Muon Collider

D. Schulte for the International Muon Collider Collaboration

IMCC meeting
October 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, the reason for a muon collider
    - potential initial energy stage (e.g. 3 TeV)
- **Technology** and **design advances**

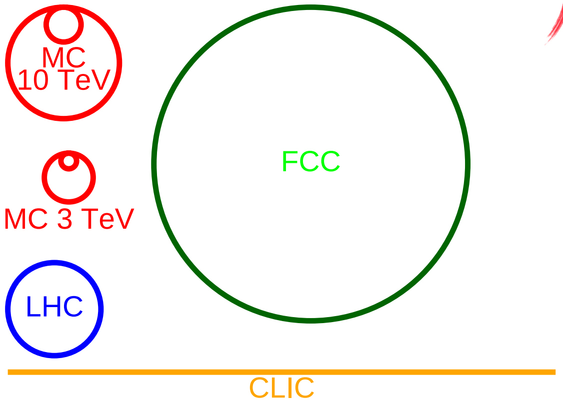
Combines **precision physics** and **discovery reach**

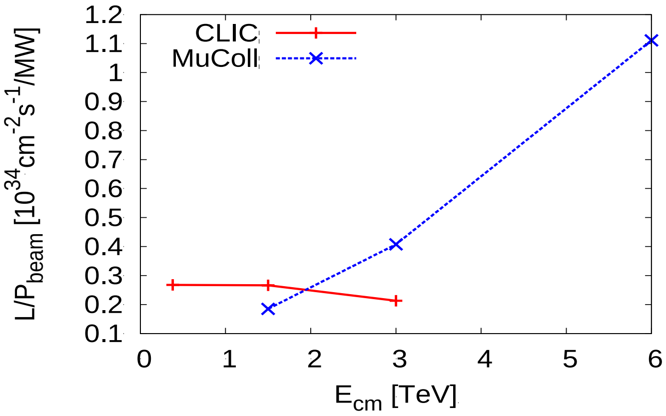
Increasing luminosity to power efficiency make it likely that we can meet **increasing luminosity demands**

Compactness makes it likely to be **cost effective**

No insurmountable obstacle identified

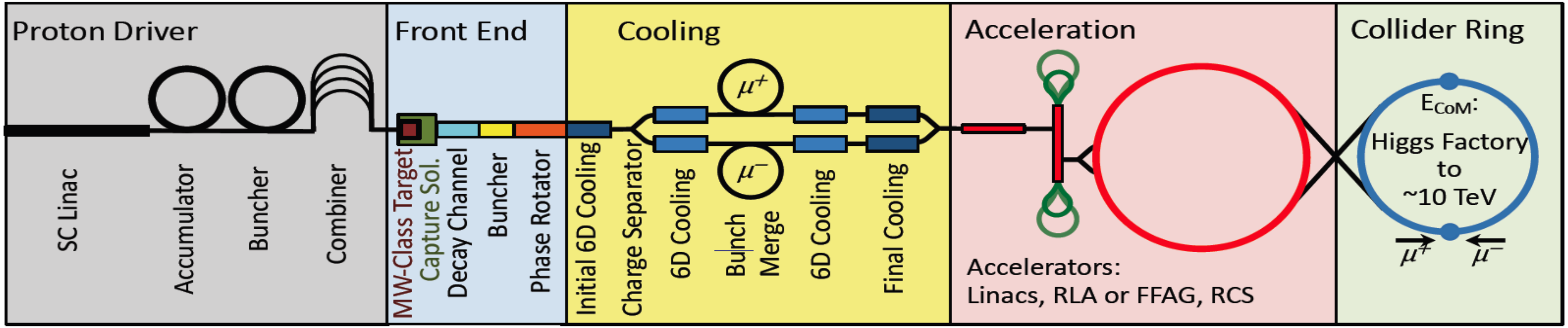
But **challenging technologies and design** require **R&D**





Collider Concept

Fully driven by muon lifetime, otherwise would be easy



Short, intense proton bunch

Ionisation cooling of muon in matter

Acceleration to collision energy

Collision

Protons produce pions which decay into muons
muons are captured

Workplan

Currently two different options considered

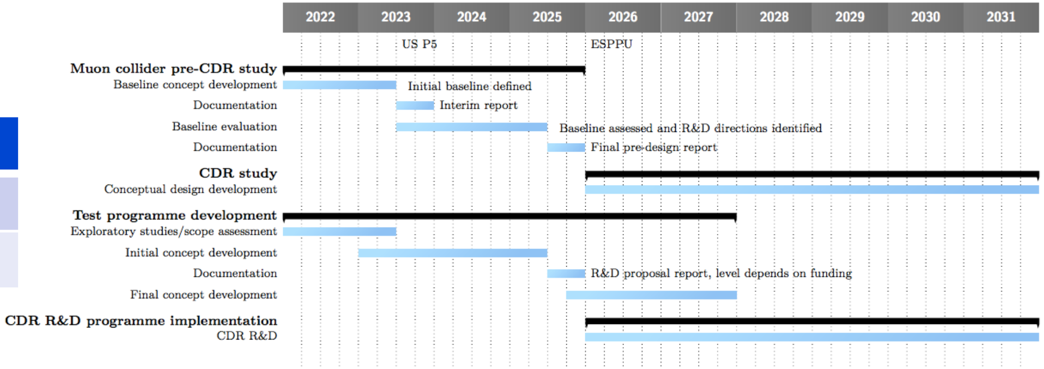
- goal is 10+ TeV, the reason to consider muons
- potential intermediate stage (e.g. 3 TeV) explored, will consider other options later

Three main deliverables are foreseen in R&D Roadmap Report:

- a **Project Evaluation Report** that assesses the muon collider potential as input to the **next ESPPU**; (Note: ESPPU because this is a European document, we want to feed into all relevant processes)
- **an R&D Plan** that describes a path towards the collider;
- **an Interim Report** by the **end of 2023** that documents progress and allows the wider community to update their view of the concept and to give feedback to the collaboration.

Scenario	FTEy	M MCHF
Full scenario	445.9	11.9
Reduced scenario	193	2.45

http://arxiv.org/abs/2201.07895



Resources and Workplan

EU Design Study proposal has been accepted
- finalising contracts
- kick-off meeting likely March 2023
- but some work already started

Current resources still **below reduced scenario**
- working on increasing them
- adjusting workplan priorities

Can only partially achieve goals before ESPPU

Workplan evolves taking in to account availability of resources and partner interest
- not strictly following reduced scenario
- leaves room for increase

Discussions ongoing in many places
- moving target
- asked Nadia Pastrone to chair Resource Task Force

