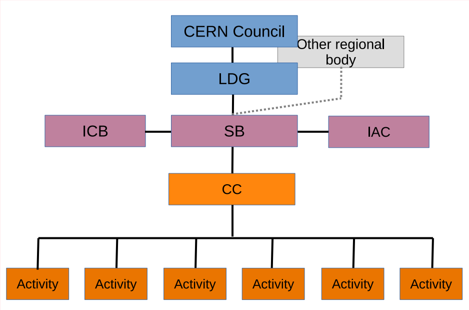
- e.g. in Europe if higgs factory built elsewhere
- **sufficient funding required now**
- very **strong ramp-up required** after 2026
- fast-track project might require some compromises on initial scope and performance
  - 3 TeV?



Muon Collider Community

International MUON Collider Collaboration

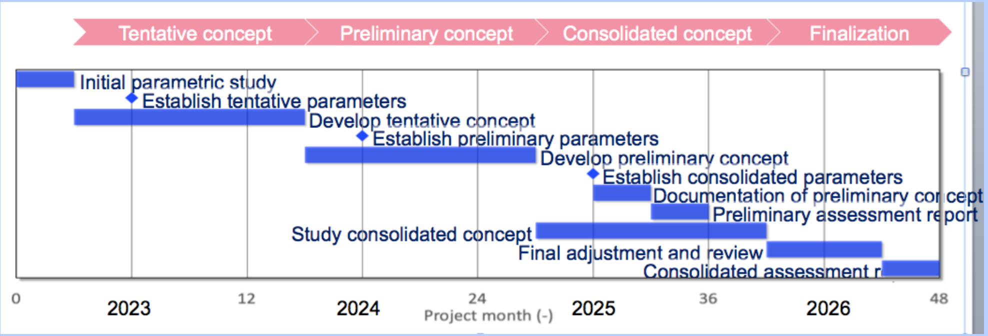
Formed **collaboration** to implement and R&D Roadmap for CERN Council



50+ partner institutions
30+ already signed formal agreement

EU Design Study approved this summer**,**
32 partners, O(7 MEUR) volume

3 (EU+Switzerland+UK), 4 from partners



Strong support for muon collider in **US Snowmass**

- contribution to collider during process
- want to participate to R&D
- would like it as project for the US

Now waiting for P5

Plan to also apply for next HORIZON-INFRA-2024-TECH call in 2024, to develop technologies (up to 10 MEUR)

Goal: prepare experimental programme, e.g. **demonstrator, prototypes, …**

Preparation to start early 2023

MoC and Design Study Partners

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

UK	**RAL**
	UK Research and Innovation
	University of Lancaster
	University of Southampton
	University of Strathclyde
	University of Sussex
	Imperial College
	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**

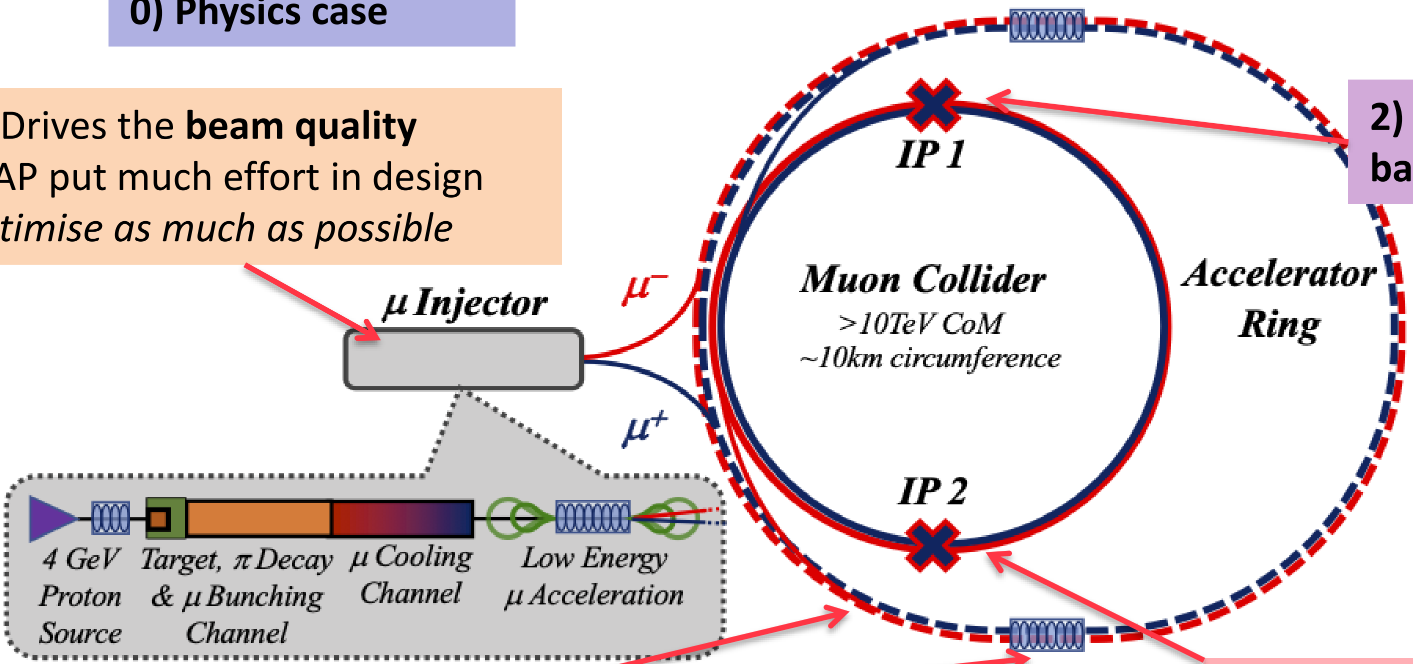
FI	**Tampere University**
US	**Iowa State University**
	Wisconsin-Madison
	BNL
China	***Sun Yat-sen University***
	IHEP
	Peking University
EST	***Tartu University***
LAT	**Riga Technical Univers.**
AU	**HEPHY**
	TU Wien
ES	***I3M***
CH	**PSI**
	University of Geneva
	EPFL
BE	***Louvain***

IT	INFN Frascati
	INFN, Univ. Ferrara
	INFN, Univ. Roma 3
	INFN Legnaro
	INFN, Univ. Milano Bicocca
	INFN Genova
	INFN Laboratori del Sud
	INFN Napoli
US	FNAL
	LBL
	JLAB
	Chicago
Japan	Akira Yamamoto
	Akira Sato
	Toru Ogitsu

Key Challenges

0) Physics case

4) Drives the **beam quality**
MAP put much effort in design
optimise as much as possible



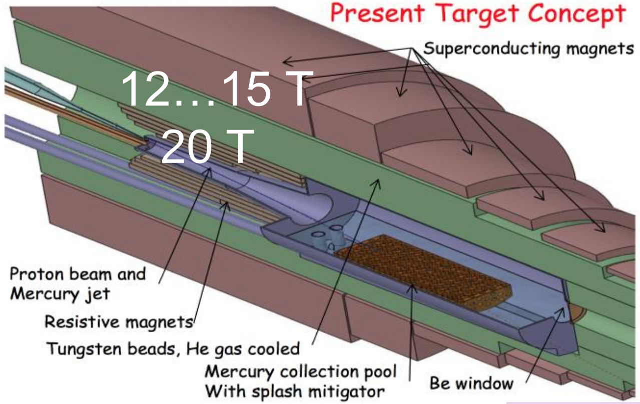
2) Beam-induced background

1) Dense neutrino flux
mitigated by mover system and site selection

3) Cost and **power** consumption limit energy reach
e.g. 35 km accelerator for 10 TeV, 10 km collider ring
Also impacts **beam quality**

Target

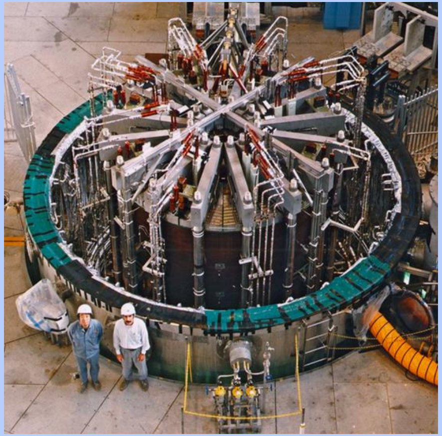
MAP target design, K. McDonald, et al.



Two approaches:
- 15 T outer superconducting
  + 5 T inner resistive solenoid
- O(20 T) HTS solenoid

Shield superconducting solenoid
⇒ larger aperture
Synergy with ITER

A. Lechner et al.
L. Bottura et al.



ITER Central Solenoid Model Coil
13 T in 1.7 m (LTS)

2 MW proton beam is OK
bunching challenge will be addressed by ESS experts

N. Milas et al. (ESS, Uppsala)

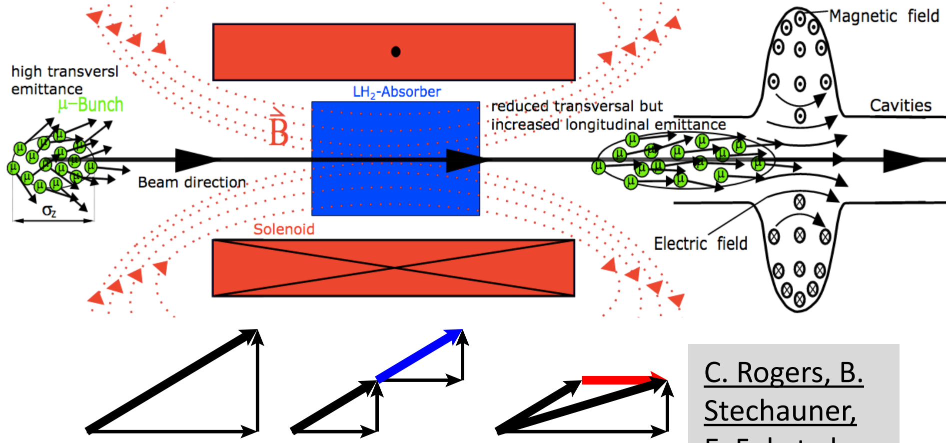
Rui Franqueira Ximenes et al.