Accelerator R&D Roadmap

Scenario	FTEy	M MCHF
Full scenario	445.9	11.9
Reduced scenario	193	2.45

Contributed to Snowmass

Many other efforts ongoing
- e.g. CHART approved some support

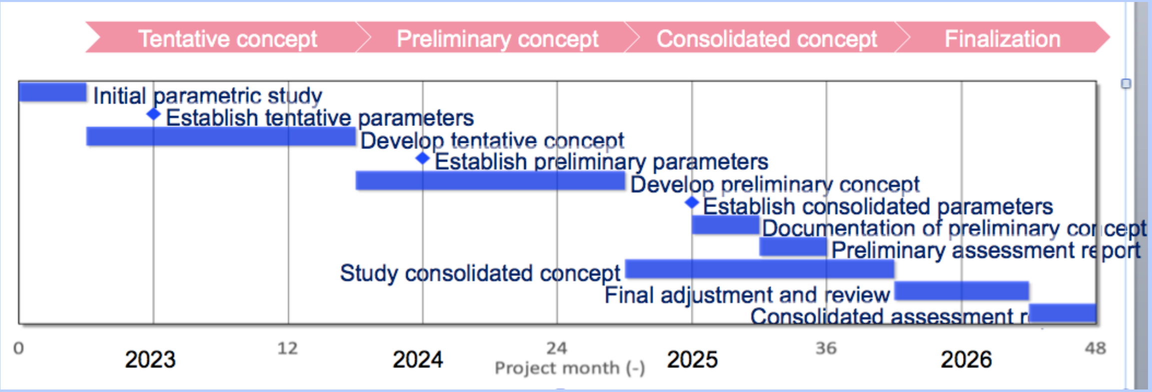
Meanwhile doing work with the resources that we have

EU Design Study

HORIZON-INFRA-2022-DEV-01-01: Research infrastructure concept development

EU contribution 3 MEUR = 580 pm, partners 680 pm,
CERN requested budget increase +1.5 MCHF

January 2023 to December 2026
Kick-off probably March 2023
Finalising Grant and Consortium Agreements
⇒ Roberto



Workpackages

1. Coordination and Communication
2. Physics/Detector Performance Requirements
3. Proton Complex
4. Muon Production and Cooling
5. High-energy Complex
6. RF Systems
7. Magnetic Systems
8. Muon Cooling Module

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

Goal is to prepare experimental programme, e.g. demonstrator, prototypes, …

Preparation to start early next year

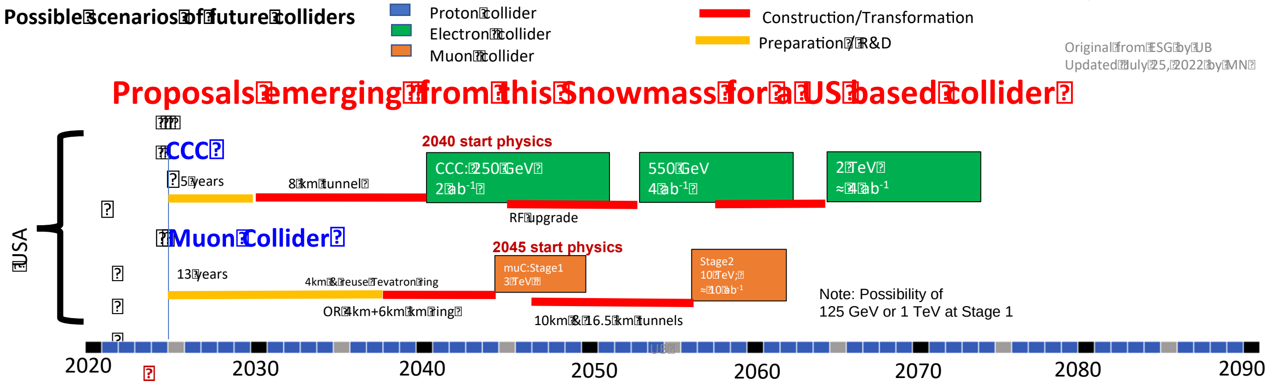
Snowmass

Strong interest in the US community in muon collider

- seen as an energy frontier machine
- decoupled from LC

US community wants funding for R&D

Community interested in the US to host a muon collider



- **Timelines technologically limited**
- Uncertainties to be sorted out
  - Find a contact lab(s)
  - Successful R&D and feasibility demonstration for CCC and Muon Collider
  - Evaluate CCC progress in the international context, and consider proposing an LC/CCC [ie CCC used as an upgrade of LC] or a CCC only option in the US.
  - International Cost Sharing
- Consider proposing hosting ILC in the US.

Meenakshi Narain: Energy Frontier / Large Experiments, Snowmass Community Summer Study July 17-26, 2022

Key Next Steps

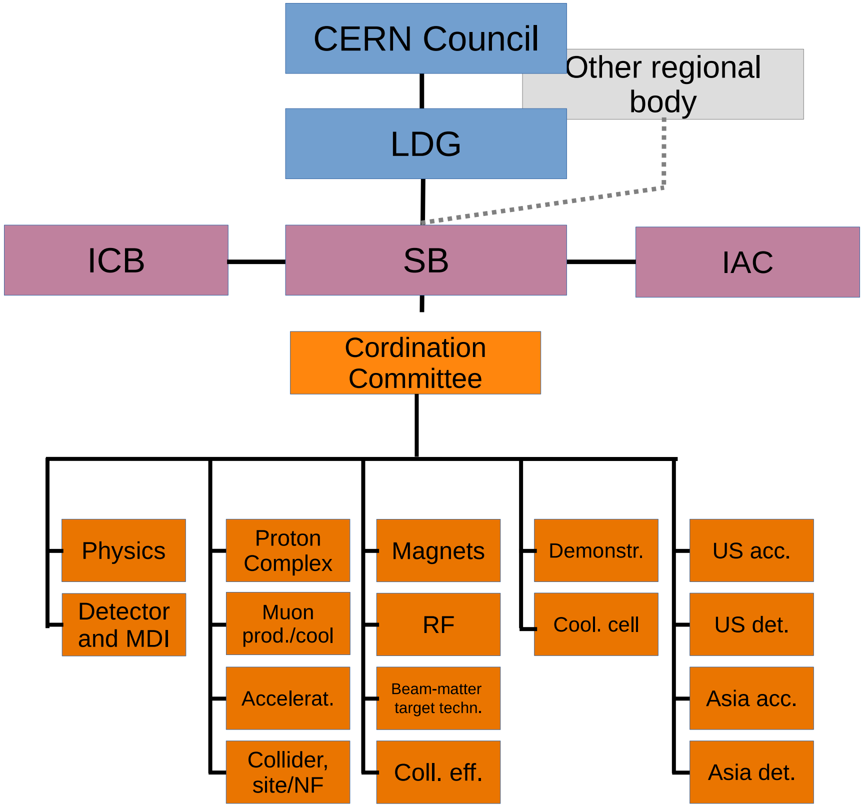
Formal organisation

- **Collaboration Board**
  - First session today => Steinar
- **Steering Board** (link to CERN Council, DoE?, …)
  - Chair Steinar Stapnes
- **Coordination committee**
  - Study Leader Daniel Schulte, deputies: Andrea Wulzer, Donatella Lucchesi, Chris Rogers, to be endorsed by CB
  - members are already working

Securing resources (not yet at reduced level)

- Institutes, national funding, EU co-funding, US Snowmass/P5, …
- your help needed

If you want to join and sign **MoC** please contact muon.collider.secretariat@cern.ch



MoC and Design Study Partners

International MUON Collider 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

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**

⇒ Steinar for detail

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

CC Members

To be endorsed by SB

Physics	Andrea Wulzer
Detector and MDI	Donatella Lucchesi

Protons	Natalia Milas
Muon production and cooling	Chris Rogers
Muon acceleration	Antoine Chance
Collider	Christian Carli

Magnets	Luca Bottura
RF	Alexej Grudiev
Beam-matter int. target systems	Anton Lechner
Collective effects	Elias Metral