Operation at 2000 °C to maximise stress resistance

Shock in target: Simulations of **graphite target** indicate 2 MW could be acceptable

STFC will also study alternatives

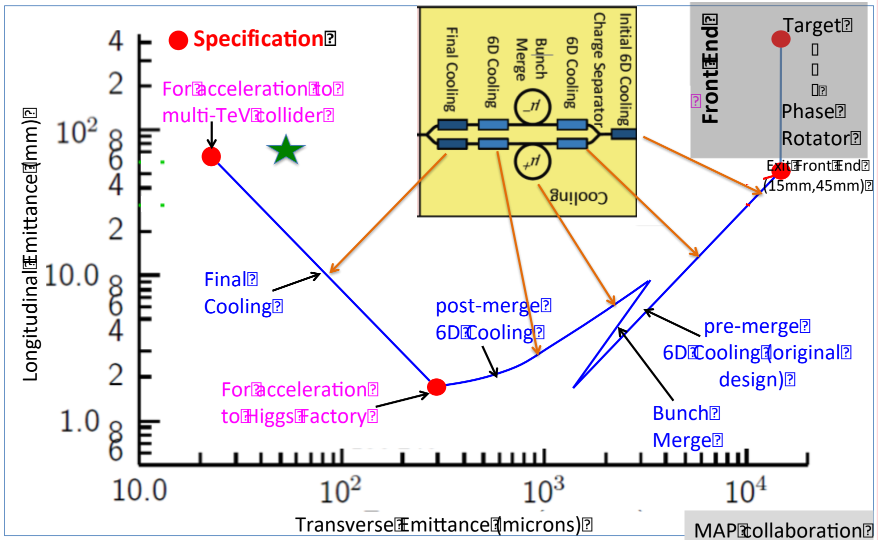
Muon Cooling



C. Rogers, B. Stechauner, E. Fol et al.

MAP designs almost achieve 10 TeV goal

- miss factor two for final cooling



Integration/optimisation of overall cooling design

Integrating **improved technology**

C. Rogers et al.

MICE Collaboration

Nature vol. 578, p. 53-59 (2020)

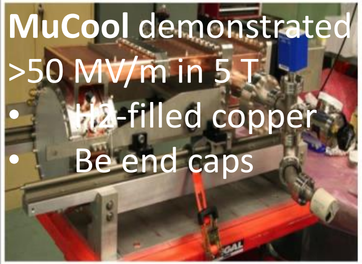
Principle of ionisation cooling with no RF has been demonstrated in **MICE at RAL**

Use of data for benchmarking is still ongoing

Cooling Cell Technology

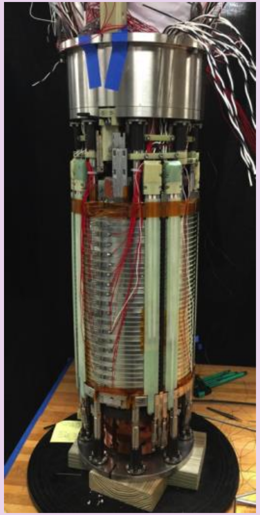
C. Marchand, Alexej Grudiev et al. (CEA, Milano, CERN, Tartu)

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



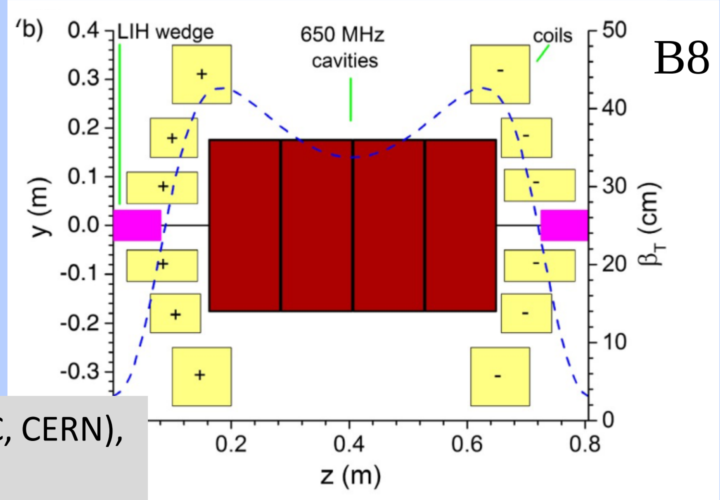
MuCool demonstrated >50 MV/m in 5 T
- H2-filled copper
- Be end caps

MAP demonstrated 30 T solenoid
- now magnets aim for 40+ T
- even more can be possible
- synergy with high-field research



L. Bottura et al. INFN (Task Leader), CEA, CERN, LNCMI, PSI, SOTON, UNIGE and TWENTE, in collaboration with KEK and US-MDP

Will develop **cooling cell integration**
- tight constraints
- additional technologies (**absorbers**, instrumentation,…)
- early preparation of **demonstrator facility**



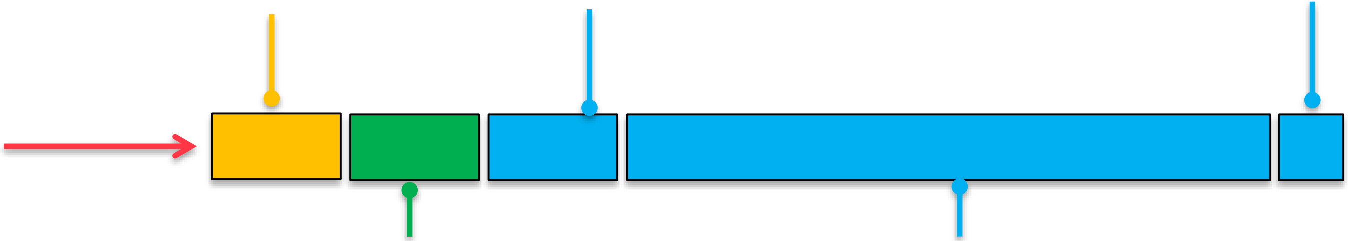
L. Rossi et al. (INFN, Milano, STFC, CERN), J. Ferreira Somoza et al.

Test Facility Dimensions

Target
+ horn (1st phase) /
+ superconducting solenoid (2nd phase)

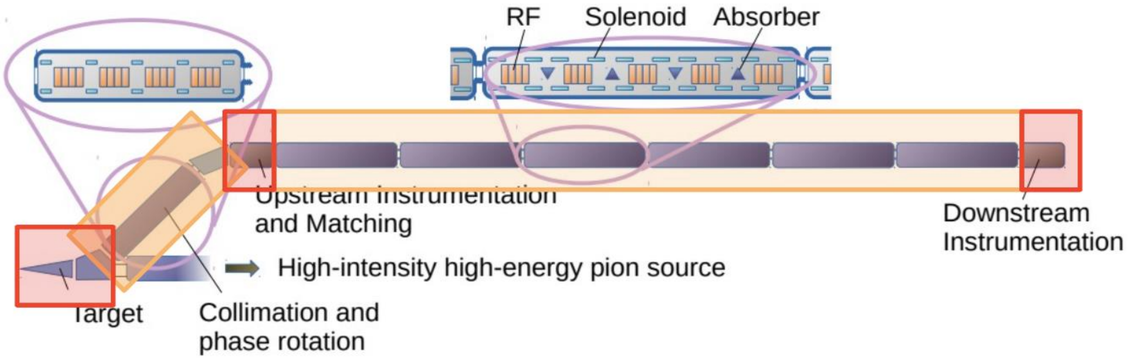
Collimation and **upstream diagnostics** area, 10 m

Downstream diagnostics area, 5 m



Momentum selection chicane, 10 m

Cooling area, 50 m



Look for an existing proton beam with significant power

Different sites are being considered

- CERN, FNAL, ESS are being discussed
- J-PARC may be an option

Possible CERN Locations

Use PS beam

Consider nTOF-like beam for cooling experiment:

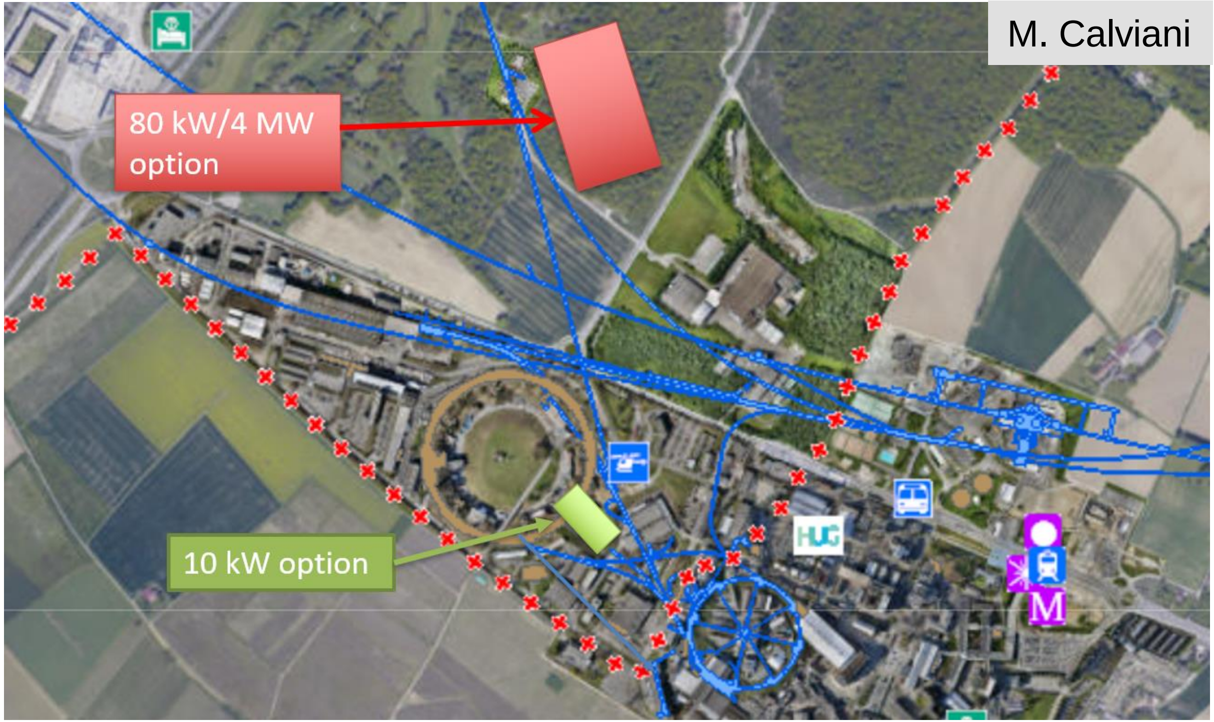
- 10^{13} p at 20 GeV per pulse
- 1 pulse per 1.2 s
- 27 kW