Cooling cell design	to be filled after EU decision
Demonstrator	Roberto Losito

US (detector)	Sergo Jindariani
US (accelerator)	Mark Palmer
Asia (China)	Jingyu Tang
Asia (Japan)	tbd

EU Design Study WP leaders:

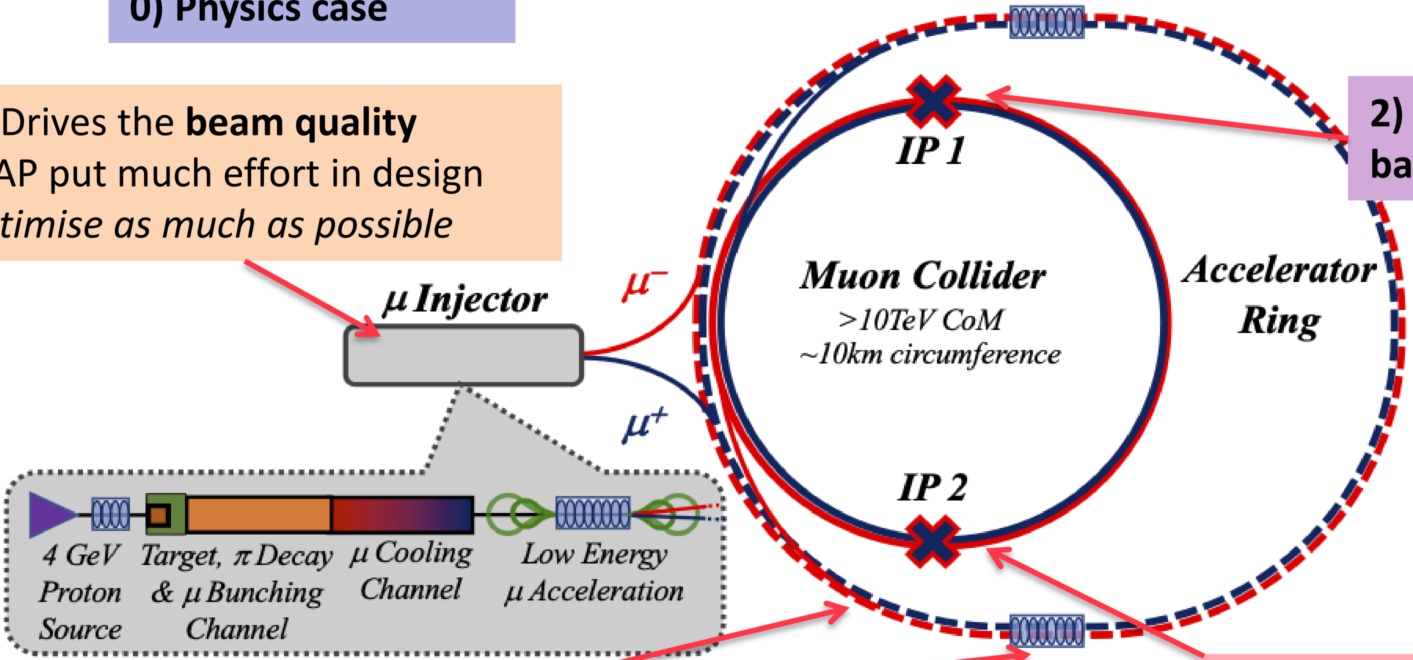
EU RF WP	Claude Marchand
Cooling cell	Lucio Rossi

Proposal for deputies (to be endorsed by ICB):
Andrea Wulzer
Donatella Lucchesi
Chris Rogers

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**

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}

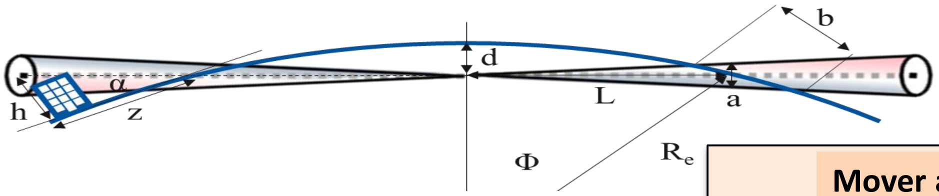
Note: currently focus on 10 TeV, also explore 3 TeV

- 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

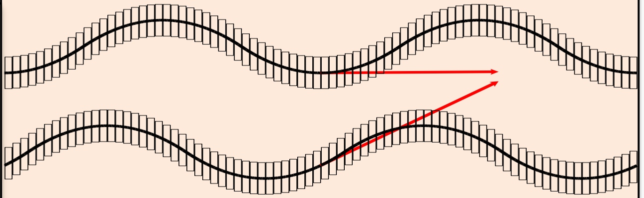
Parameter	Unit	3 TeV	10 TeV	14 TeV	CLIC at 3 TeV
L	10^{34} $cm^{-2}s^{-1}$	1.8	20	40	2 (6)
N	10^{12}	2.2	1.8	1.8	
f_r	Hz	5	5	5	
P_{beam}	MW	5.3	14.4	20	28
C	km	4.5	10	14	
<B>	T	7	10.5	10.5	
ε_L	MeV m	7.5	7.5	7.5	
σ_E / E	%	0.1	0.1	0.1	
σ_z	mm	5	1.5	1.07	
β	mm	5	1.5	1.07	
ε	µm	25	25	25	
$\sigma_{x,y}$	µm	3.0	0.9	0.63	

Neutrino Flux

Goal: **similar to LHC**: limit neutrino flux to have **negligible impact**, "fully optimised" (10% of MAP goal)
likely OK for 14 TeV

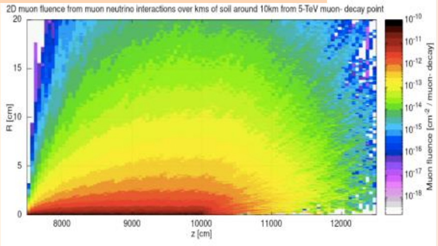


Mover and support system



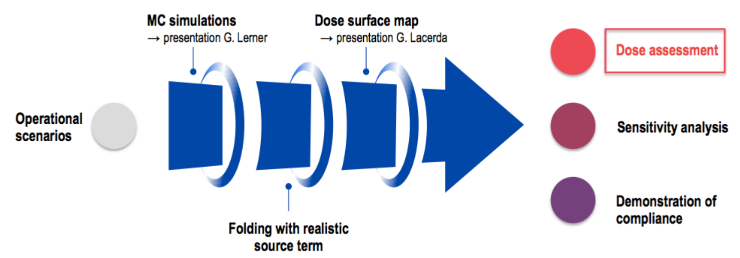
F. Bertinelli et al. (CERN, Riga)

FLUKA dose studies



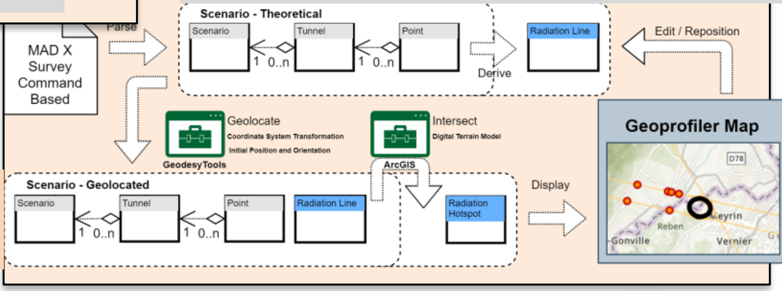
G. Lerner, D. Calzolari, A. Lechner, C. Ahdida

Conformity Verification Scheme

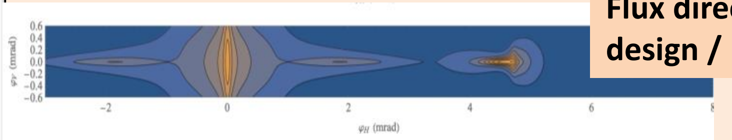


C. Ahdida, P. Vojtyla, M. Widorski, H. Vincke

G. Lacerda, Y. Robert, N. Guilhaudin (CERN)



Flux direction map / lattice design / mover impact on beam

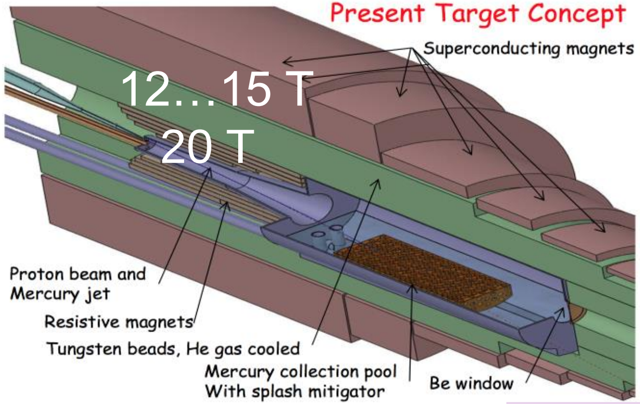


C. Carli, K. Skoufaris (CERN)

Mitigation: Site choice tool

Target

MAP target design, K. McDonald, et al.



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

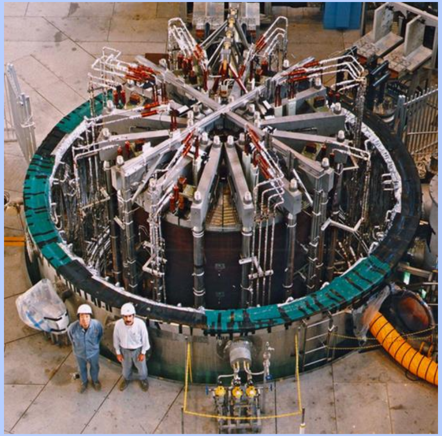
N. Milas et al. (ESS, Uppsala)

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)

Rui Franqueira Ximenes et al.

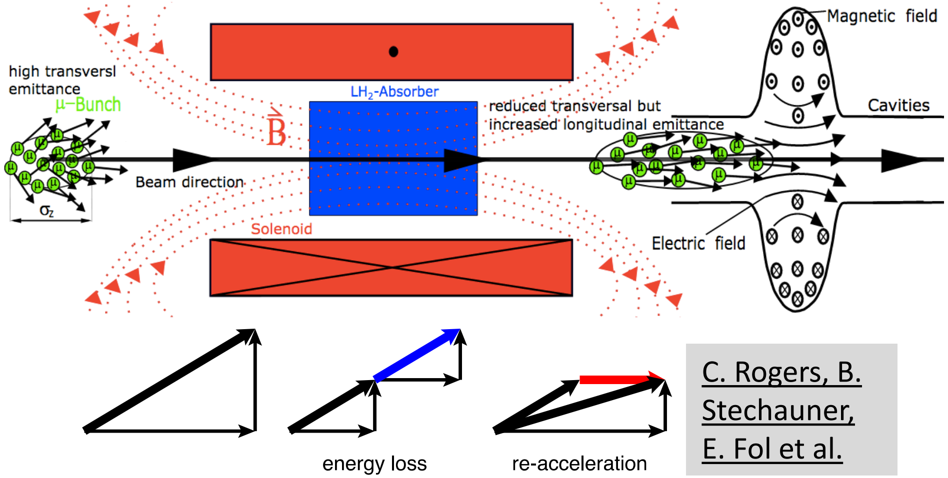
Operation at 2000 °C to maximise stress resistance

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

STFC will also study alternatives

Muon Cooling

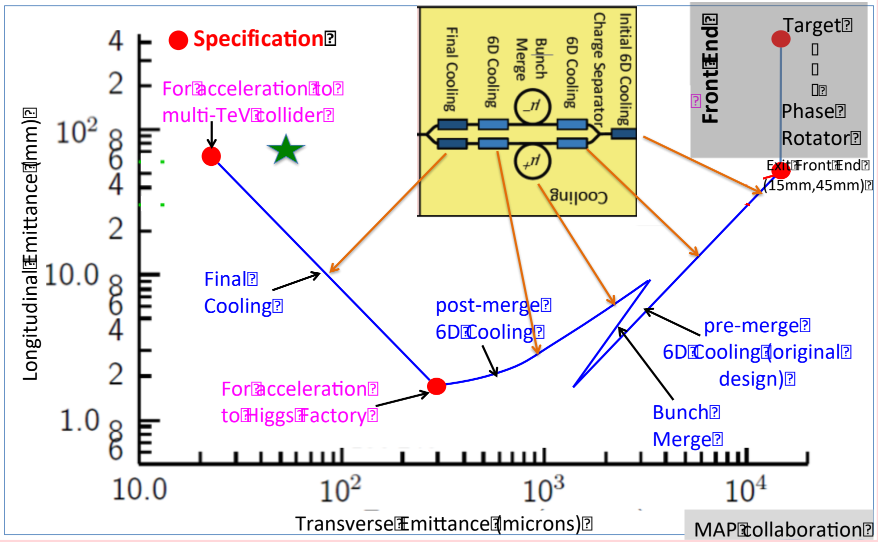
International MUON Collider Collaboration



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)

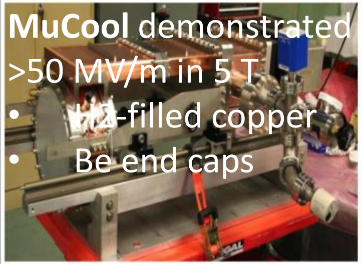
RF cavities

MAP demonstrated higher than goal gradient

Improve design based on theoretical understanding

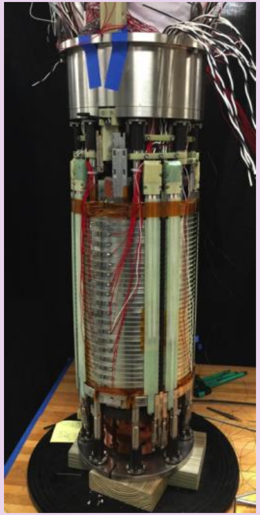
Preparation of new experiments

- Test stand at CEA (700 MHz, need funding)
- Test at other frequencies in the UK considered
- Use of CLIC breakdown experiment considered