Higher power for other test and for physics operation

- up to O(100 kW), to be discussed

If SPL were, installed could use its beam, e.g. 5 GeV, 4 MW

- the site allows for this power



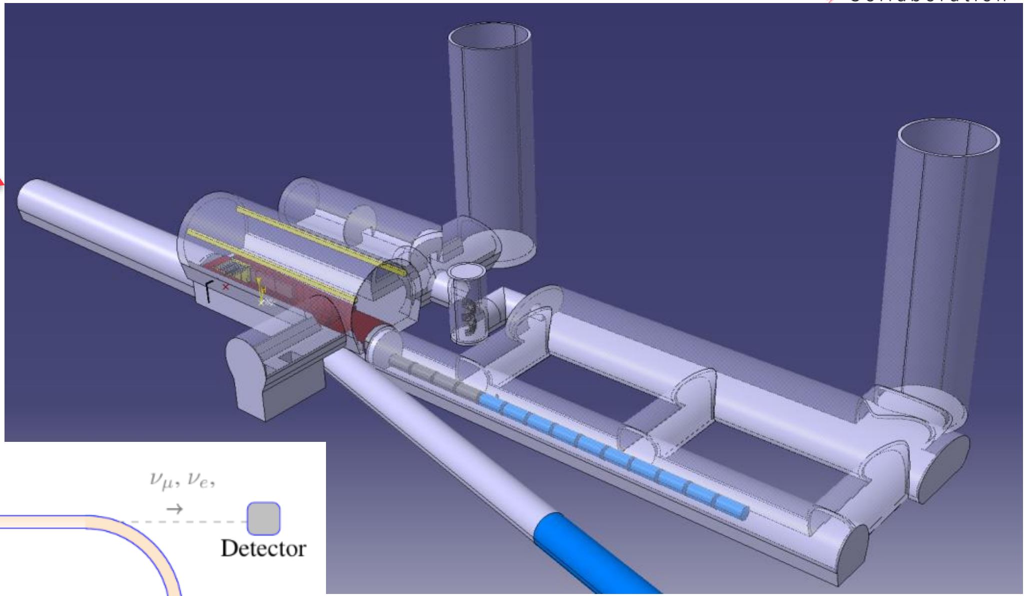
Tentative Concept of Complex

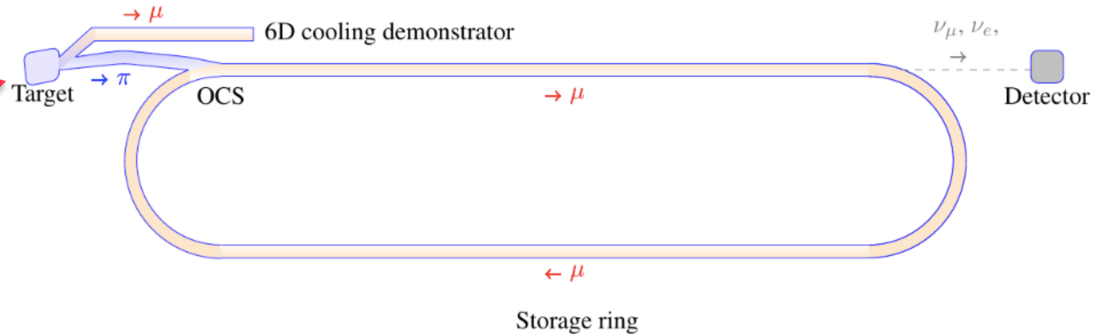
Could split beamline after target

Allows to also feed physics facility

Example: NuStorm

- could share until after the target
- about 50% of NuStorm cost





Conclusion

- Muon collider is unique opportunity for high-energy, high-luminosity lepton collider
- Currently two different options considered
  - goal of 10+ TeV, potential 3 TeV intermediate stage explored
- Muon cooling technology is key novel technology requiring beam tests
  - Demonstrator required
  - using existing proton infrastructure
  - consisting of target and cooling stages
- Demonstrator could have synergy with other programs
- Plan a **workshop** to develop scenarios with physics on the way to the muon collider

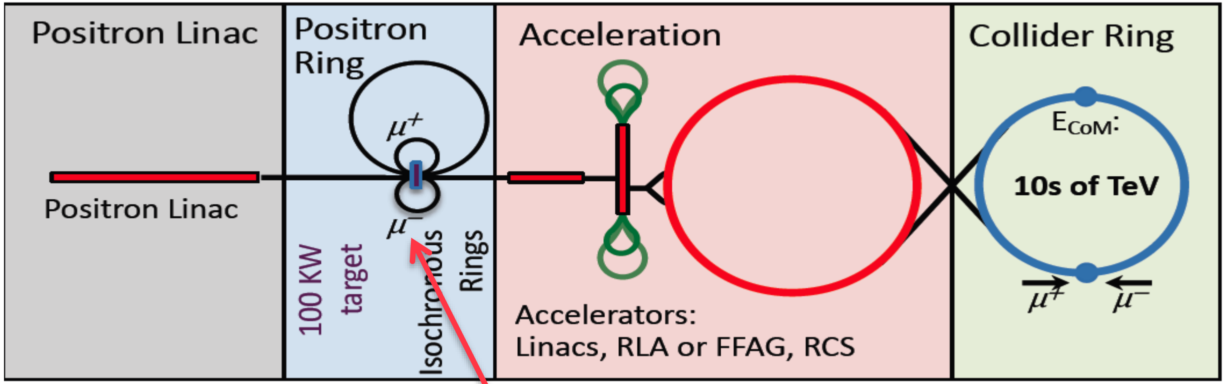
Many thanks to the Muon Beam Panel, the collaboration, the MAP study, the MICE collaboration, and many others

http://muoncollider.web.cern.ch

Reserve

Alternatives: The LEMMA Scheme

LEMMA scheme (INFN) P. Raimondi et al.