MAP demonstrated 30 T solenoid

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

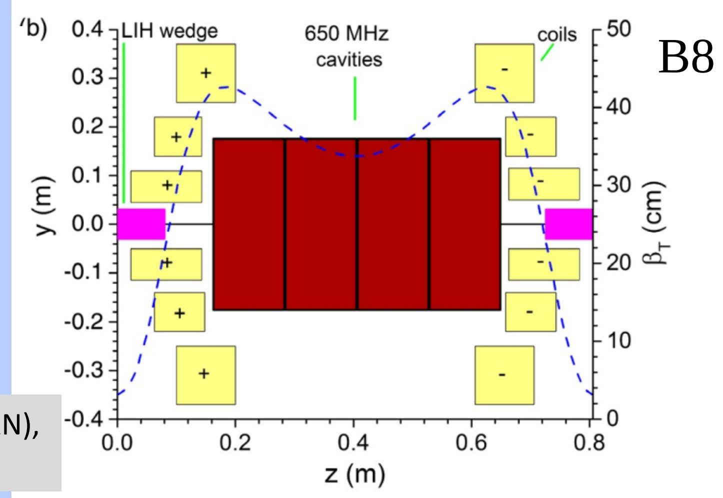


L. Bottura et al. INFN (Task Leader), CEA, CERN, LNCMI, PSI, SOTON, UNIGE and TWENTE, in collaboration with KEK and US-MDP

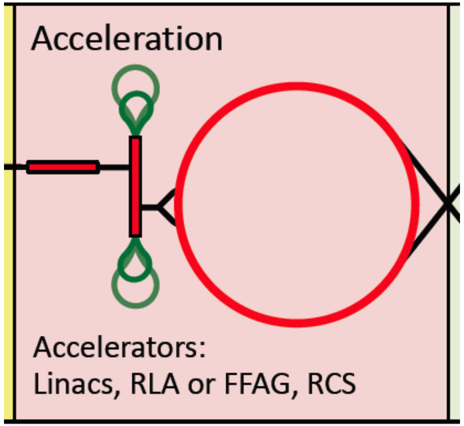
Will develop **cooling cell integration**

- tight constraints
- additional technologies (**absorbers**, instrumentation,…)
- early preparation of **demonstrator facility**

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



Acceleration Complex



Baseline is sequence of pulsed synchrotron (0.4-11 ms)

Started to develop integrated design

- Lattice design for larger energy bandwidth

A. Chance et al. (CEA)

- Fast-ramping normal magnets
  - HTS starts to look interesting
  - profit from MAP study and US

L. Bottura et al. (LNCMI, Darmstadt, Bologna, Twente)

- First models of power converter with energy recovery

F. Boattini et al.

- RF with high transient beam loading
  - seems 1.3 GHZ could be possible
- Impedance and beam stability

H. Damerell, F. Batsch, U. van Rienen, A. Grudiev, E. Matral et al. (Rostock, Milano, CERN)

Exploration of FFA as an alternative

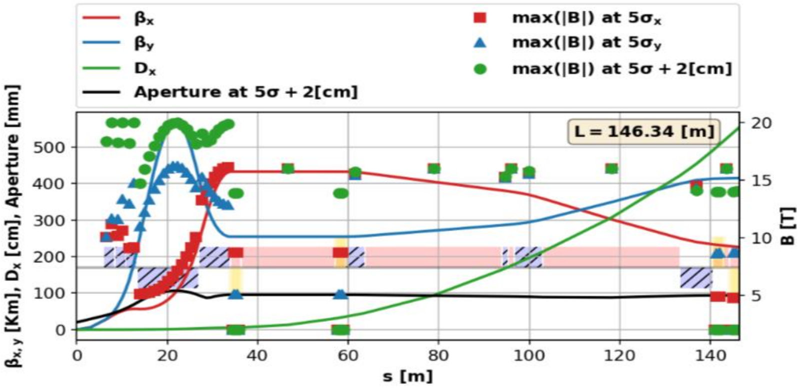
FNAL 1 kT/s HTS magnet

Alternative FFA

Collider Ring

MAP developed 4.5 km ring for 3 TeV with Nb_3Sn
- magnet specifications in the HL-LHC range
- 5 mm beta-function at IP

Work on 10 km ring for 10 TeV collider ring
- around 16 T Nb_3Sn or HTS dipole field around 15 cm
- final focus based on HTS
- 1.5 mm beta-function at IP



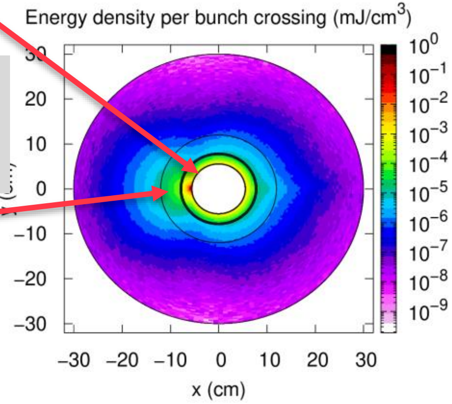
C. Carli, K. Skoufaris (CERN)

15 cm aperture for shielding to ensure magnet lifetime

Shielding

A. Lechner
D. Calzolari
(CERN)

Coil



Need stress managed magnet designs

INFN, Milano, Kyoto, CERN, profit from US

Field choice will be reviewed for cost

Example alternatives:
- a 6 km 3 TeV ring with **NbTi** at 8 T in arcs
- a 15 km 10 TeV ring with HL-LHC performances
- slight reduction in luminosity

Demonstrator Facility Consideration

Planning **demonstrator** facility with muon production target and cooling stations

Suitable **site exists** on CERN land and can use **PS proton beam**

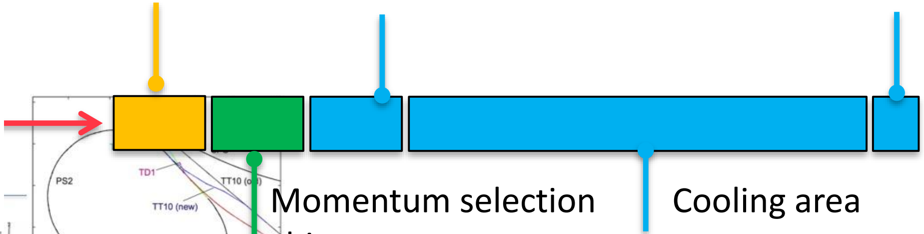
- could combine with **NuStorm** or other option

Other sites should be explored (FNAL?)

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

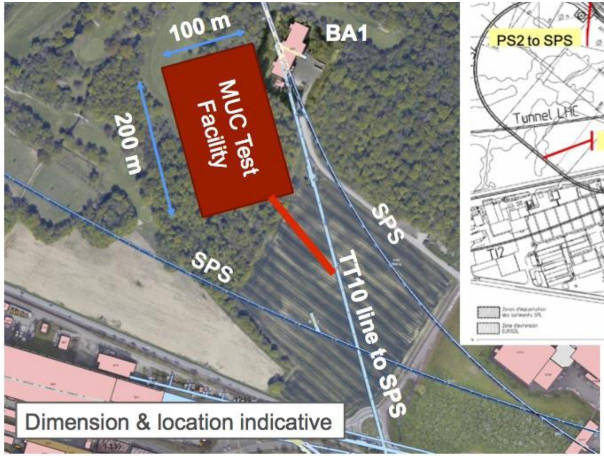
Collimation and upstream diagnostics area

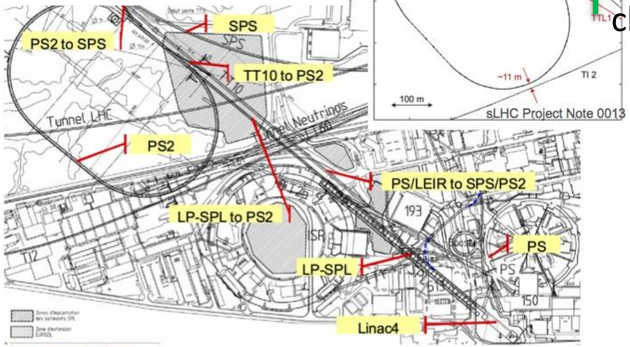
Downstream diagnostics area



Momentum selection chicane

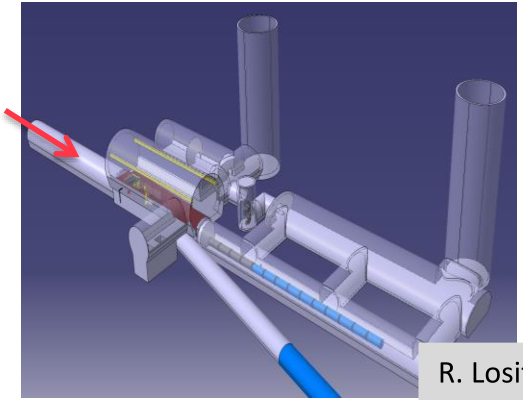
Cooling area





M. Benedikt, LHC Performance Workshop, Chamonix 2010

CERN-AB-2007-061



R. Losito, C. Rogers et al.

Short-term Goals

- Start Design Study
- Increase resources and integrate more partners
  - react to P5, INFRA-TECH proposal, other opportunities
  - ICB will be instrumental

- Continue and ramp up work
  - Technologies and design
  - Develop alternative parameter sets to explore parameter space
  - Consider re-use of existing infrastructure
  - Start to develop scenarios toward a collider consistent with HL-LHC operation until 2042 and considering opportunities on the way (proton complex, NuStorm, …)
    - workshop on non-collider physics at muon collider, demonstrator and synergies

- Provide interim report by the end of 2023
  - Workplan, resources, initial results

Conclusion

- First important results are being obtained

- We started turning Roadmap into a workplan
- Managed to gain support from EU
- Strong support in US Snowmass process

- Important goals for next year
  - successful start of Design Study
  - preparation of INFRA-TECH study
  - Fostering the collaboration with help of ICB
    - integration of more partners
    - increase in resources
  - Interim Report
  - **continue and ramp up good work**

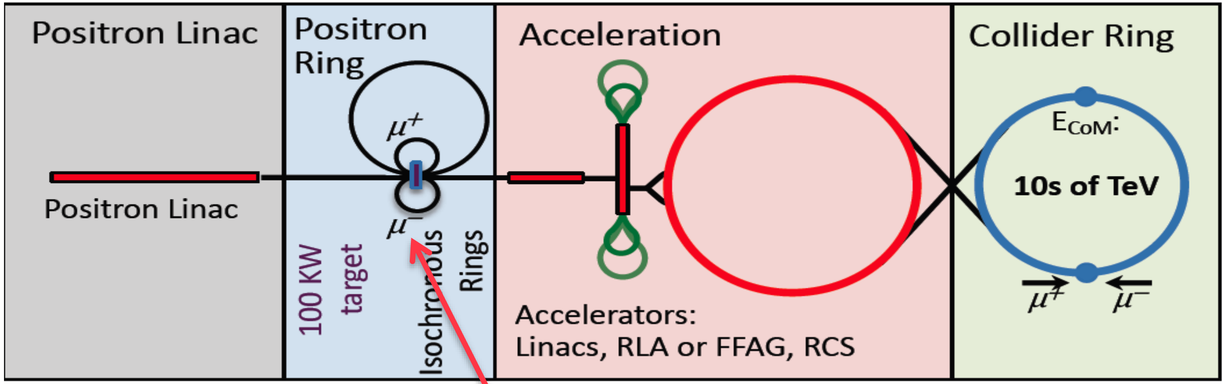
Many thanks to the many people that helped with the work

http://muoncollider.web.cern.ch

Reserve

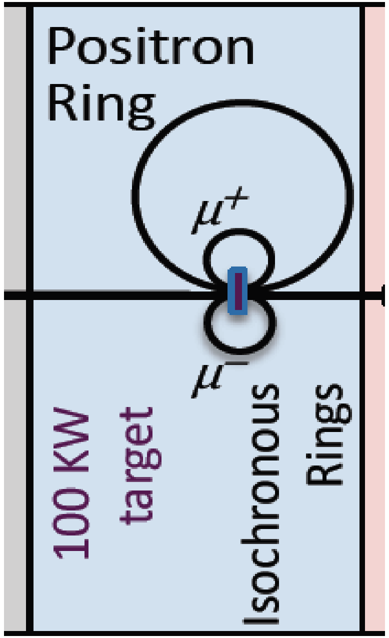
Alternatives: The LEMMA Scheme

LEMMA scheme (INFN) P. Raimondi et al.



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

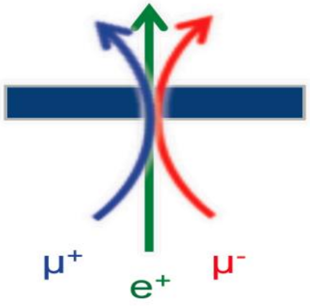
- Uses Bethe-Heitler production with electrons