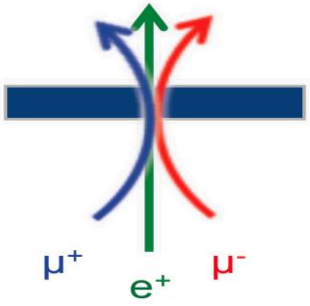


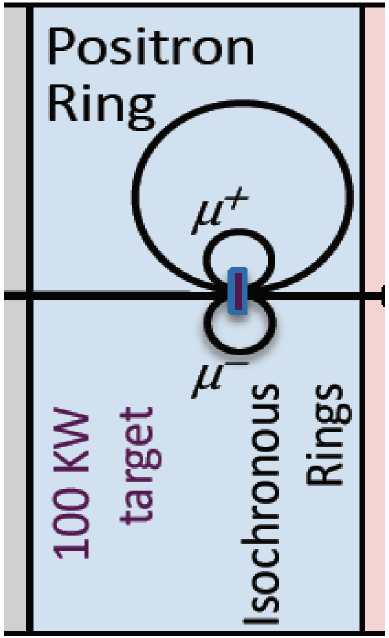
Note: New proposal by C. Curatolo and L. Serafini needs to be looked at

- Uses Bethe-Heitler production with electrons

45 GeV positrons to produce muon pairs
Accumulate muons from several passages

$$e^+e^- \to \mu^+\mu^-$$





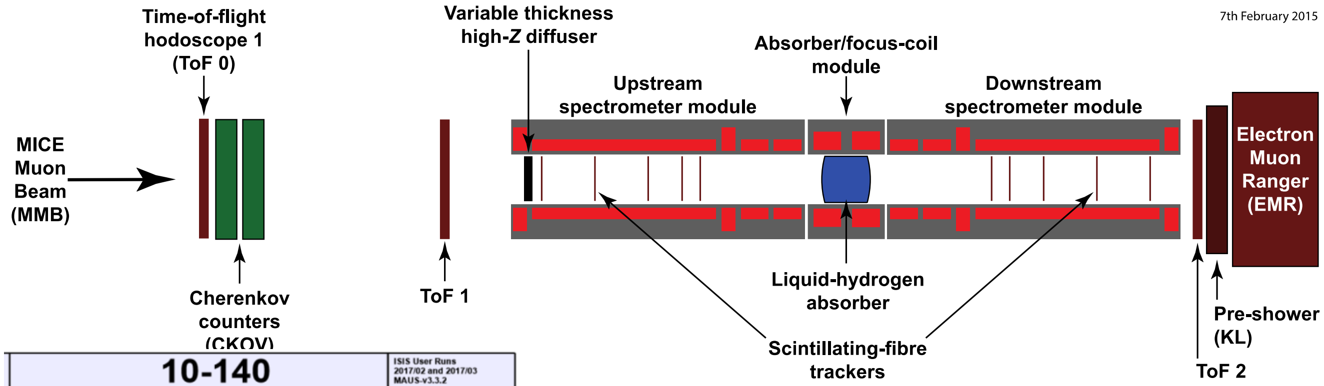
Excellent idea, but nature is cruel

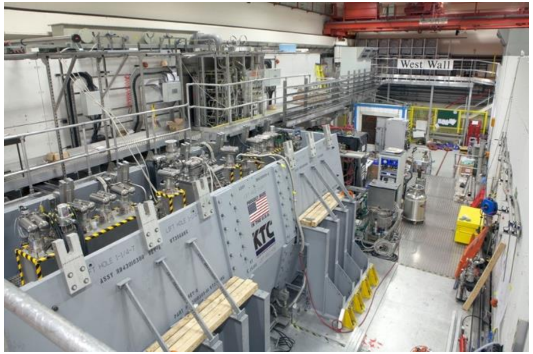
Detailed estimates of fundamental limits show that we require a very large positron bunch charge to reach the same luminosity as the proton-based scheme

$\Rightarrow$ **Need same game changing invention**

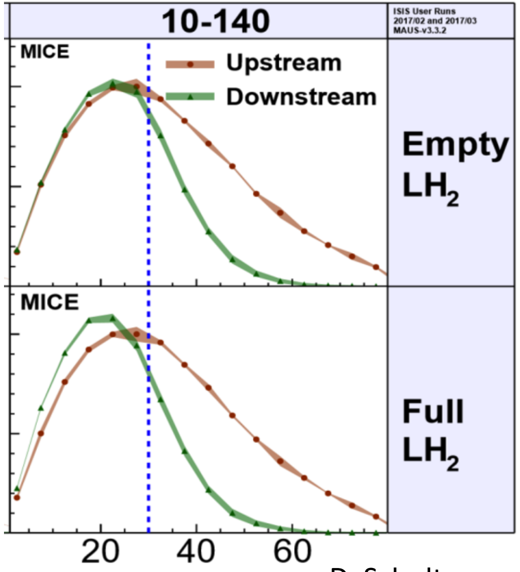
MICE: Cooling Demonstration

International
UON Collider
Collaboration





Nature vol. 578, p. 53-59 (2020)