45 GeV positrons to produce muon pairs

Accumulate muons from several passages

$$e^+e^- \rightarrow \mu^+\mu^-$$

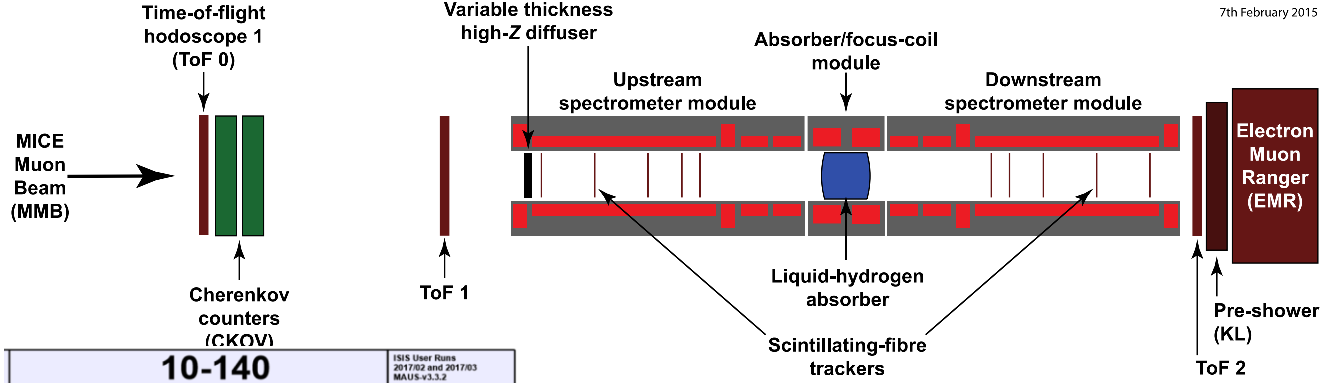


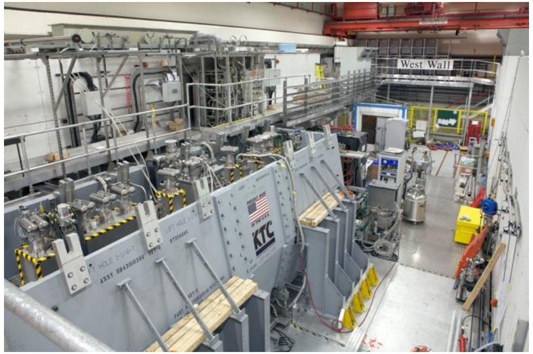
Excellent idea, but nature is cruel

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

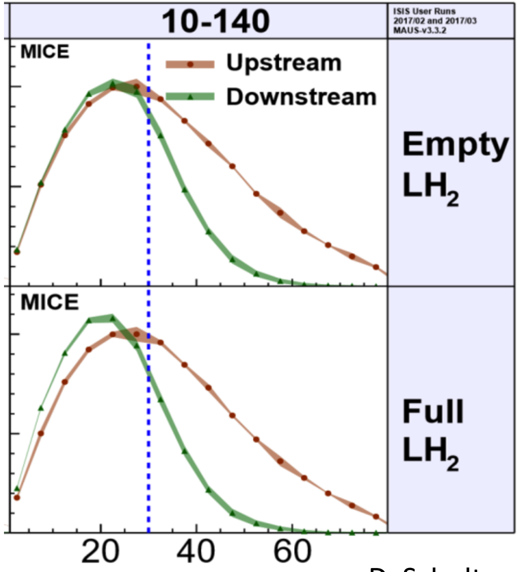
$\Rightarrow$ **Need same game changing invention**

MICE: Cooling Demonstration





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

International MUON Collider Collaboration

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

Goal is to reduce to negligible level, similar to LHC

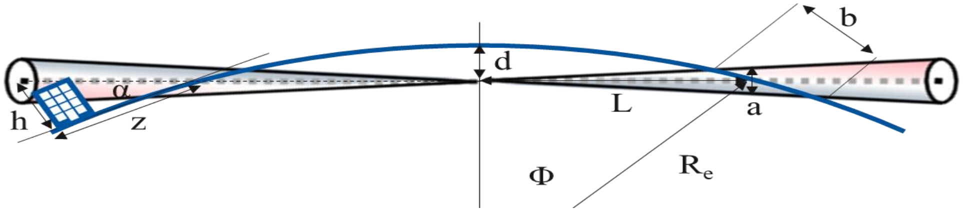
- **3 TeV, 200 m deep tunnel is about OK**

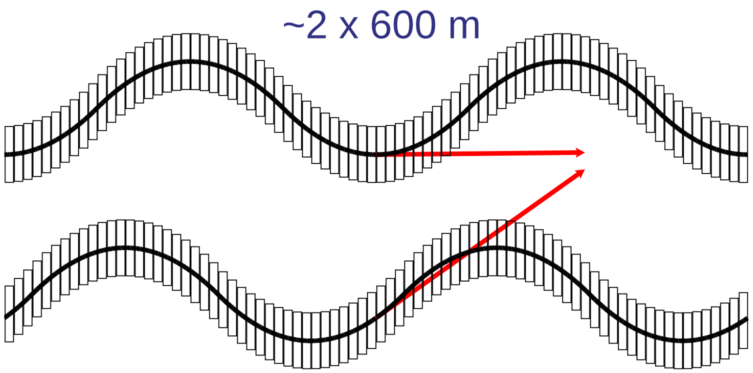
Expand idea of Mokhov, Ginneken to move beam in aperture: move collider ring components, e.g. vertical bending with 1% of main field

- **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

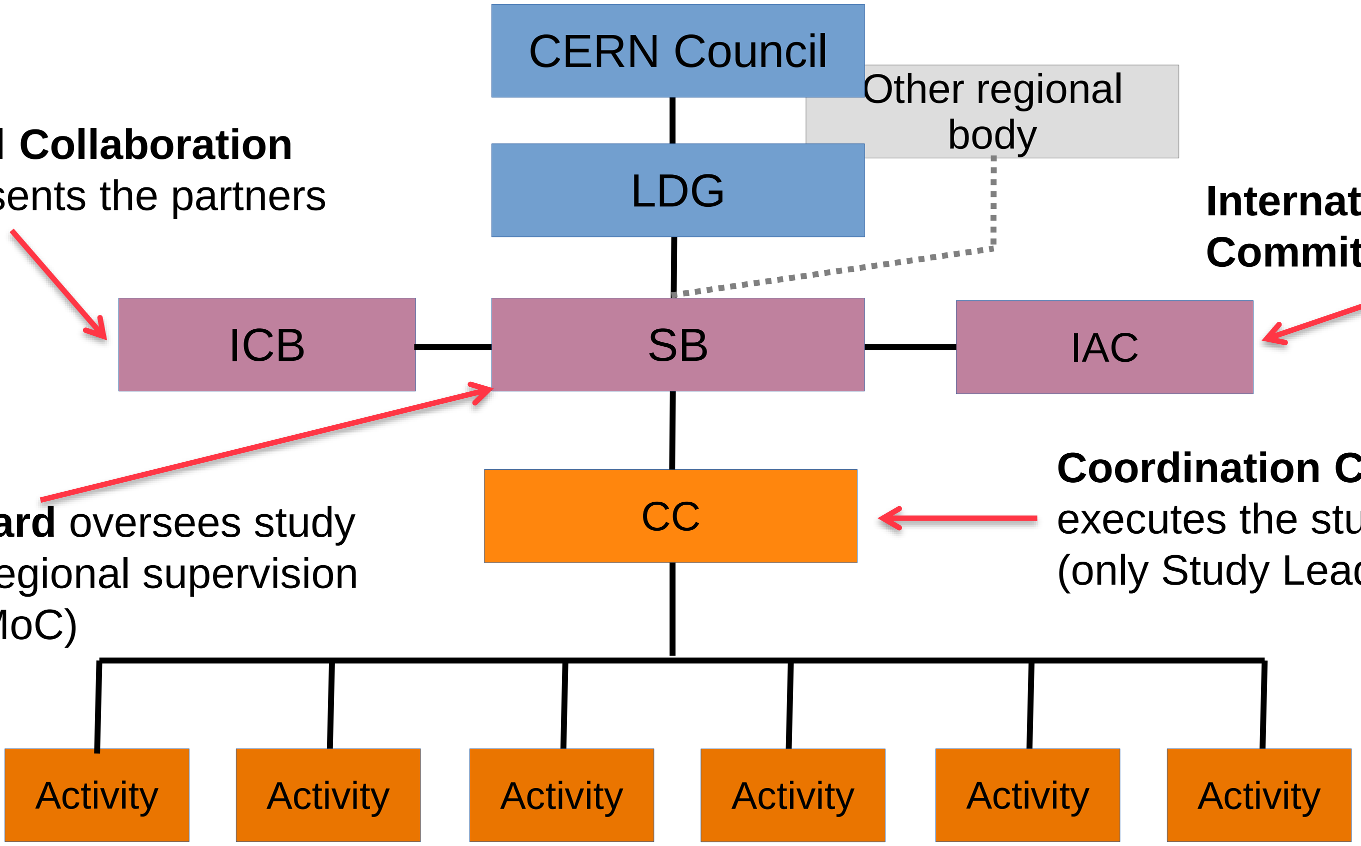
Working on different approaches for experimental insertion





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

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

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

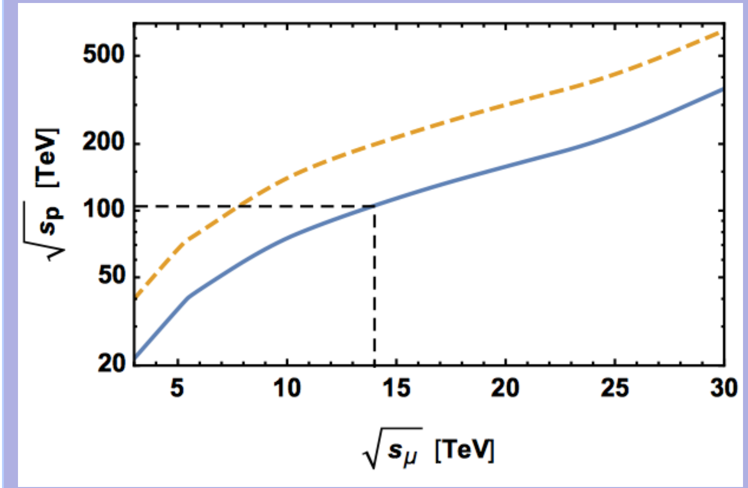
(Similar to L(E_{CM} > 0.99 $E_{CM,0}$) CLIC at 3 TeV)

$4\text{x}10^{35}$ $\text{cm}^{-2}\text{s}^{-1}$ at 14 TeV

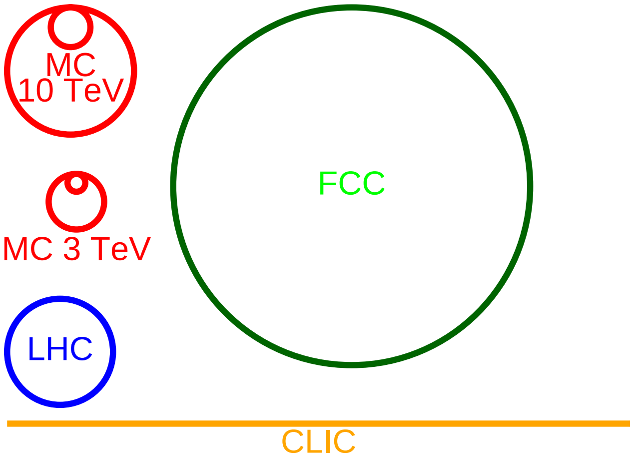
$$L \gtrsim \frac{5\,\text{years}}{\text{time}} \left(\frac{\sqrt{s_\mu}}{10\,\text{TeV}} \right)^2 2 \cdot 10^{35} \text{cm}^{-2}\text{s}^{-1}$$

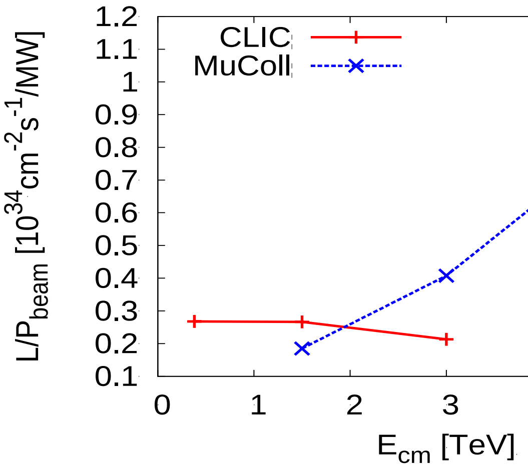
Discovery reach

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



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**

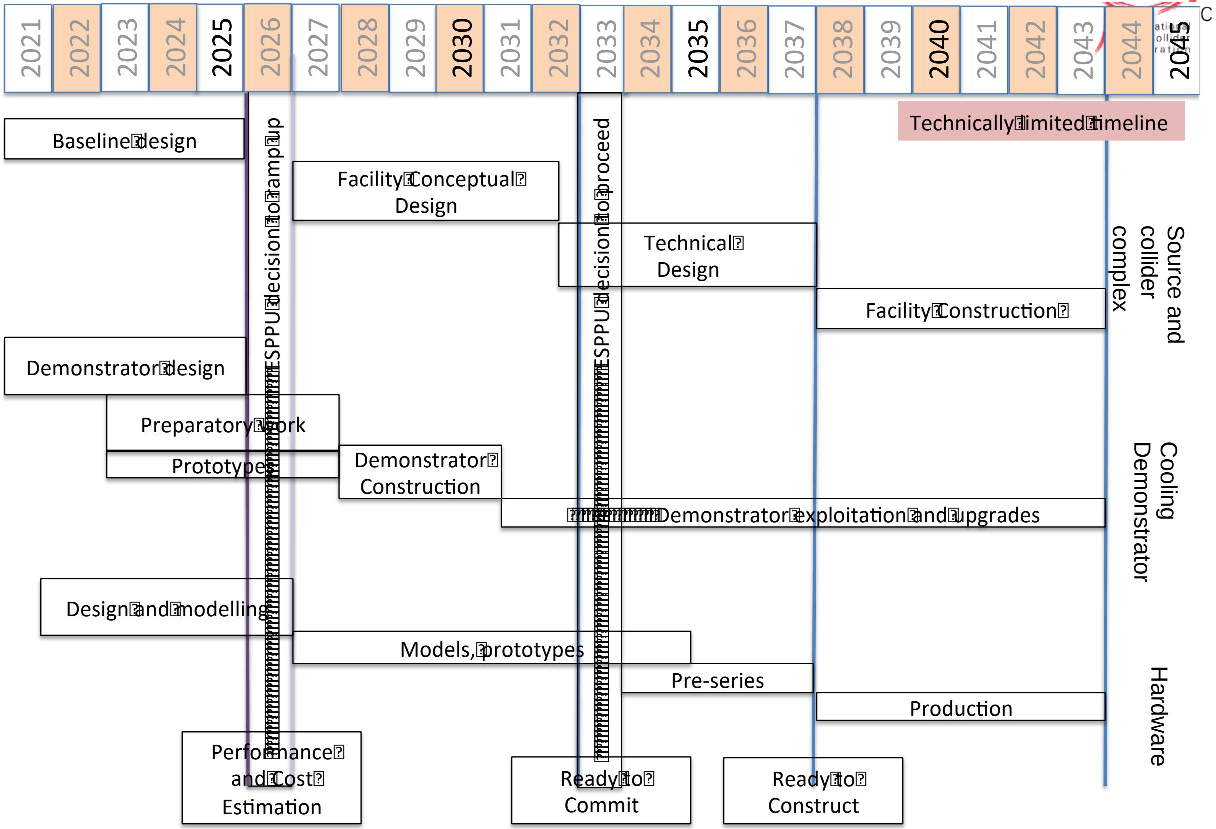
Staging is possible
Synergies exist (neutrino/higgs)
Unique opportunity for a **high-energy, high-luminosity lepton collider**

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?



Test Facility, Staging and Physics Programme

- Can envisage a **staged approach** to a muon collider
  - Tentatively 3 TeV considered
    - to be able to profit from CLIC detector work and to be able to compare to CLIC
    - probably splits cost in half
  - Need to refine choice
    - In particular if no other collider is being built in the coming years

- Can also provide **non-collider physics**
  - test facility could be synergistic with neutrino user facility

- **Synergies** on technology development exist (targets, …)

- Plan **a workshop on test facility, synergies and non-collider physics** next year
  - please let me know if you want to contribute