More particles at smaller amplitude after absorber is put in place

Principle of ionisation cooling has been demonstrated
Use of data for benchmarking is still ongoing

WEPOPT053

More complete experiment with higher statistics, more than one stage required

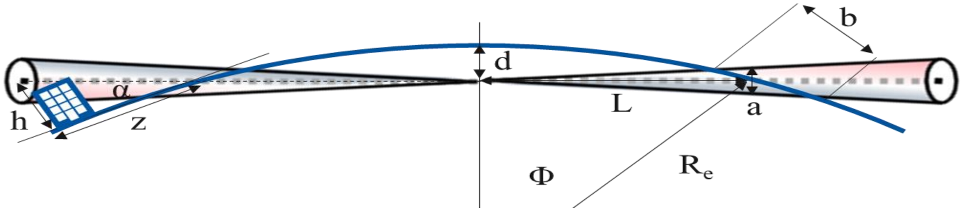
Integration of magnets, RF, absorbers, vacuum is engineering challenge

Neutrino Flux

Dense neutrino flux cone can impact environment
Challenge scales with **E x L**

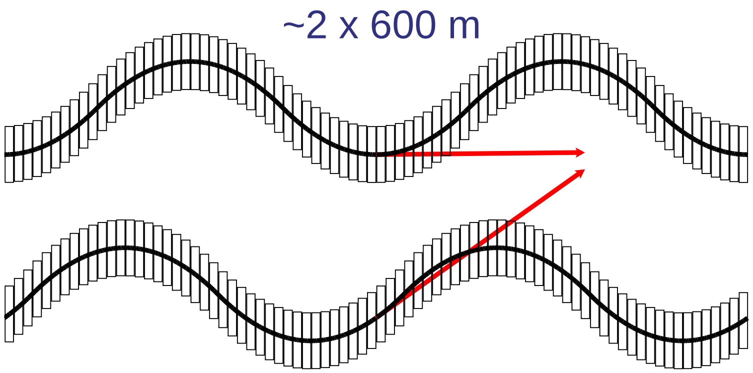
Goal is to reduce to negligible level, similar to LHC

- **3 TeV, 200 m deep tunnel is about OK**



Expand idea of Mokhov, Ginneken to move beam in aperture: move collider ring components, e.g. vertical bending with 1% of main field

- **14 TeV, in 200 m deep tunnel comparable to LHC case with +/- 1 mradian**
- **scales with luminosity toward higher E**



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

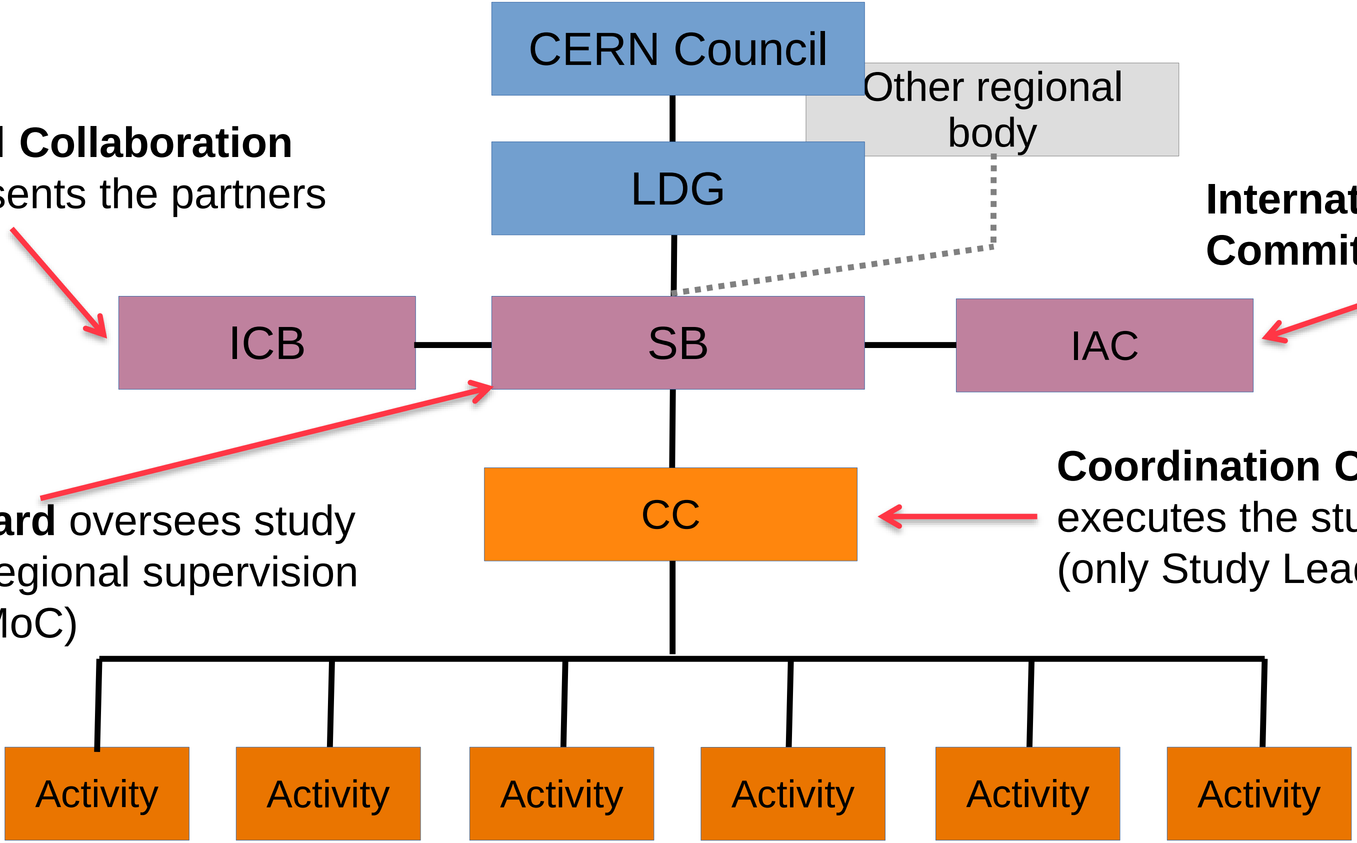
Working on different approaches for experimental insertion

Other optimisations are possible (magnetic field, emittance etc.)

Organisation

International Collaboration Board represents the partners

International Advisory Committee



Steering Board oversees study and links to regional supervision (addition to MoC)

Coordination Committee executes the study (only Study Leader in MoC)

Thanks

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), Roberto Losito (CERN), Donatella Lucchesi (INFN)

Community conveners: *Radio-Frequency (RF):* Alexej Grudiev (CERN), Jean-Pierre Delahaye (CERN retiree), Derun Li (LBNL), Akira Yamamoto (KEK). *Magnets:* Lionel Quettier (CEA), Toru Ogitsu (KEK), Soren Prestemon (LBNL), Sasha Zlobin (FNAL), Emanuela Barzi (FNAL). *High-Energy Complex (HEC):* Antoine Chance (CEA), J. Scott Berg (BNL), Alex Bogacz (JLAB), Christian Carli (CERN), Angeles Faus-Golfe (IJCLab), Eliana Gianfelice-Wendt (FNAL), Shinji Machida (RAL). *Muon Production and Cooling (MPC):* Chris Rogers (RAL), Marco Calviani (CERN), Chris Densham (RAL), Diktys Stratakis (FNAL), Akira Sato (Osaka University), Katsuya Yonehara (FNAL). *Proton Complex (PC):* Simone Gilardoni (CERN), Hannes Bartosik (CERN), Frank Gerigk (CERN), Natalia Milas (ESS). *Beam Dynamics (BD):* Elias Metral (CERN), Tor Raubenheimer (SLAC and Stanford University), Rob Ryne (LBNL). *Radiation Protection (RP):* Claudia Ahdida (CERN). *Parameters, Power and Cost (PPC):* Daniel Schulte (CERN), Mark Palmer (BNL), Jean-Pierre Delahaye (CERN retiree), Philippe Lebrun (CERN retiree and ESI), Mike Seidel (PSI), Vladimir Shiltsev (FNAL), Jingyu Tang (IHEP), Akira Yamamoto (KEK). *Machine Detector Interface (MDI):* Donatella Lucchesi (University of Padova), Christian Carli (CERN), Anton Lechner (CERN), Nicolai Mokhov (FNAL), Nadia Pastrone (INFN), Sergo R Jindariani (FNAL). *Synergy:* Kenneth Long (Imperial College), Roger Ruber (Uppsala University), Koichiro Shimomura (KEK). *Test Facility (TF):* Roberto Losito (CERN), Alan Bross (FNAL), Tord Ekelof (ESS,Uppsala University).

And the participants to the community meetings and the study

Other Key Studies

International MUON Collider Collaboration

Review **proton complex**
- average power of 2 MW is no problem
- but merging into 5 pulses of 400 kJ per second needs to be verified

N. Milas et al. (ESS, Uppsala)

Collective effects across the whole complex to identify bottlenecks
- review apertures, feedback and other specifications
  - first results for aperture requirements
- potential instability of interaction of muon beam with matter

E. Metral et al. (CERN, EPFL/CHART)

Power and **cost optimisation**

J. Ferreira Somoza, M. Wendt, et al.

Vacuum and **absorber, instrumentation, cryogenics**, …

Reuse of **existing infrastructure**, e.g. **LHC tunnel** to house accelerator

Initial Target Parameters

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 focus on 10 TeV, also explore 3 TeV

- Tentative parameters based on MAP study, might add margins
- Achieve goal in 5 years
- FCC-hh to operate for 25 years
- Aim to have two detectors

Parameter	Unit	3 TeV	10 TeV	14 TeV	CLIC at 3 TeV
L	10^{34} $cm^{-2}s^{-1}$	1.8	20	40	2 (6)
N	10^{12}	2.2	1.8	1.8	
f_r	Hz	5	5	5	
P_{beam}	MW	5.3	14.4	20	28
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	

Available Power

Consider nTOF-like beam for cooling experiment

Higher power for target (and maybe cooling) tests if possible, up to O(100 kW)

If SPL were, installed could use its beam, e.g. 5 GeV, 4 MW

	ISOLDE	nTOF	AD
Total Energy [GeV]	2.4/3.0	20	26
Total intensity [1×10^{13} p]	6.4	1.0	1.40
Cycle length [s]	1.2	1.2	2.4
Beam power per cycle [kW]	20/26	27	24
Total bunch length [ns]	230/200	20	38
Number of bunches	4	1	4
Bunch spacing [ns]	572	-	100
Extraction type	fast	fast	fast